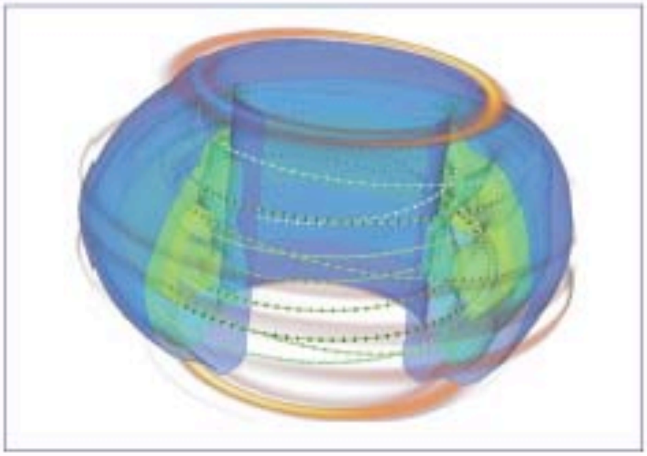
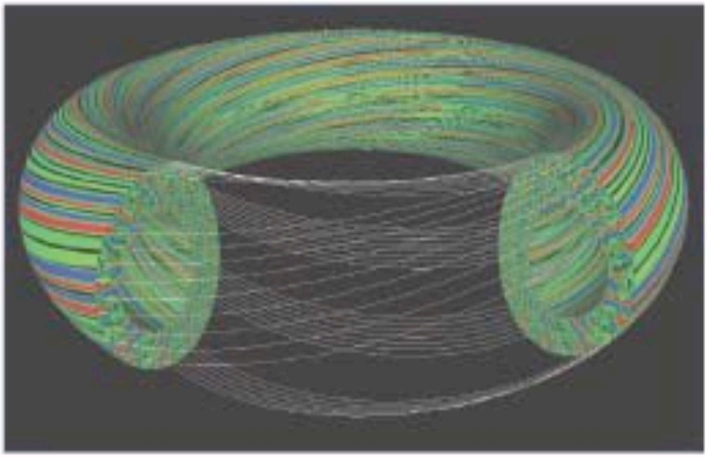
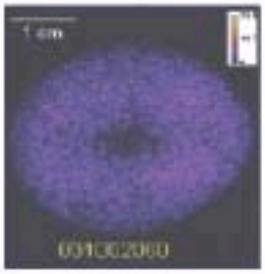
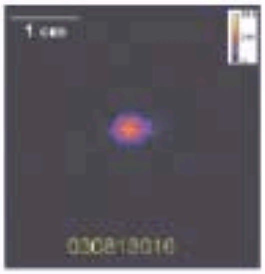
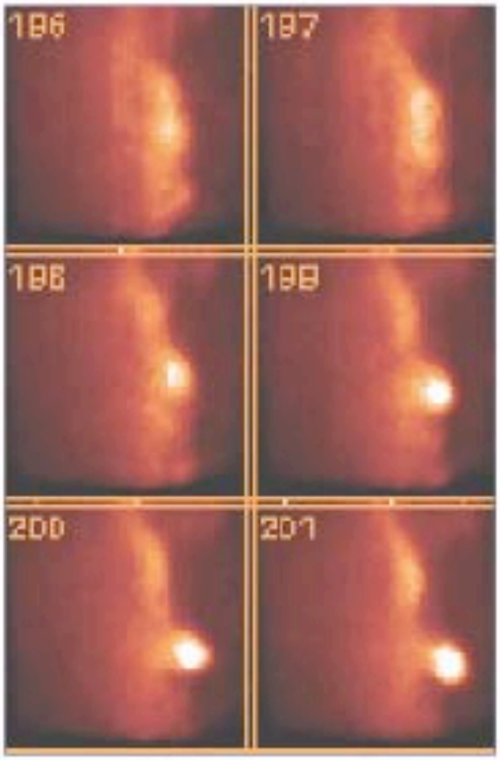
Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program

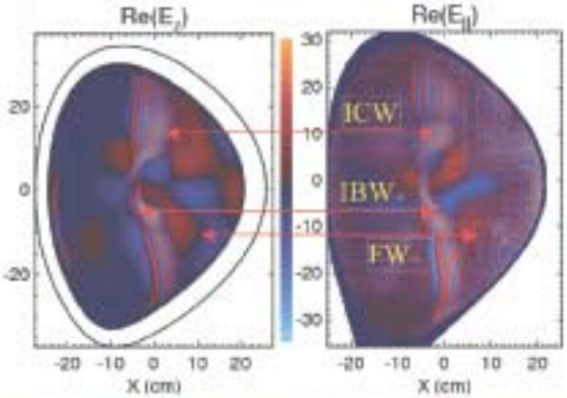












A Report to the Fusion Energy Sciences Advisory Committee

APRIL 2005

About the Cover

Upper left: time slice from a 3D simulation of a plasma disruption on DIII-D using NIMROD. Upper right: Computer simulations of early nonlinear development of electron gyroscale turbulence. Center left: Plasma neutralization reduces the final focus spot size of an intense ion beam. Center: Measurements of plasma turbulence in the edge region of NSTX. Center right: Computer calculations show that the fast wave launched into a plasma from a radio-frequency source are changed into ion Bernstein waves and ion cyclotron at the mode-conversion surface. Lower right: In support of ITER, the U.S. and Japan constructed the superconducting central solenoid model coil.

PREFACE

In October 2003, Dr. Raymond Orbach, Director of the Department of Energy's Office of Science, issued a charge to the Fusion Energy Sciences Advisory Committee (FESAC) "to identify the major science and technology issues that need to be addressed, recommend how to organize campaigns to address these issues, and recommend the priority order for these campaigns." (The charge letter is included as Appendix A.)

This charge to FESAC follows from the recently completed study by the National Research Council entitled *Burning Plasma—Bringing a Star to Earth* (National Academies Press, 2004). The NRC report recommended that the United States join the international negotiations to build and operate ITER. In this context, the NRC also recommended that "although active planning has been undertaken by the U.S. fusion community in recent years, the addition of so major a new element as ITER requires that to ensure the continued success and leadership of the U.S. fusion science program, the content, scope, and level of U.S. activity in fusion should be defined through a prioritized balancing of the program."

The charge letter states that FESAC "will need to assemble a balanced domestic program that takes account of fusion programs abroad and that includes ITER as an integrated part of the whole." The charge letter further states that the "funding for ITER construction is provided in addition to these (base program) funds." While recognizing that the ITER negotiations are ongoing, the work in response to this charge has proceeded assuming a positive outcome from the international negotiations. Thus, the relevance and priority of research activities are discussed within the context of a positive decision on ITER construction. However, most tasks are equally important for the broader topic of burning plasma research.

The charge to the panel includes both magnetic and inertial fusion topics. All aspects of magnetic fusion research are contained within the U.S. Department of Energy's Office of Fusion Energy Sciences (OFES), but inertial fusion research is conducted both in the Department of Energy's National Nuclear Security Administration (NNSA) and OFES. This presented a special issue for the work of the panel. After consultations with OFES Director Dr. N. Anne Davies and FESAC Chair Professor Richard Hazeltine, it was decided to include key aspects of inertial fusion research when describing research challenges, but to consider only those inertial fusion topics currently funded by OFES when considering future priorities. The priorities panel was also greatly aided by the input from the previously established FESAC panel on inertial fusion energy.

To carry out the charge, the FESAC chair, Professor Richard Hazeltine, appointed a Priorities Panel (see Appendix B). The panel is composed of 25 members selected to ensure a broad representation of disciplines and institutions important to the fusion energy sciences program. This broad representation was enhanced by community participation in developing the technical basis for the panel's assessments through a general access panel website (with the opportunity to post comments), broad participation by specialists in working groups discussions including the use of websites and discussions at topical meetings and summary briefings at many community meetings.

The panel began its work by carefully reviewing recent reports from other fields of science that address a particular field's scientific challenges and priorities. Examples include the following:

- *Connecting Quarks with the Cosmos* (National Academies Press, 2003).
- *Frontiers in High Energy Density Physics* (National Academies Press, 2003).
- *The Science Ahead—The Way to Discovery* (DOE High Energy Physics Advisory Panel, 2003).
- *The Sun to the Earth and Beyond (Solar and Space Physics)* (National Academies Press, 2003).
- *Astronomy and Astrophysics in the New Millennium* (National Academies Press, 2003).
- *Astrobiology Roadmap* (National Aeronautics and Space Administration, 2003).

To conclude ultimately with a set of scientific campaigns, with priorities assigned to the major campaigns, the panel worked through four stages. First, the panel expressed the mission of the research program through the statement of three overarching themes that motivate the entire research activity. The second step was to develop fifteen scientific topical questions that express the intellectual challenges and opportunities offered by fusion science research. This step was completed early in 2004, and the questions were made available to the fusion research community for comments. The third step was to define the research approaches and thrusts needed to address the scientific topical questions. To carry out this step and to encourage further participation by the community, the fifteen questions were grouped into six theme areas and national working groups were formed to prepare the research approach and thrusts for each question in a given theme area. The chairs/co-chairs/vice-chairs are shown in Appendix C. The fourth step was to define a set of scientific campaigns that can then be used to describe and prioritize the program. This deliberative process has enabled the panel to extract the essential issues and opportunities of the program and to engage the broader fusion community in the activity.

The following chapters in this report document the results of the Panel's work. The first two chapters describe the concepts of the overarching themes, topical scientific questions, and campaigns. The next six chapters (Chapters 3–8) describe in detail the six scientific campaigns. Chapter 9 describes some important enabling research activities necessary for the campaigns. Chapters 10 through 12 describe the overarching themes, which provide a crosscutting perspective of the activities in the six campaigns. Finally, the Panel's recommendations are set forth in Chapter 13.

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EXECUTIVE SUMMARY

Fusion energy science research combines fundamental and applied science. On the one hand, the research aims to discover the underlying principles of high-temperature plasma physics. On the other hand, an important aim is to use this knowledge to control plasma behavior and devise systems suitable for a future fusion power source.

Fundamental plasma physics has far-reaching impact. The research addresses the behavior of nonequilibrium gases of charged particles undergoing long-range interactions, where each particle interacts with the collective fields of billions of other charged particles. Such gases, called plasmas, are the prevalent state of matter in the visible universe, as well as in a fusion energy system. In addition, plasma physics has well-known applications to adjacent fields, such as nonlinear science and astrophysics. The further development of plasma physics is essential to understand the behavior of visible matter at all scales in the universe, from atomic to cosmological.

The development of fusion energy is a prime motivator and benefactor of plasma physics. The benefit to humankind of an essentially inexhaustible, environmentally clean, safe energy source available to all nations would be vast. Fusion energy would have profound beneficial impact on the global problems of the change of climate, the elevation of the standard of living of the world population, and the security of nations. An important aim is to use the knowledge of plasma physics to realize fusion energy. Equally essential is the development of new engineering principles needed to create and confine fusion plasmas in the laboratory, as well as to extract the fusion heat and produce the fuel.

Today's research into the physics of high-temperature plasmas and controlled fusion energy is occurring during a period of great discovery. Through a combination of sophisticated experiments and diagnostics, comprehensive theory, and computations, fusion researchers are now able to probe, understand, and control several of the complex, nonlinear processes within hot plasmas.

The knowledge base is now in hand to produce a burning plasma–a plasma whose high temperature is sustained predominantly by energy from alpha particles produced by fusion reactions. This will be realized in experiments on ITER. The U.S. contribution to the construction of ITER and preparation for operations will subsequently enable access to and exploration of magnetically confined burning plasmas. The Office of Science has designated ITER as its highest-priority new facility. The Office of Science report, *Facilities for the Future of Science* (2004), stated, "ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a 'burning plasma' It is the next essential and critical step on the path toward demonstrating the scientific and technical feasibility of fusion energy." As noted in the charge letter to the Panel (see Preface), construction of ITER will require additional financial resources.

As the National Research Council Burning Plasma Assessment Committee concluded, “The opportunity for advancing the science of fusion energy has never been greater or more compelling, and the fusion community has never been so ready to take this step.”

OVERARCHING THEMES

The first overarching theme of the fusion energy sciences program is to ***understand matter in the high temperature plasma state***. The program addresses the collective dynamics of non-equilibrium gases of charged particles. This dynamic is complex because of the nearly collisionless environment of many plasmas of interest and because of the intrinsic nonlinearity of the plasma medium. Often a consequence of this nonlinearity is the development of turbulence and the associated generation of plasma motions involving a vast range of spatial and temporal scales. The imperative to describe such dynamics has fostered the design of powerful new computational algorithms that have application to both fusion plasmas and those in the broader context of space and astrophysics. The further development of plasma physics is essential to understand the behavior of visible matter at all scales in the universe, from the magnetosphere, to solar and to the cosmos.

The second overarching theme of the program is to ***create a star on earth***. The knowledge is now in hand to produce, study and control a burning plasma - plasma whose high temperature is sustained by the heat produced by fusion reactions. ITER will investigate the new physics regime of magnetically-confined burning plasmas, develop and test engineering systems suitable for the burning plasma environment, and generate some 500 megawatts of fusion power for periods from minutes to hours.

A second approach, employing inertial confinement, will be studied in the National Ignition Facility (NIF), funded by the DOE’s National Nuclear Security Administration. While stockpile stewardship is the major focus of research on NIF, its contributions to understanding the underlying physics of burning plasmas in inertially confined plasmas are expected to play a major role in establishing the foundations of inertial fusion energy.

The third overarching theme of the program is to ***develop the science and technology to realize fusion energy***. The high-pressure high-temperature plasma must be confined in a way that permits efficient steady-state or quasi-steady-state operation. This requires optimization of the plasma configuration for magnetically-confined plasmas or the efficient compression and heating of high-density matter for inertial confinement fusion. The creation, measurement and control of an energy-producing plasma would engender research and development in large-scale high-field magnets, in materials and structures that handle the plasma power and produce the fuel in radio-frequency actuators for control of the plasma profiles and stabilization of plasma instabilities, in techniques for tritium extraction and control, and in instrumentation for measuring detailed properties of the plasma.

The scientific challenge of fusion research, the importance of the challenge, and the opportunities available to fusion researchers are captured by these three overarching themes.

They motivate fifteen topical scientific questions that express the outstanding research questions facing fusion scientists today.

TOPICAL SCIENTIFIC QUESTIONS

Motivated by the three overarching themes, fifteen topical scientific questions of high intellectual value have been formulated which communicate the key scientific research to be carried out in fusion energy science over the next ten years. They are as follows:

T1. How does magnetic field structure impact fusion plasma confinement?

T2. What limits the maximum pressure that can be achieved in laboratory plasmas?

T3. How can external control and plasma self-organization be used to improve fusion performance?

T4. How does turbulence cause heat, particles, and momentum to escape from plasmas?

T5. How are electromagnetic fields and mass flows generated in plasmas?

T6. How do magnetic fields in plasmas reconnect and dissipate their energy?

T7. How can high energy density plasmas be assembled and ignited in the laboratory?

T8. How do hydrodynamic instabilities affect implosions to high energy density?

T9. How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?

T10. How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?

T11. How do electromagnetic waves interact with plasma?

T12. How do high-energy particles interact with plasma?

T13. How does the challenging fusion environment affect plasma chamber systems?

T14. What are the operating limits for materials in the harsh fusion environment?

T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively-pulsed burning plasma?

CAMPAIGNS

The fifteen scientific questions have been grouped into six campaigns. A campaign is a set of experimental and theoretical activities needed to answer the questions. Six campaigns are used to plan, organize, and coordinate the research activities. They are:

Macroscopic plasma physics*:* Understand the role of magnetic structure on plasma confinement and the limits to plasma pressure in sustained magnetic configurations. (Questions T1, T2, and T3)

Multi-scale transport physics: Understand and control the physical processes that govern the confinement of heat, momentum, and particles in plasmas. (Questions T4, T5, and T6)

High energy density physics: Investigate the assembly, heating, and burning of high energy density plasmas. (Questions T7, T8 and T9)

***Plasma boundary interfaces**:* Learn to control the interface between the 100-million-degree-C plasma and its room temperature surroundings. (Question T10)

Waves and energetic particles: Learn to use waves and energetic particles to sustain and control high-temperature plasmas. (Questions T11 and T12)

Fusion engineering science: Understand the fundamental properties of materials, and the engineering science of the harsh fusion environment. (Questions T13, T14, and T15)

For each scientific question, an accompanying research approach has been formulated, spanning the next ten years. The approaches are formulated by considering the required research thrusts (experimental, theoretical, computational), the required capabilities, the expected results and impact, and their relation to the three overarching themes. For each campaign, research thrusts, ten-year goals, and specific research activities have been identified.

A striking feature of fusion research is that a majority of the activities contribute to each of the overarching themes—understanding the high-temperature plasma state, creating a star on earth, and developing the science and technology to realize fusion power.

RECOMMENDATIONS

The Panel's recommendations regarding the scientific priorities of the U.S. Department of Energy Office of Fusion Energy Sciences' research activities focus on the next ten years and on the scientific campaigns and the related topical scientific questions.

Recommendation 1: The scientific challenges of fusion energy and the opportunities for discovery in plasma physics should be addressed by a research program that encompasses a broad range of key scientific questions.

In plasma, many physical effects couple together to form a complex, nonlinear system. These effects need to be understood in isolation as well as in combination. The development of engineering systems to control the plasma and extract the fusion heat requires extensive engineering research. The interface between the hot plasma and surrounding material structure requires advances in both physics and engineering. The attainment of fusion energy demands an understanding of this full range of scientific issues. The panel has grouped the issues into six scientific campaigns, illustrated in Figure 1. Since progress in all six campaigns is essential, it is not possible to prioritize them by rank ordering. However, the level of effort devoted to each campaign should not necessarily be the same. After carefully examining the scientific advances needed in each campaign, the panel recommends the approximate division of effort for the next ten years as shown in the figure. This division of effort is similar to that of the present program, however the activities within each category will evolve over the next decade as the first operation of a burning plasma experiment is approached.

Substantial progress can be made in addressing the fifteen topical scientific questions described in the report under the assumption of constant level-of-effort for the domestic program (in addition to ITER construction), over the next decade. Anticipated advances in each area were identified through extensive interactions with the fusion community through the working groups (see Appendix C). These efforts will broaden and advance the basic understanding of plasma physics and related sciences, enable effective utilization of a burning plasma experiment, and provide the underpinnings to realize the advancement of fusion energy.

For example, in the macroscopic plasma physics area, substantial progress is expected in understanding the role of the magnetic field structure on plasma confinement, including the effects of 3D shaping and different types of symmetry. The studies of the role of internal magnetic structure on confinement will be nearly completed for tokamaks, in preparation for ITER. Experiments attempting to understand and control pressure-limiting phenomena and to mitigate the consequences of any rapid current quenches or 'disruptions' are presently being conducted. Within ten years, a detailed understanding of pressure limits in rotating plasmas with resistive walls should be completed, and studies of active stabilization without rotation will be well underway. Disruption mitigation techniques for ITER will have been developed. An understanding of magnetic reconnection, including methods of suppression, should be complete and documented in axisymmetric configurations. Methods to sustain the plasma duration will have been developed, including methods to enable operation of ITER as a long-pulse, burning plasma experiment.

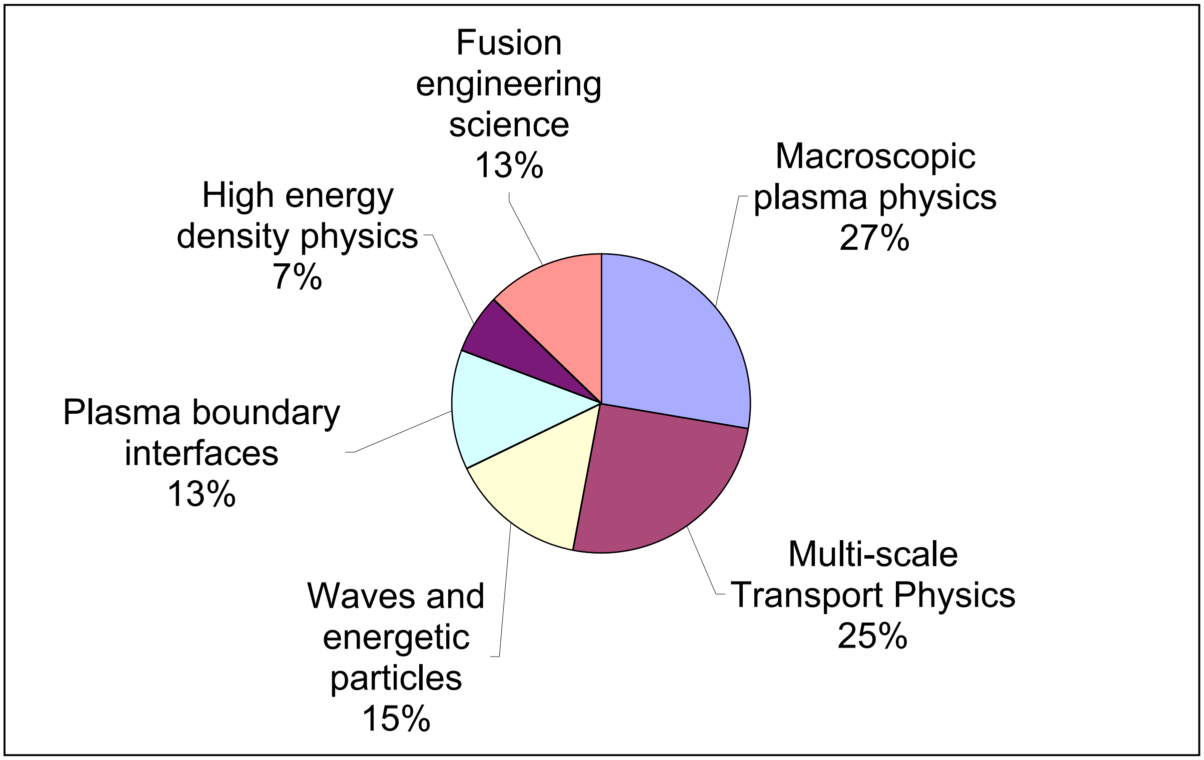

Figure 1: Approximate recommended distribution of effort among the six scientific campaigns.

In the multi-scale transport physics area, the goal of developing a predictive capability for ion thermal transport is within reach for the tokamak. The understanding of electron thermal transport is not as advanced but progress is expected in understanding the role of turbulence. While particle and momentum transport studies are less mature, the most important mechanisms will be incorporated into transport models and the models will be tested against experimental results. A more complete understanding of the conditions and thresholds for edge and core transport barrier formation, and of their dynamics, will be obtained and used to control the levels of core transport. In addition, experiments to detect zonal flows and their effects have begun, and within ten years it will be possible to make comparisons with theoretical and numerical models. Large scale flows, especially in plasmas without dominant external flow drive, will be documented, and analysis should enable predictions for ITER-relevant burning plasma regimes. Understanding and control of transport will have a direct impact on the performance of ITER, and substantial progress is expected in this area. Significant advances are anticipated in understanding and controlling transport in the range of magnetic configurations that are less well developed. Studies of large-scale magnetic field generation should lead to identification of the dominant mechanisms by which turbulence generates and sustains large-scale magnetic fields (the dynamo) in high-temperature plasma. Finally, experiments and modeling of magnetic reconnection in laboratory plasmas will identify the dominant processes that facilitate the breaking of magnetic field lines.

In the high energy density physics area, an integrated program of beam experiments with theory and simulations will be carried out to understand the limits to neutralized drift compression and focusing of intense ion beams onto targets. Experiments with short-pulse lasers and simulations will be carried out to develop a basic understanding of the electron generation for high incident laser intensities and relativistic electron transport in dense matter. Experiments of magnetized plasma compression (with minimal theory support) will also be carried out sufficient to understand the scientific and engineering basis for magnetized target fusion.

In the plasma-boundary interface area, simplified first-principle models will be developed of the edge transport barrier to reproduce many of the measured characteristics of the boundary plasma in current fusion experiments. This will result in improved predictions of ITER's performance. The fundamental characteristics of edge turbulence in high-confinement plasmas will also be determined. There should be a sufficient set of data, with supporting theoretical analysis, to quantify the major impurity sources and the physics, which determines the observed divertor and first-wall erosion and redeposition rates. The distribution of expected tritium trapped in carbon-based plasma-facing components will be largely understood in terms of plasma conditions observed in present-day experiments, and candidate techniques for tritium removal will be tested. Also, qualification of alternative high-heat-flux components will bring us to the point of readiness for testing in longer-pulse confinement experiments.

The research activities in the wave and energetic particle physics area are expected to make considerable advances in developing the fundamental physics models for wave coupling, propagation, absorption and plasma responses that will enable coupling on critical time scales with plasma stability and transport models for validation against experiments. The understanding of radio-frequency sheath effects and edge parameters on antenna loading will be improved. In the validation of wave propagation, absorption, and current-drive physics, more widespread deployment of advanced diagnostics for wave detection will quantify the theoretical models. Progress in understanding the behavior of energetic particles and unstable waves that can be excited by energetic particles for regimes of high pressure and strong flow is expected to enable exploration of improved plasma performance in future burning plasma devices.

In the fusion engineering science area, the U.S. program will continue to perform much of the R&D and design work needed for the provisionally assigned U.S. in-kind contributions to ITER. The research on enabling technology will directly contribute to experiments on heating and current drive, plasma fueling, disruption mitigation, and power and particle control. Considerable progress is expected in developing the knowledge base required to determine the performance limits and identifying innovative solutions for the plasma chamber systems and materials. A comprehensive, experimentally validated suite of multi-scale material-modeling codes will be developed. The ten-year goal is to deliver to ITER the blanket test modules required to understand the behavior of materials and blankets in the integrated fusion environment. Under constant level-of-effort, the U.S. will rely mostly on variations of designs led by Europe and Japan for the full test modules. Also, progress is expected in determining the "phase space" of plasma, nuclear, material, and technological conditions in which tritium self-sufficiency and power extraction can be attained.

Recommendation 2: U.S. strength in fusion energy sciences research, U.S. impact on international burning plasma research, and progress towards answering the key scientific questions will be enhanced by an additional allocation of $100M per year for the domestic program for the following selected high-priority activities:

- Carry out additional science and technology activities supporting ITER including diagnostic development, integrated predictive modeling and enabling technologies. *(Most campaigns)*
- Predict the formation, structure, and transient evolution of edge transport barriers. *(Plasma boundary interfaces)*
- Mount a focused enhanced effort to understand electron transport. *(Multi-scale transport physics)*
- Pursue an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas. *(Macroscopic plasma physics)*
- Study relativistic electron transport and laser-plasma interaction for fast ignition high energy density physics. *(High energy density physics)*
- Extend understanding and capability to control and manipulate plasmas with external waves. *(Waves and energetic particles)*
- Increase energy ion pulse compression in plasma for high energy density physics experiments. *(High energy density physics)*
- Simulate through experiment and modeling the synergistic behavior of alpha-particle-dominated burning plasmas. *(Waves and energetic particles)*
- Conduct enhanced modeling and laboratory experiments for ITER test blankets. (*Fusion engineering science)*
- Pursue optimization of magnetic confinement configurations. *(Macroscopic plasma physics)*

- Resolve the key plasma-material interactions, which govern material selection and tritium retention for high-power fusion experiments. *(Plasma boundary interfaces)*
- Extend the understanding of reconnection processes and their influence on plasma instabilities. *(Multi-scale transport physics)*
- Carry out experiments and simulation of multi-kilo-electron-volt megabar plasmas. *(High energy density physics)*
- Expand the effort to understand the transport of particles and momentum. *(Multi-scale transport physics)*

Each of these high-priority activities is described in the following chapters that describe in detail the six scientific campaigns (Chapters 3-8). Each campaign identifies the important opportunities for making enhanced progress in answering the key scientific questions. The highest-priority activities listed above represent the most important of these opportunities. While many activities can be pursued at a reduced pace under level resources, opportunities exist for substantially enhanced progress on critical ongoing research programs with additional funding.

Recommendation 3: If less incremental funding were available, in the range of $50M per year, then the first six activities identified above should receive priority attention.

The first six activities are viewed today as the most critical in further preparing the U.S. to participate in a burning plasma experiment and for enhancing progress in vital aspects of the six scientific campaigns.

Recommendation 4: The fusion energy sciences program should assess the need for additional major domestic experimental facilities in about five years.

The study of burning plasmas is one of the overarching themes of the program. Present facilities are not able to access this important scientific regime thus requiring the construction of a new facility. In particular, existing facilities are not able to create plasmas with sufficient confinement and pressure to achieve conditions under which the heating from the fusion reactions is equal to or greater than the auxiliary heating power—the essence of "burning plasma." The U.S. contribution to the construction of ITER and preparation for operations will subsequently enable access to and exploration of magnetically confined burning plasmas. As noted in the charge letter to the Panel (see Preface), construction of ITER will require additional financial resources.

Just as the construction of ITER is driven by compelling scientific questions requiring scientific regimes with unique combinations of confinement and pressure, other scientific questions may motivate the construction of major new facilities beyond those currently under construction, or major upgrades to existing facilities. The duration of design and construction of new facilities ranges from typically four-to-six years for significant facilities to typically five-to-ten years for major U.S. facilities. It is anticipated that substantial progress on the scientific issues described in this report will generate new scientific questions. Design studies and rigorous proposal reviews during the second five-year period of this ten-year research activities enable the program to move ahead with the construction of new facilities, when ITER construction will be nearing completion.

1

MAJOR SCIENTIFIC CHALLENGES

INTRODUCTION

Fusion energy science research combines fundamental and applied science. On the one hand, the research program aims to discover the principles of high-temperature plasma physics. On the other hand, an important aim is to use this knowledge to control plasma behavior and devise systems suitable for a fusion power source.

Fundamental plasma physics has far-reaching impact. In some ways, plasma physics research resembles the development of equilibrium statistical mechanics that began more than a century ago. The goal then was to understand the behavior of *equilibrium* gases of neutral atoms undergoing *short-range* interactions. With contributions from physicists such as Boltzmann and Maxwell, that effort produced concepts such as entropy and the Maxwell-Boltzmann distribution function. The relevance of these concepts is pervasive, even though most gases in the universe are neither neutral nor in equilibrium. The fusion energy sciences program aims to understand the behavior of *nonequilibrium* gases of charged particles undergoing *long-range* interactions, where each particle interacts with the collective fields of billions of other particles. These ionized gases, called plasmas, are the prevalent state of matter in the visible universe, as well as in a fusion energy system. The ensuing principles should be as far-reaching and enduring as those developed for the special case where statistical mechanics is applied to the lower-temperature states of matter, fluids and gases. The description of plasma dynamics is challenging because plasmas are intrinsically nonlinear. Scientists have established fundamental principles of the complex plasma state that include wave propagation and absorption, plasma hydrodynamics, and the very first elements of a comprehensive theory of transport from plasma turbulence. Today's plasma scientists apply these principles to understand a wide range of laboratory, astrophysical, and industrial plasmas. The further development of plasma physics is essential to understand the behavior of visible matter at all scales in the universe, from atomic to cosmological.

The development of fusion energy is a prime motivator and benefactor of plasma physics research. The benefit to humankind of an essentially inexhaustible, environmentally clean, safe energy source available to all nations would be vast. Fusion energy would have profound beneficial impact on the global problems of the change of climate, the elevation of the standard of living of the world population, and the security of nations. An important aim is to use the knowledge of plasma physics to control plasma behavior and devise systems suitable for a fusion power source. Equally important, new engineering principles will be developed that are needed to create and confine fusion plasmas in the laboratory, as well as to extract the fusion heat and breed tritium.

These two overlapping goals, fundamental and applied science, are essential for a task as challenging and important as fusion energy, and they guide the research priorities. This dual nature is also a strength of the program: the impact of the research is multiplied by its simultaneous fundamental import and contribution to the fusion energy goal.

Today's research into the physics of high-temperature plasmas and fusion energy is occurring during a period of great discovery. Through a combination of sophisticated experiments and diagnostics, comprehensive theory, and computations, fusion researchers are now able to probe, understand, and control some of the complex, nonlinear processes within hot plasmas. The knowledge is now in hand to produce a burning plasma—a plasma in which the necessary high temperature is sustained by the heat produced by the fusion reactions. This will be realized in the ITER experiment which will investigate the new physics regime of burning plasmas, develop and test engineering systems suitable for the burning plasma environment, and generate some 500 MW of fusion power. As concluded by the recent NRC Burning Plasma Assessment Committee, *"The opportunity for advancing the science of fusion energy has never been greater or more compelling, and the fusion community has never been so ready to take this step."*

OVERARCHING THEMES

The scientific challenge of the fusion program, the importance of the challenge, and the opportunities available to fusion researchers are captured by the following three overarching themes.

O1. Understand matter in the high-temperature plasma state.

The plasma state of matter demands new physics understanding because its properties are emergent: they are not readily derivable from understanding the properties of single particles but arise from the collective interaction of billions of particles. Yet, it is remarkable that much of the complex, nonlinear phenomena of plasmas can be reduced to simple physical principles. Discovery and advancement of these principles is of great importance since hot plasmas constitute the core of fusion plasmas and much of the visible universe. The principles of plasma physics apply from spatial scales of microns in fusion plasmas and industrial-processing plasmas to millions of light years in extra-galactic structures, and from time scales of a billionth of a second in inertially confined laboratory fusion plasmas to billions of years in galaxies. Understanding how plasma, electromagnetic fields, and the other states of matter interact and organize is crucial to understanding the universe and to discovering methods for generating fusion energy.

O2. Create a star on earth.

In burning plasma, the energy released from fusion reactions will sustain the very high temperature (>100 million °C) required for fusion power, introducing significant new nonlinear plasma behaviors. Burning fusion plasma is energy-producing and largely self-controlled. It represents a new plasma physics regime in which the plasma is strongly influenced by self-heating. The production of a laboratory burning plasma will be an enormous physics and engineering accomplishment, and it will demonstrate the scientific feasibility of fusion power. The creation of burning plasma will permit numerous scientific and technical investigations of plasma self-heating, self-organization, and fusion energy production.

O3. Develop the science and technology to realize fusion energy.

It is a grand scientific and technical challenge to configure an energy-producing fusion system to provide practical fusion energy. Sufficient energy gain must be achieved to sustain the fusion system. The high-pressure high-temperature plasma must be confined in a way permitting efficient steady-state or quasi-steady-state operation. This requires optimization of the structure of the confining magnetic field. Stellar-grade plasmas with large heat and energetic particle fluxes must be interfaced to solid and liquid materials. The interaction of the fusion-produced neutrons with the surrounding materials must be understood. Novel materials must be developed to ensure attractive environmental properties. All parts of the fusion fuel cycle must be developed and understood. Configuring and controlling these elements simultaneously to provide practical fusion energy is a significant challenge to both physics and engineering science.

COMPELLING QUESTIONS

Motivated by the three overarching themes, the panel formulated fifteen detailed scientific questions, which capture the critical issues in fusion energy science to be addressed in the next ten years. The questions, displayed later in this chapter, include fundamental physics and engineering science. The report treats both the science relevant to magnetic fusion energy (of relatively low density but very high-temperature plasmas confined by magnetic fields) and the related science relevant to inertial fusion energy (of high energy density plasmas). The engineering challenges of controlling, heating, and confining 100-million-degree plasma are also addressed. These engineering problems must be solved to enable experimental research in the near-term and fusion power in the longer term. Most questions are stated as a search for the understanding of key phenomena. Unstated, but implicit in each question, is the companion goal of using that understanding to control a particular plasma phenomenon or process. For example, it is aimed to understand plasma transport by turbulence, and then to control the turbulent loss of energy from the plasma.

The fifteen questions can be conveniently grouped into six categories that, in the next chapter, will be identified with research campaigns.

The fundamental plasma physics of magnetic confinement is the focus of the areas of *macroscopic plasma physics* and *multi-scale transport physics*. These areas address the connection between the macroscopic properties of plasma (*e.g.*, pressure, temperature, density), the magnetic field, and the underlying nonlinear dynamics of plasma turbulence and self-organization.

The area *of high energy density physics* similarly investigates the attainment of the macroscopic high energy density plasma state, its relation to naturally occurring plasma instabilities, and scientific techniques to attain the state.

Plasma-boundary interfaces represents the challenge of interfacing a 100-million-degree burning plasma to its room-temperature surroundings–a goal requiring a combination of physics control of the outer plasma boundary and engineering control of the plasma-surface dynamics.

Waves and energetic particles interact with plasmas in complex ways, important for manipulation of magnetically confined plasmas by electromagnetic waves, and for the behavior of a burning plasma in the presence of energetic fusion-produced alpha particles, and the attainment of high energy density plasmas by intensive ion beams.

In *fusion engineering science* innovations in materials and advances in engineering systems are sought that will be required to confine and control fusion plasma.

The fifteen topical questions of high intellectual value are provided below.

Macroscopic Plasma Physics

T1. How does magnetic field structure impact fusion plasma confinement?

The properties of all magnetized plasma, whether created in the laboratory or found in space or astrophysical objects, depend sensitively on the structure of the magnetic field. The field's curvature twist, spatial symmetries, strength, and topology determine the existence of plasma equilibrium and strongly affect plasma flows and transport. Understanding their influence provides the basis to design configurations most favorable to fusion energy and establishes physics principles that give insight into the dynamics of plasma confined in solar magnetic arcades, in planetary magnetospheres, in jets emanating from black holes, and in extra-galactic regions.

T2. What limits the maximum pressure that can be achieved in laboratory plasmas?

For all magnetic field configurations used to confine plasma in the laboratory, there is an upper limit to the plasma pressure. Beyond this limit, the plasma will disassemble, expand, or lose its energy content. Since fusion energy production increases with the square of the plasma pressure, understanding the cause of the pressure limit and optimizing the confinement configuration to achieve high pressure is an essential question for fusion scientists.

T3. How can external control and plasma self-organization be used to improve fusion performance?

Magnetically confined plasmas exhibit complex nonlinear interactions that govern their dynamical properties and potential for fusion energy production. These interactions can be controlled externally or, sometimes, when created with minimal control, they can become self-organized through naturally occurring internal dynamics. In burning plasmas, strong self-heating due to alpha particles introduces another nonlinear process that provides new opportunities to study highly coupled plasma dynamics and optimized control. Understanding self-organized plasma phenomena and the improvements in plasma behavior (*e.g.*, internal transport barriers, edge pressure pedestals) that can result from external control through complex linkages are major fusion research questions. Finding the proper balance between internal and external control contributes to understanding the fundamental physical processes and improves the prospect for fusion energy.

Multi-scale Transport Physics

T4. How does turbulence cause heat, particles, and momentum to escape from plasmas?

Variations in pressure or density across plasma generate electrostatic and electromagnetic waves and may result in plasma turbulence that drives the loss of heat, particles, or momentum. Turbulent plasma transport is also a process active throughout the universe. Turbulence controls, in part, how energy produced by fusion reactions in the sun reaches the solar surface, how rotating plasma falls onto a black hole, and how cosmic rays diffuse through galaxies. Because of the development of massively parallel simulation tools and the installation of new detectors to resolve details of turbulence in experiments, fusion scientists are now poised to answer fundamental physics questions such as: How do the shape and twist of the magnetic field influence turbulence? What controls the level of turbulent-driven transport? Can transport be controlled? What are the important nonturbulent transport mechanisms, and under what plasma conditions do they dominate? Transport barriers, regions where self-generated equilibrium and zonal flows stabilize turbulence and suppress transport, and the measurement and prediction of the smaller-scale turbulence that affects electron transport have become topics of great importance and significance.

T5. How are electromagnetic fields and mass flows generated in plasmas?

Plasmas possess a remarkable tendency to generate spontaneously ordered, large-scale electrical currents and mass flows. These create magnetic field structures and flow patterns resembling similar plasma structures seen astronomically. In some laboratory fusion plasmas, the magnetic field that confines the plasma is determined by a dynamo effect, in analogy to astrophysical dynamos that are responsible for magnetic field generation throughout the universe. In other fusion plasmas, the magnetic field is partially generated by a thermoelectric effect (called the “bootstrap current”). Complex mass flow patterns in the core and boundary of fusion plasmas can also play a dominant role in plasma dynamics and the interface of hot plasma to material walls. The generation of mass flow is also critical to astrophysics, for example, to flows within the sun, and the accretion of rotating matter onto neutron stars and black holes. The physical origins and methods to control these large-scale currents and flows remain unanswered questions of fundamental importance.

T6. How do magnetic fields in plasmas reconnect and dissipate their energy?

Magnetic fields in laboratory and astrophysical plasmas tend to spontaneously rearrange to create a new magnetic topology through the fundamental plasma process called “magnetic reconnection.” Magnetic reconnection is believed to be ubiquitous in the universe: driving solar flares, regulating star formation, and accelerating particles to high energy. For many fusion configurations, magnetic field lines can tear and reconnect in sudden, sometimes drastic ways–events that may lead to loss of energy. A fundamental theory for magnetic reconnection, applicable to the wide variety of venues, is not yet in hand.

High Energy Density Physics

T7. How can high energy density plasmas be assembled and ignited in the laboratory?

With the advent of the present generation of high-power lasers, Z-pinches and liner implosions, a high energy density environment can be routinely achieved in the laboratory. Energy densities in excess of tens or hundreds of megabars exist in the core of planets and stars and, until recently, could be reproduced only through nuclear explosions. Now energy densities greater than in the center of the sun can be achieved in the laboratory by igniting high-density thermonuclear fuel. Once ignited, the plasma energy density reaches enormous levels in the terabar range, one order-of-magnitude larger than in the solar core. To achieve ignition, the fuel must be compressed to densities that are ten times higher than that of the center of the sun. To achieve these densities, the fuel must remain nearly Fermi-degenerate as the pressure generated by the fusion driver varies from about 1 megabar to 100 megabars, and the radius of the capsules (initially about a few millimeters) collapse by a factor of 30. To trigger ignition, a small volume of the dense fuel must be heated to hundreds of millions of degrees. This extreme heating can be achieved either by converting a fraction of the compression energy into heat or by using an external energy source such as an ultra-intense petawatt laser pulse. The energy of the petawatt pulse is converted into relativistic electrons delivering their energy within a tiny volume of the dense fuel. Understanding how fast electrons are generated and how they transport energy in ultra-dense matter is essential for igniting plasmas via intense lasers.

Another promising approach to high energy density conditions employs a combination of magnetic fields and inertial compression where the thermonuclear fuel is compressed and heated by a liner implosion. When a small magnetized plasma target is compressed by an electromagnetically–driven metal liner (or other drivers), the magnetic field embedded in the target plasma increases the thermal insulation allowing the achievement of fusion conditions at energy densities in the megabar range. Understanding the energy confinement and stability properties, as well as the interaction between the hot plasma and the imploding liner, are the key scientific issues to be resolved for imploding magnetically insulated plasmas.

T8. How do hydrodynamic instabilities affect implosions to high energy density?

In inertial confinement fusion, a spherical shell of cryogenic thermonuclear fuel is imploded either by direct laser irradiation or by the x-ray emission from a heated enclosure, or “hohlraum.” In order to achieve high-energy densities of several gigabars, the implosion must be nearly spherical. This is a challenging task since imploding shells are hydrodynamically unstable. As the shell accelerates inward, the outer surface is unstable to the Rayleigh-Taylor instability, which may cause a large shell distortion and degrade the compression. In order to reduce the seeds for this instability, the nonuniformities in the target and the illumination must be minimized. If the compressed thermonuclear fuel is ignited from a central hot spark then the resulting high-energy densities reach hundreds of gigabar and exceed those in the solar core. However, even when the shell integrity is preserved during the acceleration phase, the ignition process can be quenched by the deceleration-phase Rayleigh-Taylor instability. The latter is the instability of the inner shell surface that occurs when the shell is decelerated by the high pressure building up inside the spark. The deceleration phase Rayleigh-Taylor instability causes the cold shell material to penetrate and cool the central spark, preventing it from achieving ignition conditions. Understanding how to predict and control the Rayleigh-Taylor instability is key to the understanding of high energy density plasma and to the success of inertial fusion energy.

T9. How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?

Charged-particle beams are one-component nonneutral plasmas that have been accelerated to high-kinetic energy. High intensity beams are created when the beam is compressed along the direction of motion and focused to a small spot size. Very high-beam intensities that have highly directed kinetic energy and particle density can be used to create high energy density matter and propagate fusion burn. A basic understanding of the collective processes and nonlinear dynamics of intense, high-brightness, heavy ion beams, and a determination of how best to create, accelerate, transport, compress and focus these beams to a small spot size are critical to achieving the scientific objectives of heavy ion fusion, the creation of high energy density matter using intense ion beams, and related applications in high energy and nuclear physics.

Plasma-boundary Interfaces

T10. How can a 100-million-degree burning plasma be interfaced to its room temperature surroundings?

At the edge of magnetically confined plasma exists a region where the hot plasma interacts with material surfaces and is fueled by ionized gas. The boundary plasma must provide exhaust of power, fuel, helium, and impurity ions. Material surfaces must absorb high-heat fluxes, and eroded material is either redeposited or carried to the core plasma. Tritium fuel retention in redeposited material is a crucial factor in materials selection. Strong edge flows exist and instabilities can greatly increase heat and particle flow to the surfaces. Under the right conditions, turbulent transport can be suppressed by sheared flows.

A recent key result of plasma experiments, theory, and modeling is that the plasma near the edge sets boundary conditions that strongly influence transport in the hot core. Understanding and predicting these conditions, which are set by a complex interaction of turbulence, stability limits, atomic physics, and plasma-surface effects, is crucial. The key challenge is to demonstrate plasma regimes and surface materials, which are compatible with both a burning plasma core and tolerable surface heat loads and erosion.

Waves and Energetic Particles

T11. How do electromagnetic waves interact with plasma?

Many types of electromagnetic wave excitations are unique to the plasma state of matter. The waves range from low-frequency radio waves to intense beams of laser light. Electromagnetic waves can arise spontaneously in the plasma, or they can be excited by external sources, such as radio-frequency antenna and launchers. The resulting wave excitations can accelerate particles, increase plasma temperature, and drive electrical current or mass flows. Understanding the propagation of waves and their nonlinear interactions with plasmas will lead to new techniques to control plasma behavior, and will be key to optimizing the conditions for burning of the fusion fuel.

T12. How do high-energy particles interact with plasma?

