

# The U.S. Fusion Energy Sciences Program Overview and Update

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U.S. DEPARTMENT OF  
**ENERGY**

Office of Science

Fusion Energy Sciences Advisory Committee Meeting  
January 13-14, 2016



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***Welcome!***

***And thank you***



# New FESAC members as of June 3, 2015



**Robert Cauble (LLNL)**



**Kristina Lynch (Dartmouth)**



**Stephen Knowlton (Auburn)**



**Brian Wirth (Tennessee)**

## **New FESAC deputy chair**

- Don Rej (LANL)

## **Change in one of the three *ex officio* members**

- Chair of APS-DPP
- Chair of ANS-FED
- President, IEEE-Nuclear and Plasma Science Society (formerly, IEEE-USA President)

# Last year's outgoing FESAC members



**Bruce Cohen**



**Chris Keane**



**Bob Rosner**



**Steve Zinkle**

Retiring Member	Institution	On FESAC Since
Bruce Cohen	LLNL	January 2009
Christopher Keane	Washington State	August 2010
Robert Rosner	University of Chicago	August 2010
Stephen Zinkle	ORNL	January 2009

*Sincere thanks to all of them for their service*



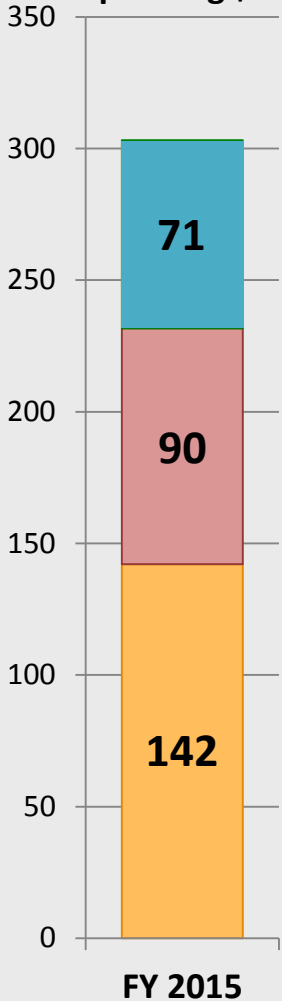
*Aspects of the program*

*Developments in capabilities*



# FES research is carried out at a diversity of US institutions

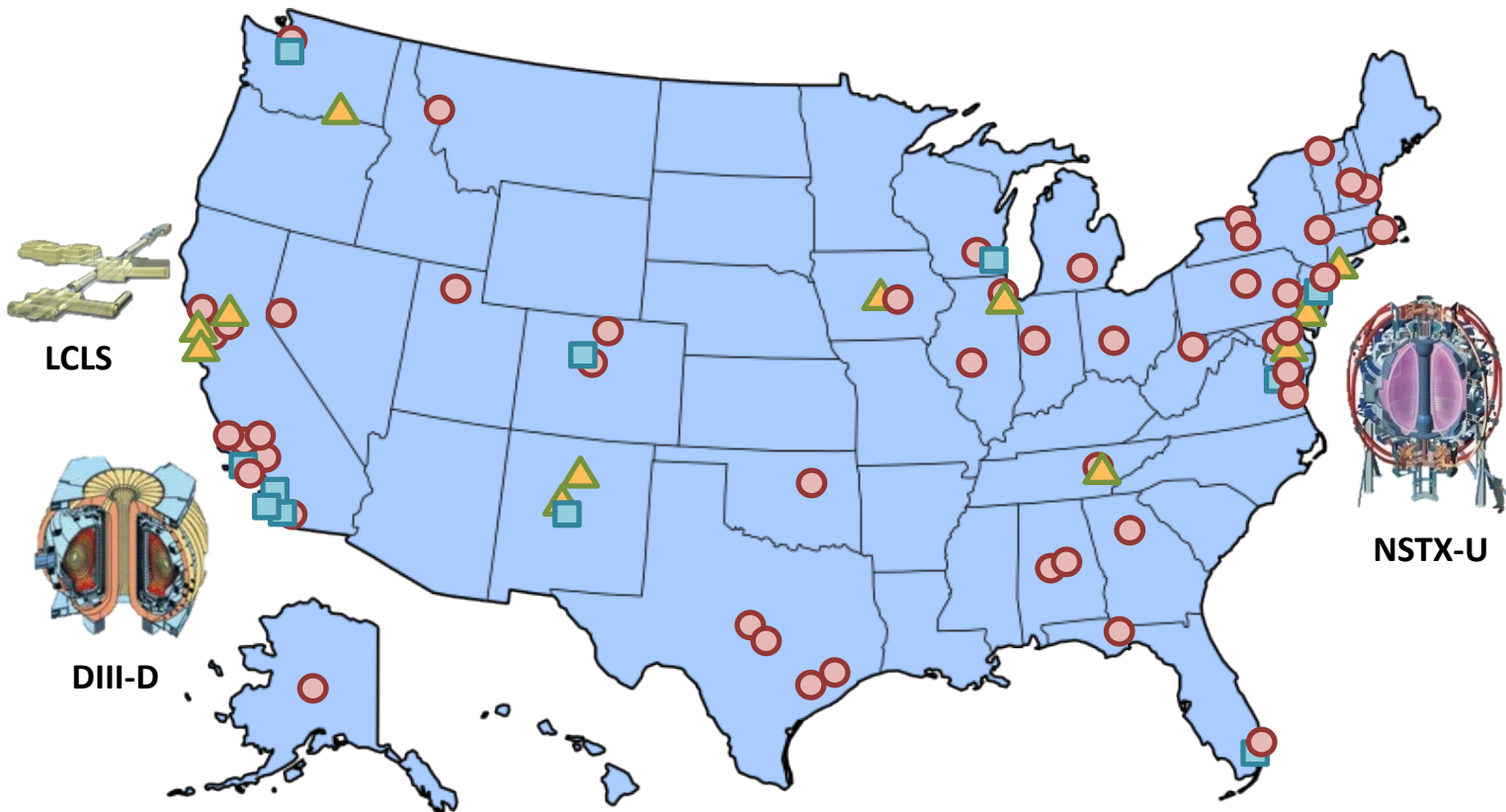
Spending \$M



**53**  
universities

**12**  
businesses

**10**  
laboratories



# The FES program is organized along scientific topical lines

## *Burning Plasma Science*

**Foundations** Focusing on domestic capabilities; major and university facilities in partnership, targeting key scientific issues. Theory and computation focus on questions central to understanding the burning plasma state

**Challenge:** Understand the fundamentals of transport, macro-stability, wave-particle physics, plasma-wall interactions

**Long Pulse** Building on domestic capabilities and furthered by international partnership

**Challenge:** Establish the basis for indefinitely maintaining the burning plasma state including: maintaining magnetic field structure to enable burning plasma confinement and developing the materials to endure and function in this environment

**High Power** ITER is the keystone as it strives to integrate foundational burning plasma science with the science and technology girding long pulse, sustained operations.

