Nuclear power—fusion

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In the 1990s, experiments in tokamak magnetic fusion devices have finally approached "breakeven"—power out equal to power in—at fusion power levels exceeding 10 MW, and great progress has also been made with inertial-confinement fusion laser experiments. Based on these results, the requirements to achieve ignition and high-energy gain are now fairly clear for both approaches. This article focuses on developments in modern plasma physics that led to these achievements and outlines the historical development of the field. Topics include the stability of magnetic fields, field reconnection and the magnetic dynamo, turbulent heat transport, and plasma absorption of intense beams of light. The article concludes with a brief discussion of future research directions. [S0034-6861(99)00902-2]

I. INTRODUCTION

The earliest speculations about nuclear power—first, about nuclear fusion—followed soon after the publication of Albert Einstein's special theory of relativity. A story related by Edward Teller tells of the young George Gamow's being offered, in 1929, the nightly use of the full electric power grid of Leningrad if he would undertake to create in the laboratory the fusion energy that Atkinson and Houtermans were claiming to be sufficient to explain stars (Teller, 1981). Then, when fission was discovered in 1939, fusion took a back seat as the more readily exploitable fission process forged ahead, culminating in the first fission power reactors in the 1950s.

While the early success of fission reactors came at dazzling speed, the story of fusion power—still in the research stage—is one of persistent determination driven on the one hand by the alluring goal of virtually unlimited and environmentally attractive nuclear power, and on the other by the intellectual appeal of unprecedented technical and scientific challenges that have created the field of modern plasma physics.

Both the allure and the challenges of fusion arise from the nature of the fusion process. Fusion fuel is abundant and cheap, the most easily exploitable fuels being deuterium, occurring naturally in all water, and tritium, which can easily be manufactured inside the fusion reactor by the neutron bombardment of lithium, also abundant in nature. And fusion does not produce nuclear waste directly, though tritium is mildly radioactive and neutron activation of the reactor chamber dictates which structural materials are most useful to minimize waste disposal of components discarded in maintenance or the entire reactor assembly at the end of its life. However, whereas fission occurs at normal temperatures, fusion occurs only at the extreme temperatures characteristic of stars (aside from muon catalysis, which does not require high temperatures but thus far poses other unsolved problems). The fuel with the lowest kindling point is a mixture of deuterium and tritium that ignites at temperatures around 50 keV or 50 million degrees Kelvin. At such high temperatures, the fuel becomes a fully ionized gas, or plasma, hence the prominence of plasma physics in fusion research.

Two approaches to obtaining high-temperature plasmas have dominated the field. One is the confinement of the fuel at moderate pressure by means of magnetic fields, and the other—called inertial-confinement fusion (ICF)—utilizes solid DT targets heated by intense laser beams or ion beams. Impressive progress has been made. While self-sustaining ignition has not yet been achieved, experiments in tokamak magnetic fusion devices have approached "breakeven"—power out equal to the power in—at fusion power levels exceeding 10 MW (Strachan *et al.*, 1994; JET Team, 1997), and great progress has also been made with ICF laser experiments (Lindl, 1995). Based on these results, the physics requirements for achieving ignition are now fairly clear, for both approaches (Fowler, 1997).

In this article, we shall focus on the scientific developments that led to these achievements. Largely through the impetus of fusion research, plasma physics has reached a level of sophistication comparable to older fields of applied science, such as solid-state physics and fluid mechanics. Mastery of plasma physics at a level adequate for understanding fusion plasmas requires a complete synthesis of classical physics. A resurgence of interest in this fundamental discipline has benefited astrophysics, space physics, and applied mathematics and has trained many scientists and engineers who have made outstanding contributions in industry and academia.

