Fusion Energy Sciences Program Update

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Office of Science
Fusion Energy Sciences

U.S. DEPARTMENT OF ENERGY
Office of Science

April 25, 2019
NASEM Board on Physics & Astronomy Meeting

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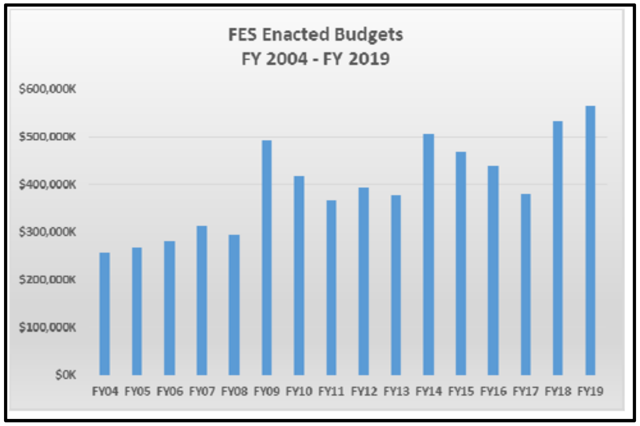
1. Budget Updates

Robust FY 2018 and FY 2019 enacted budgets

Enacted FES appropriations for FY 2018 ($532M) and FY 2019 ($564M) enable accelerated progress throughout the program:

- **ITER**: Continued progress on U.S. Contribution to ITER project with emphasis on highest-priority First Plasma activities
- **DIII-D**: Initiated over $20M of enhancements and infrastructure improvements for the DIII-D user facility to maintain and advance its world-leading research capabilities
- **NTSX-U**: Accelerate the Recovery efforts
- **LaserNetUS**: Established a U.S.-wide network of nine mid-scale laser facilities at universities and national laboratories to expand user access to high-power lasers
- **MPEX Facility**: Initiated the Materials Plasma Exposure eXperiment (MPEX) MIE project as a new world-class high-heat-exposure facility for testing fusion materials
- **Theory & Simulation**: Accelerate progress in Whole-Device Modeling and Exascale readiness; strengthen support for fusion-relevant Machine Learning applications
- **Private-Public Partnerships**: Planning underway to initiate high-impact public-private partnerships as a pilot program to leverage opportunities in critical fusion research areas and accelerate progress toward the development of fusion energy
- **QIS**: Start pilot efforts in Quantum Information Science that can advance both the FES mission and also the development of QIS

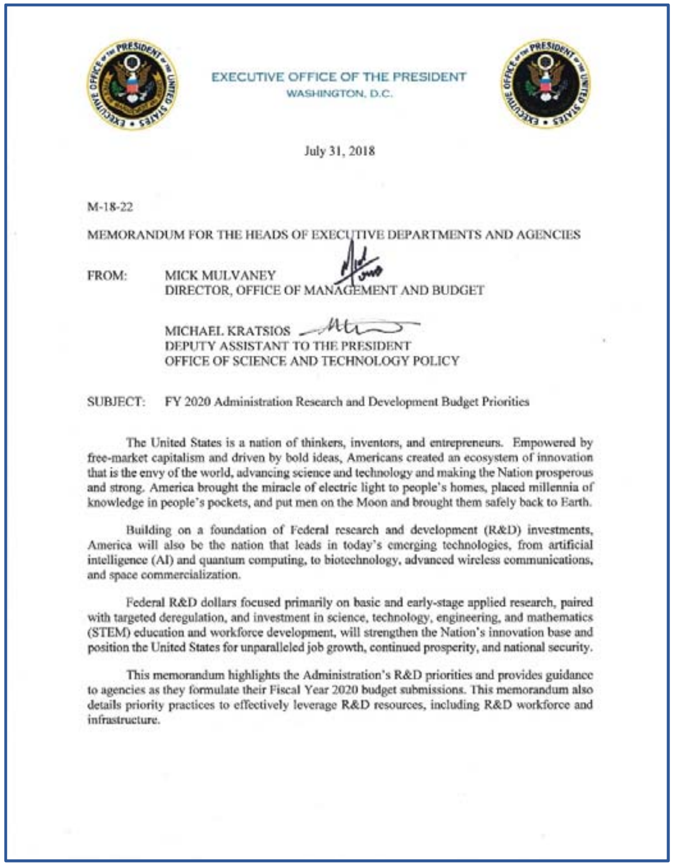
DOE Website (August 2, 2018)



Budget Trends

FES program can address several Administration R&D priorities and practices

- **American Leadership in emerging technologies**: FES investments in transformational technologies such as machine learning, quantum information science (QIS), microelectronics, and high-performance computing could accelerate progress in several mission areas.
- **American Energy Dominance**: Research in fusion could contribute to American energy dominance by making available to the American people a robust base-load electricity clean energy technology that relies on widely available and virtually inexhaustible fuel sources.
- **Managing and Modernizing R&D Infrastructure**: Investments in our major fusion facilities and smaller-scale experiments would maintain and modernize our research infrastructure for continuing to conduct world-leading research.
- **Maximizing Agency Coordination :** Established partnerships within DOE (ASCR, BES, NNSA) and outside (NSF) maximize leverage and increase the cost effectiveness of FES research activities.
- **Partnering with Industry:** Private-public collaborations would leverage opportunities in critical fusion research areas (e.g., diagnostics, theory and simulation, materials science, and magnet technology).
- **Technology Transfer**: Research on high-temperature superconductors, additive manufacturing, low-temperature plasmas, and high-energy-density plasmas lead to connections with and spinoffs for U.S. industry.
- **Workforce Training & Education:** The scientific challenges and rigor of fusion plasma physics research contribute to the development of a well-trained STEM-focused workforce, which would help maintain and advance U.S. competitiveness and world-leadership in key areas of future technological and economic importance, as well as national security.



EXECUTIVE OFFICE OF THE PRESIDENT
WASHINGTON, D.C.

July 31, 2018

M-18-22

MEMORANDUM FOR THE HEADS OF EXECUTIVE DEPARTMENTS AND AGENCIES

FROM: MICK MULVANEY
DIRECTOR, OFFICE OF MANAGEMENT AND BUDGET

MICHAEL KRATSIOS
DEPUTY ASSISTANT TO THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY

SUBJECT: FY 2020 Administration Research and Development Budget Priorities

The United States is a nation of thinkers, inventors, and entrepreneurs. Empowered by free-market capitalism and driven by bold ideas, Americans created an ecosystem of innovation that is the envy of the world, advancing science and technology and making the Nation prosperous and strong. America brought the miracle of electric light to people's homes, placed millennia of knowledge in people's pockets, and put men on the Moon and brought them safely back to Earth.

Building on a foundation of Federal research and development (R&D) investments, America will also be the nation that leads in today's emerging technologies, from artificial intelligence (AI) and quantum computing, to biotechnology, advanced wireless communications, and space commercialization.

Federal R&D dollars focused primarily on basic and early-stage applied research, paired with targeted deregulation, and investment in science, technology, engineering, and mathematics (STEM) education and workforce development, will strengthen the Nation's innovation base and position the United States for unparalleled job growth, continued prosperity, and national security.

This memorandum highlights the Administration's R&D priorities and provides guidance to agencies as they formulate their Fiscal Year 2020 budget submissions. This memorandum also details priority practices to effectively leverage R&D resources, including R&D workforce and infrastructure.

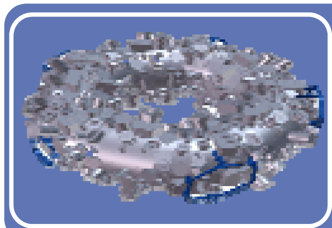
July 31, 2018 OMB memo on the FY 2020 Administration R&D priorities

2. Programmatic Updates

The FES program structure reflects the scientific challenges of fusion and broader plasma science

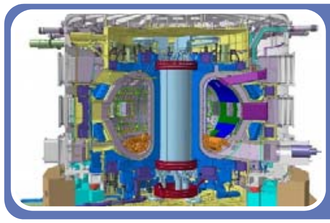
Burning Plasma Science: Foundations – *Advances the predictive understanding of plasma confinement, dynamics, and interactions with surrounding materials*

- Research at major facilities (DIII-D & NSTX-U) and at small-scale MFE experiments
- Enabling R&D
- Theory & Simulation



Burning Plasma Science: Long Pulse – *Explores new scientific regimes achievable on long-duration superconducting international machines or other machines with unique capabilities, and addresses the development of fusion materials*

- International Superconducting Tokamaks & Stellarators (e.g., EAST, KSTAR, W7-X)
- Materials & Fusion Nuclear Science



Burning Plasma Science: High Power

- ITER Construction

Discovery Plasma Science – *Explores the fundamental properties and complex behavior of matter in the plasma state*

- Plasma Science Frontiers (*General Plasma Science, HEDLP, Exploratory Magnetized Plasma*)
- Measurement Innovation

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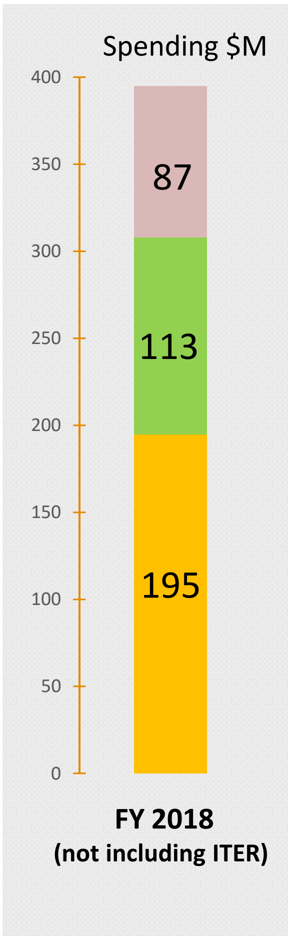
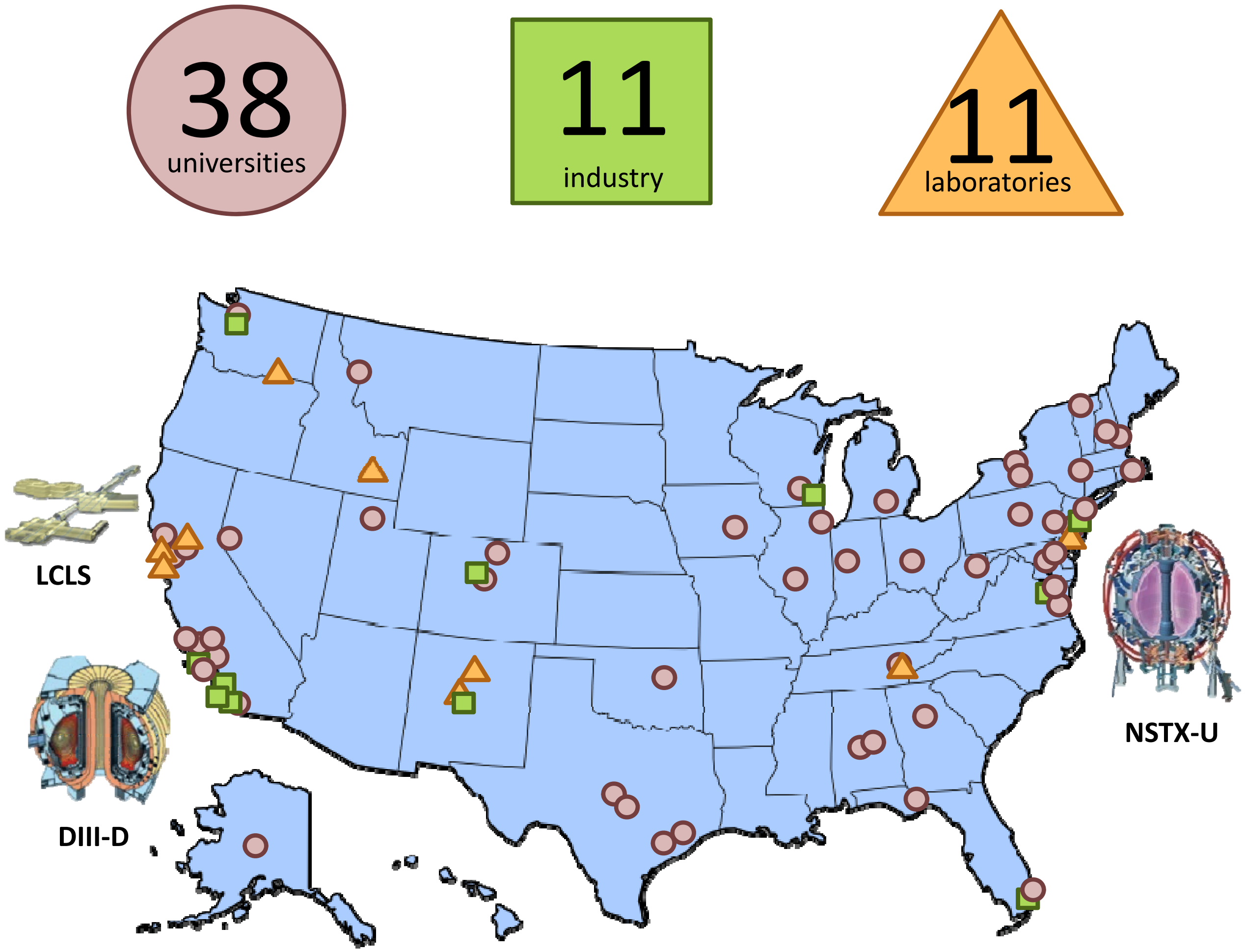
FES research is carried out at a diversity of US institutions





