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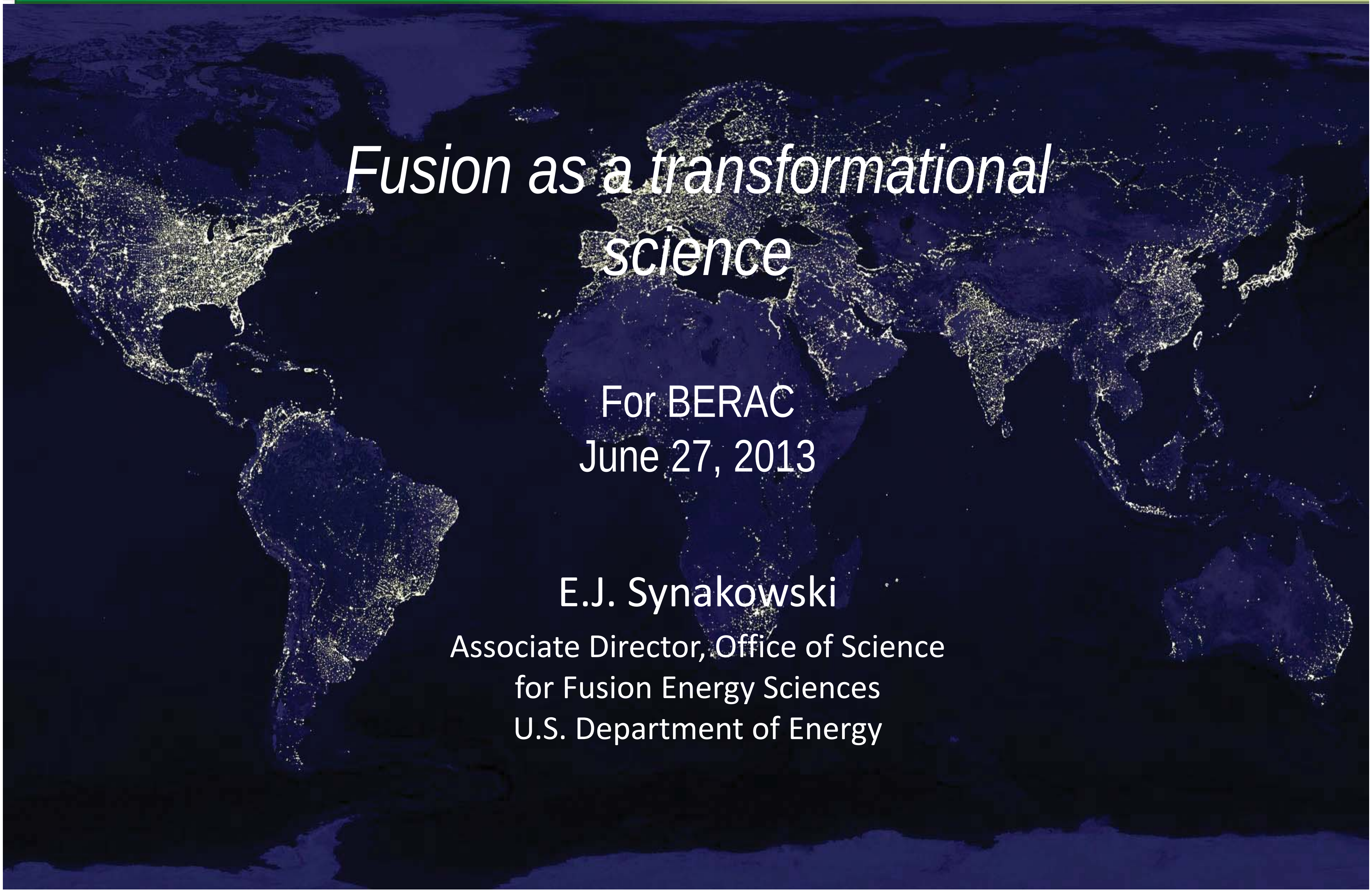


Fusion as a transformational science

For BERAC
June 27, 2013

E.J. Synakowski

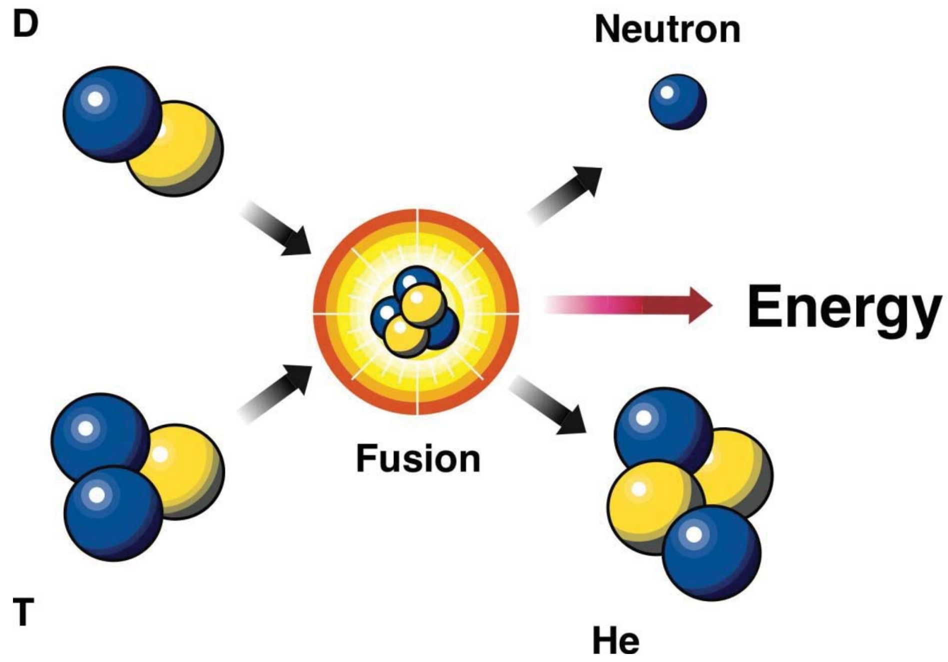
Associate Director, Office of Science
for Fusion Energy Sciences
U.S. Department of Energy

Our ambition has to be commensurate with the challenges of the times

- *For fusion, the ambition is to power the planet* with a carbon-free energy source

At the heart of fusion: converting mass into energy

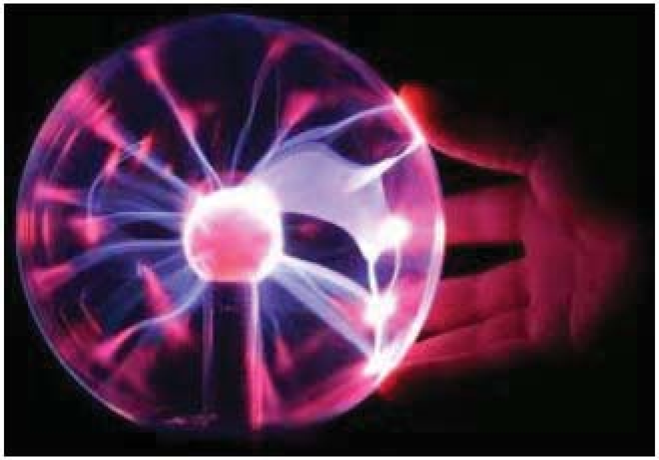
- A little mass of the fuel, D and T (isotopes of hydrogen), is converted into a huge amount of energy in the neutron and the helium
- D is plentiful
- T can be generated from lithium (plentiful)
- Helium is a byproduct
- Zero carbon emissions; short lifetime radioactive byproducts

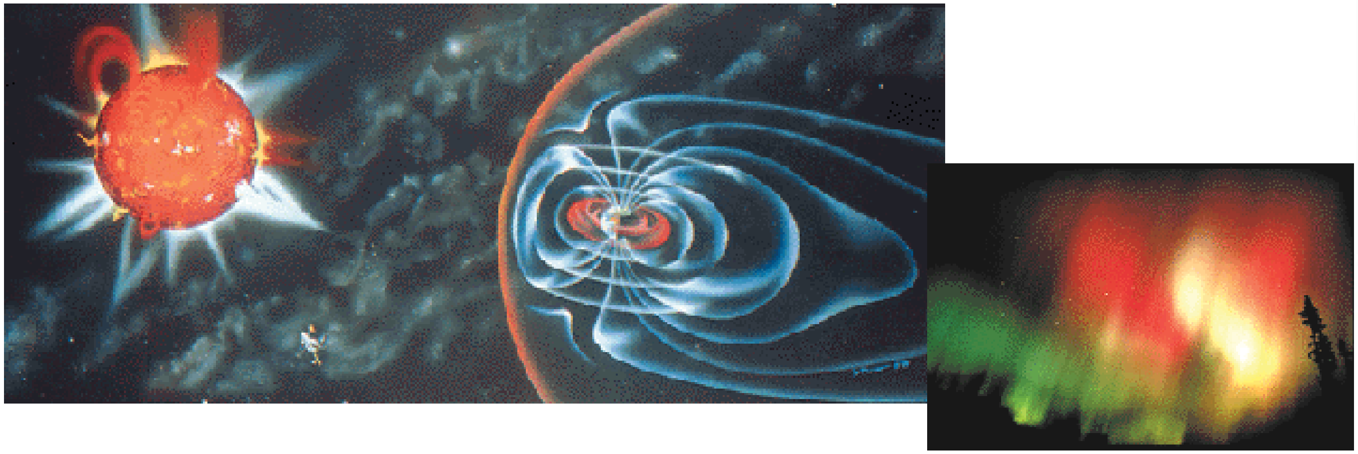


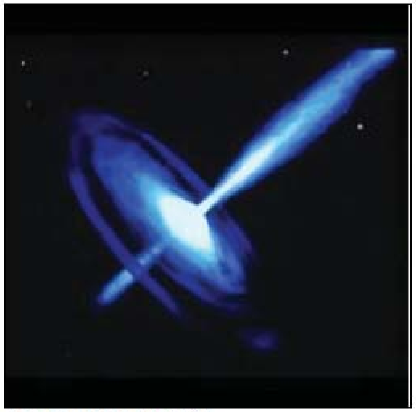
If we are smart and committed, and nature complies: mid-century deployment

