Fusion Energy Sciences

Funding Profile by Subprogram

(dollars in thousands)

	FY 2009 Current Appropriation	FY 2009 Current Recovery Act Appropriation[a]	FY 2010 Current Appropriation	FY 2011 Request
Fusion Energy Sciences				
Science	163,479	+57,399	182,092	185,940
Facility Operations	207,649	+33,624	220,717	170,020
Enabling R&D	23,390	0	23,191	24,040
Total, Fusion Energy Sciences	394,518[b]	+91,023	426,000	380,000

Public Law Authorizations:
Public Law 95–91, "Department of Energy Organization Act", 1977
Public Law 109–58, "Energy Policy Act of 2005"
Public Law 110–69, "America COMPETES Act of 2007"

Program Overview

Mission

The FES mission is to expand the fundamental understanding of matter at very high temperatures and densities and to develop the scientific foundations needed to develop a fusion energy source. This is accomplished by studying plasmas and their interactions with their surroundings under a wide range of temperature and density, developing advanced diagnostics to make detailed measurements of their properties, and creating theoretical and computational models to resolve the essential physics.

Background

The physics of plasmas is at the heart of understanding how stars shine and evolve over billions of years. Plasmas, essentially hot gases of ions and electrons, are found in environments as familiar as fluorescent lighting and lightning bolts, as unimaginably harsh as the centers of stars, and as exotic as the environments surrounding super massive black holes. The science of plasma physics that describes the plasmas in these environments also describes the auroras that gently illuminate the northern and southern skies and the solar corona, where temperatures are far higher than on the sun's surface. At the scale of the very small, plasma physics and materials science combine to enable the exquisitely precise manufacture of semiconductors. Plasma science is also at the heart of advances in efficiencies in the lighting industry.

Plasma science forms the basis for research that is needed to establish our ability to harness the power of the stars in order to generate fusion energy on earth. The successful development of this science and relevant supporting sciences may have enormous implications for the future. The plasma and materials science needed to form the essential understanding required for fusion energy is both rich and far-reaching. The research central to the highest level goals of fusion research—the creation of an energy source with a virtually limitless fuel supply, with low level radioactive waste, and with no carbon emission—has a reach even broader than these ambitious goals suggest. The research required for

[a] The Recovery Act Current Appropriation column reflects the allocation of funding as of September 30, 2009.
[b] Total is reduced by $8,032,000: $7,171,000 of which was transferred to the SBIR program and $861,000 of which was transferred to the STTR program.

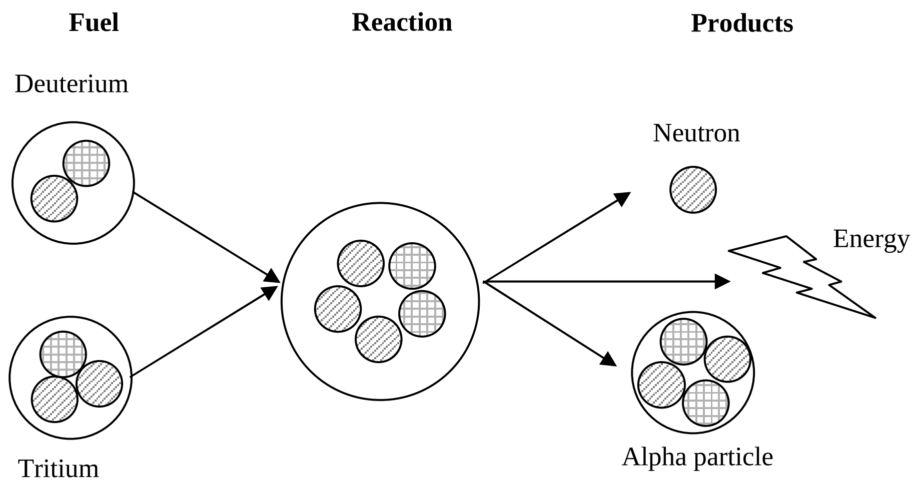
fusion energy's success is intimately tied to rich scientific questions about some of nature's most extreme environments, inside and outside of stars, and has practical implications to industry beyond energy as well.

One measure of the progress in plasma physics to date can in part be seen in the fact that the densities and temperatures required for fusion on earth are now routinely obtained in the laboratory. Scaling the results from present fusion experiments to those required for energy production, this research is providing a stronger experimental basis for future fusion. But while experimental scaling of results is encouraging and important, progress in fusion science goes beyond this. It is grounded in an increasingly deep, experimentally validated theoretical understanding that is growing in parallel with these empirical accomplishments. This validation forms the foundation of computational tools used to understand and predict the behavior of natural and man-made plasmas systems, including burning plasmas for fusion energy. From this foundation, the ever-increasing sophistication of simulation with massively parallel computing is improving our ability to predict the performance of experimental systems. Such simulation is being used as a tool for discovery in itself and is guiding experimental choices, a sign of increasing maturity of the field and increasing readiness to embrace the practical challenges of fusion energy development.

The tools developed for advancing fusion's scientific base are also being used as tools for general scientific discovery beyond the fusion realm. An example is our increasing understanding of the anomalous heating of the solar corona, where plasma physics common to both fusion energy in the laboratory and plasmas in the natural world provides the basis for unraveling this mystery. Fusion's theory-based computational tools have also recently been used to explain the unexpectedly low brightness of the accretion of plasma in the extraordinary environment surrounding super massive black holes in the center of our galaxy. Once regarded as too complex to allow anything except an empirical approach, our understanding of the fundamental laws governing the gross dynamics of plasmas, including the challenge of understanding the nonlinearly saturated state of plasmas turbulence, has undergone significant transformation in the past 20 years.

The transformation of plasma science from empirical to predictive has come from a sustained investment in flexible experiments that can explore an ever-increasing range of plasma conditions, advanced diagnostics that sample plasma phenomena at temporal and spatial scales covering many orders of magnitude, and simulation capability that also can capture these disparate scales and offers the promise of integrated, validated simulation of burning plasmas in the laboratory and in future energy producing reactors. Importantly, plasma science has also been advanced by vigorous national and international collaboration where fusion's puzzles and challenges have been addressed in joint experiments promoted by international physics activities.

Today, FES investments are focused on extending this progress into the yet unexplored regime of self-sustaining, or burning, fusion reactions. Since the earliest work on fusion energy, most fusion reactor concepts have shared a common approach—the fusion fuel (usually a mixture of the hydrogen isotopes deuterium and tritium) is heated to extremely high temperatures (on the order of 100 million degrees) creating a plasma of ionized deuterium and tritium. Under these conditions, the deuterium and tritium nuclei fuse, releasing substantial amounts of energy.



The Fusion Process

Creating a burning plasma is the crucial next step in both the magnetic fusion energy science (MFES) and inertial fusion energy science (IFES) programs. A burning plasma is fundamentally different from the plasmas that have been created in research facilities to date, which have all been sustained entirely by external energy sources. In a burning plasma, the plasma temperature is sustained by the fusion reaction itself, primarily by the self-heating from alpha particles, energetic helium ions produced by the fusion reactions.

To sustain the fusion reactions and keep the fusion fuel at thermonuclear temperatures, the plasma must be contained and prevented from coming into contact with the comparatively cool walls of the confining vessel. In the decades that followed the first attempts at controlled thermonuclear fusion, two main approaches for confining fusion plasmas emerged: magnetic confinement and inertial confinement. FES supports research programs in magnetic fusion energy science and in plasma science, including activities related to IFES through investigation of the fundamental science of high energy density laboratory plasmas (HEDLP).

The MFES program is now moving into the burning plasma regime through the U.S. participation in ITER, an international fusion research facility under construction in Cadarache, France, which will be the world's first magnetic fusion facility large enough to achieve a burning plasma and investigate its characteristics. Under the ITER Joint Implementation Agreement (JIA), the United States is a full Member of the International ITER project—an unprecedented international scientific endeavor to explore the physics of burning plasmas. The 9.09% share of ITER construction gives the U.S. access to all scientific data, gives the U.S. the right to propose and carry out experiments, and creates new opportunities for U.S. industry to manufacture high-technology components to fulfill a large part (roughly 80%) of the U.S. contribution. In addition to ITER, the United States collaborates with these partners on current fusion research facilities and programs through International Energy Agency and bilateral agreements. The inertial fusion program within the National Nuclear Security Administration (NNSA) is also moving into the burning plasma regime with the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory.

With the initiation of the ITER project and the recent completion of NIF, plasma science research is at the threshold of new discoveries that will transform the field. Both magnetic fusion and inertial fusion sciences have progressed to the point where the fusion community has the knowledge not only to design a burning plasma device, but also to identify the broader scientific and technical questions that remain to be answered on the path to fusion energy. It is thus an opportune time for the FES program to tackle a wide range of scientific and technical challenges to the development of practical fusion energy.

The FES mission is advanced by four strategic goals:

- Advance the fundamental science of magnetically confined plasmas to develop the predictive capability needed for a sustainable fusion energy source;
- Pursue scientific opportunities and grand challenges in high energy density plasma science to explore the feasibility of the inertial confinement approach as a fusion energy source, to better understand our universe, and to enhance national security and economic competitiveness;
- Support the development of the scientific understanding required to design and deploy the materials needed to support a burning plasma environment; and
- Increase the fundamental understanding of basic plasma science, including both burning plasma and low temperature plasma science and engineering, to enhance economic competiveness and to create opportunities for a broader range of science-based applications.

These distinct but strongly linked and synergistic goals are unified by fundamental plasma science, the scientific foundation for a fusion energy source. The goals also reflect a synthesis of input from the National Academies, the Fusion Energy Sciences Advisory Committee (FESAC), and the U.S. fusion community.

The research activities supported by FES have led to a wide range of advances in fusion related sciences. Some representative advances include the achievement of an increase in fusion power output in laboratory experiments by 12 orders of magnitude over the past three decades, the development of advanced computation and simulation capability in the areas of energy transport and plasma stability needed to design a device capable of achieving a burning plasma with significant fusion energy output, and the demonstrated control of plasma states that scale favorably to burning plasmas and future fusion reactors.

Subprograms

To accomplish its mission and address the strategic goals described above, the FES program is organized into three subprograms—Science, Facility Operations, and Enabling R&D.

- The *Science* subprogram is developing a predictive understanding of plasmas properties, including their dynamics and their interactions with surrounding materials. The emphasis is presently weighted towards understanding the plasma state and its properties for stable magnetically confined fusion systems, but increasing emphasis is expected in the areas of plasma-material interaction and the simultaneous effects of high heat and neutron fluxes that will be encountered in a burning plasma environment. Also, plans call for extending this class of research activity, further leveraging the scientific basis established for magnetic fusion to other areas. This includes research to investigate the fundamental science of HEDLP.
- The *Facility Operations* subprogram includes efforts to build, operate, maintain, and upgrade the large facilities needed to carry out research on fusion energy science. It also includes funding for the U.S. share of the ITER project. The three major experimental facilities in the FES program—DIII-D tokamak at General Atomics in San Diego, California; the Alcator C-Mod tokamak at the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts; and the National Spherical Torus Experiment (NSTX) at Princeton Plasma Physics Laboratory (PPPL) in Princeton, New Jersey—provide the essential tools for the U.S. research community to explore and solve fundamental issues of fusion plasma physics. All three are operated as national facilities and involve

users from many laboratories and universities. The funding for facility operations includes expenses for running the facility; providing the required plasma diagnostics; and for facility maintenance, refurbishment, and minor upgrades.

- The *Enabling R&D* subprogram supports research to optimize and control plasma states in the laboratory, increasing the scientific output of present experiments and the likelihood of success of future fusion facilities. Research is aimed at improving the components and systems that are used to build present and future fusion facilities, thereby enabling them to achieve improved performance and scientific output and bring us closer to the goal of achieving practical fusion energy.

