Fusion:

Lighting a Star on Earth

PPPL Open House 2004

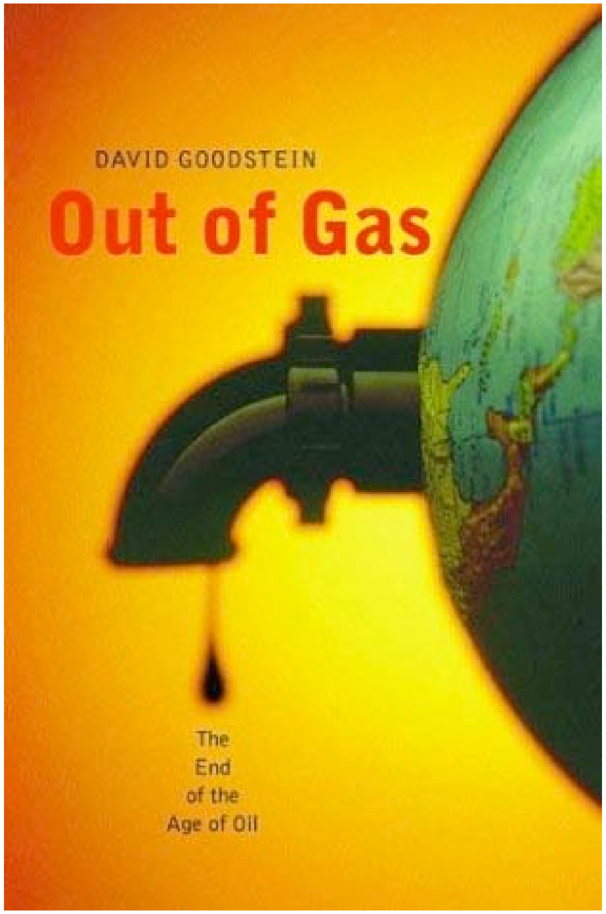
Professor Rob Goldston, Director
DOE Princeton University Plasma Physics Laboratory

June 12, 2004

The Issue of Climate Change is Increasing Attention to Fusion Energy

Jerry Mahlman, former Director of the NOAA Geophysical Fluid Dynamics Laboratory

What Will We do When the World Runs Out of Gas ?



"Most likely, progress will lie in incremental advances on many simultaneous fronts, based on principles we already understand: controlled nuclear fusion, safe breeder reactors, better materials for manipulating electricity, more efficient fuel cells, better means of generating hydrogen, and so on. Developing these technologies will require a massive, focused commitment to scientific and technological research. This is a commitment we have not yet made. We urgently need to make it."

David Goodstein
Vice Provost, California Institute of Technology
Out of Gas, 2004, p. 115

