



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 trade-offs 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.

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

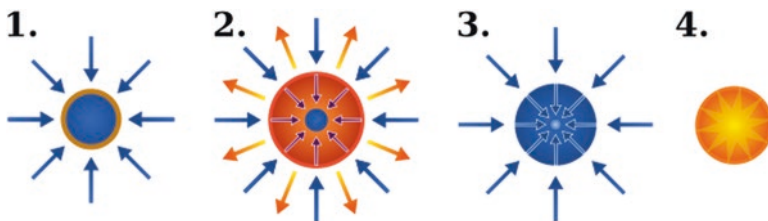


Fig. 8.2 The four steps of direct drive ICF fusion experiments: (1) provide an implosive force on the target and (2) blow off an energy wave of vaporized material, which (3) creates a compression wave and (4) ignites fusion in the material. This approach is known as direct drive because the lasers hit 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.

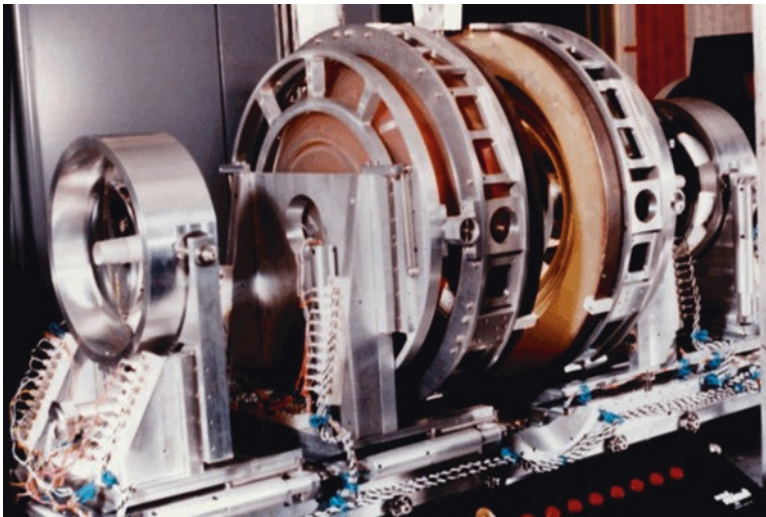


Fig. 8.4 The double-bounce illumination system (DBIS), the first machine in the world to carry out a laser-induced fusion event in a deuterium-tritium (DT) pellet. The machine was unique because it was done by a private company, KMS Fusion. The DBIS achieved fusion on May 1, 1974. This machine used mirrors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

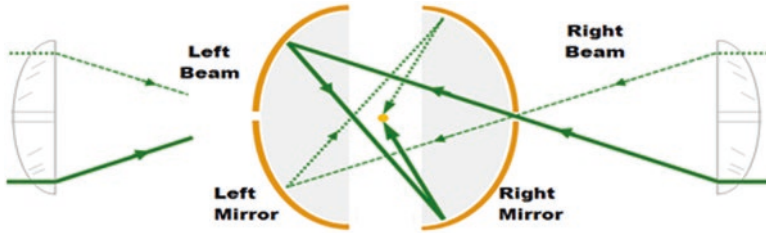


Fig. 8.5 A schematic showing how the double-bounce illumination system worked. Beams would pass through pinholes into a mirror chamber. Those beams would reflect and strike a pellet of DT fusion fuel from different directions, compressing it to ignite fusion. (Image source: Wikipedia)

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).

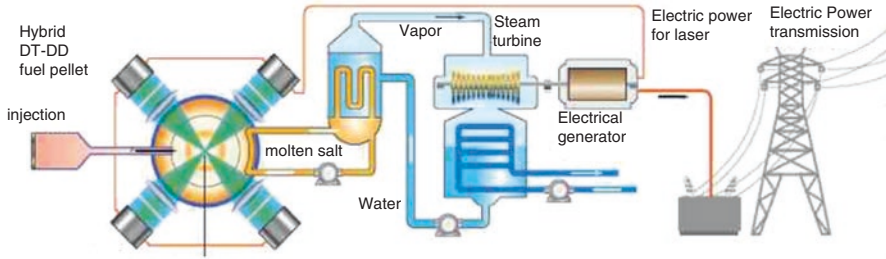


Fig. 8.6 The basic scheme of a power plant based on an ICF fusion approach. (Image from Wikipedia)