For any version of fusion: plasma physics will be central

- **Plasma**: a hot, ionized gas. Plasmas are *everywhere*
- **Self heating a fusion fuel**: When D and T fuse in a plasma, the helium nucleus can share its energy with the plasma itself, heating it
- **Goal of a fusion reactor**: fusion reactions heat the plasma itself, reducing or eliminating the need for external heating, creating **fusion power gain**



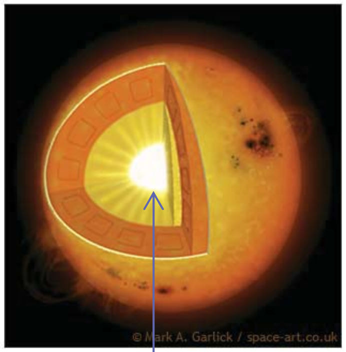




STScI-PRC1990-29 *Hubble ST image*

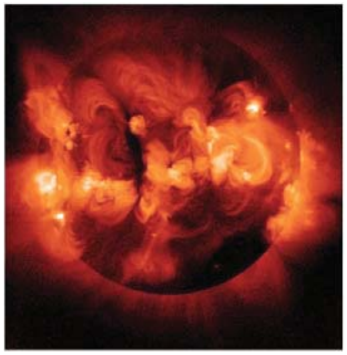
The science of fusion and plasmas extends from the laboratory to the stars and beyond

Sun: interior…

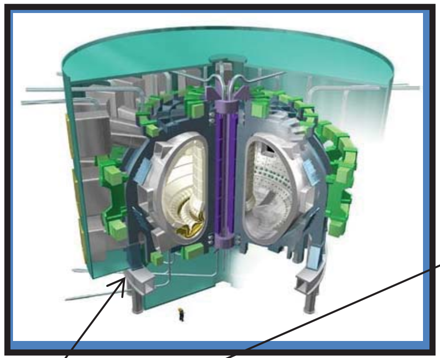


© Mark A. Garlick / space-art.co.uk

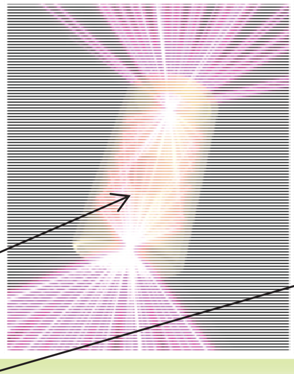
and in x-rays



ITER



NIF hohlraum

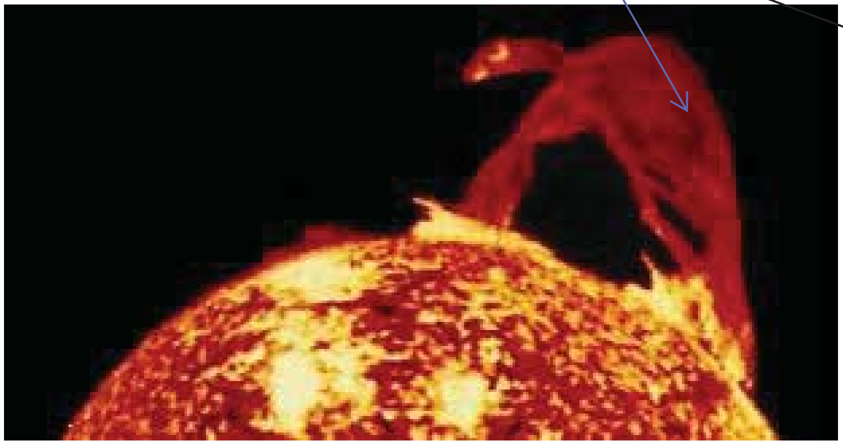


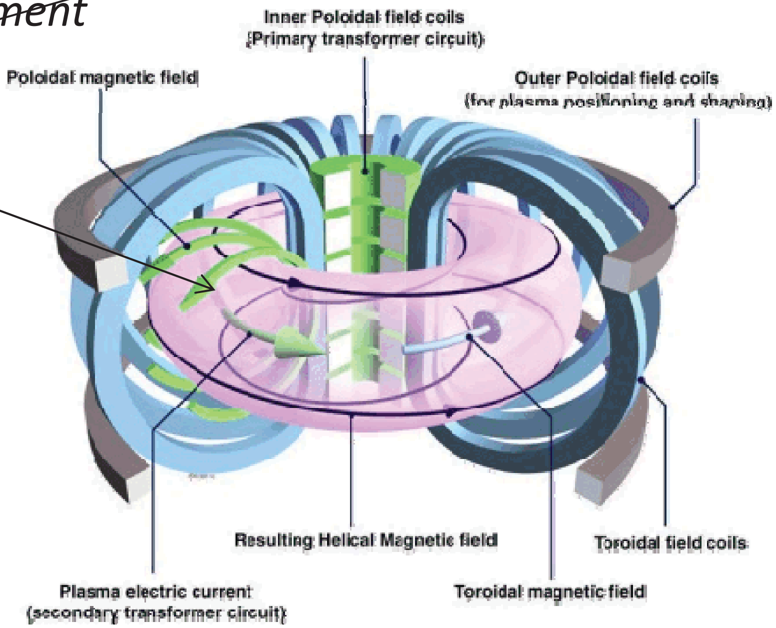
aurora

gravitational confinement

inertial confinement

magnetic confinement





Leading magnetic confinement concept for fusion: a **tokamak**

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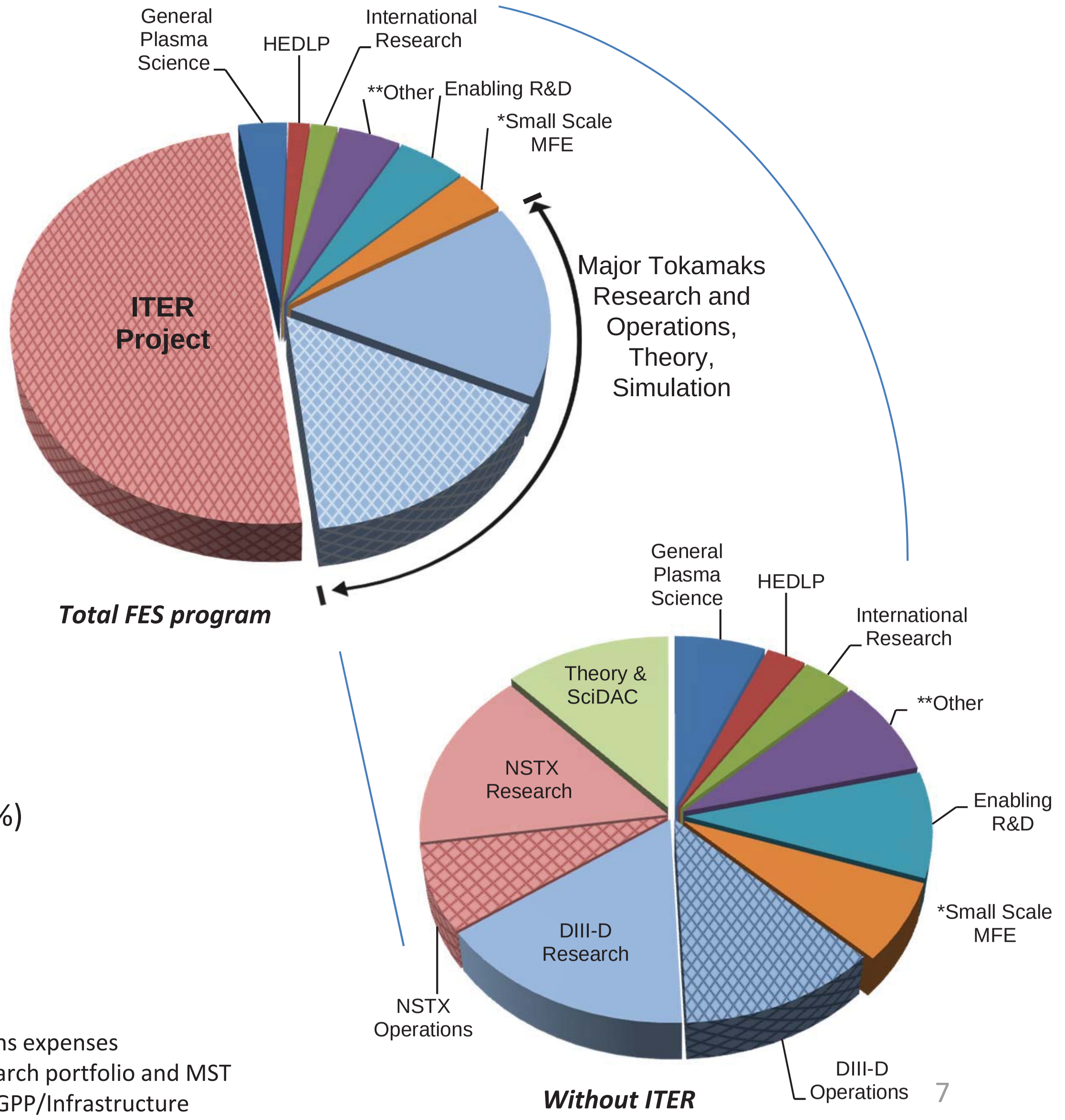
US fusion energy science research is institutionally and scientifically diverse