Benefits

The development of plasma science has been motivated by a diverse set of applications such as astrophysics, space science, plasma processing, national defense, and fusion energy. Advances in plasma science have led to significant applications, such as plasma processing of semiconductors and computer chips, material hardening for industrial and biological uses, waste management techniques, lighting and plasma displays, space propulsion, and non-contact infection-free surgical scalpels. Particle accelerators and free electron lasers also rely on plasma science concepts.

Plasma science is essential to the development of fusion energy. Fusion has the potential to provide an energy source that is virtually inexhaustible and environmentally benign, producing no combustion products or greenhouse gases. While fusion is a nuclear process, the products of the fusion reaction (helium and neutrons) are not intrinsically radioactive. Short-lived radioactivity may result from interactions of the fusion products with the reactor walls, but with proper design a fusion power plant would be passively safe and would produce no long-lived radioactive waste. Design studies show that electricity from fusion could cost about the same as electricity from other sources.

The extreme states of matter studied in HEDLP and encountered in inertial confinement fusion studies may offer an alternate path to a fusion energy source. This research is also related to the NNSA stockpile stewardship program and, hence, indirectly supports the national security program of DOE. Related areas of science addressed in these research programs include turbulence and complex systems, multiphase interactions and plasma-material interactions, self-organization of complex systems, astrophysics, geodynamics, and fluids.

Program Planning and Management

FES uses a variety of external entities to gather input for making informed decisions on programmatic priorities and allocation of resources. As part of this effort, FES has developed a system of planning and priority setting that draws on advice from groups of outside experts. FES has also instituted a number of peer review and oversight measures designed to assess productivity and maintain effective communication and coordination among participants in FES activities.

During 2008 and 2009, FES sponsored a series of workshops focused on providing input for a new FES strategic plan. The first workshop covered the field of low temperature plasma physics and produced the report entitled *Low Temperature Plasma Science: Not only the Fourth State of Matter but All of Them*[a] in September 2008. More recently, FES organized a community-wide effort that culminated in an MFES Research Needs Workshop (ReNeW) in June 2009 to describe the scientific research required during the ITER era to develop the knowledge needed for a practical fusion power source. The report on the results from this workshop entitled *Research Needs for Magnetic Fusion Energy Sciences*[a] was published in September 2009. Two FESAC reports, *Priorities, Gaps and Opportunities: Towards a Long-Range*

[a] The 2008/2009 reports are located at http://www.science.doe.gov/ofes/programdocuments.shtml.

Strategic Plan for Magnetic Fusion Energy (October 2007)[a] and *Report of the FESAC Toroidal Alternates Panel* (December 2008)[a], and a series of topical workshops provided the technical basis for this ReNeW workshop.

A Research Needs Workshop for HEDLP was held in November 2009 to evaluate research opportunities in fundamental high energy density plasma science and in inertial fusion energy related high energy density plasma science. A FESAC report on scientific issues and opportunities in both fundamental and mission-driven HEDLP, entitled *Advancing the Science of High Energy Density Laboratory Plasmas*, was used as the technical basis for the workshop. This report documents the issues and opportunities that can be pursued over the next decade through the joint program in HEDLP. SC and NNSA have jointly appointed FESAC as the federal Advisory Committee for the FES-NNSA joint program in HEDLP. The HEDLP ReNeW report is expected to be published in the March 2010 timeframe.

The reports from the research needs workshops will be used by FES as a major part of the input used in its strategic planning activities. The planning is aimed, in part, at accelerating work on the scientific and technical foundations for a fusion energy source. The planning activities will also describe increased FES stewardship of general plasma science as recommended by the National Research Council (NRC) report entitled *Plasma Science: Advancing Knowledge in the National Interest* [a].

To assist in the management and coordination of U.S. scientific and technical activities in support of ITER, and to prepare for the eventual participation by U.S. scientists in ITER operations and research, FES established the U.S. Burning Plasma Organization (USBPO). The USBPO Director is also the chief scientist for the U.S. ITER Project Office (USIPO), thus providing close coupling between the ITER Project and these scientific activities. The U.S. is also a very active member of the International Tokamak Physics Activity (ITPA) which facilitates international coordination of tokamak research in support of ITER.

FES requires the three major experimental facilities supported by the program to have Program Advisory Committees (PACs). The PACs serve an important role in providing guidance to the facility directors in the form of program review and advice regarding allocation of facility run-time. Composed primarily of researchers from outside the host facility, these PACs also include non-U.S. members.

FES charges FESAC to convene a Committee of Visitors (COV) panel every three years to assess the efficacy and quality of the processes used to solicit, review, recommend, monitor, and document application, proposal, and award actions and the quality of the resulting portfolio. A new COV charge was given to FESAC in November 2008 asking FESAC to review the entire FES program and report its findings. The COV has conducted its review, meeting with the FES program staff in August 2009. The COV will present its findings to the full committee at the first FESAC meeting of 2010. The final FESAC report on this COV activity is expected to be published about one month after that FESAC meeting.

Basic and Applied R&D Coordination

As recommended in 2007 by the National Science and Technology Council in the *Report of the Interagency Task Force on High Energy Density Physics*[a], FES and NNSA have established a joint program in HEDLP to provide stewardship of high energy density laboratory plasma physics. The benefits of this joint program are that it will avoid duplication of effort, provide better leverage for the FES high energy density physics projects at the NNSA high energy density facilities, and stimulate synergies between the two programs and interactions among the researchers. High energy density plasmas are plasmas with pressures exceeding one million atmospheres (greater than 1 megabar). The

[a] The 2008/2009 reports are located at http://www.science.doe.gov/ofes/programdocuments.shtml.

science of high energy density plasmas is important to science-based nuclear stockpile stewardship as well as to inertial fusion energy. The FES high energy density physics program includes energy-related science and other fundamental research (e.g., laboratory astrophysics). At the present time this research includes the science of fast ignition, laser-plasma interaction, magnetized high energy density plasmas, high-density high Mach-number plasma jets, and heavy-ion-beam driven warm dense matter. This research overlaps with HEDLP areas funded by NNSA, including compressible and radiative hydrodynamics, laser-plasma interactions, material properties under extreme conditions, and laboratory astrophysics. FES and NNSA HEDLP research is being coordinated through the joint program, with coordinated solicitations, peer reviews, scientific workshops, and Federal Advisory Committee input.

Budget Overview

The FES program is the primary supporter of research in the field of plasma physics in the United States. The FY 2011 budget request is designed to optimize the scientific productivity of the program. The FES program funds activities involving over 1,100 researchers and students in 31 states at approximately 63 universities, 9 industrial firms, 10 national laboratories, and 2 Federal laboratories. Some of the key activities of the FES program and their status in the FY 2011 budget request follow:

- The United States will continue funding to meet our obligations in the Construction Phase of the ITER Project (U.S. Contributions to ITER Project) including research and development of key components, long-lead procurements, and contributions of personnel and funds to the ITER Organization (IO). In addition, the U.S., working in conjunction with the other partners, will continue to emphasize the importance of formal, coherent, and disciplined project management practices by the IO as a means to control schedule and cost.

- Research at the major experimental facilities in the FES program—DIII-D, Alcator C-Mod, and NSTX—will continue to focus on building the predictive science needed for ITER operations and providing solutions to high-priority ITER technical issues. More specifically, these facilities will conduct experiments to improve active control of various plasma parameters, measure the effects and mitigation of disruptions in the plasma, develop a better understanding of the physics of the plasma edge in the presence of large heat flows, control the current density profile for better stability, and develop a scientific basis of advanced operating scenarios for ITER. Maintaining a high level of facility usage and upgrades so as to best exploit these investments is a priority.

- The Fusion Simulation Program (FSP) transitions from its 2-year (FY 2009-FY 2010) planning phase to the full program. The FSP is a computational initiative led by FES with collaborative support from the Office of Advanced Scientific Computing Research (ASCR). It is aimed at the development of a world-leading, experimentally validated, predictive simulation capability for fusion plasmas in the regimes and geometries relevant for practical fusion energy.

- Plasma Science Centers (PSCs) support multi-institutional teams to work on some of the most important and challenging plasma science problems of our time. Recognizing this, FES will continue to provide support for the operation of three plasma science centers. The PSCs are intended to establish academic centers of excellence that will focus on fundamental issues of widely recognized importance to plasma science. In addition to the science that is fostered in this research, the education and training of plasma scientists is a major goal of this program.

- FES investments in emerging scientific opportunities in HEDLP are positioning the U.S. to assert strong leadership in this growing field of plasma science. FES and NNSA intend to expand the joint research program that was initiated in FY 2009. The Materials in Extreme Conditions (MEC) end station at the recently commissioned Linac Coherent Light Source at SLAC will permit studies of high energy states of matter with unprecedented precision. The Neutralized Drift Compression

Experiment-II (NDCX-II) will enable enhanced warm dense matter experiments relevant to the interiors of giant planets and to the high energy density science underpinning the concept of heavy ion fusion. This program will continue to explore a number of fields of research identified as priorities by both the National Academies and FESAC, including basic research on the science of fast ignition, laser-plasma interaction, magnetized high energy density plasmas, plasma jets, and warm dense matter. An increase is proposed in FY 2011 with further increases planned for future years.

- A modest increase in fusion-related materials science research is proposed in this budget. One of the clearest recommendations that comes from the magnetic fusion community from the ReNeW process and underscored by the FESAC report entitled "*Priorities, Gaps, and Opportunities*," described above, is the need to develop the materials science essential to practical fusion energy. Indeed, pursuit of this research by the United States provides an opportunity to assert leadership worldwide in this important area. Full maturation of this endeavor in the coming years will require sensible collaboration with other research programs in the Department, including those stewarded by Basic Energy Sciences.

Annual Performance Results and Targets

Secretarial Priority: Innovation: Lead the world in science, technology, and engineering.

GPRA Unit Program Goal: Fusion Energy Sciences Program Goal: Bring the Power of the Stars to Earth - Answer the key scientific questions and overcome enormous technical challenges to harness the power that fuels our Sun.

Annual Performance Measure: Conduct experiments on the major fusion facilities (DIII-D, Alcator C-Mod, NSTX) leading toward the predictive capability for burning plasmas and configuration optimization.

