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SUBCOMMITTEE ON ENERGY

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Chairman Weber, Ranking Member Veasey, and Members of the Subcommittee, thank you for the invitation to testify before you today on fusion energy research. I appreciate this opportunity to review the status of research in this scientific area and to describe programmatic directions going forward.

Mission:

The mission of the Fusion Energy Sciences (FES) program is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundation needed to develop a fusion energy source. This is accomplished through the study of plasma, often called the fourth state of matter, and how it interacts with its surroundings.

Plasma science is wide-ranging, since 99% of the visible universe is composed of plasmas of various types. High-temperature fusion plasmas at hundreds of millions of degrees occur in national-security applications, albeit for very short times. The same fusion plasmas could be exploited in the laboratory in a controlled fashion to become the basis for a future clean nuclear power source, which will provide domestic energy independence and security. This is a large driver for the FES subprograms focused on the scientific study of "burning plasma." In the burning plasma state of matter, the nuclear fusion process itself provides the dominant heat source for sustaining the plasma temperature. Such a self-heated plasma can continue to undergo fusion reactions that produce energy, while requiring little input of heating power from the outside resulting in large net energy yield.

Administration R&D priorities and FES

The FES program addresses several of the Administration's research and development budget priorities. Research in fusion has the potential to contribute to American energy dominance by making available to the American people a robust, clean base-load electricity technology that relies on widely available and virtually inexhaustible fuel sources. Research in plasma science, within and beyond fusion, will contribute to American prosperity through the tremendous potential for spinoff applications as well as targeted investments in early-stage low temperature plasma research that has the potential to lead to the development of transformative technologies. Investments in our major fusion facilities and smaller-scale experiments will help maintain and modernize our research infrastructure for continuing to conduct world-leading research. Established partnerships within and outside DOE maximize leverage and increase the cost-effectiveness of FES research activities. Finally, the unique scientific challenges and rigor of fusion and plasma physics research lead to the development of a well-trained STEM-focused workforce, which will contribute to maintaining and advancing U.S. competitiveness and world leadership in key areas of future technological and economic importance, as well as national security.

Status of FES research

The FES program is organized into four subprograms: (1) *Burning Plasma Science--Foundations*, (2) *Burning Plasma Science--Long Pulse*, (3) *Burning Plasma Science--High Power*, and (4) *Discovery Plasma Science*

In the ***Burning Plasma Science--Foundations subprogram***, the behavior of laboratory fusion plasmas confined with strong magnetic fields is investigated. The DIII-D National Fusion Facility and the National Spherical Torus Experiment-Upgrade (NSTX-U) are world-leading Office of Science (SC) user facilities for experimental research available to and used by scientists from national laboratories, universities, and industry research groups.

- **DIII-D** (operated by General Atomics) is a world-class tokamak facility. This facility is highly flexible, with extensive diagnostics to measure plasma behavior. The DIII-D scientific team consists of 439 researchers from 49 institutions in the U.S. and 164 researchers from 46 institutions across seven other countries. These numbers include 64 postdoctoral researchers, 75 graduate students, 13 Master's degree students, and 21 undergraduates.

  DIII-D plans to operate 18 run weeks in FY 2018 and then go into a facility outage (called Long Torus Opening) for facility enhancements. The Long Torus Opening is planned to extend into the first part of FY 2019, after which the machine will resume operation for 12 weeks. The scientific results from DIII-D for magnetic confinement fusion research are highly recognized worldwide. Additionally, during FY 2017, FES supported a new initiative to carry out experiments on DIII-D for basic plasma science, not directly related to fusion energy issues; this successful initiative will be repeated in FY 2018.

- **NSTX-Upgrade** (operated by PPPL) is the world's highest performance spherical tokamak, a magnetic confinement configuration invented in the U.S, which has the attractive advantages of compactness and component testing. NSTX-U is currently not operating, due to a magnetic coil failure and other hardware issues.

  During FY 2017, PPPL conducted an extensive series of reviews to identify the design, construction, and operational deficiencies of the facility. The laboratory has developed an integrated corrective action plan for repair and recovery of reliable experimental operation. The lab is currently formulating a baseline. SC is conducting an internal assessment of the recovery scope, the mission need, and the laboratory's capabilities. By the end of the year, cost and schedule implications will be in hand.

