U.S. Department of Energy

Office of Science

Overview of the Fusion Energy Sciences Program

Office of Fusion Energy Sciences

Excellent Science Attractive Energy

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Road Map

This talk will address your objectives by discussing DOE's Fusion Energy Sciences Program in the following topics:

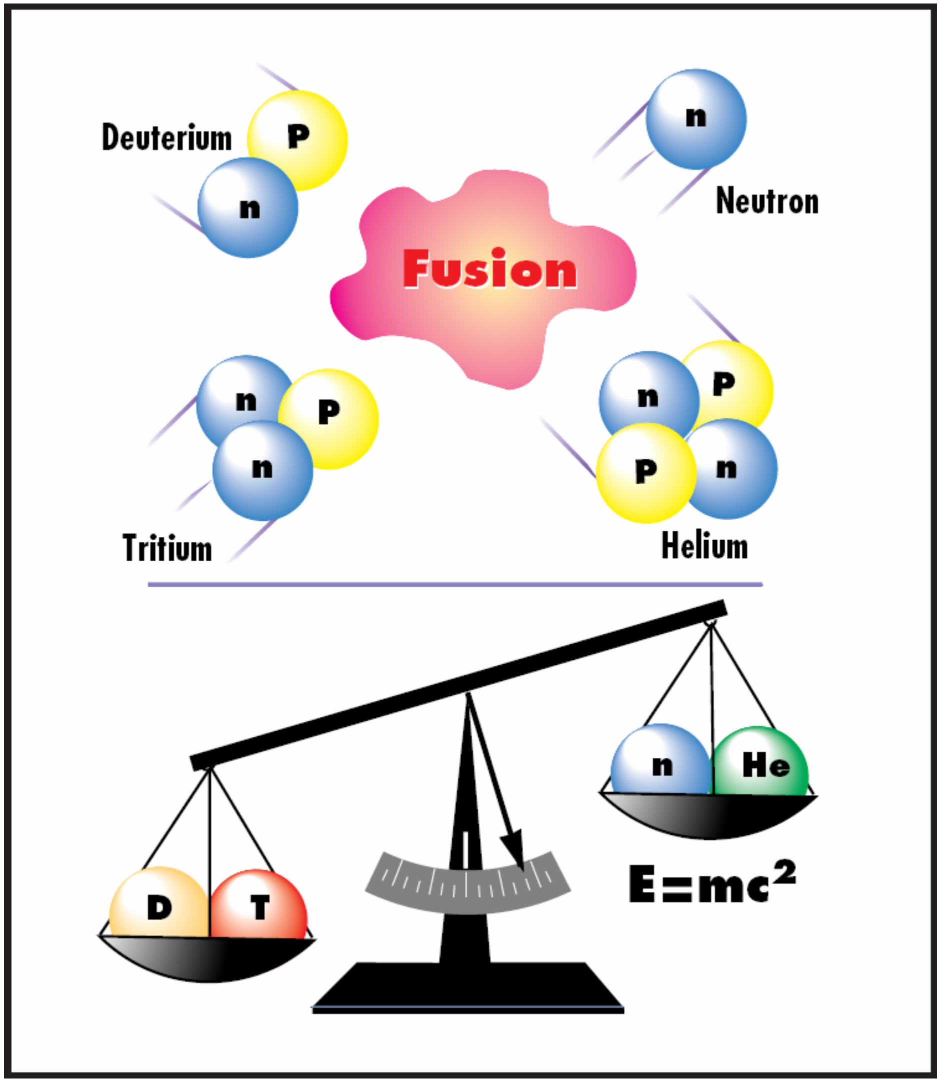
- Mission
- What is Fusion
- ITER
- U.S. Magnetic Fusion Facilities
- Theory and Computation
- Enabling Technologies
- Innovative Confinement Concepts
- Inertial Fusion Energy and High Energy Density Plasma Physics

Mission

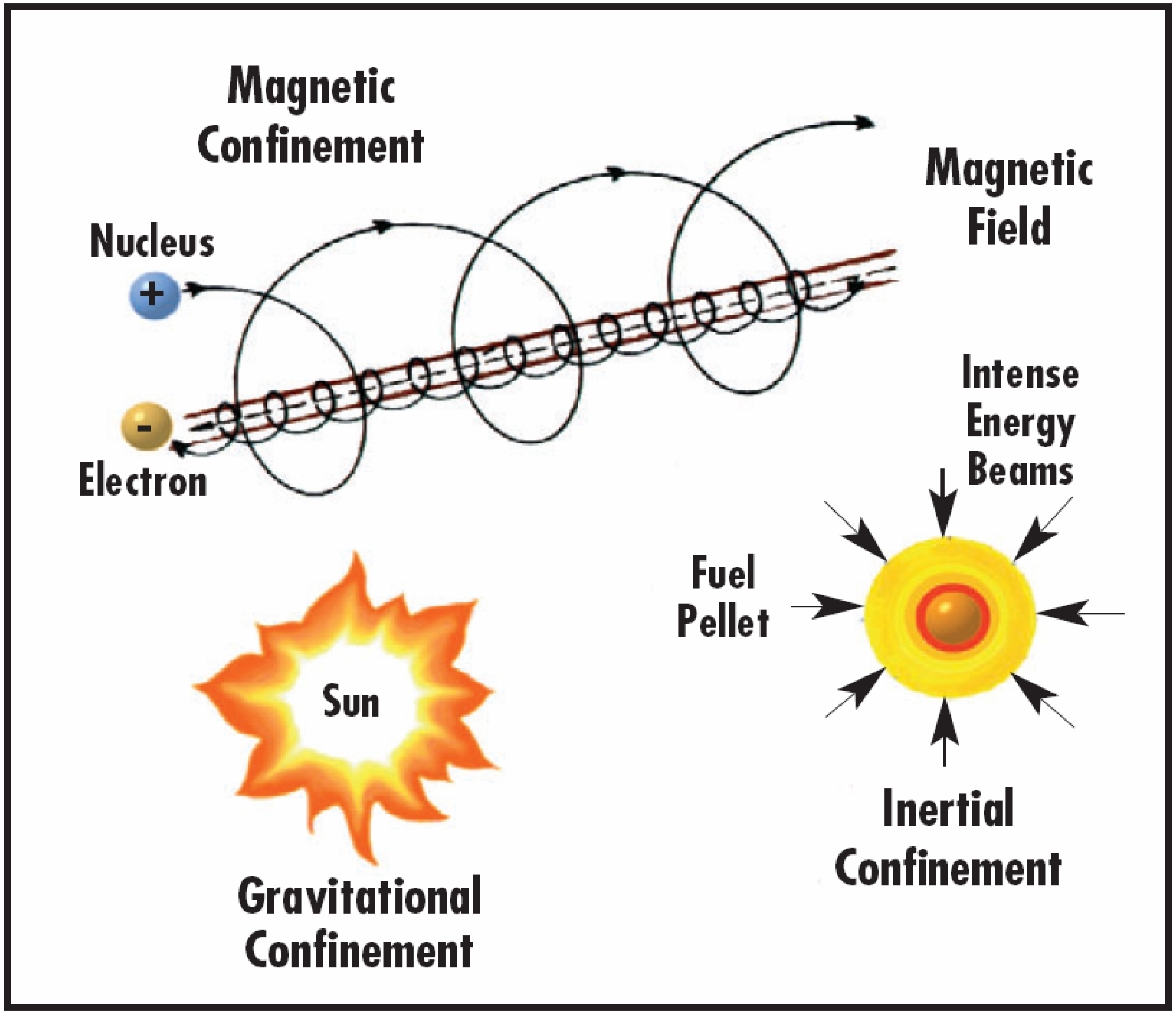
"Advance plasma science, fusion science, and fusion technology – the knowledge base needed for an economically and environmentally attractive fusion energy source."

