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Interim Assessment

The birth of modern plasma science

The development of a practical fusion energy source remains one of the most challenging scientific endeavors undertaken by mankind. The early predictions of tabletop-scale fusion energy machines based on "back of the envelope" calculations very quickly confronted the reality of the plasma state as a complex nonlinear medium. Early plasma experiments more often than not ended with the plasma splattered against the walls of the containment vessels rather than confined within the magnetic bottle as intended. The production of a fusion-grade plasma at a temperature of 100 million Kelvin required the development of the field of plasma science. Scientific tools had to be developed to describe plasma equilibrium, the balance between plasma pressure forces and the confining magnetic forces, and stability. Why do large-scale instabilities cause the plasma to break up and why do instabilities at small scale cause the energy to leak across the magnetic field? How do you heat an essentially collisionless plasma to the temperatures required for fusion and how do you accurately remotely diagnose the complex dynamics of the plasma at both large and small scales to test your understanding of the system? These questions and many more must be answered to establish the firm knowledge base required for the achievement of practical fusion energy production.

Fundamental scientific insights from plasma physics and their impact on other scientific disciplines and industry

The historical development of the fusion program has involved both basic physics and the applied and engineering sciences. Because of the explicitly applied goal of the fusion program, the larger scientific community can lose sight of the contributions the program has made to our understanding of fundamental physics. Basic plasma experiments elucidated the nonlinear properties of the plasma medium. As a consequence, a number of areas in modern nonlinear physics found some of their principal applications in fusion plasma science. In some of these cases, plasma scientists became leaders of these emerging fields—solitons, chaos, and stochasticity are noteworthy examples. Basic tools developed in the fusion program ranging from computer-based algebra to particle simulation techniques have found widespread applications in allied fields.

One measure of the quality of a scientific field is its impact on and acceptance by other fields. Some examples of important topical areas that have had a broad impact on the broader scientific and industrial community include:

Stability: The understanding of the complex plasma dynamics observed in early plasma experiments was initiated with the development of powerful energy principles and eigenmode techniques to explore the linear stability of plasma equilibria. The wide variety of instabilities in plasma with an enormous range of spatial scales serves to define the richness of the plasma medium and the challenge to understand its dynamics. Predictions for the thermal pressure beyond which the plasma will disassemble have been confirmed in experiments in which the temperatures of the plasmas are in excess of those found on the surface of the Sun. In addition, experimental explorations have led to the development of methods that significantly increase the plasma pressure limits set by stability. Many of these stability analysis techniques are now essential tools not only in the field of plasma science but also in allied fields such as astrophysics and solar, ionospheric, and magnetospheric physics.

Stochasticity and chaos: The effort to understand how the magnetic surfaces that confine hot plasma in fusion experiments break up led to the development of the standard map, which allowed the generic exploration of the onset of stochasticity. Understanding of the onset of stochasticity in velocity space was also intrinsic to modeling heating in essentially collisionless plasmas. Finally, senior scientists trained in the physics of plasmas developed the first published method for controlling chaos.

Reconnection, field topology, and magnetic dynamos: A three-decade challenge of plasma physicists has been to explain the very short time scales that characterize the release of magnetic energy in the solar corona, in planetary magnetospheres (including Earth's), and in fusion experiments. Classical collisional dissipative processes are orders of magnitude too weak to explain the time scales observed. The difficulty lies in the extreme range in the spatial scales, from the macroscopic to the microscales associated with kinetic boundary layers, and in the necessity to include kinetic processes to provide collisionless dissipation. An emerging understanding based on theory, computation, and basic experiments is linked to the mediating role of dispersive waves, which act at the small scales where the "frozen-in" condition is broken. For the first time the predictions of energy release rates in fusion experiments are consistent with observations. A consequence of the fast release of magnetic energy associated with magnetic reconnection in some fusion experiments is the evolution to a minimum energy state where the magnetic field is partially self-generated by the plasma. The resulting "dynamo" action is related to magnetic dynamo processes in astrophysical systems such as the Sun and the planets. These fusion-sponsored experiments remain among the few laboratory demonstrations of a turbulent dynamo.

Wave dynamics: The plasma state is unique in the rich variety of waves that are supported by the medium. Waves in plasmas not only appear spontaneously as a consequence of instabilities, but also can be generated to control plasma temperature and currents. Understanding how waves propagate and are absorbed in nearly collisionless plasma was a scientific challenge. Building on Landau's idea of the wave-particle resonance as a mechanism for collisionless dissipation, fusion scientists developed models to describe the absorption of high-power radio frequency waves and benchmarked the predictions in fusion experiments. Waves could then be used to engineer the phase space of particle distribution functions. Waves can now be excited in plasmas to generate intense current or to accelerate particles to high energies—a technique that can be applied to the next generation of high-energy accelerators. The nonlinear behavior of waves has also been an intrinsic component of the science of plasma wave dynamics, and knowledge of this phenomenon has spread widely to many other branches of physics. Indeed, such ubiquitous concepts as absolute and convective instabilities, solitons (nonlinear waves that persist through collisions), and parametric instabilities saw extensive development in the fusion context. Important industrial applications include the use of radio frequency technologies for plasma processing in semiconductor manufacturing. Finally, plasma physicists introduced the idea of using solitons in commercial high-speed communications.

