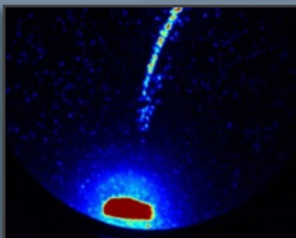
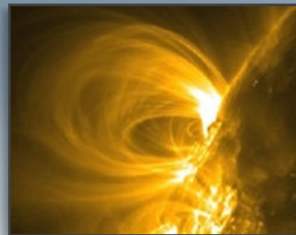
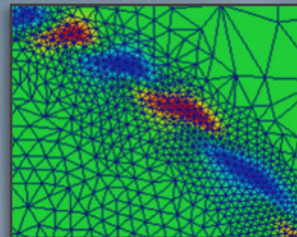
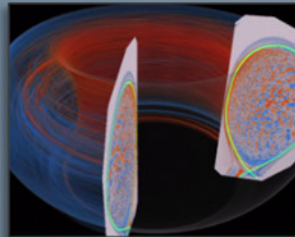
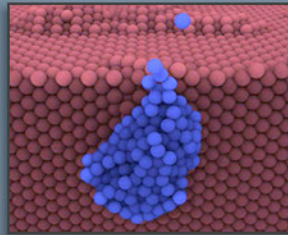
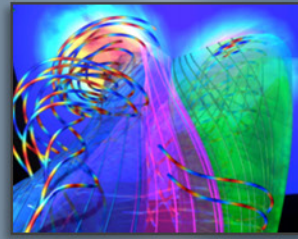


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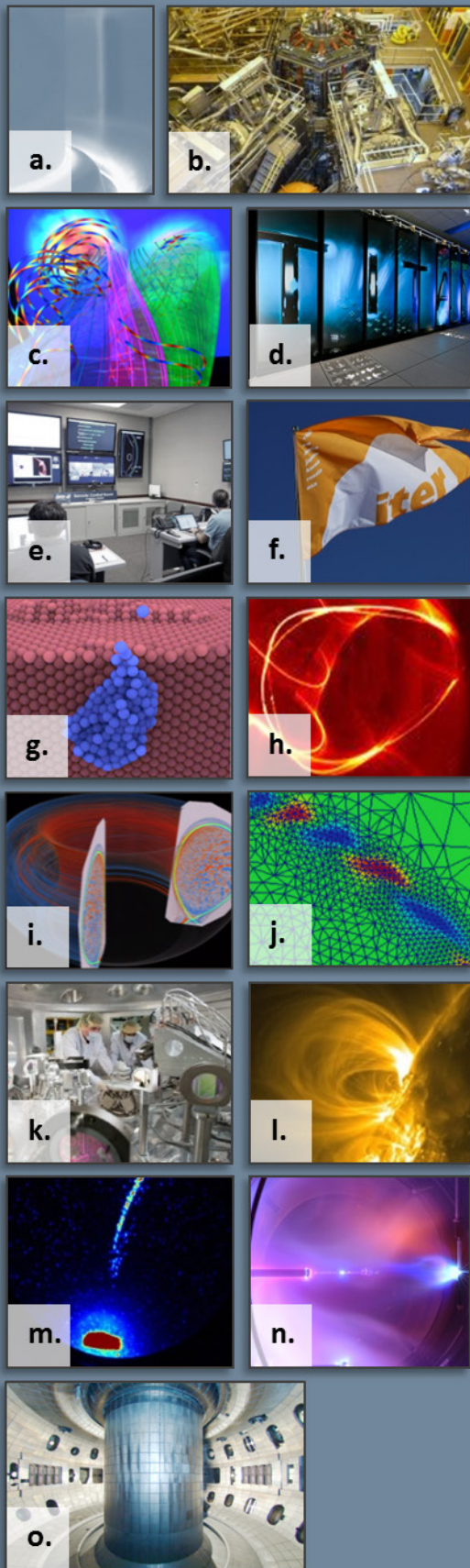
**A Ten-Year
Perspective**
(2015-2025)



U.S. DEPARTMENT OF
ENERGY

Office of
Science

On the Cover



- a) Plasma discharge in the DIII-D tokamak at General Atomics. (Courtesy of DIII-D/General Atomics)
- b) National Spherical Torus Experiment-Upgrade at Princeton Plasma Physics Laboratory. (Courtesy of Princeton Plasma Physics Laboratory)
- c) Magnetic reconnection in two interacting flux ropes. (Courtesy of Basic Plasma Science Facility at University of California, Los Angeles)
- d) Titan supercomputer at the Oak Ridge Leadership Computing Facility. (Courtesy of Oak Ridge National Laboratory)
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- f) ITER flag. The U.S. is a member of the ITER project, constructing the world's first facility for burning plasma experiments. (Courtesy of ITER Organization)
- g) Atomistic simulations of helium bubble formation and growth in tungsten. (Courtesy of Los Alamos National Laboratory)
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- i) Simulation of turbulent fluctuations in a tokamak. (Courtesy of Choong-Seock Chang, PPPL, visualization by Prof. Kwan-Liu's group, University of California-Davis)
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- o) Inside of the DIII-D vacuum vessel at General Atomics. (Courtesy of DIII-D/General Atomics)

Executive Summary

The vision described here builds on the present U.S. activities in fusion plasma and materials science relevant to the energy goal and extends plasma science at the frontier of discovery. The plan is founded on recommendations made by the National Academies, a number of recent studies by the Fusion Energy Sciences Advisory Committee (FESAC), and the Administration's views on the greatest opportunities for U.S. scientific leadership.

This report highlights five areas of critical importance for the U.S. fusion energy sciences enterprise over the next decade:

- 1) Massively parallel computing with the goal of validated whole-fusion-device modeling will enable a transformation in predictive power, which is required to minimize risk in future fusion energy development steps.
- 2) Materials science as it relates to plasma and fusion sciences will provide the scientific foundations for greatly improved plasma confinement and heat exhaust.
- 3) Research in the prediction and control of transient events that can be deleterious to toroidal fusion plasma confinement will provide greater confidence in machine designs and operation with stable plasmas.
- 4) Continued stewardship of discovery in plasma science that is not expressly driven by the energy goal will address frontier science issues underpinning great mysteries of the visible universe and help attract and retain a new generation of plasma/fusion science leaders.
- 5) FES user facilities will be kept world-leading through robust operations support and regular upgrades.

Finally, we will continue leveraging resources among agencies and institutions and strengthening our partnerships with international research facilities.



THE OFFICE OF SCIENCE FUSION ENERGY SCIENCE PROGRAM: A TEN-YEAR PERSPECTIVE

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Legislative Language

This report responds to legislative language set forth in the Explanatory Statement accompanying the Consolidated Appropriations Act, 2014, for a strategic plan for fusion energy sciences research in the United States:

“Not later than 12 months after enactment of this Act, the Department shall submit a ten-year strategic fusion plan to the Committees on Appropriations of the House of Representatives and the Senate. The ten-year plan should assume U.S. participation in ITER and assess priorities for the domestic fusion program based on three funding scenarios with the fiscal year 2014 enacted level as the funding baseline: (1) modest growth, (2) budget growth based only on a cost-of-living adjusted fiscal year 2014 budget, and (3) flat funding. The January 2013 Nuclear Science Advisory Committee report on priorities for nuclear physics used similar funding scenarios and should serve as a model for assessing priorities for the fusion program.”

In that same Congressional report was a request for a plan for implementing a validated, predictive, integrated simulation program for fusion energy sciences:

“Not later than 180 days after enactment of this Act, the Department shall submit to the Committees on Appropriations of the House of Representatives and the Senate a plan with research goals and resource needs to implement a Fusion Simulation program.”

Further, this report responds to the request expressed in the Explanatory Statement accompanying the Consolidated and Further Continuing Appropriations Act, 2015:

“The Office of Science is further directed to seek community engagement on the strategic planning and priorities report through a series of scientific workshops on research topics that would benefit from a review of recent progress, would have potential for broadening connections between the fusion energy sciences portfolio and related fields, and would identify scientific research opportunities. The Department is directed to submit to the Committees on Appropriations of the House of Representatives and the Senate not later than 180 days after enactment of this Act a report on its community engagement efforts.”

In addition, this report covers the Department’s response to the following legacy reporting requirements):

- Energy and Water Development Appropriations Bill, 2009, House Report 110-921, page 115
- Fiscal Year 2012 Conference Report to accompany H.R. 2055, page 855); House Report 112-118, page 113; Senate Report 112-75, page 94
- Energy and Water Development Appropriations Bill, 2014, Senate Report 113-47, page 95

- Energy and Water Development Appropriations Bill, 2014, House Report 113-135, page 109

1. Progress in Fusion Energy Sciences

1.1: The Promise and Scientific Character of Fusion Energy Sciences Research

The frontiers of fusion science exist at the extremes of the plasma state, the state of matter of which stars and well over 99 percent of the visible universe are composed. These extremes range from very small to extremely large, from very slow to very fast, from diffuse to extremely dense, and from ultra-cold to ultra-hot. The Fusion Energy Sciences program supports research extending from end to end of each of these ranges, challenging our ability to produce and measure matter at the extremes.

