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Research Briefing on Contemporary Problems in Plasma Science

Plasma Science Committee

Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Preface

The Plasma Science Committee of the National Research Council has prepared this research briefing, at the request of the director of the Office of Energy Research of the Department of Energy (DOE), to provide DOE, other federal agencies, and the plasma science community at large with a rapid assessment of plasma science. This briefing may be the first unified assessment of plasma science in its entirety.

In addition to giving a glimpse of forefront research in plasma science, this research briefing identifies and discusses selected opportunities for new research and applications, and identifies some problems associated with these areas of opportunity. Although the areas of research discussed in this briefing were not selected on the basis of any perceived relation to missions of the DOE, there is a clear connection with a number of DOE programs, including, for example, the magnetic fusion energy program. No attempt has been made to conduct a detailed assessment of plasma science or to develop recommendations or set programmatic priorities. As explained further below, the committee has recommended that such a detailed evaluation of plasma science be carried out. In the meantime, the committee hopes that this briefing will be of use in assisting federal agencies and others with near-term program planning.

The Plasma Science Committee was created by the National Research Council in 1989, upon the recommendation of the executive committee of the Division of Plasma Physics of the American Physical Society. Currently funded by the National Science Foundation, the Department of Energy, the National Aeronautics and Space Administration, and the Office of Naval Research, the Plasma Science Committee is now a permanent standing committee that reports to the Board on Physics and Astronomy. Its terms of reference are to appraise the development of plasma science as a whole, to foster a sense of unity and commonality in the field, to promote the teaching of plasma science, to assess the need for new facilities, to encourage interagency cooperation, and to oversee the interfaces of plasma science with other sciences.

The Plasma Science Committee has undertaken three major projects since its inception. First, it cosponsored, with the Office of Naval Research, a workshop on nonneutral plasmas that brought together many of the hitherto loosely affiliated practitioners of this rapidly growing new field of plasma science. Next, it sponsored a study on plasma processing of materials that is now nearing completion. Finally, the committee has developed a proposal for a detailed study to assess the health of basic plasma science in the United States, to highlight new opportunities for research and applications, to assess the quality and size of the educational programs in plasma science, to characterize basic experimental facilities needed, and to identify changes in institutional infrastructure that could improve research and education. The present briefing is based on the work of the Plasma Science Committee done in preparation for this broad assessment of the field, which will focus on new opportunities in plasma science and technology. The Plasma Science Committee, the only committee on the national level with responsibility for the health of basic plasma science, regards this kind of periodic assessment of the field as central to its role.

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Introduction

This research briefing presents the Plasma Science Committee's rationale for the need for a comprehensive study of plasma science. Plasma science often seems to be a collection of independent applications. The programs that provide support for plasma science generally have as their primary objective developing various applications. This central fact has made it difficult for committees and decisionmakers to take a comprehensive view of the whole subject, even though the vitality of one branch of plasma science can be seriously affected by events occurring in neighboring branches. For example, the steady decline in the funding for fusion research in the past decade has indirectly hurt all of plasma science. It has proven difficult to organize and support basic research that has not yet led to an identifiable application. Educational programs in plasma science may not reflect the breadth and depth of the subject.

Nearly all the problems and areas of concern identified in this briefing are related to the committee's perception that the present organization of plasma science around its applications may lead to missed opportunities, either for basic research or for new applications. There are some areas in which the opportunities seem clear cut, and the question is whether and how to capitalize on them. There are also areas of plasma science where structural impediments have prevented asking whether new opportunities exist. This research briefing touches on situations of both types.

This briefing starts with an overview, the goal of which is to provide a broad perspective on all of plasma science. The next section contains detailed discussions of scientific opportunities in various subdisciplines of plasma science. The first subdiscipline to be discussed is the area where the contemporary applications of plasma science are the most widespread—low-temperature plasma science. Opportunities for new research and technology development that have emerged as byproducts of research in magnetic and inertial fusion are then highlighted. There follows a discussion of new opportunities in ultrafast plasma science opened up by recent developments in laser and particle-beam technology. The briefing then turns to laboratory research that uses smaller-scale facilities, taking up first a success story, the new field of nonneutral plasmas, and then the area of greatest concern to the committee, basic plasma experiments. Discussions of analytic theory and computational plasma physics and of space and astrophysical plasma physics complete the presentations in this section. Concluding remarks are presented in the final section.

PERSPECTIVE AND OUTLOOK

With the rise of electrical science in the nineteenth century came intimations of plasma effects. In the 1830s, Michael Faraday created electrical discharges to study the chemical transformations induced by electrical currents. These discharges exhibited unusual structured glows that were manifestations of a new state of matter—plasma. The study of low-temperature, partially ionized plasmas, initiated then, continues today to be a productive enterprise, rich now in useful and widespread applications, as detailed below. With the discovery of the electron in 1895 and of the atomic theory of matter shortly thereafter, plasma science was poised for takeoff in the twentieth century. The disciplines of electromagnetism, fluid mechanics, statistical mechanics, and atomic physics were eventually assembled into a unified methodology for the study of the nonlinear collective interactions of electrically charged particles with one another and with electric and magnetic fields, *i.e.*, plasma physics.

In the 1920s, Irving Langmuir discovered collective plasma oscillations in laboratory gas discharges and radio waves were first reflected from the earth's ionosphere, the very edge of space. Until the late 1950s, plasma science developed along the two distinct lines exemplified above. One line was a byproduct of ionospheric, solar-terrestrial, and astrophysical research, motivated by such things as the desire to understand how radio waves propagate, how solar activity leads to auroral displays and magnetic storms on the earth, and how magnetic fields influence the behavior of stars, galaxies, and the interstellar medium. In the laboratory, the study of low-temperature collisional plasmas was pursued vigorously, focusing on electron conduction and breakdown in gases, electron emission and other cathode phenomena, and collisional excitation of atoms and molecules. These studies shaped what is today called the subject of gaseous electronics.

In 1946, the existence of a collective interaction between waves and resonant particles in a plasma without collisions was proposed theoretically. By the 1950s, it was clear that collective interactions are an essential property that highlights the physics of hot, fully ionized, collision-free plasmas.

The present phase in the development of plasma science began in the late 1950s. Two events symbolizing the deeper intellectual currents of those years were the first successful launch of an artificial earth-orbiting satellite by the Soviet Union in 1957 and the revelation in 1958, through declassification, that both the United States and the Soviet Union had been trying to use plasmas to harness the energy source of the sun—thermonuclear fusion—for peaceful purposes. The discoveries of the earth's radiation belts and the solar wind showed that our exploration and future understanding of the earth and the sun's space environment would also be couched in terms of plasma science. Thus two powerful motivations awakened interest in the physics of hot plasmas. Fusion research seeks a source of clean energy for human use that will last for a time comparable with the present age of the earth. Space research seeks useful comprehension of nature's processes on a global and, indeed, solar-system scale, reflecting mankind's dependence on the terrestrial environment and curiosity about the cosmos.

The international effort to achieve controlled thermonuclear fusion has been the primary stimulus to the development of laboratory experiments on collisionless plasmas. As early as 1958, the theta-pinch configuration produced fusion temperatures at high plasma densities. However, the energy confinement time was orders of magnitude lower than that required for net energy production. The simultaneous achievement of high temperatures, densities, and confinement times, similar to the plasma conditions at the centers of stars, required significant improvements in forming and understanding plasmas. The technology needed to create fusion plasma conditions in the laboratory—high-field, large-volume superconducting magnets, intense energetic neutral beams, powerful lasers, vacuum and surface techniques, and high-power radio-frequency sources spanning a wide range of frequencies—was systematically assembled. As fusion-quality plasmas were diagnosed with increasing precision, theory was stimulated to explain observations made possible by more detailed and complete measurements.