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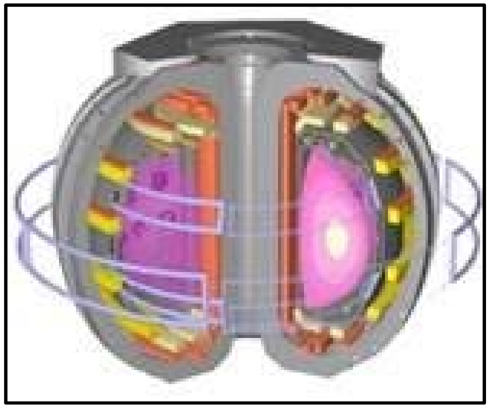
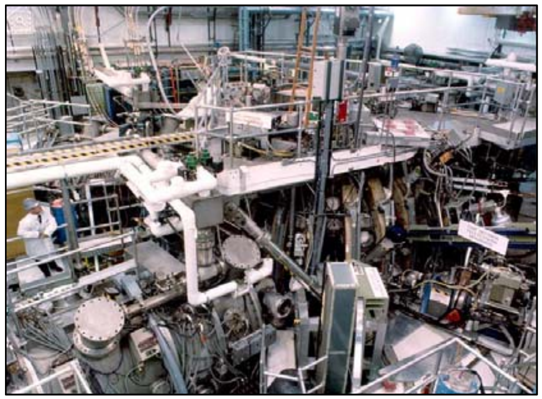
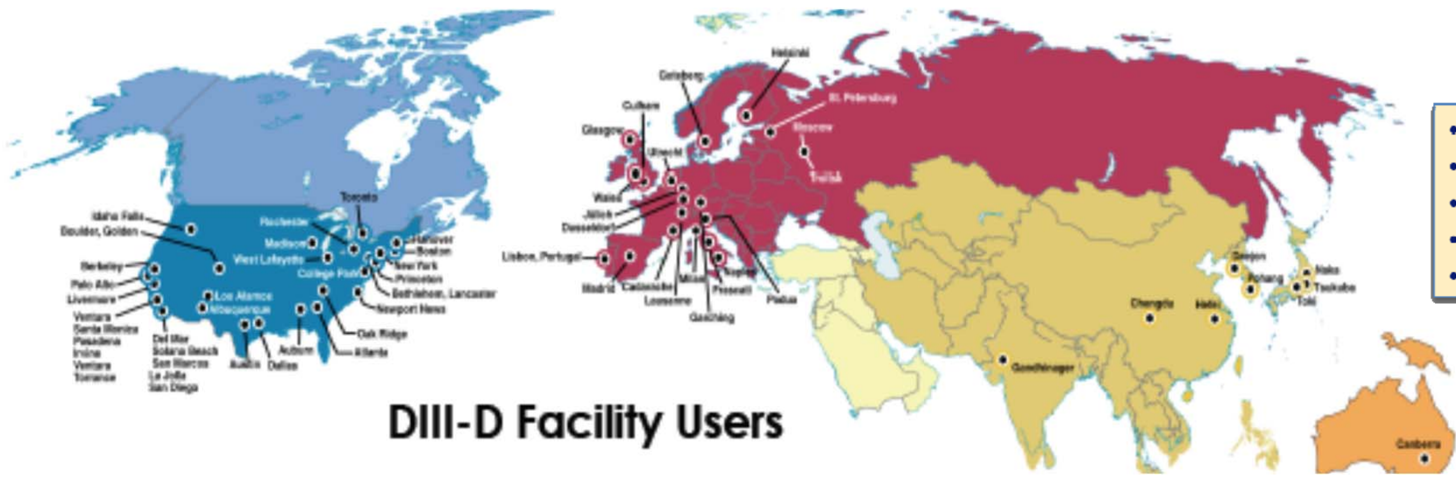
The DIII-D program is a world-leading contributor to magnetic fusion research

DIII-D tokamak @ General Atomics

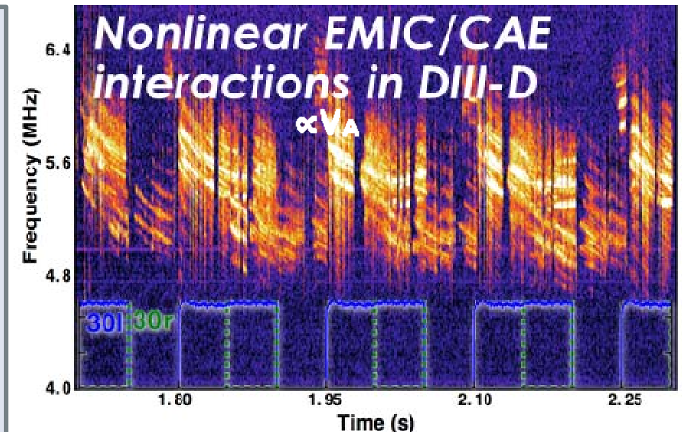



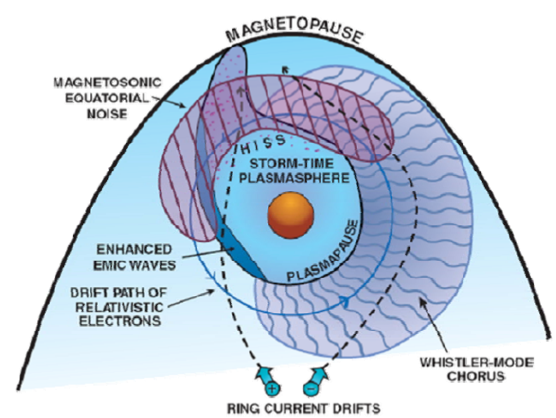
- >600 users (270 on site)
- >100 Institutions
- 23 U.S. Universities
- 71 Grad Student Users
- 64 Post Doc Users

Frontier science experiments on DIII-D

- **In FY 2017, FES started a new initiative to focus some DIII-D experiments on frontier plasma science**
  - Whistler wave experiment led to post-deadline invited paper at 2017 APS-DPP meeting, a recent PRL paper (Spong et al., 2018 *PRL* 120, 155002), and 2018 APS-DPP oral presentation by Z. Williams (U. Wisc)
- **Four experiments selected in 2018 utilizing 5 run days:**
  - ➢ EMIC waves: led by W. Heidbrink (UCI)/S. Vincena (UCLA)
  - ➢ Runaway electrons & plasma waves: led by D. Spong (ORNL)
  - ➢ Positron generation by runaways: led by P. Aleynikov (MPIPP)
  - ➢ Sawtooth reconnection studies: led by W. Fox (PPPL)
- **Overall status:**
  - Engagement very positive, with visiting scientists impressed by the quality of DIII-D data
  - Focus is now on analysis to obtain results from each study
  - In FY 2019, the program is being assessed to evaluate progress and to integrate review and selection processes



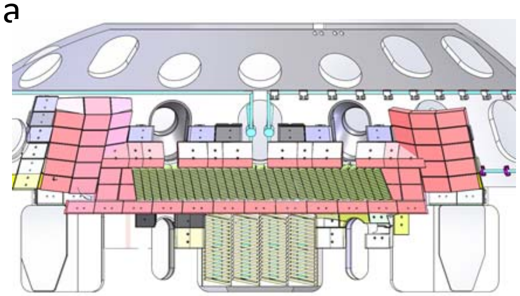
EMICs de-populate magnetosphere

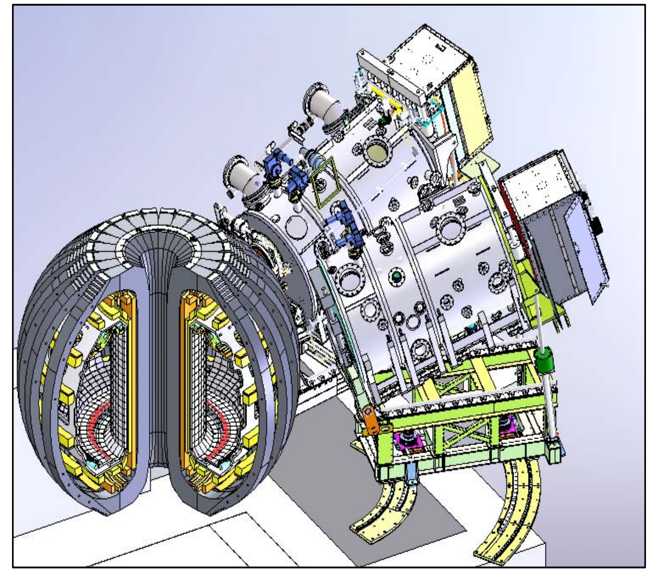


DIII-D Long Torus Opening (LTO) for facility enhancements

- **LTO began May 2018 and will be completed in April 2019, after which DIII-D will operate for 12 weeks in FY 2019**
- **Major ongoing LTO tasks include:**
  - New co/counter off-axis neutral beam modification
  - Top-launch ECCD capability
  - Installation of helicon strip-line antenna
  - New/upgraded diagnostics