In addition to these experimental and diagnostic challenges, numerically simulating such systems requires the development of sophisticated modeling tools and use of advanced computing platforms based on fundamental theoretical understanding.

The scientific knowledge necessary to create fusion energy under controlled conditions is centered on the study of plasmas and their interactions with the materials that enclose them. Plasmas—the fourth state of matter—are gases hot enough that electrons have been knocked free of atomic nuclei, forming an ensemble of ions and electrons that can conduct electrical currents and respond to electric and magnetic fields. Stars, lightning bolts, flames, and halogen lighting consist of plasma. Inside the Sun, tremendous gravitational forces create plasma pressures high enough that hydrogen nuclei frequently collide and fuse into new atomic nuclei. The end products following the fusion event actually weigh less than the original colliding nuclei; some of the mass is converted into tremendous energy of motion of the fusion products according to Einstein's famous formula, $E = mc^2$. With the Sun, it is this energy released from the fusion process that becomes the radiant energy that warms the Earth.

Successful development of fusion energy science and technology in the laboratory would lead to a base-load power source for developed and emerging economies, with a fuel supply that is abundant. Since the earliest experiments conducted over 60 years ago, the pursuit of fusion energy has been a challenging program of research and development. Establishing a deep scientific understanding of the requirements for harnessing and optimizing this process on Earth is critical, and is the driving force behind the Department of Energy's (DOE) programmatic investments in this area. The progress to date warrants major new steps in critical areas so as to further advance fusion's scientific and technical viability. This document describes what is required for the U.S. to take those steps.

The scientific progress has been tremendous, and fusion's remaining research frontiers are replete with questions of the highest scientific order. Although producing prodigious amounts of energy is the ultimate goal, over the years research progress in fusion has broadened and deepened scientific knowledge in numerous areas with broader impact, such as self-organized

system complexity, non-linear turbulent energy transport processes, magnetohydrodynamics, energy exchange between dynamic magnetic fields and particles, energy exchange between plasma waves and energetic particles, and the interactions between materials and the unimaginably harsh environment of a fusion plasma. In addition, studies of fusion, astrophysics, and industrial plasma applications have benefited from significant synergy, yielding, for example, the ability to confidently study in the laboratory phenomena relevant to exotic astrophysical processes as well as to perform precise manipulation of plasmas for industrial applications. Indeed, many of the mysteries of the visible universe present scientific challenges in the realm of plasma physics, fusion's original scientific discipline.

All of these achievements have been enabled by, and have themselves promoted, first-of-a-kind capabilities in massively parallel computing and innovations in detailed measurement of the plasma state. The National Energy Research Scientific Computing Center (NERSC), one of the premier supercomputing centers in the U.S. today, was originally called the Controlled Thermonuclear Fusion Computing Center when it was founded in 1974 and was dedicated to simulations of the behavior of plasma in fusion reactors. Its name was subsequently changed to National Magnetic Fusion Energy Computer Center (MFEECC) and then to NERSC as its mission was expanded beyond fusion to provide supercomputing services to all of the Office of Science program offices. NERSC was the first unclassified supercomputer center and became the model for others that followed.

Historically the United States has been a global leader in fusion energy research. In the years after World War II, scientists, buoyed by the rapid progress in nuclear physics and the successful Manhattan Project efforts to control fission processes, were optimistic that practical fusion energy would follow quickly. However, fusion proved to be more challenging than anticipated, largely due to the difficulty in achieving and controlling the extreme physical conditions required to sustain fusion reactions. These form the basis of the scientific research program pursued today by DOE and others worldwide.

The vision of a working fusion energy reactor is as follows: Fusion fuel atoms (usually a mixture of the hydrogen isotopes deuterium and tritium) will be ionized to form the plasma state and further heated to extremely high temperatures on the order of 100 million degrees, where the nuclei fuse. Some of the fusion energy released will be shared with the plasma itself, and the plasma will self-heat, promoting more fusion reactions. Energy released in fusion reactions and carried by energetic ions and neutrons will then be captured and converted into heat, which is used to drive conventional power plant equipment to put useable electric power on the grid.

Today, fusion reactions are created and controlled in research laboratories. Leading experiments have generated megawatts of fusion power for seconds at a time. While rich in scientific value, experiments to date have had a negative energy balance: in other words, more energy has been required to create the fusion reactions than has been released. Experimental efforts are now on the verge of realizing the long-sought goal of creating fusion reactions with net energy gain, an achievement that would enable a new era of science and that would provide the platform for a demonstration power plant. What is missing is an experimental

effort of appropriate scale that will generate the self-heated plasma state so as to test and advance the knowledge base required for being able to control it in an attractive manner, to extract energy from that plasma, and to generate the fuel in a closed cycle from the fusion reactions themselves.

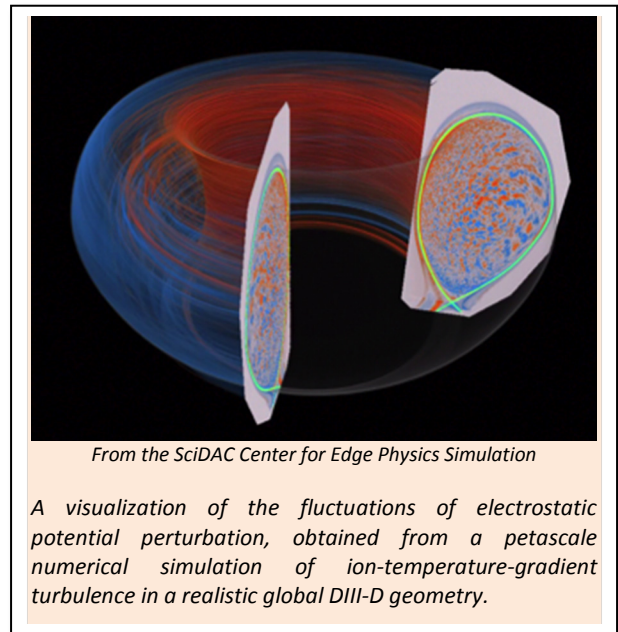
There are two different technological approaches to fusion energy: magnetic-confinement fusion energy (MFE) and inertial-confinement fusion energy (IFE). It is the science of MFE that is predominantly supported by FES, because this is the approach that has shown the most progress in realizing the conditions required for high power and sustained operation. In MFE, carefully arranged magnetic fields are used to physically confine plasma inside a vacuum vessel, where it is isolated in a controlled environment. To create the conditions for fusion to occur, the plasma is heated with energetic particle beams and radio-frequency waves to thermonuclear temperatures. Fusion fuel can then be introduced into the plasma to initiate the reaction. To sustain the fusion reaction process and keep the fusion fuel at thermonuclear temperatures, the plasma must be contained and effectively insulated from the comparatively cool walls of the confining vessel.

Keeping the plasma confined and well-behaved under the extreme conditions required for fusion reactions is challenging, but progress has been dramatic. Indeed, while larger and more capable fusion devices were being constructed during the past three decades that took advantage of increases in scientific understanding, the performance for magnetic-confinement fusion research has increased by a factor of 100,000 (where performance is measured by the triple product of plasma density, plasma temperature, and energy confinement time). In particular, deuterium-tritium experiments conducted in the 1990's on the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory in the U.S. and on the Joint European Torus in the U.K. achieved a central fusion power density that met reactor requirements, and plasma self-heating from energy released in the fusion process was observed. Progress in understanding the dynamical behavior of plasmas and how to control it has been equally dramatic.

Fusion energy sciences research routinely involves the synergy of experiments, theory, computational science, and diagnostic development. The U.S. has been a world leader in establishing this synergistic scientific foundation. Examples include the following:

- Fusion-grade plasmas that match the extraordinary conditions of fuel temperature required in a fusion reactor are now routinely created in U.S. laboratory experiments. The understanding developed from these experiments is enabling optimization of fusion plasma conditions for ITER and other future burning plasma experiments.
- Fine details determining the heat confinement of the fusing plasma state, including temperatures of hundreds of millions of degrees centigrade and fuel fluctuation levels smaller than 0.1 percent of the average fuel density, are routinely measured with precision. Rapid analysis of such measurements is now used by scientists in real time to guide the generation of successive plasma pulses during experiments.