**Challenge:** Establishing the scientific basis for attractive, robust control of the self-heated, burning plasma state

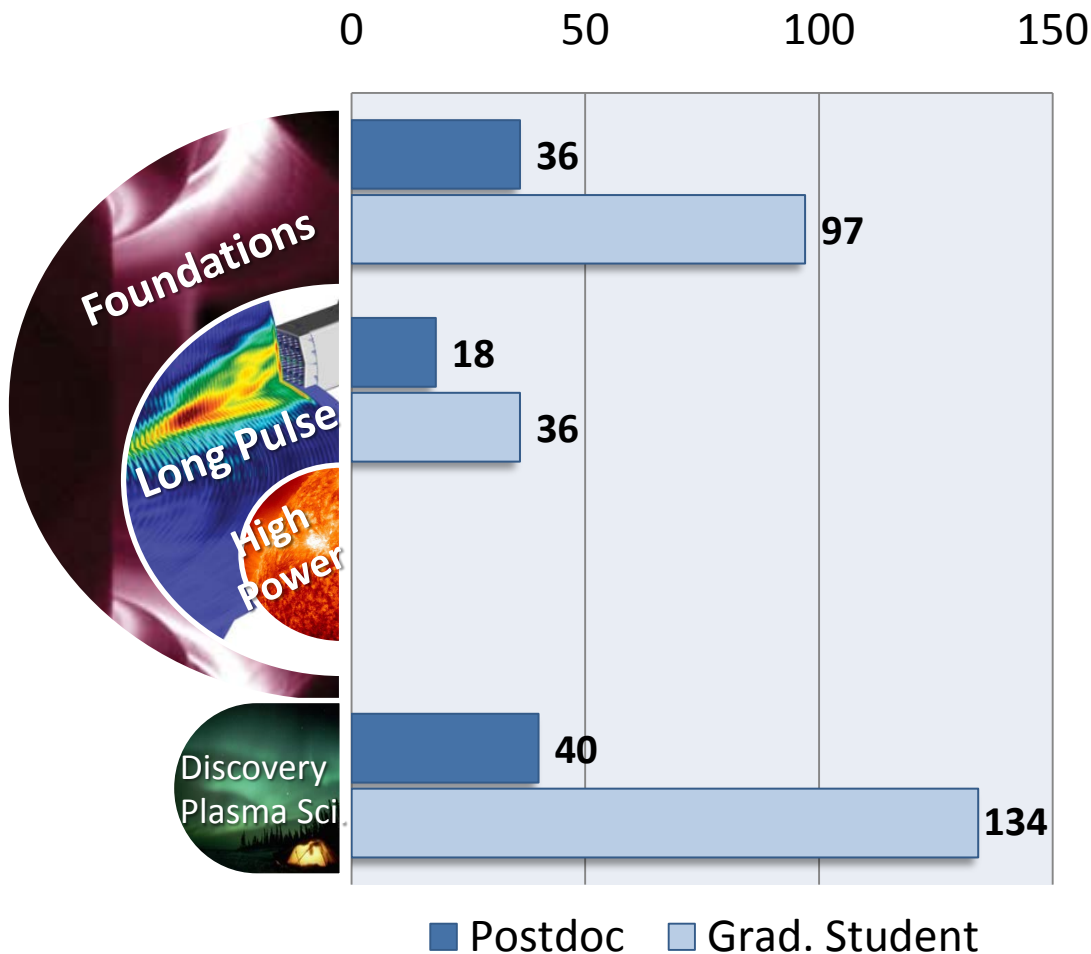
## *Discovery Science*

### **Plasma Science Frontiers & Measurement Innovation**

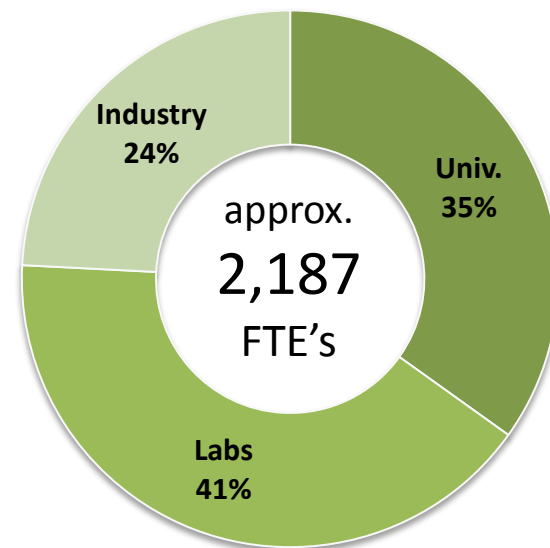
General plasma science, exploratory magnetized plasma, HEDLP, and diagnostics

