Fusion Energy Sciences Vision and Update

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For the Board of Physics and Astronomy
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The science that undergirds fusion energy is far-reaching and is poised for a transformation

- The science pursued by FES may form the basis for powering the planet through fusion energy: bringing a star to earth.
  - This science enables a deeper understanding of our universe and has a wide range of practical applications.
The U.S. is a world leader in establishing the scientific basis for fusion energy and understanding the plasma universe.

**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 develop the scientific foundations needed to develop a fusion energy source. This is accomplished by the study of the plasma state and its interactions with its surroundings.

**Priorities**

- Advance the fundamental science of magnetically confined plasmas
- Pursue scientific opportunities and grand challenges in high energy density plasma science
- Support the development of the scientific understanding required to design and deploy fusion materials
- Increase the fundamental understanding of plasma science beyond burning plasmas
Fusion Energy Science Research is Institutionally and Scientifically Diverse

FES research funding touches the education of about 490 students participating in every element of the FES research portfolio.
FY 2012 FES Congressional Request ($399.7M)

**Research: $177,816K**
- DIII-D, C-Mod, NSTX
- International Collaborations
- High Energy Density Laboratory Plasmas
- Outreach & Education
- Innovative Confinement Concepts (ICCs) - Experimental Plasma Research
- Diagnostics
- Madison Symmetric Torus (MST)
- Theory and Modeling
- SciDAC
- General Plasma Science
- SBIR/STTR

**Facility Operations: $195,882K**
- ITER at $105M
- 13 Weeks of post-upgrade DIII-D operations
- 17 run weeks of Alcator C-Mod
- 10 Weeks of NSTX operations prior to major upgrade shutdown
- NSTX MIE Upgrade
- General Plant Projects/Infrastructure

**Enabling R&D: $26,002K**
- Plasma Technology
- Advanced Design Studies
- Materials Research

*Smaller Scale MFE includes ICCs and MST
**Other includes SBIR/STTR, Outreach, Education & Diagnostics
The National Academies underscores the urgency for a burning experiment for fusion, and ITER has been identified as the vehicle

- The National Academies of Science concluded that a magnetically confined burning plasma experiment is the next step for fusion research, and that the world fusion community has established the scientific basis for taking this step.

- The U.S. concluded that ITER is the most scientifically and technically compelling step to take (Snowmass 2002 Study).
ITER is the keystone for establishing the scientific and technological feasibility of magnetic fusion energy.

ITER will advance every element of science and technology required to establish the basis for fusion: burning plasma science, plasma control science, technology, and discovery.

Understanding for fusion on earth and of the plasma universe

Burning plasma science

Plasma dynamics and control science

Plasma-materials science and technology

Discovery science

Request reflects funds necessary to meet obligations according to a baselined international project schedule.

Designs will be completed with industry input for the majority of U.S. hardware needed for first plasmar.

Long-lead items for magnet materials and Ion/Electron Cyclotron heating systems will be initiated and R&D will continue to support finalization of design efforts for diagnostics and other systems. Purchase of hardware for the U.S share of the Steady State Electrical system will also be initiated. Toroidal field magnet conductor production will be largely completed.
There has been important progress in constructing ITER

Poloidal winding building construction

Site construction is underway

New project leadership

Director General Motojima

Rich Hawryluk (U.S., from PPPL); new Deputy Director General for Administration

Rem Haange (Netherlands), new Deputy Director General for ITER Construction

The ITER Device
The U.S. is responsible for a wide range of in-kind contributions. A wide range of institutions and businesses work with these lead labs.
Research using the major U.S. facilities is highly impactful, and is acknowledged by the international community.

Four of the first five recipients of the IAEA’s Nuclear Fusion Prize are U.S. researchers. The prize is awarded annually to the researcher who authored the most impactful publication in the field of fusion energy research worldwide. Two are from universities and all awards are for research conducted on our three major facilities.

Previous winners: Timothy Luce (General Atomics, San Diego; 2006) and Todd Evans (General Atomics, 2008).

John Rice (MIT, 2010 recipient, and Steve Sabbagh, Columbia University, 2009 recipient for research carried out on NSTX and DIII-D) were awarded their prizes in 2010 at the IAEA meeting in Daejeon, South Korea.
We need to grow our internationally based research efforts

Leading-edge technologies are overseas. We’ve been offered program leadership seats and can have major impact on their directions.

How we respond with labs and universities in the next decade will be a major factor determining our place on the world stage.

Such efforts will define our work approach on ITER.

