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ORIGINAL RESEARCH

Some Observations on Future Directions in Fusion Energy Research

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Abstract Over the years the author has written, coordinated, or contributed to numerous reviews of fusion energy. In revisiting them, he is encouraged by the tremendous progress that has been made across the board. Nevertheless, while he believes that a viable fusion reactor could be made in both magnetic and inertial fusion energy, he doesn't think the best approach has yet been identified in either area. Also there remain a number of critical, hardly-explored areas. The author identifies three key issues. Finally, he comments briefly on all the major confinement approaches.

Keywords Fusion energy · Magnetic fusion · Inertial fusion

Introduction

Over the years I have written or helped coordinate reviews of fusion energy: "Status of the Tokamak Program," 1981 [1]; "The Physics of Magnetic Fusion Reactors", 1994 [2]; *Opportunities in the Fusion Energy Sciences Program,* 1999 [3]; and the National Academies, "An Assessment of the Prospects for Inertial Fusion Energy," 2013 [4].

Revisiting these papers I can see the huge advances that have been made. I believe firmly that a viable fusion power plant is possible in both the magnetic (MFE) and inertial (IFE) fusion areas. Nevertheless, I don't think the best approach has yet been identified in either case, there remain number of critical, hardly explored areas; and, repeatedly, the program has missed the boat by terminating interesting experiments before they could answer significant questions.

The overriding issue that confronts the field on the path to the realization of useful fusion energy is obtaining an adequate availability (f_{av}). The capacity factor, which is the equivalent availability at full power (P_e) is sometimes used. The cost of electricity COE is proportional to $1/(f_{av} \cdot P_e)$. Three critical issue that contribute to the present uncertainty are:

1. There is no data at the necessary fusion energy-level, high-power density: in MFE in steady state or repetitive, ultra-long pulse plasma operation; nor in IFE repetitively pulsed.
2. There is no material demonstrated to be able to handle the required 14 MeV neutron fluence for a D-T fueled power reactor.
3. There is hardly any data on reliability and availability under power plant conditions. For example, the availability will be affected by how often the first wall and divertor targets will need replacement.

In regard to all three points it would be worth investigating how low a power flux might be acceptable from a cost of electricity point of view (discussed below).

In the same vein, it would be worth finding out for D-T systems what 14 MeV flux and fluence would be acceptable. In addition, it makes sense to support the study of approaches to reduce the neutron flux through the use of alternative fuels. I'll return to that later.

Nevertheless, in principle, there are solutions to all these problems.

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High Power Flux, Reactor Time-Scale Operation

In the magnetic fusion (MFE) area, the field is fortunate to have a number of tokamaks and stellarators, built or in construction, which can operate either long pulse or steady state. Data from them will be crucial to identifying the optimum path forward. It is most important that these facilities push the power flux and fluence to reactor levels to demonstrate that erosion rates are acceptable. ITER will eventually, I hope, add to that data base with D-T fuel, albeit at less than reactor neutron level power flux. Consequently, a steady state (ultra-long pulse) D-T burning system will be desirable to qualify the divertor approach and other technologies that have to handle both the heat and particle flux at the economically necessary neutron flux and fluence.

In the inertial fusion (IFE) area, the field is fortunate to have the large facilities NIF, Omega, Z, and LMJ. But these only give single shot data. In NIF, assuming significant gain with half the lasers, it should be possible to do a two shot test. However, in the end, a facility will be required to demonstrate repetitively pulsed, high-power D-T shots. Obviously, efficient, repetitively-pulsed drivers will be needed. Good progress has been made in both the diode-pumped solid state and KrF laser approaches [4]. There also appear to be options for ion beams and pulsed power [4].