FY 2006	T: Inject 2 MW of neutral beam power in the counter direction on DIII-D and begin physics experiments. A: Goal met
FY 2007	T: Measure and identify magnetic modes on NSTX that are driven by energetic ions traveling faster than the speed of magnetic perturbations (Alfvén speed); such modes are expected in burning plasmas such as ITER. A: Goal met
FY 2008	T: Evaluate the generation of plasma rotation and momentum transport, and assess the impact of plasma rotation on stability and confinement. Alcator-Mod will investigate rotation without external momentum input, NSTX will examine very high rotation speeds, and DIII-D will vary rotation speeds with neutral beams. The results achieved at the major facilities will provide important new data for estimating the magnitude of and assessing the impact of rotation on ITER plasmas. A: Goal met

FY 2009	T: Identify the fundamental processes governing particle balance by systematically investigating a combination of divertor geometries, particle exhaust capabilities, and wall materials. Alcator C-Mod operates with high-Z metal walls, NSTX is pursuing the use of lithium surfaces in the divertor, and DIII-D continues operating with all graphite walls. Edge diagnostics measuring the heat and particle flux to walls and divertor surfaces, coupled with plasma profile data and material surface analysis, will provide input for validating simulation codes. The results achieved will be used to improve extrapolations to planned ITER operation. A: Goal met
FY 2010	T: Conduct experiments on major fusion facilities to improve understanding of the heat transport in the tokamak scrape-off layer (SOL) plasma, strengthening the basis for projecting divertor conditions in ITER. The divertor heat flux profiles and plasma characteristics in the tokamak SOL will be measured in multiple devices to investigate the underlying thermal transport processes. The unique characteristics of C-Mod, DIII-D, and NSTX will enable collection of data over a broad range of SOL and divertor parameters (e.g., collisionality, beta, parallel heat flux, and divertor geometry). Coordinated experiments using common analysis methods will generate data that will be compared with theory and simulation. A: TBD
FY 2011	T: Improve the understanding of the physics mechanisms responsible for the structure of the pedestal and compare with the predictive models described in the companion theory milestone. Perform experiments to test theoretical physics models in the pedestal region on multiple devices over a broad range of plasma parameters (e.g., collisionality, beta, and aspect ratio). Detailed measurements of the height and width of the pedestal will be performed augmented by measurements of the radial electric field. The evolution of these parameters during the discharge will be studied. Initial measurements of the turbulence in the pedestal region will also be performed to improve understanding of the relationship between edge turbulent transport and pedestal structure. A: TBD
FY 2012–2015	T: TBD based on research needs and FY 2011 through 2014 results A: TBD

Annual Performance Measure: <u>Continue to increase resolution in simulations of plasma phenomena—optimizing confinement and predicting the behavior of burning plasmas require improved simulations of edge and core plasma phenomena, as the characteristics of the edge can strongly affect core confinement.</u>

FY 2006	T: Simulate nonlinear plasma edge phenomena using extended MHD codes with a resolution of 40 Toroidal modes. A: Goal met

FY 2007	T: Improve the simulation resolution of linear stability properties of Toroidal Alfvén Eigenmodes driven by energetic particles and neutral beams in ITER by increasing the number of Toroidal modes used to 15. A: Goal met
FY 2008	T: Improve the simulation resolution of ITER-relevant modeling of lower hybrid current drive experiments on Alcator C-Mod by increasing the number of poloidal modes used to 2,000 and the number of radial elements used to 1,000 using the SC's high performance computing resources. A: Goal met
FY 2009	T: Gyrokinetic edge electrostatic turbulence simulations will be carried out across the divertor separatrix with enhanced resolution down to the ion gyroradius scale. A: Goal met
FY 2010	T: Gyrokinetic simulations of turbulent transport of toroidal momentum with both kinetic and Boltzmann electrons will be carried out. These simulations will explore the Ion Temperature Gradient (ITG) and the Collisionless Trapped Electron Mode (CTEM) regimes. A: TBD
FY 2011	T: A focused analytic theory and computational effort, including large-scale simulations, will be used to identify and quantify relevant physics mechanisms controlling the structure of the pedestal. The performance of future burning plasmas is strongly correlated with the pressure at the top of the edge transport barrier (or pedestal height). Predicting the pedestal height has proved challenging due to a wide and overlapping range of relevant spatiotemporal scales, geometrical complexity, and a variety of potentially important physics mechanisms. Predictive models will be developed and key features of each model will be tested against observations, to clarify the relative importance of various physics mechanisms, and to make progress in developing a validated physics model for the pedestal height. A: TBD
FY 2012–2015	T: TBD based on research needs and FY 2011 through 2014 results A: TBD

Annual Performance Measure: Average achieved operation time of the major national fusion facilities (DIII-D, Alcator C-Mod, NSTX) as a percentage of the total planned operation time is greater than 90%.

FY 2006	T: 90% of scheduled operating time A: Goal met

FY 2007	T: 90% of scheduled operating time A: Goal met
FY 2008	T: 90% of scheduled operating time A: Goal met
FY 2009	T: 90% of scheduled operating time A: Goal met
FY 2010–2015	T: 90% of scheduled operating time A: TBD

Annual Performance Measure: Cost-weighted mean percent variance from established cost and schedule baselines for major construction, upgrade, or equipment procurement projects kept to less than 10%.

FY 2006	T: Cost and schedule variance are both less than 10% A: Goal met
FY 2007	T: Cost and schedule variance are both less than 10% A: Goal not met
FY 2008	T: Cost and schedule variance are both less than 10% A: Goal not met
FY 2009	T: N/A, no major construction project/MIE tracked this fiscal year.
FY 2010	T: N/A, no major construction project/MIE tracked this fiscal year.
FY 2011–2015	T: Cost and schedule variance are both less than 10% A: TBD

Science

Funding Schedule by Activity

	FY 2009	FY 2010	FY 2011
	(dollars in thousands)		
Science			
Tokamak Experimental Research	50,121	58,177	53,781
Alternative Concept Experimental Research	65,684	65,780	72,269
Theory	24,014	24,348	24,348
Advanced Fusion Simulations	9,163	11,212	13,212
General Plasma Science	14,497	14,193	14,193
SBIR/STTR	0	8,382	8,137
Total, Science	163,479	182,092	185,940

Description

The Science subprogram supports preparation for the eventual exploration of burning plasmas by developing a scientific understanding of how high temperature plasmas behave in a tokamak magnetic confinement configuration. The Science subprogram is focused on advancing understanding of plasmas and the fusion environment through an integrated program of experiments, theory, and simulation as outlined in FESAC's *Scientific Challenges, Opportunities and Priorities for the Fusion Energy Sciences Program, July 2004*[a] report.

Plasmas are gases comprising of a mixture of ions and electrons that are influenced by the long range interactions with each other and by magnetic and electric fields, either externally applied or generated by the plasma itself. The Science subprogram focuses on two key questions: What are the physical processes that govern the behavior of a plasma, especially a high temperature plasma, and how do you create, confine, heat, and control a burning plasma to make fusion power a reality? These questions are inherently linked, since a profound understanding of plasma science will be needed to learn how to bring the power of the stars to Earth. This linkage is captured in a major goal of the Science subprogram: to develop a predictive understanding of high temperature fusion burning plasmas in a range of confinement configurations.

The Science subprogram is actively pursuing the development of a broad range of advanced computational simulation tools, taking advantage of emerging petascale computing resources, to address and predict in an integrated manner the questions of how a burning plasma will behave. This effort will yield the computational tools needed to help fully utilize ITER and should also keep the U.S. science community in the lead in using high performance computers to advance understanding of the plasma state. Ultimately, research on ITER is expected to provide sufficient information on burning plasmas to make a definitive assessment of the scientific feasibility of fusion power.

Selected FY 2009 Accomplishments

- *Low absorption of fusion fuel by material walls in high-confinement plasma experiments*: A major concern for ITER is the need to minimize the amount of the tritium fuel absorbed into the vessel walls, as high absorption rates could shorten the lifetimes of components. A set of coordinated

[a] The 2008/2009 reports are located at http://www.science.doe.gov/ofes/programdocuments.shtml.

experiments in the DIII-D and Alcator C-Mod tokamaks demonstrated that particle absorption into the wall in the operational regime favored for ITER is very small, perhaps zero. Virtually the entire uptake of the wall materials may only occur during the short, early phase of the discharge prior to the transition to the operating regime. This finding has significant implications for ITER operations.

- *Advances in predicting plasma behavior:* The NSTX team has detected theoretically-predicted small scale density fluctuations by observing scattered microwaves launched into the plasma. This turbulence is challenging to measure because of its small scale size and amplitude, yet is of potentially high importance to determining how energy created by the fusion process diffuses to the reactor walls. Researchers at the Madison Symmetric Torus (MST) reversed-field pinch have made the first ever measurement of electromagnetic turbulence in the core of a high-temperature plasma. Using newly developed laser-based techniques they were able to simultaneously measure electron density fluctuations and magnetic field fluctuations, providing a direct glimpse into the nature of the transport of electrons in a stochastic magnetic field. This is of critical interest to magnetic fusion energy research as stochastic fields may be applied in a reactor to control undesirable pulses of heat from the plasma boundary to the reactor walls. On the DIII-D tokamak, scientists used localized microwave heating to vary the turbulence in a reproducible manner by controlling local temperature gradients. Comparison between measurement and state-of-the-art plasma simulations shows general agreement with the computed turbulence, but not with the resulting energy transport, thus motivating further improvements to the theory.

- *Improved understanding of plasma viscosity in 3D magnetic fields:* Recent advances in the theory of the coupling between plasmas and 3D magnetic field perturbations have provided new insight for controlling plasma rotational shear in tokamaks. Strong rotation improves plasma stability and strong rotational shear reduces turbulent transport, leading to high energy confinement. Recent experiments in DIII-D that measured the applied torque and resulting plasma rotation have observed a dependence on plasma collisionality as predicted by theory. Related experiments used static 3D fields to produce the high edge rotational shear needed to produce high confinement. These results have important positive implications for achieving and maintaining the required edge rotation in ITER.

- *Exploration of possible improved confinement mode for ITER*: Achieving good energy confinement without deleterious effects such as edge-localized modes (ELMs) or impurity accumulation is a critical issue for ITER. An improved energy confinement mode was discovered and is being explored on the Alcator C-Mod tokamak. The characteristics of the new mode include: normalized energy confinement at the level required by ITER, while keeping the plasma clean of impurity particles, and enabling high temperatures due to the good energy confinement. Separating energy and particle confinement, this improved confinement mode also avoids edge-localized plasma instabilities (ELMs). The possible extrapolation of this regime to ITER is currently under active investigation.

- *Fast ignition:* The first instrumented integrated fast ignition experiment in the United States has just been performed in the OMEGA Laser Facility at the University of Rochester. Preliminary assessment of the experimental data indicated that when a second (short) laser pulse was applied during inertial confinement of the target, the neutron yield was increased by two to three fold.

Detailed Justification

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
Tokamak Experimental Research	**50,121**	**58,177**	**53,781**

The tokamak magnetic confinement concept has been the most effective approach to date for confining high-temperature plasmas in a laboratory environment. Many of the important issues in fusion science are being studied in tokamaks, including the two major U.S. tokamak facilities: DIII-D and Alcator C-Mod. In association with the International Tokamak Physics Activity (ITPA), U.S. tokamaks continue to give high priority to joint experiments with tokamak facilities in Europe and Japan to resolve ITER-relevant physics issues.

Today, tokamak experimental research is marked by plasma measurements of unprecedented detail and accuracy, excellent plasma control, and strong connections to theory and simulation efforts. Both DIII-D and Alcator C-Mod use flexible plasma shaping and dynamic control capabilities to attain good confinement and stability. They control the distribution of current in the plasma with electromagnetic wave heating and current drive. The interface between the plasma edge and the material walls of the confinement vessel is managed by means of a magnetic divertor and magnet coils for fine control. Through tokamak research, the science of plasma confinement, plasma control, plasma responses to heating and fueling sources, and plasma-wall interactions has matured sufficiently to establish the physics basis for ITER and continues to advance rapidly.

Both DIII-D and Alcator C-Mod are operated as national collaborative science facilities with research programs established through public research forums, program advisory committee recommendations, and peer review. Both programs are also closely coordinated with international tokamak research through collaborations with major foreign tokamaks in the European Union, Japan, China, and Korea. As JET and ASDEX-UG in Europe undergo hardware modifications in 2010 and as the new superconducting tokamak programs in China (Experimental Advanced Superconducting Tokamak, EAST) and Korea (Korean Superconducting Tokamak Advanced Research, KSTAR) advance their research operations, increases in international collaborations are planned. These will address ITER physics, steady-state physics, and technology issues that are not currently being addressed in U.S. facilities.

In FY 2011, U.S. tokamak researchers will continue to expand the frontiers of fusion science, both to address remaining ITER questions and to develop the basis for practical fusion power plants.

▪ **DIII-D Research**	**25,740**	**27,504**	**26,604**

The DIII-D tokamak at General Atomics in San Diego, California, is the largest magnetic fusion facility in the United States. DIII-D provides for considerable experimental flexibility and has extensive diagnostic instrumentation to measure the properties of high temperature plasmas. It also has unique capabilities to shape the plasma and provide feedback control of error fields that, in turn, affect particle transport and plasma stability. DIII-D has been a major contributor to the world fusion program over the past two decades.