- ■ National Laboratory
- ▲ Industry
- ● University
- ⬢ Inter-Government Agency

At a glance: FES at $458M in FY 2014

Science: $160,064K
- Major Tokamak's Research (45.7 %)
  - DIII-D
  - NSTX
  - Theory & SciDAC
- Small Scale Magnetic Fusion Energy (10.1 %)
  - Experimental Plasma Research
  - Madison Symmetric Torus
- Enabling R&D (13.3 %)
  - Plasma Technology
  - Advanced Design
  - Materials
- International Collaborations (5.2 %)
- High Energy Density Laboratory Plasmas (4.1 %)
- General Plasma Science (9.4 %)

Facility Operations: $299,160K
- ITER at $225M, per Administration agreement (75 %)
- DIII-D (12 %)
- NSTX Upgrade (12 %)
- GPE/GPP/Infrastructure



Total FES program

Without ITER

Hatched areas indicate project and operations expenses
*Smaller Scale MFE includes Experimental Plasma Research portfolio and MST
**Other includes SBIR/STTR, Diagnostics, and GPE/GPP/Infrastructure

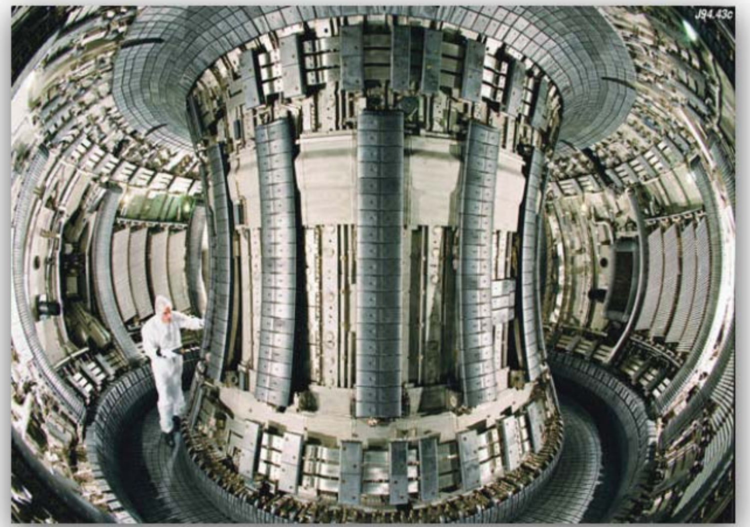
Magnetic fusion: from modest beginnings…

The first stellarator ("star maker")

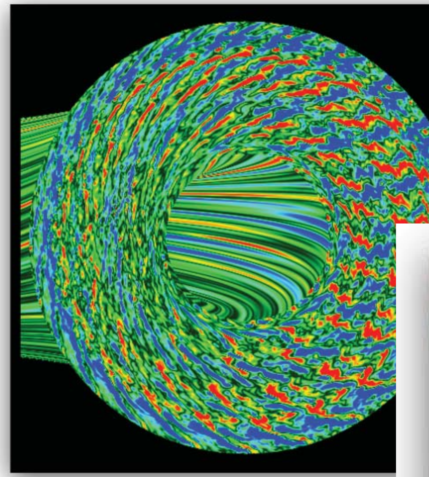
Lyman Spitzer, 1951
PPPL

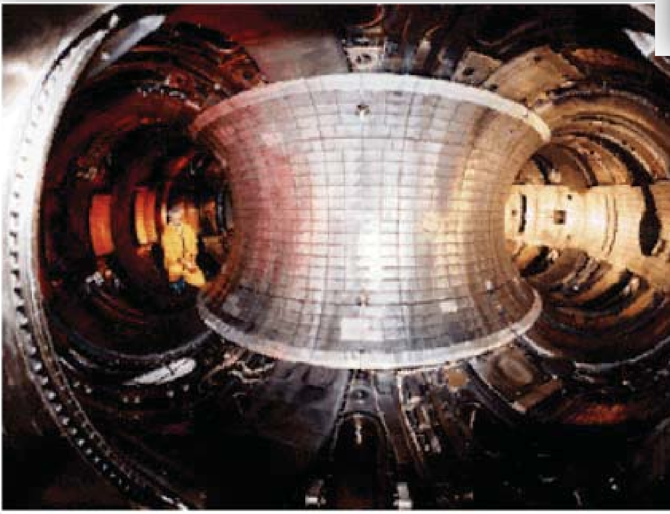
To present day achievements…

JET tokamak (England)
16 MW fusion power



Simulation



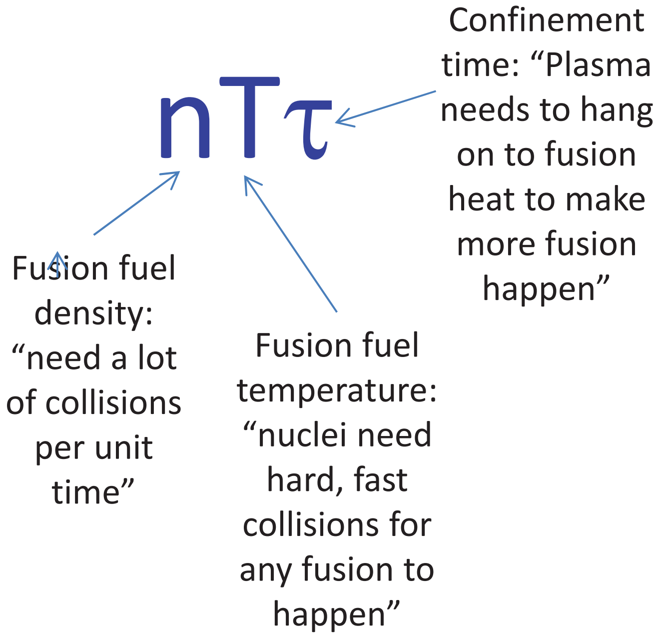


TFTR tokamak (US)
10.7 MW fusion power

Some like it hot: 44 keV ion temperatures on TFTR (US) and JT-60U (Japan): *<u>about 1 billion degrees F, much higher than required for a reactor</u>*

Progress in the fusion triple product has been remarkable: faster than computer chips

fusion triple product

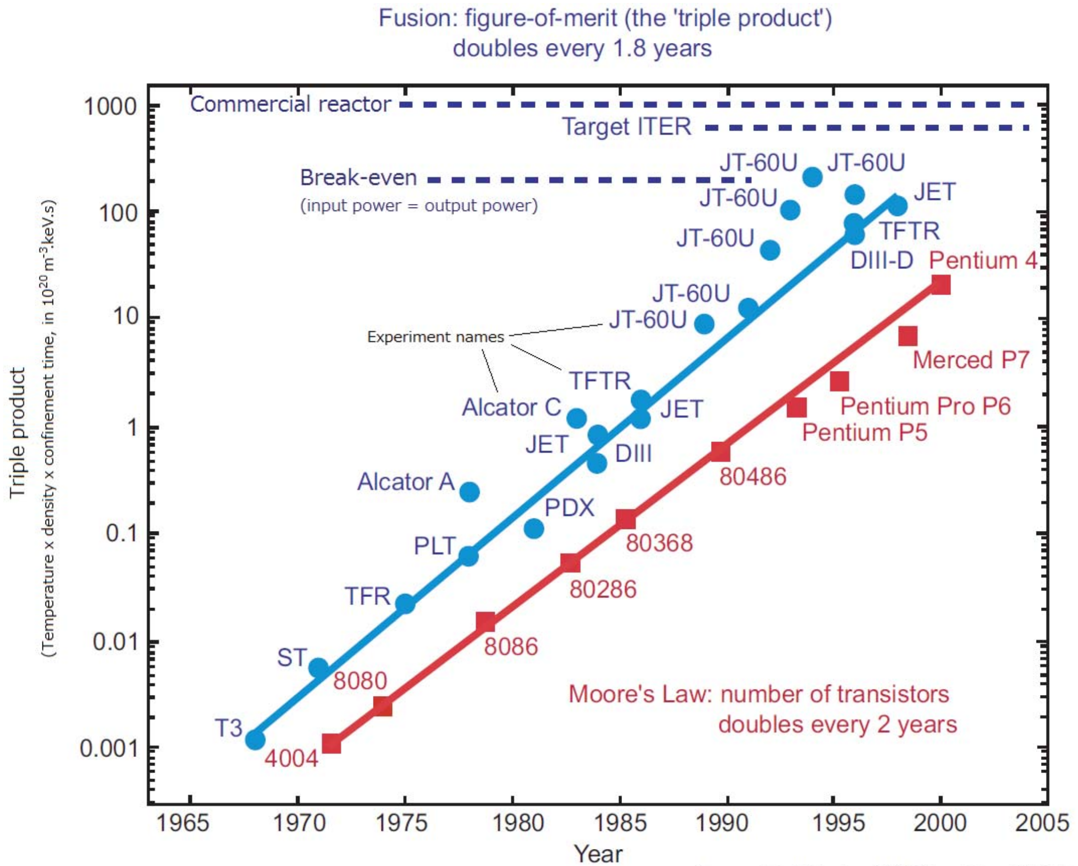


$n T \tau$

Confinement time: “Plasma needs to hang on to fusion heat to make more fusion happen”