Complementing these experimental activities is a world leadership effort in fusion theoretical modeling and high-performance computer simulations to predict and interpret the complex behavior of plasmas as self-organized systems. As part of this effort, FES supports eight Scientific Discovery through Advanced Computing (SciDAC) centers, involving scientists from 11 universities, 8 DOE laboratories, and 5 industry R&D groups. Seven of these SciDAC centers are supported in partnership with the Advanced Scientific Computing Research (ASCR) program office. The FES SciDAC centers were re-competed in FY 2017. In addition, scientists from PPPL lead a national team working on whole-device modeling of magnetically confined fusion plasmas, which is one of the 22 ASCR-funded Exascale Computing Projects.

In the ***Burning Plasma Science--Long Pulse subprogram***, FES investigates the behavior of plasmas that are confined near steady state. U.S. scientists take advantage of international partnerships to conduct research on superconducting tokamaks and stellarators with long-duration capabilities that are not available in the U.S. This includes:

- Three multi-institutional teams of U.S. researchers carry out collaborative research on the long-pulse tokamak facilities in China and Korea.
- Another multi-institutional U.S. team cooperates in research on the new superconducting stellarator facility in Germany.
- Other teams work on several other overseas experimental facilities that are not superconducting but have unique capabilities.
- A useful recent development is the establishment of remote collaboration/connectivity centers (e.g., at GA, PPPL, and MIT) that allow U.S. scientists to participate and lead experiments on overseas facilities, thus reducing the need for travel and creating collaboration efficiencies.

In addition, the development of novel materials, a research area of high interest to many scientific fields, is especially important for fusion energy sciences since fusion plasmas create an environment of high-energy neutrons and huge heat fluxes that impinge on and damage the material structures containing the plasmas. The FY 2019 budget request proposes to initiate design and some fabrication activities for a new linear divertor simulator facility that will have world-leading capabilities to test materials under extreme-heat-flux fusion conditions.

The ***Burning Plasma Science--High Power subprogram*** refers to the frontier scientific area of the actual creation of strongly self-heated fusion burning plasmas, which will allow the discovery and study of new scientific phenomena relevant to fusion as a future energy source.

Currently the Burning Plasma Science--High Power subprogram is focused on the U.S. Contributions to ITER, a construction project. ITER is a large, international project, involving the U.S., European Union (EU), Russia, China, Japan, India, and South Korea, which aims to construct a full-scale experimental fusion reactor, located in southern France, about 50 miles north of Marseille. In 2007, the ITER project was scheduled to be complete (i.e., achieve deuterium-tritium burn) by 2016, with the U.S. share, at that time, approved to be $1.1 billion. To date, U.S. in-kind contributions to ITER have been $1.06 billion. Under the present schedule approved by the ITER Organization, ITER will achieve the first-plasma milestone in 2025-26 and be complete (achieve D-T burn) in 2035. The U.S. cost is presently estimated to be $4.7-6.5 billion.

The U.S. is responsible for delivering a number of hardware systems, which are being fabricated by industries, national laboratories, and universities in the U.S. The largest of these U.S. hardware systems are the seven modules for the central solenoid magnet of ITER, which when completed will be the world's largest superconducting pulsed electromagnet - the so-called "heartbeat of ITER." The First Plasma subproject of the U.S. Contributions to ITER project is more than halfway complete. Fabrication of the ITER central solenoid magnet assembly, which is the U.S.'s highest-priority activity, is, as of January 2018, 68% complete.

So far, slightly more than $1B has been spent, with more than 90% of the U.S. ITER funding for hardware systems spent within the U.S., through more than 600 contracts in 44 states. Two hardware systems were completed and delivered in 2017: the Steady-State Electrical Network for the ITER site, and the superconducting conductor for the ITER toroidal field coils. (Detailed information about the U.S. ITER fabrication activities is contained in the four graphs attached to this testimony.) The U.S. Contributions to ITER project is efficiently and effectively managed by the U.S. ITER Project Office at ORNL in partnership with PPPL and SRNL (cf. supplemental attached pages). The subject of continued U.S. participation in the ITER project is included in the Administration's ongoing civil nuclear review.

The ITER Organization in France has very significantly improved its project management since the appointment of the current Director General, Dr. Bernard Bigot, in 2015. Construction progress on the ITER site is quite substantial. In December 2017, the ITER Organization celebrated 50% completion to First Plasma, as reported in many media outlets.