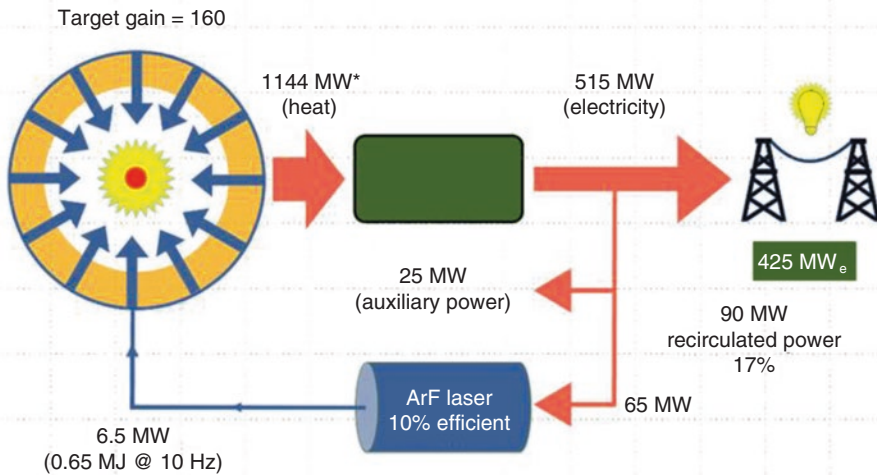


Fig. 8.7 Projected power plant efficiency for a typical ICF reactor, based on Ref. [22]. (Image courtesy of Dr. Stephen Obenschain, Naval Research Laboratory)

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,

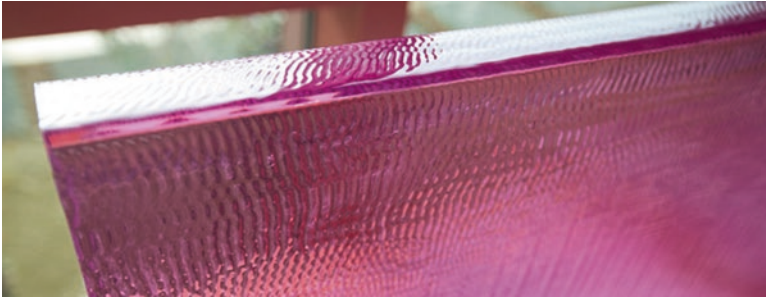


Fig. 8.10 Laser glass is a beautifully pure and heavy crystal that has the right chemical composition to produce and amplify a coherent light beam. As a photon with a certain wavelength passes through the glass, it stimulates more photons in lockstep with the initial one. Coherent light can be sharply 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,

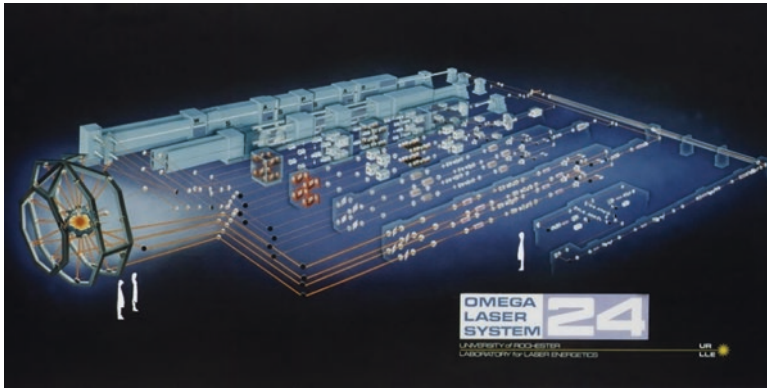


Fig. 8.11 Omega-24, a typical laser ICF facility layout setup in the 1980s. This system focused multiple laser beams onto glass targets to create fusion reactions. (Image courtesy of the Laboratory for Laser Energetics, University of Rochester)



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.

