GA–A23372

WHAT IS HAPPENING WITH FUSION ENERGY?

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APRIL 2000

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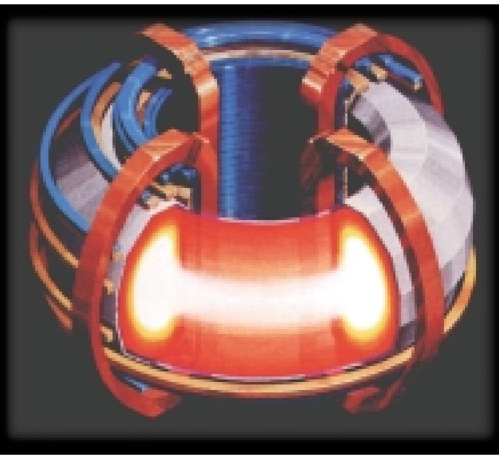
This is a preprint of a paper to be submitted for publication in *The Industrial Physicist*.

Work supported by
General Atomics
under IR&D Funding

GA PROJECT 09491
APRIL 2000

CAN THE POWER OF THE SUN REALLY BE HARNESSED?

Fusion energy, the result of fusing light atoms such as hydrogen to form heavier lements, powers the sun and the stars. Controlling the fusion process to produce electricity would offer tremendous benefits over fossil-fuel and nuclear fission power plants. Like fission, fusion causes no air pollution. Fusion could reduce nuclear waste and eliminate public concern about nuclear accidents. Moreover, the major fuel of fusion, deuterium, is abundant, inexhaustible, and readily extracted from water. The trace deuterium in a gallon of water would provide as much energy as 300 gallons of gasoline wiht just a little helium exhaust.



THE ADVANCED TOKAMAK

Russian scientists invented the tokamak, a toroidal vacuum chamber for plasma confinement, in the 1950s. The name is a contraction of the Russian words for “toroidal,” “chamber,” and “magnetic.”

The conventional pulsed tokamak combines magnetic fields generated by magnetic coils encircling the donut-shaped device with electric currents flowing within the plasma to create a magnetic field configuration that confines a high temperature plasma. An electrical transformer induces a voltage in the plasma to generate the plasma current. However, because transformers can only use alternating currents, the current delivered to the plasma is in pulses, and so the plasma's magnetic field has a finite duration, which can be restored with the next pulse.

The new generation tokamak, called the steady-state advanced tokamak, would use microwaves, radio waves, or other waves to drive the plasma currents to maintain a high temperature plasma for long periods. These waves do not need to be pulsed; hence, the term steady state.

The advanced tokamak also uses a D-shaped plasma, such as in the Department of Energy sponsored DIII–D tokamak operated at General Atomics (Fig. 1). A demonstrated advantage of the D-shaped configuration is that it can confine higher plasma pressures, which results in more efficient fusion. System studies indicate that the steady-state advanced tokamak can produce electricity with a smaller plasma volume and at half the cost of a pulsed conventional tokamak.

Fusion would typically use a mixture of deuterium and tritium in a plasma. When a deuterium ion (one proton and one neutron) fuses with a tritium ion (one proton and two neutrons) and release a neutron. Free neutrons easily sail through the magnetic field confining the plasma and strike the container’s inner wall. Lithium compound-filled “blankets” lining the wall absorb the neutrons, generate tritium, and heat fluids flowing through them. In an operating power plant, this heat would be used to produce steam or high-temperature gas to generate electricity.

Fusion research links compelling science to a big payoff. The extreme temperatures needed for fusion — greater than 1×10^8°C — have been reached by using magnetic fields to confine the plasma. Researchers have now produced fusion power up to 16 MW. New diagnostic instruments and improved simulation capabilities have deepened our understanding of the process to the point that we know we can make fusion-generated electricity a reality. The future challenge is to make fusion energy economical, environmentally practical (fusion turns the interiors of chambers mildly radioactive), reliable, and safe.