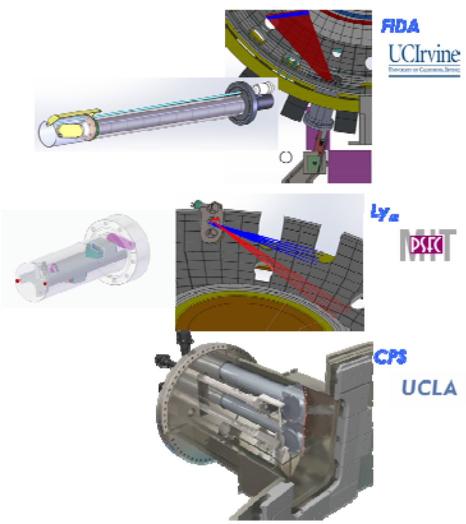
Helicon antenna

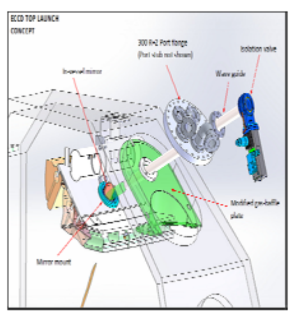




Co/counter off-axis neutral beam

New diagnostics





Top launch ECCD

- **Other activities enabled by FY 2018/19 funding include:**
  - New helium liquefier and 3 replacement gyrotrons on order
  - Start of high-field-side Lower Hybrid Current Drive project
  - Increased number of collaboration grants
  - Sustained engineering work to increase facility reliability

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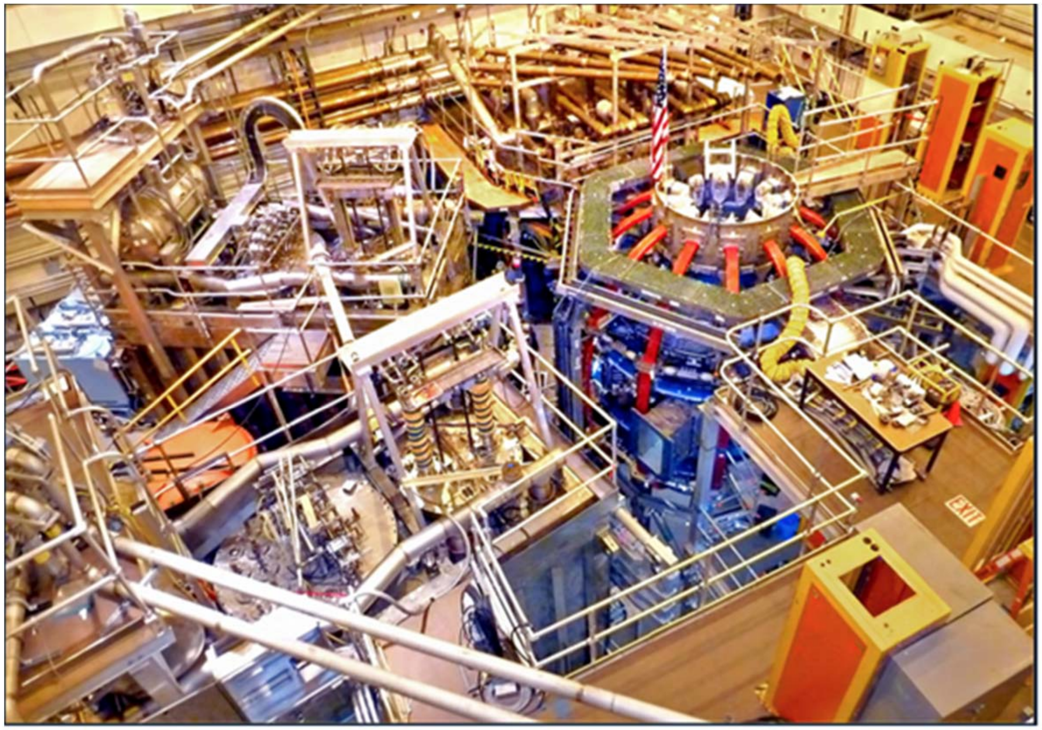
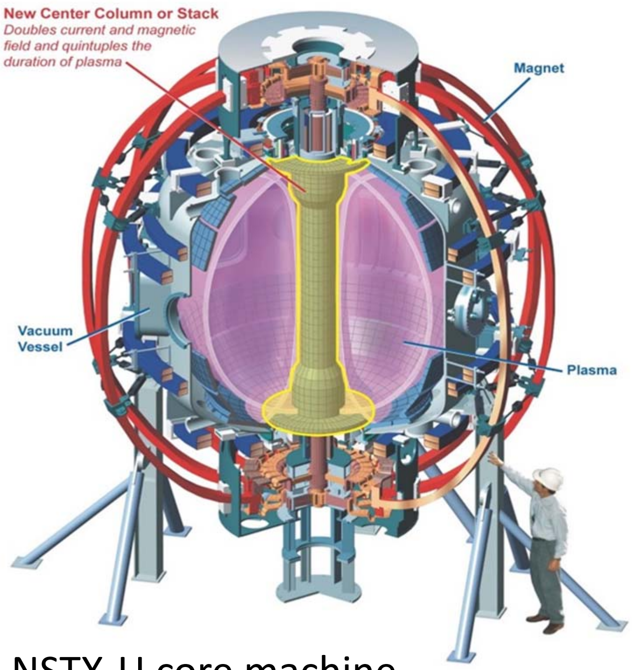
NSTX-U research at PPPL, a national lab focused on fusion and plasma science



The NSTX-U Test Cell



NSTX-U core machine

- The "spherical" tokamak has advantages of compactness and component testing
- A major upgrade made NSTX-U the world's highest-performance spherical tokamak
- During FY 2016 operation, significant hardware malfunctions shut down the NSTX-U facility

The PPPL project team has made progress towards recovery of NSTX-U

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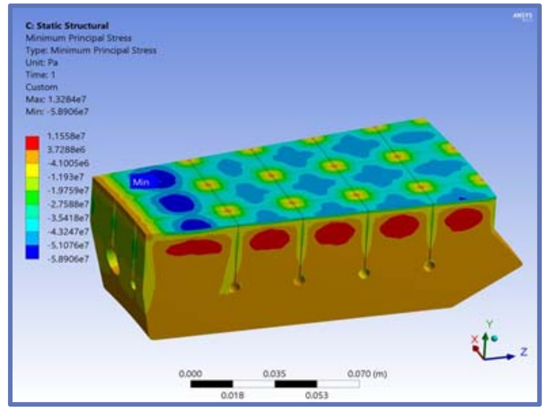
Important reviews, design work, and project activities:

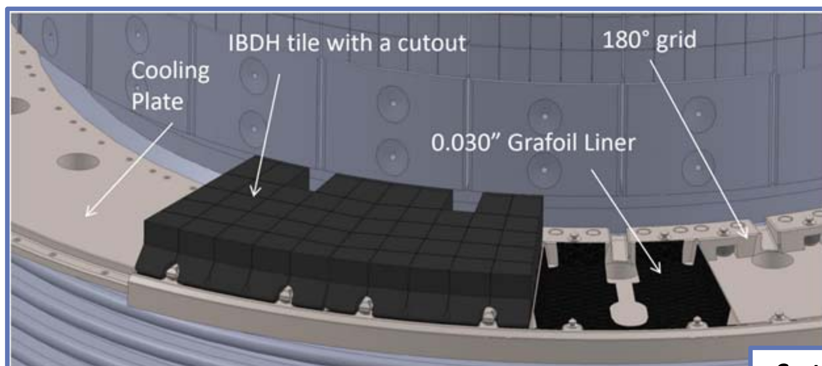
- ✓ A thorough assessment, conducted by 50+ external reviewers, identified all problems requiring repair to recover robust plasma operations
- ✓ PPPL has completed the preliminary design of the NSTX-U Recovery scope
- ✓ Early material procurements, coil prototyping and testing
- ✓ A baseline review of the total project cost and schedule is slated to take place in FY 2019



Engineering analysis of new castellated PFC tile design

TF/OH conductor bundle prior to a casing fit-up lift

Prototype coil testing to full field and current



Castellated tile in situ

Congratulations to Sir Steve

Investiture ceremony at Buckingham Palace (October 11, 2018)

- KNIGHTS BACHELOR, Sir Steven Charles Cowley FRS FREng
- "For services to Science and to the Development of Fusion Energy"

Prof. Steve Cowley became the new director of PPPL on July 1, 2019

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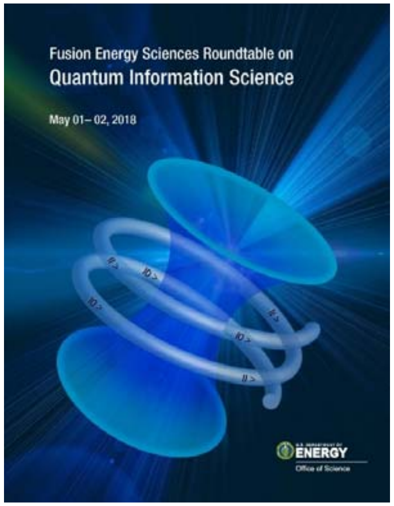
SciDAC, *Exascale*, QIS, and Machine Learning

- **The current FES SciDAC-4 portfolio has 9 multi-institutional and interdisciplinary partnerships (seven jointly supported with ASCR)**
  - The ninth project added in FY 2018 is focused on runaway electron avoidance and mitigation
  - Involves 11 universities, 8 DOE national laboratories, and 5 private industry institutions (including small businesses) in 13 states
- FES SciDAC research activities accelerate progress toward Whole-Device Modeling
- The SciDAC portfolio strengthens U.S. domestic fusion program, advances U.S. world leadership and competitiveness in fusion simulations, and addresses research opportunities identified in recent community workshops

- **FES held a Roundtable meeting on May 1-2, 2018, to explore its role in Quantum Information Science (QIS)**
- The meeting objectives were to:
  - Identify fundamental science supported by FES that could advance QIS development; and
  - Explore QIS applications that could have transformative impact on FES mission areas (e.g., fusion and discovery plasma science)
- Identified six compelling **Priority Research Opportunities**
- An **FOA and Lab Announcement** are being issued in FY 2019

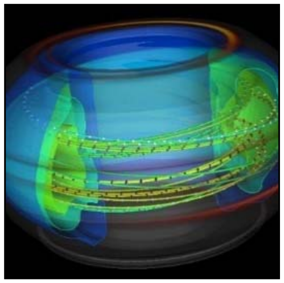


Report available from:
https://science.energy.gov/~/media/fes/pdf/workshop-reports/FES-QIS_report_final-2018-Sept14.pdf