Fusion produces energetic charged particles, such as alpha particles from the fusion of deuterium and tritium that have energies much greater than the plasma that produced them. These energetic fusion products help to sustain the hot burning plasma; however, these energetic particles may also excite electromagnetic waves, alter plasma temperature profiles, and affect plasma turbulence, causing unpredictable changes in plasma or alpha particle confinement. The interaction of the energetic particle population with the background plasma is a complex process, and a basic understanding of this interaction is critical to practical applications of fusion.

Fusion Engineering Science

T13. How does the challenging fusion environment affect plasma chamber systems?

New phenomena occur within the fusion components closest to an energy producing, burning plasma. These fusion components must slow down and capture the fusion neutrons, creating heat for electricity generation, while simultaneously regenerating the tritium fuel by allowing fusion neutrons to interact with lithium-containing liquids or ceramics. Advances in nuclear physics, chemistry, thermodynamics, magnetohydrodynamics, and other engineering sciences will result from addressing important technical challenges, especially at the interfaces among coolants, tritium breeders, neutron multipliers, structural materials, conducting shells, insulators, and tritium permeation barriers in the environment of energetic neutrons, high heat and neutron fluxes, and intense magnetic fields.

Inertial fusion systems present related scientific issues pertaining to the interaction between a fusion target with surrounding chamber and components. A variety of gas-dynamic and materials science issues need to be understood better to determine how rapidly inertial fusion chambers can be pulsed, and how long they can sustain the target neutrons, x-rays, and plasma emissions. Research topics include materials responses at a microscopic level, hydrodynamics and radiation transport in the partially ionized afterglow plasma, and gas and liquid hydrodynamics for recovery rates of chamber pressure and liquid-flow configurations.

T14. What are the operating limits for materials in the harsh fusion environment?

A key feasibility issue for fusion energy is the development of materials for the plasma chamber systems that will provide acceptably high performance and reliability, and exhibit favorable safety and environmental features. The fusion environment will be significantly more harsh than any existing terrestrial nuclear system, with each atom in the material surrounding the fusion core being displaced from its lattice position thousands of times over the lifetime of the device. The design of fusion materials must utilize revolutionary advances in computational and experimental methods to control at the nanoscale the structural stability of the material. The knowledge base obtained from designing these advanced materials will directly contribute to the development of new high-performance materials for a wide range of nuclear and non-nuclear applications, and will contribute to the resolution of fundamental questions in materials science.

T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively pulsed burning plasmas?

Fusion burning plasmas require a variety of plasma support systems that will lead to broad advancements in technical capabilities. For example, magnetic plasma confinement requires complex coils and superconductors. Long-pulse operation requires delivery of fuel to the burning plasma in the form of frozen pellets and gas injection. Pumping systems are needed that can continuously remove fusion products. Heating of the plasma requires placing multifaceted structures near the plasma that can efficiently launch high-power radio-frequency or millimeter waves.

In inertial fusion energy concepts, fusion targets must be repetitively injected into a chamber where fusion yields will interact with the chamber walls and associated equipment. The repetition rate of this process ranges from once every 10 seconds, to several times per second. The system driver (laser, heavy ions, or pulsed power) must be durable, efficient, and able to operate with sufficient repetition rate. Realizing these goals will require advanced science and technology development in laser physics, optics, materials, and pulsed power.

2

SCIENTIFIC CAMPAIGNS

The fifteen scientific questions of high intellectual value that motivate the fusion research program were presented and briefly described in Chapter 1. The questions are arranged into six groups. For each group a "campaign" has been formulated which defines the set of experimental and theoretical activities to address the scientific questions during the next ten years. The campaigns are used to plan, organize, and coordinate the research activities. Hence, in this report, the fusion research program is described in terms of the six campaigns corresponding to: macroscopic plasma physics, multi-scale transport physics, high-energy density physics, plasma-boundary interfaces, waves and energetic particles, and fusion engineering science, with the following major goals.

> ***Macroscopic plasma physics:*** Understand the role of magnetic structure in plasma confinement and the limits to plasma pressure in sustained magnetic configurations.
>
> ***Multi-scale transport physics:*** Understand and control the physical processes that govern the confinement of heat, momentum, and particles in plasmas.
>
> ***High energy density physics:*** Investigate the assembly, heating, and burning of high-energy density plasmas.
>
> ***Plasma-boundary interfaces:*** Learn to control the interface between the 100-million-degree plasma and its room temperature surroundings.
>
> ***Waves and energetic particles:*** Learn to use waves and energetic particles to sustain and control high-temperature plasmas.
>
> ***Fusion engineering science:*** Understand the fundamental properties of materials, and the engineering science of the harsh fusion environment.

For each topical scientific question, an accompanying research approach has been formulated spanning the next ten years. The approaches are formulated by considering the required research thrusts (experimental, theoretical, computational), the required capabilities, the expected results and impact on the overarching themes. These research thrusts provide much of the core information required to develop the scientific campaigns. The campaigns are constructed to make large, specific strides in the next ten years. For each campaign, the panel has formulated research thrusts, ten-year goals, and specific research activities, as described in Chapters 3-8.

The research approaches employ a variety of experiments that span a range of configurations and sizes. This is the optimal approach to fusion energy science research for two reasons. First, a range of experiments provides the scientific conditions needed to unravel the physics of plasmas. For example, experiments with differing magnetic configurations, taken together, can reveal the effects of magnetic field properties on plasma behavior. In addition, plasmas are described by a large number of important physical parameters; hence, a range of experimental scales is needed for a comprehensive, and cost-effective, study of plasma behavior. The new generation of computer models now has the capability to explore various configurations. The theory program therefore provides the necessary glue to tie together the research programs of differing configurations and sizes. Second, there are various possible attractive solutions to both magnetic and inertial fusion energy. Hence, a study of a select group of plasma configurations will evolve the optimal approach to fusion energy.

A striking feature of fusion research is that a majority of the activities contribute to each of the overarching themes–understanding the high-temperature plasma state, creating a star on earth, and developing the science and technology to realize fusion power. For example, the study of magnetic reconnection–how magnetic fields spontaneously rearrange their spatial structure–is of great fundamental significance to understanding a process ubiquitous in the universe, from stellar flares to star formation. But magnetic reconnection also can also disrupt a burning plasma and must be tamed to realize fusion energy.

Or consider how waves propagate through plasmas–mixtures of electromagnetic and sound waves unlike those observed in any other medium. Understanding the wide variety of these unique “plasma waves” is a fascinating physics challenge. The same waves can travel through a laboratory plasma, through a stellar atmosphere, and through plasmas used to fabricate semiconductors. Plasma waves are now used as tools to control fusion plasmas: for example, to heat plasmas to burn conditions or to drive electrical current in order to produce favorable magnetic configurations.

Or consider the onset of instabilities excited by the “effective gravity” of an imploding pellet of fusion fuel as it compresses to the high density state of an inertially confined fusion plasma. The nonlinear evolution of growing surface distortions has strong physics similarity to the instabilities that develop on the leading edge of an exploding supernova. Yet in the laboratory the instabilities can prevent attainment of the hot, compressed plasma; thus in fusion plasmas they must be controlled.

Continuing through the entire research program, it can be seen that the majority of research supports all three overarching themes. The connections of the overarching themes to the six campaigns is represented schematically in Figure 2.1, and is described in Chapters 10–12.

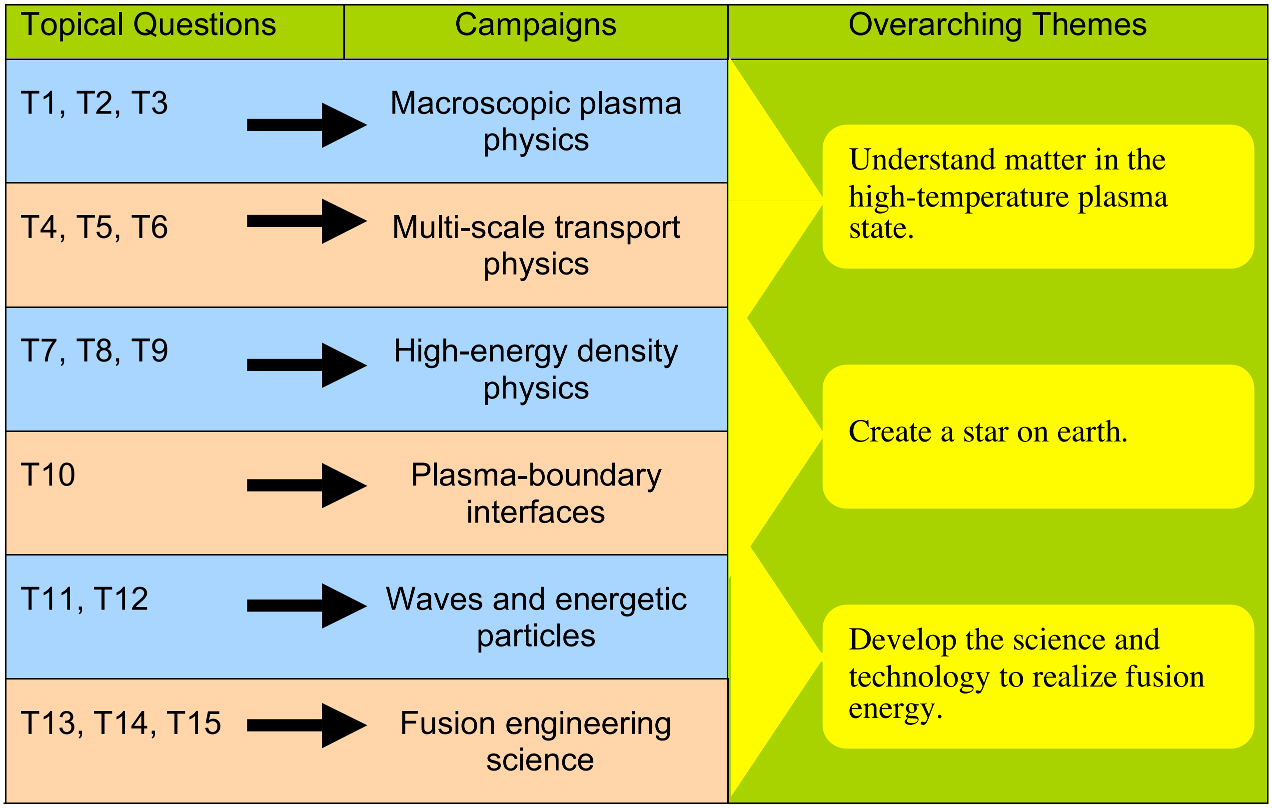

Figure 2.1. *Illustration of the relationship between the topical science questions, which are grouped into six campaigns. The three overarching themes each overlap with a majority of the campaign activities.*

3

MACROSCOPIC PLASMA PHYSICS

Understanding the role of magnetic structure on plasma confinement and the limits to plasma pressure in sustained configurations

OVERALL SCOPE OF THE CAMPAIGN

The macroscopic behavior of magnetically confined plasma is due to the nonlinear interaction of the plasma with the confining magnetic field, electric fields, and plasma flows. These determine and are determined, self-consistently, by the cross-field transport and confinement of the plasma, the presence of instabilities, and the generation of plasma currents. This interaction of the plasma and the fields determines the maximum pressure that can be reliably confined in a given magnetic field configuration, and thereby the fusion power that can be produced. Modification of the magnetic field by plasma currents can determine whether the plasma confinement can be sustained efficiently. Thus, understanding and controlling these phenomena in high-pressure plasmas is crucial to developing the fundamental understanding of magnetically confined plasmas (O1), producing configurations that can confine a burning plasma (O2), and for developing fusion energy (O3). This campaign focuses on the following topical scientific questions:

T1: How does magnetic field structure impact plasma confinement?

T2: What limits the maximum pressure that can be achieved in laboratory plasmas?

T3: How can external control and plasma self-organization be used to improve fusion performance?

RESEARCH THRUSTS

The campaign consists of a series of research thrusts, organized by the topical scientific questions listed above. For each of the thrusts, a ten-year goal is provided, along with specific research activities for attaining this goal, and a description of some past achievements for perspective.

T1: How does magnetic field structure impact plasma confinement?

The properties of all magnetized plasmas, whether created in the laboratory or found in space or astrophysical objects, depend sensitively on the structure of the magnetic field surrounding the plasma and embedded within it. The magnetic field's curvature, twist, spatial symmetry, strength, and topology all combine to determine the existence of equilibria and strongly affect plasma confinement and stability. Understanding their influence provides the basis to design configurations most favorable to fusion energy and establishes physics principles that give insight into the dynamics of plasma confined in solar magnetic arcades, in planetary magnetospheres, in jets emanating from black holes, and in extra-galactic regions. Indeed, the ability to manipulate the magnetic structure is one of the most potent knobs for controlling the plasma behavior.

There are many possible variations of magnetic structure that successfully confine plasma and a large number have been studied theoretically and in past experiments. A number of promising configurations are being actively studied with different magnetic structure characteristics providing a suite for developing and validating the understanding of the underlying physics. A description of the different configurations can be found in Appendix F of the National Research Council's report *"Burning Plasma: Bringing a Star to Earth,"* and the major configuration are depicted in Figure 3.1. The different magnetic configurations offer various natural advantages for fusion energy and reveal issues that are not fully understood.

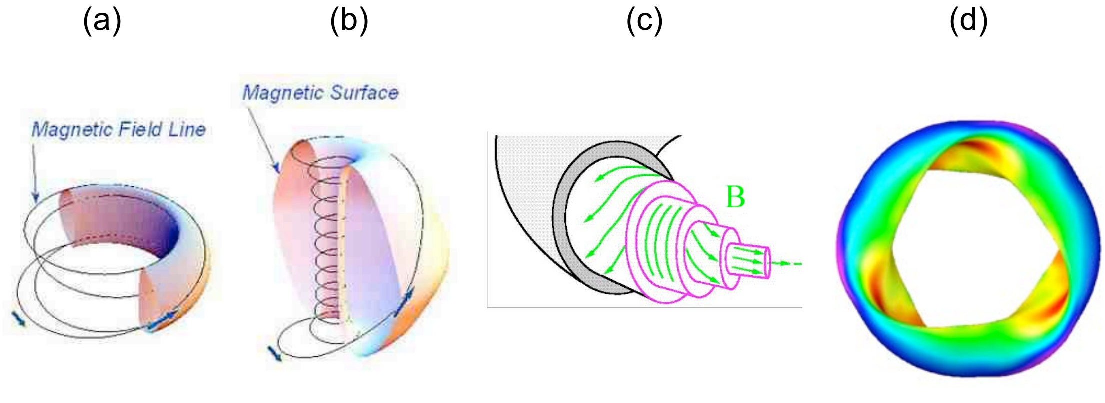

Figure 3.1. Examples of major configurations currently under study in the U.S. fusion science program. Trajectory of magnetic field lines for (a) tokamak, (b) spherical torus, and (c) reversed-field pinch configurations. (d) shows the shape of the plasma surface for a quasi-axisymmetric stellarator, with the false-color coding showing that the magnetic field strength is approximately independent of toroidal angle .

Historically, experiments varying the magnetic structure have produced many exciting discoveries, including suppression of turbulence, stable confinement of higher plasma pressure, and generation of transport barriers. Investigation of these discoveries has played a key role in developing the understanding of plasma confinement, turbulence, and methods to achieve burning plasmas.

The interaction of the plasma with the magnetic field depends strongly on the effective size of the plasma (physical size divided by particle gyroradius), the plasma pressure (normalized to the magnetic field pressure), and the plasma collisionality. These affect the onset of instabilities, cross-field transport, the response of the plasma to magnetic perturbations, the generation of flows, and other processes. The effective size of burning plasmas and reactors is significantly larger than in present experiments. Thus, the plasma response to variation of the effective size must also be investigated (at high normalized pressure and relevant collisionality) to confidently project physics results in present devices to future larger devices.

To understand the effect of magnetic structure on plasma confinement and achieve the overarching themes, three research thrusts should be pursued during the next ten years employing a spectrum of promising configurations to study (a) the role of plasma shape and size on plasma confinement, (b) the effect of magnetic structure within the plasma, and (c) the effect of self-generated plasma currents, which introduce additional nonlinear interactions. Theory and computation must be employed to guide and interpret experimental research and to place results from a specific configuration in a broader context. The research embodied in these thrusts includes the development of methods to control the effects of magnetic structure to improve fusion performance.

Role of plasma shape and size on plasma confinement

Variations in plasma boundary shape (e.g., triangular shaping of the cross section, 3D shaping, and aspect ratio) control the distribution of the magnetic field at the plasma boundary and strongly affect plasma stability and cross-field transport. This has been extensively studied in tokamaks and in the spherical torus, but a full theoretical understanding continues to be developed. The mechanisms by which plasma confinement is modified by plasma shape and size are expected to be configuration dependent. While some theoretical predictions are available (e.g., theoretical predictions that 3D shaping can improve the plasma stability in stellarators) and have motivated particular experiments, understanding the effect of plasma shaping in a variety of configurations

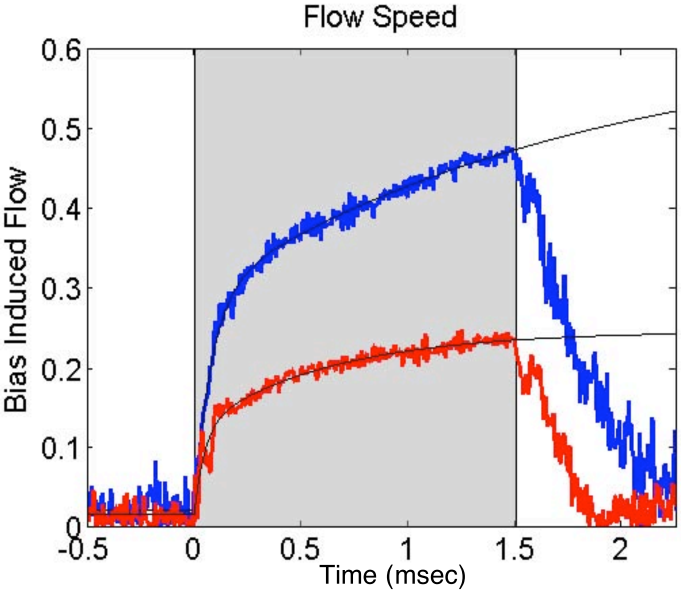

Figure 3.2. Flow speed induced in the Helically Symmetric eXperiment (HSX) stellarator by a biased electrode in two configurations: (blue) quasi-helically symmetric and (red) nonsymmetric. The bias drive is applied during the shaded period, and is 20% higher in the nonsymmetric case. The flow in the symmetric configuration is larger (with lower drive) and damps more slowly after the drive is terminated (Courtesy of S. Gerhardt).

remains to be investigated. An example of a recent experiment exploring the effect of plasma shaping on momentum confinement is shown in Figure 3.2.

Ten-Year Goal: Understand the coupled dependencies of plasma shape, edge topology, and size on confinement in a range of plasma confinement configurations.

Research activities include:

- Understand the coupled dependencies of plasma boundary shape, divertor topology, and size in the tokamak and spherical torus configurations.
- Develop models and diagnostics needed to prepare for ITER as a size-scaling experiment.
- Understand the role of plasma shape on stability and transport in a compact stellarator. Validate or extend the theoretical models of collisional transport in these optimized 3D systems.
- Determine whether one or more of the attractive confinement configurations shows sufficient promise to motivate studying at larger effective size.

Effect of magnetic structure within the plasma on plasma confinement

The characteristics of the magnetic field inside the plasma also strongly affect plasma confinement. These include the magnetic rotational transform (or safety factor), the local and global shear of the rotational transform, the local curvature of the magnetic field, and the topology of the magnetic field. These internal characteristics depend on the distribution of pressure and current within the plasma, as well as the externally imposed magnetic fields, and have a direct effect on the local stability and cross-field transport properties of the plasma. The significance of these effects has been demonstrated in all configurations, with some understanding having been achieved in the major configurations.

Ten-Year Goal: Identify the mechanisms whereby internal magnetic structure controls plasma confinement.

Research activities include:

- Understand the effect of internal magnetic characteristics on the plasma confinement and performance for ITER. Develop the scientific basis of interior plasma control that will allow long-pulse, high-performance operation of ITER.
- Characterize the effects of the internal magnetic field structure on plasma confinement in a quasi-symmetric stellarator. Test whether the predictive understanding developed on tokamaks can be extended to such stellarators. Explore the ability to access improved confinement regimes.
- Develop an understanding of the effect of the internal magnetic structure on plasmas confined by self-organized fields. Optimize the rotational transform distribution for high-pressure confinement in a sustained configuration.

Effect of self-generated currents on plasma confinement

As mentioned above, in all plasma configurations with large normalized plasma pressure (beta), pressure-driven current can modify the magnetic field or generate part of it. In some configurations, a significant portion of the magnetic field is self-generated by plasma dynamos or by reconnection of externally injected magnetic helicity. In all these cases, the nonlinear effect of the plasma-generated currents can modify the magnetic equilibrium geometry and topology, and provide an additional source of energy for instabilities. This can result in either positive or negative effects on plasma confinement. Understanding these effects and developing methods to avoid or control them will be highly advantageous for a successful burning plasma experiment. Understanding and control of these effects is crucial for achieving practical fusion energy using the advanced tokamak, reversed-field pinch, and spherical torus configurations. These effects may be less important for configurations dominated by external control of the magnetic field (e.g., stellarators), but this has not been explored.

Ten-Year Goal: Identify the effects and consequences on confinement of large self-generated plasma current.

Research activities include:

- Test the understanding of plasma confinement in sustained high-bootstrap-fraction tokamak and spherical torus configurations for pulse lengths much longer than the current relaxation time.
- Understand the effect of bootstrap current on plasma confinement in quasi-symmetric stellarators.
- Determine and understand the ability of helicity injection to initiate and sustain confined plasmas with closed flux surfaces.
- Understand the coupling between internal modification of magnetic structure by fluctuations and their effect on confinement.

T2: What limits the maximum pressure that can be achieved in laboratory plasmas?

The energy in a magnetically confined plasma can be released through the many available degrees of freedom. This limits the maximum pressure that can be confined. Understanding the processes that set these limits and how to optimize the magnetic configuration or apply external controls to extend the limits is critical to the study of burning plasma and making practical fusion energy, since the fusion reactivity and power production varies roughly as the square of plasma pressure.

The basic sources of free energy that can be tapped by pressure limiting phenomena in a confined plasma are: (i) the thermodynamic energy stored in the plasma pressure itself, which can be released by expansion of the plasma volume, and (ii) the energy stored in the magnetic fields generated by the plasma current. A substantial base understanding of the pressure-limiting phenomena driven by these two free energy sources has been developed over the past fifty years of plasma physics research. There has been substantial recent progress in controlling pressure driven long-wavelength instabilities using nearby electrically conducting walls along with rotation and active feedback (see Figures 3.3 and 3.4). This may allow significant increases in the plasma pressure. Similarly, tearing instabilities relaxing the energy in the magnetic field distribution have been stabilized using localized externally driven currents. Theoretically, these instabilities can also be stabilized using 3D plasma shaping. Further research is needed to extend the understanding and stabilization techniques into the regime of burning plasmas and high-pressure sustained configurations.

Three research thrust areas on pressure-limiting effects are required to further advance the fundamental understanding and achieve the overarching themes. These thrusts will develop the understanding of (a) long scale-length electromagnetic phenomena characterized by the system size, (b) short scale-length electromagnetic phenomena characterized by the Larmor radius, and (c) equilibrium limits and the onset of magnetic stochasticity. Each of these thrusts includes several distinct plasma phenomena and requires an integrated effort in experiment, modeling, and theory. Advances are required both in quantitative predictive understanding of the basic phenomena and in developing means to control them or mitigate their consequences. Since developing control of these phenomena is integral to developing understanding, this is a critical implementation element in each research thrust area.

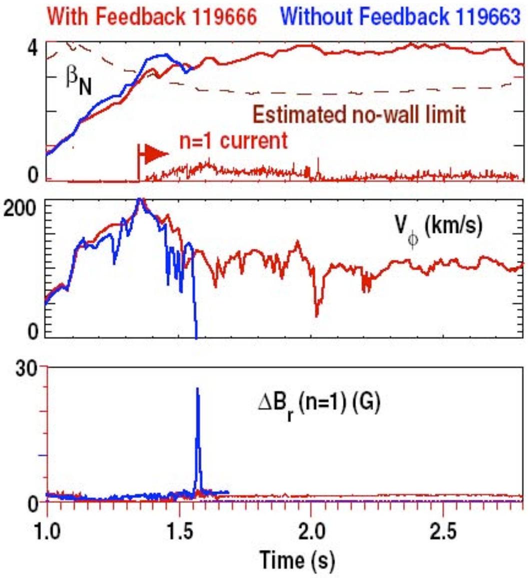

Figure 3.3. Stabilization of resistive wall mode in the DIII-D tokamak. The red curves show a plasma stabilized with active feedback. The plasma pressure, in terms of normalized beta (β_N) exceeds the limit calculated without a nearby conducting wall. The blue curves show a plasma without feedback that disrupts soon after crossing the no-wall limit, showing that the stabilization is not due to rotation. (Courtesy of M. Okabayashi)

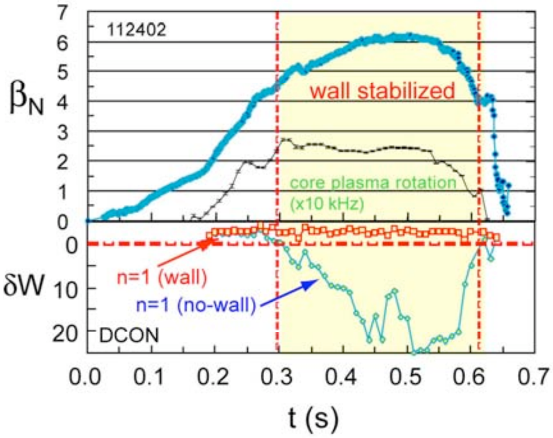

Figure 3.4. Stabilization of the resistive-wall mode in the National Spherical Torus Experiment due to rotation. In the lower panel, numerical calculations by the DCON code indicate that the n=1 instability would be unstable during the shaded period without the nearby conducting wall. Calculations including the wall indicate that the instability is stable while the plasma rotates, as observed. (Courtesy of S. Sabbagh)

Long-scale-length phenomena characterized by the system size

This thrust is directed at understanding and control of long-scale-length phenomena in two basic manifestations: (i) the release of free energy through long-scale-length displacements of the equilibrium fields (internal and external) resulting in quenching of the plasma through contact with the surrounding material structure ("disruptions"), and (ii) the release of free energy through the reconnection of magnetic flux surfaces inside the confined plasma resulting in loss of plasma pressure and in some cases the loss of plasma equilibrium.

Ten-Year Goal: Learn how to control the long scale-length instabilities that limit plasma pressure.

Research activities includes:

- Understand how to control plasma stability with nearby conducting walls to increase the maximum stable plasma pressure.
- Understand the stability limit to plasma pressure in 3D quasi-symmetric and reversed-field pinch configurations, and determine any limiting instabilities.
- Assess whether long-wavelength (neoclassical) tearing instabilities in high-pressure plasmas can be actively controlled or eliminated by design.
- Understand whether the long-wavelength instabilities and disruptions can be practically avoided or mitigated, allowing efficiently sustained operation near the pressure limit, and extrapolation to steady-state burning plasma regimes.
- Understand the effect of suprathermal energetic particle drive on Alfvénic eigenmodes and their implications for the burning plasma configurations.
- Understand kinetic stabilization of high-pressure compact equilibria (e.g., spheromaks and field-reversed configurations).

Short-scale-length phenomena characterized by the Larmor radius

This research thrust is directed at understanding and control of short-scale-length pressure limiting phenomena down to the Larmor radius scale size. These local phenomena do not destroy the global plasma equilibrium, but rather set local maximum values of the allowed local pressure gradient through enhanced transport or through cyclic relaxation processes, and hence limit the maximum value of plasma pressure. Such instabilities are a common feature at the plasma edge and can determine the edge plasma pressure, which in turn influences the overall system confinement. These edge instabilities can also result in large heat pulses that damage the nearby material surfaces.

Ten-Year Goal: Understand and control intermediate to short wavelength modes responsible for limiting the plasma pressure, particularly at the edge, and extrapolate their effects to the burning plasma regime.

Research activities include:

- Understand and control intermediate-to-short wavelength modes at the boundary of the advanced tokamak and spherical torus configurations responsible for edge relaxation events, and extrapolate to the burning plasma regime.

- Investigate and understand whether intermediate-to-short wavelength modes at the boundary limit the edge pressure in a range of configurations.
- Understand whether toroidally localized ballooning modes limit the pressure in 3D quasi-symmetric stellarators.
- Test and understand whether Mercier or resistive interchange instabilities limit the plasma pressure in high-temperature plasmas.
- Understand the effect of plasma-boundary shape and topology on short-scale instabilities.

Equilibrium limits and the onset of magnetic stochasticity

In magnetically confined plasmas, the plasma pressure is limited by the ability of the external coils to maintain a suitable magnetic equilibrium, with magnetic field lines confining the plasma but not intersecting the surrounding structure. In magnetic fields with a continuous symmetry (e.g., axisymmetric toroidal configurations), these limits are well established and are set by the geometry and strength of the external magnetic fields. In fully three-dimensional magnetic fields or in magnetic fields produced by turbulent self-organization, the equilibrium pressure limits are not established or understood. In these cases, the magnetic field could develop island structures or become stochastic, due to the plasma-pressure-driven current, leading to a significant loss of plasma energy that may limit the plasma pressure, see Figure 3.5. This is very challenging to diagnose experimentally or model theoretically.

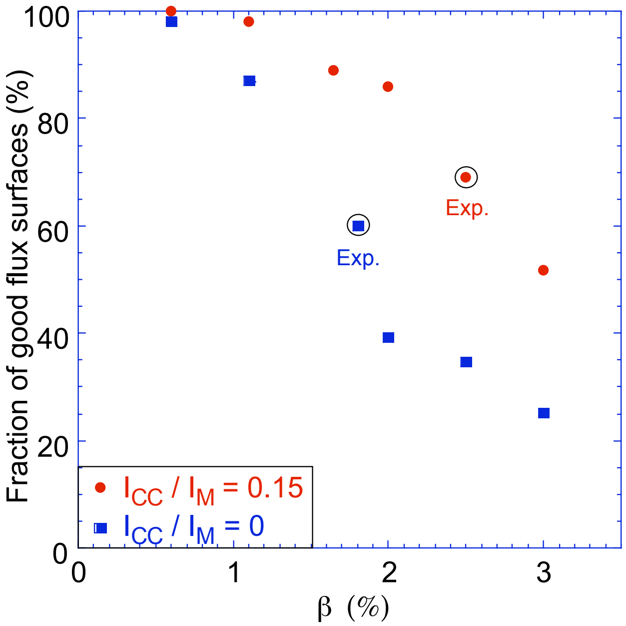

Figure 3.5. Calculated fraction of good flux surfaces in Wendelstein 7-AS stellarator versus ⟨β⟩ for two configurations, with (red) and without (blue) magnetic perturbations from edge divertor control coil. The experimentally attained ⟨β⟩ values for the two configurations are indicated, and correlate with a loss of about one-third of the flux surfaces, which may be limiting ⟨β⟩ (Courtesy of A. Reiman and M. Zarnstorff).

Ten-Year Goal: Understand the equilibrium pressure limits in a range of magnetic configurations, including the effects of islands, stochastic magnetic fields, and helical states.

Research activities include:

- Understand the use of symmetry breaking and local stochasticity at the plasma edge to control edge-relaxation instabilities in the advanced tokamak and spherical torus configurations, and the extrapolation of these results to the burning plasma regime.

- Understand the equilibrium pressure limits in 3D quasi-symmetric stellarator configurations, including the onset of islands and stochastic magnetic fields
- Develop and validate a predictive nonlinear model for the interaction of the plasma pressure and currents with the topology of the magnetic field, including islands and stochastic regions.
- Investigate and understand equilibrium pressure limits in reversed-field pinch and spheromak configurations, and in configurations with purely poloidal magnetic fields.

T3: How can external control and plasma self-organization be used to improve fusion performance?

All confined plasmas interact with a combination of externally applied magnetic and electric fields (external control) together with plasma-generated magnetic and electric fields generated by the plasma current, pressure gradient, and mass flow (self-organization). The plasma current, pressure gradient, and mass flow are determined by the sources (current, heat, or momentum) and the local transport processes, which depend on the magnetic structure. In a burning plasma the heating is dominantly due to fusion produced alpha particles, which adds an important new nonlinear element to the complex interaction between external control and self-organized behavior of the plasma. Further, for practical steady-state plasma confinement, the plasma current and mass flow must be dominantly self-generated, not externally imposed. Hence, these plasma confinement aspects are strongly interlinked in a burning plasma, and will determine the plasma confinement, pressure limits, and ability to sustain the burning plasma configuration. Studying and understanding this cross-coupled system will be a principal area of research in ITER. Preparatory research is essential.

The degree to which self-organized phenomena dominate the plasma behavior varies with magnetic configuration. Optimizing the potentially desirable aspects of self-organized behavior (e.g., efficient steady-state current drive, simplified external coil geometry, or high plasma pressure limits relative to magnetic field strength) in combination with desirable aspects of external control (e.g., steady-state external fields or improved equilibrium stability or greatly improved particle-orbit confinement or radio-frequency wave-driven flows) offers several options for improved fusion power systems that are critical to achieving the goal of practical fusion energy.

The three primary drivers of confined plasma self-organization on a macroscopic plasma scale are the plasma pressure gradient, plasma current gradient, and large-scale plasma flows (or radial electric fields). On a fundamental level, the plasma pressure gradient and mass flow are determined by sources of heat, particles, and momentum, and the local transport processes being explored in response to topical questions T4 and T5, and magnetic dynamo driven by magnetic reconnection and turbulent fields being explored in response to topical questions T5 and T6. The research approach for this topical question (T3) focuses on how the interplay between external control and self-organizing effects of these basic phenomena produce global effects on the macroscopic plasma equilibrium, plasma sustainment at high pressure, and improved fusion energy performance. Three research thrusts are identified to advance the understanding of (a) control of pressure-gradient-driven plasma currents and flow self-organization, (b) the use of dominant external control (e.g., externally generated confining magnetic fields or flows), and (c) control of magnetic-fluctuation-driven plasma current self organization. In all three cases, the goal is to understand these mechanisms and their potential to improve fusion performance in sustained plasma configurations.

Pressure-driven self-organization

In all magnetically confined plasmas the pressure-gradient-driven electric currents and mass flows will modify or sustain the equilibrium confining magnetic fields as the plasma pressure is increased. This thrust seeks to understand and use these self-driven currents and mass flows to improve fusion energy performance with emphasis on achieving steady-state high-pressure confined plasmas or confined plasmas with relatively high pressure and simplified external equilibrium field coil structure.

Ten-Year Goal: Understand and demonstrate the use of self-generated currents and mass flows to achieve steady-state high pressure confined plasmas and improve fusion energy performance.

Research activities include:

- Understand and validate self-consistent, steady-state advanced tokamak and spherical torus configurations at high plasma pressure and high self-driven current fractions.
- Establish the confinement properties of 3D quasi-symmetric stellarator configurations compatible with steady-state operation including the effects of the pressure-driven bootstrap current, and assess prospects for extrapolation to steady-state configurations in the burning plasma regime.
- Understand the self-organized pressure distribution and limits in purely poloidal field configurations.

Dominant external control

In conjunction with plasma self-organization, the imposition of external control through (i) shaped external magnetic fields imposing symmetry or local stochastic symmetry breaking, or (ii) through driven mass flows, currents, and electric fields, can lead to steady-state equilibria, plasma flow through symmetry effects, improved single particle confinement, reduced turbulent transport, or enhanced stability at high pressure. All of these have the potential to improve fusion performance of the confined plasma. This research thrust is directed at advancing the understanding across a broad class of external control approaches ranging from application of 3D quasi-symmetric equilibrium magnetic fields, application of a strong external dipole equilibrium magnetic field, and application of strong externally applied electric fields or torques to produce equilibria with dominant E × B mass flow. An example is shown in Figure 3.6.

Ten-Year Goal: Understand how external control can lead to improved stability and confinement in sustained plasmas in a range of magnetic configurations.

Research activities include:

- Understand the equilibrium and confinement in optimized 3D stellarator configurations and extrapolate to the burning plasma regime.
- Understand confinement and sustainment in nonturbulent reverse-field pinch configurations where the internal current profile is largely driven externally.

- Explore the use of external heating and control of the magnetic rotational transform and mass-flow profiles to optimize transport and stability, and the prospects for extrapolation to burning plasmas.
- Understand the effect of externally applied 3D fields on the onset and dynamics of disruption phenomena in high-pressure toroidal plasmas.

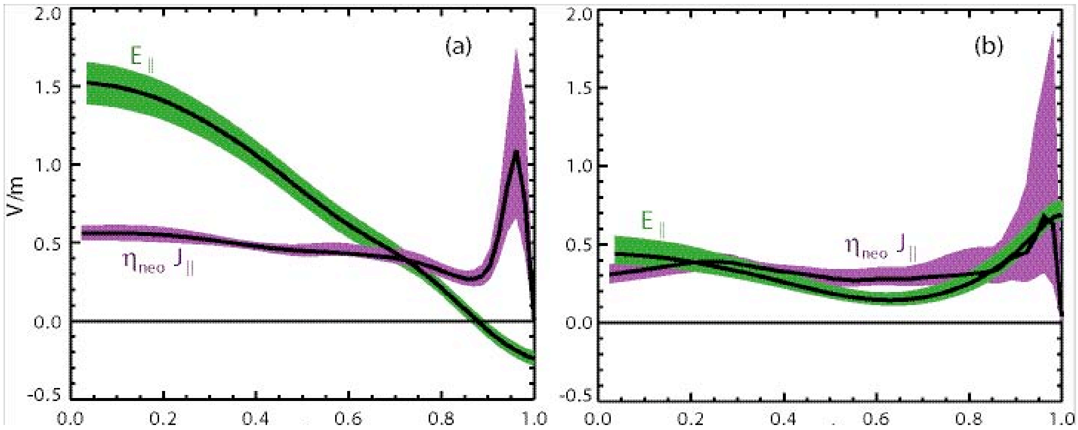

Figure 3.6. (a) In the standard reversed-field pinch, a simple Ohm's law with E = ηJ is not satisfied. Instead, magnetic fluctuations self-organize the current, reducing the current in the center of the plasma and driving additional current at the edge. (b) This self-organization can be reduced by tailoring the externally applied electric field to more directly drive the natural current profile. In this case, a simple Ohm's law with E = ηJ is satisfied. The energy confinement time of the plasma is extremely sensitive to this change, increasing by an order-of-magnitude in the transition from self-organized to externally driven (Courtesy of J. Anderson).

Magnetic-fluctuation-driven self-organization

All confined plasmas seek to reduce their stored energy so as to approach a minimum energy state. In some systems, this reduction is due to the excitation of magnetic fluctuations, which can maintain or reorganize the equilibrium magnetic field by the conversion of momentum or magnetic flux into plasma current. This process is known to be important in the reversed-field pinch and spheromak configurations, which operate near to a magnetic "minimum energy" state. A similar process may be responsible for the ordering of large-scale magnetic fields throughout the universe. This research thrust seeks to understand and use this self-organized current to maintain high-pressure plasmas with relatively weak externally supplied confining magnetic field.

Ten-Year Goal: Understand the pressure limits and confinement properties in configurations where magnetic turbulence controls the distribution of the equilibrium magnetic field and for similar configurations with reduced turbulence. Assess their prospects for study in more collisionless plasma regimes for possible extrapolation to practical sustained burning plasmas.

Research activities include:

- Establish the plasma confinement of helicity-driven spheromak configurations and assess prospects for study in more collisionless plasma regimes.
- Understand the pressure limits and confinement properties in sustained reversed-field pinch configurations in the presence of magnetohydrodynamic turbulence and for reduced turbulence states.

RELEVANCE TO ITER AND OTHER CAMPAIGNS

The physics of the macroscopic behavior of confined plasmas is inherently connected with almost all of the other campaigns. The plasma transport is strongly affected by the distribution of the magnetic field and plasma shaping. The magnetic configuration determines which instabilities participate in plasma turbulence, and can control the strength of turbulence-produced transport. The plasma shape and magnetic configuration also influence how the plasma interacts with the boundary interface, and how heat and particles are exhausted. The resulting edge plasma parameters set the boundary condition for the core confinement and influence global stability. Edge instabilities are highly sensitive to magnetic structure and can produce large transient heat loads on surrounding structures. The maximum stable confined pressure ultimately determines the fusion energy production and whether the plasma can burn.

Improved understanding of plasma macroscopic behavior is crucial to achieve the goals of ITER and burning plasma experiments in general. Development of methods to increase the maximum plasma pressure will directly lead to increased fusion power and energy gain. In addition, improved understanding and control of plasma stability will reduce the likelihood of disruptions. Development of methods to sustain the plasma configuration at high pressure and high fusion gain will enable ITER to achieve its long-pulse goals and develop the strategies needed for follow-on experiments.

In many ways, ITER will be a natural integral part of this campaign to understand macroscopic plasma behavior. In particular, it will extend the exploration of confinement to larger effective-size than available in any other experiment. This will change the strength and character of instabilities and their nonlinear saturating effects. It will also give access to new phenomena, allowing the exploration and understanding of the dynamics of plasma self-heating in combination with the other plasma nonlinearities.

EXPECTED ACCOMPLISHMENTS WITHIN TEN YEARS

Substantial progress is expected on the thrusts of this campaign over the next ten years, even assuming constant level-of-effort. Here we summarize this expected progress followed by a discussion of the opportunities for significantly enhanced research progress in three particular thrust areas with increased resources.

At a constant level-of-effort, substantial progress is expected on many of the campaign's activities, broadening and advancing the understanding of the role of the magnetic field structure on plasma confinement, including the effect of 3D shaping and different types of symmetry. New experiments have begun or are under construction, testing novel magnetic configurations motivated by theoretical predictions and advances in understanding during the last decade. The studies of the role of internal magnetic structure on confinement will near completion for tokamaks, in preparation for ITER.

Experiments attempting to understand the pressure-limiting phenomena and overcome them are underway. Within ten years, a detailed understanding of pressure limits in rotating plasmas with resistive walls should be completed, and studies of active stabilization without rotation will be well underway. An understanding of neoclassical tearing instabilities, including methods of suppression, should be complete and documented in axisymmetric configurations. For both of these, predictions for ITER will be refined in preparation for ITER operation. Experiments exploring the pressure limit in 3D configurations and in reversed-field pinches will be underway, characterizing limiting phenomena, and initial comparisons with theoretical predictions will be available.

Studies of different types of plasma self-organization and their interaction with external control methods are underway for several magnetic configurations. These studies of the nonlinear interactions in the plasma will continue throughout the next ten years. Methods to sustain the plasma duration have been developed, including methods to enable operation of ITER as a long-pulse operation burning plasma (e.g., “hybrid” scenarios). Within the next ten years, these methods will be well understood and ready for application to ITER. The scientific issues associated with the integration of high plasma pressure, good confinement, and efficient sustainment of plasmas (e.g., high bootstrap current fraction) will be under study in several configurations.

OPPORTUNITIES FOR ENHANCED PROGRESS

While much progress will and should be made with level resources, the research opportunities associated with three particular areas are so compelling that increased funding should be sought to expedite scientific progress.

- Pursue an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas. This is a combination of the research thrusts under T3, and will study sustained plasmas at the stability limit. It will result in an integrated understanding of the mutually interacting nonlinearities that self-organize and constrain high-pressure plasmas. It would include developing improved models of confinement and stability, including effects of 3D magnetic field structure, and the comparison of observed pressure limits for sustained plasmas to theory. Carrying out this research will involve developing plasma control tools and diagnostics to systematically vary and study the internal structure and profiles and control instabilities in a range of configurations.
- Optimize magnetic confinement configurations based on the expected improvement in the understanding of plasma confinement. Proposals to study new, optimized configurations would be expected in the second half of the next ten years. Such proposals could involve studying plasmas closer to burning plasma conditions to test and broaden the understanding.
- Simulate through experiment and modeling the synergistic behavior of alpha-particle-dominated burning plasmas, further developing the integrated understanding. This activity would enhance the optimization of magnetic confinement configurations (above) to better prepare for the burning plasma experiment. The effects of burning

plasma on the plasma self-organization and external control methods would be studied on existing facilities using neutral beam and radio-frequency-generated fast ions to simulate fusion alpha behavior and wave interactions. New diagnostics to measure internal fluctuations and energetic particle properties will be developed that can operate in a burning plasma environment.

4

MULTI-SCALE TRANSPORT PHYSICS

Understand and control the physical processes that govern the confinement of heat, momentum, and particles in plasmas

OVERALL SCOPE OF THE CAMPAIGN

The study of dynamical processes in magnetized plasmas presents one of the "grand challenges" of physics. Complexity arises from the extremely wide range of spatial and temporal scales, strong intrinsic nonlinearities, and the importance of geometric detail. Even in plasmas that are free from macroscopic instabilities, plasmas remain dynamically rich. The free energy from the plasma pressure or rotational motion drives small-scale turbulence that dominates energy, momentum, and particle transport across the confining field. Additional complexity arises from the extreme anisotropy between transport along and across the magnetic field. The turbulence can self-organize into medium or large-scale structures and can generate significant time-averaged mass flows and magnetic fields. Magnetic fields can tear and reconnect, thereby modifying the magnetic topology.

Turbulence and transport are sensitive to magnetic field topology, collision rates among electron and ion species, the ratio of the plasma to magnetic pressure, and the normalized size of the device (measured by the ratio of ion gyroradius to machine size). Thus, being able to vary key parameters within a given experimental configuration and comparing turbulence in a variety of configurations are drivers for the range of experiments that constitute the fusion effort and are essential in the strategy to develop the full understanding required for extrapolation to next-step burning plasma experiments. The theory and modeling program provides the necessary glue to tie together the research on differing configurations.

