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

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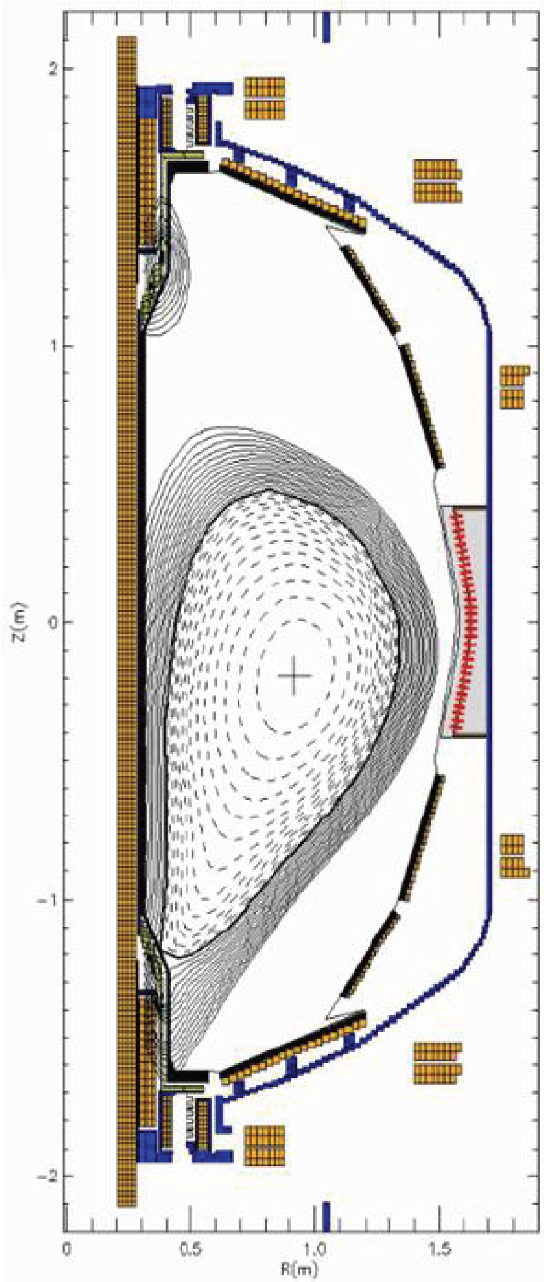
U.S. DEPARTMENT OF ENERGY
Office of Science

Fusion Power Associates Annual Meeting
December 17, 2015

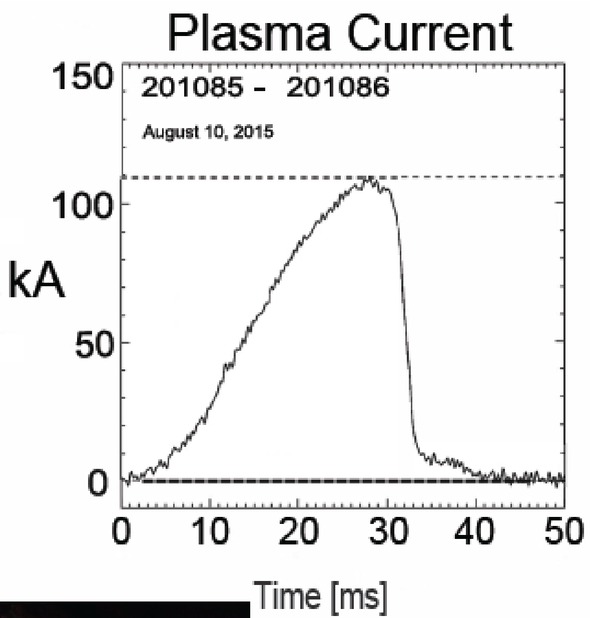
Developments in capabilities

Highlight: NSTX Upgrade project completed



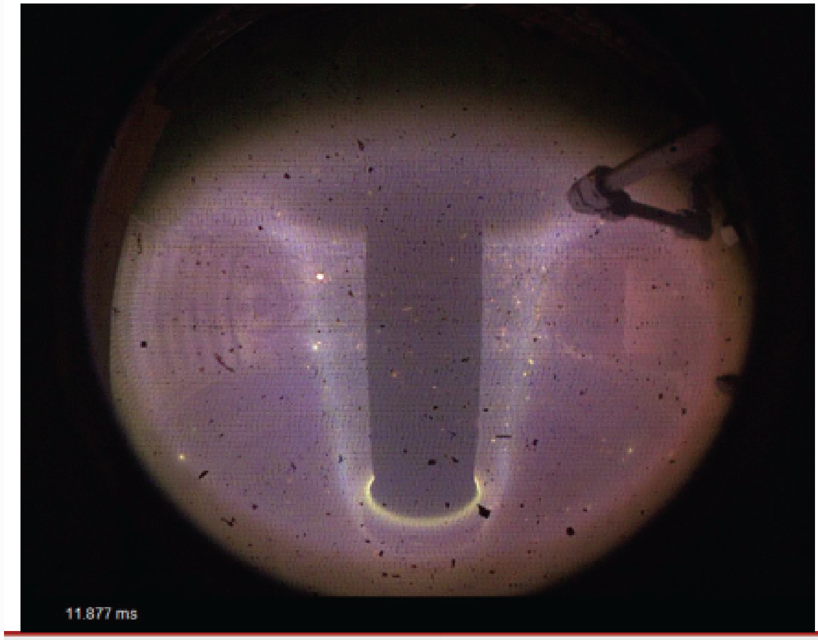
8/10/2015

!! 110 kA Plasma !!



EFIT Reconstruction of the Plasma Shape Available on Very 1st Shot!

