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ALFRED B. BORTZ

Fusion's PROMISE

How Technological Breakthroughs in Nuclear Fusion Can Conquer Climate Change on Earth (And Carry Humans To Mars, Too)

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This book is dedicated to future generations, with the hope that they will live in a world where human ingenuity, including fusion power, has mitigated the impact of climate change. This book is also dedicated to fusioneers, past and present, who have struggled to pull this technology forward.

Foreword for "Fusion's Promise"

FUSION
ENERGY
INSIGHTS

Now is really an exciting time for fusion. We've seen huge changes in the last 5 years, perhaps the biggest of which is the increase in the amount of private investment going into the field. Additionally, there have been announcements of scientific progress in both the public and private sectors.

Last year scientists at the National Ignition Facility (NIF) achieved their main goal of ignition in their inertial fusion (laser fusion) experiment—where fusion becomes self-sustaining by generating sufficient heat to exceed the losses. Then the JET tokamak broke the record for fusion energy produced, sustaining an average of 11 MW over 5 s, which is a sufficiently long timescale to give confidence that this timescale can be extended on future tokamaks with superconducting magnets.

In private companies, Commonwealth Fusion Systems demonstrated key new magnet technology, First Light Fusion and HB11 announced their first achievements of fusion (notable in their original and untested approaches) and Tokamak Energy achieved plasma temperatures of 100 million degrees in their spherical tokamak—fusion temperatures and the highest achieved in any privately funded tokamak.

And then there's the money.

Over the past 5 years, we've seen a steep rise in the number of private companies and, alongside that, the private investment going into fusion. The survey by the Fusion Industry Association in Q2 of 2022 showed that over half of the 33 featured private fusion companies had been founded since 2018. They also found that private funding into fusion exceeds \$4.8 bn (including \$117 million in grants and other funding from governments), which is a 139% increase in funding since the survey was conducted just the previous year. One private company alone secured \$1.8 bn. The industry is changing from being dominated by government-funded research.

Ready When Society Needs It…

A key factor in this progress is the increased will to achieve fusion.

Fusion has a long history dating back to around the 1940s. It has taken a long time to develop, partly because it's so challenging. We're trying to replicate the conditions in the centres of stars to make a clean energy source here on Earth! It's not trivial at all—it's a huge engineering challenge even beyond the scientific challenge of getting the stellar conditions (That in itself is exciting and inspiring). But there also wasn't the collective will.

We've known about the issues of climate change and energy security for some time, but until very recently people seemed content to continue to burn fossil fuels. Now we see more public demands for climate action, driving government pledges and increasing investment in clean technologies. There is a sense of urgency that motivates many fusion teams and, equally, investors.

Fusion will be a transformational energy technology. Not only would it produce clean, green, safe and abundant energy, it would enable developing countries to have an access to the energy they need to improve their lifestyles. It's a versatile energy source—it could be used to generate electricity, but could also be used with modifications to provide industrial heat or desalination. That kind of versatility is what's needed to fully decarbonise our society. Moreover, in a world with a surfeit of clean energy, we could imagine powering Direct Air Capture systems to remove carbon dioxide from the atmosphere to, hopefully, undo some of the climate harm we have already done.

The greater will to achieve fusion, coupled with scientific maturity of the field and new technologies and capabilities (such as high-temperature superconductors, improved lasers and digital technologies) is driving investment and progress.

Moving Forward

We now see an array of private companies with different concepts and different approaches, all trying to commercialise fusion energy faster.

These private companies are viewing the challenge from a different perspective than the government laboratories. They need to create a product for the market, not simply a fusion device that works. They have aggressive timetables and motivated employees. Government labs are increasingly taking notice and we are moving into a phase of partnership between the public and private fusion sectors, which will be essential to develop fusion energy into a commercial reality.

I'm excited to watch the evolution over the coming decades.

Different Approaches

The fusion landscape can seem a mind-boggling place now with so many different laboratories and companies with their own concepts and niches. If only there was a way to help us navigate….

This book is important because it looks at some of the different approaches to fusion. Historically, the tokamak approach and the laser fusion/Inertial Confinement approach have received the majority of government funding, but there are many other approaches. Some of these have been less thoroughly studied in the past and some are newer concepts that are opening up as new technologies emerge.

This is significant because different concepts and strategies might be appropriate in certain situations. In the future, we may well find a variety of fusion reactors employed in various applications, rather than one overall winner in the field. For instance, some power plants could be large gigawatt-scale suitable for powering entire cities, while others might be ~100-megawatt units. Some companies are working on generating electricity directly without producing heat first. So we could imagine that there could be different concepts finding different niches in the future energy market.

This book examines the various approaches and technologies of fusion. Alongside the science, the authors present some of the history of how the technology has evolved over time, as well as individual experiences of the scientists who have been working on these concepts. It gives a thorough overview of the fusion space, what is out there and how scientists are coming closer to harnessing the energy of the stars. It will be useful for anybody wishing to gain a more detailed knowledge of the breadth of fusion technology and insight into the benefits and difficulties of each, or those wishing to take inspiration from the people behind the work.

Now is a crucial time as we move towards the era of commercial fusion. We need dedication, investment, smart people, collaboration and public support. I hope that you enjoy reading this book and learning about this transformational energy technology and the people devoted to its success.

Founder and CEO of Fusion Energy Insights Melanie Windridge,
London, UK
August 20, 2022

Preface: The Current State of Fusion

Summary This book takes on this burning question: Isn't nuclear fusion one of those technologies that always promises a future that can never be achieved? Our answer, of course, is no. We would never have decided to write this book if we thought otherwise. Commercialization of nuclear fusion, the energy source of stars like our sun, for electric power or propulsion would be one of the greatest technical accomplishments of human history, akin to landing humans on the surface of the Moon and returning them safely, or the first powered flight. Like those other technological breakthroughs, its achievement will require a steady progression of significant but obscure precursor events. Our task is to bring to light the science and technology of fusion and the work of innovative fusioneers who will bring about a future of nearly unlimited green energy as well as other applications of fusion technology.

Reframing the Argument

This is a book for open-minded skeptics. You probably have heard some version of the old saw, "Nuclear fusion is the energy source of the future, and it always will be." That skeptical view is amusing because it has a ring of truth. But we hope our readers are willing to consider that only the first clause of that sentence is true. Nuclear fusion is the energy source of the future—and that future is "green."

It is useful to compare the current state of nuclear technology to powered flight just before the Wright brothers' first success at Kitty Hawk NC in 1903. Achieving powered flight required a steady progression of significant but obscure precursor events. The Wrights often used an 1894 book that cataloged over 200 years of research, *Progress in Flying Machines* by Octave Chanute (reprinted in 1998 by Dover Publishing), as a reference as they refined their flyer (Fig. 1).

Before their achievement, most people were unaware of what the Wrights were doing, and many people viewed heavier-than-air flying machines as impossible. Likewise, today's public is generally unaware of significant progress toward viable nuclear fusion power plants. And if that milestone is achieved—as we argue here that it will—the accomplishment and its dramatic ripple effects will suddenly be seen as the inevitable progression of technology.

Fig. 1 The public believed that powered flight was impossible despite—or perhaps because of—several centuries of attempts. Real progress was not made until the 1890s when Octave Chanute published his 1894 book, *Progress in Flying Machines*, which cataloged over 200 years of research (reprinted in 1998 by Dover Publishing). It was a key reference for the Wright brothers, helping them avoid bad ideas and eventually leading to the first successful powered human flight at Kitty Hawk NC in 1903. Nuclear fusion is now at a similar point, scientifically understood but seemingly beyond humanity's ability to harness in useful technologies. Is a Kitty Hawk moment in fusion's future? We argue that the answer is yes. (Photo credit: Library of Congress https://www.loc.gov/pictures/item/00652085/)

That is the usual progression of public opinion: a technology never seems real until people can see it, touch it, and understand it. And that is the state of fusion technology today. While most of the public still believes practical fusion systems or devices will never be achieved, an intrepid band of scientists, engineers, and entrepreneurs are hard at work behind the scenes on projects designed to achieve fusion's promise and prove the doubters wrong. They and their work are the focus of this book.

Controlled nuclear energy dates back to the 1950s when engineers harnessed nuclear fission, the phenomenon that led to the atomic bomb, as a source of electrical power. At that time, it was natural to think that the next step would be controlling nuclear fusion, the energy source of hydrogen bombs, in a similar way.

True, engineers were aware of technological hurdles, but many were confident that those would be overcome in two decades, or perhaps three at most. One of us (Bortz) recalls those optimistic predictions. He was an adolescent in 1957 when electrical energy from the first commercial power plant in the United States in Shippingport, PA began flowing to his home in Pittsburgh.

By the mid-1970s, having completed a doctorate and postdoc in computational physics, he found a job as a nuclear engineer, working on computer modeling of advanced fission reactors for the Westinghouse Electric Corporation. Still excited about the prospects of fusion power, he eagerly took a temporary assignment with a group that was seeking a government contract where he could apply his skills to fusion power research and development.

The contract went to another company, and he soon left the nuclear industry. He still expected fusion power to be a major source of electrical energy before the end of the twentieth century, but he decided to take his career in a different direction. That ultimately led to writing about science and technology for young readers. Over the next four decades, his interest in fusion faded along with the industry's prospects, but did not entirely disappear.

Some scientists and engineers, whom we call fusioneers, continued to be optimistic about the field. For them, fusion power has remained a long-term target, and they have worked on a number of different technological approaches that continue to show promise. One of those fusioneers is author Moynihan, who did fusion-related doctoral work in mechanical engineering at the University of Rochester. He continues to be inspired by the possibility of making a significant contribution to a technology that produces abundant power without emitting greenhouse gases and with much less radioactive waste than fission.

Even while working on other projects in several cities, he has maintained his presence in the field by blogging, podcasting, interviewing, and organizing online meetings with other fusioneers. This book is an outgrowth of those activities. Moynihan wanted his ideas and enthusiasm to reach educated but non-expert readers, and he knew that he needed the help of a professional writer to shape his work for that readership. When he discovered that Bortz lived a few miles away, he reached out, and they arranged to meet.

Bortz was skeptical, asking, "Aren't fusioneers chasing steadily moving goalposts?" Moynihan said no, and eagerly began explaining why the technology is within reach. In fact, fusion is already finding commercial application in other economic sectors.

Moynihan's knowledge and enthusiasm were persuasive. Bortz, though remaining a skeptic, shared Moynihan's desire to find economically viable "green" alternatives to fossil fuels. If the goalposts had finally stopped moving, then fusion might well have a role in our energy future. He could see a book taking shape. You are reading the result.

A Rapidly Changing Field for a Rapidly Changing World

This book is, by necessity, a snapshot of a field in flux. Though scientists and engineers have studied nuclear fusion for more than seven decades and have consistently encountered obstacles to successful technological development, they have also found avenues that might lead to future success. As a result, both government agencies and private corporations and investors continue to commit financial support to large- and small-scale fusion projects. In fact, as we completed the writing of this book in early 2022, new achievements in fusion research and development led to a flurry of new government and private investment (See Epilogue for details).

As in any rapidly evolving field, practitioners are passionate about their own projects. Likewise, they may tend to disparage competing efforts. We as authors have chosen to take a broad view of fusion research and development. We have shared our ideas and benefited from the generous advice of many experts (see Acknowledgments). However, the descriptions and conclusions are our own.

Even though experts and their colleagues may disagree with some of our analyses, we hope they will appreciate the book for its goal of enabling the broader public to understand and appreciate their work. We want you, our readers, whose tax and investment dollars support those efforts, to have the knowledge you need to develop informed opinions about the investigations you are funding.

We begin with this point: We live in a world that is warming due to human production of greenhouse gases. Experts have calculated a carbon dioxide budget that will keep the average temperature within 2 °C of pre-industrial times—viewed as necessary to avoid catastrophic climate-related events. Many experts recommend a lower target of 1.5 °C.

Yet Earth's growing population and the need for economic development lead to a rapidly increasing demand for electrical energy. That creates an urgent need for "green" technologies. Technological breakthroughs in magnet and computer technology, which we describe in this book, have dramatically changed the trajectory of fusion power; and the urgent need to reduce greenhouse gas production has provided a strong incentive to fund necessary fusion R&D. Fusion's promise of a low-cost, low-pollution, and abundant energy source is, at last, on track to being realized. Fusioneers can now make a strong case that their field is on the verge of commercial viability and will make up a significant fraction of the green energy mix in the coming decades.

Why This Matters

(Both Authors)

Why is this subject so important? Although we are at different stages of life, each of us feels the urgency of reducing greenhouse gas emissions. Bortz looks at his grandchildren, who are young adults, and worries that his generation has created a climate crisis that will dominate the world they are about to inherit. No longer working as a scientist, he hopes that his active support of the bipartisan Citizens Climate Lobby and its policy proposals can make a difference. On the local level, he hopes his letters to the editor of his hometown newspaper raise his neighbors' awareness of the need to transform our energy usage. In his writing for young readers, he hopes to encourage his audience to avoid simplistic answers and ask critical questions (See for example *Meltdown! The Nuclear Disaster in Japan and Our Energy Future*, Lerner 2012. That book raises important questions about the future role of nuclear fission as an energy source but leaves them unanswered, recognizing that his readers will be the ones to decide among many alternatives in a rapidly changing world).

Moynihan, who is currently raising a toddler, will confront the problems of climate change more directly in his lifetime. That motivates his work as an engineer and advocate for nuclear fusion. The following paragraphs note his motivation for bringing the promise of nuclear fusion technology to the attention of our audience of educated non-specialists whose political and financial support will be essential to bringing that promise to fruition.

(Matthew Moynihan)

Besides the implications for climate change, achieving controlled nuclear fusion could be the greatest technological advancement of the twenty-first century and could significantly change the political and military calculus of nations around the world. Those governments would view it as a potential disaster if an adversary achieves fusion first. Controlled fusion could be exceedingly disruptive to the global economy, and governments need to be prepared to adapt.

From my perspective as an American with a front-row seat in the field, I have been concerned that my country has been falling behind in this field. My view comes from conversations with government officials on the sidelines of conferences, on college campuses, and over the phone. The refrain has been universal. Although I have watched worldwide fusion research escalate in its scale and pace, those officials widely consider controlled fusion as impossible. Consequently, there is a lack of breadth or depth of knowledge within both the executive and legislative branches as well as within the federal bureaucracy.

This lack of expertise translates into low public enthusiasm for the subject—which translates into insufficient funding. For roughly a generation, from the middle 1980s through the 2010s, fusion was not a priority for the United States. This becomes especially apparent when you compare US funding for another national science priority—NASA (See Fig. 2). This has created a vicious cycle for nuclear fusion. With insufficient funding, the problem is harder to solve. By making it harder to solve, the problem looks more difficult than it would otherwise be.

Breaking this cycle has been the goal of fusioneers for the past 30 years. Fortunately, it finally feels as though this is starting to change (see Epilogue). By reading this book, you are getting involved at the beginning of this shift. It is going to be intriguing to see what happens next.

Why Cold Fusion Is No Longer Hot

Many readers of this book will recall the hullabaloo surrounding the March 1989 claim by Martin Fleischmann and Stanley Pons that they had achieved fusion in a tabletop apparatus, specifically an electrolysis cell with a palladium electrode filled with heavy water (see next paragraph for definition) [1]. The claim was soon dubbed “cold fusion” in the popular press because it did not require the high temperatures and pressures like those in the interior of a star believed necessary for fusion to

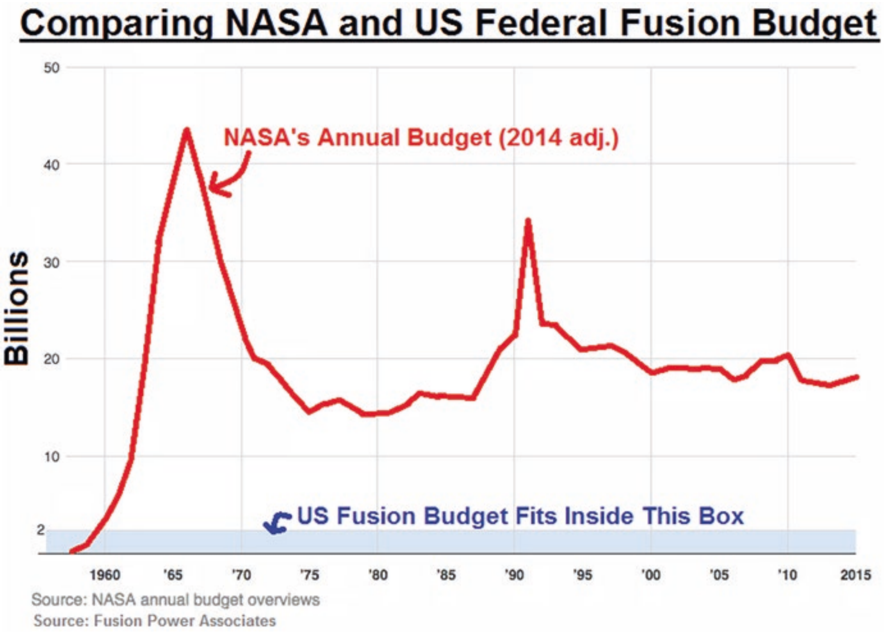

Fig. 2 US funding for fusion is dwarfed by the spending for NASA

occur. If their result could be commercialized, it would mark the beginning of an inexhaustible and virtually pollution-free source of energy from the Earth's most abundant natural resource, water.

Their evidence was excess heat and the production of neutrons and tritium, which would be the result of a fusion reaction of two deuterium nuclei. (Deuterium and tritium are heavy isotopes of hydrogen with one or two neutrons, respectively. Heavy water has two deuterium atoms instead of the most common hydrogen isotope with a single proton and no neutrons.) Unfortunately, no other experimenters could replicate their results, and instead uncovered flaws and experimental errors. Furthermore, no one developed a credible suggestion of a theoretical mechanism that could produce the claimed observations. By the end of the year, cold fusion had become a laughing stock, and Pons and Fleischmann's reputations were permanently tarnished.

Because of the enormous technological upside of such a discovery, a small but undaunted community of researchers remains on the case. They now describe their effort as a search for low-energy nuclear reactions (LENR), but so far it appears to be as fruitless as the Pons and Fleischmann work [2, 3]. For that reason, we have decided not to include it in this book.

A Partnership

We view this book as a partnership between you as readers and us as authors. Our goal is to pull together all the disparate threads, efforts, and projects that fusioneers have undertaken over the past 70 years to produce electrical energy from fusion. In that sense, we serve as historians.

However, we also recognize that the quest for fusion power is an intergenerational relay race. In one sense, the publication of this book marks the end of our leg of the relay. By reading it, you have agreed to accept the baton.

In another sense, we are spectators watching the race together but with different roles. We are the public address announcers, introducing the fusioneers and their work, while you cheer them onward toward an indefinite finish line that may be just out of view.

We are particularly proud to describe the latest entries in the race, the risk-takers discussed in the sections on fusion startups. They and their companies are driven, creative, and determined to push this field forward. They are trying to do something new in the course of human history: to develop an entirely new energy technology and to build a market-based, commercially viable path to bring it to fruition.

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From Matthew Moynihan (Except Where Noted Otherwise)

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Bob Mummgraad graciously found time to review the Tokamak chapter despite his exceedingly busy schedule. Likewise, my thanks go to Commonwealth Fusion Systems for allowing a site visit when the company was just getting off the ground.

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Both authors are grateful to Fred Bortz's graduate school buddy and long-time friend Mike Walker, author of *Quantum Fuzz: The Strange True Makeup of Everything Around Us* (Prometheus Books, 2017), for commiserating about the process of finding the right publisher for a book on a highly technical topic for readers who may have limited technical backgrounds. If you enjoy *Fusion's Promise*, you may want to add *Quantum Fuzz* to your reading list.

We also like to thank Dr. Sam Harris, the editor at Nature-Springer, whose support of the project ensured its successful completion. Finally, the authors want to thank their wives for being supportive of the project. Without their support and patience, this book would have never been completed.

Contents

About the Authors

Matthew Moynihan(Matt) has been keenly interested in nuclear fusion since he first took physics in high school. For the past 15 years, he has been working to build the broader fusion community and to explain the value of fusion as a green energy source to everyday citizens. He has been the host of a popular fusion podcast, written a fusion blog, and his work has appeared in *Forbes*, *CNBC*, *Bloomberg News*, *The Boston Globe*, and *IEEE Spectrum*. He holds a bachelor's degree in engineering from the University at Buffalo and a doctorate focused on fusion from the University of Rochester. Currently working as a consultant on fusion, he was previously a senior nuclear engineer for the US Navy, studying the safety of nuclear submarines and aircraft carriers. He lives in Fairport NY with his wife, Alison, and his son, Peter.

Alfred B. Bortz has lived in or near Pittsburgh, PA all his life, with the exception of a 4-year interlude early in his working career. He earned his Ph.D. in Physics from Carnegie Mellon University in 1971 and spent the next 25 years working in academic and industrial physics and engineering groups. Since then, he has forged a second career as Dr. Fred Bortz, an author of more than 30 science books for young readers. His most significant research publication, "A New Algorithm for Monte Carlo Simulation of Ising Spin Systems" (with M. H. Kalos and J. L. Lebowitz) published in the *Journal of Computational Physics* in 1975, is often described as seminal and is still frequently cited in research journals after nearly five decades. His best-known books for young readers are *Catastrophe! Great Engineering Failure—and Success* (a selector's choice on the 1996 National Science Teachers Association list of Outstanding Science Books for Children), *Meltdown! The Nuclear Disaster in Japan and Our Energy Future* (a 2012 Junior Library Guild Selection), and *Techno-Matter: The Materials Behind the Marvels*, which won the 2002 American Institute of Physics Science Writing Award for works intended for young readers. He and his wife, Susan, are the proud parents of a STEM educator and a librarian and grandparents of three young adults.

Plasma Science

1

Summary

This chapter covers the basic theory and modeling of the state of matter known as plasma, in which nuclear fusion can take place. It begins with an overview of the particles that make up atoms and nuclei and the forces that bind them together. It then describes how nuclei react and transform via fission and fusion to yield energy. Finally, it takes a deep dive into the ways that scientists create mathematical models that enable them to simulate and analyze the behavior of plasmas.

1.1 The Nature of Matter

The modern understanding of matter emerged in the first decade of the nineteenth century. John Dalton's landmark text *A New Theory of Chemical Philosophy*, published in 1808, described chemical elements (atoms) and compounds (molecules) and their properties. Throughout that century, chemists discovered numerous elements with a large range of atomic weights. As they began to see similarities and patterns in the properties of the elements, researchers sought a new way to organize them. Finally, in 1869, the Russian chemist Dmitri Ivanovich Mendeleev created the periodic table of elements that is familiar to all of us today. He ordered the 63 known elements by atomic weight and arranged them in rows and columns with several gaps, which were eventually filled by subsequent discoveries. Each row (today's columns) had atoms with similar chemical properties (Fig. 1.1).

At the time, atoms were regarded as the smallest particles of matter. In fact, the word atom came from the Greek *atomos*, meaning indivisible. Despite the atomic theory's many successes, important questions remained, including what makes atoms of one element different from another and why their properties are periodic.

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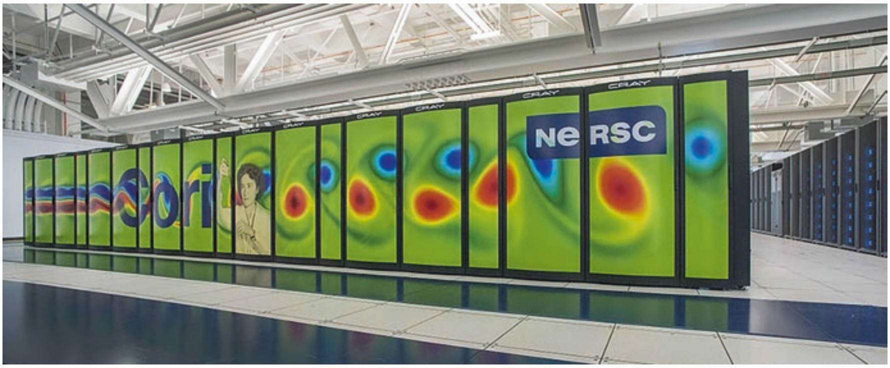


Fig. 1.1 Large fusion models drove the creation of large supercomputers, such as the Cori supercomputer at the National Energy Research Scientific Computing Center (NERSC). The computer is named after Gerty Cori, the third woman to win the Nobel Prize in medicine for discovering glycogen metabolism. The computer can execute 30 petaflops or 30 quadrillion calculations per second. Fusion researchers from around the United States apply for time on Cori and use it to run large plasma simulations

1.1.1 Subatomic Particles

Answering those questions required a dramatic change in thinking, which began to emerge as the nineteenth century was nearing an end. Atoms, it turned out, are not indivisible at all. Rather, they are comprised of smaller particles that we now call protons, neutrons, and electrons. (Protons and neutrons also have smaller components, known as quarks, but we will not need to go to that level of detail to explain the science and technology of nuclear fusion.)

The first indication that atoms have component parts came in 1897 at the famous Cavendish Laboratory of the University of Cambridge in England, then headed by noted physicist Joseph John (J. J.) Thomson. Thomson and his students, including a young New Zealander by the name of Ernest Rutherford, were studying the phenomenon of cathode rays, which were emitted from heated metal filaments. They discovered that the rays were made up of tiny particles all carrying the same small amount of negative electric charge and having a mass much less than a thousandth of that of a hydrogen atom. They were the same no matter what metal the filament was made from. Thomson called them corpuscles.

That research led him to conclude that the corpuscles, which we now call electrons, came from inside atoms. Because they were so light, he theorized that an atom was like a “plum pudding” with tiny electrons distributed throughout a positively charged bulk that carried the rest of the atom’s mass. That idea, though useful, turned out to be spectacularly wrong, and it was Rutherford’s work that overturned it.

After completing his fellowship with Thomson, Rutherford accepted a position at McGill University in Montreal, where he did groundbreaking research in radioactivity. In 1907, he returned to England as chair of physics at Victoria University of

Manchester (now the University of Manchester). There, in 1909, with students Hans Geiger and Ernest Marsden, Rutherford's research revealed that atoms were not at all like plum pudding. Most of their mass was contained in a tiny nucleus that was less than ten thousandth the size of the atom itself and carried a positive electric charge. That positive charge was equal to the negative charge of all the atom's electrons, which Rutherford viewed as orbiting the nucleus bound by electrostatic attraction, analogous to planets orbiting the Sun bound by gravity.

In 1919, Rutherford succeeded Thomson as the head of the Cavendish Laboratory. By then, scientists had come to understand that the periodic table should be ordered not by atomic weight but by nuclear charge, which they called the atomic number. The atomic weight (more correctly the atomic mass) generally increased as the atomic number did but was not proportional to it. As the atomic number increased one unit at a time through the periodic table, the atomic mass generally increased faster.

It became apparent that an atomic nucleus contained the atomic number of positively charged particles, which Rutherford named protons, plus something else. That "something else" had to be very important because it held the protons together much more strongly than the electric repulsion between them pushed them apart. Rutherford proposed that the extra mass came from neutrally charged particles that he called neutrons. In 1931, James Chadwick, a colleague of Rutherford at the Cavendish, did an experiment that demonstrated the existence of neutrons, which had just slightly more mass than protons.

At that point, the basic components of the atomic structure were known. Atoms are comprised of very light negatively charged electrons surrounding and bound electrically to a very dense nucleus of protons and neutrons.

1.1.2 Isotopes and Binding Energy

This knowledge led to a new understanding of atomic mass. Just as the atomic number corresponds to the number of protons in the nucleus, the atomic mass number is the number of nucleons, i.e., the number of protons plus the number of neutrons. That explains the phenomenon of isotopes, in which atoms having the same chemistry (because of their electrons) can have different masses. The number of protons is the same in the nucleus of two different isotopes of an element, but the number of neutrons is different.

From this discussion, you might think that the mass of a nucleus could be calculated by this simple formula: the number of protons times the mass of a proton plus the number of neutrons times the mass of a neutron. Yet in every case (except for the hydrogen nucleus, which is a single proton), that simple formula leads to an overestimate by an amount known as the mass defect. The difference is due to perhaps the most famous formula in physics, $E = mc^2$. Einstein's theory of relativity describes the equivalence of mass and energy. In order to break a nucleus into its component nucleons, you need to add energy, which means that the total mass of the products will be greater than the original mass.

Another way to describe this is by saying that a nucleus is held together by a negative binding energy. In this book, we will be describing nuclear reactions that release vast amounts of energy because the products have less mass (or more binding energy) than the reactants.

That may lead you to question what you learned in chemistry class, namely the "law" of conservation of mass. You are surely familiar with chemical reactions, such as combustion, that release energy. You probably learned that the mass of the combustion products is equal to the mass of the reacting atoms and molecules. In fact, that is not true. The energy released in combustion does indeed correspond to a very slight decrease in mass. But the amount of lost mass is so small that it is not measurable by typical chemistry lab instruments. The actual law is the conservation of mass plus energy, which your chemistry teachers almost certainly knew, but they also recognized that it was beyond the scope of the course.

1.2 Nuclear Reactions and Transformations

Nuclear reactions take two forms: fission, in which large nuclei break apart and release energy, and fusion, in which small nuclei combine to release energy. Figure 1.2 shows how these processes relate to binding energy. The vertical axis is

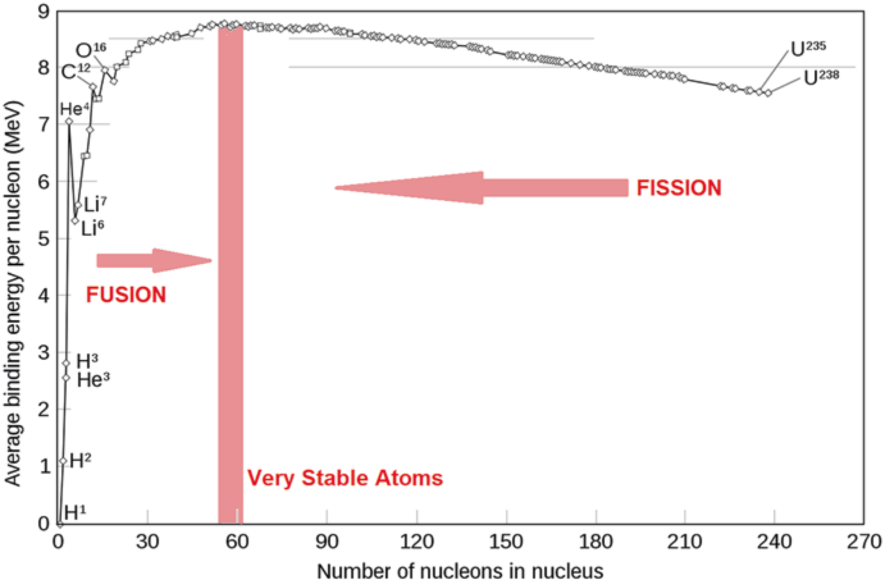


Fig. 1.2 The binding energy per nucleon of each isotope. The isotope with the highest energy per nucleon is Nickel-62, with Iron-58 and Iron-56 very close behind, which makes them the hardest nuclei to change. (Image based on https://en.wikipedia.org/wiki/Helium-4#/media/File:Binding_energy_curve-common_isotopes.svg*)

(negative) binding energy per nucleon, while the horizontal axis is the number of nucleons.

The shape of the curve results from the nature of the "strong" nuclear force that binds nucleons together in a nucleus. (There is a second nuclear force, called the weak nuclear force, which comes into play in the process of transforming one form of nucleon into the other.) It peaks at Nickel-62, a nucleus with 28 protons and 34 neutrons, with Iron-58 and Iron-56 (26 protons, 32 or 30 neutrons) very close behind. (Iron-56 has the largest mass defect per nucleon.) Natural processes favor the lowest energy state, i.e., more negative energy and thus higher on the graph. So fusion processes take place on the left side of the graph, while the fission process occurs on the right.

The strong force between two nucleons differs from the more familiar (attractive) gravitational and (attractive or repulsive depending on relative charge) electromagnetic forces in a significant way. Those forces are inverse-square forces, meaning that their strength is inversely proportional to the square of the separation of the interacting particles. The strong nuclear force is attractive and more powerful than electrostatic repulsion at distances comparable to the size of the nucleus but, unlike the electrostatic force, drops off more sharply than the inverse square of the distance between them as their separation increases. It also becomes less attractive and eventually repulsive at separations smaller than the nuclear size, as if the nucleons have a hard core.

Besides showing the comparison between those two forces between nucleons, Fig. 1.3 can also help us understand why neutrons are necessary for a nucleus larger than hydrogen to be stable. Imagine that two protons approach each other within the

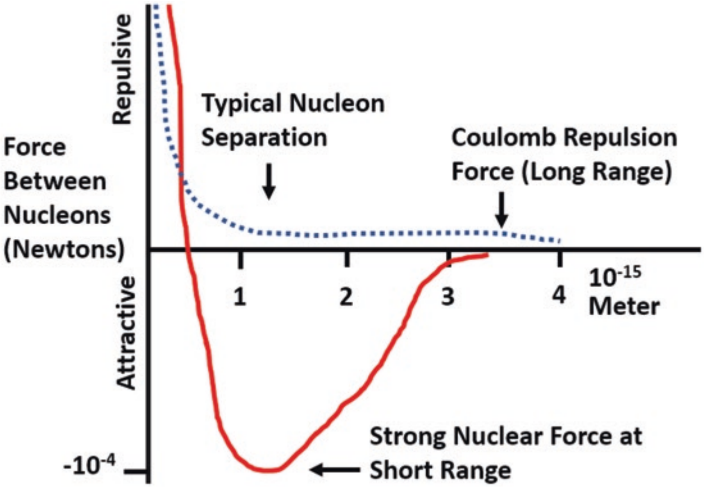


Fig. 1.3 Comparison of the strong nuclear force between two nucleons and the electrostatic repulsion (Coulomb's inverse-square law) between two protons. Neutrons experience no electrostatic forces

distance that the nuclear force dominates. They continue to move closer and closer until the electrostatic and hard-core repulsion takes over and sends them flying apart.

That is an essentially unstable situation, but adding a neutron changes things. It can prevent the two protons from getting so close that they repel each other. The same kind of effect takes place in nuclei of various sizes. There is an optimum range of isotopes that can be stable. Too many neutrons means that the protons are too far apart on average, and their nuclear attraction is not large enough to overcome their electrostatic repulsion. Too few neutrons means the protons can approach each other too closely and repulsive forces can dominate.

1.2.1 Radioactivity and Nuclear Fission

Although this book focuses on the science and technology of nuclear fusion, especially as a possible future commercial source of electric power, it is important to understand a nuclear technology that already has commercial application: nuclear fission.

Our understanding of fission begins with Rutherford's work on radioactivity. Along with his English colleague Frederick Soddy at McGill, he recognized and named two forms of radioactive decay and their associated products, which he designated alpha and beta, in order of their ability to penetrate matter. Frenchman Paul Villard discovered an even more penetrating form of radioactivity, which Rutherford recognized as fundamentally different from the other two, and designated it gamma rays.

Rutherford and Soddy discovered that alpha radiation and beta radiation are associated with chemical changes. When an atom (often called the parent) emits an alpha or beta ray, it becomes a different element (often called the daughter element). Emitting an alpha ray reduces its atomic number by two and its atomic weight by four. Emitting a beta ray increases the atomic number by one but does not change the atomic weight.

We now know, and Rutherford quickly realized, that alpha rays are helium atoms without their electrons. (He did not call them nuclei because he had not yet discovered the nucleus.) Frenchman Henri Becquerel's research revealed that beta rays are electrons. Finally, the work of many researchers, including Rutherford, showed that gamma rays were high-energy photons (packets of electromagnetic energy), though the term was not yet in use, similar to X-rays but more intense.

Alpha radiation is associated with the strong nuclear force. The sum of the masses of the daughter element and alpha particle is less than the mass of the parent. The difference is equivalent (by $E = mc^2$) to the kinetic energy carried by the alpha particle.

Beta radiation is associated with the weak nuclear force. A neutron inside the nucleus transforms into a proton plus an electron and a tiny neutral particle, unknown to Rutherford, called a neutrino (actually an antineutrino, but that is beyond the scope of our explanation). The electron has a maximum energy equivalent to the difference in mass between the parent and daughter nuclei. The neutrino carries the remaining energy required by the conservation law.

Gamma rays result because in either alpha or beta decay, the daughter nucleus may be left in what physicists call an excited state. Eventually, that nucleus returns to its minimum energy or ground state, emitting excess energy as a gamma ray.

Related to alpha radioactivity is a different way that a heavy nucleus can split apart, which physicists call nuclear fission. Both phenomena can be understood by imagining a nucleus as a collection of constantly rearranging protons and neutrons. If two protons and two neutrons happen to come together to form an alpha particle, while the remaining nucleons can also exist as a nucleus, the two parts repel each other electrically, sending the lighter alpha particle flying out, carrying an amount of energy equal to the difference between the mass of the parent nucleus and the sum of the masses of the daughter nucleus and the alpha particle. That arrangement of nucleons does not happen very often, which explains why the parent nucleus can be stable for a long time before decaying. How long? It is a statistical phenomenon that is best described by half-life, or the time it takes for half of the original parent nucleus to emit alpha particles.

Fission occurs when the nucleons of a heavy nucleus, like Uranium 235 (92 protons, 143 neutrons), happen to rearrange to form two medium-size nuclei with a few neutrons left over. That nucleus might break apart in what we call a spontaneous fission event. An induced fission event might occur when small particles bombard a large fissile (or fissionable) nucleus.

In 1934, though neither phenomenon had ever been observed, German physicist Ida Noddack first suggested that induced fission might occur in ongoing experiments involving the bombardment of large nuclei with beams of neutrons, but no one pursued that idea. Then in 1938, Austrian physicist Lise Meitner and her German colleagues at the University of Berlin, Otto Hahn and Fritz Strassman, discovered an unexpected result when bombarding uranium with neutrons. Meitner, who was born Jewish, had just fled to Sweden to escape the invading Nazis and learned about that result in a letter from Hahn. He was puzzled because he found atoms of barium in the bombarded material. The letter arrived when Meitner's nephew and fellow refugee physicist, Otto Frisch, was visiting. Together, the two of them proposed an explanation—induced nuclear fission (see Fig. 1.4) had occurred. (Spontaneous fission was not observed until the early 1940s.)

A number of physicists soon recognized the possibilities. If one or more of the neutrons produced in the fission event could go on to induce another fission, it would be possible to create a chain reaction and produce an enormous amount of energy in a very short time. This led to two important technologies: (1) the atomic bomb, in which the chain reaction is uncontrolled and quickly releases its energy in a powerful blast, and (2) a nuclear power plant, in which a controlled sustained nuclear fission chain reaction occurs. In the second case, every induced fission event, on average, leads to exactly one more, resulting in a steady production of energy to drive a steam turbine electrical generator.

Building a nuclear fission device requires arranging enough fissile nuclei in a configuration that can support a chain reaction. That does not happen in natural

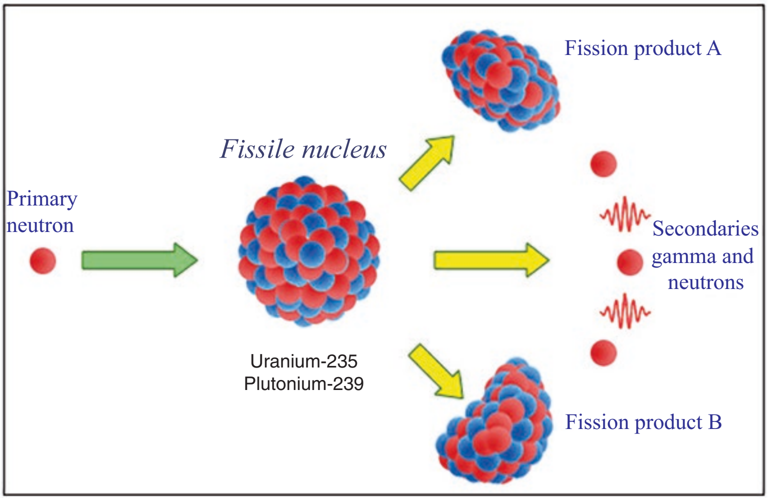


Fig. 1.4 Induced nuclear fission can occur when a neutron impacts a large nucleus, causing it to split into two smaller nuclei and several additional neutrons. A chain reaction can occur if more than one of those neutrons on average induces fission in other nuclei. (Image credit: https://en.wikipedia.org/wiki/Discovery_of_nuclear_fission#/media/File:Nuclear_fission_reaction.svg)

uranium because the fissile isotope Uranium-235 is only about 0.7% of the atoms. The remaining 99.3% of the atoms are U^{238}, except for two of every million uranium atoms being nonfissile U^{234}. In the rare event of a spontaneous fission, the neutrons are unlikely to hit another U^{235} nucleus. Even if one happens to strike another U^{235} nucleus, it is unlikely to induce another fission. The likelihood of inducing a fission event depends on the speed of the incoming neutron and is most likely when the incoming neutron is moving at a relatively slow speed.

Nuclear power reactors require enriched uranium with about 3.5–4.5% U^{235} and a moderator (most commonly water) that slows down the neutrons. Because the nuclear fuel is solid and holds together, the reaction continues indefinitely as long as the moderator is present. Control rods made of materials that absorb neutrons can be inserted to prevent a runaway chain reaction. This enables the reactor to produce steady power without being explosive.

Nuclear weapons use uranium that has been enriched to about 90% U^{235}. Even without a moderator, spontaneous fission in weapon-grade uranium is common enough to produce an explosive chain reaction when there is enough U^{235} (a critical mass, in other words) in one piece. In smaller pieces, most spontaneous fission neutrons escape before encountering another nucleus, and a chain reaction does not occur. The weapon explodes when two subcritical masses come together to form a critical mass. The chain reaction occurs so fast that most of the fissile nuclei undergo fission before the explosion can blow them apart.

1.2.2 Nuclear Fusion Reactions

Although nuclear fusion does not occur naturally on Earth, we owe our lives to it. It is the source of the Sun's energy. Figure 1.5 shows the most common sequence of fusion events that takes place in the central, or core, region of the Sun.

It begins with a rare event in which two protons (hydrogen nuclei) collide with high energy and undergo a process that is essentially the reverse of beta radiation. Thanks to the added energy of collision, one of the protons transforms into a neutron while emitting an antielectron (or positron) and a neutrino. (Although that event is rare in an individual collision, there is so much densely packed hydrogen in the Sun that the number of such collisions is huge at all times.)

The neutron and proton then bond together by means of the strong nuclear force, creating a particle called a deuteron, which is the nucleus of deuterium, an isotope of hydrogen with atomic mass 2. The deuteron collides with another proton, and

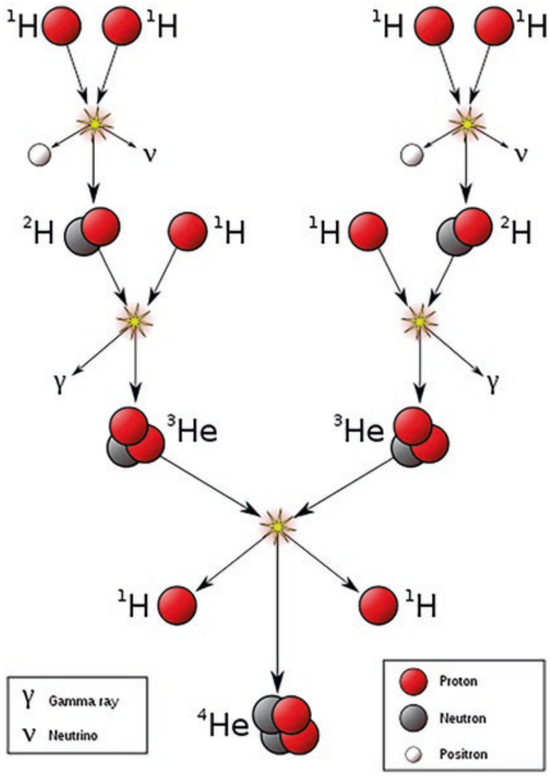


Fig. 1.5 The most common sequence of interactions in the Sun that transforms four hydrogen nuclei into an alpha particle or helium-4 nucleus. (Source and credit info https://en.wikipedia.org/wiki/Proton%E2%80%93proton_chain_reaction#/media/File:Fusion_in_the_Sun.svg)

they bind via the strong nuclear force to form a helium-3 nucleus, emitting a gamma ray in the process. Two helium-3 nuclei then collide to yield one helium-4 nucleus and two protons.

Other fusion sequences involving the nuclei of lithium, boron, and beryllium isotopes, as well as helium, also produce significant amounts of energy in the Sun's core.

Looking at Fig. 1.2, we note that the binding energy per nucleon changes much more sharply in fusion than in fission. That is one significant advantage that a fusion energy system can offer over fission. Another is that the fuel is abundant and not radioactive. So why have humans not yet managed to exploit fusion for electric power?

The answer is that fission takes place in solid materials, but fusion requires a state of matter known as plasma, which is so hot that atoms are stripped of their electrons and under such high pressure that nuclei can collide despite their strong mutual electrical repulsion. In fact, the Sun is a huge ball of plasma that formed in a gravitational collapse of an enormous cloud of gas and dust approximately 4.6 billion years ago. Its immense gravitational field keeps it stable despite the intense energy and stream of particles emerging from its core.

In this book, we will be describing ways that humans have created plasma on Earth and the attempts we have made to keep it stable long enough to extract useful energy. Before we do so, we need to mention one application of fusion that does not require long-term stability: the hydrogen (or thermonuclear) bomb. That bomb releases energy from the fusion of not only deuterium but also tritium, a radioactive isotope of hydrogen with two neutrons and thus an atomic mass of three. To heat and compress that gas sufficiently to ignite fusion requires a conventional fission bomb as a trigger.

Thermonuclear weapons illustrate the enormous potential of fusion energy, if only we can produce it in manageable amounts and control it, that is, if only we can become fusioneers. The first step toward that goal is developing computational tools needed to design a fusion system.

1.3 Modeling Plasmas

Plasma is a complex fluid. In nature, it is created when material is at such extreme pressures and temperatures that atomic electrons are stripped away from their nuclei. This occurs inside the interior of stars, creating positively charged nuclei that move rapidly in a seething negatively charged electron broth.

In this very dynamic system, nuclei experience a huge number of interactions in very short time intervals. That number and rate are too high for fusioneers to include their full complexity in their design computations. Instead, they create simplified mathematical models of how the system evolves over time.

The basic unit in those models is the interaction of two nuclei. By far, the most common type of interaction is an elastic collision in which the outgoing nuclei are the same isotopes as the incoming ones but with different velocities (speeds and directions). These collisions follow the laws of conservation of momentum and kinetic energy and establish an equilibrium distribution of speeds and directions.

But of more interest are the rare fusion interactions, such as those shown in Fig. 1.5, in which the interacting nuclei redistribute their protons and neutrons and transform some of them, resulting in different outgoing isotopes with a smaller total mass than the incoming ones. These interactions still conserve momentum, but lost mass appears as additional kinetic energy. The likelihood of such inelastic interactions occurring depends on several factors, including the relative velocities of the colliding particles and their “impact parameter,” which is closely related to the distance of closest approach.

Including every collision between pairs of nuclei in a microscopic model is an impossible computational task. The challenge is creating a mathematical approximation that yields the same macroscopic behavior. A useful model also requires an accurate representation of the physical environment, the reactor geometry, the applied electromagnetic fields that confine or manipulate the plasma and, in some cases, incoming laser pulses. Finally, our discussion to this point has left out an important aspect of plasma, namely its ability to create internally generated electromagnetic forces. *External* electric and magnetic fields are typically more important in designing plasma devices. In modeling these systems, fusioneers tend to neglect the *internal* electromagnetic forces because the negative electrons and positive nuclei cancel each other out in large numbers and over relevant time spans, leading to effectively a zero net charge. Though there are examples of fusioneers creating models with internal plasma currents and structures, these are less common.

The plasma can be modeled as two moving fluids that do not interact significantly, one made up of negatively charged electrons and the other consisting of positively charged nuclei. Because they do not interact with each other, the two fluids establish separate equilibrium temperatures and energy distributions, as shown in Fig. 1.6.

As noted, a plasma consists of a vast number of particles interacting under extreme conditions. A fusioneer’s task is not to describe it at a microscopic level but rather to predict its macroscopic behavior. That requires the creation of simplified mathematical descriptions or models. The models need to predict three macroscopic factors that are important to generate useful electric power: plasma temperature, plasma density, and the amount of time that the plasma can be confined. (The product of these three quantities, often called the triple product, is an important metric for measuring the performance of a fusion power reactor.)

Plasma temperature dictates how fast a pair of nuclei can approach each other and thus overcome electrostatic repulsion to get close enough for nuclear attraction to take over, possibly leading to a fusion reaction. Plasma density determines how many fusion events take place in a given volume. And confinement time determines the total number of fusion events taking place before the plasma dissipates or is lost.

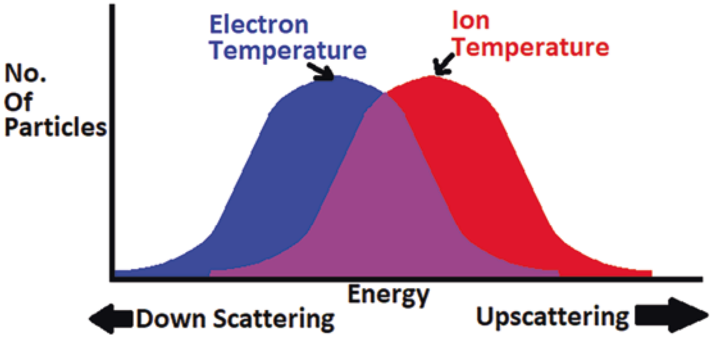


Fig. 1.6 A plasma can be thought of as two fluids with minimal interaction between them. This means that the electrons and ions can have different distributions of energy and temperatures

The remainder of this chapter summarizes several basic types of plasma models, each with its own approximations, strengths, and limitations. The objective of each model is to enable fusioneers to address these questions, among others: How many fusion events would occur? What is the energy distribution of those events? How much energy would a given device produce?

Various approaches to modeling a plasma have evolved over approximately 70 years. Later chapters will discuss how fusioneers apply those modeling techniques in developing a variety of fusion devices.

Fusion modeling was a significant driver of large-scale computing in the United States. One example is the National Energy Research Scientific Computing Center (NERSC) in California. As of 2020, NERSC had the 16th fastest supercomputer in the world, the Cori (see Fig. 1.1). The center was founded in 1974 to support fusion research. NERSC models have been used to model instabilities, diagnostics, and shockwaves in plasmas. Scientists from around the world can apply for time to run their models on these machines.

1.3.1 Elements of Plasma Models

The goal of any plasma model is to provide a better understanding or to predict how plasma will behave macroscopically in a given design configuration. Plasma scientists use a wide variety of modeling approaches and implementations. We summarize the most important ones here.

At one extreme is a model that tracks every particle and every interaction, known as the Klimontovich [7, 8] model. This is obviously limited by computational power and can at best follow a relatively small volume. Currently, the most advanced Klimontovich plasma codes can model only a few cubic centimeters containing a few billion particles while keeping the total energy of the system constant [12].

(Astute readers might note that the particle density described here is much less than the density of the Sun's interior, which is roughly 10^{26} particles per cubic centimeter or about a factor of 10^{16} times as large as the Klimontovich models. Thus, the commonly used description of fusion devices as "the Sun in a bottle" is not particularly apt.)

Even these models, requiring the most advanced computers at expensive government-run computing centers, are limited in their capabilities. In order to produce useful results, these models have to omit some unlikely nuclear interactions. As with all models, there is also a trade-off between the level of detail in the simulation (in space, time, or types of interactions) and the computational resources required.

Other models do not attempt to track every particle and interaction but rather make different approximations about the system. Developing any model includes these general aspects:

1. *External conditions:* all plasma models seek to describe or simulate what happens in a particular physical environment under particular external (or boundary) conditions. The simulation includes a starting condition and an initiating event. Examples include plasma compressed by liquid metal or magnetic fields. Boundary conditions are expressed mathematically and then applied to the governing equations. The resulting equations have no explicit mathematical solution, so fusioneers rely on computational approaches.
2. *Assumptions:* all practical models make simplifying assumptions about the plasma to make the computation workable. One example is the gyrokinetic model, which ignores the tendency of plasma motion to include a corkscrewing component (gyromotion). Another example is the two-fluid model, which treats plasma as electron and ion fluids that overlap. Each assumption trades off the accuracy of the system's physical behavior for computational feasibility. Since the goal is an accurate evaluation of macroscopic properties, fusioneers need to understand the uncertainty that those trade-offs create in their designs.
3. *Adapting the math:* physical laws that govern the behavior of a plasma system can be expressed as mathematical formulas or equations. Fusioneers rely on computer programs that translate those mathematics into codes. This is not an exact process. Depending on the physical circumstances, different programs use different adaptations of those equations to fit different scales of the plasma behavior or to answer different questions. For example, a model may need to be simplified by neglecting terms that are expected to be unimportant in the computation or by eliminating dimensions that complicate the computation without significantly changing the values of the macroscopic properties needed to evaluate the system.

   Fusioneers choose the set of equations used in their computation based on what they are trying to accomplish. For example, under some circumstances, the programs use magnetohydrodynamic equations that treat the plasma as a bulk fluid that can conduct electricity and has specifiable electromagnetic properties. In other cases, programs use the electromagnetic (Lorentz) force and the equa-

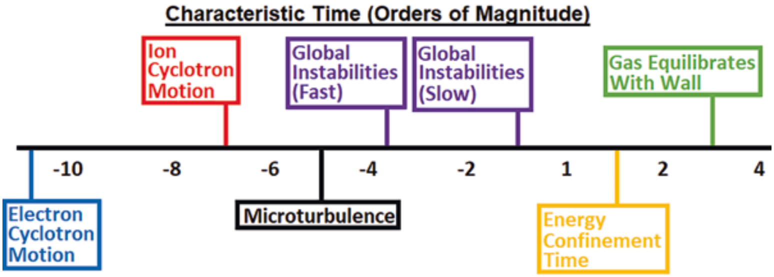


Fig. 1.7 the relative timescales in seconds (by orders of magnitude) for different plasma effects range from hundreds of seconds down to tens of picoseconds, a factor of 10^{14} [14, 15]

tions of motion to track how a single particle will behave under various conditions. These equations have quite different scales: the first models the whole system in aggregate, while the second models a single particle as it moves through a plasma. In yet another situation, the Vlasov-Maxwell system of equations applies statistics to a plasma to predict what percentage of particles will be in which states. Those probabilities can then be used to predict the behavior of the system as a whole.

4. *Implementation:* the purpose of a plasma model is to predict the evolution of the system in time. To do that, fusioneers use an iterative approach that can be described as implicit modeling. Particles are placed in starting locations, and then the system is allowed to evolve for a short interval in time using different approximations. If the results are sufficiently in agreement, they proceed to the next time interval. If not, they adjust the model or the time step and repeat the process until the positions and variables converge.

A full discussion of plasma models is outside of the scope of this book. Good information can be found in Refs. [11–15]. One of the most challenging aspects of modeling plasma is that important effects happen on very different timescales, as shown in Fig. 1.7. Any simulation has to account for each of these scales simultaneously.

1.4 A "Deep Dive" into Plasma Models

What approximations do fusioneers use in developing their models? For most readers, that question is not relevant to understanding the technology that results, and they can safely skip over this section. However, for the readers who are seeking more detail, we take a deep dive into the various modeling approaches.

This section looks at the underlying assumptions and techniques that give rise to the different ways that plasma can be modeled. In practice, models are used to answer questions about an experimental reactor design, for example, how many fusion events will happen? What is the energy distribution of those events? How much energy would a given device produce? Finally, it is critical to remember that models are merely attempts to understand an actual system. When models and measurements disagree, the model needs to be modified. Such disagreements provide a guide for refining the model for future use.

1.4.1 Model 1: One Particle

One of the best ways to develop an intuitive feel for a new fusion reactor is to model the motion of a single particle. Of course, no fusion reactor ever has just one particle, but this calculation provides a starting point for what might happen when other particles are added later. This approach is like following a single race car on an empty track. The course has jumps, U-turns, and stop signs. Modeling the motion of this particle will give you an intuitive feel for this obstacle course. It will allow you to see where the particle speeds up, turns, and stops. It will show you where the magnetic fields are the strongest and where the particle will likely escape.

The motion of a single particle can be addressed with basic engineering tools, specifically Newtonian physics and vector mechanics (assuming the speeds involved are nonrelativistic, i.e., not near the speed of light). For our purposes in this book, these can be carried out with basic and widely available programs such as Excel. (Practicing fusioneers may use more elaborate and more abstract tools for modeling plasma behavior, such as COMSOL, MATLAB, and ANSYS, as well as custom software.) However, simple models allow us to think through the reactor physics, which is the goal of modeling single-particle motion. They provide an intuitive understanding of the machine under consideration.

The basic equations for modeling particle motion are the following.

$$\begin{matrix}\textbf{Lorentz}\\\textbf{Force}\end{matrix} = \begin{matrix}\textbf{Charge On}\\\textbf{Particle}\end{matrix}\left(\begin{matrix}\textbf{Electric}\\\textbf{Field}\end{matrix} + \begin{matrix}\textbf{Particle}\\\textbf{Velocity}\end{matrix} \times \begin{matrix}\textbf{Magnetic}\\\textbf{Field}\end{matrix}\right) = \begin{matrix}\textbf{Particle}\\\textbf{Mass}\end{matrix} * \textbf{Acceleration}$$

(The electromagnetic force experienced by a moving charged particle depends on its charge, velocity, and the local electric and magnetic fields. This force is equal to the mass of the particle times its acceleration, according to Newton’s second law. Note that x signifies a vector product, while we use * for a scalar, or ordinary arithmetic, product.)

$$\textbf{Velocity}_{\textbf{New}} = \textbf{Acceleration} * \textbf{Time} + \textbf{Velocity}_{\textbf{Old}}$$

(Acceleration is the rate of change in the particle’s velocity. Multiplying it by the time interval gives the change in velocity between the beginning and end of the time step)

$$\textbf{Position}_{\textbf{New}} = \textbf{Position}_{\textbf{Old}} + \textbf{Velocity}_{\textbf{New}} * \textbf{Time} + \frac{1}{2}\textbf{Acceleration} * \textbf{Time}^{2}$$

(Velocity is the rate of change of position. To calculate the final position of the particle, multiply the average velocity by the time interval and add it to the initial position. Under the assumption that acceleration is constant during the time interval, this is the result.)

The first step in modeling is to estimate the fields at different locations inside the machine. Many reactors can be approximated using simpler systems like current loops, bar magnets, or current within wires. From those fields, we can calculate the electromagnetic force on the particle and use the above equations to follow it step by step through the machine. In practice, this approach looks like an accounting spreadsheet on Excel. Each row of the sheet represents another step in time, and the position and velocity of the particle are recalculated for each interval. Building such a model can help a fusioneer gain an intuitive feel for the behavior of a new reactor design.

1.4.2 Model 2: Fluid Dynamics

The single-particle model may provide a starting point of our analysis, but like a single car on a racetrack, it is not representative of the actual race. To predict what happens in an actual fusion machine, we need to account for interactions between particles. The presence of other moving charged particles changes the local electric and magnetic fields in dynamic ways.

The Klimontovich model, discussed above, is a microscopic approach and thus runs into computational limitations in practice. To overcome those, fusioneers treat the plasma on a macroscopic level, i.e., as a fluid. This is similar to describing hydraulic flow using viscosity rather than considering the motion and collisions of each individual molecule with other fluid molecules and the walls of the pipes. The microscopic approach is more precise on a detailed level but is untenable computationally. The macroscopic approach is computationally feasible and may produce results that are correct for all practical purposes.

One fluid dynamics approach to modeling a fusion reactor uses a set of master equations, known as the Vlasov equations. These model the fusion plasma as a fluid of moving electrically charged particles, governed by the laws of both fluid mechanics and electromagnetism. Those laws can be expressed mathematically: fluidic behavior by the Navier-Stokes equations and electromagnetism by Maxwell's equations. The Vlasov set includes both phenomena, with six equations in all.

Each expression is shown and explained below in Fig. 1.8. We do not expect readers to follow the math here, but we hope to convey the complexity of the computations they require while keeping our discussion on a phenomenological level.

To implement these equations in a computer program, the fusioneer divides the space containing the plasma into small elements of volume, each containing particles with a distribution of speeds corresponding to a particular temperature. Each element experiences a local electric and magnetic field that is a combination of external fields and the fields produced by the other elements of the plasma itself.

Charged fluid motion: these two equations govern how a charged fluid moves. They are adapted from the Navier-Stokes equations, modified for a fluid that is electrically charged. The original Navier-Stokes equations express the conservation of momentum and mass in a flowing viscous fluid. The modification includes the conservation of electric charge.

1. Negative fluid motion: this equation governs the flow of electrons in the electromagnetic environment (electric field **E** and magnetic field **B**, both vector quantities).

$$\frac{\partial f_e}{\partial t} + \boldsymbol{v_e} \cdot \nabla f_e - e\left(\boldsymbol{E} + \frac{\boldsymbol{v_e}}{c} \times \boldsymbol{B}\right) \cdot \frac{\partial f_e}{\partial \boldsymbol{p}} = 0$$

2. Positive fluid motion : this equation governs the flow of positive ions in the electromagnetic environment, where Z_i is the positive charge of the ion.

$$\frac{\partial f_i}{\partial t} + \boldsymbol{v_i} \cdot \nabla f_i - Z_i e\left(\boldsymbol{E} + \frac{\boldsymbol{v_i}}{c} \times \boldsymbol{B}\right) \cdot \frac{\partial f_i}{\partial \boldsymbol{p}} = 0$$

Maxwell's equations: these four equations govern how electric and magnetic fields behave and interact. Together, they also predict the existence of electromagnetic waves, which travel at the speed of light.

3. Faraday's law : this equation shows how a magnetic field impacts an electric field. It states that a changing magnetic field can induce an electric field.

$$\nabla \times \boldsymbol{B} = \frac{4\pi \boldsymbol{j}}{c} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$$

4. Ampere's law : this equation shows how an electric field will impact a magnetic field. It states that an electric current or a changing electric field can induce a magnetic field.

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}$$

5. Gauss's law for electric fields : this is the equation that governs electric fields. The net electric flux into and out of a volume is proportional to the charge inside that volume.

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho$$

6. Gauss's law for magnetism : the equation governs magnetic fields. If you enclose a magnet, the flux that enters and leaves that volume must be equal. This means that magnets always have paired north and south (dipoles). A single-pole magnet can not exist.

$$\nabla \cdot \boldsymbol{B} = 0$$

Fig. 1.8 These six Vlasov equations describe how plasma evolves in an external electric and magnetic field

Those fields are assumed to remain constant over a very short increment of time, after which the program recalculates the contents and speed distribution within each element. There is always a trade-off between computation time and the ability to produce useful results. If either the elements of volume or the time interval is too large, the model deviates too far from reality to make useful predictions. If they are too small, the computation time becomes unmanageable.

1.4.3 Model 3: Ideal Magnetohydrodynamics

At the opposite end of the modeling spectrum from the single-particle Klimontovich approach is ideal magnetohydrodynamics (MHD), which takes a big-picture view of the plasma, treating it as a single, continuous, conducting fluid contained in a big balloon with a certain shape and volume while ignoring the details of the plasma inside. Ideal MHD makes the following assumptions:

1. The external electromagnetic field is strong enough to overwhelm any electromagnetic effects from the plasma motion. Any external field—electric or magnetic—can pass through the plasma unaffected, unperturbed, and with no problems. This is often described as the magnetic field "frozen" or fixed inside the plasma.
2. The plasma is ideal; i.e., it has no electrical resistivity. Mathematically, this means that the resistivity term in Ohm's equation is set to zero.
3. The plasma motion is completely dictated by the fields applied to it. If there is a magnetic field, the plasma will corkscrew around it, following the field like a highway. In the ideal MHD model, the plasma is too weak to change those applied fields. Unfortunately, this means ideal MHD does not model plasma structures well in occasions where plasma self-generates its own substantial fields.

Real-life plasma can be far messier. The motion of the electrons and ions can self-create fields. They can twist, shape, or shift the applied electromagnetic fields. This contrast is shown in Fig. 1.9. Collectively, this means that the plasma resists the applied field similar to the resistivity of a wire as an electric current passes through it. Real plasma has a natural resistivity to the applied field; the field weakens as it passes through, and the plasma heats up as a consequence. Despite these major differences, it is possible for the ideal MHD model to make useful some predictions of macroscopic phenomena—within limits.

Like any simplified approach, magnetohydrodynamics has its flaws. For example, a designer can use MHD to predict the behavior of a plasma trap, such as the

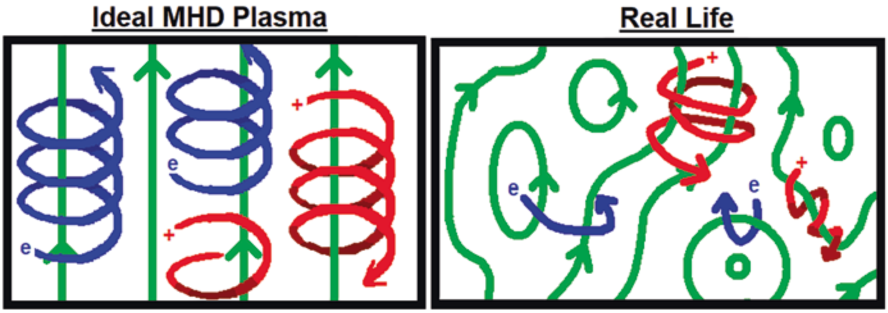


Fig. 1.9 A comparison between the fields and motion of charges in a real plasma (right) and an idealized MHD plasma (left). Despite these major differences, it is possible for the ideal MHD model to make useful predictions of macroscopic phenomena

magnetic mirror machine shown in Fig. 1.10 below. The magnetic field in the mirror is high at its two ends and lower in the middle. The electromagnetic equations predict that when the plasma moves from lower to higher density fields, it can reflect. The mirror machine design has two plasma mirrors facing one another. The goal is to have the plasma ricochet back and forth until some of its nuclei slam together in the center and fuse.

MHD can easily model this system. It is not difficult to describe the boundary conditions in mathematical terms, and the resulting equations can often be solved by pencil-and-paper techniques. Unfortunately, actual mirror machines are not ideal and have a problem that cannot be captured by MHD mathematics: some plasma leaks out the ends.

This example highlights an important concept in plasma modeling (or physical modeling of any kind). The simpler the math is, the more its predictions deviate from the behavior of actual devices. This will become more apparent as we move through other modeling approaches in this book.

(This example also illuminates a very different issue with fusion technology that goes beyond science and technology. T. K. Fowler and colleagues have recently posited a strong argument for a configuration of a mirror machine that produces enough electric power to be economically viable [3]. But, like so many other fusion technologies, the United States is failing to invest in this and is leaving the door open to other nations. Today, we have no large mirror machines anywhere in the United States.)

Featured Fusioneers, MHD Pioneers Hannes Alfvén and Harold Grad
Magnetohydrodynamics began with a 1942 publication by Swedish physics professor Dr. Hannes Alfvén [1], which described how plasmas move under electric and magnetic fields. MHD mathematics was subsequently found to have applications across many physics areas, including astrophysics, water chemistry, and optics, earning Alfvén the 1970 Nobel Prize in Physics. It continues to be a tool for fusion researchers seeking electromagnetic field configurations to control plasmas in fusion power plants (Fig. 1.11).

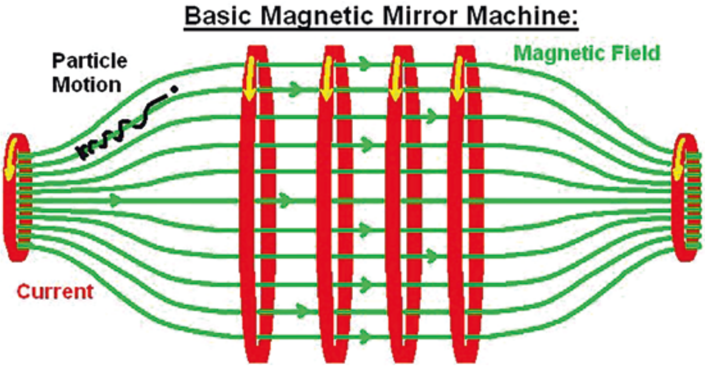


Fig. 1.10 The basic fields and current used in a magnetic mirror

Fig. 1.11 Hannes Alfvén (left) and Dr. Harold Grad (right), who both did work to start and expand the use of ideal MHD in the 1940s through the 1960s. Ideal MHD was one the first mathematical frameworks for modeling plasma, where actual analytical solutions could be found. (Image credit: Wikimedia)

One of the powerhouse institutions of ideal MHD modeling was the Courant Institute of Mathematical Sciences at New York University in the 1950s and 1960s, where researchers led by Professor Harold Grad specialized in applying advanced mathematics to physics. The foundational concept of the NYU fusion model is that when the magnetic field is strong, the Vlasov equations can be simplified enough to become workable for many different scenarios. For about 20 years, Dr. Grad published paper after paper that solved MHD equations for a variety of geometries, many of which we will discuss later in this book: pinches, mirrors, tokamaks, spheres, and cylinders. At that time, computers were not advanced enough to be used for modeling; "pen and paper" solutions were all that physicists could rely upon. A similar path developed in fluid mechanics: before computers, simplified analytical solutions of complex math were the only way to model flushing toilets, flow in pipes, or jets of water.

1.4.4 Model 4: Two Fluids

The two-fluid approach improves on MHD by accounting for the fact, noted above, that plasma is made up of two very different fluids of opposite electric charge, namely, positive ions and electrons. The components of these fluids have very different masses. The smallest ions are hydrogen nuclei (protons), which are 1836 times as massive as electrons. The ions in fusion devices of interest in this book are mainly twice to four times as massive as protons. The mass of the electrons is so small that it can be neglected in computing the flow of positive ions. Their charge and the electromagnetic fields they produce, however, matter in the computations.

Obviously, a two-fluid model can capture more effects than a one-fluid model. The downside is that these equations are harder to solve. From a computational perspective, any solution will take many multiples of computing time longer than MHD [6, 8]. The two-fluid approach accounts for effects where the distribution of positive and negative charges is not uniform, such as when ions bunch together. Those effects are important for understanding the behavior of plasmas in various devices.

One example of this is a drift wave, which often forms inside the fusion devices, such as tokamaks, which we describe in detail in later chapters. In a drift wave, ions gather together, forming a swell and wave of plasma, with electrons clumping together between the ion waves. Figure 1.12 shows some nice results of a two-fluid model of a tokamak, which illustrate this plasma behavior.

The best source for two-fluid mathematics is the Naval Research Laboratory (NRL) Plasma Formulary. This is a pocket-sized book of equations, which has been published since 1975 and is still considered a bible for plasma modelers. Though it has other information, the two-fluid model makes up the core of this little book. The Navy reissues this book every year and makes it available for free on the NRL website. Below is a selection of some of these equations (Fig. 1.13). It is important to understand that this method cannot capture everything that happens inside a fusion reactor. These equations are practically useful because they allow a fusioneer to quickly estimate rates, for example, what is the expected rate of X-rays emitted by a plasma with a certain density? Or if you release an ion into that same plasma, about how many collisions will it have before it fuses? Like all models, these equations are rules of thumb; the results are limited by the basic assumptions of the two-fluid model.

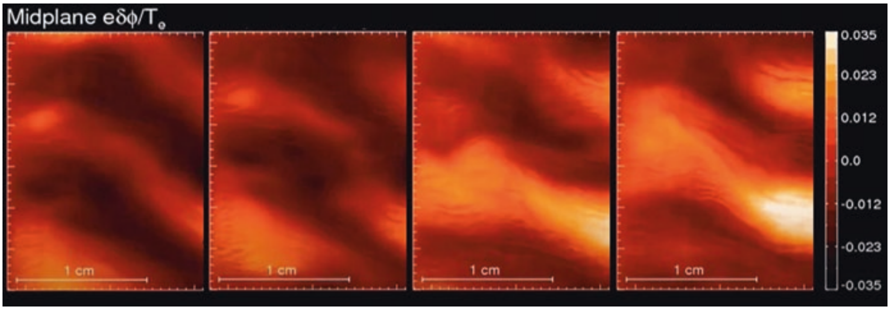
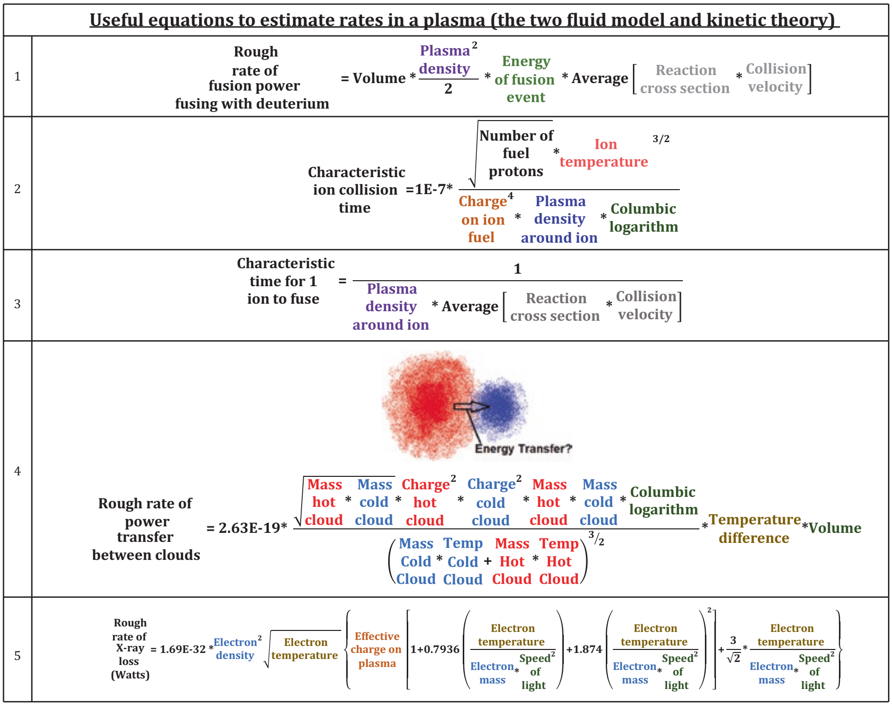


Fig. 1.12 A time series of energy and mass inside a tokamak made by a supercomputing model in 2015 [12]. The brighter areas are places where there is more, and hotter, plasma. What is important to notice is how energy and mass ripple like water waves through the machine. A collection of charges can do the same—with a ripple of (+) and (−) material bunching together and then dissipating. This behavior underpins several instabilities and effects in fusion plasmas. Photo credit: Chris Holland and Nathan Howard



Useful equations to estimate rates in a plasma (the two fluid model and kinetic theory)	
1	$\text{Rough rate of fusion power fusing with deuterium} = \text{Volume} * \frac{\text{Plasma density}^2}{2} * \text{Energy of fusion event} * \text{Average}\left[\text{Reaction cross section} * \text{Collision velocity}\right]$
2	$\text{Characteristic ion collision time} = 1\text{E-}7 * \frac{\sqrt{\text{Number of fuel protons}} * \text{Ion temperature}^{3/2}}{\text{Charge on ion fuel}^4 * \text{Plasma density around ion} * \text{Columbic logarithm}}$
3	$\text{Characteristic time for 1 ion to fuse} = \frac{1}{\text{Plasma density around ion} * \text{Average}\left[\text{Reaction cross section} * \text{Collision velocity}\right]}$
4	Energy Transfer? $\text{Rough rate of power transfer between clouds} = 2.63\text{E-}19 * \frac{\sqrt{\text{Mass hot cloud} * \text{Mass cold cloud}}\ \text{Charge hot cloud}^2 * \text{Charge cold cloud}^2 * \text{Mass hot cloud} * \text{Mass cold cloud} * \text{Columbic logarithm}}{\left(\text{Mass Cold Cloud} * \text{Temp Cold Cloud} + \text{Mass Hot Cloud} * \text{Temp Hot Cloud}\right)^{3/2}} * \text{Temperature difference} * \text{Volume}$
5	$\text{Rough rate of X-ray loss (Watts)} = 1.69\text{E-}32 * \text{Electron density}^2 \sqrt{\text{Electron temperature}} \left\{\text{Effective charge on plasma}\left[1+0.7936\left(\frac{\text{Electron temperature}}{\text{Electron mass} * \text{Speed of light}^2}\right)+1.874\left(\frac{\text{Electron temperature}}{\text{Electron mass} * \text{Speed of light}^2}\right)^2\right]+\frac{3}{\sqrt{2}} * \frac{\text{Electron temperature}}{\text{Electron mass} * \text{Speed of light}^2}\right\}$

Fig. 1.13 Estimates based on the two-fluid model, which can be used to find the rates of different effects in plasma. (This is included as an illustration of how fusioneers approach their models, but we do not attempt to describe the full terminology for nonexpert readers.) These equations are pulled from Ref. [10]. Equation 1 is the rate of fusion power from a fusing and uniform plasma that is all one kind of ion. Equation 2 estimates the time it takes for one ion to collide with another inside a plasma. Equation 3 estimates how long it takes for one ion to fuse into a plasma (This expression uses the density that the plasma sees as it moves through the cloud). Equation 4 roughly estimates the rate of energy transfer as a hot cloud to a cold cloud. Equation 5 estimates the rate of energy loss as X-rays in a hot, uniform plasma. *These expressions are good for rough estimations only*

Important Considerations for Two-Fluid Models

In 1995, researchers at the Massachusetts Institute of Technology (MIT) used the two-fluid and other modeling techniques to systematically study and critique a whole class of fusion reactors [2]. Their work had far-reaching implications, which continue to be important today. Its results made sweeping statements about reactor design. The work examined reactors where the plasma was not in thermodynamic equilibrium. In that case, the behavior of the device can be unstable, and such instabilities create serious limitations in fusion reactor design.