- Fusion scientists have made significant contributions to the fields of turbulence, complex dynamics, and self-organization, subjects that are important not only for fusion, but also many other scientific endeavors, such as climate research. Computational and measurement advances regarding plasma turbulence have led to a revolution in the understanding of fusion system containment properties and the likely characteristics of future experiments, including ITER.
- Scientists are able to exert exquisite control of plasmas for fusion research as well as other applications. This control includes active feedback between real-time measurements and heating and magnetic field actuators that react within milliseconds to the early detection of potentially deleterious instabilities, allowing their targeted suppression before fusion plasma performance is degraded.
- Precisely configured magnetic fields safely direct enormous heat fluxes (many millions of watts per square meter) from fusion plasmas onto material structures that are designed to endure this harsh environment.
- Fusion researchers led the nation in developing the first supercomputing applications supported by DOE. Nowadays, at DOE-sponsored national supercomputer centers, U.S. researchers carry out numerical simulations that continue to push the state of the computational art. Present-day codes capture the complex details of fusion plasma, and its interactions with the materials that surround it.
- Fusion scientists have been among the leaders in materials science, identifying materials that can endure the many atomic displacements that will occur in an eventual fusion reactor, and understanding their properties with theoretical and computational analyses.

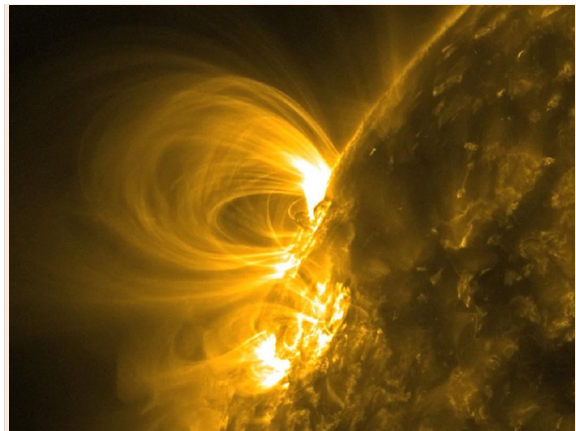


The science of high energy density laboratory plasmas (HEDLP) underlies the inertial fusion energy (IFE) approach, in which the fuel is rapidly compressed under enormous pressure to reach fusion conditions and then the inertia of the fuel keeps it together long enough for fusion to occur. HEDLP research is supported by FES and is important for understanding not only the fusion process but also astrophysical systems. Laboratory experiments and sophisticated simulations are used to investigate the physics of stellar interiors as well as their atmospheres

and, in another regime, to understand and control low-temperature plasmas for industrial applications as well as for the sake of unraveling their fundamental physics.

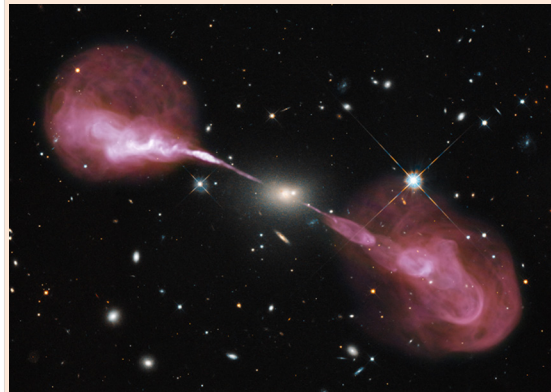
Research accomplishments in plasma astrophysics are many and include the following:

- Laboratory experiments and numerical simulations are being used to understand the generation of solar prominences and the formation of plasma jets that extend hundreds or even thousands of light years from a galactic core.
- Understanding the mystery of the surprisingly high temperature of the solar corona – over 1,000,000 kelvin measured 10,000 km above the Sun’s photosphere, while the Sun’s photosphere resides at a comparatively cool 4,500 kelvin – has benefited from major discoveries in laboratory experiments. These confirm that the process of magnetic reconnection can efficiently convert the energy of the Sun’s tangled magnetic field into thermal energy of solar corona ions. Theory and experiment also indicate that this energy can be efficiently transported to the outer reaches of the corona via plasma waves.
- Plasma environments that simulate the conditions on the surfaces of white dwarf stars that eventually become Type IA supernova have been generated in the laboratory, providing a platform to perform detailed assessments of the intrinsic brightness of these stars. Astronomers use Type-IA supernova as “standard candles” to evaluate intergalactic distances. This research may improve the accuracy of our best “cosmic yardsticks,” allowing a precise determination of the age of the universe.
- Fundamental principles of plasma physics have been applied to measurements obtained by Voyager 1 and 2 missions of the solar wind near Pluto to set the internationally



Solar flare, photo courtesy of NASA

Research on the formation of solar flares and intergalactic jets is supported by FES in a partnership with the National Science Foundation.



Credit: NASA, ESA, S. Baum, C. O’Dea, R. Perley, W. Cotton, Hubble Heritage Team (<https://science.nrao.edu/facilities/vla>)

A combined radio and optical image of Hercules A. The galaxy is the patch in the center; the radio jets, driven by plasma processes, extend far beyond.

accepted upper bound on the mass of the photon at nearly 10^{-51} grams, a dramatic improvement over previous such estimates.

- Computer codes used to understand fusion plasmas are being applied to the extraordinary conditions in the accretion disks of black holes, including research to understand the apparent deficit in luminosity of the accretion disk surrounding the massive black hole at the center of the Milky Way galaxy.

These research examples highlight the reach of fusion and plasma science and only scratch the surface of what has been accomplished. The great drive now is to extend the intellectual framework of the fusion sciences into the next essential frontier, that of burning plasma science.

1.2: Leading Frontiers in Fusion and Plasma Science

Today there are several frontiers in fusion and plasma science. The global magnetic fusion research community is focused primarily on the commencement of the “burning plasma” era. While many of the essentials of burning plasma science are mature, some critical pieces remain unexplored and will remain so until experimentation at the necessary scale and capability is undertaken. ITER is the vehicle for gaining access to these critical pieces, including the physics of the self-heated burning plasma state, which opens up a new frontier in science and also will enable questions critical to advancing fusion energy to be engaged and ultimately answered.

Burning plasma is fundamentally different from plasmas that have been created in research facilities to date. It is essential to create and study burning plasma in order to advance fusion energy, because it is only in burning plasma that the issues of energy confinement, heating, and stability are fully coupled, along with nuclear science issues. The importance of moving into this era was affirmed in a 2004 National Academy of Sciences review, *Burning Plasmas – Bringing a Star to Earth*.¹ This report recognized that a burning plasma experiment is essential to assessing the scientific and technical feasibility of fusion as an energy source. Its strongest recommendation was that the U.S. fusion science research program should pursue the rich and important scientific questions that will only be accessible by the creation of burning plasma in the laboratory.

A second great scientific challenge for fusion is to develop materials that can tolerate the extreme conditions created by burning plasma in a fusion reactor. Plasma at a high enough temperature and density to undergo nuclear fusion in a reactor generates close to a billion watts of fusion power. This presents a uniquely hostile environment to the materials of the reactor, both due to enormous heat fluxes—tens of millions of watts per square meter impinging on a wall—and to a harsh shower of neutrons that will displace their constituent

¹ <http://www.nap.edu/catalog/10816/burning-plasma-bringing-a-star-to-earth>

atoms and thus qualitatively change their material strength and other characteristics. There is a clear opportunity for the U.S. to seize international leadership in the broad area of material science relevant to fusion energy systems and technologies over the next decade. A 2007 FESAC report identified a broad range of fusion materials research needs. This knowledge gap must be filled if ITER is to be a penultimate step to a demonstration fusion reactor.

A third broad frontier is termed “discovery plasma science”—the fundamental study of a wide variety of plasma systems. This field is not only fundamental to facilitating the production and control of fusion energy, but also to understanding the nature of visible matter throughout the cosmos. Additionally, discoveries in plasma science are leading to an ever-increasing array of practical applications, ranging from energy-efficient lighting, to low-heat, chemical-free sterilization processes. The ability to create and manipulate plasmas with densities and temperatures spanning many orders of magnitude has led to the establishment of plasma science as a multi-disciplinary field, which is necessary for understanding the flow of energy and momentum in the universe as well as enabling the development of various breakthrough technologies.

The ten-year vision for the FES program presented in this report would promote U.S. scientific leadership in each of these three areas. We anticipate continuing to work closely with the fusion and plasma science research community to refine the vision on an evolving basis.

2. Community Input

This report is based on a variety of types of input from the scientific community, including a number of important recent studies, which are described below. Further evolution of the vision will be informed by continual engagement with the community, most immediately through a series of “research needs” community workshops scheduled for mid-2015.

2.1: Recent FESAC Assessment of Program Priorities

In April 2014, in response to the congressional reporting requirement, the Acting Director of the Office of Science charged the Fusion Energy Sciences Advisory Committee (FESAC) to provide a report prioritizing elements of the FES program within explicit budget constraints. The resulting report, *Report on Strategic Planning: Priorities Assessment and Budget Scenarios*² (hereafter referred to as *FESAC 2014*), emphasized four primary research thrusts that are rooted in a number of highly regarded community studies (cf. Section 2.3).