What is fusion?

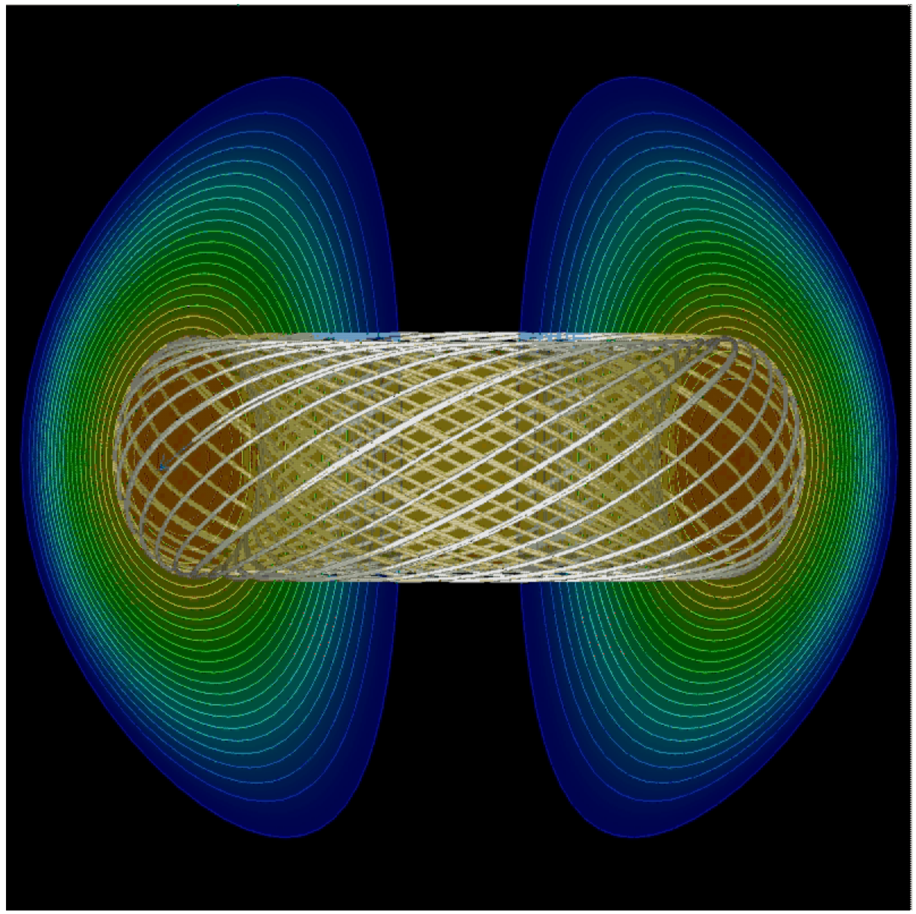
- Two light atoms combine into a larger atom
- In the process, mass is converted into energy
- Easiest reaction to induce combines deuterium ("heavy hydrogen") with tritium ("heavy-heavy hydrogen") to make helium and a neutron



Earth-bound suns use either magnetic or inertial confinement for practical energy production



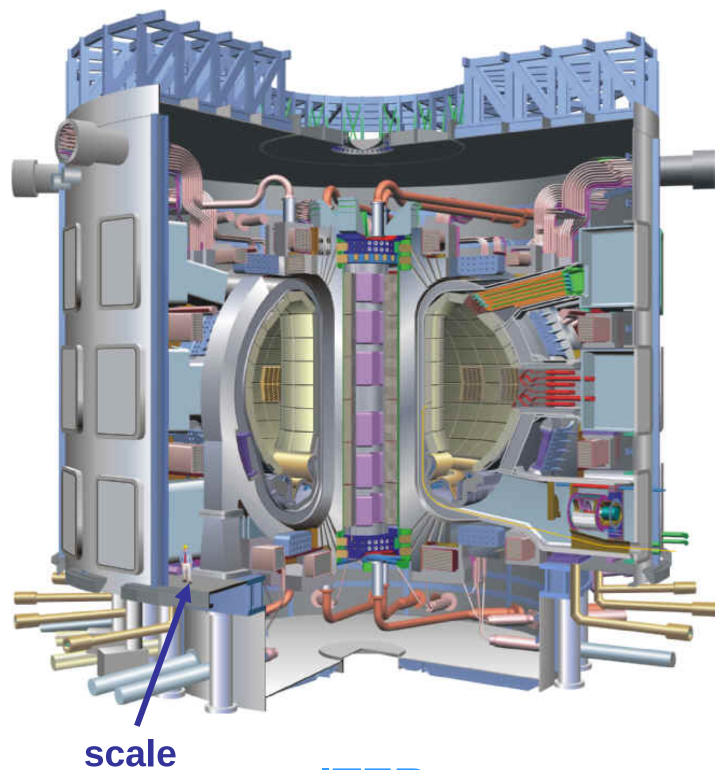
The tokamak is the most advanced magnetic bottle