The DIII-D program is operated as a national research effort, with extensive participation from many U.S. laboratories and universities who receive direct funding from FES. The DIII-D program also plays a central role in U.S. international collaborations with the European Union, Japan, Korea, China, India, and the Russian Federation, hosting many foreign scientists, as well as sending DIII-D scientists overseas to participate in foreign experiments. The primary goal of the DIII-D program is to establish the scientific basis for the optimization of the tokamak approach to fusion energy. This is

	(dollars in thousands)	
FY 2009	FY 2010	FY 2011

being accomplished by advancing basic scientific understanding across a broad front of fusion plasma topical areas including transport, stability, plasma-wave physics, and boundary layer physics using a magnetic divertor to control the magnetic field configuration at the edge of the plasma. These topics are integral parts of six physics groups in the DIII-D Experimental Science Division: Steady State Integration, Integrated Modeling, ITER Physics, Plasma Control and Operations, Fusion Science, and Plasma Boundary Interfaces. In addition, three cross-cutting task groups focus on rapid shutdown schemes for ITER, the physics of non-axisymmetric field effects for ITER, and transport model validation. Over the past few years, the investigation of ITER-relevant discharge scenarios, including the development of advanced enhanced performance scenarios, has gained emphasis in the DIII-D experimental program.

The FY 2011 experimental program on DIII-D will commence in April 2011, after a year-long shutdown from April 2010 to March 2011 for facility modifications. These modifications primarily include re-orientation of one of the neutral beam lines for off-axis current drive capability and installation of plasma control coils on the tokamak center post. The FY 2011 experimental program will exploit these new facility modifications and continue to focus on experiments to provide solutions to key ITER issues and build a firm physics basis for ITER program planning. The DIII-D program will also continue to accommodate a number of joint experiments in collaboration with the international community.

	FY 2009	FY 2010	FY 2011
▪ **Alcator C-Mod Research**	**9,002**	**9,045**	**9,045**

Alcator C-Mod is a unique, compact tokamak facility that uses intense magnetic fields to confine high-temperature, high-density plasmas in a small volume. It is the only tokamak in the world operating at and above the ITER design magnetic field and plasma densities, and it produces the highest pressure tokamak plasma in the world, approaching pressures expected in ITER. It is also unique in the use of all-metal walls to accommodate high power densities. By virtue of these characteristics, Alcator C-Mod is particularly well suited to operate in plasma regimes that are relevant to ITER. The facility has made significant contributions to the world’s fusion program in the areas of plasma heating, stability, confinement, non-inductive current drive, and rotational flows in high field tokamaks, all of which are important integrating issues for burning plasmas.

In FY 2011, Alcator C-Mod will continue a strong research program, while providing support of ITER. Experiments will address issues with the generation of sheaths by radio frequency (RF) heating of the plasma discharge. A new type of ion cyclotron range of frequency antenna that better matches the geometry of the C-Mod magnetic field lines will be the primary tool in these experiments. Impurity generation via the formation of sheaths is an undesirable byproduct of RF heating in present day plasmas. Current drive experiments using a new type of microwave launcher at the lower hybrid range of frequencies will also be possible at high powers as more klystrons are currently being purchased using Recovery Act funding.

Other ITER-relevant topics that the Alcator C-Mod team will continue to focus on in FY 2011 include characterization of the H-mode pedestal at the edge of the plasma, plasma surface interaction with all-metal walls (especially in the divertor area), measuring the effects of and mitigating disruptions in the plasma, understanding the physics of the plasma edge in the presence of large heat flows, controlling the current density profile for better stability, and helping to build international cross-machine databases using dimensionless parameter techniques. The main effort will shift to developing accurate models of the plasma edge, an activity important to both ITER and to a potential

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011

future demonstration project. C-Mod will also continue participation in many joint international experiments.

▪ **International Research**	**5,487**	**4,935**	**4,935**

In addition to their work on domestic experiments, scientists from the FES program participate in leading-edge scientific experiments on fusion facilities abroad in Europe, Japan, China, South Korea, the Russian Federation, and India—the ITER members—and conduct comparative studies to enhance the understanding of underlying physics of fusion plasmas. The FES program, in return, hosts visiting scientists from the international community for participation in U.S. experiments. The FES program has a long-standing policy of seeking international collaboration. This allows U.S. scientists to have access to the unique capabilities of fusion facilities around the world. These include the world's highest performance tokamak, the Joint European Torus (JET) in England; a stellarator, the Large Helical Device in Japan; a superconducting tokamak, Tore Supra in France; the AxiSymmetric Divertor Experiment Upgrade (ASDEX-U) and Tokamak Experiment for Technology Oriented Research (TEXTOR) in Germany; and several smaller devices. In addition, the U.S. is collaborating with China and South Korea on EAST and KSTAR respectively, which have become operational in the past two years. The U.S. collaborations on these two new superconducting tokamaks were instrumental in achieving their first plasmas in September 2006 and June 2008, respectively. These collaborations provide a valuable link with the 80% of the world's fusion research that is conducted outside the U.S. and provide a firm foundation to support ITER activities.

In FY 2011, the U.S. will continue to be a major participant in the ITPA, which identifies experimental and computational studies to resolve high priority ITER physics design needs and implements these studies through collaborative work among the world's leading experimental and theoretical research teams. These studies include joint ITPA experiments and other joint ITER-relevant experiments in the areas of plasma wall interactions, plasma instabilities, and first wall design considerations for ITER. The JET tokamak in the United Kingdom and the ASDEX-U tokamak in Germany will be restarting after year-long shutdowns in 2010 for facility modifications involving an ITER-like wall and internal control coils. The KSTAR and EAST tokamaks in Korea and China respectively will be maturing in their operational capability. All of these modifications and improvements in the international tokamaks will provide an opportunity to expand collaborations and joint experiments utilizing these new tools. To develop these collaboration options, a national committee has been assembled to identify further U.S. international research opportunities that can be developed in the coming years.

▪ **Diagnostics**	**4,082**	**3,912**	**3,920**

Support for the development of unique measurement capabilities (diagnostic instruments) will continue. Diagnostic instruments serve two important functions: to provide a link between theory/computation and experiments, thereby increasing the understanding of the complex behavior of the plasma in fusion research devices; and to provide sensory tools for feedback control of plasma properties in order to enhance device operation.

In FY 2011, research will include the development of diagnostics for fundamental plasma parameter measurements, state-of-the-art measurement techniques, and R&D for ITER-relevant diagnostic systems. Diagnostic systems will be installed and operated on current experiments in the U.S. and on non-U.S. fusion devices, where appropriate, through collaborative programs.

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011

A competitive peer review of the national laboratory component of the diagnostics development program will be conducted in FY 2011.

▪ **Other**	**5,810**	**12,781**	**9,277**

Funding in this category supports educational activities such as research at historically black colleges and universities, postgraduate fellowships in fusion science and technology, and summer internships for undergraduates. In addition, funding in this category supports outreach efforts related to fusion science and enabling R&D, and the activities of the U.S. Burning Plasma Organization and the Fusion Energy Sciences Advisory Committee. Beginning in FY 2011 new fellowships will be funded through the Office of Science Graduate Fellowship (SCGF) program, which is funded by the Workforce Development for Teachers and Scientists program. This program was initiated in FY 2010 and supports graduate students pursing advanced degrees in areas of basic research supported by the Office of Science, including fusion science.

Alternative Concept Experimental Research	**65,684**	**65,780**	**72,269**

This program element broadens the fusion program by exploring the science of confinement optimization in the extended fusion parameter space, with plasma densities spanning twelve orders of magnitude, by seeking physics pathways to improve confinement, stability, and reactor configurations. Through this scientific diversity, the program element adds strength and robustness to the overall fusion program by lowering overall programmatic risks in the quest for practical fusion power in the long term, for which economic and environmental factors are important. At present, two alternate concepts are being pursued at the larger-scale, proof-of-principle level. A number of concepts are also being pursued at a concept-exploration level, as well as research in establishing a knowledge base for high energy density plasmas. The smaller scale experiments and the cutting-edge research have proven to be effective in attracting students and strongly contribute to fusion workforce development and the intellectual base of the fusion program. The research has also resulted in new ideas for the larger toroidal devices, including ITER.

▪ **NSTX Research**	**17,104**	**17,549**	**17,549**

The National Spherical Torus Experiment (NSTX) is one of only two large research facilities in the world that are exploring the spherical torus (ST) confinement configuration; the other is the MegaAmp Spherical Tokamak (MAST) in the United Kingdom. The ST is an innovative confinement configuration that produces a plasma that is shaped like a sphere with a narrow cylindrical hole through its center. The properties of an ST plasma are significantly different from a conventional tokamak plasma, which is shaped like a donut with a large hole through the center. Results to date indicate that STs can achieve a higher plasma pressure for a given applied magnetic field than conventional tokamaks and could, therefore, lead to a cost-effective facility for carrying out the nuclear engineering science research needed to design the power extraction and tritium breeding systems for a fusion power plant.

NSTX is operated as a national collaborative research facility, with extensive involvement of researchers from other national laboratories, universities, and industry who receive their funding from FES via a competitive peer review process.

In FY 2011 the NSTX program will continue to explore and understand the unique physics properties of STs, exploit these unique properties to contribute to the physics basis for ITER, and advance the fundamental understanding of ST plasmas to establish attractive scenarios for future

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011

fusion facilities. Using a liquid lithium divertor to confront the harsh plasma environment and new diagnostic capabilities, NSTX researchers will perform critical experiments to understand non-inductive current drive at reduced collisionality. In addition, they will investigate means to handle the large heat and particle fluxes that will fall on the divertor surface. They will also seek to understand the relation between electron energy confinement and fluctuations in the plasma density and electron temperature. This knowledge is needed to extrapolate to next-step facilities, and NSTX has unique capabilities to investigate this topic. NSTX researchers will continue studying macroscopic instabilities and will focus on sustaining high pressure plasmas and understanding disruption limits. The basic principles of error field correction and resistive wall mode control have been demonstrated, so future work will focus on developing reliable active control techniques to stabilize these modes. Plasma-wave interaction studies will concentrate on developing a predictive understanding of the redistribution/loss of fast-ions due to energetic particle modes. Research on energetic particle modes will also lead to increased knowledge of how the plasma current density is modified by energetic ion driven instabilities and how this will affect the ability to sustain the plasma with currents driven by injected high energy particle beams. Finally, experiments on solenoid-free start-up and current ramp-up, capabilities needed for future ST devices, will focus on reducing impurity influx during co-axial helicity injection start-up and using radio frequency waves to ramp-up the plasma current.

	FY 2009	FY 2010	FY 2011
▪ **Experimental Plasma Research**	**16,975**	**16,765**	**16,765**

The Experimental Plasma Research activity focuses on the exploration of Innovative Confinement Concepts (ICC)—small-scale facilities that explore emerging concepts for plasma confinement and stability. Recent investments have supported construction and operation of a range of facilities, an ICC-centric theory center, and several small topic-specific investigations. The facilities built include stellarators, spheromaks, field-reversed configurations, a levitated dipole, a flow-stabilized z-pinch, centrifugally confined magnetic mirrors, and electrostatic confinement. These studies have intrinsic value to FES's plasma science and fusion energy missions since they provide unique tests and extensions to enhance the understanding of confined plasmas, complementing the larger tokamak programs and helping to establish the predictive understanding of fusion plasma behavior. The program is undergoing a peer review in FY 2010, the goal of which is to select a portfolio of concepts to generate sufficient experimental data to elucidate the underlying physics principles upon which these concepts are based and, as needed, to develop computational models of promising concepts to a sufficient degree of scientific fidelity to allow an assessment of the relevance of those concepts to future fusion energy systems. New emphasis will be placed on the ability of some elements in this portfolio to contribute to the science needed in order to deepen our understanding of burning plasmas such as ITER.