The scientific feasibility of controlled fusion will likely be demonstrated in the coming decade. Already, non-burning experiments in deuterium have achieved densities, confinement times, and temperatures essentially consistent with "break even," where the energy produced by the deuterium-tritium reaction would equal that required to heat the plasma. The key tokamak fusion power parameter has increased by 10,000 in the past 15 years, and only an additional factor of seven is needed to achieve ignition. The U.S. Department of Energy has proposed construction of a burning plasma experiment (BPX) to study the physical processes occurring in a tokamak fusion reactor that will produce several hundred megawatts of fusion power. The United States, the Soviet Union, Japan, and the European Community have arrived jointly at a conceptual design for the International Toroidal Experimental Reactor (ITER), which will address the network of interacting physics and engineering issues associated with practical tokamak reactors. The ITER project is moving into the engineering design phase.

In inertial confinement fusion, pellet compressions of several hundred times liquid density at temperatures of several KeV have been attained.

While DOE funding of research in inertial confinement has been provided almost entirely on the basis of defense applications, the energy application has played an important philosophical role as a long-term goal. A proposed upgrade of the present NOVA facility will produce fusion yields of interest for defense applications. The laboratory microfusion facility currently being planned will be designed to demonstrate ignition, of importance to the energy application.

In September 1990, DOE's Fusion Policy Advisory Committee recommended to the Secretary of Energy that the magnetic fusion program change its emphasis from research to development and that a program in inertial fusion energy development be initiated. The goal of each will be an operating fusion power plant by the year 2040; a choice between the two approaches will be made at a later date. The change in emphasis from research to development, and the necessary narrowing of focus accompanying it, will inevitably affect all parts of plasma science.

It is significant that one discipline, plasma science, defines the basic language now used both in fusion and space plasma research. Space plasma research is concerned with plasmas in the solar system, those occurring at the surface of the sun, in the solar wind, and in the magnetospheres and upper atmospheres of the planets and comets. Space plasma physicists are beginning to understand quantitatively the interconnected chain of plasma processes that link solar flares and coronal mass ejections at the sun to magnetic storms and auroral displays on the earth. The same types of plasma processes are found to be at work in the magnetospheres of the various planets, a graphic illustration of the generality of the principles of plasma physics.

The American programs of research on fusion and space plasmas are of comparable scale. The earth's magnetosphere proves to be as challenging to understand as a fusion tokamak, and in the 1990s an international flotilla of spacecraft will be sent on a coordinated study of the earth's magnetosphere as part of the International Solar-Terrestrial Physics Program—the space physics analog of the ITER fusion program. The *Galileo* spacecraft will study plasma processes in Jupiter's magnetosphere. NASA is planning a mission to study the plasma in the solar corona *in situ*. These are the largest elements of a broad U.S. program of research on solar system plasmas in the 1990s.

Space plasma research is now an important source of ideas for other branches of plasma science. The experimental diagnosis and theoretical interpretation of many space plasma processes now match in precision the best of current laboratory practice. As a result, space has become one of the primary experimental arenas for basic plasma research. The present understanding of collisionless shocks is mainly a result of solar-system plasma research. Finally, the plasma phenomena in the solar system have proven to be examples of general astrophysical processes. The solar system has become a laboratory in which astrophysical processes of great generality can be studied *in situ*. Observations of particles accelerated by solar-system shocks are providing a basis for understanding the origin of galactic cosmic rays. Research on astrophysical plasmas will continue long after the goal of fusion energy has been achieved.

As the science and related experimental techniques have developed, other applications of plasma science have come into view. One such application is the free-electron laser, which can generate coherent radiation from microwaves to optical frequencies and perhaps even into the x-ray range. The free-electron laser will find applications in fusion research, many other branches of physics, other sciences, industry, and medicine. New methods of particle acceleration using collective plasma effects are a second application. Plasma scientists are working with accelerator designers to create a new generation of devices, such as the beat-wave accelerator, which will operate at the frontiers of high-energy particle physics. Intense, pulsed, relativistic electrons have been used to generate intense high-power sources of microwaves, for collective accelerators, in high-current betatrons. These and other recent developments in laser and particle-beam technology have opened up a new field, ultrafast plasma science, for exploitation.

Microwave tubes, free-electron lasers, and electron and ion traps all involve nonneutral plasmas, in other words, those in which the electron and ion densities are unequal. This subfield, which has had notable and visible scientific successes in recent years, involves elegant experiments that are well suited to universities. Two-dimensional fluid turbulence can be studied at higher Reynolds numbers in a nonneutral plasma than it can in an ordinary fluid. Recent experiments in ion traps have succeeded in creating a two-dimensional Coulomb lattice for the first time. The area of nonneutral plasmas is the most recent example of a successful investment in basic plasma science.

The scope of gaseous electronics and its applications multiplied after World War II. Low-temperature plasma science now supports major industries and is an indispensable part of many military technologies. The newest, and perhaps the largest, business employing plasma science is the $50-billion-per-year electronics industry. Plasma processing is now used in about 30 percent of the steps in manufacturing semiconductor chips, and there is no known alternative to these plasma techniques on the technological horizon.

Numerical modeling of many-particle kinetic systems has been advanced very significantly by plasma science. While modeling does not replace discovery, it has made quantitative the study of complex plasma systems such as tokamaks and magnetospheres, and it has clarified the nonlinear collective processes that regulate plasma transport in such systems. The microscopic plasma processes in distant astrophysical systems cannot be observed directly, as they can in space and in the laboratory. Now, however, modern computational techniques have opened the door to modeling of the plasmas in the exotic environments of astrophysics, ranging from stellar atmospheres to quasars. The same techniques are being applied to down-to-earth problems in the area of plasma processing of materials.

II
Plasma Science

LOW-TEMPERATURE PLASMAS

The Technology

Although ionospheric and some space and astrophysical plasmas are classified as low-temperature plasmas, the bulk of plasma science currently practiced in this domain is gaseous-electronics based. In its original form, the gas discharge branch of Langmuir's plasma physics, founded in the early part of this century, focused on electron conduction and breakdown in gases; electron emission and other cathode phenomena; and excitation of atomic and molecular species by electron collisions. The carbon-arc light source invented in the 1880s was perhaps the first application of plasma science. It was followed by gas-discharge rectification, high-power switch gear, and welding arcs. The ubiquitous mercury arc lamp and the more sophisticated fluorescent discharge lamp were developed somewhat later.

These and related applications have drawn heavily on plasma science in their evolution since World War II and have enlarged the scope of the science to include plasma chemistry, atomic and molecular physics, surface chemistry and physics, optics, high-temperature physics and chemistry, electrical engineering, and computer science. This new science supports many of the world's major industries and is an indispensable part of many military technologies. For example:

- The use of plasma-based switch gear persists in the now huge power industry, while pulse power switches have been developed for use in high-power radars, discharge laser systems, and, indeed, in the switching of stored electrical power for high-temperature plasma experimentation.
- The early work on discharge light sources has evolved as the core technology in the lighting industry, now a $10-billion business worldwide, with these efficient plasmas consuming 10^{11} watts of electrical

power. Here, the earlier carbon and mercury arcs have been supplanted with arcs containing sodium-mercury mixtures as well as rare-earth additives to improve color and efficiency.

- New lasing species, including excimers, have been discovered and exploited through the efforts of plasma science investigators with the result that plasma-based, high-power lasers have formed a new and robust technology.
- Thermal arcs for welding have evolved into high-power devices with the ability to melt and spray refractory coatings for wear and corrosion resistance and to form new alloys and composite materials for many special purposes in the aerospace and automotive industries, as well as in subordinate industries such as the cutting-tool industry. Modern jet engines depend critically on plasma coating techniques. More recently, thermal plasmas are finding growing application in the destruction and disposal of biological and other hazardous wastes.
- The newest, and perhaps the largest, technology employing plasma science is the electronics industry. Low-pressure plasmas are vital in many plasma etching, deposition, and surface modification steps in the manufacture of nearly all integrated circuits.
- New technologies such as plasma-aided chemical vapor deposition (CVD) and plasma spray preparation of diamond as well as superconducting films comprise a new wave of applications.