Neutron-Resistant Materials

In regards to alternative fuels, there is unlikely to be any fusion fuel that has no neutrons. Even p-B^{11}, which produces 3 He^4, also produces a neutron through the B^{11}–He^4 reaction, see McNally [5]. Therefore any fusion power plant will become radioactive and likely require remote handling. The whole field is fortunate that JET has demonstrated practical remote handling. Importantly on two issues: the first in replacing a toroidal field/vacuum vessel octant; and second in recently replacing all the vacuum vessel internals. ITER is now the driver for this critical area.

Back to the materials issue: Until we know (and I mean by experiment) what neutron fluence our best material can withstand, we are in no position to pick a system. Options depending on the results are shown in Table 1. The assumption is that replacements of the first wall elements should not be more than once every 5 years at 80 % capacity factor.

Capacity Factor

As stated above, the cost of electricity is inversely proportional to the capacity factor, and we have no idea whether this could be 10 %, let alone the 80 % or so required for economic viability.

The capacity factor will be higher if replacements requiring downtime are less frequent [11]. Because first wall/blanket replacement is likely to be very time consuming, higher neutron fluence materials and lower power density would be an advantage in this regard. Mitigating against the advantages of lower power density is the increase in capital cost per unit of power. Over the years many reactor studies have investigated lower power densities e.g., ARIES [6] and European studies [8] and a recent generic reactor study [7]. This is an area that would benefit from further investigations.

In principle, a thick liquid wall might overcome this problem, but it is an option available to only a few configurations, notably some IFE options and compact toroids.

As a final comment, I note that fission reactors were developed and deployed primarily by governments. Early reactors had availabilities around 50 %. In most countries, it was governments that supported the continuing program that led, eventually, to the 80–90 % availabilities found today. I expect the same approach will be needed for fusion to gain a solid position in the marketplace.

Taking these points into consideration, here is my assessment of the various approaches to fusion energy.

Magnetic Fusion

Tokamak has good enough confinement and adequate beta to make an energy producing reactor. The axi-symmetric divertor is an attractive feature. However, it is not inherently steady state and suffers major disruptions. Also the density limit makes it harder to find a convenient operating range. It is not totally clear to me that there is a good combination of safety factor q_a, q-profile, density, and beta that allows acceptable non-inductive current drive and steady-state. Repetitive long pulse operation is a possibility but has the penalty of needing massive energy storage to maintain blanket temperature and gradients. Also pulsing probably enhances the possibility of disruptions.

Spherical torus is simply a low aspect ratio tokamak. It has higher beta, but what matters for power density is beta $\times$ B^2 and the ratio B/B_{max} (where B_{max} is the field on the toroidal coils) decreases rapidly with decreasing aspect ratio. In total there may not be a great advantage over the tokamak because of the likely need for copper coils which allow less shielding in the bore to maximize field ratio. In my opinion it is a good option for a high power density, neutron and plasma test facility (see the analysis of options in Ref. [12]).

Modular stellarator has comparable confinement to a tokamak (tested to low collisionality), and a potentially higher range of beta. Has no damaging density limit. The only truly steady state option and it does not need current

Table 1 The permitted neutron fluence (primarily in relation to 14 MeV) is shown for various fuel options

Permitted fluence MW y m^{-2}	D-T[a] MW m^{-2}	Catalyzed D–D MW m^{-2}	Other alternative fuels. MW m^{-2}
15	≤3.75	≤3.75	Yes
10	≤2.5	≤2.5	Yes
5	Marginal for < 1.25[b]	≤1.25[c]	Yes
1	Not economic	Not economic	≤0.25

[a] Most MFE and IFE power plants e.g., ARIES [6] and LIFE [4] have been designed in the upper levels shown here, but, in principle, similar results to MFE [7] should be possible for IFE, e.g., the lower neutron flux should improve the capacity factor

[b] A recent generic analysis for toroidal systems shows relatively small cost penalties down to 1.5 MW y m^{-2} [7], see also [8]

[c] A study of catalyzed D-D stellarators suggests that a neutron flux down to 0.75 MW y m^{-2} or even lower might be possible [9, 10]

drive. The modular coil options pioneered by the Germans [13] appear to be the best bet, but the divertor is the main issue. Some people fear the twisty coils but they are a well-posed engineering problem and approaches exist for making reactor scale versions. A problem at the moment is that there are many options. And we need tests of more configurations to determine the optimum coils set (in my opinion, it's a pity the Princeton Plasma Physics Laboratory didn't get a chance to assemble NCSX). I believe that one of the lower aspect ratio modular stellarators will make the best MFE reactor [14].