In FY 2011, experimental plasma research will continue to examine novel three-dimensional confinement systems that address potential deficiencies in the tokamak and support development of instability mitigation techniques for ITER. Stellarators remain a top alternative confinement concept that can mitigate several of the potential deficiencies of the tokamak configuration. Research on the stellarator concept is continuing in FY 2011 within this program, such as developing knowledge of quasi-symmetric stellarator confinement as the basis for a credible, innovative approach to fusion energy.

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
▪ **High Energy Density Laboratory Plasmas**	**24,753**	**24,551**	**31,040**

High energy density laboratory plasma physics is the study of ionized matter at extremely high density and temperature. According to the 2007 National Academies report on *Plasma Science: Advancing Knowledge in the National Interest*, high energy density (HED) physics begins when matter is heated or compressed (or both) to a point that the stored energy in the matter reaches approximately 10 billion Joules per cubic meter. This corresponds to a pressure of approximately 100,000 atmospheres. HED conditions exist in the interior of the Sun where hydrogen has been fused to produce energy. Supernovae, gamma ray bursts, accretion disks around black holes, pulsars, and astrophysical jets are examples of HED astrophysical phenomena. On Earth, HED conditions can only be created transiently in the laboratory by using intense pulses of lasers, particle beams (electrons or ions), plasma jets, magnetic pinches, or their combinations. Because of its potentially immense impact on energy security, the National Academies report recommended that SC provide stewardship of HED plasma science related to inertial fusion including the use of magnetized targets.

In FY 2011, the proposed budget will allow a significant expansion of the FES HEDLP initiative launched in FY 2009. On-going research includes studies of warm dense matter driven by heavy ion beams, fast ignition, magnetized high energy density plasmas, and high mach number and high density plasma jets. Funding awards will be determined by competitive peer-review and recommendations from workshops and conferences.

To enhance the study of the field of high energy density matter, FES is building a Matter in Extreme Conditions (MEC) Instrument project at the SLAC National Accelerator Laboratory Linac Coherent Light Source (LCLS) with Recovery Act funding. LCLS is the world's first coherent hard x-ray laser and the MEC project will enable high energy density matter to be probed and controlled by this advanced coherent x-ray source with unprecedented spatial and temporal resolution. Recovery Act funding will be used to expedite completion of the MEC instrument. Recovery Act funding is also enabling the construction of the Neutralized Drift Compression Experiment-II (NDCX-II), which will facilitate studies of warm dense matter and the high energy density physics intrinsic to the science of heavy ion fusion.

▪ **Madison Symmetrical Torus**	**6,852**	**6,915**	**6,915**

The goals of the Madison Symmetrical Torus (MST) at the University of Wisconsin-Madison are to obtain a fundamental understanding of the physics of reversed field pinches (RFPs), particularly magnetic fluctuations and their macroscopic consequences, and to use this understanding to develop the RFP fusion configuration. The RFP is geometrically similar to a tokamak, but with a much weaker externally applied magnetic field that reverses direction near the edge of the plasma. Research in the RFP's self-organization properties has astrophysical applications and may lead to a more cost-effective fusion system. The plasma dynamics that limit the energy confinement and plasma pressure, as well as novel means to the sustainment of the plasma current, are being investigated in this experiment. MST is one of the four leading RFP experiments in the world and is unique in that it pioneered the reduction of magnetic fluctuations by current density profile control. Since 2005 this approach has led to a ten-fold increase in energy confinement time.

In FY 2011, the major plans for the MST program are to assess the confinement of energetic ions using approximately 1 megawatt neutral beam injection, advance inductive current profile control and sustainment methods using a programmable power supply for the toroidal field, and assess the

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011

anisotropy of ion heating from magnetic reconnection using parallel and perpendicular charge exchange recombination spectroscopy.

Theory	**24,014**	**24,348**	**24,348**

The Theory program provides the conceptual scientific underpinning of the magnetic fusion energy sciences program by supporting three thrust areas: burning plasmas, fundamental understanding, and configuration improvement. Theory efforts describe the complex multiphysics, multiscale, non-linear plasma systems at the most fundamental level and, in doing so, generate world-class science. These descriptions—ranging from analytic theory to highly sophisticated computer simulation codes—are used to interpret results from current experiments, plan new experiments on existing facilities, design future experimental facilities, and assess projections of facility performance. The program focuses on both tokamaks and alternate concepts. Work on tokamaks is aimed at developing a predictive understanding of advanced tokamak operating modes and burning plasmas—both of which are important to ITER—while the emphasis on alternate concepts is on understanding the fundamental processes determining equilibrium, stability, and confinement for each concept. The theory program also provides the input needed in the FES large-scale simulation efforts that are part of the SciDAC portfolio and, together with SciDAC, is expected to lead to a predictive understanding of how fusion plasmas can be sustained and controlled.

The Theory program is a broad-based program with researchers located at six national and federal laboratories, over thirty universities, and several private companies. Theorists in larger groups, located mainly at national laboratories and in private industry, generally support major experiments, work on large problems requiring a team effort, or tackle complex issues requiring multidisciplinary teams. Those at universities tend to support smaller, innovative experiments or work on more fundamental problems in plasma physics while training the next generation of fusion plasma scientists.

In FY 2011 the Theory Program will focus particular attention on many important scientific issues, including:

- turbulent transport of toroidal and poloidal momentum in tokamak plasmas and the understanding of spontaneous toroidal rotation,
- progress toward a predictive understanding of particle and electron transport,
- the physics of the edge pedestal and the transition from low to the high confinement modes in tokamaks,
- the formation of edge and internal transport barriers,
- a first-principles formulation of moment closures in extended magnetohydrodynamics models,
- calculations atomic and molecular collision processes of importance in fusion reactors,
- studies of how to improve the stellarator concept and find configurations that are less prone to the formation of islands, the study of other innovative confinement concepts,
- understanding fast magnetic reconnection in high temperature fusion plasmas, and
- development of predictive integrated computational models for tokamak plasmas.

Developing a validated predictive capability is very important, and in FY 2011, the theory program is exploring the possibility of having, as its annual performance target, a joint theory/computational/experiment milestone aimed at understanding the physics mechanisms responsible for the structure of the pedestal and developing a predictive capability. If this happens, it will be the first time that the theory program has been joined with the experimental and computational programs in an

	FY 2009	FY 2010	FY 2011
	(dollars in thousands)		

integrated joint research effort in support of an annual performance target.

Advanced Fusion Simulations	**9,163**	**11,212**	**13,212**

The FES Advanced Fusion Simulations program includes projects funded under the auspices of the SC Scientific Discovery through Advanced Computing (SciDAC) program as well as a new computational activity focused on integrated modeling, the Fusion Simulation Program (FSP).

▪ **SciDAC**	**7,163**	**7,212**	**7,212**

The SciDAC program is a set of coordinated research efforts across all SC programs overseen by the Advanced Scientific Computing Research (ASCR) program with the goal of achieving breakthrough scientific advances through computer simulation that would have been impossible using theoretical or laboratory studies alone. By taking advantage of significant recent advances in computing technologies, the SciDAC program encourages and enables a new model of multi-disciplinary collaboration among physical scientists, mathematicians, computer scientists, and computational scientists. The product of this collaborative approach is a new generation of scientific simulation codes with high physics fidelity that can fully exploit the emerging capabilities of petascale computing resources.

The current FES SciDAC portfolio includes eight projects focused on the plasma science of magnetic fusion. Of these projects, five are focused on single-issue topical science areas, such as macroscopic stability, the simulation of electromagnetic wave-plasma interaction, the study of turbulent transport in burning plasmas, and the physics of energetic particles. The remaining three projects are known as *Fusion Simulation Prototype Centers* or proto-FSPs and focus on code integration and computational framework development in the areas of edge plasma transport, interaction of RF waves with magnetohydrodynamic instabilities, and the coupling of the edge and core regions of tokamak plasmas.

In FY 2011, following a peer review scheduled for mid-2010, the projects of the resulting FES SciDAC portfolio will continue to focus their efforts on grand challenge scientific questions of importance to burning plasmas and ITER and will also address high-priority issues identified during the recently held Research Needs Workshop (ReNeW) for the Magnetic Fusion Sciences part of the FES program.

In FY 2011, the proto-FSP Centers will continue to focus their efforts on issues of importance to burning plasmas and ITER such as using RF waves to control and mitigate performance-limiting macroscopic instabilities in fusion devices, the development of a first-principles predictive edge pedestal and edge localized modes model for ITER, and the development of advanced computational frameworks for integrated fusion simulations that enable the seamless coupling of the edge and core regions of tokamak plasmas. In addition, as the FES program starts the full Fusion Simulation Program in FY 2011 following a 2-year planning study, the proto-FSPs will work with the FSP team to coordinate their eventual integration within the larger program.

▪ **Fusion Simulation Program**	**2,000**	**4,000**	**6,000**

The Fusion Simulation Program (FSP) is a computational initiative led by FES with collaborative support from ASCR. It is aimed at the development of a world-leading, experimentally validated, predictive simulation capability for fusion plasmas in the regimes and geometries relevant for practical fusion energy. The FSP will take advantage of the emergence of SC petascale computing

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011

capabilities and the scientific knowledge enabled by the FES and ASCR research programs, in particular those under the auspices of the SciDAC program. The FSP will contribute significantly toward the FES mission of developing the scientific basis for fusion energy, as well as its long term goal of developing a predictive capability for burning plasmas. It will also help the U.S. sustain and strengthen its leadership in advanced fusion computations.

In FY 2009, following peer review, FES selected a multi-institutional interdisciplinary team of six national laboratories, nine universities, and two private companies to carry out a two-year detailed planning study for the FSP. The FSP planning team, led by the Princeton Plasma Physics Laboratory, includes scientists with a broad range of expertise in computational, theoretical, and experimental plasma science, applied mathematics, computer and computational science, and software engineering. The FSP planning team is expected to complete its design report by the end of FY 2010, which will then undergo an independent review.

In FY 2011 the increase in funding will allow FES to start implementing the plan developed by the FSP planning team. The FSP research team will begin to develop the scientific software deliverables identified and prioritized during the two-year planning study and take the first steps toward the verification and validation of these components.

General Plasma Science	**14,497**	**14,193**	**14,193**

The General Plasma Science program is directed toward basic plasma science and engineering research. This research strengthens the fundamental underpinnings of the discipline of plasma physics that complements burning plasma science and reaches beyond into many basic and applied physics areas. Principal investigators at universities, laboratories, and private industry carry out the research. A critically important element is the education of plasma physicists. Continuing elements of this program are the NSF/DOE Partnership in Basic Plasma Science and Engineering, the Plasma Science Centers (PSCs), the General Plasma Science program at the DOE laboratories, and basic plasma physics user facilities at laboratories and universities (sharing costs with NSF where appropriate). The PSCs perform plasma science research in areas of such wide scope and complexity that it would not be feasible for individual investigators or small groups to make significant progress. Atomic and molecular data for fusion will continue to be generated and distributed through openly available databases. FES will continue to share the cost with NSF of the multi-institutional plasma physics Frontier Center started in FY 2003 and renewed by NSF for five years in FY 2008. In FY 2009, the PSCs program was renewed following an intensive merit review process. Of the seven applications for PSC funding in FY 2009, one center was selected for funding with regular appropriations and two additional centers were selected with one fully funded for five years and the second funded for approximately three years using Recovery Act funding. In FY 2011, the third year of funding is provided for the PSC funded through regular appropriations.