[S. Sabbagh Columbia University]



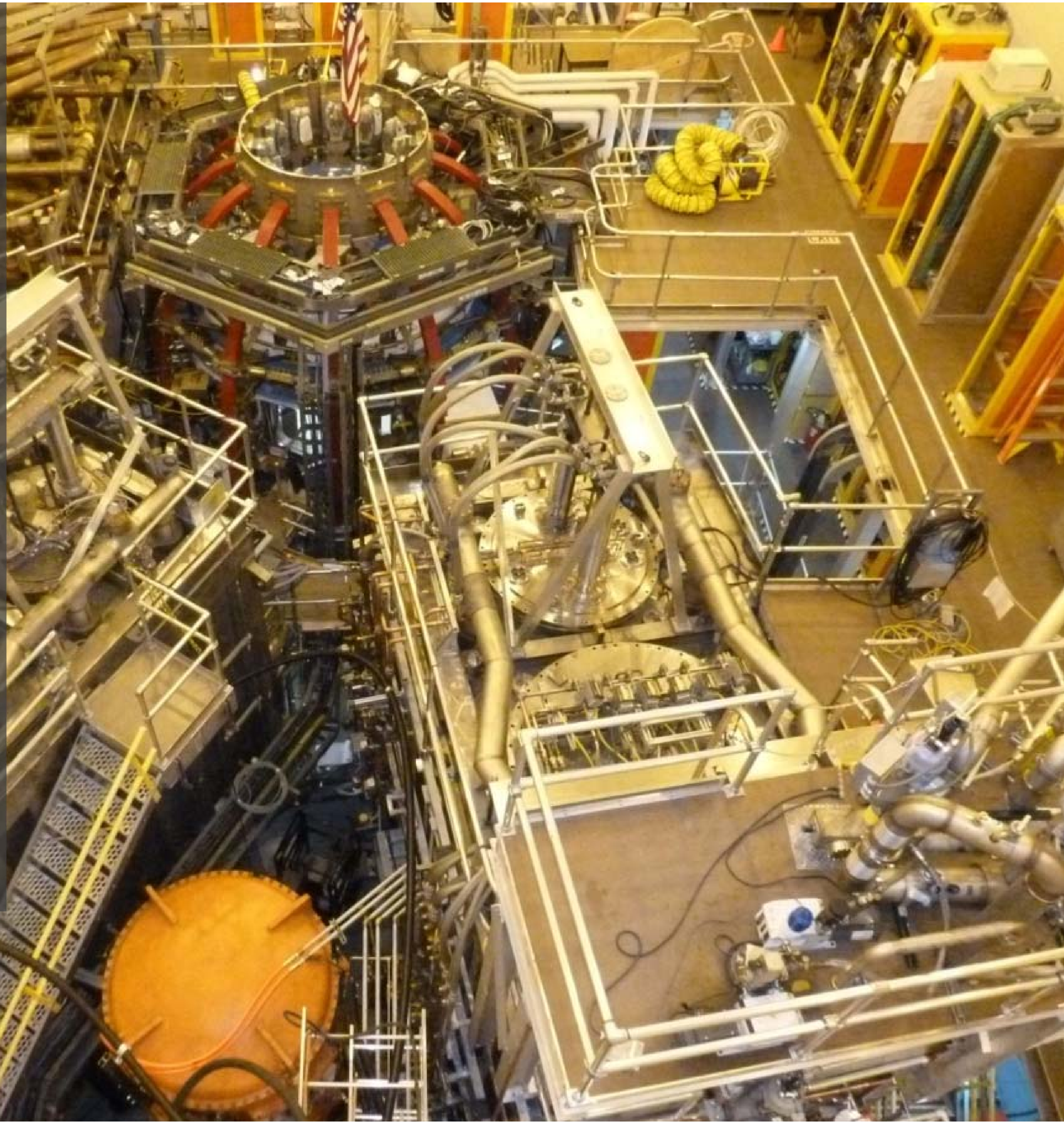
Fast Color Camera Image

[F. Scotti, LLNL]

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



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Highlight: Vertical control experiments via remote operation of EAST 3rd 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:

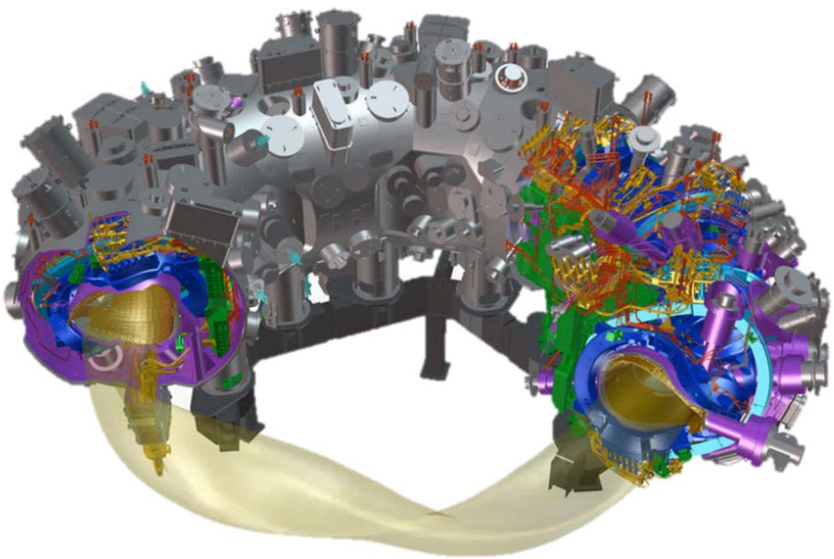
- Dedicated network and cyberspace for between-shot transfer of data to GA
- DIII-D provides EAST data repository for all U.S. collaborators
- Data mirror at GA serves all US collaborators