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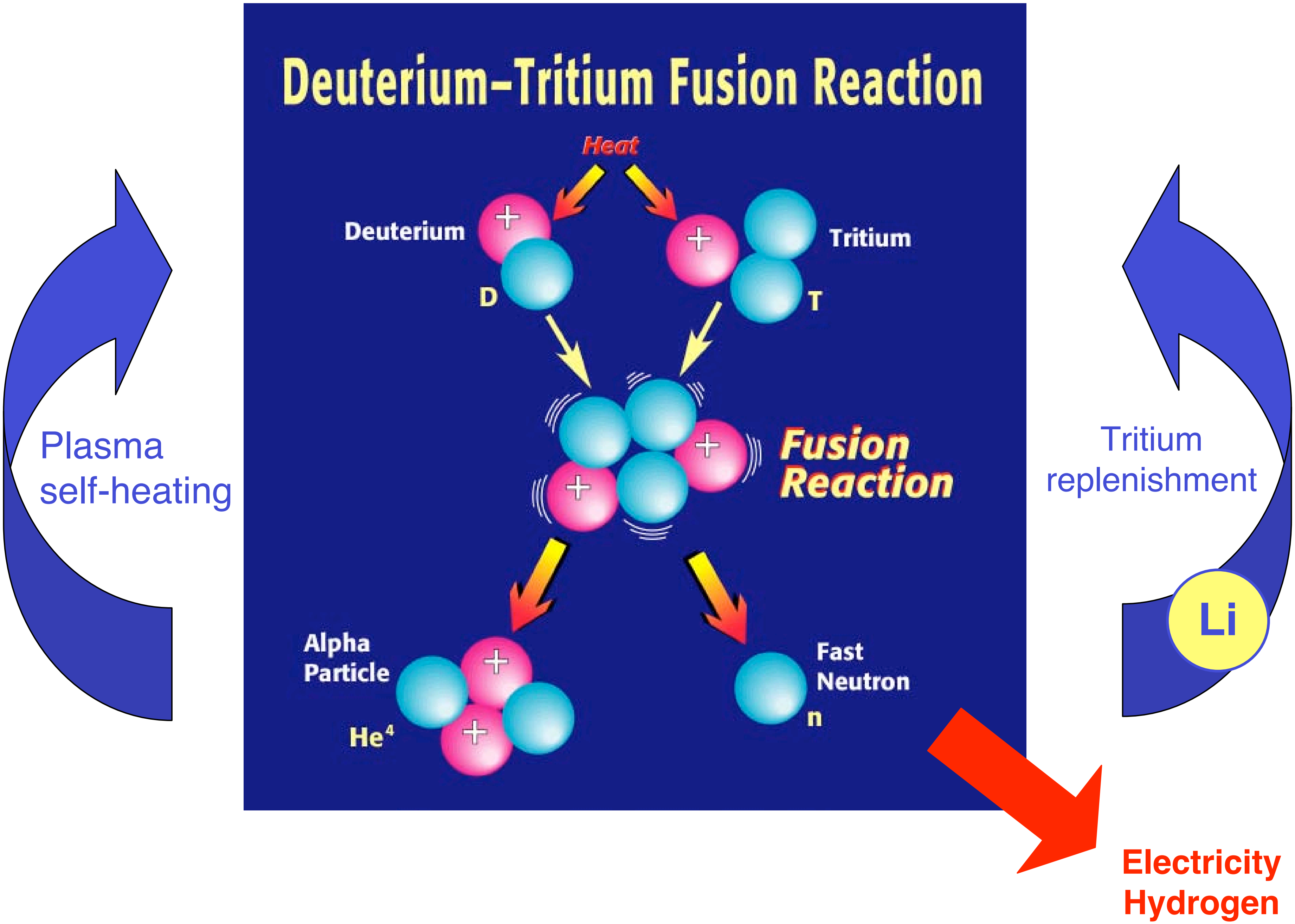
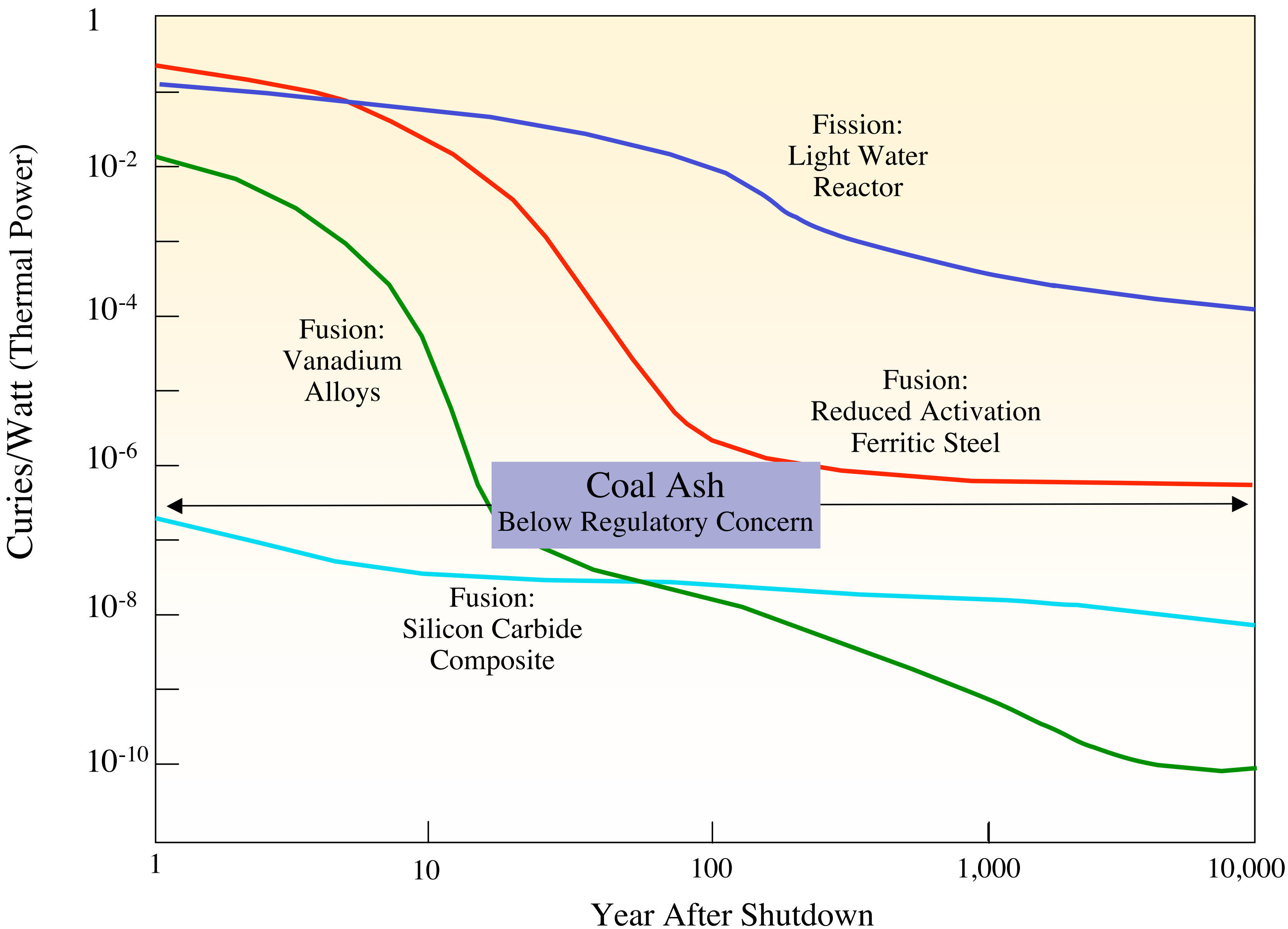


