Fusion Energy: Research At the Crossroads

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February 2019

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Submitted to Joule
Introduction:

Fusion is the process by which light elements combine to form heavier elements releasing enormous amounts of energy. It is the ultimate source of energy in the universe, powering the sun and the stars and creating all the elements of the periodic table. The fuels for fusion are deuterium, a naturally occurring form of hydrogen, and lithium - each sufficient on Earth to meet humankind’s energy needs for millions of years. The energy density contained in fusion fuels is so large that a mere 0.1 g of deuterium, what is found in 3 gallons of ordinary water, would provide the domestic and industrial electricity demands for a typical American for a year. Fusion does not create greenhouse gases like carbon dioxide, or pollutants like sulfur dioxide or nitrogen dioxide, nor particulates like soot. The fusion reaction would simply be a new source of heat used to create steam to drive a turbine and generator - exactly the way that most electricity is produced today. The need and the promise of fusion energy are clear. The big question is whether it can be brought on line soon enough to be part of the solution to global warming.

Fusion Basics:

Practical fusion energy requires heating matter to extreme temperatures, on the order of 200 million degrees. For two nuclei to fuse with useful probability, they must approach each other to distances comparable to the range of the strong nuclear force – about $10^{-15}$ m. Given their electrostatic repulsion, this can only occur when they have kinetic energies above 20 keV. Even at these energies, elastic scattering is about 100 times more likely than a fusion reaction, so particles in a fusion device scatter and thermalize. At such elevated temperatures, fuel atoms are fully ionized becoming an electrically conductive fluid called a plasma – the fourth state of matter.

We can only reach these sorts of temperatures if the plasma is very well insulated from ordinary matter. Ordinary insulation cannot be used because of the temperatures involved, however plasma is electrically conductive and can be controlled and contained by strong magnetic fields. The basic principle is simple – charged particles in a magnetic field revolve or “gyrate” in circular motion with a radius $\rho \propto \sqrt{mE / B}$ (where m and E are the mass and energy of the particle and B is the magnetic field strength). This is only true for motion across a magnetic field – along the direction of the field lines, the particles move freely and would escape that way if allowed. So, to fully confine the plasma, the field is arranged to eliminate the losses out the ends by eliminating the ends, leading to configurations with a characteristic toroidal or donut shape. The quality of thermal insulation is measured as an energy confinement time $\tau_E$ which in most cases is
dominated by turbulent transport, driven by temperature and pressure gradients. A simplified, single-parameter performance metric for fusion devices can be constructed as the product of the fuel density, n, confinement time and temperature (T), forming the so-called triple product nτE. The dynamics of a magnetized plasma is essentially a problem in classical statistical physics, governed by Boltzmann’s equation, which describes the plasma evolution in a six dimensional phase space. The scientific challenge is substantial; the systems have an enormous range of spatial and temporal scales in complex geometry, are intrinsically nonlinear, strongly anisotropic and multi-physics through coupling to nuclear, atomic and materials processes.

**The Situation Today:**

Fusion’s promise has spurred intense worldwide interest for decades. Years of patient theoretical and experimental research has led to vastly increased understanding about how fusion systems work. In terms of performance, there was a period of great progress from the late 1960s through to the late 1990s. Over those 30 years, nτE increased by a factor of 10,000 (fig. 1). This built confidence in the next step, construction of an experiment that would produce a plasma which produced more fusion power than what was required to sustain it and where self-heating from fusion would dominate. One such device, named ITER, is now under construction in the south of France by a consortium including China, the European Union, India, Japan, Korea, Russia and the United States1.

![Graph showing nτE vs. Year](image1)

*Fig 1. The fusion “triple product” nτE (10^{23} \text{ eV}\cdot\text{s/m}^3) is plotted vs calendar year. In the 30 years between 1968 and 1998 the rate of progress exceeded Moore’s law. The dashed line shows the present time (as of this publication). Projected schedule and performance are shown for two planned experiments.*

At the same time, the fusion ecosystem is broadening. Privately funded efforts are growing and seeking to accelerate the move out of the lab and into the marketplace. These efforts validate the basic value proposition for fusion and have provided new sources of ideas, expertise and
funding. Given the scale of research funded by national governments, the private programs have sought unique niches where their impact can be felt. An industry association formed to promote fusion as a practical energy source and to advocate policies that would speed its realization. The relationship between the private and public fusion sectors is evolving rapidly with opportunities for private-public partnerships under discussion.

Challenge - How To Realize The Potential Of The Technology Soon Enough To Make A Difference:

It is notable that the last point on the $n_T$ curve in figure 1 is 20 years old. The apparent lack of recent progress is not due to fundamental physical limits, rather, it is driven by the scale required. The cost for possible next step devices were very high, difficult to fund and hard to organize. Costing the equivalent of several 10’s of billion US dollars, ITER is the largest research device ever built. Technical issues, that will remain after ITER’s successful completion have been recognized and extensively document by the community, but there is no programmatic sense of urgency to address them. As a result, most national roadmaps don’t see fusion power making much of an impact before the end of this century. The disconnect, between the pace of the national programs versus the needs and expectations of stakeholders outside the program is profound and gives rise to existential concerns. At some point delay may be the equivalent to failure if policy makers and industry conclude that no solution will be forthcoming.