Understanding the rich dynamics of turbulent transport, mean flows, and magnetic field rearrangement is a fundamental scientific issue in laboratory and astrophysical plasmas (O1), of central importance for the exploration of burning plasmas (O2), and the realization of fusion energy (O3). The surprising discovery that small-scale turbulence and therefore energy containment can be controlled or at least mitigated has created a sense of expectation and urgency in this topic. The rapid emergence of ideas for advanced diagnostic techniques and the development of new computational algorithms for exploring critical dynamics portend a period of rapid discovery through detailed comparisons between theoretical predictions and experimental measurements. The goal of this campaign is to answer the following three topical scientific questions:

T4: How does turbulence cause heat, particles, and momentum to escape from plasmas?

T5: How are electromagnetic fields and mass flows generated in plasmas?

T6: How do magnetic fields in plasmas rearrange and dissipate their energy?

RESEARCH THRUSTS

The topical scientific questions for this campaign will be addressed by several research thrusts, each having a specific ten-year goal and associated research activities.

Understand the physics of cross-field ion thermal transport in magnetized plasmas

Ion thermal transport has strong conceptual underpinning, the most mature modeling effort, and the most thorough set of experimental observations. Existing fluctuation diagnostics have largely focused on turbulence with spatial scales around the ion gyroradius. Progress toward the goal of characterizing fluctuations and transport at these scales has been substantial. Advances in the understanding of ion transport dynamics and their role in the formation of transport barriers are striking. Intensified efforts in model verification and validation can now be undertaken to build progress toward the goals of understanding and control. Hence, the following research thrust: Understand the physics of cross-field ion thermal transport in magnetized plasmas.

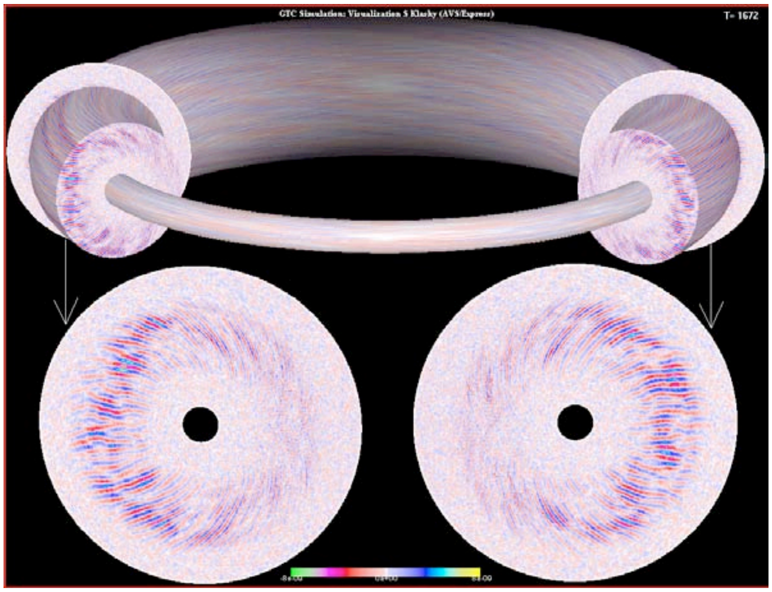

Figure 4.1. Three-dimensional gyrokinetic simulation of the nonlinear dynamics of turbulence in toroidal geometry. (Courtesy of Z. Lin)

The ten-year goal is to develop predictive capability for ion thermal transport using simulations validated by comparison with fluctuation measurements.

This thrust involves three associated research activities:

- Comprehensive comparisons will be made among theory, experiment, and modeling at the basic level (linear and nonlinear coupling coefficients, free energy sources, dissipation rates, etc.) using bispectral analysis, synthetic diagnostics, and specialized probes.
- The capability to characterize the nonlinear state, including simultaneous measurement of several fluctuating quantities (e.g., density, temperature, potential) with multidimensional fluctuation measurements will be developed.
- The dynamics of electrons and magnetic fields will be included and documented in modeling codes and their effects on ion thermal transport will be explored, including detailed comparisons with experiments.

What regulates particle and momentum transport?

Particle and momentum transport are central to the dynamics of transport barriers and the suppression of turbulence and therefore to the control of energy confinement, but have not yet been studied as extensively as ion heat transport. In addition to the experimental challenges, the exploration of these topics has also been hindered by significant computational challenges associated with modeling the dynamics of high-velocity electrons in fusion-grade plasmas. Because of the importance of confinement control through transport barrier manipulation, efforts in these areas should accelerate. The exploration of general phenomenology and the establishment of conceptual underpinnings (characterization) are still in progress, and must proceed before more quantitative understanding and modeling can be undertaken. The former is expected to occupy the first half of the next decade, with the latter becoming the focus of the second half. These considerations lead to two thrusts.

The first research thrust is: What regulates particle transport?

The associated ten-year goal is to identify the dominant particle transport mechanisms, including the conditions under which pinch/convective processes compete with diffusive processes.

This thrust area has six associated research activities:

- Correlate particle transport with fluctuations at different spatial scales, including modes associated with ion and electron temperature gradients (ITG and ETG), and trapped electrons (TEM).
- Understand the extent to which particle transport is coupled to energy transport. Determine the conditions under which impurity transport is anomalous (driven by turbulence) versus when it is dominated by collisions.
- Explore tools for density profile control through transport modification.
- Understand and model the particle pinch, which drives particle motion into the core of the confinement zone.
- Characterize nonlinear density-potential correlations.

- Characterize nonlocal effects, including, for example, avalanches.

The second thrust is: What regulates momentum transport?

The ten-year goal is to identify the dominant mechanisms responsible for momentum transport and their relationship to thermal transport.

This thrust area has eight associated research activities:

- Characterize boundary conditions on flows created by plasma edge transport and magnetic topology.
- Assess the role of neutrals in transporting momentum in the plasma edge.
- Clarify the role of classical collisions in momentum transport.
- Understand the extent to which anomalous momentum transport is coupled to ion, particle, and electron energy transport.
- Explore tools for velocity profile control through transport modification.
- Explore velocity profile control through radio frequency wave injection. Characterize and model Reynolds stress induced by turbulence, including the dynamics of electrons.
- Apply realistic flow profiles in assessing the effects of flow.
- Determine the influence of magnetic fluctuations on momentum transport.

Understand the physics of turbulence suppression and transport barrier dynamics

Transport in the edge, including transport barriers in this region (the “edge pedestal”), along with electron thermal transport, is arguably the most pressing transport problem for a future burning plasma experiment. The formation of this edge transport barrier drives a transition in the plasma confinement from a low value (L-mode) to a high value (H-mode). Core transport barriers can also be applied as a valuable tool for pressure profile control and enhanced confinement and much of the physics is expected to be common between core and edge barriers. Edge transport barriers are routinely produced in high-pressure plasmas. In tokamaks there is an extensive database on the onset of these barriers and the scaling of the resulting pedestal, and there is good evidence for the importance of underlying physical processes, like the shear in the plasma rotation. However, to date, virtually all models for the L/H threshold and threshold scalings have been based on simplified models. There is no accepted model for pedestal physics and scalings. Efforts to build more complete models based on the tight interaction among theory, simulation, and observation are underway, and this area is poised for progress. This motivates the thrust: Understand the physics of turbulence suppression and transport barrier dynamics.

The ten-year goal for this thrust is to understand generation of flow shear, regulation of turbulence, and self-consistent profile dynamics and local steepening, and to identify conditions and thresholds for edge and core barrier formation.

Seven research activities are associated with this thrust:

- Test the validity of existing fluid and kinetic turbulence models for barriers with experimental measurements, comparing the evolution of profiles and measured turbulence characteristics.

- Compare electron and ion energy transport.
- Develop models and equations appropriate to the steep-gradient region of the pedestal and core barriers.
- Determine which processes among those active in the edge region make significant contributions to pedestal physics and L/H transition thresholds and dynamics.
- Expand and improve the experimental database as groundwork for developing predictive capability.
- Develop integrated models for pedestal structure including realistic heat and particle fluxes from the core, realistic 2D particle sources, integration of magnetohydrodynamic stability to determine cyclic divertor heat loads associated with the periodic collapse of the pedestal seen in experiments, and realistic treatment of edge plasma including divertor geometry and neutral fueling.
- Develop and apply self-consistent models of transport barrier formation and compare with experiments.

Understand the physics of electron thermal transport

Electron thermal transport has been the focus of considerable analytical and computational work, pushing the frontiers of computational research. Nevertheless, it is not yet known whether electron thermal transport is dominated by turbulence at short wavelengths (on the scale of the electron gyroradius) or at longer wavelengths. Experimental measurements are just beginning to address the issue. Diagnostics capable of measuring electron-scale fluctuations, once beyond our technical grasp, are now underpinned by well-developed ideas and techniques for their design, realization, and implementation. This thrust is therefore well poised for significant progress, provided sufficient resources become available to acquire the needed diagnostics on a range of devices. The U.S. Transport Task Force has recently concluded a study[1] of the needs of transport research that recommends incremental funding beyond present levels to pursue opportunities in this and the transport barrier thrust areas. This study includes an initial costing analysis. This leads to the thrust: Understand the physics of electron thermal transport.

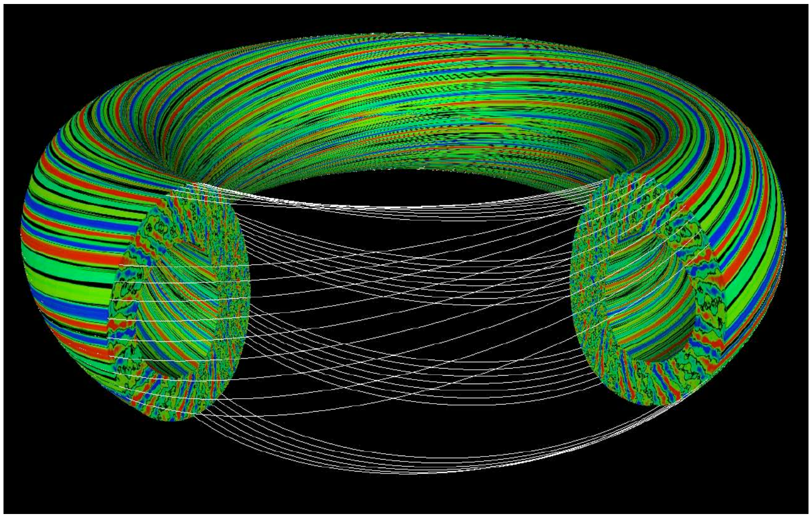

Figure 4.2. Computer calculation showing the early nonlinear development of electron gyroscale turbulence associated with electron temperature gradient modes. (Courtesy of W. Dorland)

The ten-year goal for this thrust is to identify the dominant electron thermal transport mechanisms, including the role of electromagnetic fluctuations, short-scale versus long-scale turbulence, and spectral anisotropy.

Eight associated research activities that are associated with this thrust area are summarized below:

- Experimentally characterize the fluctuation spectrum at the electron gyroradius scale, including spectral anisotropy, wavenumber range, and spectral energy distribution.
- Measure the basic properties of the short-wavelength turbulence to determine the direction of energy transfer.
- Measure ion- and electron-scale fluctuations simultaneously to assess their interaction.
- Measure and characterize magnetic fluctuation spectra.
- Determine how electron thermal transport changes in plasmas that can be varied from electrostatic fluctuation-dominated to magnetic fluctuation-dominated, including the dependence on the ratio of plasma pressure to magnetic pressure.
- Verify and validate computational predictions of the development of nonlinear structures such as streamers (spatially extended flows across the magnetic field) by comparison with experiment and analytical theory.
- Develop a theory for large-scale magnetic turbulence.
- Evaluate the possible role of nonturbulence-driven mechanisms for electron transport.

Explore and understand large-scale and zonal flow generation

Achieving plasma flow with shear is critical for achieving the H-mode, and flow shear is more generally of significant benefit in reducing and controlling turbulence and transport. Therefore, understanding and manipulating the generation of large-scale flows and zonal flows (stratified within a magnetic surface), both those arising spontaneously and those tied to external momentum sources, is essential for modeling ITER, for the device(s) that will follow ITER, and for the variety of configurations presently under study. The magnitude and structure of flows, including those that have a significant driving source, cannot yet be predicted. Hence the development of both spontaneous and externally driven flows must be studied. This leads to the thrust: Explore and understand large-scale and zonal flow generation.

The ten-year goal for this thrust is to

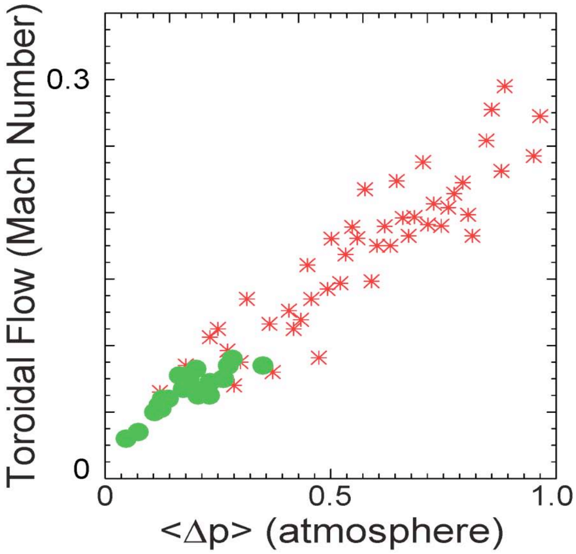

Figure 4.3. Even in the absence of external momentum input, toroidal plasmas can develop very strong self-generated rotation. In this example, from the Alcator C-Mod tokamak, the rotation increases monotonically with increasing plasma pressure. (Courtesy of J. Rice)

identify the dominant driving and damping mechanisms for large-scale and zonal flows, including turbulent stresses and cascades.

There are nine research activities associated with this thrust:

- Make comprehensive measurements of the Reynolds stress in edge and core transport barriers.
- Make comprehensive measurements of the Maxwell (magnetic Reynolds) stress, under conditions with high-power radio-frequency wave injection and/or large magnetic fluctuations.
- Simulate the generation of mean flow in turbulence codes.
- Develop nonlinear theory of Reynolds stress for relevant transport causing fluctuations.
- Identify the mechanisms responsible for mean flow drive in plasmas with no external momentum input.
- Understand the dominant mechanisms affecting large-scale fields and flows.
- Accomplish comprehensive development and testing of radio-frequency flow drive.
- Measure wavenumber-frequency spectra, for flow and density, from zonal-flow scales to high-wavenumber turbulence scales, and compare with theory.
- Test zonal flow generation theories in simple experimental configurations.

What is the physics of large-scale magnetic field generation?

Self-generated magnetic fields are a feature of a number of confinement concepts currently studied in the U.S. fusion program. For such concepts to advance in attractiveness as potential fusion devices, the fluctuations and transport associated with field generation must be characterized and controlled. This requires an understanding of the role played by all possible dynamo mechanisms. These questions should be pursued as part of an overall strategy for understanding, characterizing, and controlling transport. In addition, the magnetic dynamo has broad importance in stars, galaxies, and planetary bodies. Yet, it is only in laboratory experiments where direct measurements of dynamo activity can be carried out. These experiments can therefore play a critical role in benchmarking codes and physics hypotheses to the benefit of a broader scientific agenda. The research thrust in this area is: What is the physics of large-scale magnetic field generation?

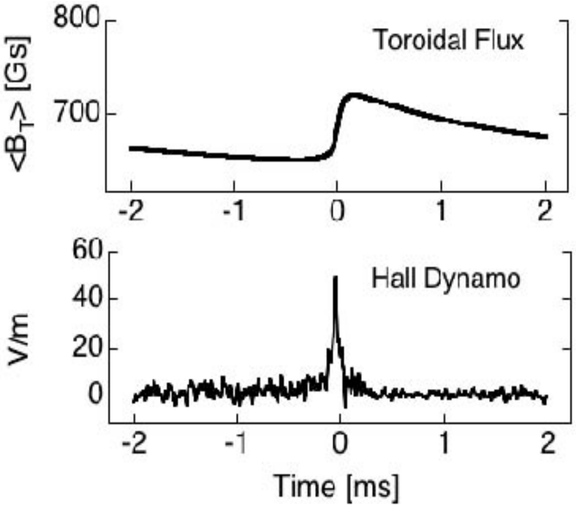

Figure 4.4. Observation of the dynamo in the MST reverse field pinch experiment. The top figure shows the generation, sudden in time, of magnetic flux in the plasma. The magnetic flux generation arises from plasma fluctuations. The bottom figure shows a new dynamo effect, known as the Hall dynamo, discovered to be partly responsible for the laboratory dynamo. (Courtesy of S. Prager)

The ten-year goal is to identify the dominant mechanisms by which turbulence generates and sustains large-scale magnetic fields in high-temperature plasma.

There are four research activities associated with this thrust:

- Measure the relative size of the various mechanisms that can drive large-scale magnetic fields (dynamo drivers), including those associated with the conventional magnetohydrodynamic equations and those arising from kinetic processes, in devices with large-scale magnetic field generation.
- Perform measurements of the dynamo and accompanying transport under a variety of plasma formation and sustainment scenarios.
- Compare dynamo mechanisms in different magnetic configurations.
- Use kinetic models to analyze the dynamo and compare with experiment, theory, and fluid models.

Explore the dominant spatial and temporal dynamics of reconnection

Magnetic containment in fusion plasmas can be disrupted as magnetic fields break and rearrange in a process called magnetic reconnection. Magnetic reconnection allows energetic particles to escape by following wandering magnetic field lines. The same process drives solar flares into the Earth's magnetosphere (space weather) and is more broadly important in astrophysics. Understanding reconnection is challenging because of its multi-scale nature—breaking of magnetic field lines occurs in spatially localized regions where a turbulent bath of waves and particles dissipates the released magnetic energy. At the same time, the release of energy depends on global constraints linked to topology and geometry. The multi-scale nature of the problem and the inability to probe the internal dynamics in high-temperature fusion plasmas has forced a multi-faceted approach to the problem, including the construction of specialized experiments to address reconnection and the application of kinetic simulations to simplified geometries. Thus, work in this area has broad science relevance to the basic understanding of high-temperature plasma (O1). The research thrust in this area is: Explore the dominant spatial and temporal dynamics of reconnection.

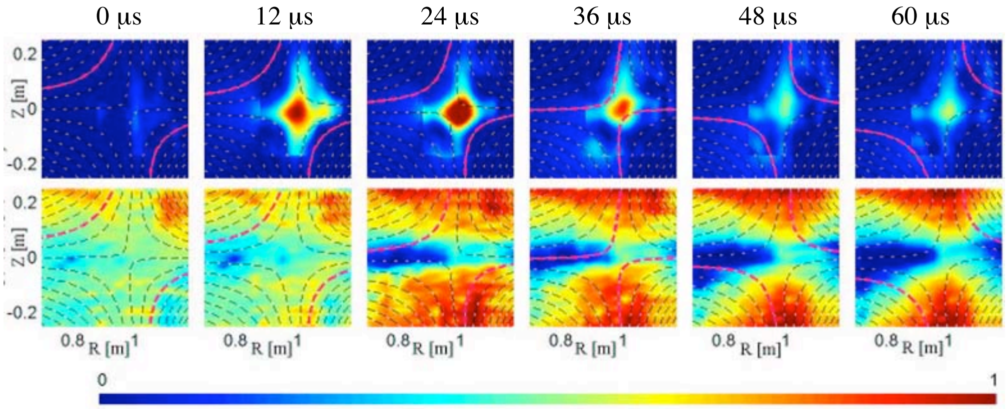

Figure 4.5. Two-dimensional contours of current density (top) and plasma potential (bottom) at 12-μs intervals during a forced reconnection event in VTF, a toroidal magnetic cusp experiment. (Courtesy of J. Egedal)

The ten-year goal for this thrust is to identify the mechanisms and structure of magnetic reconnection, including the role of turbulent and laminar processes, energy flow, and the production of energetic particles.

There are nine research activities associated with this thrust:

- Measure and model the relevant spatial and temporal scales of fast reconnection.
- Determine the source and dynamics of the turbulence that has been measured in the narrow boundary layers where magnetic fields change their topology (dissipation region).
- Determine the role played by kinetic processes.
- Characterize the 3D geometry of reconnection in experiments.
- Fully characterize the structure and magnitude of flows in all regions.
- Understand the physics of fast particle generation.
- Understand the energy budget of reconnection, including magnetic energy, kinetic energy, and plasma heating.
- Investigate possible applications of reconnection to current drive.
- Distinguish the relevant similarities and differences among laboratory and astrophysics reconnection processes.

Explore the initiation and dynamics of magnetic islands

Instabilities involving reconnection are a serious operating issue for virtually all existing fusion devices and for a burning plasma experiment. Hence this area has continued to be a focus of considerable effort. Such efforts encompass modeling instability evolution, predicting and establishing operational parameter spaces free of instability, and the development and implementation of control strategies for when they are triggered. Achieving these goals will extend measurement capabilities to smaller spatial scales and faster time scales and will further the general understanding of reconnection. This leads to the research thrust: Explore the initiation and dynamics of magnetic islands.

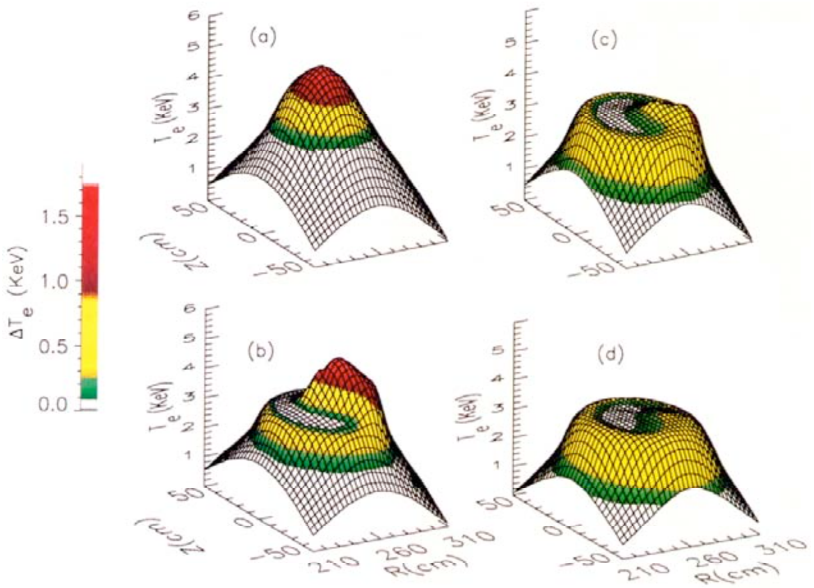

Figure 4.6. Electron temperature profile evolution during a sawtooth collapse. The data clearly demonstrate the effects of the magnetic island. (Courtesy of M. Yamada)

The ten-year goal is to identify the conditions for onset of island growth and the factors controlling saturation and coupling with transport.

There are five research activities associated with this thrust area.

- Resolve issues concerning neoclassical tearing mode threshold and seeding physics.
- Develop a detailed understanding of the spatial/temporal structure of magnetic islands, including local temperature, density and flow profiles.
- Explore mechanisms by which sawtooth oscillations expel the high temperature core without completely reconnecting.
- Examine the applicability of fluid models in describing reconnection-relevant instabilities and evaluate the role of non-magnetohydrodynamic physics.
- Implement and test control methods for neoclassical tearing modes and sawteeth

RELEVANCE TO ITER AND OTHER CAMPAIGNS

Achieving an energy gain sufficient for a burning plasma requires sufficient confinement. Specifically, ITER must operate near known limits of density and pressure and in a high confinement mode (H-mode) with a minimum pedestal temperature. The cost, complexity, and potential for damage associated with operating a burning plasma experiment will require predictive pre-discharge modeling of plasma behavior from ionization to termination.

The strong reduction of ion heat transport and particle transport in the presence of self-generated, large-scale shear flow of the H-mode is crucial for ITER. The ITER will operate in the regime with strongly coupled electrons and ions, making electron transport particularly relevant. Flow is also central to other types of transport barriers. It has an important effect on unstable modes—including the edge instabilities that can limit high-beta long-pulse operation in burning plasma experiments—and tearing modes. Additionally, according to computer models, the intensity of ion-scale fluctuations, believed to govern ion thermal transport in ITER, is also strongly reduced by turbulently generated zonal flows. The spontaneous generation of these flows in present-day devices has made it possible to enjoy their benefits without understanding their origin. To ensure they arise in future machines outside existing parameter ranges (ITER), and to harness them for controlling transport and profiles requires a thorough understanding of their generation mechanisms.

The effective size of ITER (in terms of ion gyroradi) is greater than in current experiments for conditions of low collisionality, and understanding transport scaling with system size is therefore an important component of our confidence in scaling to ITER. Instabilities involving reconnection set operating limits for fusion devices, including ITER, because they can disrupt the plasma, terminate the discharge, cause heat and particle losses, and impact burn initiation.

The physics of multi-scale transport in magnetized plasmas is intimately related to virtually all of the other scientific campaigns. Macroscopic plasma behavior is strongly influenced by transport processes, and plasma shaping and proximity to pressure limits modify transport. Transport helps to determine the pedestal dynamics, scrape-off layer power flows, and resulting plasma-surface interactions. Plasma profiles and distribution functions strongly influence wave and particle interactions. Transport is directly linked to fusion engineering science through influence on such issues as the magnetic field, auxiliary-heating power and fueling technologies. While the regimes are different, there is significant physics overlap in the transport processes encountered in magnetically confined and inertially confined plasmas.

EXPECTED ACCOMPLISHMENTS WITHIN TEN YEARS

Building on the many successes of the recent past, and assuming constant level-of-effort over the next ten years, striking progress can be expected on many of the important transport questions. With anticipated advances in computational tools and more routine and detailed measurements of ion-scale turbulence, the goal of developing a predictive capability for ion thermal transport in the tokamak is within reach. The first small-scale turbulence diagnostics are being implemented now to explore the role of this turbulence on electron thermal transport and, within ten years, the full wavelength and frequency ranges of the dominant turbulence should be identified. Particle and momentum transport studies are less mature; within ten years, some convergence can be expected on what physical mechanisms are most important in these areas. Significant advances are anticipated in understanding and controlling transport in the range of magnetic configurations that are less well developed. A more complete understanding of the conditions and thresholds for the formation of edge and core transport barriers, and their dynamics, will be obtained. The expectation is that transport barriers can then be used as a tool to control the levels of core transport.

Experiments to detect zonal flows and their effects have begun, and within ten years it will be possible to make comparisons with theoretical and numerical models. Large-scale flows, especially in plasmas without dominant external flow drive, will be documented, and analysis should enable predictions for ITER-relevant burning plasma regimes. Studies on large-scale magnetic field generation over the next ten years should lead to identification the dominant mechanisms by which turbulence generates and sustains large-scale magnetic fields in high-temperature plasma.

Experiments and modeling of magnetic reconnection in laboratory plasmas will identify the dominant processes that facilitate the “breaking” of magnetic field lines, including the possible role of turbulence, that control the rate of release of magnetic energy and that produce the high-energy particles seen as a consequence of reconnection. In the area of magnetic island dynamics, evaluation of the role of magnetic islands driven by local pressure gradients (neoclassical tearing modes) in limiting the pressure in fusion experiments will be complete. The development of new multi-scale computational techniques, an emerging focus of the program, and comparisons of the results with experimental observations promise to resolve longstanding uncertainties about the mechanism driving sawteeth. Evaluation of the feasibility of applying reconnection techniques to drive current will be completed.

OPPORTUNITIES FOR ENHANCED PROGRESS

The current U.S. program of research on multi-scale transport can be enhanced by targeting additional resources in key areas of opportunity. In regimes with tightly coupled electrons and ions, typical of burning plasmas, electron thermal transport is expected to be a very important heat-loss channel. Accelerated development of diagnostics and numerical models, focused on small-scale turbulence, will enable identification of the dominant electron thermal transport mechanisms, including the role of electromagnetic fluctuations, short-scale versus long-scale turbulence, and wavenumber spectral anisotropy.

Particle and momentum transport are strongly linked to thermal transport through density and rotation profiles, but are currently less well understood. While significant progress will be made with a constant level-of-effort, enhancements of diagnostics and control tools, especially aimed at plasma flow, as well as a focused effort to include particle and momentum transport in predictive models, are required to meet the ten-year goals: (a) to identify the dominant particle transport mechanisms, including the conditions under which pinch/convective processes compete with diffusive processes and (b) to identify the dominant mechanisms responsible for momentum transport and their relationship to thermal transport.

The broad impact of reconnection on the integrity of the confining fields in nearly all magnetic configurations makes enhanced progress in this area important. New developments on this topic will also have broad significance beyond fusion. New diagnostics are required to extract detailed information on the structure of the localized dissipation region where the magnetic field lines break and to explore the localized pressure gradients that drive islands. New multi-scale computational techniques will be developed to treat the enormous range of spatial scales that characterize the reconnection process and for carrying out simulations that can be compared with observations. Finally, machine run time dedicated to reconnection studies will be made available.

REFERENCE

1. *A New Initiative in Transport Studies*, a white paper by the U.S. Transport Task Force (2003). This paper can be found at: http://www.psfc.mit.edu/ttf/transp_init_wht_paper_2003.pdf (active as of 30 November 2004).

5

HIGH ENERGY DENSITY PHYSICS

Investigate the assembly, heating, and burning of high energy density plasmas

OVERALL SCOPE OF THE CAMPAIGN

High energy density plasmas of interest for inertial fusion energy have time scales and spatial scales vastly different from that of magnetic fusion, and different physics as well. High energy density plasmas span a wide range of plasma densities and temperatures, and are characterized by energy densities exceeding 100 kilojoules per cubic centimeter, or equivalently, pressures exceeding one megabar—conditions attained in the centers of stars and in giant planets. As noted in the National Task Force Report, *Frontiers for Discovery in High Energy Density Physics* (July 2004)[1]:

> "High energy density physics is a rapidly growing field that spans a wide range of physics areas including plasma physics, laser and particle beam physics, nuclear physics, astrophysics, atomic and molecular physics, materials science and condensed matter physics, intense radiation-matter interaction physics, fluid dynamics, and magnetohydrodynamics. New astrophysical observatories have enabled studies of high energy density physics on the stellar and even galactic scales, and new laboratory facilities are allowing controlled and precise investigations of matter under extreme conditions."

The recent FESAC Report on *A Review of the Inertial Fusion Energy Program* (March 2004)[2] comments on the strong synergy between the science and enabling technology needed for inertial fusion energy and for high energy density physics:

> "Inertial fusion energy capabilities have the potential for significantly contributing to high energy density physics and other areas of science. Isochoric heating of substantial volumes to uniform, elevated temperatures should be achievable using heavy ion beams. Investigations of the fast ignition concept can lead to exploration of exotic high energy density physics regimes. Moreover, the rapid turn-around capabilities envisioned for inertial fusion energy drivers could accelerate progress in high energy density science by enabling a wide community of users to conduct "shot-on-demand" experiments with data rates and volumes far exceeding those obtained on large systems that currently require long times between shots."

The range of high energy density physics research thrusts described in the National Task Force Report[1] is very broad, and different aspects are being pursued by several federal agencies, including the U.S. Department of Energy's Office of Fusion Energy Sciences (OFES), National Nuclear Security Administration (NNSA), Office of High Energy Physics, Office of Nuclear Physics, and Office of Basic Energy Sciences, the National Science Foundation, and the National Aeronautics and Space Administration. The research thrusts incorporated in this chapter focus on the OFES science campaign on high energy density physics:

- Offer high discovery potential for exciting new physics relevant to both high energy density physics and fusion;
- Use of existing facilities and experimental equipment in OFES programs, or facilities developed by other programs/agencies; and
- Perform experiments and theory/simulations supported by OFES for science campaigns not pursued by other agencies.

This chapter focuses on campaign activities pertaining to (a) heavy-ion-driven high energy density physics, (b) fast ignition high energy density physics, and (c) magnetized plasma-liner high energy density physics. These diverse approaches make use of intense ion beams, short-pulse lasers, and plasma-liner implosions to create matter under extreme conditions, which are relevant to both basic high energy density physics and fusion.

This section identifies the motivating topical scientific questions, research thrusts, and the principal ten-year goal and supporting goals included in the high energy density physics campaign.

T9: How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?

The primary scientific challenge in creating high energy density matter and fusion conditions in the laboratory with intense ion beams is to compress the beam in time (by 1000 times overall, requiring 10–100 times more longitudinal bunch compression than present state-of-the-art) to a pulse length that is short compared to the target disassembly time, while also compressing the beam in the transverse direction (by 10 times) to a small focal spot size for high local deposition energy density. Planned new experiments, compressing intense ion beams within neutralizing plasma, would significantly extend the beam current into high-intensity regimes where the beam would not otherwise propagate in the absence of background plasma, and where beam-plasma collective effects with longitudinal and azimuthal magnetic focusing fields have not been previously explored.

The heavy ion beams, once compressed in time and radially focused, will not themselves alone reach an energy density that satisfies the definition of high energy density physics (>100 kJ per cubic centimeter), but will be able to deposit an energy density in the targets sufficient to reach high energy density conditions, because the ion stopping range at energies near the Bragg peak in energy loss rate dE/dx (a few to tens of microns) in near-solid targets is much shorter than the compressed beam bunch length. The resulting near-solid-density target plasmas can exhibit strong-coupling effects between the target ions at temperatures below 10 eV, conditions where there have not been accurate enough measurements to validate equation-of-state theories for such non-ideal plasmas characteristic of the interiors of giant planets and brown dwarfs. In particular, it is planned to study plasmas of about 1 eV at densities 0.01 to 0.1 times solid density, because there is very little data in such regimes, while predicted pressures from existing equation-of-state models differ the most. To improve measurement accuracy in such strongly coupled plasmas, it is planned to use tailored ion beams with the Bragg peak located in the center of the target diagnostic volume to achieve unprecedented uniformities (<5 % nonuniformity in temperature and density) in the target.

A basic understanding of the collective processes and nonlinear dynamics of intense, high-brightness, heavy ion beams, and a determination of how best to create, accelerate, transport, compress, and focus these beams to a small spot size are critical to achieving the scientific objectives of heavy ion fusion and ion-beam-driven studies of warm dense matter. There are key synergistic relationships of the research on intense heavy ion beams to understanding the nonlinear dynamics of intense charged-particle beams for high energy and nuclear physics applications, including minimization of the deleterious effects of collective processes such as the two-stream (electron cloud) instability, the use of a charge-neutralizing background plasma to assist in focusing intense beams to a small focal spot size (plasma lens effect), the production and control of halo particle production by beam mismatch and collective excitations, and the development of advanced numerical simulation techniques, theoretical models, and diagnostic instruments to understand and control charged-particle beam propagation at high intensities, to mention a few examples.

T8: How do hydrodynamic instabilities affect implosions to high energy density?

In inertial confinement fusion (ICF), a spherical shell of cryogenic thermonuclear fuel is imploded either by direct laser irradiation or by the x-ray emission from a high-Z enclosure (hohlraum). In order to achieve high energy densities of gigabars, the implosion must be nearly spherical. This is a challenging task since imploding shells are hydrodynamically unstable. As the shell accelerates inward, the outer surface is unstable to the Rayleigh-Taylor (RT) instability, which causes a large shell distortion leading to significant degradation of the maximum compression. In order to reduce the seeds for this instability, the nonuniformities in the target and illumination must be reduced to a minimum. If the compressed thermonuclear fuel is ignited from a central hot spark then the resulting high energy densities reach hundreds of gigabars thus exceeding those in the solar core. However, even when the shell integrity is preserved during the acceleration-phase, the ignition process can be quenched by the deceleration-phase Rayleigh-Taylor instability. The latter is the instability of the inner shell surface that occurs when the shell is decelerated by the high pressure building up inside the spark. The deceleration Rayleigh-Taylor causes the cold shell material to penetrate and cool the central spark, preventing it from achieving ignition conditions. Improving the capability to predict and control the Rayleigh-Taylor instability is key to the success of inertial fusion energy. This research is a key part of the physics in pursuit of inertial fusion ignition in the National Ignition Facility, but because it is funded by the NNSA and not by OFES, research related to topical question T8 will not be discussed further in this report.

T7: How can high energy density fusion plasmas be assembled and ignited in the laboratory?

A fundamental aspect of high energy density physics is the creation and exploration of extreme states of matter in the laboratory. By combining the compression by a high energy density driver with heating by a short-pulse, petawatt-laser beam, extreme states of matter can be generated. Such novel states are in the ultra-high energy density regime, potentially reaching energy densities of 10^{17} J/m^3 or pressures of terabars (10^6 megabar), thus exceeding the high energy density threshold of 1 megabar by six orders-of-magnitude. Such ultra-high energy density physics regimes even exceed the energy density of the core of stars, such as our own sun, where the peak pressure is a few hundred gigabars (10^5 megabar). Attaining these extreme states in the laboratory requires the heating to a multi-kilo-electron-volt temperature (1 keV ~ 10^7 °C) of ultra-dense matter at hundreds of grams per cubic centimeter. This can be accomplished through a combination of high-energy drivers and fast-heating beams that are not currently available in the U.S. However, since the National Nuclear Security Agency is developing short-pulse petawatt lasers systems integrated with high energy drivers (such as OMEGA, Z, and the National Ignition Facility), the capability of carrying out fast-heating experiments of ultra-dense matter will soon be available to U.S. scientists.

In addition to exploring such ultra-high energy density physics regimes, fast heating of ultra-dense matter provides a novel path towards igniting high-density thermonuclear fuel. Such fuel is assembled by imploding a cryogenic deuterium-tritium (D-T) capsule with a high-energy driver. In a conventional inertial confinement fusion (ICF) scheme, the fuel is compressed and ignited by the same driver. The main difficulties in assembling and igniting thermonuclear fuel in conventional ICF are: the control of hydrodynamic instabilities during the implosion, the control of driver asymmetries in the illumination of the target, and the control of the capsule's entropy during the implosion. Understanding the limits of driver asymmetry and driver intensity required to achieve ignition will define the requirements for the drivers required for fusion energy applications. An alternative path to inertial confinement fusion is the so-called "fast ignition" scheme where a cryogenic D-T capsule is compressed by a high-energy driver and ignited by a particle beam consisting of relativistic electrons generated by the interaction of an ultra-intense short-laser pulse with the coronal plasma of the compressed fuel. With an appropriate target, fast ions can also be produced with intense laser pulses and then used to ignite the compressed fuel in place of fast electrons. By reducing the requirements on the compression symmetry, and by separating the heating from the compression, the fast ignition concept has the potential to achieve higher energy gains with smaller high-energy drivers, thus significantly reducing the cost and scale of an inertial fusion electrical power plant.

The main scientific challenge in fast ignition research is the laser-generation and collimation of a powerful particle beam with enough energy to ignite a dense thermonuclear fuel. The physics pertinent to the laser generation of relativistic electrons and their interaction with dense matter is a fascinating area of plasma physics and high energy density science. Understanding this fundamental science is key to the success of the fast ignition scheme.

Another approach for accessing the high energy density regime is the so-called "magneto-inertial fusion (MIF)" approach. Magneto-inertial fusion involves adding a magnetic field to the fuel, thereby increasing the thermal insulation, and then inertially compressing the fuel to fusion conditions. Recognizing the wide difference in densities (many orders-of-magnitude) between conventional magnetic fusion and conventional inertial fusion, the question can be asked: “Is there a regime somewhere in-between which may combine features of both?”

Magneto-inertial fusion has the potential to dramatically improve the economic outlook of inertial fusion energy by lowering the power requirements of the high-energy driver. Part of the attractiveness of magneto-inertial fusion is that megabar plasma pressures at fusion-relevant temperatures may be achievable in the laboratory, in the near-term, using existing Defense Programs pulsed-power driver facilities, combined with target plasmas (compact tori) that have been studied by the Office of Fusion Energy Sciences for many years. This approach is referred to as magnetized target fusion (MTF). By leveraging prior Department of Energy investments in the technology of driving metal liners to 5–10 km/sec speeds, large energies (~1 MJ) are available today to compress a warm magnetized target plasma to extreme conditions. The resulting possibility would allow study of the physics of deuterium plasmas with plasma betas of order unity in 300–500 Tesla magnetic fields, at multi-kilo-electron-volt temperatures, in close proximity to a stabilizing metallic wall.

RESEARCH THRUSTS

The following provides a brief summary of the principal research thrusts in the three areas: (a) heavy-ion-driven high energy density physics, (b) fast-ignition high energy density physics, and (c) magnetized plasma-liner high energy density physics.

Heavy-ion-driven High Energy Density Physics

High-brightness heavy ion beam transport

Develop a basic understanding of the limits on beam-channel wall clearance (aperture fill) imposed by gas and electron cloud effects, together with beam matching and magnet nonlinearities.

Longitudinal compression of intense ion beams

Develop a basic understanding of the limits on longitudinal compression within neutralizing background plasma, and the effects of beam-plasma instabilities over distances *greater than one* meter.

Transverse focusing onto targets

Develop a basic understanding of the limits on focal spot size set by chromatic aberrations due to uncompensated velocity spreads from upstream longitudinal compression, and the beam temperature growth from imperfect charge neutralization.

Advanced beam theory and simulation

Develop, optimize, and validate multi-species beam transport codes that can predict self-consistently the beam loss with gas and electron clouds, and develop integrated beam simulation models required to analyze source-to-target beam brightness (temperature) evolution.

Beam-target interactions

Develop a basic understanding of the beam deposition profiles within thin-foil targets and the uniformity of isochoric heating, accounting for target and beam ion charge state conditions, including the development of accurate beam deposition and laser-generated x-ray target diagnostics, and extension of integrated beam simulation models from the source through the target.

Fast-ignition High Energy Density Physics

Fast particle transport in high energy density plasmas

Develop a basic understanding of the transport and stopping of particle beams in plasmas with densities ranging from 0.01 to 100,000 times the critical density, using particle-in-cell (PIC), hybrid-PIC, and Fokker-Planck codes, coupled with experiments.

Relativistic laser-plasma interactions

Develop a basic understanding of the hole boring and fast-particle generation by ultra-intense laser pulses for relevant incident intensities (10^{18}–10^{21} W/cm^2), angles of incidence, and pulse lengths (>10 ps).

Hydrodynamic assembly of high energy density plasmas

Design targets and carry out implosion experiments to identify the optimal assembly of high energy density plasmas at densities of hundreds of grams per cubic centimeter.

Magnetized Plasma-liner High Energy Density Physics (Magneto-inertial Fusion)

Energy confinement and macroscopic stability properties of magnetically insulated plasmas compressed to high energy densities

Demonstrate the physics of liner-plasma implosions at the megajoule level using a field-reversed configuration target plasma. This includes: (a) modeling the overall physical processes involved and benchmarking the numerical simulations against experiment and (b) studying the role of the field-reversed configuration plasma interacting with the nearby metallic wall—an essential element of this megabar, multi-kilo-electron-volt plasma regime.

The principal ten-year goal for the high energy density physics campaign is to develop an understanding of the underlying physics governing the use of highly compressed heavy ion beams, fast ignition with short-pulse lasers, and magnetized plasma-liner implosions for the creation of high energy density matter.

The supporting ten-year goals in the three high energy density physics campaign areas are:

> *Understand the beam and plasma target science for accelerator-driven high energy density physics that exploits the unique deposition properties of intense ion beams.*
>
> *Understand the relativistic laser-plasma interaction, relativistic electron transport and hydrodynamic fuel assembly required to carry out integrated fast ignition experiments.*

Understand the physics of magnetized plasma-liner implosions at the megajoule level by performing experiments and by developing and comparing to numerical simulations.

RELEVANCE TO ITER AND OTHER CAMPAIGNS

The high energy density physics campaign provides important diversity to the U.S. fusion energy sciences program that is complementary to ITER and other magnetic fusion research, by providing very different plasma regimes to study the properties of extreme states of matter. The high energy density physics campaign highly leverages domestic fusion facilities supported by the Department of Energy's Office of Fusion Energy Sciences (OFES) and National Nuclear Security Administration. The high energy density physics campaign also offers U.S. students and researchers an excellent opportunity to work on discovery-rich plasma science experiments at a variety of U.S. facilities over the next ten years. The achievement of ignition on the National Ignition Facility within the next ten years will, of course, provide burning plasma physics complementary to ITER in the high energy density physics regime.

Heavy-ion-driven High Energy Density Physics

The U.S. is the world leader in inertial fusion physics, primarily using large laser systems and z-pinch facilities for stockpile stewardship research. The OFES program in heavy ion fusion is the world leader in space-charge-dominated beam research. This combination offers a unique tool to explore intense beam-target interactions using ions instead of photons. Ions have different deposition characteristics, and thus the OFES program complements the larger national security facilities, while contributing to other common target physics issues. The planned application of ion-target interactions at the dE/dx Bragg peak is unique, as giga-electron-volt accelerators in Germany, Japan and Russia must use massive targets with beams operating at energies much higher than the peak in dE/dx .

Fast-ignition High Energy Density Physics and Inertial Fusion

In laser-plasma interactions, there are strong international efforts in Europe, Japan, and China. In the electron transport area, there are experiments and theory in Japan, France, and Germany. In laser-produced ion acceleration, there is strong international interest, principally in the United Kingdom and France. Research in the U.S. on the Nova petawatt laser was seminal in this regard. In integrated experiments for fast ignition, Japan plays a leadership role with the GEKKO experiment, which is being upgraded to the FIREX facility. U.S. petawatt facilities will be available in several years, including the OMEGA facility at the University of Rochester. In hydrodynamic fuel assembly experiments, there is a strong Japanese program, often building on U.S. ideas and calculations. In the design of implosion systems, the U.S. is a world leader.

Magnetized Plasma-liner High Energy Density Physics

The U.S. is a leader in the field of magnetized plasma-liner high energy density physics. However, Russia has a long historical interest. Joint U.S.-Russian experiments, aimed at developing energetic target plasmas, have been conducted in the past.

TECHNICAL PROGRESS AND CAMPAIGN READINESS

Heavy-ion-driven High Energy Density Physics

Advances over the past several years include: (i) high-current ion sources and injectors (0.1 to 1 Ampere using a potassium source) have been shown to have adequate initial beam brightness (sufficiently low transverse and parallel temperatures) to meet the above requirements at injection; (ii) negligible beam brightness degradation has been observed in transport of 200-milliamperes using potassium ion beams through electric quadrupole focusing magnets; and (iii) more than 95% of potassium beam space-charge has been neutralized with pre-formed plasma over one meter lengths without deleterious beam-plasma instabilities.