# Summary of FES research participants in FY 2015

## Graduate Student and Postdoc FTE Estimates in FY 2015

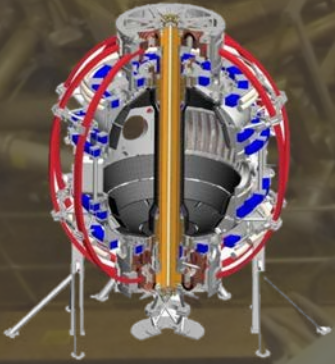


## Scientific Employment Estimate in FY 2015



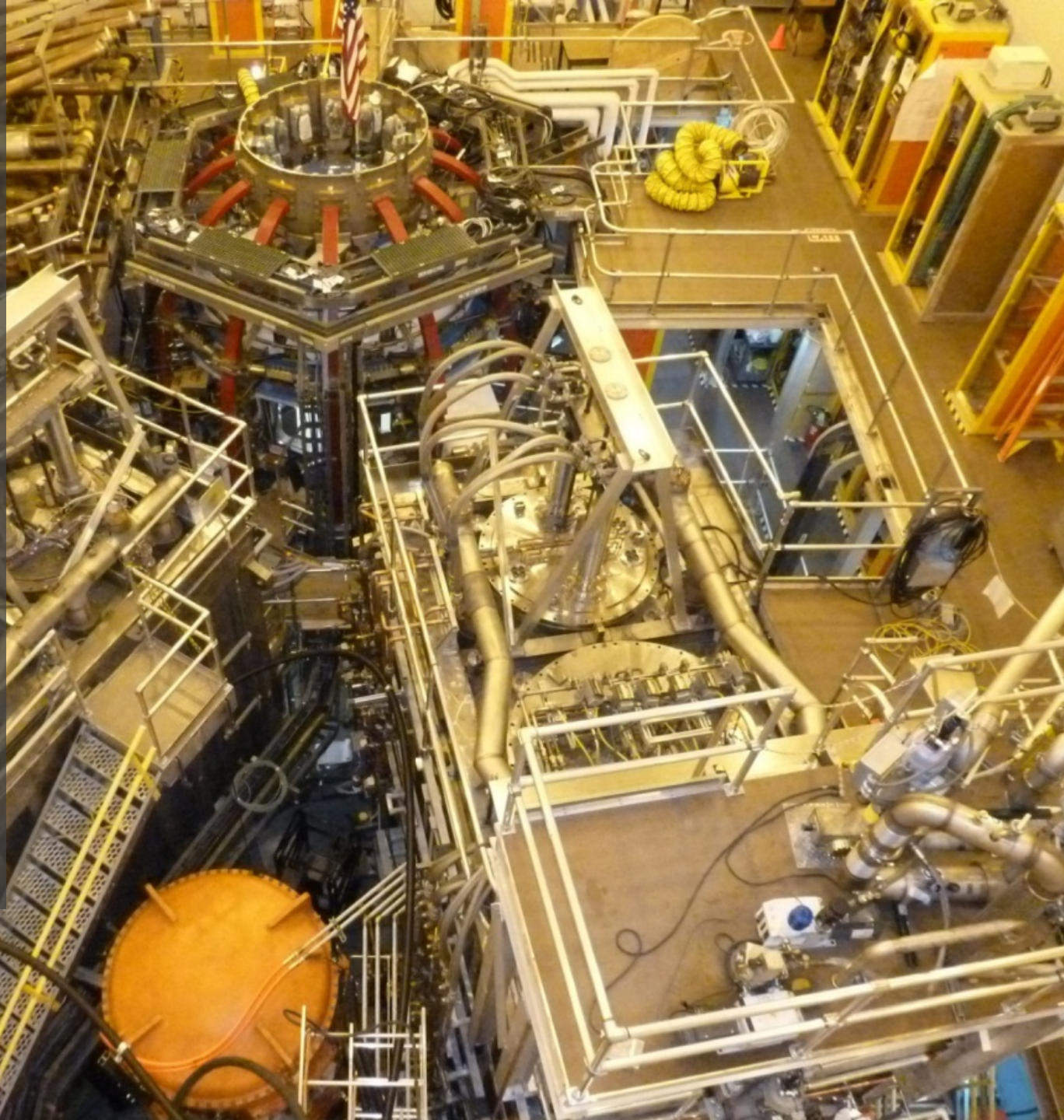


# NSTX-U Project



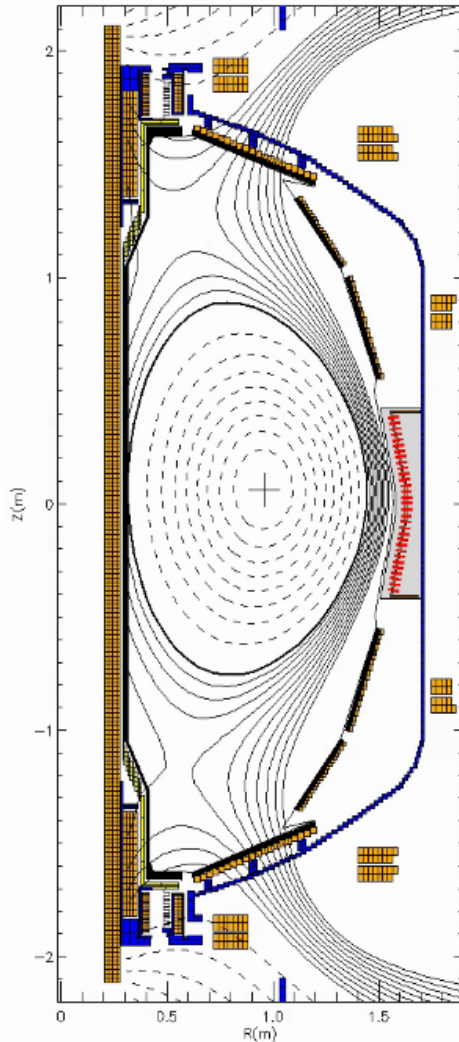
NSTX-U is the world's highest-performance spherical torus

	NSTX	NSTX-U
Toroidal Field	< 0.5 T	< 1.0 T
Plasma Current	< 1 MA	< 2 MA
Pulse Length	~1.0 s	~ 5 s
NB Heating	5-9 MW	10-18 MW



# Foundations highlight: NSTX-U ohmic plasmas have rapidly reached high plasma current (0.7 MA) and significant pulse length (0.7s)

## NSTX-U High $I_p = 0.7$ MA ohmic plasma



- **High plasma current (202440)**
  - $I_p = 701$  kA from NSTX-U EFIT (accurate wall current model. Reconstructed  $I_{p\text{ EFIT}} = 0.962 * I_{\text{Rog}}$ )
  - $q_{95} = 4.07$
  - $t_{\text{pulse}} = 0.46\text{s}$
- **Long pulse length (202438)**
  - $t_{\text{pulse}} = 0.707\text{s}$
  - $I_p = 480$  kA from NSTX-U EFIT
- **Just the start! Not near optimal yet.**
  - The first plasmas in NSTX-U with  $I_p \gg I_{\text{wall}}$
  - No NBI yet, no boronized or Li wall
  - Plasma shaping not optimized, still relatively modest elongation

# Foundations highlight: unprecedented computing resources enable confronting the challenge of electron thermal transport

## ***Massively parallel multiscale gyrokinetic simulations with realistic mass ratio shed light on the origin of “anomalous” electron transport in tokamak plasmas***

- ❑ Simulations of ion transport and confinement in high-temperature tokamak plasmas are now fairly standard, but the simultaneous simulation of the transport of electrons has been very difficult due to their factor-of-2000 mass difference with ions.
- ❑ Recently, gyrokinetic simulations of both ion and electron transport dynamics, involving widely disparate time and space scales, have been successfully performed for the first time with realistic mass ratio. The simulations used 100 million CPU hours, mostly on the Edison supercomputer at the National Energy Research Scientific Computing Center (NERSC) user facility.
- ❑ The results demonstrate that such multi-scale simulations are required to match with the experimentally measured ion and electron thermal fluxes and profiles and thus resolve a longstanding mystery of electron heat conduction in tokamaks.



# Long Pulse Highlight: Vertical control experiments via remote operation of EAST 3<sup>rd</sup> shift from GA

## GA Remote Control Room:

Display hardware and software to provide control room experience remotely

Real-time audio/video, streaming of data during shot, display of real-time boundary/signal traces

## GA Science Collaboration Zone:

Dedicated network and cyberspace for between-shot transfer of data to GA

DIII-D provides EAST data repository for all U.S. collaborators

Data mirror at GA serves all US collaborators

## First full 3<sup>rd</sup> shift remote operation July 22-23:

Two 3<sup>rd</sup> shift periods (overnight in China)

Triggered vertical displacement events to assess growth rates, controllability

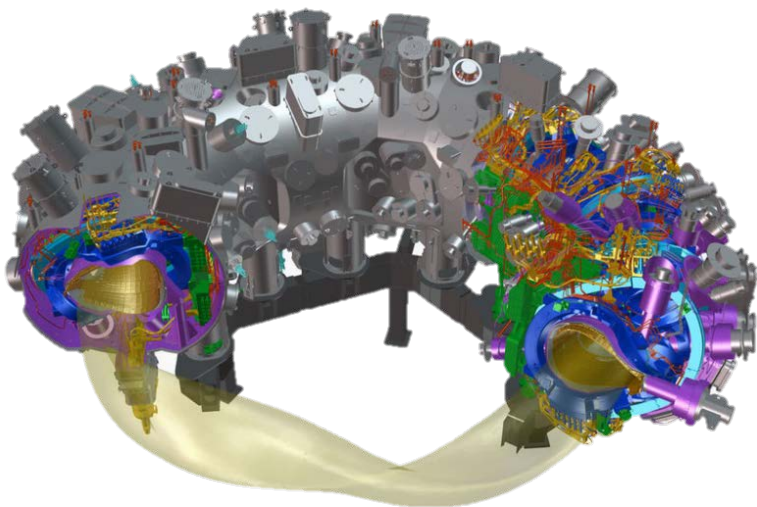
Validated EAST models & quantified stability effects of new passive plate/coil geometry

