Context for an NAS study on burning plasma research and a magnetic fusion strategy

Edmund J. Synakowski
Associate Director, Office of Science
Fusion Energy Sciences

U.S. DEPARTMENT OF ENERGY
Office of Science

For the Committee addressing “A Strategic Plan for U.S. Burning Plasma Research”

National Academies June 5, 2017

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DOE requests an NAS study on strategic priorities for fusion energy for the long range, and the place of burning plasma science

- Progress in magnetic fusion energy research has been tremendous on many fronts in the last 20 years, and serves as the underpinning of the community's readiness for studying high gain, energy producing burning plasmas

- However, while study of the self-heated plasma state – burning plasma – is essential, it has not yet been achieved in the laboratory and remains the leading grand challenge for fusion energy science

- The 2004 NAS study states burning plasma science represents an essential next step for fusion

- Many countries are developing and acting on plans that embrace burning plasma research and aim to impact the world energy scene in the 2nd half of this century

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U.S. Fusion Energy Sciences program supports both fusion and plasma science

Mission

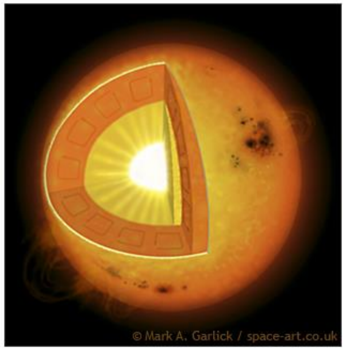
The mission of the U.S. Fusion Energy Sciences (FES) program is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundations needed to develop a fusion energy source. This is accomplished by the study of the plasma state and its interactions with its surroundings.

Objectives

- Advance the fundamental science of magnetically confined plasmas for fusion energy
- 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

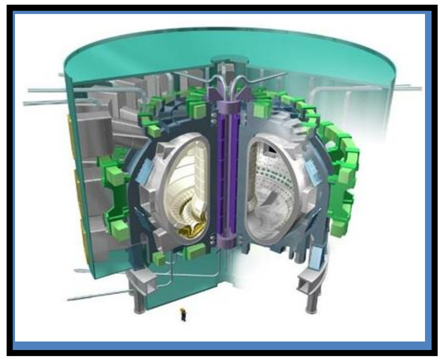
The science of fusion and plasmas extends from the laboratory to the stars and beyond

Sun: interior…

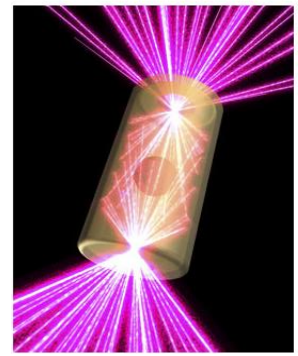


gravitational confinement

magnetic confinement for energy

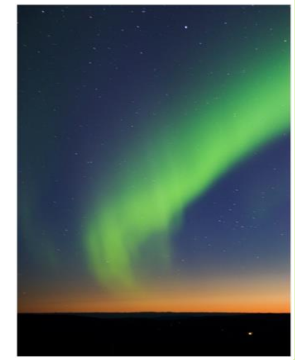


NIF hohlraum

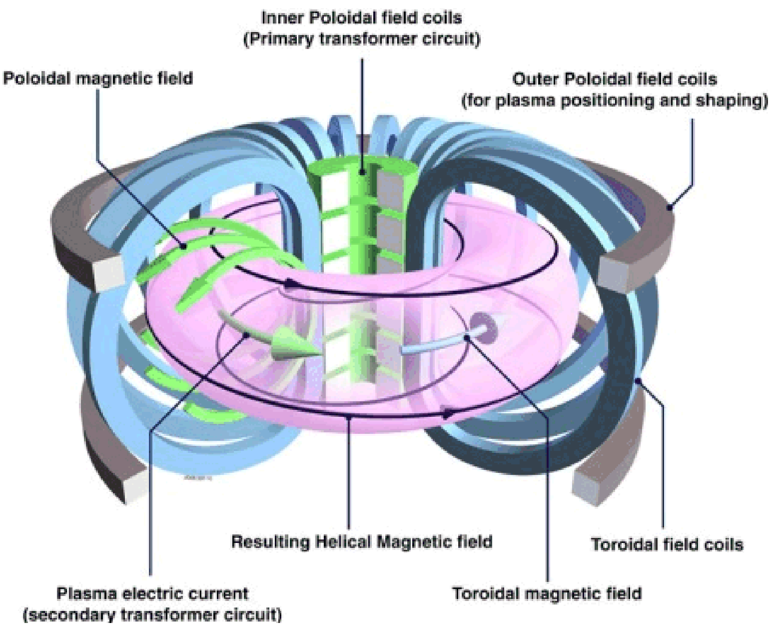


inertial confinement

aurora



magnetic confinement near the sun



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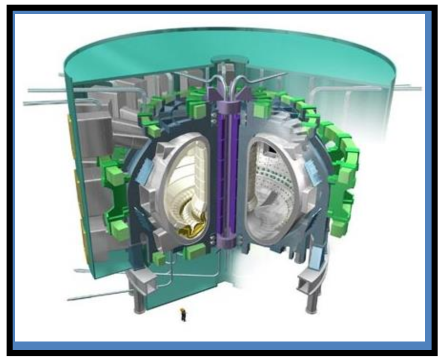
The study being requested by DOE focuses on magnetic confinement fusion for energy

Sun: interior…

gravitational confinement

magnetic confinement for energy



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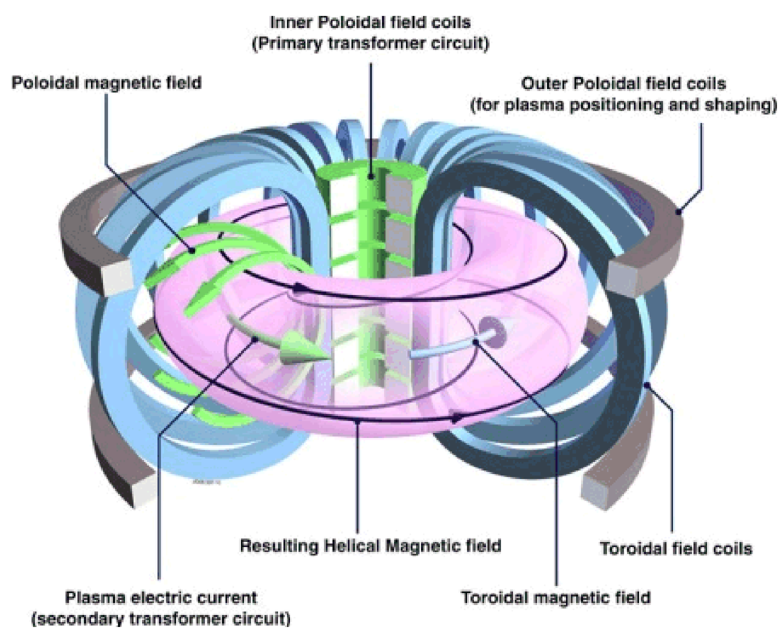
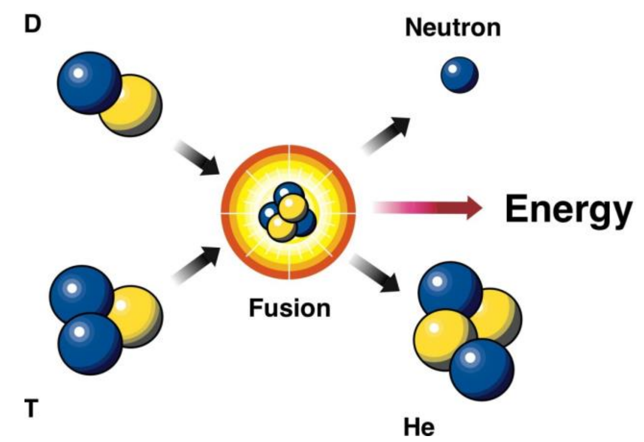
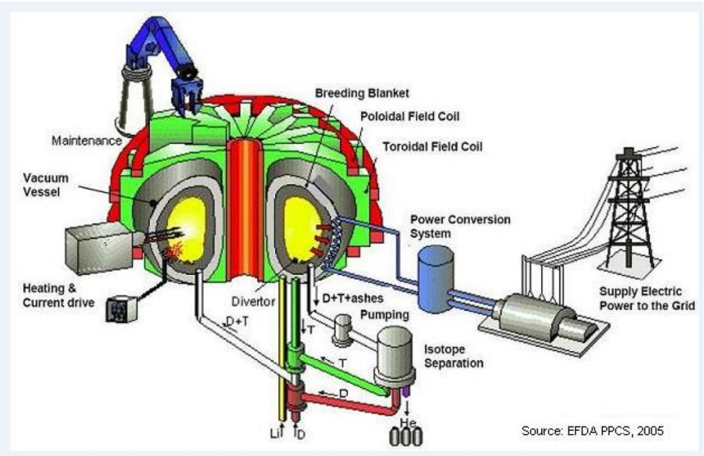
magnetic confinement near the sun



Vision: fusion could create baseload power with zero carbon emissions

- A little mass of the fuel, D and T (isotopes of hydrogen), is converted into a huge amount of energy in the neutron and the helium
- D is plentiful
- T can be generated from lithium (plentiful)
- Helium is a byproduct
- Zero carbon emissions





In the last two decades, there has been significant scientific advance (1)

- The causes of cross-field transport of heat and fuel in prototypical magnetic fusion reactor experiments are now known
  - This "standard model" for confinement based on an understanding of underlying turbulence at ion and electron scales is maturing

- Macroscopic stability has gone from "well-characterized stability limits" of the fusion plasma to *"controlled, with precision"*
  - Active feedback control reduces risks of deleterious instabilities in a reactor
  - Increases the fusion power for a given magnetic confinement system size