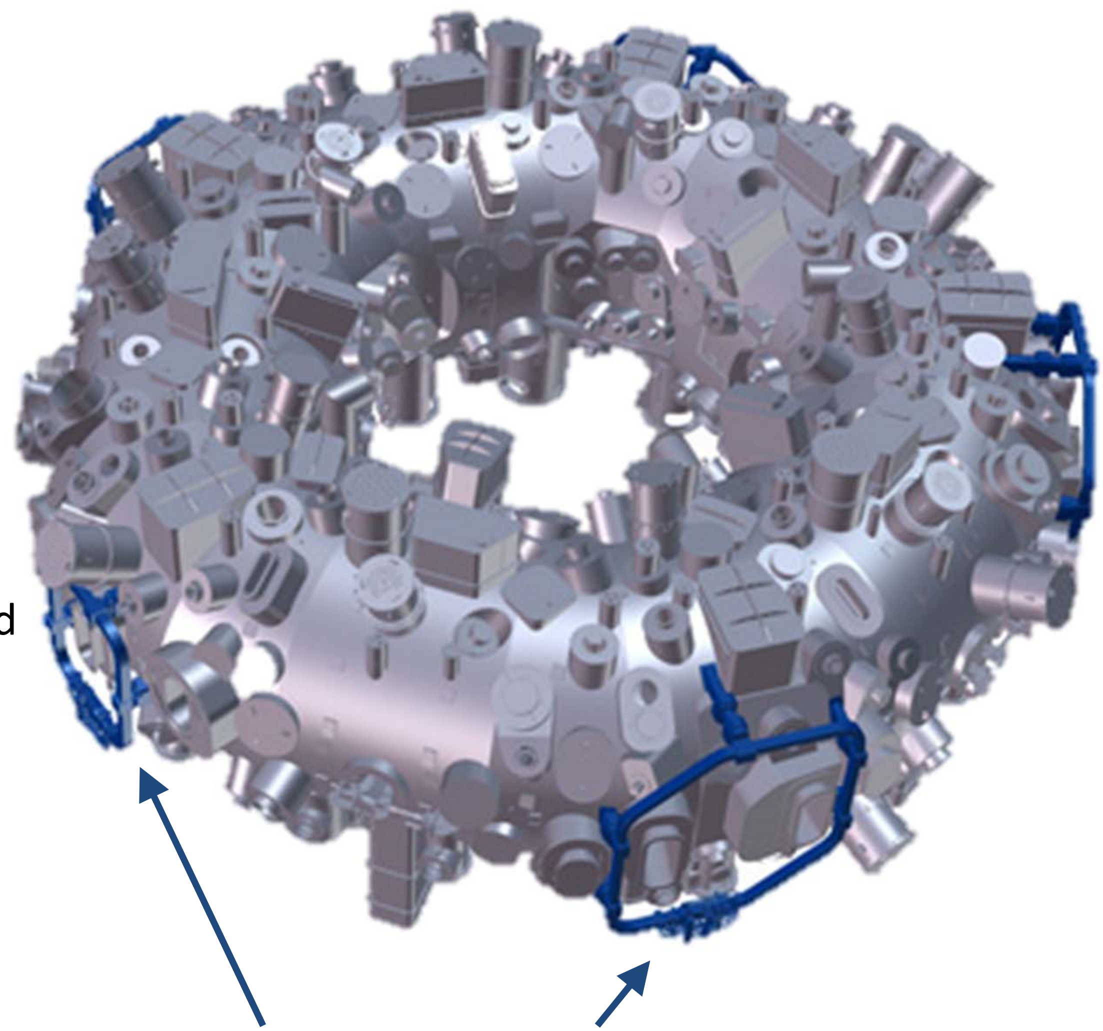
First full 3rd shift remote operation July 22-23:

- Two 3rd 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 3rd shift will enable US scientists to execute full EAST campaign each time EAST runs

General Atomics Remote Control Room supports 3rd shift operation of EAST by US scientists

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





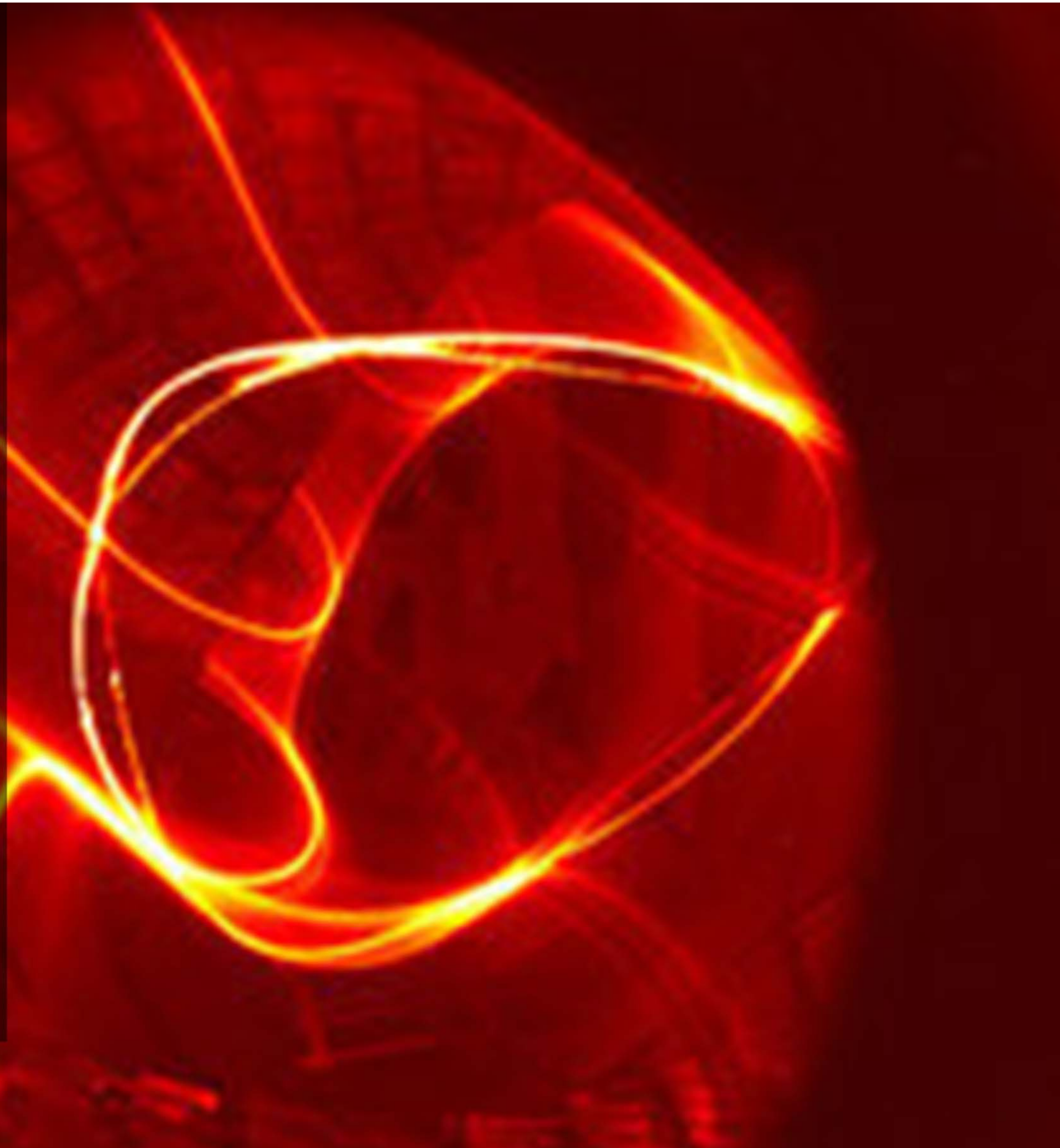
The 2,400-pound **trim coils** have been produced at PPPL for the Wendelstein 7-X stellarator, or W7-X, that the Max Planck Institute for Plasma Physics (IPP) has built in Greifswald, Germany. When the machine begins operating in 2015, he powerful coils will fine-tune the shape of the superhot, charged 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.