The ITER tokamak is the next major step

ITER Marks a Bold New Era for the World Fusion Program

- ITER will be the world's first experiment capable of sustaining burning plasmas
  - Most plasma heating provided by the internal fusion process
  - Goals: 500 MW produced for 500 seconds, Power gain of 10
- Seven ITER parties represent over half of the world's population
  - China, European Union, India, Japan, Russia, South Korea, and United States
- ITER Agreement establishes a 35 year program of construction, operation, deactivation and decommissioning
  - Initiated at Reagan-Gorbachev summit in 1985
  - Operations begin ~2015
- Well-integrated with world-wide fusion development program
  - Will provide experimental results and validated suite of codes for design of demonstration power plant



ITER
Cadarache, France

Conceptual and Engineering Design Activities 1986-2001

- ✓ **CDA 1986-1990** resulted in a completed Conceptual Design for ITER. Participants includes US, EC, USSR, and JA.
- ✓ **EDA 1992-1998** resulted in completed ITER design, R&D validation, and estimated total cost of ~$10 billion
- ✓ **Extended EDA 1999-2001** resulted in an essentially completed revised ITER design and a total project cost of ~$5 billion

Legend:

Black = International
Green = US only

✓Indicates completion
• Indicates future milestone

ITER Preparations 2004-2006

- ✓ Lengthy and intense **international negotiations** following site selection stalemate in Dec 2003 resulted in:
  - ✓ **Site Selection Decision** in June 2005
  - ✓ **Reallocation of ITER hardware** to accommodate India joining as equal, non-host partner.
  - ✓ **ITER Agreement Text** completed in Dec 2005
  - ✓ **Top Management Staff Designated** in Nov and Dec 2005
- ✓ U.S. Contributions to ITER becomes Major Item of Equipment in the FY06 Congressional Budget
- ✓ DOE Project Review Conducted - March 2005
- ✓ Mission Need Statement Approved - July 2005

Construction 2006--2014

- ✓ DOE Project Review of HW Reallocation - Feb 2006
- ✓ Initialing of the ITER Agreement – May 2006
- ✓ May 2006 – DOE/OECM/LMI Review of ITER Agreement
- ✓ Top Management Selects Deputy Directors General – July 2006
- ✓ September 2006 - DOE Project Cost Review
- ✓ Signing of the ITER Agreement – Nov 2006
- ✓ First Interim ITER Council Meeting – Nov 2006
- • Initiate Project Design Review – Jan 2007
- • Ratification of the ITER Agreement – mid 2007
- • CD-1/2a/3a - Late 2007/Early 2008
- • CD-2b – Late 2008
- • License to Construct – 2008
- • Excavate, Build and Complete Tokamak Complex
- • Tokamak Assembly Starts – 2012
- • Install/test