Figure 5.1 shows the beam focal spot sizes for three cases of space-charge neutralization: a large focal spot of several centimeters without any pre-formed plasma (left panel), a spot size reduced by almost a factor of 10 with a localized “plug” plasma just beyond the last focusing magnet (center panel), and a further 25% reduction in the full-width-at-half-maximum of the spot size is seen (right panel) when both “plug” and “volume” plasmas are used. Particle-in-cell calculations using the hybrid LSP code predict a root-mean-square spot radius of 1.4 mm for the case of a plug plasma (center panel), in very good agreement with the experimental results.

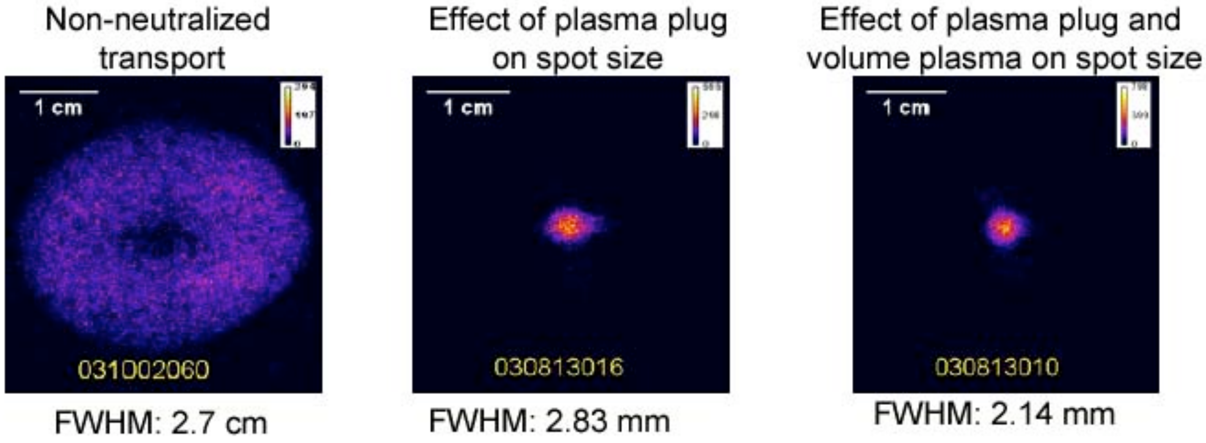

Figure 5.1. Plasma neutralization reduces the final focus spot size of an intense heavy ion beam, encouraging experiments on longitudinal and transverse compression for neutralized beams. (Courtesy of Simon Yu)

Over the next five years, the research will use existing experimental facilities, with modest upgrades of equipment, to test the limits of longitudinal as well as transverse compression of neutralized beams. This is the key to enable creation of uniform 1 eV, 0.01 solid density plasmas where the predictions of equation-of-state models can best be discriminated.

Fast-ignition High Energy Density Physics and Inertial Fusion

A significant research effort in the areas of fuel assembly and hot-spot ignition for conventional inertial confinement fusion (ICF) is carried out under the target physics research thrust area within the ICF program supported by the National Nuclear Security Administration (NNSA). The main research thrusts in conventional ICF physics are:

- Achieving the high level of uniformity in the driver illumination required for a symmetric compression.
- Achieving the pulse-shaping capabilities to control the fuel and ablator entropy; determining the equation-of-state of material in high energy density conditions.
- Controlling hydrodynamic instabilities of the imploding shell; investigating the effects of laser-plasma instabilities on capsule performance.
- Fabricating cryogenic targets within the required tolerances of surface roughness.
- Validating the available simulation codes through hydrodynamic and radiation transport experiments.

While conventional inertial confinement fusion research is primarily supported by the National Nuclear Security Administration, research in inertial fusion by fast ignition is sponsored primarily by the Office of Fusion Energy Sciences. However, in the case of fast ignition, the research is heavily leveraged by NNSA-sponsored high energy driver and petawatt laser facilities. Fast ignition continues to be a rapidly developing field.

Understanding the generation and transport of fast electrons in ultra-dense plasmas is key to the success of fast ignition. The fast electron beam generated by the laser-plasma interaction near the critical surface propagates into the high-density plasma and drives a return current in the thermal electrons. In order to provide an efficient localized heating of the dense plasma, the

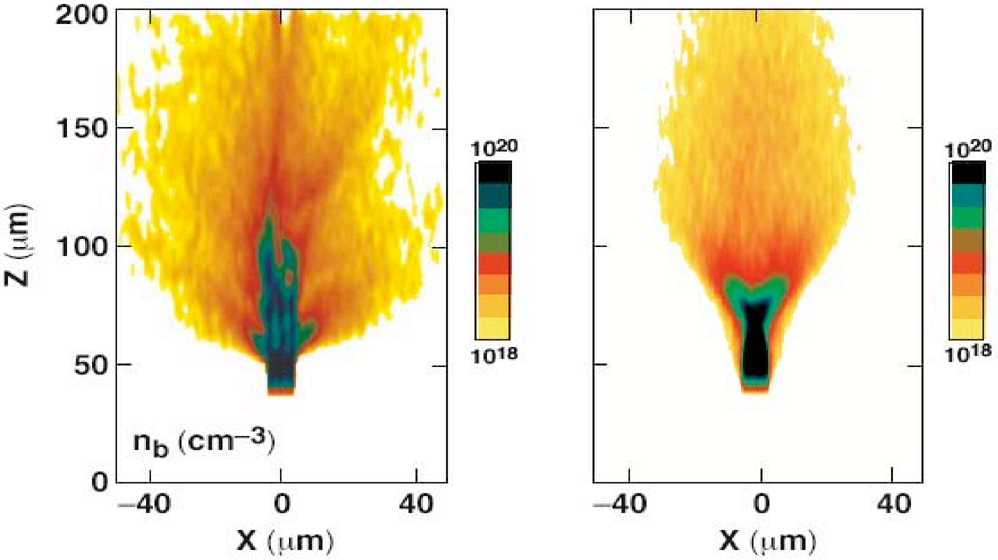

Figure 5.2. Hybrid simulation of the resistive-Weibel filamentation of a 1-MeV relativistic electron beam with a 10-keV (left) and a 200-keV (right) thermal spread. (Courtesy of J. Myatt)

electron beam must remain focused and release its energy within a small volume of the compressed core. Since the electron beam current is well above the Alfvén limit, a return current must flow in the background plasma in order to balance the beam current and allow the propagation of such an intense beam. By damping the return current flow, the thermal electron resistivity can significantly impede the fast-electron transport for high-atomic-number targets. Furthermore, Weibel-like instabilities (see Figure 5.2) can develop in the underdense plasma region leading to the break-up of the electron beam into smaller diverging filaments. Such instabilities are suppressed in the overdense plasma and by a significant thermal spread of the beam electrons. When the fast electrons penetrate the high-density core, they must release their energy to the background plasma through collisions. The physics of the collisional slowing-down and scattering of relativistic electrons in dense plasma is not well established, and the available experimental data are scarce.

In order to carry out proof-of-principle experiments on planned NNSA-integrated facilities (petawatt lasers combined with high-energy drivers), it is necessary to develop a thorough understanding of the physics underlying the laser generation of relativistic electrons and their interaction with matter.

Magnetized Plasma-liner High Energy Density Physics

With the present generation of pulsed-power facilities (Shiva-Star, Atlas, Z) and the knowledge base of compact toroid physics developed over the past twenty years, the opportunity exists for producing high energy density plasmas relevant to achieving hot plasma fusion conditions.

Magneto-inertial fusion involves adding a magnetic field to the fuel, thereby increasing the thermal insulation, and then inertially compressing the fuel to fusion conditions. Magnetized target fusion is a subset of magneto-inertial fusion that involves compressing a warm magnetized plasma to fusion conditions. Leveraging on the Department of Defense and NNSA investments in pulsed-power facilities, the physics understanding required to test the magneto-inertial fusion concept is being developed with a relatively modest investment over the next ten years. Recent experiments have produced high-density field-reversed configuration target plasmas that are ready to be translated into a suitable liner. Data from such target plasmas is shown in Figure 5.3. Additionally, test aluminum metal liners have been imploded at the Air Force Research Laboratory (AFRL), achieving

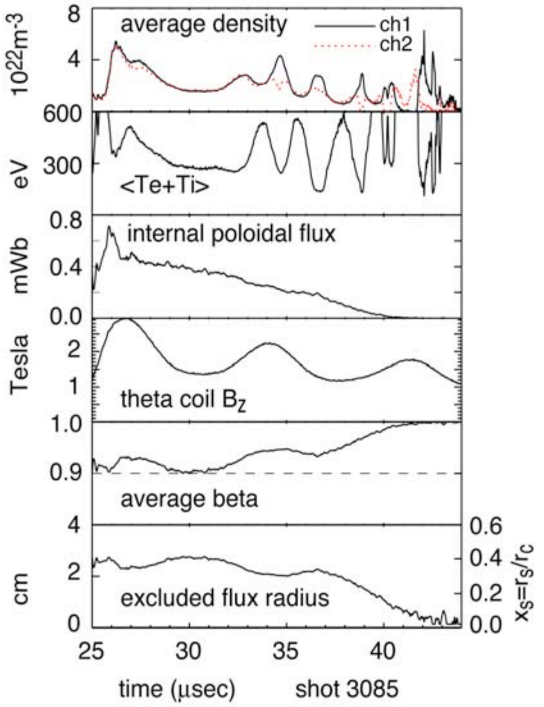

Figure 5.3 Nominal FRX-L time history of two chords of electron density, total temperature from force balance, estimated internal magnetic flux, external magnetic field, volume averaged <β>, and calculated separatrix radius, for 50 mTorr static deuterium fill. (Courtesy of Glen Wurden)

cylindrical compression factors of 13-17, suitable for use in magnetized target fusion experiments. The Shiva-Star bank energy is 4.5 megajoules, of which 1.4 megajoules is delivered to the liner, and available to compress and heat the plasma.

EXPECTED ACCOMPLISHMENTS WITHIN TEN YEARS

This section summarizes the research progress and accomplishments expected for the research thrust areas previously described assuming constant level-of-effort, followed by a description of opportunities that could significantly enhance the research progress in selected thrust areas of the high energy density physics campaign.

Heavy-ion-driven high energy density physics

Over the next five years, an integrated program of beam experiments, theory, and simulations will be carried out to understand the limits to neutralized drift compression and the focusing of intense ion beams onto targets (Heavy Ion Research Thrusts in high-brightness beam transport, longitudinal compression, transverse focusing, and advanced theory and simulation). If the optimized beam parameters are found to be sufficient to create and study 1-eV warm dense matter with sufficient spatial uniformity, over the following five years experiments will be conducted to measure the equations-of-state for 1-eV targets in the range of 0.01 to 0.1 solid density (Heavy Ion Research Thrust in beam-target interaction). Predictive models will also be developed for gas and electron cloud effects in short (<10 magnet) transport sections (Heavy Ion Research Thrust in high-brightness beam transport).

Fast-ignition high energy density physics

Over the next five years, experiments with short-pulse lasers and simulations with 3-D particle-in-cell (PIC) codes will be carried out to develop a thorough understanding of the electron output phase space for high-incident-laser intensities (10^{18}–10^{21} W/cm^2), angles of incidence, and pulse lengths (>10 ps) relevant to fast ignition (Fast Ignition Research Thrusts in fast particle transport and relativistic laser-plasma interactions). Experiments on cold targets and hybrid simulations will be used to explore the physics of fast electron transport in moderate-to-high-Z materials. As soon as integrated facilities become available within the next three to five years, the first experiments on petawatt laser-pulse interaction with hydrogenic plasmas as well as integrated experiments with surrogate (noncryogenic) cone targets will be carried out and simulated with integrated hybrid codes (Fast Ignition Research Thrust in hydrodynamic assembly of high energy density plasmas).

Magnetized plasma-liner high energy density physics

Over the next five years, experiments and theory/simulations of magnetized plasma compression will be carried out sufficient to understand the scientific and engineering basis for magnetized target fusion (Magnetized Target Research Thrust in energy confinement and stability of magnetically-insulated plasmas compressed to high energy density). If the physics is found to scale favorably, liner-on-plasma implosion experiments would be designed at the megajoule energy scale which could be carried out on available high energy facilities.

OPPORTUNITIES FOR ENHANCED PROGRESS

Summarized below are the research opportunities to enhance technical progress in selected research thrust areas of the high energy density physics campaign, which assumes incremental funding. This section characterizes how these enhancements would add new capability or augment the capability in the recommended program at constant level-of-effort. But because these enhancements require incremental funding, they have lower priority than the research activities at constant level-of-effort.

Extend the temperature and density range of Ion-beam-driven high energy density physics experiments

With incremental funding, enhanced priority would be given to the following activities:

- Add 3 to 10 MeV additional beam energy to existing experiments.
- Develop a Thomson scattering diagnostic for higher precision measurements of equation-of-state and plasma properties.
- Develop means to increase the shot rate for low-density (0.01 to 0.001 solid density) foam and wire-array experimental targets (to improve data statistics).
- Evaluate achromatic neutralized beam bending to enable multiple equation-of-state experiments driven by one accelerator (augments all Heavy Ion Research Thrusts except high-brightness beam transport).

The quadrupole lattice lengths in high-brightness beam transport experiments would also be extended to improve the precision of predictive models for gas/electron effects in high-intensity ion accelerators (extends Heavy Ion Research Thrust in high-brightness beam transport). These enhancements would provide a more robust pulse energy and ion range to extend the temperature and density range to study strongly-coupled plasmas, and extend the data productivity of the target experiments. The aggregate impact of these enhancements could be to achieve a full heavy-ion-driven high energy density science user capability in less than ten years.

Fusion-grade relativistic electron transport and laser-plasma interaction for fast ignition

With incremental funding, priority would be given to the following activities:

- Investigate electron transport, stopping and hole boring in hydrogenic dense laser-produced plasmas using modeling and experiments at higher laser energies (augments Fast Ignition Research Thrusts in fast-particle transport and relativistic laser-plasma interactions).
- Develop cryogenic targets for fast ignition implosions on the OMEGA and Z facilities (new fast ignition activity for OFES).
- Carry out integrated fast ignition cryogenic experiments on OMEGA with and without gold cones and validate particle-in-cell and hybrid codes (new fast ignition activity for OFES).

- Develop integrated hybrid-simulation capability for fast ignition including fast particle generation and transport (augments Fast Ignition Research Thrust in fast-particle transport).
- Evaluate the potential for proton-driven fast ignition (new fast ignition activity for OFES).
- Develop the physics basis for proton fast ignition using integrated petawatt laser interaction experiments with solid targets (new fast ignition activity for OFES).
- Develop target designs for high-gain fast ignition (new fast ignition activity for OFES).
- Prepare for proof-of-principle ignition experiments on the National Ignition Facility (new fast ignition activity for OFES).

These increments would allow the U.S. to be competitive with the Japanese fast ignition effort by expediting the research needed to reach fusion-grade plasma conditions in integrated fast ignition experiments in the United States.

Experiments and simulations of multi-kilo-electron-volt, megabar, magnetized plasmas

With incremental funding, emphasis would be placed on (a) increased theory and integrated modeling and (b) an increase in the pace of plasma-liner experiments (augments Magnetized Target Fusion Research Thrust in energy confinement and stability of magnetically-insulated plasmas compressed to high energy density). The enhanced effort would also (c) upgrade the energy through use of the Atlas facility at the Nevada Test Site (new magnetized target fusion activity for OFES). This additional effort in high energy density physics for magnetized target fusion could possibly lead to the exploration of more energetic fusion-grade plasma conditions within ten years.

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Frontiers in High Energy Density Physics: The X-Games of Contemporary Science (National Academies Press, 2003).

6

PLASMA-BOUNDARY INTERFACES

Learn to control the interface between the 100-million-degree plasma and its room temperature surroundings

OVERALL SCOPE OF THE CAMPAIGN

The boundary conditions for the core plasma require a high-temperature edge plasma, i.e., the surface of the confined plasma cannot be at "room temperature." Also, even if the hot burning core plasma is well confined by the closed magnetic field lines, a small leakage of particles or power from the core can damage the walls of the plasma device. The physics of the thin transitional plasma that connects the hot core (of order tens of keV, 10^8 °C) with the "room temperature" material walls (actually in the range of 300-1500 °C) is the subject of this research question. Within this few-centimeter-wide region, the magnetic field topology changes from closed magnetic surfaces to open field lines, large electric fields form spontaneously, magnetohydrodynamic stability continually evolves, and plasma transport changes dramatically. At the walls, the plasma on the open field lines interacts with the material surfaces through complex surface chemistry, multi-step ionization processes, and multi-species ion and neutral transport, all of which depend on the material surface composition and geometry.

Surprisingly, small changes in the equilibrium of the boundary plasma can dramatically affect the overall performance of a burning plasma. Understanding the dynamic physics of this region with sufficient clarity to reliably predict the behavior of a burning plasma experiment presents one of the greatest challenges to the fusion community. Developing understanding of the boundary plasma requires a well-coordinated effort between simulation and experiment that covers time scales spanning six orders of magnitude and spatial scales from microns to meters.

This campaign aims to answer the following topical scientific question:

T10: How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?

RESEARCH THRUSTS

Four major research thrusts have been defined for the boundary-plasma interfaces campaign. They follow from the natural division of the boundary-plasma interface into four regions whose behavior is governed by their own unique physical processes. Thrust 1 is focused on the thin transport barrier lying at the edge of the core plasma, where there exist strong gradients in plasma temperature and density (or plasma pressure), as illustrated in Figure 6.1. Significant progress has been made in characterizing this "edge pedestal" over the past decade, but significant gaps remain in the understanding of how the height and width of this barrier are determined. Uncertainty in predicting the pedestal parameters still represents the largest uncertainty in predicting the performance of a burning plasma device.

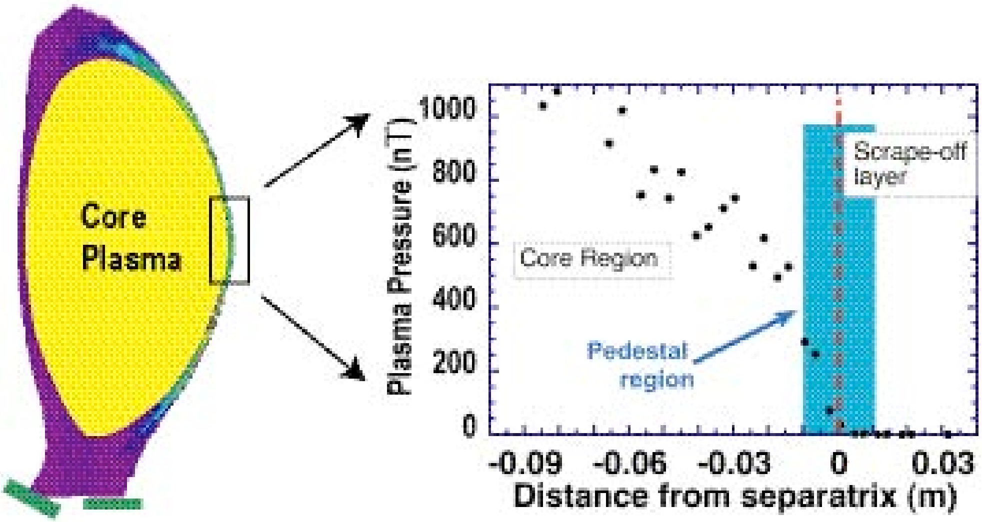

Figure 6.1. Cross section of a typical tokamak plasma showing the hot core surrounded by a cooler scrape-off layer which intersects material walls. The plot to the right shows the steep gradient in plasma pressure (10^{20}eVm^{-3})which is observed at the plasma surface. These general features of the tokamak are representative of many magnetic fusion concepts. (Courtesy DIII-D group)

Just outside the pedestal is the edge or scrape-off layer plasma (Thrust 2) which surrounds the hot core and has "open" field lines that connect to the wall. The heat and plasma from the core primarily move along the open field lines in the scrape-off layer to a special, armored area where the main interaction with the wall occurs; this is called a "divertor." A major accomplishment of experiments and modeling has been the demonstration that at high core plasma density, the scrape-off layer plasma can be well isolated (or partially detached) from the divertor—this is the essence of the ITER design. While most of the plasma interactions with the wall are at the scrape-off layer-divertor interface, there can also be radial losses in the scrape-off layer that result in less severe, but significant interactions with other surfaces (the "first wall"). Bursts of heat and particles originate from the pedestal (called edge-localized modes, as they are edge-magnetohydrodynamic modes), are transported through the scrape-off layer and cause large, repetitive loads on the divertor and first wall.

All of these plasma-material interactions involve heat and particle fluxes on the first wall and divertor (Thrust 3). Examples of plasma-material interactions include collisions of ions with the wall (sputtering), chemical processes (e.g., chemical sputtering), and the deposition of impurities and particles in the walls. Plasma-facing components must absorb large heat and particle fluxes while minimizing erosion and plasma contamination. These are competing requirements, as a thin plate optimizes heat conduction out of the system, but a thicker plate is required to handle erosion processes. The plasma fuel—tritium—can be deposited and trapped in the material walls, which in turn can present a safety issue if it results in a large in-vessel inventory of nuclear fuel.

Finally there is the composition of the divertor and first wall (Thrust 4). Extensive research has been carried out to develop and characterize the material properties used in fusion devices. Current devices and laboratory experiments have developed a large knowledge base of the interactions with carbon walls. Carbon can absorb large heat and particle fluxes, but can be problematic due to the resulting large tritium inventories. Metal walls such as tungsten and molybdenum are used successfully in two devices, but these metals can melt significantly during off-normal events such as edge-localized modes or rapid terminations of the core plasma (disruptions). Liquid walls, such as lithium, offer self-healing properties and control of tritium inventory, but are not ready for use in a fusion device. Magnetohydrodynamic forces on these liquids must be evaluated in the geometry of a fusion device.

Research over the next decade in each thrust area aims to increase understanding of the key physical processes in each region and to test the understanding against experiment. In the pedestal region (Thrust 1), it is necessary to understand the physics of the plasma turbulence and stability that sets the edge transport barrier and provides the required high-temperature boundary to the hot core plasma. Outside the pedestal, in the scrape-off layer (Thrust 2), research focuses on the flow of particles and heat along the open field lines to the divertor, including the "detachment" of the divertor plasma. The relationship between turbulence and radial transport in the scrape-off layer is just starting to be understood; radial transport results in fluxes to the "main chamber" walls. Plasma-surface interactions (Thrust 3), primarily at the divertor but also at the first wall, are being researched both in fusion devices and fundamental surface-science studies. Finally, the choice of the divertor and material walls (Thrust 4) requires close collaboration between plasma and materials scientists. Tritium inventory, steady-state operation, and recovery from off-normal events are key topics in the research. While solids are used in current devices, liquid walls are being researched for future devices.

Physics of formation, structure, and stability of the pedestal

A strong edge transport barrier (a high H-mode "pedestal" as in Figure 6.2) is thought to be required to obtain good global energy confinement in a burning plasma experiment. The strong-gradient region spans the separatrix and can extend over 5-10% of the minor radius into the core plasma. The physical processes, which govern the barrier formation, are still not fully known, although flow shear is generally believed to play an important role. While edge gradients in the barrier are believed limited by peeling-ballooning instabilities, the width of the barrier region cannot yet be predicted accurately. The plasma temperature at the top of the pedestal edge is arguably the biggest uncertainty in predicting the fusion performance of ITER. There is a crucial need for more complete models of this region, benchmarked against well-diagnosed experiments in a range of plasma parameters. Also of concern are transient heat pulses created by periodic large-scale edge modes known as edge-localized modes; the ability to predict the frequency and amplitude of such transients is limited. There is concern that the strong edge gradients associated with good confinement may lead to unacceptable transient heat pulses, so further research is needed to develop active edge-localized modes control and/or operating regimes with smaller transients.

Ten-year Goal: Predict the expected magnetohydrodynamic stability and plasma parameters for the ITER H-mode edge pedestal with high confidence. This is a time-sensitive issue relevant to the success of ITER.

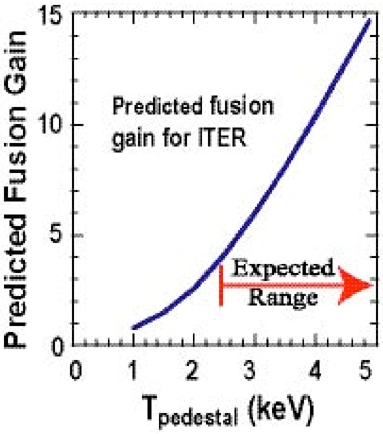

Figure 6.2. Predicted fusion gain in ITER as a function of edge pedestal temperature. (Courtesy of R. Waltz)

Supporting activities include:

Measure steady-state and transient H-mode pedestal profiles over a wide range of operating conditions and geometries, with sufficient resolution to guide theory development. U.S. and international experiments have made significant progress in developing high-resolution diagnostics of the pedestal region, particularly of electron profiles. Other parameters, such as ion temperature, flows and E_r, and edge current profile, have more limited coverage and need to be further developed to allow more routine operation and inter-machine comparisons. Measurements of particle sources are needed at several poloidal and toroidal locations.

In the edge, where atomic processes play a role in at least some components of the physics, it is seldom clear how to scale results from a single device to a burning plasma. Multiple experiments spanning a range of dimensional as well as dimensionless parameters are essential. Simple empirical scalings of pedestal widths and heights have not proven satisfactory, indicating the complexity of the physics. Regimes on one device can be hard to obtain in another. Existing experimental facilities are equipped to carry out this experimental program. Sufficient run time for dedicated experiments and some diagnostic improvements, are needed, as indicated above. Collaboration with international facilities, which is already strong in this area, will further leverage the U.S. effort.

Develop testable pedestal simulation codes that incorporate the relevant spectrum of physical processes (e.g., topology, magnetohydrodynamic stability, flows, transport, and atomic physics) and span the range of plasma parameters relevant to ITER. Unique complications arise for pedestal and edge-localized mode modeling, including the transition from closed to open flux surfaces, sharp radial scale lengths, and extreme parameter variations, all of which violate usual assumptions of core transport models. Magnetohydrodynamic limits, neutral ionization, and turbulent transport, which are inherently 2D or 3D, must also be included in computing pedestal profiles. In the near term, different models, backed up by analytic understanding, will be required to treat different issues. Understanding the radial structure of boundary plasma particle, electron temperature and ion temperature profiles will require 3D fluid codes (which are in-hand) and/or 5D kinetic codes (which must still be developed) to investigate the absence of strong turbulent transport in this very high-gradient region. These codes must model both particle sources and edge flows if edge turbulence suppression is to be understood, as it has been shown that scrape-off layer densities and parallel flows can affect the pedestal and the low-to-high confinement mode power threshold. Present peeling-ballooning models such as ELITE appear to adequately predict edge pressure (but not density, electron temperature or ion temperature) gradients. They do not predict edge-localized mode extent and size, or the transient heat loads to the divertor. Theoretical development of nonlinear magnetohydrodynamic evolution and resulting transport is needed. Coupling between 2D transport and 3D turbulence/ magnetohydrodynamic simulation is beginning. A long-term goal, once individual components of models are well developed and benchmarked against experiment, is a complete, preferably kinetic, 5D model of the scrape-off layer to core region including predictions of barrier formation, evolution, size, transport, and edge-localized modes, including the more benign forms of edge fluctuations such as the quasi-coherent mode and edge harmonic oscillation.

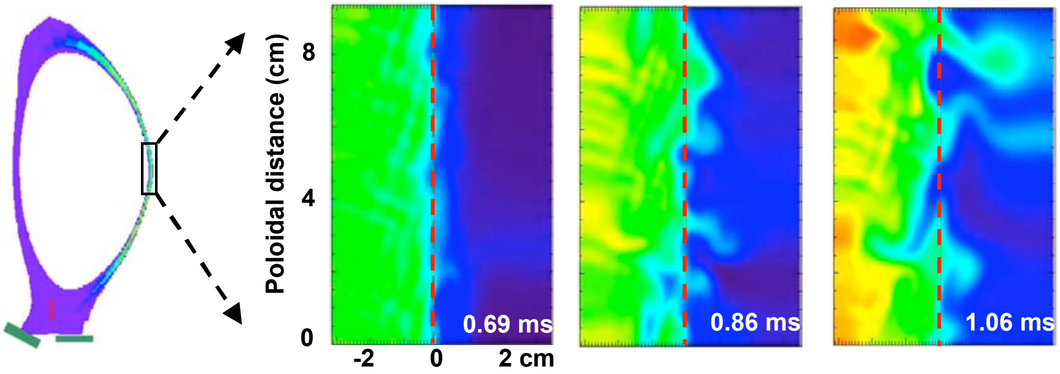

Figure 6.3. Simulation of boundary plasma turbulence showing the growth of small-scale density fluctuations at the plasma surface. The simulation covers the whole region shown in the cross section to the left, but only the region enclosed by the box in the snapshots on the left. (Courtesy of X. Xu)

Compare computer simulations and experimental data over a wide range of plasma parameters to confirm physics understanding. An expanded effort to compare improved simulations against experimental data will be needed to reduce the large uncertainty in extrapolation to a burning plasma experiment. Inter-machine dimensionless experiments have proven valuable in understanding core transport; they are starting to be extended into the pedestal region. Dedicated sets of experiments to test emerging models are key to code validation. The existing effort in support of the International Tokamak Physics Activity (ITPA) will continue to provide a structure for growing inter-machine and experiment-theory coordination and collaboration between researchers within the U.S. and abroad.

Investigate promising H-mode regimes and/or edge-localized mode control methodologies that feature reduced transients and improved confinement. A key question is whether edge-localize modes are basically enhanced transport on intact flux surfaces or involve tearing and reconnection. Improved edge-localized mode diagnostics, such as fast imaging of the edge-localized mode evolution in the pedestal and measurements of heat loading, are required. Understanding of the access conditions and confinement properties of the various “small” edge-localized mode (ELM) regimes is well behind that of the standard Type I ELMy H-mode. Given the desirability, and possible necessity, of such a regime to reduce pulsed heat loads in ITER, further experiments are required on these regimes. In the event that edge-localized modes cannot be naturally avoided, an active means to control their size, without decreasing confinement, may be required. Investigations into control coils, pellet injection, and other techniques are just beginning and need to be increased.

Understand the transport of plasma and impurities in the scrape-off layer.

Plasma heat and particle transport along and across open magnetic field lines will play a key role in the performance and operation of a burning plasma experiment: setting the width of the heat flux channel into the divertor, regulating the energetic particle fluxes onto first-wall components and associated impurity generation rates, and governing impurity migration around the plasma periphery and into the confined plasma. In addition, the balance between parallel and cross-field particle transport determines the effectiveness of the divertor in receiving particle exhaust and entraining impurities for helium-ash removal and enhanced divertor radiation. Heat transport along field lines is reasonably well described by fluid transport with kinetic corrections. In contrast, cross-field heat and particle transport in experiments often involve intermittent, bursty, plasma turbulence. Moreover, configuration-dependent near-sonic parallel plasma flows are found in the scrape-off layer affecting impurity migration and the toroidal rotation of the confined plasma, yet such flows are not presently calculable from codes. Transport phenomena in the scrape-off layer are intimately coupled to the confined plasma in other ways: neutral fueling locations can impact pedestal height and cross-field transport in the scrape-off layer increases with plasma density (collisionality) and may be connected to the discharge density limit. The attainment of a partially detached radiative divertor could lower surface heat loads significantly and improve overall component reliability, nevertheless, present 2D fluid models are unable to fully match current experiments, most notably the hydrogenic emissivity seen in the private flux region. The physics of the private flux region may be critical for helium-ash removal, affecting the rate of neutral leakage from the pumping ducts into the confined plasma. Progress in this area requires three essential activities, centered on a physics exploration mission for present plasma fusion experiments.

Ten-year Goal: Identify the underlying driving mechanisms for mass flow and cross-field transport in the scrape-off-layer plasma, in H-mode attached and detached plasmas.

Supporting activities include:

Measure the 3D spatial structure of scrape-off layer plasma parameters, ionization sources, and scrape-off layer plasma flows (for both hydrogen and impurity ions) using appropriate plasma diagnostic techniques applied to a range of plasma configurations. U.S. fusion experiments have proven to be excellent facilities for this mission because they span a wide range of dimensionless plasma physics parameters while operating at complementary ranges of densities, magnetic field strengths, and geometry. Stellarator experiments should additionally allow magnetic islands or stochastic layers to be explored, providing further insights into plasma transport dynamics in the edge region. A full array of measurements in these devices is required, covering from the divertor to the scrape-off layer to inside the pedestal: plasma profiles (density, electron temperature, ion temperature), flows, neutral densities, and hydrogen and impurity radiation distributions. Expanded plasma flow measurements (Mach probes, impurity dispersal experiments) will be needed. Temporal resolution must be sufficient to identify the effects of common transient phenomenon such as edge-localized modes.

Measure the characteristics of edge fluctuations at select regions of the scrape-off layer to identify the fundamental transport processes. Rapid progress has been made in recent years in understanding the general phenomenology of edge plasma turbulence and associated plasma flows. This is largely due to improvements in turbulence measurements (probes, beam-emission spectroscopy, gas-puff turbulence, 2D imaging) and plasma flow measurements (Mach probes, impurity dispersal experiments). More complete sets of data (greater spatial coverage and longer data records) will be needed to identify plasma modes in order to compare with stability calculations. Expanded measurements in the appropriate high-confinement operating regimes in several devices will also be needed.

Develop an integrated computational model that includes the pedestal and the scrape-off layer (e.g., kinetic pedestal model coupled to fluid scrape-off layer model). Ultimately, a first-principles numerical simulation of the edge plasma, from pedestal to divertor target, is desired. Progress towards this goal requires efforts in two key areas: (i) detailed comparisons between experiment and numerical simulations of turbulence (fluctuation spectra, statistics, coherent structures, transport levels, geometrical effects), allowing a critical assessment and refinement of turbulence models, and (ii) a coupling between first-principles turbulence simulations (e.g., BOUT) and the codes which relax plasma profiles and flows over transport time scales (e.g., UEDGE). This work is beginning now and will need further enhancement to reach its ten-year goal.

Use numerical simulation (interpretive and predictive) to relate measured profiles to the underlying physics of particle and energy transport. The goal of "interpretive modeling" (via 2D or 3D coupled plasma fluid and Monte-Carlo neutral modeling) is to attempt to match time-averaged plasma conditions from all plasma diagnostics using the best available models for classical processes and turbulent plasma transport phenomena. Discrepancies between such models and experiment are expected and important; they point toward areas requiring further understanding and model refinement, including the development of scalings for the underlying turbulence and transport. A key part of this process is the formulation of theoretical models that identify and highlight the truly essential components of the underlying physics. Over the next five years, continued iteration between interpretive models and detailed experimental measurements (with improved capability in both areas) should identify robust empirical prescriptions for the underlying turbulent transport processes as well as validate and extend the classical physics descriptions in the codes. At this level of understanding, reasonable projections to the operating point for burning plasma experiments can be explored by these models.

Plasma materials interactions (erosion, deposition, trapping, material modification, wall conditioning).

Plasma bombardment of plasma-facing surfaces causes erosion of the plasma-facing material. The eroded material acts as an impurity in the hydrogen plasma and may be transported to the core plasma where it adversely affects fusion performance; it can also be locally redeposited or recycled causing enhanced erosion. At locations where the impurities build up deposition layers, the radioactive tritium hydrogen fuel can be trapped effectively and accumulate at high rates; tritium inventory in deposit layers is a concern for burning plasmas. Effective methods for tritium inventory control and understanding impurity transport are essential for long-pulse burning plasma operation.

Carbon is one of the most valuable plasma-facing component materials, but one of its chief deficiencies is chemical sputtering. The role of chemical sputtering in carbon-based plasma chambers is not well understood at present. In all carbon plasma-facing component single-null divertor tokamaks, there is a broadly consistent deposition feature: carbon deposits almost entirely in the inner divertor. The location of the deposition is sometimes in regions where it could be easily removed and sometimes in areas that are very inaccessible to cleaning. Tritium trapping in redeposited carbon layers has been observed on the Joint European Torus (JET) and the Tokamak Fusion Test Reactor (TFTR) tokamaks. In JT60-U, however, the carbon co-deposits were found to contain very little deuterium, possibly because of high tile temperature. The precise amount of tritium retention is a key issue for ITER. Several methods have been investigated for removing tritium from carbon surface layers, but the efficiency of removal may not be adequate and removal of tritium from hidden surfaces is still a problem. The effect of mixed materials on surface erosion, and tritium retention and removal is just beginning to be studied. Tritium retention is expected to be less severe in metals, although they are less tolerant to transient loads. Therefore, a better understanding is required of what these transients will be, and how they might be controlled.

Ten-year Goal: Resolve the key boundary-physics processes governing selection of plasma-facing components for ITER. This is a time-sensitive issue relevant to the success of ITER.

Supporting activities include:

Characterize plasma-wall interactions (e.g., particle and energy fluxes, sputtering rates, and erosion/redeposition profiles) and material migration in H-mode plasmas by means of focused measurements in devices with carbon and metallic walls. A full range of measurements is required on both single and multiple-element plasma-facing component devices to improve the interpretive, extrapolative, and predictive capability for understanding erosion in carbon-only and in multi-element plasma-facing component systems. Diagnostic coverage will be expanded to measure erosion and deposition rates in existing devices. Measurements of electron temperature, heat and particle flux to the surface need to be performed on several tokamaks to interpret erosion and redeposition measurement; methods for measuring ion temperature near targets need to be developed. Tests need to be carried out in tokamaks using a range of temperatures of the inner divertor structure and employing various materials and inner divertor geometries to determine the retention of hydrogen isotopes on exposed and hidden surfaces.

More experimental work, particularly on devices that rely solely on radio-frequency heating schemes, is required to study enhanced erosion with radio-frequency heating. Data should be obtained from plasma-facing components at ITER-relevant surface temperatures to account for surface chemistry effects. This activity will benefit from many of the measurements required for Thrust 2.

Develop techniques for mitigating tritium retention in plasma-facing components using both laboratory simulators and fusion devices. It is important to establish what controls the location of carbon co-deposition and to learn how to manipulate the process. Additional recovery methods such as oxygen baking and mitigated disruption radiative heating release have been proposed and will need to be tested in both the laboratory and existing fusion experiments.

Develop and test a model for the scrape-off layer that self-consistently includes plasma-material interactions. This may represent an extension of the code development effort under Thrust 1. While new codes are under development, existing 2D fluid codes and “empirically reconstructed” plasma solutions for the detached plasma, as can be produced using the interpretive OEDGE code, together with Monte Carlo impurity codes should be used to study erosion under detached divertor conditions.

Develop the capability for high-temperature mixed-material plasmas-material interaction studies. The effects of mixed materials on erosion and redeposition are just beginning to be studied in the laboratory but are common in fusion devices. Studies at elevated temperatures (800–2000 °C) are essential to prepare for ITER operation.

Plasma facing materials and components research

Burning plasmas will have a stored energy two orders-of-magnitude greater than present devices. The off-normal heat loads (due to edge-localized modes and disruptions) will be proportionately greater. Typical operating heat loads are about ten times higher because radiating impurities are assumed to create a partially detached divertor condition. Long-pulse lengths in a burning plasma device imply significant neutron fluence to the plasma-facing materials and heat sinks. The best material for the first wall or divertor targets depends on the pulse length and objectives of the device and is still the subject of debate even for ITER. In a fusion reactor, the neutron fluence will damage carbon based materials and make them unsuitable for plasma-facing materials even if tritium retention is fully resolved. Other materials, such as molybdenum, tungsten, and beryllium are being used successfully as plasma-facing components. Eventually coolants other than water, such as helium gas, must be introduced to plasma-facing components. Erosion damage to solid plasma-facing components can be avoided with a flowing liquid plasma-facing component. Flowing liquid surfaces can handle high heat fluxes and provide particle control (possibly including helium). Liquid lithium strongly absorbs hydrogen and substantially alters plasma material interactions (possibly creating the first low-recycling device). Challenges for liquid plasma-facing components arise in dealing with the potentially large magnetohydrodynamic forces associated with a moving liquid metal in spatially and temporally varying magnetic fields and the limited useful temperature range of liquid surfaces due to high evaporation rates.

Ten-year Goal: Complete the evaluation of candidate plasma-facing materials and technologies for high-power, long-pulse fusion experiments. This is a time-sensitive issue relevant to the success of ITER.

Supporting activities include:

Qualify tungsten-rod plasma-facing component concepts for ITER applications using laboratory simulation experiments. Tungsten rods have been developed as an alternative to carbon-based plasma-facing components in the ITER project. The tungsten alternative needs to be more fully qualified for use in ITER by fabrication and testing of large-size mock-ups of ITER components. Building on the development of actively cooled tungsten rod plasma-facing components and the improvements in helium-gas-cooled heat sinks, the next logical step for plasma-facing component development is to combine refractory metals with helium-gas-cooled substrates. Advances in molybdenum and tungsten materials and novel fabrication techniques hold the possibility of reduced irradiation effects. Prototype helium-cooled plasma-facing components should be fabricated for high-heat-flux testing. The successful option(s) should be used to fabricate near full-size components for reliability testing. Deployment on a long-pulse fusion device is the final proof of usefulness.

Molybdenum is being used successfully for plasma-facing components and there are plans to test tungsten brush tiles (inertially cooled). This would be the first real test of tungsten brush plasma-facing components in a fusion device. Testing of new concepts is carried out at dedicated materials research facilities in national laboratories and universities.

Test the reliability of actively cooled plasma-facing component designs under transient loads using laboratory simulators and high-power plasma confinement experiments. The development of actively-cooled carbon plasma-facing components has been completed during the ITER research and development phase, and prototype components have been extensively tested under normal ITER heat load conditions. Measurements of the damage expected from disruptions has been studied in the U.S., Europe, and Russia and compared to models. Studies of edge-localized-mode effects are just beginning in the U.S. and Russia. Since edge-localized modes are repetitive events (a few Hertz), the effect of edge-localized modes on the reliability and lifetime of actively-cooled components must be studied to predict the maintenance needs on ITER. Tens of thousands of edge-localized modes must be simulated to determine damage thresholds, erosion rates, and fatigue effects on the plasma-facing component.

Figure 6.4. Mock-up of an ITER first-wall component fabricated by plasma spray of beryllium onto a copper alloy heat sink ready for high-heat-flux testing. (Courtesy of D.Youchison, SNL, and K.Hollis, LANL)

Pursue development of suitable new technologies for long-pulse, high-power fusion experiments through research at dedicated plasma-facing component test facilities. Experiments with evaporated lithium coatings are planned on existing fusion experiments and dedicated materials research facilities. Initial experiments with liquid lithium are underway now and more are planned. The DiMES probe will continue to be used to study liquid lithium exposed to fusion plasmas. Experiments on flowing liquid surfaces are needed to measure heat removal capability versus flow velocity, hydrogen and helium pumping capability, etc. Magnetohdyrodynamic and external current effects are being studied in the U.S. These experiments provide a combination of field gradients, temporal variation, or simulated plasma heat loads, and investigation of helium pumping. The use of flowing liquid surface plasma-facing components in the divertor on existing experiments is also being considered. Methods for driving liquid metal flows with geometries and magnetic fields suitable for use in fusion devices need to be developed and tested. Various means for controlling forces on flowing liquids must be studied to find suitable combinations. Computational models for flowing liquid metals in magnetic fields are being developed, as are models for disruption and edge-localized mode damage.

RELEVANCE TO ITER AND OTHER CAMPAIGNS

Enhanced core confinement is required to achieve burning plasmas in ITER. As mentioned above, calculating the plasma temperature at the top of the pedestal edge is arguably the biggest uncertainty in predicting the fusion performance of ITER. The activities in this campaign are immediately and directly relevant to the success of the ITER experiment. The development of a predictive integrated model of the edge pedestal will increase confidence in the performance of ITER and will provide an invaluable tool for exploring other, advanced operating modes for

ITER and other future burning plasma devices. The experimental activities required to validate the model will confirm the physics basis for the model and for the planned operation of ITER.

The success of ITER depends not only on good physics, but reliable operation of the plasma-facing components, which will see both high steady-state and transient heat and particle flux. Understanding the physics of the pedestal may well lead to finding ways to have high confinement while mitigating edge-localized mode severity. Control of plasma impurities and tritium retention are key issues for achieving high performance and the neutron fluence goals for ITER. Understanding plasma-material interaction and scrape-off layer transport are crucial to controlling impurity influx and tritium trapping. Adequate lifetime of the ITER plasma-facing components depends on controlling edge-localized mode energy content, having adequate impurities to radiate some scrape-off layer power, and a reliable, actively cooled plasma-facing component. Successful completion of the goals of this campaign is required to impact the choice of plasma-facing component materials and achieve the scientific goals of the ITER device.

Because of the strong effect of pedestal parameters on global confinement, there is a strong connection with macroscopic plasma physics and multi-scale plasma physics. Because of the need for materials and technology for active cooling, there is a strong tie to fusion engineering science.

EXPECTED ACCOMPLISHMENTS WITHIN TEN YEARS

Over the next decade, significant progress is expected in boundary plasma science. At existing effort levels, the availability of simplified first-principles models of the edge pedestal is anticipated that incorporates several simulation codes to reproduce many of the measured characteristics of the boundary plasma in one or more fusion experiments. These improved models will be used to explore the edge pedestal parameters for ITER. The physics governing the size and frequency of edge-localized modes and their impact on the scrape-off layer will be largely understood, enabling development of new mitigation techniques and operating regimes to minimize their impact. The fundamental characteristics of scrape-off-layer turbulence in high-confinement plasmas will be determined. There should be sufficient data from fusion experiments and laboratory divertor-plasma simulators to quantify the major impurity sources, including divertor and first-wall mixed-material erosion and redeposition rates. Simplified theoretical models with coupling between kinetic or fluid scrape-off layer codes and plasma-surface-interaction codes will be developed. The distribution of expected tritium trapped in carbon-based plasma-facing components will be largely understood in terms of plasma conditions observed in present-day experiments. Candidate techniques for removing tritium will be developed and tested. Qualification of alternative high-heat flux components such as liquid lithium divertors and tungsten brush divertor plates will bring readiness for testing in longer-pulse high-power confinement experiments.