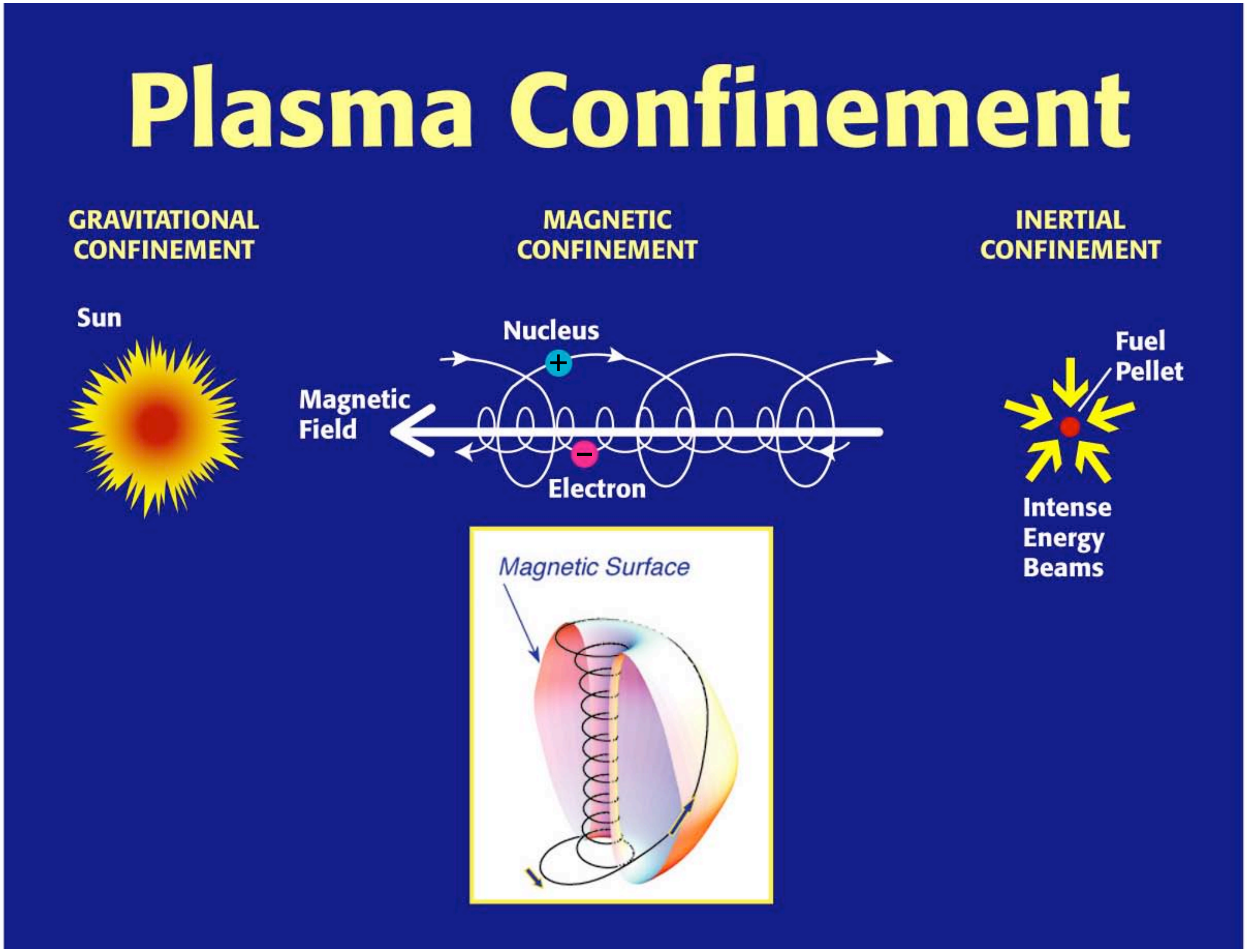
Deuterium-Tritium Fusion Reaction
Heat
Deuterium
D
Tritium
T
Fusion Reaction
Alpha Particle
He4
Fast Neutron
n
Plasma self-heating
Tritium replenishment
Li
Electricity
Hydrogen