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.



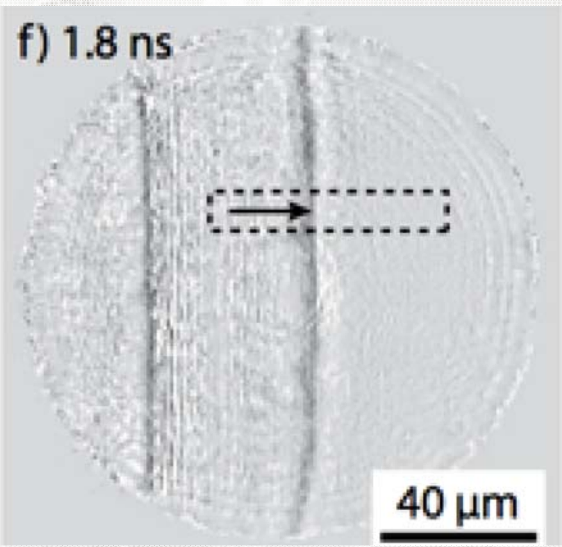
Since this time: W7-X has generated its first plasmas

the Instrument

- Worlds 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.

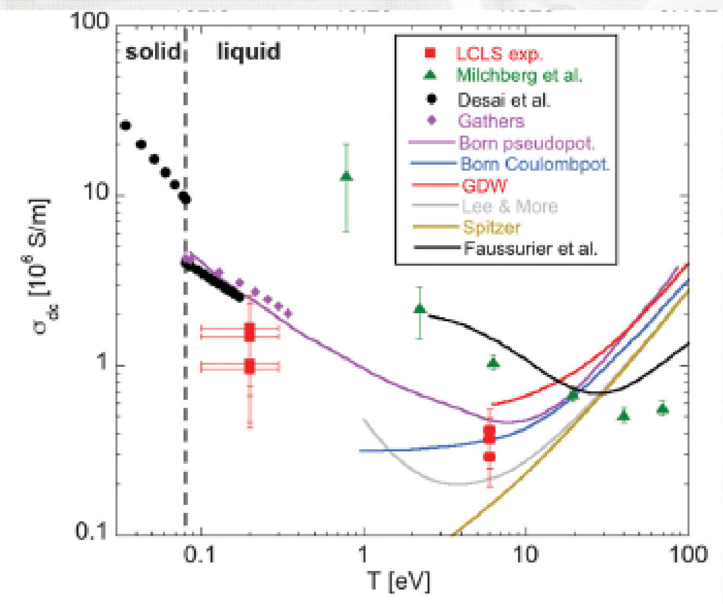
High Impact Science in 2015

Measuring shock fronts with sub-micron resolution



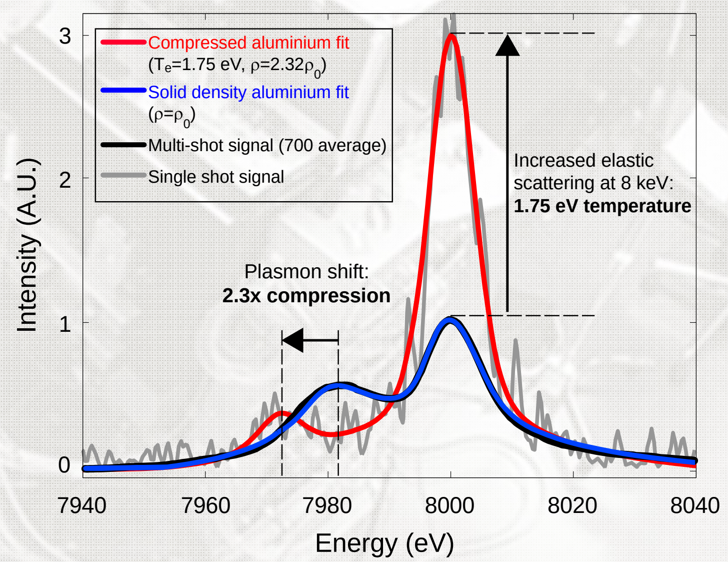
Nature: Scientific Reports 5, Article number: 11089 (2015)

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)

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

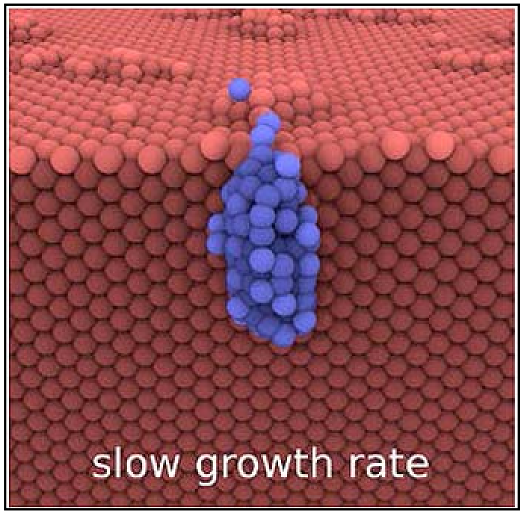
- Simulations of ion transport and confinement in high-temperature tokamak plasmas are now fairly standard, but the simultaneous simulation of the transport of electrons has been very difficult due to their factor-of-2000 mass difference with ions.
- Recently, gyrokinetic simulations of both ion and 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.