A good example of this circumstance is a plasma that is made *solely* from trillions of positive ions. Such a concentration of positively charged material is inherently unstable. Either the cloud will pull negatively charged electrons from the environment or the repulsive forces will rip the plasma apart in order to achieve an equilibrium state. Nonequilibrium states are transitory. Eventually, reactors will settle down to a new state, which we will call “the blob.”

Featured Fusion Skeptics, Todd Harrison Rider and Lawrence Lidsky

Todd Rider entered MIT's graduate program in the early 1990s with the hope of working on a class of fusion reactors where the plasma was not in thermodynamic equilibrium. His advisor was nuclear engineering professor Lawrence Lidsky, who had already made a name for himself as a critic of fusion for a 1983 article, "The Trouble with Fusion," in the *MIT Technology Review*. This led to a hearing in front of Congress, where he repeated these criticisms. Lidsky suggested that Rider do a systematic study of reactors not at thermodynamic equilibrium, expecting to see a focus on their limitations [10].

Rider reluctantly agreed, and over time, he turned from being enthusiastic to being pessimistic about these kinds of machines. Rider's technical argument can be broadly broken into five parts: (1) a mathematical description of a nonequilibrium plasma; (2) using the two-fluid model and other equations to estimate the rates of different effects in that plasma (some examples: How long does it take for the ions and electrons to mix together, and how much energy will be lost as light is emitted from this plasma?); he developed any expressions he needed and published them as important papers in their own right; (3) determining the amount of energy needed to maintain a nonequilibrium system, i.e., to keep the plasma from collapsing into equilibrium; (4) determining how much fusion energy plasma will make and how much it will lose; (5) finally, comparing both values, he argues that these reactors cannot reach net power. This was a critical conclusion, that systems not at thermodynamic equilibrium were unable to reach net power, and it impacted a wide class of machines.

In 1995, Rider published this argument as his MIT doctoral thesis [2]. He went on to work on fighting diseases, founding the Rider Institute and developing an antiviral therapeutic. Lidsky and Rider are shown in Fig. 1.14.

Fig. 1.14 On the left: MIT's Lawrence Lidsky was a major critic of fusion power (Reprinted with permission of MIT News). Lidsky wrote the famous article "The Trouble with Fusion" and spoke before Congress in the 1980s. In the center is Dr. Todd Rider, who was Lidsky's graduate student (Photo credit: Lori Rider). On the far right is a photo of the pocket-sized NRL plasma formulary, which contains the two-fluid equations used by Rider for his modeling work

It has been over 25 years since Todd Rider published his critique of fusion reactors, but its conclusions are still relevant to fusioneers. Some fusion researchers, most notably Dr. George Miley at the University of Illinois at Urbana–Champaign [13], dispute some of Rider's assumptions. However, the critique lays out an important point that often gets lost. Rider showed us what *not* to do. In his technical argument, he argued that a plasma not at equilibrium will collapse into a state we are calling "the blob." That concept is very useful because it provides an overall direction for fusion reactor approaches to avoid.

A plasma blob has five basic characteristics, each illustrated graphically in Fig. 1.15:

1. *Quasi-neutrality:* the plasma is electrically quasi-neutral. This means that the positive ions and negative electrons are locally and evenly mixed together.
2. *Isotropic:* the plasma is isotropic. This means that plasma looks relatively the same throughout and in every direction. This is related to the third assumption that the plasma has no structure.
3. *Unstructured:* a plasma that is uniform in all directions is inherently unstructured. Useful plasma structures, which we will discuss elsewhere in this book, include field-reversed configurations, spheromaks, plectonemes, or plasmoids. These can occur anywhere where the plasma creates its own electromagnetic fields.
4. *Thermalized:* Rider assumed that the plasma was thermalized, that is, its particles have a bell-shaped energy distribution that is a characteristic of a system in thermal equilibrium. If the plasma is thermalized, only a certain percentage of its ions—those particles at the high-energy end of the distribution—are moving fast enough to fuse.
5. *Uniform temperature:* Rider assumed that the temperature is uniform throughout the cloud. On a very small local scale, the ions might be hotter than average, but

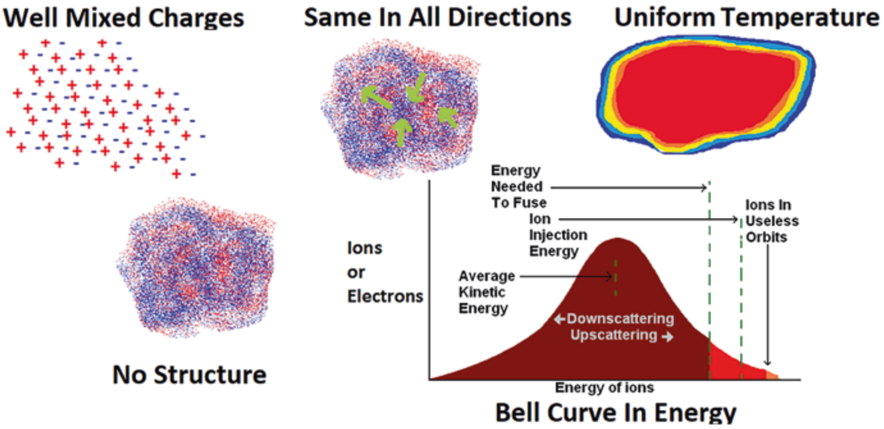


Fig. 1.15 A visual depiction of the five characteristics of a blob. (Taken from Rider's work [10, 13])

on a scale large enough to be practical, the temperature evens out to the same average throughout.

It is important to realize that these assumptions are closely interrelated. If the plasma has no structure, then it is expected that there is no temperature difference. If the plasma has a bell curve in energy, then it is expected that there will be no structure. As a thought experiment, consider how these conditions apply to the Sun, a natural body of fusing plasma. Locally, these conditions seem to apply to solar plasma, but on a huge scale, the Sun does not meet these conditions. The Sun's temperature varies from a hot dense core to a relatively cool surface. The Sun also forms large plasma structures like solar flares, sunspots, and plasma filaments.

Using the two-fluid model, Rider argued that all reactors that hold plasma blobs will be fundamentally limited and will likely fail. This argument was based partially on the conclusion that heating a plasma blob is a lost cause because it loses so much energy in X-rays. We take that conclusion with a grain of salt; this work was theoretical. Rider made assumptions that have been contested, and the two-fluid model is also limited [9, 13, 14]. Still, Rider actually made deep and profound statements about fusion plasma design. If you want to make net power, your goal should be to make your plasma as non-blob-like as possible. This leads to several principles for designing plasma inside a reactor:

- *Shape it:* you have to shape your plasma. One example is the flowing Z-pinch, where the plasma takes the shape of a rippling beam. Another example is the Lockheed-Martin Compact Fusion Reactor, where the plasma assumes some sharply bent shape based on the rejection of the containing fields. Another example is the magnetic mirror, where the plasma assumes a cigar shape. Finally, tokamaks, stellarators, and spherical tokamaks all have distinct shapes to their plasmas—D shape, squashed ring, or twisted ring. All of these machines will be discussed in subsequent chapters.
- *Structure it:* use magnetic or electric fields to structure the plasma, including the fields produced by the plasma itself. Some of the structures we will discuss include spheromaks, plectonemes, field-reversed configurations, tokamaks (which structure their plasma by twisting its flow around a central column), and stellarators (which create a structure more directly by twisting the magnetic fields). Other approaches attempt to make a structure by clumping the positive or negative electric charges together. But structuring has its limits. The enemy of any structure is any inherent instability, which tends to return the plasma to an unstructured state.
- *Avoid thermalization:* producing useful energy requires a nonequilibrium process. Thus, it is important to avoid a bell-shaped plasma energy distribution. A fusioneer's goal is to keep the plasma hot and moving, say in a beam or loop. The ideal plasma should have extremely hot ions and cold electrons. Hot ions mean more fusion. Cold electrons mean less energy lost as light.

All of these concepts are connected. If you have a plasma structure, you may have a concentration of charge. If ions are in a beam, they will not have a bell-curve distribution of energy. If you can shape the plasma, you may be able to get both effects. These conclusions are useful takeaways from Rider's sweeping two-fluid model, which represented the best two-fluid theoretical and modeling option available to him in the early 1990s. In subsequent decades, due to great advances in computing, plasma modeling has seen great improvement.

1.5 Computer Simulation of Fusion Systems

All the models to this point can—in principle—be solved using a pen and paper. Now we move to models that require computer simulation. In fact, fusion research has historically been one of the major drivers of the development of computational hardware and techniques. Those computations begin by dividing space into small cells containing single particles, groups of particles, or small amounts of a uniform fluid.

Computational models produce greater detail as they track the movement of particles through a simulated reactor design. The calculations allow designers to capture granular details that MHD and two-fluid models can miss, like microturbulence or instabilities. Computational models can also simplify the representation of the fusion device in certain geometries, such as when a three-dimensional system has cylindrical symmetry and thus can be modeled by rotating a simulated two-dimensional system around an axis.

Today, computer simulation is the most common method to model plasma devices, but it is easy for designers to rely so heavily on computation that they lose track of scientific or engineering insights, which simpler models can provide. Thus, we recommend beginning with a simple model before developing a fully detailed one. Computers can never substitute for a person's intuitive understanding of reactor physics.

1.5.1 Particles in Cells

In the 1960s, Los Alamos National Labs was the place to be if you wanted to do computing [4]. Workers there had access to supercomputers long before most other engineers. Thus, it is no surprise that Los Alamos was one of the birthplaces of computational modeling. One group, the T3 group headed by Frank Harlow, led the way. That team developed what is now a common practice in plasma simulations—particles in cells (PIC). Interestingly, when the T3 group started this work, it was ignored and even criticized by scientific peers [5]. Nevertheless, they continued to publish papers, and they were ultimately vindicated by the strength of their approach. Figure 1.16 is a visual homage to the team [5].

The particle in a cell divides the reactor into small cells and tracks the plasma, represented by super particles, as it moves through each one. One super particle

Fig. 1.16 Frank Harlow was a pioneer engineer when he led the T3 group at Los Alamos into the development of computational fluid dynamics. This work was ignored by the general physics community for years until it came to dominate the field. (Image courtesy of Los Alamos National Laboratory)

might represent 1000 real ions. The equations controlling the motion of these objects can be simple, or it can be complex. Different models have different mathematics and different basic assumptions included. We discuss two such models here. Within each cell, the computer finds the Lorentz force acting on that particle using the local magnetic and electric environment. That force is assumed to be constant for a short interval of time, producing a new position and velocity of the superparticle and a corresponding new electromagnetic field in each cell.

That process repeats step by step and, over time, predicts the motion and electromagnetic environment of the plasma. Such a simulation always has a trade-off between the accuracy of the predictions and computational resources. The smaller the time step or the cell size is, the more accurate is the simulation but the more computation time is needed. Another consideration in such simulations is how accurately the computer code matches physical reality. Sometimes simplifications necessary to create a manageable computation lead to a divergence between the mathematical predictions of the model and the physical behavior of an actual device. These trade-offs are illustrated in Fig. 1.17.

Inside these little cells, the most common motion of a particle is a corkscrewing one. This is because fusion reactors have both electric and magnetic fields within them. A charged particle moving in a magnetic field experiences a force perpendicular to its direction of motion, which is why it moves in a corkscrew path. The handedness of that corkscrew depends on the charge of the particle and the relative directions of its motion and the magnetic field. If a negatively charged electron or super particle moves in a right-handed corkscrew, a positively charged particle moving in the same direction in the same field would execute a left-handed corkscrew. Because that motion is accelerated, according to the equations of electromagnetism, the particle emits electromagnetic energy, typically in the visible light portion of the spectrum, and thus tends to slow down. This motion and the mathematics governing it are shown in Fig. 1.18.

In real plasmas, everything is constantly moving. Materials swirl and mix. This motion can be a chaotic melee. However, in this chaos, the corkscrewing motion around a magnetic field line is the most common behavior. The magnetic field lines

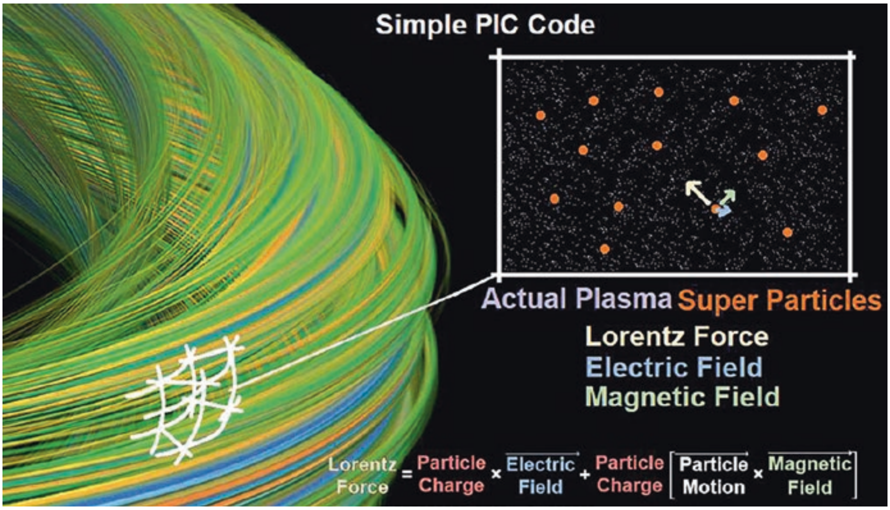


Fig. 1.17 A graphical illustration of how PIC works. It shows the results from a full tokamak model and how inside a single volume the computer uses superparticles to represent real particles. The computer can model the local electromagnetic environment, calculate the Lorentz force, and predict the motion of the particles

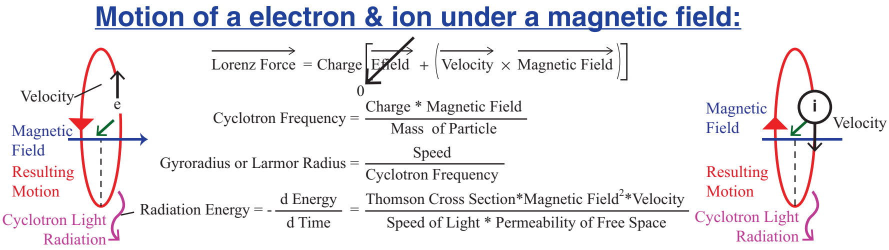


Fig. 1.18 A visual and mathematical description of an ion and electron under the influence of a magnetic field

direct ions and electrons like cars on a highway. Meanwhile, an applied electric field accelerates (or decelerates) electrons and ions along the direction of that field. As a general rule, that means any good reactor design creates electric and magnetic fields that limit the chaotic motion of plasma, creating a stable flow and confining enough plasma for enough time that enough fusion takes place to produce more energy than the device requires to operate.

1.5.2 Models 5–6: Gyrokinetics and Kinetics

A modeling technique called gyrokinetics simplifies plasma motion by replacing the corkscrew motion with a ring that is the size of the corkscrew's cross section and follows the path of the corkscrew's axis, as depicted in Fig. 1.19. The computer

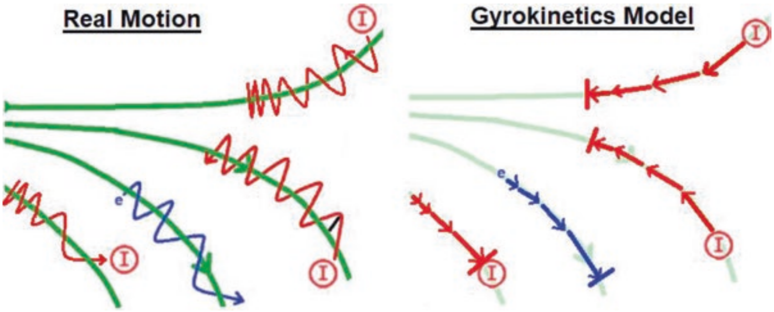


Fig. 1.19 A comparison of real particle motion and the gyrokinetic model

follows this ring as it moves through the different cells of the simulation. This assumption reduces the number of parameters needed to track each particle's motion from six to five: three for position and two for velocity [11]. Removing the rotational motion of the corkscrew simplifies the calculations significantly, which is very important in a massive simulation with billions of ions.

A gyrokinetics code (integrated with PIC framework) is simple enough to run models of small systems on desktop computers. In fact, communities of users have developed open-source gyrokinetic codes, which can be downloaded for free. An important caveat is that because the model is missing some information, the longer it runs, the further its predictions will stray from reality.

Gyrokinetics is a subset of a more detailed approach to plasma modeling called kinetics, which incorporates the full corkscrewing motion of the charged particles. Kinetics models, which are commercially available, incorporate the most plasma information of any current approach while still being practical enough to run on a mainframe computer. Advances in computer technology will allow future kinetics simulations of larger or more complex plasma system designs.

Other approaches, such as Klimontovich models and methods that use the mathematics of quantum field theory (which is beyond the scope of this book), are more advanced but currently computationally impractical—and likely to remain so.

1.5.3 Model 7: Discretizing Vlasov

Another comprehensive approach is to discretize the Vlasov equation, dividing the simulated plasma into blobs that occupy individual cells [14]. This method can alternatively be described as modeling plasma with a blob-in-cell approach. In this case, blobs are simulated chunks of the material, each representing a population of particles with an evolving distribution of positions and energies. Each blob occupies a cell inside the plasma volume. The computer operates on these distributions, changing their energies appropriately. The computer also tracks the mass and energy that are transferred between the blobs and cells.

The difference between the blob-in-cell approach and gyrokinetics or kinetics is stark. In those models, the computer will track a single particle. In this model, the computer only works on large populations. Whereas kinetics uses representative superparticles, blob-in-cell uses volumes of plasma. These are little volumes of fluid, which we treat as thousands of charged droplets floating inside the reactor. At its heart, the blob-in-cell approach is a mixture of PIC and the mathematics used in the Vlasov equation. The discretized Vlasov equation describes how a population will change as it is impacted by an electromagnetic field, while PIC discretizes the plasma volume to improve the quality of the simulation.

1.6 Applying the Models

How do fusioneers use those modeling techniques with the blobs? As noted, each blob represents a population of particles with a particular distribution of energy that changes over time as it interacts with other blobs and applied fields (Fig. 1.20).

The code breaks the calculation into a series of time steps, starting from a known initial set of conditions. For each step, the code computes the net charge and the velocity (speed and direction) of the blob in each cell. It also computes the net flow of charge into or out of the cell. This yields a current density that varies from one cell to another and a resulting magnetic field. Based on that, it calculates a Lorentz force on each cell and the resulting position and net charge of each cell at the end of the time step. Shorter time steps allow for a more accurate simulation of the plasma, but at the cost of simulating less actual time, using more computer time, or both.

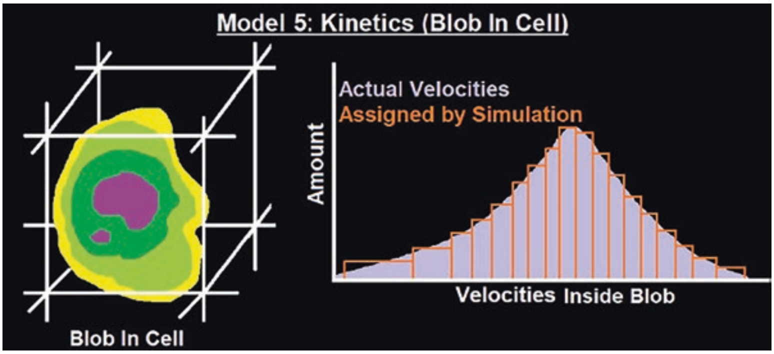


Fig. 1.20 An illustration of the blob in a cell kinetics model

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Fusion Technology

2

Summary

This chapter is an overview of the current state of the art of fusion technology. Because of the imperative of dealing with climate change, most fusioneers are focusing on earth-bound technologies that can produce useful electric power without adding to our planet's atmospheric greenhouse gases. Still, the book would be incomplete—and less exciting—without discussing other applications of fusion, including the out-of-this-world potential for space propulsion systems. This chapter is an overview of those applications showing the connections and interrelationships between various families of fusion technologies. Later chapters will look at each of those families in detail.

2.1 Fusion Science and Technology

In fusion, science and technology are two sides of the same coin. Science helps us understand fusion at the fundamental nuclear level, while technology—the focus of this chapter—deals with applying that science in the service of human needs. This chapter is an overview of technological applications of fusion, many of which are then described in detail in subsequent chapters.

This book reflects the confidence of author Moynihan that at least one of those approaches to fusion energy will emerge as a major contributor to ending the existential threat of human-caused climate change. Author Bortz remains agnostic, recognizing that other "green" technologies and nuclear fission are already emerging as strong competitors in the low-carbon power generation sector but agreeing that the need for reducing greenhouse gases is too great to ignore the possibilities offered by fusion.

Our primary audience is not professionals working in fusion technology, though we expect many of them to enjoy seeing how their specific work fits into the broader

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industry. We are writing mainly for people who are interested in the field, either out of simple curiosity or because they are would-be fusioneers or investors who need a starting point to ponder the future.

As noted in the previous chapter, the greatest challenge for fusioneers is creating, maintaining, and confining a phase of matter—plasma—that is at such high temperatures that its atoms are stripped of their electrons. The resulting nuclei can produce energy if they fuse, but fusion happens only if a pair of particles gets close enough that the strong attractive nuclear force overcomes their mutual electrostatic repulsion. The nuclei need to get within 2 femtometers to undergo a fusion event, which requires a high-speed, nearly head-on collision between the pair. In fusion devices, three conditions are necessary for that to happen.

The first condition is high temperature, which makes such relative velocities possible. Head-on collisions are still rare because most particles pass each other like cars in opposite lanes on the highway. (Good for cars but bad for fusion.) More head-on collisions occur when particles are packed more closely together; thus, the second condition is high density. The third condition is keeping the particles confined long enough that they are more likely to collide and less likely to escape the system before fusing. That leads to the previously mentioned triple product metric for the performance of a fusion reactor: temperature times density times confinement time.

Confinement is challenging: because of the intense temperatures involved, most plasmas cannot be confined by physical materials. Fusioneers rely on two different approaches to confinement to create useful energy: electromagnetic and inertial, which are sometimes combined. Electromagnetic confinement is a dynamic process in which the plasma flows within carefully shaped magnetic fields, which may vary in time to match plasma conditions. In inertial confinement, the material to be fused (usually a solid pellet) is imploded by a set of intense laser pulses. This creates a dense, hot plasma in which significant fusion takes place in a short time before repulsive electrostatic forces blow it apart.

Our presentation is often historical, covering roughly 70 years of fusion research and development. In that time, hundreds of large machines have been built, encompassing many different physical mechanisms. Researchers have made significant progress, but the field is littered with concepts that have failed because of technological problems or have remained underdeveloped due to a lack of support. Our goal is for readers to be able to compare old ideas with new technologies, understand the unique problems of different reactor designs, and explore the frontiers of the field.

2.2 Types of Fusion Devices

If fusioneers were painters, their palettes would have five colors: magnetic fields, electric fields, mechanical compression, electrons, and ions. Their canvas would be plasma, which can be compared to a soup of positive ions and electrons. The goal for all fusioneers is to cause those ions to collide and fuse in sufficient numbers to produce useful energy. To do so, they have investigated numerous designs and techniques, each of which has its own advantages and limitations.

Those techniques involve manipulating the surrounding electromagnetic fields, changing the internal nature of the plasma, or physically compressing it. This has led to a plethora of devices, which can be viewed as a family tree, shown in Fig. 2.1.

One goal of this book is to give readers a basic understanding of each family of fusion approaches and their interrelationships with one another. They fall into the following major family types, which will be listed below. Each family can have several variations, with different approaches evolving to meet specific technical challenges or arising when two approaches are merged together.

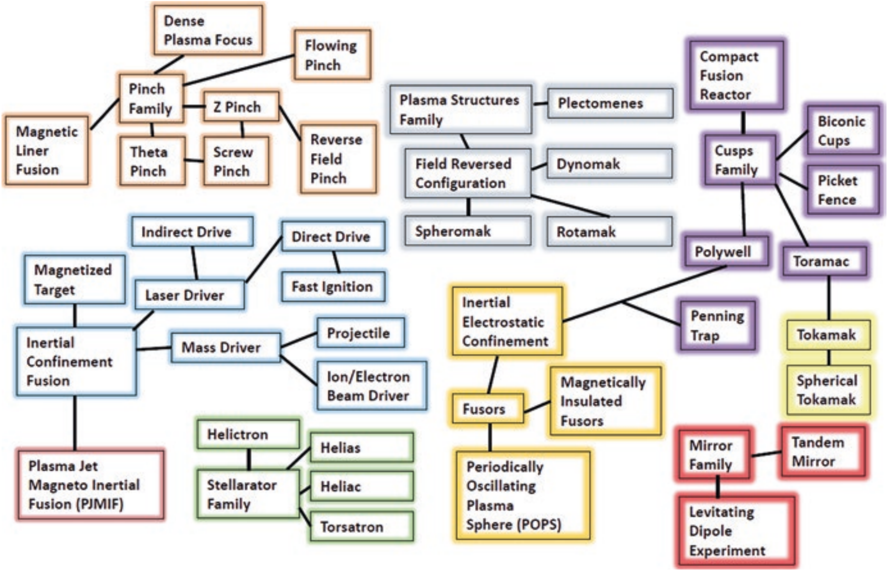


Fig. 2.1 The families of fusion technologies that will be covered in this book are organized here in a color-coded chart by chapter. They will be presented in the following order: the **pinch family** (orange), which will be covered first because it was the earliest technology to work; the **mirror family** (red), which was a major US effort in the 1970s and 1980s; the **cusp systems (violet)**., an early and unconventional concept that was explored mostly theoretically; **tokamaks and stellarators** (green),, currently the dominant fusion power approach because they have the best performance; **plasma structures** (gray) which harness the ability of plasmas to self-organize to form quasi-stable structures that can be manipulated using magnetic fields; **inertial electrostatic confinement** (dark yellow), which has been pursued by hobbyist fusioneers working in their homes, schools, and garages and has been applied to commercial products; **inertial confinement fusion** (ICF, blue), which compresses plasma with shockwaves and is closely associated with the development of nuclear weapons; **plasma jet magneto inertial fusion** (PJMIF, dark pink), which is unique because it is a hybrid of ICF and magnetic confinement. These eight chapters cover the majority of ideas that have been explored over the last 70 years of fusion research

- *Chapter 3—Pinches*: pinches work by squeezing columns of plasma together using powerful electromagnetic fields. Other than thermonuclear bombs and particle accelerators, they were the first machines to fuse nuclei. Today, flowing pinches are being explored commercially.
- *Chapter 4—Magnetic mirrors*: mirrors are a type of magnetic confinement device in which the plasma ricochets back and forth along an axis. Mirror programs were massively funded by the United States from the late 1960s to 1986. This culminated in a $376 million science experiment that was finished—but never tested.
- *Chapter 5—Cusps*: cusp systems use opposing magnetic fields to create a central region of zero field strength surrounded by high-field areas, which create a plasma trap. Due to the tendency of the plasma to leak out, they have not performed well. The most famous research into cusps is the Lockheed-Martin Compact Fusion Reactor.
- *Chapter 6—Tokamaks and stellarators*: tokamaks are currently the dominant design in the electromagnetic confinement of plasmas for electric power generation. No other concept has performed as well. A consortium of 28 nations is currently building a giant tokamak called ITER (International Thermonuclear Experimental Reactor) in the south of France.
- *Chapter 7—Plasmoids*: because plasmas conduct electricity, they can self-structure into sheets, donuts, and twisted ribbons called plasmoids. These plasmoids are hot and dense and can be easily manipulated, making them particularly well suited for fusing inside a reactor. Several commercial companies are following this approach with almost a billion dollars raised in private funding.
- *Chapter 8—Inertial confinement*: this approach squeezes plasma (mainly) using shockwaves produced by laser pulses. This approach has long been driven by American nuclear weapon research since its founding. An inertial confinement device became the first approach to demonstrate fusion chain reactions in 2021.
- *Chapter 9—Plasma jet magneto inertial fusion*: this approach fires jets of high-velocity plasma together into a central sphere, where they compress together. This approach can reach conditions that are halfway between an extremely dense inertial confinement fusion compression and a low-density tokamak device.
- *Chapter 10—Inertial electrostatic confinement*: this approach uses electric fields to heat ions to fusion conditions. It is the simplest, cheapest, and easiest way to start a fusion reaction. These machines have been used by hundreds of hobbyists to do fusion in their garages and led to the world's first commercial fusion devices in 2000.

Each of these families of approaches has strengths and weaknesses, and each has its own advocates and detractors. Each approach has seen some technological development—some certainly more strongly than others. Engineers rank these approaches through a measure called their technology readiness level (TRL), which ranges from one (lowest) to nine (ready for deployment). As this book discusses, fusion technology has advanced significantly over the past 70 years, but none of the approaches have yet reached that final stage of maturity.

2.3 Fusion Device Design

The goal of the people who invested their time and energy into these concepts has always been optimization. Optimization of a fusion reactor means trading off different aspects of the design and operation to get better behavior. The goal is to both design and run these machines in a way that realizes more behavior that you *want* and less that you *hate*, essentially tuning the machine to get the best outcome. Depending on how the machine is designed and run, it can be operated in different modes. For example, a fusor has three modes of operation: star, halo, and converged core. You can see this in photos of these fusor modes in Fig. 2.2.

Operators can switch between each fusor mode by changing a single operating parameter: the pressure of the surrounding gas. More generally, a fusion reactor can have hundreds of controlling parameters. Table 2.1 lists several of the most important ones.

When designing a fusion reactor, scientists are faced with the daunting task of trying to sort through dozens or even hundreds of variables. They need to rank these parameters by their importance on the overall machine behavior. Some are very important and can determine which mode the machine runs in. Others are less impactful. For example, fusioneers must determine which factor will have a bigger impact on the reactor behavior, magnetic field or the plasma injection rate. Does this fusion machine need to be the size of a house, or can strong fields allow for a smaller reactor? How many magnets does this machine need? The goal is to figure out how to build and run these fusion machines to produce the highest fusion rate for the longest time and the best power efficiency, with the objective of making more energy than it takes to drive it—thus achieving net power.

Fig. 2.2 The three modes of a fusor. On the left is the "halo mode," which is characterized by a broad glowing cloud of plasma and gas. In the center is the "star mode," which looks like a shining star. In the "converged core" on the right, gas pressure is so low that the glowing effect is very weak. Changing the gas pressure inside the fusor results in causes switching between these three modes of operation. The star mode gives you the most fusion reactions, though, as discussed later, fusors will never lead to net power

Table 2.1 Several of the most important design parameters to consider in designing and building a fusion reactor

Some fusion design parameters		
Overall size	Electric field	Timing
Geometry	Injection rate	Fusion rate
Magnetic strength	Number of electrons	Run time
Compression	Number of ions	Temperature

The controlling parameters are shown in black; the output parameters are shown in red

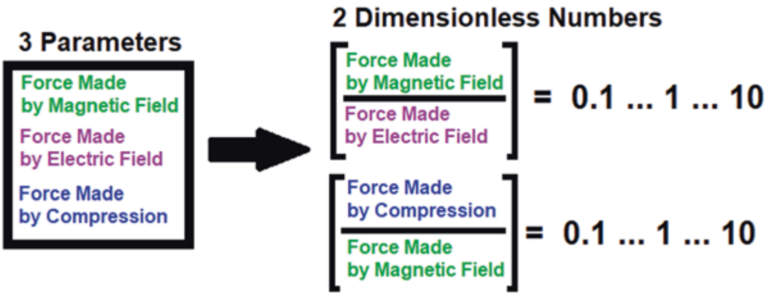


Fig. 2.3 Dimensional analysis is a technique to reduce the number of variables in a problem by identifying interdependences among them. This gives a quicker path to optimizing the fusion reactor. In this example, three variables are reduced to two ratios

2.3.1 Dimensional Analysis

Scientists often navigate the optimization problem using dimensional analysis to reduce the complexity of their problem. Dimensional analysis is the art of recognizing and taking advantage of relationships between different parameters. For example, the fusion startup General Fusion compresses a spinning plasma with liquid metal. General Fusion can change the machine's design in several ways. It can increase the magnetic and electric fields inside the plasma or squeeze the plasma more forcefully with liquid metal. Three parameters are in play here: the magnetic force inside the plasma, the electric force, and the mechanical force of the liquid metal. But to simplify the analysis, the relationships of these parameters can be expressed as two ratios, illustrated in Fig. 2.3.

2.3.2 Dimensional Analysis, Simulation, and Machine Learning

Dimensional analysis is the first step in a larger process that can be used to design any technological system, such as a fusion reactor. A fusion reactor is a complex machine that can have over a hundred variables that need to be optimized to get the best performance. Dimensional analysis reduces the number of variables that a designer has to worry about by combining them into ratios. Once simplified, the next step is to model different designs of the reactor on a computer. Modern simulation tools allow engineers to create complete virtual twins of real-world fusion reactors. With a few mouse clicks, virtual machines can be as large as a building or as small as a car. Simulations like this allow organizations to eliminate configurations that will not work and to narrow the set of machines that could actually be built and tested.

Done skillfully, that process guides fusioneers to designing the next machine. Once enough data from a real fusion device has been collected, further optimization can occur by applying artificial intelligence (AI) to that data set. Fusion companies TAE Technologies and General Fusion have already used artificial intelligence to optimize their fusion reactors. TAE Technologies worked with Google's AI team to sort through the more than 130 different operating parameters to find the best settings for each one and get the best performance for their fusion reactor [23, 24]. All of these tools—device modes, dimensional analysis, simulations, and machine learning—give fusioneers a direct path to building the optimum fusion reactor.

2.4 Fuels

Once a fusion reactor is built and operating, there is a set of different fuels that can be loaded into the machine and fused to create energy. In doing this, people are duplicating the fusion reactions that occur naturally inside the Sun. Hypothetically, we could fuse any two nuclei if we had access to infinite pressure and temperature. But in practice, only a handful of fuels can be fused. Loading a fuel means injecting it as a gas into the reactor chamber and then ionizing it (most simply with microwaves), creating a plasma. Then the ions can be manipulated with magnetic and electric fields to initiate the desired fusion reactions.

Fusioneers are considering several fusion reactions for their devices. A particularly desirable reaction is fusing boron-11 (five protons, six neutrons) with a proton, producing three alpha particles (He^4 nuclei). That process produces no neutrons, which is desirable because the surrounding materials can capture neutrons, often producing radioactive isotopes. The technological barrier to boron-11 fusion is that it requires a much higher temperature. Still, some teams argue that there are practical pathways to making this fuel work inside fusion reactors. Innovations include unique laser technologies and plasma pinches. Below is a summary of each fuel that fusioneers are currently giving serious consideration:

- *Deuterium*: this is a rare but naturally occurring isotope of hydrogen with one proton and one neutron. On Earth, it accounts for about one hydrogen atom out of 6420. Deuterium is the easiest fuel to use because it can be separated from normal hydrogen by mass-separation techniques. Because it can be purchased online for a reasonable price, hobbyists use it in fusors and other small devices. For several hundred dollars, an amateur fusioneer can buy enough deuterium to last for several years of fusor tests. Another advantage is that it is very easy to ionize; only about 16 V are needed to strip off its electron. The reaction below is the most common process in deuterium fusion. (Tritium is a radioactive isotope of hydrogen with atomic mass 3: a proton plus two neutrons.) Typical fusors ignite fusion reactions by exciting deuterium nuclei to energies between 10 KeV and 120 KeV, where an electron volt (eV) is the energy gained by an electron that has been accelerated through a volt of electric potential. The two reactions below occur with equal probability:

$$\text{Deuterium} + \text{Deuterium} \rightarrow \text{Tritium}\left(1.01\, MeV\right) + \text{Proton}\left(3.02\, MeV\right)$$

$$\text{Deuterium} + \text{Deuterium} \rightarrow \text{Helium3}\left(1.01\, MeV\right) + \text{Neutron}\left(3.02\, MeV\right)$$

- *Tritium + deuterium*: adding tritium to a fusion reactor significantly boosts its output, sometimes by as much as 20-fold. Unfortunately, tritium is expensive, hard to use, hard to stockpile, and, because it is radioactive, a hassle from an environmental health and safety standpoint. At one university, it took a team of a dozen professionals 4 years and millions of dollars to design, build, and license a tritium-handling facility. The challenge was getting the Nuclear Regulatory Commission and Environmental Protection Agency (EPA) licenses needed to use tritium. Most of the facilities that use tritium are government labs. Given these problems, many researchers choose to try to improve their fusion approach rather than add tritium to their fusion fuel. Those that choose to use tritium use this fusion reaction:

$$\text{Deuterium} + \text{Tritium} \rightarrow \text{Helium4}\left(3.5\, MeV\right) + \text{Neutron}\left(14.1\, MeV\right)$$

- *Boron-11*: as noted above, the fusion of a boron-11 nucleus with a proton is highly desirable because it most commonly produces three helium nuclei and almost no neutrons. Advocates of boron-11 fusion tout it as a power source that could change the course of human civilization. A minor issue is that the fusion reaction has a small chance of resulting in a different set of products, including neutrons. But a bigger obstacle to boron fusion is that it has much higher ignition energy, between 550 KeV and 600 KeV, or as much as 50 times as high as a deuterium-deuterium fusion [12]:

$$\text{Proton} + \text{Boron11} \rightarrow 3\,\text{Helium4}\left(8.7\, MeV\right)$$

- *Others*: for decades, fusion researchers have also discussed adding helium3 (He3) as a fuel. This isotope is rare in Earth's atmosphere but abundant on the Moon, where it is the result of capturing the solar wind in the lunar regolith. Presently, this fuel is not commonly used in government or university laboratories. Here are a few potential He3 fusion reactions:

$$\text{Helium3} + \text{Helium3} \to \text{Helium4} + 2\,\text{Proton}\left(12.9\,MeV\right)$$

$$\text{Deuterium} + \text{Helium3} \to \text{Helium4}\left(3.6\,MeV\right) + \text{Proton}\left(14.7\,MeV\right)$$

$$\text{Tritium} + \text{Helium3} \to \text{Helium4}\left(3.6\,MeV\right) + \text{Proton} + \text{Neutron}\left(12.1\,MeV\right)57\%$$

$$\text{or} \to \text{Helium4}\left(4.8\,MeV\right) + \text{Deuterium}\left(9.5\,MeV\right)43\%$$

$$\text{Lithium} + \text{Helium3} \to 2\,\text{Helium4} + \text{Proton}\left(16.9\,MeV\right)$$

2.4.1 Cross Sections

The choice of fuels depends on more than which reactions you are trying to achieve. It also depends on how hard or easy it is to produce a particular fusion reaction. This is determined in part by the ignition energy, as noted, and also by how likely an interaction is to lead to the desired fusion event, which designers describe by a key parameter known as the cross section.

As the name suggests, cross sections are measured in units of area. In nuclear physics, the preferred unit is the barn, which is equal to 10^{-28} square meters or roughly the cross-sectional area of a uranium nucleus. The choice of that unit is from the top-secret World War II Manhattan Project, which led to the first atomic (fission) bomb. The scientists wanted a unit that was appropriate for their use but unknown to adversaries. (See below for the humorous origin of the name of the unit.)

To understand why that unit of area is important, consider the interaction of two nuclei, which may or may not fuse when they collide. Physicists like to choose a convenient frame of reference for collisions, and our choice here is the one where one of the nuclei is at rest. We call that the target, and the other nucleus is the projectile.

We begin when the particles are too far apart to be interacting. If the projectile were to continue on a straight line, its center would pass by the center of the target by a distance we call the impact parameter. Most interactions are elastic, meaning the nuclei scatter off of one another rather than fuse, and both momentum and total kinetic energy do not change. The forces between the two nuclei cause the projectile not to continue on a straight line but rather to go off in a different direction, called the scattering angle. Figure 2.4 shows the relationship between the probability of a particular range of scattering angles and the cross section for elastic collisions.

This relationship between cross section and probability also applies in instances of inelastic collisions. Those can occur when the impact parameter falls below a few femtometers (10^{-15} m), at which point the strong nuclear force can take over and pull these two nuclei together and produce a fusion event. In that case, the outgoing particles are different from the colliding pair. Momentum is always conserved in such an interaction, but kinetic energy is not. Rather, the mass of the outgoing

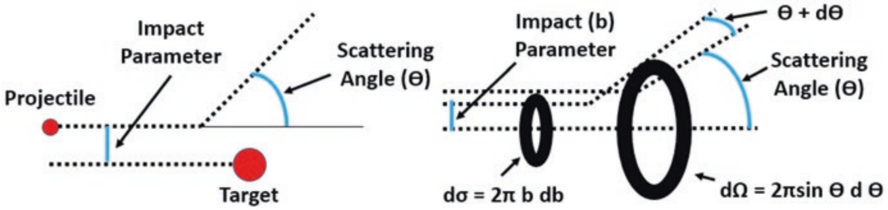


Fig. 2.4 Left: an elastic interaction between two nuclei with impact parameter b produces a change in the direction of the projectile with a scattering angle θ. Right: a slight increase in the impact parameter (db) changes the scattering angle by an amount $d\theta$. The cross section for elastic collisions that produce scattering angles between θ and $\theta + d\theta$ is thus the area of the annular ring, $2\pi bdb$. In a uniform plasma, any impact parameter is equally likely, which means that the collision cross section is a measure of the probability of a particular scattering angle

particles is less than the colliding ones. The lost mass is transformed into its equivalent amount of kinetic energy (according to Albert Einstein's famous eq. $E = mc^2$), which is noted in the fusion reactions described in the preceding section. Because those inelastic collisions are much rarer, their cross sections are correspondingly smaller. In some cases, more than one type of inelastic collision can occur, such as the two different outcomes of collision between tritium and helium3 nuclei, noted above. The 57/43 percentage split corresponds to a 57/43 ratio of the cross sections for their occurrence.

Inset: Featured Fusioneer, Dr. George Miley

A major research area in fusion was the extensive determination and cataloging of cross sections for various scattering events and fusion reactions. The United States sponsored this work in the 1950s, 1960s, and 1970s at various particle accelerators around the country in connection with weapon research. The data were generated by firing beams of nuclei at fixed targets and measuring how many fusion events occurred at different angles and speeds. Pulling this information together was a difficult and critical step for determining the ideal conditions for nuclear fusion reactions. Much of that tabulation work was done by Dr. George Miley at the University of Illinois in his famous "Barns Book." Miley and the book are shown in Fig. 2.5. Today; this cross-sectional data can be readily accessed using any good software modeling package.

End Inset

As noted, a fusion event is governed by the strong nuclear force. The cross section for a given fusion reaction depends on the kinetic energy of the projectile nucleus for the following reason: if the energy is small, electrostatic repulsion keeps the target and projectile too far apart for the nuclear force to be significant. However, if the impact parameter is small and the kinetic energy is large enough, they may overcome the electrostatic repulsion and pass close enough to interact through the strong nuclear force. Even in that case, however, it is not certain that a fusion event will occur. Because the kinetic energy is high, they may pass by each other too quickly to exchange protons or neutrons. Thus there is a kinetic energy "sweet spot" for fusion to occur, as illustrated by Fig. 2.6. Note that the scale is logarithmic, which

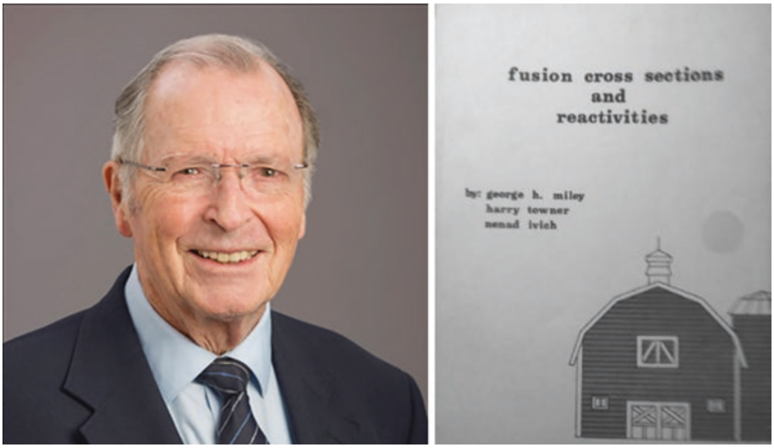


Fig. 2.5 On the left is Prof. George H. Miley (1933–) of the University of Illinois, who dedicated over 60 years to developing nuclear fusion devices for electric power. Dr. Miley's work included a wide range of fusion technologies from inertial confinement fusion to fusors [12]. On the right is the cover of his famous "Barns book" on fusion cross sections

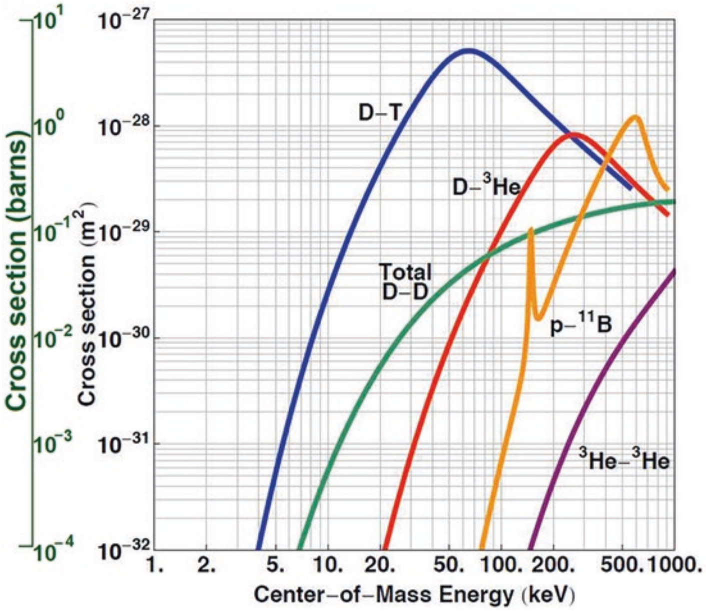


Fig. 2.6 Energy dependence of the fusion cross sections (logarithmic plot) for various fuels. Note the strong blue curve for deuterium-tritium fusion. The cross section is an order of magnitude larger than any of the other possible fusion reactions, and the peak occurs at a lower, and thus more easily [13] achieved, temperature

means the cross sections—and thus fusion events of significance to designers—peak sharply, often rising by a factor of several orders of magnitude at certain energies.

Fusion researchers have now built up a detailed catalog of cross sections, such as those included in featured fusioneer George H. Miley's "Barns book," which was the product of decades of intensive research. They and other researchers gathered data by firing beams of nuclei at fixed targets and measuring how many fusion events occurred at different angles and speeds. The book's nickname resulted from people comparing these experiments to shooting a rifle at the side of a barn and measuring how likely it was to hit something inside.

Miley's team was one of the first to tabulate and publicly publish the cross sections for different fusion reactions. The Barns book is a catalog of data pulled from years of measurements made by the United States at particle accelerators around the country. The graphs produced demonstrate why deuterium-tritium is currently the best fuel for a fusion reactor; it has a much larger fusion cross section at a significantly lower temperature.

2.4.2 Chain Reactions, Ignition, and Burning Plasmas

Can fusion reactions be chained together? For example, one branch of the deuterium-deuterium fusion reaction creates helium3. These helium3 nuclei could then be fused with more deuterium, resulting in a secondary fusion reaction. Chaining is common in chemical engineering, where the products can be used for more reactions, and several teams have proposed ways that it could be possible under extreme conditions in fusion [17]. But generally, the products of a fusion reaction are so exceedingly hot that they are difficult to capture and control. The particles simply whiz away from the fusion event that produced them.

Instead of reusing the products, researchers have instead focused on repurposing the energy that fusion creates into generating more reactions. In this scenario, the hot fusion products created by the reaction are kept around long enough to recycle their energy back into the plasma. This reheating effect will spur more reactions. Chaining in this way would allow fusioneers to leverage the hard-won conditions that led to fusion, thus getting more energy out of the plasma. This would raise the overall efficiency of any fusion power plant that can achieve this condition. Both the inertial confinement fusion and magnetic confinement fusion communities have built or planned for machines that attempt to chain fusion reactions.

In the inertial confinement fusion (ICF or laser fusion) community, this concept is known as ignition, and it has been a goal for that community since the 1970s. In laser fusion, a pellet of frozen fusion fuel is compressed to very high densities. Ideally, the density of the compressed plasma is so high that the escaping fusion products cannot leave without losing much of their energy. In the 1990s, the Lawrence Livermore Laboratory mobilized around building a machine that could achieve ignition, the National Ignition Facility (NIF). In 1995, Livermore researcher Dr. John Lindl published a tour de force paper laying out a path to the National

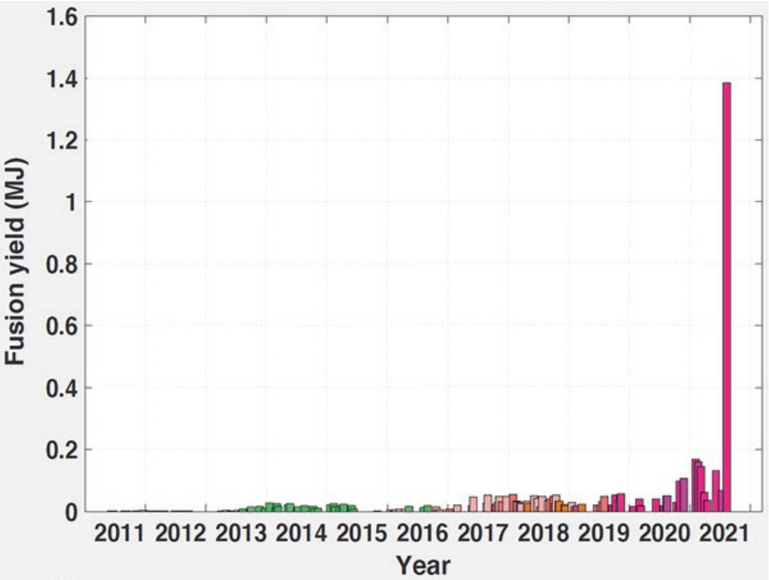


Fig. 2.7 After almost a decade of continuous improvement, the National Ignition Facility saw a dramatic increase in the power generated from a fusion reaction on August 8, 2021 [21]. This breakthrough was the first evidence of fusion ignition or a fusion chain reaction

Ignition Facility [15]. Advocates used this work to build support for the project within the federal government. Ground was broken on May 29, 1997, and the machine was finished exactly 12 years later. This will be discussed in more detail in Chap. 10.

On August 8, 2021, Sunday, the NIF machine was able to produce a breakthrough that the researchers had been working on for decades. Researchers saw the first evidence of an igniting plasma. The shot (#N210808) created almost seven times more energy than any other experiment ever done before (see Fig. 2.7). This dramatic change in the energy created could have only arisen from fusion chain reactions.

Today, a similar effort is underway in the magnetic confinement fusion community to achieve fusion chain reactions. This concept is known as a burning plasma. It is one of the goals of the International Thermonuclear Experimental Reactor (ITER), currently being built in France. This will be discussed in more detail in Chap. 6.

2.5 Fusion's Broad Impact

It is hard to predict what fusion power would mean for society, and there are no formal surveys for public opinion on this subject. In 2012, author Moynihan reviewed 429 posts made on an online fusion forum over a 3-year period as an ad hoc survey on fusion power. A summary of these points of view is presented in Table 2.2. Specifically, the survey was to check how fusion power would impact a particular area of society. People talked about the interplay of fusion power and a remarkably broad set of other scientific, technological, and political issues. Responses varied widely, and the biggest takeaway was this: fusion is so new that most people are not sure what to make of it. Fusion was particularly associated with other frontier technologies, like terraforming Mars or advanced weapon systems. A decade later, we have not seen any shifts in these viewpoints.

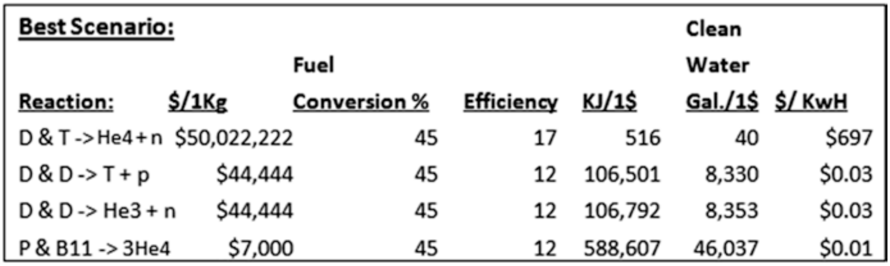
Given that wide set of perceptions, it is important to lay out what fusion is and what it is not. Fusion power would be a new tool in our collective toolkit. The feature that most distinguishes humans from other species is the variety and sophistication of the tools we have developed: from hammers to factories, fires to nuclear energy systems, and bicycles to airplanes to spacecraft. We can use these tools for good or evil. Though our purpose in writing this book is not to be political, we will note that our choices of leadership impact how these tools are used. Nations can use fusion energy for beneficial purposes or for destructive practices, like deforestation and war.

In this book, we focus on the benefits of fusion technology. Even though its first application has been in thermonuclear weapons, we will focus on ways to control and use the vast amounts of electrical energy it can produce with a very low radioactive and carbon footprint. This is especially important as the world strives to minimize the production of greenhouse gases and the threat of climate change they cause.

Predicting the impact of fusion power on the price of electricity is a challenging exercise. The further forward in time a prediction is, the more inaccurate it must inherently be. (A Google search reveals that numerous celebrities, from Mark Twain to Yogi Berra to the founder of the atomic model, Nobel Laureate Niels Bohr, have

Table 2.2 Moynihan's summary of posts on an online fusion forum, 2009–2012. Specifically, the survey was about how fusion power would impact a particular area of society. Obviously, the participants all had a strong interest in the technology, but the most striking result of the analysis is the breadth of potential impacts of fusion on many—and very different—aspects of civilization. A decade later, the depth and breadth of interest in the potential of fusion continue to be strong

	Good	Bad	No position
World resources	32	36	37
Global pollution	5	8	10
Frontier technologies	10	8	14
American influence	13	8	15
Warfare	7	18	23
Existing energy systems	23	1	21
Space exploration	28	5	33
Food production	10	5	39
Shipping	9		
Computers	1		
Human health		1	
Totals	138	89	192



Best Scenario:

Reaction:	$/1Kg	Fuel Conversion %	Efficiency	KJ/1$	Clean Water Gal./1$	$/ KwH
D & T -> He4 + n	$50,022,222	45	17	516	40	$697
D & D -> T + p	$44,444	45	12	106,501	8,330	$0.03
D & D -> He3 + n	$44,444	45	12	106,792	8,353	$0.03
P & B11 -> 3He4	$7,000	45	12	588,607	46,037	$0.01

Fig. 2.8 Moynihan's 2011 analysis of the economic and energy impacts of fusion power on the grid [7], including the potential for desalinization of seawater. Except for inflation, the results are still valid. (KJ is kilojoules of energy, where one KJ is equivalent to 1/3600 KwH)

been quoted as saying some variants of "It is difficult to make predictions, especially about the future.") With that caveat, we can look at author Moynihan's 2011 rough estimate of the impact of fusion on electricity prices [7]. It was a quick analysis based on the limited knowledge then, and a comprehensive study for fusion is still impossible today since we do not know which fusion approach will succeed, much less how much such a plant will cost.

In the electric power industry, the relevant measurement is levelized cost of electricity (LCOE), or how much money goes into producing a kilowatt-hour (KwH) of energy. An LCOE calculation includes the cost and time to build the system, with the price of running the power plant divided by all the electricity the plant generates over its lifetime. The 2011 analysis was based on an assumed price of the fusion fuel fed into the reactor and the plant's efficiency in turning that fuel into electricity. The estimate included worst-, better-, and best-case scenarios to cover a wide set of situations. A summary of the findings is shown in Fig. 2.8.

As of 2022, the average American was paying 13.7 cents per kilowatt-hour across the country, and this cost has changed only slightly over the past decade. A fusion power plant could conceivably make that same kilowatt-hour for a fraction of a penny. Fusion power implications get far more interesting when we think about what to do with all this excess energy. For example, there is a worldwide shortage of clean water. Generally, it takes about 2.8 KJ of energy to create a liter of drinkable water from the sea [16]. So connecting a fusion plant to a desalinization process can generate thousands of gallons of water cheaply. Another way to think about the impact of fusion is to compare it to other power sources. Figure 2.9 shows that comparison for 1000 megawatt-hours of energy based on 2014 technologies [1–6].

2.5.1 The Lawson Energy Balance Criteria

The above analysis describes how much energy a fusion reactor can produce, but it does not consider how much energy it takes to run that reactor. The key question is this: What does it take to get net power?

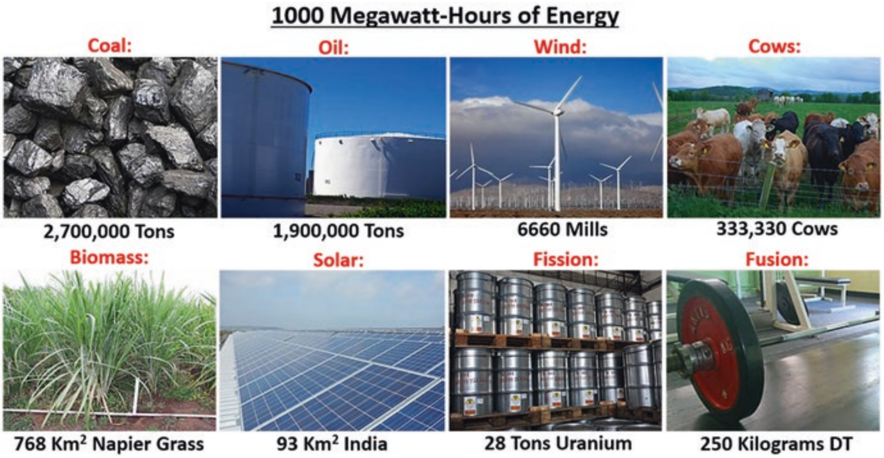


Fig. 2.9 A comparison of the mass of fuel required to produce 1000 megawatt-hours of energy from various sources, circa 2014. (Calculations are drawn from references [1–6])

Net Power = (Fusion Rate - Conduction - Radiation) X Efficiency

Triple Product = Density x Temperature x Trapping Time

Fig. 2.10 Two simple but important equations for plasma fusion power are (1) the Lawson energy balance, which must be made positive for a device to have value as an electric power generator, and (2) the triple product of three important design parameters

This is the next great milestone in nuclear fusion. In many ways, this is the "Wright Brothers Moment" for fusion, equivalent to not only producing aerodynamic lift but also achieving more lift than the weight of the aircraft. As of this writing, no fusion machine has achieved this anywhere in the world, even after more than 70 years of research and development.

Officially, the world record is held by the Joint European Torus (JET). JET is a large tokamak. At the end of 2021, the machine produced 59 megawatts of fusion power on 100 MW needed to drive the machine [9, 22]. This puts the record in fusion at more than halfway to what is needed for breakeven. This is one of several important records for fusion. Others are the longest runtime (thousands of hours), hottest temperature (510 million degrees), and highest plasma density (10^{23} particles per cubic meter, or about three-tenths of one percent of the density of air at sea level), achieved in various labs.

In 1957, John Lawson, an engineer in the UK, applied an energy balance formulation to describe what it takes to get to net power from a plasma-based fusion reactor [8]. His analysis treated the machine as a miniature sun locked inside a building. That energy balance is shown in Fig. 2.10. The maximum net power is the rate of producing energy from fusion minus energy losses due to heat conduction and radiation. This is decreased by the efficiency of transforming that heat energy into electrical energy. This equation became known as the Lawson energy balance, and it provides a good way to think about a fusion power plant.

This energy balance is a great way to understand a power plant because each term can be connected to an important effort within the fusion community. Keep this in mind as we examine each term of Lawson's energy balance equation in this chapter and as you read the rest of this book.

Thus far, the research community has been primarily focused on driving up the fusion energy term in this expression. Getting more energy out of these machines has involved improving the plasma density, temperature, and trapping time, all of which contribute to the fusion rate term. As noted in the previous chapter, this is known as the triple product. This is considered a quick and useful way to compare different fusion approaches. How well does an approach heat, trap, and compress the plasma? How well does it do all three things simultaneously? Researchers have also combined the equations with other considerations to argue that fusion machines must meet a minimum triple for net power. We take that statement with a grain of salt. The calculation for minimum triple product assumes facts about the plasma that do not always apply to every scenario, such as the assumed rates of radiation and conduction losses. Because of this, getting a high triple product is very important, but it is not the whole story for building a power plant.

For example, today, we have huge machines that can reach remarkable triple products but are nowhere near a power plant. The triple product works for fusion as a *science project* but falls short when fusion is used for a *power plant*. For example, efficiency is not considered in the triple product comparison. Two approaches may achieve the same triple product, but one is horribly inefficient and should never be considered for a viable power plant. Two approaches may also have the same triple product, but one may be exceedingly expensive and oversized by comparison. For these and other reasons, this book will focus on John Lawson's original energy balance. The original energy balance is much more relevant to fusion power plants.

As you read through this book, try to connect each term of this equation to the subject you are learning about. For example, you will learn about new superconducting materials that are a huge innovation for magnetic confinement fusion; such an innovation improves the efficiency of the power plant.

Fusion rate is how much fusion energy the machine is generating. It is directly connected to the triple product. Historically, research has focused on raising this fusion rate as high as possible by raising the triple product. Teams have run roughshod over cost, scale, maintainability, and size to achieve the highest fusion rate. Many have argued that there is a minimum triple product needed to make net power in fusion. But built into that statement are assumptions about plasma energy distribution, structure, and behavior, which may not be ultimately true [13].

Conduction is all the energy lost when mass leaves the fusing plasma. This includes all the escaping particles: ions, electrons, fusion products, neutrons, and anything else that carries off energy. Fusing plasmas are constantly bleeding away particles. Ions touch metal surfaces. Hot helium blasts through the containing field. Electrons leak through the walls. All this escaping mass carries energy away with it, depleting the fusion plasma.

The goal of any fusion reactor design is to retain plasma mass and stop mass leaks. One easy trick is to put a space around the plasma. Plasma can be confined by magnetic fields. This allows fusioneers to design their devices with a space between the plasma and the first wall. The containing field “lines of force” (a common and useful representation of a magnetic field, like iron filings that form lines around a magnetic field) should never run into a wall. Charged particles follow those field lines in helical paths. If the field lines run into the wall, the plasma will escape the reactor and kill the machine’s usefulness. For example, the field designs of the tokamak, stellarator, and spherical tokamak all have lines that never hit a metal surface.

A second method to stop mass leaks is to design the walls of the fusion reactor to be very smooth and made out of a nonconductive material. This is especially important for reactors with embedded magnets (examples are dynomak, compact fusion reactor, and polywell). If the walls of the reactor have bumps, edges, points, or corners, these provide places for a charge to accumulate. In extreme cases, this can lead to arcing inside the machine. Some teams have gone so far as to encase their fusing plasma inside glass [14], which is an electrical insulator. Figure 2.11 shows a polywell, which is designed to retain plasma mass and thus minimize conduction.

Mass leaks are the primary reason why fusors cannot make net power. A fusor is made by placing two wire cages inside one another and using a voltage between these cages to heat nuclei to fusion conditions. This will be discussed in more detail in Chap. 10. If the fusor did not have such high mass leaks, it would be an ultrasimple and ultracheap path to a fusion reactor. Sadly, a typical fusor loses about 10,000 times the energy it makes from fusion in conduction losses [10]. This happens because it has a giant metal cage in the center. This wire cage acts like a giant sponge, attracting most of the particles and thus reducing the plasma mass. This highlights an important design principle for all fusion reactors: *retain plasma mass.*

Radiation is energy that leaves the plasma in the form of electromagnetic waves, such as light. This radiation is generated through a natural process described by Maxwell’s equations governing plasma motion. Maxwell’s equations dictate that

Fig. 2.11 The polywell has plasma-facing magnets. The surface of these magnets is designed to be ultrasmooth to minimize plasma conduction. Its design keeps the magnetic field lines from running into surfaces and thus maintains a space between the plasma and the magnets. Over time, these magnets would crack and swell under the neutron load. (Image credit: Dr. Jaeyoung Park)

the acceleration (change in speed, direction, or both) of electrically charged particles produces electromagnetic waves. In a plasma filled with billions of charged particles, there is a constant set of particles that are changing directions or speed, and as such, there is a constant stream of electromagnetic energy exiting the plasma over a broad spectrum of wavelengths, from infrared (IR) through visible light, through ultraviolet (UV), and even X-rays.

Historically, radiation has been categorized by the wavelength of light detected and by which machine generated it. For example, the light emitted from a particle accelerator called a cyclotron was always defined as cyclotron radiation. This has led to plasma radiation being taught in universities as siloed, unconnected topics, such as the cyclotron, synchrotron, and bremsstrahlung radiation effects. But the reality is that all radiation coming from a fusing plasma is created using the same physical mechanism: a particle changing speed, direction, or both, which results in its emitting some of its energy as electromagnetic waves. By its very nature, plasma inside a fusion reactor must be hot enough to generate all these forms of radiation. The reactor is in fact constantly bleeding energy away in this manner, and the goal of any reactor designer *is to limit these radiation losses* as much as possible.

Plasma inside a fusion reactor must be hot enough to undergo fusion events, and generally a higher temperature creates more of these events. Higher temperatures allow nuclei to better overcome their electrostatic repulsive forces. Unfortunately, this also leads—unavoidably—to more radiation losses. Hence, as fusioneers raise the temperature of their machines, they are also fighting against the rising radiation losses that are happening simultaneously.

The ideal fusion plasma would only contain hot ions and very cold electrons. The reason for this is twofold: The hotter ions are more likely to fuse, and the colder electrons would leak less energy as radiation. Such a plasma exploits the fact that the electrons do not undergo fusion and thus do not need to be at high temperatures. If we can create a plasma with hot nuclei and much cooler electrons, we can minimize the radiation loss of the electrons inside a fusion reactor. Unfortunately, as you will read in later chapters, it is not clear to what extent such a distribution is possible since the ions and electrons are constantly exchanging energy and charge (Fig. 2.12).

Efficiency is the fraction of the net fusion power (fusion rate less radiation and conduction losses) that is transformed into useful electric power output. It takes into

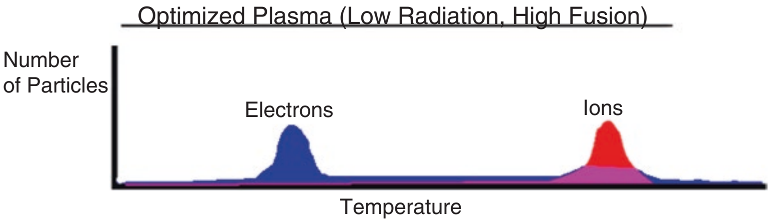


Fig. 2.12 The optimum energy distribution for plasma in a fusion reactor would have the electrons and ions at very different temperatures. Because they interact electrically with each other, maintaining a large difference in temperature is very challenging if not impossible

account the input power necessary to operate the fusion reactor and is influenced in some way by almost every element of the fusion reactor's design and construction. Yet because the focus has been on achieving and sustaining ignition, efficiency is probably the least explored area in fusion research. That makes it the most promising target for future development.

For example, fusion power plants could become far more efficient with the addition of superconducting materials. There is a great deal of technological promise in this area. On the magnetic confinement side, using superconductors allows designers to reach much higher electromagnetic fields in a much more efficient and compact way. Superconducting magnets can produce fields a thousand times stronger than those of conventional electromagnets without significant electrical resistive losses in the coils. Additionally, because superconductors can run continuously with little to no resistance, they can lead to a million-fold increase in confinement time. In fusion devices that do not rely on magnetic fields for confinement, superconductors allow an efficient way for high currents to be transferred inside the machine. This is helpful because fusion machines need large amounts of current to operate. Superconductors come with challenges in cost and design, but we consider them to be the most exciting development in all of nuclear fusion—though we have not yet fully appreciated their impact on fusion technology.

Another area for improving efficiency is how to heat the plasma. One method is to use magnetic reconnection. Magnetic reconnection occurs when two magnetic fields merge to become one field. In fusion power devices, the electromagnetic properties of the plasma itself can lead to a connection of different magnetic fields inside the machine. A reconnection event draws a significant jolt of energy from the magnetic field directly into the plasma. It can pull as much as 45% of the energy in the magnetic field into ion heat [19, 20]. Several tokamaks are already using this to start up their reactor; the process works by merging two rings of plasma from the top and bottom of the machine. Figure 2.13 shows the basic mechanics of a reconnection event.

Other examples of innovation to improve efficiency relate to capturing fusion energy. One particularly promising method (among many possibilities) is called a direct conversion. In 1982, a demonstration of direct conversion achieved 48%

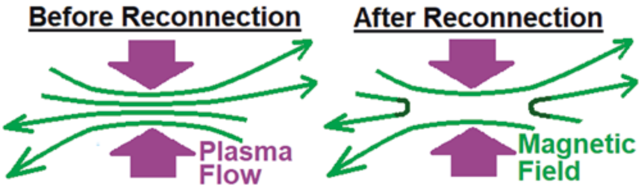


Fig. 2.13 Heating a plasma using magnetic reconnection. Before the reconnection event, a high-density plasma begins flowing between two magnetic fields pointing in opposite directions. The electromagnetic properties of the plasma cause the magnetic field lines between the magnets to join. When this happens, a huge amount of energy comes out of the magnetic field and is deposited directly into the plasma

energy capture in a mirror machine fusion experiment [11]. If we could consistently capture 48% of the net energy from the greatest power source known to humanity, that would be a truly remarkable technological achievement.

2.6 Analytical and Medical Applications

So far, we have focused on using fusion to make electricity, but fusion has several other applications even without producing net energy. Most people are surprised by this. Fusion has actually been on the marketplace since 2000. In the 1990s, John Sved at Daimler Aerospace in Germany was determined to see inertial electrostatic confinement (IEC) move into a commercial product. When Daimler decided to shelve the development of fusor devices, Sved and his wife, Pamela, decided to start their own fusion company, NSD-Gradel-Fusion, in Luxembourg to modify fusors to function as neutron generators. Their company produced its first commercial product, a neutron generator, in 2000.

Neutron generators have many important applications. Among the most important is in neutron activation analysis (NAA), which is a very sensitive technique for identifying minor and trace elements in a sample of material. Such identification has many important analytical applications in the oil and gas, electronics, and mining industries. Neutron beams can also be used to treat cancer or to create medical-grade radioactive isotopes.

Fusors, which we discuss in more detail in Chap. 10, are simple and inexpensive devices that fusion hobbyists can—and often do—build in their garages. NSD-Gradel took fusors in a different direction. They reworked the fusor design to produce a steady, directed beam of neutrons. The company sells products that (such as the one shown in Fig. 2.14) can operate continuously for over 20,000 hours, producing about five billion neutrons per second. The market for NAA and nuclear medicine is large enough that several other companies have followed NSD-Gradel's lead.

One of those companies is SHINE Technologies, formerly known as Phoenix Nuclear Laboratories (Phoenix). It traces its beginnings to 2005, when two doctoral candidates, Greg Piefer and Ross Radel, were defending their doctoral theses at the University of Wisconsin-Madison. Both had worked with fusors as part of their research. Piefer saw a huge possibility for future fusion-based commercial products. When he graduated, he founded a company called Phoenix, which later became SHINE. Meanwhile, Radel had accepted a staff scientist position at a national laboratory.

Phoenix started as a contract house, winning Small Business Innovation Research (SBIR) grants. Its first contract was for approximately $100,000 to build a power supply for the fusor at the University of Wisconsin-Madison. It was the only subcontractor willing to design a power supply that could fit through the door of the laboratory. With this small amount of seed capital, the company began applying for and winning other nuclear SBIR grants. This stream of revenue allowed Piefer to hire his first employees and develop Phoenix's first neutron generators. His goal was to create the world's best neutron generators. The company aimed to go well beyond

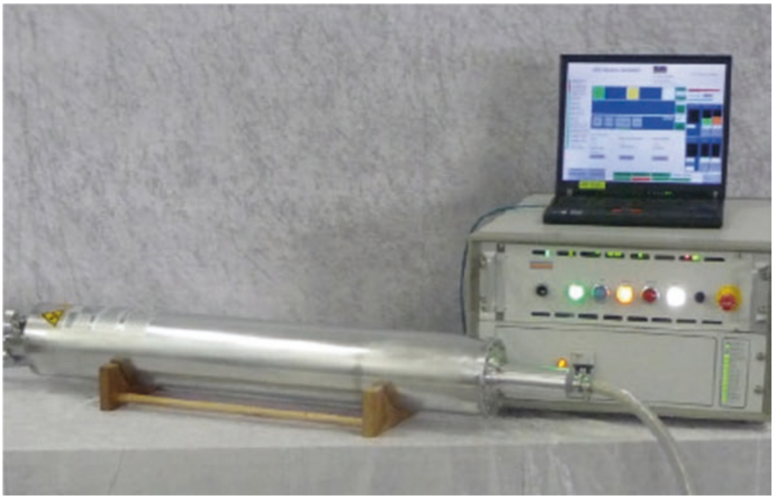


Fig. 2.14 The NSD-50 neutron generator from NSD-Gradel was the first commercial product that used fusion; the first unit was on the market by the mid-2000s. Deuterium and/or tritium gas flows into the inner volume of the tube, where it is heated and ionized. A high voltage accelerates the ions, which collide and fuse, producing DD or DT neutrons as one of the reaction products that exit the tube isotropically

what NSD-Gradel had developed by incorporating fission reactions to amplify the neutron output. On March 22, 2016, the company announced that it had achieved 100 billion neutrons per second for 132 h [18].

2.6.1 Imaging and Analysis Applications

By 2016, Phoenix was selling its first neutron generators for imaging applications like neutron radiography, and Piefer had convinced Radel to come back to run the company. The company has since opened a national neutron radiography center in Fitchburg, Wisconsin, where clients can get parts imaged using neutrons (Fig. 2.15).