Fusion can be a Very Attractive Domestic Energy Source

- Abundant fuel, available to all nations
  - Deuterium and lithium easily available for thousands of years
- Environmental advantages
  - No carbon emissions, short-lived radioactivity
- Can't blow up, resistant to terrorist attack
  - Less than a minute's worth of fuel in the chamber
- Low risk of nuclear materials proliferation
  - No fissile or fertile materials required
- Compact relative to solar, wind and biomass
  - Modest land usage
- Not subject to daily, seasonal or regional weather variation, no requirement for local CO_2 sequestration.
  - Not limited in its contribution by need for large-scale energy storage or extreme-distance transmission
- Cost of power estimated similar to coal, fission
- Can produce electricity and hydrogen
  - Complements other nearer-term energy sources

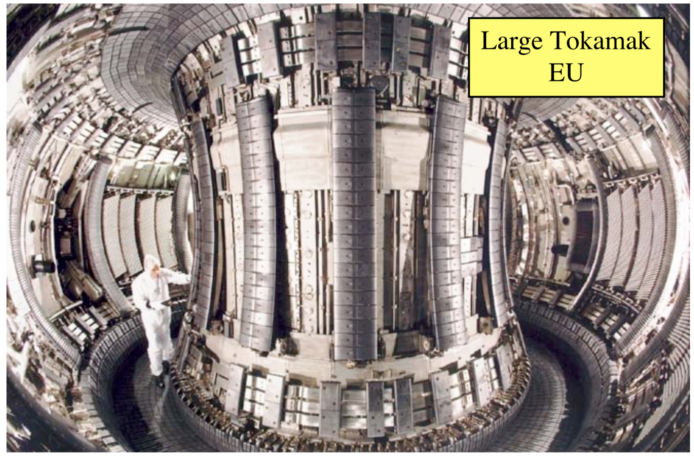
Comparison of Fission and Fusion Radioactivity After Shutdown