By FY 2017, experiments during EAST 3<sup>rd</sup> shift will enable US scientists to execute full EAST campaign each time EAST runs

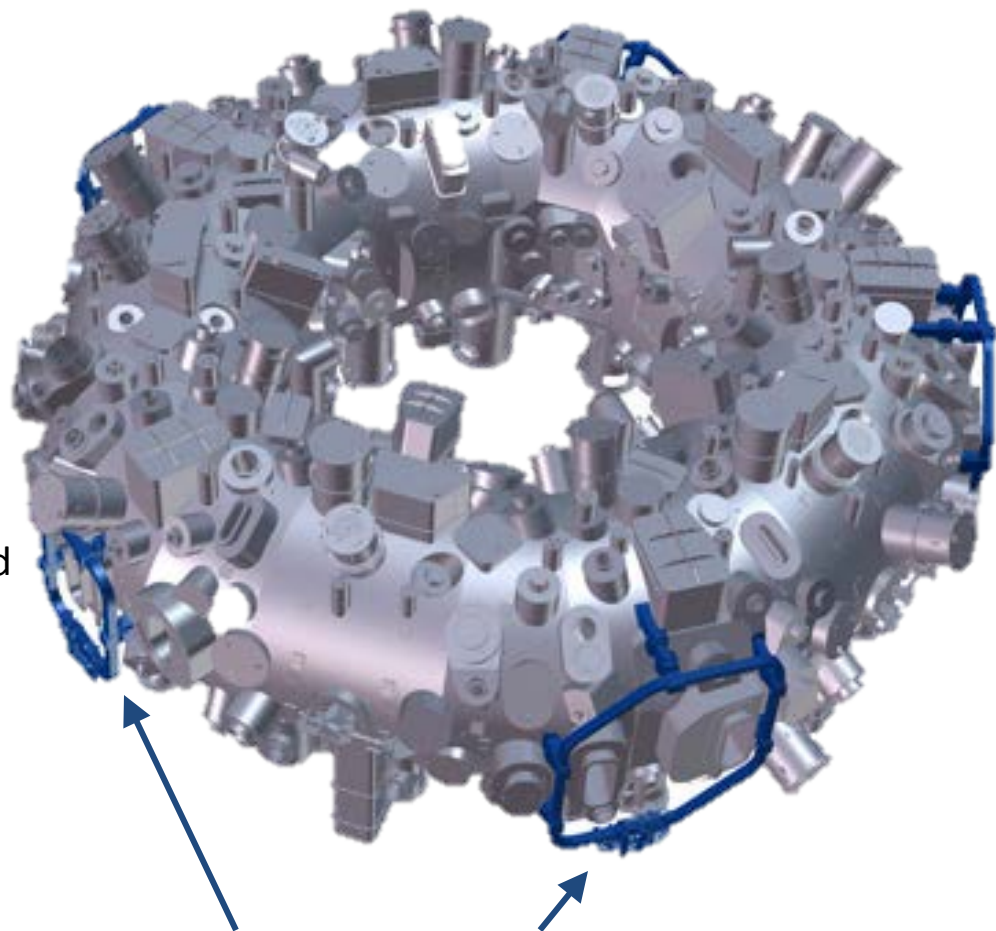
*General Atomics Remote Control Room supports 3<sup>rd</sup> shift operation of EAST by US scientists*



# Long Pulse Highlight: In-kind contribution from U.S. for Wendelstein 7-X



The 2,400-pound **trim coils** have been produced at PPPL for the Wendelstein 7-X stellarator, or W7-X, that the Max Planck Institute for Plasma Physics (IPP) has built in Greifswald, Germany. When the machine begins operating in 2015, the powerful coils will fine-tune the shape of the superhot, charged plasma gas that W7-X will use to study conditions required for fusion. In exchange for the coils, U.S. scientists will be able to lead and carry out experiments on W7-X.



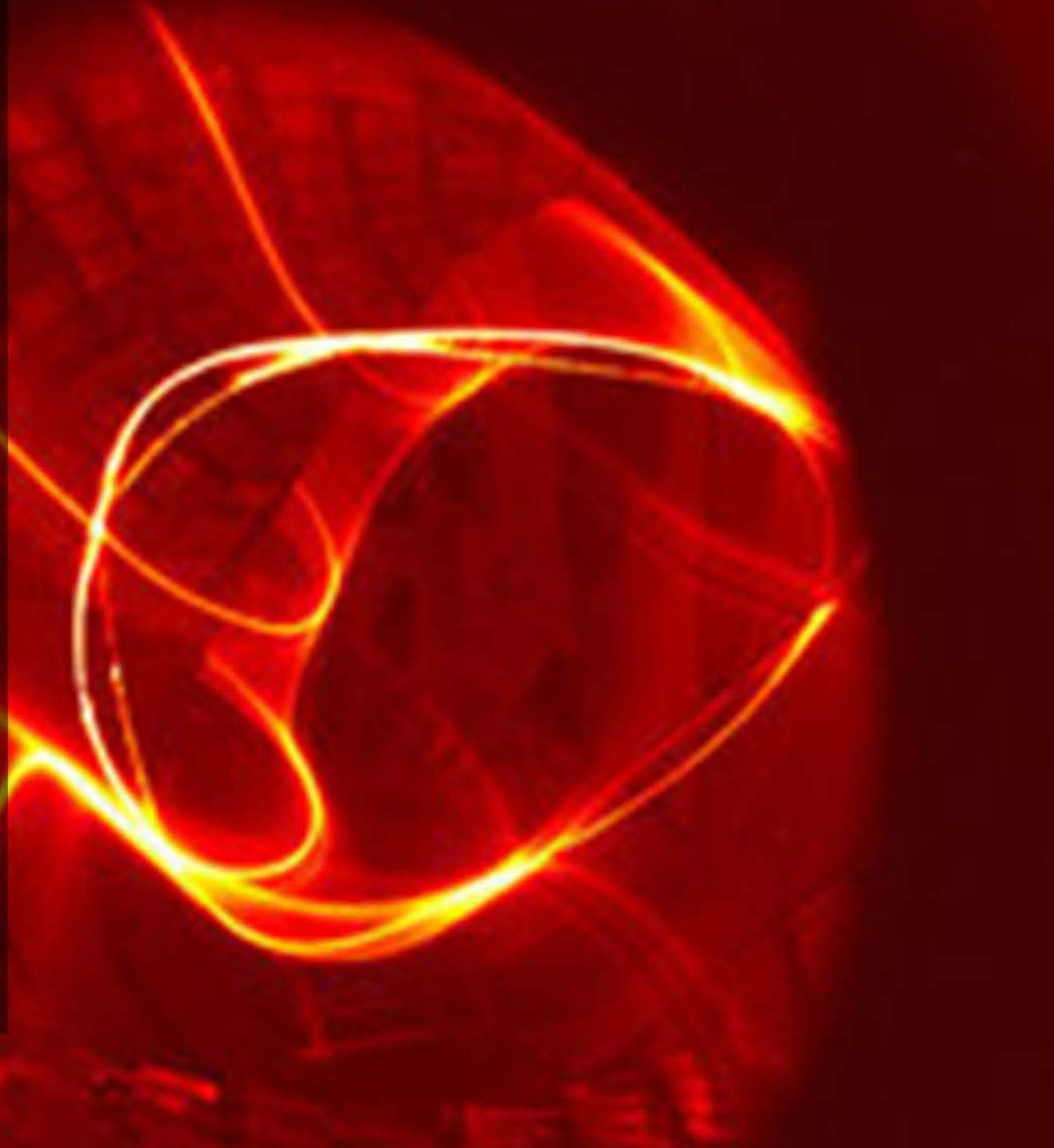
**Trim coils (5 total)**

A recent set of magnet tests on the **W7-X stellarator** has confirmed the accuracy of its three-dimensional magnetic configuration and its technical readiness for plasma operation

After confirming the proper functioning of the coils, the magnetic flux surfaces were measured (see figure), using an electron beam that clearly showed six magnetic islands around the poloidal cross-section, as predicted.