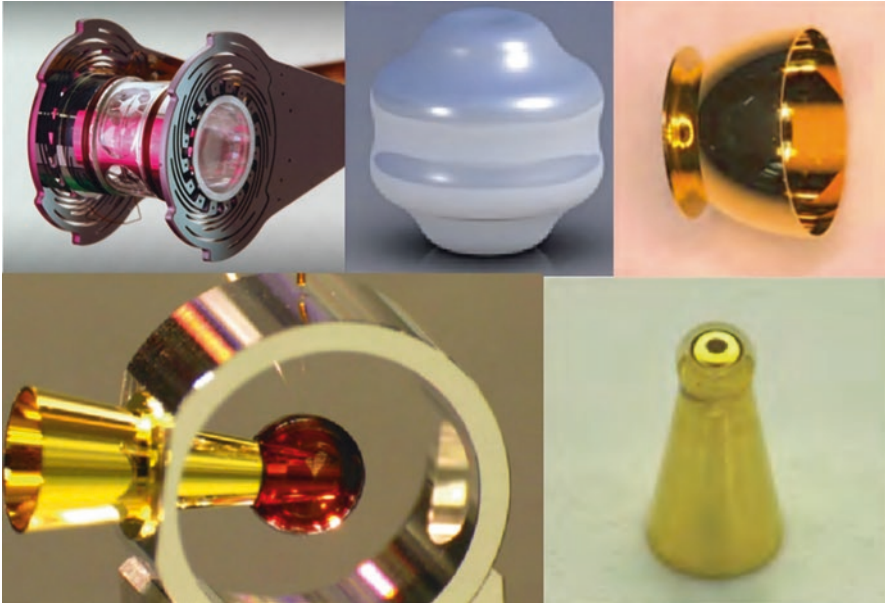


Fig. 8.13 Many different objects have acted as targets inside an ICF chamber. Above are some examples of targets through the years [24]. Target construction is a delicate art in its own right. Fusion targets contain cryogenically frozen spheres of hydrogen gas with temperatures below 14 kelvins. These 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

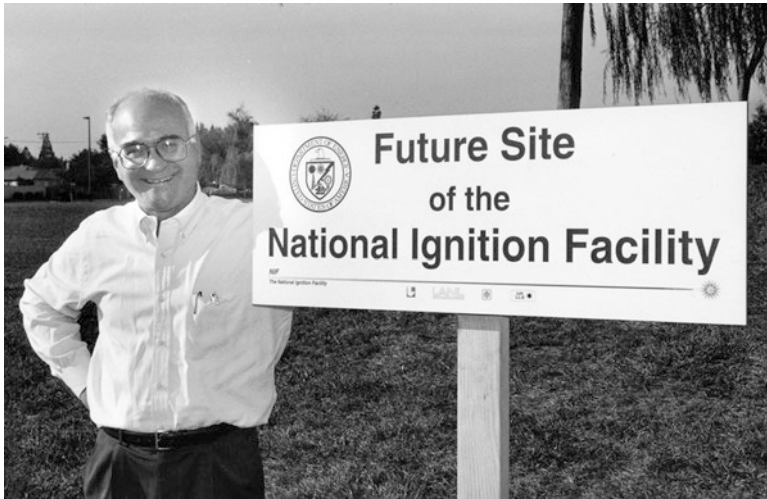


Fig. 8.14 Victor Reis, the assistant secretary for the Department of Energy’s Defense Programs, poses by a sign marking the location of the future National Ignition Facility. In the 1990s, Reis played a key leadership role in defining the emerging Stockpile Stewardship Program and the need for NIF. (Photo by Bryan Quintard/LLNL)

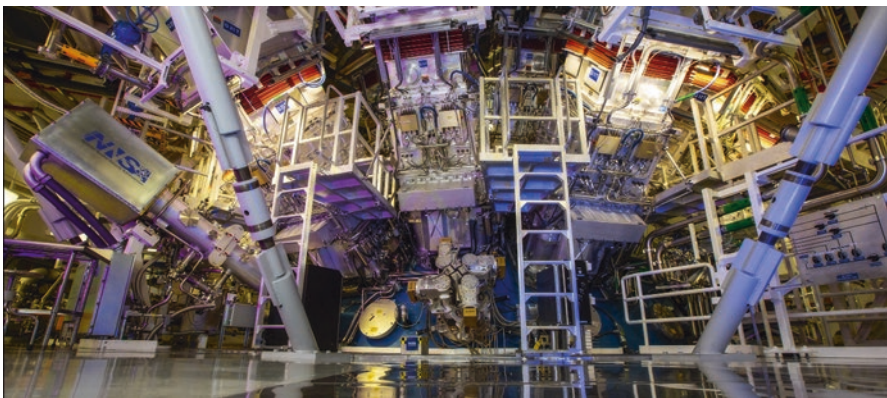


Fig. 8.15 The outside of the target bay at the National Ignition Facility. This exterior shot was used in the 2013 movie *Star Trek: Into Darkness*. (Image courtesy of Lawrence Livermore National Laboratory)