Next Three Project Phases 2015-2039

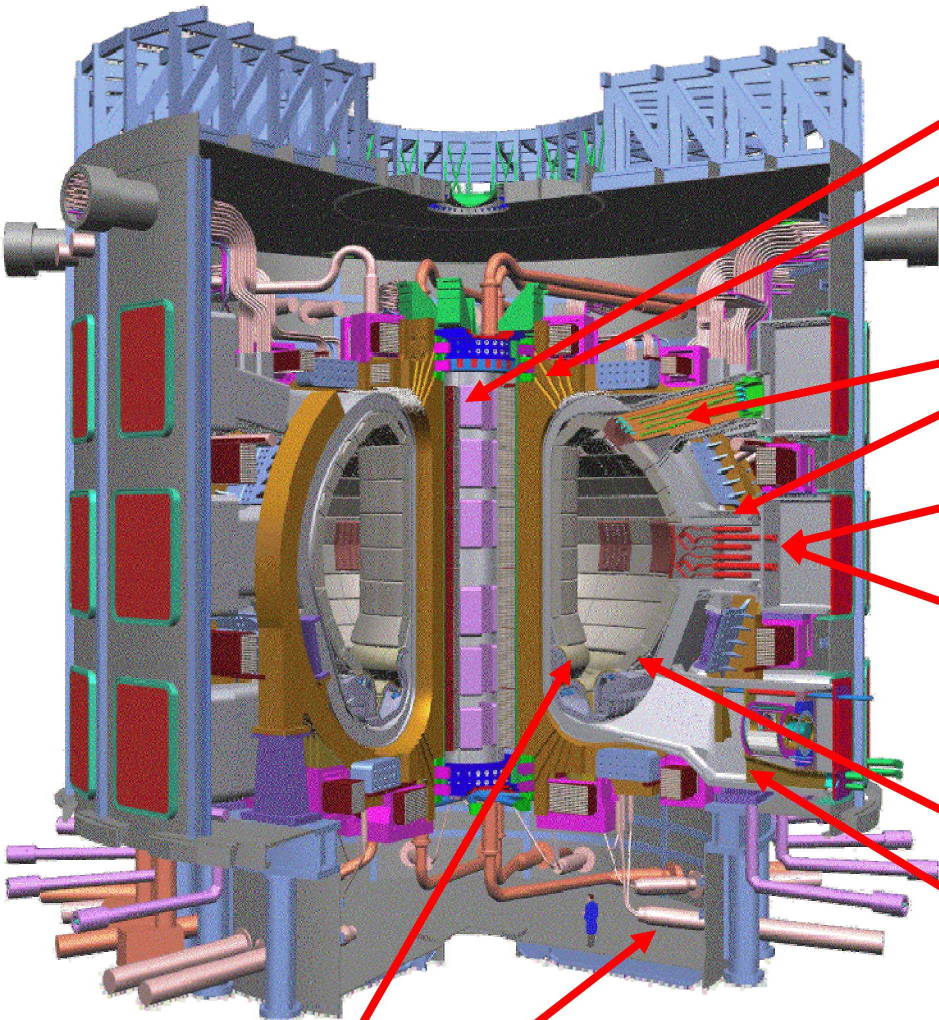
Operations 2015-2034

First Plasma 2016

Deactivation 2034-2039

Decommissioning

U.S. “in-kind contribution” Hardware Scopes



7 Central Solenoid windings

8% of Toroidal Field conductor

15% of port-based diagnostics

all Ion Cyclotron transmission lines

all Electron Cyclotron Transmission Lines

Blanket/Shield 20%

Roughing pumps, standard components

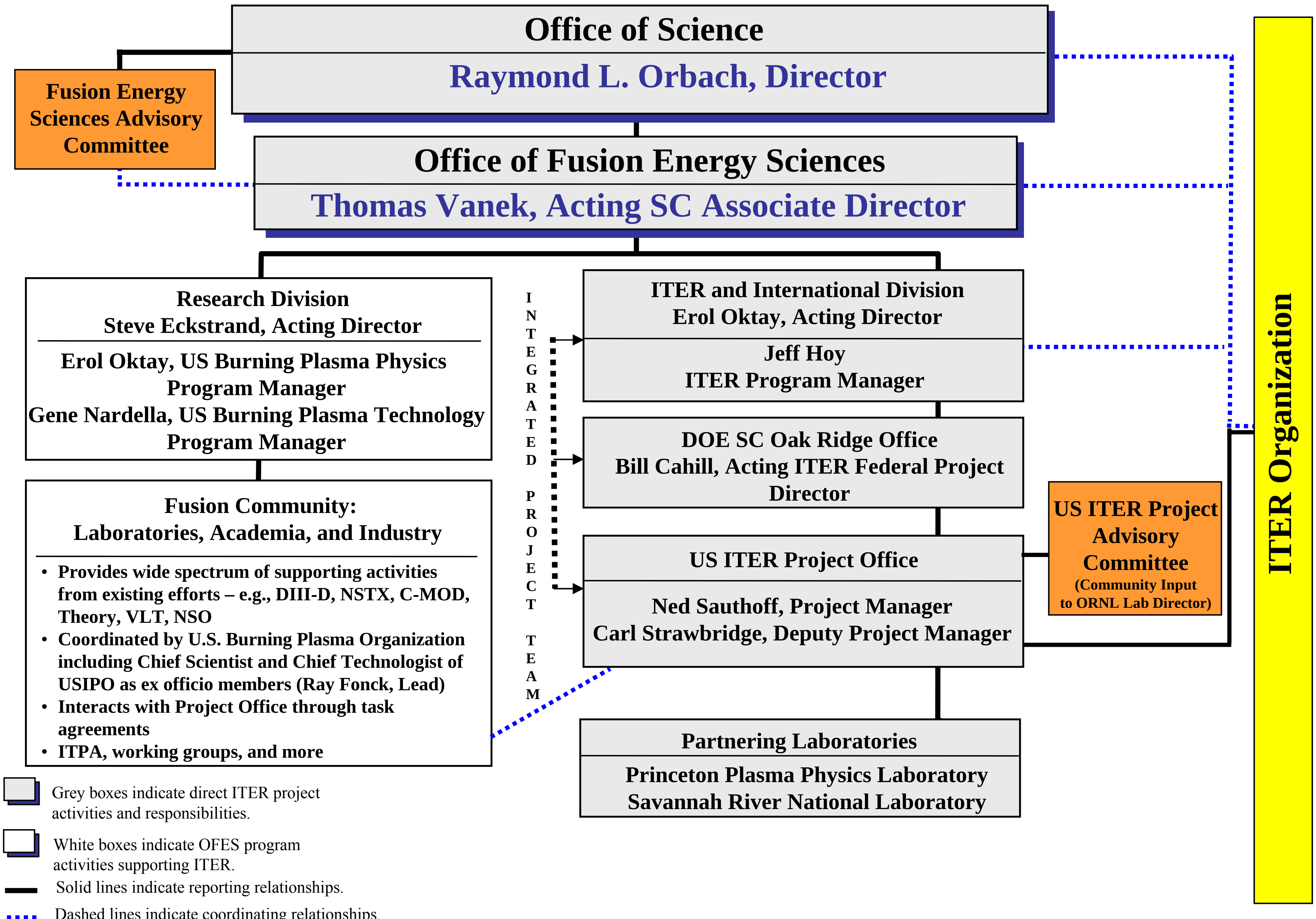
pellet injector

75% Cooling for divertor, vacuum vessel, …

Steady-state power supplies

Tokamak exhaust processing system

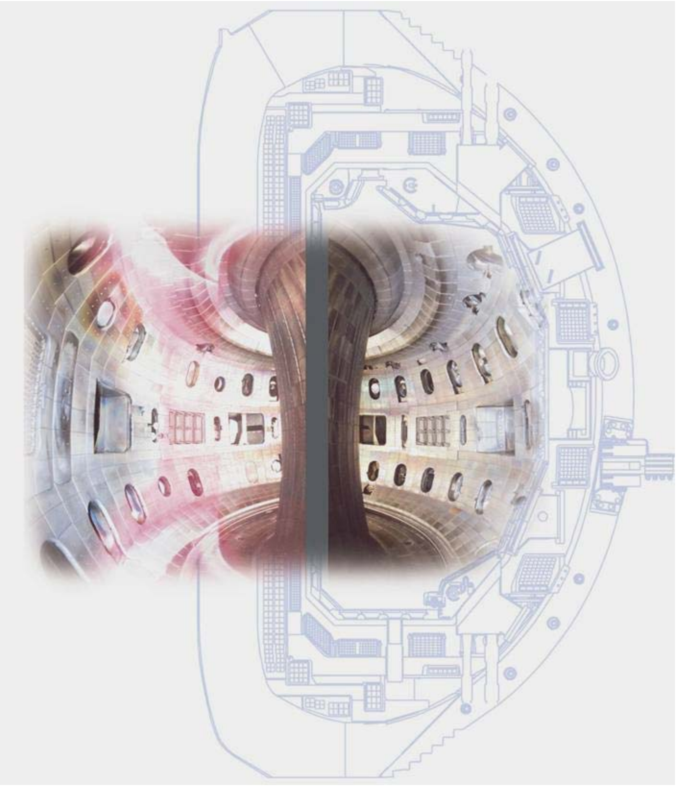
Management Structure for the US ITER Project and Program



Note: This chart does not display the organizational relationships with legal, financial, and construction mgmt offices within DOE.

The four major U.S. facilities advance fusion science and support ITER

- **These facilities cover a wide range of toroidal plasma parameters necessary to understand the science:**
  - **DIII-D** tokamak at General Atomics (Flexible heating, shaping & control tools, medium field and aspect ratio, ample diagnostics…)
  - **C-Mod** tokamak at MIT (ITER-level field, density & pressure, metal walls, unique radio-frequency current drive capabilities…)
  - **NSTX** – National Spherical Torus Experiment at PPPL (Small aspect ratio, low field, high ratio of plasma pressure to magnetic pressure…)