These measurements confirm that the W7-X magnet system has been built and assembled with the accuracy required for good plasma confinement.

The start of plasma operations is expected soon.

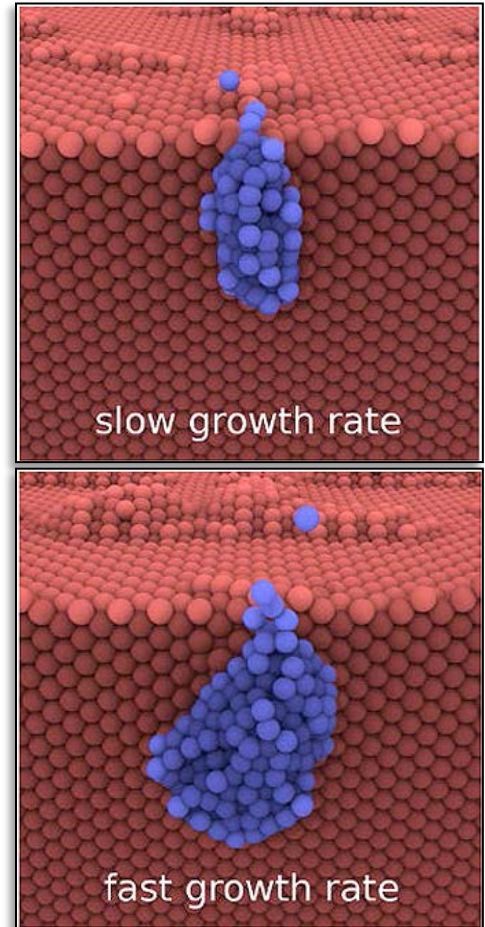


*Since this time: W7-X has  
generated its first plasmas*



# Long Pulse highlight: compute power enables more realistic at helium bubble morphology in tungsten

- ❑ Helium bubbles are detrimental to plasma-facing materials such as tungsten. Understanding how helium bubbles form and grow is important for predicting large-scale material response to the extreme fusion environment. The helium simulations find a qualitatively different growth mode when helium arrival rates approach experimental values.
- ❑ When simulated helium bubbles grow quickly, the surrounding tungsten cannot respond, leading to over-pressurized bubbles that burst violently when they reach the surface. When the bubbles grow more slowly, the tungsten atoms pressed against the bubble's surface can diffuse around it, leading to a smaller bubble when it ultimately bursts.
- ❑ These results highlight the importance of accounting for all relevant kinetic processes and how these kinetic processes enhance the interaction of, in this case, the helium bubble with the local microstructure. The results further have consequences for the nucleation of surface morphology on the tungsten, which is ultimately the source of fuzz, a nanostructured “steel wool”-like structure that causes significant degradation in performance of the material.



**L. Sandoval et al.,  
Phys. Rev. Lett (2015);  
PSI-SciDAC (PI: Brian Wirth)**

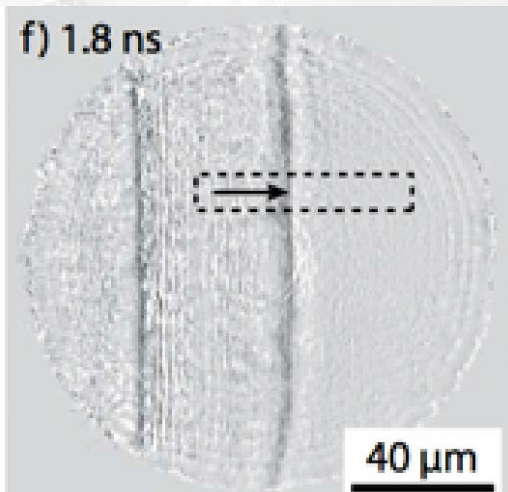
# Discovery Science highlight: The Matter in Extreme Conditions Instrument uses X-ray light sources to advance plasma science

## the Instrument

- World's only facility coupling high power lasers with femtosecond, coherent x-rays
- Pushing the frontiers of warm dense matter and high energy density science contributing to discovery and ICF.

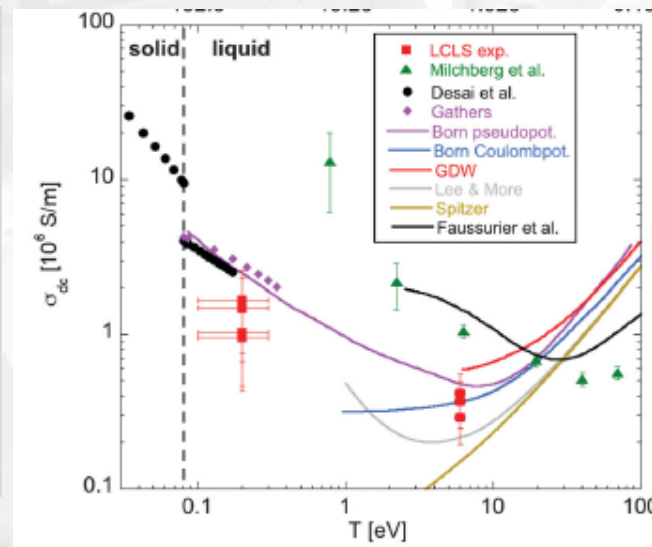
## High Impact Science in 2015

Measuring shock fronts with sub-micron resolution



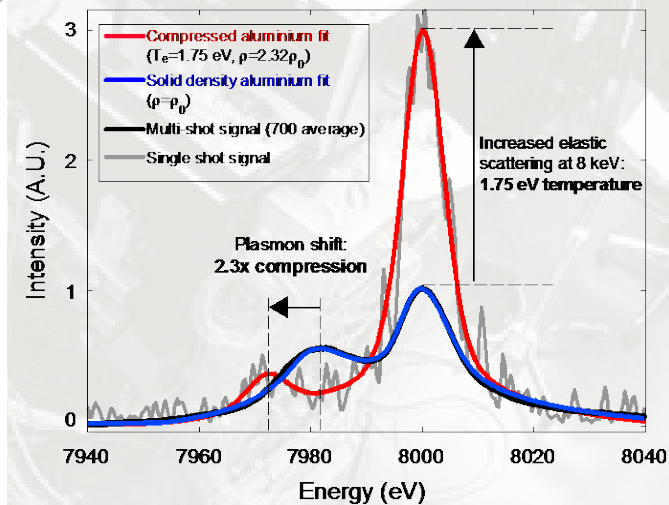
Nature: Scientific Reports 5,  
Article number: 11089 (2015)