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

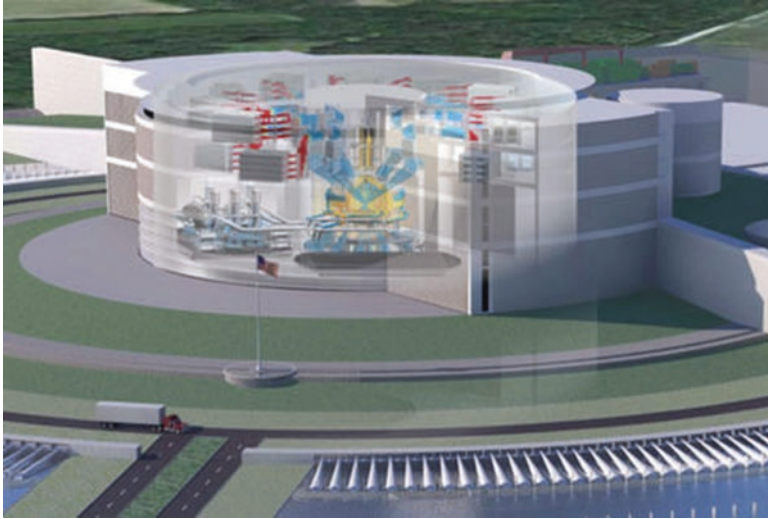


Fig. 8.16 An artist's conception of the Laser Inertial Fusion Energy (LIFE) reactor. (Image courtesy of Lawrence Livermore National Laboratory)

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 over-selling 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.)

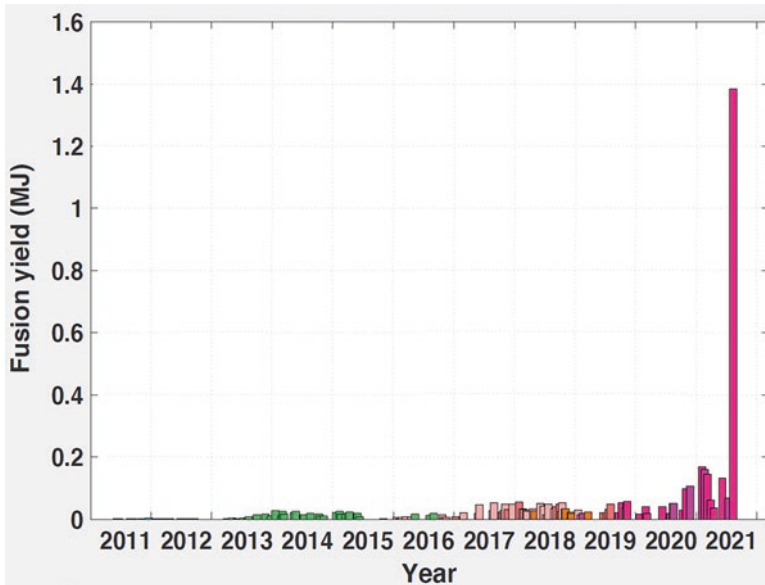


Fig. 8.17 After almost a decade of continuous improvement, the National Ignition Facility saw a dramatic increase in the power generated from a fusion reaction on August 8, 2021 [26]. This breakthrough was the first evidence of fusion ignition or a fusion chain reaction. Image courtesy of Dr. Tammy Ma, 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

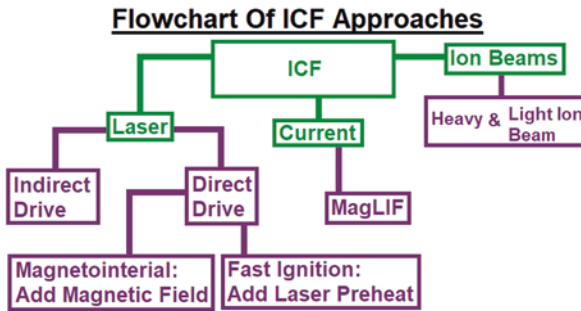


Fig. 8.18 A family tree of six different ICF approaches, which will be discussed in this chapter. The approaches are laid out in dark purple; the driver is shown in green

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.