Fusion fuel density: “need a lot of collisions per unit time”

Fusion fuel temperature: “nuclei need hard, fast collisions for any fusion to happen”



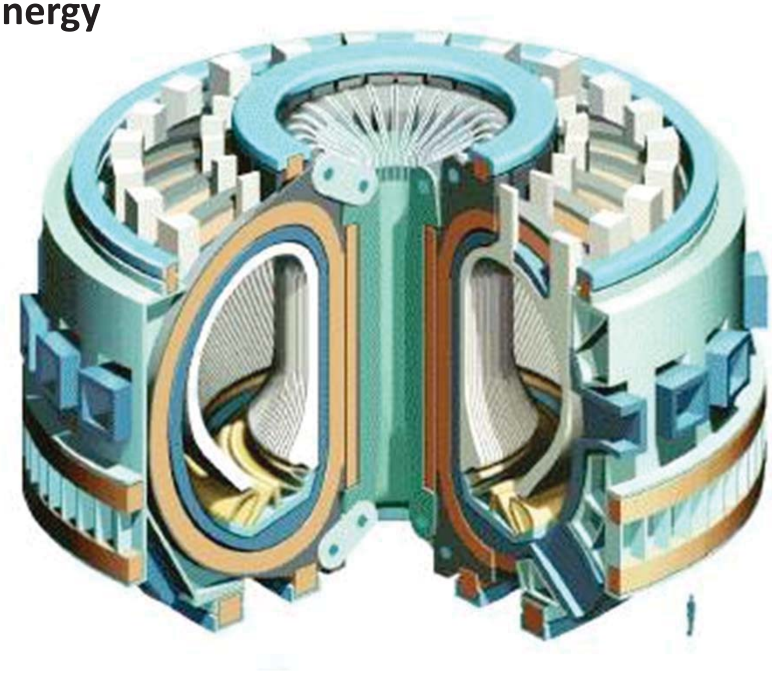
Fusion: figure-of-merit (the 'triple product') doubles every 1.8 years

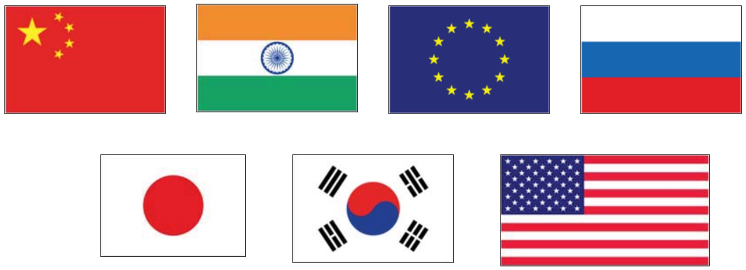
Source: A.J. Webster, 2003 Phys. Educ. 38 135

10,000-fold increase in 30 years, another factor of 6 for a power plant

The US is a partner in the world's major step in fusion research: ITER

ITER will demonstrate scientific and technical feasibility of fusion energy





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

- Today: 10 MW, 1 sec, gain < 1
- ITER: 500 MW, > 400 sec, gain ≥ 10;
  3000 seconds, gain = 5.
- Uncharted science, levering US intellectual investments
- Major contributions from US industry

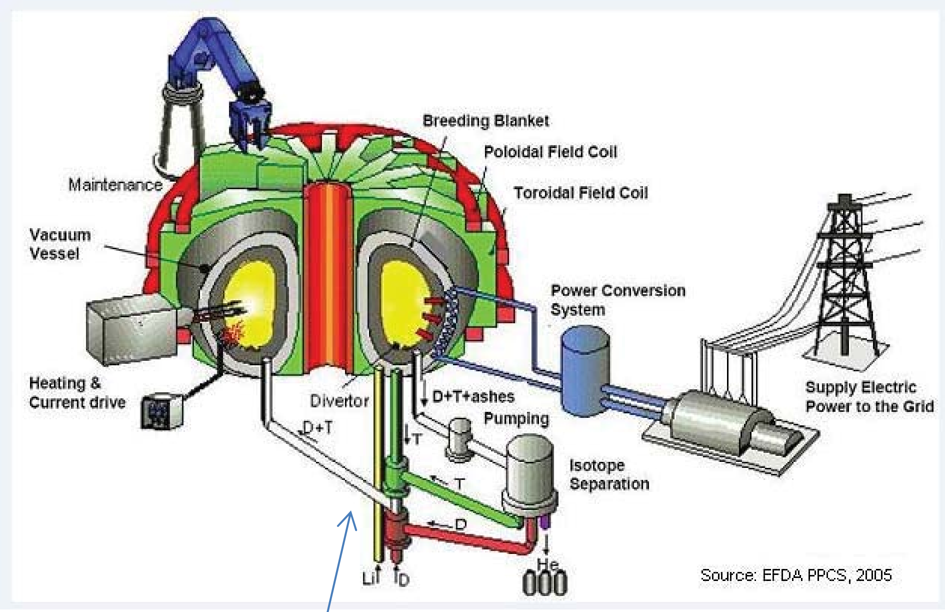
The world's biggest fusion energy research project ("burning plasma")

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

An international collaboration

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

A fusion power plant would be of a scale comparable to fission, coal, or other large systems



Source: EFDA PPCS, 2005


Plant Vogtle 3 and 4 construction site

January 2013 ©2013 Georgia Power Company All rights reserved

Watts Barr fission site (US)

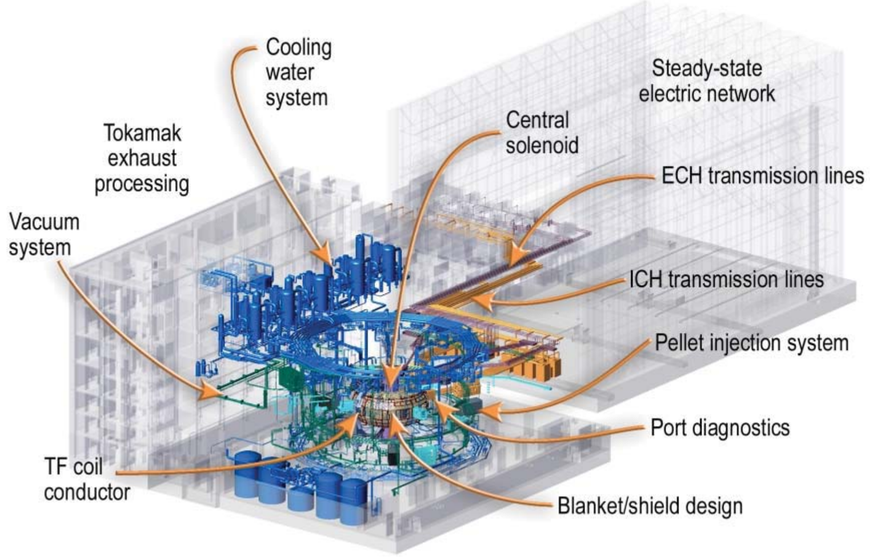
- Elements of a fusion power plant

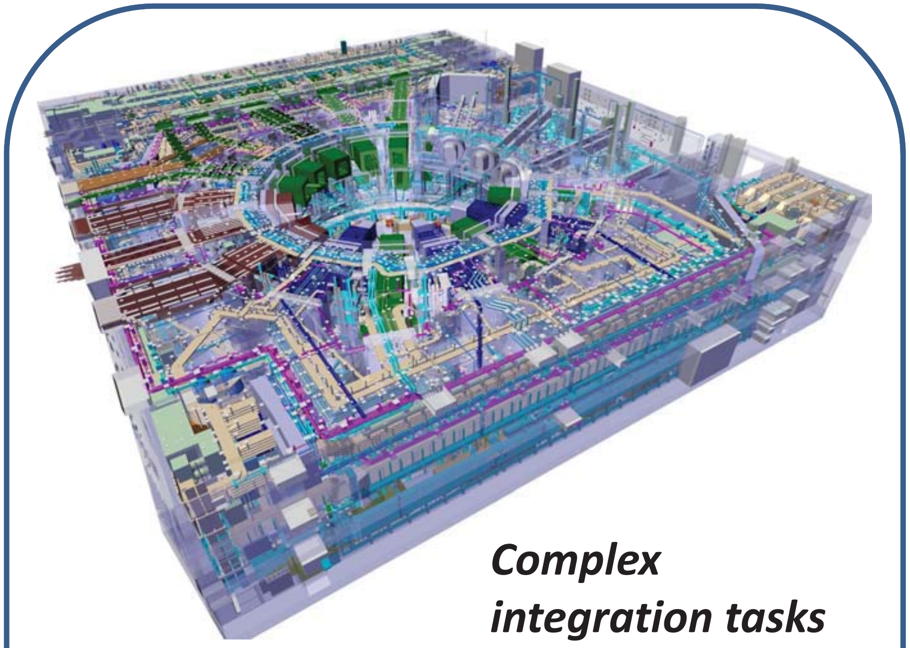
- ITER construction site – not a fusion reactor, but reactor scale
  - About 100 acres