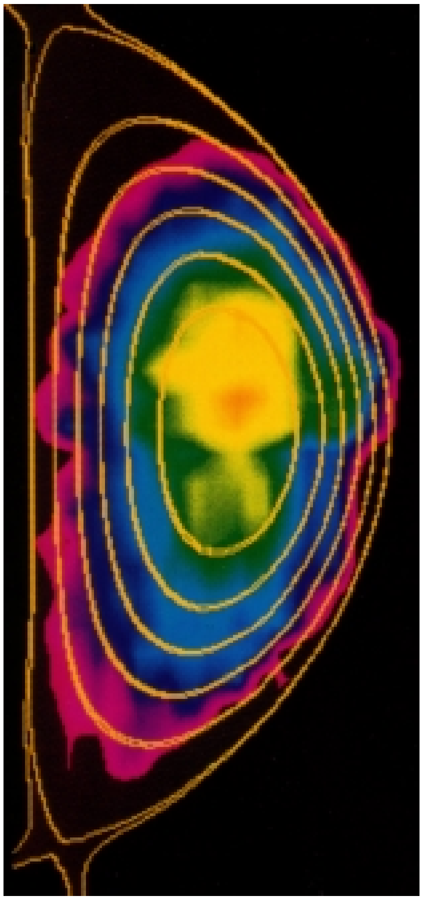


Fig. 1. This soft x-ray emission from a high pressure D-shaped tokamak shows color-coded temperature and magnetic flux surfaces.

The possibility of controlling thermunuclear fusion was suggested in the 1920s and serious efforts to do so began after World War II. During nearly a half-century, scientists have made remarkable advances. Yet despite that progress and the potential payoff, Congress sharply cut fusion funding in 1996, largely because of a desire to reduce the federal budget deficit, a lack of urgency about energy research, and the expense of building the next-step in fusion research facilities.

The cutbacks have changed the character of U.S. fusion research from a program to develop and demonstrate fusion technology to one more focussed on developing a better understanding of the physics involved. The goal today is to establish a stronger scientific base on which to eventually create economically and environmentally attractive fusion power. On the basis of this program restructuring, congressional support has increased and funding has been partially restored.

ADVANCES IN FUSION PHYSICS

Plasmas with the temperatures and densities necessary for fusion are now commonplace in the laboratory, although no one has gotten more power out of a controlled fusion reaction than was put into run it. High — although brief — bursts of fusion energy have been produced in tokamaks that operate with deuterium-tritium plasmas. For example, the Joint European Tokamak (Abingdon, England) recently produced a peak power output of 16 MW after the plasma was heated for 1 s with a power of 25 MW. To build on this base will require a new facility, one capable of heating ionized gases by "plasma burning," a state in which most of the heat needed to maintain temperatures high enough for fusion comes from the fusion reaction itself.

Today, researchers are investigating very high temperature plasmas to determine such things as how energy leaks out across the magnetic field and how currents within the plasma help or hinder heat flow. They are also tackling the challenge of sustaiing high temperature plasmas for the long operational periods demanded by power plants and solving such issues as heat removal, maintaining the plasma's purity, and indefinitely sustaining plasma currents, which greatly influence fusion efficiency. Such experiments have maintained plasmas at high temperatures for up to 2 h.

The concept of a steady-state advanced tokamak, which was pioneered in the United States, is a hot topic of fusion research. It involves shaping the plasma and controlling the profile of plasma currents to enable higher plasma pressures, which generate steady-state plasma currents. Estimates put the cost of electricity to consumers from such an advanced tokamak at $0.05/kWh, which is comparable to that of electricity produced by today's fossil-fuel and nuclear power plants. Electricity produced in advanced tokamaks should be competitive in future energy markets.

Other concepts are also being explored in magnetic and inertial fusion. In magnetic fusion, a group of donut-shaped configurations similar to the tokamak have drawn interest. For example, Japanese and German stellaratros use various magnet shapes to confine plasma without the need to rely on plasma currents. A spherical storus in England and one at the Princeton Plasma Physics Laboratory (Fig. 2) will test the potential of confinement high-pressure plasmas in weak magnetic fields. Several other magnetic concepts are also being investigated in smaller scale experiments.

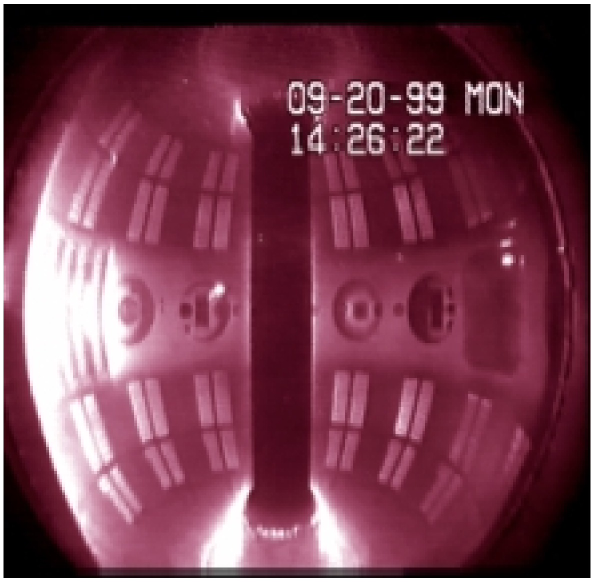


Fig. 2. The spherical torus such as this one at Princeton University, has a central conductor with an extremely small radius and an optimum shape for containing high pressure.