OPPORTUNITIES FOR ENHANCED PROGRESS

Progress within each thrust area could be accelerated with increased support applied to key research problems:

Predict the formation, structure, and transient evolution of edge transport barriers

- An expanded effort to develop a fully integrated edge simulation code would allow calculation of the self-consistent dynamic evolution of the edge pedestal from first principles using state-of-the-art large-scale computing facilities.
- Enhanced turbulence imaging (longer times and measurements at several locations), coupled with higher spatial resolution 3D measurements of pedestal profiles and particle sources, in a wide range of devices, would provide the data necessary to benchmark fully integrated simulation codes to predict the edge-pedestal conditions in ITER.

Resolve the key plasma material interactions, which govern material selection and tritium retention for high-power fusion experiments

- New diagnostics with expanded coverage to measure particle erosion and deposition rates over large areas of the first wall in a number of machines will provide the data necessary to understand impurity generation and transport in the scrape-off-layer plasma. Such understanding would allow the prediction of tritium retention in ITER with high confidence.
- Increased support for laboratory facilities to evaluate new materials and mixed-material components will provide understanding of plasma material interactions in realistic systems. Support of large-scale testing of new components in high-temperature confinement experiments would provide timely information for qualifying first-wall component designs for ITER.

7

WAVES AND ENERGETIC PARTICLES

Learning to use energetic particles and electromagnetic waves
to sustain and control high-temperature plasma

OVERALL SCOPE OF THE CAMPAIGN

The plasma medium can support an impressive array of electromagnetic waves not possible in other states of matter (overarching theme O1). These waves may arise spontaneously or be excited by external sources. Waves and particles can be strongly coupled through resonant interactions, which can accelerate the particles, thereby increasing the plasma temperature and electric current, or drive mass flows with application to steady-state high-performance operation (overarching theme O3). Plasmas in the laboratory (and in space) often contain a special population of highly energetic particles, which can significantly affect the plasma behavior. In particular, high-energy alpha particles created in a burning plasma can establish favorable conditions for self-sustained fusion burn (overarching theme O2) and possibly control certain bulk plasma instabilities. The alpha particles can also excite unstable waves and turbulence in the plasma, causing particle and energy loss. Thus, the Waves and Energetic Particles campaign is relevant to all three overarching goals and critically linked to the needs and objectives of a burning plasma experiment. This campaign is based on the following two topical scientific questions:

T11: How do electromagnetic waves interact with plasmas?

T12: How do high-energy particles interact with plasma?

RESEARCH THRUSTS

Topical questions T11 and T12 for this campaign can be addressed by the several research thrusts described in this section. For each of the thrusts, a ten-year goal is provided, along with specific research activities for attaining this goal and a description of past achievements and present readiness.

Understand the most important processes that determine the electromagnetic spectra of launched waves and constrain the power that can be coupled into magnetically confined plasmas

Electromagnetic waves interact with plasmas in many important ways. For example, waves created by radio-frequency, microwave, and laser sources and applied in various frequency ranges are capable of heating plasmas, driving localized currents and plasma flows, and modifying the distribution of plasma particles. To be effective, the waves launched from sources must be able to couple into the core plasma through a nonstationary plasma boundary. Understanding this interactive wave coupling at the plasma edge is both a fundamental science question and also of significance for manipulating plasma behavior.

The ten-year goal for this thrust area is to develop the capability to design high-power electromagnetic wave launching systems that couple efficiently and according to predictions for a wide range of edge plasma conditions.

For coupling of ion cyclotron and lower hybrid waves, the expeditious design of couplers which efficiently launch only the desired wave spectrum and occupy minimal vessel area requires a better understanding of the effects of strong fields in plasmas with sharp gradients adjacent to material surfaces with complex geometry. Progress in this area requires implementation of extensive in-situ diagnostics in high-power heating experiments and the development of reliable 3-D modeling of the plasma-coupler region.

This thrust calls for the following two research activities. The first would be the development of in-situ antenna wave field and particle diagnostics that can provide information for quantitative comparison with numerical models. The second activity, for wave applications to non-axisymmetric magnetic confinement devices, would be extending antenna-coupling codes to be three-dimensional to take into account both complicated magnetic geometries and realistic boundary conditions, with the incorporation of wave-particle interactions, nonlinear wave interactions, and plasma sheath formation.

The external application of waves in the ion cyclotron, lower hybrid, and electron cyclotron frequency ranges has been well investigated. In many cases of experimental interest, only a fraction of the launched wave energy reaches the core plasma. This physics is at best qualitatively understood, and a range of wave-particle and nonlinear wave-plasma interactions are thought to be responsible. Improved radio-frequency launcher designs could significantly benefit present experiments and ITER operation. The needed modeling activities have been identified and are within present computing capabilities. Existing diagnostics can be adapted or improved to make the required measurements.

Understand the physics of wave propagation and absorption in magnetized plasmas and understand the plasma response to high-power injected waves

Once launched, the fate of the wave energy depends on its propagation characteristics in hot, inhomogeneous, anisotropic plasmas with two- or three-dimensional spatial variations. In all three of the frequency ranges, important roles are played by mode conversion of an incident wave into two or more outgoing waves at plasma resonances or cut-offs (see Figure 7.1) and by wave-particle interactions with thermal and nonthermal particle distributions. Diagnosis of the wave structure and comparison with numerical simulations of wave propagation and absorption are required to better understand and ultimately to optimize heating and control.

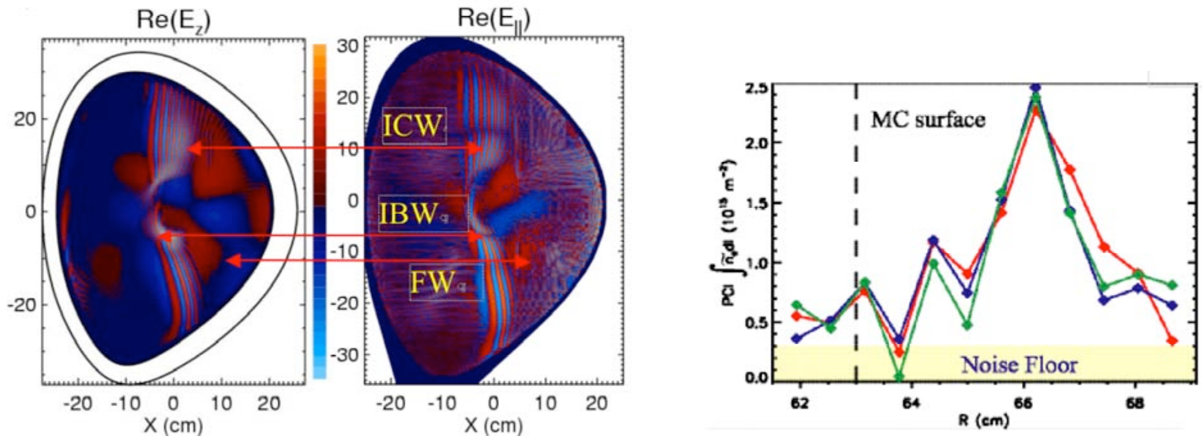

Figure 7.1. Massively parallel computer calculations (left) show that fast waves (FW) launched into a plasma from a radio-frequency source are changed into ion Bernstein waves (IBW) and ion cyclotron waves (ICW) at the mode-conversion surface. These results explain the recent experimental discovery (right) of the ion cyclotron wave. (Courtesy of J. Wright, E.F. Jaeger and E. Nelson-Melby and M. Porkolab)

The ten-year goal for this thrust is to produce, diagnose in detail, and model with nonlinear, closed-loop simulations the macroscopic plasma responses produced by wave-particle interactions, including localized current generation, plasma flows, and heating, in both axisymmetric and non-axisymmetric configurations.

This thrust involves the following four research activities. The formulation of the resonant plasma response in the presence of multi-dimensional plasma gradients and energetic particle distributions should be improved. Full-wave and Fokker-Planck solvers could be upgraded to implement improved theoretical models for the plasma response. Advanced diagnostics need to be deployed for wave detection in axisymmetric and non-axisymmetric toroidally confined plasmas, and for measurement of the configuration and velocity-space distribution of nonthermal ion and electron distributions and ion

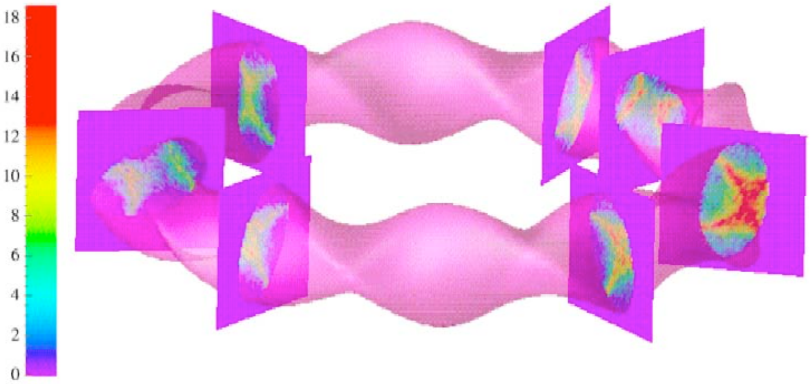

Figure 7.2. Calculation of fast-wave heating of minority ions in a three-dimensional helical plasma confinement experiment. This gigantic calculation, carried out on a supercomputer, provides insights on where wave power is absorbed in this complex geometry. (Courtesy of E.F. Jaeger)

minority species concentrations. Electron Bernstein waves can be used as an electron temperature diagnostic in high-beta plasmas, and Alfvén wave spectroscopy can be used to measure low-level magnetic fluctuations.

For many conditions, a quantitative understanding of wave propagation and absorption for one- and two-dimensional thermalized plasmas is emerging. However, self-consistency for nonthermal particle distributions and plasmas with strong gradients, such as those encountered in certain advanced confinement regimes and in a burning plasma, has not been achieved, and modeling of three-dimensional magnetic configurations with needed resolution is just now beginning (see Figure 7.2). The understanding of nonlinear responses to high-power waves also requires improvements. The self-consistent coupling of wave solvers and Fokker-Planck codes is presently close to demonstration and should be available to model the core plasma. Advances in developing the fundamental physics models for complex plasma systems and for some plasma responses will be needed before these phenomena can be integrated into the computational models for validation against experiments. Upgrades and new power system capability will be required in some cases.

Understand how waves affect magnetohydrodynamic stability and transport in fusion plasmas and use these effects to control profiles and develop attractive integrated burning plasma scenarios

Recent high-power ion cyclotron resonance, lower hybrid, and electron cyclotron resonance experiments show that waves can have strong influences on plasma equilibrium, stability, and transport properties. This provides a challenging opportunity to better understand–and through that understanding, to better control–the plasma pressure and confinement limits in future experiments, including burning plasmas such as ITER. For example, understanding the basic interaction and coupling of a specified wave spectrum to a local region of the plasma could provide a basis to control fusion plasmas for optimum performance, to extend plasma duration towards steady-state, and also to probe the plasma state, yielding an understanding of other fundamental processes. An improved understanding of these processes will also benefit other plasma research including plasma processing and space physics applications. Thus, integration of the experimentally validated models into full plasma simulations will enable the discovery of extended operating space for burning plasma experiments and the eventual optimization of a fusion reactor.

The ten-year goal for this thrust is to develop long-pulse radio-frequency wave scenarios for optimizing plasma confinement and stability and to benchmark against models that integrate wave coupling, propagation, and absorption physics with transport codes (including microturbulence and barrier dynamics) and with magnetohydrodynamic stability models.

Several research activities would be associated with this thrust. One activity is to develop a coupled package of simulation codes that self-consistently integrate the time evolution of the magnetic equilibrium with the wave-driven modifications of current, heating, and flow profiles and include transport modification and macrostability limits. Also, on multiple existing facilities, magnetic confinement experiments should be performed with a pulse length that is long compared to magnetic field diffusion times, which can simulate important aspects of the scenarios for a burning plasma. A third activity is to demonstrate the capability for locally adjustable, well-off-axis current drive for control of current profile evolution with the use of lower hybrid waves, fast waves, electron cyclotron waves, and electron Bernstein waves, and detailed diagnostics of current, pressure, fluctuations, and flows, ideally in real time for control. Finally, appropriate radio-frequency actuators should be identified and developed for feedback control.

Localized radio-frequency wave-driven currents, both on-axis and off-axis, have been demonstrated in the electron cyclotron, lower hybrid, and ion cyclotron frequency regimes, and quantitative current drive models exist which have been validated against experiments. Stabilization of magnetohydrodynamic modes, establishment of transport barriers, and modification of plasma flow have been observed with the application of radio-frequency waves. However, understanding is at best qualitative and in some cases nonexistent, especially concerning the nonlinear linkages among different phenomena. Integrated computer models and efforts to develop the required algorithms and physics are at the conceptual stage. With adequate resources, these efforts could provide validation, development, and testing of advanced plasma scenarios in about three years.

An example of the beneficial effect of radio-frequency waves on plasma stability is illustrated in Figure 7.3. In the two discharges that are shown, an unstable neoclassical tearing mode of low order (toroidal mode number n=1 and poloidal mode number m=2) is generated when the plasma pressure exceeds a certain threshold. In the absence of electron cyclotron current drive, the amplitude of the mode grows larger, while its frequency slows down until it becomes zero. At this point the mode locks onto the wall of vacuum vessel, and this leads to a strong loss of confinement (or possibly to a disruption), as shown in the blue curves of Figure 7.3. However, when electron cyclotron current drive is applied precisely at the radial location where the neoclassical tearing mode develops, the amplitude of the mode (in red) is reduced to almost nothing while the frequency stays high, and thus the confinement is not impacted. In this way, a modest amount of wave current drive can enormously improve the performance of the plasma discharge. This stabilization process was actually predicted by theory prior to the experiments, and the successful stabilization provides indirect experimental support for the theory of wave

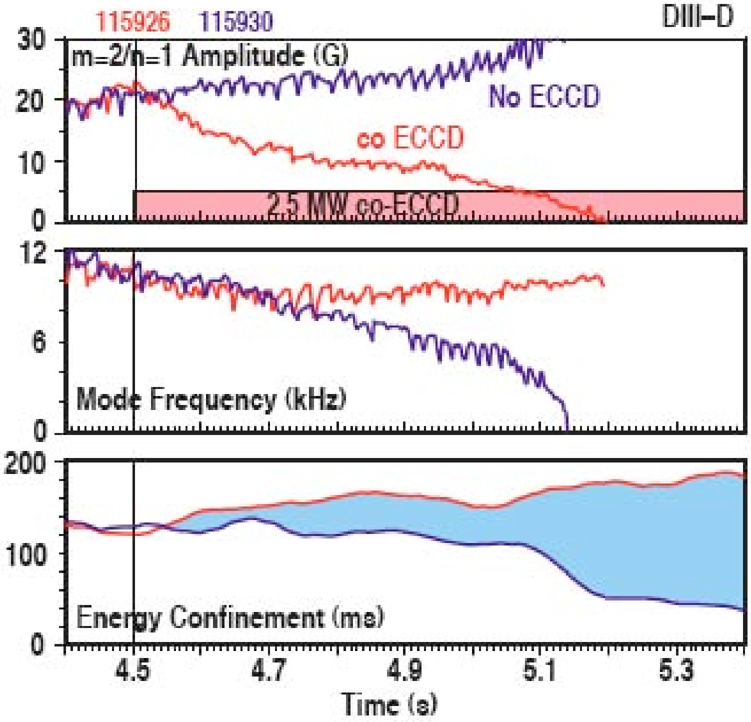

Figure 7.3. Spatially localized application of electron cyclotron frequency waves can almost completely suppress neoclassical tearing mode instability (red), compared to the case without electron cyclotron current drive (blue). The top, middle, and bottom panels show the amplitude of the m=2/n=1 neoclassical tearing mode, its frequency, and the energy confinement time, as functions of time. (Courtesy of R. Prater)

propagation, absorption, and current drive. Recently, feedback control to stabilize neoclassical tearing modes in real time has also been demonstrated.

Explore the internal features of energetic particle-excited instabilities in new plasma regimes

Recent advances in experimental studies and theoretical modeling of fast ions in magnetized plasmas indicate the need and opportunity to assess the potential effect of energetic particles on plasma confinement. An important concern is that fast ions provide free energy to drive plasma waves, which may degrade energetic particle confinement. The energetic particles can also affect the magnetohydrodynamic stability of the bulk plasma. A related issue is that high-energy runaway electrons, produced occasionally, may damage the plasma containment vessel. Understanding the interaction of the energetic particle population with unstable waves becomes critical as studies of plasma confinement push into new regimes in which the plasma pressure is high, the magnetic field shear is reversed, and rotation is strong.

The ten-year goal for this thrust is to improve analysis and models to match the experimental measurements and scale the understanding to predict the dynamics of energetic particle-excited modes in advanced regimes of operation with high pressure, inverted magnetic shear, and strong flow.

Research activities associated with this thrust would be as follows. Existing codes will be improved to model the main excitation and damping mechanisms predicted by theory for energetic particle-driven modes, and then compared with experimental results, including regimes for which the energetic particle velocity exceeds the Alfvén velocity. Also, experiments will be carried out with external antennas to excite stable modes in the frequency range for energetic particle-induced waves and directly measure wave damping. The excited mode properties should be compared in different magnetic confinement configurations, with emphasis on fusion-relevant conditions. Improved understanding will be exploited in order to use energetic particle modes to diagnose plasma conditions, such as the safety factor profile of the magnetic field (see Figure 7.4). Finally, detailed diagnostics should be developed to measure the wave-field structure in the plasma and the energetic particle phase-space profiles. In particular, experiments will be

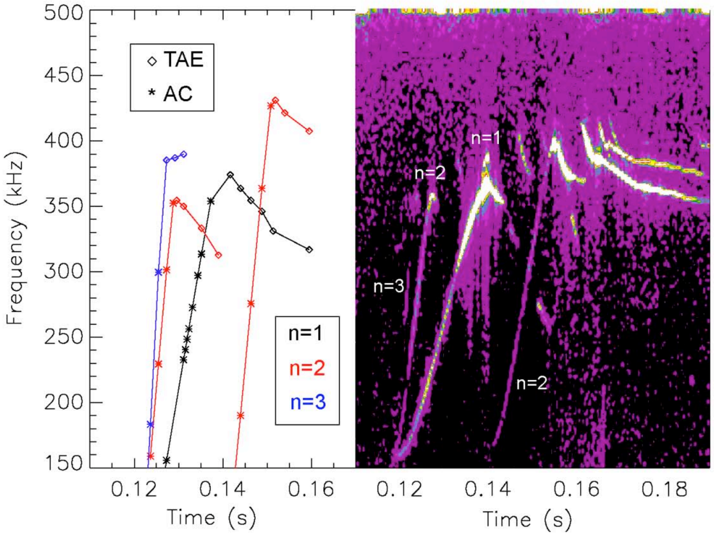

Figure 7.4. Two waves excited by ultra-fast ions, the Toroidal Alfvén Eigenmode (TAE) and the Alfvén Cascade (AC), are observed experimentally (right) for several values of the toroidal mode number n. Theory (left) confirms that the latter wave makes a transition into the former as its frequency increases in time. The existence of the Cascade mode allows an indirect measurement of the pitch of the magnetic field inside the plasma. (Courtesy of J. Snipes)

performed to measure loss and spatial redistribution of energetic particles caused by instabilities, and this will be compared with simulations (see Figure 7.5).

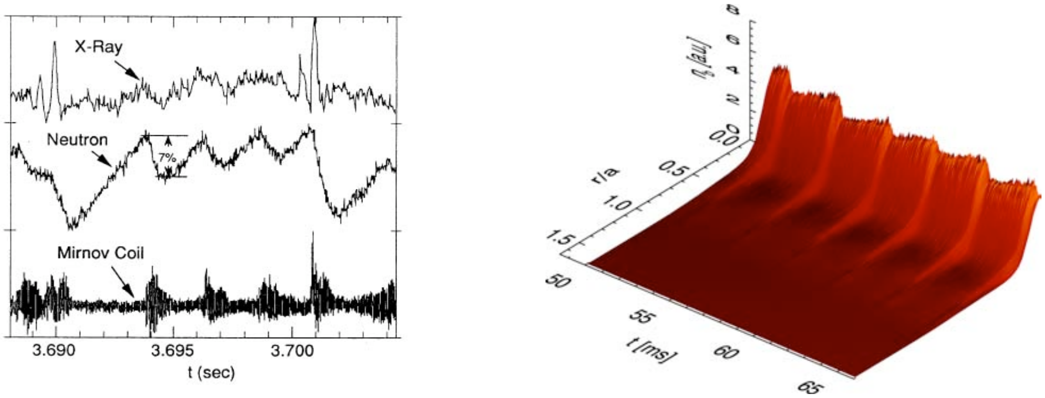

Figure 7.5. Energetic beam ions can be kicked out of a plasma by the waves that they excite, as shown in the experimental observations (left) of drops in the neutron yield correlated with wave fluctuation signals on the Mirnov diagnostic and as pictured in numerical simulations (right) of the radial beam ion profile periodically collapsing and building up in time. (Courtesy of K.-L. Wong and Y. Todo)

The understanding of the behavior of energetic particles has advanced significantly, due to new theoretical methods, powerful simulation codes, and numerous fast particle experiments. The types of unstable waves that can be excited by energetic particles (including alpha particles) have been fairly well scoped out—although not yet for the regimes of operation with high pressure, inverted magnetic shear, and strong flow, which have potential for improved plasma performance. In addition, work is needed to quantify the effects of instabilities on fast ions and to learn to control stochastic diffusion of the energetic particles. Such studies would be the focus of this thrust.

Simulate the synergistic behavior of alpha-particle-dominated burning plasmas

The fusion of deuterium and tritium nuclei produces 3.5 MeV alpha particles, whose energy deposition into the confined plasma is required for sustained burn. Since the behavior of burning plasmas will be dominated by this large population of energetic alpha particles, it is important to investigate whether there is a sufficiently broad operating space for stable confinement of alpha particles in a burning plasma, what new methods can be developed to measure critical energetic particle properties in a burning plasma, what are the consequences of fast ion transport resulting from instabilities and how such transport can be controlled, and how energetic particle behavior in present-day experiments can be extrapolated to alpha-particle behavior in burning plasma regimes. Significantly, these issues must be addressed in an integrated manner, since all aspects of burning plasma behavior–stability, transport, burn control, etc.,–are nonlinearly coupled.

The ten-year goal for this thrust is to identify the character of Alfvén turbulence and the evolution of the energetic particle distribution in a nonlinear system, which can be used to predict alpha-particle transport in a burning tokamak experiment; and to evaluate and *extrapolate energetic particle behavior in present-day confinement systems to reactor parameters.*

Research activities associated with this thrust would be as follows. Theory and numerical simulations will work to develop predictive capability that self-consistently integrates the nonlinear effects of energetic particles on equilibrium, stability, transport, and fueling. Reduced models, extensively benchmarked by experiments, will be used to guide nonlinear code development for treating both fluid and wave-particle nonlinearities. The orbit loss of alpha particles and the risks of high-energy runaway electrons will be evaluated. New energetic particle diagnostics that can withstand the high-neutron-fluence environment of a burning plasma will be developed. Operational regimes will be sought that ameliorate fast particle-driven instabilities, and the performance expectations for such regimes will be calculated. In addition, ideas for performance improvement will be investigated, such as the self-organization of the energetic particle profile due to instabilities and the use of energetic particles for enhancing plasma rotation, creating transport barriers, and directly heating ions. Analytical studies will be carried out to characterize physics distinctions of high-pressure plasmas, such as strong ion-Landau damping and the mixing of acoustic and Alfvén modes. Finally, experimental data from high-pressure, super-Alfvénic experiments (including low-aspect-ratio tokamaks) will be extrapolated to fusion plasma conditions.

The alpha-particle physics of a burning plasma such as ITER has been tested to some extent in existing facilities, either with fast ions (created by neutral beams and radio-frequency wave heating) or with small alpha-particle populations. However, direct extrapolations from the behavior in present-day fast ion experiments to ITER-like burning plasmas are limited because the experimental conditions are rather different. Also, theoretical predictions of stability and confinement in an alpha-particle-dominated burning plasma are not yet complete.

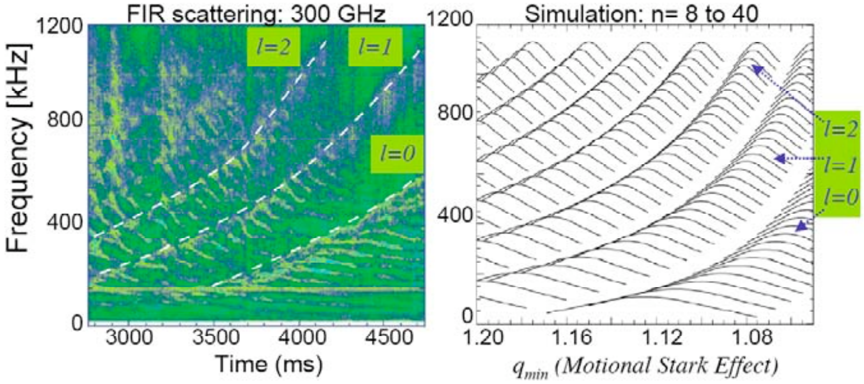

Figure 7.6. A “sea” of multiple Alfvén eigenmodes in several bands, simultaneously excited in the plasma core region by fast ions from neutral beam injection, are observed experimentally with far infrared laser scattering (left) and simulated numerically (right). (Courtesy of R. Nazikian)

Moreover, energetic particle diagnostics are not comprehensive even in present experiments, and the fusion environment poses even greater challenges. Thus, a major objective of energetic particle research is to prepare for burning plasma experiments, which would be the focus of this thrust. Many important science questions can be properly explored in an ITER-like burning plasma experiment because it would fully enter the new regime in which the plasma heats itself. Meanwhile, prior to ITER operation, U.S. and international facilities will provide a wide range of configurations and plasma conditions for studying energetic particle interactions with plasmas (see Figure 7.6) and testing innovative diagnostics (see Figure 7.7).

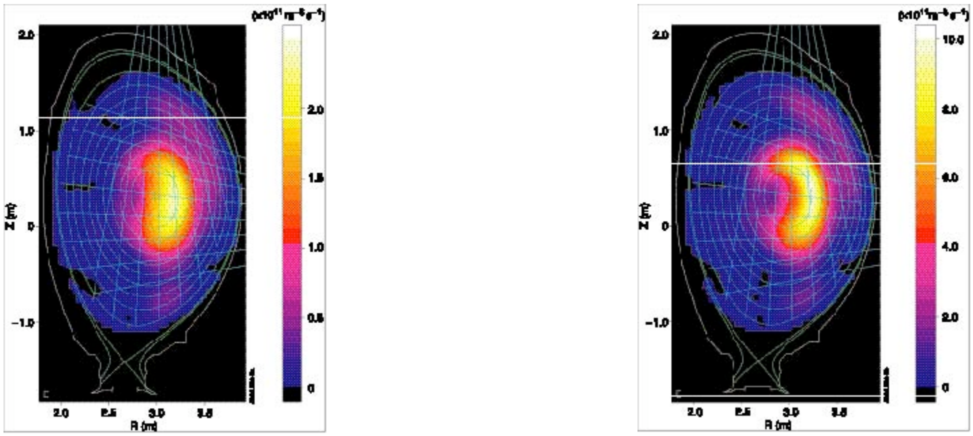

Figure 7.7. Gamma ray tomography, one of the modern diagnostics for energetic particles, can visualize the time evolution of the two-dimensional spatial profile of fast ions (deuterium on left and helium-4 on right) and how they behave in the presence of unstable waves inside a plasma (blue flux surfaces). (Courtesy of V. Kiptily)

RELEVANCE TO ITER AND OTHER CAMPAIGNS

Effective plasma heating and control techniques using radio-frequency power are essential to the success of ITER. The attainment of fusion temperatures and the control of plasma stability using radio-frequency waves is part of the planned baseline operation, while advanced operating modes use radio-frequency waves for maintaining and controlling plasma current profiles and for optimizing plasma confinement and stability. The physics of waves is closely related to virtually all of the other campaigns since radio-frequency power is required either to produce specific plasma conditions or to modify and control stability, transport, steady-state operation, etc.

Because the behavior of burning plasmas will be dominated by fusion-product alpha particles, understanding their effects is vitally relevant to the successful operation of ITER. In particular, both the report of the 2002 Snowmass Fusion Workshop[1] and also the recent report "Burning Plasma: Bringing A Star To Earth"[2] from the National Research Council noted that the exploration of alpha-particle-driven instabilities in reactor-relevant temperatures is a primary motivation for and expected benefit from a burning plasma experiment. Also, since the presence of suprathermal particles is known to affect plasma stability and to heat, drive currents, and apply torque in plasmas, the Waves and Energetic Particles campaign is relevant to the Macroscopic Plasma Physics campaign and to the Multi-scale Transport Physics campaign.

The Waves and Energetic Particles campaign will be set in an international context. Major elements of the U.S. program are dedicated to the exploration of radio-frequency tools for such advanced operations, complemented by radio-frequency heating experiments worldwide that contribute to the knowledge base of wave-plasma interactions. In energetic particle theory and experiments, U.S. scientists maintained a leadership role during much of the past decade. Strong collaborative links have been established with the European and Japanese energetic particle research programs by providing theoretical insight and actively participating in experiments on major overseas facilities. Also, international scientists have been collaborating in this problem area on U.S. experiments. In anticipation of the next-generation fusion facilities, our international colleagues have put an increasing emphasis on wave and energetic particle studies, which makes it important to invigorate the U.S. research in this critical area in order to continue strong U.S. contributions to the field.

EXPECTED ACCOMPLISHMENTS WITHIN TEN YEARS

The existing program in wave and energetic particle studies is expected to make considerable advances in developing the fundamental physics models for wave coupling, propagation, absorption, and plasma responses that will enable coupling on critical time scales with plasma stability and transport models for validation against experiments. This progress will provide timely information for planning of ITER operation.

Numerical modeling of antenna plasma coupling in tokamaks has advanced considerably in recent years and is now ready for detailed comparison with experimental data using in-situ diagnostics. The understanding of radio-frequency sheath effects and edge parameters on antenna loading will be improved. In validation of wave propagation, absorption, and current drive physics, more widespread deployment of advanced diagnostics for wave detection will quantify the theoretical models. Microscopic plasma responses associated with wave–particle interactions will include measurements of configuration and velocity space distribution of nonthermal ion and electron distributions. Wave heating and current drive models coupled to transport and magnetohydrodynamic stability codes and extensively benchmarked with experiments will provide a working tool for modeling ITER experiments. All three major U.S. facilities have radio-frequency heating systems that, together, span the frequency spectrum, affording an opportunity for significant progress with a comparatively modest investment in diagnostics.

In the absence of a burning plasma experiment in the next decade, progress in understanding the behavior of energetic particles and unstable waves that can be excited by energetic particles for regimes of high pressure, inverted magnetic shear, and strong flow, is expected to enable exploration of improved plasma performance in burning plasma devices.

Analytical theory and advanced numerical tools will be developed to evaluate energetic particle transport in magnetically confined plasmas. Linear stability codes will be enhanced to treat kinetic effects of thermal particles adequately and to allow relevant description of collective modes in high-pressure and low-aspect-ratio configurations. Nonlinear evolution of fast-particle-driven instabilities will be characterized quantitatively to delineate conditions for global transport of energetic particles and to properly model interplay between kinetic and magnetohydrodynamic resonant phenomena. Experimental simulations of alpha particle confinement with the use of fast helium ions from auxiliary heating will be performed on several facilities. Possibilities to manipulate energetic ion distribution to improve plasma performance will be tested. The viability of direct energy transfer from alpha particles to bulk ions via high-frequency waves will be examined further. Additional means to control runaway electrons will be developed.

OPPORTUNITIES FOR ENHANCED PROGRESS

Opportunities exist in planning for advanced operating regimes in ITER and fully exploring the capabilities of other confinement concepts, which are limited by current research funding. The U.S. program of research on waves and energetic particles could make more timely progress toward the goals described in this chapter by the targeting of additional resources in the following areas of opportunity.

Extend understanding and capability to control and manipulate plasmas with external waves

Radio-frequency can be used to generate transport barriers or stabilize magneto–hydrodynamic modes. In turn, these processes modify the plasma and influence the coupling, propagation and absorption of the waves. These complex nonlinear interactions lead to multiple feedback loops. Fusion products will further complicate wave-particle interactions in a burning plasma. Steady-state operation of a tokamak or other current-carrying device will require a combination of external current drive including radio-frequency and self-generated "bootstrap" current generated by controlled pressure profiles. It is a challenge to simultaneously control and optimize the pressure and current profiles for long time scales, under fusion-relevant conditions, so as to demonstrate the most attractive fusion performance of a given magnetic configuration.

Additional resources are needed to develop a coupled package of simulation codes that self-consistently integrate magnetic equilibrium evolution with the wave-driven modifications of current, heating and flow profiles and include transport modification and macrostability limits. While several components exist or are under development, this will require progressive extension of the present capability to include wave-induced transport of particles, energy and momentum, and wave-generated energetic particles and their impact on magnetohydrodynamic stability as well as better transport predictions including barrier. Multiple magnetic confinement experiments with pulse length long compared to current diffusion times and radio-frequency wave sources with real-time feedback capabilities will be required.

Simulate the synergistic behavior of alpha-particle-dominated burning plasmas

The problems that need to be addressed with regards to energetic particles in burning plasmas include the following key questions.

- Is there a sufficiently broad operating space for stable confinement of alpha particles in a burning plasma?
- Is it feasible to use waves to enhance alpha particle energy transfer to plasma ions and/or to remove helium ash?
- How much fast-ion transport can result from instabilities once they occur and to what extent can the instabilities be controlled?

No validated answers to these questions currently exist. Large fast-ion losses caused by Alfvén instabilities are measured under some conditions but quantitative understanding of the observed losses is still a challenge to both experiment and theory.

Another important topic is the use of energetic particles to establish favorable conditions for self-sustained fusion burn, including open questions of energetic particle effects on plasma rotation and plasma current. It is also conceivable that the energetic particles can help to control some of the bulk plasma instabilities.

Additional resources are required for theory and code development, new diagnostics, and experiments on multiple facilities. Self-consistent nonlinear predictions for the wave fields and the fast-ion transport are needed. Significant modification of existing codes is required to model energetic particle phenomena in high-pressure plasmas with strongly nonuniform magnetic fields. Ion cyclotron resonance heating and neutral beam injection provide two complementary ways for creating fast-ion population to model alpha-particle confinement that can mark out favorable regimes for stable alpha-particle confinement. Trace tritium experiments are also highly desirable. National and international facilities are important in an effort to study and control fast-ion-driven instabilities. Detailed measurements of the fast-ion distribution function and the wave structure are needed, as are techniques to manipulate the distribution function.

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8

FUSION ENGINEERING SCIENCE

Understand the fundamental properties of materials, and the engineering science of the harsh fusion environment

OVERALL SCOPE OF THE CAMPAIGN

As the U.S. actively seeks opportunities to explore the physics of deuterium-tritium (D-T) burning plasma, the importance of establishing the material and plasma chamber engineering science knowledge base moves to the forefront of issues. The fusion program also requires advances in plasma technology for heating and current drive, stabilization, fueling, and magnet technologies. Advancing the knowledge base for materials, plasma chamber, and plasma technology is required to: support the construction and safe operation of ITER (O2); provide the capabilities for testing blankets in ITER (O2); demonstrate the feasibility of the D-T fusion fuel cycle in a practical, safe system compatible with plasma operation (O3); and develop the enabling technologies required to create, confine, and maintain the plasma (O1, O2, and O3).

The plasma chamber and its materials must provide simultaneously for power extraction: tritium breeding, extraction, and control; structural integrity; high performance; high temperature; reliability; and maintainability under extreme conditions of high heat and particle fluxes, energetic neutrons, intense magnetic field, large mechanical and electromagnetic forces, and complex geometry. The components and materials surrounding the plasma must be compatible with plasma stability and operation and exhibit favorable safety and environmental features, while withstanding a fusion environment significantly harsher than any existing nuclear system. Many complex scientific phenomena occur within and at the interfaces among coolants, tritium breeders, neutron multipliers, structural materials, conducting shells, insulators, and tritium permeation barriers. Examples of such scientific phenomena are magnetohydrodynamic reorganization and damping of turbulent flow structures and transport phenomena in electrically conducting coolants, neutron-induced ballistic mixing of nano-scale strengthening features in structural materials, fundamental deformation and fracture mechanisms in materials, and surface chemistry desorption and recombination phenomena in tritium breeding ceramics. Understanding these phenomena requires utilizing and expanding on advances in computational and experimental methods in material science, fluid mechanics, magnetohydrodynamics, chemistry, nuclear physics, particle transport, plasma-material interactions, and other disciplines.

Assessing the principles of tritium self-sufficiency is not just about plasma chamber and materials. It is about all aspects of the fusion system including: the plasma physics operation (tritium fractional burn-up, plasma edge recycling, tritium recycling, power excursions, disruptions), the control systems for plasma stability that need to be embedded in the blanket (shells, coils), the requirements for heating and exhaust (radio-frequency systems and beam ports, divertors), magnet and vacuum vessel shielding requirements, tritium processing systems and safety considerations, and many other factors. Therefore, assessing the feasibility of the D-T cycle requires parallel and highly interactive research in plasma physics, plasma control technologies, plasma chamber systems, materials science, safety, and systems analysis.

The fusion program also requires the development and deployment of improved plasma technology for heating and current drive, stabilization, fueling, pumping and magnet technologies to enhance and extend performance and reliability to meet the requirements of long-pulse burning plasmas, and to tailor the technologies to meet the specific needs of other developing concepts. These technologies are essential to enable existing and near-term experiments to achieve their scientific research and performance goals: the dynamics of matter and fields in the high-temperature plasma state (O1), the exploration of burning plasmas (O2), and the achievement of fusion energy (O3).

This campaign aims to answer three topical scientific and engineering questions:

T13: How does the challenging fusion environment affect plasma chamber systems?

T14: What are the operating limits for materials in the harsh fusion environment?

T15: How can systems be engineered to measure, heat, fuel, pump, and confine steady-state or repetitively pulsed burning plasmas?

RESEARCH THRUSTS

The topical scientific questions for this campaign can be addressed by several research thrusts, each having a specific ten-year goal and associated research activities.

Develop plasma chamber systems and materials knowledge to support the construction and operation of ITER, including blanket testing capability in the fusion environment

ITER, as the first large-scale, long-pulse D-T burning machine, presents many challenges for safety and nuclear design, some of which still need more accurate predictive capability and more detailed analysis to fully resolve. In addition, ITER will be utilized as the first integrated nuclear fusion environment for testing of blanket designs and materials to investigate issues such as tritium breeding and recovery, materials interactions, magnetohydrodynamic flows, turbulence suppression, and thermomechanical interactions. Hence, this research thrust aims to address the following question: What will be the true nuclear environment and machine response in ITER? How will blanket components and materials behave in an integrated fusion environment?

The ten-year goal is to deliver to ITER the blanket test modules required to understand the behavior of materials and blankets in the integrated fusion environment.

Key research activities include completion of materials and engineering sciences research in support of construction and licensing, and providing the scientific and engineering basis for the ITER blanket test modules. The development of a test blanket capability includes development of experimentally validated mechanical-property and dimensional stability models of the effects of combined material and environmental variables on the behavior of low activation martensitic steel. Another required capability is the simulation of 3D magnetohydrodynamic force distribution in liquid breeder flows and effects on drag, turbulent mixing, and flow distribution in complex geometry, interconnected, materially heterogeneous blanket structures. Experiments and phenomenological and computational models will address other key issues for blanket modules, such as behavior of electrical and thermal insulators and tritium permeation barriers, coolant chemistry control and material compatibility, and effects of cyclic loading on ceramic breeder pebble-bed thermomechanical interactions. Most of these research activities will continue to be carried out in the context of ongoing international collaborations.

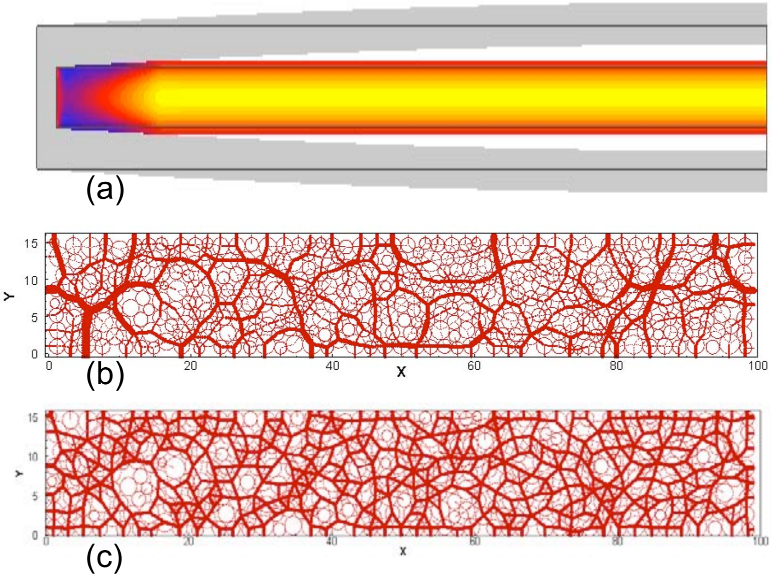

Figure 8.1. Macroscale finite element analysis relies on accurate micromechanical models and empirically derived and validated constitutive equations for modulus and stress-strain relationship. (a) FEM simulation of breeder pebble-bed material system showing stress levels in the ceramic and deformation of ferritic steel structure. The analysis shows formation of a gap (and thus thermal resistance) at the breeder pebble/ferritic steel interface. (b) and (c) Force distributions at breeder particle contacts based on a discrete element micromechanical modeling technique similar to molecular dynamics. The width of the contact lines reflects the contact force magnitude. Stress accumulated at the pebble contacts (b) is able to relax after onset of creep deformation (c). A near term R&D goal is to include and understand the effect of pulsed operations, which is of particular importance for interpreting ITER test blanket experiments intended to study pebble-bed thermomechanical integrity and performance. (Courtesy of A.Ying and J. An)

Recent Progress: The performance of key construction materials (stainless steel, copper alloys), radio-frequency heating feed-throughs, and plasma diagnostic insulator materials for ITER was obtained from a series of controlled experimental studies. Progress has been very strong on simulation of conducting liquid coolant flows in strong magnetic field in recent years, largely due to the emphasis of the APEX (Advanced Power

Extraction) study on fundamental understanding of phenomena. Simulation tools that take advantage of parallel processing and large memory capabilities, unstructured meshes and interfaces with commercial meshing and solid modeling tools, as well as numerical formulations including dissimilar materials and multiple liquids, have allowed very complicated flow geometries with various electrical insulators to be simulated, even at high Hartmann number and magnetic interaction parameter. Similar advances in neutron and photon transport, especially in implementing interfaces to solid modeling tools to allow better modeling of complex ITER components, are also underway. Multi-scale material simulation tools combined with innovative laboratory experiments has led to understanding of solid breeder pebble-bed thermomechanical response in material systems including creep deformation (see Figure 8.1).

Establish the engineering science base required for the D-T cycle

Tritium self-sufficiency is affected by all aspects of the fusion system including: the plasma configuration, operation modes, and parameters (fractional burn-up, edge recycling, power excursions, disruptions); the control systems for plasma stability, heating and exhaust embedded in the blanket (shells, coils, radio-frequency systems and beam ports, divertors); safety considerations; and many other factors in addition to the blanket and tritium processing systems. Therefore, parallel and highly interactive research in plasma physics, plasma control technologies, plasma chamber systems, materials science, safety, and systems analysis is required. A critical element in assessing the engineering feasibility of the D-T cycle in a practical system is the development and testing of blankets and materials that can safely operate in the integrated fusion environment at reactor-relevant neutron and surface heat fluxes for prolonged periods of time at high temperature with sufficient reliability and maintainability. Hence, the research thrust here aims to address the following question: What is the “phase-space” of plasma, nuclear and technological conditions in which tritium self-sufficiency can be attained? Is there a practical blanket system that can exist in this phase-space?

The ten-year goal is to determine the “phase-space” of plasma, nuclear, material, and technological conditions in which tritium self-sufficiency and power extraction can be attained.