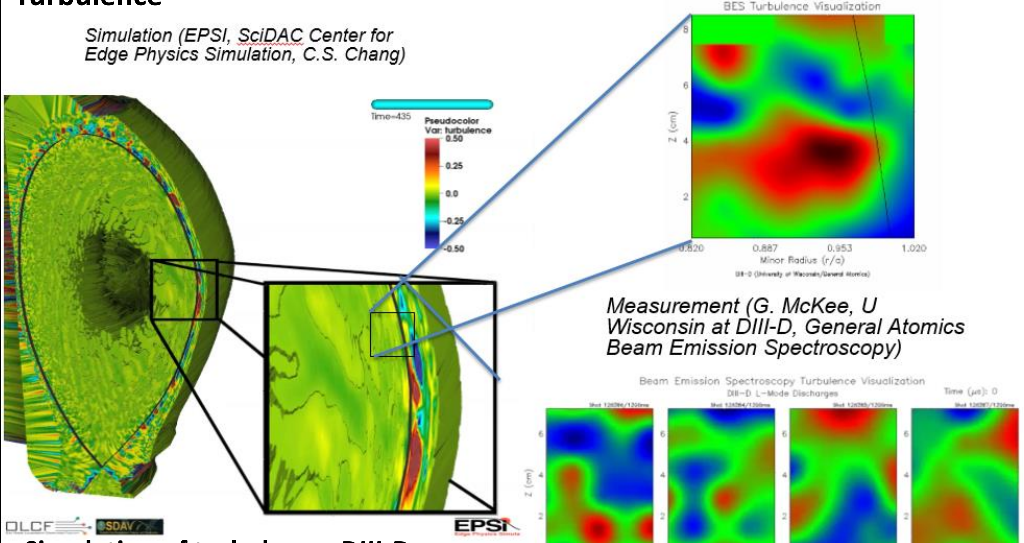
- While still a leading challenge, candidate materials for withstanding fusion's harsh heat fluxes and neutron fluences are being developed, and "materials by design" promises to advance them further

In the last two decades, there has been significant scientific advance (2)

- Computing and detailed measurement have ushered in an age of predictability that can impact fusion's development path

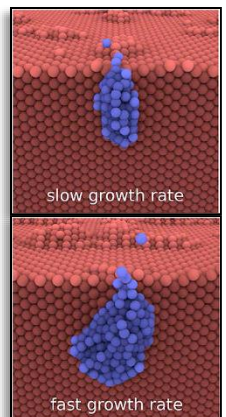
- Validated, whole device modeling is within reach

Turbulence



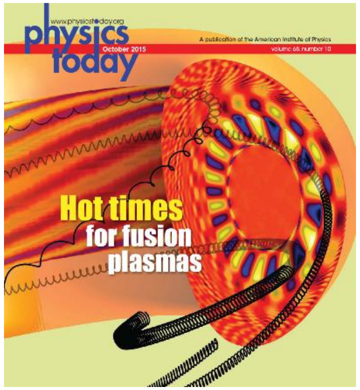
Simulation of turbulence, DIII-D tokamak plasma cross section

Materials



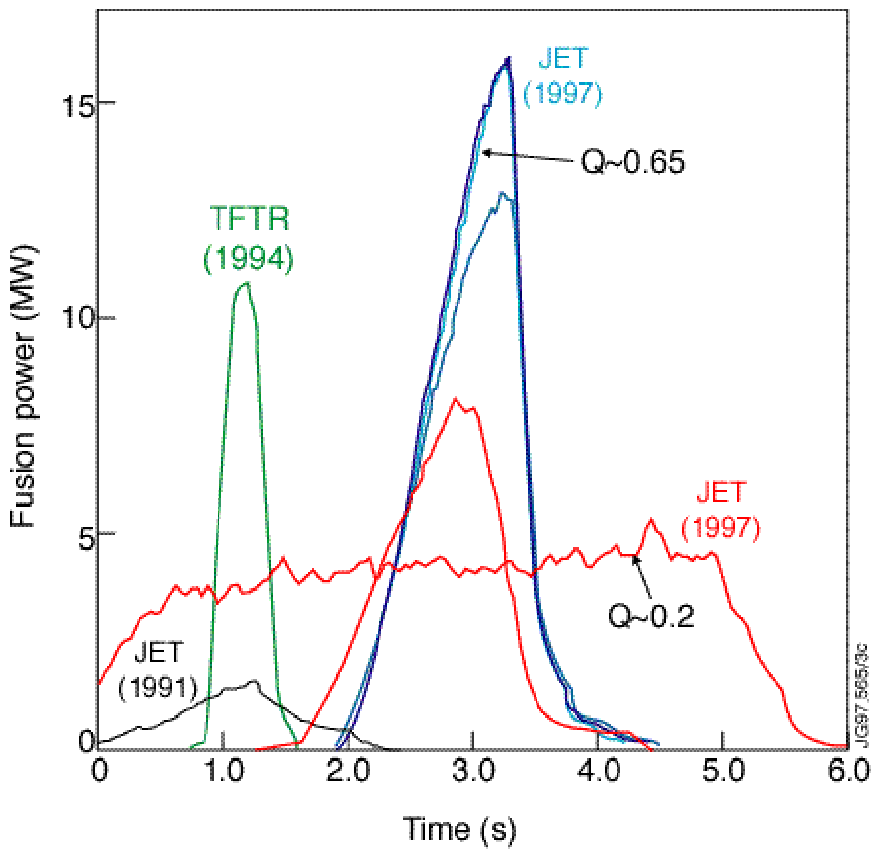
L. Sandoval et al., Phys. Rev. Lett (2015); PSI-SciDAC (PI: Brian Wirth)

Fast Ions



In the last two decades, there has been significant scientific advance (3)

- Megawatts of fusion power have been generated in the laboratory

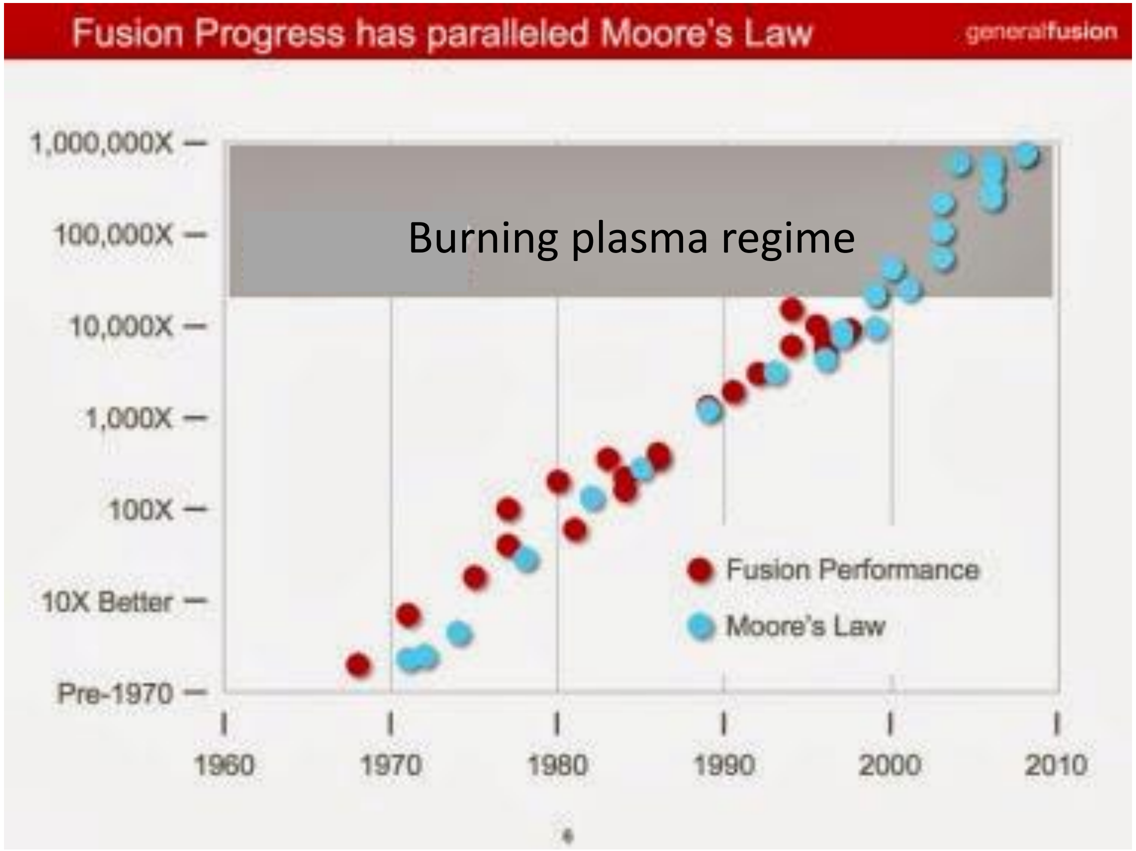


- **Joint European Torus (JET)**
  - “Preliminary Tritium Experiment” (1991): 90/10 DT, $P_{DT} > 1$ MW
  - Subsequently: 50/50 DT
    - Q=0.65 (transient breakeven)
    - Q=0.2 (long pulse)
    - 16 MW fusion power, 100 discharges

- **Tokamak Fusion Test Reactor (TFTR)**
  - Dec 1993 to Apr 1997: 1000 discharges with 50/50 D-T fuel
  - P_{DT} = 10.7 MW, Q=0.2 (long pulse)
  - Results:
    - Favorable isotope scaling
    - Self-heating by alpha particles
    - Alpha-driven instability
    - Tritium and helium “ash” transport
    - Tritium retention in walls and dust
    - Safe tritium handling (1M curies)

Yet, despite progress in performance that rivals that of computer chips, the critical step to the reactor regime remains to be taken

- The burning plasma" state, where the fusion fuel heats itself, is required
- To achieve it, what is needed is to take the next step to reactor scale