The FES ***Discovery Plasma Science subprogram*** involves research in areas such as plasma astrophysics, high energy density laboratory plasmas (HEDLP), and low temperature plasmas. Some of this research is carried out through a partnership on basic plasma science and engineering with the National Science Foundation (NSF) and a joint program on high energy density laboratory plasmas with the National Nuclear Security Administration (NNSA). A few examples of Discovery Plasma Science research programs are the following:

- The Large Area Plasma Device at the University of California, Los Angeles is a world-unique device for simulating the behavior of plasma-loaded magnetic field lines. One such ubiquitous behavior is called reconnection, when magnetic field lines rip apart and reconnect—which occurs in the Earth's magnetic field due to the solar wind, in solar flare eruptions, in the formation of astrophysical neutron stars and black holes, and in laboratory fusion plasmas.
- Recently FES solidified the U.S. leadership in reconnection physics by funding an intermediate-scale, integrated, collaborative science user facility at the University of Wisconsin-Madison.
- FES has supported a multi-institutional plasma science center that performs early-stage research on the detailed dynamics of low-temperature plasmas, which have future spin-off applications.
- The Matter in Extreme Conditions instrument, one of six end stations at the Linac Coherent Light Sources user facility at SLAC National Accelerator Laboratory, is a world-leading facility for the study of high energy density plasmas, which underlies the understanding of laser-plasma interactions, astrophysical processes, and inertial confinement fusion. Some recent highlights are the production of "diamond rain" (predicted to occur in the interior of Icy Giant Planets) and the discovery of a new form of water that is simultaneously solid and liquid.
- Plasma techniques are being used to capture and cool anti-hydrogen atoms at CERN so that experiments can be performed that might explain why there is so little anti-matter in the universe.

Also, U.S. scientists are world leaders in the invention and development of high-resolution plasma measurement techniques. One such example is the x-ray crystal spectrometer, a versatile diagnostic that has been utilized on several different magnetic confinement fusion facilities and, more recently, on inertial confinement facilities.

Strategic directions going forward for the FES program are informed by several sources, including the following:

- The priorities described in the document "The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective" (submitted by DOE to Congress in December 2015): These priorities include keeping SC fusion user facilities world-leading, investing in high performance computing and preparing for Exascale, supporting high-impact research in fusion materials, strengthening partnerships for access to international facilities with unique capabilities, learning how to predict and control transient events in fusion plasmas, and continuing stewardship of discovery plasma science (e.g., via intermediate-scale basic facilities).
- The research opportunities identified in a series of four community engagement workshops held in 2015, whose written reports were finalized in 2016 and are available online.[1]

[1] https://science.energy.gov/fes/community-resources/workshop-reports/

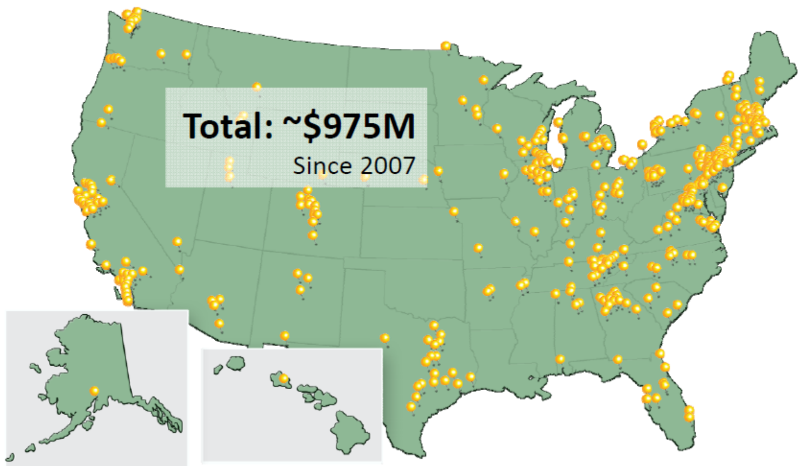
- Other community interactions: In recent years, the fusion community self-organized to hold several workshops: a stellarator research opportunities conference, two workshops to provide input to the National Academy of Sciences (NAS) burning plasma study, three high energy density science workshops, and an exascale computing requirements workshop.
- Reports from the Fusion Energy Sciences Advisory Committee (FESAC), a federal advisory committee chartered under the Federal Advisory Committee Act: Two recent examples are the (1) the 2016 FESAC report[2] that describes how plasma science advances have led to spinoff applications and enabling technologies with considerable economic and societal impact for the American quality of life, and (2) the 2018 FESAC report about the potential for transformative enabling capabilities in fusion science and technology that could accelerate progress toward fusion energy.
- Reports from the NAS: Currently, the NAS is performing a study entitled "A strategic plan for U.S. burning plasma research," which was requested by SC. This study released an interim report on December 21, 2017; its final report is expected toward the end of 2018. Another NAS study, soon to be launched, is the Plasma Decadal Survey. This Survey has multiple federal sponsors, including DOE, NSF, and the Department of Defense, and its report is expected in 24 months. The two previous Plasma Decadal Survey reports from NAS have been influential. In addition, the NAS recently released a report on Intense Ultrafast Lasers[3], which is of high interest to the part of the FES program for research on high energy density laboratory plasmas.