The pervasive use of low-temperature plasmas in modern technology occurs because they provide physical conditions that are inaccessible by any other means. No other medium can provide gas temperatures or current densities as high as those achievable with plasmas, no other medium can excite atomic and molecular species to radiate as efficiently, and no other medium can be arranged to provide similar transient and nonequilibrium conditions. Plasma technology provides a unique capability to obtain high temperatures in a chemically controlled environment. In materials processing, plasma conditions provide pathways for chemical reactions that cannot be realized by any other means.

The Science

Low-temperature plasmas occupy a large portion of the density-temperature plane, with electron densities ranging from 10^5 to $10^{17}/\text{cm}^3$ and electron temperatures (kT) ranging from 0.01 to 10 electron volts (eV). These plasmas are classical in the sense that the thermal kinetic energy is large in comparison to the average Coulomb interaction energy. Thus, the charged particles interact weakly with each other, and most electron collisions are with neutral atoms and molecules. The degree of ionization may vary from close to 100 percent to well below one part per billion.

Low-temperature plasmas are governed by the laws of collective phenomena and atomic physics. They exhibit nonequilibrium conditions with wide differences in electron, neutral, ion, vibrational, and rotational temperatures. Moreover, within each plasma species there are departures from equilibrium, and Maxwellian energy distributions are seldom observed. This highly nonequilibrium character and the myriad interactions that can occur in the volume and at surfaces present both challenges and opportunities. The fact that a highly excited medium can be obtained that has no chemical or physical counterpart in thermodynamic equilibrium provides the opportunity.

The diversity of applications of plasma-based systems used to process materials is matched by the diversity of plasma conditions, geometries, and excitation methods. In just one segment of the applications—plasma-enhanced CVD and etching—the gas pressures vary from atmospheric to millitorr, and the gas composition includes rare gases, highly reactive gases, complex molecules, and the products of reaction. Indeed, the complexity of the gas itself is a general condition found in most of the new plasma science applications and has prompted a more descriptive label: "reactive plasmas." To achieve progress, the practitioners of this composite science must call upon a number of science resources that include plasma electrodynamics and kinetics, plasma and surface chemistry, basic data for cross-sections and rates, diagnostics of discharge and surface processes, theory and predictive modeling, and scaling and process control.

Key Issues

The key issues affecting the progress of low-temperature plasma science are related to its diversity and complexity. The present strong technology pull now far outstrips its scientific underpinning. Rapid growth and numerous demands to use plasmas immediately in a vast array of applications have led to a system-specific approach that renders haphazard—and inhibits—not only scientific understanding but also technology transfer and process scaling. Many manufacturers of semiconductor fabrication equipment are small firms financially ill-equipped to contribute to research and development. Many practitioners of plasma technology are not trained in the appropriate science disciplines.[1]

BASIC PLASMA SCIENCE OPPORTUNITIES IN FUSION ENERGY

The Department of Energy has invested heavily to develop outstanding plasma physics, laser, and particle beam facilities in its magnetic fusion and inertial fusion energy programs. In this section, the Plasma Science Committee touches briefly upon two questions. How important is research in basic plasma science to the fusion program? Could fusion energy facilities also be used for basic plasma science research? Definitive answers to these and related questions await the conclusion of the proposed "New Opportunities" study. Presented here are examples of issues that the committee hopes will be examined in that study.

Magnetic Fusion

The committee cites the specific example of toroidal eigenmodes not to advocate one research program over another but to illustrate more general issues.

Until this past year, experimental studies of stable magnetohydrodynamic (MHD) modes in tokamaks have focused on a single application—Alfvén wave heating—and neglected possible modes of much lower frequency, gap modes, which are now considered by theorists to be leading candidates for destabilization by alpha particles in the proposed Burning Plasma Experiment. In other words, the theoretical framework of MHD, developed in the late 1950s, has not been subject to a comprehensive experimental examination. Because Alfvén wave heating appeared unattractive relative to ion cyclotron heating, the United States did not undertake the necessary experiments, and the research effort became centered in Europe. Recent observations on the large U.S. fusion devices, TFTR and DIII-D, have discovered magnetic oscillations that are driven by energetic particles and appear to be consistent with gap modes. The threshold for these modes remains unexplained, however, because of our lack of detailed understanding of the underlying stable MHD gap mode, whose damping decrement is sensitive to the plasma profile. What is needed experimentally is for low-power Alfvén wave antennas to excite stable MHD modes in tokamaks and explore their frequency, damping decrements, and spatial eigenfunctions over as wide a range of plasma parameters as is practicable, including parameter regimes that are not on the path to fusion energy.

Several object lessons can be drawn from this illustrative example. First, fusion energy research itself appears to have suffered from earlier neglect of a rather basic investigation of relatively modest scale. Second, the problem of stable MHD modes illustrates the commonality of plasma principles. The concepts applied to Alfvén wave heating—wave absorption via geometric resonances—have also been used and tested in the earth's magnetosphere. More generally speaking, much of the physics of high-temperature plasmas confined in toroidal magnetic field experiments has application to the hot plasma contained in the closed loops of the solar magnetic field. Finally, there is a related, but even more general, point. Although magnetohydrodynamic theory is the fundamental description of plasma dynamics on scales larger than the ion Larmor radius and is used to describe nearly all magnetic fusion, space, and astrophysical plasma configurations, very few of the predictions of magnetohydrodynamic theory have been reduced to laboratory practice. This is particularly true in the case of magnetohydrodynamic flows, which have no relevance to fusion research.

Part of the difficulty appears to be that, on the one hand, any apparatus dealing with plasma hot enough to exhibit collisionless phenomena and large enough to support magnetohydrodynamic phenomena is a costly facility by prevailing basic research standards. On the other hand, those who allocate research time on the even more costly and complex devices designed for fusion research are naturally reluctant to spend resources on activities that do not unquestionably contribute to the fusion energy goal.

There are also suggestions for utilizing existing magnetic fusion devices in different ways that will benefit plasma science. For example, magnetic mirror confinement of collisionless charged particles is one of the fundamental topics of plasma physics. Of its many applications, that to Earth's and Jupiter's radiation belts may be the best known. Although magnetic mirrors no longer are part of the U.S. fusion program, magnetic mirror research could be resurrected by operating shaped tokamaks with and without toroidal magnetic field and plasma current. From the point of view of gaining fundamental new insights into the physics of mirror confinement, the ability to produce toroidal as well as poloidal magnetic field components of variable relative strength could well be one of the more attractive aspects of tokamak devices. In addition, such fusion devices as reversed field pinches and spheromaks generate force-free plasmas whose behavior is interesting in its own right and, with proper interpretation, can be used to gain some understanding of the quiet solar corona and the fundamental processes governing rapid energy release in solar flares.

In sum, basic results obtained in fusion plasmas are important not only to fusion research but also to many other parts of plasma science. Existing constraints on resource allocation often preclude using general importance to plasma science as a criterion in the allocation of research time on facilities originally designed for fusion research. The decoupling of hot plasma research from the constraints imposed by fusion reactor prototyping could open the way to important experimental efficiencies. There is a need to reduce the predictions of magnetohydrodynamic theory to laboratory practice. To the Plasma Science Committee's knowledge, these and similar suggestions have not been the subject of formal evaluation, and so it is difficult to determine whether important opportunities are being overlooked.