2.6.2 Medical Isotopes

In 2010, Piefer (Fig. 2.16) moved on to start a second company, SHINE Technologies (formerly known as SHINE Medical Technologies), to use the Phoenix neutron generator technology to make medical isotopes. At that time, medical isotopes were roughly a billion-dollar-a-year market, and their production involved neutrons from aging nuclear power plants. SHINE's process instead involves neutrons from fusion neutron generators designed and manufactured by Phoenix. The neutrons bombard a uranium target material, which causes fissions. The fission products are highly radioactive. Traditional chemical engineering techniques process the target material

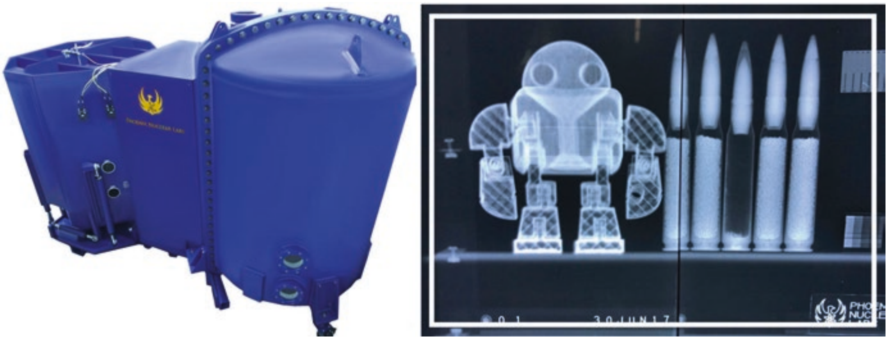


Fig. 2.15 Left, Phoenix Nuclear Laboratories’ Thunderbird machine, which has produced 100 billion neutrons per second for 131 hours continuously. This machine costs about $1 million and is a bit smaller than a car. Right: examples of parts that have been imaged using neutron radiography

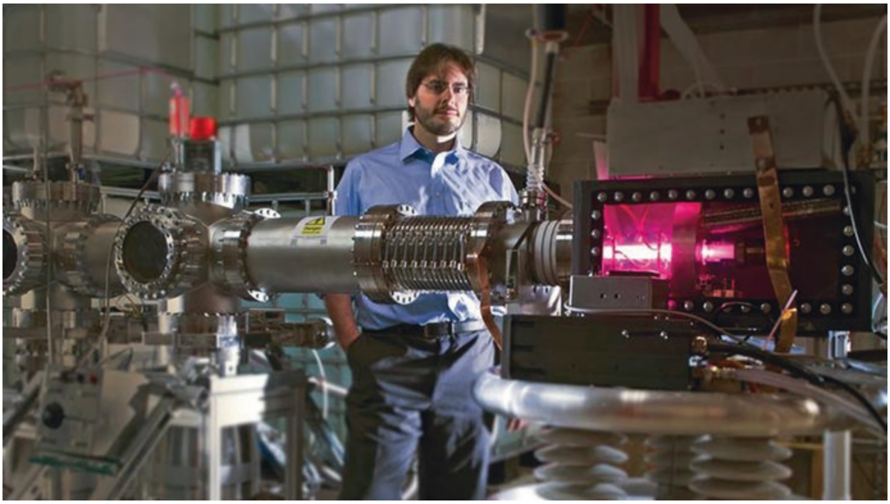


Fig. 2.16 SHINE Technologies’ first neutron generator prototype and the company’s founder and CEO, Dr. Greg Piefer

to separate the radioisotopes, which are used in hospitals worldwide for cancer treatments and physiological tests. As of this writing, SHINE has finished the shell construction of its first medical isotope production facility in Janesville, Wisconsin. The company has contracts with GE Healthcare, Lantheus Medical Imaging, and Health Technology Assessment (HTA), China’s largest medical isotope dealer, to purchase the first batches upon operation of its facility.

Cancer Therapy

Aside from making medical isotopes, neutrons from fusion can also be used directly to treat cancer. The technique is known as boron neutron capture therapy (BNCT).

This method, which was developed in the 1930s, attaches a boron atom to a protein molecule and injects it into a tumor cell. The protein binds inside the tumor, where a neutron collides with the boron nucleus, which splits into energetic alpha particles and lithium nuclei. This kills the tumor cell. Creating a nuclear reaction inside the human body is a radical idea, but, in many cases, cancer leaves the patient with a few options. Moreover, the BNCT process is easily controlled by the proteins used, the number of boron atoms, and the neutron beam passing through the body. The proteins can be specific enough that the material only goes into specific tumor cells, and the energy of the neutrons can be selected such that they either are captured by boron nuclei or pass harmlessly through the body.

For that reason, researchers refer to BNCT as a sniper for cancer. The fusion company TAE Technologies first spun off a BNCT business unit in 2017. The goal was to commercialize this medical process and sell it to hospitals and cancer treatment centers around the world. In 2021, that American company started operating its first machines at the Xiamen Humanity Hospital in China. Even if net power is still distant, this technology provides a substantial market for fusion devices (Fig. 2.17).

2.7 Space Propulsion

Ultimately, the most innovative application for fusion may be in the propulsion of deep-space vehicles. This potential application has a long history. In the 1960s, physicist Dr. Robert Bussard proposed a concept called a ramjet. The ramjet would fly through space and funnel all the particles (mainly hydrogen and helium atoms) into a fusion chamber that acts as a jet engine. Once fusion had occurred, the

Fig. 2.17 A CAD model of boron neutron capture therapy machine now being developed by TAE Life Sciences

products of the reaction would be exhausted out of the back of the ramjet at exceedingly high speeds. Calculations indicate that the ramjet design would be able to accelerate the spacecraft to a speed of 100 kilometers per second, or more than eight times the speed needed to escape Earth's gravity. A ramjet-powered spacecraft could reach Mars in about 1 month rather than the typical minimum of about 6 months achievable with the current technology.

Bussard never did tests to prove the ramjet approach, but modern teams have gone further with their concepts for a fusion rocket. We close this chapter with brief descriptions of three fusion-based space propulsion systems. All of these machines offer significant performance improvements over current space propulsion technologies. Many current rocket thrusters use plasma in their inner workings, but no existing rocket has been able to demonstrate fusion. One of the advantages of the fusion rocket is that needs only to produce useful energy, not net energy. This has led supporters of fusion rockets, such as Fusion Industry Association Space Comittee, to argue that fusion rockets are inherently easier to build then a fusion power plant that produces more energy than it consumes. These efforts will be reviewed below.

Helicity Space is a promising space propulsion startup that was founded in 2018 in Berkeley, California. Its design uses reconnection to quickly heat plasma and initiate fusion reactions. Figure 2.18 shows one of the company's experimental machines.

This machine sends a pulse of four plasma jets into a chamber. These jets of plasma twist together. They wrap around one another like strands of a rope. As the plasma wraps together, so do their corresponding magnetic fields. This gives ideal conditions for reconnection. Magnetic reconnection happens when these jets merge. Reconnection dumps energy into the plasma, as much as 45% of the energy in the magnetic field [19, 20]. That preheats the plasma to a temperature suitable for fusion. This hot material then travels down a magnetic nozzle, where it is compressed, initiating fusion events. These fusion reactions make the material even hotter. The now superheated plasma expands through an exhaust nozzle and shoots out of the back of the ship, producing a high thrust.

MSNW is a small business located in the greater Seattle area that has devoted years of research into developing a fusion-driven rocket. The company's general approach involves using a field-reversed configuration, also known as a plasma structure or plasmoid. (Plasma structures will be covered in greater detail in Chap. 7). Briefly, a field-reversed configuration is a loop of plasma that creates a magnetic field that acts to contain itself. Critically, the plasma density is higher inside this plasma loop, improving the odds that fusion reactions will take place. As of 2018, MSNW was being funded by the National Aeronautics and Space Administration (NASA) through a series of small business research initiatives. Figure 2.19 shows an example of an experimental rocket prototype built by the company. In this approach, the company creates a smoke ring of hot plasma and attempts to compress it by passing it through a magnetic nozzle. Ideally, this compression pushes the material up to fusion conditions, and the resulting hot fusing plume passes through the exhaust nozzle and pushes the ship forward. The performance of this rocket design could be enhanced using superconducting magnets.

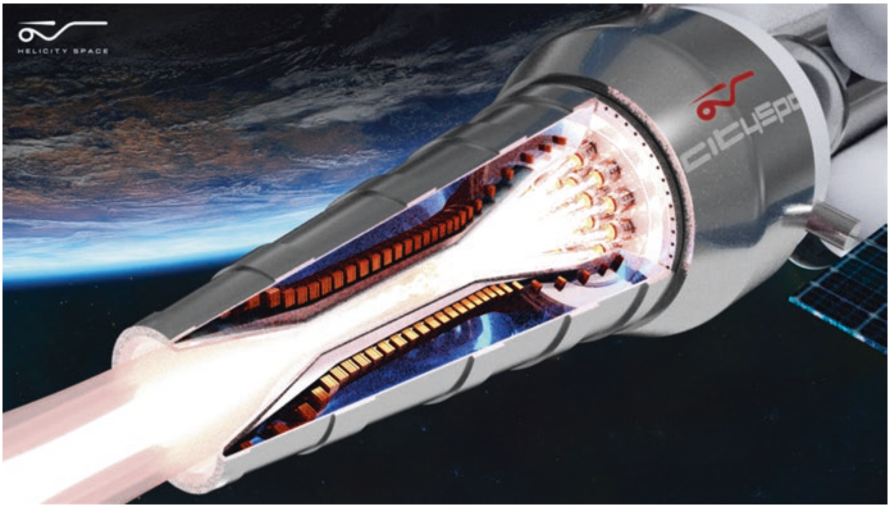


Fig. 2.18 A fusion rocket designed and modeled by Helicity Space, a fusion startup in California. This machine has four stages. First, it injects jets of plasma. Next, those jets twist together and merge. This initiates a magnetic reconnection event, releasing a huge amount of energy and preheating the plasma. This hot material passes into a magnetic nozzle. The third compression step starts fusion reactions in the core. The remaining plasma is superheated, expanded, and shot out of the back of the ship

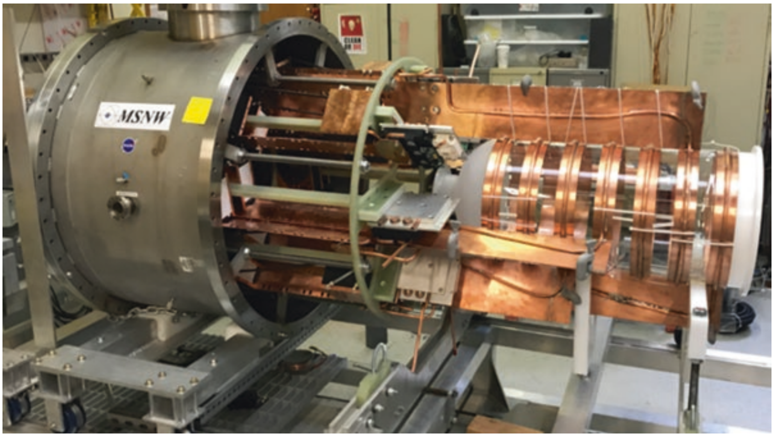


Fig. 2.19 A prototype of a fusion rocket developed and tested by the company MSNW between 2000 and 2018. This work was funded by Small Business Research Initiatives through NASA. The device shown here is made with all copper magnets and tested inside a vacuum chamber to simulate space. The approach creates a small ring of plasma and passes through a magnetic nozzle before ejecting the exhaust cone

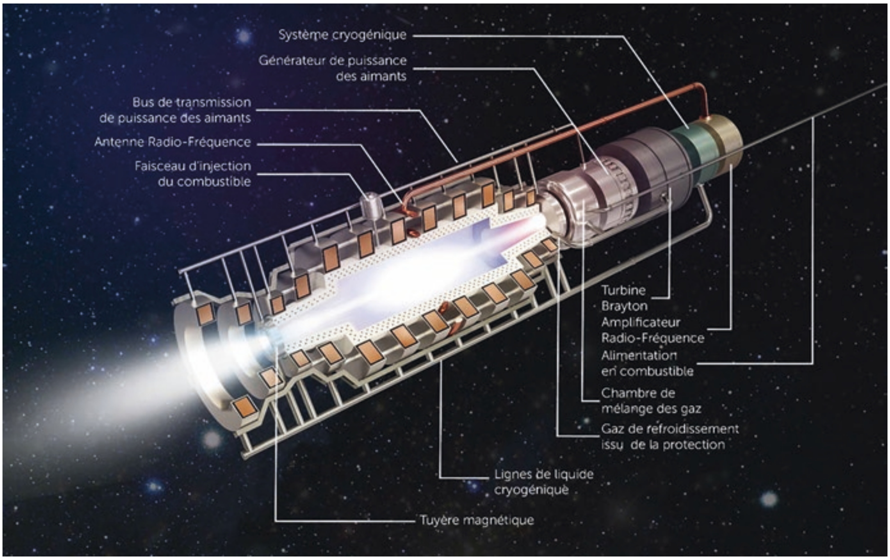


Fig. 2.20 An artist's conception of a fusion-driven engine built around the field-reversed configuration. Plasma flows through this long tube, past the FRC-fusing core; is superheated; and exits out of the back of the ship. Superconducting magnets encircle all of this, controlling the direction and structure of the plasma inside

Princeton Fusion Systems is another company whose fusion rocket approach relies on a field-reversed configuration. The company is located in Princeton, New Jersey, and has won a string of funding awards from NASA to develop its rocket approach since 2000. This approach holds a hot fusing plasma inside a structure at the back of the ship. As material passes around the outside of this structure, it is superheated by the fusion reactions. The remaining plasma is ejected from the back of the ship in a rocket exhaust plume. The team is basing its rocket on the Princeton field-reversed configuration, an experimental device at the Princeton Plasma Physics Laboratory. This will be covered in more detail in Chap. 7 (Fig. 2.20).

Princeton Fusion Systems expects that its fusion rocket engine, when fully developed, will generate up to 280 newtons (63 pounds) of thrust. This makes this rocket ten times better than the most advanced space thrusters in development. To get a handle on what that means, author Moynihan reached out to the company's Vice President, Stephanie Thomas. She plugged that thrust into orbital software that the company sells and predicted that their FRC rocket could get from Earth to Mars in 30 days, allowing humans to spend a month on Mars and take 60 days for a return flight. This shortened duration has a significant advantage for the crew because it will minimize their exposure to harmful radiation in interplanetary space.

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The Pinch Family

3

Summary

The first successful attempt to produce fusion reactions in the laboratory occurred in the early months of 1958 at the Los Alamos National Laboratory. Researchers there used strong magnetic fields to compress—or pinch—a plasma. This was the first time that humans had gotten bulk fusion reactions in a device that was not a bomb. But since the tests were classified at the time, only the people who knew understood the significance. Humanity had silently slipped into the age of controlled nuclear fusion. Even today, this event is underappreciated and undervalued and receives far too little attention in history books. In our view, it ought to be marked as a monumental accomplishment by the human race. The first device to do it was a pinch machine, and that is topic of this chapter.

3.1 Introduction

If fusion approaches were a big extended family, the pinch would be the tribal elder, with its lineage dating back to James (Jim) L. Tuck's work in the early 1950s. Not only was it the first device for working controlled fusion, but its influence also shows up in many modern approaches (Fig. 3.1).

True, fusion had occurred in a laboratory many years earlier. It was famously discovered by Dr. Mark Oliphant in 1933 at the Cavendish Laboratory in England [5]. But that lab was just experimenting with a particle accelerator and was not attempting to create a sustained fusion reaction. Fusion had also taken place in thermonuclear explosions. In November of 1952, the United States tested the first device that used a fission bomb as a trigger for a massive explosive fusion reaction—the hydrogen bomb.

But creating a controlled fusion process proved far more difficult than just building a bomb. Three countries started research programs after the war: the United

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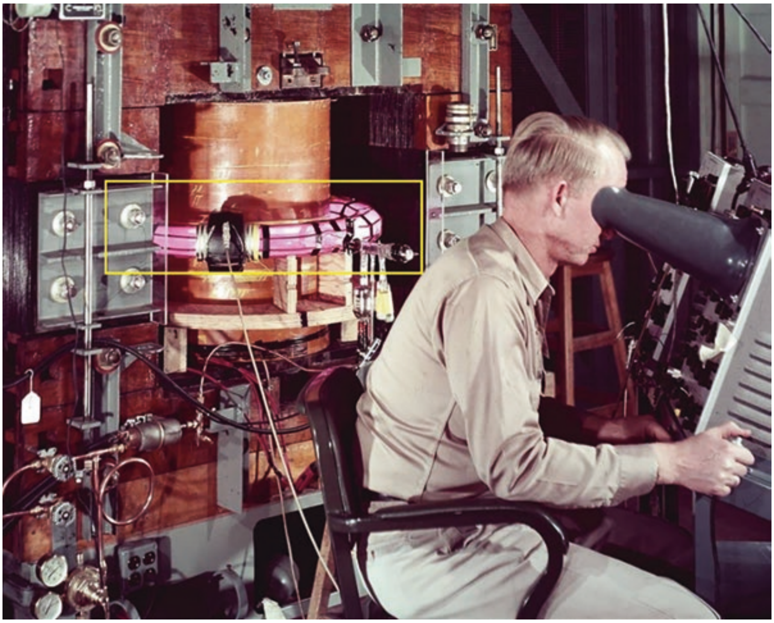

Fig. 3.1 The Perhapsatron, an early fusion device developed by Dr. Jim Tuck. The device creates a region of high magnetic field (inside the yellow box) that compresses, or pinches, plasma flowing in the torus, highlighted by the yellow box

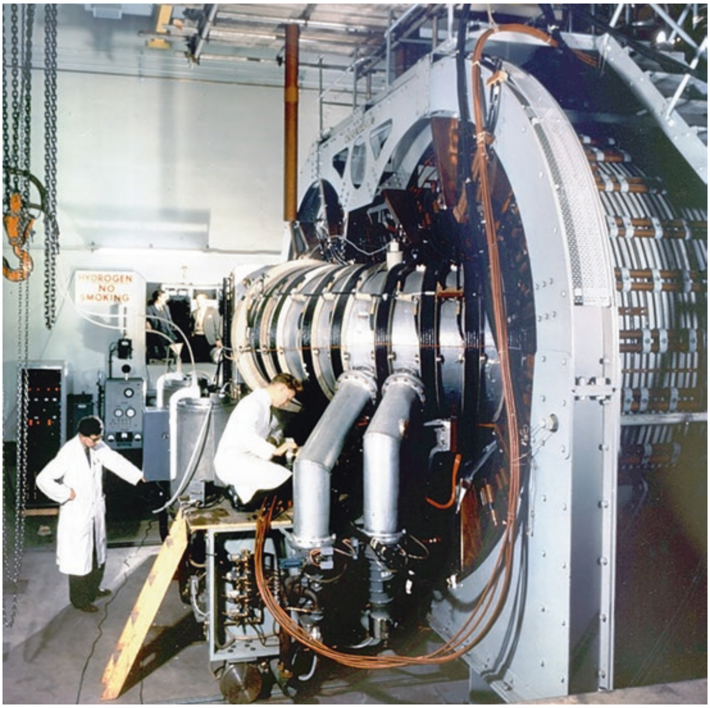

Fig. 3.2 ZETA (Zero Energy Thermonuclear Assembly), a large pinch machine [17] built in England

States, the United Kingdom, and the USSR. The UK program started their work at an airfield outside Harwell. They built a large toroidal pinch machine called ZETA (Zero Energy Thermonuclear Apparatus). In August of 1957, they claimed that this machine had achieved fusion, but this turned out to be false [16]. The neutrons that had been detected were not actually from fusion. This was an embarrassment for the UK atomic program. It had been a very public announcement and the retraction was also very public (Fig. 3.2).

Sadly for the UK but not for science, the first working bulk fusion device was built only a few months later in the United States. The key difference between the American and British efforts was that the United States managed to keep their discovery secret. When they finally achieved fusion with a theta-pinch (see below) machine named Scylla I, only a few people outside of Los Alamos National Laboratory knew that it had even occurred [2]. Humanity had silently slipped into the controlled fusion age [7].

3.2 Types of Pinch Machines

Figure 3.3 shows the seven pinch approaches, which will be discussed in this chapter, and how they are related.

3.3 Z, Theta, and Screw Pinch

Los Alamos had been working on pinches since the beginning of 1952. An early champion for the idea was Jim Tuck. To kick the effort off, the federal government held a fusion competition in Washington. The best proposal got a $50 thousand grant to develop its idea. Tuck entered the contest with a pinch concept, but he ended up losing. Undeterred, he returned to the lab and got the director to fund the project using laboratory funds. Tuck assembled a small team. Over the next 60 years, they would follow several dead ends before achieving fusion.

The simplest approach in this family of fusion concepts is the Z-pinch, which is illustrated in Fig. 3.4. It starts with a toroidal vacuum tube that is filled with

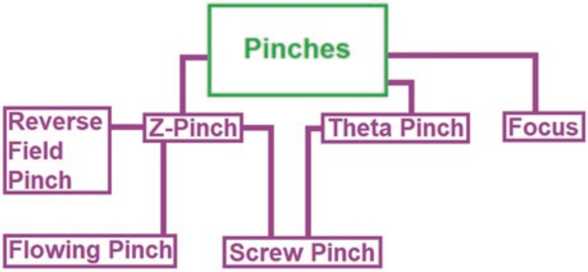

Fig. 3.3 The seven pinch approaches discussed in this chapter and how they are related. Scylla I, the first device to produce bulk fusion in a laboratory, was a theta pinch

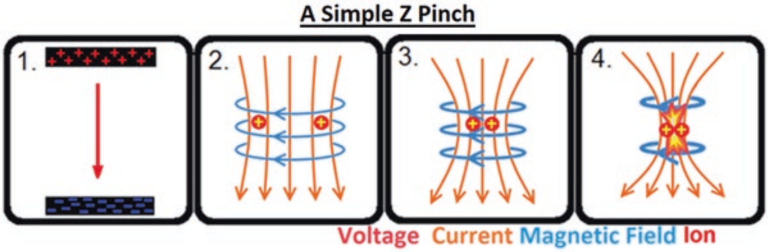

Fig. 3.4 The most basic pinch concept is the simple Z-pinch

deuterium plasma. A burst of electric current is shot along the direction of the tube's central axis, either inside the tube walls or within the tube center itself. This passing current creates a pulse of magnetic field that wraps around the plasma, which should in theory squeeze it inward toward a pinch point and heat it to ignite fusion. The resulting fusion products would fly out in all directions.

Tuck called his first Z-pinch machine the Perhapsatron (Fig. 3.1). The machine was designed to create a pinch that raced along the central axis of the torus. It failed [2]. Yes, it was pinching the plasma, but the effect was messy. Instabilities, largely due to the tendency of accelerated charged particles to radiate electromagnetic energy (X-rays in this case), made the plasma wiggle apart before fusion could occur. No fusion neutrons were detected.

One of the younger team members, Marshall Rosenbluth, set about redesigning the device. Instead of running the current around the toroidal tube that contained the plasma, he made it flow in a circle around the outside of the tube. This makes a magnetic field that runs down the middle [1, 2]. That redesign led to Scylla I, the first successful controlled fusion machine.

Rosenbluth's idea led to a classic example of a theta pinch. The names Z and theta refer to the direction the current is traveling along the plasma cylinder. Z is along the central axis of the cylinder, while theta is the angular position around the outside. In a theta pinch (Fig. 3.5), the magnetic field cannot penetrate the electrically charged plasma. Instead, the field presses in, squeezing and further heating the plasma. Material inside the Scylla I machine reached 15 million kelvins [1], starting fusion reactions. The reaction products (neutrons, hot helium, unfused ions, X-rays, etc.) flew out in all directions.

The difference between a theta pinch and a Z-pinch is that the fields are swapped. If you send a magnetic field in the center, you get a theta pinch. If you send an electric field in the center, you get a Z-pinch. Eventually, each pinch approach succeeded in starting fusion reactions, but both also suffered from plasma instabilities [7, 11, 18]. In an attempt to stabilize the pinch against these problems, the Los Alamos team tried to combine both designs. In the process, the team created a screw pinch. This helped stabilize the plasma but only slightly [30] (See Fig. 3.6).

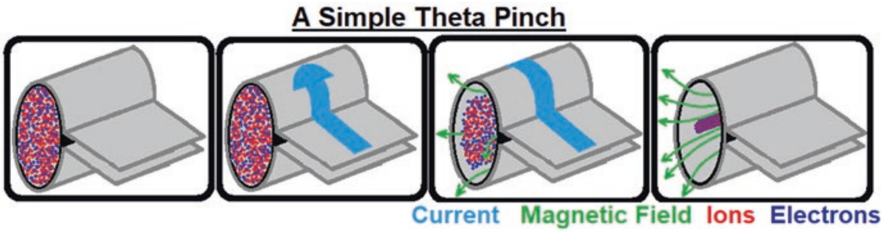

Fig. 3.5 How a basic theta pinch works [7]. Current is passed around the outside of a gas- or plasma-filled tube. A magnetic field forms in the center and presses inward. This forms a pinch

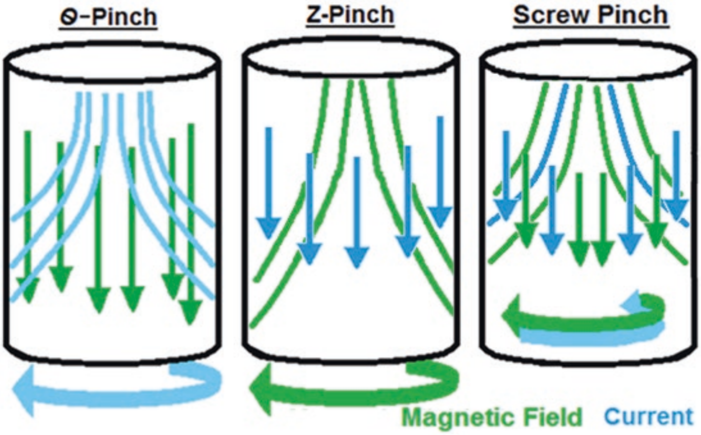

Fig. 3.6 A basic comparison of three kinds of pinches: theta, Z-, and screw pinch. Note that the devices use short bursts of current; they make temporary, transient magnetic fields

Unfortunately, none of the Scylla machines got close to fusion power. The program ended in 1977 [2]. Over 25 years, Los Alamos built five of these Scylla pinches. The program had received a seemingly blank check for funding. Over 13 years, $21 million was spent [6]. This amount of funding speaks to how easily and readily fusion research was supported in those days.

Even though the Scylla program ended, it did not mean the end of pinch research. Pinch machines continue to be built and are still in use today. Machines like MAGPIE (in the UK), SHIVA (New Mexico), FuZe (Washington), and the Z-machine (Sandia) are all examples of pinch machines. Today, some groups are still actively trying to turn the pinch into a fusion power source [13, 20]. Some of these groups are housed in traditional universities and laboratories, while others are private companies. These modern pinches are more exotic than the earlier versions. They are designed to overcome specific problems faced by the first pinch machines, but none have succeeded to date.

3.4 MagLIF

One of the modern efforts to test the Z-Pinch is called MagLIF, which will be discussed in greater detail in Chap. 9 [47]. This acronym stands for magnetized linear inertial fusion and is currently being tested at Sandia National Laboratory. Research into this started in the late 2000s and was led by Dr. Daniel Sinars. The idea is to preheat the plasma with a laser beam before it is pinched using a Z-pinch. This approach is going to be discussed in more detail in later chapters on inertial confinement fusion.

3.5 Pinch Problems

One of the basic problems that emerged from pinch research was the **snowplow effect** [3]. Encountered early in pinch development, this was easily fixed. As the effect pinch moved forward along a tube of plasma, material would pile up in front of it like snow in front of a plow. This could be a mix of charged and noncharged particles [34]. This mixture was not harmless. If there were neutrals, they would clog up the fusion mechanism. If the particles were charged, they could make their own disruptive field as they moved. This instability is very devastating in a dense plasma focus. Eventually, the effect could make the pinch unstable, causing it to collapse. When it did, material would spill out. Figure 3.7 depicts this effect and the Reversed Field Pinch, a device that evolved to study it.

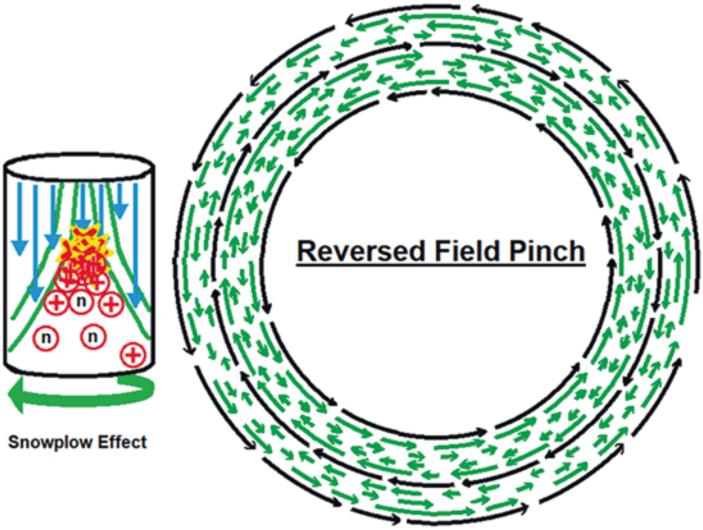

Fig. 3.7 The “snowplow effect” and one device that evolved to study it, the Reversed Field Pinch (RFP). The RFP is a very strange pinch because it reverses field direction [33] in the center

One way to beat the snowplow effect was to race the pinched plasma around in a circle [34]. The logic was that they could keep the pinch running to outlast the snowplow. This led to a whole new kind of device called the “Reversed Field Pinch,” also called the “toroidal pinch.” This is a pinch running around a loop. The most remarkable aspect of this approach is that the field switches in the center. This field may flow clockwise in the center and counterclockwise on the outside. Such a flip in direction is very odd.

Today, the best example of the toroidal pinch is at the University of Wisconsin, the Madison Symmetric Torus [34]. This machine was first opened in 1988, so it is from a much later era than Scylla. Creating such unique fields, which are delicate and odd and make the RFP susceptible to known instabilities, was an important but difficult challenge [35].

In fact, one of the project’s goals was to do a controlled study of those instabilities and apply them to fusion research [36]. First, in the ring’s center, there is a magnetized iron bar. Next, a field inside the device’s shell creates a current inside a weak plasma. The third step is to make a strong magnetic field around the ring using current in the center. At that point, most of the plasma is injected. Finally, as the central current dies, a small reversed field is applied at the edge, creating the delicate Reversed Field Pinch. That field only exists in bursts of about 100 milliseconds [35]. The Reversed Field Pinch is not a strong candidate for a fusion power plant because it is intentionally unstable. However, it has been a good platform for studying instabilities, primarily in tokamaks.

3.5.1 Interchange Instabilities

If you ranked all the problems faced by early pinch researchers, the snowplow would be a minor issue. More pressing are three instabilities, which will be discussed below: the interchange, sausage, and kink instabilities. As is often the case in technology development, addressing one problem often leads to a new advance. Beating these instabilities has led to two significant modern fusion approaches: the LDX and the flowing Z-pinch.

Interchange instability occurs when the plasma is adjacent to an empty void of space. The natural tendency is for the plasma to bleed into that void. To prevent this from happening, researchers create high magnetic fields in the void, causing magnetic pressure to keep the plasma out. If the plasma had a perfectly smooth surface, that strategy could be successful [22], but ripples naturally form, and that poses a problem. It sets up the interchange instability.

The problem is that the ripples between a plasma surface and a void never form uncharged. The ion and electron motions are opposite from each other. The result is that positive and negative charges move as waves and separate across the ripple, creating an electric field [10]. The electric and magnetic fields interact to amplify the waves in a positive feedback loop. The ripples grow until the system becomes unstable, forming an interchange instability (see Fig. 3.8).

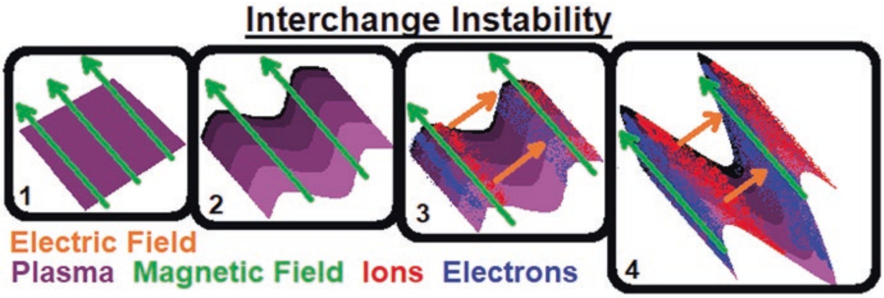

Fig. 3.8 Interchange instability happens as a small ripple on the plasma amplifies itself into a huge wave, which can disrupt the pinch. The plasma sits next to a void with a magnetic field. Ripples form on the surface. The positively charged surface ions move left, and the (negatively charged) electrons move right. This creates an electric field that forms across the ripple [10]. That leads to an electromagnetic force that amplifies the effect, in a positive feedback loop

The most destructive part of this mechanism is that it has a positive feedback loop. That makes it so easy for the instability to form, grow, and rip the pinch apart. This instability has also been called flute instability because the plasma forms into something that looks like a fluted Roman column when this happens [9, 10, 19]. Interchange instabilities can start when there is a slight ripple on the surface of the plasma or when there is a density mismatch in the plasma. A density difference—where a heavier fluid pushes on a lighter fluid—can also cause this ripple to form and amplify.

The pinch is a prime candidate for forming an interchange instability [11, 21]. It is a classic example of a plasma adjacent to a void, with a surrounding magnetic field. The magnetic field is a necessary evil in this scenario because it is needed to compress the plasma column. Of course, the surface of the plasma column is not perfectly smooth, so ripples form, which create the interchange instability [8].

As noted above, these ripples are not neutral; rather, they have positive and negative portions, which separate from each other [10]. This generates an electric field on the surface, which is perpendicular to the magnetic field, creating a Lorentz force. This force pushes the tops of the ripples out into the void and deepens the wave troughs. The ripples grow and grow until the pinch is ripped apart. Figure 3.9 illustrates this sequence of events.

Interchange instability can form in many common fusion systems, including tokamaks, plasma cannons, and spheromaks. Any time a plasma surface is next to a void, ripples can form, which leads to interchange instabilities. Over the decades, fusioneers have ways to build and operate these devices to avoid some or many of these instabilities; this will be discussed further on in the chapter.

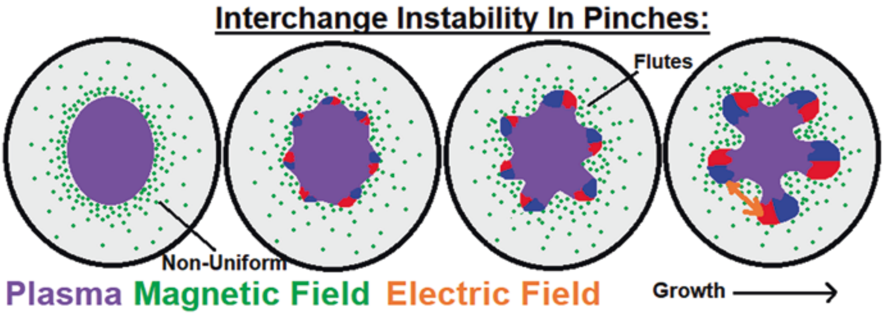

Fig. 3.9 Interchange instability in pinches [10]. The plasma is surrounded by a void with a magnetic field. Positive and negative ripples form on the surface of the plasma. This sets up a Lorentz force that deepens the ripples [8], which grow until they eventually rip the pinch apart

3.5.2 Kink and Sausage Instabilities

The pinch is also susceptible to **kink and sausage instabilities**. Kink and sausage effects can happen in many situations but occur mainly when the plasma has two characteristics. First, the plasma is tube shaped, and second, an electric current is flowing through the plasma [28]. Sometimes plasma currents are part of the design. For example, tokamaks run a current around their ring to heat up [22]. But sometimes plasma currents are unwanted and end up destabilizing the fusion device.

The terms kink and sausage come from descriptions of what plasma looks like when these instabilities are happening. A plasma column undergoing a kink instability is similar to a tube kinking up into a bent or twisted shape. Similarly, sausage instability happens when the plasma forms sausage-like shapes along the plasma column.

Both instabilities form when there is current flowing inside a column of plasma, creating a magnetic field around the outside. This field has a magnetic pressure that pushes into the plasma, crushing it inward. If the plasma column bends, bows, or develops a neck-like structure, the current and its related pressure both become uneven. If the plasma necks, it will lead to sausage instability. If the plasma bows, it will lead to kink instability. Sausage instability is shown in Fig. 3.10 [29].

Sausage instability is another example of a mechanism with a built-in positive feedback loop. It starts when the plasma necks, narrows, or thins out. When it does so, the surrounding field gets stronger. This happens because the same amount of current has to move through a tighter column. The denser current leads to an even higher magnetic field, which puts even more pressure on the plasma. The result is that the plasma will neck off, like sausages being formed. This effect can rip the pinch apart.

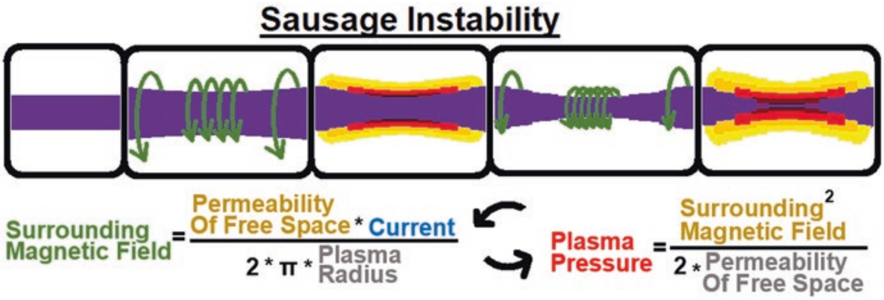

Fig. 3.10 The mechanism for sausage instability is another example of a positive feedback loop that can destroy plasma conditions [29]. The plasma column necks. This forces more current through a thinner column, driving the magnetic pressure higher around the neck. This squeezes the column thinner, creating a feedback loop. The increasing magnetic pressure creates a shape like adjacent sausage links, which eventually leads to a break in the plasma

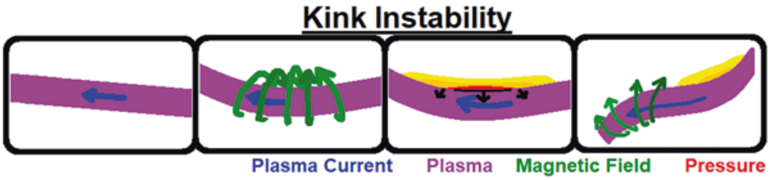

Fig. 3.11 The mechanism for kink instability [14, 22]

3.5.3 Kink Instabilities

The same uneven magnetic pressure that drives plasma to neck off also drives it to form kinks when a plasma column starts to bend [22]. A bend will naturally start to form whenever pressure around the plasma column is slightly unequal. This also kicks off a positive feedback loop, which can lead to destroying the fusing plasma. When the plasma bends, the density rises on the inside of the curve. Pressure is higher on the inside of the bend. It pushes back, straightening the plasma. But this causes another bend to form. In real life, kinked plasma can look like a wriggling snake, as in Fig. 3.11.

Bottom line: if you get a column of plasma with a current flowing through it, it can behave badly. It will want to bend, neck, narrow, or wriggle. It will do so on its own, in an uncontrollable way. This was a problem for all the early pinches because they have tube-like shapes, and they use an internal plasma current to drive the pinch.

3.6 Dealing with Instabilities

Fusioneers can do one of three things with instabilities: accept, restrict, or try to kill them off. The interchange, kink, and sausage instabilities are just examples of a bigger class of fusion problems. The plasma just seems to do what it wants sometimes. Fusion researchers are constantly faced with how to deal with this.

Accepting instabilities means exploiting them to help drive the reactor. For years, this was considered a fringe idea. But today, there is at least one effort that is trying to do this: the dense plasma focus. The dense plasma focus uses a series of instabilities to heat, stabilize, and trap its plasma [37]. Supporters sell the device as a set of naturally occurring unstable states in plasma [38]. The focus has been researched continuously since the early 1960s and for most of that time in Russia. However, using instabilities can create problems because it gives the researcher less control over how the plasma is going to behave.

Instabilities can also be restricted. They all have conditions in which their feedback loops will grow more slowly rather than disruptively [12]. None of this was understood at the beginning of fusion technology. Early researchers did not have the tools to conquer these problems. Over decades, researchers worked out ways to stabilize the pinch [30–32]. This was normally done with math first and then later tested in real life. One approach to stabilizing pinches is to control the pressure. If the plasma pressure stays below a certain level, the system is more stable. A second method is using shear flow, produced by buffeting the pinch with a high-velocity, flowing plasma, an approach developed by Uri Shumlak in 1995 [39]. The plasma inside a shear-flow-stablized pinch has an increasing velocity inside the pinch from the center to the edge. A high plasma speed inside the pinch helps stabilize it [31]. This is a deep and profound idea and a direct approach to stabilizing the pinch.

The last option is to kill off these effects. The most direct way to do this is to make the plasma device too small for them to form [27]. If the size of the instability is bigger than the plasma itself, then these instabilities cannot form. This concept is known in fusion research as a safety factor, which is the ratio of the size of the machine to the size of the instabilities. To design to meet this safety factor, researchers have to know the size of the instability before they build their machine. All three instabilities in this chapter have a typical size: the ripple wavelength on interchange and widths for kinks and necking (See Fig. 3.12).

A safety factor is a deep and fundamental idea around how to design a fusion device. This factor can be applied to many plasma devices and instabilities, not just the ones described in this chapter. It has been applied to ropes of plasma, pinches, loops, and plasma thrusters [22–26]. In tokamaks, it manifests itself as the mathematical definition shown in Fig. 3.12, which is related to the dimensions of the plasma and the applied magnetic field. If that factor is greater than 1, the tokamak is too small for instabilities to form.

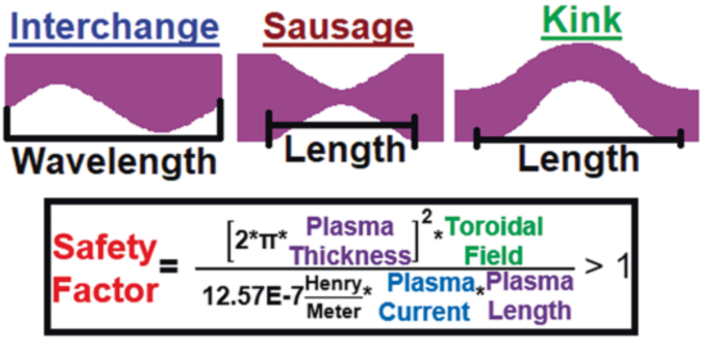

Fig. 3.12 The typical size of each of the three instabilities that plagued the pinch. Also included is one example of a safety factor for a tokamak, which is a mathematical expression needed for making a fusion device too small for these instabilities to form

3.7 The Flowing Pinch

In 1995, Uri Shumlak was at a turning point in his career. He was coming off a job at Kirtland Air Force Base in New Mexico, which was home to two large pinch machines [45]. On paper, he had found a way to stabilize the pinch. The idea was to create a stream of plasma and get it moving through a pinch. The key was to get the edges of this stream moving faster than the middle. This could theoretically stabilize the pinch [31]. A stable fusion pinch would be a big innovation en route to creating fusion power.

Theoreticians like Harold Grad at New York University (NYU) proposed the idea in the 1950s and 1960s, but they never attempted to test it out experimentally. But by the 1980s, it became clear that this idea could work because shear flow was being used to stabilize the tokamak. By the time Shumlak began pursuing this research, there was a body of work inside tokamaks that he could draw from.

The idea was exciting for Shumlak. He decided to keep pursuing it when he got to the University of Washington in 1998. This project eventually became a whole new approach to fusion: the flowing Z-pinch, which his group spent over 20 years developing. They pushed the lifetime of the pinch to thousands of times longer than any previous machine, a record of 70 microseconds [40], and it could probably have attained even better performance with more money. To do that, he needed to get out of the University. So in 2017, he formed a company that today is known as Zap Energy (Fig. 3.13).

The flowing pinch produces fusion in what is essentially a flowing lightning bolt. It has four steps, shown in Fig. 3.14 [41]. The first step is to create the fields inside a tube-shaped vacuum chamber. This tube has a long negative electrode in the center and a magnetic field wrapped around the outside. This creates a voltage and a magnetic field at right angles to each other, resulting in a Lorentz force that would push any plasma in the chamber forward. The second step is to form a plasma by puffing in fusion fuel, which the voltage separates into positive ions and electrons.

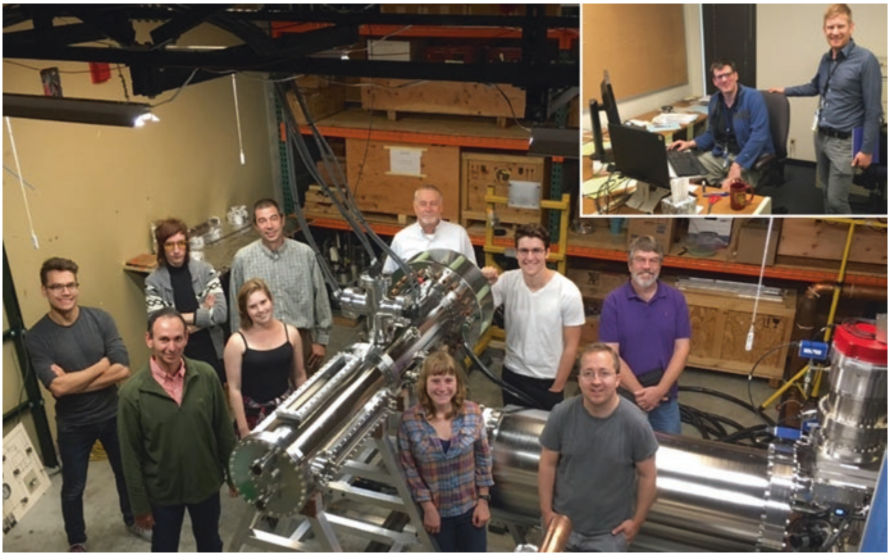

Fig. 3.13 The Zap energy team, circa 2017 [46]

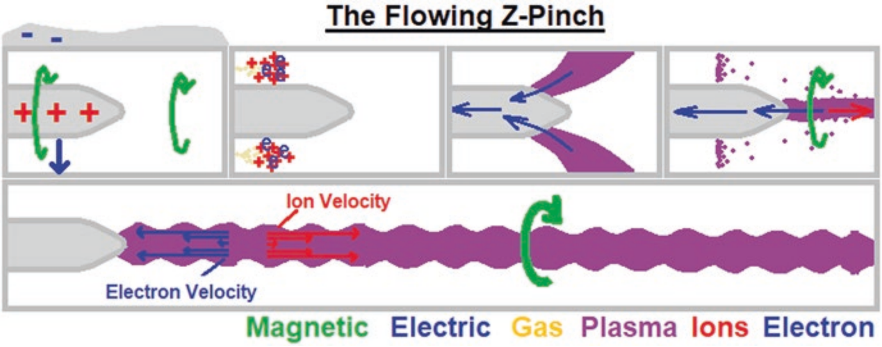

Fig. 3.14 The multistep process for creating and sustaining a flowing Z-pinch. The sides of the tube are negative against a positive inner electrode. A magnetic field swirls around the outside. A sheet of plasma forms. This sweeps forward and forms a flowing column. From here, the electrons flow left into the electrode, and the ions flow right into the end of the tube. A hole at the end of the chamber allows the ions to flow out. This moving charge makes a surrounding magnetic field, which pinches on the column. The pinch is stabilized by shear, namely the increasing speed from slow in the center to fast on its edges [15, 43]

In the third step, a sheet of plasma sweeps forward, forming a lightning bolt—a flowing, fast-moving column of hot plasma—in front of the device. Electrons flow along the column, making a pinching magnetic field around the outside. Critically, the edges of the beam move about ten times faster than the core, a shear that helps stabilize the plasma.

The flowing pinch has achieved some impressive results. In 2018, the team could keep it stable for 100 microseconds [44]. That is about 10,000 times as long as previous pinches, a major improvement. During tests, fusion happens only during 8 percent of their run. The plasma they used was only 20 percent fusion fuel; the rest was normal hydrogen. In 2021, the company partnered with national laboratories to get an independent, third-party test that proved large-scale fusion reactions [50]. The proof was to use detectors to measure the energy of the fusion neutrons and show that they match those expected from deuterium fusion.

One of the strengths of this fusion approach is that it can reach high densities very cheaply and easily. The flowing pinch can achieve 10^{23} ions per cubic meter. That density is roughly halfway between a tokamak and a laser fusion system but at a fraction of the price. The density actually compensates somewhat for relatively cold ion temperatures. As of this writing, the best the team can achieve is 2000 electron inch with a liquid metal. Volts [42]. That is relatively cold for ions inside a plasma. So, in reality, the fusion rate in this approach is driven more by ions being packed together rather than by collision speeds. The flowing pinch makes up for cold ion temperatures via higher densities and longer run times. The final advantage of this machine is its relatively small size. Small is always cheaper. The pinch itself is a beam about 3 feet long and the width of a cell phone charger cable [42], and the whole setup is about the size of a car.

However, what is described here is just a lab experiment. The device would need major changes to become a power plant. In 2014, the Zap team won a $5.2 million grant to find a way to make a power plant using the flowing Z-pinch. They had three immediate problems to solve: run time, scale, and extracting power. Achieving longer runs likely meant finding better ways to start and hold the plasma [42]. Odd things tend to happen when the pinch is first formed, which can lead to its falling apart later on. To run longer involves beating these problems. Moreover, long runs will require a stream of plasma to feed and sustain the pinch and more durable electrodes inside the machine. Longer run time alone was not enough; the pinch also had to get bigger. On paper, scaling seemed possible. On paper, this stabilization effect should scale up [46]. But real-life effects often show up that were not anticipated in the paper studies. A bigger pinch means higher temperatures, magnetic pressures, sizes, and currents. Finally, even if the run-time and scaling-up issues could be solved, the team still had to find a way to capture the energy. Their design was to surround the pinch with liquid metal. Several fusion teams are using liquid metal in their plant design [46, 48]. Figure 3.15 shows a possible design for a flowing Z-pinch fusion power plant.

Liquid metal has four advantages for a flowing Z-pinch reactor. The first is that it absorbs the harmful products of fusion—neutrons, X-rays, unfused atoms, and, recently, fused atoms. Of these, neutrons are the most harmful. They penetrate deeply and harm the structural integrity of metal parts. They can also be captured by nuclei and create radioactive elements. (This is an advantage for neutron activation analysis but a disadvantage otherwise.) So neutron shielding is very helpful. Second, neutrons carry away a lot of energy from a fusion reaction. Depending on the type of fuel, this can be 33% or 83% of the reaction energy [49]. Lithium is especially

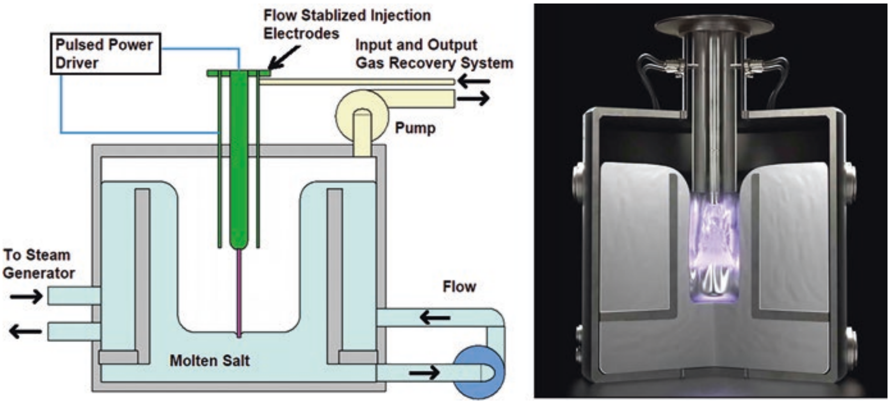

Fig. 3.15 One concept for a power plant based on the flowing Z-pinch [4, 46]. In this design, the pinch is surrounded by a molten lithium salt

good for absorbing neutrons, so all these liquid metal blankets include lithium salt. The liquid blanket also captures the kinetic energy of other reaction products, converting it into heat, which boils the water for steam-turbine electric power generation. The third advantage is that this liquid metal conducts electricity. This is essential for the flowing Z-pinch. The pinch forms across a gap, from the electrodes to the opposite surface. In the plant, this conducting wall could be liquid metal.

The last advantage of a liquid blanket is that it can be used to breed more fuel. When the most common isotope of lithium (Li^{6}) absorbs a neutron, it breaks apart into tritium and an alpha particle. Hypothetically, this tritium could be recycled for more fusion fuel. As of this writing, no team has successfully done this to scale. Another more exotic option is to load the liquid metal with spent fission fuel. In that scheme, the neutrons from a fusion reaction would recharge the fission material. One example is liquid FLiBe with uranium dissolved in it. (A nonfissile uranium 238 nucleus absorbs a neutron and, in a short time, undergoes two beta decays to become highly fissionable plutonium 239.)

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Magnetic Mirrors

4

Summary

Following the pinch in the historical development of fusion devices were magnetic mirrors, which confined plasmas by magnetic fields. The machines cause particles in plasmas to oscillate back and forth, leading to high-energy collisions and fusion reactions. These machines were the focus of fusion research at Lawrence Livermore National Laboratory and continued to show great promise until they lost federal funding. The culmination of the program came when the Magnetic Fusion Test Facility, built at a cost of $372 million, opened on February 21, 1986, and was promptly shut down the same day. Despite that unfortunate and short-sighted decision, mirror technology has left its mark on current fusion research and development.

4.1 Fusion's Golden Age

If there ever was a golden age of fusion in America, it was in California at the Lawrence Livermore National Laboratory (LLNL) between 1972 and 1986. The Cold War and the oil crisis forced the Carter administration to start pushing for alternative energy aggressively. The administration decided that the fusion program needed a huge boost to its funding, and budgets shot upward from 150 million to over 800 million dollars. Administrators like Dr. Robert Hirsch and Dr. Stephen O. Dean of the United States Department of Energy (DOE) were given generous budgets to build staffs, fund machines, and encourage researchers. The Department of Energy hired fusion experts and built integrated teams that were closely watching results from the national laboratories (Fig. 4.1).

Publications from this time describe a machine operated by hundreds of scientists and engineers within Livermore. Funding was also pushed into the supporting technologies and side projects, including the first direct conversion experiments and

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
https://doi.org/10.1007/978-3-031-22906-0_4

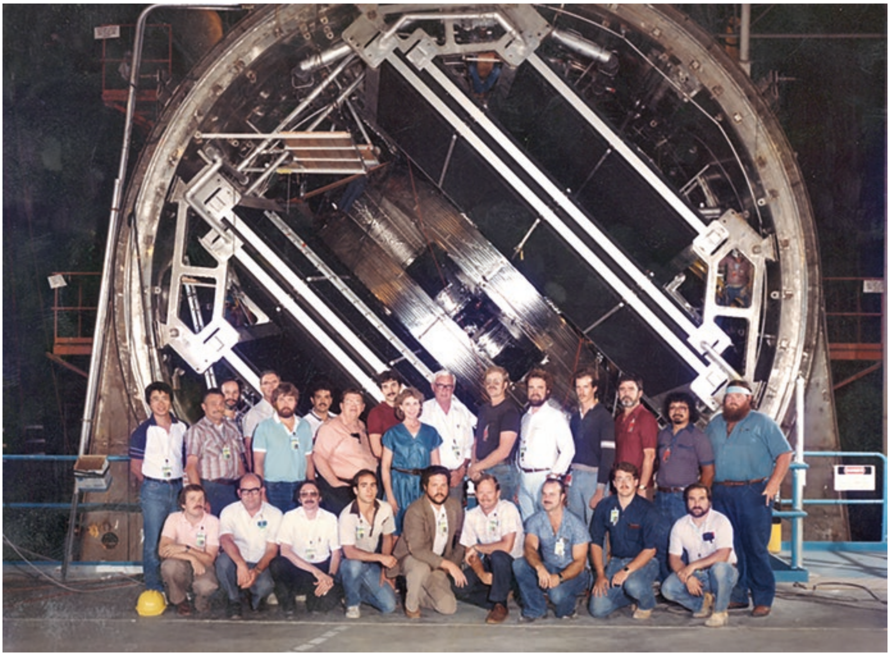


Fig. 4.1 The Magnetic Fusion Test Facility (MFTF) was built in the 1980s at a cost of $372 million. This mirror machine was the most expensive science experiment in Livermore history to that date. It was finished on February 21, 1986, and was shut down the same day. Livermore never even turned it on

the first application of superconducting magnets in fusion. It was also when the first large-scale computer control systems and plasma diagnostics were developed. Hopes were sky high. The pace at which fusion was developing was unprecedented; no sustained effort like this had happened before or since within the United States.

For about 15 years, the United States funded this extensive fusion research, and Livermore's mirror program was at the center of this effort. LLNL built a series of massive mirror machines. Squadrons of scientists and engineers worked on this effort, with teams coordinating with universities and labs around the country, which built machines such as Baseball, Baseball II, TMX, TMX-U, and 2X and its successor machines, 2XI, 2XII, and 2XIIB (see Fig. 4.2).

The mirror program provided the data that today form the bedrock of many of our plasma models. It also spurred research into several fusion-related topics, including superconductors and direct conversion energy capture. All of this culminated in the Magnetic Fusion Test Facility (MFTF). At a cost of $372 million, this was the most expensive machine in Livermore history, but they never even turned it on. In probably the most shortsighted decision in fusion history, this whole program came a screeching halt on February 21, 1986, the day that MFTF was finished. They threw an opening day celebration and then promptly closed the facility and fired everyone [1].

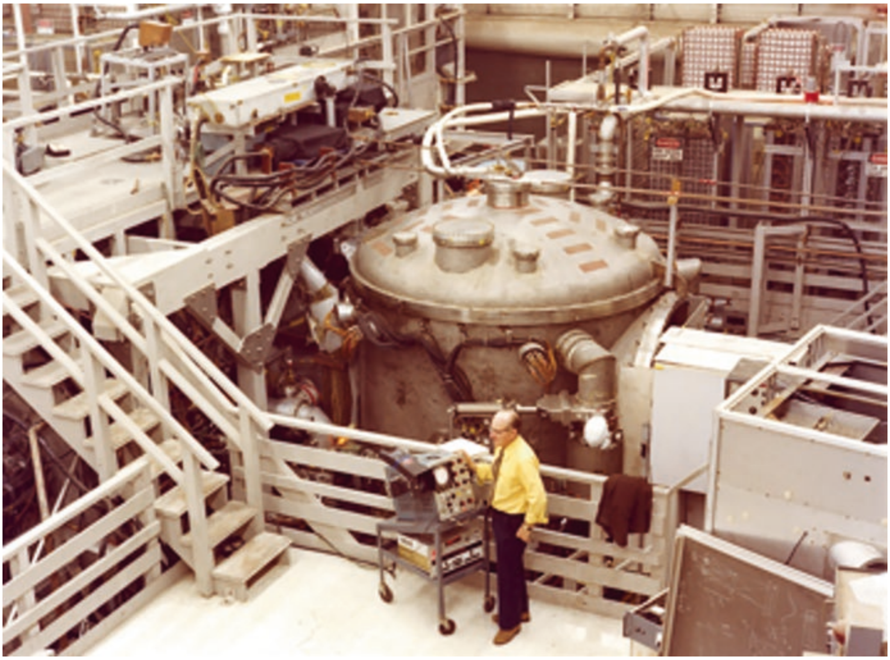


Fig. 4.2 Dr. Fred Coensgen standing next to the 2XII magnetic bottle experiment in 1978 at Lawrence Livermore National Laboratory. This was one of multiple fusion machines that were running simultaneously at the lab during those years. This machine was upgraded multiple times: 2XI, 2XII, 2XIIB

4.2 Richard Post and the Mirror Fusion Concept

The mirror program can trace its lineage to the work of one scientist named Dr. Richard Post. He was a newly minted Stanford Ph.D. when he first caught the fusion bug. It was December of 1952, and he was attending a classified lecture by Dr. Herbert York. York was excited about both the prospect of nuclear fusion and the newly opened Radiation Laboratory being built over the hill in Livermore, California [4]. York was challenging the class to see if they could devise a way to trap plasma and build a fusion reactor. Post was intrigued. He went home and wrote out a long memo on different ideas for how to do this. He sent it to York, who promptly offered him a job. But before Post could start, he needed to pass a tough job interview with the new lab director, Edward Teller (see Fig. 4.3). Fortunately for fusion, Teller offered him a job. Richard Post worked at Livermore for the next 64 years, well into the Obama Administration.

Post's most significant claim to fame is as the person who first developed and pushed the concept of the magnetic mirror in the early 1960s [3]. In contrast to pinch machines, which operate in toroidal tubes, mirror machines are linear and use shaped magnetic fields to confine the plasma. The mirror effect causes the plasma to be reflected as it moves from a low-intensity field to a high-intensity field (Fig. 4.4).

Fig. 4.3 Three leaders of Livermore's magnetic mirror program. Left to right: Richard Post, Edward Teller, and Ralph Moir. Dr. Moir came to the lab as a fission expert but quickly began leading scientific studies on fusion technologies. He also became one of Dr. Teller's closest friends. (Photo credit: Dr. Ralph Moir and Lawrence Livermore National Laboratory)

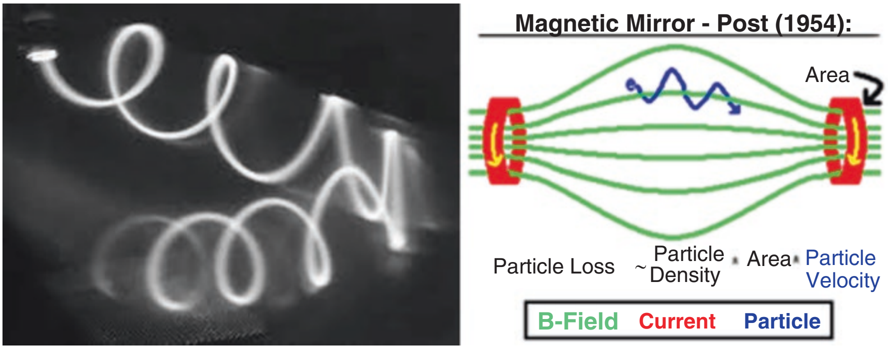


Fig. 4.4 (Left) An example of a plasma exhibiting the mirror effect as it reverses direction. Photo credit: Lawrence Livermore National Laboratory. (Right) A basic illustration of a magnetic mirror, with a simple equation showing particle loss

This reflection occurs because a magnetic field gradient produces a force on moving charged particles, directing them toward regions of a lower gradient. As shown in the figure, particles in the plasma oscillate between two electromagnets, following helical paths around magnetic field lines while responding to forces toward the central region.

Achieving the mirror effect is a delicate trick. The plasma must be injected within a certain range of directions, and the mirroring can sometimes be overwhelmed by another plasma effect. But regardless, Dr. Post's idea was to have two magnetic gradients facing one another. As the plasma ricochets back and forth, the goal was for some of the ions to slam together and fuse. Post envisioned a big cavity device—about the size of two double-decker buses with magnetic mirrors on both sides and a steering field between them. This is what Livermore ultimately built and paid for (Fig. 4.5).

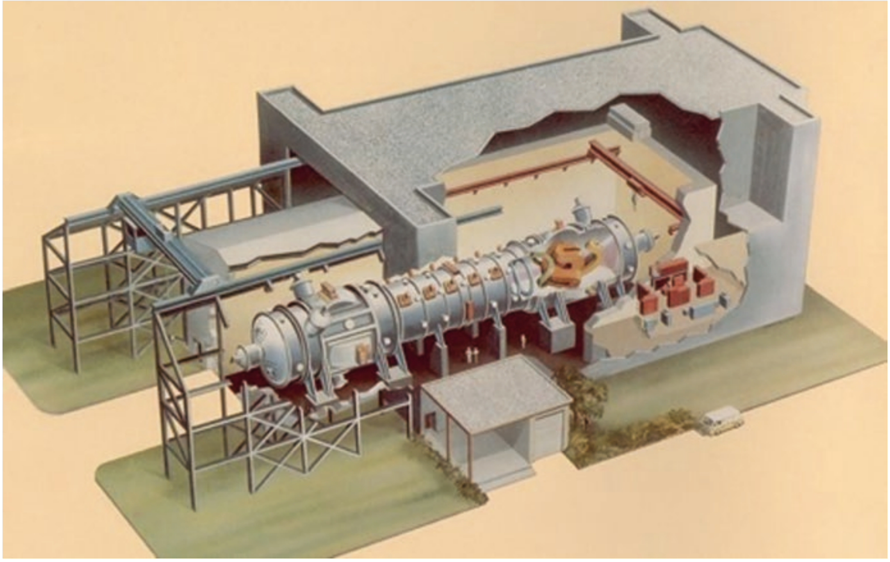


Fig. 4.5 An artist's conception of a mirror fusion reactor from the 1980s. This machine is a long hot-dog-shaped device. Plasma is injected, on an angle, from the side and (ideally) bounces back and forth from end to end. The drawing captures the dominant magnetic rings in the center and the U-shaped mirror magnets that can be seen in the cutaway at the ends of the coils. Photo credit: Lawrence Livermore National Laboratory

4.3 Mirror Machine Design Parameters

Understanding how a single electron or ion would be reflected inside a magnetic mirror is not difficult, but building a machine that reflects a bulk plasma is much more difficult. To produce the mirror effect with trillions of ions and electrons, fusioneers must control the containing field and plasma velocity. Ideally, the machine should have a sizable yet stable magnetic field transition from low-field strength in the middle to ultrahigh-field strength at the ends. After establishing that field, the next design challenge is to inject plasma with fine control over its velocity, both along the center line (axial) and the corkscrewing speed (radial). This is tuning the machine. The goal is to get the right conditions so that the plasma is reflected back and forth. Basic physics leads to Formula 4.1, an inequality that puts a limit on the ratio of the axial and radial velocities based on the ratio of the high and low magnetic fields.

$$\frac{V_{\text{Axial}}}{V_{\text{Radial}}} < \sqrt{\frac{B_{Min}}{B_{\max}} - 1}$$

Formula 4.1 A mathematical condition that must be met to get the magnetic mirror effect, where V is the velocity of the charged particles and B is the magnetic field strength

4.3.1 Pitch

Where and at what angle the plasma is injected makes a huge difference. If the plasma is injected straight down the axis of the mirror machine, it will fly straight through the end and be lost. If the injection is perpendicular to the axis, it will not feel a force to move either left or right and thus also pass directly through. Ideally, plasma should be injected on an angle from the wall of the machine. That angle is known as its pitch, and choosing the optimal pitch is an important element in designing the machine (see Fig. 4.6).

4.3.2 Reducing Leakage

If the motion of a plasma particle in a mirror machine was determined only by its pitch and the magnetic field, the design would be straightforward. But the problem is much more complicated. For example, particles collide with each other or the walls of the machine and change direction, which allows them to escape the confining field. Also, as previously noted, accelerated charged particles radiate electromagnetic waves, slowing them and reducing the chances to do fusion. To maximize the efficiency of the machines, fusioneers look for ways to reduce the leakage and return the particles to the oscillating stream. The goal is to keep material trapped and hot. One way to do that is by essentially plugging the ends with carefully shaped magnetic fields.

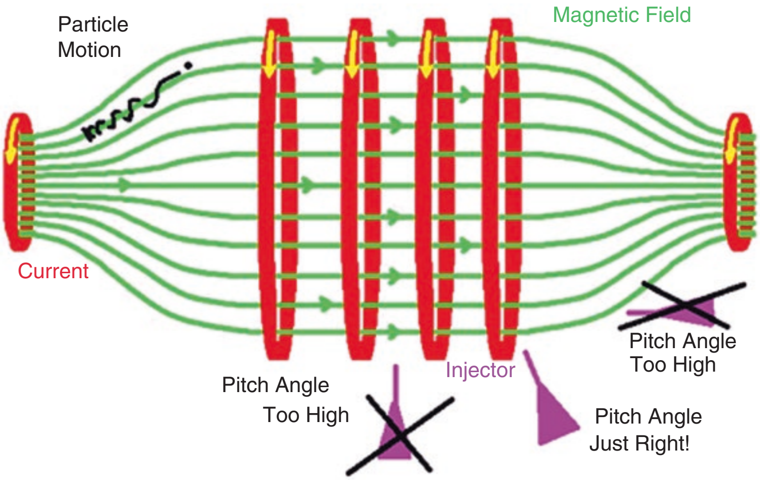


Fig. 4.6 Choosing the ideal pitch angle. For a mirror machine to produce maximum fusion, the plasma fuel needs to be injected into the magnetic region at just the ideal pitch angle. Once in the machine, a nucleus in the fuel follows a helical path around a magnetic field line. As it approaches the high-field end, it experiences a force toward the center, which ultimately causes it to reverse direction, enabling it to follow an oscillatory path. If the pitch is too close to the direction of the axis, it will escape through the ends. If it is too close to the radial direction, it will not feel a strong enough force to oscillate and escape through the side. The optimal angle depends on the precise shape of the confining magnetic field

Although this chapter focuses on mirror machines at LLNL, the United States was not the only nation looking at magnetic mirrors during this time frame. This was the Cold War, and the USSR had also committed significant resources to fusion development. The first magnet end for the mirror machine came not from Livermore but instead from Dr. Mikhail S. Ioffe at the Kurchatov Institute in Moscow. Ioffe was born in Russia on September 2, 1917. He studied physics in St. Petersburg, getting his master's in 1940. After a stint in the Soviet Army, he got his Ph.D. in physics in 1953 and went to work at the Kurchatov Institute in Moscow.

The problem Ioffe faced was how to design an end magnet that had the sharp magnetic transition necessary for a mirror machine but also kept the plasma stable. To maintain stability, he designed end magnets that were "magnetic wells," where the field increases in all directions from a central region at the end of the machine. His design is called, with some humor, an Ioffe bar (rhymes with coffee bar).

When Ioffe presented his concept at the first International Atomic Energy Agency (IAEA) Conference on Fusion Research at Salzburg, Austria, in September 1961, it was immediately the talk of the conference. With an Ioffe bar end magnet, mirror machines went from concept to feasibility. Livermore built a machine called Table Top in 1957 (Fig. 4.7), but it had been giving miserable results. Table Top had succeeded in confining a hot electron plasma for only about a millisecond. What was

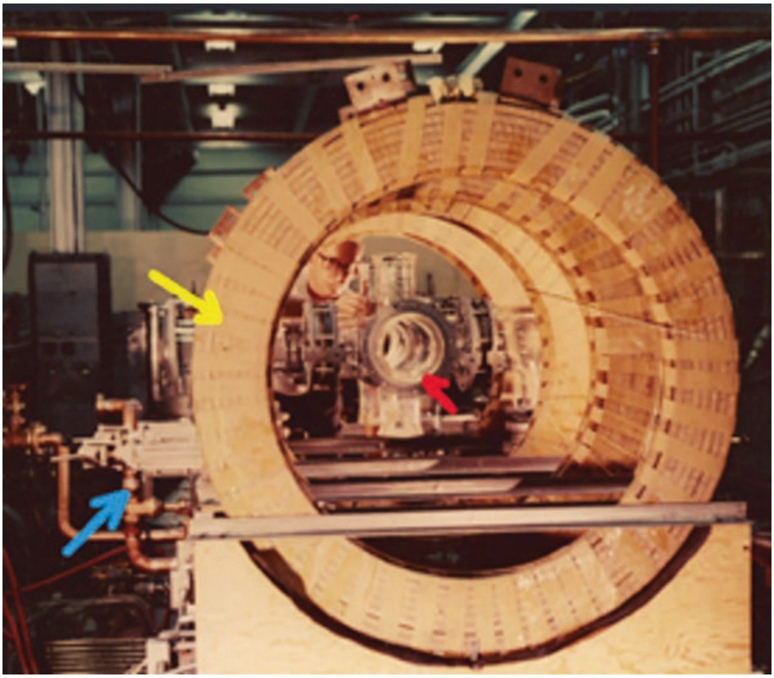


Fig. 4.7 Table Top, one of the first mirror machines in 1957. This image shows how the basic rudiments of fusion were being addressed. Magnetic coils were needed (yellow arrow), and they needed brass piping (blue arrow) supplying coolant to remove the heat produced by electrical resistance. This design did not integrate the magnets with the vacuum chamber (red arrow). Table Top did not have end magnets and therefore was not successful in containing or stabilizing the plasma

worse, Table Top was unable to achieve gross plasma stability. Ioffe bars offered a path to achieving that. The Livermore staff quickly duplicated and tested the Ioffe bar, discovered that it facilitated plasma stability, and thus enabled the mirror machine to be built.

4.4 Further Progress

With the Ioffe bar design, it became possible to carry out a full-fledged mirror program. Richard Post and his scientific team laid out a plan to develop a mirror fusion reactor in 1969. His paper laid out the power balance across the machine, described possible fuel types, and included the first mention of a new method for energy capture called a direct conversion. Direct conversion was an exciting idea for capturing energy from a mirror machine. A fusion reaction creates a very hot helium atom (about three million electron volts). This atom is typically too hot and is traveling too fast to be contained by most fusion reactors. It typically escapes from the plasma as well as the containing fields and leaves the machine. In direct conversion, those hot helium ions all hit a spot of metal on the wall. Because of this constant stream of high-voltage particles, that spot achieves a high positive voltage, as much as three million volts. This becomes the positive end of an electrical circuit. That voltage remains high, while the current flows elsewhere, converting the fusion energy into electrical energy. Once Post's plan was presented, the laboratory started building experimental mirror machines.

One of the early mirror machines was the 2X machine, which was based on two Ioffe bars. In the 1960s, Livermore secured a large facility with an overhead crane and began assembling the experiment. The 2X machine was completed in the mid-1960s and remained in that lab until the late 1970s. It was continuously upgraded throughout that period. Its successors were named 2XII, 2XIIB, Baseball, and Baseball 2, which were all housed there (Fig. 4.8).

As the machine was improved and refined, the team developed several methods that have now become commonplace in nuclear fusion. For example, the B in the 2XIIB machine stood for beam. Livermore found a way to beam in plasma neutrally. 2XIIB used 12 neutral-beam injectors, each producing a 20-keV beam with 1 megawatt of power. This pushed the machine to higher temperatures and densities.

In the summer of 1975, this machine was the first fusion machine to crack 100 million kelvin ion temperatures. This was a huge accomplishment for a mirror machine or any fusion machine.

After the success of 2X, 2XII, and 2XB, Livermore developed the Baseball coil based on the Ioffe bar design, which was named as such for its resemblance to the stitching of a baseball (see Fig. 4.9). This innovation gave the United States an advantage over the USSR for several years. The joke around Livermore was that the Russians did not play baseball and therefore missed the design.

Building a baseball-shaped electromagnet was challenging. It basically involved twisting a conductor, like a thick cable or superconductor, into a twisted knot that

Fig. 4.8 A 1978 photo of the LLNL laboratory, which housed the 2X and baseball mirror machines. The end coils were housed in large vacuum chambers that look like big stove pots on either end of the laboratory (yellow arrows). The plasma oscillated between these. (Photo credit: Lawrence Livermore National Laboratory)

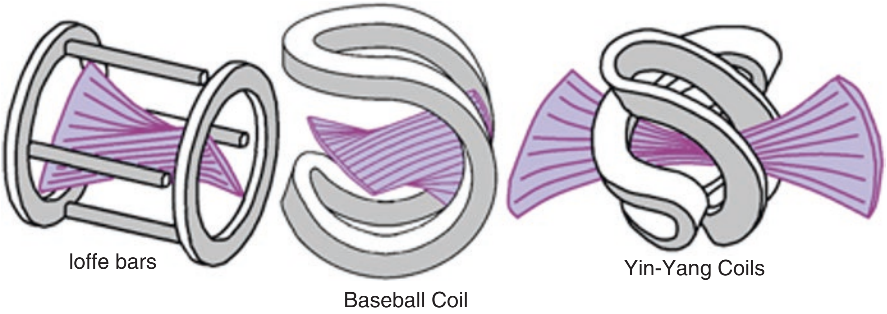


Fig. 4.9 The evolution of the magnetic mirror end magnets. Leftmost is the Ioffe bar, developed in Russia in the early 1960s by Mikhail Ioffe. In the middle are the baseball coils, which were a significant improvement over Ioffe bars in the late 1960s and early 1970s, which gave US researchers a significant advantage over their USSR counterparts for many years. On the right are the yin-yang coils that were designed in the late 1970s and early 1980s and were ultimately used in the Mirror Fusion Test Facility (MFTF) in 1986

held its shape when turned on. These magnets would exert powerful mechanical forces onto the reactor, which could creak under the strain. The Baseball I coil was 6½ feet in diameter, weighed seven tons, and was wound with more than 7 miles of niobium-titanium filament, an early example of superconductors being applied to fusion (Figs. 4.10 and 4.11).