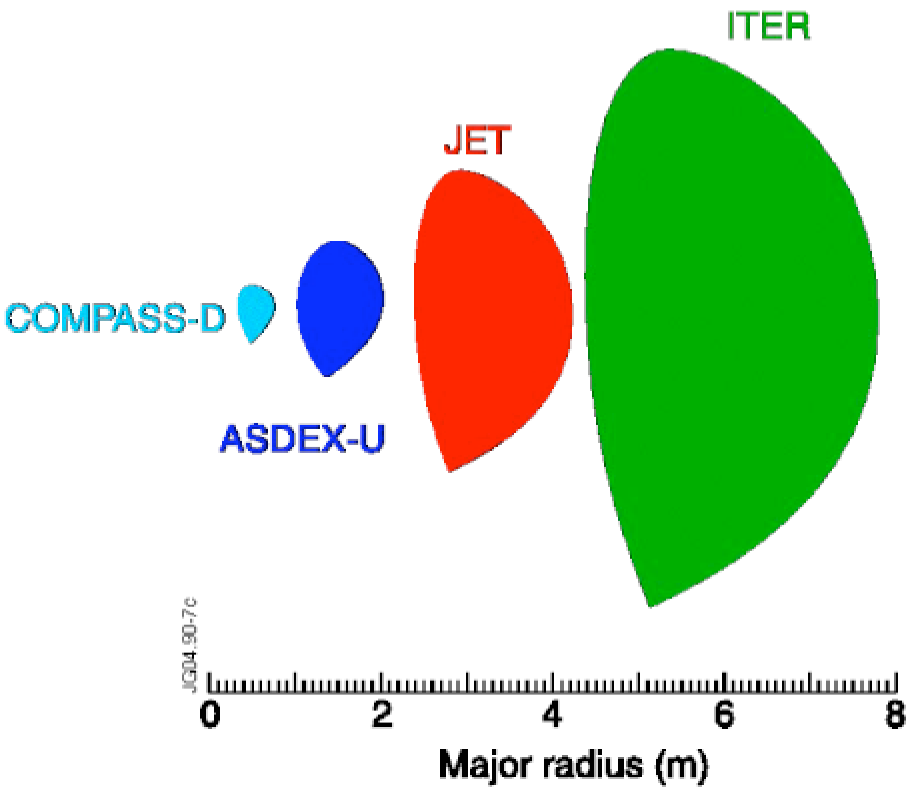
Breakeven: $Q = P_{fusion} / P_{in} = 1$

Burning Plasma: $Q = 5$

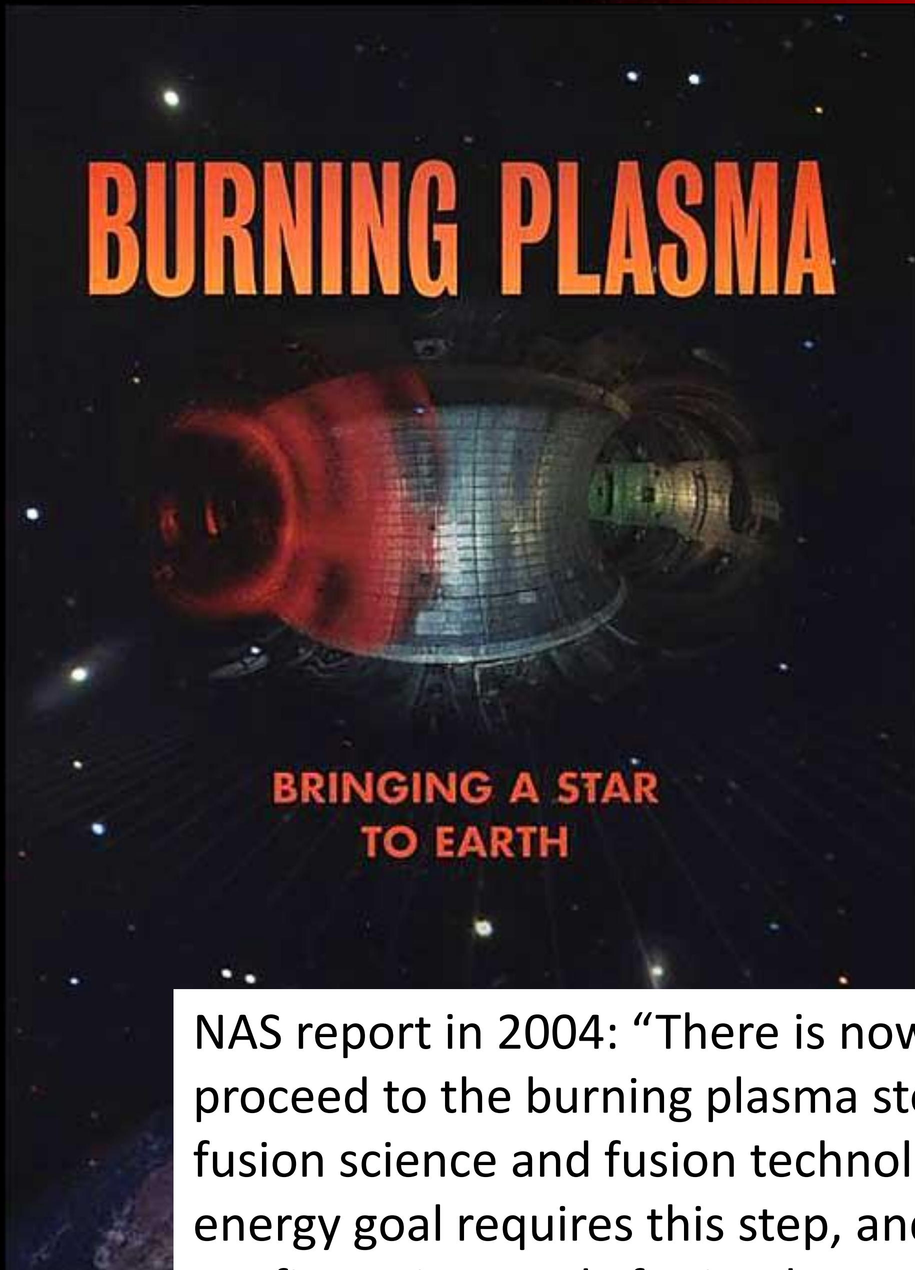
Ignition: $Q = \infty$

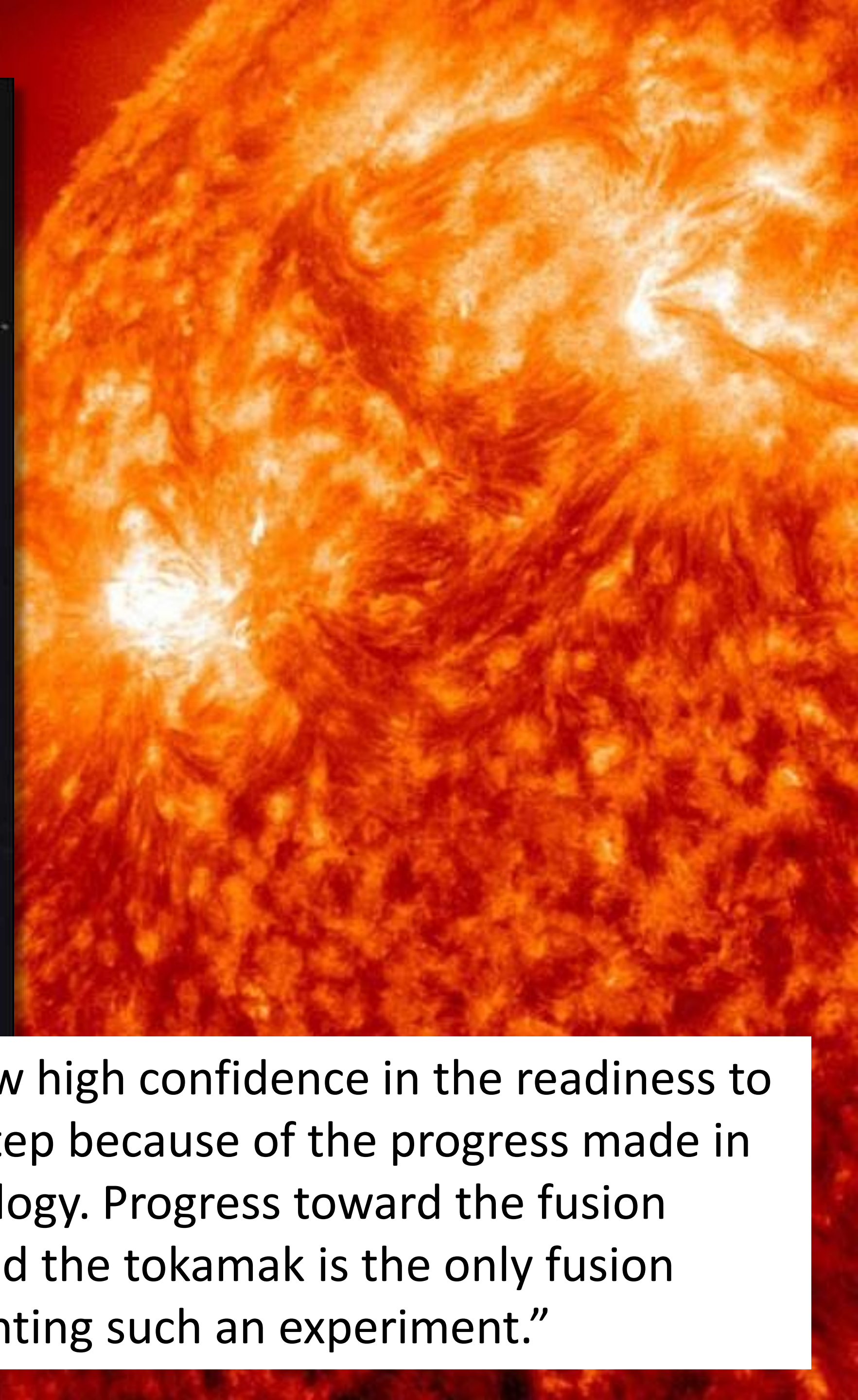
Essential, new burning plasma science will be revealed at reactor scale