Inertial Fusion

Inertial fusion research has led to major advances in high-peak-power laser and particle beam systems that provide several new research opportunities at reasonable incremental cost. Lasers with intensities in the range of 10^{19} to 10^{21} W/cm^2 will soon be available in the laboratory. Such lasers can produce electric fields in excess of 10^{14} V/m, energy densities greater than 3×10^{10} J/cm^3, and ponderomotive potentials exceeding 100 MV.

Ionization Physics. The ionization of atoms and ions in a high-intensity laser field allows the study of atomic structure under extreme conditions. The electric field of the laser can approach or exceed the electric field binding an electron to a nucleus. At even higher intensities, electron motion in the laser field can become relativistic. Short-wavelength lasers (0.35 to 1.05 μm) have recently been used to study ionization for values of the Keldysh parameter that are less than unity.

Coherent XUV/X-ray Generation. The development of x-ray lasers requires controlling populations of two excited levels in a hot plasma containing many charge states and thousands of excited levels. Therefore, x-ray laser research poses an interesting and difficult combination of atomic physics and plasma physics problems that test present capabilities to model and characterize plasmas that are not in local thermodynamic equilibrium. X-ray laser research benefits from synergism between two branches of plasma science: nonneutral plasma traps formed by relativistic electron beams are used to measure the complex spectra of highly stripped ions.

Laser exploding foil concepts have been used to demonstrate x-ray lasing in the laboratory (e.g., 206.8-Å lasing of Ne-like Se has been amplified to 17 gainlengths). Other techniques have been used to demonstrate lasing in collisionally pumped Ne-like Ge (at 196 to 287 Å), Li-like Aℓ (at 105 to 154 Å), and in Li-like Ti at 47 Å. The development of high-power, short-wavelength sources is important for a variety of applications such as (1) holography of living cells, (2) x-ray microscopy, (3) x-ray laser-produced plasmas, (4) nonlinear optics and quantum electronics at XUV and x-ray wavelengths, and (5) phase-sensitive detection and measurement techniques at XUV and x-ray wavelengths.

X-Ray Lithography. The use of intense lasers to produce a point source of nearly monochromatic x rays may make possible the mass production of submicron-resolution, very large scale integrated circuits. For resolution below 0.1 μm, basic collective phenomena occur in circuits that will be a new challenge to solid-state physicists in the electronics industry. X-ray lithographic techniques are also spawning a new generation of x-ray optics and advanced diagnostic measurement techniques.

Strongly Coupled Plasmas. High-density compressions of inertial fusion targets provide an opportunity to study strongly coupled plasmas, in which the potential energy of the Coulomb electrostatic interaction between particles far exceeds the energy in thermal motion. Experiments with argon (Ar)-filled capsules have shown evidence of band structure in Ar; new satellite lines have been seen on the short-wavelength side of the resonance line of Ar ionized 16 times, for example.

Intense Charged Particle Beams. Beams of ions and electrons with powers exceeding 10^{13} watts with 50-nanosecond pulse durations are available for various applications such as (1) the generation of internal currents in a plasma to create particular magnetic field configurations, (2) beam-plasma interaction, (3) beam-condensed matter interaction, and (4) intense radiation and x-ray sources. The focusing of such high-power beams by magnetic lenses is an important issue.

In summary, research in inertial fusion has stimulated technological developments that in turn create opportunities for research in other fields. It is one objective of the proposed "New Opportunities" study to evaluate such opportunities as those described above and to suggest ways in which they may be exploited.

ULTRAFAST PLASMA SCIENCE

The research topics in this section resemble those in the previous section in the sense of relating to very high plasma temperatures and fast pulses of power, but they differ in the sense of being oriented to the acceleration of charged particles, rather than toward the release of nuclear energy. As in the preceding case of fusion energy research, there is an inspiring long-term goal, namely, the use of intense collective plasma phenomena for the advancement of high-energy physics into otherwise unaffordable ranges of energy, and there is a selection of near-term objectives as well.

Applications of plasma involving beams and accelerators have led to research opportunities in the emerging fields of ultrafast and relativistic plasma phenomena. "Ultrafast" means plasma dynamics on time scales shorter than an ion plasma period, and "relativistic" means wave or plasma electron velocities approaching the speed of light. Ultrafast plasma science emphasizes transient rather than steady behavior on time scales for which many competing plasma instabilities can be avoided. The plasma dynamics are nevertheless rich in nonlinear phenomena, including period doubling routes to chaos, relativistic self-focusing of light, excitation of plasma wakes by short pulses of light or particles, optical guiding of light by electron beams, particle beam focusing, relativistic particle acceleration or bunching in plasma waves, photon acceleration in plasma waves, FEL/CARM-type radiation sources, and frequency shifting of electromagnetic waves in temporal density gradients created by fast ionization of a plasma.

Materials Research. Inertial fusion research has spawned new development to investigate the interaction of short optical pulses (picosecond and femtosecond) with matter. Of particular significance is the fact that such intense, ultrafast laser facilities are suitable for university-scale research. These sources have been used to characterize high-temperature, superconducting transmission lines, biological processes involving photosynthesis and the properties of DNA, surface heating and melting as measured by picosecond electron diffraction, and tunneling times for electrons in coupled quantum wells, among others.

Relativistic Self-Focusing and Guiding of Light. Self-focusing of electromagnetic waves in a plasma is important to plasma accelerators, laser fusion, and ionospheric interactions. One mechanism yet to be observed experimentally is the focusing in a laser channel due to the refractive index increase that follows from the relativistic mass increase of the oscillating electrons. High-brightness lasers (e.g., 10-terawatt power, 1-picosecond pulse duration) now being developed will be short enough and powerful enough to isolate this basic effect from other self-focusing mechanisms (e.g., ponderomotive and thermal) that operate on longer time scales.

Plasma Wake Excitation. The plasma response to short pulses, either electrons or intense light (time scales on the order of the plasma period) is dominated by the excitation of wake fields. The phase velocity of the wake fields is tied to the velocity of the disturbance and so can easily be relativistic. The peak fields associated with such waves are extremely large and can approach wavebreaking for recently developed intense e-beams and laser sources.

The study of wake-field excitation and short-pulse beam propagation in plasmas is basic to several plasma accelerator and lens concepts, to stable transmission of beams through the ionosphere, and possibly to the evolution of energy bursts from pulsars. Important research topics include wake enhancement by shaped beams and wake steepening and radial shock generation by narrow beams.

Particle Beam Focusing in Plasmas and in Other Beams. When a particle beam enters a plasma, the plasma can cause its strong focusing by shielding the beam's space charge and allowing the beam's azimuthal magnetic field to self-pinch it. The application of this well-known mechanism to high-energy colliders has opened basic questions in regimes previously not considered. Examples are the focusing of positron beams in the nonlinear regime, where the positron density exceeds the electron density, and the adiabatic "squeezing" of a beam in a slowly ramped plasma density. Finally, collider beams are now becoming so dense that the interaction of colliding electron-positron beams will be dominated by collective (*i.e.*, plasma) behavior—important questions such as the equilibrium radius and stability of the overlapping beams are yet to be answered.

Acceleration of Relativistic Particles and Photons in Plasma Waves. The acceleration of relativistic particles in plasma waves is emerging as an exciting area of plasma science research. Because of their large amplitudes (on the order of 10 GeV/m), such waves offer the potential to miniaturize accelerators. While test particle acceleration has been recently demonstrated, critical issues such as beam quality and maximum current are yet to be investigated experimentally.

Other interesting topics include the bunching of long copropagated beams and the wiggling (as in a free-electron laser) of counterpropagated beams. Long electron beams (several wavelengths long) could be tightly bunched by a plasma wave field into bunchlets shorter in length than 1/4 of a plasma wavelength and in time less than 100 fsec. The use of such bunches in free-electron lasers or other radiation sources can produce new sources of femtosecond radiation.