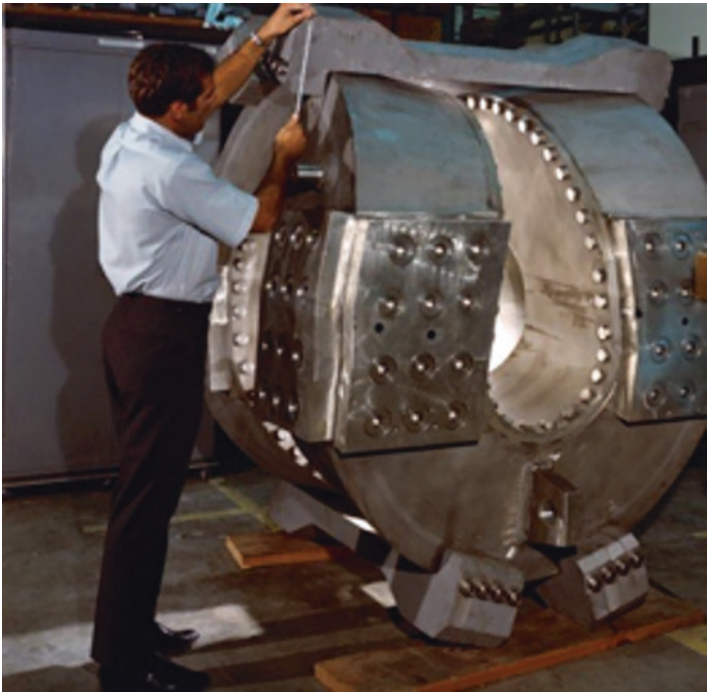
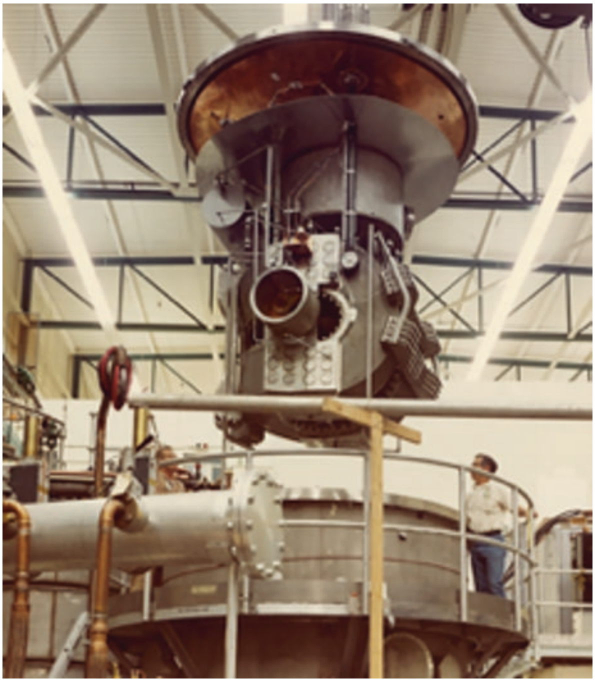


Fig. 4.10 One of the first superconducting magnets used in fusion is the Baseball I coil. It was used to plug the ends of a steady-state magnetic mirror. (Photo taken by Livermore National Laboratory, 1971)

Fig. 4.11 The Baseball coil being loaded into the end chamber of a magnetic mirror. (Photo taken by Livermore National Laboratory)



4.5 The Tandem Mirror

Toward the latter half of the 1970s, it became apparent to mirror researchers that the mirror effect alone was not enough to contain the plasma. Leakage rates had gone down through steady progress and redesign of the machine. But to take mirrors to the next level, researchers needed more ways to keep the plasma contained. They came up with a plan to do so and called it the Tandem mirror. The Tandem mirror was based on manipulating the charge distribution inside the machine. For example, if they could make the ends of the trap highly positive, it would repel the positive ions inside the machine.

Normally, making a part of the machine at a highly positive (or negative) voltage is not feasible because charges mix together quickly and charge differentials are erased. The only way to do it is to constantly feed positive or negative plasma into a region of the mirror. That way, a charge differential could be maintained. Fortunately, they were already doing this with their neutral beam injectors. The idea became to inject plasma at the ends of the machine, which solved two problems. It allowed for plasma injection, but it also kept the ends of the mirror predominately positive. In order to make all this work logistically, researchers also needed to further change the ends of this device. They developed what they called tandem magnets, which would allow for injection and keep the ends at a controlled voltage. One example of a tandem mirror is shown in Fig. 4.12. This is the Gamma-10 tandem mirror machine, housed in Japan.

The Tandem Mirror Experiment (TMX) was built at the end of the 1970s based on this idea from Dr. Fred Coensgen (formally proposed to the US Department of Energy on January 12, 1977). The cost to build the machine was $11 million, and it operated for about 10 years, including its upgrade known as TMX-U (see Fig. 4.13). The TMX was a very successful mirror machine. It produced strong plasma

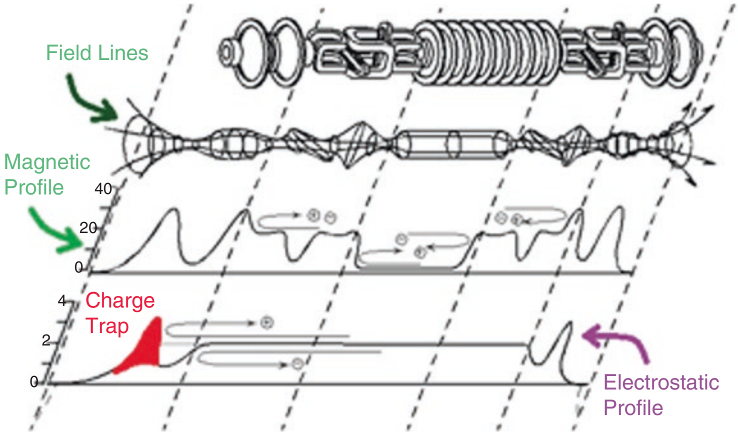


Fig. 4.12 The magnetic and electrical environment inside the Gamma-10 Tandem mirror design. Note that the end of the mirror had unusually shaped coils. Some of this engineering would likely be replaced today because modern magnets can make such stronger fields

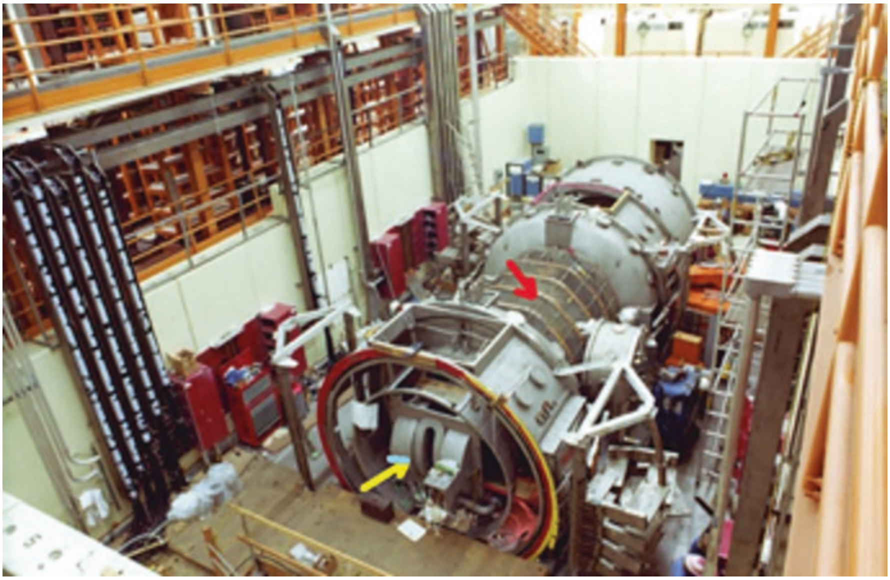


Fig. 4.13 The area of LLNL that housed the Tandem Mirror Experiment (TMX) and Tandem Mirror Experiment Upgrade (TMX-U), shown here. These mirror machines were built and operated there from the late 1970s to the late 1980s. Note the unique yin-yang end coils (yellow arrow) and the steady middle coils (red arrow). (Photo credit: Lawrence Livermore National Laboratory)

temperatures and good plasma confinement. This was the machine on which the first direct conversion experiments were conducted, led by Dr. Ralph Moir and Dr. William Pickles in a multiyear effort to model, design, build, and test a direct converter. Their results were impressive. The system they put in place demonstrated an energy capture of 48% of the incoming fusion energy of the TMX. This is astounding since fusion produces the most energy of any known method, and this 48% energy capture would rival most conventional power plants.

4.6 The Magnetic Fusion Test Facility (MFTF)

All this mirror work was pushed along politically by factors well outside of Livermore. An organization called the Fusion Energy Foundation (FEF), started by wealthy businessman and political radical Lyndon LaRouche, began a nationwide campaign to push fusion forward. This organization produced and distributed newsletters to over 100,000 people, spreading the physics and benefits of fusion power. FEF also targeted lawmakers on Capitol Hill, including Reps. Mike McCormack (D-Washington) and Charles Rangel (D-New York). FEF organized educational lunches and pushed stories out to conventional newspapers about the benefits of fusion. Despite LaRouche's dubious character and personal history, these efforts culminated in the Fusion Energy Act of 1980, which passed the Senate on September

23, 1980, and was signed into law by President Carter exactly 2 weeks later. The bill got national coverage in newspapers and on TV. It laid out a roadmap for the United States to develop a fusion reactor and set out the funding levels to get there (Fig. 4.14).

With the Fusion Energy Act in place, Livermore was given the green light to build its most ambitious mirror project ever, the Magnetic Fusion Test Facility (MFTF). At a cost of $372 million, the MFTF was the most expensive machine built at the lab to that point. It took 9 years to complete and, in many ways, is still the archetype of the fusion machines we see today. It was large and complex. It was a "big science" project, designed and managed using classic project management techniques and requiring hundreds of people to build.

The MFTF set the tone for machines like Nova, National Ignition Facility (NIF), and International Thermonuclear Experimental Reactor (ITER)—all multiyear, multidisciplinary, and group-designed efforts. The machine was massive. Its internal cavity was the size of a double-decker bus. The large yin-yang end coils were the size of a typical garage (Fig. 4.15). The MFTF used large neutral beam injectors and powerful vacuum pumps in its vacuum chamber. It also had a fully integrated computer control system, revolutionary for its time.

Although the building of the MFTF was a great technological accomplishment, it is also one of the greatest examples of bureaucratic folly in the history of American technology. The day that it was opened, February 21, 1986, was also the day the program was shut down as part of the Reagan administration's cuts to government. The stated reason given was that the United States needed to bring down its federal deficit, and the MFTF cost about a million dollars to run every shot. DOE official Edwin Kintner, who was known for his leadership in decontaminating the damaged Three Mile Island reactor, resigned in protest over this decision.

A $20 Billion Program to Harness Star Powe

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Fusion Bill Signed; Economic Boom Possible

• Sponsor McCormack: 'Greatest Thing Since Moon Landing'

• FEF's Levitt: 'Historic Victory for Scientific Progress'

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Fusion: A 'National Goal' in the U.S.?

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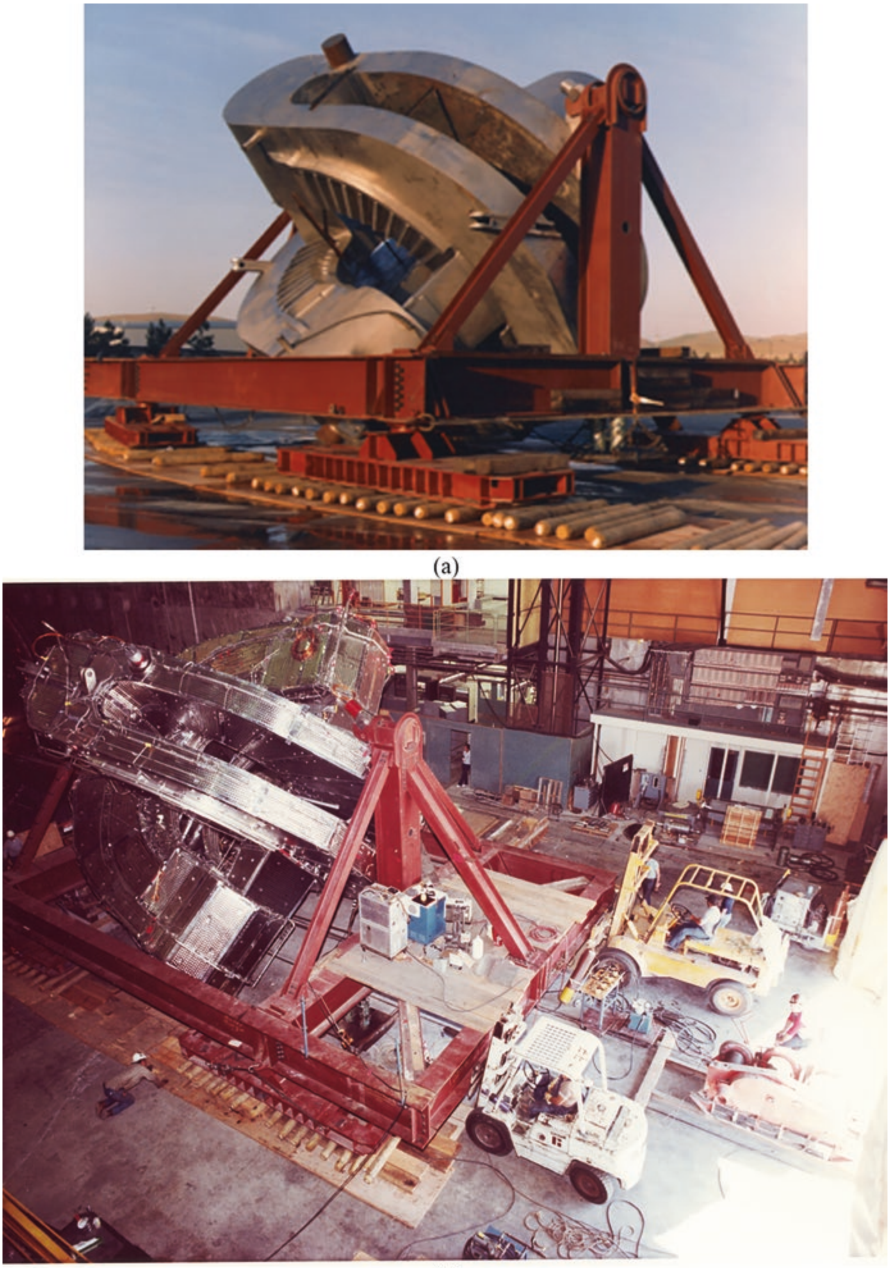
Fig. 4.14 A selection of national headlines after the passage of the Fusion Energy Act of 1980, which made fusion a national priority for the United States. (Image courtesy of Marsha Freeman.)



(a)

(b)

Fig. 4.15 (**a**) The yin-yang magnetic coils built for the MFTF; (**b**) the coils being installed in the MFTF lab space, which was opened and shuttered on February 21, 1986. (Photo credit: Lawrence Livermore National Laboratory)

Fortunately, the MFTF team was notified a few months in advance that this was going to happen [1]. Thousands of employees and several hundred scientists and engineers suddenly had to find new jobs in the greater Bay Area in the 1980s. It inadvertently turned out to be a boon for the budding tech industry as highly skilled engineers who had pioneered revolutionary computer control systems and trained in project management were suddenly on the market. A smaller team stuck around to see the 9-year, 372-million-dollar project to the bitter end. On the last day, the team threw a somber party with a cake and balloons. Glen Speckert, who was a control system engineer, described the very last day as dismal [7]. He described a very subdued party, celebrating all the years of hard work and effort, after which they all packed up their offices and left the building. Project director Dr. Kenneth Fowler read a melancholy letter from the US Secretary of Energy that commended the team on a great effort even though the machine was being "put on standby." The letter went on to say, "This is frustrating and perhaps not the best use of national talent and resources, but we must bring the deficit under control." Dr. Fowler commented that "in my wildest dreams, or rather my wildest nightmares, I never envisioned it coming to this." History will never know if the MFTF would have worked. The machine was never turned on, not even once. This is the single most frustrating moment in fusion history.

The funding for the US mirror program also faced other pressures. As noted in Chapter 1, in 1983, Massachusetts Institute of Technology (MIT) professor Lawrence Lidsky famously published *The Trouble with Fusion* [8]. Later, in a famous Congressional hearing, Dr. Lidsky was quick to criticize the mirror program. His comment was that mirror researchers "kept adding one set of magnets a year until it collapsed under its own weight." These criticisms were widely reported in the press and corresponded with the Reagan administration's attitude that "government is not the solution to our problem; government is the problem." Taken together, these forces eventually led to drastic budget cuts for the MFTF and the larger US mirror program.

4.7 Modern Mirrors

The fall of the MFTF marked the end of the mirror program in the United States. It also marked the rise of the tokamak as the dominant fusion energy approach. Several planned mirror machines went on hold and were eventually scrapped. A machine at Wisconsin and MIT, called TARA, was abandoned, and the parts were used to build the Alcator tokamak, housed at MIT.

For about a generation, from the late 1980s to the 2010s, the United States had no large mirror research effort anywhere in the country. Russia, however, continued its mirror work at the Budker Institute of Nuclear Physics, a national lab in Siberia (Fig. 4.16). Their machine, the Gas Dynamic Trap, has made steady progress. Russia found that mirror trapping could be improved significantly by raising the difference between the center and the end fields. The Gas Dynamic Trap has very strong end fields (10 and 15 teslas) and weak central fields (less than a third of a tesla) [2]. Since a new world record for these kinds of magnets, 42 teslas, was set in 2022, it is worth noting that mirror fusion machines with better magnets can realistically be expected to advance a great deal.

At the end of 2016, American experts Kenneth Fowler, Ralph Moir, and Thomas Simonen wrote a paper arguing that the United States should restart the mirror program [2]. It noted that the Gas Dynamic Trap had shown that mirrors could work and were far simpler and smaller than a tokamak. The paper also argued that plasma science had advanced so much that mirrors were much easier to understand today than they were in the 1980s. Computer models and data collected from tokamak research could be applied to magnetic mirror design. These arguments resonated: in 2020, the Department of Energy funded the first US mirror machine in more than three decades. The Wisconsin HTS Axisymmetric Mirror (WHAM), a significantly advanced fusion machine, is now under development. This very compact device will have 17 tesla superconducting end coils and include the most advanced plasma heating technologies.

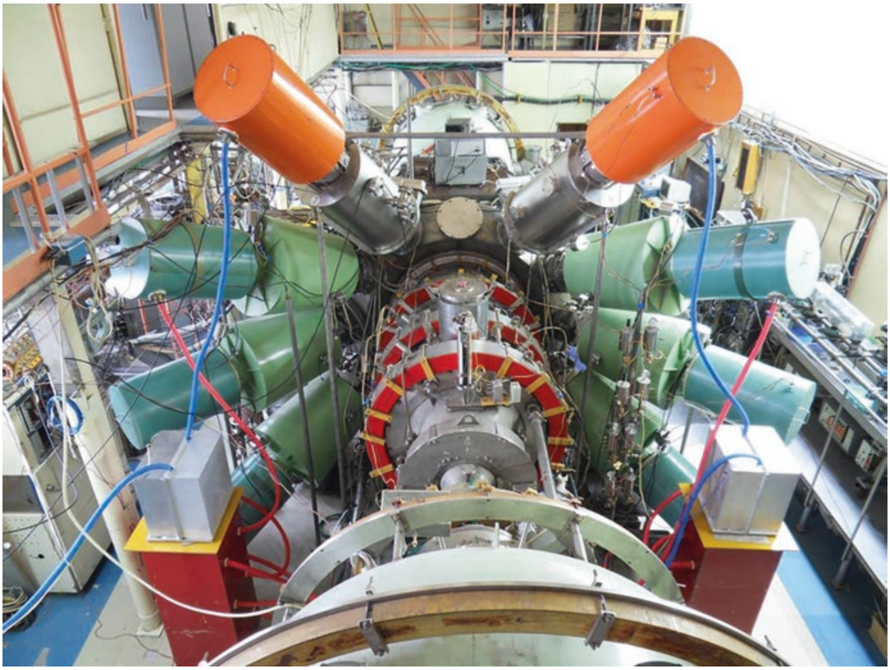


Fig. 4.16 The Gas Dynamic Trap. This is a modern mirror machine at the Budker Institute in Russia. It is 7 meters long and has multiple beam injectors, mean ion energy of 10 keV, mean electron energy of 250 eV, and a high confinement ratio. (Image credit: Wikipedia)

4.8 Levitating Dipole Experiment (LDX)

In the late 1990s, an MIT researcher named Jay Kesner was being badgered about a novel idea by his colleague Dr. Michael Mauel at Columbia. Mauel wanted to see if one could "wrap the mirror around in a loop," in other words, to form a mirror field but connect the end to itself. This led Kesner to develop a totally new and innovative machine called the Levitating Dipole Experiment (LDX). The LDX was similar to a mirror in that it had regions of high and low magnetic field strength. However, the LDX formed these regions using a single-looped electromagnet. Particles could travel from a strong to a weak magnetic field and back. However, unlike a mirror, if the particle leaked through the end fields, it would be cycled back into the reactor. From the particles' perspective, this was like leaking through the end field and ending up back inside another mirror field. The LDX was like a magnetic mirror with no end losses. A comparison of the magnetic fields in a mirror and the LDX are shown in Fig. 4.17.

In a sea of fusion approaches, the levitating dipole stands out as a very odd contraption. The LDX is a mirror machine wrapped around a levitating donut. The machine also mimics the plasmas created by large astrophysical bodies like planets and stars. Dr. Kesner used this similarity as a way to get funding for the machine. Plasma swoops into similar fields made by planets and comes down the field in a "toilet bowl" fashion along the poles. The LDX team reasoned that if enough material swirled into the field, it could reach a high enough density to fuse [6]. Figure 4.18 follows the motion of one particle to illustrate this phenomenon. Fusion would occur when the plasma reached the center of the ring because this was when the plasma would be the densest. The figure also shows what happens to the bulk plasma. Two regions form around the ring, the red region being the denser plasma.

To build the LDX, the team needed to develop a floating donut magnet. The team applied and won a few million dollars a year in federal funding. Construction started in 1999, and the LDX achieved its first plasma in 2004. The LDX team could levitate the magnet for about 8 hours, though they never ran experiments for that long.

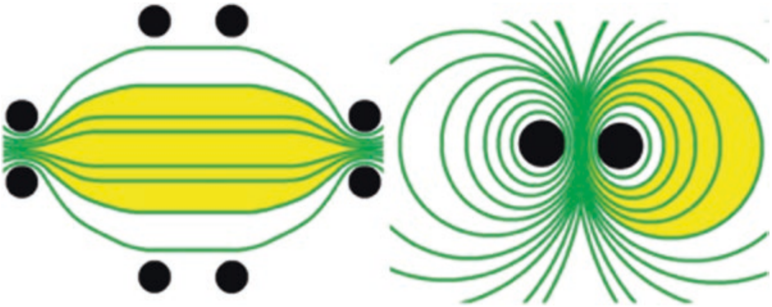


Fig. 4.17 A comparison of the fields in the magnetic mirror (left) and the Levitating Dipole Experiment (LDX). Particles move linearly from a strong to a weak field in the mirror, while in the LDX, the particles follow a closed curved path around the electromagnet.

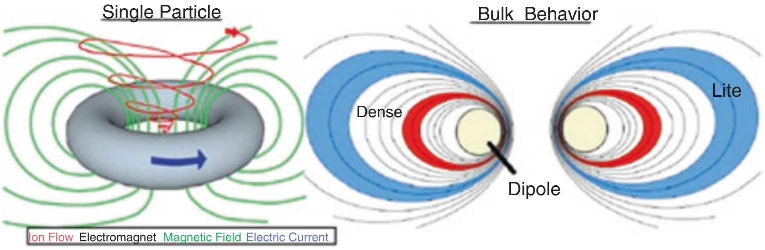


Fig. 4.18 The plasma behavior in the LDX. The motion of a single particle is shown on the left, where the plasma moves in a toilet bowl motion. The behavior of a large population of plasma is shown on the right—which delineates where high- and low-density plasma forms

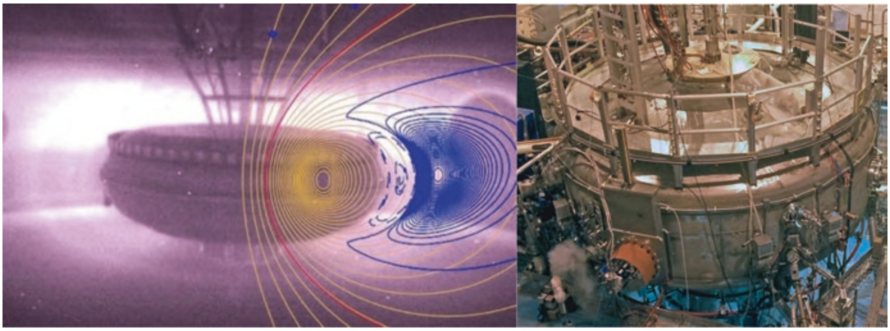


Fig. 4.19 Internal (left) and external (right) photos of the Levitating Dipole Experiment (LDX). (Photo courtesy of Dr. Michael Mauel and Dr. Jay Kesner)

The ring could generate a magnetic field of about 5 teslas, which was higher than the Joint European Torus (3 teslas) at that time. Present superconductors could reach still stronger fields. The LDX produced plasmas that reached temperatures of approximately ten million kelvins. This effort was also unique because the team valued communicating their work openly to the public over the Internet. Their website includes data, movies, and descriptions. Internal and external photos of the machine are shown in Fig. 4.19.

The LDX was, sadly, also a tragedy of the US government's narrow focus. Though LDX showed good progress and had a strong and credible development team behind it, the team could not secure a few million dollars a year from the Department of Energy to gear up for ignition experiments [7]. At the time, the Department of Energy was culling all kinds of fusion projects to reallocate money for the International Thermonuclear Experimental Reactor (ITER). The ITER project consumed the budgets of multiple fusion efforts because Congress wanted to hold the overall funding level relatively constant. Dr. Kesner had to cease fusion experiments after 2011 [5].

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Cusp Systems

5

Summary

A magnetic cusp forms when two like poles face one another. Since the 1950s, people have explored if there were ways to hold plasma inside such a magnetic field by using the inherent plasma properties. If such a system were to work, it would lead to an exciting new way to design a fusion reactor. However, results so far suggest that cusp fields may not confine the plasma long enough to reach a full-scale fusion reactor. Dr. Harold Grad at New York University's renowned Courant Institute of Mathematical Sciences developed the first mathematical models of cusp confinement in the 1950s and 1960s. Since then, the effect has been studied by a handful of experimental teams. This chapter goes through the history of cusp research at two commercial fusion companies, the University of Sydney, and finally the Lockheed-Martin Skunkworks.

5.1 Introduction

In contrast to a magnetic mirror, where the two electromagnets attract each other, a cusp is formed when their magnets repel each other. These cusp fields can be arranged in many configurations. The simplest cusp is known as a biconic cusp or spindle cusp. (Fig. 5.2) Biconic cusps form when two like poles (north and north or south and south) face one another and repel. Their field lines spread out in all directions. In the center of the biconic cusp, there is a spot with no magnetic field. This is called a null point, and it is where plasma tends to get trapped in cusp systems. The system is the opposite of the magnetic mirror where two unlike poles face each other and attract. In mirrors, the field lines easily flow from one pole to the next like water in a river, and there is no null point. Both designs have high and low magnetic fields. High-density fields have a lot of potential energy—think of them as mountain tops. It takes a great deal of energy for particles to reach these higher-density fields.

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
https://doi.org/10.1007/978-3-031-22906-0_5

Fig. 5.1 Dr. Harold Grad and Dr. Cathleen Morawetz at NYU's Courant Institute. Dr. Grad specialized in applying advanced mathematics to the behavior of plasma. This field became known as magnetohydrodynamics—now a popular method for modeling plasma behavior. Dr. Grad developed the early models for cusp confinement. Dr. Morawetz went on to be celebrated as a female pioneer in the application of advanced mathematics to everyday problems. (Photo courtesy of New York University)

As a particle of the plasma moves up the field, it slows, reverses direction, and rolls back down. Both mirror and cusp designs exhibit this plasma behavior. In mirrors, the plasma feels a reversing force when it is moving from a low- to a high-density field. The same thing occurs in cusp systems, but instead of the plasma flow seen in mirrors, this effect tends to trap plasma in the center of a cusp (Fig. 5.1).

Dr. Harold Grad, a professor at New York University, performed the first extensive mathematical studies of cusp systems in the 1950s and 1960s [1, 2]. His specialty was applying advanced mathematics to plasma behavior. His pioneering work was to apply math to explore the nuances of different magnetic plasma systems to identify both good and bad fusion reactor approaches. Plasma can be treated mathematically as a fluid that also happens to conduct electricity. This led him to develop a new field called magnetohydrodynamics, a mathematical merger of the equations for fluids (the Navier-Stokes equations) and electromagnetics (Maxwell's equations). Grad probed this math for the quirks and properties of plasmas that could be used to build a fusion reactor. His favorite geometry was biconic cusp. In 1961, he moved his modeling of plasmas in biconic cusps to computers [18]. Later, Dr. George Schmidt of the Stevens Institute of Technology also studied cusps theoretically in the 1960s [52, 53].

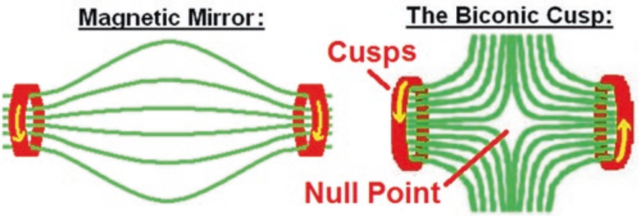

Fig. 5.2 A comparison between a magnetic mirror and a biconic cusp. Both have high- and low-density magnetic field regions, and both are made of two magnets facing one another. The difference is that the mirror magnets create fields that are in the same direction, while the cusp magnetic fields are opposite. In a mirror, plasma flows back and forth along a line, whereas in a cusp, plasma tends to sit in the central null point

5.2 Cusp Fusion Reactor Technology

As of this writing, the most serious cusp-driven effort being pursued is by the compact fusion reactor team at Lockheed-Martin. Building a power plant out of a magnetic cusp involves several key steps, each of which must work. First, the cusp field must be created by two or more opposing magnets. Next, hot plasma must be injected into this cusp field and trapped long enough for significant fusion reactions to occur. For a power reactor, this must result in fusion energy that exceeds the input energy. Finally, the fusion energy must be converted into electricity. A cusp machine, if it works, would have a significant size advantage over the current leading contender for fusion power, the tokamak. It could be 100 times smaller and therefore much cheaper. The biggest disadvantage of cusp systems is that, experimentally, these machines have not performed well thus far. They have also not been the subject of significant development work, which means there may be many unexplored pitfalls that could ultimately lead to a dead end. It is not clear yet what direction this family of fusion machines will take, if any.

5.2.1 Biconic Cusps

A biconic cusp system (Fig. 5.3) includes two-point cusps, which create a null region in the center, and a ring cusp around the midplane.

The null region in the center is the key to how this approach could work. When you inject plasma into this field, it tends to pool in this central region [11, 28]. The fields around the center are higher. Thus, plasma that is on a path to escaping the center region will either leak out along field lines or be reflected by the increasing magnetic field. There are several overlapping and competing physical mechanisms in play here. These include the following:

- *Mirror effect*: plasma will be reflected as it moves from low-density fields to high-density fields. This generally means that material is reflected back into the

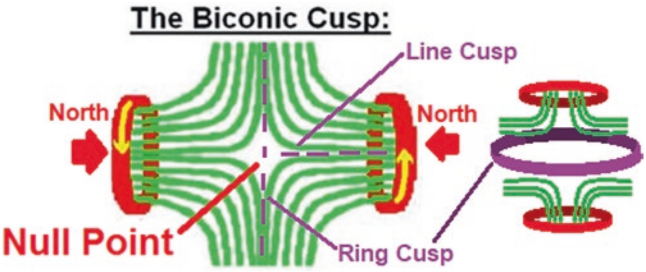

Fig. 5.3 The magnetic field of the simplest cusp design, the biconic cusp. It is formed by two like magnetic poles facing one another. The field lines spray out in the middle

center. The mirror effect does not work for all particles (see the mirror chapter), and electrons or ions injected at certain angles can slip through.

- *Cusp leakage*: because the field lines steer the ions, plasma will tend to leak through the cusps at the ends of the trap fields. Significant leakage can truly hurt this approach.
- *Up scattering*: ions or electrons that ricochet off one another can be knocked into higher energy paths and eventually escape from the trap.
- *Down scattering*: particles can also be scattered in lower energy paths. This happens when the particle is knocked closer to the center of the cusp fields. A similar effect happens in tokamaks when plasma is scattered to the edge of the machine and eventually knocked into the wall. Ions that are scattered to lower energy are colder and therefore less likely to undergo fusion reactions.
- *Diamagnetism*: plasma generates its own magnetic field. This is an important property if you want to make a structure out of plasma (see Chap. 7). But it is also important in a cusp system because creating highly diamagnetic plasma (*i.e.*, a plasma that produces an internal magnetic field that is opposite to an applied external one) can improve the overall trapping effect. In this effect, the plasma's diamagnetism rejects the outside field, increasing the volume of hot plasma that can be held inside the reactor. Recent cusp research has focused mainly on trying to get this effect to work.

Each effect will be outlined here. Like all fusion reactors, operating a cusp system is like turning a dial that adjusts the relative strength of these different physical effects. Getting a fusion reactor to work is a matter of running the machine to get more *good* and less *bad* behavior. Ideally, the cusp machine should be tuned so that diamagnetism dominates. Unfortunately, in practice, leakage appears to be the dominant effect. Because cusp systems have leaked so readily, they have often been dismissed as unable to hold plasma well (Fig. 5.4).

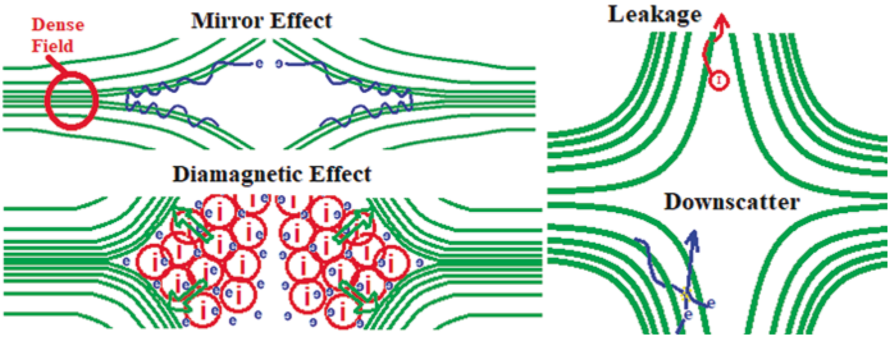

Fig. 5.4 The four mechanisms in a biconic cusp system (mirror, leakage, diamagnetic, and scattering) illustrated graphically. Understanding these mechanisms is the key to distinguishing among the operation of many different kinds of cusp systems

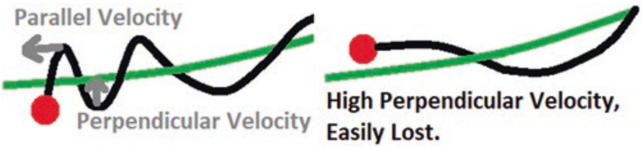

Fig. 5.5 The motion of particles moving into a mirror field. The particle corkscrews around a magnetic field line (green). The particle has both perpendicular and parallel velocity components (left). Particles with a high parallel velocity (right) tend to seep through a mirror (or cusp) field. The radius within which the particle will rotate around this field line is called the Larmor radius

5.2.2 Mirror Effect and Scattering in Cusp Systems

If a cusp system is ever to work as a fusion reactor, it must confine plasma well. Plasma trapping can occur inside the system because of the mirror effect. The mirror effect repulses plasma that is trying to move from a lower to a higher density field, an effect that was discussed in the mirror chapter. The mirror effect occurs as a single particle corkscrews around a magnetic field line and moves into a denser field. A corkscrewing motion has a velocity that is both perpendicular and parallel to the field line (see Fig. 5.5).

As the particles spiral into denser fields, the velocity parallel to the field shrinks and eventually flips direction. The mirror effect fails for particles whose velocity is mainly parallel to the field lines. Particles that move in the center of a cusp trap occupy low-density fields. Consequently, they tend to have a high parallel velocity and tend to stream out of the cusp trap. This is another fundamental reason why cusp systems have not been pursued as vigorously as other fusion approaches.

This analysis neglects particle interactions and collisions, which change their energy and, thus, their motion in the magnetic field [27]. When two ions or electrons bounce off one another, they can be knocked into lower energy conditions. In practice, the corkscrew motion of a lower-energy particle around a magnetic field line will have a lower curvature. You can compare this to runners on a crowded track.

When the runners bump into one another, they get knocked into the outside lanes [6]. In tokamaks, this means the ions are pushed to the edges of the field, eventually scattering into the walls. That leads to mass loss, always a bad thing in a fusion reactor.

But cusp systems have an advantage in this regard because their low curvature fields are near the center of the trap [28]. That means that anything that is scattered is pushed into the center of the cusp trap. However, once inside the center, these particles can easily leak out since the field is at its weakest point there. This means that an unmodified cusp system does not have enough pressure to hold in plasma. This can change if the plasma's diamagnetism can be used to reject, or push back against, the cusp fields. Hence, cusp systems do not work unless you can amplify this diamagnetic effect and get it working in your favor. This is, at best, an enhanced trap that leads to a better reactor, or it is, at worst, a terribly weak effect that cannot help performance. This will be discussed further below.

5.2.3 Superconducting Biconic Cusps

Cusp systems may be worth a second glance by a major American university or laboratory because of the development of new superconducting materials, which make possible more powerful magnetic fields. Superconducting magnets are so different from conventional electromagnets that a cusp system built with them can almost be considered an entirely new kind of machine. Figure 5.6 shows a simple, working, superconducting biconic cusp built by Tanner Horne of Boulder, Colorado. To get the photo of the device in operation, Horne had to raise his chamber pressure so that the gas would light up. Ideally, a fusion reactor would be dark to the naked eye to reduce energy leakage as light. A dark fusion plasma is much more efficient.

Horne built this cusp machine with two loops of superconducting wires facing one another inside a vacuum chamber. Because he is using superconductors, he can create a steady, stable magnetic field arrangement that runs continuously with low power demand and resistive heating. In 2016, Horne was able to run his machine for upward of 20 min with no problem [20, 21]. When the Navy did this experiment with conventional electromagnets in 1980, tests ran for only 0.12 milliseconds [19, 26]. This is a stark example of the impact that superconductors will have on fusion reactor systems: much more powerful fields (a 1000-fold increase) with much longer run times (a million-fold increase). Superconductor technology offers the hope of fresh cusp research within the United States.

5.2.4 Cusp Leakage and Diamagnetic Trapping

There are two other mechanisms in a biconic cusp that need to be discussed: leakage and diamagnetic trapping. Obviously, leakage represents the enemy of this approach. Leakage out of the cusp is a function of the size of the hole in the cusp field; the bigger the leak is, the higher are the losses. There is some debate over the exact size

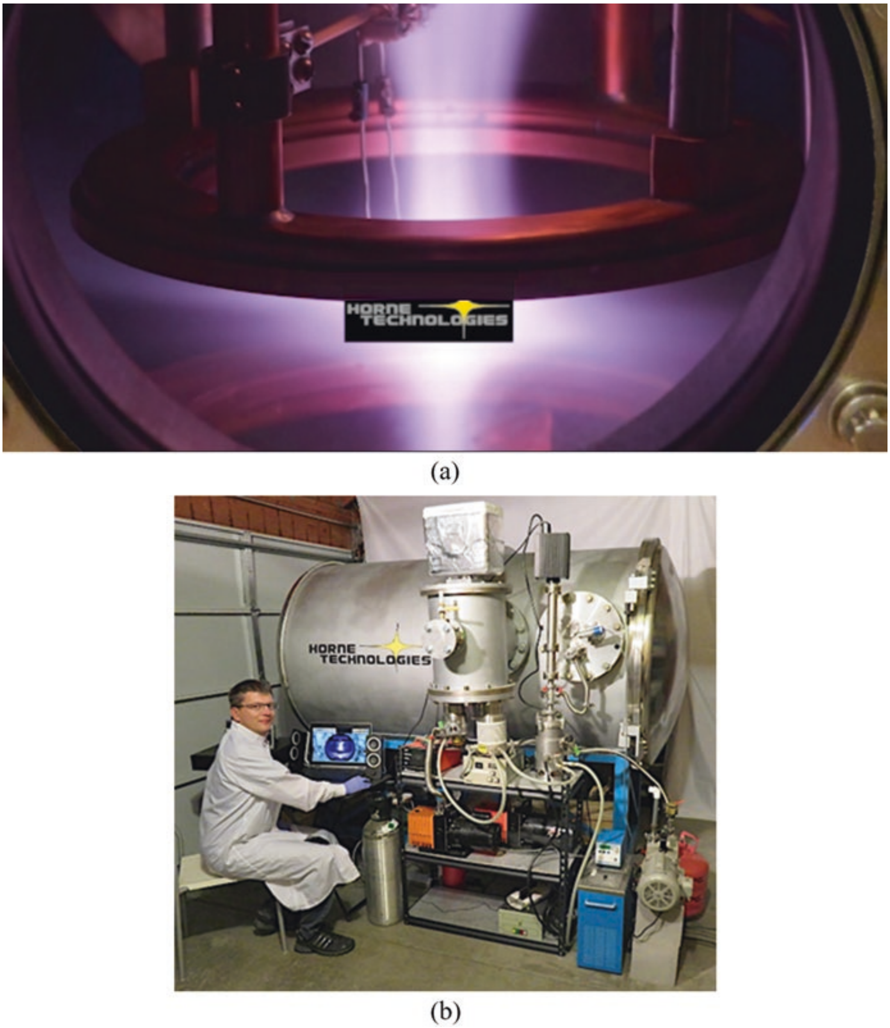

Fig. 5.6 (**a**) Tanner Horne's spindle cusp chamber, filled with shining plasma; (**b**) Horne sitting next to the device

of this hole, which depends on the plasma conditions within the cusp. Table 5.1 is a chart of different estimates of cusp hole size from different publications over the years. The hole size is ranked from the smallest to the largest estimates [44–51]. As a general rule for fusion, higher-density fields will leak less plasma. In the biconic cusp, one gets a higher density field by placing two very powerful magnets closer together. The goal of any cusp field designer is to shrink both the number and overall size of the cusp hole to improve plasma trapping.

Shrinking the area through which material can leak from a cusp system helps a lot, but Dr. Harold Grad found a way to go further. He researched a situation where

Table 5.1 Estimates of cusp hole size by a variety of analytical techniques are based on the Larmor radius, which is the distance that an ion or an electron will rotate around a field line (see Fig. 5.5 for an illustration of this)

Relative	Estimate	Expression	Typical dimensions
Smallest	Twice the electron Larmor radius	$2*\begin{matrix}\text{Electron}\\ \text{Larmor}\\ \text{radius}\end{matrix} = 2.14*10^{-4}*\frac{\sqrt{\begin{matrix}\text{Electron}\\ \text{temperature}\end{matrix}}}{\begin{matrix}\text{Magnetic}\\ \text{field strengh}\end{matrix}}$	10^{-9} to 10^{-12} m
	Four times the hybrid radius	$4*\sqrt{\begin{matrix}\text{Ion}\\ \text{Larmor}\\ \text{radius}\end{matrix}*\begin{matrix}\text{Electron}\\ \text{Larmor}\\ \text{radius}\end{matrix}}$	
Biggest	Twice the ion Larmor radius	$2*4.57*10^{-3}*\left[\frac{\sqrt{\begin{matrix}\text{Mass}\\ \text{number}\end{matrix}}}{\begin{matrix}\text{Ion}\\ \text{number}\end{matrix}}\right]\left[\frac{\sqrt{\begin{matrix}\text{Electron}\\ \text{temperature}\end{matrix}}}{\begin{matrix}\text{Magnetic}\\ \text{field strengh}\end{matrix}}\right]$	10^{-8} to 10^{-12} m

This number can be estimated for different plasmas based on field strength and density

the plasma's diamagnetism rejects the outside field and starts to plug up the cusps. Plugging the cusps shrinks the overall size of the holes in these fields [10, 17, 36]. Since plasma is a moving soup of charged material, it can do one of three things: first, it can conduct applied magnetic or electric fields [29]. Second, internal currents can generate self-magnetic field components. Self-generation can facilitate plasma structures like spheromaks and field-reversed configurations (FRCs) [30]. Finally, the plasma can *reject* the outside field [10] via diamagnetism, where the self-magnetic field opposes the applied external field. A diamagnetic plasma is one where the material's own internal fields reject the outside fields. In this situation, the plasma presses against the outside field, both hollowing out a space in the center and squeezing off the cusp holes at the edges [10]. The effect is measured using something called beta, which is the ratio of plasma pressure to external field pressure.

In simulations, Grad saw a way to harness this rejection to plug up the leaks in the biconic cusp, but to get the effect to work would likely require a great deal of high-density plasma in the center. A nice comparison of a cusp field that is modified in this way is shown below. Other researchers have proposed other ways to plug up a cusp field. Methods include using electric fields to push plasma back into the center or applying radiofrequency waves to warm the plasma at the fringes of the trap.

Rejecting the outside field leads to several useful behaviors. First, a plugged cusp should generally have a lower plasma loss rate. If enough plasma material is present, the plasma pressure may swell up like a balloon inside the cusp field [17]. This condition would involve plasma pressing against the surrounding field everywhere. In simulations, the plasma forms two regions [4, 15], but this behavior is not well studied experimentally. Each region is laid out below and illustrated in Fig. 5.7:

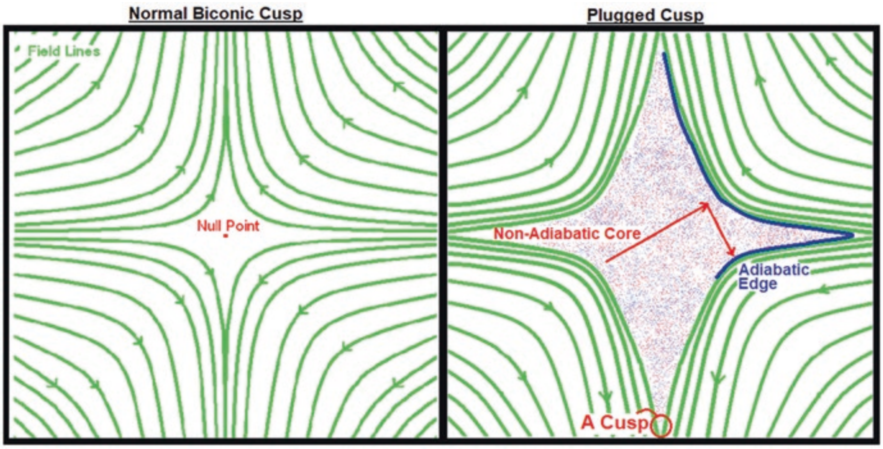

Fig. 5.7 A comparison between a normal biconic cusp field and a plugged-up cusp field

- *Adiabatic edge*: ideally, the edge of this system would hold in mass and energy inside this cusp-trapped plasma. This is known as an adiabatic edge, where "adiabatic" refers to a process that does not transfer either heat or mass to the outside surroundings. The edge has a pressure gradient where the diamagnetic plasma is pressing against the surrounding field. Such an edge is also subject to plasma instabilities (interchange, Rayleigh-Taylor, etc.), similar to those discussed elsewhere in this book.
- *Nonadiabatic core*: material at the center of the cusp trap is in such a condition that mass and energy are allowed to move freely about in the center. This is where the term "nonadiabatic" comes from. Inside this high-pressure core, the magnetic field could be zero. In a nonadiabatic core, ions and electrons can move in relatively straight lines, except for scattering collisions between other particles [4, 5, 15].

Any pressure gradient on the edge would induce a current flow on the surface of the trap. The current density along the edge would be such that the following would be true.

Pressure Gradient ≈ Edge Surface Current x Magnetic Field

Simulations and theory have shown that a sheet of moving electrons forms on this edge [10, 15–17]. This is similar to the so-called Chapman-Ferraro sheath, which is seen in large astrophysical plasmas. Such a sheet surrounds our planet and blocks it from solar wind material streaming from the Sun. Plasma in this system is also fundamentally warmer [9, 22, 26, 55]. A more complete definition of this kind of sheath is given in the Glossary. Theoretically, this system has a sharp boundary with a sheet of electrons moving on its surface [14, 15]. Figure 5.8 compares such a system with a typical fusion plasma in a magnetic field. It is important to note that this system relies on the plasma *rejecting* the outside field. That creates a

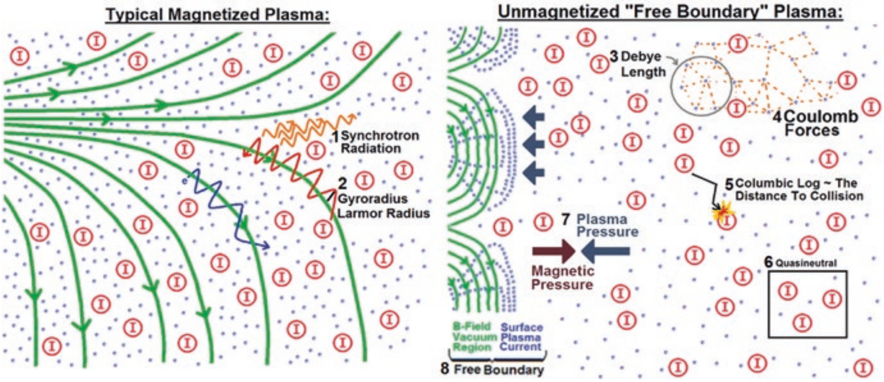

Fig. 5.8 An illustration that compares a magnetized plasma to a diamagnetic, cusp-confined, nonmagnetized plasma. This illustration also has a depiction of several key concepts used in plasma physics. (1) Synchrotron radiation is light generated as any particle travels along a curved magnetic field and is a way that a cusp plasma would lose energy. (2) Larmor radius, also known as the gyroradius, is a measure of how far a particle will rotate around a magnetic field line. (3) Debye length is the distance over which a particle will interact with the particles around it; beyond the Debye length, other particles are invisible. (4) Coulomb forces are electric forces between different particles in the plasma; it is this web of forces that make a plasma a fluid that conducts. (5) Columbic logarithm is a way to measure the average distance between a population of plasma at certain conditions. (6) Quasi-neutrality is the idea that in a given volume of plasma, there are roughly equal numbers of (+) and (−) charges. (7) Beta number is the ratio of the plasma and the magnetic field pressure on the plasma. Finally, (8) free boundary is the surface of the cusp-confined plasma; this surface should have a skin current if the diamagnetic effect is working properly

nonmagnetized plasma; a magnetized plasma, where the outside field penetrates, is far more common [31].

Researchers looking at cusp machines have been focused on measuring the thickness of this plasma "skin" and the size of the "gaps" in the sheath. The skin is the boundary layer between the center and the surrounding plasma, *i.e.*, between the nonadiabatic and adiabatic regions. The thickness of this sheath is also an open question as well as the size of the "gaps" where the plasma leaks out. The table earlier in this chapter laid out estimates for hole size, but the effect of skin and gaps is also an open question. A review paper from 1994 gives a nice summary of work into electrostatically plugged cusp systems [9].

5.2.5 Radiation Losses in Cusps

Radiation is energy leaving a plasma core as light. Fusion plasmas can emit light in the visible, ultraviolet, infrared, X-ray, and other parts of the electromagnetic spectrum. Any time a charged particle changes velocity (either speed or direction), Maxwell's equations dictate that it emits electromagnetic radiation. This happens in a swarm of ions and electrons for many reasons, including particles interacting with each other and external electric or magnetic fields. The result is that the plasma loses energy, and its particles generally slow down.

Historically, radiation has been categorized based on the mechanism or machine in which it was observed in. Hence, radiation has been classified as cyclotron, synchrotron, *bremsstrahlung*, line radiation, etc. But all these types of radiation are driven by the same mechanism: a particle slowing down because it is impacted by something else. Lost power (the rate at which energy leaves) depends on the density, temperature, and electromagnetic fields of the plasma.

Radiation losses are unavoidable; Maxwell's equations are nonnegotiable. But their impact can be minimized. One concept that has not been fully pursued is reflecting the radiation back into the core plasma. Such an approach would reduce radiation losses and drive the reactor to run more efficiently. One of the perks of a cusp device is that it will radiate less energy. The plasma inside such a machine is nonmagnetized, which removes one of the driving mechanisms behind the plasma radiation. A cusp system would see lower energy losses due to less cyclotron radiation, which is proportional to the square of the magnetic field intensity. Despite this advantage, the plasma is still losing energy through bremsstrahlung and line radiation.

5.3 Other Cusp Concepts

Although Harold Grad was one of the pioneers to explore and simulate (mathematically and by means of rudimentary computer models) cusp systems and published seminal papers about them, he could never build a machine. He did not have the tools, team, or money to do so. That was not the case with Dr. Jim Tuck at Los Alamos [8]. Famous for his work on the atomic bomb [33], Tuck turned his attention to fusion power after World War II. Chapter 3 discusses his work with pinches, but he also developed many concepts for fusion reactors based on a cusp system, such as those in Fig. 5.9.

Each idea shown in the figure is a cusp system. As noted, the biconic cusp is the simplest approach in this family. They all share the advantage that cusps reduce leakage. However, they have quite different histories. Tuck is the originator of four of the ideas. In 1960, he laid out the cross-field, tormac, picket fence, and ringed picket fence approaches [3, 8]. But Tuck was not able to experiment with any of these concepts. Instead, Los Alamos National Labs focused on the pinch approaches during the 1950s and 1960s (Chap. 3). Two concepts, the compact fusion reactor by Lockheed Martin and the polywell, are more modern ideas, and these will be discussed in the next section.

The biconic cusp has been tested experimentally many times but never made it into mainstream fusion research. For example, in 1980, a small group built one at the Naval Research Labs [19]. This machine, discussed briefly above, could only run for about 0.12 milliseconds and had a relatively small ring cusp field strength of about 0.2 tesla [19]. But testing was also hobbled because this machine could not run for very long. It used capacitors to power its magnets, which could only create

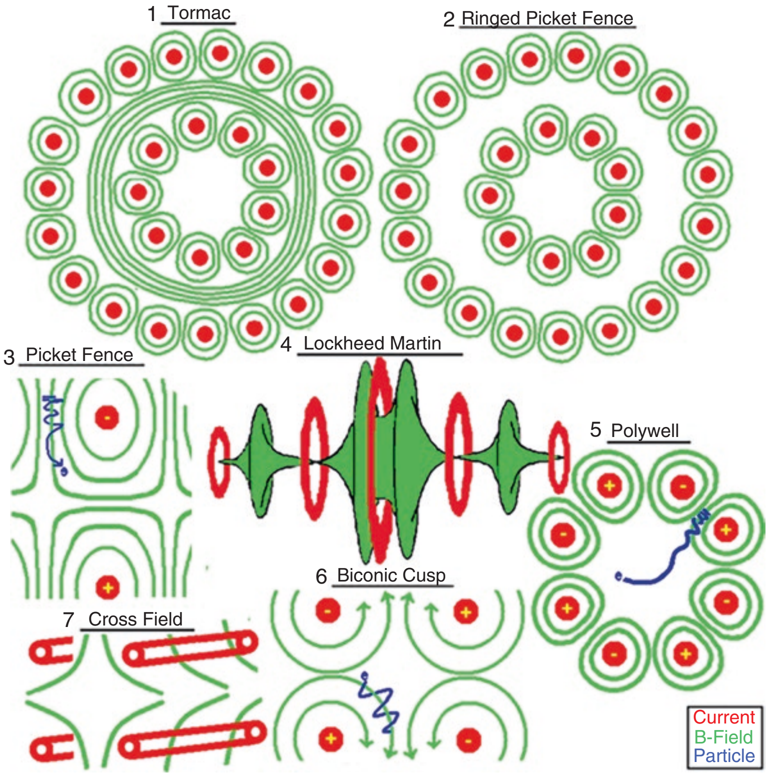

Fig. 5.9 A collection of cusp confinement concepts that have been proposed or tested since the 1950s [13]. The tormac (1) was a combination of a tokamak and a cusp-confined edge. The (2) ringed picket fence was a concept for a ring of cusps that created a barrier to escaping plasma. The (3) picket fence was a barrier to a plasma created by a series of cusp fields. The cross-field (7) approach attempted to create a long tube of plasma surrounded by cusp fields. The biconic cusp (6) is the simplest device in this family and is made of two electromagnets facing each other. The most recent cusp designs, the polywell (5) and the Lockheed-Martin compact fusion reactor (4), are described in detail below [7]

a pulse of magnetism that would quickly pass. Today, because of superconducting magnets, the field should be able to reach much higher, and testing should be able to last much longer. A cusp with superconducting magnets can run for tens of minutes and reach fields that are many teslas [20, 21]. This will enable teams to get long-term measurements of the reactors' performance. High-temperature superconductors should allow cusp machines to be explored in practice for the first time.

5.4 Current Cusp Systems

Cusp systems have never been funded as well as other concepts, such as the tokamak and laser approach. But a small effort to research this approach led by Dr. Robert Bussard started in 1989, and with support from the Navy, it continued for more than two decades. His company pursued cusp systems consistently until the end of 2014 and received over $45 million in military funding over that time period. Ultimately, this work produced the most complete information on cusp systems that is publicly available today.

5.4.1 Polywell

The system that the Navy funded was called the polywell, and Bussard proposed it as a blend of cusp-trapped plasma and electrostatically heated plasma. The approach was fundamentally flawed because of its approach to heating. The idea was to trap a negative plasma to then pull in ions and get them to fuse. Such a field could not be maintained because it tried to use electrostatics to heat the plasma. For that to work successfully, it would require a plasma with more negative electrons than positive ions. This breaks quasi-neutrality, a fundamental rule where the positive and negative charges must stay well-mixed together. The best that experimenters could do was to hold a plasma that created a weak negative (<5 volts) field [29, 55]. This was nowhere near the ~10,000 volts stable field needed to start deuterium-deuterium fusion [34]. A mostly negative plasma was hard to form because positive charges kept flowing into the cloud, causing any charge differential to simply vanish. Bussard believed that the cusp trap would be strong enough to overcome this, but it proved to be folly. This approach will also be discussed in more detail in the inertial electrostatic confinement chapter.

The biconic cusp system has two magnets that face one another. On the other hand, the polywell has six magnetic poles that face inward, toward one another. These are arranged in a box. Like the biconic cusp, these fields repel, and there is a null point with no magnetic field in the center where all the injected plasma tends to pool. The polywell concept is intended to collect enough plasma to make it diamagnetic and thus reject the outside field. This should lead to a stronger trap, with less plasma leakage.

Dr. Bussard died in 2007, and his research and the ownership of his company were eventually transferred to Dr. Jaeyoung Park, who left a staff position as a senior scientist at Los Alamos to run this effort full-time. Dr. Park came to the effort from a different perspective. He saw this effort as simply a way to prove or disprove the presence of the cusp trapping effect. If experiments proved that a diamagnetic plasma could reject the outside cusp field, then this approach had a path forward. If data showed something else, then this approach would not work. Figure 5.10 shows a picture of the machine that Dr. Park and his team built in 2013.

One problem with proving this diamagnetic effect inside a polywell was that it needed to start with very dense plasma. To do this, the team rigged up a plasma

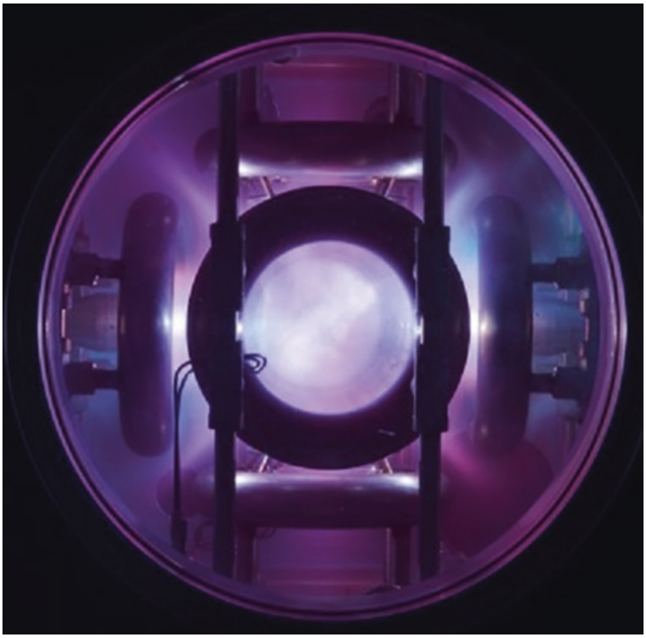

Fig. 5.10 A picture of the polywell during operation, from experiments led by Dr. Jaeyoung Park. The machine creates a field with six electromagnets (the smooth rings) that faced one another. This photo also shows how plasma will stream out of the edges of the cusp trap in the corners of the box. The plasma in this photo is not fusion fuel but a soup of fully ionized carbon and hydrogen

cannon that vaporized thin sheets of plastic. This resulted in the injection of hydrogen plasma, as well as a big heap of carbon, into this magnetic trap. Once this plasma was injected, the team measured its diamagnetic effects as it interacted with the surrounding field. The goal was to see if this plasma had magnetic effects and (if so) whether they would reject the outside field. The company also used X-ray emissions to determine if the plasma lasted longer than expected after the field is switched off, which would indicate that the plasma was self-organizing and rejecting the outside field. This experimental effort demonstrated this effect, and later simulations provided supporting evidence for that behavior [12]. Figure 5.11 shows a summary of this trapping mechanism and how the fields, particle motions, and plasma densities would all change as it happens. Hammering out this mechanism was the main contribution of the polywell research effort.

5.4.2 Compact Fusion Reactor

Up to the time of this writing, the most advanced cusp effort in the world was a concept called the compact fusion reactor (CFR) at the Lockheed-Martin Skunkworks in Palmdale, California, shown in Fig. 5.12. The CFR used the same

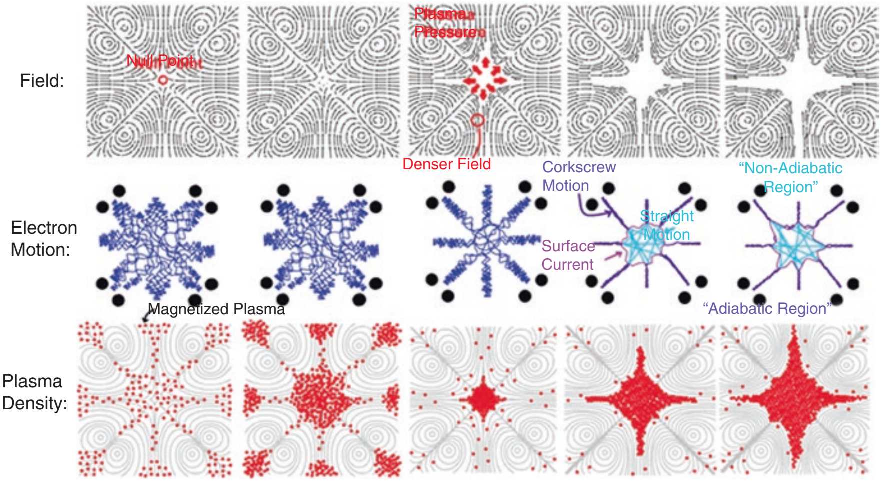

Fig. 5.11 The two-dimensional magnetic field, plasma motion, and plasma density inside a polywell during the formation of a trap. As the diamagnetic plasma inflates in the center, it rejects the external magnetic field. This creates two regions, nonadiabatic and adiabatic regions, where the plasma moves in straight and nonstraight lines [4, 23, 54]

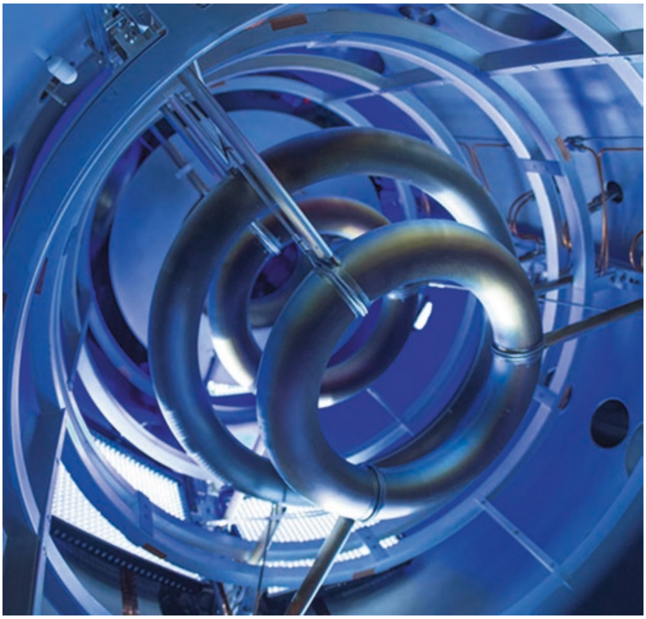

Fig. 5.12 The view inside of the compact fusion reactor built by Lockheed-Martin. Note the smooth ring design. These rings sit very close to the plasma. This makes the CFR a Galatea, a reactor where the magnets are embedded with the plasma [25, 35]

trapping approach as the polywell but with a more standard heating mechanism. It was championed by Dr. Thomas McGuire, who has been in fusion since the early 2000s. Dr. McGuire started as a graduate student at the Massachusetts Institute of Technology (MIT), where he did his thesis on multicage fusors. When he graduated in the winter of 2007, it was unclear what he was going to do next. His lab mate, Carl Dietrich, decided he was done with fusion and went off to found a company making flying cars [24]. But like many in this field, McGuire wanted to continue to pursue a concept and develop it into a power plant, and Skunkworks gave him the opportunity to try it. McGuire was inspired at the time by a recently written review article by the famous Russian physicist Alexey Morozov. In the article, Morozov discussed a class of fusion approaches, which he called Galateas, where the electromagnets are embedded inside the plasma [25, 26]. These kinds of devices, of which cusp systems are a subset, had been examined at the University of Wisconsin, Livermore, General Atomics, and Columbia University.

Any Galatea is characterized by a very smooth electromagnetic ring that sits very close to the plasma. Putting metal that close to the plasma creates several potential problems. If the ions and electrons contact the metal, they can be lost, and a fusion power plant cannot succeed if you are constantly bleeding away mass and energy. Contact can also cause arcs and melt components. These Galateas have metal parts inside high electric field environments; with such high voltages around, there is a chance that electricity can arc between the rings and break the machine. Therefore, Galateas must always have *very* smooth electromagnets, placed with ample space around them. Under McGuire's guidance, Lockheed-Martin ended up designing the CFR using these principles [35].

Dr. McGuire was brought in by a longtime manager at the Lockheed-Martin Skunkworks named Charles Chase. Over the next few years, McGuire and Chase collaborated to develop the CFR. Unfortunately, the company has restricted what it will say about its work, but Lockheed has given academic presentations and conference talks, filed patents, and shared information with journalists [35–42]. One magnetic design they have tested is shown in Ref. [36], but it is likely that multiple configurations were tested inside the CFR system. The experimental team at Lockheed (approximately 60 people since its beginning in the middle of the first decade of the new millennium) cycled through many (perhaps five) reactor configurations, such as the one in Fig. 5.13. The design shown in the figure has like poles facing one another. Lockheed is hoping that, like all the approaches mentioned here, the plasma will pool between these magnetic cusps and reject the external field. The figure shows an interesting feature of the CFR: the cusp volumes are not equal.

To get the proper trapping effect, a cusp reactor should always strive for balanced magnetic strengths. This was the principle that governed the placement and power of the polywell magnets. The design was such that magnetic field strengths at the corners, center, and sides were roughly the same. As noted above, plasma will leak through the edges and sides of the cusp. The Lockheed team is clearly anticipating and planning for these kinds of losses. The team plans to have a second, containing field produced by magnets around the outside of the CFR chamber designed to recycle as much plasma that leaks out as possible [36]. Recycling—or plasma

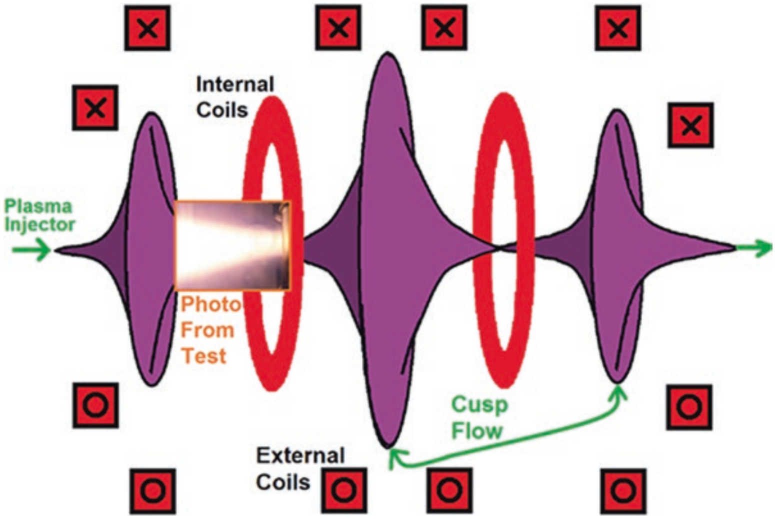

Fig. 5.13 One design for the fields inside the compact fusion reactor developed by Lockheed-Martin [36]. The photo in the box is a picture of the plasma from the experimental machine

recirculation—would be highly valuable for reducing mass losses in any fusion reactor. Some experts argue that it should be a requirement for all plasma reactors that are not at thermodynamic equilibrium [43]. Ideally, the plasma would move around the reactor without hitting anything since that would result in mass being conducted away.

Lockheed first went public with this design in the spring of 2013. Chase was invited to speak at the *Solve for X* conference. This event was organized by a Google think tank, and both Google cofounders, Sergey Brin and Larry Page, attended this talk. Lockheed has also presented its work at several small venues [35–42]. Of these presentations, Lockheed's plasma modeling has yielded some of the most interesting results. Figure 5.14 shows results from a two-dimensional, axisymmetric, particle-in-cell model [42]. That model represents the plasma in a computer as small volumes (cells), each containing a particle that is the equivalent of thousands of real ions and electrons. It tracks these particles as they move through the machine. In this case, Lockheed simulated two-dimensional slices of the machine, which were then rotated around an axis to produce a three-dimensional representation.

These results offer a simplified view of plasma behavior inside the CFR. Nevertheless, the model illustrated several characteristics of a cusp-confined plasma. First, there was relatively no magnetic field in the center. Second, a sheet of current has formed on the edges. Third, there was a sharp boundary at the edge of the trap with high-density plasma contained within. Finally, the ions were shown to be hot enough (over 10,000 eV) for fusion to occur.

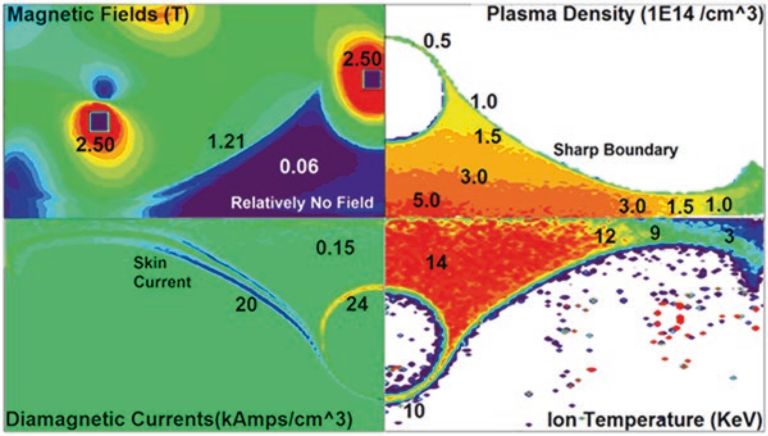

Fig. 5.14 Simulation results from the compact fusion reactor [17]. In the upper left is a picture of the field. It is important to note that there is relatively no magnetic field inside the plasma area. This implies that the diamagnetic plasma would be screening out the external field. On the lower left is a simulation of the plasma-generated current. Notably, there is a diamagnetic surface current on the trap, another sign of proper cusp confinement. On the right, the figure shows the mass (top) and energy (bottom) confinement in this simulation, which shows a sharp boundary

5.5 A Call for Transparency

In science, simulation is useful but data is king—and cusp systems truly lack sufficient data to be well understood. Both of the main cusp efforts have been funded by the US military, which has placed restrictions on how much information can be shared. Experimental data from this approach have not been sufficiently published, and any team following this concept needs to be aware of that. There are likely unknown pitfalls that folks following this concept may encounter, and it may ultimately be a dead end. To understand what lies ahead, it is important to understand the work that has already been completed. There are experimental data on ring devices that date back decades, but very little data were published on modern efforts like the polywell and CFR. Both research efforts have received tens of millions of dollars of government funding, so their data should be made accessible to the fusion community in order that the performance of this concept can be more widely understood and evaluated. Unfortunately, much of the funding went toward classified projects. The polywell team accepted Navy funding and was thus under a gag order for 11 years, whereas the CFR is a classified defense project, and hence Lockheed-Martin has been extremely selective about what information it gives out.

The problem with secrecy in fusion is that it kills collaboration, kills the growth of parallel efforts, and perpetuates the public's view that fusion is too challenging to be achieved. Groups often think that they are protecting some great technology by keeping it hidden when in reality, no team is chasing after their research. In a few years' time, after a great deal of money and effort was spent, the team often finds out that it has no one else to collaborate with when it hits a new challenge. What is worse, the same approaches get attempted again and again because the community is not aware of efforts that were kept secret. The only way to reverse this trend is to get this information out of silos and into the general public and research community.

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Tokamaks and Spherical Tokamaks

6

Summary

Anyone with a rudimentary knowledge of the quest for fusion power will know that for many years, the leading candidate has been a magnetic confinement device called the tokamak, from a Russian acronym for toroidal chamber with an axial magnetic field. At least 221 tokamaks have been built, planned, or decommissioned worldwide. Almost every modern nation interested in fusion has had a tokamak machine—from Kazakhstan to Russia to Japan to Brazil. For almost a generation, a large majority of Americans involved in fusion—researchers, government officials, scientists, and university professors—have been tokamak people. This chapter is an overview of the development of the tokamak, its successes to date, and how it eventually became the most dominant fusion reactor approach. Readers looking for more detail on its history and technology should consult the Recommended Reading section, which lists several excellent books on the subject.

6.1 A Brief History of Tokamaks

In the late 1950s and early 1960s, while the United States and the United Kingdom focused their fusion research on pinches and a complicated but promising machine called the stellarator (discussed below), Oleg Lavrentiev in the Soviet Union (USSR) was working on a different type of toroidal fusion reactor that his colleague Igor Golovin called the tokamak, an acronym for **то**роидальная **ка**мера с **ма**гнитными **к**атушками (transliterated as ***to**roidal'naya **ka**mera s **ma**gnitnymi **k**atushkami*), meaning "**to**roidal **cha**mber with **ma**gnetic **c**oils" (Fig. 6.1).

The machine, made public in 1965, was initially dismissed by Western researchers. Then in 1968, the head of Soviet fusion, Dr. Andrei Sakharov, announced that their T-3 machine had kept electrons hotter than 10 million degrees, corresponding

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
https://doi.org/10.1007/978-3-031-22906-0_6

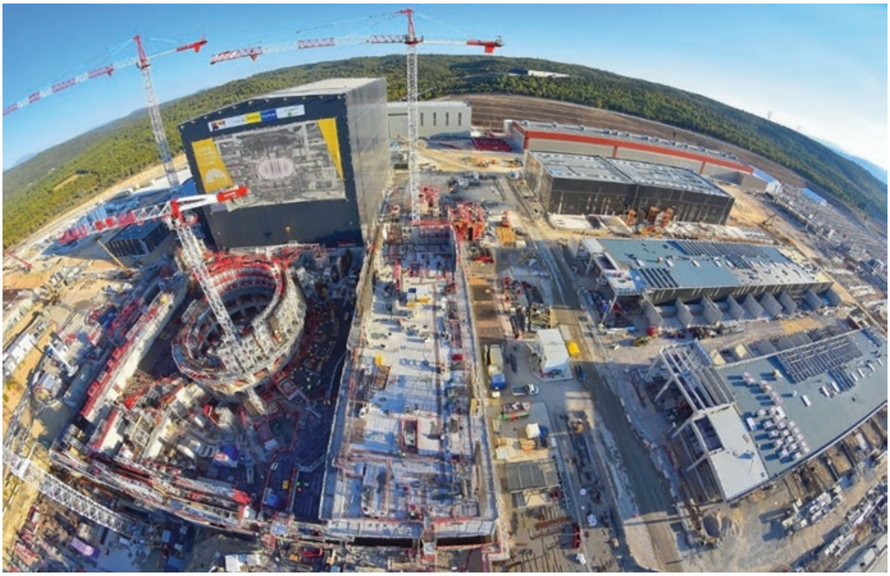

Fig. 6.1 The International Thermonuclear Experimental Reactor (ITER, pronounced "eater") tokamak under development in France in December 2017. ITER is expected to become operational in 2025 [8]. (Photo courtesy of the ITER organization)

to an energy of more than 1 keV, ten times hotter than the US program had achieved. In order to check the validity, a British team traveled to the USSR to test the machine's temperature. The team was shocked to find a plasma temperature that indeed exceeded 1 keV. Today, this 1 keV temperature is used as a benchmark by many fusion researchers to test whether such an approach can be taken seriously.