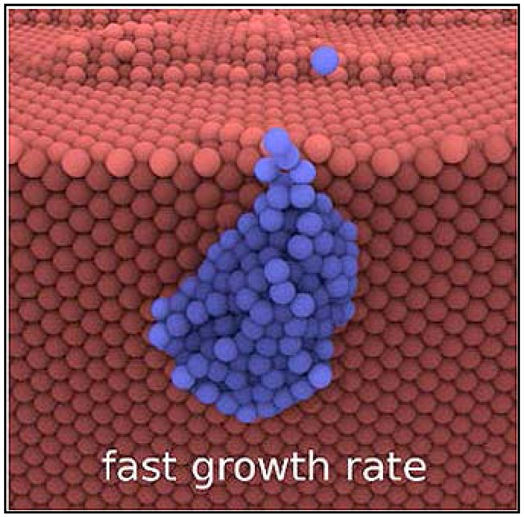
- The results demonstrate that such multi-scale simulations are required to match with the experimentally measured ion and electron thermal fluxes and profiles and thus resolve a longstanding mystery of electron heat conduction in tokamaks.

N.T. Howard et al., to be published in *Nuclear Fusion*

Compute power enables most realistic look yet at helium bubble morphology in tungsten

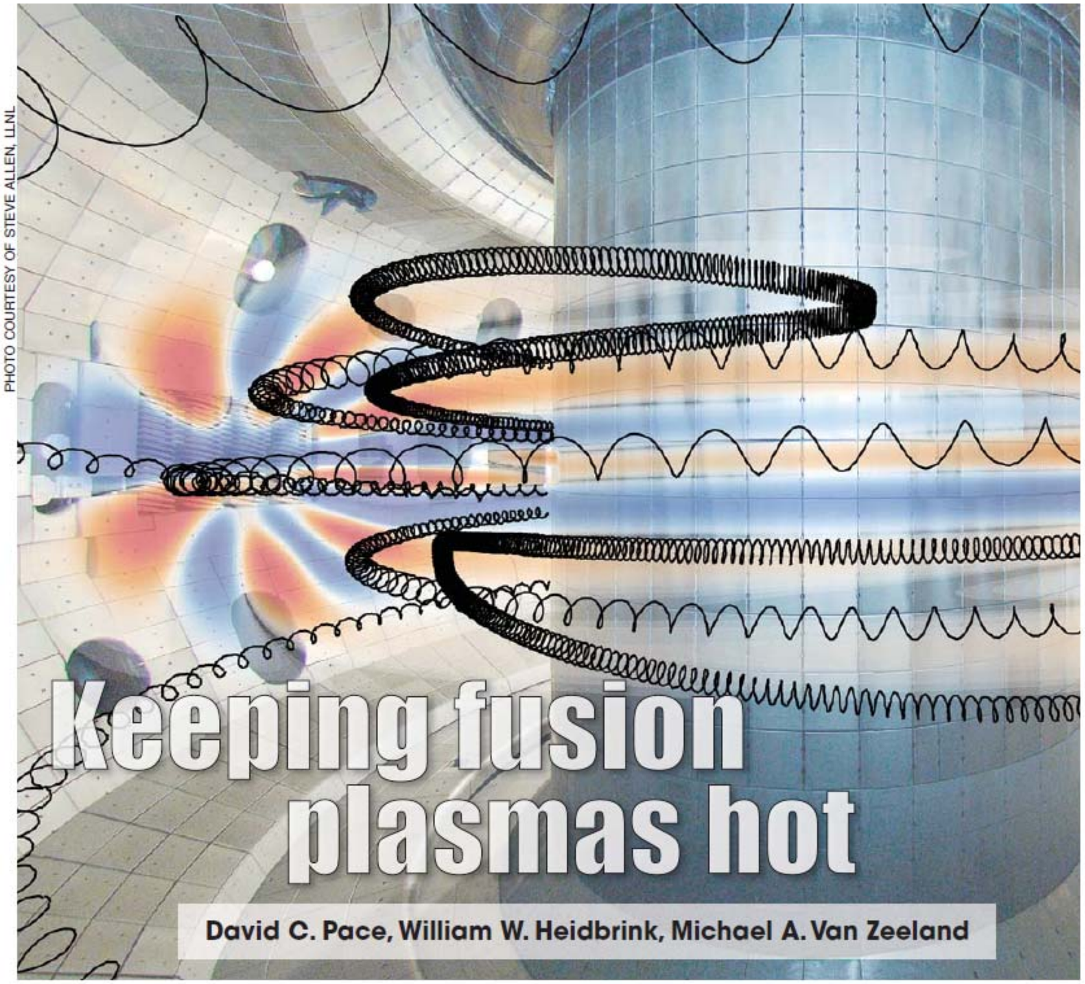
- Helium bubbles are detrimental to plasma-facing materials such as tungsten. Understanding how helium bubbles form and grow is important for predicting large-scale material response to the extreme fusion environment. The helium simulations find a qualitatively different growth mode when helium arrival 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)

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

FES strategic plan

- 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**

FES strategic plan: Contents

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


Community engagement workshops: Status

- 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 will report about the workshops at the next FESAC meeting (January 13-14, 2016)

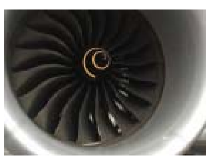
Recent FESAC report on non-fusion-energy applications

A FESAC subcommittee prepared a report, which was approved by FESAC in July. The final edited and formatted version of the report is available on the FES website.