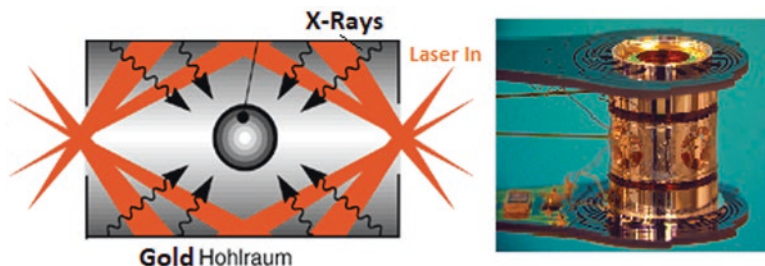


Fig. 8.19 Indirect drive ICF takes place in a gold foil tube known as a *hohlräum* (German for hollow space or cavity). (Image courtesy of Lawrence Livermore National Laboratory)

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.

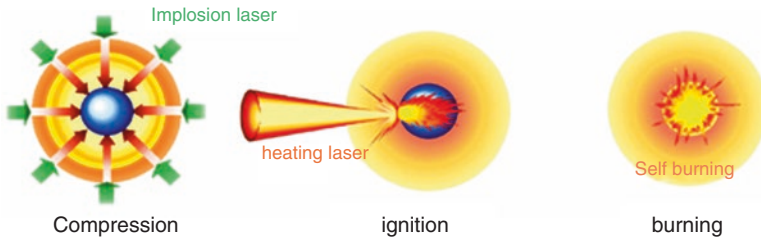


Fig. 8.20 The two-step fast ignition process, developed at the University of Rochester

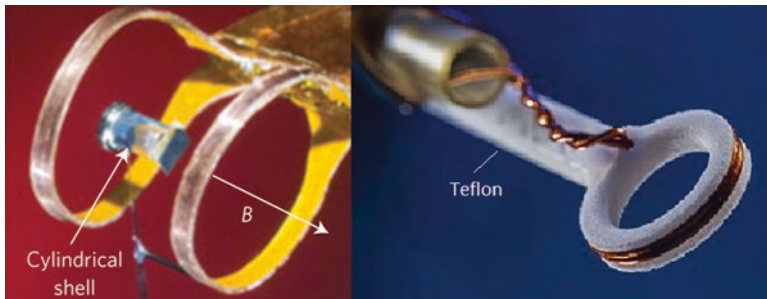


Fig. 8.21 Two-wire looped targets, which the University of Rochester used to combine ICF implosions with magnetic fields. Note the use of Teflon in the right photo. Teflon is relatively transparent to magnetic fields, which makes it uniquely useful in many fusion experiments. (Credit: Eugene Kowaluk, 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 Rummier 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.

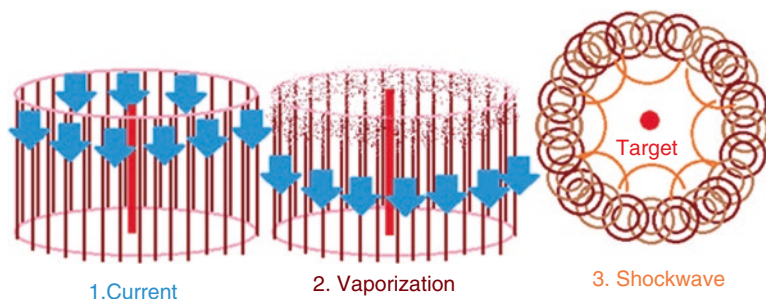


Fig. 8.23 The three basic steps of a fusion shot on the Z-Machine. First, current passes down small tungsten wires, which make up the target. There is so much current that it instantly vaporizes the wires, taking them directly to plasma conditions. This process also creates X-rays. A shock wave of plasma jets outward from the vaporizing wires. Both the shock wave and X-rays compress the target in the center