Understanding for fusion on earth and of the plasma universe

First-of-kind superconducting tokamaks (based on U.S. designs) now in China (EAST, Hefei) and South Korea (K-STAR, Daejeon). Also superconducting stellarators (Japan and Germany). All major new facilities have offered the U.S. a leadership seat at the program governance table.

U.S. teams, formed by national labs, private industry, and universities, will participate on-site and with remote data centers.

This will lead to a research team model to be implemented on ITER.

Plasma dynamics and control science

Burning plasma science

Major opportunities and needs

Discovery science

Plasma-materials science and technology
Emergent opportunities for plasma control research, with superconducting magnetic technology, reside overseas.

**K-STAR**
Daejeon, S. Korea
Goal: 300 s pulse 2 MA

**EAST**
Hefei, China
Goal: 1000 s 1 MA

The U.S. DIII-D control system has been implemented on K-STAR and EAST devices.

**LHD stellarator**
(Japan – operating)

**W7-X stellarator**
(Germany – 2014)
A Fusion Pathways Assessment is ongoing that will identify research needs at a level to enable new solicitations

- This year-long study is enabled by a detailed assessment of Gaps and Opportunities in the world program identified by FESAC subpanel (“Greenwald Report”)

- This was taken further by the ReNeW process in magnetic fusion that was completed in 2009

Establish the basis for a significant move into materials science, both nuclear and non-nuclear.
- Lever common interests in MFE, IFE, NE, SC, NNSA
- Complementarity of DIII-D, C-Mod, and NSTX-Upgrade will inform the decision on a Fusion Nuclear Science Facility later in this decade.
- Launch a prerequisite computational materials and beam line programs. Strong university role

Candidate geometries for a fusion nuclear materials science facility.
Down-select late this decade
Theory and validated simulation are critical for fusion’s future success

Understanding for fusion on earth and of the plasma universe

Theory and Modeling: Higher level enacted in 2010 from a one-time addition from Congressional action to address specific needs

SciDAC: Increase will support a new computational fusion materials project

Fusion Simulation Program: The decrease in funding reflects the decision by FES to first evaluate the results of the two-year planning phase of the FSP.

How we use validated simulation as instruments of scientific discovery is a great question for science overall.

How we execute our simulation efforts in terms program governance, including the relation between universities and labs, is critical.
University-scale research is well-suited for critical tests of fundamental physics

- **Plasma Science Centers**
  - Predictive Control of Plasma Kinetics: Multi-phase and bounded systems (U. Michigan)
  - Momentum Transport and Flow Self-organization in Plasma (UCSD)
  - Bridging the PSI Knowledge Gaps - A Multiscale Approach (MIT)
  - Also a joint Frontier Science Center with NSF: Magnetic Self-Organization (U. Wisconsin)

- **Basic Plasma Science Facility (UCLA) (with NSF)**
  - User facility for Alfven-wave physics and plasma-current dynamics, relevant to geospace plasmas, fusion and astrophysics.

**Validation in fusion research: Towards guidelines and best practices**


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High Energy Density Laboratory Plasma Physics will emphasize near-term science results relevant to IFE and discovery.

A response to recent scientific developments and emergence of new, flexible and powerful tools.

In FY 2012, FES and NNSA plan to hold a joint solicitation. Emphasis will be on

- basic science
- potential for near-term output
- access to extreme states of matter
- leverage with other agencies or multiple institutions
- leverage of existing investments

Partnership with NNSA is highly valued in advancing this element of plasma science.

This research can also be framed as questions in plasma dynamics, control, and discovery.
General Plasma Science funding is proposed to increase in FY’12 to help capture the call made by the National Academies

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<th>Science Subprogram: General Plasma Science</th>
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<td>FY’12 request</td>
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<td>$16.8M</td>
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The increase will allow for preparation for new proposals in discovery science that lever cross-agency and international partnership. Also, this proposed budget will provide full funding of a Plasma Science Center which was started with Recovery Act funding.

Plasma materials science and technology
Plasma dynamics and control science
Discovery science
Burning plasma science
Understanding for fusion on earth and of the plasma universe
This area’s leading emphasis is exploration and curiosity-driven research
Leverage with other agencies and programs is of high value here
Regarding plasma dynamics and control in fusion...