Measuring electrical conductivity of warm dense aluminum



Phys. Rev. Lett. 115, 115001 (2015)

Plasmon spectra yield temperature & density with unprecedented precision



Nature Photonics 9,274–279 (2015)

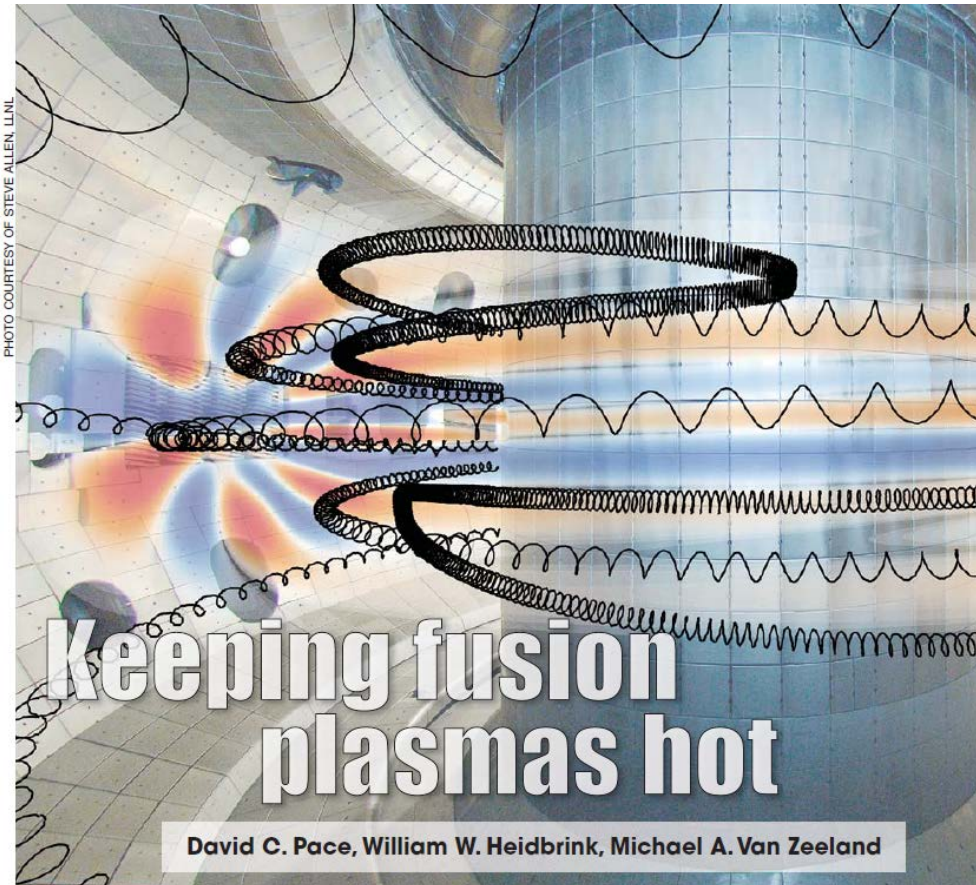




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# Fast particle physics review article on cover of *Physics Today*



Interactions between electromagnetic waves and the most energetic ions in a plasma can perturb the orbits of those ions enough to expel them from the confining magnetic field.



***Strategic planning: identifying  
and updating research  
opportunities***



- The vision described 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.
- The strategic plan responds to several recent Congressional requests, viz., concerning a strategic plan (FY14), a fusion simulation program (FY14), and community workshops (FY15). It also responds to four legacy reporting requirements.
- The plan is forward looking and is expressed at a high level. It acknowledges the role of the recent workshops and future activities in providing information and updates on research opportunities
- This document has been going through concurrence within the Administration and has recently been submitted to Congress



# FES strategic plan: Major themes

- **This document highlights five areas of critical importance for the U.S. fusion energy sciences enterprise over the next decade**
  - ***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.
  - ***Materials science*** as it relates to plasma and fusion sciences will provide the scientific foundations for greatly improved plasma confinement and heat exhaust.
  - 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.
  - 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 will help attract and retain a new generation of plasma/fusion science leaders.
  - ***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**



- **Progress in Fusion Energy Sciences**
  - The Promise and Scientific Character of Fusion Energy Sciences Research
  - Leading Frontiers in Fusion and Plasma Science
- **Community Input**
  - Recent FESAC Assessment of Program Priorities
  - Community Workshops in 2015
  - Previous Community Studies
- **Research Directions**
  - Burning Plasma Science: Foundations
  - Burning Plasma Science: Long Pulse
  - Discovery Plasma Science
- **Funding Scenarios**
  - Modest Growth Scenario
  - Cost-of-Living Budget Growth Scenario
  - Flat Funding Scenario

# Community engagement workshops

- Following the FESAC *Strategic Planning and Priorities Report* (2014), FES sought further community input about scientific challenges and opportunities through a series of technical workshops in 2015 on priority research areas.

Workshop	Date	Location	Chair / Co-Chair
<b>Workshop on Plasma-Materials Interactions</b>	May 4-7	PPPL	Rajesh Maingi (PPPL) / Steve Zinkle (Tennessee)
<b>Workshop on Integrated Simulations for Magnetic Fusion Energy Sciences</b>	June 2-4	Rockville, MD	Paul Bonoli (MIT) / Lois McInnes (ANL)
<b>Workshop on Transients</b>	June 8-12	General Atomics	Charles Greenfield (GA) / Raffi Nazikian (PPPL)
<b>Workshops on Plasma Science Frontiers (two)</b>	August 20-21 & Oct. 22-23	Washington, DC area	Fred Skiff (Iowa) / Jonathan Wurtele (UC Berkeley)





- On Nov 12, FES held an all-day meeting with the chairs and co-chairs for a briefing on the findings and recommendations from the four workshops
- On Nov 19, the chairs publicly reported about the workshops at a special Town Hall evening session at the APS-DPP Meeting
- Status of workshop reports:
  - Two reports are completed and posted online: *Plasma-Materials Interactions*, and *Integrated Simulations for Magnetically Confined Plasmas*
  - Report for *Plasma Transients* will be posted in December
  - Report for *Plasma Science Frontiers* will be available in early CY 2016
- The chairs are reporting on the workshops at this meeting



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# *ITER and the U.S. contributions*





# Recent ITER Council Meeting

- The ITER Council recognized the extensive efforts to improve the project culture. The ITER Organization has conducted an in-depth bottom-up review and analysis of all aspects of manufacturing and assembling the ITER systems, structures and components, through the completion of construction, assembly and commissioning. The Council acknowledged the much improved understanding of the scope, sequencing, risks, and costs of the ITER Project achieved by this systematic and integrated analysis and review, resulting in an overall schedule through First Plasma.
- The ITER Council approved a schedule and milestones covering 2016-17, and decided to conduct an independent review of the overall schedule and associated resources and to consider possible additional measures for expediting the schedule and reducing costs. The Council plans to complete these reviews and reach agreement on the overall schedule through First Plasma by June 2016.
- The Council said it would monitor closely the performance of the ITER Organization and Domestic Agencies in meeting the 2016-17 milestones. The Council approved the re-allocation of the necessary funding, over a period of two years, to enable adherence to these milestones.