The Office of Science supports the four primary research thrusts of *FESAC 2014* and groups them together equally rather than prioritizing them into two tiers.

- ***Control of deleterious transient events:*** The category of transient events refers to rapid plasma instabilities (specifically, disruptions and edge-localized modes) that can lead to loss of confinement and damage to the containment vessel and plasma-facing components. Timely resolution of methods to predict, avoid, mitigate, and/or suppress these events is a high priority for the world fusion program.
- ***Taming the plasma-material interface:*** Controlling the interface between the high-temperature core of fusion plasma and the low-temperature surrounding material structures is a high-priority scientific challenge. This includes understanding the formation of steep gradients in the interface layer, handling heat and particle exhaust from the core to the outside, and designing materials that can withstand the thermonuclear environment.
- ***Experimentally validated, integrated predictive capabilities:*** Massively parallel computing, grounded in experimentally validated theoretical models, will be hugely valuable for enabling whole device modeling that can integrate simulations of physics phenomena across a wide range of disparate time and space scales.
- ***A fusion nuclear science subprogram and facility:*** Research in nuclear effects on materials (e.g., neutron irradiation) will be continued and enhanced, especially when high-leverage opportunities for doing so can be captured. Due to funding

² http://science.energy.gov/~media/fes/fesac/pdf/2014/October/FESAC_strategic_planning_rept_dec14.pdf

considerations, the DOE plan for fusion energy sciences research over the next decade does not include a major new fusion nuclear science facility, in contrast to *FESAC 2014*.

2.2: Community Workshops in 2015

The Office of Science listened carefully to community critiques of *FESAC 2014* and has responded by working with community leaders to develop a series of Research Needs Workshops, which are being held during 2015. The results from these workshops will be incorporated when formulating the details for and executing future FES budgets.

Three of the five workshops being planned correspond to critical areas identified in the *FESAC 2014* report as areas where increased emphasis would be beneficial as the fusion program moves further into the burning plasma science era:

- ***Integrated Simulations for Magnetic Fusion Energy Sciences:*** Developing an experimentally validated integrated predictive simulation capability that will reduce risk in the design and operation of next-step devices as well as enhance the knowledge gained from ITER.
- ***Transients:*** Understanding and controlling deleterious transient events that can disrupt plasma operation and damage fusion devices.
- ***Plasma-Materials Interactions:*** Addressing the extreme harshness of the burning plasma environment at the plasma-materials interface and finding solutions.

Two other workshops will be held in a critical stewardship area:

- ***Plasma Science Frontiers:*** Including general plasma science, high energy density laboratory plasma, and exploratory magnetized plasma, these workshops address the Plasma Science Frontiers category in the restructured FES budget. The first workshop will identify compelling scientific challenges at the frontiers of plasma physics, and the second workshop will identify research tools and capabilities, as well as the general requirements necessary to address these challenges in the next decade.

The objectives of the five workshops include elements from among the following: (1) reviewing progress and an update about new developments since the last time organized community input was obtained, (2) identifying gaps and challenges, along with specific parameters that would need to be achieved for addressing such gaps, (3) discussing near- and long-term research tasks, such as experiments that could be performed on existing facilities, (4) describing upgrades to existing facilities and diagnostic capabilities that would enable or enhance the research tasks, (5) identifying linkages to associated research areas, (6) describing and analyzing potential new activities for addressing the gaps and challenges, and (7) identifying areas for which modeling and simulation could be impactful.

2.3: Previous Community Studies

A number of previous studies authored by the scientific community, including several Fusion Energy Sciences Advisory Committee reports responding to charges from DOE, have been and continue to be important influences on the strategic direction of the Fusion Energy Sciences program.

In 2002, a large community summer study held in Snowmass, Colorado, assessed three options for burning plasma experimental facilities and indicated a preference for the international ITER project.³ Later the same year, FESAC wrote *A Burning Plasma Program Strategy to Advance Fusion Energy*.⁴ This report observed that “there is an overwhelming consensus among fusion scientists that we are now ready scientifically, and have the full technical capability, to embark on this step” (viz., experimental study of a burning plasma).

In 2004, the National Research Council (NRC) of the National Academies of Science endorsed U.S. participation in the ITER project with its report *Burning Plasma: Bringing a Star to Earth*.⁵ The report stated: “There is now high confidence in the readiness to proceed to the burning plasma step because of the progress made in fusion science and fusion technology. Progress toward the fusion energy goal requires this step, and the tokamak is the only fusion configuration ready for implementing such an experiment.” This report, together with the Snowmass report and the 2004 FESAC report, helped propel the U.S. to formally rejoin the ITER project. The Energy Policy Act of 2005 (P.L. 109-58) directed a follow-up NRC study of U.S. participation in ITER, released in 2008, entitled *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program*.⁶

Contemporaneously, DOE charged FESAC to undertake a broad study to identify the major scientific knowledge gaps that must be overcome to achieve practical fusion energy. In 2007, FESAC issued a report, *Priorities, Gaps, and Opportunities: Towards a Long Range Strategic Plan for Magnetic Fusion Energy*, which has proved to be a major influence on FES program planning.⁷ Emphasized in this report were challenges related to plasma transients, fusion materials science, and high-performance computing.

Also in 2007, FESAC considered the final report from the DOE-supported Fusion Simulation Project Workshop and issued its own assessment: *FESAC Fusion Simulation Project Panel Final Report*.⁸ The same workshop output was also assessed in a report issued by the Advanced

³ http://fire.pppl.gov/snowmass02_report.pdf

⁴ http://science.energy.gov/~media/fes/fesac/pdf/2002/Austin_final_full_2002.pdf

⁵ <http://www.nap.edu/catalog/10816/burning-plasma-bringing-a-star-to-earth>

⁶ <http://www.nap.edu/catalog/12449/a-review-of-the-doe-plan-for-us-fusion-community-participation-in-the-iter-program>

⁷ http://science.energy.gov/~media/fes/fesac/pdf/2007/Fesac_planning_report.pdf

⁸ http://science.energy.gov/~media/fes/fesac/pdf/2007/Fesac_fsp_report.pdf

Scientific Computing Advisory Committee (ASCAC).⁹ Although DOE ultimately did not support the approach espoused in the 2007 Fusion Simulation Project vision, the FESAC and ASCAC reports and related community activities have affirmed the readiness for making whole-device modeling an FES priority.

The same year, the NRC completed its Plasma 2010 Decadal Report entitled *Plasma Science: Advancing Knowledge in the National Interest*.¹⁰ This report articulated the importance of discovery plasma science as a core element of the FES program and affirmed FES's role as a leading steward of this science for the nation.

In 2008, FESAC evaluated magnetic confinement configurations other than tokamaks. This resulted in the *Report of the FESAC Toroidal Alternates Panel*.¹¹ The report underscores the complementarity of confinement science for systems ranging from compact toroids to tokamaks to stellarators. The report also argued for continued support of research in three-dimensional (3D) magnetic topologies, which is relevant to tokamaks (which have inherent and applied 3D magnetic fields), as well as to stellarators as a potential future confinement concept.

An FES-sponsored workshop in 2008 led to the report *Low Temperature Plasma Science: Not Only the Fourth State of Matter but All of Them*.¹² This report articulated the value of supporting this class of research within the FES portfolio.

From June 2009 through January 2010, FES conducted a series of four Research Needs Workshops (ReNeW), which resulted in the following reports: *Research Needs for Magnetic Fusion Energy Sciences* (2009);¹³ *Advancing the Science of High Energy Density Laboratory Plasmas* (2009);¹⁴ *Research Needs for Fusion-Fission Hybrid Systems* (2009);¹⁵ and *Basic Research Needs for High Energy Density Laboratory Physics* (2010).¹⁶ The HEDLP reports underscored the high scientific value of this research, as well as the need for carrying it out on well-diagnosed facilities that institute a user-facility model for program governance. For fusion-fission hybrids, however, no major programmatic initiatives could be supported, given the available resources.

A community-led workshop at Princeton Plasma Physics Laboratory in 2010 led to the report *Research Opportunities in Plasma Astrophysics*,¹⁷ which outlined many opportunities.