  - **NCSX** compact stellarator at PPPL (3D plasma physics, steady-state without current drive, quasi-symmetry providing strong links to tokamaks…)
    - NCSX begins operation in FY09



DIII-D

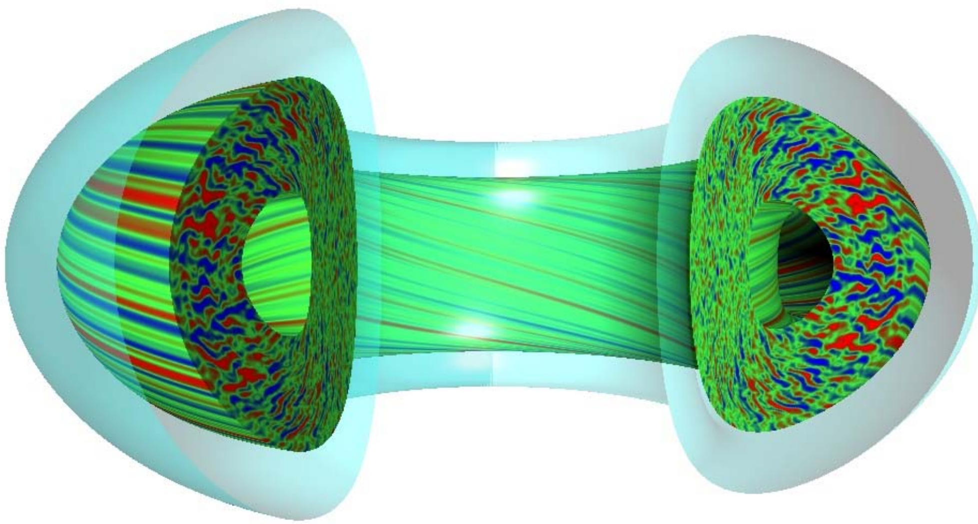
The U.S. is also a major contributor to joint international experiments

International Tokamak Physics Activity and new U.S. Burning Plasma Organization closely coordinate research with ITER Team

U.S. Tokamak Parameters vs. ITER

	C-Mod	DIII-D	NSTX	ITER
R/a	2.8-3.6	2.5-4.5	1.27-1.6	3.1
B (Tesla)	2.0-8.0	0.5-2.2	0.3-0.45	5.3
$\langle n_e \rangle$ (10^{20} m^{-3})	0.3-6.0	0.2-0.9	0.15-0.7	~1.0
$\langle \beta_T \rangle$ (%)	1.2-1.6	1.1-4.7	6.4-18.2	~2.5
V_{fast}/V_A	0.2-0.8	0.45-0.9	1.0-5.0	~1.8
RWM coils	No	Yes	Yes	Maybe?

Theory and computation enable efficient construction design, experimental modeling, and plasma control



Simulated electron density fluctuations in a shaped tokamak plasma using the GYRO code

- Accurate modeling of plasma design performance focuses the engineering and conserves construction resources of ITER
- Successful prediction of burning plasma performance will guide the design of future power plants
- This requires close interaction among theory, modeling, and experiments
- FES is collaborating with SC's Advanced Scientific Computing Research Program on the development of state-of-the-art simulation tools (SciDAC)