The study of acceleration in plasma waves can be extended to photons as well. A short light pulse loaded in the proper phase with respect to a co-moving plasma wave can be continuously upshifted in frequency, thereby increasing both the energy and the group velocity of the photon packet.

Wave Propagation in Temporal Density Gradients. The advent of intense short-pulse lasers allows rapid ionization of gases. The study of wave propagation in temporally inhomogeneous plasmas opens a rich new area of investigation in basic physics. It also promises new applications, such as tuneable radiation sources.

The emergence of ultrafast relativistic plasma phenomena as a topic of basic research coincides with the development of short-pulse laser and beam technologies capable of generating relativistic and nonlinear effects in plasmas. However, the opportunity to explore this new realm of plasma physics has not been exploited. The technologies and facilities required are new. Furthermore, many of these topics can only be explored experimentally with a test-bed facility bringing together a state-of-the-art relativistic positron beam and short-pulse high-power laser beams. These two major items do not currently exist at a single place.

NONNEUTRAL PLASMAS

Nonneutral plasmas have recently become an established subfield of basic plasma science that presents an important opportunity for research and training. Applications of nonneutral plasmas are growing steadily in number and importance as the base of fundamental understanding increases.

The term "nonneutral plasmas" refers here to collections of particles all having the same sign of charge, such as pure electron plasmas, or pure ion plasmas. Such plasmas are unusually simple both experimentally and theoretically; nevertheless, they exhibit a wide range of collective and statistical mechanics effects. The plasmas are typically confined in cylindrical geometry in a uniform magnetic field. They have been confined for much longer times than ordinary plasmas. Except for a slow rotation, nonneutral plasmas can be formed at rest in the laboratory, enabling substantially different experiments than can be performed on moving particle beams. Wall and impurity interactions can often be made negligible, and so the plasma evolution can be governed by plasma physics uncomplicated by atomic and surface physics.

Nonneutral plasmas are simple enough that direct comparisons between theory and experiment can be made. Much of this simplicity stems from the fact that nonneutral plasmas can relax to a confined thermal equilibrium state. For theory, this means that the powerful techniques of equilibrium statistical mechanics can be applied; for experiments, it means that one may create quiescent, long-lived plasmas. Both waves and transport are readily studied in nonneutral plasmas, and it seems likely that transport can be fully understood in at least some regimes. This will not in itself explain transport in neutral plasmas, but it would go a long way toward establishing a set of transport paradigms that can then be applied to more complicated systems.

Much of the early research was directed toward magnetrons, gyrotrons, and other radiation-producing devices with a high degree of success. The Hi-Pac experiment at the Avco-Everett Research Laboratory in the 1960s generated a seminal body of nonneutral plasma theory before the project terminated. Experiments and theory at the University of Maryland in the 1970s developed the field of nonneutral plasmas, albeit mostly in the direction of energetic beam dynamics. Other groups have continued developing nonneutral plasmas in the energetic regime. More recently, low-energy nonneutral plasma experiments and theory have been pursued at the Universities of California at San Diego and Los Angeles.

Recent experiments on thermal relaxation and particle transport illustrate how nonneutral plasma experiments and theory can develop "textbook" plasma physics. One set of experiments measured the relaxation that occurs after the parallel and perpendicular temperatures are made unequal. These experiments cover a very wide range of temperatures (5×10^{-3} eV $< T <$ 200 eV) and densities. The first experiments gave the first quantitative verification of this fundamental collisional relaxation process in the weakly magnetized regime. Recently, the theory was extended into the highly magnetized regime, resulting in a new theory of collisional dynamics and an unusual many-particle adiabatic invariant. Experiments in this regime then observed a dramatic five-decade drop in the collisionality as the magnetization was increased, giving detailed verification of the new theory.

Nonneutral theory and experiments on particle transport across magnetic fields have given substantial insight into this fundamental process but are far from complete. From a theory perspective, the trapped, quiescent nonneutral plasma is ideal in that all plasma parameters and boundary conditions can be determined. Recent theory work has attempted to systematize the long-range interactions between particles that arise due to shielded static fields, dynamical waves, and discrete particle fluctuations. Experiments have measured enhanced transport consistent with the new theories, but detailed comparisons have not yet been made. When understood, these nonlocal "viscosity" processes may be found to be important in neutral plasmas also.

A recent series of experiments on nonlinear vortex dynamics further illustrates how nonneutral plasmas can elucidate fundamental physics. It turns out that magnetized electron plasmas are one of the best experimental manifestations of two-dimensional inviscid fluids: the equations governing drift motions of the electrons across the magnetic field are isomorphic to the two-dimensional Euler equations for a constant-density fluid such as water. With proper imaging techniques, the flow of the electrons in the plane transverse to the magnetic field can be measured accurately, for detailed comparison to theory. Furthermore, the plasma can be formed so as to have no turbulent boundary layer at the walls, making the fluid dynamics substantially simpler. Recent electron experiments have illustrated the nonlinear interactions of vortices, extending results from computer simulations and water tanks. More generally, the plasma experiments can test fluid instabilities such as the Kelvin-Helmholtz shear instability in realistic systems, and some stimulating discrepancies between the discrete particle experiments and fluid theory have been found.

Nonneutral antimatter plasmas are a field where fundamental physics experiments and plasma applications overlap. Positron plasmas are now routinely contained and manipulated in the laboratory, and unexpected physics is emerging. A serendipitous study of positron-molecule resonances led to closer scrutiny of the standard molecular excitation model. One intended application of the positron plasma is to inject positronium into tokamak fusion plasmas and measure the transport by observing the positron-electron annihilation radiation. A new positron-trapping experiment is being developed at the Lawrence Livermore National Laboratory to study positron-electron scattering, motivated by the possibility of discovering a new particle at a few MeV.

Nonneutral plasmas have a major application to basic research on fundamental constants and time standards. Here, one or more ions are contained at low temperature in magnetostatic or shaped RF fields for detailed study. Containment of many ions, desirable from signal-to-noise considerations, is often made undesirable because of many-particle plasma physics phenomena; some of the most elegant experiments have been carried out on single particles. This line of research has recently been extended to the fundamental properties of antimatter. For example, researchers are currently attempting to measure the inertial and gravitational masses of antiprotons, and these techniques should be applicable to a variety of fundamental constants.

Recently, theory and experiments have been probing the correlated many-particle regime of crystalline ion clusters. Here, the whole range of plasma physics, many-body physics, statistical physics, and thermodynamics can be studied in an exceedingly simple experimental system. There is a direct correspondence between the thermal equilibrium properties of these trapped ions and the much-studied "one-component plasma" that occurs when one charge species is quantum-mechanically degenerate. However, in clusters of a few thousand ions, surface effects are also important, and the phase transitions from uncorrelated gas to liquid to solid become more subtle. Using sophisticated laser techniques, experimentalists are able to directly measure many properties of the correlated plasmas for comparison to theory.

Much of the research on low-energy nonneutral plasmas began as initiatives by individual principal investigators with long-term support from the National Science Foundation. Support from the Department of Energy for nonneutral plasma research has been focused on that which has direct relevance to the fusion program, such as tests of resonant particle transport theory or development of a positron diagnostic for tokamaks. The recent cutback by the Air Force Office of Scientific Research for work on ion traps and fundamental constants leaves the National Science Foundation as the mainstay of university research in the field. Recently, the Office of Naval Research sponsored a research initiative in nonneutral plasmas that has helped establish a number of new experiments and theory programs. New nonneutral plasma experiments are planned or under way at four universities and a national laboratory. In short, the subject of nonneutral plasmas is an example of a field whose potential cannot be realized by single-agency programs. Multiple-agency support is necessary to sustain the growth of this new area of basic plasma science.