The Heliotron/torsatron a stellarator with the advantage of a continuous divertor, but I don't think it has the potential for such a good combination of plasma parameters [Note: originally proposed by Gourdon and Marty (France) and Koji Uo (Japan)]. Developed and built in the present form (LHD) following ATF at Oak Ridge National Laboratory [15].

Reversed field pinch good enough beta with sort of okay confinement but it is not clear how it would usefully be run steady state and needs work on the divertor. I don't see a significant advantage over the options above.

Spheromak good enough beta, but adequacy of confinement questionable. Helicity injection for steady state is interesting. Potential for a simple divertor. Worth pursuing, see U. Washington [16], but I think it's a long shot. Needs a substantial reactor study with full consideration of 14 MeV neutron shielding and remote handling.

Field reversed configuration Highest beta of all options. Confinement questionable, so reactor solutions often involve pulsed operation with compression or colliding plasmas with beam injection. There is the potential for a simple divertor and direct recovery [16–18]. These systems are worth pursuing but I think they're a long shot. The area needs a substantial reactor study with full consideration of 14 MeV neutron shielding and remote handling if it uses D-T or D-D fuel.

Inertial Fusion

Good reviews of all areas are in Ref. [4].

Laser fusion Considerable progress has been made in this area, notable with the work at Lawrence Livermore National Laboratory, Naval Research Laboratory, U. Rochester, and U. Osaka, but as seen by the recent issues on NIF, it is clear that the existing models did not capture adequately the laser-plasma interactions. This has to be a concern for both indirect and direct drive. The Halite Centurion tests are often used to support the claim that codes exist that can simulate the operation of IFE targets. However, to the extent that one understands what was done in these tests, they didn't use lasers or particle beams. It is possible that the shortest wavelength laser light will be needed i.e., like that in the KrF laser or 4th harmonic glass laser. In the former case, the efficiency is at best 7 % or so and in the latter case there are severe issues of damage of components. Nevertheless, researchers have always shown considerable ingenuity and I am sure they will come up with something viable. Alternatively, and more worrying, the problem with low gain is simply gross instabilities at this small size.

The LIFE reactor study [19] had lots of interesting ideas, but suffers from having been oversold. What is needed is for the laser fusion community to get together and combine their best ideas.

Heavy ion-beam fusion in this system the X-rays for the indirect drive are produced by stopping the ion beams in a dense material. This process is well understood and it should be possible to provide the necessary X-ray pattern to compress the target. There are no laser-plasma instabilities. However, though good progress was made in Lawrence Berkeley National Laboratory program, the ion-beam development program is a long way from producing the necessary hardware; and demonstrating acceptable performance and cost.

Pulsed power I am certain that the pulsed powers systems being developed at Sandia National Laboratory would be capable of achieving the needed parameters for a reactor, and the cost to meet the needs of proposed targets. Also, I believe that there are number of target options, though they need to be demonstrated, e.g., the magnetized target. However, all those approaches require a target replacement system that can handle the repetitive reconnection of megamperes of current, e.g., once every 10 s. Until this capability is demonstrated the approach remains a long shot.

Lost Opportunities

Over the years, notably in the U.S., facilities have been built and either not operated or terminated before they could perform the critical tests they were designed to explore. Sometimes facilities have been built, but then were not provided with the necessary diagnostics and/or heating I'm sure that everyone has their view of which facilities I'm talking about. I'm not going to list my choices, but rather say to funding agencies that while we all see the need to delete tired old facilities, please don't build stuff if you think you may not be able to support it adequately.

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