- Strong coupling
  - The critical elements in the areas of transport, stability, boundary physics, energetic particles, heating, etc., will be strongly coupled nonlinearly due to the fusion self-heating
- Size scaling of confinement
  - Due to much larger volume than present experiments, size scaling of fundamental processes becomes important
- Large population of high energy alpha particles
  - Affect stability and confinement



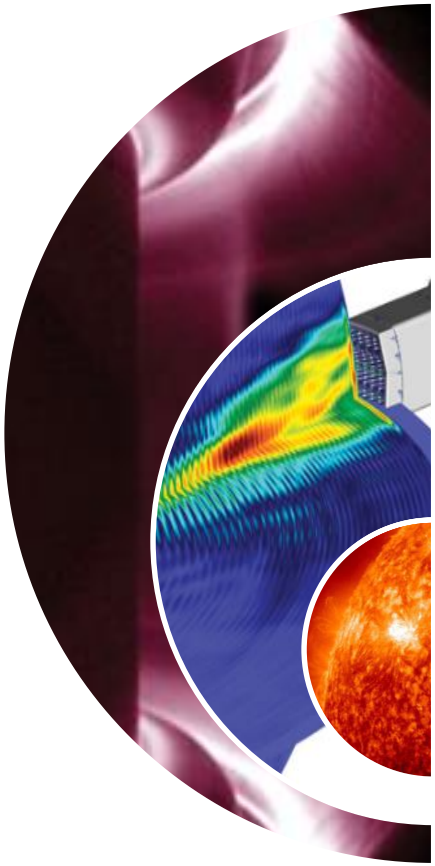
Cross sections of present EU D-shape tokamaks compared to the cross section of ITER





NAS report in 2004: “There is now high confidence in the readiness to proceed to the burning plasma step because of the progress made in fusion science and fusion technology. Progress toward the fusion energy goal requires this step, and the tokamak is the only fusion configuration ready for implementing such an experiment.”

The U.S. program is shaped around supporting burning plasma science



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

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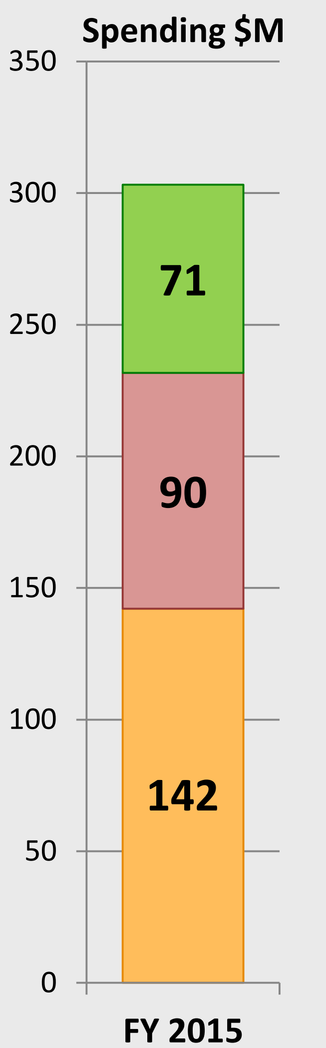
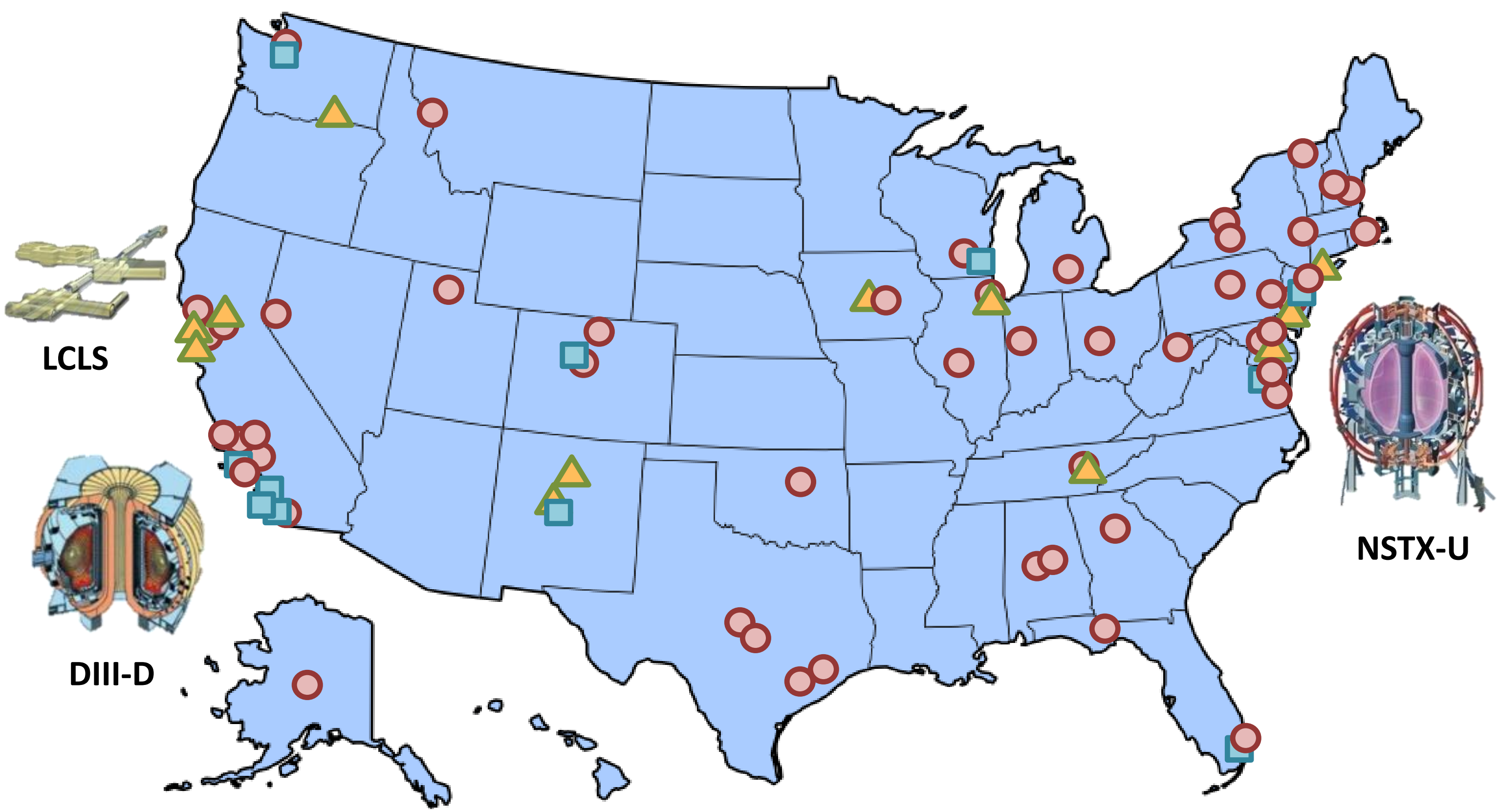
FES research is carried out at a diversity of US institutions



53 universities

12 businesses

10 laboratories



Fusion Energy Sciences

FY 2017 budget highlights

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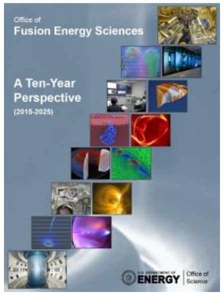


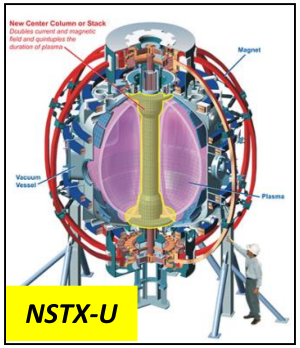
This budget proposes investments in areas of strategic importance, as described in the *FES Ten-Year Perspective* plan submitted to Congress

Community workshops in 2015 have been highly successful in identifying research opportunities and how to address them

Burning Plasma Science: Foundations

- Vigorous research and operations of NSTX-Upgrade and DIII-D, including upgrades
- Enhanced off-site research participation, including with MIT researchers
- Research on smaller platforms at universities is being aligned with the larger programs
- SciDAC targets whole device modeling, of high strategic importance

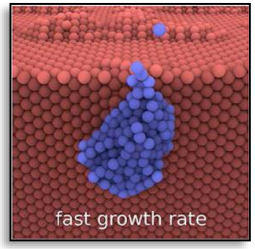
DIII-D



NSTX-U

Burning Plasma Science: Long Pulse

- U.S. research collaborations on international superconducting facilities by three lab-university-industry teams
- Materials science for first-of-a-kind, world-leading research



Computing & tungsten damage (Wirth, Lawrence Prize)

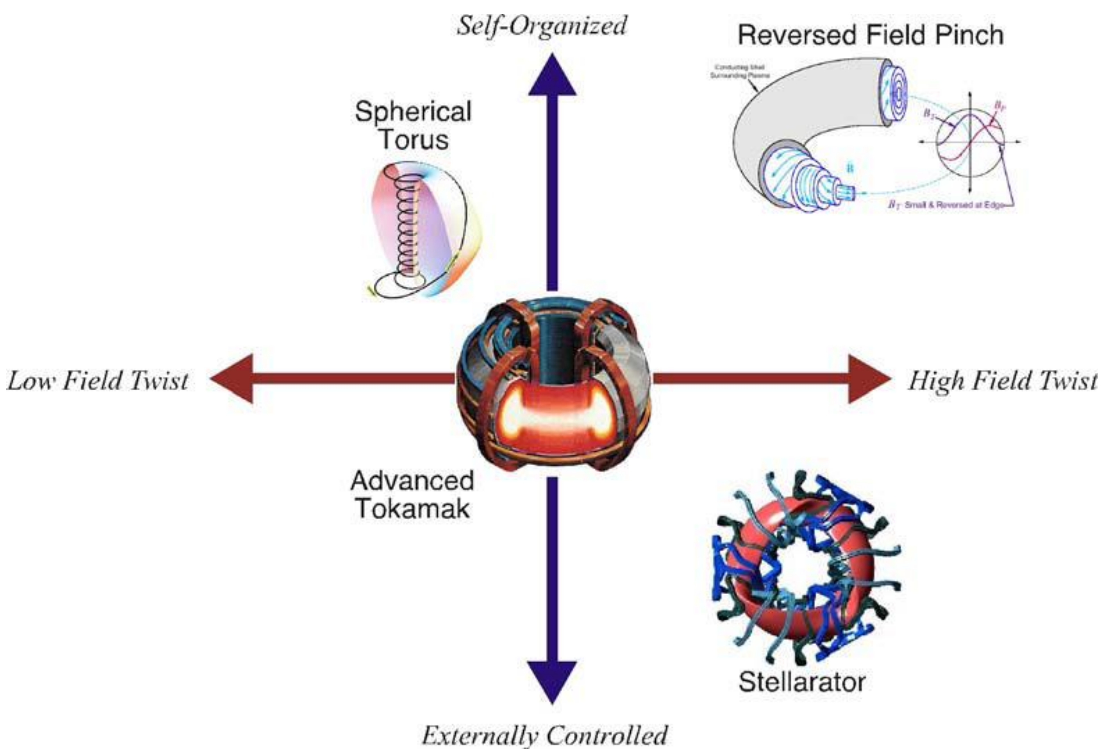
W7-X – Chancellor Merkel and Princeton U. VP for PPPL Smith