SBIR/STTR	**0**	**8,382**	**8,137**

In FY 2009, $7,171,000 and $861,000 were transferred to the congressionally mandated Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, respectively. The FY 2010 and FY 2011 amounts are the estimated requirements for the continuation of these programs.

Total, Science	**163,479**	**182,092**	**185,940**

Explanation of Funding Changes

	FY 2011 vs. FY 2010 ($000)
Tokamak Experimental Research	
▪ **DIII-D Research**	
The decrease in funding will shift resources to facility operations to support the completion of facility upgrade activities but still provide sufficient research support and analysis for the planned 14 weeks of experiments.	-900
▪ **Diagnostics**	
The increase in funding is for magnetic fusion energy research.	+8
▪ **Other**	
In the FY 2010 appropriation, FES received an overall increase of $5,000,000 for a total of $426,000,000. This funding element includes the $5,000,000 increase until it can be distributed among priority activities within the FES Science subprogram. Following the distribution of the $5,000,000 in FY 2010, the remaining increase of $1,228,000 will support continuation of Early Career and other post doctoral activities. FES support for new graduate fellowships in fusion science is completed in FY 2010 with the initiation of the DOE Office of Science Fellowship program funded within the Workforce Development for Teachers and Scientists program.	-3,504
Total, Tokamak Experimental Research	**-4,396**
Alternative Concept Experimental Research	
▪ **High Energy Density Laboratory Plasmas (HEDLP)**	
Increase will allow for an expansion of research activities supported by the HEDLP initiative, which was started in FY 2009.	+6,489
Advanced Fusion Simulations	
▪ **Fusion Simulation Program (FSP)**	
The increase will allow FES to start the ramp-up of the Fusion Simulation Program (FSP) funding as it transitions from the planning phase to the full program.	+2,000
SBIR/STTR	
The support for SBIR/STTR is funded at the mandated level.	-245
Total Funding Change, Science	**+3,848**

Facility Operations

Funding Schedule by Activity

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
Facility Operations			
DIII-D	36,456	37,480	39,751
Alcator C-Mod	15,724	17,434	18,457
NSTX	22,536	22,150	22,024
NSTX Upgrade (MIE)	5,235	6,550	7,685
Other, GPE and GPP	3,698	2,103	2,103
U.S. Contributions to ITER (MIE TPC)	124,000	135,000	80,000
Total, Facility Operations	207,649	220,717	170,020

Description

The mission of the Facility Operations subprogram is to provide for the operation, maintenance, and minor modifications of the major fusion research facilities (Alcator C-Mod, DIII-D, and NSTX), to carry out major upgrades to existing facilities, and to construct new facilities such as ITER. Periodic facility reviews are used to ensure that the facilities are operated efficiently and in a safe and environmentally sound manner. The balance between operations, maintenance, and upgrades is judiciously adjusted to ensure safe operation of each facility; provide modern experimental tools such as heating, fueling, and exhaust systems; and provide the operating time to meet the needs of scientific collaborators.

The major FES facilities enable U.S. scientists from universities, laboratories, and industry, as well as visiting foreign scientists, to conduct world-class research funded through the Science and Enabling R&D subprograms. Upgrades of the major fusion facilities, such as installation of new diagnostics, and execution of new projects, such as ITER, help to keep U.S. scientists at the forefront of plasma and fusion research.

The *DIII-D* tokamak at General Atomics in San Diego, California is the largest magnetic fusion facility in the United States. DIII-D provides for considerable experimental flexibility and has extensive diagnostic instrumentation to measure the properties of high temperature plasmas. It also has unique capabilities to shape the plasma and provide feedback control of error fields that, in turn, affect particle transport and the stability of the plasma. The extensive tokamak database from DIII-D has provided the major physics input to the ITER design.

Alcator C-Mod at MIT is the only tokamak in the world operating at and above the ITER design magnetic field and plasma densities, and it produces the highest pressure tokamak plasma in the world, approaching pressures expected in ITER. It is also unique in the use of all-metal walls to accommodate high power densities. Because of these characteristics, C-Mod is particularly well suited to examine plasma regimes that are highly relevant to ITER.

NSTX is an innovative magnetic fusion device at PPPL using the spherical torus confinement configuration. A major advantage of this configuration is the ability to confine a higher plasma pressure for a given magnetic field strength, which could enable the development of smaller, more economical fusion research facilities.

ITER is an important step between today's facilities designed to study plasma physics and a demonstration fusion power plant. It will be the only magnetic fusion facility in the foreseeable future to achieve burning plasmas, which is essential to demonstrate the scientific feasibility of fusion energy, and study its underlying physics. An international collaboration of scientists and engineers led to the design of this burning plasma physics experiment. Project partners are China, the European Union (EU), India, Japan, Russia, South Korea, and the United States. ITER is presently under construction in Cadarache, France.

Selected FY 2009 Accomplishments

- *DIII-D:* The installation of an additional power supply for the electron cyclotron heating system permitted the simultaneous operation of six long pulse, high power microwave tubes for the first time. The completed six tube system resulted in a DIII-D record of 13 megajoules of microwave energy injection into a plasma.
- *Alcator C-Mod:* An extensive set of new divertor and limiter heat-flux diagnostics was installed during C-Mod's recent maintenance shutdown, which is providing key information on energy deposition to main-chamber limiter and divertor surfaces and their relationship to upstream plasma parameters. The new diagnostics are providing critical data to advance our understanding of plasma-wall interaction physics in the unique power density regime in which C-Mod operates.
- *NSTX:* Using dual lithium evaporators to provide complete toroidal coverage of lithium to the lower divertor structure, the NSTX team has achieved plasma performance significantly higher than with one lithium evaporator. In addition, high-performance operation with no between-shot helium glow discharge cleaning is now possible, thus increasing the achievable shot-rate by more than 20%.
- *ITER Test Blanket Module Experiments on DIII-D*: To address a concern that the ferromagnetic materials in the structure of proposed ITER Test Blanket Modules (TBMs) might have a detrimental effect on the performance of ITER, DIII-D researchers have designed and installed a mockup module that can simulate the expected fields in ITER by varying currents in coils in the mockup module. The coils can produce fields that will be up to approximately three times the equivalent perturbation that would be produced by the TBMs in ITER. An international research team representing most of the ITER parties will carry out a series of experiments in FY 2010 to determine the effect that the localized non-resonant fields from the TBM mockup have on the DIII-D plasma.

Detailed Justification

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
DIII-D	**36,456**	**37,480**	**39,751**

To carry out the research funded in the Science subprogram, support is provided for operation, maintenance, and improvement of the DIII-D facility and its auxiliary systems. The DIII-D program will complete 17 weeks of FY 2010 experimental operations (including three weeks using Recovery Act funding) in April 2010 prior to a year-long shutdown for facility modifications. The primary modifications will be to move one of the neutral beam lines for off-axis power injection, installation of internal control coils on the tokamak center post for investigation of plasma edge instabilities, and diagnostics improvements. The Recovery Act funding for the DIII-D Upgrades provided for enhanced diagnostics systems and additional electron cyclotron heating. The FY 2011 experimental operations will then start in April 2011 with plans for 14 weeks of single-shift operations. Operations will continue to support experiments addressing ITER design and operations issues and developing the

	FY 2009	FY 2010	FY 2011
(dollars in thousands)			

advanced tokamak concept for fusion energy. Experiments in FY 2011 will take advantage of the recently completed off-axis neutral beam and center post coil systems.

	FY 2009	FY 2010	FY 2011
Achieved Operating Hours	559	N/A	N/A
Planned Operating Hours[a]	520	560	560
Optimal Hours	1,000	1,000	1,000
Percent of Optimal Hours	55.9%	56.0%	56.0%
Unscheduled Downtime	85	N/A	N/A
Number of Users	220	235	235

Alcator C-Mod	**15,724**	**17,434**	**18,457**

Support is provided for operation, maintenance, minor upgrades, and improvement of the Alcator C-Mod facility and its auxiliary systems, including completing and installing a second advanced 4-strap ion cyclotron radio frequency antenna, returning to full system capability (8 MW source, at least 6 MW coupled), continued planning for a second advanced lower hybrid launcher (FY 2011 installation), and the design of a high temperature tungsten divertor. In FY 2010, Alcator C-Mod will be operated for 18 weeks, which includes five weeks using Recovery Act funding, focusing on ITER design and operations issues and addressing high field and density issues. The Recovery Act funding for the Alcator C-Mod Upgrades enabled the improvements to the facility's auxiliary heating and diagnostic systems. In FY 2011, Alcator C-Mod will operate for 15 weeks.

	FY 2009	FY 2010	FY 2011
Achieved Operating Hours	291	N/A	N/A
Planned Operating Hours[a]	288	416	480
Optimal Hours	800	800	800
Percent of Optimal Hours	36.4%	52.0%	60.0%
Unscheduled Downtime	8	N/A	N/A
Number of Users	182	195	200

NSTX	**22,536**	**22,150**	**22,024**

Support is provided for operation, maintenance, and a few facility and diagnostic upgrades on NSTX, including an edge ultra-soft x-ray array, a divertor spectrometer, beam emission spectroscopy for measuring ion-scale turbulence, and an ion flow measurement diagnostic. In FY 2009, NSTX operated for 16.8 weeks, which included 5.8 weeks using Recovery Act funding. In FY 2010, 15 weeks of operation are planned, including one week using Recovery Act funding. The Recovery Act funding for NSTX enabled the facility and diagnostic upgrades. In FY 2011, there is funding for 14 weeks of operation to explore issues of sustained spherical torus (ST) operation and study ST confinement at high fields relevant to evaluating the science base for high-heat flux and plasma nuclear science

[a] Planned hours do not include Recovery Act supported operations in FY 2009 and FY2010.

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011

initiatives. In FY 2011, NSTX will fully exploit new capabilities added in FY 2009 such as the liquid lithium divertor and the upgraded high harmonic fast wave antenna.

	FY 2009	FY 2010	FY 2011
Achieved Operating Hours	440	N/A	N/A
Planned Operating Hours[a]	440	560	560
Optimal Hours	1,000	1,000	1,000
Percent of Optimal Hours	44.0%	56.0%	56.0%
Unscheduled Downtime	0	N/A	N/A
Number of Users	140	145	145

	FY 2009	FY 2010	FY 2011
NSTX Upgrade (MIE)	**5,235**	**6,550**	**7,685**

Support is provided to begin conceptual design work for a major upgrade of NSTX to keep its world-leading status. A new centerstack magnet assembly that will double the magnetic field and a second neutral beam line that will double the plasma heating power are both being considered. The proposed funding and Critical Decision (CD) schedule for these activities will be refined in FY 2010. A final decision as to whether to carry out both upgrades in parallel or in series will be made at CD-2.

	FY 2009	FY 2010	FY 2011
Other, GPE, and GPP	**3,698**	**2,103**	**2,103**

Funding for general plant projects (GPP) and general purpose equipment (GPE) provides support for general infrastructure repairs and upgrades for the PPPL site based upon quantitative analysis of safety requirements, equipment reliability, and research needs. Recovery Act funding supports a major upgrade to PPPL's electrical power distribution system, including 138 kilovolt switch gear, transformers, and associated circuit breakers.

	FY 2009	FY 2010	FY 2011
U.S. Contributions to ITER Project (MIE)	**124,000**	**135,000**	**80,000**

Background: The U.S. ITER Project is the U.S. share of a seven-member international collaboration to design and build a first-of-a-kind international research facility in Cadarache, France to demonstrate the scientific feasibility of fusion energy. The U.S. ITER Project scope consists of delivering hardware components, personnel, and funds to the ITER Organization (IO). The legal framework for construction, operation, deactivation, and decommissioning is contained in the *Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project* (or the JIA), which entered into force in October 2007 for a period of 35 years.