Inertial confinement fusion is different from magnetic confinement. It uses laser beams (or ion beams in the future) to irridiate one millimeter-size shells of deuterium and triutium fuel, as shown in Fig. 3. The beams comress and heat the fuel either directly or through x-rays to enormous pressures to trigger fusion reactions. At the Lawrence Livermore National Laboratory, researchers are building the National Ignition Facility, which is designed to produce more energy from fusion than is in the incident laser beams.

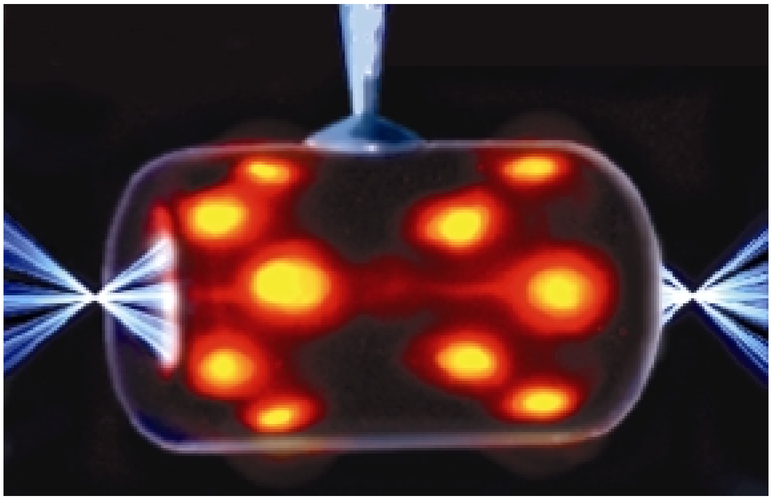


Fig. 3. In inertial confinement fusion, powerful lasers or particle beams focus on small tarts of deuterium and tritium for a few billionths of a second at higher temperature and pressure, forming helium and releasing energy. (Courtesy of Lawrence Livermore National Laboratory.)

FUNDAMENTAL PLASMA PHYSICS

Our understanding of fusion plasmas has undergone remarkable advances in the past decade. The extreme temperatures needed for fusion (up to 4×10^8°C for electrons — which is hotter than the sun) are now routinely reached. Experiments are equipped with diagnostic instruments that can measure plasma properties with high spatial and temporal resolution. Increased computational capability has advanced plasma simulations so that it is now possible to simulate many of the complex phenomena of turbulent transport of energy, plasma stability, and interactions between waves and particles, and interactions between escaped plasma and container walls.

As a result of improved diagnostics and advanced computer simulations, the understanding of turbulence is maturing rapidly. Studies are uncovering how temperature gradients within a plasma drive turbulence. The next generation of computational capabilities will enable even more comprehensive simulation of these complex interacting processes (Fig. 4).

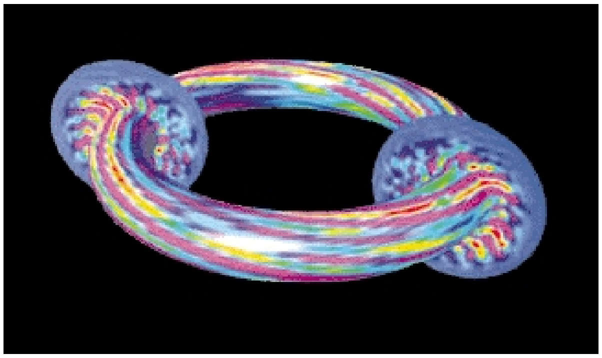


Fig. 4. The computational simulation of plasma turbulence in a tokamak ringe was constructed to aid understanding of how turbulence affects heat transfer and hence the efficiency of fusion. (Courtesy of W. Lee and S. Parker, Princeton Plasma Physics Laboratory.)