The Technical Basis For A Fusion Energy Breakthrough Is Here:

While fusion research can be carried out on machines with conventional copper electromagnets, a fusion power plant must employ superconductors or their enormous power consumption would prevent the system from ever producing net energy. Until very recently, the best performing superconductors were made from Nb$_3$Sn cooled to liquid helium temperatures. The breakthrough has come in a new class of superconductors, compounded from rare earths and barium copper oxide, (REBCO). These were first discovered in 1986 and were notable for their ability to retain superconducting properties at much higher temperatures. More importantly for this story, the new materials, labeled High Temperature Superconductors (HTS), retain their superconducting properties even when embedded in very strong magnetic fields. Their potential for fusion was recognized immediately but the new superconductors were in the form of fragile crystals and not useful for building magnets. Since then, researchers have found ways to deposit the superconducting compound as thin films on a strong, steel substrate. The resulting conductors – in the form of “tapes” or “ribbons” - have been used to build magnets with unprecedented performance.

For fusion, this changes everything. To understand why ITER had to be so big we go back to the basic ideas for magnetic fusion. The main energy loss mechanism for confined plasmas is through turbulent convection. The turbulent fluctuations, tend to be concentrated at scales that are a few times the ion gyro-radius. At higher magnetic fields, the gyro-radii are smaller so the turbulent scales and transport are reduced. The figure of merit for the quality of thermal insulation is the
number of gyro-radii across the plasma, $R/\rho$ which is proportional to $BR$. Figure 2 shows this result graphically, plotting fusion gain vs $B$ and $R$ (a fusion power plant would need gain greater than 20). The general shape of the curves is given by the simple arguments above but the precise values of each curve required a significant body of research. With conventional superconductors, the region of the figure above 6T was inaccessible, thus ITER with its older magnet technology, is as small as it could be. HTS more than doubles the range of magnetic fields achievable, opening up the possibility of smaller, higher-field devices. Since their weight and volume scale with the size cubed, this greatly reduces the costs. That is, we can trade off $B$ for $R$ in a fusion design and $B$ is much cheaper than $R$. This was demonstrated by a series of compact high-field tokamaks built and operated at MIT in the last several decades, which set a number of significant fusion plasma performance records in their time\textsuperscript{7,8}. The basic argument has been endorsed in a finding of a recent National Academy Study\textsuperscript{9}.

“The rapid progress in HTS magnets may enable significant reductions in the size of magnetic fusion devices and support the compact lower-cost pathway to fusion development.”
The High-Field Path For Fusion Energy

Producing the class of large-volume, high-field superconducting magnets needed for fusion will require overcoming significant challenges in structural and cryogenic engineering and quench dynamics. MIT and Commonwealth Fusion Systems (CFS) have partnered to carry out the necessary R&D. Strategies must also be developed for managing the heat flux and the interface between the hot plasma and ordinary matter. Work thus far, suggests that there are no fundamental obstacles in pursuit of this goal. The collaboration is structured to help bridge the “valley of death” – the gap that can open up between the level of technical readiness typically established by academic or government research and the level required to attract private investment.

Once the magnet development is successful, the next step will be to build and operate SPARC, a type of magnetic confinement device called a tokamak. SPARC could be the first fusion experiment with a plasma that produces more fusion power than what is input to keep it hot, a goal of the fusion program for more than 60 years. A rendering of the SPARC device can be seen in figure 3. With a plasma volume of 15 m$^3$, SPARC would be a mid-sized fusion experiment - of a size and configuration similar to many machines already in operation. With the new HTS magnet technology, it will have an average field in the plasma of 12 Tesla. Based on data from decades of research on dozens of experiments around the world, we can be reasonably confident that a machine with these specifications would reach the net power milestone, while producing more than 50 MW of fusion power.

The next step in this roadmap would be to build and operate a pilot plant, aimed at putting electricity from fusion power onto the grid. Its goal would be to demonstrate the science and technology required for economically competitive, mass production of fusion energy. We can get

**Fig 3.** A rendering of SPARC, a compact, high-field tokamak. With performance enabled by high-temperature superconducting magnets, the SPARC plasma should produce more power than the external heating required to sustain it.
some idea about what this might look like from the high-field ARC concept\textsuperscript{11}. Running at 9.2 Tesla, ARC is about half the linear dimension of ITER, but could produce the same fusion power. Power plants of this size are a good match to the needs of the existing electrical grid. Smaller unit sizes may also allow a deployment strategy where all components are built in factories and shipped to sites for assembly, obviating the need for expensive and inefficient on-site fabrication.

Consideration of the ARC pilot plant highlighted the opportunities for further innovations. For example, the higher specific heat of materials at higher temperatures, combined with additional operational margin afforded by HTS, should allow construction of superconducting coils with demountable joints. This concept could revolutionize construction and maintenance of fusion devices, which otherwise have components trapped by their toroidal field coils. And since fusion power plants need a “blanket” to breed tritium, shield the magnets and extract thermal energy, demountable magnets are synergistic with an additional innovation – the provision of all blanket functions through immersion of the fusion core in a bath of molten salt. This blanket concept dramatically reduces the volume of solid material exposed to high neutron flux, further simplifies maintenance and enables a development path for fusion materials in which replaceable cores are installed successively as part of the R&D program.

Prospects:

A new technology, high-temperature superconductors, provides the technical basis for acceleration of fusion energy development, by increasing the magnetic field and decreasing the size of fusion systems. The faster time scales thus enabled, drives the need for rapid innovation in other technical areas. Synergy between government funded basic research and privately funded efforts focused on commercialization is growing within the fusion ecosystem following highly successful examples from other fields. And while a great deal of work will be required, and significant hurdles must be overcome to take advantage of the confluence of needs and opportunities, there is good reason to be optimistic that the promise of fusion energy will finally be realized.

Acknowledgements

This work is a summary of ideas developed by the SPARC team in recent years. Ongoing funding is provided by Commonwealth Fusion Systems.

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