This research will involve extensive modeling of materials and plasma chamber phenomena and experiments in various laboratory-scale testing facilities, and fission reactors will be utilized to supplement ITER testing in providing the scientific and engineering capabilities for more comprehensive fusion tests in later facilities. This blanket and material research will be closely interactive with plasma physics research because the introduction of neutron absorbing materials (such as passive coils for plasma stabilization and plasma heating and current drive elements), and various operating scenarios (such as edge recycling, impacting tritium fractional burn up) will drastically change the potential for tritium self-sufficiency. An experimentally verified, comprehensive fuel cycle dynamics model will be developed to predict tritium behavior, transport, and inventories in all system components such as plasma exhaust, plasma-facing components, blankets, and tritium processing. This model, coupled with physics and engineering science modeling and experimental results, will be used in a systems studies approach to provide critical feedback on which plasma configurations, operating modes, and plasma chamber concepts have good potential for attaining tritium self-sufficiency. Focus areas will include: (1) modeling and experimental investigation of the transport, fate, and consequences of fusion-relevant levels of helium produced in neutron interactions with materials; and (2) the construction of a science-based materials design approach to managing transmutation effects and displacement damage in reduced-activation materials. Physically based interaction mechanisms will be studied in experiments with unit cells of breeder/multiplier/ coolant/structure. Experiments and microstructure modeling will be carried out to explore high-temperature radiation-induced sintering and low-temperature tritium diffusion in ceramic breeders and their effects on the allowable operating temperature "window," which is essential to assessing the tritium breeding potential. Novel methods to divert eddy currents generated in

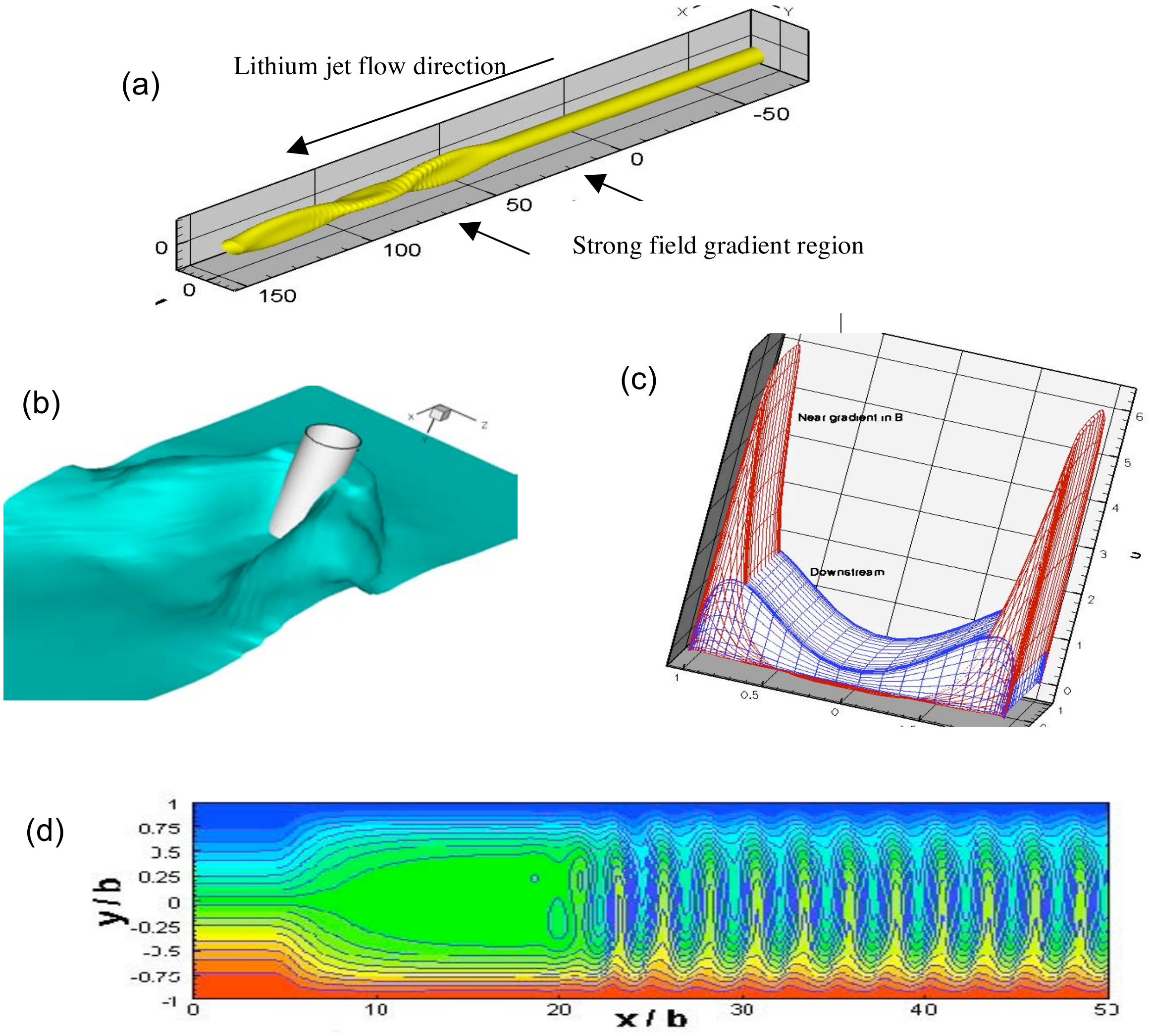

Figure 8.2. Focus on underlying physics of free surface liquid metal flows during the APEX study led to a dramatic improvement in the simulation capabilities for liquid metal magnetohydrodynamics: (a) shows the deformation of a high speed lithium jet leaving a strong magnetic field through a sharp field gradient, as seen in laboratory experiments, and (b) depicts free surface flow past a cylindrical penetration typical of a beam port in a thick liquid wall. These MHD simulation tools are now being used to study closed channel flows in complex structural geometries of various breeder blanket concepts to be tested in ITER: (c) shows velocity profiles with strong sidelayer jets that from near magnetic field gradients, and (d) depicts streamlines of a channel flow entering a strong field where von-Karma-like vortex shedding is seen as the high velocity side layer jets go unstable. (Courtesy of N. Morley)

liquid metal coolants away from the walls, and hence reduce the magnetohydrodynamic drag and suppress turbulence, will be explored.

Recent Progress: A much better understanding of the requirements of the D-T cycle has evolved based on simulations of tritium fuel cycle dynamics developed by a Plasma Chamber university research program and later used by ITER designers to explore implications on fueling and inventory for ITER. Clever blanket systems designs like the Dual Coolant Lead Lithium blanket have produced a vision of a high-performance blanket system where magnetohydrodynamic drag is mitigated by use of SiC composites as both electrical and thermal insulators. The constitutive behavior of ferritic/martensitic steel and other structural materials has been investigated under ITER-relevant temperatures and neutron doses. The basic chemical compatibility behavior of SiC with lead lithium coolant has been determined up to high temperatures. The application of molten salt breeders has been reintroduced, and key R&D issues are the subject of the JUPITER-II collaboration, including fundamental experiments to control tritium fluoride by REDOX reaction with beryllium and to understand the effect of magnetic field on turbulent heat transfer. Again as a result of the APEX and ARIES (Advanced Reactor Innovation Evaluation Study) programs, significant progress has been made in understanding the common technology, materials and plasma physics interfaces and their influence upon one another. For instance, effects on plasma edge by various plasma facing materials and effects on various plasma stabilization and control techniques by highly conducting liquid metal blankets are being considered by physicists. Also, the needs of advanced tokamak operation and stellarator geometry for blanket components and tritium breeding potential are much better understood. An example of progress in understanding and predicting magnetohydrodynamic fluid flow is shown in Figure 8.2.

Investigate performance limits for materials and plasma chamber technologies

Materials and plasma chamber systems will play a critical role in determining the ultimate attractiveness of fusion power because of the need for high power density, high thermodynamic efficiency, high reliability, fast maintainability, long lifetime, and low long-term radioactivity. Meeting these simultaneous demands in the multiple-field, intense fusion environment and complex plasma confinement configurations is a challenge that requires important advances in several scientific fields and engineering applications. Innovation in materials and technology research should continue, as more conventional materials and technology approaches may prove infeasible or not attractive in the long run. For example, materials with high-temperature potential or innovative liquid wall and divertor concepts that can reduce significantly the demands on structural materials are both pathways to enable high power density performance. The research thrust here aims to address the following questions: What are the performance limits of materials and blanket components? Can innovative material and technology solutions be found that can dramatically improve the attractiveness of and/or shorten the development path to fusion energy?

The ten-year goal is to develop the knowledge base to determine performance limits and identify innovative solutions for the plasma chamber system and materials.

In addition to the research described in thrusts described above, which will also aid in advancing aspects of this thrust, it is important to continue investigating, over the next ten years, various long-lead-time aspects of material performance limits and chamber technologies that will have the largest impact on the ultimate attractiveness of fusion energy. For example, the design of fusion materials will utilize and expand revolutionary advances in computational and experimental methods to control at the nano-scale level the structural stability of these materials during exposure to intense neutron fluxes, high mechanical loads, and corrosive environments. The knowledge base obtained from designing these advanced materials will contribute to resolution of several fundamental questions in the broader materials science field, including the maximum practical strength limits for materials and what controls the intrinsic fracture toughness of high strength materials. Advances in coating chemistry and technologies that may lead to high-performance, radiation-tough insulation, corrosion and tritium permeation barriers can open the way to self-cooled liquid metal blankets and contribute to the broader scientific quest for environmental barrier coatings in many applications. Alternative approaches to plasma chambers will be explored at the fundamental science level. For instance, innovative liquid wall and divertor concepts that can reduce significantly the demands on structural materials and enable high power density performance will require continued basic research on computational fluid dynamics development for turbulent (inertial fusion) and magnetohydrodynamic (magnetic fusion) free-surface flows. Free-surface vaporization and mass transfer model development will be critical to simulating recondensation rates in inertial fusion, and coupling to edge plasma physics codes will be necessary in magnetic fusion to assess the coupled penetration of impurity vapor and the effect on local flux tube heat loads and electrical currents back to the liquid surface. This knowledge will be crucial to determining the feasibility of revolutionary liquid wall concepts for fusion.

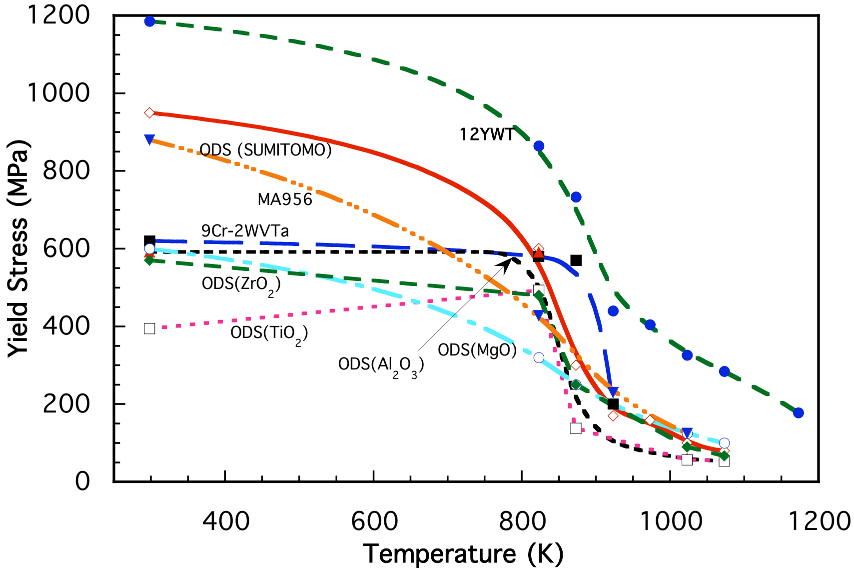

Figure 8.3. The 12YWT nano-composited ferritic steel and related new steels developed by fusion researchers have much higher tensile strength than conventional ingot metallurgy and oxide-dispersed steels. Even more dramatic improvements are observed in long-term thermal creep strength. The source of the improved performance has been shown to be due to a uniform distribution of nano-scale clusters (r~2 nm) with a spacing of ~10 nm. (Courtesy D. Hoelzer and R. Klueh)

Recent Progress: Progress has been made on development of high-temperature alloys such as oxide dispersed steel (ODS) ferritic steels and vanadium, and radiation resistant SiC composites have been developed through understanding of microstructural response to radiation damage (see Figure 8.3). Plasma chamber designs utilizing the very advanced liquid wall concept have been developed and explored with emphasis on understanding the underlying flow and heat transfer phenomena. In fact, heavy-ion-driven inertial fusion has selected a thick liquid wall concept as the primary plasma chamber candidate and the capability to generate thick liquid pockets comprised of arrays of oscillated jets has been demonstrated. A much better fundamental understanding of highly turbulent liquid jet and film flows for inertial fusion and molten salt magnetic fusion chambers have been developed through state-of-the-art turbulence modeling and laboratory experiments. Advanced ideas in liquid metal wall interaction with magnetic fields, control techniques such as magnetic propulsion, and effects of plasma contact have been explored as well. This work includes conversion of the Current Drive Experiment-Upgrade (CDX-U) spherical torus into a liquid wall device showing very good plasma characteristics with a liquid lithium divertor. Such a liquid wall experiment in the National Spherical Torus Experiment is currently under development.

Develop long-pulse plasma control technologies for tokamaks including ITER

The demands of long-pulse burning plasma experiments such as ITER and beyond require advances in plasma technologies. A key element in this thrust is to address the following question: Can the performance and reliability of plasma technologies for heating and current drive, fueling, and magnets be extended to meet the requirements of long-pulse burning tokamak plasmas?

The ten-year goal is to develop the plasma technologies required to support U.S. contributions to ITER.

This thrust utilizes the tokamak as the primary vehicle for advancing the development of critical advanced technologies. It focuses on developing the technology needed to address key elements of the tokamak development path, namely long-pulse, advanced operating regimes and burning plasma research. The technical challenges and demanding conditions associated with ITER drive the development of these technologies. This plasma control technology development thrust will enhance the ongoing coupling to the programs of major U.S. facilities and foreign collaborations and enable the execution of the U.S. commitment to the construction and operation phases of ITER. The following five- to ten-year deliverables are aimed at meeting the needs of long-pulse, advanced operating regimes and burning plasma research. The development of advanced operating regimes on existing tokamaks requires the near-term deployment of robust and reliable heating and current drive and fueling and pumping technologies. Meeting the expected U.S. commitments to ITER for magnet, heating and current drive, and fueling, pumping and diagnostic systems requires a ten-year plan. The ITER activities will initially focus on burning plasma specific R&D and hardware design and then transition to hardware qualification and commissioning.

Associated research activities:

- Develop robust and reliable plasma control technologies to meet the long-pulse, burning plasma, and advanced operating scenario requirements of tokamaks including ITER.
- Use experimental run time, diagnostic and facility support on existing tokamaks to develop and deploy the specific magnet, heating and current drive, and fueling technologies.

- Evaluate the effectiveness of the technology for burning plasma applications, with focused diagnostic measurements and experimental analysis, as part of broader experimental campaigns.
- Develop, modify and apply advanced models and theory to these technologies and their applications. Significant modeling and theory development is needed for superconductors, component structures, antennas, transmission lines, gyrotrons, plasma fueling and disruption mitigation physics, wave particle interactions, edge-localized mode and edge plasma interactions. A combination of multi-physics coupled commercial finite element codes as well as R&D single-purpose codes will be utilized.
- Utilize new and existing test facilities to verify performance and benchmark models. These include a pulse coil test facility, gyrotron test stands, radio-frequency test facilities, pellet injector and fuel recovery test stands, and a compact toroid fueling and momentum source demonstration facility.

Recent Progress: The U.S. remains a leader in the development of plasma technologies. The nation has ongoing, extensive interactions with international partners on programs involving joint development and deployment of technologies on larger tokamaks and test facilities. Future interactions will play an important role in the strategy to explore long-pulse issues and advanced tokamak and burning plasma physics. Diagnostics, heating and current-drive, stabilization, fueling, pumping and superconducting magnets are the technologies rated highest by the U.S. Burning Plasma Advisory Committee for U.S. ITER participation. The U.S. played key roles in development of these technologies during the ITER Engineering Design Activities and is expected to have major ITER commitments in these areas. An example of recent advances in pellet fueling is shown in Figure 8.4.

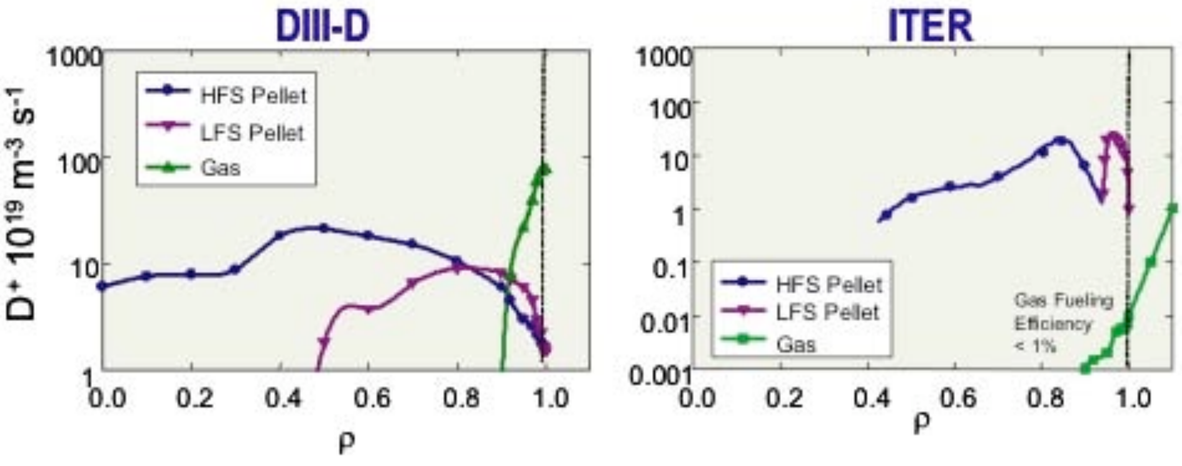

Figure 8.4. Comparison of pellet fueling and gas fueling source profiles for (right) DIII-D with experimental pellet fueling measurements extrapolated to 3 Hz, 2.7 mm, and (left) calculated for ITER using the specified 16-Hz, 5-mm pellet specification. Traditional fueling with gas puffing is <<1% efficient while high field side (HFS) pellet injection can provide 100% efficiency while depositing the D-T fuel inside the ρ=5 normalized radius.

Provide plasma control technology support for developing other confinement approaches

Research on other confinement concepts requires a wider range of plasma technologies, many of which are at an early stage of development. The physics requirements of other concepts that are relatively closely linked to the present knowledge base (such as the compact stellarator and spherical torus) will require an evolutionary rethinking of existing technologies. As the portfolio expands into emerging and new concepts that are less well linked to the present tokamak and stellarator knowledge base, it will be necessary to pursue new, revolutionary technologies as well. Hence, the following thrust seeks to address the following question: Can plasma technologies be tailored to support the needs of other confinement approaches?

The ten-year goal is to develop the plasma technologies to support the research program.

The research and development activities under this thrust will respond to the specific needs of the plasma research program. Examples include:

- Develop plasma control technology tailored to the special requirements of specific alternative confinement concepts.
- Utilize run time, diagnostic and facility support on existing alternative/innovative concept devices to develop and deploy the specific magnet, heating and current drive, and fueling technologies.
- Evaluate the effectiveness of the technology with specific diagnostic measurements and experimental analysis tailored to the alternative/innovative concepts.
- Develop, modify and apply models and theory to these technologies and their applications. This could include model/theory development of high-temperature superconductors like BSCCO-2212 and MgB2, specialized antennas and launchers, gyrotrons including tunable frequency, plasma fueling and gas-fueling physics, wave-particle interactions and edge-plasma interactions.
- Utilize existing test facilities to develop alternative/innovative concept specific technologies.

Integrate with the physics objectives of the next generation (e.g., a performance-extension-class compact stellarator, spherical torus or reversed-field pinch) of a specific alternative concept. Examples of integrated design requirements include: magnet systems configured to provide physics properties consistent with control requirements; divertors, pumps, and gas/solid/plasma fueling systems configured to test steady-state power and particle control compatible with required plasma core performance; startup heating systems configured to test reactor-like startup scenarios; and heating systems configured to sustain and test steady-state control scenarios.

Recent Progress: Advances and new directions in fusion science have been strongly coupled to advances in plasma control technology. Past and present development and deployment of superior plasma control technology tools have increased the scientific output of alternative concepts in scope and quality. Support of alternative concepts with plasma control technologies and specific analysis/modeling has complemented and challenged the understanding of tokamak plasma physics. Plasma control technology development has included significant programs in the university sector, which have been important for the development of the fusion workforce. Fusion technology has had a long history of spin-off success into other fields of science, including semiconductor fabrication, astrophysics, medicine, and material processing. The U.S. is a leader in the development of plasma control technologies and is involved in extensive interactions with international partners on programs involving joint development and deployment of technologies on other alternative/innovative concepts including spherical tori, stellarators, and reversed field pinches, and these interactions augment domestic program development activities.

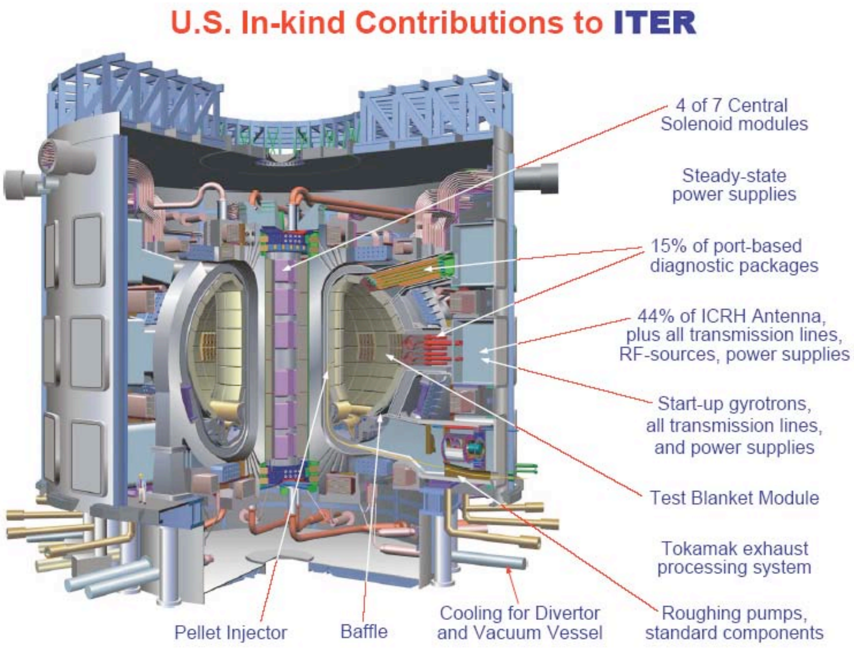

Figure 8.5. Provisional U.S. in-kind contributions. The U.S. is expected to make major technology contributions to ITER including the central solenoid magnets, electron-cyclotron heating start-up power and launching systems, ion cyclotron heating antenna, transmission line and radio-frequency sources, pellet fueling, pumping, plasma-facing components, plasma diagnostics, tritium handling, test blanket modules, and safety systems.

RELEVANCE TO ITER AND OTHER CAMPAIGNS

The existing U.S. fusion energy sciences program contributes significantly to increasing the understanding of the science and technology of burning plasmas; the majorities of programs on major toroidal facilities, in fusion technology and in fusion theory already address burning plasma topics. With the start of construction of a burning plasma experiment, an increasing focus on burning plasmas will be appropriate, with the objectives being enhanced understanding, research tool building, and preparation for research operations. This understanding and these tools will be applied to confirmation and refinement of the device design and to modeling and optimization of experiments aimed at answering burning plasma questions.

Research on plasma chamber systems and materials is critical to the successful construction and effective utilization of ITER. As the first large-scale, long-pulse D-T burning plasma experiment, ITER presents many challenges for safety and nuclear design, some of which still need more accurate predictive capability and more detailed analysis to fully resolve. Regulators will have little confidence in the behavior of such a large distributed system unless the underlying science associated with the operation, interactions, and potential for radioactive and toxic materials mobilization is established. Special nuclear analysis support will be needed for the procurement packages carried out by the U.S., including portions of the shielding blanket, diagnostics, magnets, and plasma heating and current drive systems. Also of great concern is the accurate prediction of the operation of plasma facing-components, and accounting and handling of the in-vessel tritium and dust inventories in the plasma chamber. In addition, ITER will be utilized as the first integrated nuclear fusion environment for testing blanket designs and materials in special ports. These *Test Blanket Module* (TBM) experiments are vital to: (a) begin developing and understanding the highly interdependent behavior of blanket functions and material systems which can not be effectively studied in “separate-effects” experiments, (b) provide experimental data vital to validating codes, and (c) develop the technology necessary to install near-term breeding capabilities to supply ITER/burning plasmas with the tritium necessary for operation in its extended phase of operation.

Enabling the successful operation of the ITER design is a critical element for many of the magnetic fusion plasma questions. The work on component simulation and ITER test blanket module will be most strongly related to T10 and T15 activities for basic shielding blanket and heating/ fueling/diagnostic systems development for ITER, where an accurate evaluation of the nuclear radiation level at these components is essential and test facilities for shielding blanket and divertor components can be shared. In addition, it is widely recognized that plasma control and stability will be heavily affected by the surrounding technological components, and so research in this area will contribute knowledge to T2 and T3 activities.

Research on D-T fuel cycle is related to all of the topical questions and the overarching themes of burning plasma and practicality of fusion energy. All current fusion research is based on the D-T cycle. Yet tritium self-sufficiency, a prerequisite to the viability of fusion as an energy source, is affected by all aspects of plasma configuration, operating modes and parameters, as well as the technological components of the fusion device. Therefore, it is essential to determine the “phase space” of plasma, nuclear and technological conditions in which tritium self sufficiency can be attained. This is essential to guiding fusion plasma and technology research.

Diagnostics, heating and current drive, stabilization, fueling, pumping, and superconducting magnets are the technologies rated highest by the U.S. Burning Plasma Advisory Committee for U.S. ITER participation. The U.S. played key roles in development of these technologies during the ITER Engineering Design Activities and is expected to have major ITER commitments in these areas. The long-pulse, burning plasma technology development is linked specifically to: heating, fueling, current drive, disruption mitigation (T2-T4); radio-frequency systems (T11); magnets (T1); disruption mitigation and fueling (T10). The plasma technology development for new concepts described in Thrust 15b is linked specifically to: support of alternative concepts (T1, T2, T3, T10); heating, fueling, current drive (T2, T3, T4); radio-frequency systems (T11); magnets (T1); and fueling (T10).

EXPECTED ACCOMPLISHMENTS WITHIN TEN YEARS

This section summarizes the progress and accomplishments expected for the thrust areas described earlier in this chapter assuming constant level-of-effort, followed by a description of research opportunities that could significantly enhance the research progress in selected thrust areas.

Deliver to ITER the blanket test modules

The ten-year goal is to deliver to ITER the blanket test modules required to understand the behavior of materials and blankets in the integrated fusion environment.

Under constant-level of effort, the U.S. will rely mostly on variations of designs led by Europe and Japan for the full test modules, while limiting tests of the U.S.-favored advanced concepts to key technical issues in submodules.

Advances are expected in understanding and predicting phenomena and in resolving key technical issues. Examples are liquid metal magnetohydrodynamics (see Figure 8.2), ceramic breeder thermomechanics (see Figure 8.1), behavior of low activation martensitic steel, corrosion, thermal and magnetohydrodynamic insulators, tritium permeation barriers, and neutronics.

Establish the engineering science base required for the D-T cycle

Considerable progress is expected in determining the “phase space” of plasma, nuclear, material, and technological conditions in which tritium self-sufficiency and power extraction can be attained. Laboratory experiments modeling activities (see previous sections) and completion of ongoing U.S.-Japan collaborations will contribute meaningfully to determining whether a practical blanket/material system exists in this phase space. A comprehensive fuel cycle dynamics model will be developed to predict tritium behavior, transport, and inventories in all system components such as plasma exhaust, plasma-facing components, blankets, and tritium processing. This model will help provide critical feedback to plasma, material, and blanket research. New high-performance radiation resistant materials including ferritic/martensitic steels and silicon carbide composites will be developed by utilizing the ongoing U.S.-Japan collaborations.

Investigate performance limits for materials and plasma chamber technologies

Considerable progress is expected in developing the knowledge base required to determine the performance limits and identifying innovative solutions for the plasma chamber systems and materials. A comprehensive experimentally validated suite of multi-scale material modeling codes will be developed. Advances will be made in developing predictive capabilities in a number of scientific areas (e.g., physical metallurgy, deformation physics, fracture mechanics, magnetohydrodynamic fluid flow, heat and mass transfer, liquid breeder chemistry) that are critical to understanding material and plasma chamber behavior. Expected progress in understanding and in developing predictive capabilities will aid in determining the performance limits (operating temperatures, stresses, neutron fluence, etc.) and in exploring innovative solutions for materials and the plasma chamber.

Develop the plasma technologies required to support the U.S. contribution to ITER

At a constant level of resources, the U.S. program will continue to perform much of the R&D and design work needed for the provisionally assigned U.S. in-kind contributions (Figure 8.5). For example: the magnet program will pursue paths to increased current density in Nb_3Sn superconducting strand, to developing high-performance superconducting cable, and to designing a state-of-the-art pulsed superconducting solenoidal magnet for plasma shaping and current drive; the programs in plasma-facing components and blankets will explore approaches to plasma-facing structures, which process both plasma exhaust and fusion neutrons in the environment of a fusion plasma; and the plasma technology program will perform R&D and design for the plasma-control actuators, including the repeating pellet injector and the ion cyclotron wave and electron cyclotron wave systems. Also at a constant level of resources, the plasma research program will improve and apply understandings of plasma behaviors that challenge the engineering systems: disruptions, power and particle loading, and alpha-particle loss.

OPPORTUNITIES FOR ENHANCED PROGRESS

The following summary briefly outlines the compelling research opportunities that would substantially enhance research progress in each of the fusion engineering science areas outlined in this chapter. They would enable extending the performance and operation of ITER, and would substantially increase the effectiveness of utilizing ITER's integrated fusion environment for physics and technology testing. They would also allow several of the long-term objectives to be achieved within a ten-year time frame, which would otherwise not be possible at constant level-of-effort.

ITER blanket test module

Enhanced funding will enable the U.S. to be competitive with the international partners and to deliver ITER test blanket modules based on very attractive concepts favored by the U.S. scientists and engineers. These concepts have great potential for high temperature, high power density, and other features that utilize the unique features of advanced plasma physics regimes and can deliver high performance in the challenging fusion environment.

Laboratory experiments, modeling, analysis, and testing will be enhanced in the following areas:

- Dedicated laboratory experiments for corrosion, thermofluid magnetohydrodynamics, and solid breeder thermomechanics.
- Irradiation experiments for breeder unit cells and material interactions.
- "Virtual" test blanket module modeling to predict the behavior (nuclear, mechanical, structural, thermal, etc.) of test blanket module in the integrated fusion environment of ITER.
- Scaled "mock-up" including fabrication, testing, and qualification (starting in 2008).
- Enhancement of design and analysis of test blanket module and interface with ITER.
- Development of diagnostics for test blanket module.

Nuclear science and engineering support for ITER base machine

- CAD/Monte Carlo coupling needed to facilitate effective nuclear analysis of ITER components with more accurate results and reduced time between CAD-based design changes and analysis.
- Develop instrumentation for nuclear components.
- Analyses and testing of ITER radiation sensitive components to ensure their survivability and adequate performance in the ITER nuclear environment.
- Modeling development for "deep radiation penetration problems" needed for predicting radiation dose outside ITER and impact on accessibility.

Model development for tritium cycle dynamic and tritium control

- Dynamic behavior of tritium flow rates, residence time, and inventories in plasma, blanket, plasma-facing component, tritium processing system, and other components.
- Analysis of impact of plasma operating modes (e.g., edge recycling, advanced stabilization schemes) on tritium production and tritium self-sufficiency.
- Develop effective tritium permeation barriers.
- Methods for tritium chemistry control.
- Tritium extraction system.

Explore high-temperature, high-power density capabilities including liquid walls

- High-temperature corrosion barriers.
- High-thermal conductivity, high-temperature solid breeder materials.
- Nano-composited ferritic steels.
- Laboratory-scale experiments and modeling for fluid dynamics, turbulence suppression, magnetohydrodynamic, heat transfer, chemistry.

Support high energy density physics campaign

There are new challenges in developing and fielding experimental targets and chambers in support of new high energy density physics research identified in Chapter 5. Incremental funding would be needed, in particular, to optimize target design, fabrication, and rapid replacement of targets in experimental target chambers for the study of warm dense plasma foils and fast ignition beam transport physics. Experimental target assemblies, including multi-shot target strips and wheels, in some case with cryo capability, and associated experimental chambers need to be developed to support a high experimental shot rate of at least 1 Hz in 100- to 500-shot sequences to improve the data statistics on key physics properties, and to mitigate the effects of target debris on close-in high energy density plasma diagnostics.

ITER support activities and plasma technology

With enhanced resources, the program could complete the work needed to support the in-kind contributions, and could explore opportunities for enhancing the understanding and performance of the burning plasma. Supporting the in-kind contributions, the diagnostics program could complete designs for measuring the basic set of burning plasma properties. Extending beyond the initial in-kind contributions, it could invent techniques and design additional instrument systems to measure more detailed behavior of the burning plasmas, enabling state-of-the-art research. Also with enhanced resources, strategies, tools, and algorithms for control of higher performance plasmas could be assessed; options for stabilizing instabilities that may limit the plasma pressure could be designed; and integrated simulations of burning plasmas could be developed and applied.

The development of technology for ITER over the next ten years as part of the U.S. commitments will greatly advance the tools for plasma control. Enhanced budget will allow greater utilization of the developments for ITER to make faster progress toward the development of high-reliability plasma technology for a long-pulse, advanced operating plasma regime. These technology advances can be deployed and tested on current fusion experiments. ITER also represents a major test bed for plasma control technology. The demanding environment of the fully operational long-pulse burning plasma in ITER will provide crucial information for plasma control technology requirements for a demonstration reactor.

- New facilities may be needed to effectively develop and test new plasma control technologies. Examples of new facilities include a pulse coil test facility, gyrotron test stands, radio-frequency test facilities, pellet injector and fuel recovery test stands, and a compact toroid fueling and momentum source demonstration facility. The new facilities would be a series of one-time investments spread over a five- to eight-year time period.
- The unique requirements of new concepts will require innovative plasma technologies. For instance, the compact stellarator experiments require significant improvements in all areas of plasma control technology and integration. The complex and high current density magnet designs are a good example. As in the past, plasma control technology development and deployment for new concepts will need to be carried out as a collaborative effort between the technology and experimental programs.

9

ENABLING RESEARCH ACTIVITIES

SCOPE AND ROLE OF ENABLING RESEARCH ACTIVITIES

As described in the preceding chapters, the scientific research in fusion and plasma physics can largely be described in terms of the questions it aims to address. Six scientific campaigns have been formulated that are used to identify and prioritize research needs. However, it is recognized that within the fusion program there are a number of important, ongoing areas of research that are best conducted in an integrated way and have application across a spectrum of scientific campaigns. Without them, research in all areas would be weakened. Some of these "enabling research activities" are diagnostics development, integrated simulation of fusion experiments, and advanced design studies. As has been pointed out in Chapters 3–8, activities in each of these areas are needed to advance understanding, and they are included in resource estimates for the campaigns. For clarity and cohesiveness, a brief description of some key activities is provided here.

DIAGNOSTICS DEVELOPMENT

As in any field of science, progress in plasma physics is dependent on increasingly detailed measurements of experimental properties, which can then be compared with evolving theoretical predictions. In return, new theory motivates new experimental measurements to test it. These measurements are particularly challenging for high-temperature plasmas, where temperatures have reached 500 million degrees Kelvin and, except in the extreme edge, most diagnostic measurements must be made by remote means. The number of parameters of interest is large, and the time and spatial scales small. It is fair to say that progress in plasma experiments has been closely linked to the development of improved diagnostic techniques, and that there has been impressive and steady progress in those techniques. For example, development of methods to measure the internal profile of plasma current, which were not possible until polarimetry and motional Stark effect (MSE) diagnostics were developed in the late 1980s,[1,2] has led to studies of the effect of plasma current on transport and stability, and to the discovery and exploitation of improved regimes of operation with reversed shear and transport barriers. These diagnostics have also been important in measuring radio–frequency-driven current, thus contributing to advances in several campaigns. This crosscutting application is typical of other diagnostic advances. The U.S. program has traditionally played a leading role in the development and application of new diagnostic techniques.

Diagnostic development has multiple components. First, new techniques must be conceived, developed, and tested to measure quantities not previously accessible, or at a level of detail greater than previously possible. Such development tends to require longer-term, if small-scale, research and development programs, which carry some uncertainty in outcome and can take several years to progress from initial "proof-of-principle" exploration to routine diagnostics on fusion experiments. These efforts are typically funded by the U.S. Department of Energy Office of Fusion Energy Sciences diagnostics program, through competitive selection of proposals. Equally important is the application of existing and newly developed diagnostic techniques to experimental facilities of all types and scales, so that plasma behavior in various regimes and configurations may be documented at a level of detail that will advance physical understanding. Such diagnostic applications are typically funded as part of experimental facilities, and their pace is constrained by available research budgets. This is a particular issue for smaller facilities, where the need for well-diagnosed experiments is comparable to larger devices, and the cost of diagnostics a higher fraction of the budget.

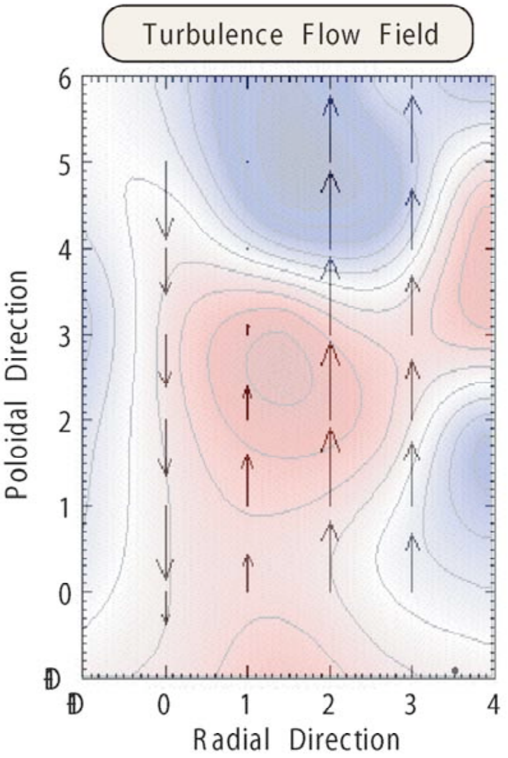

Figure 9.1 Measurement of density fluctuations and 'zonal' flows by beam emission spectroscopy on DIII-D. (Courtesy of G. McKee[3])

It is evident from the preceding chapters that a significant fraction of the proposed activities and of the opportunities for enhanced progress in each campaign involves the development and exploitation of improved diagnostics. A few high priority examples include measurements of high-wavenumber fluctuations predicted to cause electron heat transport (T4), development of sub-nanosecond diagnostics for high energy density physics targets driven by heavy ion beams (T9), high time and spatial resolution measurements of edge transport barrier profiles and instabilities (T10), and detection of radio-frequency waves and driven flows (T11). All plasma diagnostics contribute to the overarching theme O1: *Understand matter in the high-temperature plasma state*. Most also contribute to the theme O2: *Create a star on earth*. Improved measurements play an important role in the near-term research needed to optimally exploit a burning plasma experiment. In addition, new diagnostic techniques, most critically those to measure distributions of fusion-produced energetic particles, will be required on ITER. All diagnostics for ITER, whether based on proven or novel techniques, must be adapted for robustness in the extremely hostile radiation environment, for very long pulses, and produce measurements of a precision which will enable ITER to fulfill its ambitious scientific goals. Present experiments, as will ITER, rely increasingly on diagnostics for real-time control and optimization of plasmas. Such control capability in turn will play a part in overarching theme O3: *Develop the science and technology to realize fusion energy.*

Ongoing development and improvement of diagnostics are thus integral parts of the fusion energy sciences program. Priorities have been driven, and should continue to be, by the scientific needs of this program. Important spin-off benefits include the training of young scientists, who often work on diagnostics as part of their doctoral research, the involvement of many smaller research institutions, both universities and industry, and the application of fusion plasma diagnostics to plasmas in other settings, from space research to plasma processing of semiconductors.

INTEGRATED PREDICTIVE SIMULATION OF FUSION EXPERIMENTS

Progress towards the three overarching themes O1–O3 requires the acquisition of fundamental scientific understanding and the development of predictive capability. Quantified predictions can be compared with the experimental data produced by improved diagnostics on a range of experiments, and these data can be used to predict the behavior of future experiments. This capability is encapsulated in large simulation codes and theoretical models, which are used to design facilities and plan experiments. The need for accelerated development of computational tools and techniques based on first-principle theoretical models is well recognized. Progress is made possible by the rapid advances in high-performance computing technology, which allow simulations of increasing complexity and with greater scientific fidelity. Accordingly, advanced computational codes that integrate multiple physical phenomena, properly benchmarked with theory and experiment, are indispensable for the advancement of fusion science research.

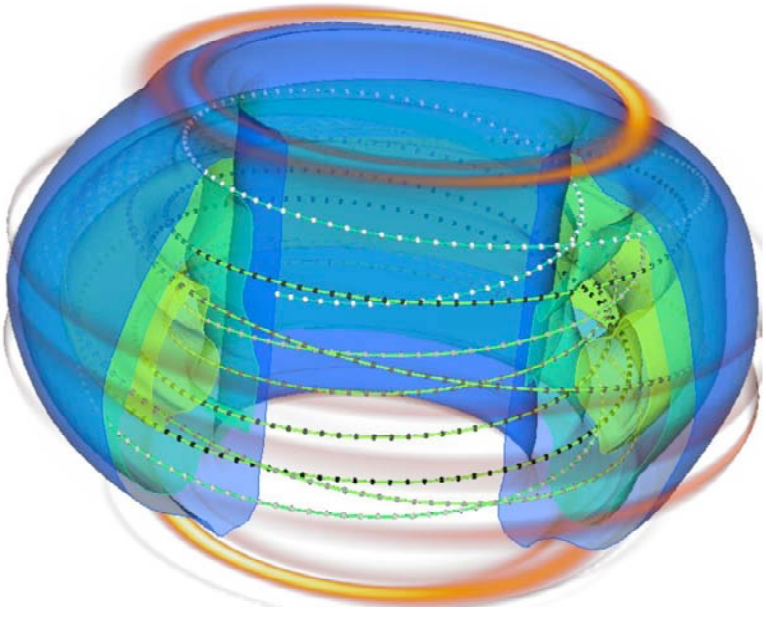

Figure 9.2. Time slice during a 3D simulation of a plasma disruption in DIII-D using the NIMROD code, showing distorted temperature iso-surfaces, field lines, and the locations of peak heat flux at the wall in orange. (Courtesy of S. Kruger)

Magnetically confined plasma supports the complex interplay between individual charged particles and the collective effects arising from the long-range nature of electromagnetic forces, leading to a wide range of waves and instabilities characterizing the medium. As a result, there is an enormous range of temporal and spatial scales involved in plasmas of interest. Fundamental processes include the fine-scale turbulence-driven transport of energy and particles across a confining magnetic field (T4), the rapid rearrangements of the magnetic fluxes caused by large-scale instabilities (T2, T5), and the interactions involving thermal plasma and energetic particles with electromagnetic waves (T11, T12). Understanding the plasma boundary dynamics, which includes plasma-wall interactions, atomic physics, magnetohydrodynamic oscillations, and turbulent transport in the geometrically complex plasma edge region (T10), represents a formidable challenge. A satisfactory physics formulation over the entire edge parameter regime is not yet in place. Simulations are also key to improved understanding of high-energy density physics (T7, T8, T9).

The goal of integrated simulation in fusion energy science is to effectively harvest the knowledge gained from the fundamental studies to provide the underpinning for predicting the behavior of fusion systems. Developing a comprehensive simulation capability for carrying out "virtual experiments" of such systems will be essential for the design and optimization of future facilities, including burning plasma experiments. For example, it is expected that proposed new plasma discharge scenarios on ITER will be modeled ahead of time to make efficient use of machine resources. An appropriate balance between pursuing a deeper fundamental understanding and developing an integrated simulation capability is needed.

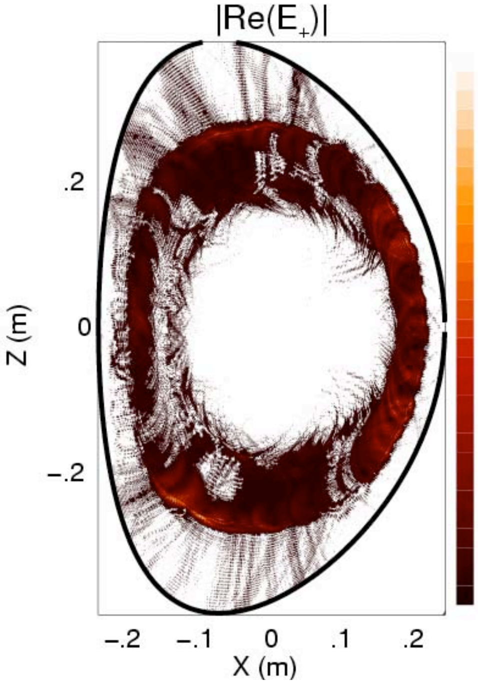

Figure 9.3. Full wave simulation of lower hybrid waves in the C-Mod tokamak, requiring about 1,000 radial and poloidal modes, recently made possible through computational advances in the radio-frequency SciDAC project. (Courtesy of J. Wright)

In recent years, dramatic progress has been made in plasma simulation capabilities in targeted scientific areas, including advances in microturbulence simulation, 3-D modeling of wave-plasma interactions, extended magnetohydrodynamic modeling, and atomic physics modeling of the plasma edge, though work on these topics is far from complete. Several projects have been supported through the U.S. Department of Energy SciDAC (Scientific Discovery through Advanced Computing) initiative, and have benefited from collaborations between applied mathematicians, computational scientists, and plasma physicists, across multiple institutions. Infrastructure enabling more effective remote collaboration among laboratories and between theory and experiments has also been developed. Other areas, such as pedestal simulation, are not yet at the same level of predictive capability.

To achieve truly integrated simulation across the plasma, including multiple physical phenomena, as called for in several of the scientific campaigns, will require not only continued advances in the understanding and modeling of individual areas, but platforms to effectively link multiple simulation codes to simultaneously address all of the physical and numerical challenges. Such an effort must start with individual physical components that are reasonably complete and have been well validated. However, given the many nonlinear linkages which exist between, for example, turbulence and transport, magnetohydrodynamic stability and current profile control, the long-term goal must be to combine the capabilities of more specialized codes and to cover the whole plasma cross section. This will require significantly increased resources and computing capabilities.

ADVANCED DESIGN STUDIES

Fusion energy sciences is a very complex area involving subtle combinations of physics, technology, and engineering. There are also many variations of the plasma configurations in which the science is studied. There is a strong need to identify, for each of the various approaches to high temperature plasma confinement, the scientific issues with the strongest leverage for fusion energy. Overarching theme O3, *Develop the science and technology to realize fusion energy,* is arguably the most demanding of the program goals. Advanced design studies of reference fusion power plants have been and remain an essential tool in guiding the program. These studies synthesize the new and disparate scientific results into a self-consistent and integrated vision of a fusion system, and identify the scientific problems that carry greatest leverage and important gaps in the present knowledge base. Advanced design studies of fusion systems are not simply an aspect of power plant development. They help extend the general scientific capability by stimulating consideration and achievement of a wider range of dimensionless and dimensional physics parameters and by stimulating more demanding technology and greater control and flexibility—all of which have importance to the three overarching themes. Studies are used to identify the most effective near-term experiments and the most cost-effective routes to the evolution of the experimental, scientific, and technological program. The U.S. is preeminent in the world in such integrating studies, which are done by national teams including members from universities, national laboratories, and industry. While the teams are adjusted to meet the needs of each study, some consistency in effort is required to avoid losing core capability. Through the work in the universities, the program provides valuable training for many fusion energy science researchers

The advanced design progress has had major impact on worldwide fusion research. The major scientific direction for tokamak research—advanced tokamak operation—is based on the fundamental issues identified by advanced design program research. Starting with identification of the trade-off between achievable plasma beta and maximizing the bootstrap current for steady-state operation, a series of tokamak power plant studies have defined the specific physics paradigms that are the goals for advanced tokamak research worldwide. Similarly, advanced design research identified a new stellarator configuration to address the issue of large projected size, which led to a substantial interest in compact stellarator research in the U.S. and the current stellarator research program. Spherical torus and reversed-field pinch configurations have also utilized the results of advanced design studies in setting research priorities. The advanced design program has also had a large impact on fusion technology research. Examples include pioneering work in the use of silicon carbide composites as major structural elements in fusion power plants, adaptation of innovative manufacturing techniques to greatly reduce the cost of major systems, and self-cooled lithium-lead blankets—all subjects of extensive worldwide fusion research and development.