Enabling Technologies help to accomplish the science and plan for the future

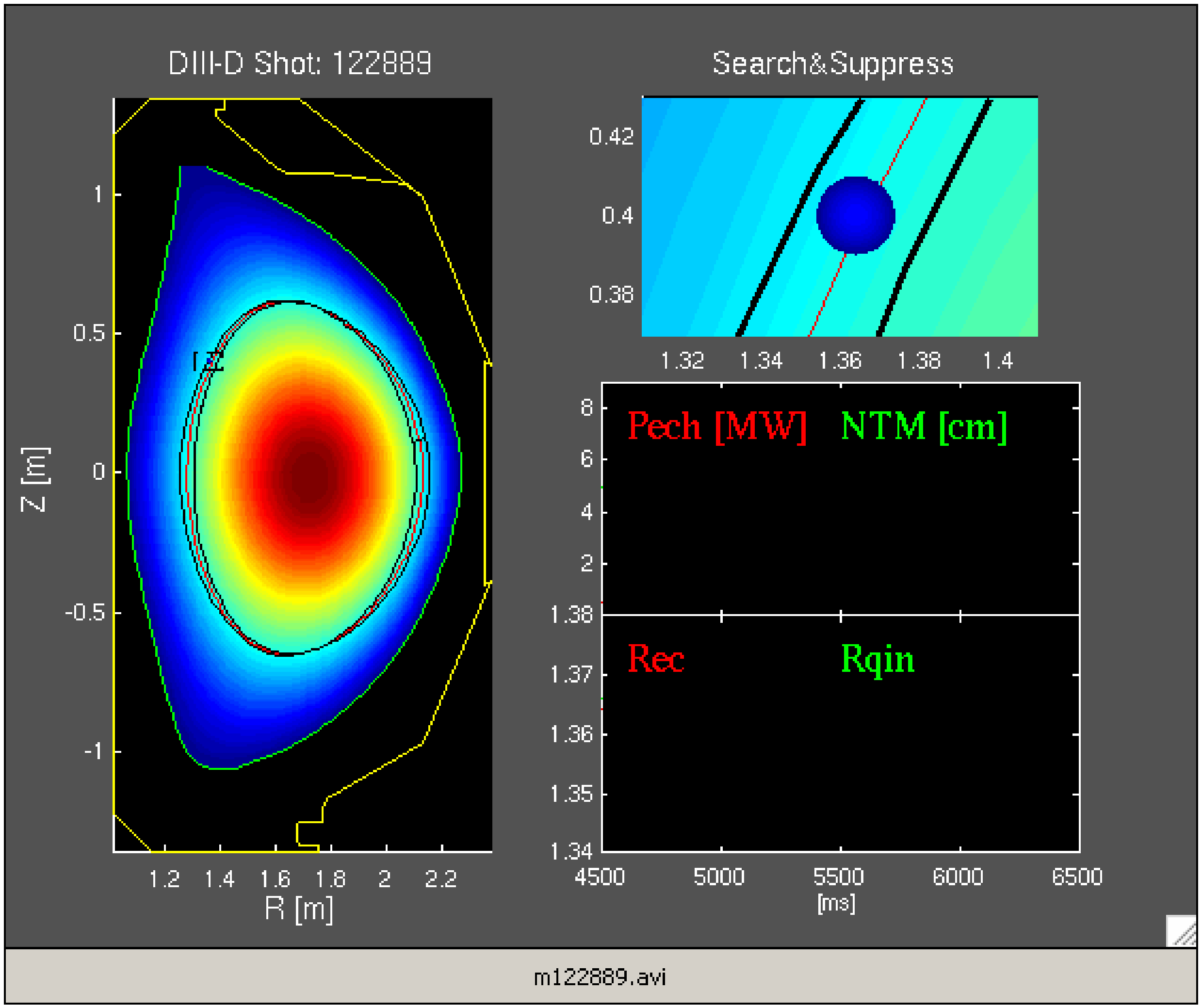
- Developing the cutting edge technologies that enable both domestic and international machines to achieve their goals
- Conducting system studies which provide guidance for future activities
- Developing the structural materials for fusion

CPI 1 MW Gyrotron enables new heating and control capabilities in DIII-D

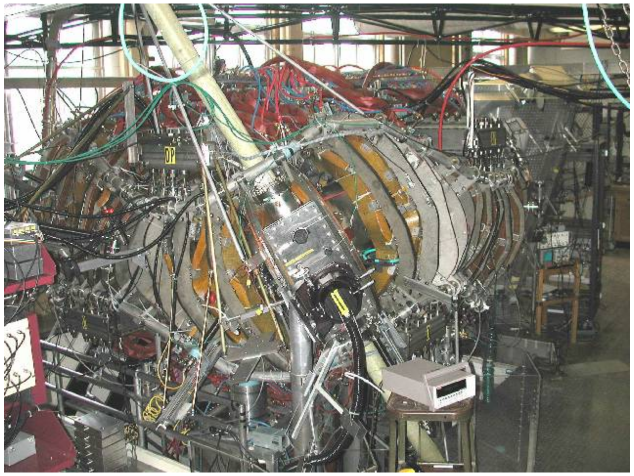
Recent U.S. Advances Relevant to ITER Design

- DIII-D and Plasma Technologies: New high power microwave sources (gyrotrons) can now be aimed to drive current at just the right spot in DIII-D plasmas to prevent or heal internal instabilities that would degrade or destroy the discharge. This may become a critical tool to maintain the integrity of ITER plasmas.
- NSTX: A new set of unique feedback coils were used to control particular instabilities, caused by plasma interaction with vessel walls, successfully at ITER-relevant plasma rotation speeds.
- C-Mod: A new radio-frequency antenna was able to sustain nearly all of C-Mod's plasma current. These results are in agreement with theoretical calculations, and imply that this type of wave could be used to sustain ITER plasmas.
- Theory and Computation: Using state of the art codes, researchers performed large scale high resolution simulations to study the physics of plasma instabilities occurring at the plasma edge. Understanding this behavior and developing techniques to control them is very important for the design and performance of ITER.