⁹ http://science.energy.gov/~media/ascr/ascac/pdf/reports/Ascac_fsp_report_final.pdf

¹⁰ <http://www.nap.edu/catalog/11960/plasma-science-advancing-knowledge-in-the-national-interest>

¹¹ http://science.energy.gov/~media/fes/fesac/pdf/2008/Toroidal_alternates_panel_report.pdf

¹² http://science.energy.gov/~media/fes/pdf/about/Low_temp_plasma_report_march_2008.pdf

¹³ http://science.energy.gov/~media/fes/pdf/about/Magnetic_fusion_report_june_2009.pdf

¹⁴ http://science.energy.gov/~media/fes/fesac/pdf/2009/Fesac_hed_lp_report.pdf

¹⁵ http://web.mit.edu/fusion-fission/Hybrid_Report_Final.pdf

¹⁶ http://science.energy.gov/~media/fes/pdf/workshop-reports/Hedlp_brn_workshop_report_oct_2010.pdf

¹⁷ http://science.energy.gov/~media/fes/pdf/about/Wopa_report_march_2011.pdf

In July 2011, DOE charged FESAC to (a) examine the opportunities and various modes for collaborations with the new billion-dollar-class international fusion facilities and (b) determine the ways to strengthen the materials/nuclear science research areas, which, in conjunction with ITER research operation, will enable the construction of a demonstration power plant. In response to (a), FESAC wrote *Opportunities for and Modes of International Collaboration in Fusion Energy Sciences Research during the ITER Era* (February 2012).¹⁸ This report emphasized the value of such partnerships when carried out from a platform of a strong domestic program. In response to (b), FESAC wrote *Opportunities for Fusion Materials Science and Technology Research Now and in the ITER Era*,¹⁹ which described a range of fusion materials science challenges, both nuclear and non-nuclear. This report recommended initiating a linear high heat flux facility for materials testing, and partnering with a spallation neutron source for fusion materials nuclear research.

In April 2012, DOE charged FESAC to assess priorities among and within the elements of the non-ITER part of the magnetic fusion energy sciences program, with special focus on research that supports burning plasma science, long-pulse/steady-state plasma operation, and fusion materials science. The report entitled *Priorities of the Magnetic Fusion Energy Program* (January 2013)²⁰ made progress in prioritizing among the thrusts in the 2009 *Research Needs for Magnetic Fusion Energy Sciences* report. Due to issues with conflict of interest, the report did not answer the full charge. This effort served to segue to the *FESAC 2014* report.

In 2013, DOE charged the federal advisory committees of all six Office of Science program offices to evaluate facility priorities for the next decade. FESAC responded with *Report of the FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science* (2013).²¹ Although budget constraints will likely prevent the support of the full palette of opportunities that were proposed in this report, its recommendations for upgrades of major confinement facilities, as well as an increased emphasis on fusion nuclear materials science research, were important.

¹⁸ http://science.energy.gov/~media/fes/pdf/workshop-reports/20120309/Intl_Collab_Final_SCSC-PRINT.pdf

¹⁹ <http://science.energy.gov/~media/fes/pdf/workshop-reports/20120309/FESAC-Materials-Science-final-report.pdf>

²⁰ <http://science.energy.gov/~media/fes/fesac/pdf/2013/Final-Report-02102013.pdf>

²¹ http://science.energy.gov/~media/fes/fesac/pdf/2013/FESAC_Facilities_Report_Final.pdf

3. Research Directions

The framework for the FES decadal strategic directions mirrors the four major research categories that define the FES program budget structure: foundational burning plasma science, burning plasma sustainment science, high gain burning plasma science, and discovery plasma science. Within this framework, and considering input from FESAC and community planning processes to date as discussed in Chapter 2, there are five areas of emphasis:

- Massively parallel computing with the goal of validated whole-fusion-device modeling
- Materials research as it relates to plasma and fusion science
- Research in the prediction and control of transient events that can be deleterious to toroidal fusion plasma confinement
- Stewardship of discovery in plasma science that is not expressly driven by the fusion energy goal but will address frontier science issues
- Robust operations support and regular upgrades of FES facilities.

3.1: Burning Plasma Science: Foundations

Goal

This research category advances the validated predictive understanding of plasma confinement, dynamics, and interactions with surrounding materials.

Objectives

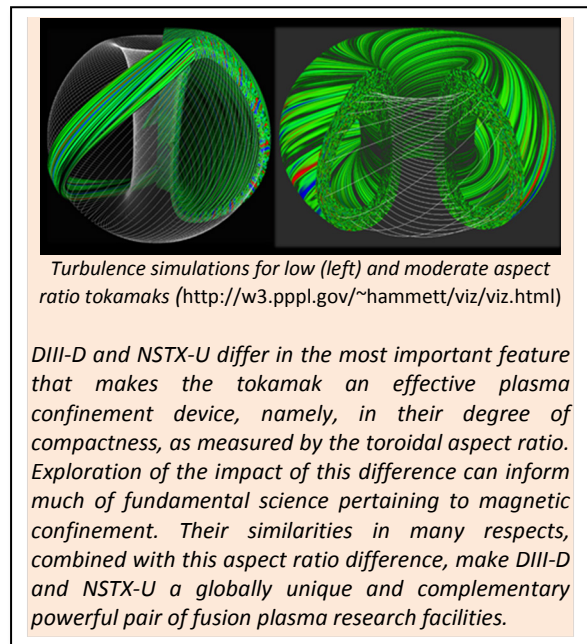
- Burning plasma-relevant science* – Answer urgent scientific questions – such as how to control transient events – required for ITER to meet the needs of the ITER project and its program once launched, including optimizing ITER operating scenarios and preparing strong research teams capable of reaping scientific reward from the ITER experiment.
- Validated predictive modeling* – Establish the basis for validated prediction and interpretation of fusion experiments so as to be used as a world-leading tool for formulating ITER operational scenarios and also reducing the risk of development steps between present-day research and a future demonstration reactor.
- Next-generation research capabilities* – Develop the scientific basis for optimizing the capabilities of next-generation research platforms.

Strategic Implementation

The foundations of burning plasma science can be explored with the use of experimental proxies for a true burning plasma state. Research at the major U.S. fusion experimental facilities will be increasingly aimed at resolving fundamental advanced tokamak and spherical tokamak science issues, including developing the predictive understanding needed for ITER operations and providing solutions to high-priority ITER concerns.

In all funding scenarios, emphasis will be on upgraded DIII-D and NSTX-U working as a complementary pair. Research will take advantage of their differing as well as overlapping access to plasma parameters that are important for understanding burning plasma science issues relevant to ITER and to any future burning plasma experiment, including steps for facilitating advanced fusion components testing.

The activities at these major facilities will also support enhanced emphases for research on potentially deleterious transients and plasma-material interaction science. As already noted, the prediction, detection, control, mitigation, and avoidance of deleterious plasma events, including disruptions and edge-localized modes, constitute a high-priority research initiative in the Foundations area. This research will take advantage of present and upgraded infrastructure at the DIII-D and NSTX-U tokamak facilities, as well as on smaller-scale facilities as appropriate. The urgency of this research is magnified by the U.S. having the responsibility to develop and fabricate disruption mitigation systems for use on ITER.



Research in the Foundations area will also help to establish the scientific basis for research on superconducting long-pulse overseas facilities that are either already in operation or soon to operate (cf. Section 3.2).

Per Congressional direction and consistent with the Administration's recent budget requests, operation of the Alcator C-Mod tokamak will cease at the end of FY 2016.

The research efforts on DIII-D and NSTX-U will continue to be joined by targeted studies on smaller-scale advanced tokamak research and spherical torus facilities at universities and national laboratories. Research on small-scale magnetic confinement experiments will be useful to elucidate physics principles underlying toroidal confinement, test innovative methods, and validate theoretical models and simulation codes.

Modeling and simulation that capitalizes on the Office of Science's world-leading capabilities in high-performance computing will be a high-priority research direction in the Foundations area. The U.S. is a world leader in theoretical work on the fundamental description of magnetically confined plasmas and in the development of advanced simulation codes on current and emerging high-performance computers. Also, the U.S. fusion community has been adopting a systematic approach to verification and validation (V&V) and uncertainty qualification (UQ).

During the coming decade, increased emphasis will be placed on integrated whole-device modeling based on massively parallel computation. This work will use multi-petascale capabilities and target the future use of exascale capabilities in partnership with the Office of Advanced Scientific Computing Research. Research activities will drive integration of code modules (e.g., stability, transport, equilibrium, etc.) that are currently separate. The two high-level goals of whole-device modeling would be (1) the development of a robust, extensible computational framework for the entire plasma cross-section (i.e., from the core to the first wall) and (2) systematic validation of codes with the use of experimental data.

The extreme computational challenges confronted in developing simulation codes for fusion plasma systems require the active involvement of applied mathematicians and computer science experts, as well as access to leadership-class computing resources. Large-scale numerical simulations and theoretical modeling will be valuable for attacking the two high-priority research areas already identified, namely, transients and plasma-material interactions. The former is associated with the Foundations area, and the latter will be discussed in the Long Pulse section. FES will explore partnership opportunities with the Advanced Scientific Computing Research (ASCR) program in the Office of Science to support an integrated whole-device modeling endeavor. Currently, FES jointly sponsors three fusion-related Scientific Discovery through Advanced Computing (SciDAC) centers with ASCR and has a long history of fruitful partnership. FES will also seek insight in large-scale computing and validation from other research communities. Cooperation with our international partners and the ITER Organization may also be valuable, as will access to validation data from long-pulse superconducting tokamaks and stellarators overseas.