At DIII-D (San Diego): Remote control of EAST (China)

DOE's view today regarding ITER's potential impact on magnetic fusion

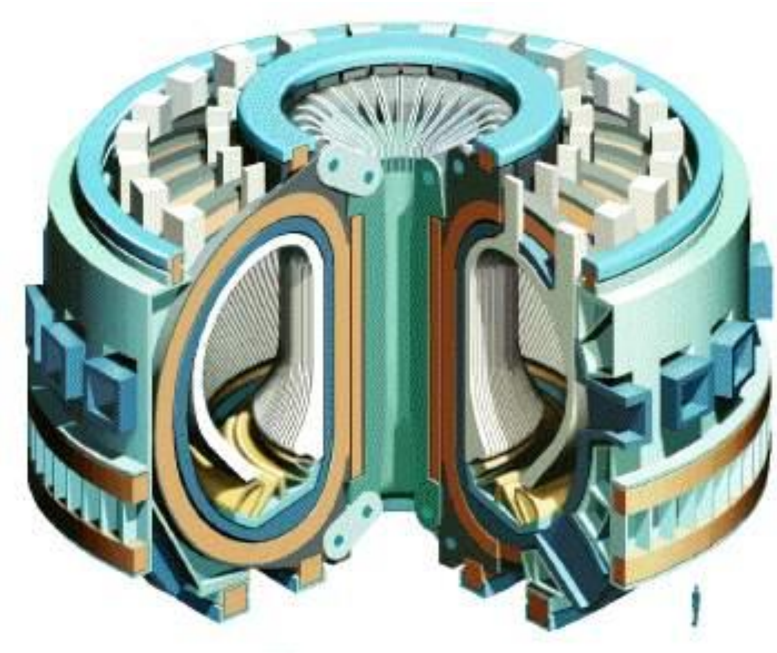
– The tokamak will inform any credible magnetic fusion energy approach regarding alpha physics, and is far and away the most mature platform for getting to this physics

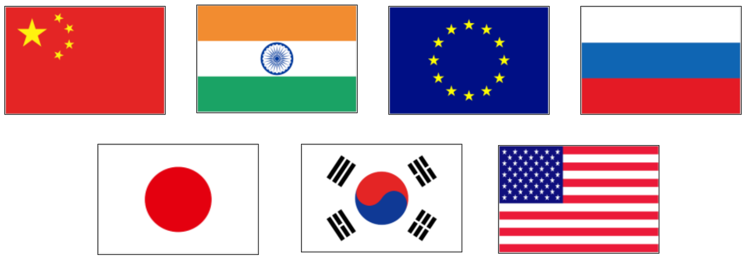
– ITER is still the platform best positioned for this



The US is a 1/11th partner in the world's major step forward in fusion research: ITER

ITER will demonstrate the scientific and technical feasibility of fusion energy





ITER ("the way") is the essential next step in development of fusion

- ***As of today***: 10 MW, 1 sec, gain < 1
- ***With ITER***: 500 MW, > 400 sec, gain ≥ 10 (and ITER Phase-II to achieve 3000 seconds, gain = 5)
- Uncharted science, leveraging US intellectual investments
- Major contributions from US industry

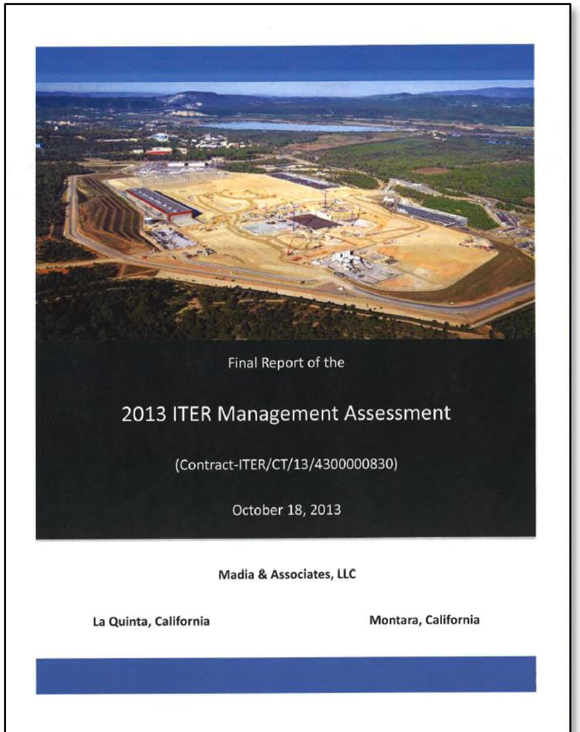
The world's biggest fusion energy research project ("burning plasma")

- 15 MA plasma current, 5.3 T magnetic field, 6.2 m major radius, 2.0 m plasma minor radius, 840 m^3 plasma volume, superconducting magnets

An international collaboration

- 7 Member partners, representing 50% of world's population
- EU the host Member, site in France

The international ITER project has experienced major challenges


Final Report of the

2013 ITER Management Assessment

(Contract-ITER/CT/13/4300000830)

October 18, 2013

Madia & Associates, LLC

La Quinta, California

Montara, California

- Delays: Previously the ITER Council approved a schedule targeting 2019 first plasma. Present technically achievable schedule is 2025, at best

- Cost: CD-1 Cost Range for the US contributions was $1.1-2.2B. Latest estimate (being reassessed) > $4B

- <u>The 2013 Management Assessment</u>, performed biannually, revealed profound management challenges at the international ITER Organization (IO). This encouraged accelerating replacement of the Director General to the spring of 2015

Management Assessment recommendations:

1. Create a Project Culture
2. Accelerate the Director-General transition
3. Hold the Director-General accountable for resolving conflicts
4. Reduce the number of senior managers in the ITER Organization
5. Strengthen Systems Engineering
6. Instill a strong Nuclear Safety Culture
7. Develop a realistic ITER Project Schedule
8. Align the interests of the ITER Organization and the Domestic Agencies
9. Simplify and reduce the ITER Organization bureaucracy
10. Use Human Resources systems and tools as a strategic asset
11. Improve Advisory Assessment responsiveness

ITER Progress under the new DG

ITER Director General Bernard Bigot
photo ITER

- The new DG has brought in new senior management and reorganized the ITER Organization
- Focus on team-based collaborative efforts to accomplish goals with the Members
- Establishment of a construction reserve fund to pay for design changes
- Acceleration of pace of construction
- An achievable updated schedule is due to the ITER Council in November 2016
- Confirmation of construction progress by both an independent Management Assessment and by an independent Schedule Review

View of the ITER construction site: May 2017

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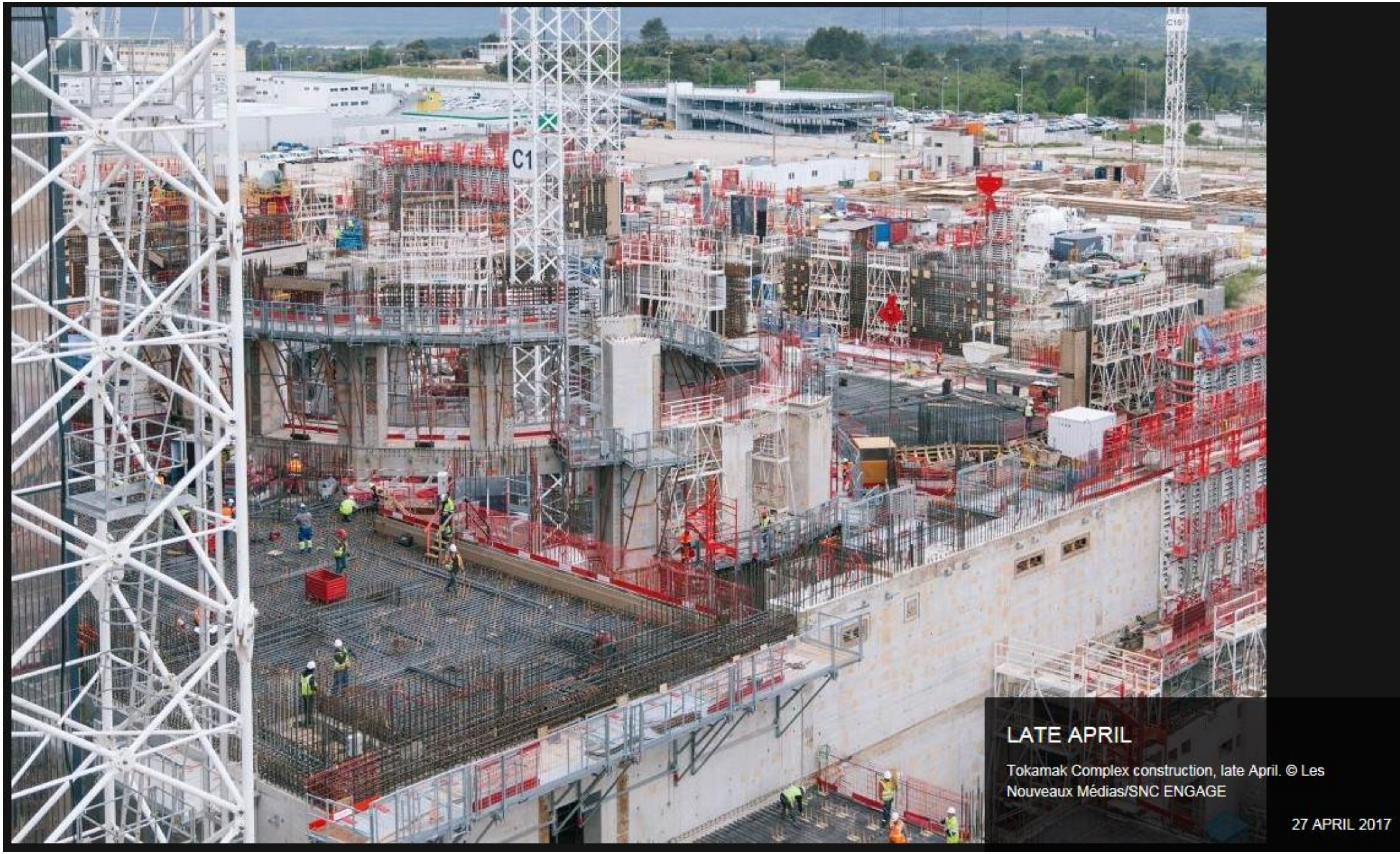
View of the ITER construction site