About 80% of US ITER funding goes towards in-kind hardware contributions developed in the US

In-kind hardware contributions are managed at the U.S. ITER Project Office (at Oak Ridge National Laboratory)

Procurements and fabrication are well underway

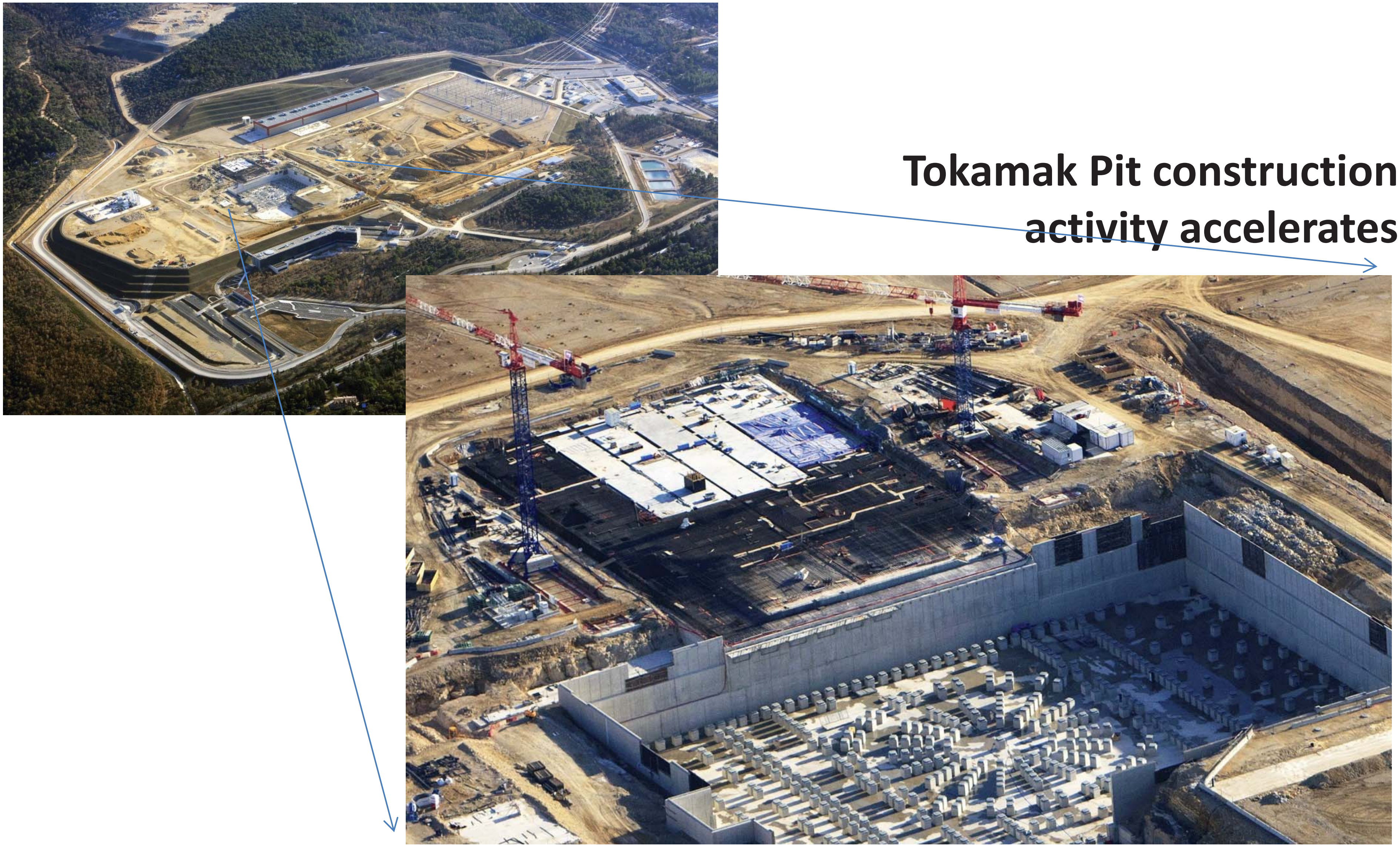




Complex integration tasks

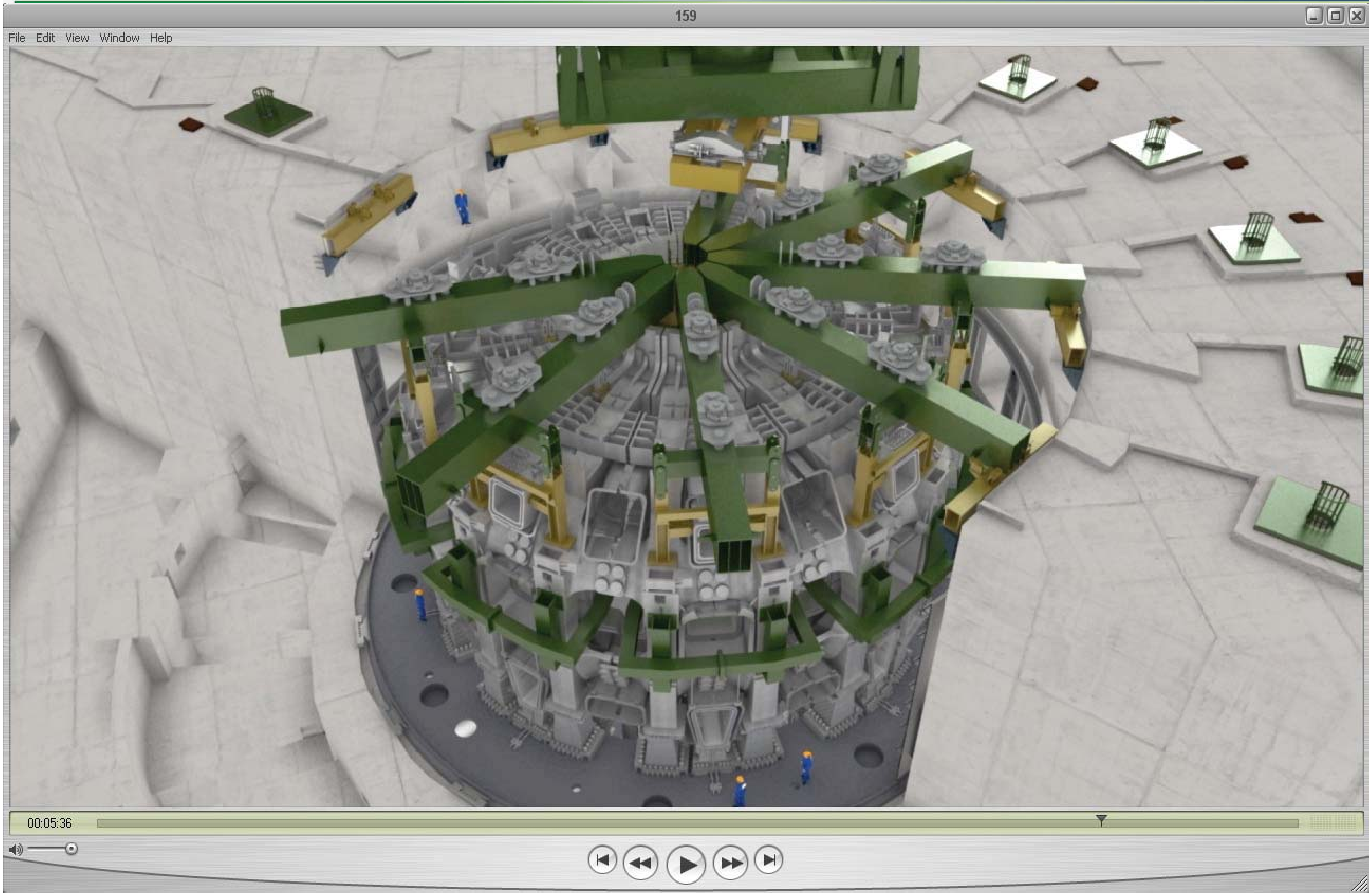
The heart of the ITER facility will be the Tokamak Complex, comprising the Tokamak Building, the Diagnostic Building, and the Tritium Plant. The seven-story Complex, measuring 118 m by 80 m and towering 57 m above the platform, will contain more than 30 different plant systems, including cooling systems and electrical power supplies, all having physical as well as functional interfaces.