The Foundations area will also continue to support research on enabling technologies needed to support the continued improvement of the experimental program and facilities. Examples of these enabling technologies are innovative magnet development and improved heating and fueling methods. The U.S. is the world leader in cryogenic pellet injection technology, used to fuel fusion plasmas and also to suppress disruptions and mitigate edge localized mode instabilities, and will design and construct the ITER pellet injector system.

Support will continue for vital general plant infrastructure improvements at Office of Science laboratories conducting fusion research.

The two major U.S. fusion research facilities, DIII-D and NSTX-U, complement each other due to their different aspect ratios (defined as the plasma radial dimension compared to the major radius size of the confinement device). This difference allows access to plasma parameters and

operational regimes that both differ and overlap, which is highly advantageous for understanding burning plasma science issues relevant to ITER and any future burning plasma experiment. In addition to the physics that is revealed by systematic studies of aspect ratio variations, systems studies reveal that aspect ratio plays a fundamental role in the ultimate economics of a magnetic confinement fusion reactor. During the next decade, these two facilities will therefore be utilized to develop the scientific basis for optimizing the capabilities of next-generation research platforms.

One of the controversial recommendations of *FESAC 2014* was to consider shutting down one of these two major facilities midway through the decade in order to initiate a move toward construction of a Fusion Nuclear Science Facility (FNSF). Although DOE recognizes the future value of such a facility for pursuing vital research in the area of fusion nuclear science (and acknowledges its absence on the recent European fusion road map, which presents a gap opportunity for the U.S.), the FES research plan for the next decade will not be predicated on the beginning of design and construction of an FNSF. Foreseeable out-year budget constraints make investment in the design and construction of an FNSF untenable.

3.2: Burning Plasma Science: Long Pulse

Goal

This research category explores new and unique scientific regimes that can be achieved with long-duration superconducting fusion confinement machines and addresses the development of advanced materials required to withstand the extreme conditions in a burning plasma environment.

Objectives

- (a) *Sustainment of long-pulse plasma equilibria* – Apply research on domestic confinement facilities (managed in the *Foundations* area) to establish the basis for sustained plasma operation and inform the long-pulse research conducted in partnerships on superconducting magnetic confinement facilities across the globe.
- (b) *Combined effects of high neutron fluences and high heat and particle fluxes* – Enable experimental access to the combined study of neutron irradiation and very high power and particle fluxes, encountered in the burning plasma environment, and investigate how these phenomena together affect plasma confinement and plasma-materials interactions.

Strategic Implementation

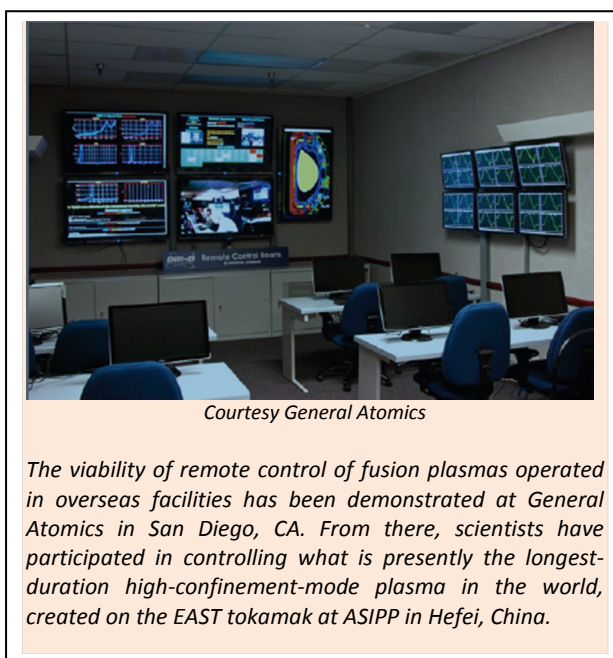
Understanding how to confine and control fusion plasmas during sustained discharges is essential expertise for U.S. scientists who may participate in research operations on ITER and future burning plasma experiments. This research frontier requires the leveraging of mature U.S. research knowledge in the Foundations area into collaborative research activities carried out on overseas facilities that have long-pulse capability enabled by superconducting magnet technologies.

The world-leading superconducting fusion devices in Asia and Europe represent a state-of-the-art capability that the U.S. does not possess on its copper coil fusion facilities, but in which it can participate as a partner – and has been invited to do so. U.S. engagement is essential to provide U.S. researchers with an opportunity to be among the leaders in this broad class of fusion science.

At present, there are two U.S. teams focusing on the superconducting tokamaks in Asia and another U.S. team focused on the superconducting stellarator in Europe. Contingent on the availability of budget resources, U.S. collaborative research on international long-pulse facilities may be expanded, with an emphasis on research that builds on scenarios and experience developed on the U.S. domestic facilities.

Many front-line research opportunities for U.S. researchers and students reside with our overseas fusion energy sciences partners. International partnerships in fusion science research go back decades, taking advantage of the great potential of mutually beneficial research arrangements.

Through present-day partnerships, U.S. scientists are already performing research on overseas superconducting facilities that have operational capabilities beyond those of any U.S. facility in some key respects. For example, General Atomics has recently demonstrated the capability for remote control of the operation of the superconducting EAST tokamak in China, applying advanced operating scenarios that were initially developed on the DIII-D tokamak. Using both federal support and its own investment of corporate funds, last year General Atomics established a remote collaboration center as a repository for EAST experimental data, which can be accessed and analyzed via ESNet by collaborators at seven other U.S. institutions. This enables a



Courtesy General Atomics

The viability of remote control of fusion plasmas operated in overseas facilities has been demonstrated at General Atomics in San Diego, CA. From there, scientists have participated in controlling what is presently the longest-duration high-confinement-mode plasma in the world, created on the EAST tokamak at ASIPP in Hefei, China.

new class of research in the U.S. wherein operating scenarios and diagnostic techniques are developed stateside and then deployed and operated overseas. With opportunities properly chosen with our international partners, such an approach can advance the research objectives of both U.S. scientists and our international colleagues.

In extending its research arms overseas, the U.S. fusion research enterprise may benefit from learning lessons from other branches of science where this leap has already been taken, such as the fields of high energy physics and astronomy. Importantly, U.S. fusion research could even set a standard for remotely controlled measurement and remote operation of experiments. Indeed, U.S. researchers could have significant impact in helping to set the research agendas for these emergent programs by means of vigorous engagement at the level of program planning and through a combination of off-site participation and on-site engagement. Also, the experience gained from U.S. research teams that are based overseas may be invaluable for U.S. scientists who will be participants on future international ITER research operations teams.

The Long Pulse area may also host enhanced research partnerships with international tokamak research programs overseas that do not utilize superconducting magnets, most notably, the Joint European Torus (JET) program in the United Kingdom.

A high-priority objective during this decade is to combine research on materials effects on plasma confinement (e.g., edge pedestal formation, and transport in the open field lines), high heat flux effects on materials, and neutron irradiation effects. The overall motivation is to gain entry into a new class of fusion materials science wherein the combined effects of fusion-relevant heat, particle, and neutron fluxes can be studied for the first time anywhere.

Fusion materials research on neutron irradiation effects presently takes advantage of the fission-based High Flux Isotope Reactor (HFIR) user facility, located at Oak Ridge National Laboratory. Along with research conducted on HFIR, FES will explore development of a new research platform that can study how material samples are impacted by neutron irradiation with high rates of atomic displacements and an energy spectrum similar to that of a fusion energy system, including neutrons at the 14-MeV fusion birth energy. FES will assess a variety of fusion materials research platforms, including new test stands and point neutron sources, as well as possible partnership with the Basic Energy Sciences program to access the Spallation Neutron Source at ORNL. FES will welcome proposals from the community on other fusion nuclear science research opportunities.

For dedicated studies of the effects of high heat and energetic particle fluxes on material properties, linear test-stand experiments will continue to be very important. Emphasis will be placed on development of a state-of-the-art linear test stand with the capability for analyzing high heat flux effects on irradiated material samples, for upwards of 1000 seconds.

Linear test-stands enable long-pulse, high-heat-flux materials testing, but cannot address the geometric effects of toroidal confinement. The interplay between plasma configuration-dependent effects and plasma-material interactions will be studied by taking advantage of

present and upgraded capabilities on the major U.S. fusion facilities. Also, cooperative fusion materials research will be conducted on overseas toroidal facilities that have long-pulse capabilities and/or that have installed ITER-like metallic plasma-facing components.

In addition, high-risk/high-reward research on liquid-metal wall materials for tokamaks will continue, with the potential of fundamentally changing the nature of the plasma-materials interface scientific challenge.