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.*

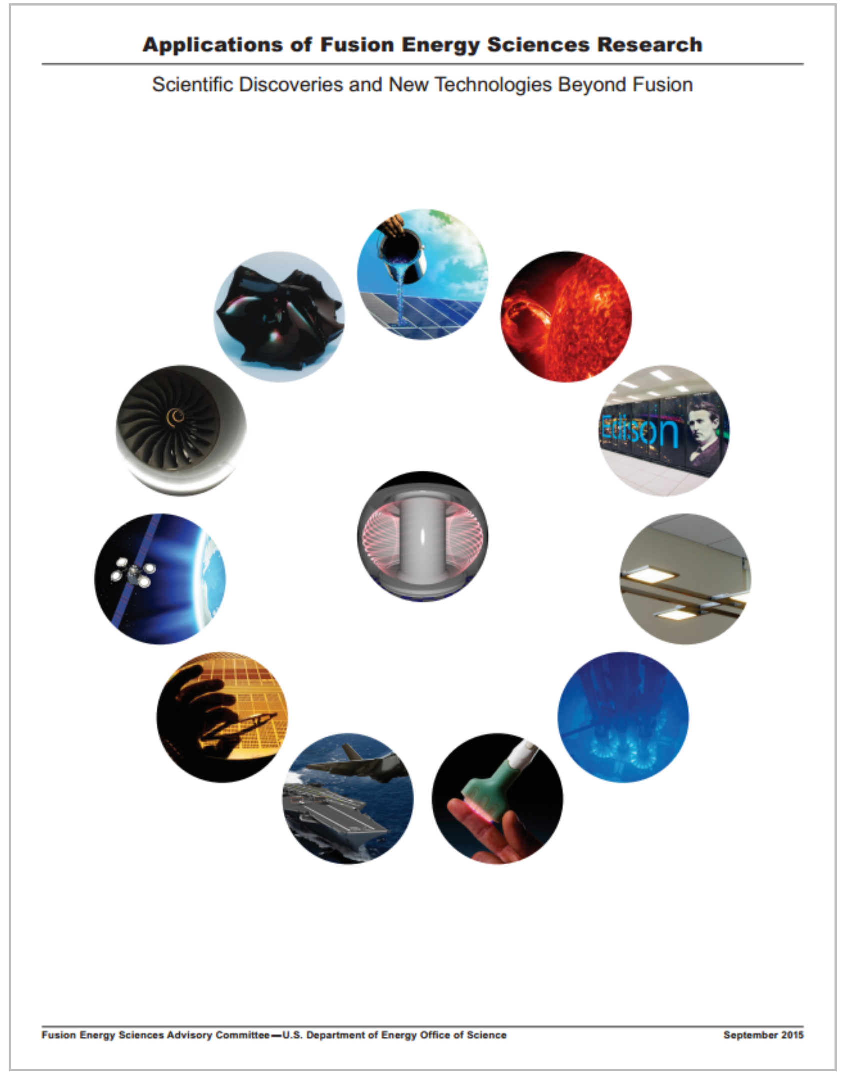
Medical/Health: Atmospheric and non-neutral plasma physics as well as FES technology spinoffs have enabled a wide range of new medical procedures ranging from plasma surgery to non-evasive imaging to cancer therapy. Plasma tissue welding. *Photo courtesy of Ion Med Ltd.*

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.*



Applications of Fusion Energy Sciences Research

Scientific Discoveries and New Technologies Beyond Fusion

Fusion Energy Sciences Advisory Committee—U.S. Department of Energy Office of Science September 2015

Regarding the next FESAC meeting

- **Next meeting is being planned for January 13-14, 2016**
  - Location details in the DC area will be announced soon

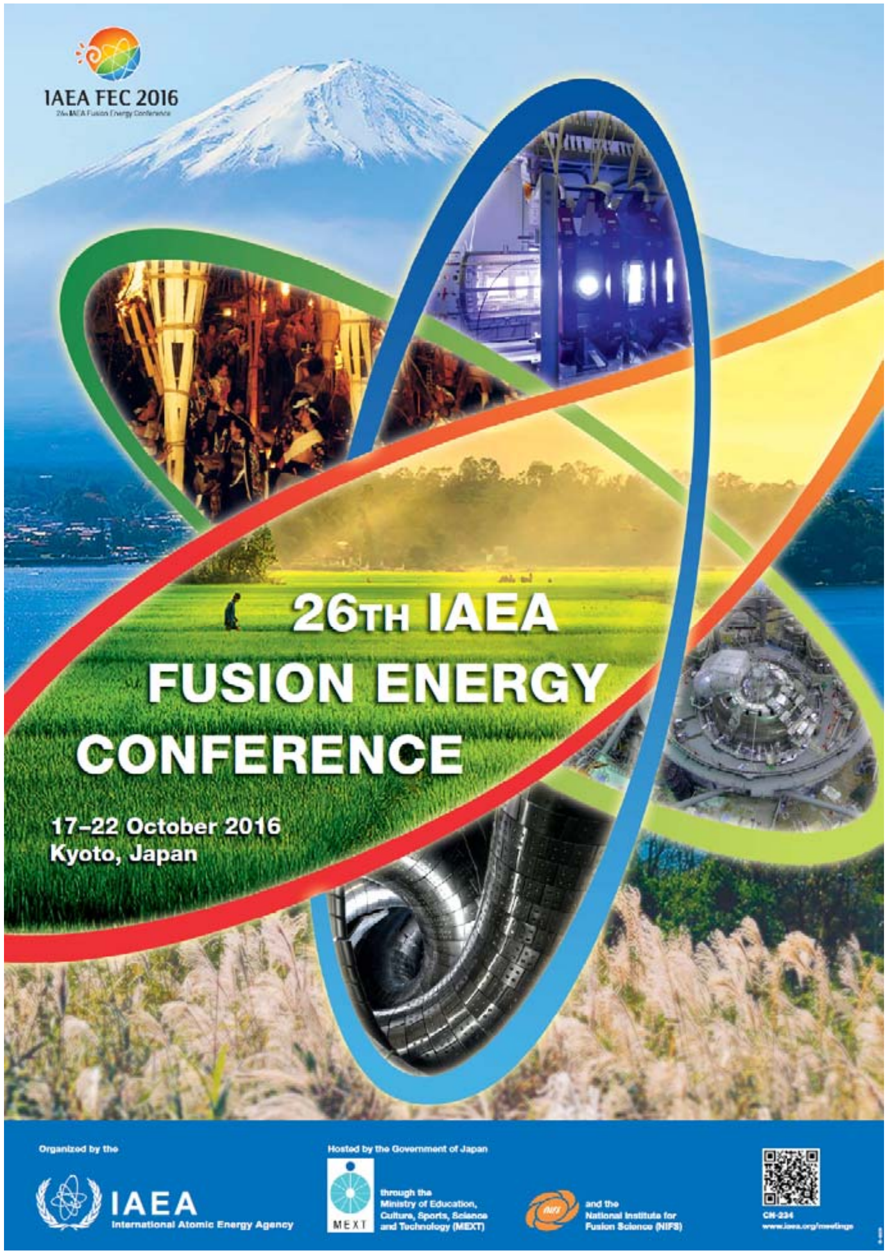
- **Some of the agenda items:**
  - Talk by Dr. Franklin Orr (Under Secretary of Science and Energy)
  - Talk by Dr. Bernard Bigot (Director-General of the ITER Organization)
  - Reports from the 2015 community engagement workshops, and discussion by FESAC
  - No new charge is anticipated at this meeting