Since funding for US and UK fusion research was heavily connected to Cold War programs, those measurements created panic among Western governments. Fusion funding increased as a stampede of institutions began rushing to build tokamaks. Dr. Stephen O. Dean, then with the Atomic Energy Commission, once explained it this way:

> …It's the concept that has had the most success. No other concept has had the performance success … All of a sudden the Russians had good confinement; everybody started building tokamaks. All these tokamaks turned out to get good results, so people built bigger ones. And so all around the world people kept building bigger and bigger ones and they all seemed to work better and better….

Since then, the tokamak has been the worldwide heavyweight in fusion. To date, over 221 tokamaks have been built, planned, or decommissioned worldwide.

Aside from competition with the Russians, another reason that the West rushed to build tokamaks was the 1973 oil crisis. In October 1973, the Organization of Petroleum Exporting Countries (OPEC) put an embargo on oil exports to several countries. The oil crisis shut down the US economy and made it clear to politicians how important it was to develop alternative sources of energy. Funding for US fusion research experienced its highest levels from 1972 to 1986.

The two leading US programs during that time were mirror and tokamak development efforts, with laser fusion (connected to weapons) and other concepts trailing. Of the two, the tokamak performed far better. It slowly began to dominate the fusion research landscape. Then on February 21, 1986, the Mirror Fusion Test Facility was shut down by the Reagan administration. That ended the mirror program and marked the point when tokamaks came to be the leading fusion approach. Most college courses in fusion shifted to focusing just on tokamaks. With the success of machines in the West, it became easier for other governments to justify building tokamaks. Tokamaks were built in Egypt, Iran, the Czech Republic, Libya, Mexico, and India. A full discussion of this history is outside the scope of this book. (See the recommended reading list for more information). Today, advancing the state of tokamak science requires a large staff and a sizeable research team. The low-hanging fruit in this field has been mostly picked over, and a small machine will not yield any scientific revelations.

6.2 The Tokamak Concept

Essentially, a tokamak is a flowing plasma that moves around a ring chamber with an applied external magnetic field. The device itself looks like a donut. The strength of this machine is that plasma particles can transit many times without leaking. This allows the plasma to get hot and stay hot. Hot plasma races around this ring in a twisted path. That is a key element of the tokamak design: it has its own current, known as the plasma current, which creates its own magnetic field. The current also changes the machine's temperature, pressure, and density. This self-created field mixes with the externally applied fields (poloidal, i.e., in the direction through the donut hole, and toroidal, i.e., in the direction around the donut) to create a new hybrid field. Plasma follows along this field in a twisted motion (see Fig. 6.2). The twisted motion of the plasma is very important to the tokamak's operation as without the twist, materials would scatter into the walls of the machine. Twisting the

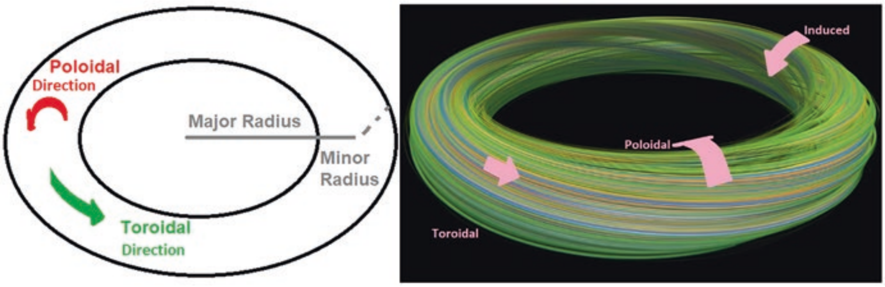

Fig. 6.2 The basic geometry of a tokamak (left) and the basic twisted motion of the plasma inside a tokamak (right). (Image source: Wikipedia)

plasma motion greatly reduces the loss of hot mass inside the machine, and, importantly, conduction losses also fall.

Tokamak plasma is entirely magnetized; i.e., it has a magnetic field that is fully embedded everywhere inside the plasma. The field inside a tokamak is a result of mixing both the self-created and imposed fields. In this way, the tokamak can be seen as a hybrid machine. Plasma inside a magnetized environment races along the field lines. Tokamaks use externally applied toroidal and poloidal fields to drive and direct the motion of the plasma as it moves around the ring. The plasma particles follow the field like a car on a highway.

The current itself is made up of both electrons and ions. It is driven by the current injection, surrounding magnetic fields, and by varying the voltage on the magnet in the center of the machine. As the plasma moves, it experiences electrical resistance, which leads to a heating of plasma, referred to as ohmic heating. Japan's JT-60 tokamak holds the present world record for the hottest plasma ever created through this approach. In 1996, the ions in that machine reached a temperature of 522 million K [22]. During that run, the hottest ions would transit around the donut over 125,000 times in one second.

6.2.1 Shaping the Plasma "Racetrack"

Over the history of fusion, engineers have broadly tried three different shapes for the "racetrack" (the path the plasma follows) in their quest for better performance. Three designs will be discussed here: tokamaks, spherical tokamaks, and stellarators. Today, these three kinds of designs have evolved into completely different machines, to the point where some consider them independent approaches. They are discussed together in this book because they share similar plasma behavior, and they are all ringed designs. The reasons behind the shape of each machine are summarized below. These reasons will be discussed in more detail later on in this chapter.

- *Stellarators*: the stellarator is a twisted loop of plasma (Fig. 6.3). This machine was invented by Lyman Spitzer at Princeton in 1951. Dr. Spitzer, who is revered in both astrophysics and fusion communities as an innovator, famously came up with the idea while riding a ski lift in Aspen [17]. He reasoned that hot ions would always scatter into tracks with wider curvature. By twisting plasma, he could continuously scatter material back into the center of the ring. So the twisted ribbon shape is meant to contain ions that would otherwise scatter and hit the walls [16].
- *Circular tokamaks*: the early Russian machines were all circular tokamaks. Ideally, these machines look like perfect donuts (Fig. 6.4). This shape was chosen because the plasma is fundamentally stable in a perfect donut [23]. Over time, researchers realized that by changing the aspect ratio to be taller and thinner, they could get hotter, denser, and better-trapped plasma. This eventually led to the spherical tokamak.

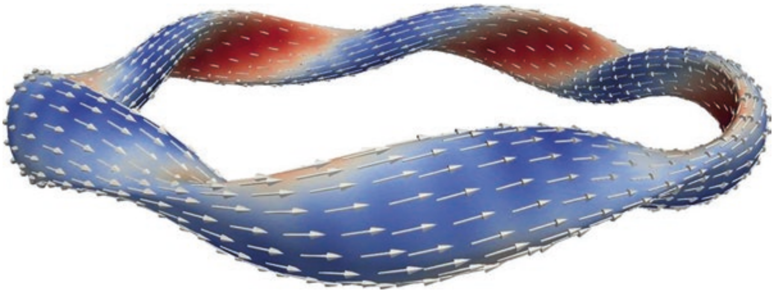

Fig. 6.3 Plasma flow inside a stellarator, where material is continuously rescattered back into the center of the ring. This illustration has six twists, but other variants can have eight. (Photo courtesy of the Princeton Plasma Physics Laboratory)

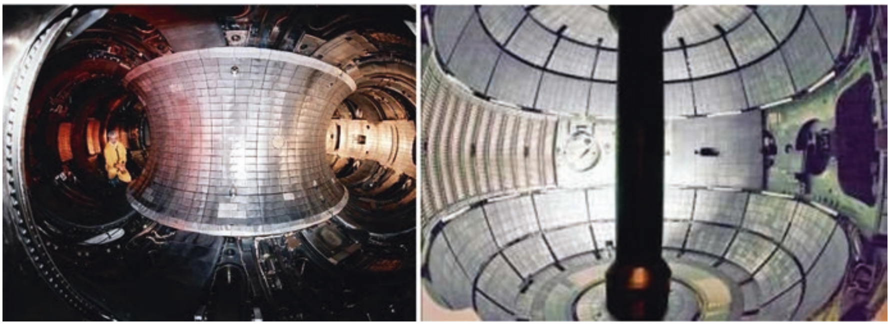

Fig. 6.4 A comparison of a circular-shaped tokamak (left) and a spherical tokamak (right). Notice how the center column shrinks from a wide ring to a thin pole. Also, notice the difference in height. The donut-shaped machine on the left has no notable height difference, while the right is very tall and skinny. The change in shape in the center column impacts the plasma current, which in turn changes the performance of the whole machine. (Photo courtesy of the Princeton Plasma Physics Laboratory)

- *Spherical tokamaks*: the spherical tokamak (ST) looks like a cored apple. It is tall and skinny, with a narrow column in the center (Fig. 6.4). A spherical tokamak has better performance because the plasma spends more time closer to the center column of the machine. Since the field here is naturally stronger, it leads to a hotter and denser plasma. Also, by reshaping the reactor, the plasma current is changed, which impacts everything about the machine's performance. The main disadvantage of an ST machine is that it is harder to build. The decision to move to ST designs emerged in the 1980s when researchers like Martin Peng in the United States and Alan Sykes and Marion Turner in the United Kingdom saw that by making the reactor tall and skinny, they would improve plasma pressure. The UK pair published a paper that became known as the Sykes-Turner Law, which predicted that the plasma could be denser as the tokamak got taller and skinnier [24].

These three machines are all looped reactors with magnetically confined plasmas, and they share common plasma physics. The effects discussed in this chapter are generally seen in all three machines. The stellarator is the oldest design, and it has four variants with different twist geometries and numbers of twists: the Heliac, Torsatron, Heliotron, and Helias machines [18–21]. Changing between each type means changing the plasma geometry: eight twists versus six twists, etc. Figure 6.3 illustrates the plasma shape inside of a stellarator.

6.2.2 Plasma Current

The plasma current can be adjusted to change the behavior of the reactor. In a tokamak, that adjustment results from an electric current that flows through the center column, creating a magnetic field inside the plasma volume, thereby influencing the plasma current. The plasma current impacts several behaviors simultaneously:

- *Toroidal field*: the flow of particles inside a tokamak (positive or negative) creates its own magnetic field. This plasma current races around the device (in the toroidal direction) and creates a magnetic field in the axial (or poloidal) direction. This self-generated field interacts with the field imposed by the machine. It is through this interaction that the particles create a twisted path around the reactor.
- *Plasma temperature*: as noted above, a flowing plasma current experiences electrical resistance, which leads to ohmic heating of the material. This was one of the first methods for heating plasma inside a tokamak, but there are other ways to heat it, which will be discussed below.
- *Plasma pressure*: the combination of better heating and a stronger, self-generated magnetic field leads to higher plasma pressures everywhere inside the vessel. At the same time, the plasma current generates a poloidal field, which imposes better containment on the reactor. Ultimately, driving a plasma current increases the overall plasma pressure of the machine.

6.3 Tokamak Engineering

Going from a concept to an actual machine is an engineering challenge. A variety of tokamak designs are possible, but all have certain basic subsystems. Broadly, a tokamak is made from a central solenoid, a poloidal and toroidal magnet, and a diverter in its base. We discuss each of these magnets below. Putting these subsystems together is like assembling a three-dimensional jigsaw puzzle. The magnets surround a vacuum chamber through which the plasma flows. Because high magnetic fields create a higher density and better confinement of the plasma, newer tokamaks take advantage of advances in superconducting magnets. This means that the newest tokamaks require a large low-temperature chamber called a cryostat inside them.

Though tokamaks remain the leading candidates for fusion power plants, none has yet achieved a “breakeven,” in which they produce more energy from fusion than it takes to operate them. At this point, every tokamak device is experimental and thus needs probes to test and monitor plasma. If and when a commercial tokamak power plant is built, many of the probes could be perfected or removed from the design entirely. The design of the tokamak may change drastically by that time from the ones described in this book. For example, some researchers are considering reducing the number of magnets by removing the central solenoid.

6.3.1 A Current Example: The Tokamak Energy ST40

The best way to understand the parts of a tokamak is by example. Our choice is a spherical tokamak designed by Tokamak Energy. Tokamak Energy is a private fusion company in the United Kingdom, which has demonstrated 100-million-degree plasma. The company was kind enough to grant permission to use images of its ST40 device in this book. Though no two tokamaks are identical, ST40 has the basic subsystems that are common to all these machines. But it also has some unique elements. First, the machine is stripped down when it comes to the magnets. Many tokamaks have extra magnets that allow them to do some exotic plasma experiments. Second, most tokamaks are built with continuous D-shape magnets. Tokamak Energy formed their Ds by fitting the central solenoid to the curved C-shaped poloidal magnets. These magnets are clamped together and affixed by adding a small weld [41]. This approach has several trade-offs. On the upside, welding saved the engineers time and money because it was easier to work with. However, welds limit the current the magnets can carry without causing mechanical failure.

With these differences in mind, ST40 is still an excellent example of a machine to explain the engineering of a tokamak (Fig. 6.5).

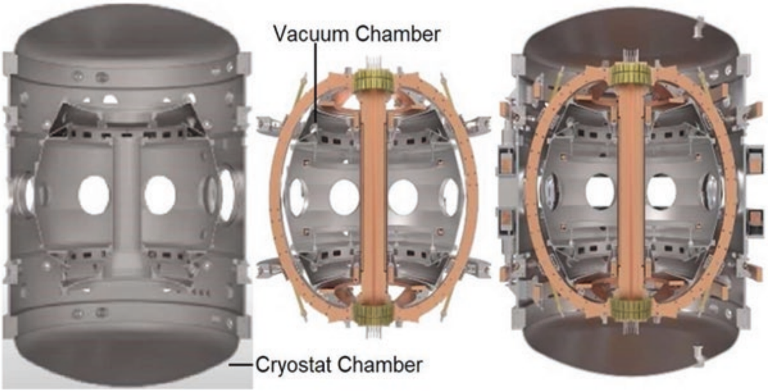

Fig. 6.5 A cutaway of the major systems of ST40 shown fitted together. The system is made of nested inner and outer vacuum chambers that fit together with the toroidal and poloidal field coils. The vacuum chamber in the center is filled with hot plasma. The outer vacuum chamber serves as a cryostat, with the chamber cooled using liquid nitrogen. (Images ©Tokamak Energy)

Figure 6.6 shows the D-shaped magnets that produce ST40's toroidal magnetic field. Each of the eight D coils has two parts, which are mated together. A wedge passes down the middle of a center column, with a curved C-shaped arm connected to it. Current passes through these D-shaped coils, creating a magnetic field that rings the plasma. ST40's coils are made from strips of copper. Though high-temperature superconductors are a better choice for a fusion power device, the

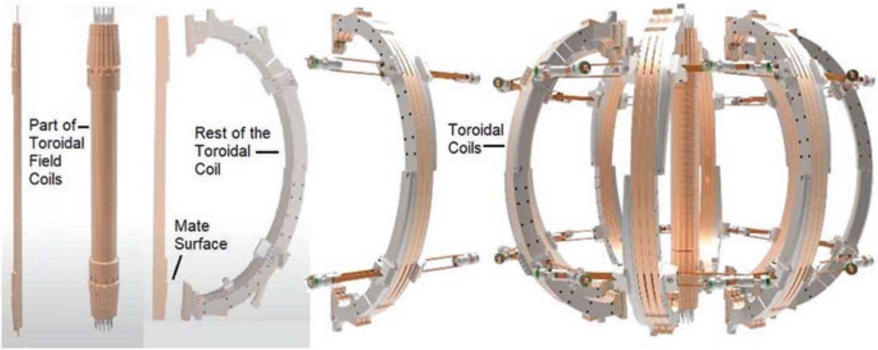

Fig. 6.6 The eight toroidal field coils in ST40 are made from central wedges, which are mated to D-shaped coils. Each coil is made from solid copper blocks held together by metal arms. (Images ©Tokamak Energy)

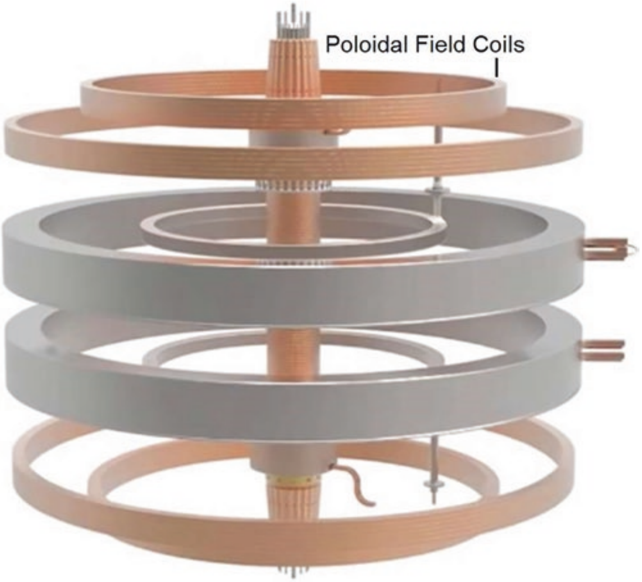

Fig. 6.7 ST40's poloidal field coils. They are rings of copper blocks around the central plasma volume. When combined with the fields made by the toroidal coils and the field made by the plasma current, it creates a twisted plasma current needed inside the tokamak. (Image ©Tokamak Energy)

designers of the ST40 decided they presented too many risks of failure to use them in their initial testing.

In the industry as a whole, a major effort is now underway to incorporate superconducting magnets into tokamaks. This will significantly lower the power necessary to run these machines and thus improve the odds of the tokamak creating net power.

The magnetic field in a tokamak is the net result of all the fields made by the coils and plasma within the machine. Engineers combine the toroidal field with a set of poloidal coils, as shown in Fig. 6.7. They are also made from copper wire, which wraps around the plasma volume.

6.4 Tokamak Operation

Tokamaks need several subsystems for starting, heating, controlling, and cleaning their plasma. Tokamaks start with a vacuum chamber, which will hold the plasma, and a magnetic field that is shaped to confine and manipulate it in that chamber long enough so significant fusion reactions can take place. The plasma can be formed in several ways inside this space. For example, plasma can be formed directly by ionizing injected fuel gas. Once the plasma has formed, there are multiple ways to heat it. Some typical ways are listed below, but more methods can be found in references [10] and [11]:

- *Plasma current*: as mentioned above, the plasma current is integral to the functioning of a tokamak. The flow of plasma through the core creates a resistance that ultimately heats the plasma, the same way that a wire heats up as current passes through it.
- *Microwaving*: tokamaks use a method similar to “microwaving” its plasma. Radio waves cause the particles in the plasma to gyrate faster, heating them. It is important that the waves are tuned to the right frequency. For ions, this approach is known as ion cyclotron resonance heating (ICRH). A similar method is used for the electrons.
- *Neutral beam injection*: this technique sends high-energy beams of particles into the tokamak to heat the plasma. The entering material acts like bullets, knocking into the ions and electrons, heating them up. It is important that these beams are neutral; otherwise, they would not be able to penetrate the magnetic fields to get into the reactor.
- *Magnetic reconnection*: reconnection is a way to pull energy directly out of the magnetic field. During a reconnection event, the magnetic field energy is transformed into heat for the plasma. Reconnection happens only when the plasma is so densely packed into a region that it changes the magnetic permittivity of that space. This allows two magnetic fields to connect and merge to form a single new field. When this happens, a huge amount of energy is released from the magnetic field, and 80% of that is transferred in order to heat the tokamak plasma.

Once the plasma is heated, the particles that are racing around the tokamak have enough energy to collide and fuse. This process produces physical phenomena on both macro- and microscopic scales, some of which are mentioned below. The colliding and fusing hydrogen nuclei form a hot helium “ash” inside the tokamak plasma. This ash can become a problem. Helium cannot be fused further in these machines, and as it forms, it dilutes the fuel. That is not the only impurity within the reactor. Dust, stray gas, and residue from the chamber can also pollute the plasma. To clean the plasma, tokamaks have a device called a diverter. The diverter is discussed in more detail later on in the chapter. It is worth pointing out that this would be an issue with many fusion approaches.

6.4.1 Operational Coils

In order to produce all the effects needed to operate as a tokamak, ST40 needs several other magnets. ST40 wraps the central wedges with a wire, creating a solenoid (see Fig. 6.8). The primary function of the central solenoid is to create a current that races around the tokamak plasma. That current and the magnetic field it produces keep the plasma stable and hot. Heating occurs because of the resistance of the surrounding plasma to the flow, ohmic heating as described earlier. Additionally, two

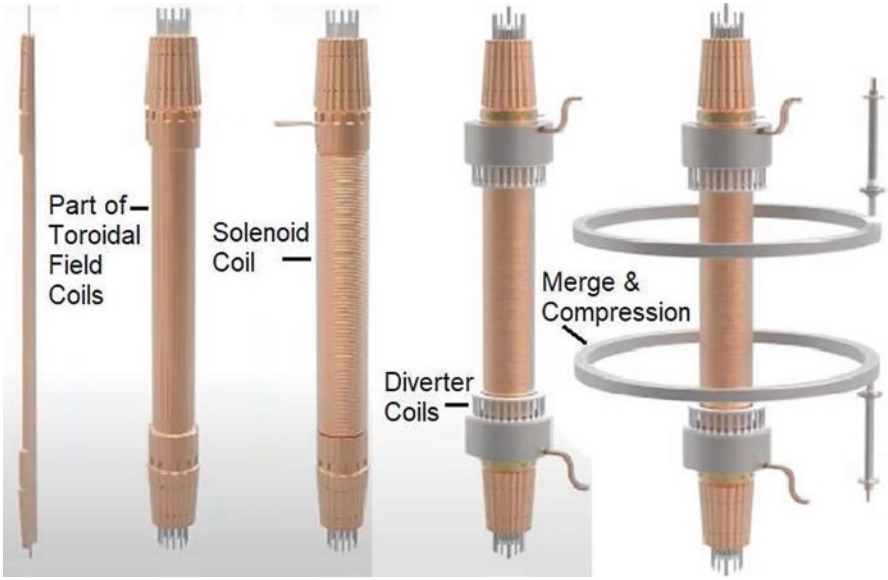

Fig. 6.8 The multistep assembly of the central column inside the spherical tokamak ST40. First, the column holds half of the toroidal field coils. Next, the column is wrapped with the central solenoid, which is used to maintain and control the plasma current. Next, the column is surrounded by the diverter field coils, which are used to clean the tokamak plasma. Finally, the column is encircled by the merging compression coils, which will be used to start the tokamak. (Images ©Tokamak Energy)

magnets, the diverter coils, ring the center column. These rings direct material into the diverter, which acts like an ashtray surrounding the base of the tokamak. Finally, the ST40 machine uses magnetic reconnection, using the two hula-hoop magnets in the diagram. The reconnection process is described in detail at the end of the chapter.

6.5 Stellarator Engineering

Stellarators are also machines that race plasma around a ring. But beyond this ring design, the machine has many significant differences from both circular and spherical tokamaks. Some might argue that the stellarator is so different that it should have its own chapter, but we elected to keep these topics together because the plasma behavior seen inside tokamaks is also seen inside stellarators.

The biggest difference between these concepts is that the stellarator has no central solenoid (or central column). In tokamaks, the central solenoid is critical for starting the reactor and heating its plasma. In spherical tokamaks, getting more plasma closer to the central solenoid for better heating is the main reason for the whole design. Instead of having a central solenoid, stellarators create their fields using rings of conductors that wrap around the plasma and are tilted into irregular shapes. The field in the center is a superposition of all the fields made by each contributing ring (see Fig. 6.9). The resulting stellarator chamber looks like a twisted ribbon wrapped into a ring. Plasma flows along this twisted path. There are many advantages to the stellarator design—and supporters have gone so far as to argue that it could be the best approach to fusion. The main advantage was previously mentioned: by twisting, the plasma's material is continuously pushed back into the

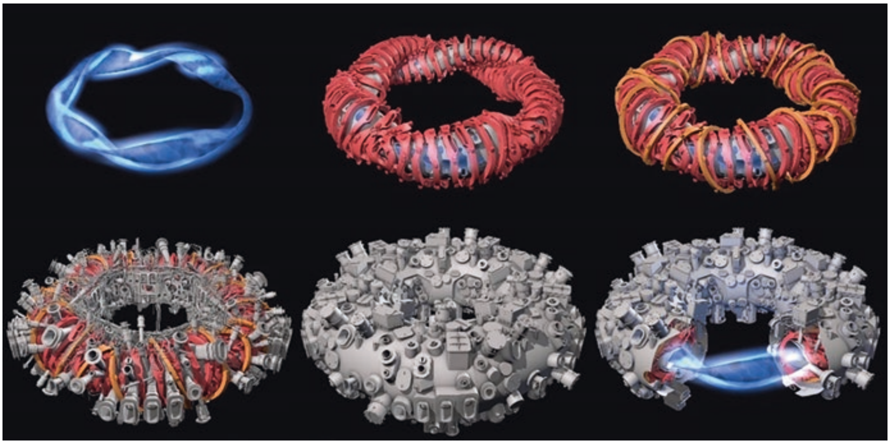

Fig. 6.9 The design of different subsystems inside W7-X. The upper left shows the overall plasma shape. This plasma is ringed by inner and outer loops of superconductors, shown in red and orange. All of that is surrounded by reactor shielding and ports for accessing the plasma. (Image courtesy of AAAS Science)

reactor core. This lowers the loss of mass and energy by keeping the hot plasma trapped.

Though several stellarators have been built or planned, the most advanced machine currently in operation is Wendelstein 7-X, which is in Germany. The planning for W7-X started in 1997. Building a large stellarator is challenging because it is made from large-scale components yet also has to meet tight engineering tolerances. Magnets that are tens of meters in size have to be aligned with micron-scale precision. Moreover, the twisted shape of the magnets presents logistical challenges when it comes to device assembly. The W7-X design group ended up using a supercomputer to design and simulate the machine. The computer had to work out the optimal shape for two different layers of magnets. The first layer of 50 magnets butted up against the inner chamber. The second layer of 20 magnets was positioned outside the main chamber for support [15]. If one coil is wider, thinner, or out of position, the resulting magnetic field can be skewed into the wall. The supercomputer accounted for all this and designed the best configuration possible. The different parts of W7-X are shown in Fig. 6.9.

W7-X was turned on in October of 2015 at a total cost of 1.06 billion euros. The machine was a feat of German engineering, which also pushed the limits of fusion materials. The inside is covered in graphite tiles arranged so that it looks like snakeskin. As of this writing, the machine has heated ions to 40 million kelvins and has reached a density of 2×10^{20} particles per cubic meter. These are impressive metrics in their own right, but remarkably, the Germans are currently working toward running the device for 30 min of operation. If they can achieve this, it will be a major milestone in human civilization's efforts to reach fusion power.

6.6 Milestones in Tokamak History from TFTR to ITER

This book does not intend to include a comprehensive history of tokamaks, spherical tokamaks, or stellarators. For that, we recommend books 3 and 4 on the Recommended Reading list. But there are a few key events in the history of these devices that everyone learning about fusion should be aware of. One such event took place on December 24, 1982, Christmas Eve, at Princeton University. On that night, the Tokamak Fusion Test Reactor (TFTR), at the time the largest tokamak in the world, achieved its first plasma. The machine famously worked at 3:06 a.m. on Christmas Eve, but everyone agreed to list the data as the day before. (See Fig. 6.10.) The TFTR would run for 15 years and go on to set several world records in fusion.

Another key event took place at the end of 2021. This was when the Joint European Torus (JET) created 59 megawatts of energy from fusion. As of this writing, this is the world record for the highest energy efficiency and highest fusion energy made by any fusion device. But it is important to understand some details because this event has been the subject of many interpretations by the science community:

Fig. 6.10 A famous image of the TFTR's first successful plasma run, which took place on Christmas Eve 1982. Dr. Harold Furth can be seen third from the right. (Photo courtesy of the Princeton Plasma Physics Laboratory)

- *The driver was 100 MW*. The Joint European Torus used large flywheels to provide pulsed power to run the machine. These flywheels created approximately 100 megawatts of power to run JET for the short amount of time (tens of seconds) needed to create 59 megawatts [3]. With that measure, the efficiency of this machine was 59%.
- *No energy capture*. JET was not set up to act like a power plant [3]. This means the reactor did not have electrical converters to translate the energy made by fusion into electricity. A typical power plant is anywhere from 25% to 35% efficient. By this measure, the efficiency of JET was roughly 17%.

In the coming years, another organization and device will likely crush this performance record. JET achieved its record by using a half-half mix of tritium and deuterium in its plasma. JET will remain the largest working tokamak in the world until the International Thermonuclear Experimental Reactor (ITER) is turned on.

Tokamaks are the most mature fusion approach; hence, they hold the most records of any fusion reactor scheme. Japan's JT-60 currently holds the record for the hottest plasma ever created, over 522 million kelvins in 1996, but the device could only run for a very short burst of time. Japan also has the current record for the longest tokamak run, nearly five hours for the TRIAM-1 M. Unfortunately, this plasma was not hot enough to start fusion reactions.

The strongest tokamak performance so far is China's EAST machine, which operated for over 17 min at 126 million degrees in early 2022. The firm Tokamak Energy has also run a cold plasma for over 26 hours continuously. Tokamaks have also been run with a variety of fuels: hydrogen, deuterium, and even tritium [47].

These plasmas are typically considered hot (approximately 100 million kelvins) but not dense (about 10^{14} ions/cm^3). By comparison, laser fusion makes plasma that is cold (10 million kelvins) but very dense (10^{25} ions/cm^3). We use “cold” in a relative sense here. However, once newer, high-magnetic-field tokamaks come online in the coming years, we expect them to smash all of these records.

Probably the most important of those future record breakers is the International Thermonuclear Experimental Reactor (ITER). Through the 1980s, there was a steady stream of tokamak successes, and their reputation grew as a dependable approach to fusion. It became clear that as machines got larger, the power output also improved. This started internal discussions in Washington and Moscow about “the big machine” to get net power. It was becoming clear that a machine large enough to reach that goal would be so expensive and complex that it would exceed the resources that any one country would be willing to commit. Physicists like Dr. Charles Newstead (in the United States) and Dr. Evgeny Velikhov (in Russia), who were close to President Ronald Reagan and General Secretary Mikhail Gorbachev, began pressing their administrations to act. Then in November of 1985, the leaders of the United States and Russia agreed to collaborate to build a large tokamak. At the time, the agreement was merely a couple of sentences on a joint statement. But this was the start of the ITER organization. That organization designed and is currently building the largest tokamak in the world in France (see Fig. 6.11). The assembly stage began in July 2020, with completion targeted for 2025.

As of this writing, the ITER machine is on schedule for its first plasma in December of 2025, more than 30 years after the joint agreement between the United States and the USSR. Why did it take so long? ITER development was stalled for many reasons, which had nothing to do with science or engineering. In his book *ITER: The Giant Fusion Reactor*, author Michel Classen details the bureaucratic history of ITER planning. Deciding on what, where, and how to pay for a machine to be built by seven or more countries was a massive diplomatic and political accomplishment in its own right. Along the way, ITER has been criticized for a whole host

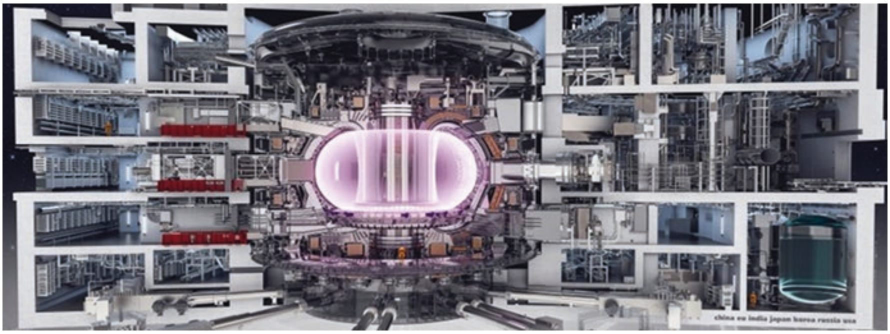

Fig. 6.11 An illustration of the ITER reactor building. ITER represents one of the most challenging construction programs in the world. It involves a massive scale, coupled with ultrasensitive construction requirements. ITER is set to open in 2025; its design and construction should seed the fusion industry in several countries. (Illustration courtesy of the ITER organization)

of issues, from management to device to schedule and cost overruns. See reference [5] for some of these criticisms and the Recommended Reading list for supporting arguments. Regardless of whether ITER succeeds, the effort is creating an industrial base for fusion, creating a pipeline of technologies, organizations, and a workforce familiar with fusion reactor design and engineering. This should help all fusion teams going forward.

6.7 Macroscopic Behavior of Tokamak Plasma

The tokamak plasma is the best studied of all the fusion reactor concepts. Both macroscopic and microscopic behaviors have been examined in great detail. The best macroscopic behavior occurs when the machine is run in high-confinement mode (H-mode), discovered in 1982 by Fritz Wagner. This was opposed to low-confinement (L-mode) mode. Researchers were pushing the density and energy inside the machine, and suddenly the whole thing stabilized. This condition became H-mode.

H-mode is the best way to run any tokamak because the plasma inside it is more stable, is better trapped, and can be heated more efficiently. Plasma in H-mode is characterized by smooth gradients throughout the bulk material and sharp gradients at the edge. If this mode is working properly, there are no sharp changes in temperature, density, field, or pressure across most of the volume. These profiles are referred to as the pedestal (Fig. 6.12). Inside the pedestal, the plasma behaves exceedingly

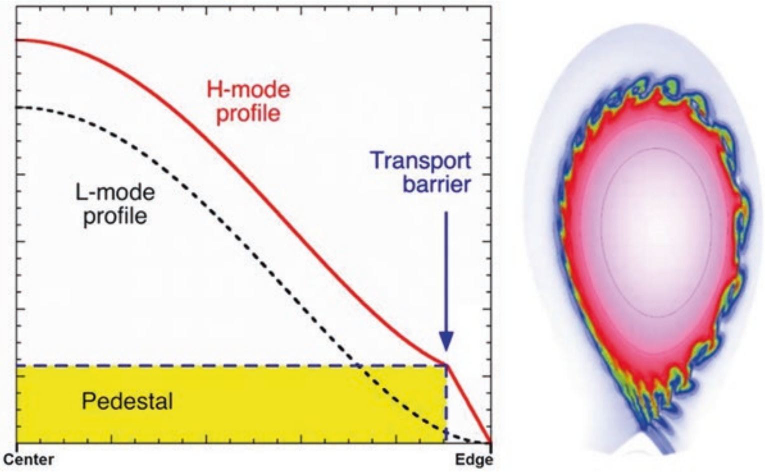

Fig. 6.12 (Left) The nominal profile of plasma properties (temperature, density, field, etc.) across the volume of the tokamak in H-mode compared to L-mode. Notice that about 90% of the volume has strong behavior and a smooth gradient. This is called the pedestal. (Right) A simulation of the plasma density inside the ITER tokamak [1]. The edge localized modes look like spurts of plasma into the surrounding tokamak

well. Outside the pedestal, the plasma is an unconfined mess that tends to wrap around the whole core.

At the plasma edge, because of the steep drop-off, the plasma behavior can unfortunately become unstable. Edge localized modes (ELMs) appear along this edge and look like chaotic jets of energy and material. They have been compared to solar flares on the edge of a tokamak. Almost as soon as H-mode was discovered, researchers started working on controlling the edge's behavior. Today, there are multiple approaches to stop these effects, including injecting small pellets or hitting them with magnetic fields along the edge. For more details about tokamak stability, see the Recommended Reading list at the end of this chapter. This is an excellent example of real progress in fusion science. Researchers find the solution to one problem, only to find another problem lurking around the corner. Now, they have solved those problems, only to find more things to address. As is typical in all major engineering projects, outsiders never fully appreciate that all of these apparently small problems require huge advances to solve them. For fusion research to develop public support, it is important that political leaders understand the efforts underlying all this progress.

6.8 Microscopic Behavior of Tokamak Plasma

The science of tokamak control has advanced far enough to where many of the remaining problems all happen on a microscale. Today, tokamak researchers deal with microinstabilities and microturbulence. Microinstability forms where there are small changes in the density, temperature, pressure, or fields inside a tokamak. Think of them as hiccups in the smooth gradient of plasma properties. For example, if a small pocket of cold plasma travels through a tokamak, it will create disruption everywhere it moves. This chunk of plasma will draw heat, disrupt fields, and impact the density of the material around it. This creates microturbulence as it moves through the tokamak. Classifying, understanding, and controlling microturbulence is its own branch of fusion research.

Another microscopic effect is the development of channels through which mass and energy can rapidly move. These effects collectively create something called anomalous transport, which was an early problem for tokamaks. Researchers would predict how mass and energy would move inside the machine, only to find that anomalous transport caused their estimates to be off, in some cases by a factor of ten. Today, expert consensus is that this is the result of microinstabilities and microturbulence. and this problem has generally been solved. To learn more about microturbulence, microinstabilities, and anomalous transport, see the Recommended Reading list.

6.9 Stability of Tokamak Plasmas

The plasma landscape inside a tokamak also has several macroscopic issues that control its stability. For example, magnetic islands—regions of self-enclosed fields—can form inside the larger field structure. They form naturally because plasma is a fluid that can generate its own magnetic field (see Fig. 6.13).

When an island forms, it usually means trouble because the plant operator cannot easily control it. Instead of all the plasma moving uniformly around the ring, the island breaks the plasma into filaments, forming rings of plasma current and pulling mass and energy from the rest of the reactor. In some examples, these rings can have higher concentrations of positively or negatively charged material. Independent fields then form around these current flows. Once the islands are formed, they create instabilities around their edges and can be disruptive when they collapse [3]. In some cases, the islands can cause a major disruption, which shuts down the whole tokamak [4].

Similar to controlling ELMs, one approach to getting rid of magnetic islands is to fire small pellets into the tokamak. These break up the structure, almost like popping a bubble.

As discussed above in the description of ST40, all tokamaks need to get rid of the helium "ash" made during fusion as well as other impurities, which are difficult to control. Helium also dilutes the fuel and pulls energy from the plasma, both of which hurt fusion rates [5]. As noted, tokamaks clear ash and other dust through the

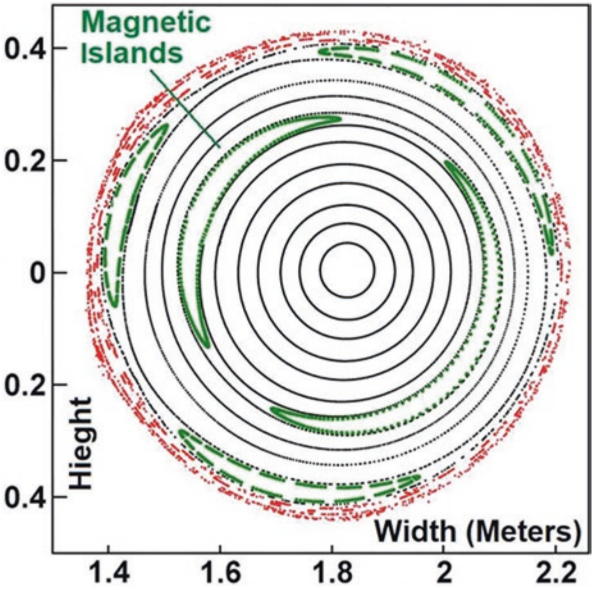

Fig. 6.13 A simulation of the magnetic fields inside the TEXTOR tokamak from reference [2]. This image shows the contours of magnetic fields as they pass through a slice of the reactor. (Image modified for custom use)

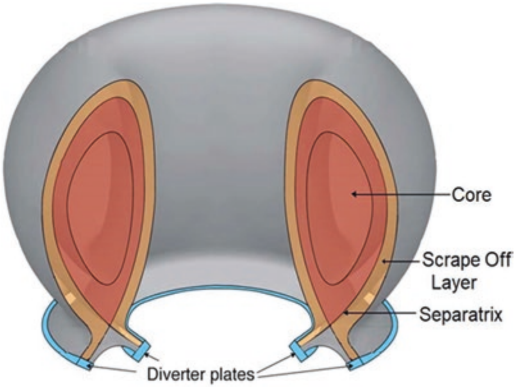

Fig. 6.14 A typical diverter geometry inside a tokamak. A diverter is a set of magnetic plates that ring the base of the tokamak. These plates create a region along the edge of the plasma volume, called the scrape-off layer. Material that passes from the center to the scrape-off layer gets funneled into the plates at the base. The diverter essentially cleans the plasma of a tokamak from impurities

use of a diverter. A diverter is a set of magnetic plates that ring the bottom of the reactor, as shown in Fig. 6.14.

Diverters create a different magnetic field that wraps around the outside of the core plasma. Any dust in that plasma moves to exit the inner magnetic field and will experience this outside field. As it exits, it passes through the separatrix—a surface that divides the inner and outer fields. This outside region is called the scrape-off layer because this material is meant to be removed. Ash in the scrape-off layer is funneled by the fields into the base of the tokamak, where it fills the diverter. In this way, the plasma inside the tokamak is kept clean of impurities and fusion products.

6.10 Key Parameters and Scaling Laws

Physicists use a vast set of parameters to size, design, and model these machines. Collectively, this work encompasses scaling laws that address how the tokamak's behavior improves when we change some set of parameters. Many teams have made predictions about this [5–9] by extrapolating real behavior to model a new tokamak design. Sometimes this comes in the form of a computer model, a mathematical expression, or a line on a graph. Below are some (but certainly not all) of the parameters used to model tokamaks:

- *Plasma current*: as mentioned above, plasma current is the defining characteristic of a tokamak. The current creates a poloidal field, stabilizes the plasma, and generates heat inside the reactor.
- *Toroidal field strength*: the poloidal and toroidal magnetic fields are critical. Without these, there would be no tokamak.

- *Density*: the density of the plasma is controlled indirectly by varying other parameters, like design, fields, and mass injection. There are limits to how dense the plasma can be [7].
- *Power input*: aside from plasma current, there are several other ways to heat a tokamak. These include ion cyclotron heating, neutral beam injection, and compression heating. Each method has to be modeled to gauge its impact.
- *Aspect ratio*: this is the ratio used to size the height and radius of a tokamak; technically, it is the ratio of the major radius to its minor radius. The major radius is the distance from the center column to the middle of the tokamak's ring. The minor radius is the distance from the center ring to the wall of the reactor. Spherical tokamaks have low aspect ratios.
- *Plasma shape*: Researchers use several geometric variables (for example, elongation, triangularity, last closed flux surface, etc.) to measure the overall plasma shape.
- *Beta*: this is the ratio of the plasma pressure to the local magnetic field. The goal is to reach the highest beta possible. Since there are several fields inside any tokamak, there are several kinds of beta numbers: normalized beta, toroidal beta, and poloidal beta.
- *Safety factor*: this is the ratio of the toroidal and poloidal fields. It is called a safety factor because this ratio governed the gross stability of the plasma.
- *Size*: building a larger tokamak is not necessarily the best path to a power plant. ITER will be the largest tokamak ever built, and designers kept increasing its size with each passing year. Larger machines are harder to build, power, and control. Researchers have also argued that other factors, such as magnetic field strength, will have a bigger impact on machine performance [5].

To test scaling, researchers model machines with different characteristics in an attempt to maximize the desired behavior. It is important to remember that these factors are interconnected. If the field strength rises, it will change the plasma density and temperature. One of the common expressions that result from scaling a tokamak design is shown in Formula 6.1. A more complete picture of the tokamak scaling law can be found in source [17] in the Recommended Reading list.

$$\begin{matrix}\text{Tokamak}\\\text{power}\end{matrix} \sim \text{Volume} * \text{Beta}^2 * \begin{matrix}\text{Magnetic}\\\text{field}\end{matrix}^4$$

Formula 6.1 A simplistic but widely known equation for scaling the power of a tokamak based on different properties of the plasma

An important point from both the scaling equation shown here and the work on microinstabilities is that magnetic fields are critical to tokamaks. Scaling clearly shows that higher fields will drive better performance. Moreover, strong fields should overwhelm many of the microinstabilities that form when plasma, fields, or energy is not uniform. Large magnetic fields simply drown out all these nonuniformities.

6.11 The Promise of Superconductors

How can we achieve such high fields? Today's highest-field tokamaks use conventional electromagnets that consume a lot of energy and get very hot due to electrical resistance in their copper wire coils. This fundamentally limits their design options to pulsed machines because the reactor will need time to cool off between shots. Such pulsed operation is undesirable for use as a commercial electric power plant.

This problem can likely be conquered using superconducting materials. A superconductor is a substance that conducts electricity with no resistance at all when cooled below a certain critical temperature. Superconductivity, discovered first in mercury cooled by liquid helium below 4.2 K in 1911, is an example of quantum physics playing out in the real world. The physics of superconductivity is beyond the scope of this book, but readers who are interested can explore the phenomenon in references [6–10] below.

A superconducting wire was first used in fusion in the 1970s for the mirror program [7]. But the technology was immature. The wire required expensive cooling systems, was not robust, and was too expensive. Those problems meant that for most of the twentieth century, most fusion systems did not use superconductors and instead relied on cooled copper magnets.

Then in 1986, two International Business Machines (IBM) researchers discovered a copper-based ceramic material that became superconducting below a much more easily achieved 35 K, which was soon followed by related materials with critical temperatures above the 77 K boiling point of liquid nitrogen. This breakthrough opened the field of "high temperature" superconductors (HTS) and was worthy of a Nobel Prize in physics. Since then, the effect has been found in several families of materials, including carbon nanotubes and iron-based ceramics (see Fig. 6.15).

Because liquid nitrogen is inexpensive and requires a much smaller and less complex cooling system than liquid helium, HTS materials are very attractive for high-field magnet technologies, including tokamaks. This will enable ITER to operate with powerful superconducting magnet systems.

Replacing copper coils with superconducting ones would allow a tokamak to run continuously. Superconducting magnets also require a much lower voltage than conventional ones, which leads to lower operating costs and a smaller physical footprint for the magnet system. So why are superconductors not more commonly used in tokamaks, or other technologies, for that matter? The primary barrier has been the overall cost of producing the wire, which has been difficult to produce in large quantities because the materials are much less malleable and ductile than copper.

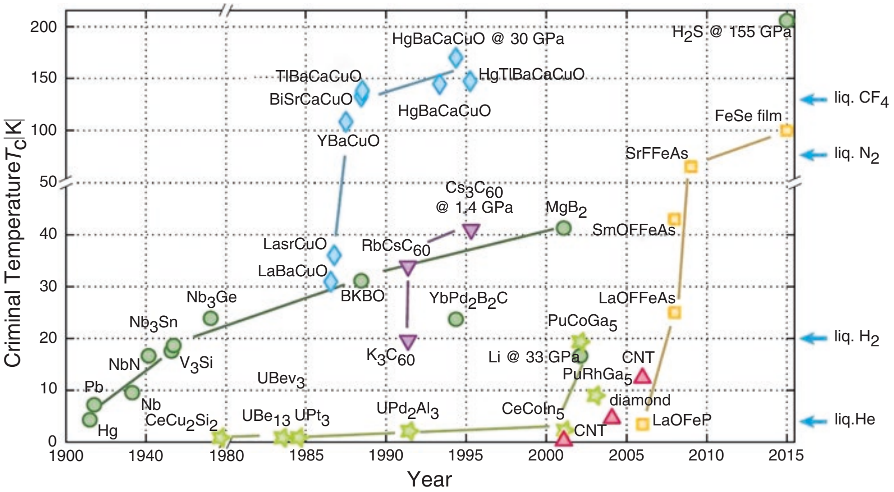

Fig. 6.15 The history of superconductors and their critical temperatures. This plot shows the critical temperatures of different superconducting materials discovered over the years. The iron-based materials are shown as yellow squares, the carbon materials are shown as red triangles, the Bardeen-Cooper-Schrieffer type superconductors (named for the physicists who developed the first successful theory of the phenomenon) are shown as green circles, and the cuprates are blue diamonds. (Note that as the temperature rises, both the cooling system and the cryogenic fluid needed (helium, hydrogen, nitrogen, etc.) get cheaper)

6.11.1 Challenge with Superconductors

The development of superconducting magnets has required solving other engineering problems that emerged. Higher-temperature superconductors have delicate crystal structures, which make them mechanically weak. To solve that problem, superconducting wire is embedded with other materials in long strands. The crystal is reinforced by these composites, a sandwich of other conductors, like steel or copper. An example is shown in Fig. 6.16. Because these materials also conduct, the flow along the wire looks like a fast-moving river. Electrons zip through the superconductor in the center with little resistance, while the current is moving far slower in the surrounding material.

Another challenge is fabrication. The superconducting material needs to be very pure; an impurity can disrupt the crystal structure and break the quantum effect. In such a case, current rushing unresisted through the wire suddenly hits a spot of resistance, leading to a buildup of heat and energy and causing the wire to melt or explode. But this fabrication bottleneck is changing rapidly. In 2020, the Russian company SuperOx developed a breakthrough process to mass-produce superconducting wire using laser deposition. The company was able to produce 186 miles of wire in 9 months.

Yet another problem is that superconductors can suddenly “go normal” due to a magnetic quench. This is a threshold phenomenon in which the increasing magnetic field suddenly disrupts the material's superconducting behavior and causes it to behave with normal resistance. This causes overheating and melts the wire [8].

A final issue is the ramp-up rate. Today, researchers can reach ultrahigh fields (45 teslas) in specialty superconducting labs around the world. But because increasing the magnetic field induces opposing electric currents, these advanced magnets cannot be switched on quickly. Just as you need a slow but steady power source to get a massive ship up to speed, those magnets need many hours of ramp-up time. This heating time makes it difficult to apply this technology to a fusion reactor. In summary, fusioneers face several practical steps to apply a superconductor to a fusion reactor.

Below is a summary of how superconductors are built, packaged, tested, and supplied to fusion companies:

- *Wire*: the most basic building block of a superconductor is the wire itself. It is a delicate crystalline material that has to be ultrapure to create the quantum mechanical effect of superconductivity.
- *Tape*: the wire is normally sandwiched together with other materials to create the tape (Fig. 6.16, left). The tape might have as many as seven layers that are optimized for strength, temperature, and current flow. Directly next to the superconducting layer is a layer of a conventional conductor (usually copper), which would provide a "slow lane" for the electrical current. When you buy a superconductor online, you are typically shipped the tape only.
- *Pancakes*: the most basic building block of a superconducting magnet is to wind the tape together into a pancake (Fig. 6.16, right). Current flows along the tape in a circle, creating a magnetic field; the pancakes are stacked together (tens of magnets) to make a single high-field magnet.
- *Cables*: to use the superconductor, the tape is packaged in a cable pack. The cable encases the tape in protective sheets of material for durability and practical use. The cable can also include add-ons like fiber optics for stress and strain assessments.

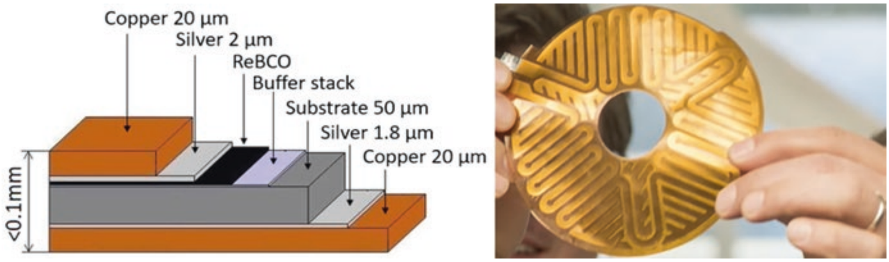

Fig. 6.16 Superconducting tape. Because high-temperature superconducting materials, such as rare-earth barium copper oxide (ReBCO), are delicate and brittle, they are embedded in a flexible surrounding tape (left) that provides reinforcement. It is then formed into an electromagnet, such as the pancake shown here (right), which has coolant channels milled on its surface

6.11.2 Achievements

One of the leading organizations in the world for high-field magnets is the National High Magnetic Field Laboratory in Tallahassee, Florida (Fig. 6.17). The Mag Lab was formally created in 1994 and specializes in ultrahigh-field magnets. The lab currently has the strongest magnet in the world for nuclear magnetic imaging. It is a user facility, offering researchers a chance to work with magnets that can operate from 1 tesla to 45 teslas. Fields as high as 100 teslas have been created, but only for a few milliseconds. The lab creates these magnets by winding the superconducting tape into pancake shapes and stacking tens of them to make ultrahigh-field magnets. The lab has dozens of such magnets and collaborates with businesses and other organizations to offer access to a variety of magnets.

As noted, tokamaks and most other fusion machines have so far not taken advantage of some of the most recent advances in superconducting magnets. But in the near future, they will be doing so. That will give rise to an entirely new class of fusion reactors, which will run longer, perform better, cost less, and occupy a smaller plant footprint. The majority of approaches discussed in this book rely on magnetic confinement, and superconducting magnets with fields as high as 20 teslas can revolutionize what we can expect from the field of fusion.

We are only at the beginning stages of pushing superconductors into fusion; at present, we can point to only a few limited applications. For example, in 1999, a superconducting wire was used in the Levitating Dipole Experiment (see Chap. 4). This material enabled their magnet to run for up to 8 h, which would have simply been impossible with conventional magnets [9]. In the 2010s, the Princeton field-reversed configuration team built a magnet out of a superconductor (see Chap. 7). The team embedded these superconductors inside copper magnets. In both cases, the superconductor enabled the teams to operate a small and cheap machine at fields much higher than would have been possible any other way.

Superconducting wire has become so available that it is also making an impact in fusion outside of academia. In 2016, a small fusion company in Colorado called Horne Technologies built a notable superconducting fusion device (see Fig. 6.18).

Fig. 6.17 The staff of the National High Field Laboratory posing in front of their facility in Tallahassee, Florida, in early 2020. (Image courtesy of the National High Magnetic Field Laboratory)

Fig. 6.18 Horne Technologies superconducting device built in Boulder, Colorado, in 2020. This machine used ReBCO superconductors to run for over 20 min at fields of 1.5 teslas. Image courtesy of Horne Technologies

Its magnets could be cooled using liquid nitrogen and could run at 1.5 teslas for over 20 min [13, 14]. When the Navy did this same test in the 1980s, their machine could only run for 4 microseconds. This shows the impact of superconductors. They offered a ten-million-fold increase in runtime and a tenfold increase in field strength [37]. As fusion embraces better superconductors, the effort will drive both technologies forward.

6.12 Featured Examples: Tokamak Energy and Commonwealth Fusion Systems

In late 2009, Dr. David Kingham, Dr. Alan Sykes, and Dr. Mikhail Gryaznevich, former researchers from the Culham Centre for Fusion Energy, founded the company Tokamak Solutions near Oxford, England. Their initial plan was to develop spherical tokamaks as a neutron source, but they pivoted to an energy mission when they realized—and verified on the GOLEM tokamak—that HTS manufacture had matured to a point where the tapes could be wound into tokamak magnets. As of this writing, the company, now called Tokamak Energy, has raised $180 million and has a staff of about 150 people.

Tokamak Energy has followed a path similar to other fusion companies. It has built machines that run long enough and hot enough, and then they go for net power. In June of 2018, the company ran its ST40 tokamak (discussed above) at 15 million degrees. In early 2022, the company was able to reach 100 million degrees in an upgraded version of this machine. The company is following a two-pronged strategy to develop this technology. They are studying plasma behavior using their copper wound ST40 machine while developing HTS wire technology in parallel. This two-prong approach also plays into how they communicate with the public; they are very open about plasma physics, while the innovations with the magnets are kept proprietary to the company.

This is a nice balanced approach that many fusion organizations should consider mimicking. The company is very open and collaborative about plasma physics and ST40. This builds widespread support within the plasma and investment communities. They are more guarded about the HTS research. The wire is the enabling technology for this approach. The two tracks will come together into the design of their next device, an HTS spherical tokamak to demonstrate fusion power.

In September of 2019, the company announced the creation of a 24.4 tesla field with a robust and defect-tolerant magnet cooled to 21 K. (See Fig. 6.19). Producing over 20 T with an all-HTS magnet at a fusion-relevant operating temperature is an unprecedented achievement. This temperature is considered to be high because the magnet was cooled using just conduction instead of liquid helium. But superconductors can likely reach much higher magnetic fields. The current record for the highest field ever generated by a superconductor, 1200 teslas, was reported by the University of Tokyo in August 2018. This field was reached by compressing the field after generation (and destroying the device)—but it does hint at the technology's immense potential.

Tokamak Energy has also developed a major innovation that will likely be used in other fusion experiments: magnetic reconnection heating. Reconnection is the process of two magnetic fields merging to become one field. When this happens, it releases a huge amount of energy that can bootstrap plasma to fusion conditions [15]. It occurs in plasma environments where the charged material is dense enough to impact the magnetic permittivity of that volume. Reconnection cannot occur in everyday environments; it requires extreme environments like solar flares or inside fusion reactors. The effect was first mapped out theoretically in the 1950s and 1960s. Researchers first modeled these events in solar plasma and fusion experiments in the 1980s [12, 14], but the first time that controlled reconnection was used to start a tokamak was in 1998 [16]. A team in England working on the MAST

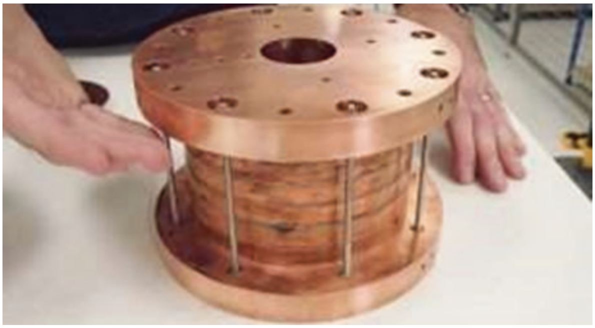

Fig. 6.19 Tokamak Energy's superconducting magnet, which reached 24.4 teslas at 21 K, was built in the summer of 2019. As of this writing, this magnet holds a superconducting record for a field, for runtime, and for temperature. Image courtesy of Tokamak Energy

tokamak used it to double the world record in plasma pressure and containment inside a tokamak.

Since 2000, teams have slowly but steadily developed techniques to initiate, control, and monitor these reconnection events in the fields of inertial confinement fusion (ICF), tokamaks, and astrophysics. Today, Tokamak Energy can routinely use reconnection to heat its plasmas. The process starts with two rings of plasma current inside the machine. One ring loops around the top of the machine, while the other encircles the bottom. By changing the flow of the current in the surrounding magnets, the magnetic field can be varied. This allows researchers to merge the two plasma loops together. A similar process is used in other fusion approaches, like field-reversed configurations (FRCs). When the plasma combines, the surrounding magnetic fields merge as well. This process is shown in Fig. 6.20. As the plasma is pushed together, the fields reconnect, releasing an immense amount of energy, heating the plasma.

Tokamak Energy is not the only company chasing a small, superconducting tokamak. In the summer of 2017, a small group at the Massachusetts Institute of Technology (MIT) gathered together to create a new company. By that point, the researchers had been struggling with intermittent government funding for years. Funding for MIT’s tokamak had been in question since 2012. In fact, the Department of Energy had ended funding that year to reallocate resources to support the ITER effort. Alcator was the pride of the MIT plasma community, so the university undertook an effort to save the machine. Graduate students Arturo Dominguez, Geoff Olynyk, Zach Hartwig, and others went on a public relations campaign. They met with Congressional staff, wrote articles, and broadcasted their support for the machine online. They succeeded in getting funding for a few more years, but the machine was finally shut down in 2016. MIT attempted to generate interest in a superconducting tokamak from federal sources without progress. The head of the department, Dennis Whyte, went on a publicity campaign. Dr. Whyte gave interviews, wrote articles, met with congressional staff, and gave lectures on smaller machines that included superconductors. But ITER needed those resources. So in the summer of 2017, a small team, pictured in Fig. 6.21, assembled and decided to go private as a new company called Commonwealth Fusion Systems.

To date, Commonwealth has raised over $2 billion dollars in public and private funding. It has a staff of more than 300 employees, consultants, and contractors, and the company is backed by a consortium of institutional partners and venture capital firms. It also has a lot of momentum stemming from MIT’s institutional credibility, support from the greater Boston area, and collaborators at other institutions. Like Tokamak Energy, Commonwealth is protecting its superconducting technology through patents and licensing agreements while making the plasma physics open and public. Commonwealth’s plan is to build a compact tokamak called SPARC. The current design calls for a plasma donut about 6 feet tall with a magnetic field of over 12 teslas [16]. Physically, this is about the same size as many previous machines, but that field strength is unheard of. The SPARC field is more than three times

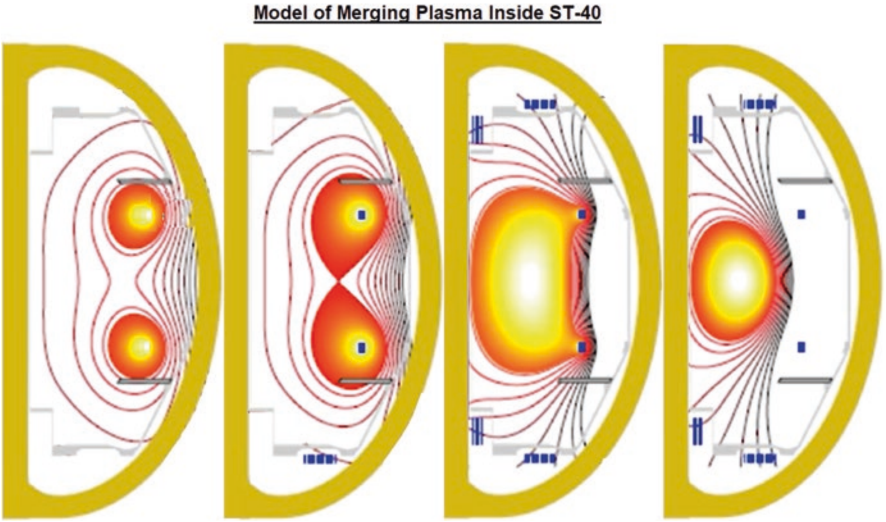

Fig. 6.20 Magnetic reconnection inside a tokamak plasma (red circles). As the plasma is pushed together, the magnetic fields (black lines) merge, releasing an immense amount of energy. Image courtesy of Tokamak Energy

Fig. 6.21 The cofounders of Commonwealth Fusion Systems. From left: Dr. Martin Greenwald, Dr. Dan Brunner, Dr. Zach Hartwig, Dr. Brandon Sorbom, Dr. Bob Mumgaard, and Dr. Dennis Whyte. Image by Bryce Vickmark

higher than its closest competing operational device [17]. The high field should drive, stabilize, and help control all the material inside the tokamak. They hope this will enable the machine to be the first to ever create net electrical energy from fusion.

Fusion enthusiasts hope that one of the trio of fusion organizations—Commonwealth, ITER, and Tokamak Energy—can generate net power within the next 5–10 years. Tokamaks are the most mature fusion design and have the most robust research base on which to build an effort. Furthermore, superconducting magnets will have a huge impact on the performance of a tokamak, enabling a new class of devices that the world has never before encountered.

If all goes well, these factors will combine to yield a zero-carbon energy source that will combat climate change. But we are also concerned that success in tokamaks will drown out good ideas and valuable insights from elsewhere within the fusion field. This could limit cross-pollination between the different fusion communities. Ideally, net power from a tokamak will drive support for the whole field. Time will tell what happens next, but climate change will not wait for any of these advances. Fusioneers need to move aggressively if they want to do their part to stave off the worst effects of this global crisis.

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Plasmoids

7

Summary

Electromagnetic effects in plasmas can create various structures, such as smoke rings, sheets, and strands, often referred to generically as plasmoids. For fusion devices, plasmoids typically have the advantage of being hotter, denser, and more easily moved around. Unfortunately, plasmoid structures are inherently unstable, so every fusion research team that is pursuing this technology is also devising some method to stabilize these structures. This chapter explores strategies that fusioneers have developed to create, control, measure, compress, and stabilize different kinds of plasmoids, with the goal of establishing conditions in which the material inside the plasmoid undergoes fusion as well as eventually building reactors based on this approach.

7.1 Introduction

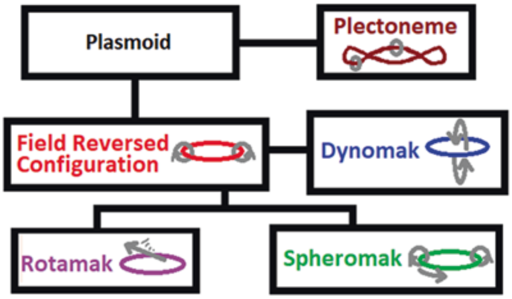
As we have discussed, plasma is an electrically charged fluid. All flowing charge—an electric current— will generate a magnetic field, which in turn can reinforce the flow. Fusioneers can take advantage of this property to create various plasma structures, such as smoke rings, sheets, or strands of flowing charge, often referred to generically as plasmoids.

A plasmoid presents several advantages for creating a fusion power plant. It can be controlled, shaped, or moved once it is organized. Structured plasma is also denser and hotter, which helps drive up fusion rates in such devices [33] (Fig. 7.1). The problem with organized plasma is that it is inherently unstable. A fusion device needs magnetic fields shaped in ways to keep the plasma organized and in place; otherwise, it will fly apart. Similarly, if the structure is nonneutral and nonuniform—too much charge packed in one place—then electric forces will rip it apart.

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
https://doi.org/10.1007/978-3-031-22906-0_7

Fig. 7.1 The C-2 W ("Norman") field-reversed configuration (FRC) machine at TAE Technologies in 2018 and the team that made it possible. TAE is a private fusion company in Foothill Ranch, CA. This machine generates and forms the advanced beam-driven FRC by colliding two plasmoids, which merge in the central containment vessel. The machine heats, stabilizes, and controls the FRC in the center with particle beams on the surface of the plasma. Image credit: TAE Technologies

Fig. 7.2 The plasmoid branch of the fusion family tree shows five different approaches. Each one will be discussed in this chapter



Instabilities are the main enemy of all plasmoids, so dealing with them is a central challenge of every approach developed in this branch of fusion. This chapter describes various approaches to doing that, with a focus on five of them (see Fig. 7.2). These approaches either exploit the instabilities by harnessing them, reduce or remove these instabilities by feeding the plasma with more mass or energy, or capitalize on a structure quickly before instabilities kill it.

7.2 Field Reversed Configurations

The first plasmoid used for fusion was the field-reversed configuration (FRC). (We discuss the reason for this name below.) It was discovered accidently during pinch research in 1959 [1–3, 30]. When the pinch occurred, the plasma would knot up and become oddly stable. This was a problem because it hindered the squeezing mechanism that researchers were trying to exploit for fusion. Over time, researchers realized that what had formed was a field-reversed configuration. The plasma had essentially self-organized into a self-contained loop. Its electric charges were flowing around this loop. This current induces a magnetic field at a right angle to it, and this magnetic field in turn constrained the plasma (see Fig. 7.3).

In the FRC system, the plasma current and magnetic field have a feedback relationship. Moving through a magnetic field or experiencing a changing magnetic field will drive a current—this is how generators work—while a current will induce a magnetic field. The two effects feed one another. However, this loop will not run forever. Internal resistance will slow down the current over time. As the current slows, the magnetic field weakens. This is the same feedback effect working backward. Eventually, the current will slow down, and the FRC will collapse.

In practice, the FRC plasma structure does not form a distinct loop like the idealized one shown in Fig. 7.3. Instead, it looks more like a rotating sphere or an elongated football. As the plasma in this ball spins, it induces a magnetic field that envelops it. Inside this ball, the plasma is denser, hotter, and self-contained by the magnetic field [33]. Early fusioneers attempted to harness these processes to improve the performance of their fusion machines.

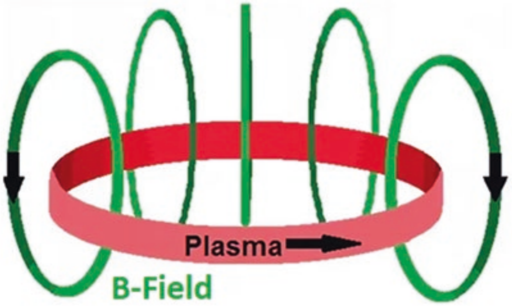


Fig. 7.3 An idealized representation of the field-reversed configuration (FRC), a plasmoid that forms in the shape of a loop. Plasma current flows in a circle, which creates a magnetic field that reinforces that current. Such a structure is inherently unstable, but fusion researchers began to find ways to stabilize it

7.3 The Spheromak

Following the accidental discovery of FRCs, fusioneers began to study them directly in the 1960s, building a series of machines to create them. To date, at least 42 experimental FRC machines have been built. Almost as soon as research began, the experimenters faced a problem with FRCs' stability. An early way to improve stability was to add another magnetic field, creating what they have since called the spheromak. To create a spheromak, researchers added a toroidal magnetic field to the FRC by adding a large poloidal internal current in addition to the rotational current [4]. The difference between an FRC and a spheromak is shown in Fig. 7.4. These two structures are members of the same family of fusion concepts. As a general rule, a spheromak is more stable than an FRC. Both structures are nested inside an external magnetic field that is reversed as compared to the internal field. This is where the name field- reversed configuration comes from.

By the 1980s, these structures had been measured and modeled using both computer simulations and mathematical formulas. The stability of these objects relied on keeping disruptions from starting along their surface and at the X point, a spot on the bottom of the FRC where the opposing fields butted up against each other (Fig. 7.5). An instability there would spread and eventually rip these structures apart. An easy way to limit this is to stretch the structure from a ball to a spinning hot dog. Several modern FRC devices take this approach.

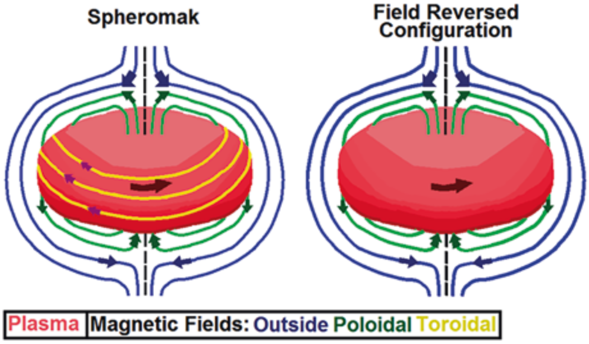


Fig. 7.4 A comparison of a field-reversed configuration (right) and a spheromak (left). The plasma structure is drawn here as a three-dimensional spinning ball of electrically charged matter. The spheromak has the same basic structure as the FRC, but it has a toroidal magnetic field imposed around the center of it, produced by a poloidal electric current

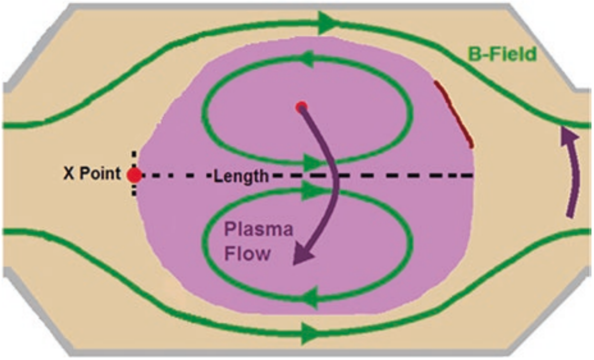


Fig. 7.5 A different view of the structure of an FRC showing the X point and skin of the structure 47

7.4 Rotamaks

One early and very clever method for initiating an FRC was suggested by Henry Blevin in 1962 [40]. Blevin's idea was to exploit the differences in mass between ions and electrons. A deuterium nucleus is more than 3600 times as massive as an electron [38, 39]. Because of their light mass, electrons can move quickly through plasma. Additionally, because their charges are opposite, positive ions and electrons spin in opposing directions in a magnetic field [41]. Blevin realized that he could move just the electrons, but not the ions, by applying a rotating magnetic field at precisely the right frequency, known as resonant frequency.

You can think of this as similar to a child on a playground swing. If she kicks back and forth at just the right rate in the right direction, she can swing higher and higher. If she kicks too fast, too slowly, or in the wrong direction, she never gets far off the ground. And if someone adds a heavy weight to the swing, she has a much harder time getting it to move. Spinning the poles of a magnet around a loop or ball of plasma at its resonant frequency generates a current of light electrons, while its much heavier positive ions stay put. The motion of the electrons whips up the plasma into a smoke ring structure.

This solves three problems simultaneously. First, it creates the plasmoid. Second, the rotating field merges with the self-generated field, which improves stability. Finally, the applied field keeps the plasma spinning, stabilizing the structure. This approach is known as a rotamak. A rotamak is considered a third type of plasmoid, unique from both the FRC and spheromak. Figure 7.6 illustrates how the rotating magnetic fields impact the plasma.

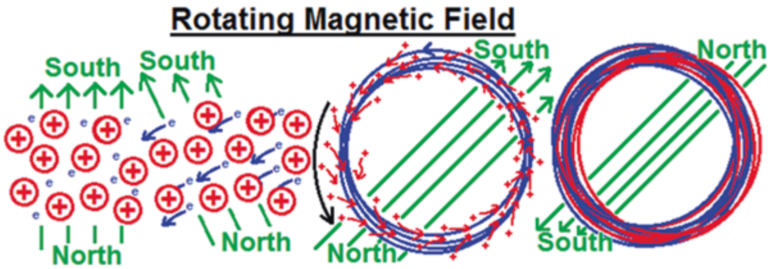


Fig. 7.6 The rotamak. This illustration shows the steps to form an FRC by spinning a magnet around a plasma. Done correctly, the field will drag the light electrons but not much heavier ions, creating a plasma current. This will whip up a self-organized plasma structure

Fig. 7.7 Key contributors to the development of FRC, spheromak and rotamak. From left to right: Dr. Ieuan Jones of Flinders University, Dr. Alan Hoffman and Dr. John Slough, both professors at the University of Washington; Dr. Sam Cohen of Princeton [10, 23]; and Dr. Michl Binderbauer of TAE Technologies

7.5 Plasmoid History and Its Research Community

For decades, the FRC, spheromak, and rotamak approaches were not a part of mainstream paths to fusion. The community of researchers was small. Figure 7.7 shows several of the most important community members, whose contributions and roles in the technological development of these plasmoids are featured in this chapter [14, 15, 17, 18].

Although Blevin had the original idea, the person who deserves the most credit for developing the rotamak was Welsh researcher Dr. Ieuan Jones, who earned his doctorate in plasma physics in the 1950s [14]. He was a professor at Flinders University in Australia for more than two decades, during which he developed and refined the rotamak concept, publishing paper after paper on the research [9]. Figure 7.8 shows his best-known machine called the Flinders Rotamak, plus some of its more advanced successors.

Dr. Jones‘s work did not go unnoticed. In 1986, the US Department of Energy took an interest [19]. It commissioned a company named STI to build a machine for

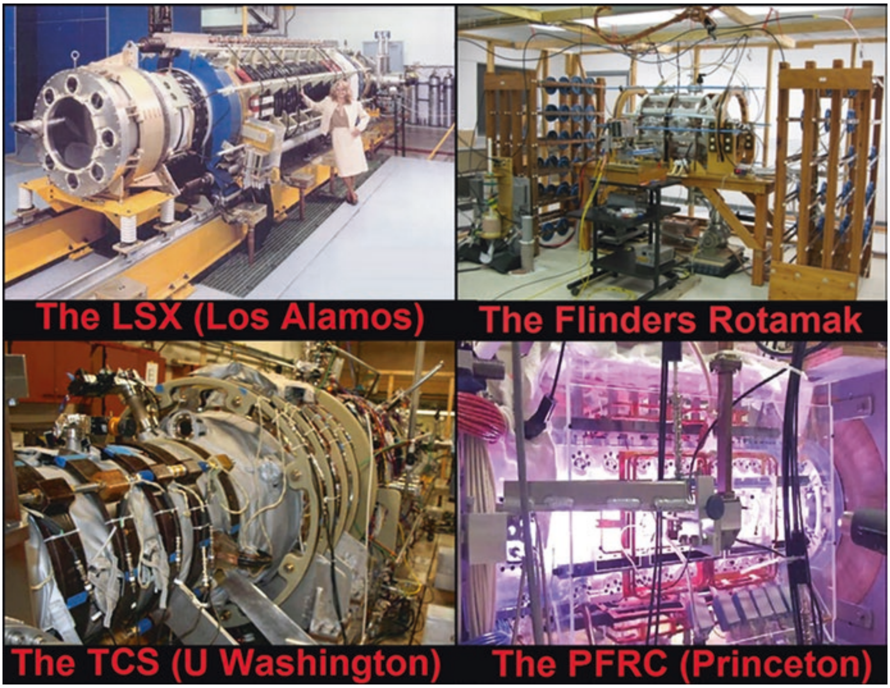


Fig. 7.8 Four examples of machines built to create and sustain plasma structures (plasmoids). The Prairie View Rotamak (upper right) was an early machine made from wood [27]. The Large S Experiment (LSX, upper left) was built at Los Alamos and was shut down in 1990 [11]. The TCS (lower left) was built from the LSX at the University of Washington. The PFRC was built at Princeton. Image credit: Prairie View University, Los Alamos National Laboratory, Sam Cohen and John Slough

the Los Alamos National Laboratory. Construction took 4 long years. Once finished, the Large S Experiment (LSX) was installed at Los Alamos [16]. It was an exciting time, but then the government nixed the program just 1 year after it was finished. Spending 4 years for just 1 year of testing is, in our view, one of many examples of government shortsightedness and unreliability in its support for fusion.