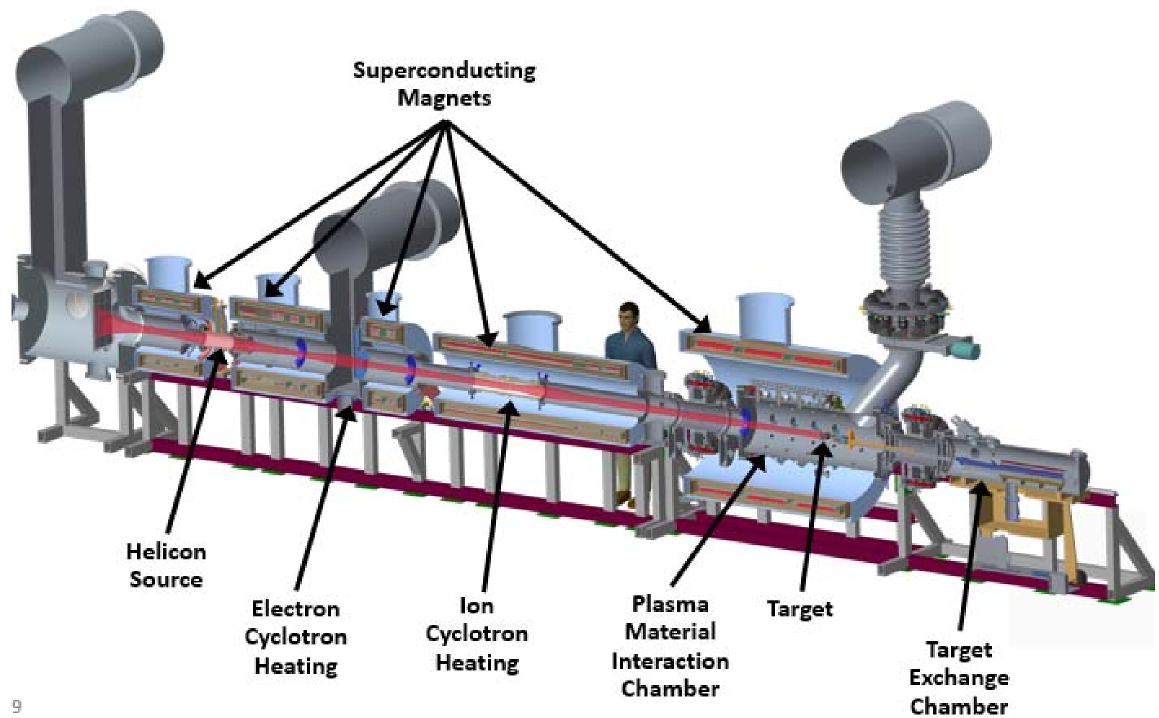
- **FES (with ASCR) will hold a meeting on April 30-May 2, 2019**, to explore its role in **Machine Learning**

- **The upcoming Exascale era will enable transformative advances in predictive power for fusion systems**, based on fundamental science and high-performance computing
- Two fusion-relevant multi-institutional efforts are part of the DOE/ASCR Exascale Computing Project (ECP); universities participate through subcontracts with DOE Labs

High-Fidelity Whole-Device Modeling of Magnetically Confined Fusion Plasma
(ECP project led by PPPL)



New MIE project for fusion materials testing facility



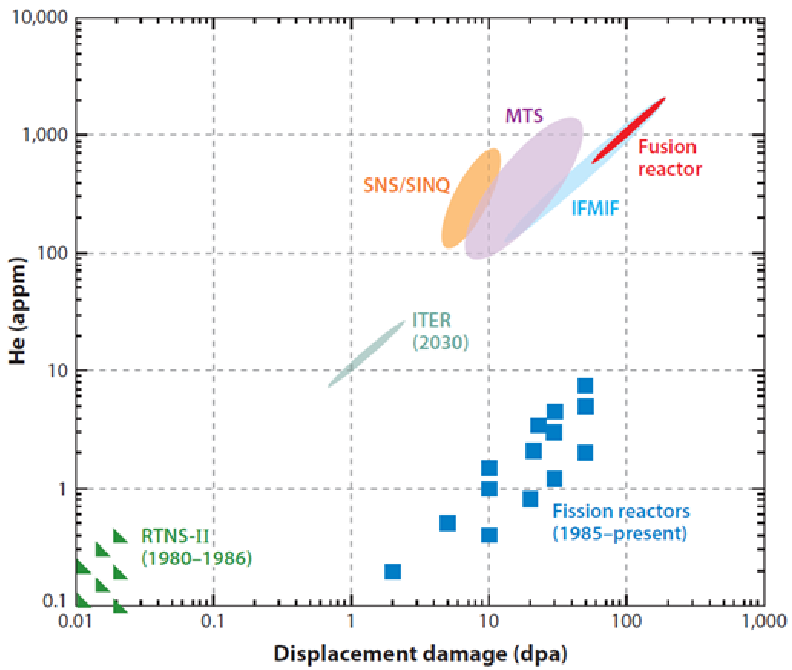
MPEX

- **Plasma-material interactions**
  - Need to test materials in fusion-reactor environment with high temperatures, reactive chemicals, large time-dependent thermal-mechanical stresses, and damaging radiation

- **Fusion materials testing facility**
  - FES has begun development of the Materials Plasma Exposure eXperiment (MPEX) as a new MIE project
  - Conceptual design of the MPEX device began at ORNL in the summer of 2018 and is currently ongoing, with completion by end of summer 2019
  - MPEX will enable new experimental capability for reactor-relevant plasma-materials interaction studies, including high-heat exposure of neutron-irradiated samples

Fusion Prototypic Neutron Source

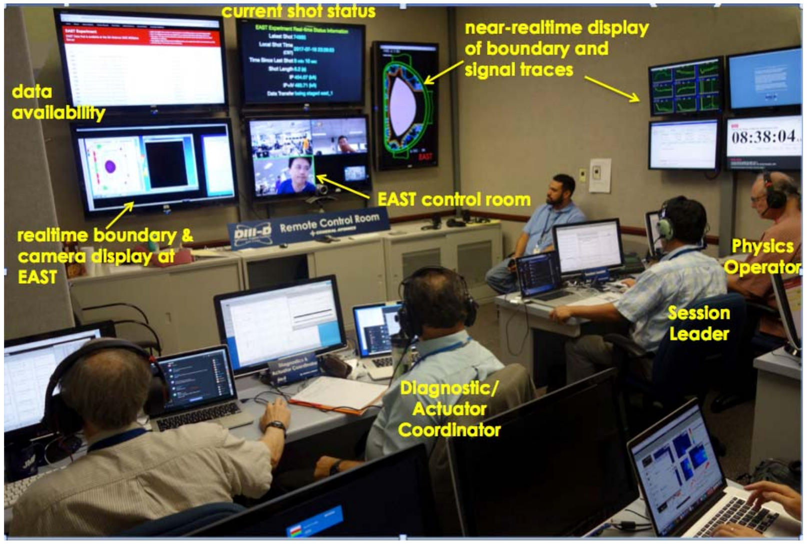
- **Need:** A neutron irradiation source able to expose materials to high energy fusion neutrons and to high damage levels.
- **Issue:** The front-running concept to meet this need, the International Fusion Materials Irradiation Facility (IFMIF) has never been constructed due to its large capital cost (>$1 B)
- **Opportunity:** The US, the current world leader for nuclear damaged studies in materials, could further expand world leadership by investing in a near-term, relatively low cost, fusion irradiation capability
- **Process:** The US fusion materials community, the Virtual Laboratory for Technology, and private industry met on August 20-22, 2018 to discuss the possibility of the US exploring a near-term, low-cost Fusion Prototypic Neutron Source.
- **Outcome:** There is significant scientific value in an intermediate next-step device delivered before an IFMIF or one of its “scaled down” variants being explored internationally.
  - The source must be “near term” (construction possible in ≤ 3 years) and of moderate cost
  - The goal is to provide scientific understanding to enable a Fusion Nuclear Science Facility, not engineering data required for full licensing
- **Path Forward:** FES is currently exploring several possible neutron source concepts which could meet the scope, schedule, and cost outlined in the document.

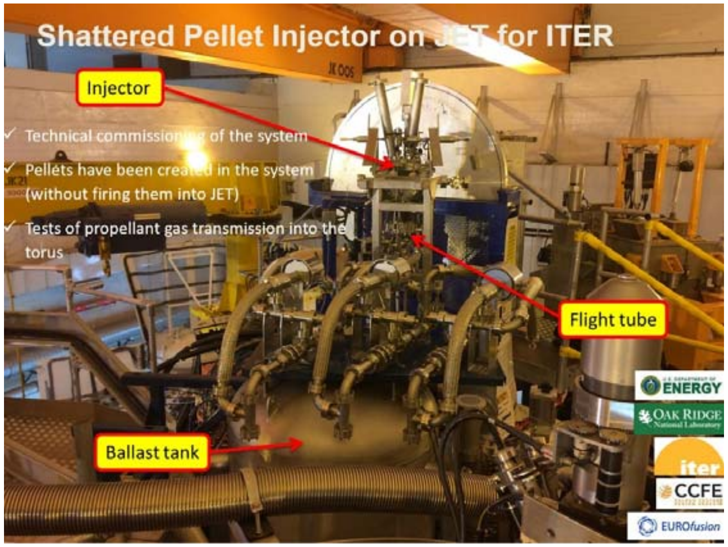


Summary of He dose relationships important for steels

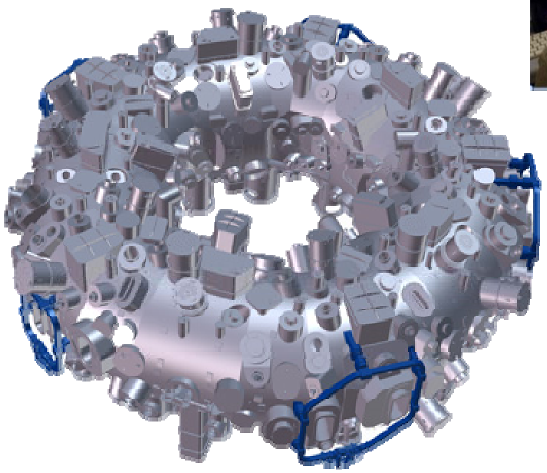
New international research projects

Remote control collaboration capabilities for EAST research

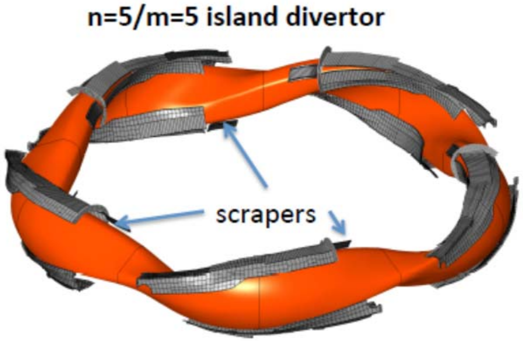




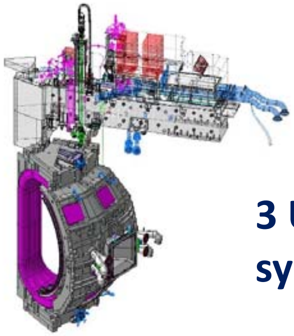
Shattered pellet injector on JET for disruption mitigation



5 trim coils (blue)