In conclusion, the FES program is actively engaged at the forefront of fundamental research in burning plasma science and discovery plasma science, with the use of domestic facilities and through international partnerships. Thank you for the opportunity to come before you today to describe DOE's efforts in fusion energy sciences. I look forward to discussing this topic with you and answering your questions.

[2] https://science.energy.gov/~/media/fes/fesac/pdf/2015/2101507/FINAL_FES_NonFusionAppReport_090215.pdf
[3] https://www.nap.edu/catalog/24939/opportunities-in-intense-ultrafast-lasers-reaching-for-the-brightest-light

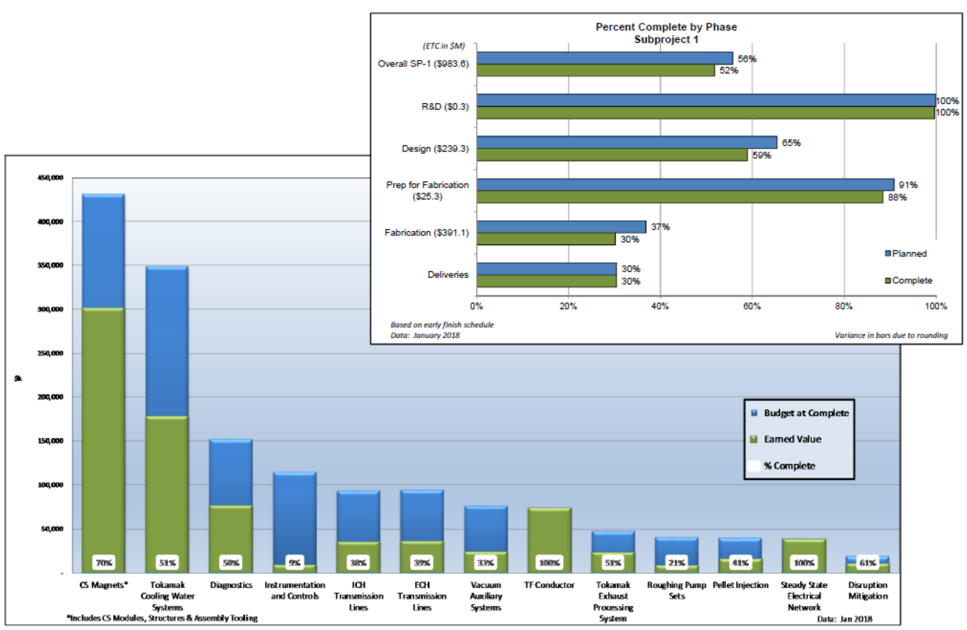
Over 80% of Awards and Obligations Remain in the US

- 600+ contracts awarded to US industry and universities, and obligated to DOE national laboratories in 44 states
- 500+ direct jobs and 1100+ indirect jobs created or maintained per year



Data as of December 31, 2017

Progress of US ITER Subproject 1

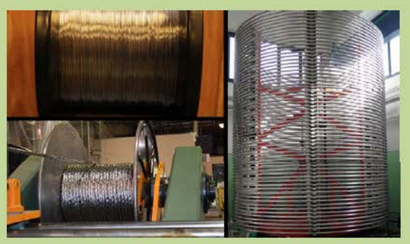


Examples of US hardware for ITER
First Plasma Subproject deliveries 30% complete

Central solenoid (CS) modules are in serial fabrication at General Atomics' Poway, CA facility.

The CS assembly platform was delivered in 2017.

Piping fabrication for the Tokamak Cooling Water System is underway at Schulz XP in Robinsonville, MS



US completed Toroidal Field Coil Conductor deliveries and acceptance in 2017.

US completed delivery of Steady State Electrical Network components to the ITER site in 2017.

Central Solenoid Module Fabrication Progressing