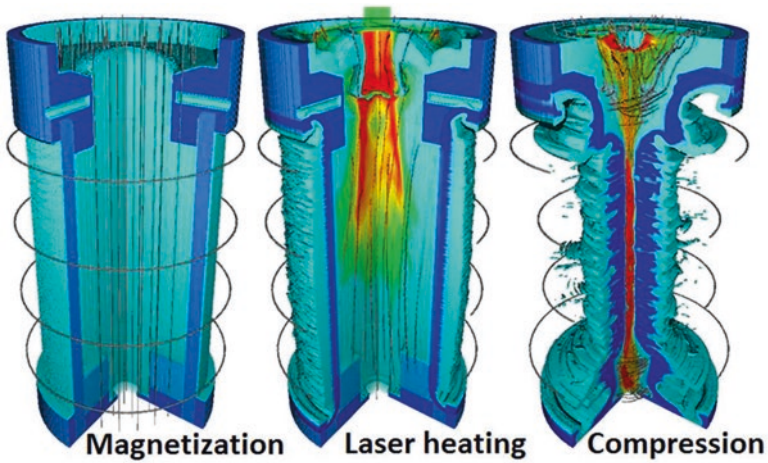


Fig. 8.24 The three stages of MagLIF compression [4]. First, a magnetic field fills the inside of the plasma; the plasma is now magnetized. Second, a laser prepulse is sent in to heat the plasma. Last, the plasma is compressed using a Z-Machine shot. (Image permissions from Troy Rummler of Sandia National Laboratory)

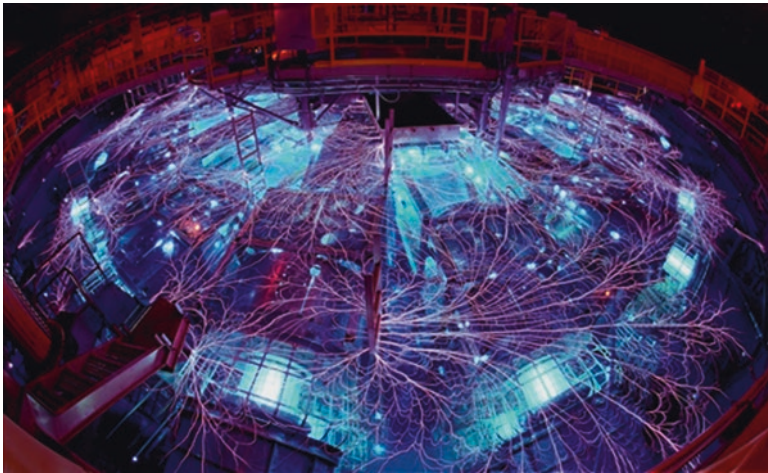


Fig. 8.25 The Z-Machine in operation. This is one of the most epic pictures in all of fusion research. The machine uses so much electrical charge that all the parts must be bathed in a fluid bath to control the arcing. (Image permissions from Troy Rummler of Sandia National Laboratory)

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

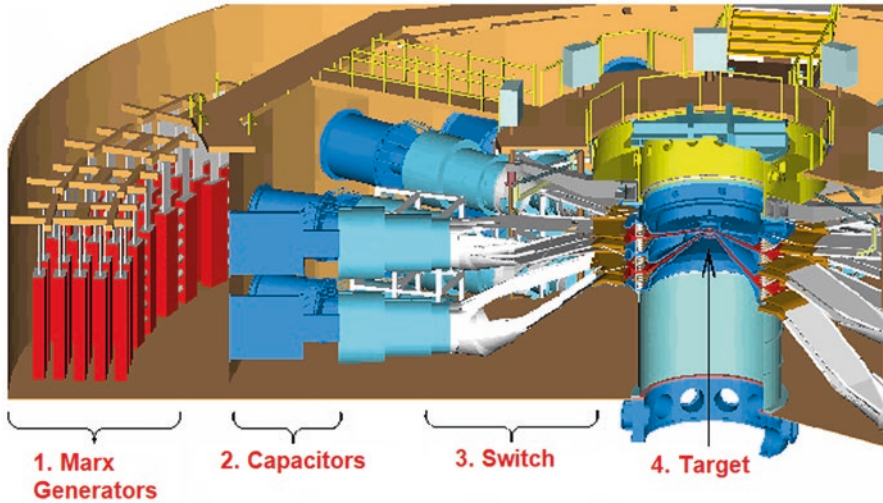


Fig 8.26 A cutaway view of the Z-Machine design from the side [7, 8]. The current travels into the center, passing through four stages. First, the Marx generators create a huge current. The current charges giant capacitors that ring the device and store the electric charge. A switch is then thrown, which 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,