2016 IAEA Fusion Energy Conference

- **26th IAEA Fusion Energy Conference (FES 2016)**
  - To be held in Kyoto, Japan, 17-22 October 2016

- **US paper selection**
  - Mark Foster (FES) is the lead
  - Short abstracts and two-page extended synopses (including ITPA and ITER-related submissions) must be submitted to U.S. Paper Selection Committee by **January 18, 2016**
  - US Paper Selection Committee meeting will meet the first week in February

- **IAEA FEC International Programme Committee**
  - Will meet in Vienna in April
  - US to be represented by five persons: Buttery, Gates, Izzo, Spong, and Foster



ITER and the U.S. contributions

Recent ITER Council Meeting

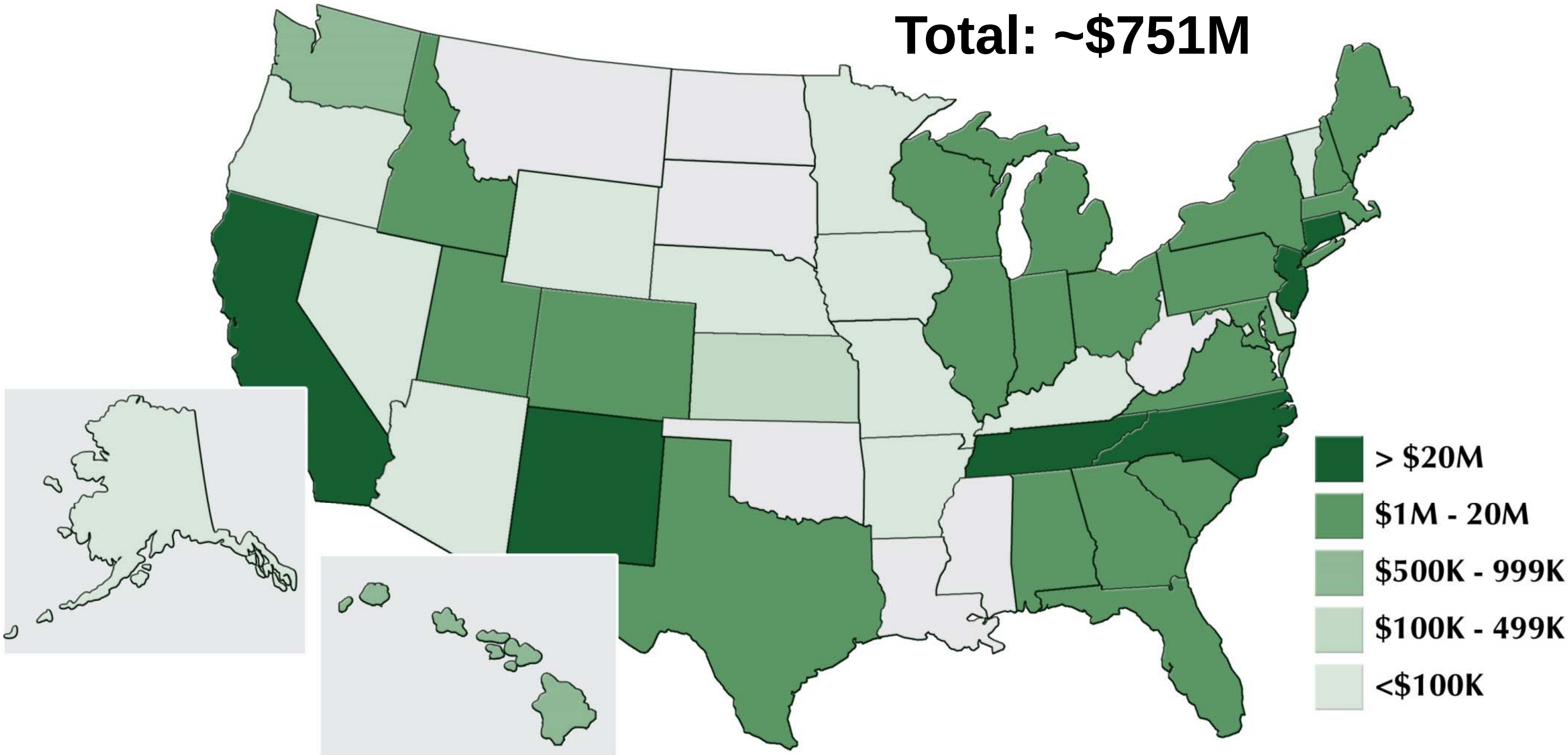
- The ITER Council recognized the extensive efforts to improve the project culture. The ITER Organization has conducted an in-depth bottom-up review and analysis of all aspects of manufacturing and assembling the ITER systems, structures and components, through the completion of construction, assembly 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.

Over 80% of awards and obligations is being spent in the U.S.

As of June 2015, over $751M has been awarded to U.S. industry and universities and obligated to DOE national laboratories in 43 states plus the District of Columbia.



This data does not include contracts awarded to U.S. Industry by the EU (>$55M) and by Korea (>$23M).