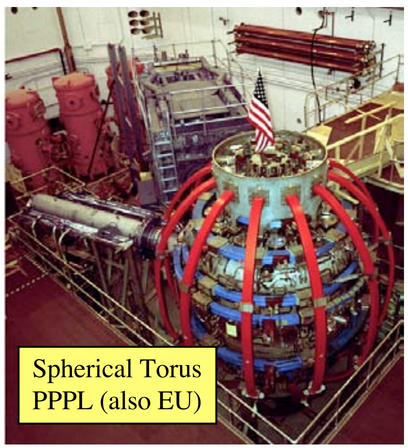


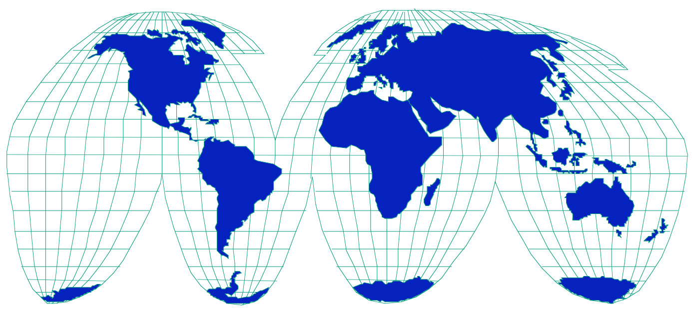


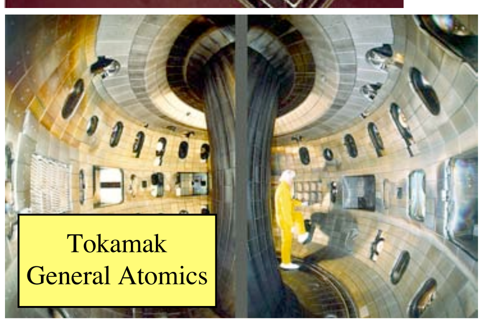
Plasma science also has impacts far beyond fusion energy – in computer chip processing, fuel efficiency, astrophysics…

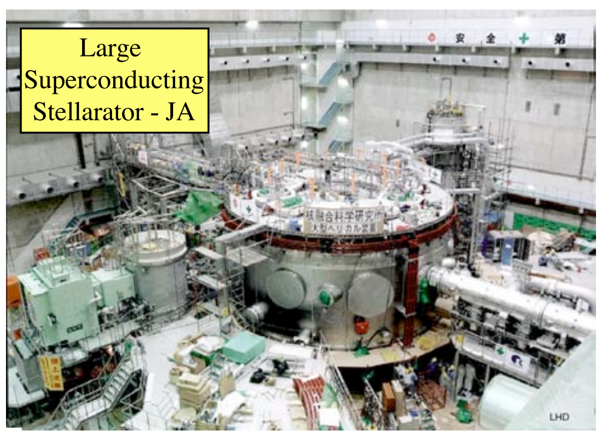
Fusion Development is a Worldwide Activity