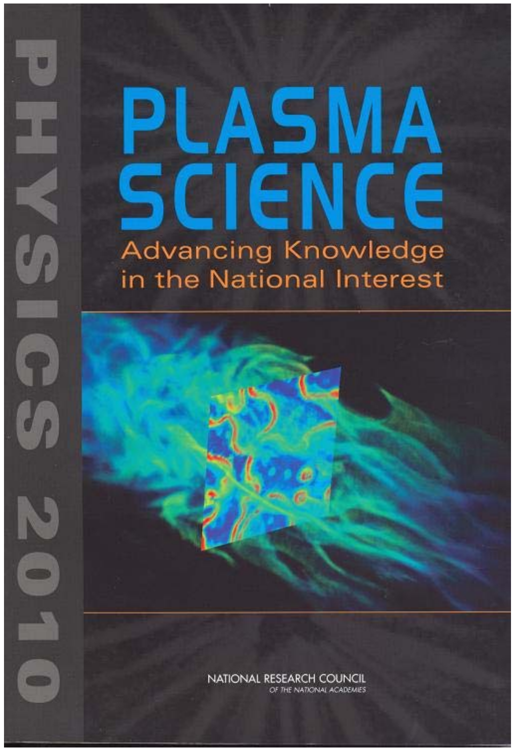
Divertor scraper elements



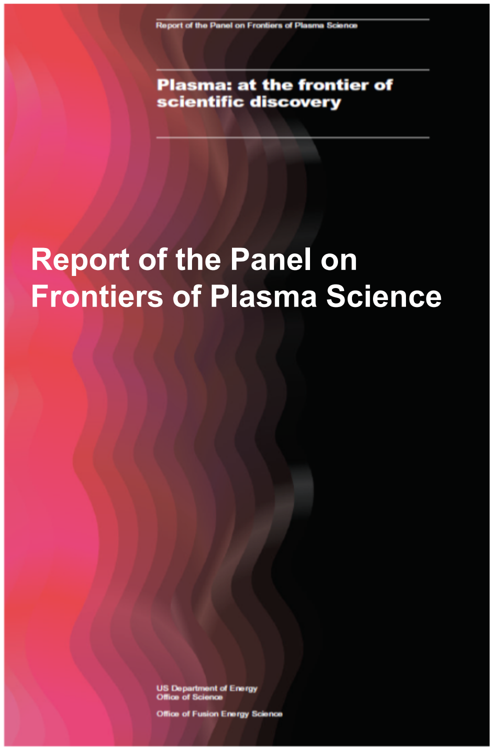
Fueling pellet injector (new)

3 US experimental systems on W7-X

A new intermediate-scale user facility for dusty plasma research was awarded in 2018



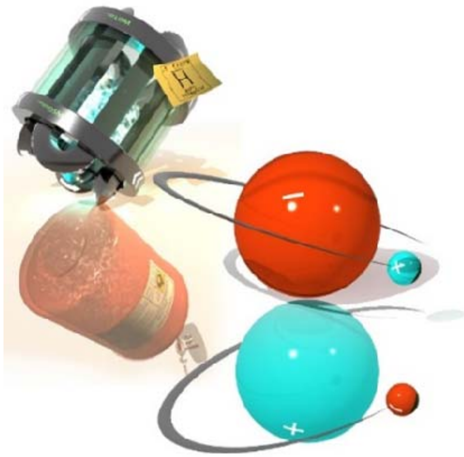
"Several areas of basic plasma science would benefit from new intermediate-scale facilities." (2010 Decadal Study)

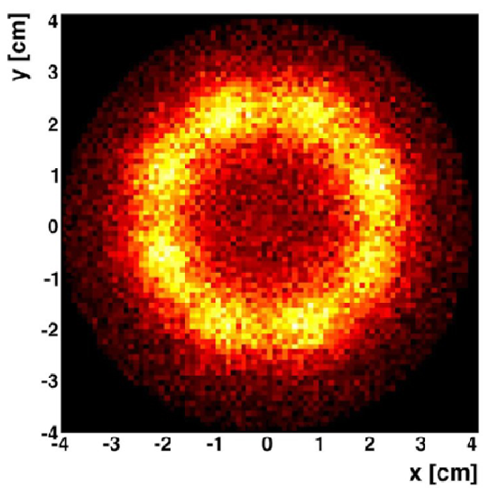


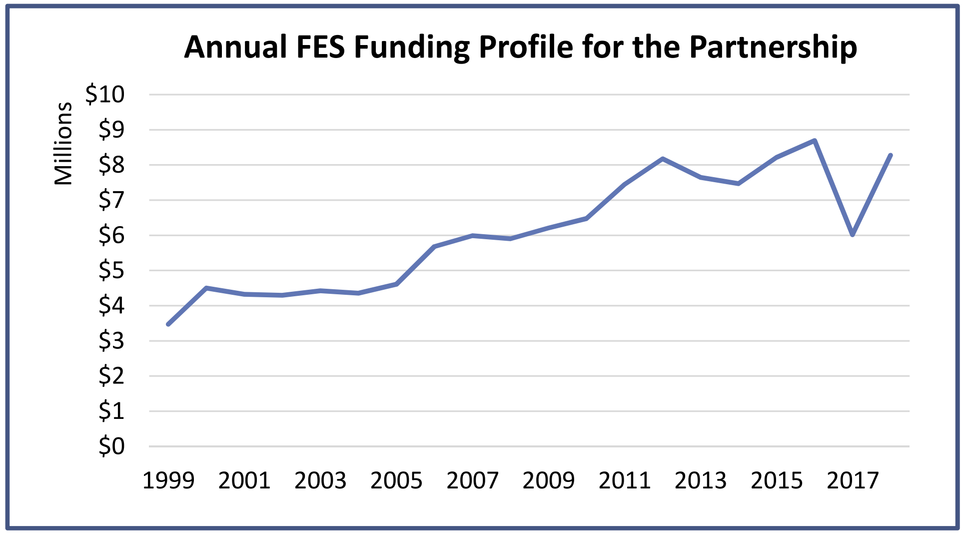
"There is a need for creation and exploration of new regimes in the laboratory." (2016 PSF Report)

FES awarded $1.5M of FY18 funds over three years to Auburn University to operate the Magnetized Dusty Plasma Experiment (MDPX), an intermediate-scale, integrated, collaborative plasma science user facility

NSF/DOE Partnership: Over $8 million funded by FES in 2018







- FES provided $8.3 million FY18 funds for the Partnership, supporting 11 new or renewal proposals in basic plasma, non-neutral/dusty plasma, HED plasma, and low temperature plasma
- This includes $2.5 million over five years for antihydrogen research led by the University of California-Berkeley, collaborating with ALPHA
- Also, includes $2.3 million for Basic Plasma Science User Facility's (BaPSF) continuing operation and research at UCLA

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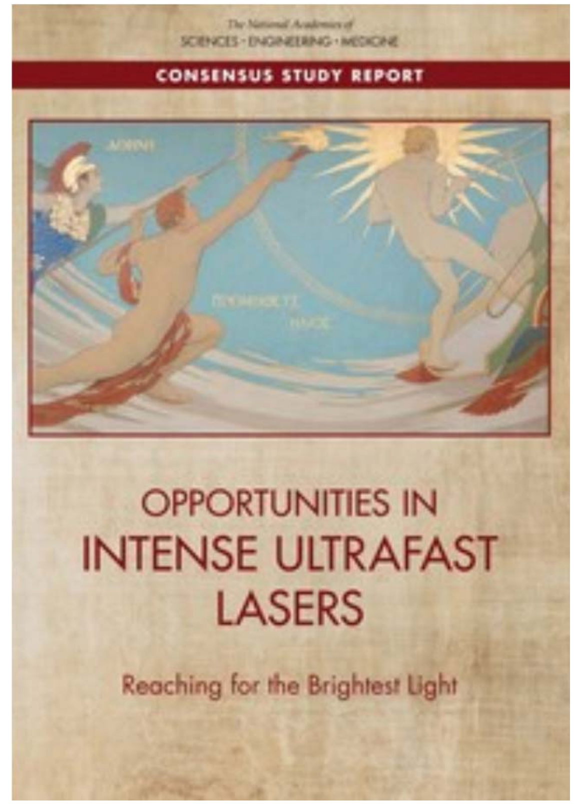
Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light (NAS, 2017)

Recommendations

1. DOE should create a broad **national network (universities, industry, government labs)** in coordination with OSTP, DOD, NSF, and others. **LaserNetUS**
2. US research agencies should engage stakeholders to **define facilities and laser parameters** that will best serve research needs.
3. DOE should lead development of **an interagency national strategy** for developing and operating large- and mid-scale projects, and developing technology.
4. DOE should plan **for at least one large-scale open-access, high-intensity laser facility** that leverages other major science infrastructure in the DOE complex.

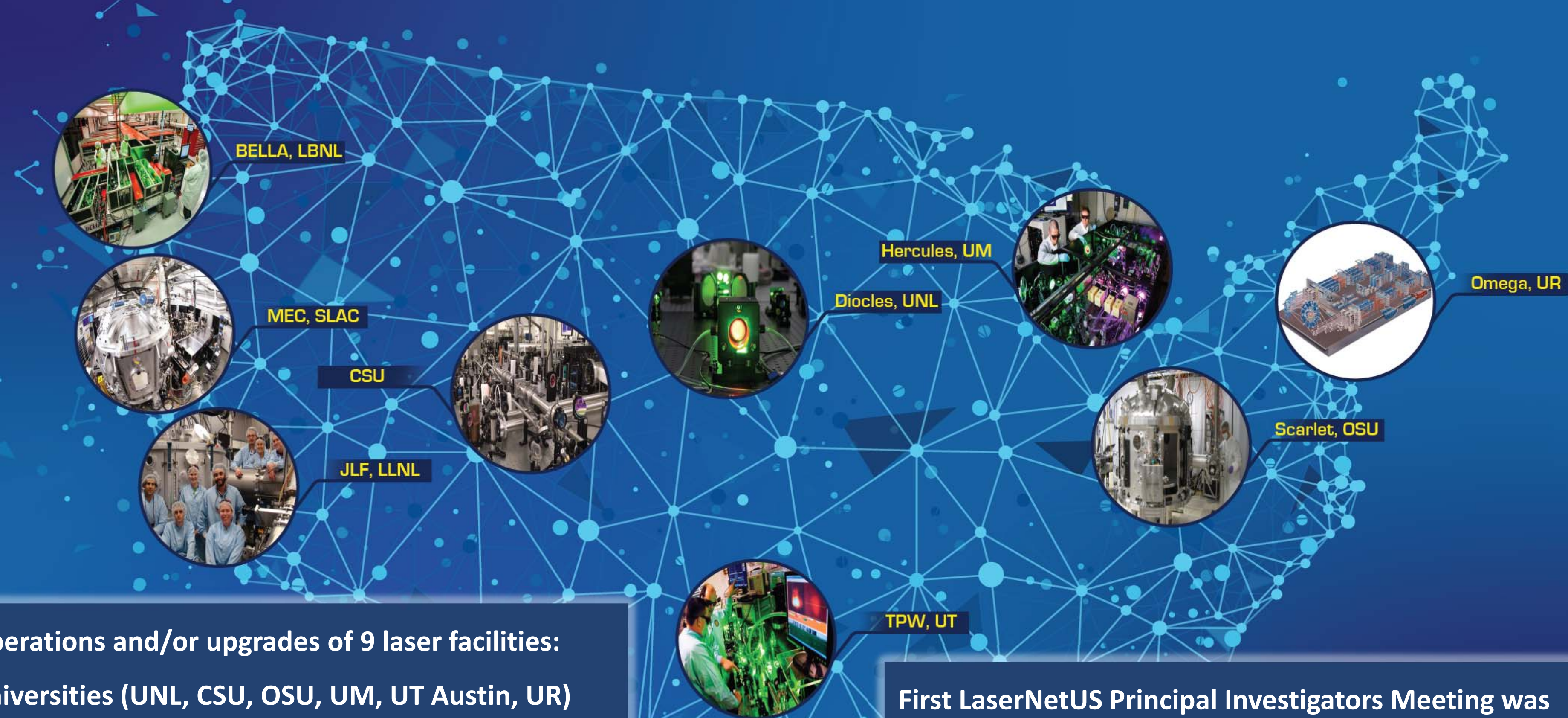
CD-0 for Petawatt Laser Facility

5. Agencies should create U.S. programs that **include mid-scale infrastructure, project operations, development of technologies; and engagement in research at international facilities such as ELI.**