LATE APRIL

Tokamak Complex construction, late April. © Les Nouveaux Médias/SNC ENGAGE

27 APRIL 2017

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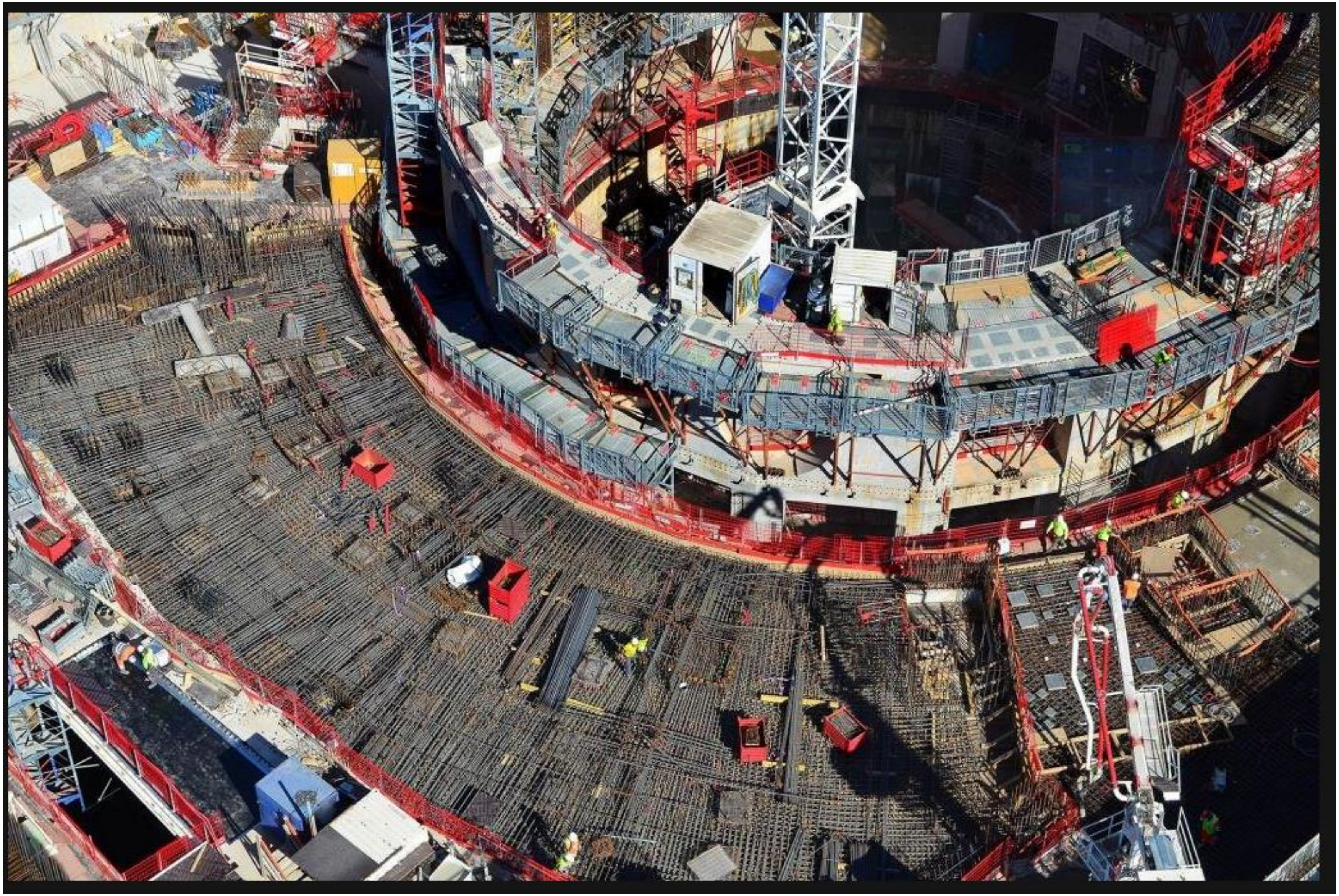
View of the ITER construction site: April 2017

View of the ITER construction site: April 2017



Contrast with February 2015

ITER Site as of November 2015

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

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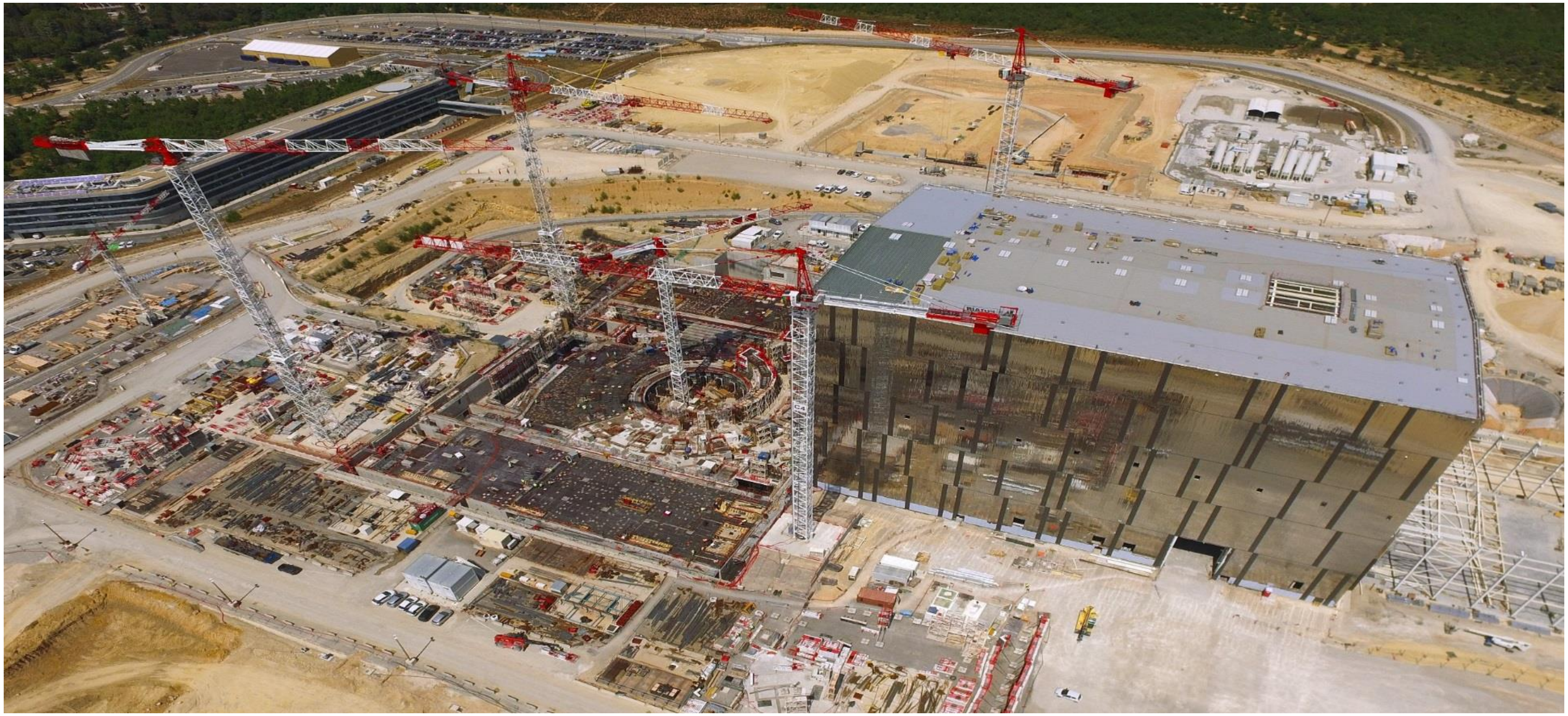
ITER Site Progress (through August 2016)



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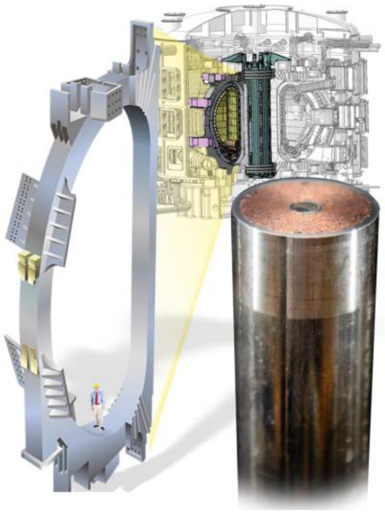
U.S. Fabrication of ITER Hardware Progressing