# ITER Site as of November 2015



Tokamak Assembly Hall at the left background; tokamak pit in the center foreground





## Central solenoid fabrication facility ramping up at General Atomics in Poway, California

- 5 of 11 tooling stations in place
- 2 of 11 tooling stations in operation
- Mock-up winding completed
- First production module winding started

## Completed Shipments of Toroidal Field (TF) Conductor to EU:

US TF 800 m sample (non-superconducting) conductor – *Delivered June 2014*

US TF 100 m active (superconducting) conductor – *Delivered July 2014*

US TF 800 m production (superconducting) conductor – *Delivered January 2015*

## Upcoming Shipments:

US TF 100 m active conductor – *Packaged and ready for shipment*

US TF 800 m production conductor – *September/October 2015*



Close-up view of the Oxford 100 m active conductor before packaging.

Photo US ITER

Two high voltage substation transformers (lots 3 and 4) loaded for delivery to the ITER site.

Photo: HHI

### Upcoming FY15 deliveries

- HV substation transformers (lots 1,3,4): May 2015
- 22 kV switchgear (lots 1,2): May 2015
- 6.6 kV switchgear (lot 1): June 2015



A 61,000 gallon drain tank (below) is part of the first shipment of two tanks; the tanks were delivered to Fos-sur-Mer, France on April 26, 2015.

Photo: US ITER





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# *Budget*





# FY 2016 Energy and Water Development Appropriations Act (Dec 18)

<b>Fusion energy sciences:</b>			
<b>Research.....</b>	<b>317,500</b>	<b>270,000</b>	<b>323,000</b>
<b>Construction:</b>			
<b>14-SC-80 ITER.....</b>	<b>150,000</b>	<b>150,000</b>	<b>115,000</b>
<b>Subtotal, Fusion energy sciences.....</b>	<b>467,500</b>	<b>420,000</b>	<b>438,000</b>

- The agreement continues the new budget structure for fusion energy sciences and provides funding accordingly.
- The agreement provides \$214,755,000 for burning plasma science foundations; \$41,021,000 for burning plasma science long pulse; and \$67,224,000 for discovery plasma science, including \$2,750,000 for high energy density science and discovery plasma science opportunities at NDCX-II in support of the mission of Fusion Energy Sciences.
- The agreement provides not less than \$71,000,000 for the National Spherical Torus Experiment, not less than \$80,000,000 for DIII-D, and not less than \$18,000,000 for Alcator C-Mod.
- The agreement includes funding for the in-kind contributions and related support activities of ITER. In addition to the reporting language included in the bill, the Department shall provide to the Committees on Appropriations of both Houses of Congress not later than February 15, 2016, and again on August 15, 2016, a report on the status of the ITER project and the implementation of the Director General's Action Plan, including new budget projections, project schedule, cost overruns, delays, organizational structure changes, manufacturing deliveries, assembly, and installation.



# FY 2016 Energy and Water Development Appropriations Act (Dec 18): concerning ITER

- The agreement provides \$5,350,200,000 for the Office of Science. The agreement includes legislative language restricting cash contributions to the ITER Organization and directing a report from the Secretary of Energy on U.S. participation in the ITER project.
- The agreement includes funding for the in-kind contributions and related support activities of ITER. In addition to the reporting language included in the bill, the Department shall provide to the Committees on Appropriations of both Houses of Congress not later than **February 15, 2016**, and again on **August 15, 2016**, a report on the status of the ITER project and the implementation of the Director General's Action Plan, including new budget projections, project schedule, cost overruns, delays, organizational structure changes, manufacturing deliveries, assembly, and installation.
- *Provided further*, That **not later than May 2, 2016**, the Secretary of Energy shall submit to the Committees on Appropriations of both Houses of Congress a report recommending either that the United States remain a partner in the ITER project after October 2017 or terminate participation, which shall include, as applicable, an estimate of either the full cost, by fiscal year, of all future Federal funding requirements for construction, operation, and maintenance of ITER or the cost of termination. [from TEXT OF HOUSE AMENDMENT #1 TO THE SENATE AMENDMENT TO H.R. 2029, MILITARY CONSTRUCTION AND VETERANS AFFAIRS AND RELATED AGENCIES APPROPRIATIONS ACT, 2016]



# ***FESAC business follow-up***



## Status

- COV had 15 members and was chaired by Prof. A. Bhattacharjee
- On-site meeting was held December 2-4, 2014 at DOE-GTN
- Final report was received May 4, 2015
- FES written response was submitted to Office of Science on Dec 10

## Scope of the COV review (FY 2010-2013)

- The panel should consider and provide evaluation of:
  - **Process**: The efficiency and quality of the processes used by FES to solicit, review, recommend, monitor, and document awards and declinations for universities, national laboratories, and industry
  - **Quality and Standing**: The breadth, depth, and quality of the resulting program portfolio, and providing an evaluation of the program's national and international standing
  - **Project Management**: FES's management of its portfolio of line item construction and Major Items of Equipment projects, including the U.S. Contributions to ITER project
- The panel should also comment on FES's progress in addressing action items from the previous COV review

## Some examples of COV recommendations and FES responses

Recommendation	Response
Revise VLT structure to move leadership of the program to outside of FES.	FES will appoint a new VLT director, outside of FES,.
Offer regular, targeted FOAs for research on DIII-D and future major tokamak facilities as well as the EPR program	FES issued a new DIII-D collaborative research FOA on July 22. An FOA for the small-scale AT, ST, and stellarator s (formerly EPR) was issued on June 1.
Encourage more site visits as travel budgets allow	If travel budgets allow, FES will increase the number of such visits.
Encourage the use of open-source codes and open proxy applications	FES continues to encourage this
Restore the annual Budget Planning Meetings (or variant thereof).	FES is considering options for a meeting that will provide budgetary information needed by FES and allow sharing of program plans across the U.S. community.

A FESAC subcommittee prepared a report, which was approved by FESAC in July. The final edited and formatted version of the report (Sept) is available online.