II. CREATING MAGNETIC FUSION SCIENCE

Magnetic fusion research began in the 1950s, initially in secret but soon declassified, in 1958, in recognition of the fact that the research would benefit greatly from a concerted world effort and had little connection with nuclear weapons technology or weapons proliferation. Research on the ICF approach began about a decade later and remained classified for a longer time, especially in the U.S., but it too is now largely declassified. The value of international cooperation in fusion research cannot be overstated, in terms both of science and of its contributions to East-West communication during the Cold War. A famous event in fusion history, which heralded the dominant role of the Russian tokamak in magnetic fusion research, was the "airlift" to Moscow, in

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1969, of a British research team using their own equipment to verify Russian claims that they had achieved new records of plasma confinement and the then-unprecedented temperature of 10 million degrees Kelvin. This event, soon followed by confirming experiments in the U.S. and Europe, paved the way for the large tokamak facilities constructed in aftermath of the oil crises of the 1970s—the facilities that have now achieved near-breakeven in the 1990s.

The development of plasma physics for magnetic fusion research has been strongly influenced by the requirements for achieving ignition. It is useful to think of ignition requirements in two steps—first, the creation of a stable magnetic configuration to confine the fuel plasma, and, second, doing so at a critical size large enough so that the fusion reactions heat the fuel faster than the heat can leak away. Examining the history of the tokamak in light of these two requirements will serve to illustrate how and why fusion science developed as it did. A more thorough discussion of tokamaks and other magnetic configurations can be found in Teller (1981) and Sheffield (1994) and a discussion of fusion nuclear engineering in Holdren *et al.* (1988), which compares safety and nuclear waste characteristics of fusion and fission reactors.

The starting point is a magnetic configuration to confine the plasma in a state of equilibrium between magnetic forces and pressure forces. Whereas gravitational forces are symmetrical, so that stars are spheres, the magnetic force is two-dimensional, acting only perpendicular to a current, so that a magnetically confined plasma is a cylinder. The tokamak, invented by Igor Tamm and Andrei Sakharov in the Soviet Union, is descended from the linear ''pinch,'' a plasma column carrying currents along its length whose mutual attraction constricts the plasma away from the walls of the tube that contains it, as discovered by Willard Bennett in 1934. Early linear pinch experiments at Los Alamos and elsewhere proved to be unstable, and heat leaked out the ends, defects remedied in the tokamak by bending the cylinder into a closed ring or torus, stabilized by a strong field generated by a solenoid wrapped around the toroidally shaped vacuum vessel. Bending the current channel into a circle requires an additional ''vertical'' field perpendicular to the plane of the torus. Thus the tokamak solves the requirement of stable confinement using three sources of magnetic field—the vertical field to confine the current, the current to confine the plasma, and the solenoid to stabilize the current channel.

The stability of the tokamak follows from its magnetic geometry, in which the field lines produced by the toroidal solenoid are given a helical twist by the current. Ideally, these twisting field lines trace out symmetric, closed toroidal surfaces—called flux surfaces—nested one inside the other. A similar concept, not requiring currents in the plasma, is the stellarator, invented by Lyman Spitzer in the early 1950s. A major theoretical achievement, published by Bernstein, Frieman, Kruskal, and Kulsrud (1958), is the energy principle, whereby the stability of tokamaks or any other magnetic configuration can be determined exactly within the constraints of magnetohydrodynamic (MHD) theory borrowed from astrophysics, in which the plasma is treated as a fluid represented by averaging the equations of motion over all particles in the plasma.

By the late 1960s, fusion scientists had repaid their debt to astrophysics by their own extensions of the theory including the effects of resistivity due to Coulomb collisions between electrons and ions. In fusion devices carrying current, the magnetic structure can be disrupted by breaking or ''tearing'' of the field lines due to resistivity—an example of magnetic reconnection prevalent in many astrophysical phenomena and in planetary magnetic fields, and an early example of ''chaos'' in which the current channel breaks up into filaments that create islands in the field structure or field lines wandering out of the machine. For tokamaks, the study of tearing was motivated by occasional violent disruptions of the current channel, which must be understood and controlled to avoid severe damage to the machine. In other magnetic confinement geometries, discussed below, tearing can actually serve the useful purpose of self-organization of plasma currents into a stable configuration. Thus we see how, in concentrating on the creation of stable magnetic configurations to meet a basic ignition requirement, fusion science has evolved a fundamental understanding of magnetized plasmas that has simultaneously contributed to solving a practical problem in tokamak design, shed light on phenomena ubiquitous in nature, contributed to the development of chaos theory in applied mathematics and many fields of physics, and stimulated new inventions in fusion research.