Throughout the decade, FES will continue to pursue partnerships with other SC programs, DOE offices, and federal agencies in the area of materials science. Perhaps no other science and technology agency has a broader or deeper materials science R&D portfolio than the Department of Energy. FES should seize the opportunity for the U.S. to be a world leader in fusion materials science in the burning plasma era and beyond.

Throughout the Long Pulse research portfolio, strong linkages with massively parallel computation will be emphasized. Also, to the degree that funding enables the creation of new fusion materials science experimental platforms, FES will emphasize that they be operated under a user facility model.

3.3: Burning Plasma Science: High Power

Goal

This research category pursues demonstrating the scientific feasibility of high-gain fusion energy.

Objectives

- (a) *U.S. contributions to the ITER project* – In-kind hardware and support to the ITER Organization for project construction.

Strategic Implementation

Currently under construction in France, ITER is the world's flagship project for burning plasma science. It is designed to create and study the science of the sustained burning plasma state for the first time. ITER will enable a tremendous leap forward for fusion science since it will provide scientific access to plasmas in the burning-plasma reactor regime. Expected to operate for 20 years, ITER is designed to surpass the energy "break even" point and demonstrate production of at least ten times the power used to heat the fusion fuel. 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 experiment would be needed to create and study the physical

conditions expected in a fusion system and to demonstrate its feasibility. The idea to cooperatively design and build such a device originated from the Geneva Summit between the United States and the former Soviet Union held in November 1985. During the 1980s and 1990s, the U.S. participated in the conceptual design activity and, after a hiatus, joined the ITER negotiations in early 2003. A formal international agreement adopted in 2006 by seven partner Members – the U.S., European Union, Japan, Russian Federation, China, India, and South Korea – marked the formal inception of the project.

The 2013 Management Assessment report recommended a number of reforms and improvements at the ITER Organization. Two major recommendations were the accelerated appointment of a new Director-General and the creation of a resource-loaded schedule and baseline. A new Director-General, Dr. Bernard Bigot, was appointed on March 5, 2015, and has begun work on reforming the ITER Organization. He has also taken control of the preparation of the resource-loaded schedule and baseline, which is now expected in November 2015. We look forward to the review and consideration of the revised baseline and schedule by the ITER Members. While structural and management reforms have begun and will hopefully have the effect of transforming the ITER Organization into a more efficient and effective construction management organization, we acknowledge that it takes time to effect change and understand what the updated ITER cost and schedule will be.

Under the terms of the ITER Joint Implementing Agreement, the U.S. contributes a 9.09 percent share of the construction costs and a 13 percent share of the operating costs and will be entitled to full and equal access to the science to be performed at ITER. Unlike other large international scientific projects, the contributions of the ITER Members are mostly in-kind hardware rather than monetary in nature. In practical terms, this means that the U.S. has the benefit of domestically producing many of the major hardware components that constitute the U.S. in-kind contribution to the project.

The Congressional request for an FES strategic plan states that the “plan should assume U.S. participation in ITER.” Assuming successful completion of ITER construction, the U.S. should be in a position to field a world-class ITER research team by the commencement of ITER operations in order to reap the highest scientific return for the U.S. in the 2020s and 2030s. Achieving this goal will depend on maintaining an impactful U.S. burning plasma science research program in both the Foundations and Long Pulse areas.

3.4: Discovery Plasma Science

Goal

This research area explores the fundamental properties and complex behavior of matter in the plasma state to improve the understanding required to control and manipulate plasmas for a broad range of applications.

Objectives

- (a) *General plasma science* – Understand the behavior of non-neutral and single-component plasmas, ultra-cold neutral plasmas, dusty plasmas, and micro-plasmas, as well as the study of dynamical processes in classical plasmas including turbulence and turbulent transport, magnetic reconnection, and plasma waves, structures, and flows.
- (b) *High-energy-density laboratory plasmas* – Investigate the structural and dynamical behavior of ionized matter at extreme densities and temperatures.
- (c) *Exploratory magnetized plasma* – Conduct research on complex, magnetized plasma systems that spontaneously evolve toward a state of long-range order through dissipative processes.
- (d) *Measurement innovation* – Develop novel diagnostic techniques and their applications to new, unexplored, or unfamiliar plasma regimes and scenarios.

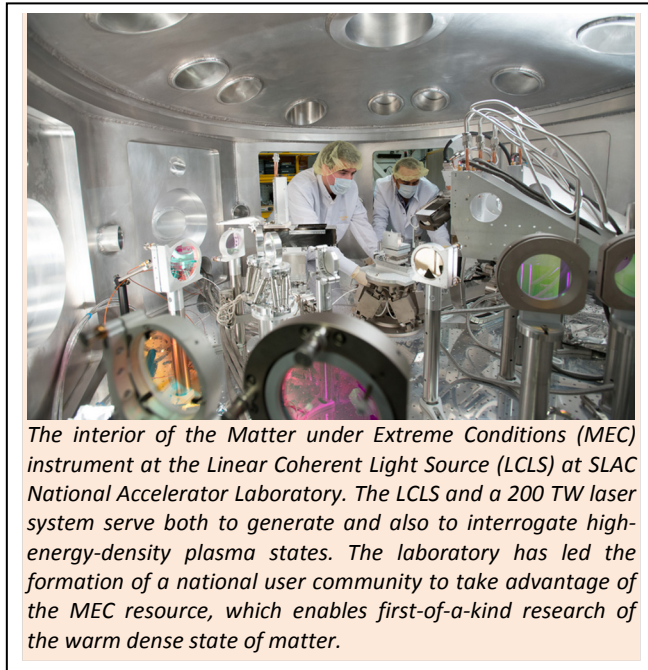
Strategic Implementation

While discovery is woven throughout the Foundations, Long Pulse, and High Power burning plasma research activities described above, the Discovery Plasma Science element of the Fusion Energy Sciences program emphasizes broad investigation of plasmas for discovery itself, as well as for non-fusion related applications. The interactions between discovery plasma science research and fusion energy science-related research are rich and important. Indeed, plasma science is not only the basic context in which is embedded the special application to the production and control of fusion energy, but it is also fundamental to understanding the nature of visible matter throughout the cosmos.

Discovery plasma science is a multi-disciplinary endeavor that explores the extremes of the plasma state, ranging from the very small (several atom systems) to the extremely large (astrophysical plasma structures spanning light years in length), from the very fast (attosecond processes) to the very slow (hours), from the diffuse (interstellar medium) to the extremely dense (diamond compressed to tens of gigabar pressures), and from the ultracold (tens of micro kelvin) to the extremely hot (stellar core). FES will continue to support research at the

forefront of each of these ranges, challenging our ability to produce and measure matter at the extremes. Discovery plasma science will continue to be a high-priority research area. DOE reaffirms the National Academies' conclusion that the FES program is the lead federal steward of this branch of science.²² The FES commitment to discovery plasma science will also deepen the connections between the fusion/plasma science community and other fields of science.

In general plasma science, FES will continue to invest in research facilities and activities to address astrophysical problems involving plasma phenomena such as dynamo behavior, radiative shocks, magnetic reconnection, turbulence, and stellar opacities. FES will continue to encourage research of controlled manipulation of the distribution of charged particles in low-temperature plasmas, which are the basis for an ever-increasing array of practical applications ranging from energy-efficient lighting to low-heat, chemical-free sterilization processes. Much of this research will continue to be supported through FES's joint partnership program in plasma science and engineering with the National Science Foundation, subject to review and with an increased emphasis on university-laboratory partnership opportunities.



The interior of the Matter under Extreme Conditions (MEC) instrument at the Linear Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory. The LCLS and a 200 TW laser system serve both to generate and also to interrogate high-energy-density plasma states. The laboratory has led the formation of a national user community to take advantage of the MEC resource, which enables first-of-a-kind research of the warm dense state of matter.

In high-energy-density laboratory plasma (HEDLP) science, FES will emphasize research conducted on the Matter in Extreme Conditions (MEC) instrument, one of six end stations on the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory. LCLS is a world-class x-ray free electron laser facility whose unique ultrashort- x-ray laser pulses provide novel scientific opportunities in HEDLP science. The MEC instrument has the potential to revolutionize our understanding of laser-plasma interactions and the unusual plasma state called "warm dense matter" by exploitation of the LCLS x-ray beam as both a target-driver and diagnostic. FES will support research using this facility through

competitive solicitations. FES has been supporting academic research awards through the NNSA-SC Joint Program in High Energy Density Physics, although with recent constrained budgets FES has had to withdraw its portion of the support for these activities in its budget proposals to Congress.