Turbulent transport: Understanding transport driven by turbulence is critical to solving such important problems as the accretion of matter into black holes, energy transport in the solar convection zone, and energy confinement in fusion experiments. Gradients in pressure, angular momentum, or other free energy sources drive small-scale turbulent flows that act to relax the gradient. This “anomalous transport” process should be contrasted with classical transport, which arises from two particle coulomb interactions in magnetic fusion plasmas and can include photon diffusion in astrophysical systems. The identification of anomalous transport in fusion experiments (and the corresponding theoretical work) sparked the recognition of its importance in space science and astrophysics, fields in which concepts such as anomalous transport and heat flux inhibition are now common language. Because of its fundamentally nonlinear and turbulent nature, understanding anomalous transport has been one of the significant scientific challenges of the fusion program. Diagnostics to remotely measure turbulent fluctuations as well as computer codes to describe the nonlinear dynamics of small-scale flows in a collisionless medium were developed. Experimental work in fusion has shown that turbulence can be spontaneously suppressed and a transport barrier formed, and that the mechanism was linked to the development of local zonal flows, which shred the vortices driving transport. The dynamics of this process parallels that of zonal flows in Jupiter’s atmosphere.

Outstanding problems

In its preliminary discussions, the committee has begun to identify critical unresolved problems in fusion science. The following includes some examples.

Turbulence and transport: Despite the scientific success in understanding the turbulent transport of ion thermal energy in magnetic containers, formidable challenges remain. The mechanism by which particles and electron thermal energy are lost from magnetic containers has not yet been clearly identified. This is a key issue for an energy-producing plasma, in which high-energy alpha particles produced during fusion deposit their energy in electrons. A paradox is that the electron energy-loss rate appears to be greatest in the core region of tokamak plasmas where theories based on linearization of equations for small-amplitude disturbances predict no linear instabilities. The source of the turbulence driving transport remains a mystery. The present experiments in tokamaks are in a regime in which magnetic field fluctuations associated with small-scale vortices driving transport are important, yet progress has been slow in developing the computational and diagnostic tools required to include these effects. The exploration of the role of magnetic fluctuations is especially critical for modeling experiments in the innovative magnetic containers now coming on line. Predictions of performance in proposed magnetic confinement experiments have traditionally been based on scaling laws deduced from existing and previous experiments rather than from first-principles theories of turbulent transport. The reliance on this approach over the long term, though previously grounded in necessity since there were no reliable theories of transport, should be re-evaluated in light of the new developments in theory and computation and the emergence of control techniques for manipulating transport. Finally, the role of alpha particles in turbulence and transport, which will be an important issue for burning plasmas, is not well understood.

Energy density limits: The success in understanding pressure limits in confined plasma has been based largely on the ideal (dissipation-free) magnetohydrodynamic description. There is now substantial experimental evidence that, under some circumstances, the plasma pressure can be limited below these "ideal" limits by instabilities whose growth is facilitated by resistive or kinetic effects. Nonlinear instabilities, which self-sustain only when their amplitudes exceed a threshold value, are being studied as a possible mechanism for such limits. A major challenge for the field is to develop the computational tools to study the macroscopic nonlinear development of instabilities that constrain the global pressure of a system and that at the same time resolve the small time and space scales required to describe critical kinetic features. Until this challenge is met, numerical models of the large-scale plasma dynamics will be subject to the criticism that they are too primitive to fully describe the high-temperature regime of present and future fusion-grade plasmas. The duality of a medium that behaves like a continuum fluid at large scales and yet displays the effects of discrete particles at small scales is a recurring theme of plasma science.

Integrated physics of self-heated plasmas: While the past DT tokamak experiments that produced weakly burning plasma were a milestone, a broad range of scientific and technological issues nevertheless remain to be explored in the strong self-heating regime, where the local energy deposited by fusion-produced alpha particles exceeds the energy from external sources. Key scientific questions concern the stability of the profiles, including transport barriers, in the self-heating regime. As the plasma pressure exceeds stability limits because of self-heating, will transport rise to balance the source in a benign manner or will large-scale instabilities lead to a loss of global confinement? Will a high density of energetic alpha particles destabilize waves and degrade alpha confinement so as to reduce the efficiency of alpha particle heating? Will helium ash accumulation continue to be minimal? On the positive side, will ideas for channeling alpha-particle energy directly into ions rather than electrons be successful and therefore ultimately lead to a more attractive fusion energy source? Conclusive answers to such questions will require experiments in the burning plasma regime.

Summary

The worldwide fusion energy program, with vigorous U.S. participation in all areas and leadership in many, has achieved much in its 40-year history. The fusion energy goal also has driven the development of the modern phase of plasma science. Plasma science, in turn, has contributed to many fields of science and technology during this time.

The reorientation of the U.S. fusion program in 1996 had as its aims the stimulation of innovation and the strengthening of the scientific focus of the program. The extent to which the full promise of this approach has begun to be realized will be addressed in the committee's final report.

FuSAC can say with confidence now that the technology needed to create, diagnose, and model sophisticated experiments on fusion-grade plasmas has been developed. The critical materials science issues of fusion energy have been scoped. The progress can be measured in other ways as well: The first preliminary fusion-burning experiments were recently completed. Scientific and engineering understanding of the concepts required for future fusion energy systems is being continually deepened. Nonetheless, the distance to the ultimate goal remains large.