Central Solenoid (CS) fabrication facility is in operation at General Atomics

CS Module 1 being prepared for insulation

- U.S. Toroidal Field (TF) conductor contributions are complete
- All U.S. supplied TF conductor has been delivered and accepted
- Final conductor delivered to EU winding facility in January 2017



Electrical Power Transformers delivered to the ITER site

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From the Secretary's Report to Congress (May 2016)

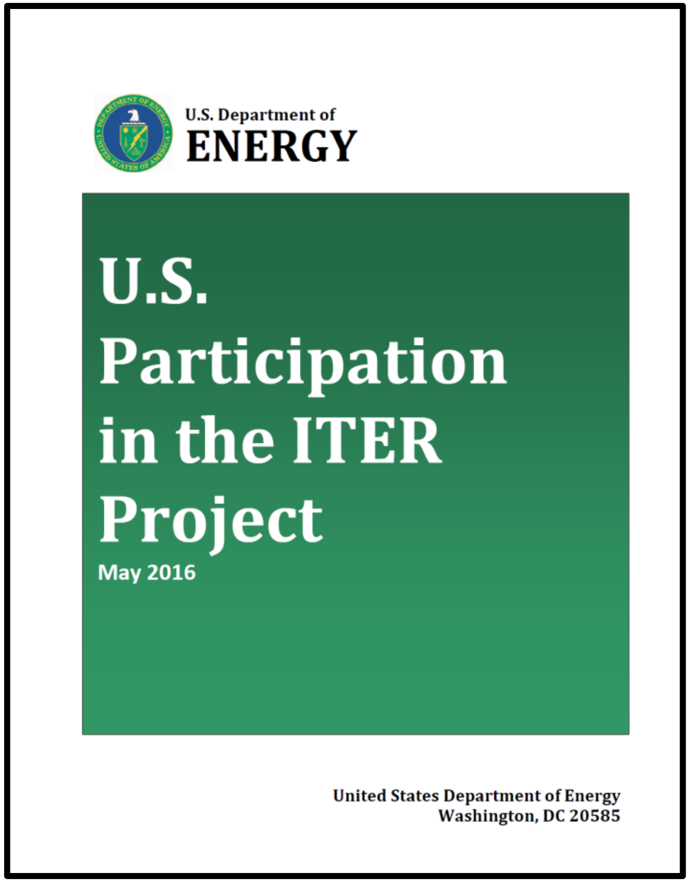
Department of Energy | May 2016
Report on the U.S. Participation in the ITER Project

Message from the Secretary

ITER remains the best candidate today to demonstrate sustained burning plasma, which is a necessary precursor to demonstrating fusion energy power. Having fully assessed the facts regarding the U.S. contributions to the ITER project**, I recommend that the U.S. remain a partner in the ITER project through FY 2018** and focus on efforts related to First Plasma. The U.S. along with all ITER Members across the world have witnessed and acknowledged the significant progress made at ITER by the new leadership, but there is still much that remains to be done. **Prior to the FY 2019 budget submittal (late in calendar year 2017 to early 2018), I recommend that the U.S. re-evaluate its participation** in the ITER project to assess if it remains in our best interests to continue our participation. My recommendation to support First Plasma cash and in-kind contributions is predicated on continued and sustained progress on the project, increased transparency of the ITER project risk management process, as well as a suite of management reforms proposed in this report that we expect will be agreed upon by the ITER Council. **At this time, our continued participation in the fashion recommended is consistent with DOE's science mission and is in the best interest of the nation.** The report discusses the critical issues that factored in this recommendation. (**bold** added for emphasis here)

Sincerely,

Ernest J. Moniz


U.S. Department of ENERGY

U.S. Participation in the ITER Project

May 2016

United States Department of Energy
Washington, DC 20585

http://science.energy.gov/fes/

The DOE report to Congress states that the Department will seek an NAS study on magnetic fusion

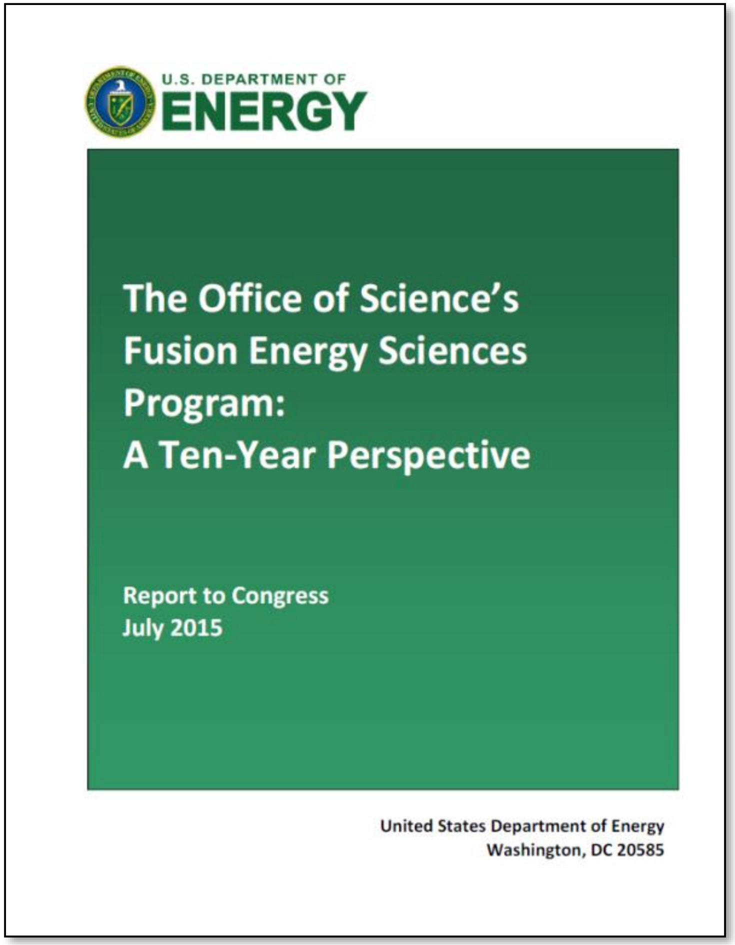
From the body of the report:

- The DOE will request that the National Academies perform a study of how to best advance the fusion energy sciences in the U.S., given the developments in the field since the last Academy studies in 2004, the specific international investments in fusion science and technology, and the priorities for the next ten years developed by the community and FES that were recently reported to Congress.

- This study will address the scientific justification and needs for strengthening the foundations for realizing fusion energy given a potential choice of U.S. participation or not in the ITER project, and will develop future scenarios in either case.

DOE has recently developed a 10 year strategic plan

- Per Congressional direction, the plan assumes ITER moves forward. It has five major themes:
  - ***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


U.S. DEPARTMENT OF ENERGY

The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective

Report to Congress
July 2015

United States Department of Energy
Washington, DC 20585

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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 (2015)	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 workshop reports

- **Each workshop is delivering a report that describes**
  - scientific challenges
  - implementation options to address the challenges
- **Three reports are completed and available online:**
  - Plasma-Materials Interactions
  - Integrated Simulations for Magnetic Fusion Energy
  - Plasma Transients

  http://science.energy.gov/fes/community-resources/workshop-reports/
- **The fourth report was just completed**
  - Frontiers of Plasma Science

  http://www.orau.gov/plasmawkshps2015/default.htm

- **FESAC commended the workshops:**
  - "At this FESAC meeting…we heard from the workshop chairs about the enormous community-wide effort to carry out these workshops, and the high degree of consensus in identifying priority research directions within these topics. We heard from FES that the workshop results are being used to help explain and shape the Fusion Energy Sciences program within the U.S. government. We were pleased to hear the workshop chairs unanimously express their satisfaction with both the community's support of the workshop goals and with FES's response to the results." [*Letter to Dr. Cherry Murray, Jan 14, 2016*]

FES and the community have been engaging in strategic planning activities for some time (1)

- FESAC's report, *Priorities, Gaps, and Opportunities: Towards a Long Range Strategic Plan for Magnetic Fusion Energy*, which has proved to be a major influence on FES program planning (2007).

- On Whole Device Modelling: *FESAC Fusion Simulation Project Panel Final Report* (2007)

- In 2008, FESAC evaluated magnetic confinement configurations other than tokamaks. This resulted in the *Report of the FESAC Toroidal Alternates Panel*

- From June 2009 through January 2010, FES conducted a series of four Research Needs Workshops (ReNeW), which resulted in the following reports: *Research Needs for Magnetic Fusion Energy Sciences* (2009);*Advancing the Science of High Energy Density Laboratory Plasmas* (2009);*Research Needs for Fusion-Fission Hybrid Systems* (2009);and *Basic Research Needs for High Energy Density Laboratory Physics* (2010)

- Regarding international partnerships, a FESAC study yielded *Opportunities for and Modes of International Collaboration in Fusion Energy Sciences Research during the ITER Era* (February 2012).

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FES and the community have been engaging in strategic planning activities for some time (2)

- In April 2012, DOE charged FESAC to assess priorities among and within the elements of the non-ITER part of the magnetic fusion energy sciences program, with special focus on research that supports burning plasma science, long-pulse/steady-state plasma operation, and fusion materials science. The report, *Priorities of the Magnetic Fusion Energy Program* (January 2013), made progress in prioritizing among the thrusts in the 2009 *Research Needs for Magnetic Fusion Energy Sciences* report. Due to issues with conflict of interest, the report did not answer the full charge.

- In 2013, DOE charged the federal advisory committees of all six Office of Science program offices to evaluate facility priorities for the next decade. FESAC responded with *Report of the FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science* (2013).

- In 2014, Congress tasked DOE to develop a strategic plan for the next ten years. It was to assume U.S. participation in ITER and assess priorities based on three funding scenarios. This led to a FESAC report, *Report on Strategic Planning*, that again was challenged by conflict of interest issues. This report, the other activities listed here, and other considerations led to the FES Ten Year Perspective, issued in 2015 to Congress.