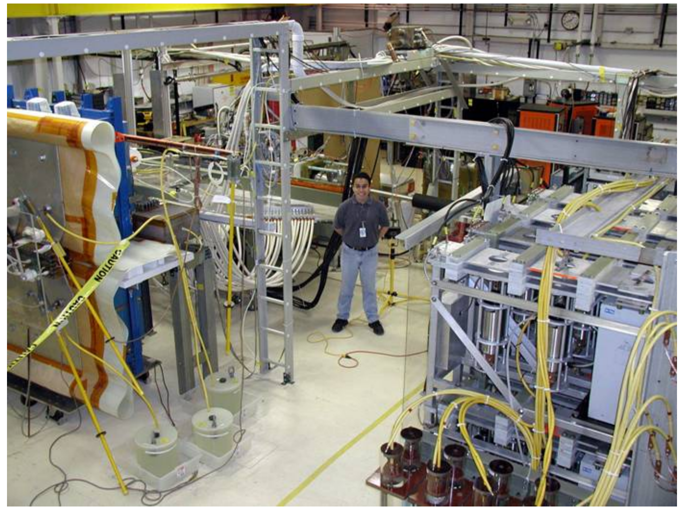
Active Tracking Maintains Alignment and Suppression of Instability



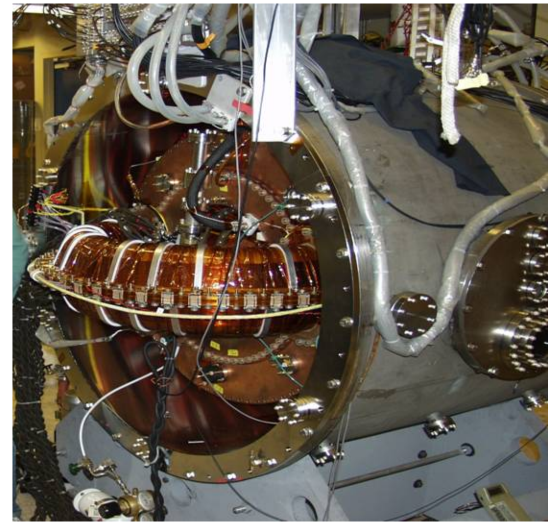
A range of small innovative facilities are exploring the potential for improved pathways to magnetic fusion



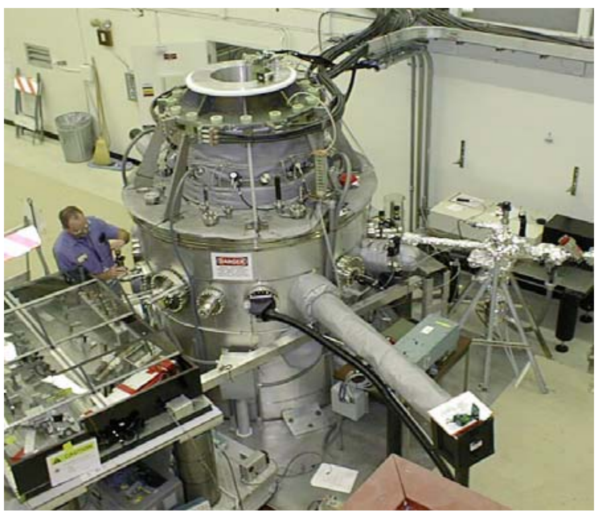
Helically Symmetric Experiment
University of Wisconsin, Madison



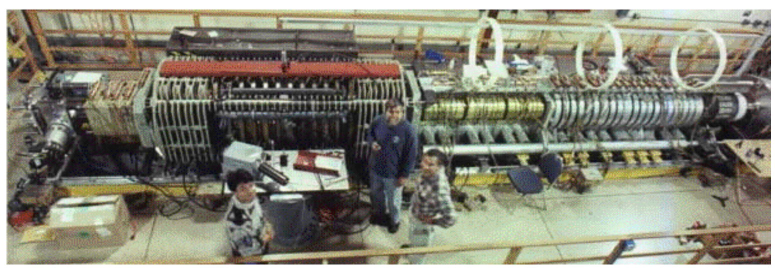
Magnetized Target Fusion
Los Alamos National Laboratory/AFRL



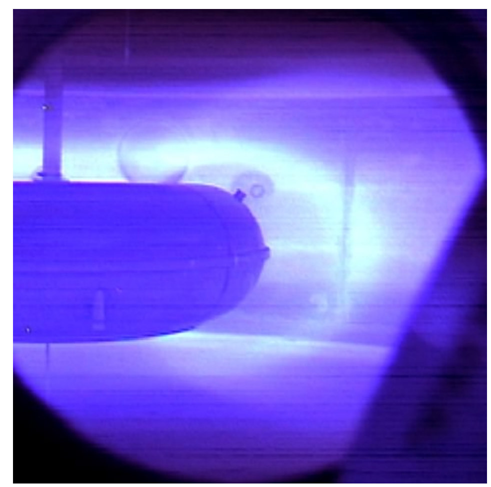
Steady Inductive Helicity Injection
University of Washington, Seattle



Sustained Spheromak Plasma Experiment
Lawrence Livermore National Laboratory



Field Reversed Configuration Formation and Sustainment
University of Washington, Seattle



Levitated Dipole Experiment
Columbia University/MIT

High Energy Density Plasma Physics and Inertial Fusion Energy

- Expanding the frontiers of high energy density physics and examining the viability of inertial fusion as an energy source
  - Research in promising new “fast ignition” technique, heavy ion beam inertial fusion, dense plasma jets
  - Heavy ion research will perform first warm dense matter experiment by 2009
  - Relates to energy, astrophysics, nuclear physics, materials science, and condensed matter physics
  - NNSA-funded National Ignition Facility (NIF) conducts its first ignition experiments in FY 2010

An Interagency Task Force has been established to sort through multiple HEDP research activities

- HEDP research conducted for numerous applications by several federal agencies
  - NSF, DOD, NIST, NASA, DOE/NNSA, DOE/Office of Science/FES, Nuclear Physics, High Energy Physics & Basic Energy Sciences Programs
- Interagency task force has been formed to better coordinate and plan research activities
- Final report nearing completion
  - FY08 FES budget will reflect recommendations

Fusion Program Requirements in Energy Policy Act of 2005

1. Secretary shall submit to Congress a plan for the implementation of the policy of the U.S. to conduct research, development, demonstration, and commercial applications to provide for the scientific, engineering, and commercial infrastructure necessary to ensure that the U.S. is competitive with other countries in providing fusion energy…
2. Secretary must submit to Congress the international ITER Agreement
3. Secretary must submit to Congress a report on ITER Management and Fixed Dollar Estimate on U.S. participation
4. Secretary must submit to Congress a report on how the ITER will be funded (without reducing funding from OFES or other SC programs)
5. Secretary, in consultation with FESAC, must develop a plan for the U.S. participation in ITER – research agenda, evaluate progress, and benefit to domestic fusion program