This report was commissioned by : DOE-SC, DOE-NNSA, DOD-AFOSR, and DOD-ONR

LaserNetUS



FES funds operations and/or upgrades of 9 laser facilities:

- Six at universities (UNL, CSU, OSU, UM, UT Austin, UR)
- Three at national laboratories (LLNL, SLAC, LBNL)

First LaserNetUS Principal Investigators Meeting was held January 16, 2019 (Rockville, MD)

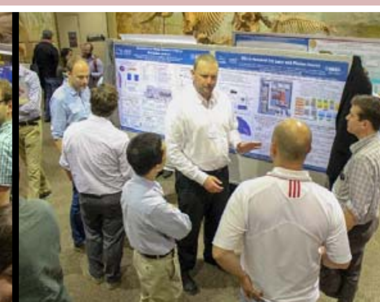
FES established LaserNetUS in FY 2018 in response to National Academy report recommendations

The network provides broad access to state-of-the-art high-power laser facilities for the entire U.S. community

LaserNetUS First Annual Meeting

University of Nebraska-Lincoln (August 20-21, 2018)

60 Posters mainly from students and postdocs



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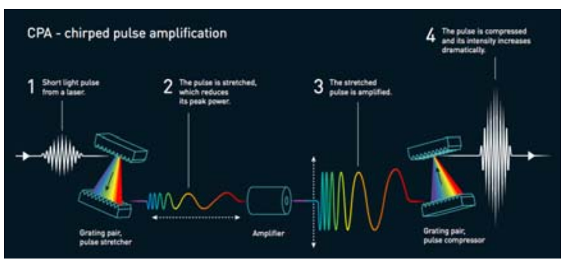
2018 Nobel Physics Prize for CPA led to the development of high-power lasers for HEDP

Arthur Ashkin | Gérard Mourou | Donna Strickland

2018 Nobel Prize in Physics

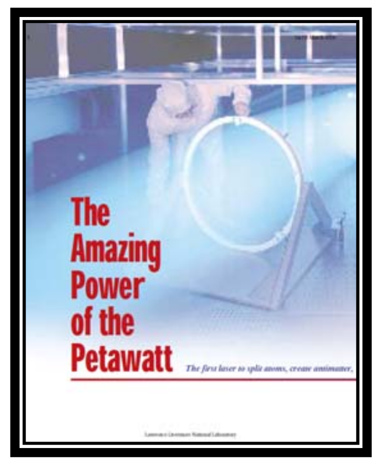
Donna Strickland & Gerard Mourou: "Compression of amplified chirped optical pulses" (Optics Communications, 1985)

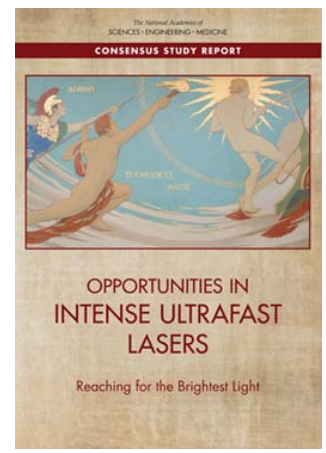
Announced 2 Oct 2018



Chirped pulse amplification (CPA)

- First Petawatt Laser
- LLNL, May 23, 1996





US-Japan Project Arrangement for High Energy Density Science signed on January 23

- A signing ceremony was held on January 23 for a new **Project Arrangement Concerning High Energy Density Science** under the DOE-MEXT Implementing Arrangement Concerning Cooperation in Research and Development in Energy and Related Fields
- This new Project Arrangement will facilitate cooperation in the area of high energy density science, specifically in the research and development of high power lasers and high energy density science with large scale laser facilities
- The signing ceremony took place during a **Japan-US Symposium on Perspective of High Energy Density Science and Technology by High Power Lasers**, held at the Embassy of Japan (Washington, DC) on January 23, 2019

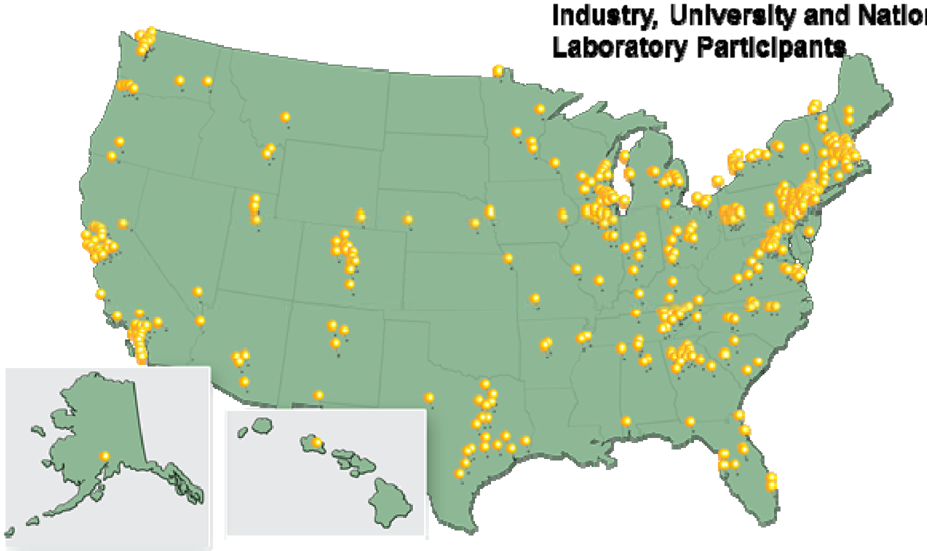
3. ITER Updates

Progress of U.S. ITER project

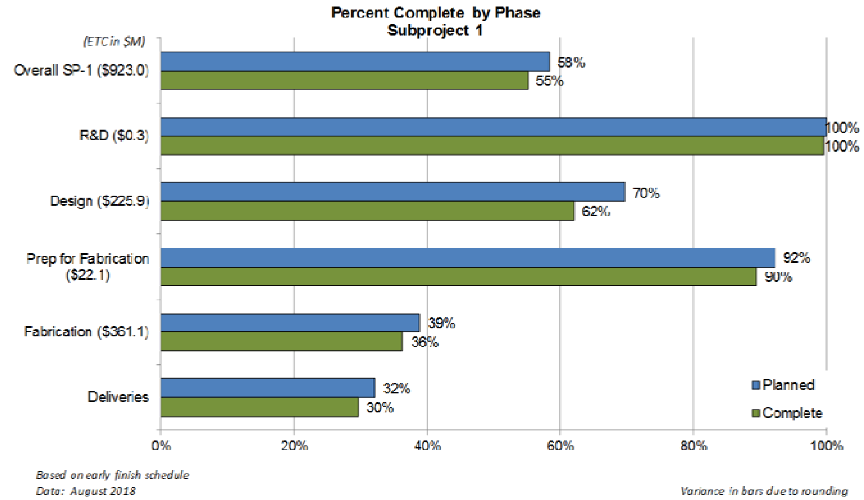
Total Contract Awards: ~$1B
as of June 2018

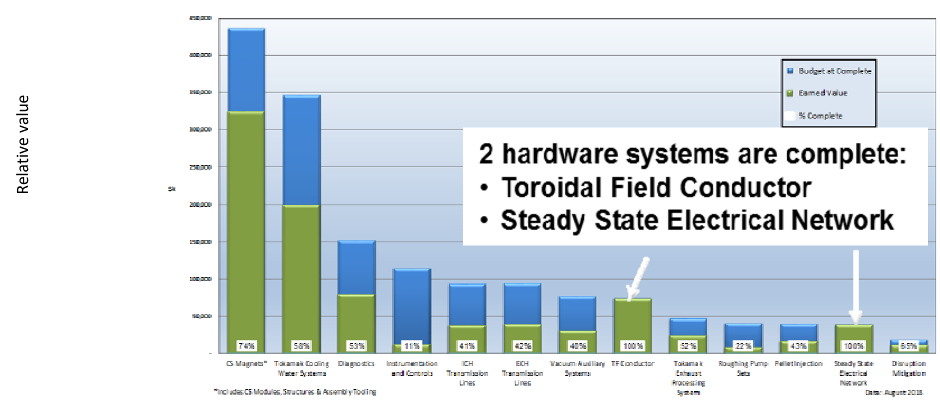
>80% of fabrication awards for U.S. ITER project remain in the U.S.

- 600+ contracts to U.S. industry, universities, and national laboratories in 44 states
- 500+ direct jobs, 1100+ indirect jobs per year



US ITER Subproject-1 (First Plasma) is 55% complete





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Examples of U.S. hardware for ITER

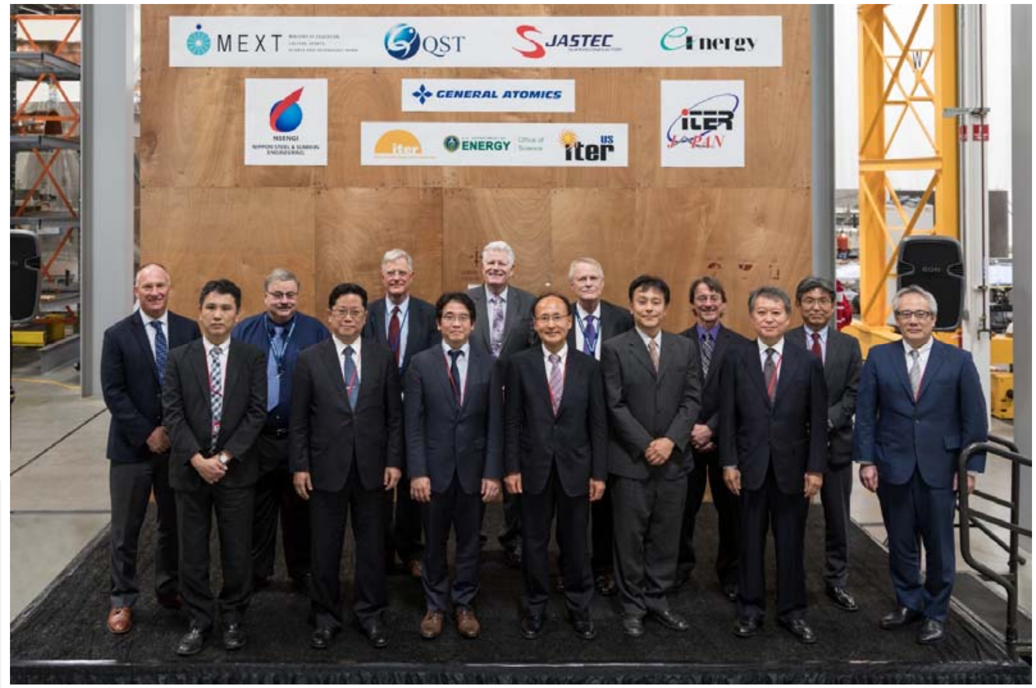
First U.S. hardware installed in the Tokamak Complex
Drain tanks fabricated in the U.S. were also the first nuclear-certified components delivered to the ITER site.