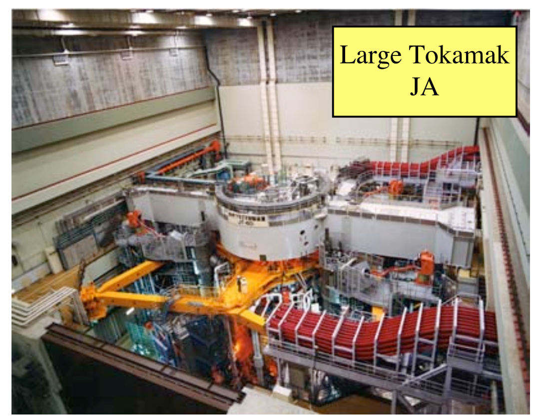








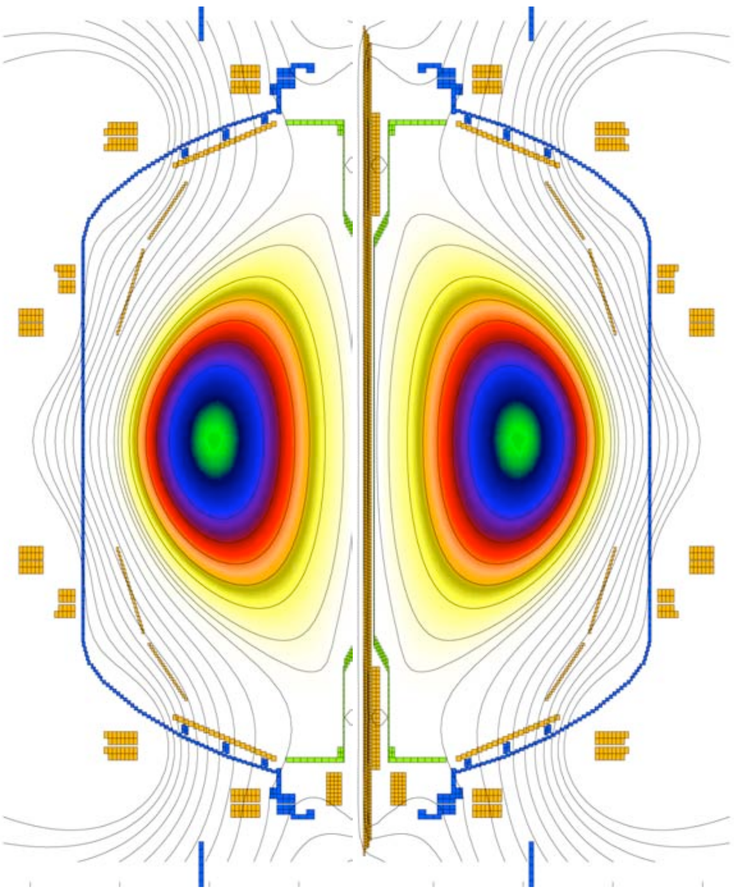




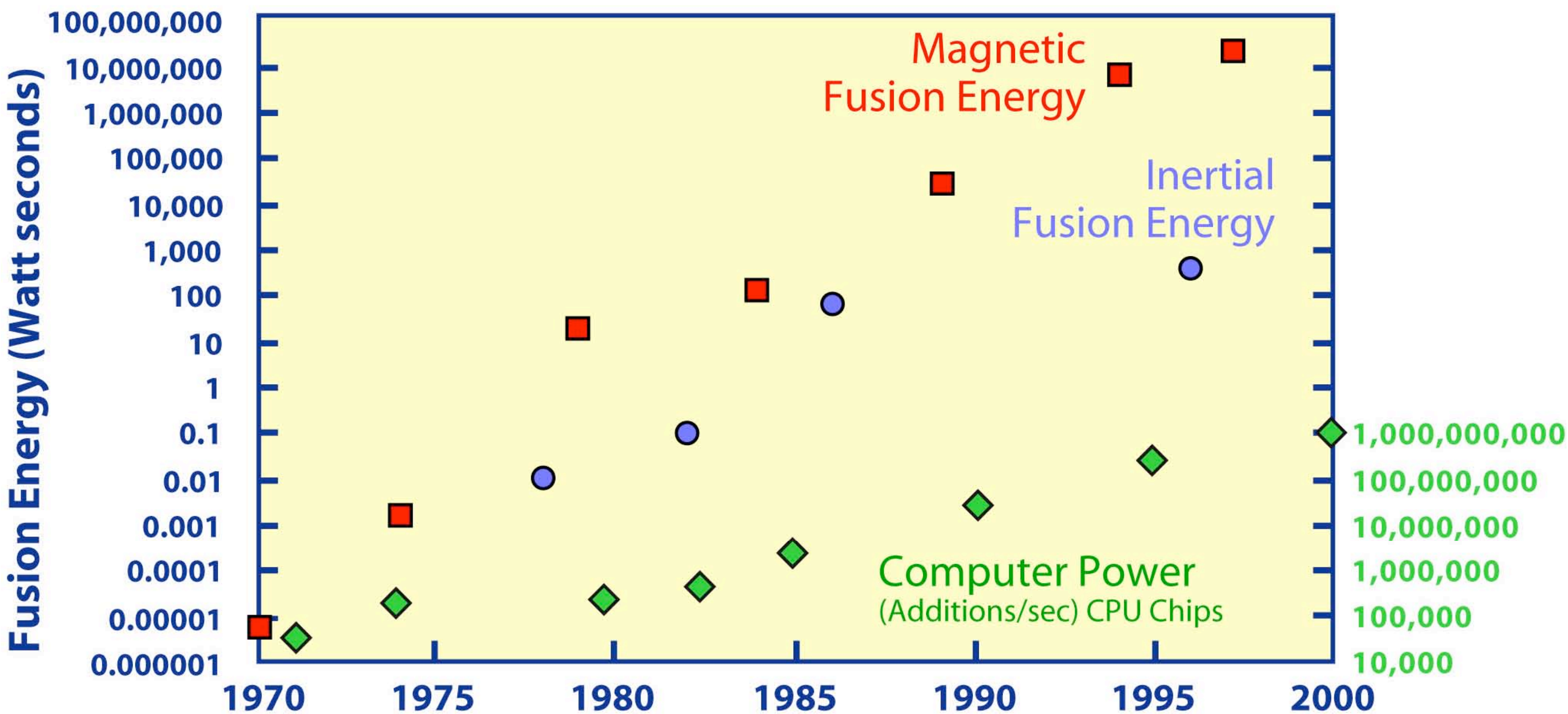
Dramatic Recent Advances in Fusion Science