**Basic Materials Science:** FES researchers have created dusty plasmas to generate nucleation ‘factories’ for the production of nanoparticles and nanocrystals developed for efficient solar cells and fuel cells. DOE Basic Energy Sciences Energy Frontier Research Centers. *Photo courtesy of Los Alamos National Lab with the University of Minnesota.*



**Medical/Health:** Atmospheric and non-neutral plasma physics as well as FES technology spinoffs have enabled a wide range of new medical procedures ranging from plasma surgery to non-invasive imaging to cancer therapy. Plasma tissue welding. *Photo courtesy of Ion Med Ltd.*



**National Security:** The Electromagnetic Aircraft Launch System, a spinoff from FES development of precision control of sequencing mag - nets, is now replacing the Navy’s steam catapults on air - craft carriers. USS Gerald Ford was the first carrier to use the Electromagnetic Aircraft Launch System. Electromagnetic Aircraft Launch Systems. *Photo courtesy of General Atomics.*



**Transportation:** Safer, more efficient jet engines have been created by spray coating their turbine blades with a ceramic powder that was injected into a flowing plasma jet. Plasma spray-coating improves jet engine turbine blade efficiency and safety. *Photo courtesy of JETPOWER.*



**Waste Treatment:** FES researchers have developed commercial plasma arc heating technologies to transform hazardous waste into vitrified products—a stable, solid form suitable for safe long-term disposal. Plasma arc vitrification. *Photo courtesy of Pacific Northwest National Laboratory.*





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# *People*



# Community leadership changes



**Smith**



**Cohen**



**Hill**



**Whyte**

- **PPPL:**
  - A.J. Stewart Smith: will retire as Princeton University VP for PPPL (Feb 2016)
  - Adam Cohen: Deputy Director for Operations → DOE Deputy Under Secretary for Science and Energy
- **General Atomics:**
  - Dave Hill: new Director of DIII-D National Fusion Program
- **MIT:**
  - Dennis Whyte: new Director of the Plasma Science Fusion Center





# More community leadership changes



**Meyerhofer**



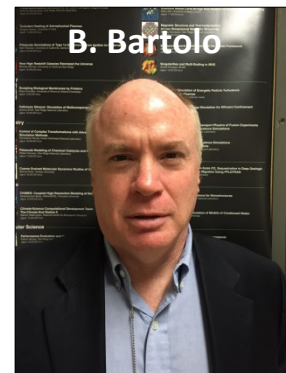
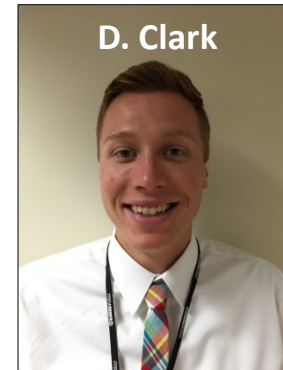
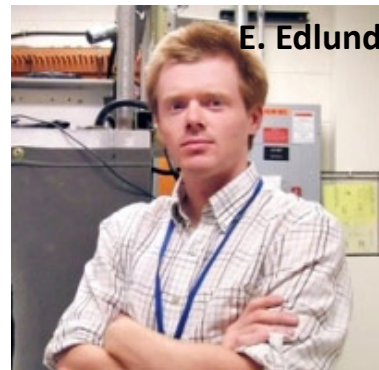
**Davidson**



**Mael**

- **LANL:**
  - David Meyerhofer: new head of Physics Division at LANL
- ***Physics of Plasmas* journal:**
  - Ron Davidson: retired as Editor after 25 years
  - Mike Mael: will replace him as the new Editor

- **Program manager retirement:**
  - Steve Eckstrand (Dec 2014): 39 years at FES (NSTX, International, TFTR, etc.)
- **New program managers:**
  - Daniel Clark: fusion materials
  - Josh King: NSTX-U
- **Short-term:**
  - Bob Bartolo (AAAS Fellow)
  - Eric Edlund (detailee from PPPL)
- **Summer interns:**
  - Cynthia Li (Columbia)
  - Darius Stanton (Duke)
- **Recent job postings:**
  - GPS/HEDLP program manager
  - MFE program manager





# Recent *Nuclear Fusion* Journal Prizes



**2014: Phil Snyder (GA)**



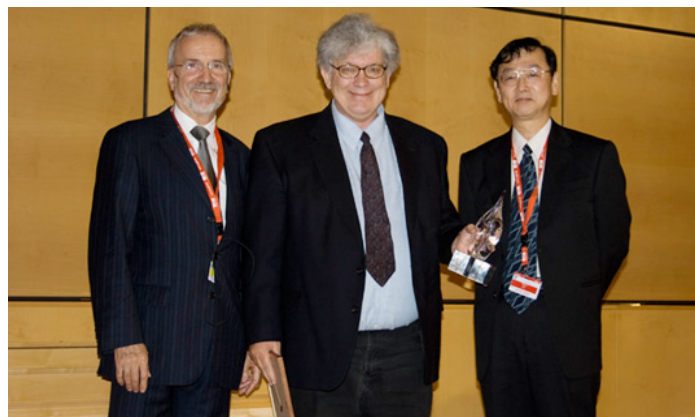
**2013: Dennis Whyte (MIT)**



**2010: John Rice  
(MIT)**



**2009: Steve Sabbagh  
(Columbia)**



**2008: Todd Evans (GA)**



**2006: Tim Luce  
(GA)**



## IAEA News release (November 18, 2015):

- Robert J. Goldston, professor of astrophysics at Princeton University and a former director of the Princeton Plasma Physics Laboratory, has won the IAEA's 2015 [\*Nuclear Fusion Journal\*](#) Prize for his development of a theoretical physics model that will ultimately enable engineers to design the wall for a vessel containing fuel used in nuclear fusion to generate electricity.
- The discovery, presented in the paper '*Heuristic drift-based model of the power scrape-off width in low-gas-puff H-mode tokamaks*,' fills a gap in the development of the tokamak, one of several types of magnetic confinement devices used in fusion research.



## Hannes Alfven Prize of the European Physical Society awarded to Prof. Nathaniel Fisch (PPPL)

- Fisch was cited *“for his contributions to the understanding of plasma wave-particle interactions and their applications to efficiently driving currents with radio-frequency waves.”*
- He received the award at the 2015 EPS Division of Plasma Physics Meeting (June, Lisbon)
- NOTE: This prize was also awarded to U.S. scientists in 2013, 2012, 2011, 2010, 2008, and 2002 (since its inception in 2000).



# 2014 E. O. Lawrence Award

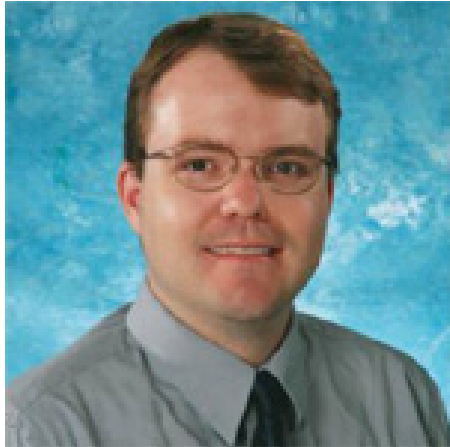


## E. O. Lawrence Award of the U.S. Department of Energy awarded to Prof. Brian Wirth (U. Tennessee-Knoxville)

- Wirth was cited *“for transformational advances in computational multiscale modeling of radiation effects in materials, and for their impact to fission and fusion energy technologies.*
- He received the award at a ceremony at the US Dept of Energy on July 23.



# 2015 FES Early Career Awards



**Dr. Oliver Schmitz** (Wisconsin)  
*Plasma Material Interaction  
with Three-Dimensional Plasma  
Boundaries*



**Dr. Chad Parish** (ORNL)  
*Damage Mechanism Interactions at the  
Plasma-Materials Interface*



**Dr. Lorenzo Mangolini** (UC Riverside)  
*On the Interaction between Non-  
Thermal Plasmas and Small Metallic  
Particles*



**Dr. Luis Aparicio-Delgado** (PPPL)  
*Active Impurity Control for  
Maximum Fusion Performance*



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***Thank you***