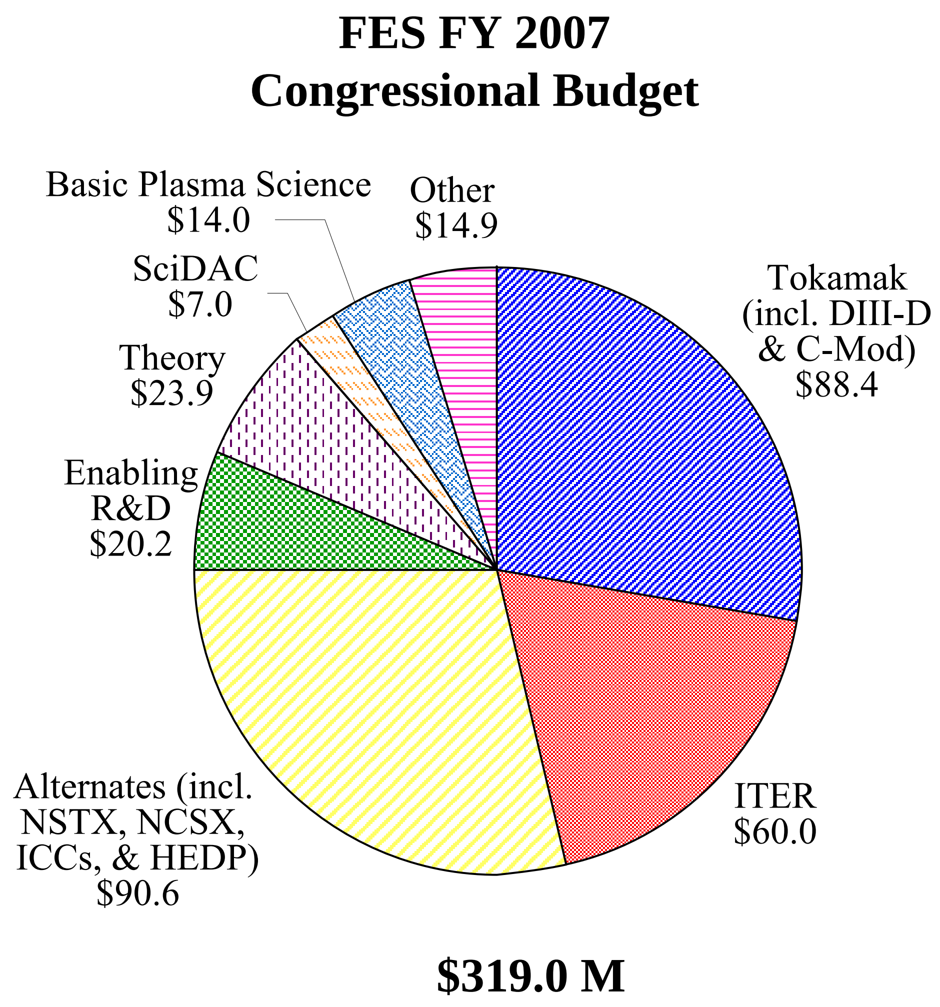
- **In a letter from Chairman Boehlert of the House Science Committee on September 29th, 2006, it was reported that DOE satisfactorily met each of these requirements**

Looking to the Future

- FES continues to plan and readjust its research campaigns to best answer critical questions in fusion energy research and development
  - How do we control a burning plasma?
  - What is the most cost-effective approach to produce fusion energy?
  - How do we best advance the field in an ever-changing international context?
- Strategic planning is underway for both magnetic and inertial fusion concepts

Fusion Energy Sciences Budget

($ in Millions)



Fusion Energy Sciences Budget

($ in thousands)

Science	FY 2006 Sept AFP	FY 2007 Cong
DIII-D Research	24,272	24,300
C-MOD Research	8,490	8,890
International Collaborations	4,951	5,064
Diagnostics	3,763	3,854
Other	4,223	3,730
SBIR/STTR (science)*	0	7,262
Subtotal Tokamaks	**45,701**	**53,100**
NSTX Research	15,539	16,696
Experimental Plasma Research	21,389	19,990
HEDP	15,470	11,949
MST Research	6,445	6,970
NCSX Research	751	697
Subtotal Alternates Research	**59,594**	**56,302**
Theory	**24,947**	**23,900**
Advanced Computing/SciDAC	**4,220**	**6,970**
General Plasma Science	**14,180**	**13,941**
Science Total	**148,642**	**154,213**
Facility Operation		
DIII-D	30,780	32,362
Alcator C-Mod	13,032	13,941
NSTX	18,681	18,422
NCSX MIE	17,019	15,900
Facility Ops times in weeks	7/14/11/0	12/15/12/0
GPP, GPE, Other	3,538	3,930
ITER Preparations	5,294	
ITER MIE TEC Cost	15,866	37,000
Facility Operations Total	**104,210**	**121,555**

Enabling R&D	FY 2006 Sept AFP	FY 2007 Cong
Engineering Research		
Plasma Technologies (MFE)	14,787	12,945
Advanced Design & Analysis (MFE)	2,529	2,550
Materials Research (MFE)	7,066	4,687
Enabling R&D for ITER (OPC)	3,449	23,000
Enabling R&D Total	**27,831**	**43,182**
Total Fusion Energy Sciences	**280,683**	**318,950**
DIII-D	55,054	56,662
Alcator C-Mod	21,522	22,831
NSTX	34,220	35,118
NCSX	17,770	16,597
ITER (Preparations, OPC & MIE)	24,609	60,000
Non-ITER	256,074	258,253

*SBIR funds transferred to separate office at beginning of each fiscal year