Of even greater impact on plasma physics, and on our understanding of turbulence in fluids, has been the extensive body of experimental and theoretical work aimed at the second ignition requirement, to determine the critical size at which fusion power production exceeds heat transport out of the plasma. Given a stable magnetic structure, heat can still be transported by entropy generation associated with processes not included in the energy principle, which assumes perfect conductivity along field lines. One such process, already mentioned, is resistivity, for which the entropy generation rate can be calculated accurately. ''Classical'' resistive transport, due to Coulomb collisions, is relatively weak and diminishes greatly at high temperatures. More important but more difficult to calculate is transport due to microscopic turbulence associated with the buildup of weak electric fields parallel to the magnetic field **B**. Though usually too weak to affect the resistivity in fusion plasmas, these weak parallel electric fields also imply components perpendicular to **B** that cause plasma particles to execute cycloidal orbits drifting between flux surfaces. Small perturbations grow into turbulence if the drifting motion is amplified, as can be true in tokamaks for perturbation wavelengths a few times the orbital radius of ions spinning in the magnetic field. At this time, the main information about turbulent transport is obtained empirically, by fitting formulas to the results of numerous tokamak experiments, guided in part by dimensional analysis to suggest scaling laws appropriate for particular physical processes. Computer codes, called particle-in-cell (PIC) codes, have been used to simulate drift motion turbulence (drift waves) by following the detailed motion of thousands of particles representing charge clouds generated by the turbulence. Other codes, focusing on magnetic turbulence, follow the nonlinear evolution of "tearing" modes. Calibration of code results with experimental data shows promise, though machine designers still must rely heavily on the empirical approach.

Theoretically, the potential for microturbulence is studied by examining the stability properties of the Vlasov equation, in which ions and electrons are represented by distribution functions $f(\mathbf{x},\mathbf{v},t)$ in the phase space of position $\mathbf{x}$ and velocity $\mathbf{v}$. The Vlasov equation is just the continuity equation in this phase space—a Liouville equation with Hamiltonian forces, coupled to Maxwell's equations in which the charge and current densities are obtained by velocity averages of the Vlasov distribution function. The MHD fluid equations can be derived as velocity moments of the Vlasov equation. Stability is studied by searching for growing eigenmodes of the Vlasov equation linearized around an equilibrium distribution. It can also be shown that, as for the MHD equations, there must exist a corresponding "energy principle" for the linearized Vlasov equation; correspondingly, the nonlinear theory should possess a generalized entropy and associated "free energy" from which transport could be derived. Though useful conceptually, this approach has not yet yielded many calculational results (Fowler, 1968).

At the time this article appears, a promising new direction—already being exploited experimentally—is the reduction of transport by the deliberate introduction of sheared flows and "reversed" magnetic shear that break up the collective motions produced by turbulence. Initially discovered experimentally in the 1980s as the "*H* mode" of operation with reduced transport at the plasma edge, with theoretical guidance this technique has now been extended throughout the plasma volume, resulting in heat transport associated with the ions at the minimum rates allowed by Coulomb collisions, though electron-related transport still appears to be governed by turbulence.

As a final example of fusion-inspired plasma physics, we return to the tokamak and its requirement for a strong current circulating around the torus. In existing tokamaks, the current is induced by the changing flux of a transformer, the plasma ring itself acting as the secondary winding, but already methods have been demonstrated that can drive a steady current (energetic atomic beams, microwaves, etc.). All such methods would be too inefficient, producing unwanted heating, were it not for the fact that, miraculously, the tokamak can generate most of its own current, called the "bootstrap" current. Again the reason lies in the equation of motion, now having to do with the nonuniformity of the magnetic field in a tokamak, which causes additional oscillatory drift motion due to changes in the orbital radius as particles spin around field lines. The enhanced transport of particles due to collisions among these magnetically drifting orbits, called "neoclassical" transport, drives a dynamo-like response as the conducting plasma flows across magnetic field lines, and this dynamo drives the bootstrap current. It is neoclassical heat transport by ions that gives the minimum possible rate of entropy generation and the minimum possible heat transport in a tokamak.