While significant technical progress has been made with large fusion experiments around the world, most of which were constructed in the 1980s, it has long been obvious that a larger and more powerful magnetic confinement device would be needed to create the physical conditions expected in a fusion power plant (i.e., a sustained "burning plasma" comprised of hot ionized deuterium and tritium gas) and to demonstrate its feasibility. The idea to cooperatively design and build such a device originated from the Geneva Summit in November 1985; the U.S. participated in the initial design activity and after a hiatus, the U.S. joined the ITER negotiations in early 2003.

[a] Planned hours do not include Recovery Act supported operations in FY 2009 and FY2010.

(dollars in thousands)		
FY 2009	FY 2010	FY 2011

International ITER Project Status: The IO, located at Cadarache, has been established as an independent international legal entity comprised of personnel from all of the Members. The IO is led by a Director General who is appointed by the ITER Council, which serves as ITER's executive governing board. The Council comprises representatives from all the Members. Like all non-host Members, the U.S. share for ITER's construction is 1/11 (9.09%) of the total value estimate—roughly 80% will be in-kind components manufactured by U.S. industry—and beyond that, the U.S. has agreed to fund 13% of the cost for operation, deactivation, and decommissioning. As the Host, the EU is obligated to provide 5/11 (45.45%) of ITER's construction value. The JIA identifies the hardware procurement allocations among the seven Members based on this cost sharing arrangement. Starting from a 'green field' site in 2006, the ITER enterprise at Cadarache had staffed up to about two thirds of its full complement of 600 personnel by the end of 2009.

An international design review in 2007 recommended several important ITER design improvements and identified some missing items of scope, such as certain test facilities and a number of spare parts. Although the JIA included a goal for construction completion and first plasma to be achieved in 2016, this has proven to be unrealistic. Together with other factors, these developments have increased the estimate for ITER's construction cost. The IO's most urgent tasks now are to complete work on the overall ITER design and systems engineering, and to establish realistic technical, schedule, and cost baselines. The ITER Council has asked the IO to prepare a baseline proposal for the Council to review and approve by mid-2010. The U.S. will continue to emphasize the importance of completing these efforts as soon as possible and provide support as needed.

U.S. ITER Project Status: The main cost risk to the U.S. ITER Project is the slow rate of progress by the IO and some Members' Domestic Agencies who are responsible for critical path hardware components, which has delayed the construction schedule. Next, there remains some ambiguity over the effect of EU/French nuclear regulatory requirements on U.S. hardware designs. Development of a realistic ITER baseline schedule and cost estimate is ongoing. Once the baseline has been established and approved by the Council, the USIPO will be able to develop schedule and cost baselines for the U.S. ITER Project scope in preparation for CD-2, Approve Performance Baselines. CD-2 is currently projected to occur in late FY 2011.

Estimated ITER TPC Range: The TPC range approved at CD-1 accounts for the magnitude of cost risks that were identified at the time the range was developed in late 2007. The sources of potential cost growth can be categorized as follows: actions taken by the ITER Council and the IO, external factors outside of the ITER project, and design maturity.

Among the aspects under the IO's purview, the principal cost drivers are the overall project schedule, design changes and other actions affecting hardware scope and manufacturing costs, and French and EU licensing/regulatory requirements. The IO is continuing to develop an integrated baseline schedule for the construction phase that includes detailed inputs from the seven Members. Likewise, there are several changes to the reference design, some of which may increase the U.S. ITER TPC.

External factors include changes in Dollar/Euro exchange rates, escalation rates, commodity prices, and market conditions for hardware procurement. The JIA requires funding contributions from the Members to be made in Euros, which has already increased U.S. ITER Project costs due to less favorable Dollar-Euro exchange rates. Prices for raw materials used in manufacturing U.S.-supplied hardware have also been steadily increasing. This remains a significant long-term concern.

Finally, the reference design for ITER is not complete in certain areas such as the blanket first wall and shield system. This means that there could be adverse cost impacts as the design is finalized prior to fabrication. A Test Blanket Module (TBM) program has been established to demonstrate a key element of fusion technology, namely the breeding of tritium for a closed fuel cycle in a fusion power plant. While not part of the construction scope of ITER, it will have near-term financial implications since certain modifications to the currently designed ITER civil infrastructure must be made to accommodate TBMs. The U.S. share of these modifications is expected to be under $10,000,000 and will be funded by the U.S. ITER Project.

All of these risks were previously evaluated to develop a TPC range for CD-1. It was determined that the bottom of the range should be set at $1.45 billion, which included a reasonable contingency amount (equal to 27 percent of the hardware cost). The difference between $1.45 billion and the top end of the TPC range, $2.2 billion, essentially provides additional contingency for known risks in the above categories as well as an amount for unidentified risks. However, the approved TPC range presumed a much more aggressive schedule than has evolved thus far.

ITER Financial Schedule Total Project Cost (TPC)[a]

(budget authority in thousands)

Fiscal Year	Total Estimated Cost	Other Project Costs	Total Project Costs
2006	15,866	3,449	19,315
2007	42,000	18,000	60,000
2008	22,500	3,570	26,070
2009	109,000	15,000	124,000
2010	115,000	20,000	135,000
2011	75,000	5,000	80,000
Outyears	TBD	TBD	TBD

In FY 2010, funds are being used to perform a variety of design, R&D, and long-lead procurement activities for the U.S. hardware contributions to ITER construction. For the two largest elements of U.S. scope, the central solenoid magnet system and the tokamak cooling water system, these include industrial design and manufacturing R&D efforts as well as long-lead procurements of materials. Long-lead procurement of toroidal field magnet conductors from industrial vendors is also continuing. In other areas of U.S. responsibility, design and R&D is continuing for the blanket first wall and shield modules, fueling pellet injector, tokamak exhaust processing system, ion and electron cyclotron heating transmission lines, steady-state electric power system, vacuum pumping system, and diagnostics. The U.S. is continuing to provide conceptual design and cost estimating services to the IO for the ITER in-vessel coil system. The balance of funds will be used to support the USIPO, provide a small number of U.S. secondees to work on the IO staff, and furnish prescribed funding contributions to the IO.

[a]A complete baseline funding profile, including the outyears, will be established at CD-2, which is anticipated to be in FY 2011.

	FY 2009	FY 2010	FY 2011

(dollars in thousands)

The $80,000,000 requested for the U.S. ITER Project in FY 2011 is a reflection of the pace of ITER construction as of the end of 2009. The Administration is engaged in a range of initiatives to implement management reforms at the IO and accelerate ITER construction with the goal of minimizing the overall cost of the Construction Phase for the U.S. and the other ITER Members.

The FY 2011 funding request will be used to make progress on all of the design, R&D, and long-lead procurement activities described above for the U.S. hardware contribution, albeit at a reduced rate. Emphasis will continue to be given to industrial involvement in completing design work in preparation for subsequent large-scale fabrication activities. Toroidal field magnet conductor production will be largely completed. The U.S. effort on the in-vessel coils will be handed over to the IO, which will be responsible for completing preliminary design, prototyping, final design, as well as fabrication. The balance of funds will be used to support the USIPO, provide a small number of U.S. secondees to work on the IO staff, and furnish prescribed funding contributions to the IO.

ITER Related Annual Funding Requirements: The current estimate in the table below incorporates the terms of the JIA on cost sharing during operations, deactivation and decommissioning. Specifically, it considers the procedure for converting currencies into Euros and the 20-year period of annual contributions to the decommissioning fund in conjunction with ITER operations.

(dollars in thousands)

	Current Estimate	Previous Estimate
FY 2015–FY 2034[a]		
U.S. share of annual facility operating costs including commissioning, maintenance, repair, utilities, power, fuel, improvements, and annual contribution to decommissioning fund for the period 2015 to 2034. Estimate is in 2015 dollars.	80,000	80,000
FY 2035–FY 2039		
U.S. share of the annual cost of deactivation of ITER facility for the period 2035–2039. Estimate is in 2037 dollars.	25,000	25,000

	FY 2009	FY 2010	FY 2011
Total, Facility Operations	**207,649**	**220,717**	**170,020**

[a] These estimates will be updated to reflect a more realistic start date for the ITER Operations Phase once the ITER Council has approved a baseline schedule for the Construction Phase.

Explanation of Funding Changes

	FY 2011 vs. FY 2010 ($000)
DIII-D	
The increase in funding for FY 2011 will allow for completion of the facility upgrades begun in FY 2010 as part of the long torus opening activity. It will also support 14 weeks of single-shift operations.	+2,271
Alcator C-Mod	
The increase in funding for FY 2011 will allow completing a new antenna for radio frequency heating experiments and installation of a second lower hybrid launcher. It will enable design of a tungsten divertor relevant to a future demonstration reactor and will support 15 weeks of operation.	+1,023
NSTX	
The decrease in funding for the NSTX Facility is applied to the increase for the NSTX Upgrade MIE project. This budget will support 14 run weeks of plasma operation.	-126
NSTX Upgrade (MIE)	
The increase will provide for continued work on two possible enhancements to the NSTX Facility. An upgrade to the magnet system, including the central solenoid, is designed to permit higher plasma currents and magnetic fields. The additional neutral beam heating power is designed to enable control of the plasma stability by modifying the plasma current. Completing both upgrades would enable higher plasma pressures to be obtained.	+1,135
U.S. Contributions to ITER Project (MIE)	
U.S. Contributions to ITER MIE funding is decreased by $55,000,000 to match the Administration's late 2009 estimation of the pace of the ITER project.	-55,000
Total Funding Change, Facility Operations	**-50,697**

Enabling R&D

Funding Schedule by Activity

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
Enabling R&D			
Engineering Research	18,573	17,974	18,311
Materials Research	4,817	5,217	5,729
Total, Enabling R&D	23,390	23,191	24,040

Description

The Enabling R&D subprogram helps the Science subprogram address its scientific challenges by developing and continually improving the hardware, materials, and technology that are incorporated into existing fusion research facilities, thereby enabling these facilities to achieve higher levels of performance. Enabling R&D also supports the development of new hardware, materials, and technology that are incorporated into the design of next generation facilities, thereby increasing confidence that the predicted performance of these new facilities will be achieved.

Selected FY 2009 Accomplishments

- *New Disruption Mitigation Tool Successfully Tested on DIII-D:* Disruptions are the sudden, uncontrolled termination of the plasma that can potentially damage the plasma chamber from sudden thermal loads and high magnetic forces. A new technique has been developed to mitigate these effects by injecting a solid hydrogen pellet nearly the size of a wine cork into the disrupting plasma. The pellet is fired by a pneumatic gun and shattered by hitting a metal plate just before entering the plasma to produce a spray of hydrogen that quickly dissipates the plasma energy in approximately $1/1000^{th}$ of a second before any plasma chamber damage can take place. A new system using this technique has been installed on DIII-D and has been shown to control the rapid termination of high performance plasmas and reduce thermal loads and forces. This technique can potentially be employed on ITER to prevent any disruptions from reducing machine availability for physics experiments.
- *Understanding plasma material interactions for ITER:* A burning plasma creates a harsh environment that challenges the materials inside the plasma chamber. During ITER operation, we must understand the very complex mechanistic effects of a burning plasma on the materials so as to optimize the design as well as ensure safe operating scenarios for the device. As part of a U.S.-Japan collaboration, which is focused on plasma chamber issues, experiments are being conducted at the University of California at San Diego to simulate fusion-type plasmas to better understand these complicated phenomena. These experiments show that helium, a byproduct of the deuterium-tritium fusion reaction, has a beneficial effect of reducing surface blistering in tungsten, which will be used as a plasma facing material in ITER. This beneficial effect is caused by nano-sized high density helium bubbles created in the near-surface region of the tungsten acting as a diffusion barrier. The implication of this result is that tritium uptake in tungsten surfaces, an important safety concern, may be reduced by the presence of helium contained in the plasma interacting with the tungsten surfaces.
- *Developing materials for use in the fusion environment:* Significant progress has been made on a new class of structural materials known as nanocomposited ferritic alloys. These materials contain an ultrahigh density of nanometer-scale particles that impart excellent high-temperature strength,

radiation damage resistance, and the potential to tolerate the high-levels of helium produced in the fusion neutron environment. Recent modeling has revealed that the basic strengthening mechanism in these alloys is due to the unique crystal structure of the nanometer-scale particles. Novel experiments performed in the High Flux Isotope Reactor have also demonstrated the capability of these materials to manage fusion-relevant helium production through the formation of numerous, very fine-scale bubbles on the nanoparticles.