Maintaining high plasma pressure and reducing plasma heat loss through magnetic field lines have been achieved by controlling the shear of magnetic field and plasma flow. Magnetic shear is the rate at which the magnetic field-line tilt changes from the plasma center to the edge. Fine tuning the tilt can improve a plasma’s capacity to maintain a high pressure. Optimizing magnetic shear through improved magnetic-coil design or positioning self-driven plasma currents is a major research focus.

Plasma-flow shear recently has been discovered to play a profoundly beneficial role in stabilizing plasma turbulence and reducing heat loss from the plasma to the theoretical minimum. Flow shear suppresses microinstabilities and tears turbulence eddies into small eddies that transport heat less effectively. Although we have gained significant insight into plasma heat loss, aspects of th eprocess remain ares of ongoing study that will require the development of even better turbulence diagnostics to test various theories.

PROGRESS IN FUSION TECHNOLOGY

Researchers worldwide have made significant advances in fusion technologies that will enable building a next-step magnetic fusion facility. Recently, they developed and tested components that include new superconducting magnet technologies, remote maintenance manipulators, and power-exhaust systems. Parts for a superconducting model coil built in the United States, Europe, Japan, and Russia were recently assembled in Japan and are now undergoing testing there.

Controlling the extraction of helium, a byproduct of fusion, has been overcome largely through a combination of physics and engineering innovation. A build-up in the plasma of helium ions — alpha particles — slows the fusion rate. So, magnetic field lines beyond the plasma boundary are directed to a locaton called the divertor, where the helium particles are removed. Ongoing challenges for fusion technology researchers include maintaining plasma purity, preventing erosion of wall materials, and producing tritium.

Improved systems are being developed to heat plasmas to fusion temperatures and drive currents. Communications Power Industries has developed 110 GHz, 1 MW gyrotron used for generating high frequency, high power microwaves. General Atomics has developed low-loss, quasi-optical waveguide transmission systems. Future challenges include increasing gyrotron frequency, power, efficiency, and reliability.

Fusion science and technology have contributed to a broad range of commercial applications and products. Plasma-aided manufacturing of integrated circuits and semiconductor chips has enabled major advances in computer technology (see *The Industrial Physicist*, October 1999, pp. 18–21). Plasma processing of engine components and tools has greatly extended their lifetimes. Superconducting magnets, microwave sources, and lasers developed for fusoin research are widely deployed in commercial products and applications. Inertial fusion researchers using high power lasers beams have created extremely dense plasmas that have enabled them to study astrophysical phenomena.

WHAT NEXT?

Megawatt fusion power pulses are routinely produced, scientific understanding of the complex physics underlying fusion plasma is maturing, technology for the next step in controlled fusion has been developed, and ideas for improving the production of fusion energy are being investigated. In light of this progress, fusion research has several future opportunities and choices. Although it has been difficult to obtain a consensus on the best course to pursue within budge constraints, the U.S. fusion community is converging on some common views.

First there is the need to deepen scientific understanding by embracing innovation, exploring a variety of concepts for magnetic and inertial confinement fusion, strengthening simulation capabilities, fostering internatinal collaboration, and sustaining university programs to educate future researchers.

Second, researchers have identified plasma burning as the next magnetic fusion scientific frontier and concluded that the science and technology exist to build a tokamak to study the process. Such a facility would address the generic issues of plasma self-heating, energetic alpha-particle physics, plasma burn control, and fusion technologies. However, opinions differ on design specifics, how comprehensive the next step should be, and how prototypical of an eventual power plant the test-bed should be.

A new facility will be required that will either need to be almost twice the size of today’s largest tokamaks or have almost twice the magnetic field strength. A larger facility would be more prototypical of eventual power plants but also more expensive to build. A smaller one with greater magnetic field strength would be less expensive but would address fewer key technical issues.

Today, the focus of magnetic fusion researchers outside the United States is one the engineering design of the International Thermonuclear Experimental Reactor (ITER), a next-step fusion facility sponsored by European nations, Russia, and Japan. U.S. participation in the collaboration ended in 1998 because the planned design was viewed as too expensive and unlikely to go to construction. Now, a new design has emerged — smaller, less expensive, and more flexible — that incorporates advanced tokamak features that the previous design lacked.

Most U.S. fusion scientists hope that the United States will be able to rejoin ITER if construction goes forward.

Third, technologies must eventually be developed for converting fusion energy to electric power and for tritium breeding blankets that will produce fuel for future deuterium-tritium reactions. Activation resistant materials will have a highly beneficial impact.

These are the steps that scientists and policymakers must undertake if magnetic-confinement is to tame the power of the sun.