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

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

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:

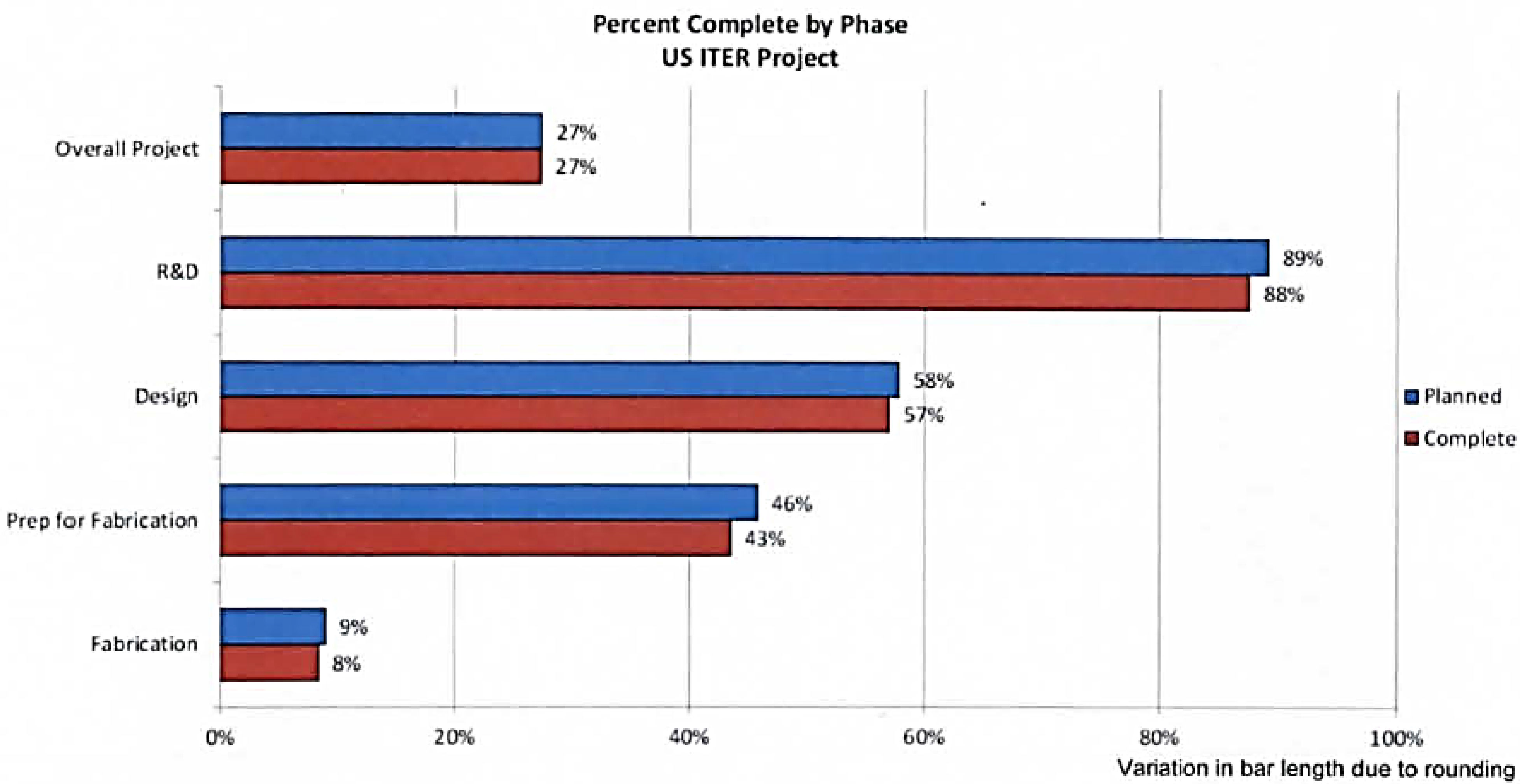
US TF 100 m active conductor – *Packaged and ready for shipment*

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

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

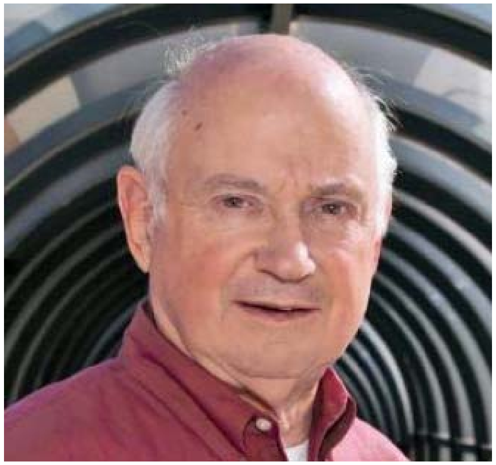
Photo US ITER

UT ITER Project execution summary



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

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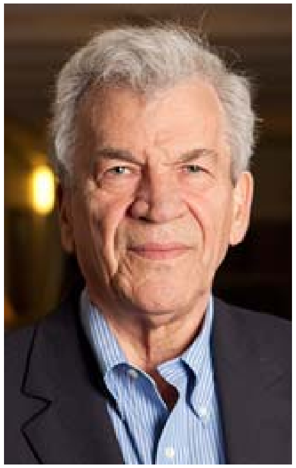
More community leadership changes

Meyerhoff



Davidson

Mauel

- **LANL:**
  - David Meyerhoffer: new head of Physics Division at LANL

- ***Physics of Plasmas* journal:**
  - Ron Davidson: retired as Editor after 25 years
  - Mike Mauel: will replace him as the new Editor

DOE leadership changes

Sherwood-Randall

Orr

Cohen

Murray

- **Deputy Secretary:**
  - Elizabeth Sherwood-Randall (began Oct 6, 2014)
- **Under Secretary for Science and Energy:**
  - Franklin “Lynn” Orr (began Dec 17, 2014)
- **Deputy Under Secretary for Science and Energy:**
  - Adam Cohen (began Nov 2, 2015)
- **New presidential nominee for Director of the Office of Science:**
  - Cherry Murray (Harvard University)

Most recent *Nuclear Fusion Journal* Prize

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.

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Thank you