Energizing of the Steady State Electrical Network delivered by the U.S. to the ITER site

Central Solenoid Module 1 at General Atomics (Poway, CA facility)

Drain tank being lifted into the tokamak facility

MEXT-QST-DOE-GA celebration of final delivery of Japanese superconductor for ITER central solenoid



May 3, 2018 at General Atomics:
51 spools of niobium-tin superconductor = 43 km

View of ITER worksite

Courtesy ITER Organization (Tim Luce, 2018 FPA talk)

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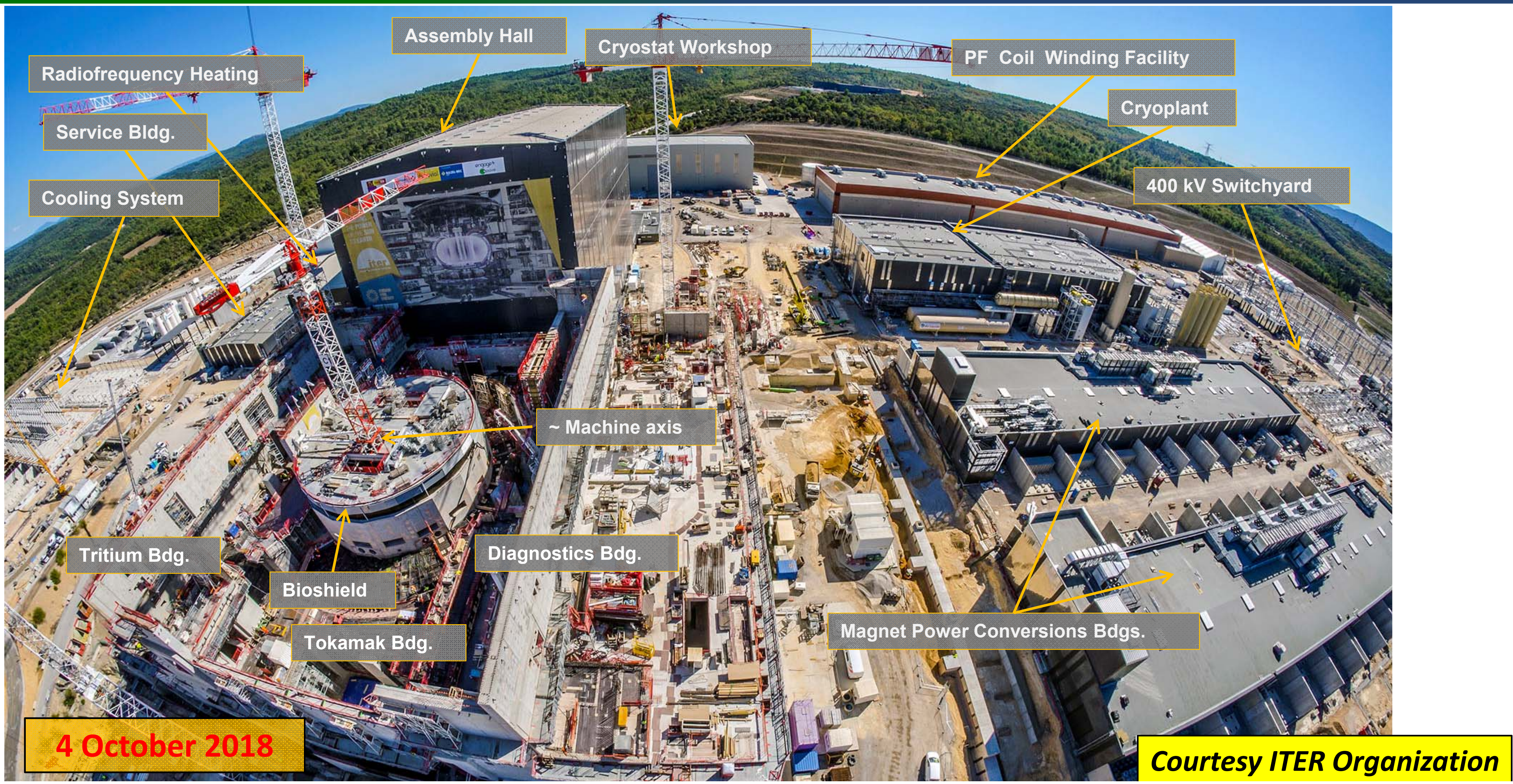
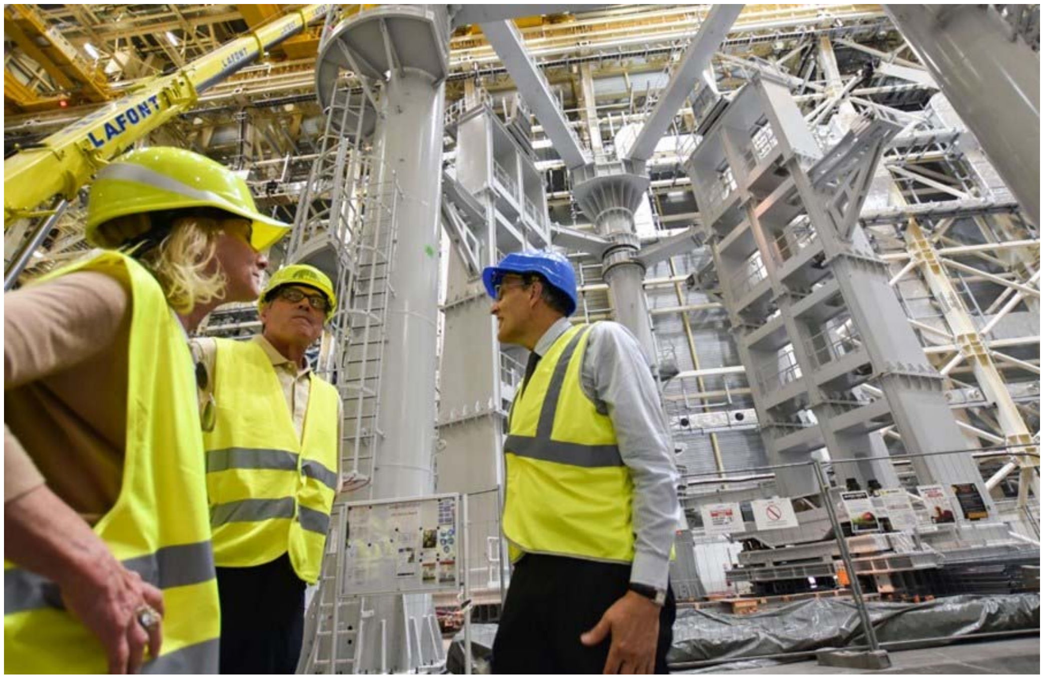
ITER worksite progress



DOE Leadership visited ITER site in 2018



Secretary of Energy Rick Perry visited ITER on July 11, 2018

DOE Under Secretary for Science, Paul Dabbar, visited ITER on December 10, 2018

Dr. Bigot has accepted the Council's offer of a second five-year term as Director-General, to begin March 2020.

Tokamak building rises

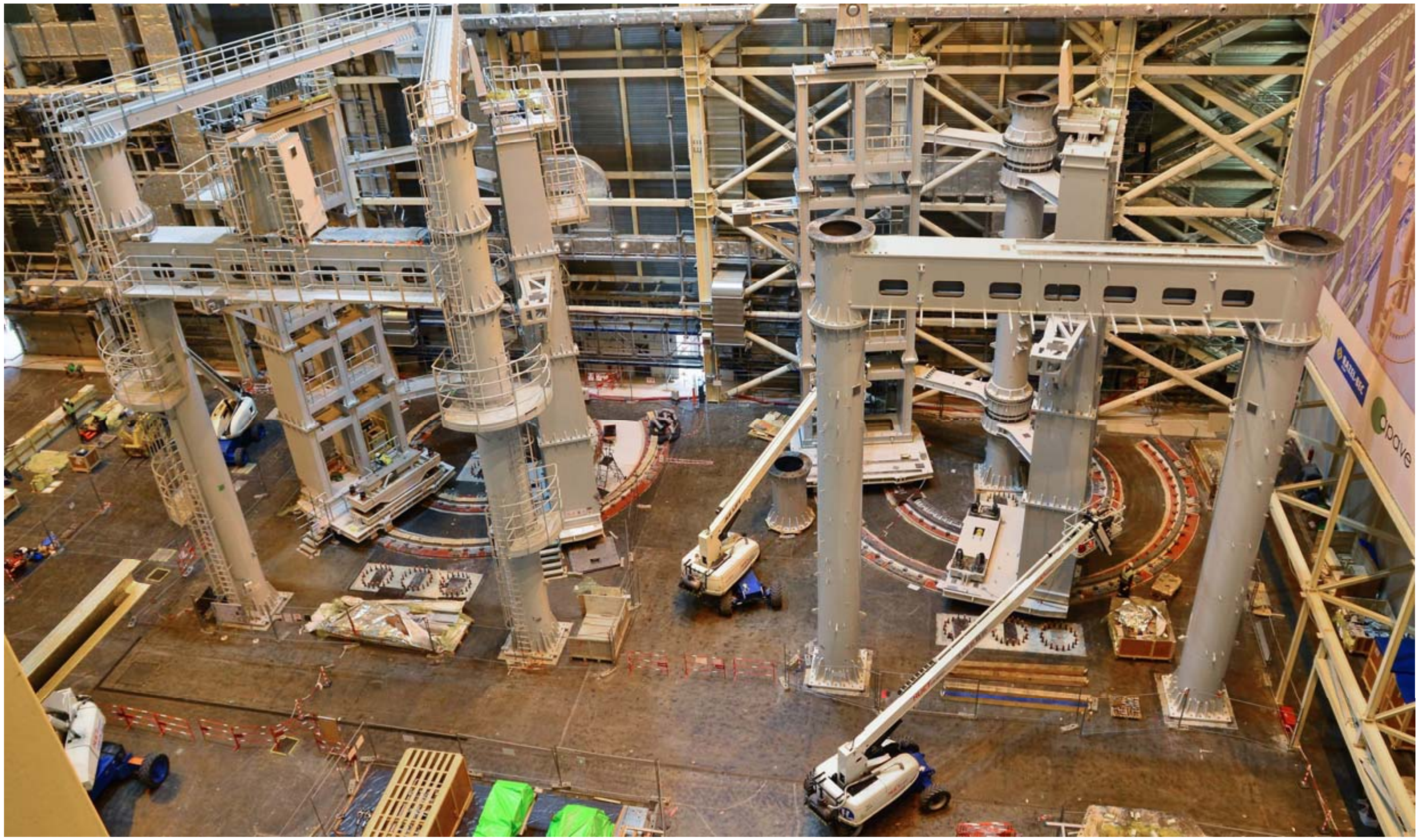
The concrete walls of the Tokamak Building are rising next to the metal-clad Assembly Building (December 2018).