Two people who were involved in the Los Alamos effort, Alan Hoffman and John Slough, did not give up on this approach. In 1992, they salvaged the neglected LSX machine, moving the abandoned device to the Redmond Plasma Physics Lab at the University of Washington in Seattle [19]. Getting funding to restart the effort was tough. Because policies by the Department of Energy demanded that fusion research efforts show relevance to ITER, they had to both rejigger the machine and refocus their efforts to include tokamaks [50].

This went on for 4 years, until August of 1996, when the team finally got the support it needed. Dr. Hoffman and Dr. Slough secured $4,018,000 for 4 years of development. They built a machine called TCS, which stood for translation, confinement, and sustainment. The TCS machine used a rotating magnetic field to study these plasma structures [7]. It worked well, showed a great deal of promise, and got additional funding until the Department of Energy killed the effort in 2003. Eventually, after 2009, the entire Redmond Plasma Physics Lab shut down due to a lack of funding [20, 24, 25]. Today, the building houses a motorcycle factory [51].

Still, Slough remained determined to continue this work. He developed two startups (Helion and MSNW), which are trying to turn this approach into commercial products [21, 22]. Today, Helion has grown to a company pursuing a power plant based on an FRC with over 575 million in funding and a staff of more than 100 people.

7.5.1 Make, Move, Hold

One of the advances in the 1990s was developing machines that could make, move, and sustain a plasma structure. It turned out that the fields suitable for creating a plasmoid, like an FRC or spheromak, were *not* best suited for stabilizing and controlling it. Hence, it made sense to create the plasma structure in one place and move it somewhere else. These three steps—make, move, and hold—can be achieved by varying the magnetic field. For example, if the field on one side of a plasmoid is stronger than on the opposite side, it will push the structure toward the lower field. In some cases, FRCs could be whipped up, pushed in a certain direction, and then sustained by a different field.

7.5.2 FRC Rockets

In 1994, Dr. John Slough founded a company called MSNW in Seattle based on the make, move, and hold approach. The goal of the company was to design and build an FRC fusion-driven rocket engine. Figures 7.9 and 7.10 show one of that company's machines and the concept behind it. The rocket has five stages of operation. The first step is to make the plasmoid, usually by rotating a magnetic field around the plasma. Next, the device manipulates the fields around the plasma loop to move it toward a magnetic nozzle. The nozzle is an orifice surrounded by more magnetic fields that squeeze the plasmoid and compresses it to fusion conditions. Hydrogen and deuterium nuclei in the plasma fuse, creating helium and releasing energy. The superheated plasma and fusion products jet out the back of the nozzle at millions of degrees, thrusting the rocket forward.

Over many years, the company received several millions of dollars from government sources to develop this technology. The National Aeronautics and Space Administration (NASA) funded several rounds of this development. The company was able to demonstrate a rocket with a velocity of more than 30 km per second [53]. If the technology can be perfected, fusion-driven rockets are the best option for reaching Mars and other planets. It is important to compare this design against the Princeton machine, discussed later in this chapter.

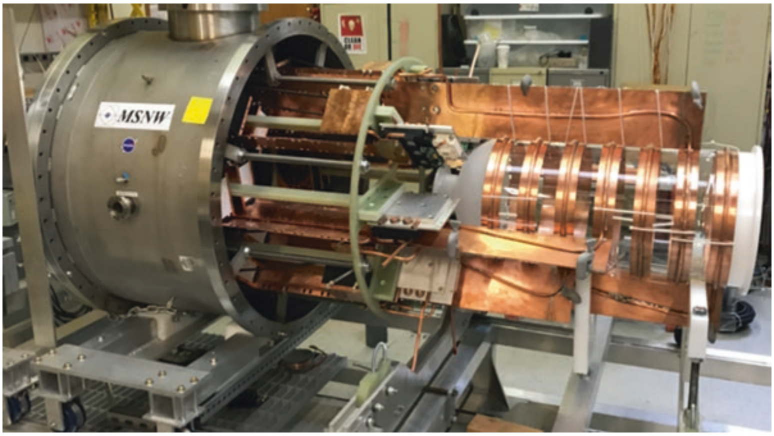


Fig. 7.9 The exposed internals of the MSNW experimental fusion rocket engine. This photo clearly shows a nozzle and chamber surrounded by copper, liquid-cooled electromagnets

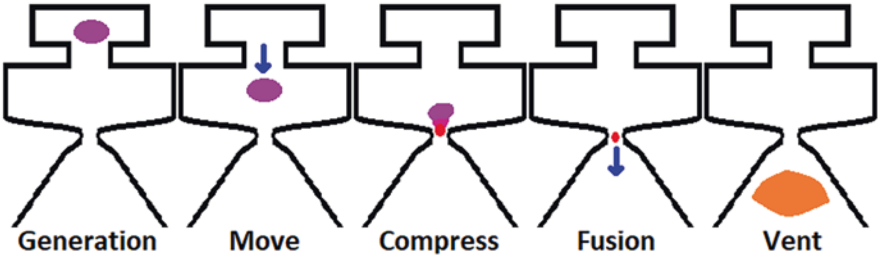


Fig. 7.10 The five stages of the FRC-driven rocket. First, a plasmoid is created in one location. Next, the material is pushed using magnetic fields into a tighter magnetic nozzle [37]. As material passes through the nozzle, it is compressed to fusion conditions. As the plasma fuses, it is superheated and vents out the back of the rocket, producing thrust

7.5.3 TAE Technologies

Slough was not the only person keenly interested in FRC technology. Dr. Norman Rostoker, a professor at the University of California, Irvine, thought that it would be possible to stabilize a plasmoid with particle beams. His thinking was as follows: an FRC is similar to a spinning top, which over time will slow down, wobble, and eventually fall over. One way to keep the top spinning is to continuously apply torque. Rostoker's idea was to do something similar to a beam of plasma. By firing plasma along the surface of the FRC, he argued that its spin could be sustained. Sustaining the plasma could keep it hot, dense, and trapped long enough for fusion to occur.

Rostoker submitted proposals to government agencies for funding to build this reactor, but he was unsuccessful in getting support. It was at that time that he met a young graduate student named Michl Binderbauer, who was pursuing a degree in plasma physics. He and Binderbauer, the son of a European businessman, joined forces to pursue an FRC fusion reactor, cofounding what became TAE Technologies in April 1998. To date, TAE has been arguably one of the most successful fusion startups in the world, staying in business for several decades [52]. The company has raised over $880 million in funding and has a staff of over 150 employees and contractors.

TAE has flourished for several fundamental reasons. First, the firm sits within wealthy Orange County, California, which gives it access to investors, talent, and resources. The company caught the early attention of Nobel Prize winner Glenn Seaborg. Seaborg legitimized and promoted the firm to some wealthy investors. The company also benefited from Rostoker‘s knowledge and reputation within the fusion community. In addition to that, the firm’s first staff came pretrained from the remnants of the company HiEnergy Technologies. This was a close-knit group of scientists who had previously worked on a failed approach to fusion.

In the first few years, the firm also caught the attention of Dr. Jim Boyden, who worked for the billionaire Paul Allen. Mr. Allen was eventually convinced to make a five-million-dollar investment in the firm. Even though the amount was relatively low, the money was critically significant. It signaled to the investment community that this fusion firm was worth taking seriously. Then in 2007, the team won its first major funding round. Ray Rothrock, a wealthy venture capitalist, convinced his company, Venrock Capital, to invest $40 million in TAE. Rothrock called this investment “the riskiest and most significant venture project of my career. It is an energy development company that, if it succeeds, would change the world in profound ways” [54, 55]. From there, TAE has flourished. It has built several large fusion machines and turned its research into medical treatments, advanced particle beams, and rocket technologies. Along the way, the company has developed important spin-off technologies in the area of accelerators, electric vehicles, and pulsed power.

TAE has perfected a new and novel way to create FRCs using the merging of two spheromaks. Figure 7.11 illustrates this approach, along with three other methods. Two of those approaches have been mentioned previously in this chapter: rotamaks and the accidental formation of an FRC in a plasma pinch [1, 4, 5], the latter being a problem for pinch researchers. The third is to pass a neutral beam through a plasma, which will “kick up” the structure.

The accidental formation of an FRC can be a problem in other fusion approaches. For example, tokamaks inject beams of particles to heat their plasma, and unwanted plasma structures can form as this happens. But in the cases discussed in this chapter, an FRC can be advantageous—which brings us to TAE’s approach: forming an FRC by merging two spheromaks. This method is tricky. As mentioned above, a field designed for creation will be poor for stabilization. Thus, fusioneers commonly make FRCs in one place, then move and stabilize them somewhere else.

Figure 7.12 shows this formation approach in action inside one of TAE’s newest fusion machines, the C-2 U (U for upgrade). This device is about the size of a school bus. The machine starts by creating two spheromaks in the wings. It then moves these plasma structures into the center chamber by varying the magnetic

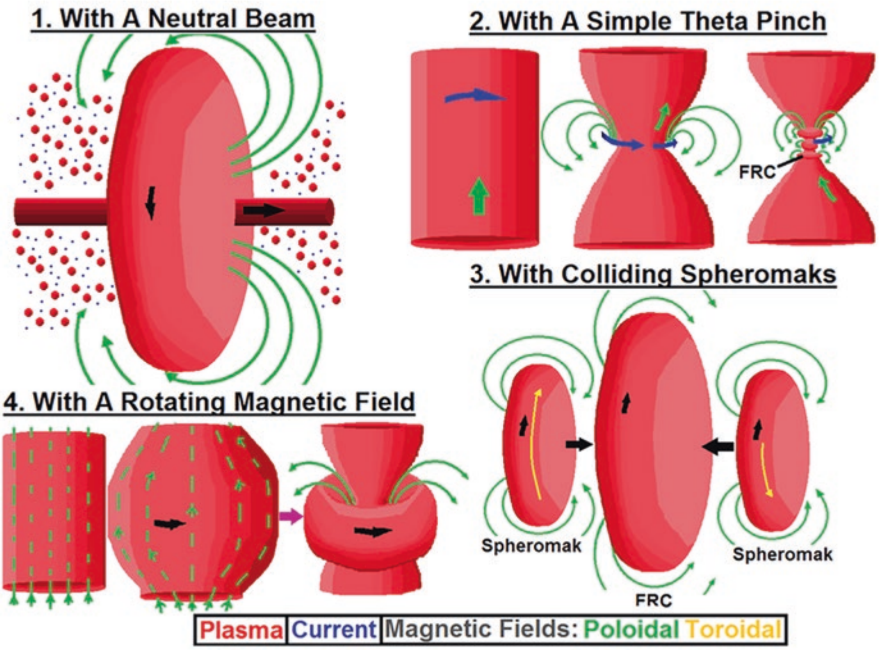


Fig. 7.11 The four ways to make an FRC, discussed in this chapter. The first is accidently with a beam passing through a plasma (upper left). The second is accidently with a pinch (upper right). The third is with a rotating magnetic field (also known as a rotamak) in the bottom left. The fourth is by merging two small spheromaks (shown in the bottom right) [32, 35]

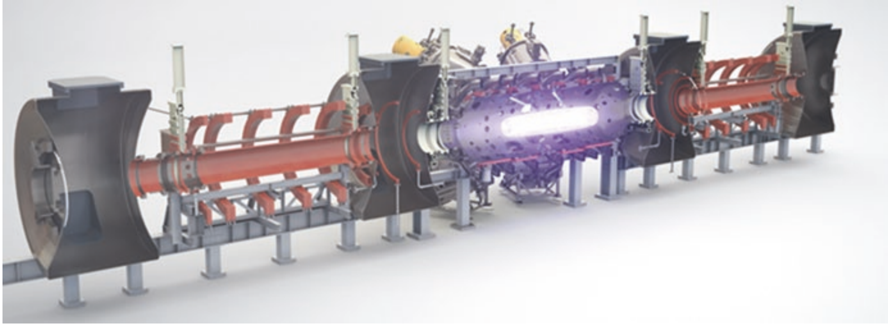


Fig. 7.12 The C-2 U machine built by the private company TAE Technologies. This machine makes two FRCs, one at each end. It then translates them into the center, merging them to form a larger, hotter, and more stable single FRC structure. The machine keeps this structure spinning by applying particle beams along its surface. Image credit: TAE Technologies

fields around them [26]. There, they merge, forming a hotter, denser, and larger structure. Finally, firing particle beams along the surface of the loop keeps the structure spinning and sustains it.

Figure 7.13 illustrates the process in more detail, showing the magnetic fields used to make, move, merge, and sustain the plasmoid structure. Metal rings at opposite ends create magnetic fields that oppose one another. Then plasma is released. The magnetic field pivots as it switches from being made by the metal rings to being made by the plasma donuts, also known as spheromaks. The device moves those structures by varying magnetic fields around them, guiding them into the center. There, they merge, forming a new hotter and denser plasma structure. The key to the TAE Technologies device is to hold and stabilize the merged structure by keeping it spinning. This is done by firing particle beams along its edge [26]. Dr. Binderbauer describes it as “keeping a top spinning by continuously flicking it” [26]. Maintaining the spin is key. If not, deadly instabilities can come in the center or along the edge to kill it [3, 34].

Despite the C2U machine‘s impressive performance records, there is at least one machine that has eclipsed it: the Princeton field-reversed configuration (PFRC) at Princeton University. TAE has set world records for the largest, hottest, and densest plasma structures ever formed. But in runtime, the machine is still fundamentally limited. The company has only run the C2U for (at most) 11 microseconds. This is because the machine is power hungry—and it is by its nature a pulsed machine.

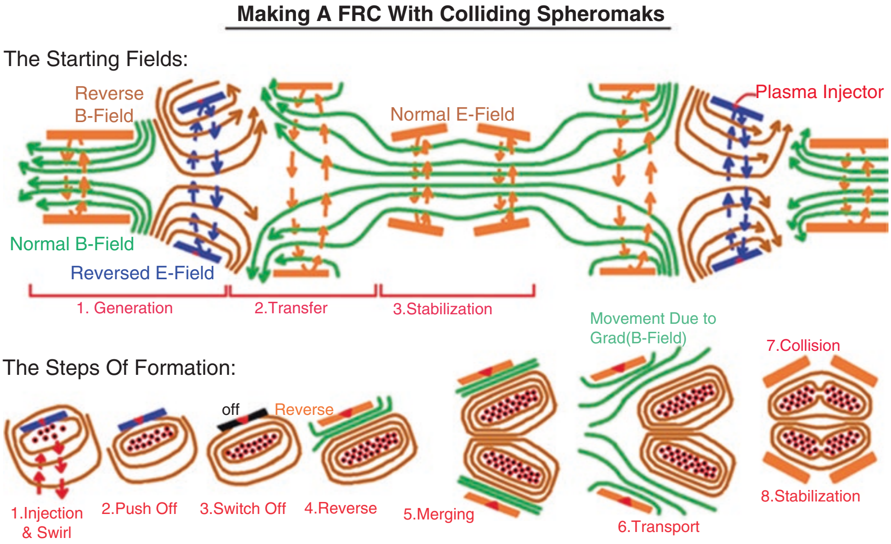


Fig. 7.13 The magnetic fields used to make, move, merge, and hold a spheromak in which fusion can take place. The magnetic fields, shown in green and brown, are controlled by directional currents. Operators can reverse the direction of the current to control the direction of the fields. To make a pair of spheromaks, they start by (1) spraying plasma into a magnetic field from opposite ends. The magnetic field causes the injected plasma to spin. (2) The spinning plasma creates its own field. Next, the direction of the current switches (3, 4), which pushes each spinning plasma away from the wall to create donut-shaped structures that can stand on their own [6, 31]. The two donuts move toward the center, where they merge. There, a particle beam spins and stabilizes the combined spheromaks

Hence, the world record for the longest-sustained FRC is currently held not by TAE Technologies but by Princeton.

7.5.4 Sam Cohen and the Princeton FRC

In the late 1990s, Dr. Sam Cohen had a big problem [8]. On paper, his life looked great: he was living in Germany and supervising a large portion of the US ITER effort. It was a big job [3]. Cohen drove a fancy car, and he had a nice salary. But he was having a personal crisis. ITER was flawed. Livermore scientists had estimated that the core would be 60 times more massive than a common fission core [2]. A 60-fold increase would likely kill the machine's commercial chances.

Cohen knew this—and it bothered him. His goal was to advance fusion to a point where it could become commercial. It was at this time that he investigated the rotamak work by Henry Blevin and Ieuan Jones [7]. He decided that this concept had the potential to be scaled all the way to a fusion power plant, yet no group was seriously pursuing it. In 1999, Cohen added his own innovation beyond the work of Blevins and Jones. He applied rotating fields that changed directions while they turned, which enabled his machine to perform much better than previous rotamaks.

Cohen decided to return to Princeton to develop the Princeton field-reversed configuration (PFRC, Fig. 7.14). Over the next 15 years, he developed an experimental machine that showed that the rotamak concept could work [3, 4]. Built on a shoestring budget, with some clever innovations and parts salvaged from other machines, the PFRC demonstrated in the summer of 2016 that it could sustain the plasma structure for 300 microseconds [4, 18, 19, 38, 42–46]. As of this writing, this is the world record for the longest-stable FRC, though it is important to note that the PFRC has not produced fusion due to a lack of proper funding.

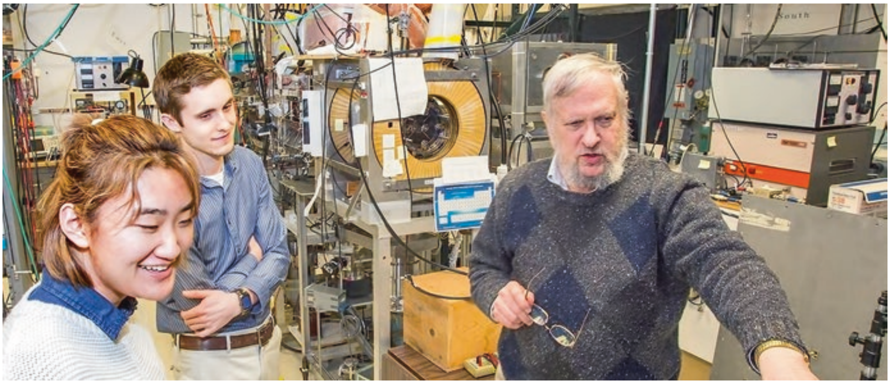


Fig. 7.14 Dr. Sam Cohen (right) shows undergraduates around his laboratory. The Princeton field-reversed configuration (PFRC) is situated directly behind him. In the summer of 2016, this machine set a world record for the longest-stable FRC ever made

The Princeton machine creates a rotamak. As described above, shown in Fig. 7.15, it works by first trapping the plasma between two magnetic mirrors. This reflects the plasma back and forth inside a long magnetic tube [25]. Once the plasma is trapped, a second, rotating, magnetic field is applied. This causes the electrons inside the machine to whip around in a loop inside the center of the machine. A current flow of electrons eventually draws in the ions. Shortly thereafter, the plasma loop self-generates a magnetic field around it. As it spins, the rotating field keeps it moving by continuously dragging the electrons through the plasma structure. What has formed is an FRC sustained by a rotating magnetic field, a rotamak. The steps laid out here are illustrated in Fig. 7.14 [1, 12, 13, 25, 43].

To take this technology further, Dr. Cohen developed a relationship with a private company that could transition this innovation out of academia and into the private industry. Starting in 2000, he developed a collaboration with the commercial company Princeton Satellite Systems (PSS). One of the advantages of the PFRC is that at fusion conditions, it will act like a source of hot plasma. Material passing over the FRC will be superheated and thus will be well suited to perform as a rocket engine. At the time of writing, PSS has been awarded funding from NASA to develop a fusion-driven rocket using Dr. Cohen's technology. In this fusion-driven rocket, gas will pass over a sustained FRC, superheating it with the energy made from fusion, and then exiting the rocket at high speeds (Fig. 7.16).

The PFRC could generate up to 280 newtons of thrust, ten times as much as the most advanced space thrusters in development. This could allow the rocket to get from Earth to Mars in 30 days using less than 1 kilogram of helium-3 fuel. It is important to note the difference in the design of the PFRC and the rocket developed by MSNW. The MSNW engine is a pulsed machine: bursts of plasma, which are ejected from the back of the ship, undergo fusion on their way out. By contrast, Princeton's concept sustains fusion continuously in the exit chamber. Any spacecraft designer could conceivably have both designs available: continuous and pulsed fusion thrusters.

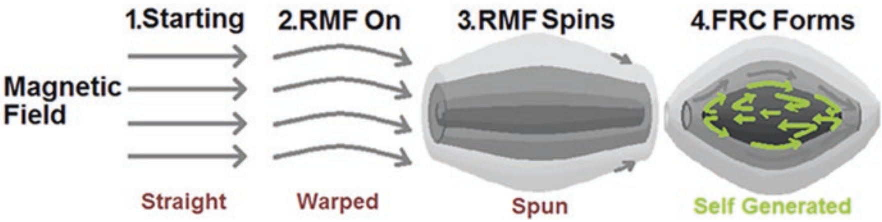


Fig. 7.15 The magnetic fields and steps used to create the rotamak structure inside the PFRC. (1) The magnetic field is initially straight between two magnetic mirrors. (2) The rotating magnetic field is switched on, which causes the mirror field to bow outward. (3) The field rotates in such a way that the electrons in the plasma spin around the center [9, 28, 29]. Finally, these conditions cause the plasma to self-generate its own internal field, which leads to the (4) self-structuring of the plasma

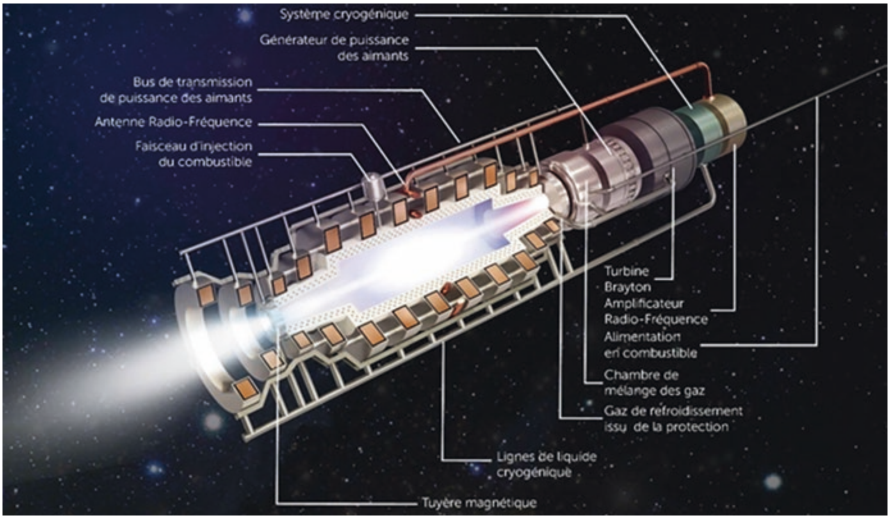


Fig. 7.16 A conceptual illustration of a fusion-driven engine built around the PFRC. Plasma flows through this long tube, past the FRC-fusing core; is superheated; and exits out of the back of the ship. (Image courtesy of Dr. Sam Cohen)

7.6 Twisted Structures

It is important to remember that the plasma structures described up to this point are all inherently unstable. They are also all looped plasma structures, and their survival comes via some trick to use to maintain them. Over time, researchers discovered that stability can be improved by twisting these internal fields. A similar story occurred in the development of tokamaks (see the previous chapter). By twisting the flow of plasma inside a tokamak, the overall plasma stability improved. Hence, the main plasma technique in a tokamak is to move the plasma along a twisted looped pathway while the machine's toroidal field wraps straight through the plasma.

7.6.1 The Dynomak

Researchers at the University of Washington have devised a machine, called the dynomak, with a plasma structure that reverses this approach. Instead of a straight field and a twisted plasma flow, the field twists and the plasma goes in a circle (Fig. 7.17). In 2017, the University of Washington spun out a private company called CT Fusion to follow this approach to fusion.

A twisted plasma flow is more organized than a simple loop structure. This is generally better suited to keep the plasma together and stable. The mathematical term for the amount of twisting in a parameter is helicity. Inside the dynomak, engineers create magnetic helicity along the edge of the plasmoid. A twist on the outside of the volume will cause the plasma to flow in a way that creates a more twisted field

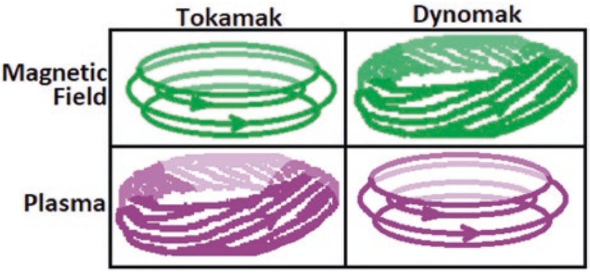


Fig. 7.17 The basic interplay between plasma motion and the fields in a tokamak and a dynomak. In a tokamak, the toroidal field runs around the donut, while the plasma moves in a twisted path around the reactor. In the dynomak, these elements are reversed. The plasma moves in a circular path around the structure, while the field is twisted. This twisted field is continuously driven and refreshed using the dynomak‘s helicity injection drive

inside. Consequently, a twisted field at the edge of the structure grows to fill the entire plasma. This is the clever innovation behind controlling the plasma structure in the dynomak. This was considered a huge breakthrough when it was discovered in 2011. A picture of the dynomak internal design is shown in Fig. 7.18.

The dynomak‘s helicity injection was originally dubbed imposed-dynamo current drive (IDCD) [57]. This drive solved several plasma problems simultaneously [48]. First, the drive stabilizes the plasma structure. By continuously twisting the field, the structure may be constantly refreshed and held in a steady state. This also gives the operator control over the plasma, a rare phenomenon in fusion research. Ideally, this would allow the operator to hold the structure in an operational sweet spot and keep the plasma instabilities at bay. The dynomak team has shown that their approach is not susceptible to kink instability [47].

A third major advantage is that it keeps the plasma continuously flowing. Driving the magnetic field, in turn, drives flow inside the plasma. Remember that fields and plasma are deeply connected within any plasmoid. A continuous flow not only helps the structure’s stability, but it also heats the plasma due to natural electrical resistance. This heating also pressurizes the plasma. Hot plasma takes up more volume, pressing it against the surrounding twisted field. Conditions in a hot, structured, and pressurized plasma are ideal for fusion reactions to take place. Since helicity injection solved so many problems simultaneously, it became clear that the University of Washington‘s dynomak was worthy of commercialization. The dynomak also had clear engineering design advantages. It needs only two magnetic coils, and these can be physically distanced from the reactor core. This was enough for the dynomak team to decide to chase after private investors.

7.6.2 Plasmoid Structural Collapse

Loops or twisted loops are not the only structures that can be formed from plasma. In outer space, plasma has been observed forming sheets, jets, and rotating discs.

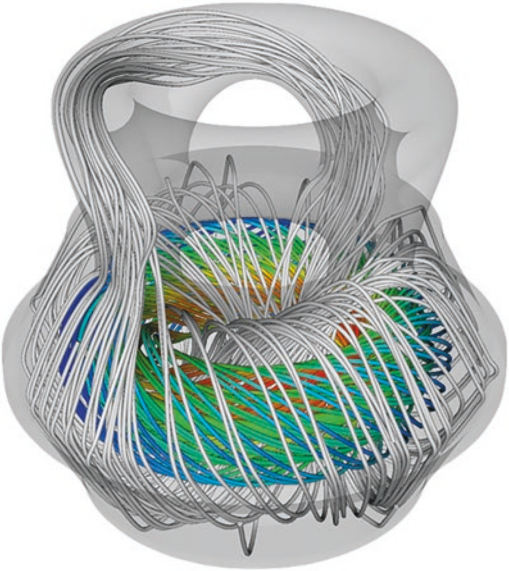


Fig. 7.18 The fields inside the dynomak (in color). Inside this colored region, fusion plasma is flowing, stabilized, and heated through the application of twisted magnetic fields around the edge of the structure. This is helicity injection. It is achieved using an external field source (on top), with the external fields shown in white. By inducing these fields around the outside, the whole plasma structure is driven, stabilized, heated, and controlled. (Image attributed to Dr. Christopher Hansen, University of Washington, Seattle)

But all of these structures are unstable and will collapse over time. Staving off collapse and driving a plasmoid is a major focus of every effort mentioned in this chapter so far. By contrast, some teams argue that real fusion gains are realized when the structure is forced to collapse in on itself. In such systems, the plasma is organized and then crushed by a surrounding field. As it does so, it compresses and heats the material to fusion conditions. Supporters of concepts like this argue that by forcing compression, the material can reach more suitable conditions. But these structures are delicate, and compressing them offers possible ways for the plasma to become unstable. Such machines are also pulsed, so fusion rates are not sustained and continuous; this makes it harder to draw net power continuously.

Structural collapse has been used as a way to study magnetic reconnection (see Chap. 6). Reconnection is an exciting method for heating plasma. It has been shown that about 90% of the energy generated in these events ends up not in the neutrons, but in heating the ions [56]. In reconnection, the plasma must be dense enough that its flowing electrical charge significantly impacts the magnetic field lines, causing previously separated magnetic fields to merge, effectively turning two magnetic field regions into one. This process releases huge amounts of energy. It is now routinely used to heat tokamak reactors as part of machine startup.

7.6.3 Helicity Space

Reconnection is exciting because it allows for a cheap and direct way to bootstrap a plasma up to fusion temperatures. But this effect alone is not enough to build a fusion reactor. Reconnection must be combined with other approaches, like plasma structuring or compression, to make a significant impact. An engineering team from Berkeley is attempting to do that through a company called Helicity Space, a firm that is trying to create a fusion rocket based on reconnecting plasma structures.

To understand Helicity Space‘s concept, it is important to understand its original research into reconnection, which did not come out of fusion but rather from NASA space funding. For example, reconnection was studied directly in a laboratory at Los Alamos in the middle of the first decade of this century, where researchers built a machine called the Reconnection Scaling Experiment (RSX). The machine stretched two long jets of electrons across a vacuum chamber. At one end, they spun a positive electrode, winding the plasma into a twisted streamer. While the plasma twisted, the jets surrounding the fields were also twisting around one another. This created a structured plasma that looks like the double helix of a deoxyribonucleic acid (DNA) (Fig. 7.19). The technical name for this shape formed by intertwined helices is a plectoneme. Eventually, the twisted fields merged together, which forced a magnetic reconnection event and raised the temperature. This was a plasma structure being forced to collapse and start a reconnection event rather than an attempt to stabilize it. The only goal of the RSX was to do this in a reliable, controlled, and repeatable way. Applying this technology to create fusion will require repeating these effects on a more advanced kind of machine with better conditions.

One of the people who worked on the RSX machine was Dr. Setthivoine You. He saw how this machine worked and how it could be used to form a fusion-driven rocket. In 2017, he left academia and formed the company Helicity Space with his long-time friend Dr. Stephane Lintner. The two are a very accomplished pair. They met years before at Berkeley, where Linter was studying mathematics and You was studying physics. Linter went to Goldman Sachs and worked as a trader on Wall Street for over 10 years. You moved around academia working at several universities in America and Japan. In 2017, they got back together to found Helicity Space to develop a fusion-driven rocket.

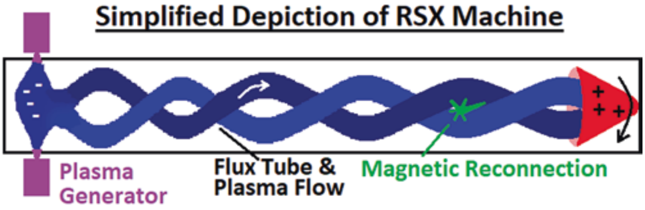


Fig. 7.19 A simplified depiction of the twisted plasma streamers formed in the RSX experiment. A stream of electrons (shown in blue) is drawn by an electric field across a vacuum chamber. As they flow, the positive electrodes are rotated, pulling the plasma into a twisted helical shape. At some point, these conditions lead to magnetic reconnection between the two electron streams [36]

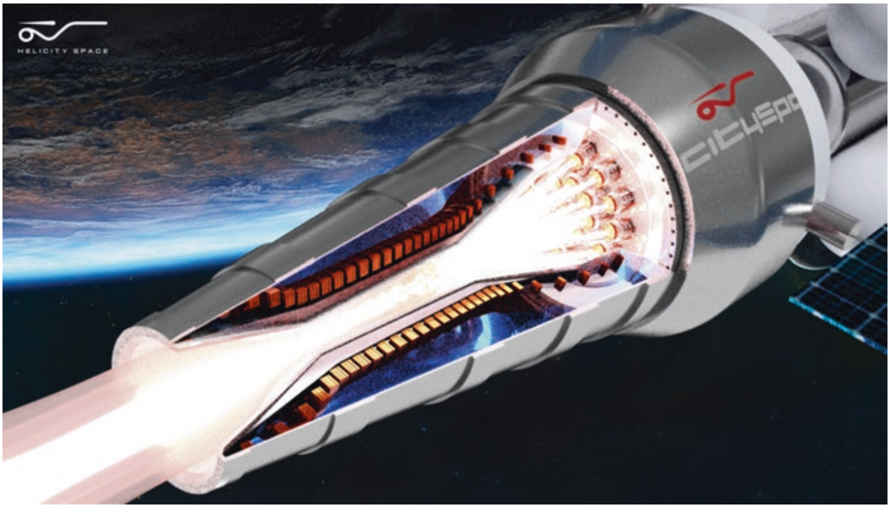


Fig. 7.20 The basic layout of the Helicity Space fusion rocket design. On the far left, plasma jets generate the plasma structure, a set of twisted plasma jets stabilized by shear flow. These jets then enter a magnetic nozzle, which compresses them to reconnection conditions. The plasma temperature rises high enough for fusion reactions, creating even higher temperatures and pressures, producing thrust as it exits the ship as rocket exhaust

Helicity Space‘s approach pulls together several of the ideas discussed in this chapter: plasma structures, magnetic twists, compression, reconnection, and the fusion-rocket concept. The company intends to start with a plasma structure that consists of multiple intertwined jets injected by plasma cannons directed into the center of a vacuum chamber. Under the right conditions, these jets are temporarily stable and enter a magnetic nozzle, a field that squeezes the plasma through a narrowed field, compressing it to reconnection conditions.

When the fields of two streams merge, magnetic reconnection releases enough energy into the plasma for fusion to occur. As the fusing plasma passes out of the back of the nozzle, the material has been superheated by both reconnection and fusion reactions. It is ejected at a high speed out of the back of the ship as rocket exhaust, accelerating the spacecraft forward (Fig. 7.20). This basic concept can be modified to include multiple (and superior) plasma jets, as well as superconductors or advanced diagnostics. The latest plasma cannon technology is discussed in later chapters. Helicity Space predicts that this rocket could produce up to 7100 newtons of thrust [56].

7.7 Conclusion

The structuring of plasma gives fusioneers several advantages that can be applied to both fusion power plants and fusion rockets. Structuring itself has several advantages and disadvantages. One of its strengths is that it shifts the overall complexity from the machine's engineering into the plasma itself, allowing reactors to be built more simply and cheaply. But the downside is that these reactors would have inherent instabilities that must be dealt with in some way. A plasma structure is forever trying to fall apart. Whether by field instabilities or internal repulsive forces, a plasmoid is fundamentally unstable and will eventually collapse. Managing these basic instabilities is an important goal for all the concepts discussed in this chapter.

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8

Inertial Confinement Fusion

Summary

So far, we have focused on fusion in plasmas that are confined by magnetic fields. Those approaches aim to maximize the time interval in which fusion can occur. Other important parameters are plasma temperature and density. Higher temperature makes fusion more likely when nuclei collide, and higher density means that more fusion events can occur in a given volume. But there are tradeoffs among those parameters. This chapter looks at an approach that produces much higher temperatures and densities but for a much shorter time. Rather than trying to confine the plasma by a magnetic field, this approach begins with a very cold pellet of solid deuterium and tritium and blasts it with high-energy pulsed lasers or particle beams that implode it, suddenly creating an extremely hot, dense plasma in which fusion events occur rapidly. Without a magnetic field to confine it, the plasma soon blows itself apart, but not before its fusing nuclei produce a powerful pulse of energy. Their natural inertia sends the nuclei inward at first, creating a plasma with very high temperature and density, and keeps them close together long enough for fusion to occur, hence the name inertial confinement fusion (ICF).

Of all the programs discussed in this book, the ICF effort is the most closely associated with the United States' development of thermonuclear weapons. In fact, it developed from a classified 1960s US program to mimic the operation of such a weapon on a laboratory scale. Over the past 60 years, the United States research community has spent tens of billions of dollars on ICF, including developing modular, cost-effective hardware for power plants. In our view, the ICF program can be considered a jewel of the American research community, producing the nation's best weapons for scientists and laser technology and driving high-performance computing.

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
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8.1 Introduction

After World War II, most nuclear engineers turned their sights toward peaceful uses of nuclear fission. By the 1950s, controlled nuclear fission emerged as a significant source of energy to create the steam that drives turbines of utility-scale electrical generators. The design of the reactors was such that a chain reaction could be maintained, but a nuclear explosion was impossible.

Naturally, the question arose: if we can tame the energy source of an atomic bomb, could we do the same for the newer and much more powerful thermonuclear (hydrogen) bomb? Nuclear fusion power was attractive because it offered significant advantages over fission. Its fuel, isotopes of hydrogen, is abundant and not dangerously radioactive (tritium's beta radiation is harmful only if the isotope is inhaled or ingested). Likewise, unlike fission, fusion did not produce large quantities of toxic and radioactive waste.

Still, fission has one significant advantage: its fuel is solid. Fusion power requires creating and confining plasma, which turns out to be a major engineering challenge. In previous chapters, we focused on fusion in plasmas that are confined by magnetic fields. Those approaches aim to maximize the time interval, temperature, and density in which fusion can occur. Higher temperature makes fusion more likely when nuclei collide, and higher density means that more fusion events can occur in a given volume.

But there are trade-offs among those parameters. This chapter looks at an approach that produces much higher temperatures and densities than magnetic confinement, but for a much shorter time. Rather than trying to confine the plasma by a magnetic field, this approach begins with a very cold pellet of solid deuterium and tritium and blasts it with high-energy pulsed laser or particle beams that implode it, suddenly creating an extremely hot, dense plasma in which fusion events occur rapidly. Without a magnetic field to confine it, the plasma blows itself apart, but not before its fusing nuclei produce a powerful pulse of energy. Their natural inertia drives the nuclei inward and keeps them together long enough for fusion to occur, hence the name inertial confinement fusion (ICF) (Fig. 8.1). We will describe many approaches to creating a power plant based on ICF. Among these are multiple targets, drivers, and methods of compression.

8.2 Early History

Unlike magnetic confinement fusion, ICF technology is closely related to thermonuclear weapons. The difference between them is in scale and the triggering mechanism. Thermonuclear fusion bombs (hydrogen bombs, or "H-bombs") use fission bombs (atomic bombs) to implode a large quantity of fusion fuel, but such a trigger mechanism clearly cannot be used for laboratory research. On the other hand, ICF operates on a much smaller scale and is thus the technology of choice for research on weapon design. This has been especially important since the signing of the Nuclear Test Ban Treaty (1963) and the Nuclear Non-Proliferation Treaty (1968).

Fig. 8.1 The Nova, a laser system built during the 1980s at Livermore National Laboratory. It was considered the flagship ignition system for inertial confinement fusion research. The system was featured in the movie *Tron*. (Image courtesy of Lawrence Livermore National Laboratory)

Because of its connection to national defense and its goal of creating electric power without producing greenhouse gases, ICF has always had some unique political characteristics that led to its support in Congress. The program has been funded in the United States since 1964 and, as of 2020, had received over $20 billion. It has steadily gotten money because it crosses ideological boundaries. It was *always* a compromise effort. In Congress, both defense hawks and green energy supporters could always agree to fund it. Steady funding also provides the continuity needed to maintain a skilled, highly educated workforce.

The program has always been partially classified. The United States always wanted to hide the “secret sauce” for creating a nuclear weapon behind classified walls. This military effort has spanned decades, making ICF a multigenerational program. But despite this connection to weapons, ICF has always had workers who want to transition its technology into electric power generation. Many of its foot soldiers hope to see their efforts applied to important civilian applications.

In the 1960s, as the United States and the USSR were competing fiercely to build more nuclear weapons, a second, but friendlier, competition began in America between the national laboratories, which wanted to outdo each other scientifically. The labs were extremely well led: scientists—not administrators—occupied the upper management. The labs also competed with each other to try to develop better technology. Los Alamos researchers were more afraid of Livermore scientists outshining their efforts than of the competition from Russia. The United States was well served by this competition. Competition led to increasingly better science and technological development.

It was in this environment that ICF research began. In 1960, a researcher named John Nuckolls at Lawrence Livermore National Laboratory began dreaming up ways to ignite fusion reactions and use them for peaceful power generation. Early designs included starting fusion reactions with electron beams or shock waves. Then in 1960, the first functioning laser was invented, and this presented a new opportunity. In the H-bomb, X-rays imploded the fusion fuel. But why could laser beams not be used instead?

In Dr. Nuckolls' first paper, he envisioned a device where laser beams would be used to compress pellets of fuel and start fusion reactions. The paper laid out the universal building blocks of any ICF system: a target and a driver of the implosion. A wide variety of targets have since been used. Lasers provide a large amount of controllable, repeatable energy into a small target; hence, they have been the most common driver. Other drivers have also been tested, including beams of electrons, light ions, heavy ions, and high-velocity impacts.

8.3 Direct Drive

The concept laid out by Nuckolls, called "direct drive" because the beams strike the target directly, is the most basic ICF approach. A ball of frozen fusion fuel is placed in the center of a chamber. Laser beams from multiple directions come in and strike the target, creating an inward shock wave, which is enhanced by the reaction pressure from outflowing vaporized material. The resulting compression leads to a very high temperature and pressure, which ignite fusion reactions. These steps are shown in Fig. 8.2.

Nuckolls began modeling, designing, and conducting small experiments on this idea at Livermore in 1960 [11]. His team was small at the time. Slowly, he built support for this research within Livermore. The lab started a small experimental program, led by Dr. Ray Kidder [12] and administrator John Foster. They recruited John Emmett, who started purifying and crystalizing neodymium, which when doped with small amounts of other elements became the workhorse material of the laser systems built to test ICF. Two of these were known as the 4Pi and Long Path laser

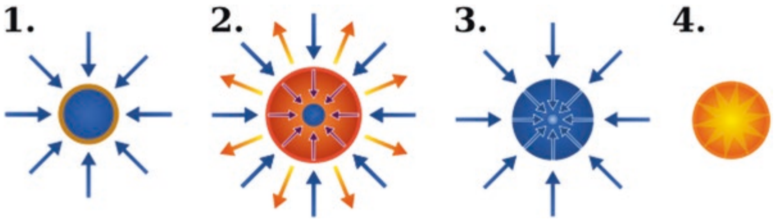

Fig. 8.2 The four steps of direct drive ICF fusion experiments: (1) provide an implosive force on the target and (2) blow off an energy wave of vaporized material, which (3) creates a compression wave and (4) ignites fusion in the material. This approach is known as direct drive because the lasers hit the target directly with no additional steps needed. Image source: Wikipedia

systems. At the same time, laser technology became critical for the US military, so funding for this program grew. The early work focused on a small laser-plasma interaction experiment. Some of the laser systems developed by Livermore are shown in Fig. 8.3.

Everything in the early days was classified. Even public lectures on this work were considered secretive. Longtime Livermore researcher Dr. Ralph Moir once told author Moynihan a story about a lecture from Edward Teller in graduate school. Before the event was to start, all foreign nationals were asked to leave the room. When he began speaking, Dr. Teller drew out on the chalkboard the two circles—signifying the two chambers of the H-bomb. The chalkboard was marked classified, and classifiers were added to their notes. They made it clear that if the information was passed on, the students could face jail time.

Despite US efforts to keep everything hidden, using lasers to create fusion was evolving in several locations simultaneously throughout the late 1960s. The Russians had a research program, as did the French, the British, and the Max Planck Institute in Germany [12]. The University of Rochester built an academic effort in parallel under the direction of Dr. Moshe Lubin [24]. All these teams were drawn to the hope of making fusion power while trying to understand nuclear weapons. As the effort grew in complexity, Livermore realized that they needed to go public. Going public meant that Livermore could collaborate with many more partners and get more development support. So in 1972, John Nuckolls published a four-page paper in *Nature* laying out ICF [10]. This article was widely cited as defining the starting

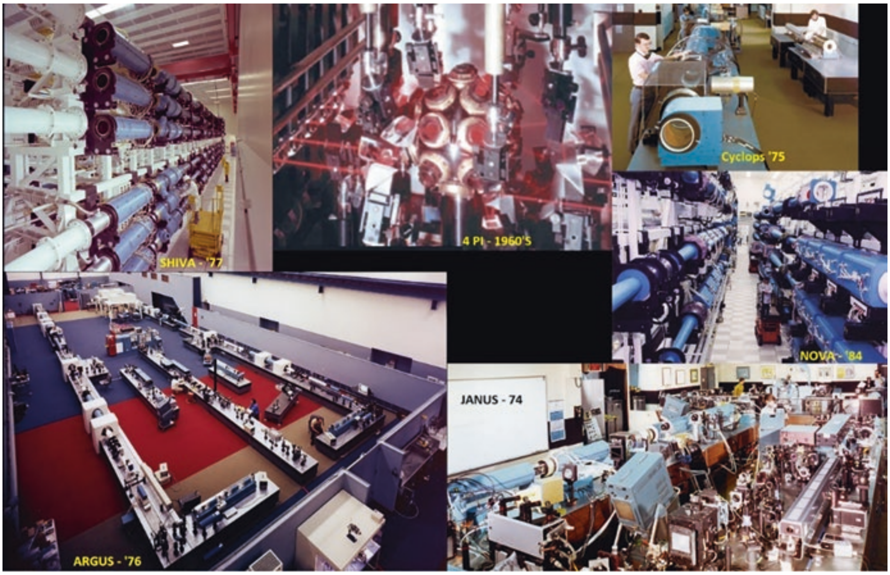

Fig. 8.3 Photos of a series of laser systems built at Livermore National Laboratory from the 1960s to 1984: 4Pi, Janus, Cyclops, Argus, Shiva, and Nova. Image courtesy of Lawrence Livermore National Laboratory

point for ICF. By going public, Livermore effectively admitted that there was now an international race to create fusion using laser beams. This created new fields of research, among them high-powered lasers, laser-plasma interactions, and shock-wave studies.

Despite all the work done at the National Labs, the world's first laser-induced fusion did not happen at a government facility. It happened not at a fancy university either but rather at a small company called KMS Fusion in Ann Arbor, Michigan, named after the initials of its founder, entrepreneur Keeve "Kip" Siegel. Siegel created the company by selling all his patents and previous products and focusing on nuclear fusion. This raised red flags with the Atomic Energy Commission because of its national security implications. Siegel recruited Keith Brueckner from UC San Diego to become the company's lead experimentalist. Using mirrors to split and shape the beams, KMS was able to uniformly compress targets with just two lasers. This was an example of a private-sector innovation that the public sector could not match. The team demonstrated fusion on May 1, 1974, the first-ever instance of laser-driven ICF. A picture of the KMS device is shown in Fig. 8.4, and an illustration of how it worked is shown in Fig. 8.5.

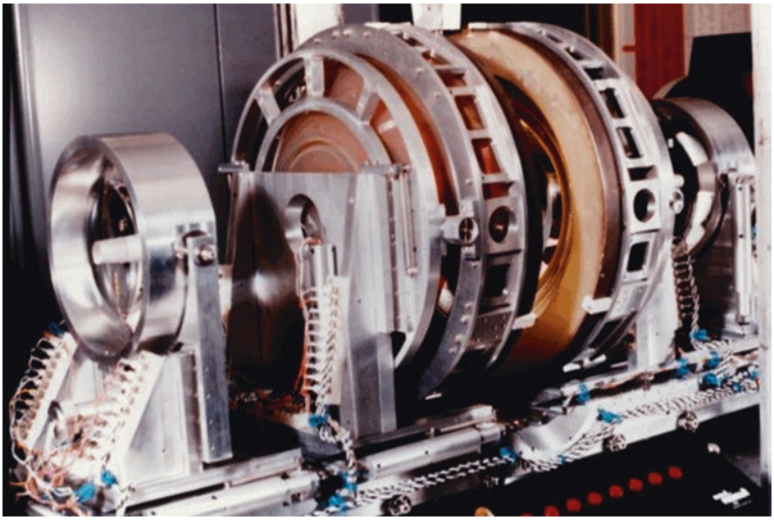

Fig. 8.4 The double-bounce illumination system (DBIS), the first machine in the world to carry out a laser-induced fusion event in a deuterium-tritium (DT) pellet. The machine was unique because it was done by a private company, KMS Fusion. The DBIS achieved fusion on May 1, 1974. This machine used mirrors to split and shape the laser beams to compress a fusion pellet. (Image source: Wikipedia)

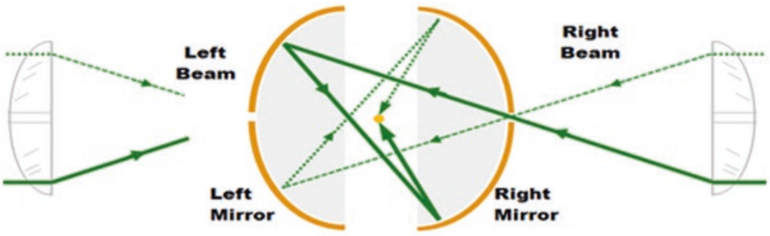

Fig. 8.5 A schematic showing how the double-bounce illumination system worked. Beams would pass through pinholes into a mirror chamber. Those beams would reflect and strike a pellet of DT fusion fuel from different directions, compressing it to ignite fusion. (Image source: Wikipedia)

8.4 An ICF Power Plant

KMS showed the world that a private company could start a fusion reaction using this approach, which gave supporters hope that a power plant could be developed using ICF. But what would such a power plant look like? Through the next decades, teams developed plant designs and commissioned studies. Some examples include the laser inertial fusion energy (LIFE) and high-yield lithium-injection fusion-energy (HYLIFE-II) designs at Livermore and the SOMBERO design by the Naval Research Laboratory (NRL). These power plants all shared the same basic design. A target would be dropped into a chamber. When it reached the center, laser beams would blast it from more than one direction. This would compress the target, creating fusion. The burning target would explode and send heat and mass into a molten lead-lithium blanket around the walls of the chamber. The liquid would absorb the heat and be pumped to transfer heat with a second loop of water. That water would be heated to superheated steam, which would turn the turbines of an electric generator (Fig. 8.6).

There were several variations of this design. In some reactors, the blanket was made of fissionable molten salt. In that case, the power plant was a nuclear hybrid plant: fusion was used to start fission reactions. In other cases, the blanket had lithium in it; when fusion neutrons react with lithium, they can breed tritium. In those reactors, the molten salt would be pumped back into a processing plant and the tritium separated. These were all exciting ideas, and some funding went into developing them, but the bulk of the money in government labs was always focused on weapons.

All the designs focused on efficiency as a way to argue that it could make electricity. The power plant requires a huge amount of input energy to create the needed laser beams. For example, it might take 5 megawatts of electrical power to create a laser beam that would deliver 200 kilowatts of laser power at the National Ignition Facility, which means an efficiency of 4% [6]. This loss would have to be made up by fusion events, which might create 1 gigawatt of power, or 200 times the electric power needed to drive it. That ratio is about what is required because the plant also loses energy on the capture side. The plant might only be able to capture 30–40% of fusion power and convert it into electricity. Taking all these efficiencies together, the whole power plant would—theoretically—create net electricity. Over the years, these projected efficiencies would change based on the efficiency of the laser and the energy capture and the frequency of shots (Fig. 8.7).

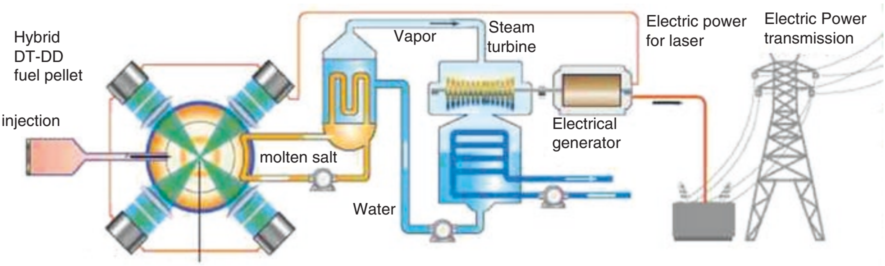

Fig. 8.6 The basic scheme of a power plant based on an ICF fusion approach. (Image from Wikipedia)

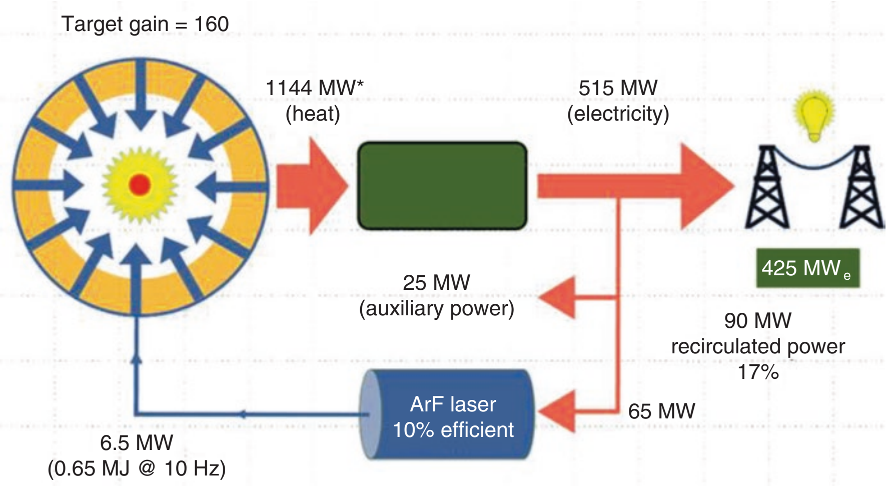

Fig. 8.7 Projected power plant efficiency for a typical ICF reactor, based on Ref. [22]. (Image courtesy of Dr. Stephen Obenschain, Naval Research Laboratory)

8.5 ICF in the 1970s

Support for ICF grew significantly during the 1970s, mainly in response to the energy crisis. President Jimmy Carter referred to the need to wean the United States from imported oil as "the moral equivalent of war." Congress was interested in finding a path to fusion power, either for its energy implications or for national security. The ICF program also led to military technology, which was critical for defending the country. Several institutions, most notably Livermore, Los Alamos, the Naval Research Laboratory, and the University of Rochester, developed significant programs. Each had a unique history.

Dr. Moshe Lubin led the University of Rochester program. He recruited a team of 13 professors, who built a four-beam laser system called Delta. They were eventually able to grow that work into the Laboratory for Laser Energetics (LLE), which has been a driving institution for ICF research since then. But Rochester's program may not have happened had it not been for a cruel twist of fate. In 1975, Lubin was asked to speak before a Congressional committee. The testimony was important for the future of the ICF program. Congress was seriously considering raising support, and several leaders from the community were speaking, including laser expert John Emmett of Los Alamos, ion beam expert Gerold Yonas from Sandia, and Kip Siegel from KMS, along with Lubin. Of all of them, Kip Siegel had the most to brag about. His team had been the first to achieve fusion by laser beam, and it had been done by the private sector. There was a strong argument that all of ICF would work best in the private sector, and Siegel planned to dominate the hearing. As it happened, Lubin spoke first. Siegel was up next and would have likely overshadowed everyone else in the room. But sadly, he had a fatal stroke right before the hearing and never got his chance to speak [13]. Congress canceled the remainder of the hearing, and Rochester got a serious amount of money. Within a year, Rochester was breaking ground on an entirely new site to house the LLE (See Fig. 8.8).

Moshe Lubin would go on to run the University of Rochester program until the early 1980s (Fig. 8.9). He then left academia to start two companies focused on microchip fabrication with lasers. Both companies burned through over 100 million dollars in venture-backed funding. In addition to the venture capital support, they had funding from the Defense Advanced Research Projects Agency (DARPA) and Harvard. Sadly, the effort eventually collapsed, and in September of 1993, Lubin decided to take his own life, leaving behind a wife and two children [24].

Throughout the 1970s, ICF grew at several institutions (Livermore, Sandia, Los Alamos, Rochester, and NRL), each following a predictable pattern. A team would build a laser system and publish a steady stream of papers, and then a new system would be needed. The old system would be replaced. Along the way, researchers improved every aspect of the technology: laser glass, target design, modeling, and

Fig. 8.8 The staff of the Laboratory for Laser Energetics at the construction of their new facility in Rochester NY in 1976. The team leader, Dr. Moshe Lubin, is standing in the center of the group in a white jacket. (Image courtesy of the Laboratory for Laser Energetics, University of Rochester)

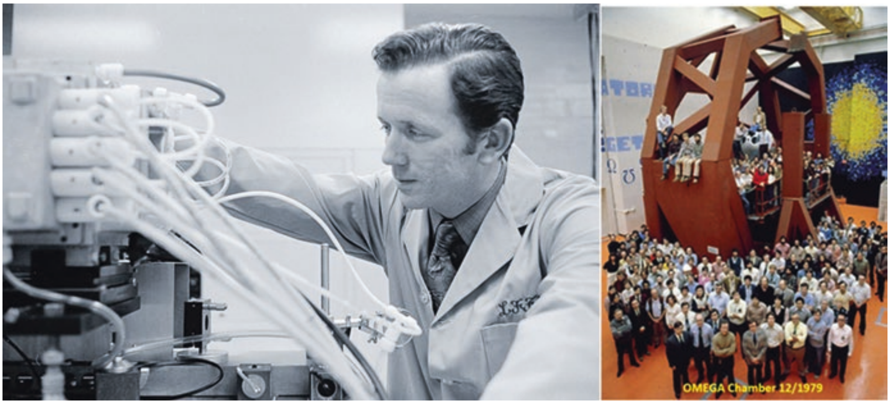

Fig. 8.9 (Left) Dr. Moshe Lubin, one of the founders and leaders of the University of Rochester Laboratory of Laser Energetics; (right) the LLE staff in December 1979. (Image courtesy of the Laboratory for Laser Energetics, University of Rochester)

diagnostics. During this period, several groups tried several novel drivers and targets. These included the following:

- *Gas-laser-driven ICF*: Los Alamos tried to create laser beams using gas, specifically CO_2 gas. They built two lasers: Gemini in 1977 and Helios in 1978. By the end of the decade, plans were in place for the much larger Antares system [14, 20]. Eventually, it became clear that these lasers did not work as well because of their longer wavelengths. Long wavelengths created instabilities as the target was compressed, resulting in poor fusion performance. Short wavelengths were better suited for ICF compression. Much of this work was classified.
- *Electron-driven ICF*: Sandia tried to implode a target with beams of electrons. Dr. Gerold Yonas was the champion of this effort, and his story is covered later in the chapter. There were several problems. Because of electrostatic repulsion, beams of electrons ripped apart into hazy clouds. But the main problem was that electrons could fly right through the solid target without interacting with the nuclei. This meant that this approach could not be used to compress a target.
- *Ion-driven ICF*: several groups, especially particle accelerator researchers, tried to compress the target with beams of ions. Like electrons, these beams would also fly apart. Overcoming this problem meant using fewer ions, accelerated across a bigger voltage gap. Ultimately, these beams consisted of kiloamps of ions accelerated through gigavolts of electrical potential. These efforts ended in the 1980s due to budget cuts.
- *Impact fusion*: among more exotic ideas was a 1979 Los Alamos proposal and project based on the concept of impact fusion [22, 23], in which an object with high velocity slams into a target. Today, as discussed at the end of this chapter, the company First Light Fusion is researching this.

Livermore focused on solid-state lasers made of glass, such as the one shown in Fig. 8.10. A full discussion of lasers is outside the scope of this book, but in brief,

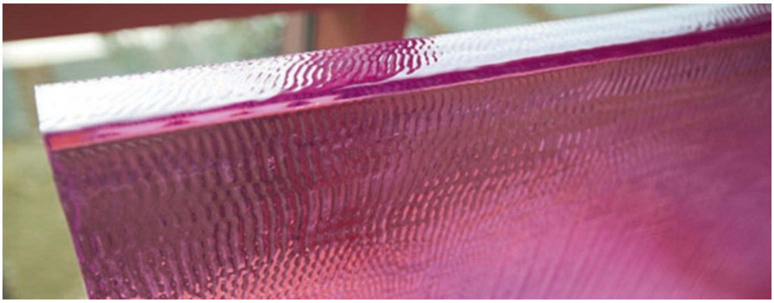

Fig. 8.10 Laser glass is a beautifully pure and heavy crystal that has the right chemical composition to produce and amplify a coherent light beam. As a photon with a certain wavelength passes through the glass, it stimulates more photons in lockstep with the initial one. Coherent light can be sharply focused to deliver intense power to a small region. It can implode and heat a fusion fuel pellet, creating a burst of energy. (Image courtesy of Lawrence Livermore National Laboratory)

the careful addition of selected elements (doping) produces a material that amplifies a particular wavelength of light, creating a coherent beam. This means that as a light wave of that wavelength passes through, it stimulates another wave with its crests and troughs in alignment with the initial one. Coherent light can be focused very sharply, and its energy is proportional to the square of its amplitude. Thus, such a laser can precisely deliver intense power to a small volume, such as a pellet of fusion fuel.

Livermore built many machines to develop this technology, beginning with the previously noted 4Pi laser system in the 1960s, then Janus in 1974, Cyclops in 1975, Argus in 1976, Shiva in 1977, Novette in 1981, and Nova in 1984. Each subsequent system was substantially larger, with more power and many more beams. From 1963 to 1980, over 2.6 billion dollars (in 2019 dollars) was invested in the program, and by 1980, ICF had become a crown jewel of government energy research programs.

8.6 ICF in the 1980s

In the 1980s, the development of ICF shifted direction. Several technical efforts lost funding because they were not showing sufficient progress. Sandia National Laboratory scrapped the effort to implode targets with electron beams because the beams were hard to control and thus did a poor job of compression. The particle accelerator researchers who were pushing ion-driven approaches also lost support because they could not make the case that their technique would work well enough. The world of ICF changed to center on large laser systems made of crystalline glass. Because shorter wavelength photons carry more energy, research teams worked on improving lasers that produced light toward the blue end of the spectrum. They tried to improve neodymium glass-based lasers and to build a krypton-fluoride laser.

Researchers also found ways to triple the power of these beams using techniques known as nonlinear optics and chirped pulse amplification (Details are beyond the scope of this book, but we note that the developers of the latter technique earned a half-share of the Nobel Prize for Physics in 2018). They also sought better ways to make the laser target, including switching from glass-filled shells to solid cryogenic balls of hydrogen isotopes. These improvements made it possible to routinely create conditions that exist in the center of stars. At the same time, the gain in energy from a single shot got much better.

Outside of the power sector, other funding for other fusion efforts also changed during that decade. The Reagan administration started to cull the fusion research space to those efforts that were making the most progress. Funding was cut for many programs and ideas, including field-reversed configurations (FRCs), mirrors, and ICF variants. At the same time, Reagan became focused on the Strategic Defense Initiative (SDI). Reagan's idea was to shoot nuclear weapons down using laser beams, leading the SDI's critics to nickname it "Star Wars," after the popular space science-fiction film series. Though this effort ultimately failed, it provided a boost of funding for laser fusion research. Large laser facilities were able to get money from the government through other programs. The field also grew outside the United States. Japan developed a series of laser systems called GECKO. Russia had a large, secret laser program in several of their hidden cities. France eventually built a Laser Megajoule Facility (MJF) in Bordeaux.

Still, by the end of the 1980s, it became clear that a megajoule-level laser facility would be needed to reach net power. Part of the evidence for this came from a secret US government test conducted in the Nevada desert. The Halite-Centurion test was a series of underground nuclear explosions to see how much energy it would take to start a fusion event. Small pellets of fusion fuel were loaded into underground chambers and blasted with X-rays from small nuclear bombs. This was a way to see how much input energy would be needed to reach net power. Decades later, ICF supporters used these tests to argue for billion-dollar laser facilities, which was an overreach since the public had not seen the data from these tests.

8.6.1 A Typical 1980s Laser ICF Facility

Omega-24 was a typical laser facility of that period (Fig. 8.11). It was about the size of a football field with two large rooms. One was filled with laser optics, and the other had a chamber holding a fusion target (Fig. 8.11). The machine started with a single seed beam, which was a packet of laser light about a foot long. This beam would pass through beam splitters while reflecting many times between two mirrors before being released as 48 separate pulses of laser light. Each of these would then pass through amplifiers and other optical instruments to focus the beam on the target, striking it simultaneously. The optics would shape and control the power of the laser beam. Beams could be front-loaded with excess energy or tapered as needed to optimize performance. All of the optical equipment was held in a thick metal superstructure on a single concrete slab. This kept everything aligned so that the beams would not misfire. That was particularly important because when the beams did miss, they would blacken parts of the laser facility. These lasers were powerful. Striking a person with an unfocused beam could cause a second-degree burn. If,

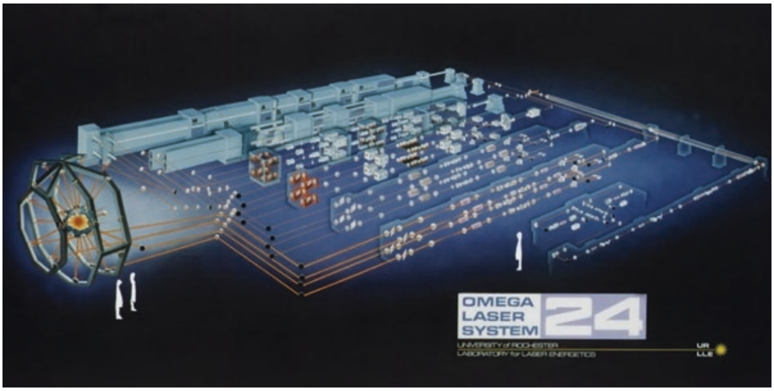

Fig. 8.11 Omega-24, a typical laser ICF facility layout setup in the 1980s. This system focused multiple laser beams onto glass targets to create fusion reactions. (Image courtesy of the Laboratory for Laser Energetics, University of Rochester)

Fig. 8.12 The interior region of a target chamber of an ICF facility; notice the large diameter. (Image courtesy of Mr. Eugene Kowaluk, Laboratory for Laser Energetics, University of Rochester)

however, a beam was focused and concentrated, it could punch a hole right through a person, causing instant death.

The target is held inside a large sphere of aluminum, such as the one pictured in Fig. 8.12. Aluminum was used for its machining, cost, and neutronic properties, but tungsten carbide would be a superior material. Tungsten carbide is a gray metal-like ceramic material, harder than any known substance except diamond. Its 2600 °C melting point is one of the highest melting points of any known material. (It actually decomposes rather than melts.) And unlike many substances, its nuclei do not easily capture neutrons to form radioactive isotopes, making it ideal for a fusion chamber.

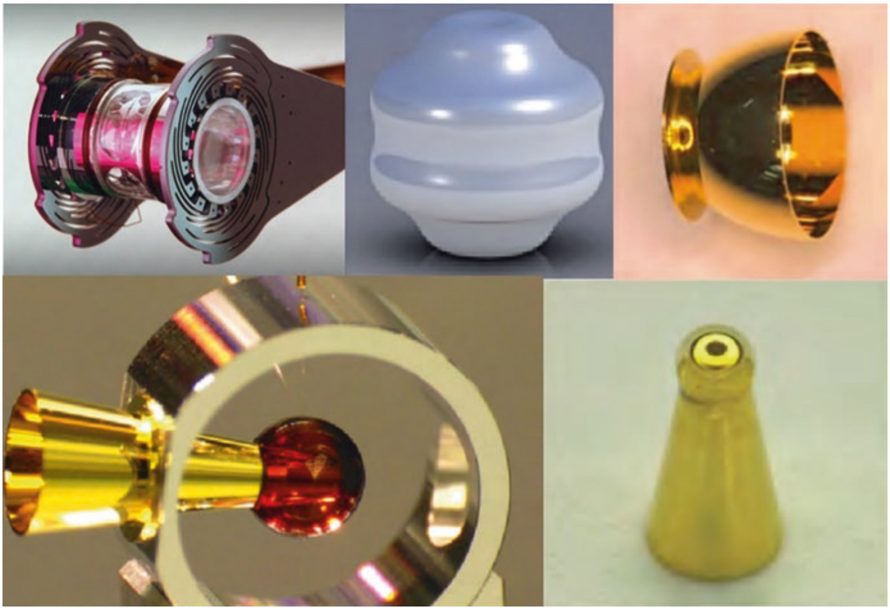

Fig. 8.13 Many different objects have acted as targets inside an ICF chamber. Above are some examples of targets through the years [24]. Target construction is a delicate art in its own right. Fusion targets contain cryogenically frozen spheres of hydrogen gas with temperatures below 14 kelvins. These targets have been coated with nanotubes, gold, or silver or formed inside foam shells. Solid targets such as cylinders of metals or glass shells have also been used. (Images courtesy of General Atomics under contract with the NNSA, Los Alamos National Laboratory, and Livermore National Laboratory)

The beams entered the chamber through ports. The beams would focus on a small target, dumping their energy into the system (Some example targets are shown in Fig. 8.13). This would create the conditions for a miniature star. This entire shot might take only a split second to start fusion. Because of the high energies involved, a typical laser facility of the 1980s could only make one to three shots every day. The intervening time was necessary for the optics to cool down, for maintenance tasks, and to reset the system for the next shot. Good facilities of that time period could do over 1000 experiments per year.

8.7 ICF in the 1990s and the Path to the NIF

By the 1990s, it was clear that the field needed one large laser facility. Several laboratories had plans to build such a machine. But the size and cost had grown immensely. Such a facility would be expensive; it would take years to secure funding from Congress and years to build. But the United States had a new reason to support this work. The country was gearing up to sign the Comprehensive Test Ban Treaty. This would ban nuclear bomb testing, and ICF was a great alternative for studying the behavior of plasmas and fusion in detail. A big machine was needed in order to approach ignition. Livermore was the leading site for this big ICF machine, which ultimately became known as the National Ignition Facility (NIF, Figs. 8.14 and 8.15).

Supporters argued that NIF would also be powerful enough to start ignition, which could make ICF viable as a power plant. Just as a fission power plant creates

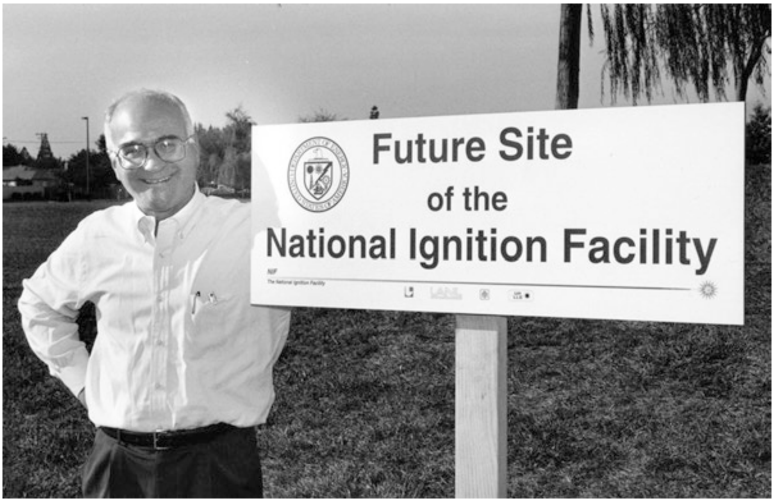

Fig. 8.14 Victor Reis, the assistant secretary for the Department of Energy's Defense Programs, poses by a sign marking the location of the future National Ignition Facility. In the 1990s, Reis played a key leadership role in defining the emerging Stockpile Stewardship Program and the need for NIF. (*Photo by Bryan Quintard/LLNL*)

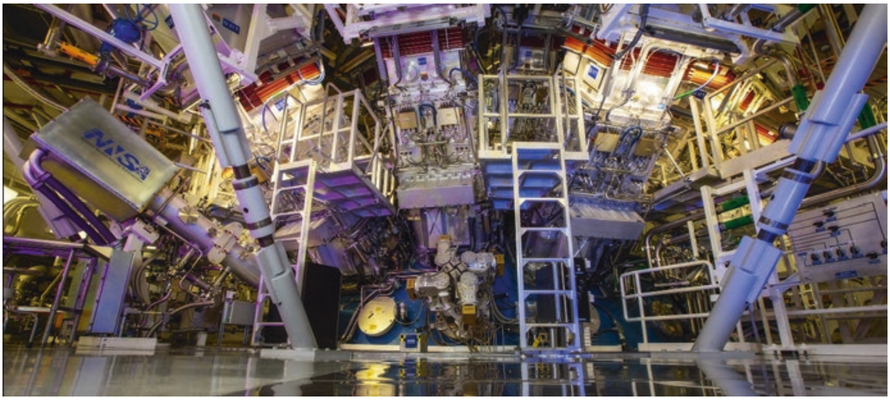

Fig. 8.15 The outside of the target bay at the National Ignition Facility. This exterior shot was used in the 2013 movie *Star Trek: Into Darkness*. (Image courtesy of Lawrence Livermore National Laboratory)

a controlled nuclear chain reaction, NIF would use the energy from fusion reactions to create conditions that could ignite more fusion reactions in the same plasma.

Selling NIF to Congress was a major priority for Livermore. The lab's leaders cycled through several plans to calculate the design, construction time, and price needed to build NIF. The first plan in 1992 estimated that the facility could be built for $400 million over 4 years. In 1995, Livermore researcher Dr. John Lindl published a tour de force paper summarizing the path to the machine [2], covering all the ICF work that had previously been done, the NIF design, and the models that predicted that the machine would work. Livermore also built a device they called Beamlet, a single laser that was a sample of the multiple lasers needed for NIF. Two science panels in the defense department endorsed the effort, and Congress conducted several hearings about it. This led to a second plan in 1996, which estimated that the machine could be built for just over a billion dollars in less than 6 years. Ultimately, NIF took a dozen years to build and cost 3.8 billion dollars.

Despite several reviews by Congress, the Department of Energy, and the National Academy of Sciences, critics derided the decision-making process. The California activist group Tri-Valley CAREs (Communities Against a Radioactive Environment) called NIF a train wreck. They argued that Livermore did not subject the plan to any serious oversight and that they had basically picked their own reviewers. Sandia fusion scientist Rick Spielman stated that the NIF plan had undergone "virtually no internal peer review," and Sandia manager Robert L. Peurifoy said that "NIF was completely worthless." Advocates eventually prevailed, and Congress finally did approve the funding for the project, and ground was broken for NIF on May 29, 1997.

8.7.1 The LIFE Concept

By the time NIF opened in May of 2009, most of the ICF community had united around preparing for the big machine. A University of Rochester team under Dr. Riccardo Betti had laid out a body of theoretical work around the conditions needed for ignition. Dr. John Sethian had built a High Average Power Laser (HAPL) program at NRL to develop all the underlying technology [21]. General Atomics had devised new ways to make cryogenic NIF-sized targets. Author Moynihan entered graduate school at that time, and his doctoral work was on developing ways to mass-produce targets for the National Ignition Facility using microfluidics [25]. The entire ICF community was very excited about the completion of the NIF machine. During those dozen years of development, Livermore also pushed the laser inertial fusion energy (LIFE) concept. LIFE was more than an engineering plan; it was also a public relations campaign to sell ICF as a power source. Livermore set up a website, did presentations, and published papers around the LIFE approach. Several doctoral theses were written on how (once NIF worked) the nation could develop LIFE, a fusion reactor based on the ICF approach (Fig. 8.16).