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10

UNDERSTAND MATTER IN THE HIGH-TEMPERATURE PLASMA STATE

INTRODUCTION

The plasma state of matter constitutes the core of fusion systems and nearly the whole of the visible universe. Progress in understanding how plasma, electromagnetic fields, and other states of matter interact and organize has been essential to the development of methods used to confine plasma and generate fusion energy. Progress in plasma physics has also led to progress in related scientific disciplines, especially in space physics, astrophysics, high energy density physics, and in the many applications of plasma important to the Nation's technology goals.

Plasma dynamics arises from the collective interaction of billions of electrically charged particles. The description of these dynamics is challenging because the plasma state is intrinsically nonlinear. The effects of the nonlinearities are magnified in high-temperature plasma because the dynamics of the constituent particles are nearly collisionless, often invalidating the statistical methods used to simplify the descriptions of gases and fluids. Despite the complexity of the plasma state, scientists have established fundamental principles of plasma physics that include wave propagation and absorption, plasma hydrodynamics, and the very first elements of a comprehensive theory of plasma transport. These principles have evolved from sophisticated theoretical models, careful experimental tests, and breakthrough laboratory discoveries. Today's plasma scientists apply these principles to understand a wide range of natural and laboratory plasma phenomena. The general behavior of plasmas is now understood with methodology that spans many orders-of-magnitude in space and time: from submicron length scales and nanosecond time scales important to fusion plasma and industrial-processing plasmas, to the millions of light years and billions of years relevant to the galactic and extra-galactic structures of the universe.

The development of the physics of high-temperature plasma during the past decades can be regarded as a major accomplishment of fusion research and the source of the significant opportunities for scientific discovery available today. The readiness to pursue a burning plasma experiment is widely acknowledged, and this readiness stems from the understanding of the high-temperature plasma state. Fusion researchers are now able to design plasma confinement experiments, plasma control tools, and detailed imaging diagnostics that provide unprecedented views of plasma phenomena. In several key areas of plasma equilibrium, stability, heating and transport, a high level of predictive capability has been or is now being developed. Measurements with increasing accuracy and detail can be compared with comprehensive theories and integrated models that are simulated using the world's most powerful supercomputers. These developments provide a scientific framework in which to understand, and ultimately control, the complex plasma dynamics that occurs in self-heated burning plasma. They also focus research on long-term challenges to the field. For the first time, fundamental questions such as how is turbulence generated and dissipated, how do magnetic fields change topology and release their energy, and how do populations of energetic particles change collective dynamics, appear within reach of clear and compelling answers.

RELATIONSHIP TO THE CAMPAIGNS

This chapter focuses on the first overarching theme of the fusion energy sciences program: to understand matter in the high-temperature plasma state. Each of the six research campaigns identified in this report describes activities that answer the high-priority questions for today's fusion energy sciences program. Taken together, these research activities will also advance the fundamental understanding of the plasma state and will contribute ideas of broad importance to other fields of science. Indeed, it is the broad understanding of the high-temperature plasma state developed during the next decade of fundamental plasma research that will assure the success of the international burning plasma program and provide the source of new discoveries and progress. The following briefly describes the opportunities to understand the high-temperature plasma state found within each research thrust area.

Macroscopic Plasma Physics

How does magnetic structure influence plasma confinement and pressure in sustained magnetic configurations?

Plasmas created in early fusion experiments were often unstable to large-scale instabilities that caused catastrophic plasma losses. The development of magnetohydrodynamic and kinetic energy principles provided a theoretical framework to understand these instabilities. Today, the relationship between the shape and structure of the magnetic field and gross stability of plasma is well established. Detailed computer codes are benchmarked with experimental measurements and allow the design of a range of plasma configurations that are, at the same time, both stable and profoundly different in their characteristics, such as pressure and density limits, the degree by which external coils or internal currents are used to sustain the magnetic fields, and the properties of the plasma turbulence and flows that appear within the plasma. The questions being asked today probe much deeper than the conditions for gross stability. What are the processes that affect plasma confinement and stability, and how can these processes be controlled and manipulated?

Research in this thrust area concerns the large-scale, macroscopic behavior of magnetically confined plasma. This behavior results from the interaction of the plasma with the confining magnetic field, electric fields, and the plasma flow. It involves understanding both the sensitive dependence of plasma properties upon the twist, spatial symmetry, and strength of the magnetic field and the nonlinear linkages between the plasma properties and the macroscopic electromagnetic fields themselves. Since the fields affect the plasma and since the plasma affects the fields, the most appropriate and effective control of the plasma state is also a question of deep significance. Nonlinear interactions govern plasma properties. Thus, the plasma state is one that is simultaneously driven by external forces and self-generated through naturally occurring internal dynamics. Understanding how the plasma behaves as the balance between external control and internal self-organization is a fundamental and unique feature of matter in the plasma state. Answering these questions will benefit the practical design decisions for fusion energy configurations and control tools and also provide critical insights into the dynamics of plasmas confined in the complex magnetic fields within the solar magnetic arcades, in jets emanating from black holes, and in extra-galactic regions.

Multi-scale Plasma Physics

What governs the confinement of heat, momentum, and particles in plasmas and how can it be controlled?

Perhaps one of the most fundamental issues that has been addressed in the effort to reach fusion conditions is the mechanism that enables plasma heat, energy, and particles to move across the confining magnetic field through turbulent field fluctuations. Though first introduced as an issue particular to fusion experiments, turbulent transport is now explored as a fundamental process throughout the natural universe. Examples range from the transport of solar wind plasma into the Earth’s magnetosphere, to the transport of angular momentum in astrophysical accretion discs. Understanding turbulent transport of heat, momentum, and particles in the plasma state is now widely recognized as a grand scientific challenge of broad importance.

The discovery of the "transport barrier" has caused a groundbreaking change in the paradigm of plasma transport research. That anomalous turbulent transport can be reduced has now been reproduced in many experiments around the world in a variety of configurations including the tokamak, reversed-field pinch, spherical torus, and stellarator configurations. Transport barriers are now created in regions internal to the plasma as well as at the boundary layer between the hot confined plasma and the cooler edge. This astonishing observation has motivated a worldwide effort to understand its cause and has led to related breakthroughs. Diagnostic tools have been developed to measure the fluctuations and transient phenomena in experiments, and new numerical and theoretical tools for calculating and simulating nonlinear microturbulence. The study of transport barriers in self-heated fusion plasma will be a major research area on the burning plasma experiment. By any measure, progress in computational capabilities and plasma measurements of turbulence during the past decade have been spectacular. Central in the effort to understand turbulent transport is the scope of experiments being carried out—the shape of the magnetic geometry, the rate of twist of the magnetic field and the ratio of the plasma pressure to magnetic pressure, all impact the type and amplitude of the fluctuations that drive turbulent transport.

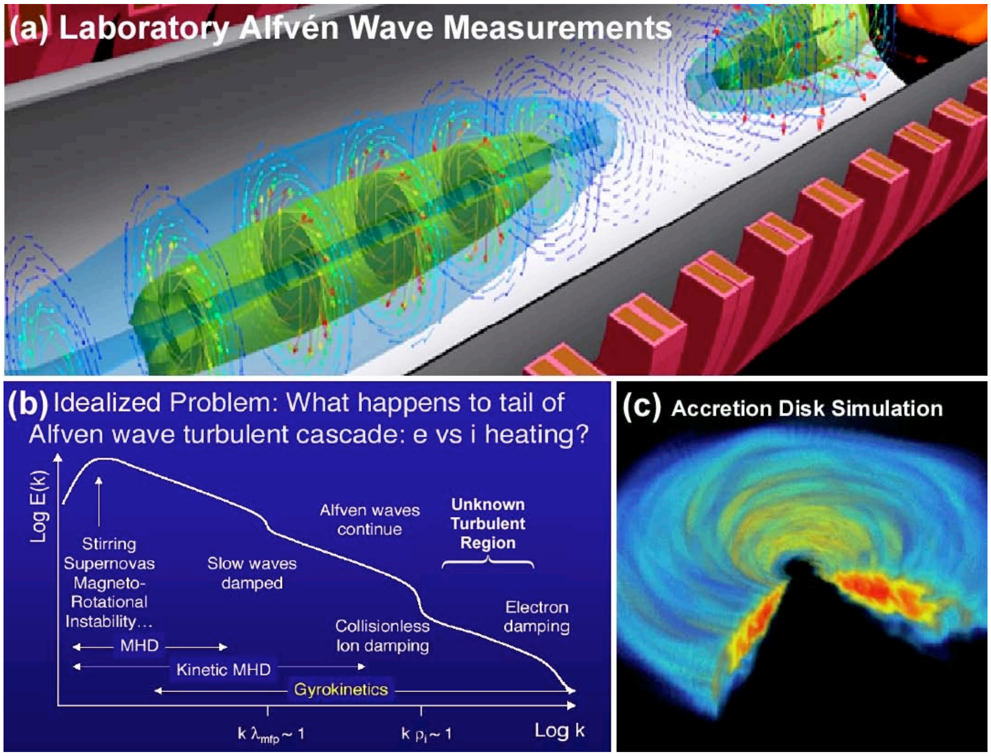

Figure 10.1. Collective plasma dynamics includes many types of waves and turbulence. This figure features Alfvén waves that exist in magnetized plasma, interact with plasma at many lengths scales, and lead to energy, momentum, and particle transport. From top to bottom, the figures show: (a) shear Alfvén waves measured in the laboratory (courtesy W. Gekkelman, UCLA), (b) idealization of the Alfvén wave turbulent spectrum showing the range of theoretical models, and (c) an MHD simulation of astrophysical turbulent accretion. (Courtesy of J. Hawley, S. Balbus, and J. Stone)

Plasma-boundary Interfaces

What happens at the interface between high-temperature plasma and its surroundings?

While plasmas comprise nearly all of the visible matter in the universe, the plasma state is unfamiliar on earth, existing mainly as a creation in the laboratory. Plasma science introduces us to unusual states of matter. Magnetically confined plasmas have set the record temperature (500 million degrees Kelvin) for matter on the earth. Inertial fusion plasmas have reached densities that show the properties of metallic hydrogen and unusual conditions of matter at extreme pressure and energy density.

At the boundary of a high-temperature plasma there is an interface with a nearly room-temperature chamber. Even if the hot plasma is well confined by the closed magnetic field lines, a small leakage of particles or power can ablate material and potentially damage the walls of the plasma device. The physics of the thin edge plasma that connects the hot plasma with the material walls has a strong influence on the properties of the plasma. Within this thin layer, the magnetic field topology changes from closed magnetic surfaces to open field lines that connect to the surrounding walls. Large electric fields form spontaneously, magnetohydrodynamic stability continually evolves, and plasma transport changes dramatically. At the walls, the plasma on the open field lines interacts with the material surfaces through complex surface chemistry, multi-step ionization processes, and multi-species ion and neutral transport, all of which depend on the material surface composition and geometry. Surprisingly, small changes in the equilibrium of the boundary plasma can dramatically affect the overall performance of a burning plasma. Understanding the dynamic physics of this region with sufficient clarity to reliably predict the behavior of a burning plasma experiment presents one of the greatest challenges to the fusion community. Developing an understanding of the boundary plasma requires a well-coordinated effort between simulation and experiment that covers time scales spanning six orders-of-magnitude and spatial scales from microns to meters.

Waves and Energetic Particles

How can energetic particles and electromagnetic waves be use to sustain and control high-temperature plasmas?

The propagation of electromagnetic waves in plasma is one of the most quantitative and best-understood phenomena in plasma physics. Indeed, Sir Edward Appleton's 1947 Nobel Prize in physics was awarded for understanding electromagnetic wave propagation in the ionosphere, and Hans Alfvén's 1970 Nobel Prize was awarded for understanding wave dynamics in magnetized plasma, and for the identification of certain electromagnetic waves found only in the plasma state exemplified by the environments in space and in magnetic fusion experiments. Plasma waves are ubiquitous in nature, and are involved directly or indirectly in nearly all the collective dynamics of plasma. This universality makes plasma waves an essential control tool, and the detection of plasma waves is an important diagnostic tool to understand the plasma state. The detailed plasma profiles and fluctuations within fusion experiments are detected with waves in a manner similar to the detection of the boundaries and structures of planetary and stellar magnetospheres. The ability to quantitatively predict the propagation of waves, as well as the orbits of energetic particles, has allowed the development of particle- and wave-based tools for precise control of plasma pressure, currents, and flows. In addition to understanding the exchange of energy and momentum between the plasma particles and fields, a major scientific achievement has been the use of waves to drive plasma currents in fusion experiments at the level of millions of amperes, and the demonstration of current-drive efficiency consistent with theoretical predictions.

This research campaign addresses important questions that apply the understanding of waves and energetic particles to explore and control plasma in new ways. In particular, research explores the electromagnetic spectra of launched waves and constraints on the power that can be coupled into magnetically confined plasma; seeks to understand in greater detail the physics of wave propagation and absorption in magnetized plasmas and the plasma response to high-power injected waves; characterizes how waves affect macroscopic stability and transport and how to use these effects to control and predict the dynamics of burning plasma; explores the internal features of energetic particle-excited instabilities; and seeks to understand the complex interactions of alpha particles in self-heated, burning plasmas.

High Energy Density Physics

What happens during the assembly, heating, and burning of high energy density plasmas?

High energy density plasma physics is an important element in the larger field of high energy density physics that concerns the behavior of matter under extreme pressures exceeding one megabar. The field of high energy density plasma physics is rapidly growing as a result of new astrophysical observatories that enable the study of high energy density physics in stars and galaxies, and as a result of a new generation of laboratory facilities that allow controlled and precise investigations of matter under extreme conditions. High energy density physics is an excellent example of research that intellectually unifies a wide range of physical parameters and fosters collaborations among related, but traditionally separate, research communities. The cross-fertilization of plasma physics with astrophysics, nuclear physics, and the physics of intense beams and lasers opens new areas for research and creates numerous opportunities for interdisciplinary discovery having broad scientific importance.

The research focus in this campaign concerns high energy density plasma physics and the continued advancement of the tools needed in the laboratory to achieve and study the properties of high energy density plasmas.

In fast ignition, the implosion stability requirements are greatly relaxed since a central hot spot need not be formed. The igniting spark is externally induced by a fast particle beam (e.g., fast electrons) depositing its energy in the compressed cold fuel. Understanding the generation and transport of such fast electrons by ultra-intensive, ultra-short-pulse lasers is key to understanding the fundamental stability and transport properties of relativistically hot plasmas, and is key to the success of fast ignition.

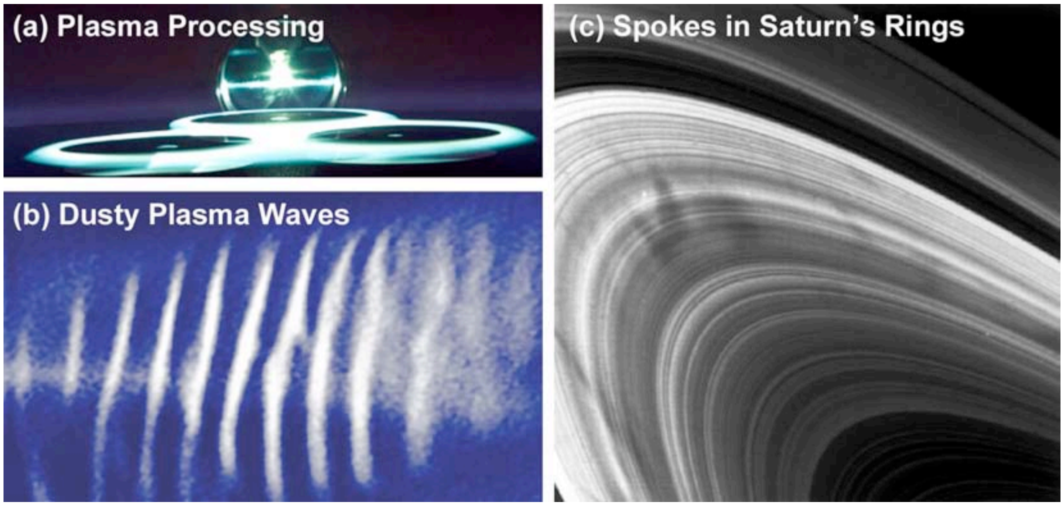

Figure 10.2. The interactions of plasma with solid materials lead to complex interactions. Dust and micron-sized particles are created during (a) industrial plasma processing, (b) laboratory experiments studying dust-acoustic waves, and (c) in the still mysterious "spokes" in the rings of Saturn. [Courtesy of R. Merlino and J. Goree, Physics Today (July, 2004)]

Computer simulations predict that use of plasma neutralization of the space charge of intense ion beams following modest acceleration can greatly shorten the achievable minimum pulse length, and that use of magnetic and plasma-based lenses can focus the resulting short ion bunches to a small focal spot size. Understanding the physics limits to compression and focusing is essential to enable beam-target interaction experiments which can explore the potential uniformity of beam heating at the deposition peak (Bragg peak), for creating and studying strongly coupled plasmas (non-ideal plasmas where the temperature is low enough and the density high enough that the inter-particle potential interaction energies can exceed the thermal energy kT). Targets near 1-eV temperature and densities from 0.01 to 0.1 solid density are especially interesting because (a) there is very little data in this regime, and (b) the predictions of different equation-of-state models differ by up to 80%, so that reliable data are required to discriminate the underlying physics of the different models.

In magneto-inertial fusion, magnetized plasma is heated and compressed to megabar pressures by an imploding shell. The imploding shell is hydrodynamically unstable and mix can occur at the fuel-shell interface. Understanding the energy transport properties of a highly compressed magnetized plasma as well as the hydrodynamic stability properties of the imploding shells are essential to validate the magneto-inertial fusion concept.

Fusion Engineering Science

What are the Fundamental Properties of Materials and Components Located in the Plasma-fusion Environment?

Unlike the previous five research campaigns, this campaign deals less with understanding the plasma state and more with the engineering sciences and the application of plasma science to near-term technology needs, such as industrial plasma applications and materials issues important to national security. The study of high-temperature plasma physics necessitates an interdisciplinary partnership between plasma physics and the engineering sciences. Plasmas must be created, heated, confined, and controlled with high-technology components that surround the plasma and are exposed to high fluxes of radiation, heat, and energetic particles. Extreme conditions exist in laboratories where fusion plasmas are studied, and it is under these conditions where plasma physicists operate at the very limits of the state-of-the-art of materials and components. These include superconducting magnets, material interfaces with demanding cooling requirements, structural and vacuum components, and the wide variety of plasma facing components, actuators, and diagnostics. The plasma-facing components involve plasma chemistry and plasma-surface interactions that have direct and fundamental relevance to understanding the plasma state. Other research activities within this theme extend the reach of fusion research into the fields of advanced materials, materials science, and the broad interdisciplinary advances in engineering sciences.

OVERARCHING RESEARCH EXAMPLES AND KEY QUESTIONS

Understanding the high-temperature plasma state cross-cuts the questions and research thrusts from all of the topical science questions and research areas. While the science campaigns represent the building blocks of fusion energy science, the table below illustrates the interconnectedness of fundamental studies of the plasmas state and the related importance to fusion science, non-fusion science, and other fields of physics.

Understand the role of magnetic structure on plasma confinement and the limits to plasma pressure in sustained magnetic configurations.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T1. How does magnetic field structure impact fusion plasma confinement?	Optimize the magnetic configuration	Coronal loops; planetary magnetospheres
T2. What limits the maximum plasma pressure that can be achieved in laboratory plasmas?	Maximize fusion power density	The Earth's magnetotail; Jupiter's magnetosphere
T3. How can external control and plasma self-organization be used to improve fusion performance?	Radio frequency, bootstrap and dynamo generated currents	Dipole confinement; Magnetospheres

Understand and control the physical processes that govern the confinement of heat, momentum, and particles in plasmas.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T4. How does turbulence cause heat, particles, and momentum to escape from plasmas?	Energy confinement, helium removal	Astrophysical accretion flows; Solar convection zone
T5. How are electromagnetic fields and mass flows generated in plasmas?	Generation of flows leading to transport barriers, and confining magnetic fields	Astrophysical, solar and planetary dynamos
T6. How do magnetic fields in plasmas reconnect and dissipate their energy?	Performance limiting instabilities	Solar flares; Magnetospheric storms

Investigate the assembly, heating, and burning of high energy density plasmas.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T7. How can high energy density fusion plasmas be assembled and ignited in the laboratory?	Implosion of plasmas to high energy density	Stellar interiors
T8. How do hydrodynamic instabilities affect implosions to high energy density?	Retention of symmetry in implosions	Stellar explosions
T9. How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion conditions?	Increased peak ion beam power for fusion targets	Multi-species beam-plasma physics for high energy ion accelerators

Learn to control the interface between the 100 million degree plasma and its room temperature surroundings.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T10. How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?	Fuel and power exhaust	Plasma processing

Learn to use energetic particles and electromagnetic waves to sustain and control high temperature plasmas.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T11. How do electromagnetic waves interact with plasma?	Heating and control of current profiles in plasmas	Radio emission from space; Communication disruptions
T12. How do high-energy particles interact with plasma?	Confining fusion alpha particles	Aurora Borealis; Astrophysical jets; Solar flares

Understand the fundamental properties of materials, and the engineering science in the harsh fusion environment.		
Key Questions	**Fusion Science Examples**	**Related Science Examples**
T13. How does the challenging fusion environment affect plasma chamber systems?	Plasma-material interactions	Plasma processing; Nuclear physics; Fluid mechanics
T14. What are the operating limits for materials in the harsh fusion environment?	Lifetimes of fusion components	Neutron effects on material structure
T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively pulsed burning plasmas?	Tools to carry out fusion science	Technical spinoffs to other areas of science

11

CREATE A STAR ON EARTH

INTRODUCTION

Stars power the universe. Star power is fusion power, the energy released by fusing together light nuclei. The gaseous fuel for fusion must be heated to over 100 million degrees for fusion reactions. Such a hot gas is in the plasma state in which all the atoms have been ionized. This hot plasma fuel must be contained in space to force the hot nuclei to collide. The sun contains its fusion plasma by enormous gravitational forces. To achieve and contain star power on earth, powerful magnetic fields or inertia are used to contain a hot plasma so that contact with the materials of its confining chamber would neither damage those materials nor cool the plasma. Achieving a star on earth, a burning plasma, provides scientific direction to the research on both magnetically and inertially confined plasma to realize fusion energy. A plasma made of the heavy isotopes of hydrogen (deuterium and tritium) is used because it has the highest reaction rate. The fruition of this grand quest to bring the power of the stars to earth is now within reach.

The worldwide fusion research community is about to embark on construction of the first magnetic confinement burning plasma experiment, ITER. The plasma will “burn” in the sense that the deuterium and tritium nuclei will be consumed in fusion reactions, releasing energetic neutrons and helium nuclei (alpha particles). The neutrons carry out eighty percent of the energy and their capture will be the source of fusion power extracted from a fusion power system. The alpha particles contain twenty percent of the energy and are retained in the plasma to heat the plasma.

Within the framework of DOE’s National Nuclear Security Administration, the National Ignition Facility in the United States is being constructed to achieve the burning plasma state though compression of small pellets of fusion fuel by powerful lasers and then fusion burning during the fuel’s short time of inertial confinement. A similar experiment, the Laser Megajoule facility is being constructed in France.

The National Ignition Facility (NIF) is designed to achieve thermonuclear ignition and energy gains. The output fusion energy of a single-shot will greatly exceed the laser on-target energy by factors ranging from 10 to 50. The energy density of an ignited NIF capsule will reach enormous levels in the terabar range exceeding the pressure in the solar core by over an order of magnitude. The NIF experiments will provide high energy-density-physics (HEDP) conditions never before achievable in the laboratory. The rich scientific opportunities in HEDP are described in a recent National Research Council report[1]. While NIF is primarily funded by the NNSA for defense purposes, its contribution to the understanding of burning plasma physics of inertial confinement systems will establish the foundations for the development of inertial fusion energy. Since the physics of ignition and propagation of the thermonuclear burn wave is independent of the compression-driver characteristics, the results from the NIF experiment will be of general applicability to laser fusion, Z-pinch and heavy-ion fusion. A panel appointed by the DOE Fusion Energy Science Advisory Committee has recently reviewed the US Inertial Fusion Energy (IFE) Program. Additional information on the NIF contribution to the development of inertial fusion energy can be found in FESAC Report on *A Review of the Inertial Fusion Energy Program* (March 2004)[2.] Since this work is funded by NNSA, the subsequent discussion will focus on magnetically-confined burning plasmas funded by OFES.

A recent National Research Council report[3] that considers the magnetic fusion burning plasma experiment states, “It is widely agreed in the plasma physics community that the next large-scale step in the effort to achieve fusion energy is to create a burning plasma—one in which alpha particles from the fusion reactions provide the dominant heating of the plasma necessary to sustain the fusion reaction. The objective of creating a burning plasma is to understand the physics of the confinement, heating, and stability of burning plasmas as well as to explore the technical problems connected with the development of a power-producing fusion reactor. A burning plasma experiment is a key scientific milestone on the road to the development of fusion power.”

ITER will be a superb burning plasma experiment. It will show a star can be created on earth by producing 500 megawatts of fusion power. It will enable the creation of a burning plasma with a nominal energy gain Q (the ratio of fusion power produced to external power applied to heat and control the plasma) of ten, sufficiently high that the plasma is dominantly self-heated by the alpha particles. This high gain also enables the alpha particle pressure to be a significant fraction of the total plasma pressure, a key factor in enabling study of the new physics to be encountered in a burning plasma. Its all superconducting magnet technology and steady-state heat removal technology (see Figure 11.1) will enable nominal 500 second pulses to allow study of the control of burning plasmas on time scales longer than the longest intrinsic timescale of the core, confined plasma, the timescale for diffusive redistribution of the electrical currents flowing in the plasma. Its extensive measurement and control systems that allow variation of the plasma state, and long pulse capability will enable understanding of

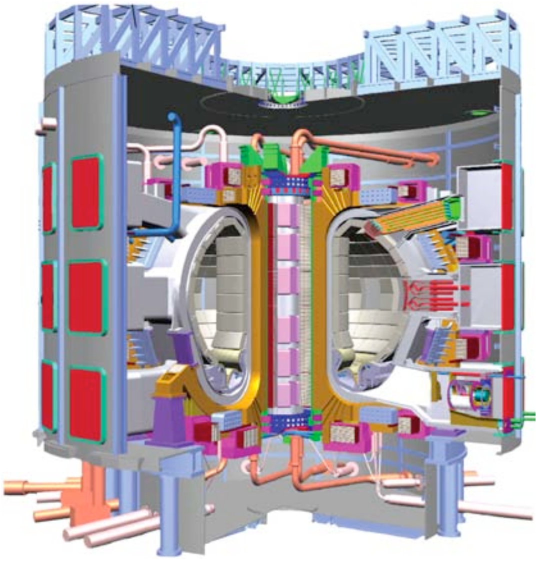

Figure 11.1. Cutaway cross-section of the ITER device.

the burning plasma state. ITER will be a suitable research vehicle for the U.S and world programs to realize the second overarching fusion program goal to create and understand a controlled, self-heated, burning star on earth. The results from ITER on burning plasma physics will be of direct benefit not only to the tokamak but to other magnetically-confined plasmas and results from those experiments will strengthen the scientific basis for experiments on ITER.

The ITER schedule envisions first plasma operation ten years from the start of construction. Hence, given the ten-year planning horizon of this report, the effort in this area will be to prepare the U.S. for a full and effective participation in ITER operation and research. During the next ten years, the U.S will contribute about ten percent of the construction of ITER, building several of its major systems. A discussion of this construction effort is outside the scope of this Report. Described below are efforts, in addition to the U.S. construction contribution, needed to be ready for the U.S. for participation in ITER operation and research.

The specific tasks to be undertaken in this scope in the next ten years are:

- Provide research results from existing U.S. experiments that can impact design decisions not yet finalized, and impact the operation of ITER from first D-T operation at high gain with the plasma lasting a few seconds (the time of energy balance equilibration) to operation where burning plasmas last for timescales longer than the diffusive redistribution time of electrical currents in the plasma (200 seconds).
- Contribute to the development of ITER's plasma measurement systems to ensure ITER can meet its scientific mission.
- Advance theory and integrated modeling derived from theory in order that an advanced simulation capability be available to design experiments on ITER.
- Prepare for exploration of the technical issues of a fusion power producing system.

PROVIDE RESEARCH RESULTS FOR BURNING PLASMA RESEARCH ON ITER

The nominal technical goal of ITER, producing 500 megawatt of fusion power with an energy gain of ten for 500 seconds, will be a major milestone in establishing the possibility of fusion power on earth. However, achievement of this technical goal must be accompanied by a rich program of scientific research. ITER is a burning plasma physics experiment and has the unique obligation to produce the knowledge base on the behavior of burning plasmas.

Continued research in existing experiments can significantly advance the research program on ITER by:

- Impacting design decisions not yet finalized.
- Enabling ITER to incorporate physics advances not made at the time of ITER's basic design.
- Showing how ITER might be initially more effectively operated on the way to its first high gain, burning plasma operation.
- Developing the physics basis for ITER to study plasmas that burn longer than the diffusive redistribution time of internal currents and possibly, eventually, in steady-state.

Provided below is a brief discussion of the main areas of research that will be of interest for burning plasma research on ITER, including a brief description of the current state of knowledge, the research directions for the next ten years, and the implications for ITER. Research issues brought into specific focus by ITER are nonetheless usually broad issues as described more fully in the various chapters on the campaigns. Examples afforded by ITER are related to these broader campaigns.

Macroscopic Plasma Physics

Pressure-limiting instabilities

Recent discoveries require follow-up to motivate possible implementation on ITER of methods to operate with a higher plasma pressure limit. All magnetic confinement configurations have an upper limit to the plasma pressure that can be contained by the magnetic field. In the tokamak, that pressure limit is set by the lowest order possible, long-wavelength helical deformations of the otherwise cylindrically symmetric plasma torus. Progress in research to date has resulted in codes that accurately calculate the thresholds and linear properties of these modes and have been abundantly confirmed by experiments. From this sound physics basis, the nominal operating points for ITER were chosen well below these limits. The study of pressure limits in other magnetic confinement configurations is just beginning. (*See the Macroscopic Plasma Physics Campaign, question T2.*)

An increased pressure limit can allow an increased fusion power output or an increased fraction of the electrical current that flows in the plasma, which is driven by the plasma itself instead of external systems. In the last three years, experiments in the U.S. have confirmed a theoretical expectation that with a metal wall close to the plasma surface this lowest order mode can be stabilized, allowing perhaps up to double the standard pressure limit. In ITER, such an increase in the pressure limit could be used either to achieve ITER's fusion power and gain goals at reduced operating parameters or to increase the self-driven current fraction, possibly enabling pulse lengths of over one hour or eventually perhaps even steady-state operation at full operating parameters.

Research in this area is making rapid progress, but must be continued to motivate implementation of this physics on ITER. To date, stabilization with a conducting wall has been clearly shown in plasmas that spin rapidly. Research is ongoing in plasmas that spin slowly, as ITER might. S*ee later discussion of the physics of spinning and the Multi-scale Transport Physics Campaign, question T5.*)

Confinement-limiting instabilities

Continued research must identify methods of stabilizing or avoiding in ITER the next most important instability, the so-called neoclassical tearing mode, in which smooth plasma surfaces break up into magnetic islands *(see the Multi-scale Transport Physics Campaign, question T6*). These modes also have a pressure threshold. They generally reach a saturated, stable island size in the plasma, forming a heat flow short circuit that lowers the confinement properties of the plasma or can cause difficulties sustaining advanced performance modes. If a tearing mode with the same helicity as the pressure-limiting mode grows too large and stops the plasma spinning, it can lead to the same pressure-limiting phenomena. Again, recent research has shown the ability to completely stabilize these modes with surgically precise microwave power beamed onto the islands. Continued research is needed to establish the best way to approach such stabilization on ITER *(see the Macroscopic Plasma Physics Campaign, question T2, and Waves and Energetic Particles Campaign, question T11*). Avoidance of these modes entirely may be possible by controlling the internal magnetic structure of the plasma, a broad research subject current in many magnetic configurations (*see the Macroscopic Plasma Physics Campaign, question T1*).

Disruption avoidance and mitigation

Research tasks in this area include the development of disruption predictors and mitigation techniques applicable to ITER. Various phenomena are expected when a magnetic confinement configuration reaches its pressure limit. In the tokamak, the pressure limit causes a disruption — an abrupt loss of the energy stored in the plasma, causing very high pulsed heat loads to plasma facing surfaces, very high electromagnetic forces on the vacuum vessel, and generation of high energy circulating beams of electrons which can cause local melting. ITER will aspire to steady-state operation in which the pressure limit will not be reached. However ITER is an experiment to test pressure limits, and because material may occasionally fall into the plasma, disruptions will occur. Their frequency must be kept low and their consequences mitigated. Experiments have recently shown the ability to mitigate all the consequences of disruptions with massive injection of noble gases when a disruption was imminent. Further research is needed to extrapolate these techniques to ITER and develop disruption predictors. *(See Multi-scale Transport Physics Campaign, question T6, and Macroscopic Plasma Physics Campaign, question T2*)

Self-driven and externally-driven electrical currents

Current research can show the way to very long-pulse, perhaps even steady-state operation of ITER with a high fraction of self-driven current. The known methods of driving electrical currents in plasmas have limited efficiencies, leading to high external current drive power requirements. Prospects for higher efficiencies probably lie in the synergistic combination of two of the current drive schemes. However, with limited efficiency, it is important to obtain at least fifty percent of the plasma current from the so-called bootstrap effect in which the current is driven by the pressure gradient. Bootstrap current fractions up to eighty-five percent have been observed, and the measurements of bootstrap current are in good agreement with theory. High bootstrap fractions require operating at lower plasma current, which then requires a higher quality of confinement and stability. *(See Macroscopic Plasma Physics Campaign, question T3.*)

Waves and Energetic Particles

Electromagnetic wave heating and current drive

Continued research with higher power wave systems is needed to establish how to control the current profile in ITER and to stabilize the tearing modes. The theory and experimental basis for using electromagnetic waves to heat plasmas and drive electrical currents in them are very advanced. Predictive codes exist that calculate wave absorption and current drive. Some particular basic physics problems remain in the areas of coupling waves into plasmas from external launching structures and in how waves convert inside the plasma from the launched mode into another mode. But the research frontier here has moved on to the applications of these heating and current drive techniques to controlling the plasma *(see the Waves and Energetic Particles Campaign, question T11*). Localized control of the spatial distribution of electrical currents in the plasma is especially important for increasing the pressure limit and confinement. ITER will be equipped with high power wave systems in two of the three useful frequency ranges. Further research is needed to establish whether including the third type of system is warranted.

Energetic-particle-driven Instabilities

Research tasks for the next ten years must include continued experiments with energetic ions simulating alpha particles, theory and code work to prepare for research on ITER, and particular attention to plasma measurement systems for the alpha particle population and the instabilities these particles may drive *(see the Waves and Energetic Particles Campaign, question T12*). In a burning plasma experiment, theory predicts that instabilities will be strongly driven by the large 3.5-MeV alpha-particle population created by the fusion reactions. Current experiments have been able to show the existence of these instabilities using energetic ion populations from injected radio-frequency waves, neutral beams and from the alpha particles created in D-T experiments at low gain. The consequences of these instabilities could range from beneficial redistribution of the alpha heating power to deleterious loss of alphas from the plasma; only the burning plasma experiments on ITER can fully answer these questions.

Multi-scale Transport Physics

Fundamentals of transport from turbulence

A research plan including codes and turbulence measurement systems must be prepared to ensure ITER can meet its unique mission of understanding transport from turbulence in the regime of low ratio of ion-gyroradius-to-system-size. The leakage of heat, particles, and momentum across the confining magnetic field is produced by turbulence–waves of instabilities on much smaller spatial scale than large scale modes that set the pressure limit. Understanding and calculating the cross-field transport from this non-linearly generated sea of instabilities is a grand physics challenge. To date, fusion researchers have achieved consensus on the basic physical mechanisms that cause heat transport in the ion fluid. The next challenge to be taken up is transport in the electron fluid, which is believed to arise from much smaller spatial scale turbulence, harder to calculate and to see experimentally. Transport of particles and momentum must be studied. These basic transport studies are probably best done in the more accessible current-day experiments. However, ITER will have a special obligation in this area of science, because only ITER can explore the regime of a very low value of one of the basic dimensionless parameters of plasma physics: the ratio of ion-gyroradius-to-system-size in collisionless plasmas. (*See Multi-scale Transport Physics Campaign, question T4.)*

Plasma spinning

Research in current machines with the capability to vary the plasma's spin rate is needed for basic understanding and suppression of turbulence and pressure limiting instabilities in ITER. Toroidal plasmas spin rapidly both the long way around the torus and the short way. Strong spin rates can enable wall stabilization and therefore an important higher-pressure limit. Shear in the plasma spin rate has also been shown to suppress turbulence, improving confinement dramatically. The physics of why plasmas spin is not well known. The simplest model of momentum input being balanced by a diffusive loss is known to be inadequate. Owing to its lower applied torque and higher moment of inertia, such a model suggests ITER will not spin as fast as the plasmas in current experiments. Research in current machines with flexibility to alter the plasma spin rates and in plasmas that spin spontaneously is needed on this fundamental physics issue *(see the Multi-scale Transport Physics Campaign, questions T4 and T5*). The results could affect ITER's neutral-beam configuration, pressure limit, and confinement.

Transport barriers

Continued research on transport barriers is important in preparation for ITER. A "stiff" transport model of plasma turbulence is emerging in which transport from turbulence increases strongly with the temperature gradient, leading to plasmas with very rigid spatial distributions of temperature *(see Multi-scale Transport Physics Campaign, question T4*). Stunning exceptions to this picture have been found in transport barrier, spatial regions about 2-20% of the radius of the plasma in which strong suppression of turbulence is seen, sometimes down to the irreducible minimum transport level set by inter-particle collisions. Two physics mechanisms have been identified for transport barrier formation: shear in E x B flow (of which flow from plasma spinning is a part) and compression of the magnetic field on the outside of the plasma. Transport barriers in ITER may afford paths to higher-gain plasmas for the burning plasma research program. Issues of barrier control and impurity accumulation need to be studied further.

Plasma-boundary Interfaces

The 100-million-degree-C confined plasma is interfaced to its room temperature surroundings through two special plasma regions known as the pedestal and the scrape-off layer (*see question T10*). The research on these two vitally important regions is described in *the Plasma-boundary Interfaces Campaign*.

The edge pedestal

A first principles understanding of the structure of the edge pedestal must be developed to underpin ITER fusion gain projections and solve the issue of pulsed heat loads from the plasma edge. The first transport barrier to be discovered was the so-called H-mode ('high' confinement mode), a transport barrier that forms in a few centimeters just inside the edge of the confined plasma. In that region, turbulence is dramatically suppressed by sheared E x B flow, and the plasma pressure rises steeply. But unknown physics limits the radial penetration of this transport barrier, resulting in an edge pressure pedestal. With the stiff transport model discussed above, the stored energy in the ITER plasma, its overall confinement, and its fusion gain essentially ride up on top of this edge pedestal. Consequently, understanding the structure of this edge pedestal is very important. (*See Plasma-boundary Interfaces Campaign, question T10.*)

Edge-localized modes

The high edge pressure gradient leads to regular periodic instabilities at the plasma edge dubbed for obvious reasons "edge localized modes" (ELMs). These modes regularly dump a large fraction of the edge plasma energy content out of the confined plasma. These modes are benign in current experiments, but in ITER the energy content of each ELM pulse may exceed the ablation threshold for the surface materials on the divertor plates, leading to excessive erosion and short replacement times. This sets up a fundamental conflict between the desire for a high edge pedestal for high energy gain and the large ELM pulses that often result from a high edge pedestal. Continued research is vital to finding a solution to this conflict and many avenues of solution can be pursued. In the U.S tokamaks, two regimes with no ELMs at all have been found. A good theoretical picture of what limits the edge pressure gradient is emerging; one of its cornerstone elements was recently confirmed by direct measurement of the large peak in the plasma current at the edge caused by the bootstrap effect. But the physics that sets the width of the pedestal remains to be discovered.

Edge plasma physics

Current research can show the way ITER can address its unique power and particle control challenges and impact remaining design decisions. Power and particles flow out of the confined plasma through the pedestal region and through the last closed, confining magnetic surface onto open magnetic surfaces. These flows on the open field lines go along the magnetic field direction in a few centimeter wide layer, the so-called scrape-off layer and connect to specially engineered divertor structures which can provide pumping of particle fluxes and steady-state removal of the concentrated high heat fluxes. The heat concentrations can be large and the divertor surfaces will be continuously eroded. The eroded material will migrate around the plasma in the scrape-off layer and redeposit somewhere. Redeposited carbon atoms can bury tritium atoms with them, potentially causing an undesirable holdup of tritium in the vacuum vessel.

Various 2D fluid and Monte-Carlo codes exist which treat the most dominant physical processes in the scrape-off layer: plasma and impurity flows, atomic radiation, plasma energy flows, and neutral fluxes. The cutting edge areas of this research both in computation and experiments are in the 2D flow patterns of the plasma, which in turn dominate the migration and redeposition of eroded divertor and first wall materials. While ITER has selected a first set of plasma facing materials to be installed in various areas, the final choice of these materials can still be affected by research results in this area until about five years before first plasma.

The density limit

Ongoing research on the cutting edge of the density limit issue is important since fusion power production and plasma purity both improve as the plasma density is raised. There is an upper limit to the plasma density, above which instabilities, like those that limit the plasma pressure, are encountered (*see Plasma-boundary Interfaces Campaign, question T10*). The density limit is very accurately described by an empirical scaling rule. A first principles physics understanding of this density limit remains to be found. Various partial answers have been developed. High density in the scrape-off layer has the benefit of lowering heat and plasma fluxes to the divertor structures (even to the limit of the plasma recombining before it reaches the divertor plate!) but thermal collapse of the plasma in the divertor and scrape-off layer can also result, leading to a density limit termination. Excessive impurity radiation in the pedestal region can also cause a density limit. The current cutting edge question regarding density limits is whether there is a rapid increase and change in the plasma's turbulence driven transport in the pedestal and scrape-off layer regions as the density limit is approached.

The Integrated Nonlinear Burning Plasma System

Continued research on present experiments and in modeling can prepare the U.S. to take a lead role in ITER's principal research challenge: the complex integration of all the previously discussed physics elements interacting non-linearly to support a stable, steadily burning plasma state. ITER has been designed to not only create a burning plasma state for one energy equilibration time (a few seconds) but also to be able to sustain such a burning plasma beyond the longest relevant time-scale for the confined plasma – the timescale for diffusive redistribution of the internal electrical currents (about 200 seconds in ITER). Burning plasma research on these timescales will enable confrontation of perhaps the most exciting challenge: the study of the total, integrated, nonlinear physical system that supports a stable, steadily burning plasma state.

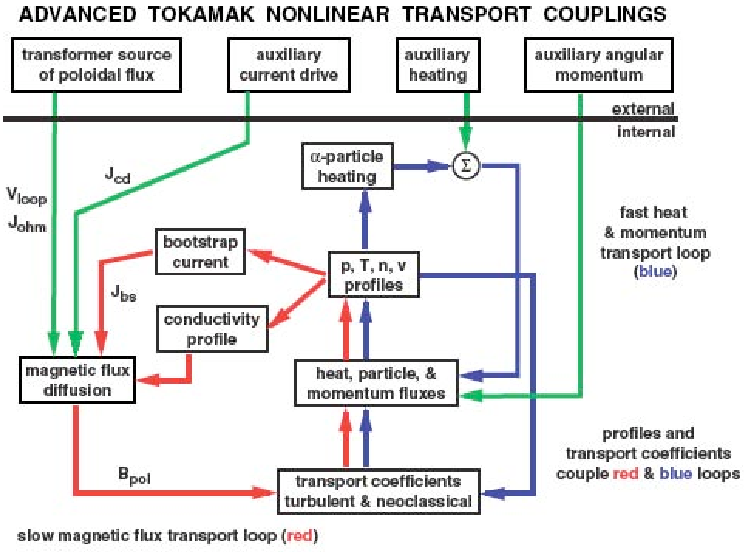

Figure 11.2. Illustration of complex feedback loops and non-linear couplings among basic plasma phenomena that result in the final burning plasma state.

Such plasma states are replete with complex internal feedback loops and couplings (see Figure 11.2). The dominant internal source of heat in the plasma will be from alpha particles produced in the fusion reactions, and the spatial distribution of that heat source will depend on the spatial distribution of the plasma pressure. But the pressure distribution itself is determined by the dominant alpha particle heat source and external sources of heat and particles and the spatial profiles of the plasma turbulence. The plasma turbulence is in turn determined by the gradients of the plasma temperature and density (which make up the plasma pressure) and is also profoundly affected by the spatial distributions of plasma current (or magnetic field) and the radial electric field.

Plasma regimes of interest for steady-state have most of the plasma current self-generated by the plasma pressure gradient (the bootstrap effect). Also the radial electric field is determined from the plasma pressure gradient and the toroidal and poloidal plasma flows, so momentum sources also enter into determining the system state. And having high values of the plasma's self-driven current and high fusion power require operating near high plasma stability limits that may require stabilization by a nearby conducting wall with sufficient plasma rotation and/or fine local control of the plasma current distribution. Hence all of these physical phenomena described in the various campaigns are linked together with complex dependencies near operating limits. Studying the complexity of this coupled physical system will be a principal area of research in ITER and the preparatory research leading up to ITER operation.