The ITER Project is in rapid transition



Tokamak Pit construction activity accelerates

ITER construction will represent a tremendous engineering achievement



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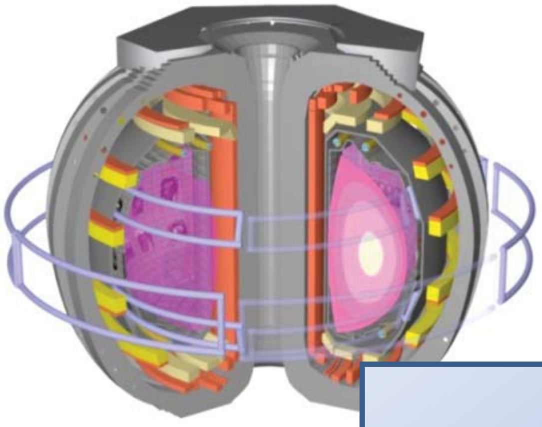
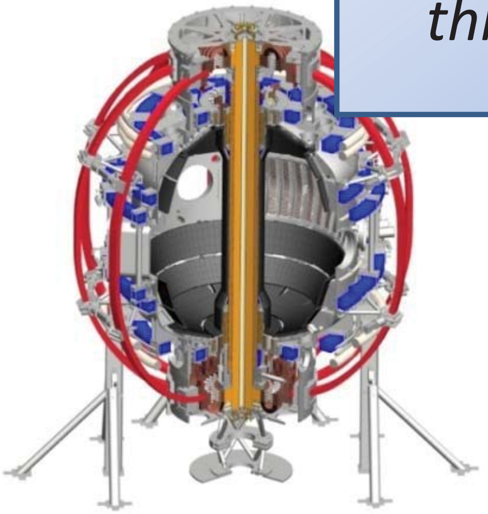
Magnetic fusion in the US feature two experiments that are a scientifically powerful pair

- ☑ Wide range of aspect ratio and β ➔ Scientific questions central to all confinement systems including ITER
- ☑ Wide fast ion space ➔ establish basis for understanding ITER’s alpha particles
- ☑ Outstanding measurement suite, strong coupling with computation
- ☑ World-leading plasma control capability

DIII-D





NSTX-U

Joint research this decade ➔

Strong basis for ITER physics and solutions, and a test bed for evaluating mission space of a future Fusion Nuclear Science program

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Science example of transformations in understanding: plasma confinement and turbulence

Planetary Atmosphere

Turbulence in geophysical fluids and magnetized plasmas exhibit many common physical features

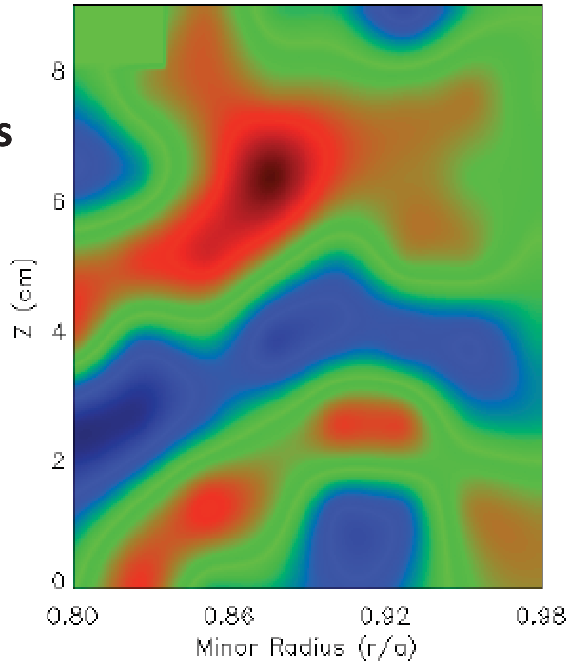
2-Dimensional
∇P-driven turbulence

Inverse Energy Cascades

From George McKee, University of Wisconsin

Plasma Turbulence

BES Turbulence Movie



DIII-D (University of Wisconsin/General Atomics), 142369,1500ms

Coriolis Force	↔	Rotation Source	↔	Lorentz (vxB)
Equatorial (Solar)	↔	Energy Source	↔	Central (Ohmic, NB, Fusion)
Polar Regions	↔	Energy Sink	↔	Divertor
Charney-Okukhov	↔	Equations	↔	Hasegawa-Mima
Rossby Waves	↔	Waves	↔	Drift Waves
Jet Stream	↔	Large-Scale Flows	↔	Zonal Flows

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George McKee - 54th Annual Meeting of the APS-Division of Plasma Physics, Providence, Rhodes Island, November, 2012

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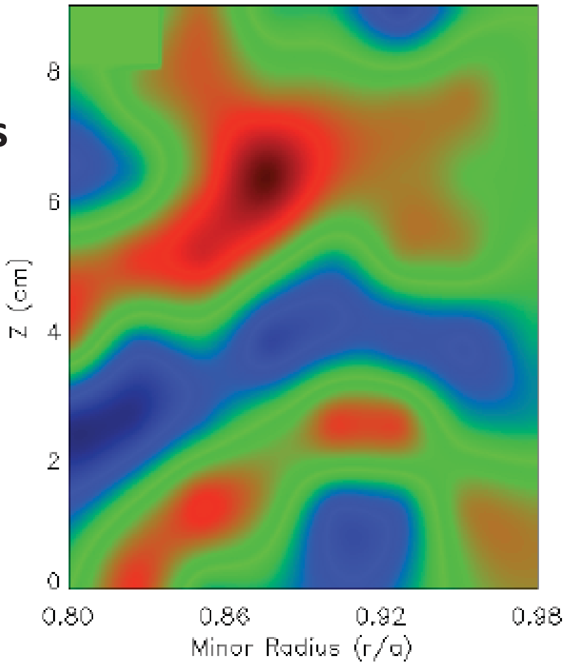

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More than pretty pictures: measurements of turbulence are demanded for challenging the codes

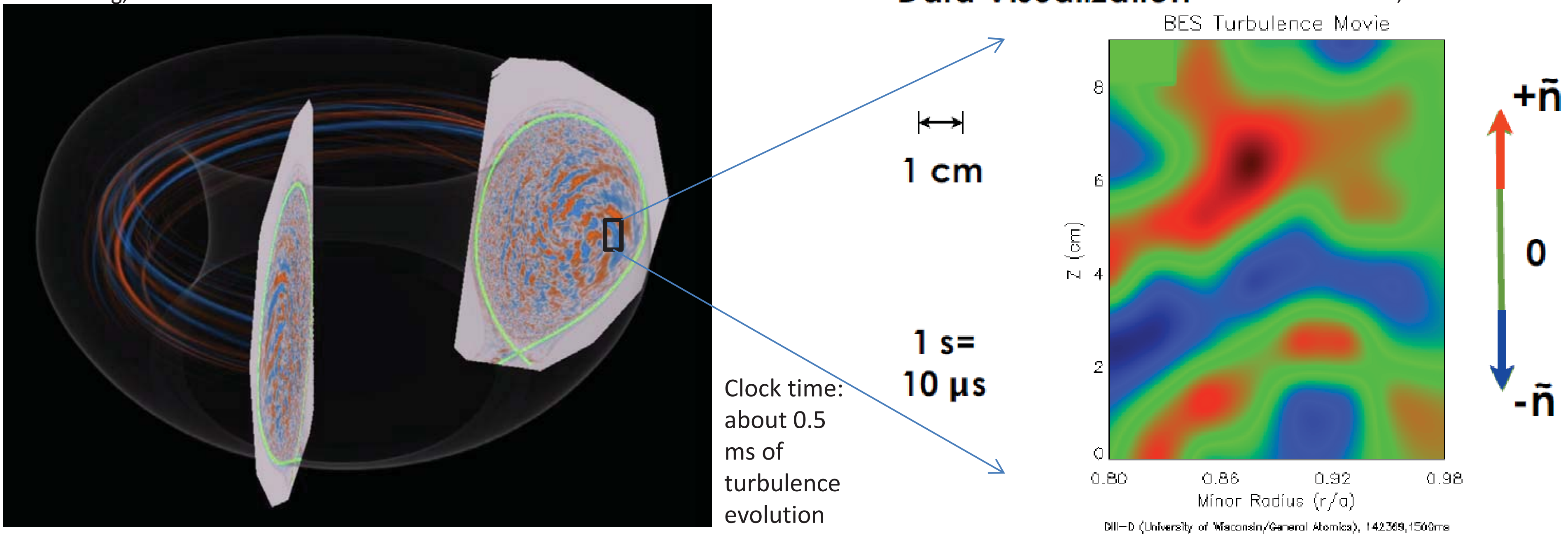
- Intellectual challenge: capture sufficient physics in simulation that engineering risks can be reduced in going from one step in fusion system development to the next

- Consider the challenge: make measurements of the hot plasma and its turbulent fluctuations (<<1%) at many MHz rate (million frames per second) with high spatial resolution. This class of measurement is required to compare to the codes

ITG Turbulence Simulation
3.5 million hrs, 170,000 cores ORNL Jaguar Computer Facility
C.S. Chang, PPPL

Data Visualization

Turbulence imaging DIII-D tokamak
G. McKee, U. of Wisconsin



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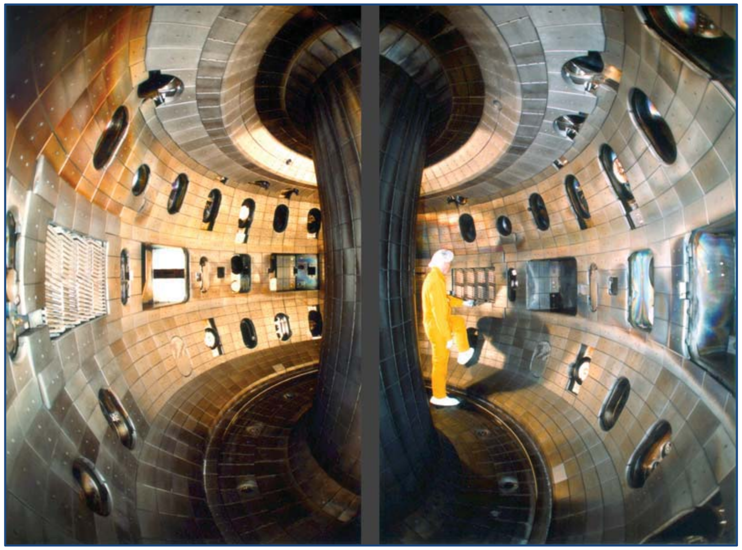
The DIII-D tokamak: overview