The LIFE reactor could make electricity in several different ways. Any version would need to be able to pulse its lasers with a high repetition rate, which would require active cooling of the lenses. In one version, the fusion target would be

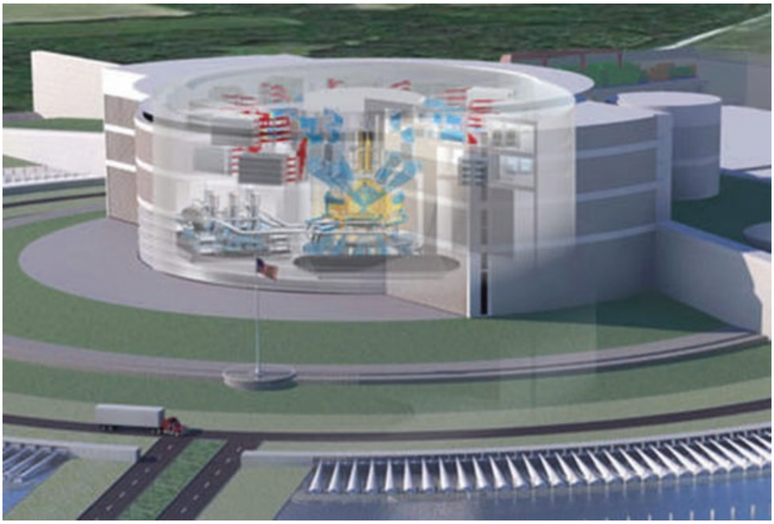

Fig. 8.16 An artist's conception of the Laser Inertial Fusion Energy (LIFE) reactor. (Image courtesy of Lawrence Livermore National Laboratory)

dropped into the laser chamber. When the target reached the center, it would be shot with laser beams. This would start a fusion reaction. The targets would need to be mass-produced, reproducible, and cheap. The heat and kinetic energy from this reaction would be captured by liquid metal flowing along the walls of the chamber. This would be used to create steam and make electricity. In other versions, LIFE would use the resulting fusion products to kick-start fission reactions. In this scheme, fission would be used as a booster to raise the energy output of the reactor.

8.7.2 NIF Performance

The LIFE design built on earlier ICF power plant designs like SOLASE-H and HYLIFE-II. Unfortunately, it did not live up to its promises by the Congressionally mandated deadline of December 2012. The NIF director, Edward Moses, was shuffled out of his job, and Livermore's credibility was damaged for about 10 years. The overselling of the LIFE approach did a general disservice to the country. Work on the National Ignition Facility continued for many more years, and on Sunday morning of August 8, 2021, it finally saw its first evidence of ignition. This historic moment was the culmination of 9 years of operation. In that time, researchers refined their control and rooted out problems in the massively complex machine [1, 3]. But on that momentous morning, and for the first time, the system achieved about two-thirds of the laser energy on target. Researchers saw a huge spike (six times the previous record) in energy output. All told, the shot produced over 1.3 Megajoules of energy (Fig. 8.17). (Note added in proof: In December, 2022, NIF reported, to great public fanfare, that they had achieved the milestone of producing more fusion energy output than the laser energy input, 3.15 megajoules of fusion energy produced from focused laser pulses that used only 2.05 megajoules input energy.)

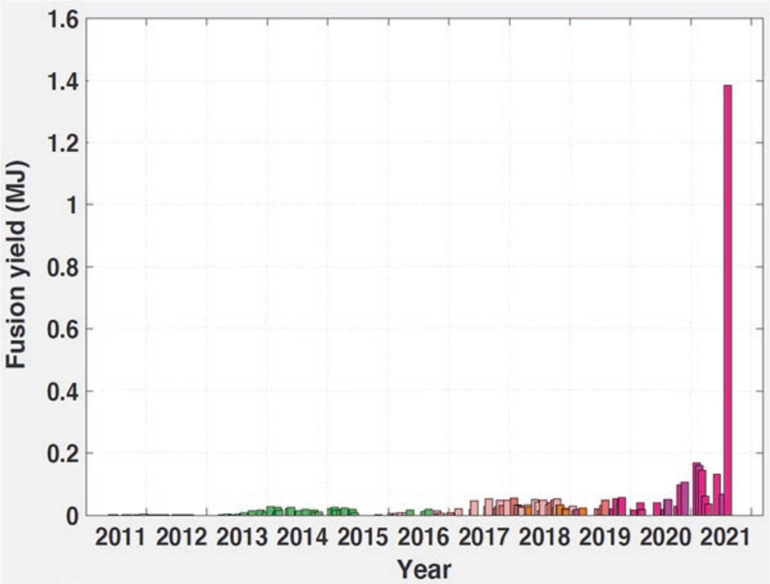

Fig. 8.17 After almost a decade of continuous improvement, the National Ignition Facility saw a dramatic increase in the power generated from a fusion reaction on August 8, 2021 [26]. This breakthrough was the first evidence of fusion ignition or a fusion chain reaction. Image courtesy of Dr. Tammy Ma, Lawrence Livermore National Laboratory

8.8 ICF Approaches

The United States ICF program continues to this day and is still one of the strongest fusion research programs in the world. From 1963 to 2020, the United States invested over $20.6 billion into the program, leading to many different approaches and applications, as well as the professional development of many fusion scientists. Today, ICF covers a whole family of approaches and variations. Not every branch of this family tree yet has been fully explored, though several start-ups are in the process of doing so. This section lays out six of these (Fig. 8.18), plus a novel approach to compression.

8.8.1 Direct Drive

Direct drive is the most basic concept in this family and is discussed above (Sect. 8.3). Current work includes developing better targets by coating them with gold, silver, or (in some cases) nanotubes—anything to improve compression. Typical conditions for this implosion are temperatures of between 10 and 15 million kelvins for Omega and 20 and 40 million kelvins on NIF. (But it is important to note that NIF uses indirect drive; see below). During an implosion, the plasma reaches pressures that compress it to about 1000 times the density of water or 10^{26} ions per cubic

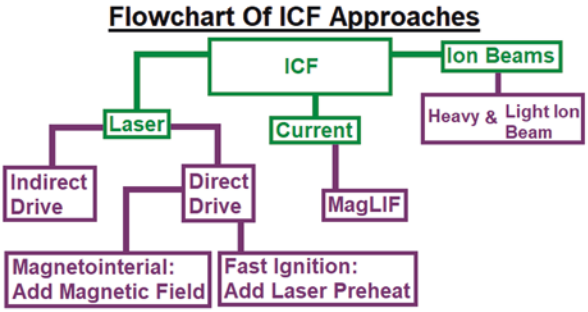

Fig. 8.18 A family tree of six different ICF approaches, which will be discussed in this chapter. The approaches are laid out in dark purple; the driver is shown in green

centimeter. The whole process typically lasts under 20 nanoseconds, and each compression step is about 100 picoseconds, during which NIF produces 3×10^{15} fusion reactions [2].

8.8.2 Indirect Drive

NIF uses a two-step, or indirect drive, approach to compression. Inside an H-bomb, the fusion fuel is compressed using high-energy X-rays. Mimicking this process was a major goal of the ICF program. X-ray lasers are challenging to work with because X-rays pass through many materials, such as mirrors. So ICF program engineers devised a method for producing powerful X-rays that struck the fuel pellet from every direction as a secondary process, which they called indirect drive ICF. This can be considered a variant of the basic ICF process.

In an indirect drive approach, the target is a fancy gold foil tube with a pellet of fusion fuel held in the center (Fig. 8.19). Technically, this is known as the *hohlraum*. First, the laser beams enter the target from the top and bottom of the tube. These lasers strike the gold foil on the tube walls. The gold vaporizes. This process creates high-energy X-rays that bathe the pellet and create the conditions for compression. Supporters argue that the indirect drive of NIF is a better path to ICF fusion. But others note that as a general rule, adding more steps to a process increases the likelihood of it being derailed.

8.8.3 Fast Ignition

Fast ignition was devised at the University of Rochester in the early 2000s. Engineers were frustrated to repeatedly see that the core of these implosions gets very hot and dense yet fail to start undergoing fusion events. They looked for a technique to get the plasma into those conditions and then kick-start ignition with more energy. This was the impetus for fast ignition, which, like indirect drive, is a two-step process.

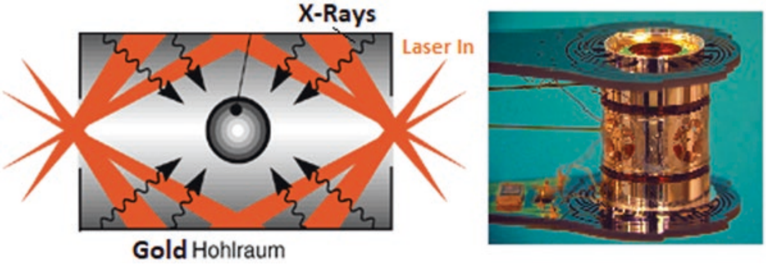

Fig. 8.19 Indirect drive ICF takes place in a gold foil tube known as a *hohlraum* (German for hollow space or cavity). (Image courtesy of Lawrence Livermore National Laboratory)

First, the target is compressed using direct drive. At the Rochester facility, this first step used 60 older laser beams. Then once the plasma is hot and dense, a second beam injects a powerful jolt of energy (Fig. 8.20). Rochester secured the funding to add the second laser in 2005, with operation starting in May of 2008.

8.8.4 Magneto-Inertial Fusion

Having a magnetic field present during compression can steer particles or otherwise improve the compression event [4]. But getting this field is a bit tricky. The implosion only lasts for a split second, and once it has happened, it will have destroyed the supporting equipment. Thus, the magnetic field must be created at the instant of implosion. Rochester achieved this using a fast supercapacitor, which can dump a large electric current into a ring of wire, making a short-lived but powerful magnetic field. Typically, the currents reached about 100 kiloamps and lasted a little more than a microsecond in a coil with a diameter of 7.8 mm and a resistance of 14 milliohms. The resulting peak magnetic field is 32 teslas [15], which lasts longer than the plasma itself. Hence, from the plasma's perspective, the field would look very steady. One name for this approach is magneto-inertial fusion. Figure 8.21 shows some of the devices they used.

8.8.5 Ion-Beam ICF

There has long been an argument that you can swap a laser for a beam of ions. In fact, ion-beam ICF has a long history in fusion, tracing back to John Nuckolls' work in the 1950s, before lasers were available. This would be direct drive ICF, but with a beam of ions rather than laser light. Critically, this should not be confused with beam-based fusion approaches, an oft-attempted but inevitably unsuccessful technique to create fusion by having two beams of deuterium and tritium ions colliding with each other. The energy needed to keep the beams coherent outweighs the energy made from beam-driven fusion reactions. For this reason, we elected not to include a chapter on beam-based fusion in this book.

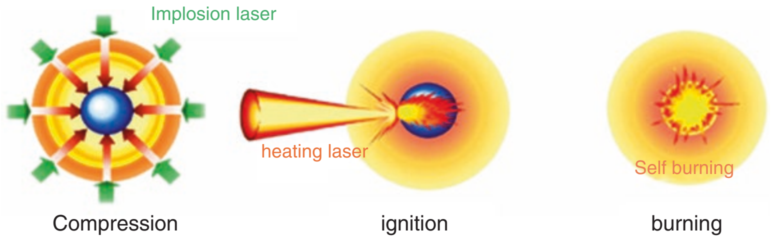

Fig. 8.20 The two-step fast ignition process, developed at the University of Rochester

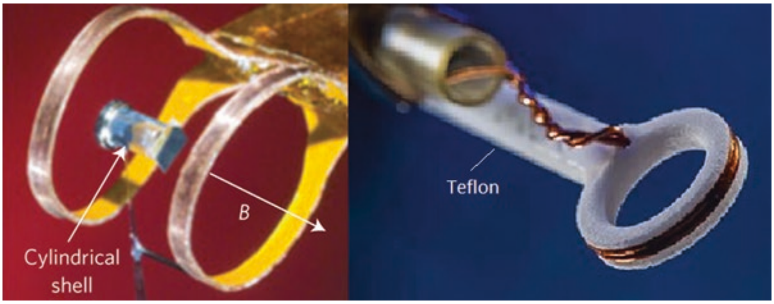

Fig. 8.21 Two-wire looped targets, which the University of Rochester used to combine ICF implosions with magnetic fields. Note the use of Teflon in the right photo. Teflon is relatively transparent to magnetic fields, which makes it uniquely useful in many fusion experiments. (Credit: Eugene Kowaluk, Laboratory for Laser Energetics, University of Rochester)

Ion beam ICF requires much more than simply replacing lasers with ions. The ions electrically repel one another so the beams tend to fly apart. Overcoming this tendency was a major part of ion beam ICF research [5, 18]. Over decades, people have tried several approaches, tuning plasma composition, distance, and voltage to try to get the best outcome. Supporters argue that these issues can all be addressed. They argue that beams add mass to the push, creating better compression, and that is worth the hassle.

The person who most vigorously championed ion-beam ICF was Dr. Gerold Yonas at Sandia National Laboratories [12]. This idea was in direct competition with laser-driven ICF research. When both fields were in their infancy, it was not clear which would be the superior approach, so at the time, the United States was funding both approaches. Supporters of beam-ICF argued that particles were easier to make than lasers. Yonas's first job after his postdoc was at a company called Physics International in 1967, and the company was trying to build a beam-target fusion reactor. But within 2 years, Yonas had moved to Sandia because he believed that the government labs were the only entity that had the money and talent to pull this off.

In 1970, Yonas built a machine called Nereus, which was the first electron beam fusion reactor at Sandia. Nereus was a desk-sized prototype aimed at proving the concepts.

A series of improvements and modifications led to a series of renaming, and the machine eventually became known as the Sandia Z-Machine (Fig. 8.22). Nereus created a 0.03-terawatt beam of electrons. Yonas published this approach in an effort to get wider support from the fusion community. His timing was fortuitous. The United States was about to experience an oil crisis. Gas lines plagued the country, and the Carter administration was forced to act. With large sums of money directed toward energy projects, the United States was willing to support more radical ideas like his. Sandia became the center of a long-term beam program. The laboratory started with electron beams in 1972. The concept was to fire a web of perhaps 36 electron beams at a fusion target. Ideally, these beams would either drop their energy into the target or initiate uniform compression. This was essentially an ion-beam-driven ICF approach to fusion. Dr. Yonas recruited a large technical and theoretical team for the effort, including Tom Melhorn and David Seidel. He was also ambitious, and so he patented the concept in 1974.

8.8.6 Pulsed Power Grows from Fusion

As a lab, Sandia specialized in building high-energy systems—the higher the energy, the better. Partially because such systems could simulate thermonuclear bombs without physical testing, Sandia wanted to drive the density and energy of that machine's beam as high as possible. To get there, the lab needed to build the critical technology for a pulsed power system. Indeed, fusion research was instrumental in the development of the whole field of pulsed power. Pulsed power is the art of producing a huge amount of energy all at once, then often using it more gradually. Sandia developed modern Marx generators, pulse transformers,

Fig. 8.22 A recent photograph of the Sandia Z-Machine. The technology for this machine evolved from many earlier facilities centered on using beams of particles to start ICF events. These machines can trace their lineage back to the work of Sandia researcher Gerold Yonas in 1970 [14]. Sandia built or planned for several of these machines, including Hydra, Proto I, Proto II, the Electronic Beam Fusion Accelerator (EPFA I and II), the Particle Beam Fusion Accelerator (PBFA-I and II) and Saturn. (Image permissions from Troy Rummler of Sandia National Laboratory)

supercapacitors, and high-voltage electrical lines for this project. Sandia also developed the first computer codes to model these beam reactors. Codes like MAGIC, SCEPTRE, and TWOQUICK were Fortran-based one-dimensional simulation codes [16].

The emphasis in the 1970s was on electron beams because they were easier to make than other particle beams [19]. But by 1978, it became clear that electrons were simply too light to impart enough energy into the fusion fuel. Electron beams would dissipate, while proton beams were less likely to. Sandia reengineered its machine again to achieve this goal. The Particle Beam Fusion Accelerator (PBFA) was built to fire protons at targets in 1980. Two beam national programs were started: one for light ions and one for heavy ions. Though this funding was low, both programs were sustained for decades. These efforts built up a large body of knowledge that anyone interested in ion-beam ICF can use today to inform about their work.

Sandia pushed PBFA I and II to higher power levels, but eventually, it became clear that proton beams would not be heavy enough and could not be focused. Sandia could make the highest energy beams in the world but could not control their focus. When a beam of ions hits a solid target, those ions can slow down and stop, but the focus needs to be sharp in order to create a plasma that will ignite fusion. Sandia found that their spot size was both too large and too hard to control. To counter this, the lab started firing carbon ions and then lithium ions.

By this point, the lab had begun to give up on this approach. In 1987, PBFA II was upgraded and was renamed Saturn, and the lab's focus shifted to nuclear weapons and missile defense. The Saturn channeled immense energy through tiny tungsten wires. This vaporized the wires into pure plasma and created magnetic shock waves. Material jets outward and pinches the center in a fusion pinch. Eventually, Saturn was reengineered and renamed again to become the Z-Machine. However, the light and heavy ion beam programs continued to be funded through the 1990s and 2000s at a low level [17]. The program was rooted in weapon research, and much of it was classified. This is partially why many Americans do not know this history.

Ion-beam ICF supporters still argue that there is a technical path for this approach. The idea is to surround the target with these ion beams and induce an implosion. They argue that making these beams requires less infrastructure than lasers. For example, in August of 2015, ARPA-E awarded Berkeley National Labs $2.43 million to try to develop a cheap ion-beam source [5]. This was important not mainly because of money but simply because it happened. For decades, fusion had been funded solely by the Department of Energy, and fusion research was viewed as having a minimum price tag in the tens of millions of dollars. ARPA-E officials argued that high-impact, innovative fusion work could be done for far less money. The Berkeley team was able to build a miniature accelerator that could get helium ions to an energy of over 10,000 electron volts, which is about the minimum condition needed for fusion.

8.8.7 MagLIF

In 2010, Sandia published a paper describing the magnetized linear inertial fusion (MagLIF) pinch approach to fusion [7], in which plasma is compressed by shock waves. This is surprising to many people; the Z-machine has that name because it started as a giant Z-pinch compression. But a shot on Z involves dumping current down thin little wires, which vaporize. This creates shock waves of hot plasma and X-rays that spread out in all directions. These shock waves will compress anything they encounter, including fusion fuel. In other words, the Z-Machine can be an ICF compression source. But the driver, in this case, is neither lasers nor ion beams but rather millions of amps of electricity (Fig. 8.23).

MagLIF uses all the compression steps outlined but also preheats the plasma with a laser pulse. This is a two-step process. It is like a reversed fast ignition. Instead of compressing and then heating, as is the case with fast ignition, MagLIF swaps these steps. First, plasma is heated by passing a laser beam through the center of the target. Z-Machine targets are ideal for this because they are cylindrically shaped. Next, the target is compressed. By combining both of these steps, engineers hope to improve the quality of the fusion event. See Fig. 8.24.

A shot on the Z-Machine is one of the most epic events in all of fusion research (Fig. 8.25). So much electricity is released that the whole machine must be bathed in a nonconducting oil. A typical shot on Z can pass over 26 million amps of current [9]. This makes a web of lightning bolts that fills the entire tank. This oil contains all this arcing and keeps it from breaking the machine. As shown in Fig. 8.26, the Z is surrounded by a ring of Marx generators, which create huge amounts of electricity. The electric charge is stored in a smaller ring of capacitors around the edge of the pool. During a shot, the current is channeled into the center and passed down a set of small wires. This machine is not only useful to create fusion, but it can also be used to study a set of extreme plasma environments.

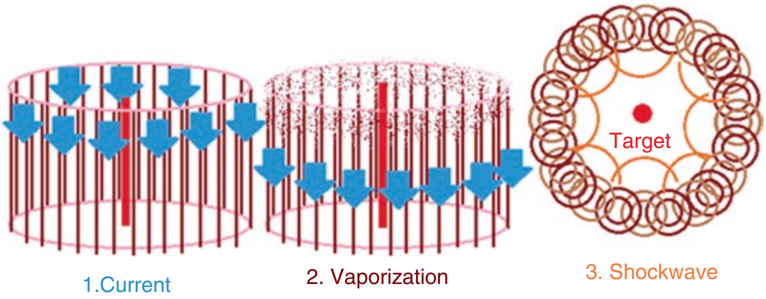

Fig. 8.23 The three basic steps of a fusion shot on the Z-Machine. First, current passes down small tungsten wires, which make up the target. There is so much current that it instantly vaporizes the wires, taking them directly to plasma conditions. This process also creates X-rays. A shock wave of plasma jets outward from the vaporizing wires. Both the shock wave and X-rays compress the target in the center

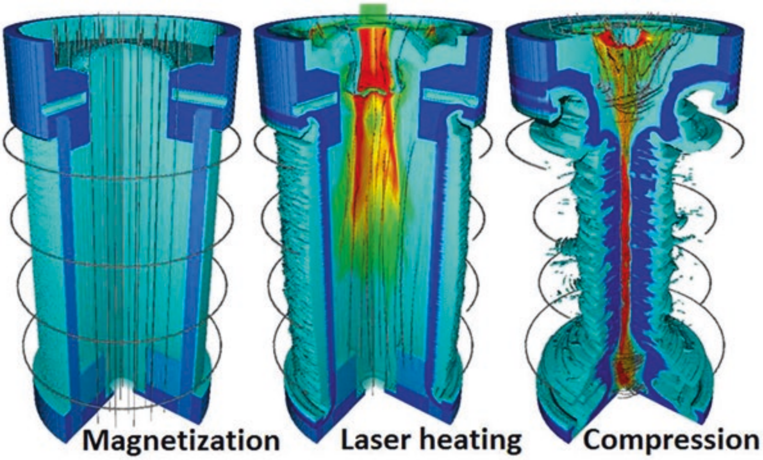

Fig. 8.24 The three stages of MagLIF compression [4]. First, a magnetic field fills the inside of the plasma; the plasma is now magnetized. Second, a laser prepulse is sent in to heat the plasma. Last, the plasma is compressed using a Z-Machine shot. (Image permissions from Troy Rummler of Sandia National Laboratory)

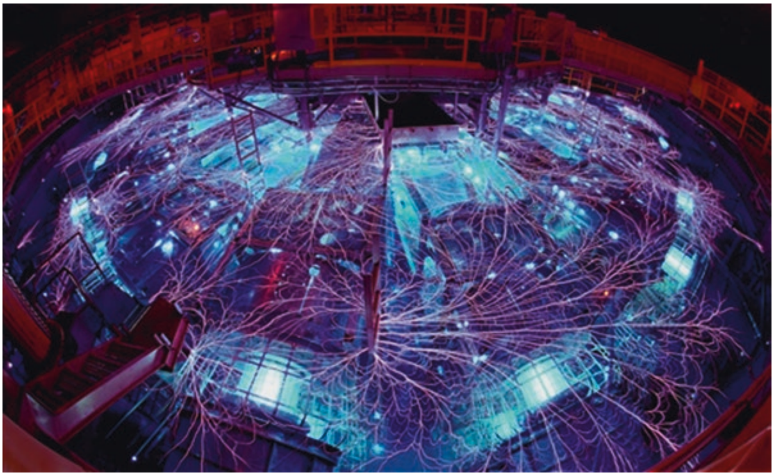

Fig. 8.25 The Z-Machine in operation. This is one of the most epic pictures in all of fusion research. The machine uses so much electrical charge that all the parts must be bathed in a fluid bath to control the arcing. (Image permissions from Troy Rummler of Sandia National Laboratory)

8.8.8 Projectile Compression

As noted at the end of this chapter, building an ICF-based power plant faces several challenges. But the biggest challenge in ICF has to do with the compression itself. It is not uniform and, by its very nature, is unstable. The compression event consists

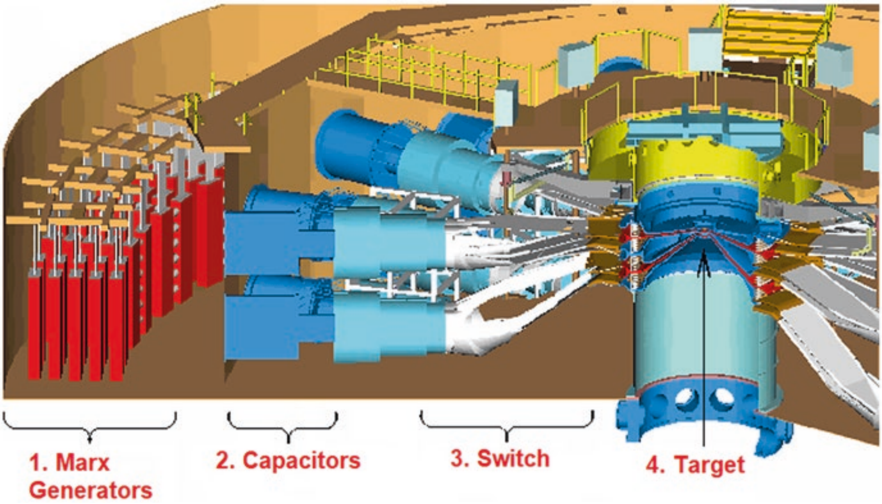

Fig 8.26 A cutaway view of the Z-Machine design from the side [7, 8]. The current travels into the center, passing through four stages. First, the Marx generators create a huge current. The current charges giant capacitors that ring the device and store the electric charge. A switch is then thrown, which releases electricity. Charge races into the center. (Image permissions from Troy Rummler of Sandia National Laboratory)

of a heavy plasma pressing on a light plasma. Imagine honey sitting on water. The honey will not push down on the water uniformly, and the surface will break apart. See Fig. 8.27. This is known as the Rayleigh-Taylor (RT) instability, and it impacts all ICFs. In fact, during an ICF compression, the physics is more complex. Not only are the two fluids pressing on one another, but a shock wave is also passing through. The name for this is the Richtmyer-Meshkov (RM) instability. It is Rayleigh-Taylor but under the special conditions of ICF.

The company First Light Fusion (FLF) was founded in 2012 by Dr. Nicholas Hawker and Dr. Yiannis Ventikos at Oxford around an idea to beat this Rayleigh-Taylor instability. The premise of this company was simple: How can we rethink everything about ICF starting with this instability and working backward? This was a radically new approach. When this field began, nobody understood this instability problem. Nobody had access to supercomputers with realistic plasma modeling. Nobody had measurements of real shock waves traveling through real plasma. But after 60 years, all of these tools were available. Why not start over from scratch? RT and RM were the primary challenges to overcome. The company hoped to rejigger the ICF approach to turn these problems into strengths by using the instability to help compress the fuel (Fig. 8.28).

By the summer of 2021, First Light had raised over $80 million in investment. They won investors using four key elements in their pitch. First, they wanted to use the RT and RM instabilities as a strength, not a weakness. Next, they wanted to cycle through lots of ideas by first simulating them before ever spending any money to build. Third, they wanted to rethink almost every aspect of ICF, including targets,

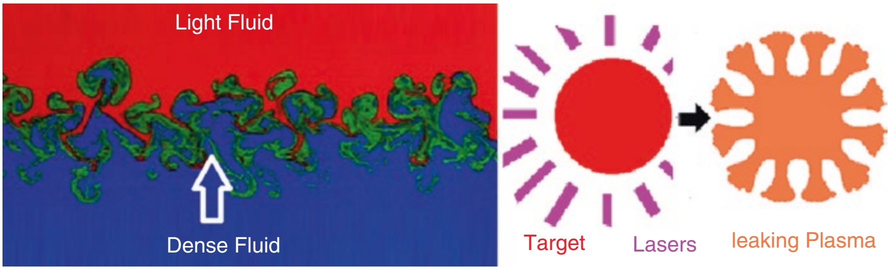

Fig. 8.27 (Left) The classical picture of the Rayleigh-Taylor instability, a dense fluid pressing on a light fluid and the surface breaking up. (Right) In ICF, this results in the leakage of plasma from a compressing target. (Image courtesy of rheologic incorporated)

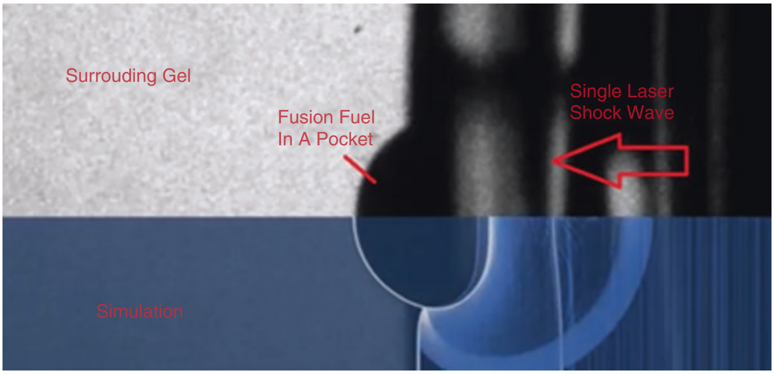

Fig. 8.28 An early image from First Light Fusion showing a model and early experiment of a one-dimensional compression. Here, the fuel is held in a pocket in a solid gel and blasted by a shock wave made by a projectile. This test was most surely used to benchmark the company's custom computer codes. (Image courtesy of Nicholas Hawker, First Light Fusion)

drivers, and materials. Last, they wanted to harness all the government money that had already been spent. It is no surprise that what emerged from this process (Fig. 8.29) looks quite different from a large laser facility.

A core part of their pitch was the second step, cycling through lots of new ideas and coupling them with advanced simulations. The number of ideas the group was kicking around at one point was impressive. The ideas fell broadly into two groups: compression and targets. In compression, the company was willing to explore several options. For example, can compression happen in one direction, as opposed to multiple directions? Can it be done by a gas piston or perhaps with a single, powerful projectile? Similarly, First Light was willing to explore new kinds of target designs and compositions. The company has explored nonspherical targets, including solid blocks, glass, and gels. The blocks have cavities filled with fusion fuel held under pressure by glass. The company has explored many of these ideas using simulations instead of experimentation. This work started with coopted government codes but by now FLF has its own custom benchmarked code. The analogy is

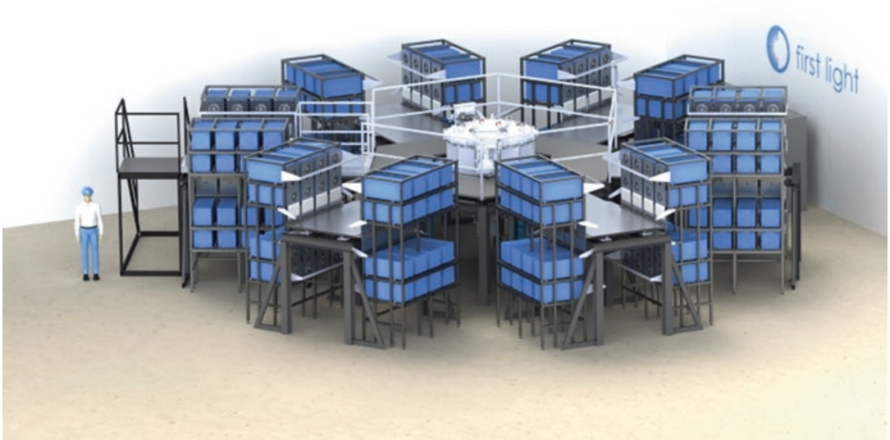

Fig. 8.29 Computer-aided design image of First Light's "Machine 3," which was ultimately built in the winter of 2018–2019. (Image courtesy of Nicholas Hawker, First Light Fusion)

Fig. 8.30 First Light Fusion's Machine 3, which went from being a computer-aided design to being operational in February 2019. (Image courtesy of Nicholas Hawker, First Light Fusion)

Boeing Dreamliner 777, which was the first plane entirely designed virtually before a prototype was ever built. Modeling allows entire fusion reactors to be built on a computer before any experimental machine is made, which is a far cheaper approach.

Ultimately, First Light's approach is compression using shock waves, but these shock waves are made using high-velocity projectiles instead of lasers. This process uses a projectile driver to initiate ICF. Figure 8.30 is a photo of Machine 3, which went operational in February of 2019. The machine is six railguns spread out in a star pattern. A railgun can fire plasma or a solid object as a projectile. The machine requires 200,000 volts and 14 million amps of electricity. It can fire material at 20,000 meters per second. The construction and testing of this machine took place through 2018 at a cost of $4.6 million. First Light was targeting conditions with high pressure (multiple gigapascals, or approaching 10,000 times Earth's surface atmospheric pressure) but low densities (100–10,000 kilograms per cubic meter, or one tenth to ten times the density of water).

8.9 ICF Power Plant Challenges

The effort around inertial confinement fusion will likely be with us for many years to come. So much momentum has been built around this approach, as well as the need to test nuclear weapons, that it will likely continue. However, turning ICF into a fusion power plant is far easier said than done. To get there, there are several challenges that would need to be overcome, and it is not clear that fusion power could not arrive via some faster, alternative method. Below are the top technical issues that need to be addressed for ICF power:

- *Instabilities*: ICF compression is naturally unstable, and working around this problem has been a major focus for many decades. Yes, this problem has been reduced, mitigated, and otherwise worked around using targets, coatings, drivers, and fields, but it will still occur whenever the conditions enable it.
- *Drivers*: no matter how it is created, ICF implosion happens because shock waves are compressing a target. This chapter has shown several different ways to make these shock waves. These include laser beams (direct drive), X-rays (indirect drive), beams of particles, copious amounts of current (Z-Machine), and projectiles (FLF). Each kind of driver has its own characteristics (efficiency, cost, maintenance, and interchangeability). For a power plant, these drivers must be reasonably priced and have a strong enough efficiency to get the rest of the power plant to net power.
- *Targets*: ICF uses a driver to blast a target. Throughout the years, tens of thousands of these targets have been shot, including glass beads, solid blocks, shells with gold foil, parts suspended on spider silk, and parts held on carbon stalks. Today, ICF engineers can deliver round shells, filled with solid, frozen, radioactive hydrogen, to the center of a laser chamber. This is a massive technical accomplishment that few in the public appreciate. But to build an ICF power plant, the target must be cheap, standardized, and mass-produced. Among the multiple ways to get cheap mass-produced targets is by utilizing microfluidics and fluid control using electrical and magnetic fields.

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Plasma Jets

9

Summary

This chapter lays out the history of plasma-jet-driven magneto-inertial fusion (PJMIF), a unique concept in fusion that merits its own categorization in this book. Also called a plasma cannon, PJMIF is a relatively new approach to fusion reactor design. A crossover between tokamaks and inertial confinement fusion (ICF), it is a particularly effective way to study conditions in a middle-density plasma, halfway between that of those two approaches. Supporters have had difficulty building momentum behind its development because it had to compete with established fusion approaches that have been better resourced. The chapter goes into the method, the technology, and some of the challenges PJMIF faces.

9.1 Background

In the 1980s, a young physicist named Yong Chia Francis Thio at the Westinghouse Research and Development Center in Pittsburgh, Pennsylvania, was developing railguns for the United States military (Fig. 9.1) [1, 5]. Those are immensely powerful weapons that use the Lorentz force (which acts on electric charges moving in a magnetic field) to fire projectiles forward. The force is perpendicular to both the field direction, a vector designated B, and the direction in which current flows. It is also known as a J × B force, where vector J represents current density, usually measured in amperes per square meter. The basic design of this system, shown in Fig. 9.2, involves a current crossing a gap and creating a perpendicular magnetic field. As the figure shows, railguns can produce large accelerations and eject bullets at speeds that are many times faster than a normal gun.

The same J × B (read J cross B) force underpins a device used in space propulsion called the Hall-effect thruster (HET, Fig. 9.3). The thruster is a ringed cavity that points outside of the spacecraft. The difference is that in a railgun, the current

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
https://doi.org/10.1007/978-3-031-22906-0_9

Fig. 9.1 Dr. Yong Chia Francis Thio, one of the early advocates for plasma-jet-driven magneto-inertial fusion (PJMIF)

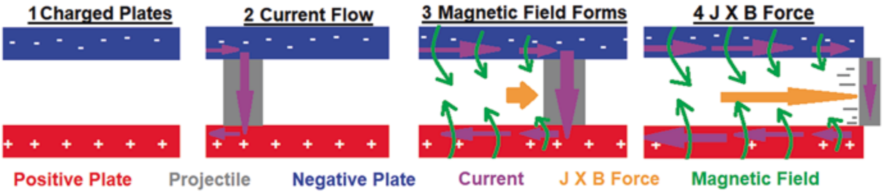

Fig. 9.2 How a railgun works. Inside the gun, a high voltage is applied between two metal strips or rails. A metal projectile completes an electric circuit. The flowing current produces a magnetic field in the direction shown by the green arrows. This results in a force that accelerates the projectile along the rails. The faster the projectile moves, the larger is the resulting force, and this results in enormous speeds by the time it leaves the gun. Railguns were of great interest to the US military in the decades of the 1990s and 2000s

flows into a solid conductor, while in HET, the current flows in an ionized gas or plasma, which produces a thrust when exhausted from the thruster chamber.

The Hall effect, which is the development of a voltage across the conductor transverse to the direction of the current flow, occurs in both devices but is not significant in the operation of a railgun. However, in HET, the Hall voltage not only acts on the current flow but also moves the propellant toward the exhaust.

When Dr. Thio looked at the operation of the Hall-effect thruster, he recognized an opportunity for fusion power. Like railguns, the strength of HET lies in rapid acceleration. And as the plasma speeds up, it also heats up. Dr. Thio wondered: Could jets like these be made hot enough to ignite fusion?

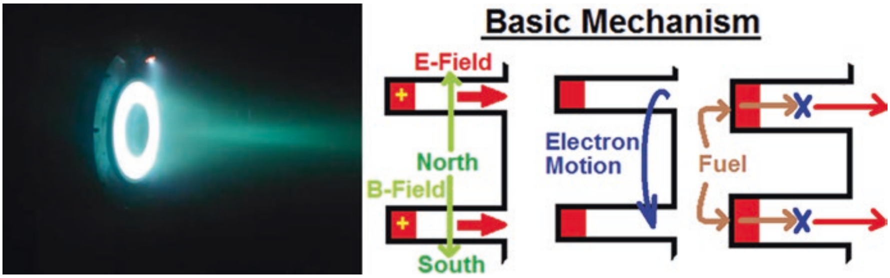

Fig. 9.3 A Hall-effect thruster (left) consists of a cylindrical cavity surrounding a magnetic coil, with one end fully closed and the other end having openings for the exhaust. Another narrower but larger-diameter magnetic coil sits inside the open end but outside the exhaust. The resulting magnetic field lines are radial within the cavity. The electron flow results from an axial electric field between the anode (in the shape of a torus surrounding the inner magnetic coils near the closed end of the chamber) and a ring-shaped cathode, which produces the electron current and sits just outside the outer magnetic coils. The propellant, most commonly krypton or xenon, enters through the anode, where it is ionized by the electrons, accelerated by the electric field, pushed toward the edge of the chamber by the Hall voltage, and ejected at high speed, creating a thrust (image credit: Wikipedia)

9.2 PJMIF Basics

The 1980s was a time of transition for fusion research. In the United States, the mirror program was ending, and two main approaches, tokamaks and inertial confinement fusion (ICF), as described in earlier chapters, were rising to dominate the field. Dr. Thio's question about the possibility of igniting fusion in plasma jets led him to envision a very different approach to ICF. Instead of using a system of lasers to implode a pellet of solid fusion fuel, he envisioned compressing a cloud of plasma in the center of a sphere using plasma jets. By merging materials in the center of a sphere, he argued that the plasma could reach fusion conditions. Dr. Thio called this idea plasma-jet-driven magneto-inertial fusion (PJMIF), or plasma jet fusion for short.

Though PJMIF was conceived in the 1980s, it would take many decades before the first prototypes were built. Not surprisingly, when the fusion reactor was ultimately tested, his basic idea had undergone significant changes and improvements. The central idea remained: compressing plasma with plasma. Dr. Thio hoped to exploit several advantages. The internal plasma, which he called the target, would form the core of the fusion reactor. The combined plasma jets, which he called the liner, would surround and compress this target [1]. By collapsing the liner around the target, Dr. Thio hoped to squeeze it to fusion conditions. Figure 9.4 shows the first six of the seven basic steps, which we elaborate on below:

1. *Step 1: Initiation of a plasma target*—there are many options here. The target could be a plasmoid (structured plasma) like a field-reversed configuration (FRC) or a spheromak, or it could be poorly organized. If it is a plasmoid, it could have embedded magnetic fields or not. In any case, it must form first from

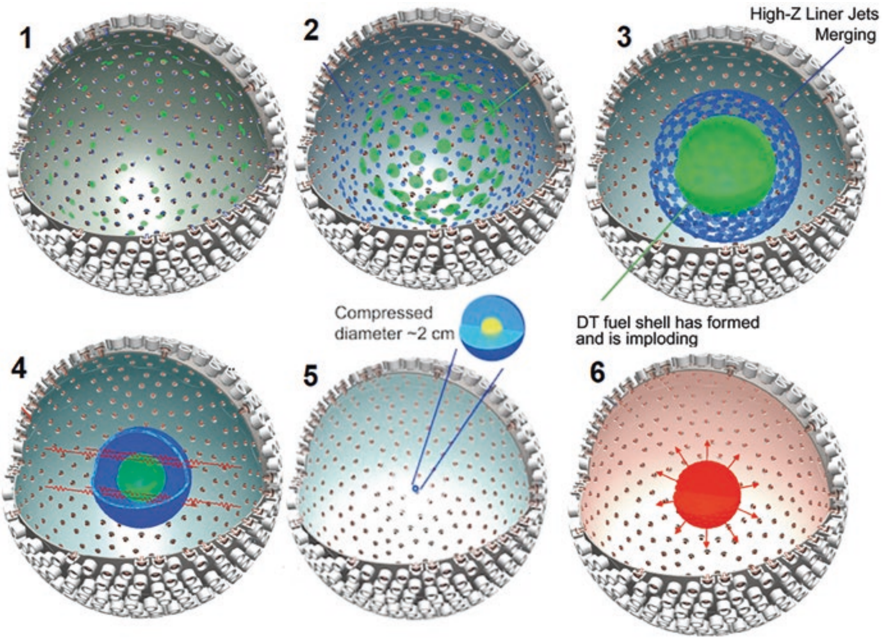

Fig. 9.4 The basic steps of a plasma jet fusion power plant. (1) The jets in the chamber's center trigger, beginning the creation of the target plasma. (2) The liner jets fire. (3) The target and the liner form. (4) The liner collapses, compressing the target into a hot small ball. (5) Fusion ignites. (6) The explosion blows material outward from the center, and a blanket of liquid metal in the walls absorbs the mass and energy from the explosion. This hot liquid metal is pumped away to make electrical power in a power plant. Not shown is step 7, clearing away the remaining plasma before the next shot. Image approval by Los Alamos (LA-UR-22-24212)

a set of jets inside the PJMIF fusion reactor. Its composition, temperature, organization, and other properties may be different from the liner plasma. This is a design optimization consideration. (See step 3.)

2. *Step 2: Initiation of the liner plasma*—the liner forms around the target from a second set of plasma jets. Ideally, these would fire while the target is still forming in the center. Precise timing is key. The coordination of these jets needs to happen with precision on the order of hundreds of nanoseconds.
3. *Step 3: Formation of the target and liner*—the target plasma starts to form in the center, while the liner forms in the outer region of the chamber. The details depend on the properties of the desired target. For example, a structured target such as a field-reversed configuration can be formed by merging two small FRCs from jets on the walls. A disorganized target can be made from the collision of generic plasma jets.
4. *Step 4: Collapse of the liner*—the liner plasma can be customized to best help with compression. Design parameters include its composition, speed, timing,

thickness, and magnetization. For example, it may make sense to use heavy ions like argon, or it may be better to make the liner cold and thicker to help with compression. Perhaps laser beams could be used to heat the plasma. Today, it is still an open question to determine the set of properties that make the best kind of liner.

5. *Step 5: Full compression and ignition of fusion*—ideally, the collapse will continue until the combined plasmas occupy a hot, tight space, smaller than a ping-pong ball. This is when most of the fusion reactions will occur.
6. *Step 6: Fusion explosion and energy extraction*—once fusion occurs, the plasma will expand in all directions. The explosion releases radiation and hot matter, including helium, neutrons, and unfused material. This will all need to be absorbed. Many fusion chambers are made from tough tungsten-carbide metal to handle the demands of energy capture. A wide gap between the chamber walls and the center makes for a safer system. To create a power plant, Dr. Thio suggested pumping liquid metal through the chamber walls to absorb the energy of the explosion. That fluid could be pumped away and its heat used to drive turbines that generate electricity.
7. *Step 7: Cleanup*—once the explosion has finished, the chamber is left with a hazy cloud of plasma. This cloud will likely have unfused hydrogen, electrons, and impurities (Fig. 9.5). The impurities could be trace amounts of air, carbon from the walls, or other ions. Pumps will need to be used to vacuum out the chamber before the next shot. Everything is reset when the chamber is totally cleared away.

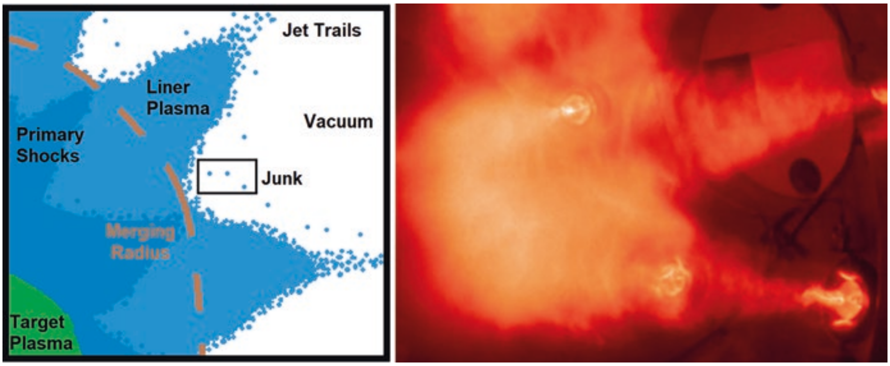

Fig. 9.5 (*Left*) A sketch of the merging liner around a central target. The target is the small green ball of plasma in the corner. A liner layer is formed around it from merging jets. Outside of this layer, there will likely be trails of plasma, junk, and a fog of plasma leftovers. Since no one has built this machine yet, it is unclear what implosions will look like. (*Right*) An experiment where plasma jets were fired. Image approval by Los Alamos (LA-UR-22-24212)

9.3 PJMIF Advantages and Challenges

PJMIF had four major advantages over the dominant candidates for fusion power, including ICF laser fusion and tokamak fusion. First, laser fusion has the inconvenient step of converting frozen fusion fuel into plasma. In any fusion approach (or any engineering process for that matter), every additional step opens the process to additional errors or problems. The fewer the steps are, the better. Jets have the advantage of a target plasma that is already premade. In addition, a ready-made plasma can give us another way to control the physics [12].

A second advantage is that the plasma jets are very efficient. The newest plasma cannons, such as those made by a company called Hyperjet Technologies, accelerate ions to 50–100 km per second, or about 100,000–200,000 miles per hour. These jets can do this while converting about 25% of the power into plasma energy [7, 15]. That efficiency is a hard-fought accomplishment, requiring years of work by the Hyperjet team. By contrast, the best efficiency of a laser used in fusion is about 7 percent [21]. Hence, this jet fusion approach will require a lot less input energy to create fusion power than ICF. Comparing two representative systems, PLX (plasma cannons) and Omega (ICF), shows a stark difference. The PLX machine uses 5–10 kJ per jet and per shot. One beam on Omega needs more than 60 times that amount of energy [2, 9, 15]. All of these improvements play into the overall efficiency of a PJMIF reactor.

The third advantage is that the premade plasma is relatively dense and controllable. The cannons can generate densities anywhere from 10^{14} to 10^{18} particles per cubic centimeter or higher [8]. This is considered a middle density for plasma fusion. The upper limit is 10,000 times denser than a tokamak but not as dense as ICF [10]. Being able to create middle densities was one of the ways PJMIF supporters got financial backing for this design (see Sect. 9.6). Moreover, the density is very controllable. The settings on the jet allow researchers to adjust the plasma conditions easily. As a general rule, higher densities are better. More density means more fusion events in a given volume. It also means a cheaper power plant overall.

The fourth and last advantage is that these jets make plasma with the magnetic fields "baked in." This happens because a jet is a moving charge—an electric current—which means it creates its own magnetic field. Unfortunately, the field in the cloud is not as controllable as fusioneers would ideally like it to be [11]. Indeed, these fields can take on random patterns as the jet moves. Still, having a field included makes it easier when two plasma jets merge [5]. Merging is important because this is the step that governs how successful this approach will be.

Since both laser fusion and PJMIF involve plasma compression, both will face the challenge of the Richtmyer-Meshkov (RM) instability, which is an extreme example of the more common Rayleigh-Taylor (RT) instability. Both instabilities occur between immiscible fluids (see Fig. 9.6). Consider a dense fluid layered on top of a lighter one, such as vinegar poured gently on top of oil to make a salad dressing. That is a metastable situation that begins to collapse when a minor disturbance occurs. Even a gentle jiggle will break the interface between the fluids, and the RT instability will cause oil globules to begin floating toward the top. Replace the gentle jiggle with an extreme disruption, such as the shock wave that occurs in a fusion implosion, and the RM instability governs the process.

This instability is a major problem for most compression approaches to fusion, which require the surface of the fuel to remain intact as it is forced inward. If the surface breaks apart, the compression ends. Researchers can minimize the instability by modifying either the target, the compressor, or both. Their ability to control the target and compressor gives them flexibility. Indeed, this control and flexibility—how well it can be adjusted to handle the instability—is one way to gauge a compression approach. Table 9.1 provides a quick look at different compression methods. Plasma jets and ICFs handle this problem very differently.

In laser fusion, trying to beat this problem has involved approaches like coating the target, shaping the beam, and creating two-step compression. But of all the compression approaches listed, ICF with lasers has the poorest control over instabilities. Supporters have argued that switching to compression with ion beams would fare better, but that remains to be seen. Liquid-metal compression may work better for ICF because it offers more control of the shape of the spinning liquid-metal surface. Of the three approaches, plasma cannons may be the winner in dealing with the Richtmyer-Meshkov instability. Plasma pushing on plasma means a smaller mismatch between pusher and target densities. The density mismatch creates instability, and not having a mismatch may give plasma cannons a distinct advantage.

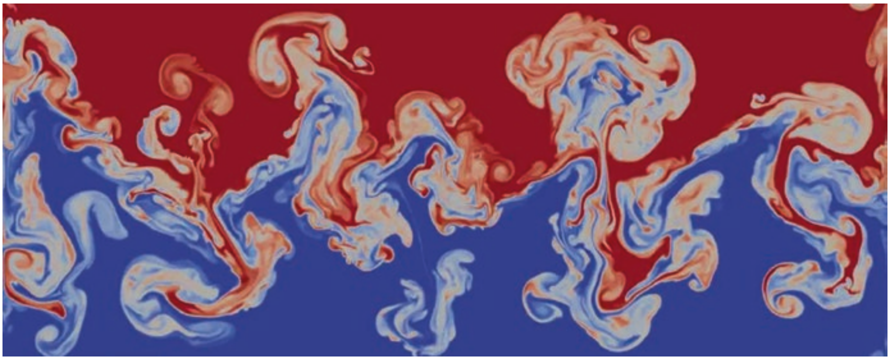

Fig. 9.6 The Richtmyer-Meshkov and Rayleigh-Taylor instabilities in action. A heavier fluid (red) is layered on top of a lighter fluid (blue). A disturbance disrupts the surface between them, allowing the blue fluid to push upward. Soon it becomes a turbulent mess. Rayleigh-Taylor instabilities happen in everyday life, such as shaking a salad dressing (where the mixing is desirable), while Richtmyer-Meshkov instabilities govern what happens in extreme situations, like when shock waves occur in fusion plasmas (where maintaining the interface is important). (Image courtesy of Rheologic GmbH)

Table 9.1 A quick comparison of four different methods used for fusion-compression

	Methods of compression	
Concept	Primary way	Secondary way
ICF – laser beams	Laser on solid	
ICF – ion beams	Ion on solid	
General fusion	Liquid on plasma	Magnetic fields
Plasma liner experiment	Ion on ion	Magnetic and electric fields

9.4 Target Design

As you may have noticed, the seven basic steps of this approach are broad rather than specific. In part, this is because PJMIF is a relatively new concept and not yet fully tested or optimized. For example, the target can have a variety of structures and compositions. The target could include a fusion fuel like tritium, while the liner could be made of a heavier ion like xenon or argon. Four different kinds of target plasma structures are shown in Fig. 9.7, ranging from poorly structured and disorganized to structured and magnetically well-ordered [11].

The simplest target is a plasma with no unifying magnetic or electric field. Any fields inside this target form accidentally as a result of the plasma‘s internal electric currents. A disorganized target would likely result from the jets firing a mostly neutral plasma. No net charge means the plasma is less likely to self-generate an electric current and a consequent magnetic field. Unstructured targets are the easiest to make but hardest to work with. With a disordered plasma, these kinds of targets are subject to several uncontrollable variables. For example, under certain conditions, plasma can diffuse across magnetic fields [14]. This effect, called perpendicular plasma diffusion (Fig. 9.8), is critical to avoid because it works against compression. But avoiding it requires better control of the plasma than may be possible when the target is disorganized.

Thus, a better option is to have the targets structured and magnetized—in other words, plasmoids [11], which are discussed in detail in Chap. 7. Plasmoid targets are easier to manipulate and control than unstructured plasmas, but they are more complicated to make. Spheromaks are probably *the* most structured plasma formations. They are the hardest to make but offer the most control.

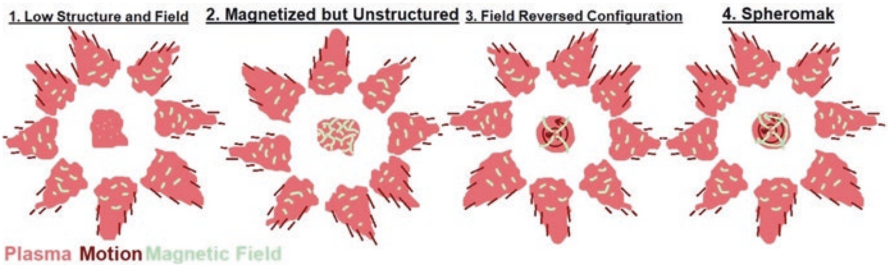

Fig. 9.7 The range of structure and organization of PJMIF targets

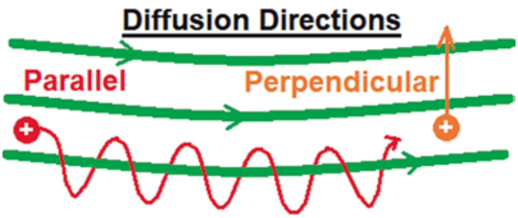

Fig. 9.8 Internal diffusion in a plasma target. Achieving ignition in fusion requires good compression of the target. The target's ions tend to diffuse along its internal magnetic field lines (green), improving the compression. But in disorganized targets, the lines are weaker and more jumbled. That allows for more perpendicular diffusion of the fuel and makes compression less effective

9.5 Liner Formation

After initiating target formation, the next step in PJMIF is the creation of the liner from several colliding plasma jets. These jets are clouds of charged particles moving at high speeds toward the target that is forming in the chamber center. These jets move like a wave with faster particles leading and a tail of cold material stretching out behind. When the clouds get close to the center, their sides start to touch, and the jets begin to merge at a distance from the center, known as the merging radius. They collide so forcefully that a primary shock wave forms between each pair [24]. The shock wave sends particles bouncing off in new directions. They meet again, forming a smaller secondary shock wave. Finally, they close in the surface of the target plasma to begin the implosion. Figure 9.9 illustrates this process in two dimensions.

In real systems, the formation of primary and secondary shock waves is much more complex. Researchers have put in considerable effort in modeling the formation of the liner because it is so critical to the operation of the machine [11, 20]. Liner formation has been modeled using at least six different kinds of plasma. As of this writing, at least six different kinds of plasma modeling software have been employed [11]. Laboratory tests have so far only looked at the liner formation; the targets have not yet been formed consistently. Results show that primary and secondary shocks are forming, just as predicted [23]. Figure 9.10 shows X-ray images of these tests with six jets. Figure 9.11 shows the design of a planned PJMIF experiment at Los Alamos National Laboratories.

9.5.1 Liner Flexibility

There is a lot of flexibility as to what liner can be used during compression. This allows for customization. Researchers can adjust the liner to address some specific problems. For example, the liner could be made of heavy ions, like xenon, because more massive ions can push on the target with more momentum, leading to better compression. Additionally, the liner thickness could be adjusted to improve

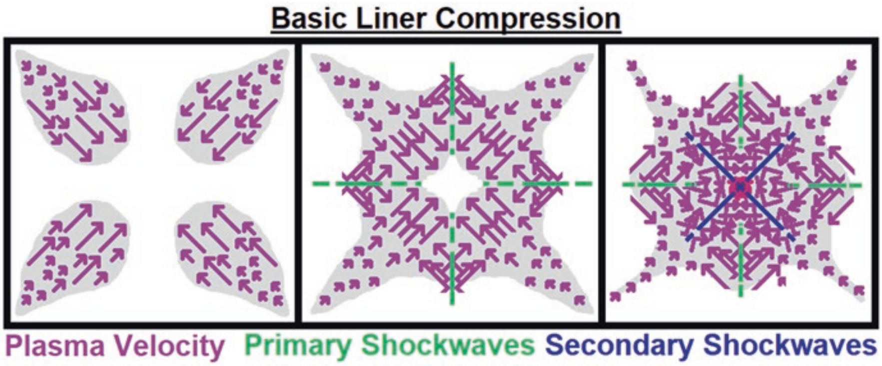

Fig. 9.9 The formation of the liner from colliding jets, shown in two dimensions. In the three-dimensional event, additional jets may be approaching from the third dimension as well. The distance at which the jets first contact each other is known as the merging radius [11]. At that point, the colliding jets form primary shock waves [13]. The reflected material flows in a new direction and collides again, forming secondary shock waves, which ultimately leads to the implosion of the target plasma

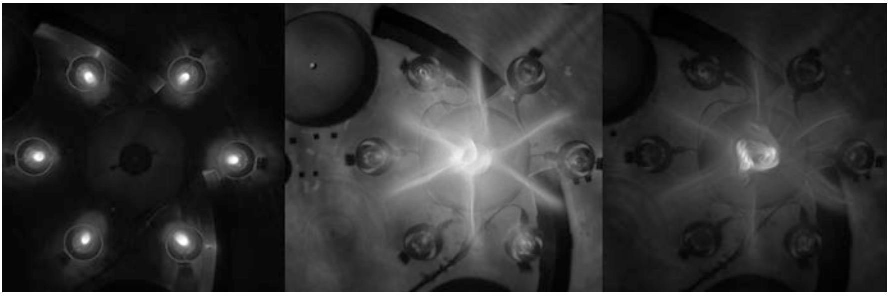

Fig. 9.10 X-ray images of tests of plasma liner formation using six plasma cannons. There was no target plasma. These images show shock waves forming as the jets meet in the center. Image approval by Los Alamos (LA-UR-22-24212)

performance. Ideally, compression would take place inside a smooth, spherical liner collapsing around a smooth spherical target. But in real systems, the surface often breaks apart. Bumps, fingers, and ripples can appear when the liner and target meet, limiting compression by the Rayleigh-Taylor and Richtmyer-Meshkov instabilities [27]. Two adjustable parameters to address these problems are plasma density and speed. Mismatched density between the liner and target is the main driver of these instabilities, so adjusting one or both of the densities will help mitigate them. Since the liner and target plasma can be changed independently of one another, the system has considerable flexibility in operation. That is an asset to plasma jet liner compression.

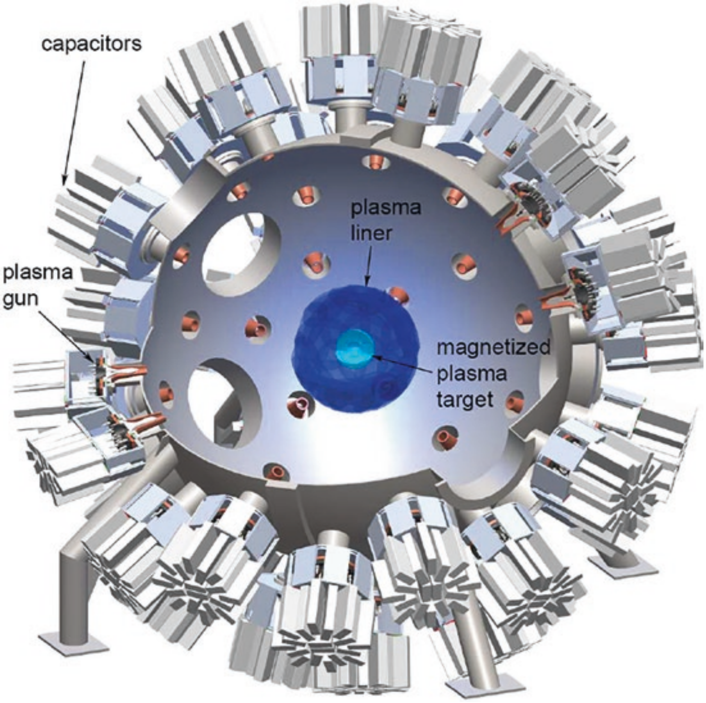

Fig. 9.11 A computer-aided design drawing of one version of the plasma liner experiment being operated at Los Alamos National Laboratories. Image approval by Los Alamos (LA-UR-22-24212)

9.6 Building Support for PJMIF

The first papers on the plasma liner approach were published during the second half of the 1980s [1]. At the outset, they did not get much attention. During this period, the United States was winnowing down the set of approaches it funded. The Reagan administration was famously about to shut down the big mirror machine at Livermore National Labs. Also, with the Cold War ending, the United States' biggest military and technological rival was gone. There was a lot less need to invest in this research. Fusion budgets were going down, and they continued to decrease well into the next decade [16]. Dr. Thio cycled through a number of jobs at companies and universities, but he never gave up on the idea of developing his fusion approach.

Things started to look up in 1999. By that time, Dr. Thio had landed a job at the National Aeronautics and Space Administration (NASA). His job was to look at ways to apply plasma cannons to spaceflight and fusion. The funding environment had also changed drastically. By the late 1990s, tokamaks and laser fusion had emerged as the US government's approaches of choice for fusion. Support for other fusion approaches was kept low. The situation created an opening for plasma liner

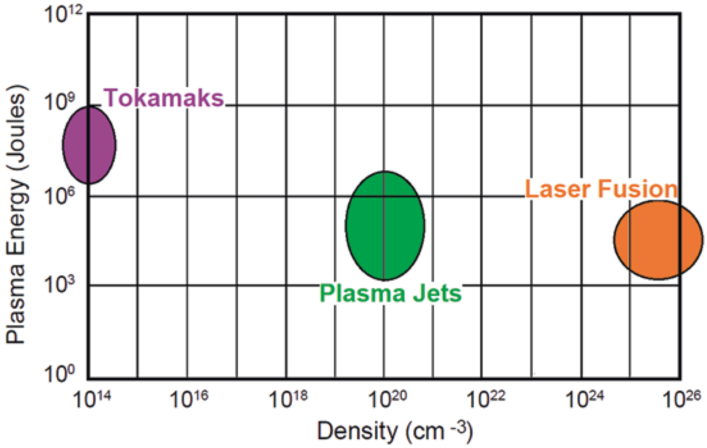

Fig. 9.12 Finding a middle ground. Using this density versus temperature plot of fusion approaches, supporters of plasma jets argued that it illustrates the need to explore the regime between tokamaks and laser and magnetized target fusion [22]. Plasma jets operate in the middle space between the other two approaches

research in the middle ground between tokamaks and lasers (Fig. 9.12). Cannon plasma would not be cold and dense like a laser fusion experiment (10^{26} ions/cm^3 and 10–15 million K). Nor would the plasma be hot and thin like a tokamak (100 million K and about 10^{14} ions/cm^3) [10]. At that time, very little work was being done to study plasma conditions in the middle. A plot of these conditions is shown in Fig. 9.12.

This middle-ground argument was a great sales pitch. It played well with officials at the Department of Energy. By 1999, the idea had gained interest from many fusion researchers, and workshops were held [18]. Several papers were written, and the idea was about to find a new home at Los Alamos. Los Alamos was trying to build interest in magnetized target fusion (MTF), also called magneto-inertial fusion (MIF) [17]. The names could be confusing. The field was just dawning, and there was no consensus on titles. Both terms refer to the compression of a plasma target inside a big sphere, but how the compression occurs could vary greatly. PJMIF uses a plasma liner to compress a target, but one could also use a solid or even a liquid for compression. General Fusion‘s approach, also included in this family of techniques, uses a liquid metal. In truth, Dr. Thio’s idea was just part of the bigger MIF/MTF family. The ideas are a subset of a bigger family.

One of the leads on this project at Los Alamos was a researcher named Scott Hsu, who was 20 years younger than Francis Thio and had already built a strong scientific reputation. Dr. Hsu had reached a point in his career where he was ready to take on a whole new fusion approach. He set his sights on developing PJMIF. Los Alamos ended up calling this machine the Plasma Liner Experiment (PLX, Fig. 9.13).

Fig. 9.13 A very early picture of the Plasma Liner Experiment (PLX) team from May 26, 2010. The effort was just getting started. The chamber itself has not yet been assembled. Dr. Hsu can be seen on the far left of the group [20]. (Image approval by Los Alamos (LA-UR-22-24212))

9.7 New Cannons

Today, the Plasma Liner Experiment has become the proving ground for PJMIF. Work has been ongoing since the experiment started at the end of 2011 [3]. Efforts could have started earlier, but it was difficult to raise the money. To get the effort moving, the PLX team had to build relationships with many other groups outside of the lab. These were collaborators and contractors, people who provided key tools to make the project go. Among those were the University of Alabama, the University of New Mexico, and TechX Corporation in Denver. But of all of these collaborations, the most important group was HyperJet Technologies, Inc., a company founded in Virginia by Doug Witherspoon in 2009. It was founded on the speculative idea that one could make money building the world's best plasma cannons. The applications for plasma jets included fusion and space thrusters. Neither generated high-volume business, and neither was very lucrative. So the company had a rough start. In 2012, the group behind HyperJet even attempted to raise money using Kickstarter. Their campaign included an impressive video explaining their jets, which are some of the best plasma cannons in the world (Fig. 9.14).

These cannons are impressive. In contrast to the unwieldy design of the Hall-effect thruster and railgun, these were designed using advanced magnetohydrodynamic and supersonic plasma software. They work by dumping a sheet of current across a gap filled with ions [19]. This creates a J × B force inside the plasma volume. The result: a sheet of current and plasma rockets forward out of the jets. A shock wave travels through the electrode cavity, pulling plasma along inside the current sheet at a speed well above Mach 1 (the speed of sound). One problem that

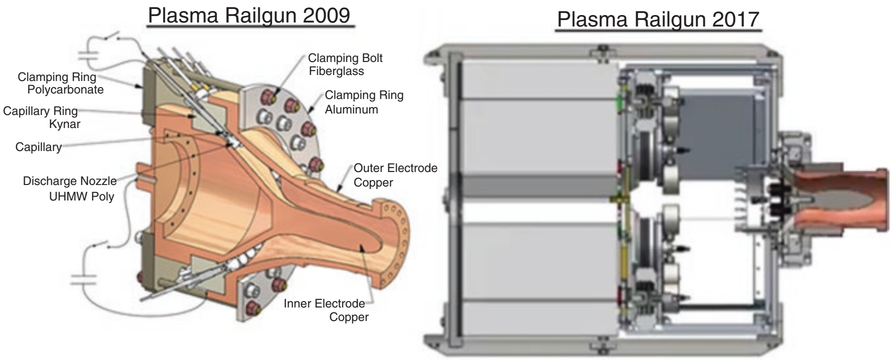

Fig. 9.14 Two plasma cannons designed by HyperJet Fusion Corporation from 2009 and 2017. Copyright: 2009 HyperV Technologies Corporation

HyperJet encountered was that the J × B force was not uniform. The voltage is weaker on the outside ring of the jet, leading to a weaker magnetic pressure there [28]. To address this, the team shaped the copper electrodes and changed the electrical loading [11]. The shape resembles a smooth flame or a bit of artwork. That design focuses the plasma before it exits and helps hold the material inside the moving current sheet. The design also exploits the high plasma speed and its self-generated fields to efficiently push the material.

Since the plasma is charged, its motion can make its own magnetic and electric fields. This can either conflict with or assist the applied fields. This creates dynamic behavior: feedback between the plasma and the applied field. The company found a way to both anticipate and exploit this behavior. One method involves adjusting the capacitor network. This is a web of electrical loads that dump current into the cavity. Tuning these capacitors can give the jet the desired behavior. Finally, the devices have advanced injection methods [19]. The injectors preionize the plasma to initiate it at a much denser, fluid-like state. All of these improvements make the company's jets state of the art, and their strengths will help advance plasma liner fusion.

9.8 Plasma Liner Experiment

Since work started in 2011, Los Alamos has been using the Plasma Liner Experiment as the testbed for PJMIF (Fig. 9.15) [6]. The machine is a large spherical chamber outfitted with a variety of plasma jets. Two jets have been shot at one another, not head-on but rather at an off-angle [23–25]. Generally, these test results agreed with the predictions. In 2015, the team won a $2.8 million grant to study six plasma cannons in different arrangements [26]. Unfortunately, none of these tests have come close to reaching fusion temperatures. The head-on-head collision tests were under 2 eV, while the six beams were under 7 eV [2, 3]. A typical fusor starts seeing fusion at 10,000 eV or higher. However, the Los Alamos team has developed several schemes for how to achieve fusion conditions. These plans change slightly,

Fig. 9.15 The Plasma Liner Experiment under construction at Los Alamos National Laboratory on January 31, 2017 [2]. Note the plasma cannons, which are the attached knobby and bulky hexagonal white blocks. (Image approval by Los Alamos (LA-UR-22-24212))

Table 9.2 Some target parameters for the liner jets. These may change depending on other test conditions [29]

Speed	Mach >10	Timing	200 nanoseconds
Density	1E18 ion/cc	Jet size	<5 cm
Speed	50 km/s		

depending on how many jets they can use. Thirty, 36, and 60 jets have all been discussed. For example, 60 jets of plasma moving at 50 km/s could collide in the center of a 2-foot sphere and achieve a density of 10^{18} particles/cm^3 [2]. This should be enough to make plasma undergo fusion. The PLX is currently working with 36 full plasma cannons in operation [15]. The team has also laid out some target parameters for their jets (Table 9.2).

9.9 The Current State of PJMIF

Supporters argue that PJMIF is the cheapest path to fusion because it sits in the middle between the extreme conditions of laser fusion and a tokamak, and both extremes are too expensive [28]. The reasoning goes as follows: the tokamak has a low-density plasma. This means it needs a large, hot volume to reach fusion power conditions, and both size and temperature drive the price up. At the other extreme, ICF starts with plasma that is at a much lower temperature, so it needs a high density to get to fusion conditions. Achieving that plasma density requires very expensive laser systems. PJMIF‘s middle ground, in theory, achieves fusion while avoiding the high cost of either extreme. It could be the best of both worlds, but no one yet knows if that claim is valid.

Their argument is rooted in one model of plasma behavior developed by Dr. Irvin Lindemuth in 2009 [30]. A detailed description of Lindemuth’s model is beyond the scope of this book, but, in brief, it begins with a set of equations that approximate plasma behavior. These expressions, which relate to parameters like density, energy, and size, can be used as a guide to design the plasma inside a fusion power plant. They allow fusioneers to determine the optimal plasma density and temperature that leads to minimum size, input power, internal energy, and cost. Cost is the hardest of these parameters to estimate, which limits the overall usefulness of Lindemuth’s model. Still, the model‘s assumptions about the physics make it useful as a very *basic* conception of plasma. For more details about this model, we recommend checking reference [30].

Cost is one of the most important variables in any fusion power plant approach, and estimating this was one of the goals of Lindemuth‘s model. Ironically, the cost is usually the hardest thing to find in any fusion experiment. Cost is almost never included in any scientific paper, and sometimes teams purposely try to hide the price from outsiders. For example, the public does not know the real cost of the International Thermonuclear Experimental Reactor (ITER) project; countries, as part of the ITER founding treaty, are under no legal obligation to disclose it [30, 31, 32]. Fortunately, the United States has disclosed the real cost of the National Ignition Facility (NIF): about $3.5 billion. Lindemuth used the costs of these two efforts as data points for his model; there are many flaws with this assumption, but this was the best he could do. He argued that a PJMIF power plant would be about 60 times cheaper than NIF and 200 times cheaper than ITER. If that prediction holds, it is a strong argument in favor of this approach.

Nobody has yet tested a PJMIF-scale power plant, so it is impossible to know how such a machine would perform. But models can give us an idea. Whenever a shot occurs, both good and bad things happen simultaneously [11]. Perfecting this machine means balancing these competing effects. Good effects include rising density, temperature, and magnetic field strength. Imploding the target plasma drives up the energy in particle collisions, helping the fusion rate. The bad effects include light emissions, shock waves, and mass leakage, all of which cost energy and degrade reactor performance.

Sometimes, the positives and negatives are inseparable. For example, a hotter plasma (good) will also decrease the magnetic field (bad) because plasma has its own magnetic properties. The challenge for the PLX team is going to be balancing these effects and settling on the optimum approach. No team has done a full-scale test of this approach, and therefore nobody can be sure of its performance until someone builds a system and tests it.

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Inertial Electrostatic Confinement

10

Summary

Inertial electrostatic confinement (IEC) uses electric fields to heat plasma to fusion conditions. In many ways, this is not a fully-fledged reactor approach but rather a heating method. However, it is simple enough that normal people can and do achieve fusion in their homes with IEC. Moreover, IEC devices can create fusion continuously for weeks on end. That is very exciting. Most fledgling technologies benefit not only from the work of professors in their ivory towers but also from hobbyists and innovators working out of their garages, and IEC fusion is no exception. This chapter will discuss real-world applications of this branch of fusion, some that found commercial markets as early as 2000 and others that show promise as sources of neutrons and helium.

10.1 Beyond Power Plants

Although the main focus of this book has been the development of fusion for electric power plants, we want to close with a look at an approach to fusion that has already found commercial application—inertial electrostatic confinement (IEC) (Fig. 10.1). In addition, the technique can also serve as a way to introduce future fusioneers, hobbyists, and garage-based entrepreneurs to the field.

The story of IEC begins with a name that most readers may recognize for another reason, Philo T. Farnsworth. Farnsworth was born on August 19, 1906, and spent his youth living in a log cabin in Rigby, Idaho. At night, he used an electric generator to provide for his bedside reading lamp and would pore over science fiction. Philo excelled at science at his local high school. He studied the physics of electrons and dreamed of a way to pass images through the air. When he was 14, he had a revelation while plowing a farm field. Plowing meant carving straight lines in the dirt. Philo realized that if he could get an electron to do the same thing, he could display

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
https://doi.org/10.1007/978-3-031-22906-0_10

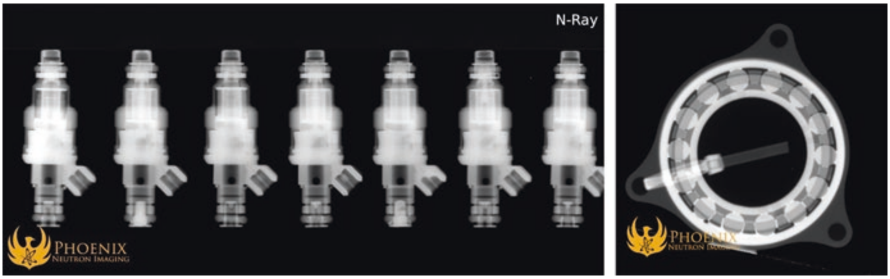

Fig. 10.1 Neutron radiography. Phoenix Imaging Center imaged these items using a beam of neutrons produced in large numbers by an inertial electrostatic confinement (IEC) fusion device

images on a screen. He rushed to his high school chemistry teacher to lay out his idea. The idea they sketched out on the chalkboard became the first patent on electronic television. Farnsworth would spend the next 30 years of his life developing, patenting, defending, and ultimately commercializing this idea. He is credited with the first electric television transmission, which occurred on September 7, 1927, in his laboratory in San Francisco. A few years later, he founded the Farnsworth Television and Radio Corporation in Fort Wayne, Indiana, to mass-produce these televisions. It was in Fort Wayne toward the end of his life that he turned his attention to nuclear fusion.