In the sub-field of exploratory magnetized plasmas, FES currently supports a number of university-based small- to intermediate-scale magnetically confined plasma experiments. The

²² <http://www.nap.edu/catalog/11960/plasma-science-advancing-knowledge-in-the-national-interest>

largest of these is the only reversed field pinch device in the U.S., which is conducive to plasma confinement research and laboratory studies of astrophysical plasma phenomena. Other smaller-scale experiments in this portfolio support validation and verification of codes and models.

The three program elements of general plasma science, high-energy-density laboratory plasma, and exploratory magnetized plasma support a rich and diverse portfolio of research at the frontiers of plasma science, sharing many common intellectual threads with the potential for broadening connections between the fusion energy sciences program and other scientific fields. Cross-cutting research themes – such as magnetic self-organization, explosive instabilities, turbulence and transport, correlations in plasmas, multiphase plasma dynamics, and plasma acceleration – allow for an intellectual juxtaposition of these program elements. Using these themes as the organizational structure, FES will hold workshops (cf. Chapter 6) to identify both the grand scientific challenges in the plasma science frontier area and also the research needs required to address them.

Innovative plasma diagnostics has been and should continue to be an area of U.S. strength in the world fusion program. FES will continue to promote breakthroughs in plasma measurement instrumentation and techniques through the development of diagnostics with the spatial, spectral, and temporal resolution necessary to validate plasma physics models used to predict the behavior of fusion plasmas. Advanced diagnostic capabilities successfully developed through this activity will continue to be migrated, when mature, to installation and utilization on major domestic and international facilities, normally then becoming supported under the Foundations and Long Pulse subprograms.

FES will continue to maintain a leadership role in the national stewardship of discovery plasma science by leveraging access to best-in-class experimental facilities through partnerships with the National Science Foundation (NSF), the National Nuclear Security Administration (NNSA), and the Office of Science's Basic Energy Sciences (BES) program.

In addition, FES will identify scientific opportunities of high impact in discovery plasma science that require access to intermediate-scale facilities with larger, hotter plasmas and more extensive diagnostic capabilities. Beyond the experimental and diagnostic challenges for intermediate-scale facilities, simulating such systems will require the development of sophisticated modeling tools and use of advanced computing platforms.

4. Funding Scenarios

The Congressional language requested that DOE assess priorities for the domestic fusion program based on three budget scenarios with the fiscal year 2014 enacted level as the funding baseline: (1) modest growth, (2) budget growth based only on a cost-of-living-adjusted fiscal year 2014 budget, and (3) flat funding.

In the Office of Science charge letter to FESAC that resulted in the *FESAC 2014* report, modest growth was interpreted as two percent above the published OMB inflators for FY 2015 through FY 2024, cost-of-living budget growth was based only on the published OMB inflators for the same years, and the flat funding scenario was pinned at the FY 2014 enacted appropriation level.

In the following discussion, the funding scenarios are understood as an exercise to confront choices and identify priorities.

4.1: Modest Growth Scenario

Burning Plasma: Foundations

For this funding scenario, priorities in this area include nearly optimal operation of the NSTX-U and DIII-D user facilities, at about 22–25 run weeks per year. This level of utilization would allow for vigorous experimentation, including expansion of research opportunities for university scientists and students, as well as routine maintenance. These run weeks might be decreased to accommodate the scheduling demands of major upgrades. Within a broad scientific research portfolio, such upgrades are envisioned to enable new investigations in plasma-materials interactions and their impact on confinement beginning midway through this ten year planning period, and to create a strengthened ability to simulate the burning plasma state on DIII-D. The run weeks would also support significant experimental investigations of deleterious plasma transients and their control on both NSTX-U and DIII-D.

Even under this modest growth budget scenario, it is unlikely that the construction of a new fusion confinement device on the scale of any of the current major facilities could be supported, since such construction would force an undesirable contraction of research portfolio breadth, which was already severely impacted in the FY 2013 budget cycle.

Development of whole-device modeling through validated computing will also be a high-priority research element. Although details need to be assessed and will be continually updated, it is anticipated that in order to successfully develop a whole-device modeling capability that can impact the early ITER program, a level of effort in massively parallel computing of about two-to-three times that presently supported by FES will be required over a ten-year time span.

Burning Plasma: Long Pulse

This funding scenario will enable research and development that, if successful, could yield the launch of a first-of-a-kind fusion materials science program by mid-2020s. Experimental capabilities to be pursued include the development of a test stand that would enable the study of materials evolution exposed to fusion reactor-relevant heat fluxes over long pulses (1000s of seconds). Studies will also be supported early in this ten-year period to support the deployment by mid-decade of a unique capability to expose materials to reactor-relevant neutron fluences and energies. If both experimental approaches can be brought to fruition, this would enable the U.S. to be in a unique position in five years to study for the first time aspects of the combined effects of long-time material exposure to fusion-reactor-relevant high heat flux, high neutron fluence environments.

This funding scenario also supports growth in select internationally-based research endeavors, with emphasis on those efforts that best position U.S. researchers to have an impact in research areas not presently accessible in the U.S., that take advantage of the foundational work carried out within the U.S., and that have the best potential for exploiting novel remote control and measurement capabilities.

Before the 2025 timeframe, the FES program does not expect to be able to initiate a major multi-billion-dollar-class domestic facility, such as the Fusion Nuclear Science Facility (FNSF) that was recommended in *FESAC 2014*. Still, fusion nuclear research issues of high general importance, which would be potentially relevant to an FNSF, will continue to guide scientific directions during this decade.

Discovery Plasma Science

This research area would experience growth, with emphasis on new and existing intermediate-scale facilities operated under a user facility model. The output from the research needs workshops in 2015 (cf. Section 2.2) will be useful in identifying research opportunities. Emphases will likely include first-of-a-kind studies in laboratory astrophysics, research leading to detailed understanding of the transition from the material state to the plasma state, and research that promotes the fundamental understanding and control of low-temperature plasmas, with potential application in industry. In all budget scenarios, FES will emphasize plasma science research that has the broadest impact across the sciences.

4.2: Cost-of-Living Budget Growth Scenario

Under this more constrained scenario, the priorities are the same as in the Modest Growth Scenario, but the pace at which deliverables can be realized will be decreased. The Cost-of-Living Budget Scenario results in a smaller research effort, at a funding level that is 20 percent less than that for the Modest Growth Scenario by the end of the decade. This impacts every major research area. Compared to the Modest Growth Scenario discussed above in which

overall research support is increased, the level of research effort in the Cost-of-Living Budget Scenario is held flat due to inflation, and the following situation is envisioned.

Burning Plasma: Foundations

Research operations on NSTX-U and DIII-D are likely to be reduced from the optimum level by several run weeks per year, slowing research progress and reducing the availability of the facilities as resources for students and researchers from universities.

Whole-device modeling based on validated, massively parallel computing would still be a high-priority goal, but the level of research would be reduced, so that what would have been achievable in ten years would likely be delayed by several years. It is likely that code validation efforts that use experimental data would be reduced compared to what would be possible in the Modest Growth Scenario.

Burning Plasma: Long Pulse

Fusion materials research would be similarly reduced. Full usage of new experimental capabilities in materials and fusion nuclear science would be pushed out to later in the decade. Supporting computational work would be decreased. Substantial growth in international partnerships would be unlikely.

Discovery Plasma Science

FES would maintain an emphasis on executing a shift towards research on intermediate scale facilities under a user facility model, but the number of such facilities supported in this budget scenario would be smaller. As above, an emphasis would be placed on plasma science research that has the broadest impact across the sciences.

4.3: Flat Funding Scenario

Under this most constrained budget scenario, the basic research priorities remain the same as above, but the pace at which deliverables can be realized will be significantly decreased, and the scope of the FES program overall will be substantially narrowed. The Flat Funding Scenario results in a much smaller research effort, at a funding level that is 45 percent less than that for the Modest Growth Scenario by the end of the decade.

Burning Plasma: Foundations

Research operations on NSTX-U and DIII-D would be reduced by as much as 40 percent below optimum by decade's end. Priorities would remain research in plasma transients, albeit with a significantly slowed pace of progress and an overall narrowing of the breadth of these activities.

Whole-device modeling based on validated, massively parallel computing would still be a high priority goal, but research activities to drive integration of currently separate code modules would be greatly diminished. Emphasis would remain on SciDAC-sponsored activities. It is likely that efforts to validate codes with experimental data would be reduced, compared to what would be possible in the two growth scenarios.

Burning Plasma: Long Pulse

Fusion materials research would be substantially reduced as compared to the effort envisioned in either of the two other budget scenarios discussed above. Development of new experimental capabilities would be pushed to later in the decade. Support for computational materials research would be reduced compared to the other scenarios. Growth in international partnerships would be reduced as compared to the other scenarios.

Discovery Plasma Science

Within this area, HEDLP research would likely be reduced from the level supported in the FY 2015 enacted budget. As in all budget scenarios, FES would emphasize plasma research that has the broadest impact across the sciences.