The DIII-D facility (General Atomics)

- ✓ World leadership in fusion plasma science in general, and in ensuring ITER’s scientific success
- ✓ Develops and focuses on extensive measurements and coupling them to theoretical and computational studies
- ✓ Develops and employs flexible heating, current drive, and plasma control systems that enable powerful, controlled scientific explorations
- ✓ Is a highly collaborative program
  - 440 researchers
  - 320 researchers are from outside General Atomics. Their affiliations include
    - 21 US and 10 overseas universities,
    - 22 overseas research groups
    - 4 national labs, and 4 private industry

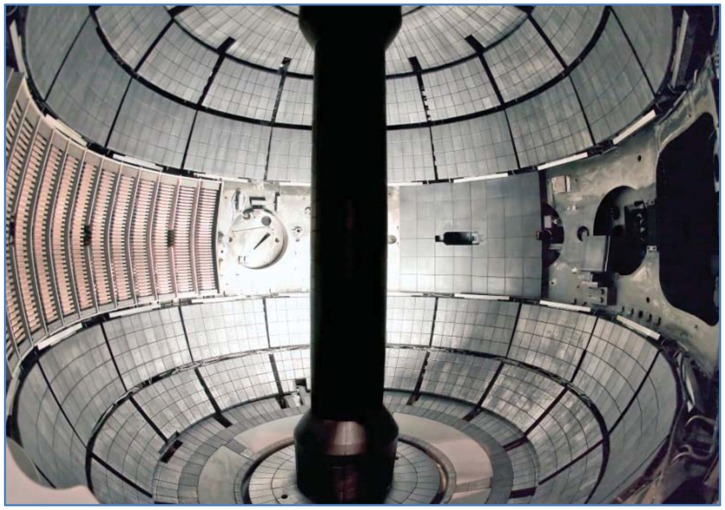


✓ Participation includes: 17 post docs and 22 graduate students

National Spherical Torus Experiment (NSTX): Overview

The NSTX facility (PPPL)

- ✓ World leader in fusion plasma science
- ✓ Low aspect ratio, unique field line geometry gives unique access to
  - very high ratio of plasma pressure to magnetic field pressure
  - ITER alpha particle-like fast ions:
    $V_{\text{beam ion}}/B_{\text{NSTX}} \sim V_{\text{alpha}}/B_{\text{ITER}}$
  - electron thermal transport phenomena critically important for ITER
  - powerful scientific complementarity with DIII-D
- ✓ Test bed for assessing potential of this configuration for a compact neutron source
- ✓ A highly collaborative program: 217 researchers, including 150 non PPPL from 21 US universities, 5 national labs, and 5 private industry groups.



✓ Research participation includes 17 post docs and 19 graduate students

Enabling access and impact for US scientists in future world-leading international programs

The International Program will give US researchers access to the world's leading challenges, leveraging US expertise and existing facility capabilities

First W7-X trim coil by Everson Tesla Nazareth, PA

Stellarators: the world of 3D magnetic fields

<u>W7-X, Greifswald, Germany; Large Helical Device, Toki, Japan</u>

US contributions of trim coils, power supplies, high heat flux divertor components, and IR imaging diagnostics will support future collaboration on Wendelstein 7-X (Germany). Innovative diagnostics on LHD (Japan). The US has been offered a role in program leadership at W7-X.

<u>EAST tokamak Hefei, China</u>
Goal: 1000s pulse, 1 MA

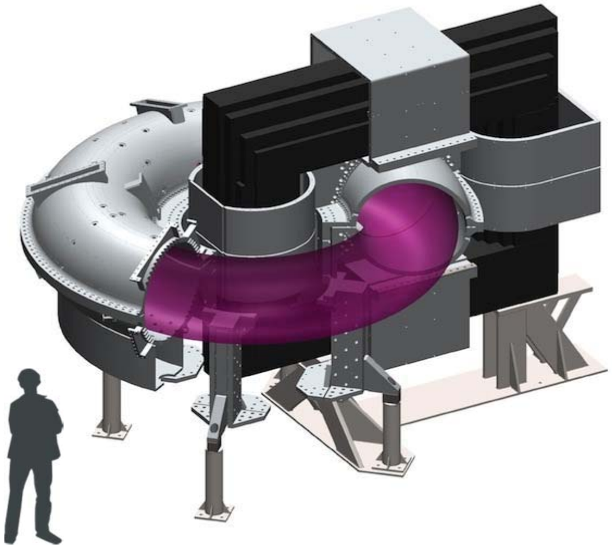
"Our machine is your machine," J. Li, EAST Program Leader

Features: Superconducting magnets, upgrades soon to high heating power. Rapidly growing diagnostic set
Heating: 2014 upgrades will yield heating capabilities rivaling DIII-D
EAST has offered to US 3rd shift operation, via remote control. Viability has already been demonstrated at General Atomics

<u>KSTAR superconducting tokamak Daejon, S. Korea</u>
Goal: 300s pulse, 2 MA

Features: 2015 plan is 50 second high power pulse, towards 300s goal. MHD mode control capability in place, an area US has pioneered on NSTX, DIII-D and at universities.

Madison Symmetric Torus (MST) and the Experimental Plasma Research (EPR) portfolio emphasize discovery and developing young researchers



The Madison Symmetric Torus is:

- ✓ Focused on the confinement of high-beta fusion plasmas using minimal external magnetization
- ✓ A world leader in reversed field pinch research located at the University of Wisconsin, Madison
- ✓ Advancing basic plasma physics and links to astrophysics (e.g., magnetic self-organization)

MST (U. Wisconsin)

- ✓ Total number of scientists involved: 15, including 8 on-site collaborators
- ✓ Student participation: 4 post docs, 12 grad students, 12 undergrad students

Other primarily university-based research

- ✓ 18 EPR projects partially support a total of 117 scientists, engineers, and technicians and 45 graduate and undergraduate students

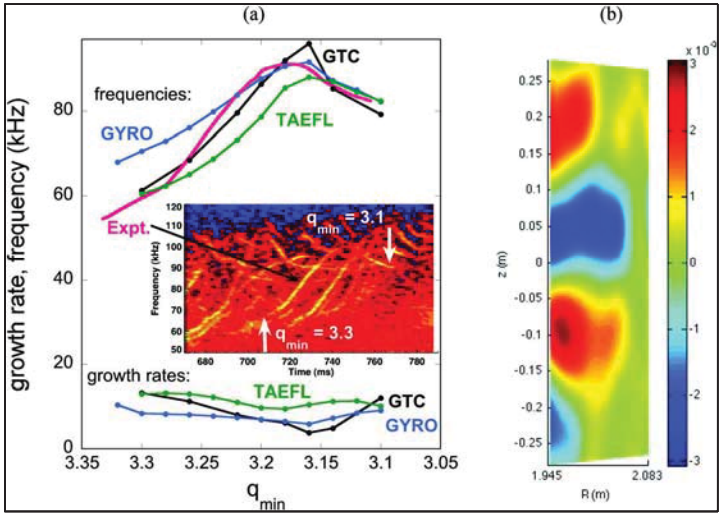
EPR emphasizes stellarators, spherical tori, field-reversed configurations, and spheromaks

Theory and SciDAC work together to advance fundamental science of magnetic confinement

Theory: fundamental plasma science of magnetic confinement

FES SciDAC: The FES Scientific Discovery through Advanced Computing (SciDAC) program:

- advances scientific discovery in fusion plasma science
- exploits SC leadership class computing resources and associated advances in computational science
- leverage with ASCR



Predictions of first-principles massively parallel simulation codes for Reversed Shear Alfvén Eigenmodes—an instability that may yield loss or redistribution of energetic particles— agree with experimental observations

✓ Theory Program researchers are located at six national laboratories, 20 universities, and 5 private companies; supports over 60 graduate students and 29 postdocs

✓ The FES SciDAC program’s seven multi-institutional, interdisciplinary Centers involve researchers located at six national laboratories, 17 universities, and 5 private companies, and support over 20 graduate students and 13 postdocs

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General Plasma Science Program

NSF/DOE Partnership and Joint Effort

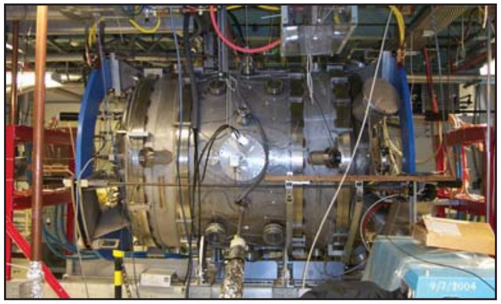
Individual Investigator: Research of fundamental plasma science and engineering issues awarded through annual joint NSF/DOE solicitation – supporting 40 projects at 24 universities

"User" Facility: Basic Plasma Science Facility (BaPSF) at UCLA

Center for Magnetic Self-Organization (CMSO) – supporting DOE Laboratory involvement in NSF Physics Frontier Center