DIAGNOSTICS AND BASIC PLASMA EXPERIMENTS

Measurement is the basis of physical knowledge, and the techniques for measuring the properties of plasmas, generally referred to as plasma diagnostics, play a critical role in advancing plasma science.

Even when the temperature is low enough to permit measurements inside the plasma, determining the many significant plasma parameters that vary in complex spatial and temporal patterns is a formidable challenge. Measurements of the temperatures of electrons and ions, of ions other than hydrogen, of the currents and electric and magnetic fields within the plasma, and of the flow, drift, or rotation velocities are needed. Understanding instabilities, fluctuations, and turbulence requires the measurement of variations in density, temperature, and fields over a broad range of spatial and temporal scales. The volume of data needed to characterize turbulent transport is impressive and requires the advanced data analysis techniques characteristic of numerical computations and of space research.

In no part of plasma science has the effort to improve diagnostics been more focused than in fusion research. In the case of fusion plasmas, the extreme temperatures constrain one to observe from the outside the hot gas itself. Improved techniques for each measurable quantity have been combined in a panoply of diagnostics to give a comprehensive, composite picture of the plasmas under study. Foremost among diagnostic developments over the past 25 years has been the establishment of Thomson scattering as a universal standard for determining electron temperature. The demonstration that many plasmas behave as black bodies at the electron cyclotron frequency has made possible another simple measurement of electron temperature. Measurements of density have also improved steadily with the development of shorter-wavelength-microwave and far-infrared interferometers. Spectroscopy has long been well established for cooler plasmas (those with temperatures lower than a million degrees), but there has been a great improvement in spectroscopic measurements of hot plasma. Ion temperatures can be measured by spectroscopic techniques using Doppler broadening or by the traditional method of charge exchange, which has been refined and improved over the past decade. Measurements of the electric potential or electric field within the plasma using energetic heavy-ion beams have been developed. Techniques from surface physics have been adapted to study the interaction of plasma with the walls of the vacuum vessel and the introduction of impurities into the plasma. Crucial to the use of all of these diagnostics has been the rapid and unceasing improvement of advanced computerized data-acquisition and data-processing systems. Online data processing has enabled far more intelligent and productive operation of very expensive experiments.

The committee has dwelled at length on the development of fusion diagnostics in order to make three points. First, plasma science is an information-hungry subject. Next, only by the early 1990s has it been possible to measure all of the quantities needed to characterize plasma dynamics and transport in the laboratory. Thus, for the first time, theory can be confronted by measurements of the comprehensiveness required for a meaningful test. This fact is implicitly recognized in the so-called "transport initiative" recently undertaken by the U.S. fusion research program. The final point is critical to the responsibilities of this committee: the use of comprehensive diagnostic techniques and other state-of-the-art experimental techniques is very unevenly spread within plasma science.

The uneven application of advanced techniques implies an uneven experimental understanding of the different types of plasmas under study, which complicates the task of identifying promising new opportunities. Nowhere is this truer than with the typically small-scale experiments whose purpose is to test our understanding of the principles of plasma physics. Here, the commitment to such desiderata as comprehensive diagnostics is an individual one, and it is often difficult to assemble the necessary capability from fractionated funding sources. Because the number of basic laboratory investigators is small, and not all of these have access to state-of-the-art techniques, it is difficult to forecast what could be done with a state-of-the-art approach to basic issues.

The situation of basic laboratory plasma experimentation in the United States has evoked expressions of concern in the past; *viz.*, the remarks of the Plasmas and Fluids Panel of the National Research Council (NRC) study, *Physics Through the 1990s* (National Academy Press, Washington, D.C., 1986): "Direct support for basic laboratory plasma physics research has practically vanished in the United States. The number of fundamental investigations . . . is small, and only a handful of universities receive support for basic research in plasma physics. . . ."

The Plasma Science Committee has found no evidence of any significant change in this state of affairs in the five years since the above statements were written, despite generalized good will. But the field has not been completely static—several extremely important basic plasma experiments have been completed in the recent past. Of the recent research carried out on small laboratory plasma devices, three efforts stand out for their general significance. A basic theory of modulational plasma turbulence was tested in the laboratory for the first time. (Similar experiments were subsequently carried out using high-power RF irradiation of the ionosphere.) This theory, developed in 1972, involves the most modern ideas in nonlinear science. It had been proposed in the 1940s that current-carrying plasmas would develop collective structures called double layers, and indirect evidence from space indicated that double layers might play a role in accelerating the electrons responsible for the aurora. However, there was no firm reason to believe in their existence until they were created and studied in the laboratory. Experiments on magnetic field reconnection, a process thought involved in such spectacular events as solar flares, magnetospheric substorms, and tokamak disruptions, were carried out with comprehensive diagnostics for the first time, but the magnetohydrodynamic range of scale lengths was not achieved.

The Plasma Science Committee is convinced that the issue of basic collisionless plasma experiments needs urgent attention. An appropriate level of basic research is necessary for the vitality of any scientific undertaking and is necessary to ensure that related applied research flourishes. Basic research may even be more important for the discovery of new applications, for it is only as understanding is distilled into fundamental form that it becomes portable, to be passed between research communities and scientific generations. From this perspective, the virtual disappearance of basic experimental research on neutral plasmas, particularly in universities, is of serious concern. Not only is experimentation the ultimate test of understanding, but no application is possible unless there has been laboratory experience with the relevant processes. The committee is made uneasy by the prospect of continued neglect of basic laboratory research in plasma science.

ANALYTICAL THEORY AND COMPUTATION

Analytical Theory

The high-temperature laboratory plasma state is characterized by an enormous range of both temporal and spatial scales: from 10^{-11} sec, the period of a plasma oscillation, to approximately 1 sec for the energy transport time, and from 10^{-3} cm for the Debye length to 10^{2} cm for the density-gradient length in a large tokamak. For astrophysical and space plasma, these ranges span even more orders of magnitude. In addition, there is a large array of dimensionless numbers that are needed to define the state of plasma. By way of contrast, relatively few quantities, like the Reynolds number, are needed in hydrodynamics. The complexity and richness of the plasma state are both daunting and challenging.

The plasma state is the preeminent candidate for the study of nonequilibrium statistical mechanics, a field of great importance and of which our present understanding is rudimentary. The path to equilibrium is determined by processes involving the huge number of collective degrees of freedom of the system. This aspect is true not only of multicomponent plasmas but also for beams of charged particles in high-energy accelerators, pulsed power machines, and so on, when the number density exceeds a critical threshold, and even for single-component plasmas.

The fundamental kinetic equations for the plasma have been available for some time, and the connection between collisionless drift orbits of particles and the fluid equations has been established. The transport of heat and particles by collisional processes in complex magnetic geometry has been successfully attacked. The situation is far less tractable when collisions are rare and collective processes intercede. A brief outline of what has been accomplished analytically so far in this direction follows:

- The linear theory of perturbations, which identifies the various collective modes of a plasma in inhomogeneous geometry, is almost a closed topic.
- The linear stability of plasma to low-frequency perturbations has been analyzed through a hierarchy of "energy principles" or variational principles of increasing sophistication.
- A quasilinear theory of perturbations has been developed to establish the lowest-order interaction between the particles and collective modes.
- The weak interaction amongst particles and dispersive collective modes is described in terms of a kinetic equation for the occupational number of the collective modes. The phases of these modes are assumed to be random with a Gaussian distribution.
- The strong interaction between particles and almost-nondispersive waves has been approached in terms of field theoretic methods that involve mass and charge renormalization and are known as the Direct Interaction Approximation (DIA). The distribution departs from the Gaussian. In this approach the principal effect of the quadratic nonlinearity is to cause the nonlinear damping of the collective mode. Coupled equations for the turbulent spectrum and nonlinear damping emerge from the analysis. Turbulent transport of heat, particles, and so on can be calculated through this technique, and it is found that Onsager's principle may be violated because the conditions are not those of equilibrium statistical mechanics.
- The renormalization group analysis (RNG) developed originally in the theory of phase transitions has been applied to plasma equations in those regimes where scale invariance holds. This approach is particularly useful for obtaining renormalized transport coefficients in the infrared limit resulting from short-wavelength fluctuations. Thus, it may be useful for developing subgrid models for computational solution of plasma equations.
- The current widespread interest in solitary waves or solitons was stimulated in significant part by problems in plasma physics. It was plasma physicists—aware of the

physics of nonlinear dispersive waves in plasmas and shallow water—who formulated the so-called inverse scattering theory 25 years ago. A large class of nonlinear dispersive systems has been shown to evolve into a sequence of robust localized structures called solitons. In multidimensional space the soliton may turn out to be unstable and lead to a collapsing soliton or caviton. Theories of high-frequency Langmuir turbulence based on solitons and cavitons as the elements of a dynamical system have been verified in experiments in the laboratory and the ionosphere. The soliton concept proved to be so general that it subsequently found fruitful application in fields ranging from polymer chemistry to quantum field theory.

- Modern developments in the theory of chaos in Hamiltonian systems have also been triggered by the problems of plasma physics; indeed the dynamics of trapped particles in waves led to the well-known Chirikov-Taylor map. The stochasticity of magnetic field lines under certain conditions and the transport of particle and wave propagation in such stochastic magnetic fields are under active discussion. The analysis of chaos in dissipative systems of low order has many applications in plasma physics.
- An example of a plasma physics problem with strong nonlinearity that has been successfully solved is the collisionless shock in which dissipation is due to collective modes. The future holds the promise of many such problems, especially in the interaction of very high power short-pulsed lasers with plasma, where an electron could reach relativistic energy in one cycle of the laser frequency, and in pulsed power applications to intense-charge-particle-beam physics and technology.
- There has been a very successful attempt at the application of boundary layer theory to an almost dissipationless plasma. But much more needs to be done, especially in space and astrophysical plasmas, where events take place on short time and spatial scales that cannot be understood in terms of the normal constraints on the motion on a highly conducting plasma.

Since, in the main, linear theory is well established, the major challenges lie in the nonlinear regime. The grand challenge in plasma theory is a compete understanding of plasma transport and its relation to plasma turbulence. However, many of the properties of transport and turbulence in fusion plasmas are specific to device geometry, and it is not yet possible to arrive at a detailed understanding that separates device-specific from fundamental phenomena. What is needed is an equivalent of the well-known Ising model in ferromagnetism, in other words, a clear theoretical paradigm, and experiments that test the paradigm.

Theoretical plasma science is now at a stage of development analogous to that of hydrodynamics in the last quarter of the nineteenth century: the fundamental equations were well understood and there was much mathematical development. However, theory could not always predict what the engineers obtained in practice. It took Prandtl with his boundary layer to bridge the gap between ideal theory and experiments. This development brought fluid mechanics to the point where today many practical engineering problems have been reduced to a matter of computation.

Today, plasma scientists face a similar situation with respect to the issue of predicting anomalous transport. It will be necessary to forge a strong link between theory and appropriately designed experiments to obtain the answers to key questions before anomalous transport is reduced to engineering practice. Forging such a link should lead, at least, to an understanding of the principles of plasma behavior and, optimistically, to stronger foundations for the theory of nonequilibrium statistical mechanics.

Computational Plasma Science

Computational plasma science has developed into a powerful tool for understanding and predicting the behavior of plasmas. The power of computers has increased by six orders of magnitude over the last 30 years and shows every indication of continuing this level of growth over the foreseeable future. During the same time, the methods of modeling plasmas have also improved greatly. Techniques are now available for looking at plasmas on the fastest time scales (particle models) or on intermediate time scales (gyrokinetic, implicit models) and on long time scales (fluid models).

Supercomputers and computational techniques have advanced to the point that it now seems possible to model tokamak behavior starting from physics-based models. This could have an important impact on the fusion program, and, in particular, such models might eventually become useful as tools to design fusion reactors.

In the realm of space plasma, computer modeling has brought new insight into the richness of the physics occurring in magnetized plasma shock waves. High-Mach-number shocks are proving to be recurrent and unsteady: they steepen, break, and steepen again. This physics was much too difficult for analytic physics to describe, and it was almost impossible to discern with clarity in space measurements. Plasma simulations are also shedding light on how particles can be accelerated in space, in the aurora, in solar flares, and in collisionless shock waves. The next generation of space plasma experiments will use computer simulations as a regular tool in data analysis: the computer will simulate what each detector ought to observe as the various spacecraft of the International Solar-Terrestrial Physics Program move across the different spatial regions of the magnetosphere. Global modeling will enable space experimentalists to visualize the time-dependent behavior of the earth's magnetosphere in three dimensions, thereby supplementing the single-point measurements obtained by spacecraft.

Computer modeling has led the way in recent studies of applications of plasma to high-energy physics. It has also shown how plasmas can be used to make new sources of light with unique properties (short pulse, chirped, up shifts of frequencies, and more). While experiments have lagged far behind the computer modeling, a number of experiments have verified the computer results. Furthermore, computer modeling has proven to be an invaluable tool in interpreting those experiments that have been carried out.

Computer models let us explore nonlinear plasma phenomenon in ways that we could not otherwise do. It seems clear that computer modeling will play a very important role in understanding plasma turbulence. Computer modeling allows us to develop our intuition and insight into what processes are really important. In the related area of the nonequilibrium statistical mechanics of plasma, modeling lets us peer much deeper into the fundamental processes at work.

Computer modeling promises to have a large impact on the teaching of plasma science. A numerical plasma laboratory would allow students to carry out fundamental experiments in plasma science. The student could try out his or her own ideas, undoubtedly the most effective way to learn about plasma behavior.

Finally, building new and better numerical models of plasmas is full of challenges. For example, how does one best model a system with an enormous number of degrees of freedom on a computer that is finite, though very large? This question strikes to the heart of statistical mechanics. Also, how does one extract useful results from the enormous mass of data provided by modern computations?

Summary

The analytic theory and computation carried out in plasma science participate with great vigor, and in several cases lead, in the practical development of new concepts in nonlinear science and nonequilibrium statistical mechanics. Theory and computation are proving to be fertile generators of new ideas in plasma science. Plasma computation is still a new and active field, and new methods are continually being developed to take advantage of the relentless advance of computing technology.

The challenge for the near future is to find the level at which the integration between theory, computation, and experimentation can be most effective. Since theory and computation cannot yet deal with the enormous complexity of many plasma configurations of contemporary interest, many plasma scientists argue that integration can best be achieved with carefully tailored experimental and computational configurations chosen for their theoretical richness and significance.

SPACE AND ASTROPHYSICAL PLASMAS

More than 99 percent of the baryonic matter in the universe is in the plasma state. Space and astrophysical plasma physicists study these plasmas. The distinction between the fields is mainly operational; space plasma physicists perform *in situ* experiments on solar system plasmas, while their astrophysical cousins rely entirely on remote sensing of more distant systems. Yet these two fields share a number of unifying themes, because the physical processes observed in space plasmas appear to be analogous to those inferred in remote astrophysical systems. Among the most important of these are the transport of heat and of angular momentum by collective processes, the acceleration of ultrahigh-energy particles in flowing plasmas, the generation of high-brightness temperature radiation by collective processes, and the generation of magnetic fields in magnetohydrodynamic dynamos.