- **Plasma dynamics and control is our defining research area now, and we arguably are or are among world leaders in terms of detailed measurement of underlying processes, connection to theory, developing an integrated understanding, and demonstration of advanced scenarios in tokamaks. However,**
  - At present world-wide investment, it will not provide the validated predictive capability we need to take a confident step beyond ITER and it’s geometry
  - International commitment in this research is impressive and worth capturing. In fact, we will need to if we are to remain at the forefront

- **International partners want our support**
Plasma dynamics and control is our defining research area now, and we arguably are or are among world leaders in terms

At this fall’s APS-DPP meeting, I raised these questions of the University Fusion Associates and the Committee for the Concerns of Junior Scientists:

What are the opportunities for universities to lead in validation and verification of theory central to how we predict and control plasma dynamics?

As we extend our reach internationally, is there a place for university-based remote participation in overseas experiments as we prepare for the ITER era?

How do we best engage the intellectual power at universities in our upcoming efforts in large-scale simulation of future fusion systems? How do we engage and interest main campuses and deliver a vision for their research that offers as direct a link as possible to where the world is going in fusion in the burning plasma era?

International partners want our support
Regarding materials in a fusion environment and harnessing fusion power


- **Nuclear effects on materials and structures**, including the effects of $>100$ dpa on structure integrity, helium creation in situ, and time evolving properties.

- **Harnessing fusion power** depends on the nuclear material science above and is extended to tritium breeding and extracting fusion power from the burning plasma.

Present investment is a fraction of what is needed. This requires the development of a new fusion materials science program for materials to define and construct a fusion nuclear science facility: benefits MFE, IFE, and other disciplines.
Regarding materials in a fusion environment and harnessing fusion power


Questions and challenge for universities include:

- What are the opportunities for universities to lead in materials science, through test stands or computation?

- Are there synergies to be levered in universities with nuclear engineering departments?

Present investment is a fraction of what is needed. This requires the development of a new fusion materials science program for materials to define and construct a fusion nuclear science facility: benefits MFE, IFE, and other disciplines.
Thank you
Examples of recent impacts and near-term potential of fusion energy science research
Superconducting Technologies: Towards a more efficient electric grid –

ORNL fusion energy researchers have worked with staff from Georgia’s Southwire Company to develop, design, and fabricate the world’s most compact superconducting power cable. This technology can help electric utilities deliver more power with greater voltage control at high current densities, resulting in less need for additional transmission towers or new underground rights-of-way.

Because an HTS cable loses little energy as heat, it can cut electrical transmission losses roughly in half (from about 8 to 4 percent). An HTS cable also is more environmentally friendly, because it is cooled with safe, inexpensive liquid nitrogen rather than oil-impregnated paper insulation, which may leak oil. The superconducting cable was initially installed, tested, and utilized in facilities at Carrollton, Ga.

Southwire, ORNL, American Supercomputer, and American Electric partnered to produce an urban power distribution project that has been delivering electric power to some 8,600 homes and businesses in Columbus, Ohio, since 2006. Southwire’s HTS Triax™ is the most compact, high-power-density cable in the world. The three alternating-current phases are concentric and contained in a single cryostat. This technology has been recognized with awards from the Federal Laboratory Consortium and DOE’s Office of Electricity Delivery and Energy Reliability.
DOE-sponsored magnetic fusion research is yielding technology that contributes to national defense

Electromagnetic Aircraft Launch System

Early work in magnetic fusion energy has led General Atomics, a San Diego-based innovation firm, to help improve power systems for government and commercial customers. Technological advances include the Electromagnetic Aircraft Launch System (EMALS), an electromagnetic catapult that will replace steam catapults used on prior generations of aircraft carriers.

EMALS will be installed on the U.S. Navy's new Gerald R. Ford-class aircraft carrier, CVN-78. A full-scale, shipboard representative catapult has been installed at the Navy's System Functional Demonstration Site at Joint Base McGuire-Dix-Lakehurst, N.J. Commissioning with dead-loads is under way, and aircraft launches will be demonstrated at this site.

Making the world a safer place: The Miniature Integrated Nuclear Detection System - The Miniature Integrated Nuclear Detection System (MINDS) was developed by engineers at DOE's Princeton Plasma Physics Laboratory. For transportation and site security, MINDS is used to scan moving vehicles, luggage, cargo vessels, and the like for specific nuclear signatures associated with materials employed in radiological weapons. It implements a technique to detect and identify nuclear materials in real time for homeland security applications.

MINDS is currently deployed at a major commuter rail station, at a military base, at workplace entrances, and at commercial shipping ports to detect the transportation of unauthorized nuclear materials.
The Compact Synchrocyclotron: Making a valuable cancer treatment more available - The effort to develop advanced superconducting coils for magnetic fusion experiments at the MIT Plasma Science and Fusion Center (PSFC) has led to a new coil design that allows cyclotrons to be very compact, an advance that could make a valuable cancer treatment more available.