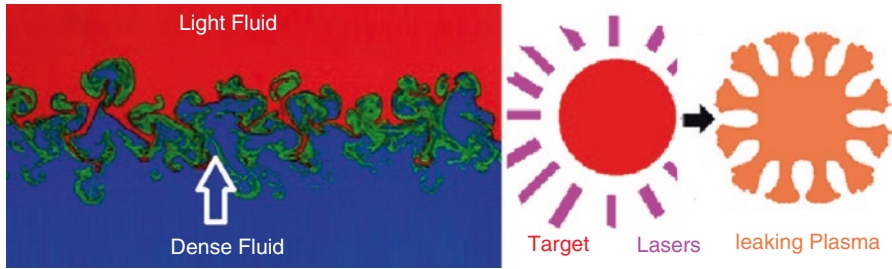


Fig. 8.27 (Left) The classical picture of the Rayleigh-Taylor instability, a dense fluid pressing on a light fluid and the surface breaking up. (Right) In ICF, this results in the leakage of plasma from a compressing target. (Image courtesy of rheologic incorporated)

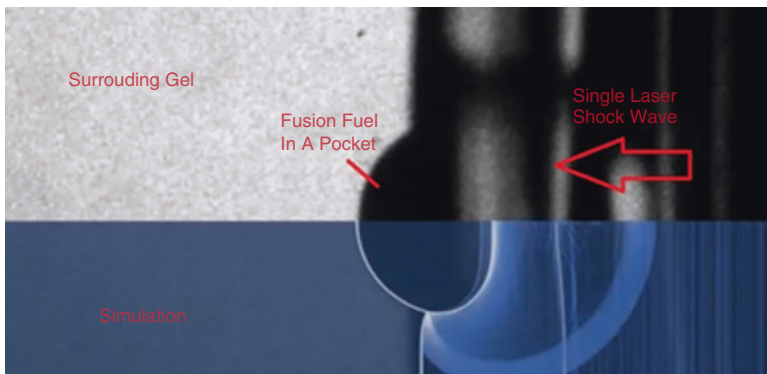


Fig. 8.28 An early image from First Light Fusion showing a model and early experiment of a one-dimensional compression. Here, the fuel is held in a pocket in a solid gel and blasted by a shock wave made by a projectile. This test was most surely used to benchmark the company's custom computer codes. (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

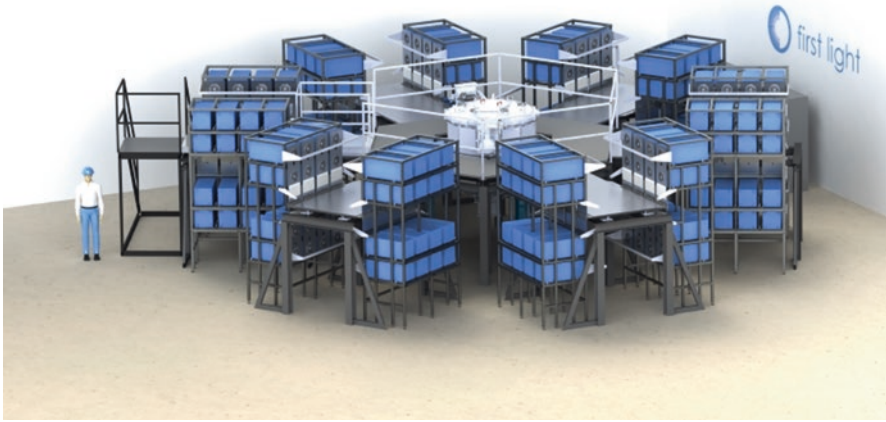


Fig. 8.29 Computer-aided design image of First Light’s “Machine 3,” which was ultimately built in the winter of 2018–2019. (Image courtesy of Nicholas Hawker, First Light Fusion)



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.

References

1. Cheng, Baolian, Thomas J. T. Kwan, Yi-Ming Wang, and Steven H. Batha. "Scaling Laws for Ignition at the National Ignition Facility from First Principles." *Physical Review E* 88.4 (2013). American Physical Society. Web. 17 May 2014.