A different mechanism of current generation is the magnetic dynamo, now arising from the statistical average of the $\mathbf{v}\times\mathbf{B}$ force in a magnetic field undergoing turbulent fluctuations due to tearing and reconnection. Whereas the collisional bootstrap current creates magnetic flux, this magnetic dynamo mainly reorganizes the field due to the approximate conservation of a quantity called "helicity," given by an integral of the scalar product of $\mathbf{B}$ and the vector potential $\mathbf{A}$. Though of limited importance in tokamaks, in which tearing is largely suppressed by the strong toroidal field, in other concepts, such as the reversed-field pinch (RFP), the plasma generates its own toroidal field as it relaxes toward a state of minimum magnetic energy at fixed helicity—known as "Taylor relaxation" (Taylor, 1986). An open question at this time is the extent to which turbulent relaxation creates unacceptable heat transport as the field continually readjusts to compensate for resistive decay near the plasma boundary where the temperature is lowest and the resistivity is highest.

III. INERTIAL-CONFINEMENT FUSION

Turning briefly to the ICF approach, we find entirely different physics issues, reflecting an entirely different solution to the basic requirements of a stable assembly of fuel and the critical size to achieve ignition. Though heating the solid target also forms a plasma, its density is so high that plasma turbulence is irrelevant in calculating the critical size. However, achieving a useful critical size requires that the fuel first be compressed to densities many hundreds of times that of ordinary materials. This is accomplished by heating the spherical target uniformly from all sides, whereby the intense heating of the surface creates an inward implosion of the fuel as the surface layer, called the ablator, explodes outward. At the intensity of giant lasers now available, implosion pressures of millions of atmospheres are created, compressing the fuel to 100 times liquid density, and a 1000-fold or more compression should be possible. The physics issues concern mainly the uniformity of illumination and target design requirements to suppress hydrodynamic instability that amplifies imperfections in the surface finish.

Plasma physics enters mainly in ensuring efficient absorption of the laser energy before the beams are reflected at the "cutoff" density at which the laser frequency matches the "plasma frequency" (the same condition as that for the reflection of light from an ordinary mirror). Two methods are employed, the direct-drive approach, in which laser beams shine directly on the target, and indirect drive, in which the target is mounted inside a tiny metal cylinder, called a hohlraum, which converts laser light to x rays that in turn irradiate the target. For both approaches, efficient absorption—either in a plasma cloud surrounding the ablator for direct drive, or in the metallic plasma formed where laser beams strike the hohlraum wall for indirect drive—requires the use of ultraviolet light to penetrate to densities where collisional absorption dominates over collective "laser-plasma interactions" (Lindl, 1995). The invention at the University of Rochester in the late 1970s of efficient methods to convert the infrared light produced by glass lasers into ultraviolet light was an important milestone in ICF research.

IV. FUTURE DIRECTIONS

Magnetic fusion research is now focused on an international effort to achieve ignition in a tokamak and on improvements in the concept, including other means for creating the nested toroidal flux surfaces so successfully utilized to confine plasmas in tokamaks. A central issue is to what extent one should rely on internal currents, as the tokamak does. As noted earlier, the stellarator avoids internal currents altogether by creating closed toroidal flux surfaces. Its external helical coils impart a twist to the field lines as current does. At the opposite extreme are the reversed-field pinch devices, with only a weak external toroidal field, and a very compact device called the spheromak, which has no external toroidal field and relies totally on Taylor relaxation to create the desired field configuration (Taylor, 1986). This is more than an intellectual exercise, since the size and cost of toroidal confinement devices tends to increase as they rely more heavily on externally generated toroidal fields, requiring large coils looping through the plasma torus. The spherical tokamak is an innovative exception designed to minimize this difficulty (Peng and Strickler, 1986).

For ICF, the immediate goal is ignition, in the National Ignition Facility now under construction in the U.S. Application of the concept to electric power production will require new laser technology, or perhaps ion beams, capable of rapid repetition—several times per second—and greater efficiency than existing glass lasers. An innovative means for reducing the laser energy required for compression is the "fast ignitor," using a small but very-high-power laser to ignite the target after it has been compressed Tabak *et al.* (1994).

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