Cyclotrons are currently used to help treat cancer with proton beam radiotherapy (PBRT). Proton beam energy deposition can be precisely tailored to target the tumor, leaving surrounding tissue unharmed. Although PBRT is in demand, a typical cyclotron is so massive (around 1000 tons) and expensive to build (around $100 million), that there are currently only five PBRT centers in the U.S.

The PSFC is developing a compact high-field synchrocyclotron that is about 40 times smaller, lighter (about 25 tons), and orders of magnitude less expensive than the equivalent machine built using conventional magnet technology, making it possible for many more hospitals to provide PBRT. Single-treatment-room systems are now being commercialized.

Semiconductor Inspection: Enabling rapid detection of chip defects –

Oak Ridge National Laboratory fusion researchers helped develop an award-winning direct-to-digital holographic (DDH) microscopy technology. This technology can rapidly find small defects in deep-lying contacts and trenches in semiconductor wafers, thus exceeding the defect detection sensitivity and wafer throughput of conventional inspection systems.

The DDH technology is more sensitive than diffraction-limited, intensity-based techniques. It also requires little laser energy, provides volumetric detection rather than surface-area measurements, and has a higher throughput than is possible with other optical surface profile imaging techniques.

This patented inspection system, which has been commercially licensed, has the capability to help keep chip production costs low and contribute to maintaining the United States semiconductor industry’s competitive edge.
Polymer-Electrode Bonding: Developing more realistic artificial muscles - Princeton Plasma Physics Laboratory (PPPL) scientists are collaborating with a research chemist to develop a method using plasma to improve polymer-electrode bonding in electro-active materials. This could lead to creating superior artificial muscles, benefiting people with disabilities.

Ras Labs, a New Jersey small business research lab, is investigating contractile electro-active polymers in prostheses, particularly for the hand and arm. Ras Labs envisioned artificial muscles comprised of an electro-active polymer gel containing embedded electrodes, all encased in a flexible coating that acts as a kind of skin. The electrodes provide the electric stimulus, much like a nerve, and also attach the polymer to a mechanism, like a tendon attaches muscle to bone.

Through a Cooperative Research and Development Agreement, Ras Labs joined with PPPL to test ways to improve the metal-polymer interface by plasma treating the actuator electrodes. Using PPPL’s plasma equipment, the team treated metal samples with plasma, studying different ions to find a suitable metal and plasma combination that solved the detachment problem. The tests provided insight into the mechanisms responsible for improved adhesion of the polymer, leading to superior electro-active actuators and lifelike muscle movement.
Plasma science has had an incredible payoff and can yield more

From Kushner, APS-DPP review talk, 2008

The new Center for Predictive Control of Plasma Kinetics: Multiphase and Bounded Systems is funded by a five-year grant from the U.S. DOE. The Center is enabling fundamental research on low-temperature plasmas — ionized gases with vast potential for practical technological advancements. In particular, the Center will investigate techniques to customize the distributions of charged particles (electrons and ions) in these plasmas. A vast array of modern technologies, including renewable energy sources, lighting, microelectronics, and medicine, would not exist in the absence of low-temperature plasmas. The fundamental research that is being conducted at the Center could lead to more efficient solar cells, finer-featured microchips and new medical tools that cut and heal tissues with plasma-activated chemistry.

From the Plasma 2010 Decadal Study of the National Academies: “To fully realize the opportunities in plasma research, a unified approach is required. Therefore, the Department of Energy’s Office of Science should reorient its research programs to incorporate magnetic and inertial fusion energy sciences, basic plasma science, non-mission-driven high-energy density plasma science, and low-temperature plasma science and engineering.”
University experimental research is important to addressing unresolved plasma science issues and for workforce development.

The Madison Symmetric Torus is one of the country’s leaders in student education in the fusion and plasma sciences ($6M request).

**Experimental Research Portfolio:** Institutions anticipated to be supported in the in FY’12 ($11M request)
- Auburn
- Caltech
- Columbia University
- UC Davis
- Swarthmore
- University of West Virginia
- University of Wisconsin
- University of Washington
- University of Texas
- Utah State
- LANL
- ORNL
- PPPL

Over 100 graduate students and 24 post-docs’ research is conducted within the Experimental Research portfolio.

Columbia University: tokamak MHD control

Auburn University: advanced compact stellarator