Detailed Justification

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
Engineering Research	**18,573**	**17,974**	**18,311**

The Engineering Research element addresses the breadth and diversity of domestic interests in enabling R&D for magnetic fusion systems as well as international collaborations with emphasis on heating, fueling, plasma chamber, safety research, and surface protection technologies. While much of the effort is focused on current devices, an increasing amount of the research is oriented toward the technology needs or issues that will be faced in future experiments, including ITER. An example is to understand scientifically what is occurring in a burning plasma with material erosion and redeposition within the fusion chamber caused by this harsh environment and what effect it can have on the plasma and ITER operation. In addition to providing the tools that help accomplish the experimental research, a part of this element also conducts system studies of the most scientifically challenging concepts for fusion research facilities that may be needed in the future as well as identifying critical scientific issues and missions for the next stage in the FES program. Finally, analysis and studies of critical scientific and technological issues are supported, the results of which will provide guidance for optimizing future experimental approaches and for understanding the implications of fusion research on applications of fusion.

▪ **Plasma Technology**	**14,471**	**13,651**	**13,651**

Plasma Technology efforts will focus resources on developing enabling technologies for current and future machines, both domestically and internationally, and on addressing potential ITER operational issues. In addition, the collaborative program on plasma facing and blanket materials for use in future facilities, Tritium Irradiation Thermofluid American-Japanese Network (TITAN), will be continued.

In FY 2011, the following specific activities will be supported:

- Continue the experimental studies and modeling activities of tungsten-carbon-beryllium mixed materials layer formation and redeposition in the University of California at San Diego experimental facility and in the Tritium Plasma Experiment at Idaho National Laboratory (INL). Results will be applied to evaluate tritium accumulation in plasma facing components that will occur during ITER operation.
- Continue a series of material science experiments under the TITAN cost-sharing collaboration with Japan in the Safety and Tritium Applied Research Facility at INL to resolve key issues of tritium behavior in materials proposed for use in fusion systems.

Research will also be conducted on plasma facing components, heating and fueling technologies, and blanket concepts that could be tested in ITER. In addition, this category funds research in safety and plasma-surface interaction and modeling to address potential issues that could be encountered during operation of ITER or future devices.

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
▪ **Advanced Design**	**4,102**	**4,323**	**4,660**

In FY 2011 this effort will continue to focus on system studies by a team from the fusion research community with a wealth of experience in fusion science, technology, and facilities. The team is known for its objective approach and its ability to develop highly innovative solutions. In the past the team has conducted studies of various types of fusion devices to help the program identify the R&D necessary to move the program forward.

Using this existing team and other resources, FES will initiate a series of strategic planning/scoping studies as follow-on to the June 2009 Research Needs Workshop on the Magnetic Fusion Energy Sciences part of the program. These studies will help identify possible approaches for the next stage in the U.S. fusion research program in the ITER era. The long-term objective is to identify potential initiatives and facilities that may be pursued at the pre-conceptual level.

Materials Research	**4,817**	**5,217**	**5,729**

The Materials Research element focuses on the key science issues of materials for practical and environmentally attractive uses in fusion research and future facilities. This element uses both experimental and modeling activities which make it more effective at using and leveraging the substantial work on nanosystems and computational materials science being funded by other programs. The long-term goal of this element is to develop experimentally validated predictive and analytical tools that can lead the way to nanoscale design of advanced fusion materials with superior performance and lifetimes.

The FY 2011 request will maintain and modestly grow a Materials Research program that addresses material needs for nearer and longer term fusion devices. The funding will be used for both modeling and experimental activities aimed at the science of materials behavior in fusion environments, including research on candidate materials for the structural and plasma facing elements of fusion chambers. Through a variety of cost-shared international collaborations, this element conducts irradiation testing of candidate fusion materials in the simulated fusion environments of fission reactors to provide data for validating and guiding the development of models for the effects of neutron bombardment on the microstructural evolution, damage accumulation, and property changes of fusion materials.

Total, Enabling R&D	**23,390**	**23,191**	**24,040**

Explanation of Funding Changes

	FY 2011 vs. FY 2010 ($000)
Engineering Research	
▪ **Advanced Design**	
The increase will support strategic planning/scoping studies on issues and topics identified during the Research Needs Workshops. The studies will help identify possible approaches for the next steps in the U.S. fusion research program.	+337

	FY 2011 vs. FY 2010 ($000)
Materials Research	
The increase will support scientific research on new nano-composited high strength materials.	+512
Total Funding Change, Enabling R&D	**+849**

Supporting Information

Operating Expenses, Capital Equipment and Construction Summary

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
Operating Expenses	273,026	298,646	290,588
Capital Equipment	118,499	125,861	87,919
General Plant Projects	2,993	1,493	1,493
Total, Fusion Energy Sciences	394,518	426,000	380,000

Funding Summary

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
Research	186,869	205,283	209,980
Scientific User Facilities Operations	74,716	77,064	80,232
Major Items of Equipment	129,235	141,550	87,685
Other (GPP, GPE and Infrastructure)	3,698	2,103	2,103
Total, Fusion Energy Sciences	394,518	426,000	380,000

Scientific User Facilities Operations and Research

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
DIII-D			
Operations	36,456	37,480	39,751
Facility Research	25,740	27,504	26,604
Total DIII-D	62,196	64,984	66,355
Alcator C-Mod			
Operations	15,724	17,434	18,457
Facility Research	9,002	9,045	9,045
Total Alcator C-Mod	24,726	26,479	27,502
NSTX			
Operations	22,536	22,150	22,024
Facility Research	17,104	17,549	17,549
Total NSTX	39,640	39,699	39,573

	(dollars in thousands)		
	FY 2009	FY 2010	FY 2011
Scientific User Facilities Operations and Research			
Operations	74,716	77,064	80,232
Facility Research	51,846	54,098	53,198
Total, Scientific User Facilities Operations and Research	126,562	131,162	133,430

Facility Users and Hours

	FY 2009	FY 2010	FY 2011
DIII-D National Fusion Facility			
Achieved Operating Hours	559	N/A	N/A
Planned Operating Hours[a]	520	560	560
Optimal Hours	1,000	1,000	1,000
Percent of Optimal Hours	55.9%	56%	56%
Unscheduled Downtime	85	N/A	N/A
Number of Users	220	235	235
Alcator C-Mod			
Achieved Operating Hours	291	N/A	N/A
Planned Operating Hours[a]	288	416	480
Optimal Hours	800	800	800
Percent of Optimal Hours	36.4%	52%	60%
Unscheduled Downtime	8	N/A	N/A
Number of Users	182	195	200
National Spherical Torus Experiment			
Achieved Operating Hours	440	N/A	N/A
Planned Operating Hours[a]	440	560	560
Optimal Hours	1,000	1,000	1,000
Percent of Optimal Hours	44.0%	56%	56%
Unscheduled Downtime	0	N/A	N/A
Number of Users	140	145	145

[a] Planned hours do not include Recovery Act supported operations in FY 2009 and FY2010.

	FY 2009	FY 2010	FY 2011
Total, Facilities Users and Hours			
Achieved Operating Hours	1,290	N/A	N/A
Planned Operating Hours[a]	1,248	1,536	1,600
Optimal Hours	2,800	2,800	2,800
Percent of Optimal Hours	46.1%	54.9%	57.1%
Unscheduled Downtime	93	N/A	N/A
Number of Users	542	575	580

Major Items of Equipment

(dollars in thousands)

	Prior Years	FY 2009	FY 2010	FY 2011	Outyears	Total
MIEs						
NSTX Upgrade						
TEC	0	0	5,550	7,685	TBD	TBD
OPC	0	5,235	1,000	0	TBD	TBD
TPC	0	5,235	6,550	7,685	TBD	TBD
ITER						
TEC	82,366	109,000	115,000	75,000	TBD	TBD
OPC	23,019	15,000	20,000	5,000	TBD	TBD
TPC	105,385	124,000	135,000	80,000	TBD	TBD
Total MIEs						
TEC		109,000	120,550	82,685	TBD	TBD
OPC		20,235	21,000	5,000	TBD	TBD
TPC		129,235	141,550	87,685	TBD	TBD

Facility Operations MIEs:

- ***National Spherical Torus Experiment Upgrade Major Item of Equipment Project***

  The NSTX Upgrade Project was initiated in FY 2009 to support major upgrades at NSTX to keep its world-leading status. As presently envisioned, this project will add a new centerstack magnet assembly that will double the magnetic field, and a second neutral beam (NB) line that will double the NB power available to heat the plasma. CD-0 (Approve Mission Need) was completed on February 23, 2009. The CD-1 Independent Project Review was completed in December 2009. Upon completion of the Departmental review and approval of CD-1, anticipated in the second quarter FY 2010, more definition on the project's scope, schedule, and cost will become available. A decision on the baseline scope, schedule, and cost of this project will be made at CD-2.

- ***U.S. Contributions to ITER***

  The objective of the U.S. ITER Project is to deliver the U.S. share of the hardware components, personnel, and funding contributions (in Euros) to the ITER Organization (IO) for the ITER construction phase per the terms of the ITER Joint Implementation Agreement. The U.S. ITER Project is being managed by the U.S. ITER Project Office (USIPO), located at Oak Ridge National Laboratory (ORNL). ORNL serves as the prime contractor to DOE, working with its partners Princeton Plasma Physics Laboratory and Savannah River National Laboratory. Each laboratory has been assigned a well-defined portion of the project's scope that takes advantage of their respective technical strengths. DOE serves as the U.S. Domestic Agency for ITER, and under its direction, the USIPO has responsibility for planning, managing, and delivering the entire scope of the U.S. ITER Project. All U.S. ITER Project activities are being overseen by a DOE Federal Project Director at the DOE Oak Ridge Office. As the design agent and eventual operator/owner of the ITER facility, the IO is responsible for specifying top level hardware design requirements and delivery schedules.

The U.S. ITER Project was formally initiated in July 2005 when Critical Decision-0 (CD-0), Mission Need, was approved by the DOE Senior Acquisition Executive, and the first year of project funding was FY 2006. CD-1, Alternative Selection and Cost Range (including authorization for long-lead procurements), was subsequently approved in January 2008. This set the Total Project Cost (TPC) range at $1.45 to $2.2 billion (as spent). A schedule range for U.S. ITER Project completion (CD-4) was set at FY 2014–2017. Current efforts are focused on completing U.S. hardware component designs and supporting R&D, and assisting the IO with establishing a functionally mature project management organization.

The $80,000,000 requested for the U.S. ITER Project in FY 2011 is a reflection of the pace of ITER construction as of the end of 2009. The Administration is engaged in a range of initiatives to implement management reforms at the IO and accelerate ITER construction with the goal of minimizing the overall cost of the construction phase for the U.S. and the other ITER Members.

Scientific Employment

	FY 2009 actual	FY 2010 estimate	FY 2011 estimate
# University Grants	305	246	320
# Laboratory Projects	158	167	166
# Permanent Ph.D's (FTEs)	725	723	763
# Postdoctoral Associates (FTEs)	113	113	118
# Graduate Students (FTEs)	327	327	344
# Ph.D.'s awarded	37	42	44