Large Collaboration: Anti-hydrogen Trapping (non-neutral plasma) for the international ALPHA collabroation at CERN

International Collaboration: Max Planck-Princeton Center for Plasma Physics



DOE Laboratory General Plasma Science

Individual and collaborative research addressing specific applied plasma, laboratory, space, and astrophysical plasma issues - competitive review in FY 2013

Center for Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems
psc
Department of Energy Plasma Science Center

Plasma Science Centers

Multi-institution collaborative teams with a unified theme focused on a critical plasma question

Low Temperature *: Center for Predictive Control of Plasma Kinetics (PSC)*, lead: U Michigan

Basic Plasma : *Center for Momentum Transport an Flow Organization (CMTFO)*, lead: UCSD

✓ Ongoing research involving 90+ graduate students

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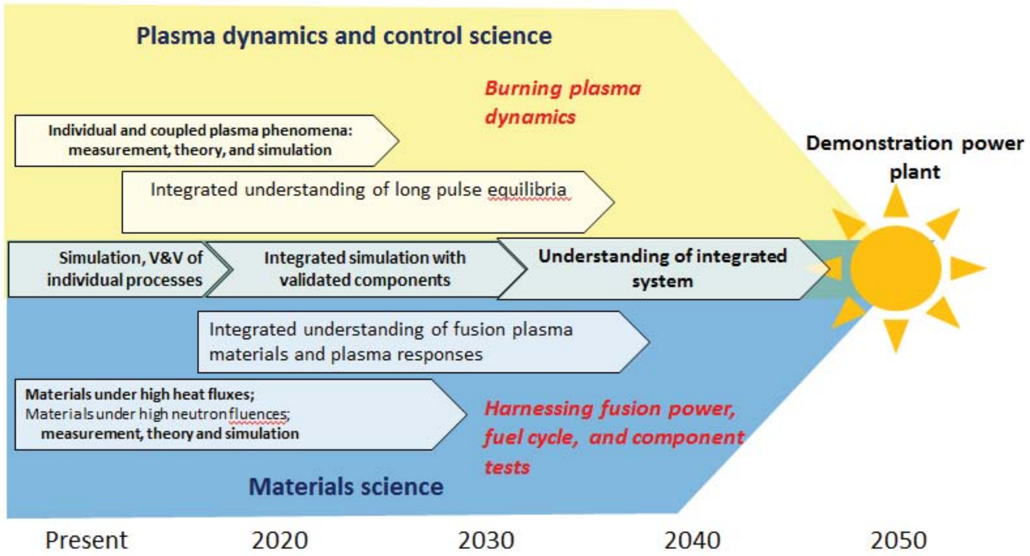
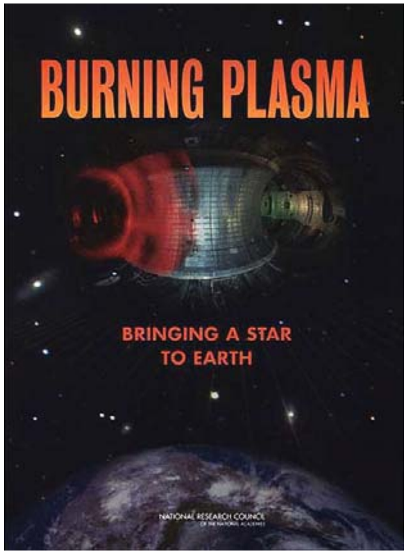
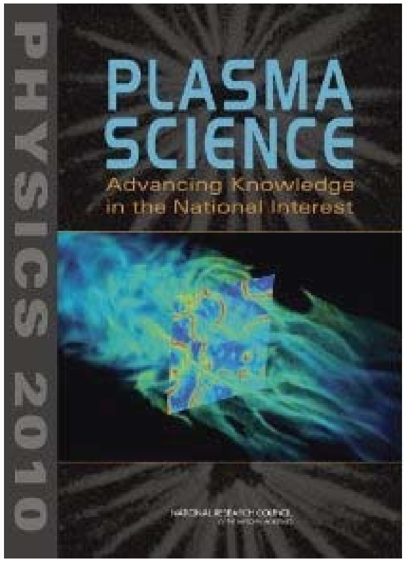
We know what we have to do for fusion to succeed



The next great step in fusion is the exploring self-heated plasmas, the burning plasma state: this is what ITER will enable

The remaining gap beyond this is fusion materials science – managing the harsh fusion environment, and closing the fuel cycle





National Academies Studies highlight the scientific needs for fusion and plasma science

Long term: if fusion is available by the second half of this century, it can be a significant player in the energy economy by 2100

- Assume ITER, DEMO, and supporting research establish the basis for fusion energy by 2050. Then
  - **Conservative assumption**: Note that **fission grew from 1975 through 1990 at 1.2%/year** of the world electric market. Then **if fusion grows at < 0.9%/year of after 2050,**

➔ ***fusion can deliver at least 30% of the world's energy production by 2100****

** Goldston, Grisham, Hammett, IAEA 2010, "Climate Change, Nuclear Proliferation, and Fusion Energy"*

➔ fusion can also contribute to fuel-switching strategies (e,g, off- peak hydrogen production)

Fusion can be transformative, and its future rests in our hands

- The well-being of all of us is intimately linked to technological transformation, whether we live in developed or developing nations

- Fusion represents a transformational science that can be part of our long-term energy and climate solutions, and can be critical in enhancing political stability

Thank you

Magnetic fusion is ready to strike for reactor conditions

- Global measure: fusion triple product (Lawson Criterion): $nT\tau$

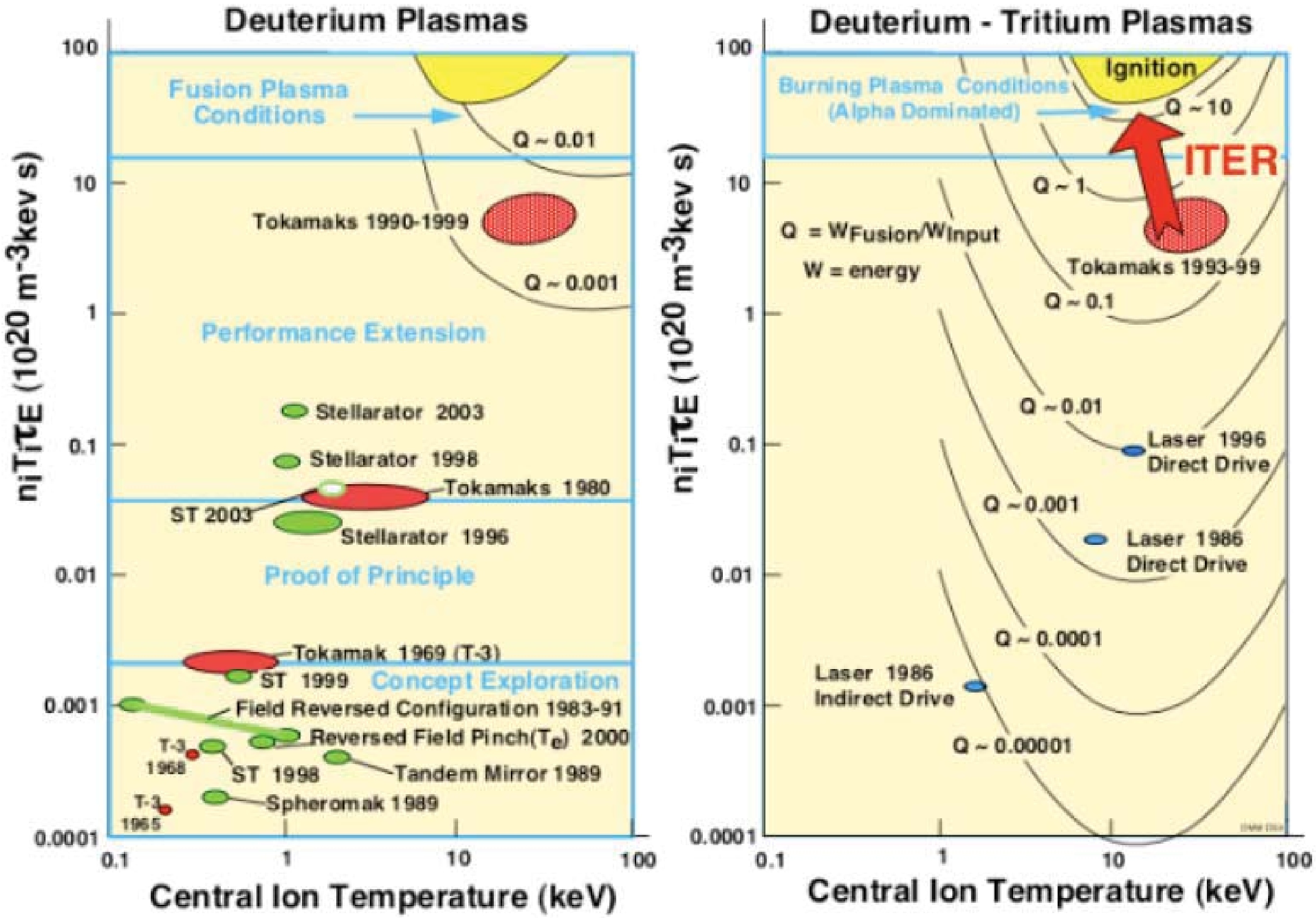


Fig. 2.b.2 Lawson Diagram for Magnetic Fusion