10.2 Farnsworth and Fusors

Farnsworth started testing fusion devices when he was in his fifties. By that time, he had sold his company to ITT to focus on his research. In 1964, he hired a 29-year-old laboratory assistant named Robert Hirsch. Dr. Hirsch would later go on to become a prominent leader in the development of the US fusion program [1]. The team developed and, in 1968, patented a device called the Hirsch-Meeks fusor, named after Hirsch and coinventor Gene A Meeks. At the beginning of fusor development, the Farnsworth team believed that this could be a shortcut to a power reactor. The fusor was small, cheap, and easy to use. Hirsch and Farnsworth even built a fusor on a cart and wheeled it in front of government officials (Fig. 10.2).

In their demonstration, they showed nuclear fusion occurring in a device the size of a refrigerator. However, despite his best efforts, Farnsworth could not get the fusor to come close to net power. Today, we know that fusors will always lose energy. Typically, they leak about 10,000 times more energy than they can make from fusion. At the time Farnsworth passed away on March 11, 1971, at the age of 65, few people understood his contributions to science and the United States. His wife, Elma Farnsworth (Fig. 10.3), who had also been his laboratory assistant, spent the remainder of her life ensuring that his story will be told. Today, Philo Farnsworth is the subject of over two dozen books, his statue sits in the US Capitol, his face adorns a postage stamp, and a museum dedicated to his life is open in his hometown

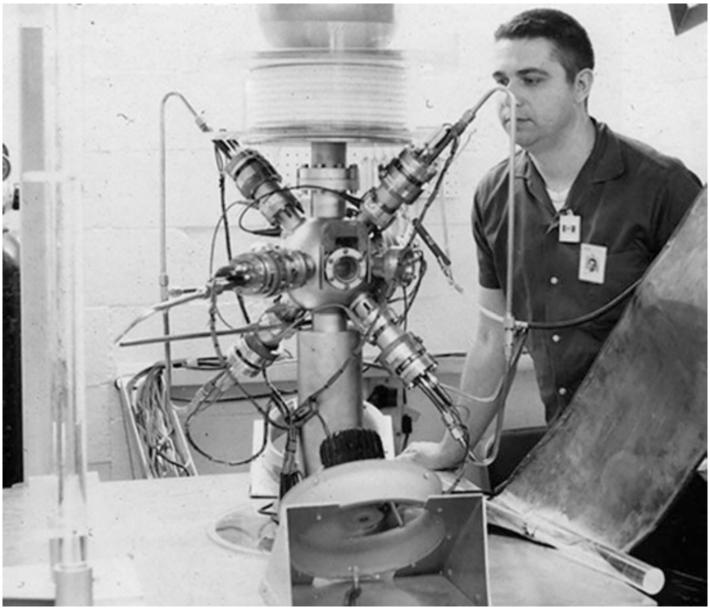

Fig. 10.2 The Hirsch-Meeks fusor under development in 1963. This device used miniature ion guns to inject ions into a vacuum chamber. The inside of this chamber had a negative wire cage. These wire cages had high voltage between the inner and outer cages, which heated the ions enough to produce fusion reactions

Fig. 10.3 Philo T Farnsworth and his wife (and laboratory assistant), Elma "Pem" Farnsworth

of Rigby, Idaho. Farnsworth's likeness was also used for a primary character in the animated television program *Futurama*.

Fusors were also proposed independently in Russia by Oleg Lavrentiev in July 1950 [9]. Lavrentiev was the son of a poor factory clerk in Pskov, Russia. With only seventh-grade education, he envisioned the hydrogen bomb, controlled nuclear fusion, and a method to use electric fields to start fusion reactions. With no resources to realize his idea, he wrote to the central government of Russia. His letter, sent as a secret mail, was submitted on July 29, 1950. Famous physicist Andrei Sakharov received this letter, saw the genius in this idea, and brought Lavrentiev to Moscow. Sakharov realized that a magnetic field would be better suited for controlling particles. Lavrentiev's ideas eventually led Sakharov to envision the tokamak.

10.3 From Fusors to IEC

The fusor is the simplest example of the broader field of inertial electrostatic confinement (IEC) fusion. IEC uses a high-voltage electric field to heat ions to fusion conditions. The voltage accelerates positive deuterium ions to high enough energy to cause fusion when they collide (Fig. 10.4). This heating mechanism is so simple that it has found its way into many fusion reactor designs.

Anyone who builds a fusor will never forget the feeling of powering one up for the first time (Fig. 10.5). As the voltage of a fusor increases, the device starts to give off a glow. When it reaches 10 kilovolts, the first fusion events will occur. These can be detected with a Geiger counter, and the rate of clicking increases as the voltage gets higher. When the voltage reaches 35 kilovolts, a good fusor can be producing a million fusion reactions per second. Unfortunately, the fusor design itself makes reaching net power impossible. As the voltage goes higher, more and more ions will pelt the inner cage, causing it to overheat and start to glow. Typically, fusors cannot get much higher than 120 kilovolts. At that point, the inner cage will often begin to melt. At no point in this voltage ramp-up does the energy made by the fusion events exceed the energy lost through inner cage heating.

For over three decades, the fusor was considered little more than a historical oddity. After Farnsworth died, fusor research and development experienced a long dry spell. Fusion research, as a field, was more focused on mirrors, pinches, field-reversed configurations (FRCs), and tokamaks. A few individuals did still dream of using the fusor, but it took until the mid-1990s for fusors to be formally studied at universities. The first work in the field was at the Fusion Technology Institute at the University of Wisconsin-Madison. Two staff members, Gerald Kulcinski and John

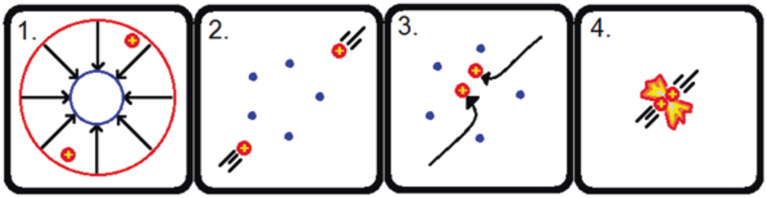

Fig. 10.4 The basic fusor design. (1) The device uses two wire cages inside a vacuum. (2) Positive deuterium ions are injected on the side. (3) They enter the outer cage and start to feel the voltage drop, which accelerates them toward the inner cage. (4) If they miss the structure of the inner cage, they pass through and can collide at high speed in the center and fuse

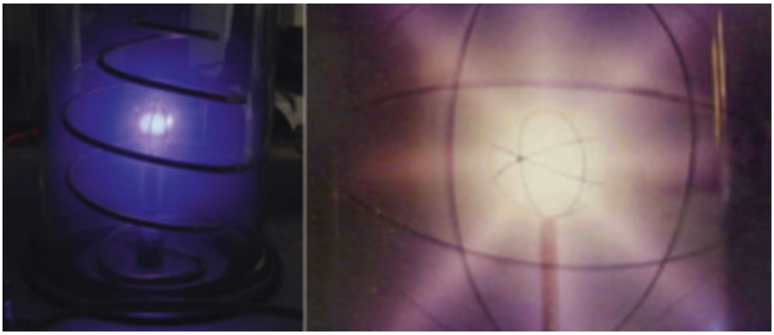

Fig. 10.5 Two examples of fusors built by amateurs in home-based laboratories. (Image source: Wikipedia)

Fig. 10.6 The three modes of fusor operation as determined by Dr. Tim Thorsen at the University of Wisconsin-Madison. (Image source: Wikipedia)

Santarius, founded and funded the construction of a large fusor called HOMER. They also formed a healthy academic group around running and testing the machine. Through this group, the world got some of the best understanding of how fusors work. For example, in his 1996 doctoral thesis research, Timothy Thorsten found that the fusor has three modes of operation: halo, star, and converged core (Fig. 10.6) [3]. These modes can be toggled by changing the chamber pressure. In another case, Thorsten also found that a fusor can form a microchannel, where plasma bunches together inside the inner cage.

Another pioneering academic center for fusor research was at the University of Illinois, led by professors Joseph Verdeyen and George Miley. The group published a series of papers on IEC beginning in the late 1960s [2]. Thomas J. Dolan built the group's first experimental IEC device in 1968–1970, with support from Robert Hirsch and the ITT Farnsworth Lab, followed by Donald Meeker and David Swanson in the 1970s. The team was the first one to identify the star mode inside the fusor.

This set of research grabbed the attention of a German engineer named John Sved, who was working for Daimler Aerospace. He recognized that the Illinois machine offered the possibility of a cheap neutron source. Although fusors cannot make net power, the fusor can sustain fusion events continuously, creating neutrons for thousands of hours. Sved convinced his managers to fund work to commercialize this technology. Over several years, he redesigned the fusor as a long tube that produced a steady spray of neutrons out of one end. When Daimler decided to cancel the project in 2000, Sved decided to start his own company to sell these generators. Called NSD-Fusion, the company offered the first commercial fusion-based product in 2003. Sved, his wife (Patricia), and Talmon Firestone worked behind the scenes to grow the company. The company was sustainable for a decade. NSD products were used in the aerospace, medical, and nuclear industries, though most of its customers had no idea about those products' historical significance.

10.4 Attempts to Improve Fusors

The fusor fails as a power source because of the wire cage in the middle. Over the years, physicists have tried to replace the cage with a negative cloud or plasma, but none of those attempts worked, most notably a cusp trap system called the polywell, proposed by physicist Robert Bussard in the 1980s. That failed because of the difficulty in maintaining a negative plasma. Its electrons quickly join positive ions and, for all practical purposes, vanish. In the 1990s, a Los Alamos physicist named Daniel Barnes proposed a different approach to holding a negative plasma using a Penning trap [4, 6]. Penning traps were first developed by Hans Dehmelt in 1959 to confine a single electron and measure some of its properties, a feat that earned Dehmelt a share of the 1989 Nobel Prize in Physics (see Fig. 10.7).

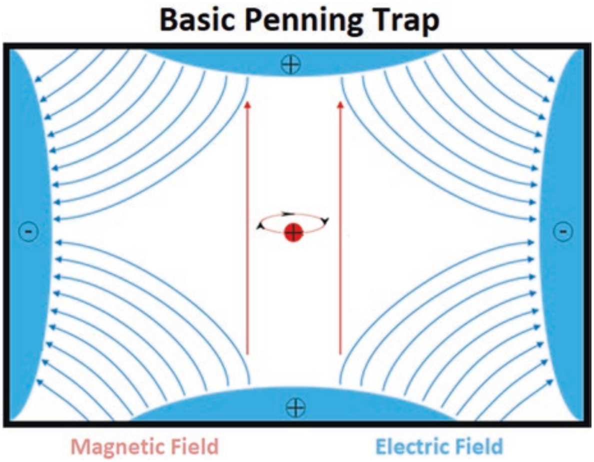

Fig. 10.7 A basic Penning trap. It uses a strong axial magnetic field and a quadrupole electric field (two anodes and two cathodes configured, as shown here). That configuration will cause a charged particle to follow a corkscrew path back and forth along the magnetic field lines [4, 7]. Originally designed to hold single charged particles, it can also confine a plasma.

Barnes realized that these traps can also be used to hold any kind of plasma, so he proposed using them as a way to improve fusors. However, like the polywell, this idea failed in practice and for the same reason. Any significant amount of negative charge just vanished before reaching a high enough voltage.

Researchers have also toyed with ways to get the plasma to avoid the inner cage. In 1999, a team at Los Alamos proposed and built a machine called POPS [5]. This machine tried to move the ions away from the inner cage by applying high-intensity radio waves. Any electromagnetic wave, including those at radio frequency, consists of electric and magnetic fields traveling together at the speed of light. Those fields can be powerful enough to cause the particles in plasma to oscillate. By getting the plasma to cycle back and forth, the POPS team also hoped to get it to avoid the fusor's inner cage. Ultimately, they succeeded in doing this, but it was not enough for power plant applications. Their models predicted that the plasma would need to avoid the cage in 99.999% of the passes to reach net power. That was just too high to meet, and the POPS machine was abandoned in 2007. This machine also had a unique feature because it flirted with the idea of building the fusor out of carbon nanotubes.

About 10 years later, a University of Sydney team proposed a different way to get the plasma to avoid the inner cage [8]. They modeled an idea where the inner cage was surrounded by magnetic fields. Unfortunately, the model said they needed to create magnetic fields higher than anyone could practically make, 16 teslas, which required an electromagnet with 700,000 ampere-turns. To date, this idea has not been tested.

10.5 IEC Products

Even though fusors are not likely to succeed as electric power plants, they still have practical uses. In fact, IEC is the branch of fusion that has best found application in commerce and everyday life. Because the fusor worked so well from the beginning as a neutron source, people began thinking of ways to commercialize it early into its development. And it is fair to say that the full commercial potential of fusors is far from being fully realized. Neutron radiography has applications in material testing, prospecting, and oil exploration.

Two people who have sought ways to commercialize fusion technology were Dr. Gregory Piefer and Dr. Ross Radel, who worked on the fusor. They earned their doctorates while working on the HOMER machine at the University of Wisconsin-Madison (described above) in the early 2000s. As he was finishing his doctoral thesis in 2005, Piefer founded a small business formerly known as Phoenix to build a power supply that could fit inside the HOMER laboratory. The company competed for and won small business innovative research (SBIR) awards to earn revenue and continue to grow. Slowly, the company began increasing the neutron output from its fusion systems, eventually developing an entirely new kind of neutron generator. One of the company's most successful first systems is called Thunderbird, which was able to make 100 billion neutrons per second continuously for 132 h. It costs around a million dollars, is the size of a golf cart, and is one of the best commercialized IEC fusion products in existence.

By the time Thunderbird was in operation, Piefer used his experience and capabilities gained from his creation of Phoenix and founded its sister company, SHINE Medical Technologies (Fig. 10.8). In 2021, Phoenix merged with SHINE, which is now formally known as SHINE Technologies. The goal of SHINE is to use neutrons, like those produced by a system such as Thunderbird, to make medical isotopes. The neutron generator designed by SHINE and Phoenix bombards an enriched target with neutrons. This bombardment creates rare radioactive elements with distinctive properties, which are then separated and processed. The worldwide annual market for those isotopes exceeds $1 billion, and SHINE would be able to take a significant share of it once its medical isotope production facility is operating at capacity. SHINE already has signed take-or-pay contracts with GE Healthcare, Lantheus Medical Imaging, and Health Technology Assessment (HTA), China's largest medical isotope distributor. In 2019, as SHINE was beginning construction of its production facility in Janesville, Wisconsin, former US Speaker of the House of Representatives Paul Ryan joined SHINE's board of directors. SHINE has since completed the external shell of its medical isotope production facility in Janesville (Fig. 10.9) and has grown to nearly 400 employees since its merger with Phoenix. Both Phoenix and SHINE are clear examples of how to commercialize fusion.

Looking beyond neutrons to future possibilities, fusors have the potential to generate helium or other light elements. Because it is so light, helium does not remain in Earth's atmosphere very long, quickly escaping into space. The planet's helium is constantly created in underground deposits of radioactive elements, where emitted alpha particles quickly find electrons to become trapped atoms of that important gas. Most commercial helium comes from liquefied natural gas plants as a gaseous leftover from the liquefaction process.

Fig. 10.8 Decked out in matching sunglasses, staff members of SHINE Technologies stand at the site of their isotope plant in Janesville, Wisconsin, prior to the start of its construction in 2018. SHINE's technology is a great example of using nuclear fusion in a practical commercial application in the real world. It is also a great example of the fruits of federal science funding and the US Small Business Innovation Research (SBIR) program. In this case, small seed investments in fusion research eventually resulted in two companies worth over 100 million dollars in combined value

Fig. 10.9 Current progress of the SHINE medical isotope production facility in Janesville, Wisconsin, taken in March 2022

Helium has numerous uses beyond being a gas to fill party balloons. It is critical for many industrial processes, in medicine, and, when liquefied, as a cryogenic coolant for superconducting magnets. The decade of the 2010s was marked by an international helium shortage, and a resurgence of demand may create another one [10]. Such surges can drive the cost of helium upward to the point that fusors can produce it at a price that is competitive with current extraction processes.

10.6 Fusion for Amateurs

Fusors' biggest contribution to society will be not only in science and technology but also in the number of people it inspired. Fusors are so simple that they can be built by any savvy engineer, hobbyist, entrepreneur—even a teenager. In fact, over 200 amateurs have achieved fusion in North America with little to no institutional support. Together, they comprise something unprecedented in human history—everyday human access to nature's most powerful energy source.

The first example of an amateur achieving fusion was FUSOR I, built by Richard Hull in Lakeside, Virginia, in 1999. Hull and his wife, Kit Hull, have lived and worked in Lakeside since the early 1970s. Richard, who has had a lifelong interest in science, engineering, and physics, began accumulating equipment in the early 1970s. He built a workshop in the back of his house to hold all his oddities. Kit told him that she was all right with the project "…as long as he does not blow up the house" [11]. Richard's machine, FUSOR I, was the first amateur device to achieve nuclear fusion in the United States in 1999. Hull proved to himself that fusion had occurred in his little workshop with these three detection techniques:

- *Bubble detector*: bubble detectors, which can be purchased inexpensively online, are glass vials filled with a clear gel. They are simple tools for detecting particles that create a string of small bubbles when passing through the gel. The particles that Hull detected were not necessarily neutrons, but he had good reason to assume that they were. The biggest problem with a bubble detector is that it can lose performance in a matter of months.
- *Neutron detector*: this device is designed specifically for spotting neutrons and measuring their energy. A quality handheld sensor costs about a thousand dollars. Neutrons from a deuterium fusion reaction have a narrow energy spread around 2.45 MeV, which was what Hull found.
- *Activated silver*: the most foolproof way to determine if fusion has occurred is by neutron activation in a block or thick foil of silver. Stable silver nuclei with atomic masses of 107 and 109 can absorb neutrons to form radioactive silver isotopes 108 and 110, with beta-decay half-lives of 2.37 minutes and 24.6 seconds, respectively. Thus, a brief observation of the changing radioactive decay rate can confirm the presence of these isotopes and confirm that neutron activation has occurred.

Hull had gained a great deal of knowledge in building his fusor, and he wanted to share that with a wider community. Along with Paul Schatzkin, he decided in 1999 to found a website dedicated to fusors. In more than two decades since fusor.net was founded, it has become a large thriving community for amateur fusioneers. Since then, over 200 amateurs in North America have achieved nuclear fusion in their garages, basements, and schools. Some of these have been as young as 12 years old. In the early years, this project was considered an automatic win for a science fair (Fig. 10.10) and college scholarships have been handed out for building fusors. Some recipients even became famous in their own communities, including Taylor Wilson, Douglas Coulter, Carl Willis, Mark Suppes, Thiago Olson, and Michael Li. The project should never be done without adult supervision; fusor construction involves vacuum equipment and high voltages, which can be dangerous.

Fig. 10.10 (Left) Richard Hull with his fusor. (Right) Taylor Wilson explains his fusor project to President Barack Obama at the White House science fair

Amateur fusion runs the gamut from high school students up to well-financed engineers. As the quality of their device improves, so does the rate of neutrons. Teenagers can expect a simple fusor to give off anywhere from 10,000 to one million neutrons per second. Well-financed experts have reached one billion neutrons per second in a fusor, with some claiming higher rates (Fig. 10.11).

However, fusors struggle to go much higher because they cannot recirculate their plasma. The negative inner cage attracts too many ions. Ions only pass a few times through the cage before being lost. This is a design flaw in the fusor: the voltage source and the ion source work against one another. The purpose of the voltage source is to hold the cage negative so positive material flows into it. The mass source struggles to keep the fusor fed while ions bleed away.

10.6.1 A High School Fusion Club

In 2010, Carl Greninger, a manager at Microsoft in Seattle, recognized that fusors could had the potential to inspire teens to pursue science or engineering in general or nuclear energy in particular. As he put it:

> An epiphany that occurred when I walked into a classroom and saw an instructor with a piece of string and a paper cup and a bunch of students all holding the same. The instructor turned to me and said that they were teaching physics. I looked at the kids and they had the word LAME tattooed across their forehead. They were humiliated. They were not impressed. I suddenly put it together: while we may be teaching the curriculum; if we're not inspiring, if we're not creating passion, we're wasting our time [12].

Carl and his wife, Lin Greninger, decided to build a fusion reactor in their home. They converted the first floor of their house into a classroom and laboratory space. They reached out to high schools and the parent-teachers association. Teenagers and their parents got involved. Together, they founded the Northwest Nuclear Consortium (NWNC), an organization set up to inspire the youth to pursue science. Every Friday

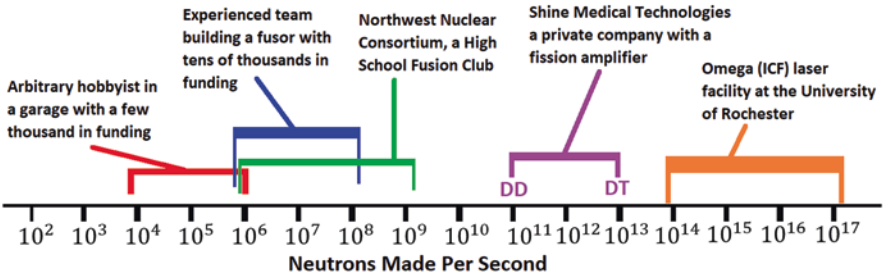

Fig. 10.11 Fusion approaches ranked by their respective neutron rates; this figure includes hobbyists, commercial efforts, and large laboratories. In amateur fusion, getting more neutrons is a bragging right. Fusors typically fall between 10,000 and one billion neutrons per second, but some well-funded amateurs have claimed higher

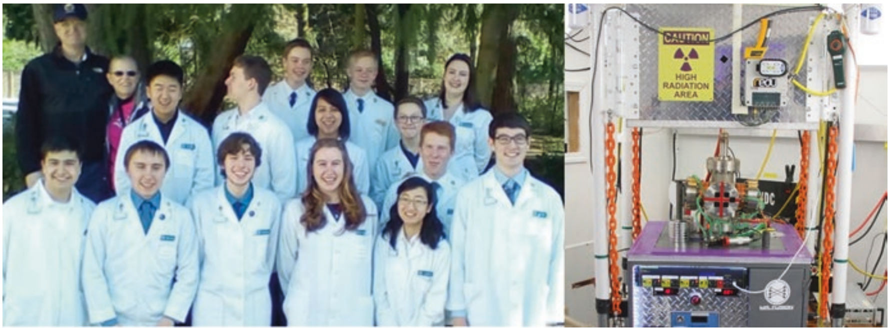

Fig. 10.12 Left, Carl and Lin Greninger posing with students from the Northwest Nuclear Consortium. Right, the NWNC fusor and neutron shield

night, about 25 teenagers and parents come to Carl's home to work on nuclear fusion. The students start by learning nuclear safety (Fig. 10.12).

The teens take the Occupational Safety and Health Administration (OSHA) and Department of Energy (DOE) certified tests needed to work in any nuclear power plant. Every student is outfitted with a dosimeter, which is recorded regularly. To date, no student has received more radiation than what one gets on a cross-country flight. Still, concerned neighbors did reach out to government officials. Carl got a visit from Washington state's Office of Radiation Protection. Inspectors were so impressed that they came back to give a lecture on becoming health physicists. Since 2010, students from NWNC have excelled at local, state, national, and international science fairs. NWNC projects have placed second, third, and fourth at the Intel International Science and Engineering Fair. Collectively, the teens have won over $800 K in college scholarships.

10.7 Conclusion

What does the future hold for inertial electrostatic confinement fusion? Regardless of whether it has commercial success, it will continue to offer an on-ramp to the fusion world for amateurs around the world. Many of the people who built fusors in their garages as teenagers have gone on to become prominent members of the professional fusion community. Moreover, with superconductors becoming cheaper and stronger, it is also becoming possible for amateurs to do home-based *magnetic* confinement fusion. Fusors and IEC in general could also be commercialized in other ways. Applications include oil exploration, rare gas generation, and material testing. No company has come along yet to capture and commercialize these, so entrepreneurial fusioneers should be aware that opportunities are still out there to develop IEC fusion for commercial uses.

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The Path Forward

11

Summary

Climate change is one the greatest threats to civilization that humans have ever faced. Figure 11.1 shows an example of the kinds of disasters that it has created. Achieving economically viable fusion electric power could constitute a major step toward replacing fossil fuels and thus avoiding the worst effects of climate change. To date, a small, poorly funded, driven, and underappreciated community of researchers have made immense progress in developing this technology. Because of their efforts, we now have tools at hand to reach a net power fusion facility in the next decade. But that is only the first step toward building industrial and commercial scale fusion power plants. What is needed now is a government development program to get us over the finish line. Any plan would also need to target core fusion support technologies, like the mass manufacturing of high-temperature superconducting wires, improved vacuum systems, and ultrahigh-field magnets. Growing a manufacturing base like that would be transformative. This chapter describes how that transformation could be achieved and argues for its benefits. Beyond the practical to the inspirational, fusion propulsion systems can also enable high-speed interplanetary travel. This technology may well provide humanity's next giant leap toward becoming a multiplanet species.

11.1 Where We Stand with Energy

Now that we have laid out the various approaches to fusion, we return to the issues noted in the Introduction. Advances in fusion technology, especially over the past decade, belie the old saw that we cited there: "Nuclear fusion is the energy source of the future, and it always will be." Progress in both magnetic confinement fusion and inertial confinement fusion have brought breakeven—the production of as much energy from fusion as needed to operate the devices—to the near horizon.

M. Moynihan, A. B. Bortz, *Fusion's Promise*,
https://doi.org/10.1007/978-3-031-22906-0_11

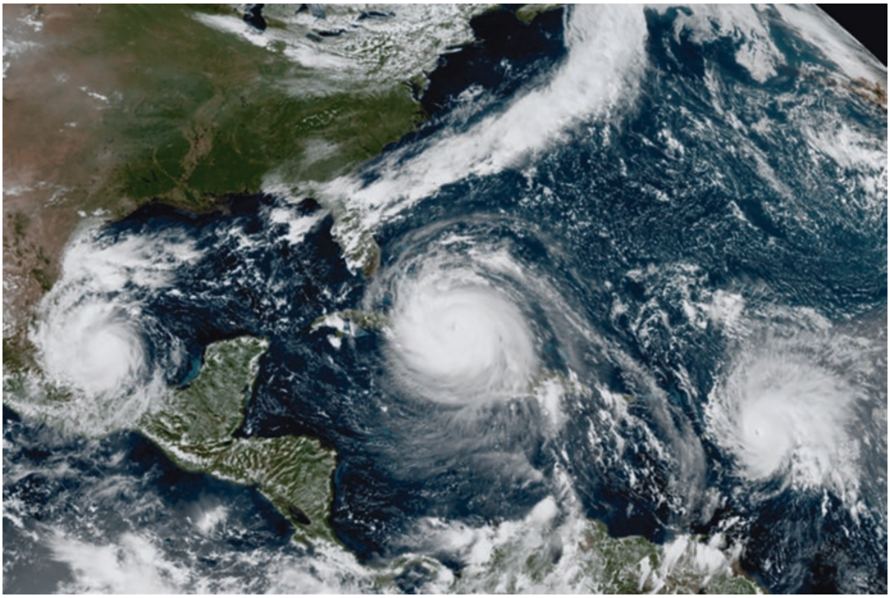

Fig. 11.1 The threat of a warming world. On September 8, 2017, the National Oceanic and Atmospheric Administration (NOAA) was able to snap a photograph of Hurricanes Katia and Irma and Tropical Storm Jose from space. Climate change is creating more extreme weather events, including historically powerful and more numerous hurricanes. Replacing fossil fuel with fusion energy for electric power generation would be a major step toward avoiding the worst effects of climate change

Advances in those approaches as well as a variety of other fusion concepts provide hope for producing net energy and the eventual commercialization of fusion power plants within two decades. We hope that the preceding ten chapters have persuaded you that net fusion power is at least a possibility. And turning that possibility into fact has become urgent due to human-caused climate change, mainly due to the burning of fossil fuels and the release of methane (Fig. 11.1).

Today, fossil fuels—coal, oil, and natural gas—account for more than 80% of the world's energy [2]. Fossil fuel has dominated the world's energy mix for more than 250 years. It has been burned through times of war and peace, in democracies and dictatorships, and in all parts of the planet. Dethroning the longtime heavyweight champion of energy is going to be tough, but climate change is going to create far bigger problems that will give us no choice. Today, excess heat is creating extreme weather events, changing ecosystems, impacting food supplies, and creating political instability. This fact is hard for many people to grasp because the situation has changed so quickly. Until very recently, climate change was being sold to the public as a "debatable" reality or problem for their grandchildren. The reality is that climate change is already here, and its effects will only become more pronounced unless we change the way we produce and use energy.

Climate change is happening at a time when demand for energy is rising. Energy is critical for raising populations out of poverty, providing drinking water, and advancing modern civilization. The US Energy Information Agency projects that global energy demand will grow by 50% between 2019 and 2050, with most of the growth coming from Asia [3]. Moreover, to avoid the worst effects of climate change, we will need to limit the extraction of coal, oil, and natural gas. Most of this fuel needs to remain in the ground, which means that powerful economic interests will no doubt exert political pressure to make the most of their soon-to-be stranded assets. To resist that pressure will require developing political will around the world. Solving this problem will be the greatest human endeavor for the next hundred years because almost every aspect of civilization needs to adapt.

Major international conferences, such as the annual United Nations Conference of the Parties (COP), have produced pledges from the United States and most other countries to rapidly reduce greenhouse gas production immediately and to eliminate the burning of fossil fuels by mid-century. This will lead to a major restructuring of the world's economy, including a revolution in transportation (especially replacing fossil-fueled vehicles with electric ones) and the generation, transmission, and storage of electrical energy.

The future "green" electric grid will have to accommodate large- and small-scale sources, including solar and wind. These will include not only large solar and wind farms but also residential and neighborhood scale sources. Because these sources are intermittent, energy storage devices, especially batteries, will become increasingly important. Even with storage, these sources will not be able to serve as baseline power plants. Currently, the only low-carbon, nonnuclear baseline power plants are hydroelectric and geothermal, and these can serve only limited areas.

Even adding other solutions such as conservation, building innovations, carbon capture and sequestration, biofuels, hydrogen produced from electrolysis of water by "green" energy, and speculative sources like wave power or ocean thermal energy conversion, achieving zero carbon appears out of reach without adding nuclear energy to the mix.

11.2 Fusion in Our Future

As we noted in Chap. 1, nuclear energy comes in two forms: fission of heavy nuclei and fusion of light ones. Both forms have been exploited in weapon technology. Fission (atomic) bombs ended World War II, and the United States tested the first fusion (hydrogen) bomb in 1952. The Soviet Union followed with its own H-bomb in 1955, creating the "balance of power" that kept the "Cold War" cold until the Soviet Union's collapse.

As fearsome as nuclear weapons can be, nuclear technology also has a positive side. Fission has been tamed as a source of energy to create the superheated water or steam that drives the turbines of electric power plants. It now supplies 20% of the electric power in the United States and 10% worldwide. As this book notes, using fusion in a similar way has proven more difficult, but it offers great promise that seems to be on the verge of being realized.

What could a fusion-powered world look like? First, fusion would transform the electrical generation industry. Fission power plants generate anywhere from about 500 megawatts to several gigawatts, and fusion plants are projected to be in a similar range, with a smaller minimum capacity of 200 megawatts [4, 5, 10]. Estimates vary, but a good rule of thumb is that a gigawatt is enough to power about 500,000 average American homes. Figure 11.2 shows a quick comparison of different power plants.

More importantly, like fission, fusion power plants would create very low amounts of greenhouse gas and other pollutants and require less land area than fossil fuel plants. (In contrast, wind and solar farms require about 100 times as much land per megawatt.) Unlike fission plants, fusion produces very little radioactive waste (tritium and neutron-activated material from the inner wall), and what it

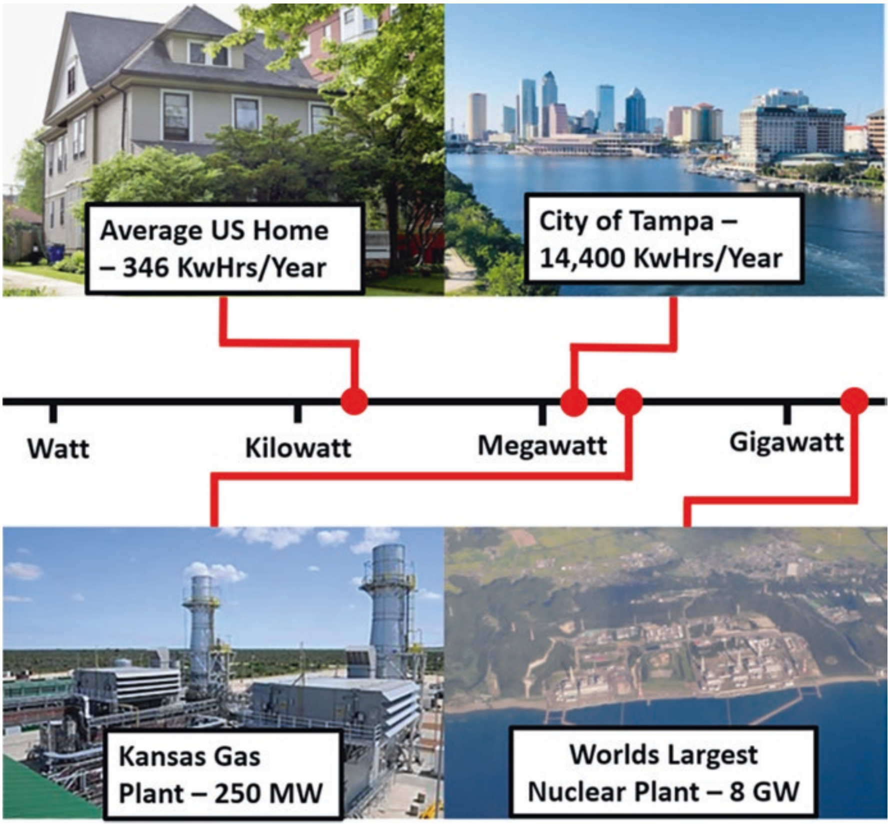

Fig. 11.2 A comparison of the relative scale of electricity on both the supply and demand sides. The fusion community has predicted power plants between 250 and 2000 MW in size, but at this time it is unclear [4, 5]. (Image: Wikipedia)

produces is much easier to manage. These would make siting requirements for the plant different but much less restrictive than for either fission or perhaps even fossil fuel units. There would be some emissions associated with a fusion plant's construction and operation but relatively little compared to other equivalent power plants. Overall, a fusion power plant would create a huge amount of energy from a very small footprint.

11.2.1 Funding Fusion

Fusion researchers have understood for decades that the current electrical grid was unsustainable and that fusion was a good alternative source. But unfortunately and despite their advocacy, they have been unable to attract sufficient financial support (see Preface Fig. 2), which for the most part was not only low but also lopsided and limited to academic settings. Government funding was always more connected to defense applications, pure science research, or Cold War competition rather than energy. Much of the work was classified, which slowed public sector development due to limited publication and collaboration.

Moreover, academic settings like universities and national laboratories are not structured to commercialize fusion. They have different priorities—the education of students and the publishing of cutting-edge papers—rather than seeking commercial application. Private companies can better organize and manage teams around specific missions. Companies can seek cost-effective solutions, nimbly pivot away from bad ideas, and create a revenue engine that can drive further improvements. This is why moving fusion into the private sector is important if we want to realize fusion power. The private sector can act in ways that universities simply cannot. Still, universities have the subject matter experts, computational resources, facilities, and public dollars that can lessen the risk for private investment.

For these reasons, the best model for fusion right now is a public-private partnership. Several governments have already recognized this, including the United States, the United Kingdom, and China. We discuss a more detailed plan later in this chapter.

11.2.2 Fusion Trends

Still, we see many good reasons to be optimistic about the future of fusion power. First, despite past funding limitations, fusion has made progress. Every approach described in this book has advanced significantly through the years. We underscore a few advances that have or will significantly change the state of the art:

- *High-temperature superconductors*: the rate of fusion in a magnetized plasma scales as the fourth power of the applied magnetic field [7]. Since almost every fusion approach discussed in this book uses magnetic or electric fields to control its plasma, superconducting magnets will be the most important technological enabler for fusion over the next 20 years. This is a field with great potential for improvement because of new materials that retain their superconductivity at temperatures above that of liquid nitrogen. These high-temperature superconductors (HTSs) offer a route to cryogenic systems that are less complicated and expensive than conventional metallic superconductors, which require liquid helium temperatures. Most importantly, HTS material enables high-field (10–40 teslas), yet smaller, magnets, which reduce the overall size and cost of the machine [6]. The ability of superconducting materials to hold their fields over long time frames changes reactor engineering from pulsed to continuously running machines. The downside of HTS materials is that they are generally ceramic and more difficult to manufacture and work with than conventional metallic superconductors. Advanced fusion device manufacturers (both for power generation and rocketry) have long sought to use HTS wire, but the superconducting industry could not make enough quality material. Hence, advances in this area will have to come from outside the fusion research community.

- *Magnetic reconnection*: reconnection involves two magnetic fields merging to become one field. The effect is important because it releases a huge amount of heat. The effect can pull as much as 45% of the energy in the magnetic field into heating the ions [8]. This makes it a fast and cheap method for bootstrapping plasma up to fusion conditions. Reconnection should be integrated into as many fusion reactors designs as possible.
- *Plasma structures (plasmoids)*: structuring plasma creates advantages in reactor design because the material can be heated, manipulated, and controlled. The fusion community has developed novel methods for the formation and control of different plasma configurations. Some fusion reactors are using this property as their primary method to heat the plasma, but this phenomenon could be integrated into other designs as well.
- *Fusion chain reactions*: chaining nuclear reactions together has long been a goal for this field. Any power plant that reaches this state will raise energy output and reactor efficiency. This concept is known as ignition in the laser fusion world and a burning plasma in the tokamak community. On August 5, 2021, the National Ignition Facility (NIF) made history by becoming the first-ever machine to demonstrate chained fusion reactions [9]. As reactors are built with higher fields, it is more likely that conditions for chain reactions will be met. This means that future plants could see a step-change improvement. (Note added in proof: In December, 2022, NIF reported, to great public fanfare, that they had achieved the milestone of producing more fusion energy output than the laser energy input, 3.15 megajoules of fusion energy produced from focused laser pulses that used only 2.05 megajoules input energy.)
- *Modeling tools*: today, modeling tools can be used to test many different reactor designs with computer simulations rather than building machines. This saves time and money by eliminating bad concepts at a lower cost. This is analogous to the Boeing Dreamliner, which was the first aircraft perfected using a supercomputer before its construction. There are half a dozen mathematical frameworks for modeling plasma, allowing teams to capture the right level of detail versus implementation practicality. Customers can buy existing software tools and can rent time on high-performance computing (HPC) platforms to set up these models. In 2019, a

supercomputer was capable of modeling tens of billions of particles in a constant energy system [10], and advances in computation hardware will steadily increase that capability. This gives teams enough insight to predict reactor performance. Even a desktop computer could handle tens of millions of particles relatively easily. Modeling tools can lower the overall cost of fusion research.

Advances made in these areas have been significant and, when combined, could be used to propel this field further forward. It is because of these technologies and trends that it is likely that a fusion team will reach net power within the next few years.

11.2.3 Every Community Can Help

Developing commercial fusion inside the United States will require involvement from the scientific, public, government, regulatory, and private sectors. No one community can act independently of the others. The scientific community needs to do a better job explaining their work to the general public. The general public needs to accept and understand how fusion works. This can lead to more political pressure for governments to act on climate change and support fusion development. Government leaders need to provide the funding, frameworks, and leadership that can coordinate the public and private sectors. The regulatory community needs to create sensible rules that enable the building and certification of fusion power plants while providing public confidence that they will operate safely. Finally, the private sector needs to join with political leaders in recognizing that the fight against climate change is a huge economic opportunity. Although nongovernment organizations, such as Strong Atomics and the Stellar Foundation, have supported fusion using foundational funding, the government, especially Congress, has to play the biggest role.

Congress has come close to supporting a large fusion program twice in its history: the Magnetic Fusion Act of 1980 and the Infrastructure Bill of 2021. In the intervening years, many different national plans have been put forward. Out of these plans, several different policy approaches have emerged:

- *Discovery pipeline*: the government could fund fusion the same way that biotech supports drug development. Biotech companies have a pipeline of products that are at different stages of development. As a product passes key tests, it becomes more important and moves forward in the pipeline (Fig. 11.3). Funding is tied directly to these development stages, with experimental concepts getting small amounts and successful efforts receiving large sums. Any fusion pipeline would need to be judged by how far along it is toward reaching power plant conditions. Fusion concepts could be broadly separated into three tiers. Experimental concepts are ideas that have not been fully tested and could receive a few million dollars a year. Mid-tier concepts could receive sustained funding at tens of millions of dollars per year. Large established programs could receive $150 million a year. The problem with a pipeline system is that it is an idealized plan for poli-

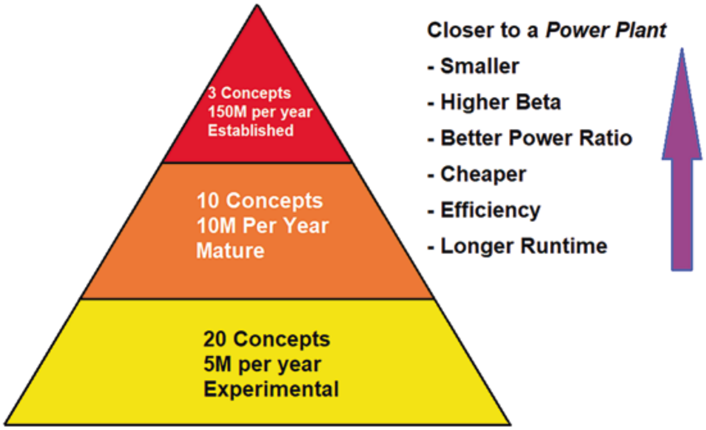

Fig. 11.3 A pipeline for fusion technology would have tiers of funding based on different levels of technological maturity

cies. Real-world arguments among the efforts, a tendency to focus on just meeting metrics, and, more than anything, the safety net of government funding are not likely to yield the best outcomes. In some ways, current government funding reflects this pipeline approach.

- *Replicating the advanced fission model*: a second funding option could be to follow a model that is already being used for advanced fission reactor development. In this approach, the government could contract with companies to build fusion power plants. In 2015, the United States started the Gateway for Accelerated Innovation in Nuclear (GAIN) program to support advanced fission. This program has done a great deal to connect companies, governments, and universities together to grow the advanced fission industry. For one thing, it helped connect different communities of fission research and development to each other, facilitating communication and industry growth. This effort has a voucher program that allows companies to receive funds for testing at government facilities. GAIN also has a demonstration program that provides up to 20% matching funds for companies that are trying to build a fusion reactor. This level of involvement lowers the capital risk for investors but also makes it very clear to the company that it needs to perform; otherwise, it will be pushed out of business. A do-or-die attitude is critical for a fusion company to succeed. Finally, GAIN helped support a Small Business Innovation Research program to fund small businesses that are developing products to support advanced fission technology. This has created an ecosystem of smaller companies that provide technology for the advanced fission industry.
- *Military support*: the US military has long been a test bed for advanced technologies that the rest of the nation benefits from. The nuclear power industry began as a Navy program to extend the performance of submarines. Admiral Hyman

Fig. 11.4 Hypersonic flight. In a single year, 2018, China tested more hypersonic rockets than the United States tested in an entire decade. Fusion thrusters would represent a significant technological leap in hypersonic devices and beyond. (Image source: Wikipedia)

Rickover built that program using his military clout, extensive funding, exceptional engineering, and managerial skills. Aside from power, the best application for fusion technology within the military is rocketry. One reason for focusing on rocketry is that energy is a crowded market, while a fusion rocket or thruster has no near-peer technology. Rockets produce their thrust by ejecting material backward from an exhaust nozzle, producing a forward change of momentum equal and opposite to the momentum of the ejected matter. Fusion rockets work by exhausting lightweight fusing plasma out of the back of the ship at exceptionally high exhaust velocity. That means they have an unmatched thrust-to-weight ratio. A fusion rocket could match the impulse of the SpaceX Raptor engine for a hundredth to a thousandth of the weight. This has potential military application for hypersonic suborbital flight (Fig. 11.4) and for maneuverability in space applications, which is particularly useful for orbital reconnaissance satellites.

11.3 To Mars and Back

Progress in fusion will be driven by practical considerations, but public support will be enhanced by aspirational goals. And what could be more aspirational than sending humans to another planet and returning them home—the obvious target: Mars!

Princeton Fusion Systems (see Chap. 7 for more details) has modeled what a fusion rocket would mean for reaching Mars [1]. The company is commercializing the Princeton field-reversed configuration (PFRC) as a fusion thruster and source of onboard power. Any fusion rocket could use the same hardware used to launch the shuttle to get into low Earth orbit. Once there, the crew would be transferred to a capsule that would sustain them for 280 days in deep space. This capsule would be outfitted with five 6 MW fusion rockets. The company chose five engines for safety and redundancy. The first step would be about a month of acceleration using the fusion rockets to reach a maximum speed of 50 kilometers per second, about four times the cruising speed of a conventional rocket trip to Mars. That high speed is particularly important because weight considerations do not allow for much radiation shielding, so minimizing the time in deep space is important for the astronauts' long-term health. The ship would then coast for about a month and then begin deceleration to reach Mars' orbit.

The trip would allow for 30 days on the Red Planet before returning. The return trip takes longer because the escape velocity from Mars is lower. Again, weight considerations mean keeping fuel weight to a minimum, so even with the fusion engine burn, they will travel more slowly on the return trip. In total, the company projects that the entire trip could take up to 310 days (Fig. 11.5). With a conventional rocket, the time in deep space would be more than a year (about as long as radiation health considerations would permit), and the stay on Mars would have to be longer before the planetary alignment is optimal for return. A trip to Mars would be one of the greatest achievements in the history of the human race, and a fusion engine may well make it possible in the lifetimes of most readers and at least one author of this book.

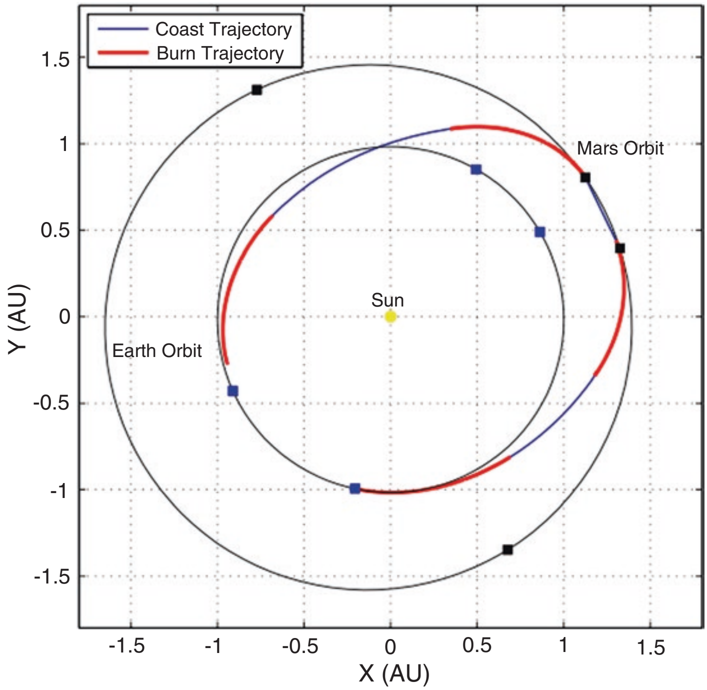

Fig. 11.5 A diagram of the orbital path taken by a round trip from Earth to Mars using a fusion rocket. The entire round trip could be achieved in 310 days with a month's stay on the Red Planet. The fusion rocket could provide steady acceleration of the spacecraft up to 50 kilometers per second on the outbound trip, shortening the astronauts' time in deep space and thus reducing radiation exposure. (Image courtesy of Stephanie Thomas, Princeton Satellite Systems)

11.4 Economic Impact

If the US government would fund a large national program for fusion, it would have benefits for not only the military but also the nation's economy and political standing in the world. The most direct economic beneficiaries would be those involved in the production of high-temperature superconducting (HTS) magnets. This industry can be separated into three segments: material mining, wire production, and finished magnet construction. Robust HTS wire production would impact dozens of other industries and technologies. A national fusion program would benefit each market segment differently:

- *Mining*: the most critical raw materials for this wire are rare-earth elements. (These are not particularly rare among all the chemical elements, but they occur together and are difficult to separate.) Since the 1990s, China has controlled more than half of the world's supply of these materials [14]. They are actually fairly plentiful in the United States, but it has never been cost-effective to mine or recycle them, especially since mining raises environmental concerns. These materials are already used for cell phones, weapons, and electric cars. So the federal government is establishing policies that will encourage the growth of a domestic industry that satisfies environmental regulations and takes advantage of recycling. If the government started a national fusion program, incentives would be even greater, and the domestic supply of rare earths would rise sharply.
- *HTS Wire*: A US domestic supplier base of HTS wire is probably the biggest missing part of this industry, but it will likely grow rapidly under a national fusion program. Presently, the largest amount of quality wire comes from Russia [13]. The domestic supply base is made up of small companies that lack the scale to meet the quality and quantity of wire needed for fusion power or fusion rockets. These companies were started in the early 1980s, and most of their products have been geared around magnetic resonance imaging (MRI) machines. Because HTS materials are ceramic and brittle, they need to be integrated with other materials to create a robust yet flexible ribbon. Government funding for fusion power and fusion rockets will create tens of thousands of jobs as this industry scales up to meet demands.
- *Finished magnets*: building a magnet means winding the HTS wire into a structure and then testing and packaging it. This is an expensive custom job within the current market. Small companies build complete turnkey magnets to meet customers' specific needs, but these are not suitable for mass production. Moreover, only a few companies can provide the high fields (5–40 teslas) required for fusion [6]. Additionally, there are also many innovations that have not been adopted by the commercial market. These include better coatings, improved manufacturing processes, and quench protection systems to avoid damage in case of a sudden loss of superconductivity. Any US fusion program will lead to a great expansion of this industry, again leading to tens of thousands of new jobs. Advanced magnets would also impact several other advanced technologies, including electric cars, fusion rockets, and healthcare (especially MRI machines).

To summarize, government investment in fusion will likely have a substantial technological and economic payoff, beginning with higher-quality, cheaper, and more abundant HTS wire that will impact dozens of other industries. It would also result in cheaper, better, and more robust superconducting, high-field (5–40 teslas) magnets [6]. Also as previously noted, fusion power scales as the fourth power of the magnetic field, so these magnets can create a step change in fusion rocket thrust. Stronger magnets mean hotter, denser, and more reactive plasma passing through the exhaust nozzle, exiting into space at an exceptionally high speed as a plume of plasma and creating high forward thrust. Forecasting the performance of these rockets is difficult, but as noted above, fusion rockets could provide anywhere from 100 to 1000 times the impulse of the SpaceX Raptor engine (or the same impulse at a small fraction of the weight) [1, 11, 12].

11.5 The Promise of Commercial Fusion Power

In order for electricity from fusion to succeed in the market, it has to be cheaper than other energy sources. It is hard to predict the cost of electricity coming from a fusion power plant because so many variables can change. A general rule for predictions is that a forecast is more uncertain the further it extends in time. Right now, it is likely that a net power fusion plant will be in operation within the next 10 years, and commercialization will follow in the 2030s and 2040s. At that time, burning fossil fuels will likely be more expensive because of supply shortages and regulations on carbon. Hence, a fusion electricity price that looks too high now may be very reasonable in 2035.

In Chap. 2, we showed Moynihan's 2011 calculation of the cost of fusion power based on the cost of its fuels. We reprint an example set of calculations here as Table 11.1. This math is very eye-opening. First, the cost of tritium fuel is high unless it is bred inside the reactor. Second, the amount of energy that can be generated by fusing boron-11 is much greater than the other fuels. The last observation is that in some situations, electricity becomes "dirt cheap." If fusion works like today's

Table 11.1 An best scenario example of the cost of electricity made from a fusion power plant based on fuel cost

Reaction:	*$/1 Kg*	*Fuel Conversion %*	*Efficiency*	*Energy production cost (KJ/1$)*	*Clean Water (Gal./1$)*	*$/KwH*
D & T -> He4+n	$50,022,222	45	17	516	40	$697
D & D -> T + p	$44,444	45	12	106,501	8330	$0.03
D & D -> He3 + n	$44,444	45	12	106,792	8353	$0.03
P & B11 -> 3He4	$7000	45	12	588,607	46,037	$0.01

This cost is the fundamental price of electricity based on straightforward math, assuming that the plant operators are paying the amounts shown for fusion fuel. The actual price would start from this floor and would add in costs for construction, safety, maintenance, etc.

natural gas plants best (about 63% efficiency) instead of the current 12%, as shown in the table, then the electricity price could be less than one fifth of a cent per kilowatt-hour. In 2021, the US consumer paid on average about 13 cents for one kilowatt-hour of power [15].

Economists compare different power sources based on a quantity called the levelized cost of energy (LCOE). This cost includes every expense that went into creating, running, operating, and maintaining the power plant. Energy forecasters use this number to understand the full cost of burning oil, building a wind farm, or designing a new nuclear reactor over its lifetime. Some examples are shown in Fig. 11.6. One study predicted that fusion would cost less than 100 dollars per megawatt-hour [17]. This price would make it competitive with the current cost of coal power.

Of course, we need to consider issues beyond just price. A fusion power plant will likely be a sizeable construction project. The companies that are the furthest along in development are projecting plants about the size of a cruise ship and with the footprint of a typical mall. With stronger fields inside the reactor, this overall size could fall considerably, but large construction efforts take sustained time and funding to complete. This means that fusion plants will need to be built in politically stable countries and by well-financed organizations. By its nature, fusion power cannot be used for every power application or in every market. Large coastal cities in developing countries would be ideal locations, as would big established cities that are looking to switch off fossil fuel plants. Fusion also works well for industrial processes that require huge amounts of energy, such as steel making or, especially, water desalinization. In 2018, the United Nations estimated that half of the world's population lives in areas where water scarcity affects their lives. Fusion energy could be a powerful tool for changing the lives of hundreds of millions of people by providing widespread access to fresh drinking water.

Between its impact on climate change and on interplanetary spaceflight, harnessing nuclear fusion could be one of the greatest technologies of this millennium. If the public and governments support fusion as a development effort and later as an

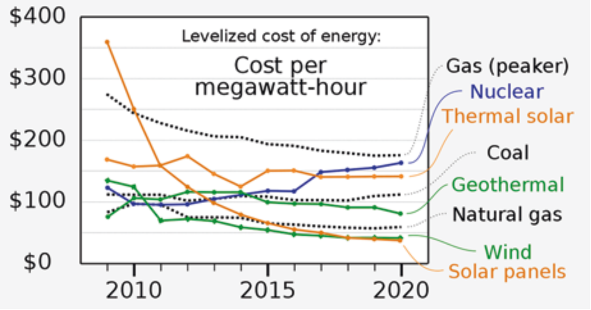

Fig. 11.6 The levelized cost of electricity for different power sources [16] in the United States. Estimating this cost for fusion is difficult, but teams have estimated it at less than 100 dollars per megawatt-hour [17]. (Image source: Wikipedia)

acceptable power source, humanity could move away from fossil fuels and avoid extreme climate change while fulfilling our aspiration to expand beyond this single planet.

That is our optimistic vision of the future and our greatest challenge: as a species, we need to push forward along the path to a future in which fusion provides the energy backbone of a thriving and aspirational civilization.

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Epilogue

12

Summary

One of the hazards of writing about a rapidly advancing field is that new developments can outpace the manuscript. In the months between the completed first draft of this book and the time the final draft went to editing, fusion technology advanced in remarkable ways. This Epilogue describes several important advances that we were unable to include in earlier chapters. We were able to update parts of the text, but it is unavoidable that other parts will be outdated by the time you read the published book. And as if to emphasize the dramatic nature of changes in the field, we even had to add a note to this Epilogue at the final proof stage!

One of the hazards of writing about a rapidly advancing field is that new developments can outpace the manuscript. In the months between the completed first draft of this book and the time the final draft went to editing, fusion technology advanced considerably. We were able to update parts of the text, but it is unavoidable that other parts will be outdated by the time you read the published book.

For example, in August 2021, the National Ignition Facility demonstrated ignition for the first time ever. A month later, the Massachusetts Institute of Technology (MIT) broke a world record (20 teslas) for a high-field cold bore magnet by wrapping over 186 miles of superconducting wire into the coil.

In January of 2022, the Chinese Experimental Advanced Superconducting Tokamak (EAST) was run continuously for more than 16 min, and in that same month, the Joint European Torus set a world record by generating 59 megawatts of energy. In March 2022, Tokamak Energy was the first private company to demonstrate 100-million-degree kelvin plasma, and in April, First Light Fusion detected evidence of fusion produced by compressing solid targets with projectiles.

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In June of 2022, the Fusion Industry Association reported that investment in private fusion companies had exceeded \$4.7 billion. Large fusion players like TAE Technologies and General Fusion have announced plans to build big (\$250–400 million) demonstration machines in the coming years, and Commonwealth is on track to open its SPARC reactor in 2026. The press has taken note of all this activity, writing articles that cover specific news stories, investors' perspectives, and interviews with fusion experts.

Public perception has driven action from established organizations like the International Atomic Energy Agency (IAEA), the United States Department of Energy (DOE), and the United Kingdom Atomic Energy Authority (UKAEA). There has also been activity from the Nuclear Regulatory Commission (NRC) and the American Society of Mechanical Engineers (ASME). Both have scheduled a flurry of fusion-related conferences and meetings. Members of the US House of Representatives have formed the first-ever US Congressional fusion caucus, and in March of 2022, the White House hosted a summit on fusion energy.

The United Kingdom has created a "fusion cluster" through a set of policies that fund, colocate, and connect different fusion organizations in one part of the country. The UK also launched a \$248 million effort to build a Spherical Tokamak for Energy Production (STEP) facility. It has also set up research centers around the robotic maintenance of fusion reactors, test stands for high-temperature superconductors, and the world's largest tritium handling facility. The country has gotten major fusion companies, like General Fusion and Tokamak Energy, to colocate large facilities in these clusters, as well as smaller firms, like Oxford-Sigma, Woodruff Scientific, Pulsar, and First Light Fusion. Established companies like Bruce Power, Google, Curtis-Wright, Framatome, Fluor Marine Propulsion, Westinghouse, and Frazer-Nash have taken an interest in this industry, in many cases dedicating staff to learning more about the field.

Note added in proof: In December, 2022, NIF reported, to great public fanfare, that they had achieved the milestone of producing more fusion energy output than the laser energy input, 3.15 megajoules of fusion energy produced from focused laser pulses that used only 2.05 megajoules input energy.

This year, 2023, Shine Medical Technologies intends to turn on its first facility to produce medical isotopes using nuclear fusion, with an additional facility being built in the Netherlands. The company is starting with Molybdenum-99 and has submitted paperwork to expand into Lutetium-177. In 2021, the size of this market was estimated to be over six billion dollars annually, and with NRC approval completed, Shine has a clear advantage over rival companies. The company has publicly laid out a vision for harnessing these profits to build fusion devices for the reprocessing of spent nuclear fuel. Processing spent fuel is a major problem for the nuclear fission power industry, which has built up stores of the material for over the past 50-plus years. That market could be worth over a billion dollars on its own. If Shine can master this task, it will be well funded and well positioned to take the final step of building fusion plants to generate electricity.

It is hard to predict where all this activity will lead, but it is clear that some parts of the book will be made irrelevant, while others will advance significantly in the coming years. The authors can only speculate as to how things will go, but several trends are very exciting.

The addition of superconducting materials is likely the most transformative innovation in fusion today. This story has already been playing out in the tokamak community; both Tokamak Energy and Commonwealth Fusion Systems were founded on the premise that adding this material to a fusion machine gets it within striking distance of net power. But nearly every approach in this book could benefit from superconducting materials! Even approaches that do not need magnetic fields could use this material to reengineer the back-end power system. Moreover, there are now efforts to form the high-temperature superconductor material in large sheets instead of just in wires. If this occurs, it opens up an entirely new design space for how to build many of the approaches in this book.

Superconductors have applications well outside of fusion, including generators, motors, medical devices, weapon systems, energy storage, transmission lines, transformers, data centers, electric vehicle charging, and high-speed rail lines. This is why reaching fusion power could be the 21st version of the space race. Putting a human on the Moon was more than just a moment for the United States. The investment to achieve that goal created dozens of spin-off technologies that drove the nation for decades thereafter. Fusion could drive a similar set of large innovations around the use of superconducting wire for a wide variety of applications.

Finally, mastering the fields of both fusion and superconductivity lend themselves to the technology of interplanetary spaceflight, including human missions. A fusion-powered rocket enables a transit time of weeks rather than months to reach nearby Mars, making such a transit technically and financially feasible while greatly reducing exposure to cosmic radiation. Going interplanetary may be the greatest outcome of investment in both fusion and superconductors.

For us, writing this book has been a thrilling ride along a road to discovery. We can only imagine where it will take us next. We hope you share our excitement.

Matt Moynihan (Fusioneer)
Fred Bortz (Scientific Wordsmith)
September 2022

Glossary

Alpha decay Alpha decay is a fission event in which a large nucleus emits an alpha particle (a helium nucleus made up of two protons and two neutrons), thereby transmuting into a different nucleus.

Beta number The ratio of the plasma pressure to the magnetic field pressure.

Binding energy The amount of energy required to break apart a nucleus or other sets of particles.

Burning plasma A term popular in tokamak research that refers to a plasma in which the heat generated by the first fusion reactions is used to kick off additional fusion reactions. In inertial confinement fusion, the same concept is known as ignition. Developing a burning plasma is a major goal for the ITER project.

Chaining A process in which one nuclear reaction is used to induce a second reaction. In fission, this happens when a neutron from an atom undergoing fission causes another atom to undergo fission as well. Each fission produces several neutrons, which means chaining needs to be limited by control rods in order to avoid exponential growth and, consequently, a dangerous meltdown. In fusion, the energy from one reaction is captured and used to heat plasma and start a secondary reaction. Such reactions cannot easily chain together, making fusion a fundamentally safer source of power.

Coulomb logarithm The Coulomb logarithm is a mathematical model of the ratio of glancing to head-on collisions inside a plasma. In practice, this is a number between 5 and 15 (nominally 10). Generally, a denser plasma has a shorter Debye length and a higher Coulomb logarithm value.

Compact fusion reactor (CFR) A fusion concept pursued by Lockheed-Martin Skunkworks from 2008 to 2021, which attempted to trap plasma inside a set of bent magnetic fields. The reactor attempted to create a diamagnetic plasma to reject the surrounding cusp field and lead to an enhanced trapping effect.

Converged core This is one of the three modes of operation inside a fusor that are controlled by the chamber pressure. A converged core occurs when the pressure has fallen and the plasma glows weakly in the center.

Coulomb force The electrostatic force between two charged particles. It is repulsive when they are alike and attractive when they are not alike. Coulomb repulsion works against fusion until the nuclei get within approximately 2

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femtometers (2×10^{-15} m) of one another. At that distance, the attractive strong nuclear force pulls them together, allowing them to fuse.

Cross section A measure of the likelihood that two interacting nuclei will fuse. Cross sections are measured in units of area called barns (10^{-28} m^2) and are functions of what nuclei are interacting, their relative speed, and the angle at which they are colliding.

Debye length In a plasma, it is the distance over which a particle's charge influences other particles around it. Beyond this length, the particle's electric field is essentially shielded by other particles. Denser plasmas have much shorter Debye lengths than less dense ones.

Deuterium An isotope of hydrogen with one proton and one neutron in its nucleus; it is the most common fuel for fusion reactors. The gas is relatively cheap, can be purchased commercially, and occurs naturally in seawater. Because deuterium is not radioactive, fusion fuel represents a lower environmental, health, and safety risk than fission fuel.

Diamagnetic plasma A diamagnetic material rejects an applied external magnetic field by producing an opposite internal one. Diamagnetism is observed in tokamaks as a natural resistance to applied poloidal and toroidal fields. It can arise in the plasma because the chaotic motion of the charged particles creates an internal field that opposes the imposed field.

Dynomak A dynomak is a spheromak (a twisted loop of plasma) structure that is formed, sustained, and heated by the injection of a twisted magnetic field into a plasma chamber. The plasma loop forms naturally through a relaxation process where the system energy is minimized and the magnetic twist is preserved. Because it forms naturally, supporters argue that it has advantages over competing fusion approaches.

Edge-localized mode (ELM) An unstable region of the plasma that forms inside tokamaks as they transition from L-mode to H-mode. It was first observed in the ASDEX tokamak in Germany in 1981. ELMs would occupy large chunks of tokamakplasmas around the edges of the core. In these regions, the material would behave chaotically and damage wall components, diagnostics, and other reactor equipment. By 2010, tokamak theory, operation, and reactor engineering had found ways to control and avoid these disruptions.

Electron volt A unit of energy equivalent to the energy gained when one electron is accelerated across a potential difference of 1 volt. Gaining 1 electron volt of energy is equivalent to raising the temperature of an electron by 11,604 kelvins.

Field-reversed configuration (FRC) A configuration of plasma, or plasmoid, that forms when it flows around a ring that self-generates a magnetic field. Over 45 machines were built between 1959 and 2011 that were explicitly designed to study some variety of the FRC. Over time, research into these structures gave rise to FRC variations, including the spheromak, rotamak, and dynomak. As of this writing, the leading fusion company that is following this approach is TAE Technologies.

Fission A process in which a larger atom's nucleus splits apart into smaller nuclei and often several neutrons, releasing considerable energy. All nuclear power plants that are currently in operation use that energy to generate electricity. Fission was first observed experimentally by Otto Hahn in 1938 and was explained theoretically by Lise Meitner.

Flowing pinch The shear flow of plasma through a pinch structure in such a way that it stabilizes the structure and suppresses the growth of instabilities. Suppression happens because different parts of the plasma move at different speeds, which gives rise to different fundamental frequencies across the pinch. Because of this, the plasma instabilities do not undergo constructive interference with each other, ultimately suppressing the overall instability growth rate.

Flux loop A measurement tool used in fusion to gauge the strength of a magnetic field made by a plasma. Whenever a plasma passes through this loop of wire, its field creates a voltage-current signal that can be interpreted to measure the magnetic and electric fields made by that plasma.

Fully magnetized plasma A plasma in an imposed magnetic field that is strong enough to completely dominate the plasma's diamagnetism and passes directly through it. A fully magnetized plasma has no resistance to the imposed field and does not have any self-generated fields.

Fusion The process where the nuclei of two smaller nuclei merge to form one nucleus. The process releases energy because the mass of the new nucleus is less than the total mass of the nuclei that formed it. The energy is equivalent to the lost mass according to the famous formula from the theory of relativity, $E = mc^2$.

Fusor A simple inertial electrostatic confinement (IEC) fusion device, developed by Philo Farnsworth in the 1950s, that uses an electric field to heat ions to fusion conditions. Its most basic design uses two wire cages, one inside and the other inside a vacuum chamber. A voltage is applied between these cages, and deuterium ions are injected (or form) inside the outer cage. These ions fall down the voltage between the two cages, and most strike the inner (negative) cage and are conducted out of the machine. Those that miss that cage can collide in the center and fuse together. Since 1999, a community of hobbyists has been building and running their own fusors in their garages.

Gyrokinetic model A model for the motion of ions that ignore their radius of rotation as they move along a magnetic field. This assumption reduces the number of parameters needed to track a single particle's motion from six to five. A particle moving along a magnetic field typically follows a corkscrewing path, and in the gyrokinetic model, the computer ignores the spiraling portion of that motion.

Gyroradius The radius of the motion of an electrically charged particle (electron or ion) as it spirals around a magnetic field line. This is closely related to gyrofrequency (the frequency over which the spiraling particle completes a circle around that field line).

Hall-effect thruster A device developed in the 1960s as a method to change the speed or direction of a traveling spacecraft. The thruster works by injecting gas into a ringed cavity that is filled with electrons. These electrons interact with the gas, ionizing it. Once ionized, the particles feel a Lorentz force, which pushes them out of the back of the cavity and exhausts them into space.

Halo mode Halo mode is one of the three modes (halo, star, and converged core) that operate inside a fusor by controlling the overall gas pressure. This mode is characterized by a broad glow of plasma inside the fusor.

H-mode One of many modes of operation inside a tokamak, in which most of the plasma performs better (hotter, denser, more reactive, etc.) inside the central region, known as the pedestal. This mode was discovered in 1982 at the ASDEX tokamak by Friedrich (Fritz) Wagner in Germany. Today, almost all tokamaks operate in H-mode. At the edge of the pedestal is a sharp transport barrier, outside of which material behaves differently and can form edge-localized modes (ELMs).

Heliac One of several variations of a stellarator. At least three heliacs were built, including TJ-II (Spain), H-1NF (Australia), and TU-Heliac (Japan).

Helias One of the four designs for a stellarator. As of this writing, the Helias is considered the most optimized for performance. The W7-X (Germany) is a Helias model that was designed by a supercomputer and was built at a cost of 1.06 billion euros over 19 years.

Ignition A concept in inertial confinement fusion where the energy made by the reaction is captured inside the plasma and used to start more reactions, essentially chaining fusion reactions together. The same concept is known as a “burning plasma” in tokamak research. Ignition was first demonstrated in a laboratory on August 8, 2021, Sunday, at the Lawrence Livermore National Laboratory.

Inertial confinement fusion (ICF) A category of fusion based on heating and compressing fuel with a shock wave. It is one of the largest, highest-funded, and longest-term approaches in fusion research, second only to tokamaks. ICF uses devices called drivers to compress targets made of materials to be fused. Drivers are most commonly laser beams or X-rays but have also been beams of ions, electrons, pressurized liquid metal, and even hard projectiles. Examples of targets include spheres of cryogenically frozen hydrogen gas, exotic gold-foil-wrapped pellets, glass blocks with cavities of fusion fuel, and exotic targets adorned with cones and metal plates.

Inertial electrostatic confinement (IEC) A category of fusion approaches that use high voltage to heat ions to fusion conditions. Positive (+) ions “fall” down to negative (−) voltage sources, picking up speed and raising their thermal energy. If they collide in the center, they can fuse.

Ioffe bar A magnet designed by Dr. Mikhail Ioffe at Kurchatov Institute in Moscow. Placed at the ends of a mirror machine, it improved the performance so much that it briefly put the Russians ahead of the Americans in developing the magnetic mirror. The Ioffe bar was later improved with baseball and yin-yang coils.

Klimontovich model A mathematical approach to simulation proposed by the Russian plasma physicist Yuri Klimontovich, which tracks every particle in a plasma. The Klimontovich model is impossible to implement for large fusing plasmas. In practice, modelers have to make some assumptions to model fusing plasma.

Lawson energy balance An equation (shown below) first published in 1955 by British engineer John Lawson, which describes the energy balance for a fusion power plant. As of this writing, no reactor has been able to make this equation positive and therefore create net power from a fusing plasma. In this equation, the fusion rate term is driven by the density, temperature, and time of the confined plasma: **Net Power = (Fusion Rate - Conduction - Radiation) X Efficiency**

Levitating Dipole Experiment (LDX) An experimental device designed by MIT to be a magnetic mirror where the end fields are connected to one another. Plasma that leaked through the end fields would recirculate through the trapping field. Physically, the machine contained a floating, superconducting donut that levitated inside a vacuum chamber. Development was stopped in November 2011 because the DOE reallocated funding to the ITER project.

Lorentz force The force that results when an electrically charged object moves in an electromagnetic field. The Lorentz force is an extremely important and common equation in all of plasma modeling. It can be used to describe material or individual particles that flow in a tokamak, Hall-effect thrusters, or particle beams, as well as many plasma phenomena. The force is named after Hendrik Lorentz, who in 1892 developed the mathematical equation shown below:

$$\begin{matrix}\textbf{Lorentz}\\ \textbf{force}\end{matrix} = \begin{matrix}\textbf{Particle}\\ \textbf{charge}\end{matrix}\left[\begin{matrix}\textbf{Electric}\\ \textbf{field}\\ (\textbf{A vector})\end{matrix} + \begin{matrix}\textbf{Particle}\\ \textbf{velocity}\\ (\textbf{vector})\end{matrix} \times \begin{matrix}\textbf{Magnetic}\\ \textbf{field}\\ (\textbf{A vector})\end{matrix}\right]$$

Magnetic mirror A type of fusion reactor that was heavily pursued by the United States between 1970 and 1986 and is still researched around the world today. This machine relies on the mirror effect, which occurs when a charged particle moves from a low-density magnetic field to a high-density one to bounce plasma back and forth between two strong electromagnets.

Particle in cell (PIC) A modeling technique first developed by Frank Harlow in the T3 group at Los Alamos National Laboratory in the 1960s. The approach breaks the volume into cells and tracks how a superparticle moves through each cell. A virtual “super particle” represents hundreds or thousands of real particles in a plasma. In 2020, the best PIC models on large high-performance computing (HPC) could track several billion particles simultaneously.

Pedestal A high-performing region of a tokamakplasma that forms when the machine is put in H-mode. Plasma inside the pedestal is hotter, denser, and more reactive than material elsewhere. See also H-mode and ELMs.

Plasmoid A structure of plasma and magnetic fields. In fusion devices, plasmoids can be hot, dense, and easily moved in a controlled fashion, but their inherent instability is a challenge for engineers attempting to develop useful devices based on them.

Screw pinch A device that simultaneously applies both voltage and magnetic fields down a cylinder filled with ions. The screw is a helical combination of the Z-pinch (a current down the center or sides of the cylinder) and the theta pinch (a current that flows around the outside wall of the cylinder) to stabilize the compression.

Self-magnetized plasma A structure in a plasma where a flowing internal current makes its own magnetic field. This allows engineers to build unstable structures out of plasma, including rings, twisted DNA structures, and sheets. Inside these structures, the material is hotter, denser, and better controlled. These structures are naturally unstable, which is challenging for developers seeking to leverage this property.

Star mode An operating condition of a fusor that is characterized by a bright shining plasma in the center of the inner cage. Star mode is mainly controlled by changing the vacuum pressure inside the fusor.

Stellarator An early concept for a fusion reactor developed by Lyman Spitzer, Jr., at Princeton University in 1951. The stellarator applies magnetic fields to send plasma around a twisted ring of magnetic fields; Princeton devised four versions of this device. Supporters argue that the machine has superior plasma behavior to a tokamak, but the device has been expensive and difficult to build. In 2022, several companies were experimenting with simpler ways to build this machine by forming sheets of superconducting material.

Superconductor A material that conducts electricity with no resistance. Superconductivity is an example of a quantum mechanical effect that can be observed in large bulk materials. As of 2022, the best commercial superconducting wire could push more than 2000 amps across a square millimeter cross section of wire.

Tandem mirror A tandem mirror is a design for a mirror machine that attempts to keep the plasma in the end coils positive (+) or negative (−) to enhance the trapping effect. This is difficult because any concentration of charge causes electrostatic forces that pull in the opposing charge, which can lead to chaotic instabilities. In practice, engineers attempted to do this by feeding a continuous stream of one charge into the end coils.

Tesla The SI unit for magnetic field strength named after the famous American Serbian inventor Nikola Tesla. It is equal to 10,000 gauss, the better-known and long-preferred unit of magnetic field strength. Newer superconducting materials have made much higher fields possible. It is now possible to achieve magnetic fields in fusion devices in the range of 1–20 teslas.

Theta pinch The first human-made device other than a thermonuclear bomb to achieve fusion. In November 1957 at the Los Alamos National Laboratory, researchers achieved fusion with a theta pinch called Scylla I.

Torsatron A torsatron is one of the four kinds of stellarator. One example is the Compact Toroidal Hybrid (CTH) machine at Auburn University in Alabama.

Tritium A radioactive isotope of hydrogen with atomic mass 3. A tritium nucleus has a proton and two neutrons. The tritium-deuterium reaction is the easiest fusion reaction to create.

Two-fluid modeling A modeling approach that treats plasma as two overlapping and interacting charged fluids. Both fluids are governed by Navier-Stokes equations. The electrons are the negative fluid, while the ions are the positive fluid.

Two-fluid modeling is good at capturing physical effects, like plasma waves, reconnection, and other "bulk-plasma" effects. The model is not good at capturing effects that are driven by ion-electron interaction, for example, instabilities or nonequilibrium effects.

Vlasov equations A set of equations that describe in complete detail how a plasma changes over time. Anatoly Vlasov first developed this model in 1938. Implementing this model on a computer requires considerable approximation and simplification.

Z-pinch A method for compressing plasma by passing a high current down the center of a cylinder of plasma. As the current passes, it creates a strong compressing magnetic force around the outside, which squeezes the plasma to fusion conditions. Stabilizing the Z-pinch with a high shear flow in plasma is a major effort being pursued in the 2020s that could lead to a compact fusion power plant.

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