2. "Development of the Indirect-drive Approach to Inertial Confinement Fusion and the Target Physics Basis for Ignition and Gain." John Lindl. AIP Physics of Plasma. American Institute of Physics, 14 June 1995.
3. Cheng, Baolian. "Thermonuclear Ignition Criterion and Scaling Laws for ICF Capsules." Invited Talk. Laboratory for Laser Energetics, Rochester New York. Mar. 2013. Lecture.
4. Chang, P. Y., et al. "Fusion yield enhancement in magnetized laser-driven implosions." *Physical review letters* 107.3 (2011): 035006.
5. Seidl, P. A., et al. "Demonstration of a compact linear accelerator." *arXiv preprint arXiv:1802.00173* (2018).
6. Moses, Edward I. "The National Ignition Facility: Exploring ICF Burning Plasmas in the Laboratory." Presentation to the American Association for the Advancement of Science. Washington DC. 18 Feb. 2005. Slide 29. Lecture.
7. Slutz, S. A., et al. "Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field." *Physics of Plasmas* 17.5 (2010): 056303.
8. "Nuclear Fusion Energy: The Race to Create a Star on Earth" Interview with Dr. Michael Cuneo, Z Machine, Managing Engineer, Oct 26, 2017, Motherboard.
9. Gomez, Matthew R., et al. "Experimental demonstration of fusion-relevant conditions in magnetized liner inertial fusion." *Physical review letters* 113.15 (2014): 155003.
10. Nuckolls, John; Wood, Lowell; Thiessen, Albert; Zimmerman, George (15 September 1972). "Laser compression of matter to super high densities: thermonuclear applications". *Nature*. 239: 139–142.
11. "Early Steps Toward Inertial Fusion Energy (IFE) (1952 to 1962)", UCRL-ID-131075, John H. Nuckoll, Livermore National Laboratory, June 12th 1998.
12. Ray Kidder: Oral History, Tuesday, 29 April 2008, Interviewed by: Alex Wellerstein, American Institute of Physics.
13. Horgan J. Infighting Among Rival Theorists Imperils "Hot" Fusion Lab Plan. *The Scientist Magazine*®. Published June 25, 1989. Accessed March 21, 2022. <https://www.the-scientist.com/news/infighting-among-rival-theorists-imperils-hot-fusion-lab-plan-61962>
14. Perkins, Roger B. Laser-fusion program at Los Alamos. No. LA-UR-77-174. Los Alamos National Lab. (LANL), Los Alamos, NM (United States), 1977.
15. Shapovalov, R. V., et al. "Design of 30-T pulsed magnetic field generator for magnetized high-energy-density plasma experiments." *Physical Review Accelerators and Beams* 22.8 (2019): 080401.
16. Clauser, M. J. "Ion-beam implosion of fusion targets." *Physical Review Letters* 35.13 (1975): 848.
17. Lawrence Berkeley National Laboratory (LBNL) | arpa-e.energy.gov. [Energy.gov](https://energy.gov). Published 2021. Accessed March 21, 2022. <https://arpa-e.energy.gov/technologies/projects/mems-based-drivers-fusion>
18. Olson, R. E., M. G. Mazarakis, and C. L. Olson. "The light ion beam approach to ICF energy production." *Fusion technology* 26.3P2 (1994): 922–925.
19. Xun, Tao, et al. "A ceramic radial insulation structure for a relativistic electron beam vacuum diode." *Review of Scientific Instruments* 79.6 (2008): 063303.
20. "Inertial-Fusion Program January—December 1980" The Inertial Fusion Program Staff LA—9086-PR, DE82 019495, May 1982.
21. "Obenschain, S. P., et al. "Direct drive with the argon fluoride laser as a path to high fusion gain with sub-megajoule laser energy." *Philosophical Transactions of the Royal Society A* 378.2184 (2020): 20200031."
22. Peaslee, Jr, A T. Proceedings of the impact fusion workshop. United States: N. p., 1979. Web.
23. "General Atomics Target Catalog" 2016.
24. Obituary for Moshe J. Lubin (Aged 55)—[Newspapers.com](https://www.newspapers.com). [Newspapers.com](https://www.newspapers.com). Published 2020. Accessed March 21, 2022. <https://www.newspapers.com/clip/55328878/obituary-for-moshe-j-lubin-aged-55/>
25. Double emulsion generation in the mass production of inertial confinement fusion targets using T-junctions—ProQuest. [Proquest.com](https://www.proquest.com). Published 2013. Accessed March 22, 2022. [https://](https://www.proquest.com)

www.proquest.com/openview/293948e4c1d7cc084e2eb75681162fca/1?pq-origsite=scholar&cbl=18750

26. “The threshold of ignition on the NIF and laying the path towards Inertial Fusion Energy (IFE)”
Tammy Ma, LLNL-PRES-XXXXXX, Presentation at the 2021 Fusion Power Associates meeting, December 15, 2021.