Several examples illustrate the close relationship between space and astrophysical plasma research. Spacecraft experiments have found that heat conduction in the low-density solar wind plasma is controlled not by electron-ion collisions, but rather by the collective processes driven by rapidly streaming electrons, together with the natural limit to heat conduction set by the fact that the heat-conducting electrons cannot travel much faster than the electron thermal speed. The problem of electron heat transport appears in many astrophysical contexts, from galaxy clusters to the solar corona. The generic issue is a cool cloud immersed in a surrounding hot gas; for "cloud," one can substitute "star" or "galaxy." As heat is conducted into the cloud, mass is evaporated ("ablated") and blows away in a "wind." In the recently discovered "black widow" pulsars, the energy lost from a neutron star in a binary star system causes mass to be lost from the "normal" star; the rate of mass loss is controlled by heat conduction, just as is the case for the solar wind.

There has been significant progress in understanding the acceleration of high-energy particles by shock waves. The original ideas were invented mostly by theoretical astrophysicists in order to understand the origin of cosmic rays. Interstellar shocks are created by stellar explosions—supernovae; observations of synchrotron radiation from supernova remnants reveal the presence of shock-accelerated relativistic electrons, and it is natural to assume that ions are accelerated also. Using these ideas, space physicists interpreted early spacecraft observations of high-energy particles associated with shock waves in the interplanetary medium. In the late 1970s, efficient conceptual models of ion acceleration were devised, which were shown later to explain observations of high-energy ions associated with interplanetary shocks. These conceptual models can now be applied with increased confidence to the acceleration of cosmic-ray ions in the astrophysical setting. Nonlinear simulations and theory are now being used to try to understand why the particle acceleration processes are so efficient.

The understanding of ion acceleration by collisionless shocks will result in increasing quantitative confidence and predictive power in the 1990s. However, understanding of shock acceleration of electrons is much less secure. This issue is essential to astrophysics, since remote sensing picks up photons emitted by accelerated electrons.

The transfer of angular momentum in rotating gaseous systems is an issue that appears both in the formation of stars and in the accretion of plasma onto compact objects. In both cases, the angular momentum of the accreting gas must be almost totally removed, if the gas is to undergo the observed infall, to form the final star or fuel the x-ray emission from the neutron star or black hole. Theorists suspect that magnetic stresses are the origin of the torques that force the gas to accrete. Understanding angular momentum transport requires the application of dissipative magnetohydrodynamics to a differentially rotating system with ill-understood sources of turbulence in the flow. Recent work has revealed a mechanism by which a magnetic field might cause an instability in a disk that causes the gas to accrete. However, real progress will come when computation and/or experiment can address the behavior of the finite-amplitude fields in the accreting matter. Here, experiments might be the more informative, since many aspects of the three-dimensional magnetic stress are reproduced in laboratory devices such as the spheromak, and rotation can be produced by application of an electric field.

The dynamo generation of magnetic fields is a problem that arises in planetary, stellar, and galactic contexts and that raises fundamental issues of how large-scale, ordered magnetic fields can be created by conducting, rotating bodies. The basic issues are not yet resolved—for example, is dynamo activity distributed throughout the medium, or is it spatially intermittent with localized regions of intense field growth on the boundaries of rotating fluid cells? Recent progress has been slow, because the simple phenomenological things have been done, and theory and numerical simulation need better computational tools. No one has considered formally whether an investment in basic experimental research on dynamo activity in highly conducting plasmas would be well spent.

Thus far, the committee has discussed the fruitful relationship between space and astrophysical plasma physics. It will not review space plasma research *per se* here, because it has frequently been reviewed elsewhere. Nonetheless, the committee has a responsibility to comment on the relation between space plasma research and laboratory plasma science. The timeless part of the relationship was eloquently addressed in the NRC study *Space Plasma Physics: The Study of Solar System Plasmas* (National Academy of Sciences, Washington, D.C., 1978):

> *Space and laboratory experiments are complementary. They explore different ranges of dimensionless parameters. Space plasma configurations usually contain a much larger number of gyroradii and Coulomb mean free paths than achieved in laboratory plasma configurations. In the laboratory, special plasma configurations are set up intentionally, whereas space plasma configurations assume spontaneous forms that are recognized only as a result of many single-point measurements. Space plasmas are free of boundary effects; laboratory plasmas are not, and often suffer severely from surface contamination. Because of the differences in scale, probing a laboratory plasma disturbs it; diagnosing a space plasma usually does not. The pursuit of static equilibria is central to high-temperature laboratory plasma physics, whereas space plasma physics is concerned with large-scale time-dependent flows.*
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> *Certain problems are best studied in space . . . certain problems could be more conveniently addressed in the laboratory . . . Theory should make the results of either laboratory or space experiments available for the benefit of the whole field of plasma physics.*

To these remarks, the Panel on Physics and Fluids added, in *Physics Through the 1990s* (National Academy Press, Washington, D.C., 1986):

> *The recent strengthening of theoretical space physics, together with the increasing capability of space plasma instrumentation and the superiority of the space plasma environment for certain types of measurements, means that the experimental diagnosis and theoretical interpretation of certain space-plasma processes now matches the best of current laboratory practice.*

In summary, the solar system is an experimental test-bed for plasma concepts that are important to astrophysics and new to the laboratory. Indeed, questions first raised in space research have stimulated experiments in the laboratory devoted to problems such as magnetic field reconnection and double layers. Nonetheless, the Plasma Science Committee sees some evidence of structural problems that limit the contributions space and laboratory plasma research can make to each other. Laboratory investigations of plasma processes discovered first in space are often considered basic plasma science by the space community and space science by the laboratory plasma science community. And rarely does anyone ask whether laboratory mastery of a plasma process that happens to have been uncovered first in space might lead to useful applications.

The so-called "critical ionization" problem is one pertinent example. Several decades ago, it was proposed on dimensional grounds that a neutral gas in a magnetic field can suddenly be brought to full ionization when a plasma streams over it with an energy equal to the ionization energy of the gas. The original application of this idea was to solar system and planetary formation. Recently, space plasma physicists, stimulated by observations of the interactions between neutral and ionized gases in the Io torus in Jupiter's magnetosphere, in artificial chemical injections in Earth's ionosphere, and in cometary atmospheres, have arrived at a firmer understanding of the microscopic plasma processes that lead to critical ionization. Without a laboratory research program to explore the usefulness of the critical ionization phenomenon, it will be difficult to determine whether the process has potential technological value. Neither space measurements nor computational modeling can answer this question.

III

Concluding Remarks

The Plasma Science Committee hopes that this research briefing, which discusses plasma science in its entirety (we believe for the first time), will not only communicate the breadth and depth of the discipline, but will also lay the foundations for a broad conceptual framework in which decisions concerning plasma science can be considered.

Plasma science is particularly rich in the area of nonequilibrium and nonlinear processes. It was one of the first disciplines to grapple with the relationship between nonlinearity and complexity, a problem that is recognized today to be a hallmark of late-twentieth-century science. Nothing clarifies better the potential impact of achieving a broad and fundamental understanding of plasmas than a survey of the diversity of the applications of plasma science. However, the communities, committees, and agencies concerned with the applications of plasma science—fusion, space and astrophysics, plasma processing, energy conversion, military-directed energy research, and others—naturally concentrate on those efforts that have a direct and immediate connection with their missions. In the committee's view, decisions that are overly constrained by considerations of relevance to one application may lead to missed opportunities, not only in basic research, but also for new and unexpected applications in other areas of plasma science. It is the committee's conviction that such opportunities for research and development in plasma science are abundant.

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1. Missed opportunities may well be the most serious consequence of the present approach. Many of these issues are being addressed by the Panel on Plasma Processing of Materials commissioned by the National Research Council. The panel will complete its review and assessment during 1991 and will formulate specific recommendations designed to improve the organization and strength of the plasma science that supports the burgeoning applications in this field.