MEASUREMENT SYSTEMS FOR BURNING PLASMA RESEARCH

The U.S. fusion program must support the development of new measurements and adaptation of known measurement techniques to enrich the research program on ITER. ITER must be an outstanding research instrument. The quality and completeness of its plasma measurement and control systems will be a determining factor in the quality of its research output. A very extensive plan of plasma measurement systems has been prepared. Various systems have been distributed among the ITER parties. The United States will fulfill its commitments to provide its assigned measurement systems within the scope of the ITER project.

Beyond these commitments, all parties to ITER have the obligation to bring to ITER their very best scientific resources, including imagination and creativity in devising new measurement systems. The plasma measurement system on a research instrument as important as ITER will continuously evolve and improve, despite the new challenges of undertaking plasma measurements in a neutron environment *(see Chapter 9*).

Two areas of particular need are plasma turbulence and energetic particle measurements. As discussed above, ITER will explore plasma turbulence in a regime not accessible by any other experiment. Consequently there is an obligation to do a superior job of turbulence and confinement studies in this regime. The creation of an energetic alpha particle population from the plasma's own fusion reactions to self-heat the plasma is almost the simplest statement of what it means to realize a burning plasma. It is vital that detailed measurements of the alpha particle population be made, and yet these measurements are among the most difficult identified in the ITER plan.

THEORY AND INTEGRATED MODELING

An integrated simulation capability is needed to draw together the building blocks of knowledge and the experts in those scientific areas in the ten years leading up to ITER operation. Perhaps the biggest and most exciting research challenge offered by ITER is to understand the total, complex, non-linear burning plasma state (see above discussion and Chapter 9). An understanding of that complex state should eventually be expressed in a theory-based, integrated computational model of all the physical phenomena discussed earlier in this chapter. Moreover, research time on ITER will be very valuable. Research proposals will be more readily accepted and lead to better experiments, if comprehensive computational simulations of the experiments can be performed to support the proposals.

The substantial progress made to date in fusion research has been largely captured in computational models of individual physical phenomena. The cutting edge effort now is to combine this body of knowledge into ever more integrated computational models, so that the complexity of the total, integrated system can be exhibited in simulations. Since these physical phenomena entail a wide range of temporal and spatial scales, self-consistent integration of all the phenomena remains an outstanding challenge.

ISSUES OF A FUSION POWER PRODUCING SYSTEM

Fusion Engineering Science

Power exhaust

ITER will challenge the fusion research community with the first large-scale production of fusion power (500 MW). The alpha particles deposit 100 MW of that power in the plasma. Up to possibly 100 MW of auxiliary power applied to heat the plasma and drive its currents will result in a total of 200 MW of power to be exhausted from the vacuum chamber with steady-state heat removal technology. No experiment to date has had anywhere near the challenge of so large a power exhaust. ITER poses new challenges to develop applicable plasma operating modes in the scrape-off layer and divertor, the development of erosion-resistant, high-heat-flux handling surfaces, and the cooling systems behind them (*see Plasma-boundary Interfaces Campaign and Fusion Engineering Science Campaign*).

Neutron effects and blankets

The U.S. fusion community must prepare for test blanket studies and the general study of neutronics in ITER. The fusion neutrons will carry 400 MW out through the first wall into the shield assembly and into the test blanket modules. No fusion experiment has had to deal with such high neutron fluxes or fluences. The subject of neutronics on ITER, how the fusion neutrons and their energy become distributed, will be an important element of science on ITER. Neutron effects on components of plasma measurement and control systems will be a primary consideration. Test blanket modules will be fielded on ITER to learn how to capture the energy of the neutrons and breed tritium from lithium using these neutrons *(see Fusion Engineering Science Campaign*). The blanket module tests will become increasingly valuable as the pulse length of ITER is extended to one hour or perhaps several hours.

Long-pulse operation

Continued research can build a basis for extended pulse or perhaps even true steady-state operation of ITER. Nominally ITER will operate in a 500-second pulsed mode with the plasma current sustained by induction from its large Ohmic heating transformer. But current research is pointing toward operating modes for ITER that could stretch the inductive pulse length to perhaps an hour. And beyond that, research on auxiliary current drive and high self-driven current fractions is promising for true steady-state, with none of the current supplied by induction. Essentially all of ITER's systems are designed for steady-state heat removal except the size of the final heat reservoir. A larger cooling reservoir or more cooling towers are modest cost upgrades, if the physics of steady-state operation can be developed (*see Campaigns on Macroscopic Plasma Physics, Waves and Energetic Particles, and Fusion Engineering Science and Enabling Research Activities*).

Particle fueling, exhaust, and tritium handling

Continued research is needed on alternatives to gas fueling and erosion of various types of plasma facing surfaces, the transport of these materials in the plasma, and the eventual redeposition of these materials. ITER will have a steady-state type closed loop recirculation system for fuel and other gases. Fuel (deuterium and tritium) and small amounts of noble gases (for radiating power) will be input to the vacuum chamber. The fuel will mostly be input as gas, but alternative methods of fueling deeper into the plasma have advantages. Deuterium, tritium, impurities, and helium ash must all be separated in the exhaust stream. Only a small amount of the fuel is burned in the plasma in one circulation pass. Tritium must be carefully accounted for in all parts of the recirculation system. Of particular concern is tritium retention in the vacuum vessel by co-deposition with eroded first wall and divertor materials (*see Campaigns on Plasma-Boundary Interfaces and Fusion Engineering Science*).

Superconducting magnets

The construction of ITER's superconducting magnets must be supported with continued R&D on strand types, conductor assembly, and full magnet systems. ITER's ability to do research on relevant, long burning plasma time scales is enabled primarily by its superconducting magnets. While benefiting from the ITER Engineering Design Activities full-scale prototype program, important details of the magnet construction need to be supported with a continued R&D program on superconducting magnet technology (*see Fusion Engineering Science Campaign*).

Auxiliary heating and current drive systems

Continued development of plasma heating and current drive systems will be a decisive factor in how far ITER can progress in advanced, long pulse or even steady-state burning plasma research. Auxiliary heating systems must heat the ITER plasma to the burning plasma condition. To sustain the burning plasma, the spatial distribution of electrical current in the plasma must be controlled by the various neutral-beam and radio-frequency auxiliary systems to enable the plasma to enter a state of high self-driven current. Continued research in current devices on the application of these current-drive techniques and research on their technical application on ITER in terms of coupling to the plasma, steady-state cooling of components, insulators in the neutron environment, and applicable radio-frequency sources is needed (*see Campaigns on Waves and Energetic Particle, and Fusion Engineering Science*).

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3. "*Burning Plasma—Bringing a Star to Earth,"* (National Academies Press, 2004)

12

DEVELOP THE SCIENCE AND TECHNOLOGY TO REALIZE FUSION ENERGY

INTRODUCTION

It is a grand scientific and technical challenge to configure an energy-producing fusion system. This requires establishing the scientific basis for systems with high mass-power density and low recirculating power to create and confine the energy-producing plasma. The high-pressure high-temperature plasma must be created and confined in steady-state or quasi-steady-state for efficient power production. For magnetic fusion energy, this requires levels of noninductive current, stability, and confinement, which have not yet been demonstrated experimentally in combination or for long pulses. For inertial fusion energy, this requires stability, effective coupling of the driver to the imploding capsule, and efficient repetitively pulsed drivers combined with the ability to rapidly manufacture fusion fuel targets. Stellar-grade plasmas with large heat and energetic particle fluxes must be interfaced to solid and liquid materials. The interaction of the fusion-produced neutrons with these surrounding materials must be understood. Advanced materials must be developed to ensure attractive environmental properties. All parts of the fusion fuel cycle must be developed and understood. Configuring and controlling these elements simultaneously to provide practical fusion energy is a major challenge to both physics and engineering science.

The past decade has seen dramatic advances in the science and technology of both magnetic and inertial fusion energy, made possible by advances in detailed plasma measurement techniques and in advanced computing. These advances are a product of progress made in developing the underlying science and technology with the goal of developing fusion energy. As noted by the National Research Council Report on Burning Plasma,[1] “The ultimate success of producing an economically attractive new energy source is far in the future, and many outstanding scientific and technical issues have to be resolved before the path forward is well-defined.” The report goes on and recommends, as has a previous NRC report that, “…the U.S. fusion program focus on addressing the compelling scientific issues and thereby strengthen the underlying science base of a fusion energy source.” While these comments were focused on the magnetic fusion program they are equally true for inertial fusion energy. The emphasis on developing the underlying science is a central theme throughout this panel report and is consonant with the goals of this overarching theme, while keeping the long-term goal of fusion energy in focus.

RELATIONSHIP TO THE CAMPAIGNS

In magnetic fusion, there is a highly nonlinear interaction between the plasma and the magnetic field configuration containing the plasma, and in inertial fusion the interaction occurs between the plasma and energetic radiation responsible for compressing the plasma. In a burning plasma experiment and even more so in a fusion power plant, there will be a similarly complex interaction between the burning plasma and the plasma chamber responsible for extracting heat, and in the case of the power plant, breeding tritium. The highly nonlinear interaction between the different scientific and technical issues creates both scientific opportunities and challenges. While the path forward to fusion energy remains to be well defined, the scientific and technical issues, which need to be addressed for the next decade, are well understood and motivate the research being conducted as described in Chapters 3 through 8. The relationship of that research to the goals of this overarching theme is summarized below.

For magnetically confined plasmas, progress in the research described in Chapters 3, 4, 6, and 7 has a direct impact on realizing fusion energy.

Macroscopic Plasma Physics

Understanding the macroscopic behavior of a plasma and how to control it is critical for fusion energy. The confining magnetic field structure is one of the primary experimental control variables and a fundamental understanding of the role of shape, internal magnetic field distribution, and self-driven currents will further the ability to optimally confine and stabilize plasmas for fusion energy applications. Understanding how long-scale instabilities, short-scale instabilities, and equilibrium control set limits on the confined plasma pressure is also critical to avoid rapid disruptive events and operate fusion devices reliably. Since the fusion reactivity and power production increases approximately as the square of plasma pressure, understanding and extending these limits is of large benefit for fusion. Understanding the way external control couples to the self-organized behavior of plasmas and how to optimize this is a necessary step for improved fusion power systems. Desirable aspects of self-organized behavior

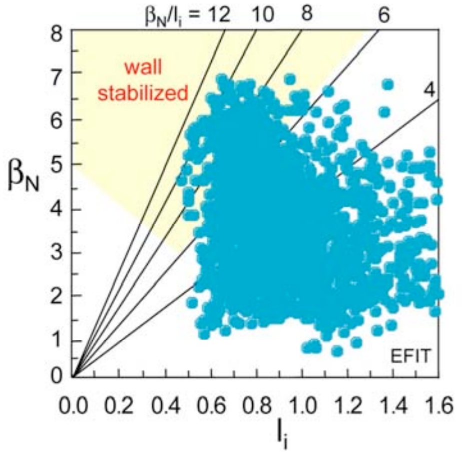


Figure 12.1. The understanding of long-scale instabilities has enabled the attainment of high values of β_N (a measure of normalized plasma pressure) in discharges with broad current profiles (low values of l_i) resulting in values of β_t ~39% in the National Spherical Torus Experiment. Spinning the plasma and using the wall to suppress the instability enables the improved performance. (Courtesy of S. Sabbagh)

include efficient steady-state current drive, simplified external coil geometry, or high plasma pressure limits relative to magnetic field strength. Desirable aspects of external control include steady-state external fields, improved equilibrium stability, improved particle-orbit confinement, or beneficial plasma flows.

Multi-scale Transport Physics

The relationship between the macroscopic properties of a plasma and the underlying nonlinear dynamics of plasma turbulence and self-organization needs to be understood to develop fusion energy. Plasma turbulence can have a profound effect on the transport of particles, heat, and momentum throughout the plasma and the formation of localized transport barriers within the plasma. Understanding and controlling these processes directly affects the plasma confinement time and the internal plasma profiles, which in turn directly affect the fusion energy gain of the whole system. In many cases, the internal profiles of magnetic field and plasma flow are strongly modified by the plasma itself. If understood and controlled, this could substantially relax the demands on external current and flow drive, resulting in more efficient fusion systems. The breaking and reconnection of magnetic field lines in microscopic regions can lead to large-scale instabilities and very energetic particles which can damage vessel components or limit plasma parameters. To adequately predict when these effects will occur and to develop methods to control them requires fundamental understanding of the spatial and temporal characteristics of the magnetic reconnection region and how this affects the evolution of the instabilities.

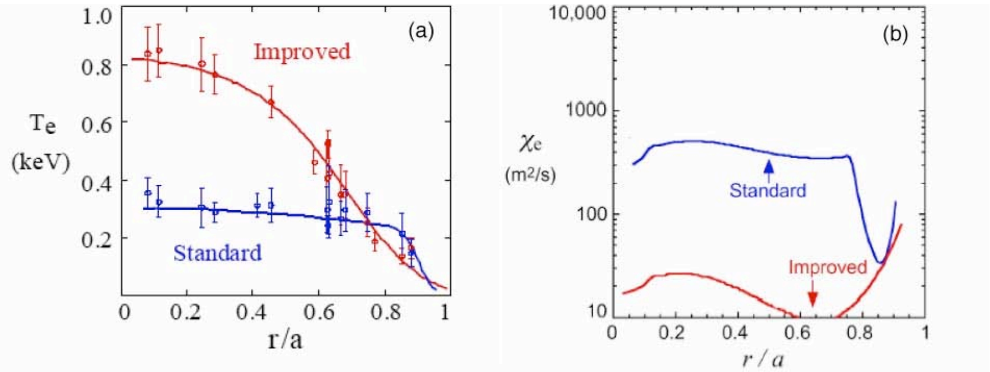


Figure 12.2. In the Reversed-field Pinch, large magnetic fluctuations driven by the current density gradient previously resulted in flat temperature profiles (a), and a large thermal diffusivity (b) in the core of the plasma. With improved control of the current density profile, the driving source for this turbulence has been reduced, resulting in peaked temperature profiles and an order-of-magnitude lower thermal diffusivity. Data shown were measured in the Madison Symmetric Torus (MST) experiment. (Courtesy of D. Craig)

Plasma-Boundary Interfaces

The challenge of interfacing a 100 million degree-C burning plasma to its room temperature surroundings requires a combination of physics control of the outer plasma boundary and engineering control of the plasma surface dynamics. The density and temperature at the very edge of the plasma is predicted and observed to have a major impact on the plasma energy and hence, the fusion energy released. The formation, structure, and stability of the edge transport barrier or “pedestal” must be understood to optimize the performance of future fusion devices. The transport of particles and heat in the transition region just outside the plasma, where magnetic field lines carry plasma directly to material surfaces, is determined by a complex set of processes including turbulence, radiation, bulk flows, macroscopic instabilities, atomic physics, and the magnetic configuration. Understanding how these effects extrapolate to long-pulse or steady-state conditions and developing materials and design solutions that can manage the heat load are critical for fusion development. The erosion, transport, and redeposition of material as a result of normal operation as well as disruptive plasma terminations can modify surface structures and strongly affect the retention of fuel gases including tritium.

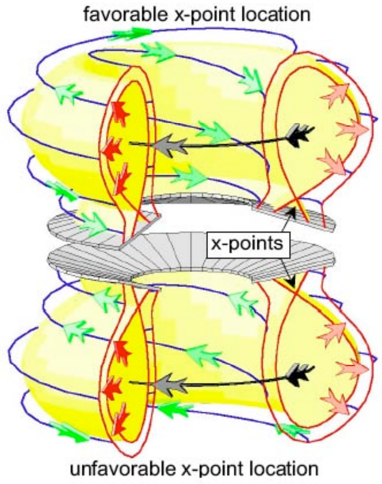


Figure 12.3. Recent experiments on Alcator C-Mod indicate that transport-driven plasma flow in the boundary can affect the conditions under which a transition to improved confinement takes place. (Courtesy of B. LaBombard)

Waves and Energetic Particles

Externally injected electromagnetic waves and energetic particles can heat a plasma, as well as drive currents and flows, providing a powerful tool to control the plasma. To fully exploit electromagnetic waves, a complete understanding of the coupling to the plasma, the wave propagation and absorption mechanisms is needed. This is required to understand how much power can be launched into the plasma and optimize the effectiveness of the waves in heating and driving currents and flows. Energetic alpha particles produced by fusion reactions can also excite plasma waves, which in turn can affect the distribution of the alpha particles.

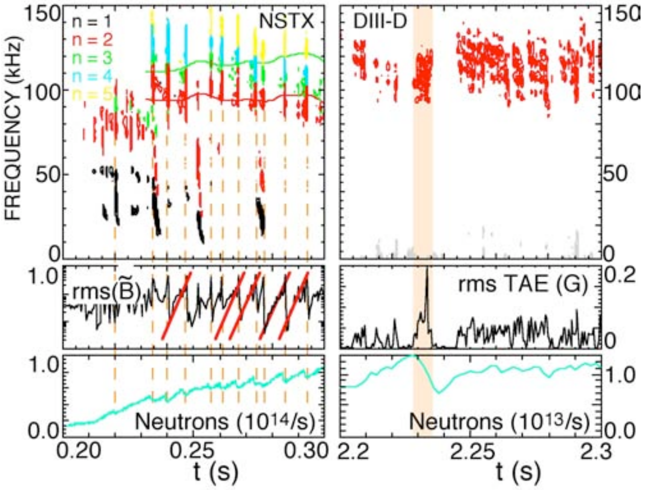


Figure 12.4. Energetic-particle-driven instabilities can result in the loss of energetic particles, as shown by the drop in neutron emission, and may have a profound effect on burning plasmas. The frequency and magnitude of the oscillating magnetic field perturbations are shown. (Courtesy of E. Fredrickson)

Understanding the excitation and damping of these instabilities and their effect on the plasma is critical for using alpha particles most efficiently and reliably in fusion devices. Coupling this understanding with the fully integrated effects of plasma transport, stability, equilibrium, and fueling is a challenging but necessary step in making fusion practical.

The phenomena in a magnetically confined plasma are mutually interacting and interconnecting across the full range of spatial and temporal scales and are typically highly nonlinear. Understanding their interaction, which self-consistently organizes the plasma state, is an important aspect of the fusion energy sciences research program. Examples of these self-organizing processes include:

- Turbulence-generated flows that regulate the turbulent transport, thus changing the pressure gradient and the macroscopic electromagnetic stability properties.
- Plasma-generated currents, including those driven by the pressure gradient, that modify the magnetic field structure, changing transport and macroscopic stability. These currents may also sustain the magnetic configuration.
- Plasma interactions with the bounding wall that control the edge source of neutral atoms and impurities, affecting the edge temperature, plasma density, and impurity content. This can modify the transport properties, the pressure profile and the macroscopic stability.
- Plasma fusion-generated alpha particles that will be produced in burning plasmas in proportion to the pressure squared and may directly affect macroscopic stability and interact with the material wall. The alpha particles will be the dominant source of heat to the plasma and, thus, will affect the pressure profile and the macroscopic stability.
- Interactions between the fusion products (neutrons and alpha-particles) that interact with the surrounding wall, coils, and tritium-producing blanket must also be considered in the self-consistent engineering of the plasma confinement in a fusion power plant.

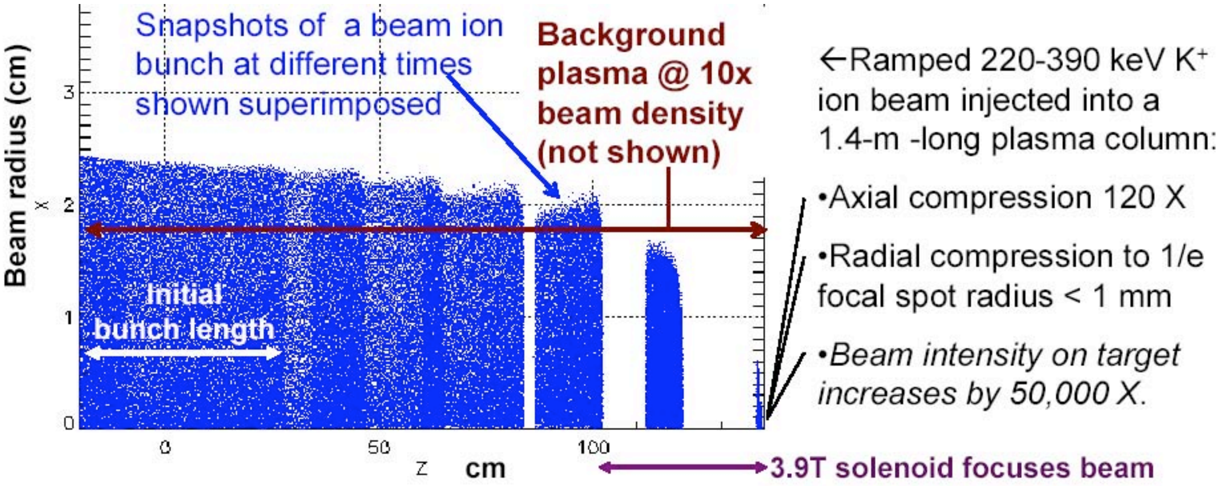
Many of these interactions are highly nonlinear, due to destabilization of particular plasma instabilities, changing the saturated state of turbulence, or the underlying fundamental nonlinearities (e.g., of the self-driven currents). In addition, these interactions depend on the configuration of the magnetic field and strongly change with plasma parameters, in particular the plasma collisionality and the effective plasma size.

The degree to which self-organized phenomena dominate the plasma equilibrium varies with magnetic configuration. Optimizing the desirable potential aspects of self-organized behavior in combination with desirable aspects of external control offers several options for improved burning plasmas that are critical to achieving burning plasmas and practical fusion energy. It is particularly important to understand self-organization and external control at the plasma parameters (collisionality, effective size, normalized pressure) approaching those encountered in a magnetically confined burning plasma.

The scientific issues for high energy density physics are described in Chapter 5. High energy density physics develops an understanding of the underlying physics governing the use of highly compressed ion beams, fast ignition with short-pulse lasers, and magnetized plasma-liner implosions for the creation of high energy density matter. This research, in conjunction with research funded by the National Nuclear Security Administration, provides the knowledge base to compress and heat matter to sufficiently high temperatures and densities in support of inertial fusion energy. In high energy density plasmas, of interest for inertial fusion energy, not only are the times scales and spatial scales vastly different from that of magnetic fusion but the physics is as well.

High Energy Density Physics

The significant advances in scientific understanding and enabling technology described in Chapter 5 in pursuit of the high energy density physics campaign objectives can be expected to lead to improved prospects for inertial fusion energy. Some examples include: The exploration of the physics limits to ion pulse compression within neutralizing background plasma, together with novel focusing methods, are essential to achieving cost-effective accelerator-driven high energy density physics in the laboratory, and may also lead to more compact, lower-cost modular accelerators for inertial fusion energy. The study of fast particle beams created by intense short-pulse lasers will allow the investigation of novel regimes of relativistically heated laboratory plasmas, and the knowledge gained for this research may also lead to so called “fast-ignition” targets that require lower driver energy for inertial fusion energy applications. The study of high-pressure, magnetically insulated plasmas driven by compressing metal liners will extend magnetically confined plasma physics to regimes intermediate in density between magnetic and inertial fusion, and may lead to an understanding of how to make low-cost, high-gain fusion energy systems that embody aspects of both inertial and magnetic confinement.



←Ramped 220-390 keV K^+ ion beam injected into a 1.4-m -long plasma column:

- Axial compression 120 X
- Radial compression to 1/e focal spot radius < 1 mm
- *Beam intensity on target increases by 50,000 X.*

Figure 12.5. The particle simulation shown in this figure (courtesy of Dale Welch) shows that injecting the charge bunch into background plasma with a velocity tilt ramping up from the bunch head to the tail can result in dramatic shortening of the beam pulse and increases in beam intensity at the focus. If successful, these experiments will enable use of intense short pulse heavy ion beams to create and study uniform, strongly coupled, high energy density plasmas (courtesy of B.G. Logan).

Finally innovations in materials and advances in engineering sciences and systems are sought that will be required to breed the fuel (tritium) and to confine and control both magnetically and inertially confined fusion plasmas.

Fusion Engineering Science

Materials and plasma chamber systems must provide simultaneously for power extraction and tritium breeding, and will play a critical role in determining the ultimate attractiveness of fusion power because of the need for high power density, high thermodynamic efficiency, high reliability, fast maintainability, long lifetime, and low long-term radioactivity. Meeting these simultaneous demands in the multiple-field, intense fusion environment, and complex plasma confinement configurations are a challenge that requires important advances in several scientific fields and engineering applications. In addition to addressing the key technical issues for the development of fusion energy, advances in engineering sciences during the next decade will have a direct impact on preparations for a burning plasma experiment, as discussed in Chapter 11, and on supporting ongoing experiments. The fusion program requires the development and deployment of various tools to create, confine, understand, and control plasmas. These technologies are essential to enable existing and near-term experiments to achieve their scientific research and performance goals. Real-time plasma control requires an integrated set of tools to monitor plasma parameters and responding technologies such as: plasma heating, current drive, and fueling systems that raise the plasma temperature and density and manipulate plasma properties to access advanced operating regimes; pumping systems for control of edge plasma conditions and particle exhaust; and magnets that provide the forces for confining, shaping and controlling the plasmas in magnetic fusion devices. In inertial fusion energy, fabrication of the fusion targets and the development of the drivers (which are durable enough to provide sufficient availability, efficient enough to realize net energy, and operate at a sufficient repetition rate to produce meaningful fusion power) and the final optics (which can withstand the intense radiation conditions) are key technical issues for the development of fusion energy.

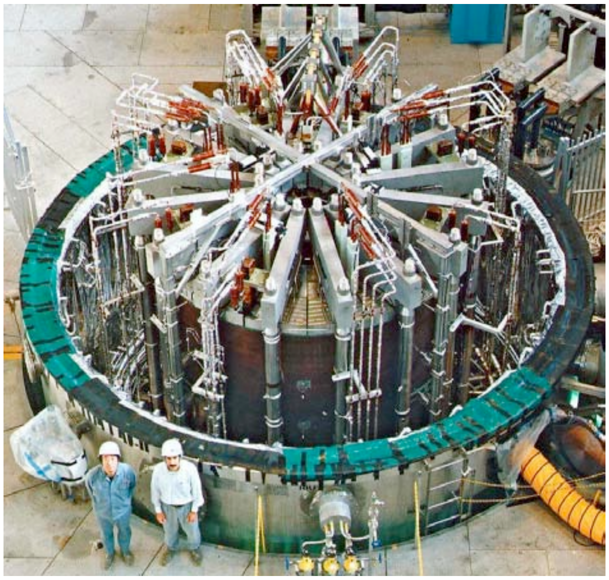


Figure 12.6. In support of ITER, the U.S. and Japan constructed the superconducting central solenoid model coil. (Courtesy of J. Minervini)

REFERENCE

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13

RECOMMENDATIONS ON PRIORITIES

This chapter deals with the Panel's considerations and recommendations regarding the scientific priorities of the U.S. Department of Energy Office of Fusion Energy Sciences' research activities. The Panel's considerations focused on the next ten years and on the scientific campaigns and their related topical scientific questions as described in the previous chapters. The panel did not deal with specific budget levels for specific years or with specific institutions or facilities. Thus, the Panel's perspective was a top-level view with an emphasis on the general scientific needs and priorities within the Office of Fusion Energy Sciences' program.

Recommendation 1: The scientific challenges of fusion energy and the opportunities for discovery in plasma physics should be addressed by a research program that encompasses a broad range of key scientific questions.

In plasma, many physical effects couple together to form a complex, nonlinear system. These effects need to be understood in isolation as well as in combination. The development of engineering systems to control the plasma and extract the fusion heat requires extensive engineering research. The interface between the hot plasma and surrounding material structure requires advances in both physics and engineering. The attainment of fusion energy demands an understanding of this full range of scientific issues. The panel has grouped the issues into six scientific campaigns, illustrated in Figure 1. Since progress in all six campaigns is essential, it is not possible to prioritize them by rank ordering. However, the level of effort devoted to each campaign should not necessarily be the same. After carefully examining the scientific advances needed in each campaign, the panel recommends the approximate division of effort for the next ten years as shown in the figure. This division of effort is similar to that of the present program, however the activities within each category will evolve over the next decade as the first operation of a burning plasma experiment is approached.

Substantial progress can be made in addressing the fifteen topical scientific questions described in the report under the assumption of constant level-of-effort for the domestic program (in addition to ITER construction), over the next decade. Anticipated advances in each area were identified through extensive interactions with the fusion community through the working groups (see Appendix C). These efforts will broaden and advance the basic understanding of plasma physics and related sciences, enable effective utilization of a burning plasma experiment, and provide the underpinnings to realize the advancement of fusion energy.

For example, in the macroscopic plasma physics area, substantial progress is expected in understanding the role of the magnetic field structure on plasma confinement, including the effects of 3D shaping and different types of symmetry. The studies of the role of internal magnetic structure on confinement will be nearly completed for tokamaks, in preparation for ITER. Experiments attempting to understand and control pressure-limiting phenomena and to mitigate the consequences of any rapid current quenches or 'disruptions' are presently being conducted. Within ten years, a detailed understanding of pressure limits in rotating plasmas with resistive walls should be completed, and studies of active stabilization without rotation will be well underway. Disruption mitigation techniques for ITER will have been developed. An understanding of magnetic reconnection, including methods of suppression, should be complete and documented in axisymmetric configurations. Methods to sustain the plasma duration will have been developed, including methods to enable operation of ITER as a long-pulse, burning plasma experiment.

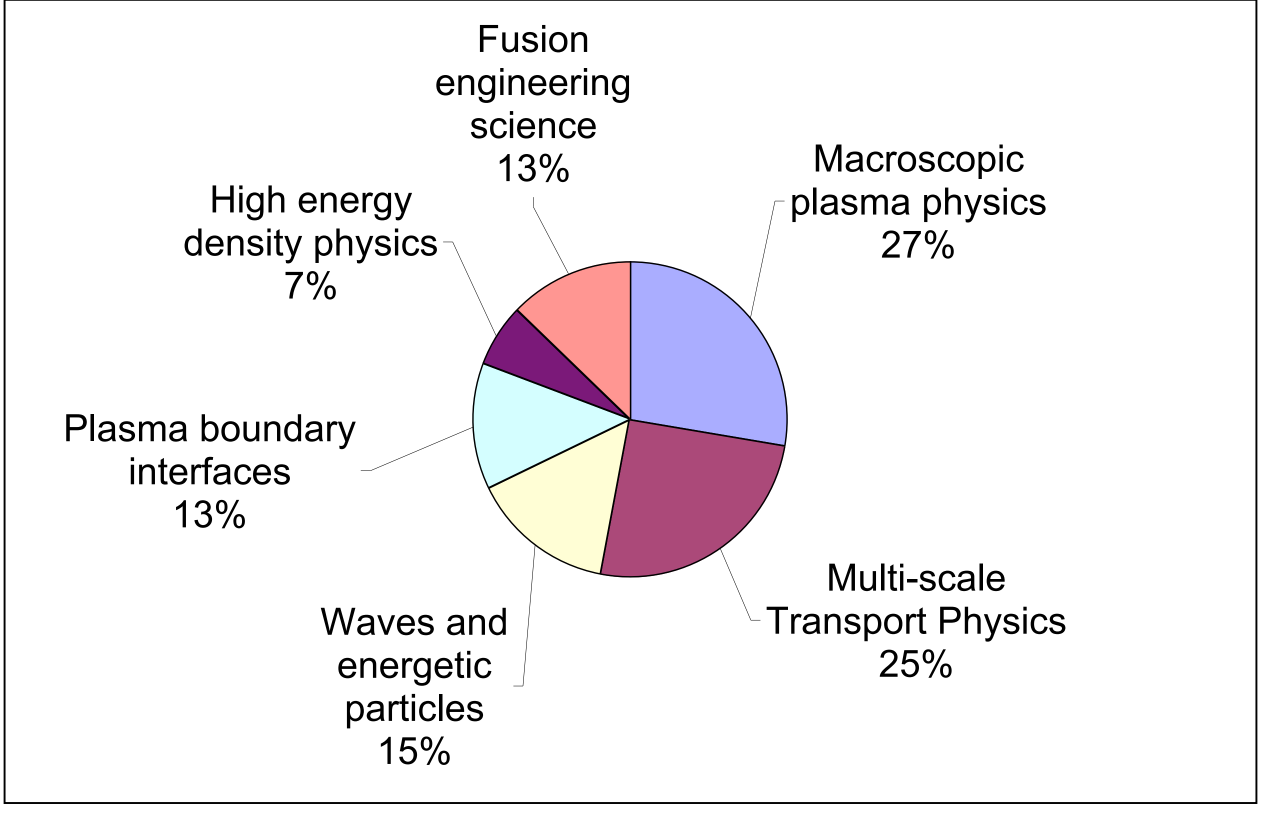

Figure 1: Approximate recommended distribution of effort among the six scientific campaigns.

In the multi-scale transport physics area, the goal of developing a predictive capability for ion thermal transport is within reach for the tokamak. The understanding of electron thermal transport is not as advanced but progress is expected in understanding the role of turbulence. While particle and momentum transport studies are less mature, the most important mechanisms will be incorporated into transport models and the models will be tested against experimental results. A more complete understanding of the conditions and thresholds for edge and core transport barrier formation, and of their dynamics, will be obtained and used to control the levels of core transport. In addition, experiments to detect zonal flows and their effects have begun, and within ten years it will be possible to make comparisons with theoretical and numerical models. Large scale flows, especially in plasmas without dominant external flow drive, will be documented, and analysis should enable predictions for ITER-relevant burning plasma regimes. Understanding and control of transport will have a direct impact on the performance of ITER, and substantial progress is expected in this area. Significant advances are anticipated in understanding and controlling transport in the range of magnetic configurations that are less well developed. Studies of large-scale magnetic field generation should lead to identification of the dominant mechanisms by which turbulence generates and sustains large-scale magnetic fields (the dynamo) in high-temperature plasma. Finally, experiments and modeling of magnetic reconnection in laboratory plasmas will identify the dominant processes that facilitate the breaking of magnetic field lines.

In the high energy density physics area, an integrated program of beam experiments with theory and simulations will be carried out to understand the limits to neutralized drift compression and focusing of intense ion beams onto targets. Experiments with short-pulse lasers and simulations will be carried out to develop a basic understanding of the electron generation for high incident laser intensities and relativistic electron transport in dense matter. Experiments of magnetized plasma compression (with minimal theory support) will also be carried out sufficient to understand the scientific and engineering basis for magnetized target fusion.

In the plasma-boundary interface area, simplified first-principle models will be developed of the edge transport barrier to reproduce many of the measured characteristics of the boundary plasma in current fusion experiments. This will result in improved predictions of ITER's performance. The fundamental characteristics of edge turbulence in high-confinement plasmas will also be determined. There should be a sufficient set of data, with supporting theoretical analysis, to quantify the major impurity sources and the physics, which determines the observed divertor and first-wall erosion and redeposition rates. The distribution of expected tritium trapped in carbon-based plasma-facing components will be largely understood in terms of plasma conditions observed in present-day experiments, and candidate techniques for tritium removal will be tested. Also, qualification of alternative high-heat-flux components will bring us to the point of readiness for testing in longer-pulse confinement experiments.

The research activities in the wave and energetic particle physics area are expected to make considerable advances in developing the fundamental physics models for wave coupling, propagation, absorption and plasma responses that will enable coupling on critical time scales with plasma stability and transport models for validation against experiments. The understanding of radio-frequency sheath effects and edge parameters on antenna loading will be improved. In the validation of wave propagation, absorption, and current-drive physics, more widespread deployment of advanced diagnostics for wave detection will quantify the theoretical models. Progress in understanding the behavior of energetic particles and unstable waves that can be excited by energetic particles for regimes of high pressure and strong flow is expected to enable exploration of improved plasma performance in future burning plasma devices.

In the fusion engineering science area, the U.S. program will continue to perform much of the R&D and design work needed for the provisionally assigned U.S. in-kind contributions to ITER. The research on enabling technology will directly contribute to experiments on heating and current drive, plasma fueling, disruption mitigation, and power and particle control.

Considerable progress is expected in developing the knowledge base required to determine the performance limits and identifying innovative solutions for the plasma chamber systems and materials. A comprehensive, experimentally validated suite of multi-scale material-modeling codes will be developed. The ten-year goal is to deliver to ITER the blanket test modules required to understand the behavior of materials and blankets in the integrated fusion environment. Under constant level-of-effort, the U.S. will rely mostly on variations of designs led by Europe and Japan for the full test modules. Also, progress is expected in determining the "phase space" of plasma, nuclear, material, and technological conditions in which tritium self-sufficiency and power extraction can be attained.

Recommendation 2: U.S. strength in fusion energy sciences research, U.S. impact on international burning plasma research, and progress towards answering the key scientific questions will be enhanced by an additional allocation of $100M per year for the domestic program for the following selected high-priority activities:

- Carry out additional science and technology activities supporting ITER including diagnostic development, integrated predictive modeling and enabling technologies. *(Most campaigns)*
- Predict the formation, structure, and transient evolution of edge transport barriers. *(Plasma boundary interfaces)*
- Mount a focused enhanced effort to understand electron transport. *(Multi-scale transport physics)*
- Pursue an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas. *(Macroscopic plasma physics)*
- Study relativistic electron transport and laser-plasma interaction for fast ignition high energy density physics. *(High energy density physics)*
- Extend understanding and capability to control and manipulate plasmas with external waves. *(Waves and energetic particles)*
- Increase energy ion pulse compression in plasma for high energy density physics experiments. *(High energy density physics)*
- Simulate through experiment and modeling the synergistic behavior of alpha-particle-dominated burning plasmas. *(Waves and energetic particles)*
- Conduct enhanced modeling and laboratory experiments for ITER test blankets. (*Fusion engineering science)*
- Pursue optimization of magnetic confinement configurations. *(Macroscopic plasma physics)*
- Resolve the key plasma-material interactions, which govern material selection and tritium retention for high-power fusion experiments. *(Plasma boundary interfaces)*
- Extend the understanding of reconnection processes and their influence on plasma instabilities. *(Multi-scale transport physics)*
- Carry out experiments and simulation of multi-kilo-electron-volt megabar plasmas. *(High energy density physics)*

- Expand the effort to understand the transport of particles and momentum. *(Multi-scale transport physics)*

Each of these high-priority activities is described in the following chapters that describe in detail the six scientific campaigns (Chapters 3-8). Each campaign identifies the important opportunities for making enhanced progress in answering the key scientific questions. The highest-priority activities listed above represent the most important of these opportunities. While many activities can be pursued at a reduced pace under level resources, opportunities exist for substantially enhanced progress on critical ongoing research programs with additional funding.

Recommendation 3: If less incremental funding were available, in the range of $50M per year, then the first six activities identified above should receive priority attention.

The first six activities are viewed today as the most critical in further preparing the U.S. to participate in a burning plasma experiment and for enhancing progress in vital aspects of the six scientific campaigns.

Recommendation 4: The fusion energy sciences program should assess the need for additional major domestic experimental facilities in about five years.

The study of burning plasmas is one of the overarching themes of the program. Present facilities are not able to access this important scientific regime thus requiring the construction of a new facility. In particular, existing facilities are not able to create plasmas with sufficient confinement and pressure to achieve conditions under which the heating from the fusion reactions is equal to or greater than the auxiliary heating power—the essence of “burning plasma.” The U.S. contribution to the construction of ITER and preparation for operations will subsequently enable access to and exploration of magnetically confined burning plasmas. As noted in the charge letter to the Panel (see Preface), construction of ITER will require additional financial resources.

Just as the construction of ITER is driven by compelling scientific questions requiring scientific regimes with unique combinations of confinement and pressure, other scientific questions may motivate the construction of major new facilities beyond those currently under construction, or major upgrades to existing facilities. The duration of design and construction of new facilities ranges from typically four-to-six years for significant facilities to typically five-to-ten years for major U.S. facilities. It is anticipated that substantial progress on the scientific issues described in this report will generate new scientific questions. Design studies and rigorous proposal reviews during the second five-year period of this ten-year research activities enable the program to move ahead with the construction of new facilities, when ITER construction will be nearing completion.

APPENDIX A
CHARGE LETTER FROM DIRECTOR RAYMOND ORBACH

October 23, 2003

Professor Richard D. Hazeltine, Chair
Fusion Energy Sciences Advisory Committee
The University of Texas at Austin
Institute for Fusion Studies
1 University Station, C 1500
Austin, TX 78712-0262

Dear Professor Hazeltine:

As you know, the National Research Council (NRC) has now completed its work on the charge to review our strategy for addressing the science of a burning plasma. This full report extends the NRC interim report of last December. I would like to have FESAC's help in responding to a key recommendation of the report.

In addition to endorsing FESAC's recommendation that the U.S. should join the negotiations to build and operate ITER, the report also recommends a new effort to integrate ITER into the U.S. domestic program. "Although active planning has been undertaken by the U.S. fusion community in recent years, the addition of so major a new element as ITER requires that to ensure the continued success and leadership of the U.S. fusion science program the content, scope, and level of U.S. activity in fusion should be defined through a prioritized balancing of the program."

I believe that the fusion community and FESAC are ready to act on this recommendation. You have considered the science and technology issues in the past; it is now time to focus the program in a more complete and fundamental way than we have done before.

Therefore, to assist us in establishing priorities for the fusion program, I would like FESAC to identify the major science and technology issues that need to be addressed, recommend how to organize campaigns to address those issues, and recommend the priority order for these campaigns. Three funding scenarios should be considered:

- The current level ($257M, increasing for inflation)
- The level authorized in the 2003 Energy Bill
    - For FY 2004, $335,000,000
    - For FY 2005, $349,000,000
    - For FY 2006, $362,000,000
    - For FY 2007, $377,000,000
    - For FY 2008, $393,000,000,
    - For FY 2009 and beyond, $393,000,000 plus inflation

- A level between today's funding level and that in the Energy Bill

It should be assumed that funding for ITER construction is provided in addition to these funds. The prioritization process should be organized using the program objectives[1], as restated by the NRC report, as the guiding principle.

For each scenario, you will need to assemble a balanced domestic program that takes account of fusion programs abroad and that includes ITER as an integrated part of the whole. In each case, please recommend the relative priority of activities to pursue at any given time, so that we will have some guidance when funding is limited and we are unable to pursue every good opportunity.

Although the NRC report is focused on the Magnetic Fusion part of the program, I would like FESAC to include Inertial Fusion and relevant aspects of High Energy Density Physics as you recommend priorities for a balanced Fusion Energy Sciences program.

Please look at the program through 2014, the year ITER operation is expected to begin. I expect that your vision will be clearer for the first five years than for the second, and I recognize that in a program such as fusion, scientific and technology results and innovations, as well as funding realities, will affect what we actually will do in future years.

I also recognize how difficult such priority setting is for any research community. Nevertheless, having a template for making program decisions during this period of preparation for ITER operation will be essential for allocating and managing our resources effectively. I would like to receive your report by the end of July 2004.

Sincerely,

/s/

Raymond L. Orbach
Director

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[1] Advance plasma science in pursuit of national science and technology goals; Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program; pursue fusion energy science and technology as a partner in the international effort.

APPENDIX B

PRIORITIES PANEL MEMBERSHIP

Charles Baker* (Chair)	Sandia National Laboratories
Stewart Prager (Vice-Chair)	University of Wisconsin - Madison
Mohamed Abdou	University of California, Los Angeles
Lee Berry	Oak Ridge National Laboratory
Riccardo Betti*	University of Rochester
Vincent Chan	General Atomics
Darren Craig	University of Wisconsin - Madison
Jill Dahlburg*	Naval Research Laboratory
Ronald Davidson	Princeton Plasma Physics Laboratory
James Drake	University of Maryland
Richard Hawryluk	Princeton Plasma Physics Laboratory
David Hill	Lawrence Livermore National Laboratory
Amanda Hubbard	Massachusetts Institute of Technology
Grant Logan	Lawrence Berkeley National Laboratory
Earl Marmar	Massachusetts Institute of Technology
Michael Mauel	Columbia University
Kathryn McCarthy*	Idaho National Engineering & Environmental Laboratory
Scott Parker	University of Colorado - Boulder
Ned Sauthoff*	Princeton Plasma Physics Laboratory
Ronald Stambaugh*	General Atomics
Michael Ulrickson	Sandia National Laboratories
James Van Dam	University of Texas-Austin
Glen Wurden	Los Alamos National Laboratory
Michael Zarnstorff	Princeton Plasma Physics Laboratory
Steven Zinkle	Oak Ridge National Laboratory

*FESAC Member

APPENDIX C
WORKING GROUPS

Macroscopic Plasma Behavior

Chair	Gerald Navratil	Columbia University
Co-Chair	Michael Zarnstorff	Princeton Plasma Physics Laboratory

Multi-Scale Transport Behavior

Chair	Paul Terry	University of Wisconsin
Co-Chair	Earl Marmar	Massachusetts Institute Technology

High-Energy Density Implosion Physics

Chair	Max Tabak	Lawrence Livermore National Laboratory
Co-Chair	Riccardo Betti	University of Rochester

Plasma-boundary Interfaces

Chair	Steve Allen	Lawrence Livermore National Laboratory
Co-Chair	Michael Ulrickson	Sandia National Laboratory

Waves and Energetic Particles

Chair	Ernest Valeo	Princeton Plasma Physics Laboratory
Co-Chair	Grant Logan	Lawrence Livermore National Laboratory

Subgroup A: Heavy Ion Beams

Subgroup Chair	John Barnard	Lawrence Livermore National Laboratory

Subgroup B: Electromagnetic Waves

Subgroup Chair	Donald Batchelor	Oak Ridge National Laboratory

Subgroup C: Energetic Particles

Subgroup Chair	Boris Breizman	University of Texas

Fusion Engineering Science

Subgroup A: Materials & Chamber Technology

Co-Chair	Mohamed Abdou	University of California, Los Angeles
Co-Chair	Steve Zinkle	Oak Ridge National Laboratory

Subgroup B: Plasma & IFE Technology

Chair	Stanley Milora	Oak Ridge National Laboratory
Vice-Chair	Wayne Meier	Lawrence Livermore National Laboratory