Photo: ITER Organization

Sub Sector Assembly Tool Installation

Assembly of the first tool (left) is complete, and the second tool is now in the final phase of assembly.

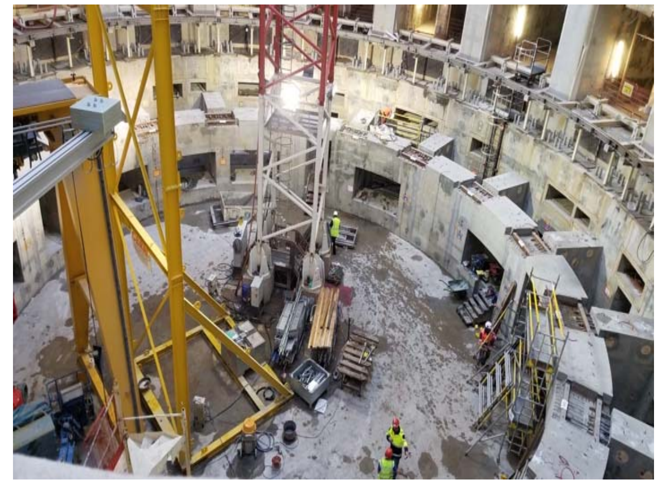
Photo: ITER Organization



ITER update: First machine component brought into tokamak pit

The tokamak complex continues to take shape. The tokamak bioshield is now hidden behind the walls of the tokamak building.

The tokamak pit is being prepared for the first tokamak components.



Photos & text from USBPO eNews and ITER Newsline

On November 26, the first machine component - a cryostat feedthrough for poloidal field coil #4 – was carefully lowered 30 meters down onto the tokamak pit floor. This is no small feat; the component is 10 meters long and weighs 6.6 tons. This auspicious occasion marks the beginning of five years of tokamak assembly activities.

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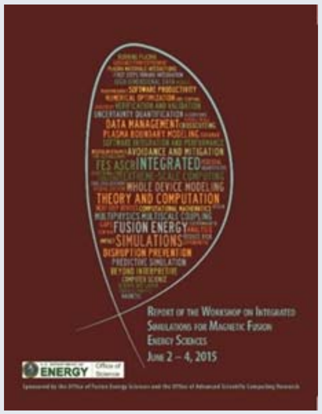
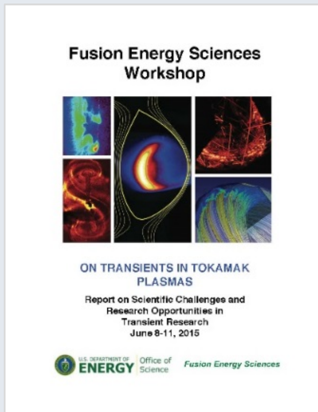
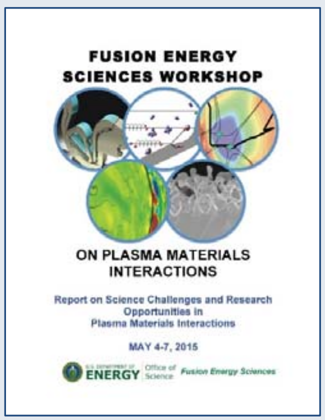
4. Program Planning

FES strategic choices are informed by community and Advisory Committee input

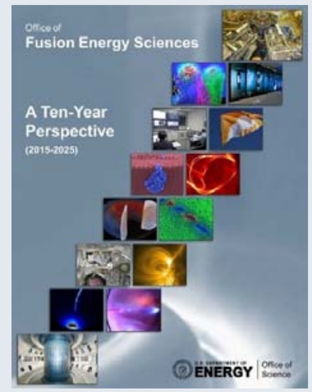




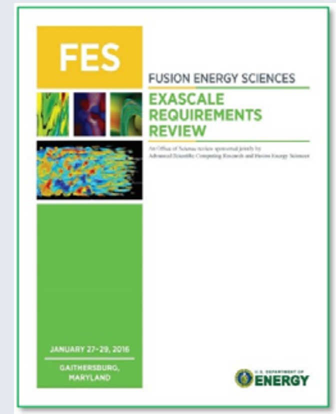


2015 Community Workshops:
Integrated Simulations, Transients, Plasma Materials Interactions, & Plasma Science Frontiers

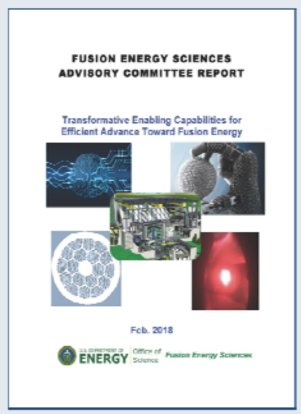
2015 Applications of Fusion Energy Sciences Research



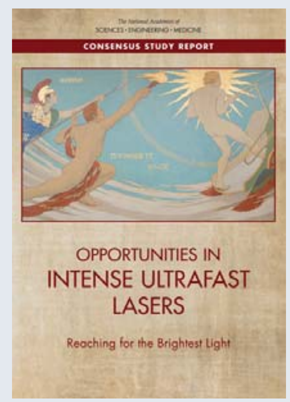
2015 FES 10-year Perspective



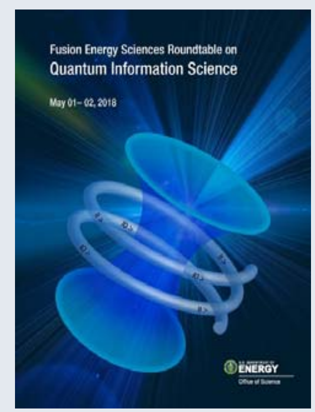
2016 FES Exascale Requirements



2018 FESAC Transformative Enabling Capabilities



2017 FES NAS Report on Intense Ultrafast Lasers



2018 FES Roundtable on QIS

National Academy burning plasma study

Part of the charge to the panel:

- <u>Charge question #4</u>: "*In two separate scenarios in which, after 2018, (1) the United States is a partner in ITER, and (2) the United States is not a partner in ITER, provide guidance on a long-term strategic plan for a national program of burning plasma science and technology research which includes supporting capabilities and which may include participation in international activities, given the U.S. strategic interest in realizing economical fusion energy in the long term.*"

Interim report (Dec 2017):

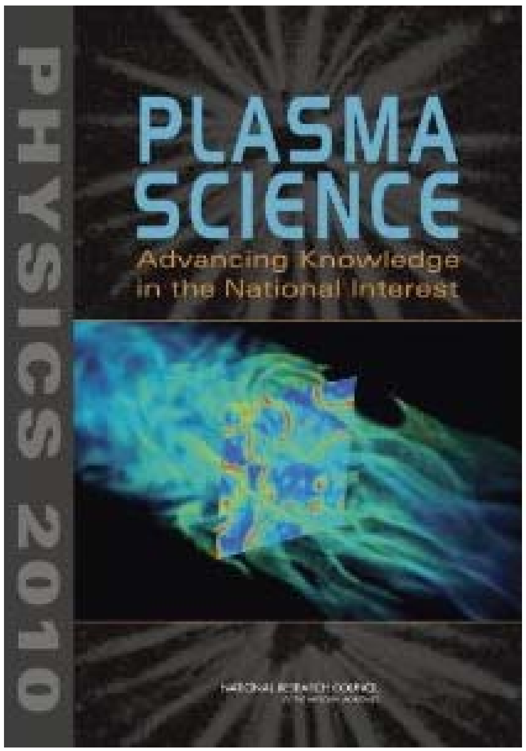
- Burning plasma research is essential to the development of magnetic fusion energy
- The U.S. has contributed leading advances in burning plasma science
- ITER is the only existing project to create burning plasma at reactor scale
- The U.S. should develop a national strategic plan leading to a fusion demonstration device

Final report (Dec 2018):

- ITER plays a central role in U.S. burning plasma research activities and is currently the only existing project to create a burning plasma at the scale of a power plant. Because the ITER partnership is the central focus in the large international effort to develop fusion energy, the United States significantly benefits from participation in the ITER partnership. The U.S. has contributed leading advances in burning plasma science.
- If the United States withdraws from the ITER project, the national research effort would be significantly disrupted, United States researchers would be isolated from the international effort, and any benefit from sharing the cost in critical burning plasma studies and fusion demonstration would be eliminated. Without ITER, the United States would need to design, license, and construct an alternative means to gain experience creating and controlling an energy- producing burning plasma. The scale of research facilities within the United States would be more costly. The achievement of electricity production from fusion in the United States would be delayed.

Physics 2020: A Decadal Assessment of Plasma Science

Previous Decadal Report



2010 Plasma Decadal Survey
(Chair: Steve Cowley)

- **Objective**
  Conduct a study of the past progress and future promise of plasma science and technology and provide recommendations to balance the objectives of the field in a sustainable and healthy manner over the long term

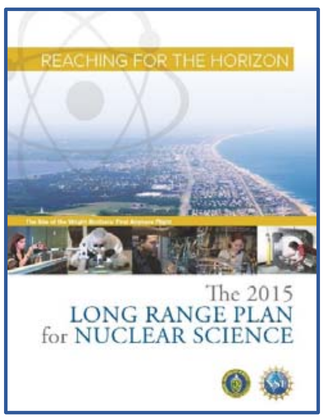
- **Multiple federal sponsors**
  - **DOE** (FES, HEP, NNSA, ARPA-E); **NSF**; **DOD** (AFOSR, ONR)

- **Co-Chairs:**
  – Prof. Mark J. Kushner (U. Michigan)
  – Prof. Gary P. Zank (U. Alabama-Huntsville)

- **Meetings so far:**
  – First public meeting: October 15 (Washington DC) – [***FES talk***]
  – Town Hall: November 6 at APS-DPP Mtg (Portland)
  – Public meeting: January 10-11 (Irvine) – [***FES talk***]
  – Public meeting: March 5-6 (virtual)
  – Public meeting: March 11-12 (Washington DC) – [***FES talk***]
  – Public meeting: April 18 (Princeton)

Long-range strategic planning activity launched in FY 2019 for FES program

- The plan will be comprehensive and will include all FES program areas
- Process is similar to that used by the Office of Science High Energy Physics (HEP) and Nuclear Physics (NP) programs for the development of the HEP-P5 report and NP-Long Range Plan



Phase 1: Community-organized activities

Community Awareness
Inform the community that a FESAC charge is coming

⇩

Subfield community self-organization

⇩

FESAC charge issued

⇩

FES tasks APS-DPP to convene topical town hall meetings

⇩

"Snowmass" meeting

Phase 2: FESAC federal advisory committee

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FES is pursuing new opportunities near-term

- **Underway:**
  - DIII-D: new facility enhancements and refurbishment; expanded user base
  - NSTX-U: Recovery/repair activities are being baselined
  - Theory/simulation: 9th SciDAC center; QIS solicitation; ML/AI workshop
  - International: W7-X pellet injection fueling system; JET shattered pellet injector; EAST 3rd shift remote operation
  - Materials: MPEX as an MIE project (CD-0)
  - General plasma science: 2nd university collaborative research facility
  - HEDLP: LaserNetUS

- **Pursuing**:
  - Enabling R&D: HTS conductor testing facility
  - Nuclear Science: Prototypic fusion neutron source
  - HEDLP: Petawatt laser facility (CD-0)
  - Private-public partnership pilot program