- A series of five community-led workshops were carried out in 2015 to identify research opportunities in the areas identified in the 2015 report

What about fusion beyond ten years, towards mid-century?

Much has happened since the NAS report in 2004

For example,

- There have been major investments in research facilities overseas, and international partners seek to grow U.S. participation

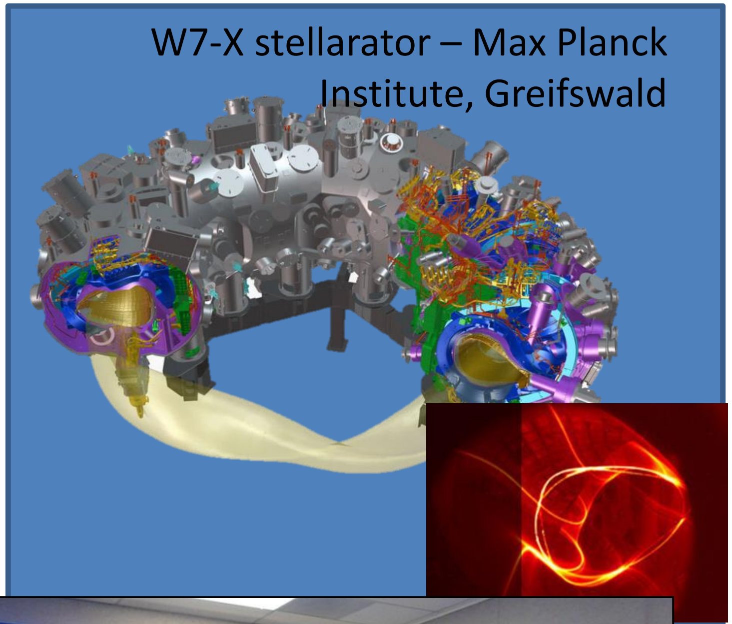
- The potential for computational research to transform the fusion landscape in ways we don’t fully appreciate is real

- Developments in fusion-related technologies, e.g., materials, high T_c magnets, precision engineering, control systems

- Other countries have developed plans that extend to mid-century

We seek guidance on long-term strategic priorities. The landscape is complex

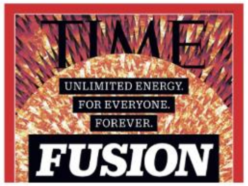
- International investment besides ITER has been aggressive and smart
  - New superconducting facilities in CN, KO, and the EU– tokamaks and stellarators, a cousin of the tokamak some see as a preferred option
  - What is the place of collaborative research in the long term?



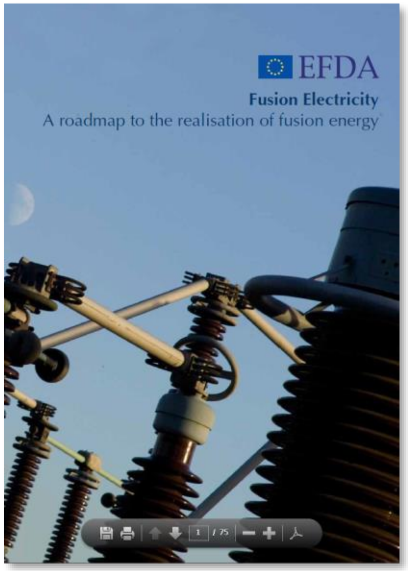
W7-X stellarator – Max Planck Institute, Greifswald

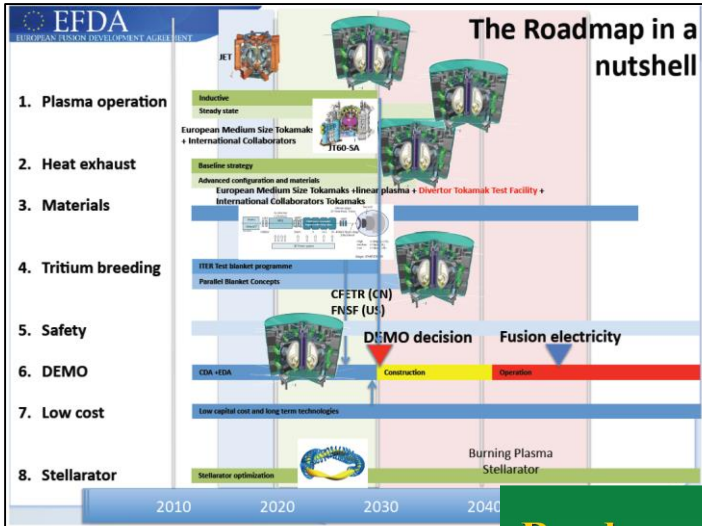
General Atomics Remote Control Room supports 3rd shift operation of EAST by US scientists

- Private industry activity is growing



The EU and China have developed roadmaps that have ITER as a centerpiece that aim to get electricity on the grid by mid century





European roadmap, published by European Fusion Development Association (EFDA), 2012

China has a roadmap, with a stronger separate emphasis on demonstrating closing the fuel cycle and materials testing

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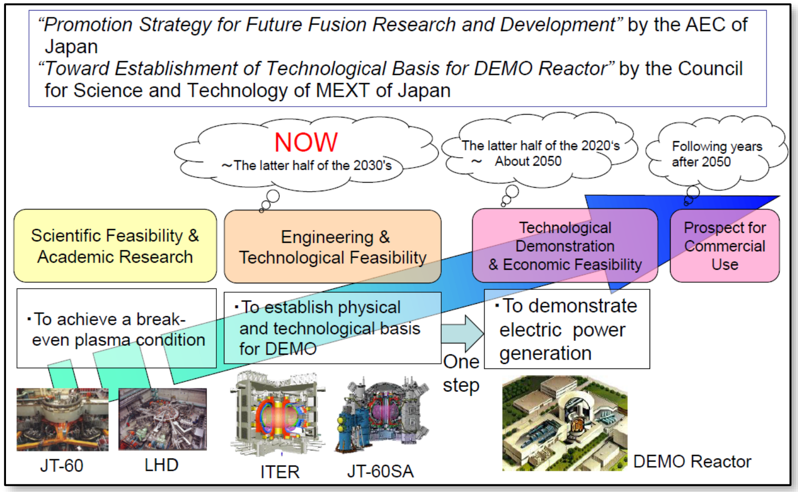
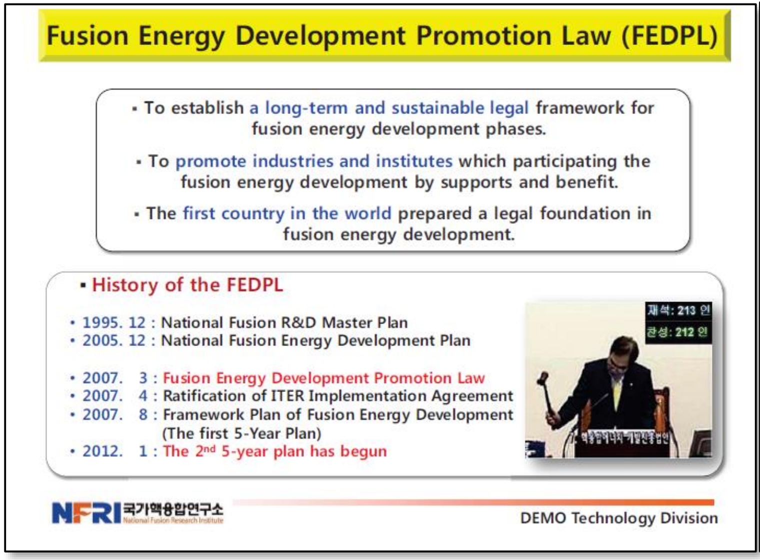
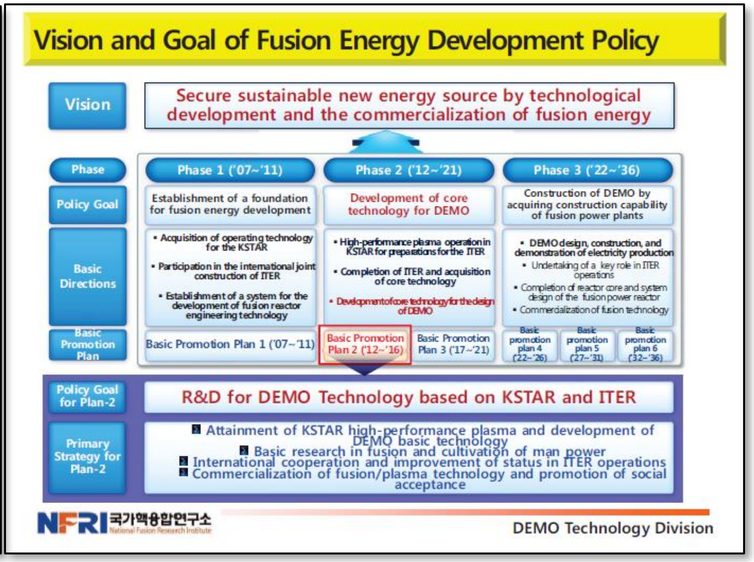
Japan and Korea also have developed roadmaps that have ITER as a centerpiece that aim to get electricity on the grid by mid century



Japan's roadmap includes ITER operations in parallel with their own emergent superconducting tokamak, JT-60SA

South Korea has a roadmap as well as a legal framework for fusion energy development phases





We ask the NAS to look beyond ten years and out several decades

- DOE is interested in NAS's view on strategic priorities in a research world with ITER and without ITER, looking out over the next several decades
- Assume a vigorous ITER program
  - Given U.S. capabilities and Administration emphases in fusion and related sciences, in what direction should magnetic fusion energy research point?
  - Consider the state and evolution of experiments, computation, materials science, global developments, university/lab/industry involvement
- Also look at the case where the US is not involved with ITER
  - What should be the major features of the US research program?
  - Consider the state and evolution of experiments, computation, materials science, global developments, university/lab/industry involvement