with Strong Connections to other Areas of Science and Technology

- **Global Stability**
  - *What limits the pressure in plasmas?*
  - Ideal understood, controlling resistive
    - Solar flares
- **Wave-particle Interactions**
  - *How do hot particles and plasma waves interact?*
  - Good understanding of linear regime
    - Magnetospheric heating
- **Microturbulence & Transport**
  - *What causes plasma transport?*
  - Well accepted model for ion transport
    - Accretion disks
- **Plasma-material Interactions**
  - *How can high-temperature plasma and material surfaces co-exist?*
  - Detached divertor regime discovered
    - Micro-electronics processing

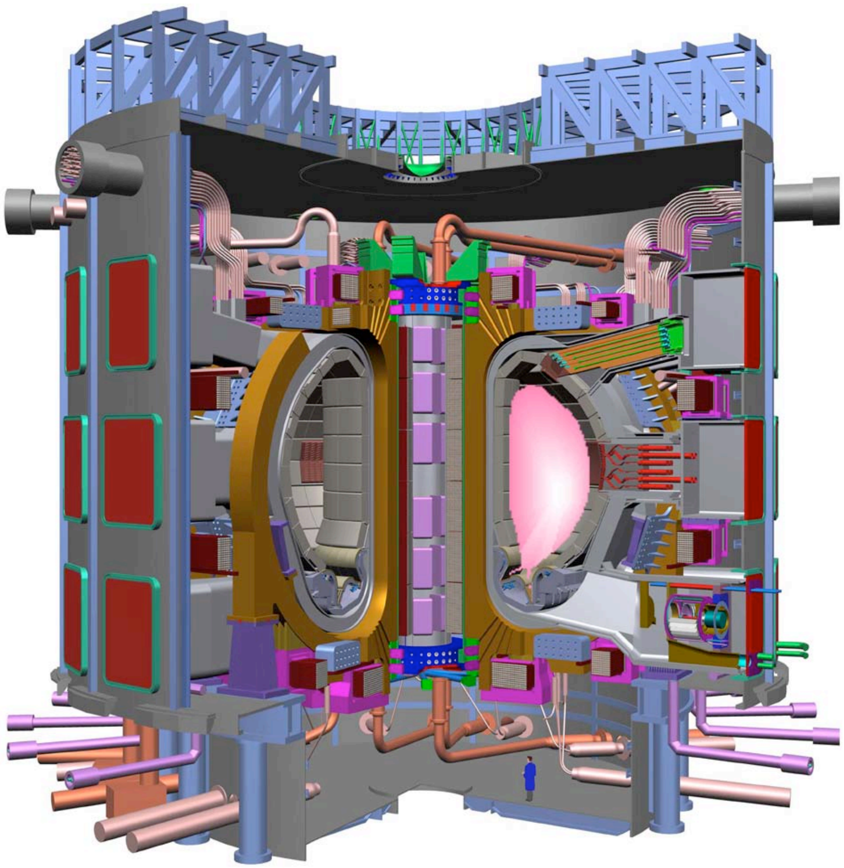


Progress in Fusion has Outpaced Computer Speed



Progress is paced by the construction of new facilities.

ITER Provides an Opportunity to *Light a Star on Earth*



Fusion Science Benefits:
Extends fusion science to larger size, burning (self-heated) plasmas – for very long pulses.

Technology Benefits:
Fusion-relevant technologies.
High duty-factor operation.

Today:	15 MW for 1 second, gain < 1
ITER:	500 MW for 10 minutes, gain > 10

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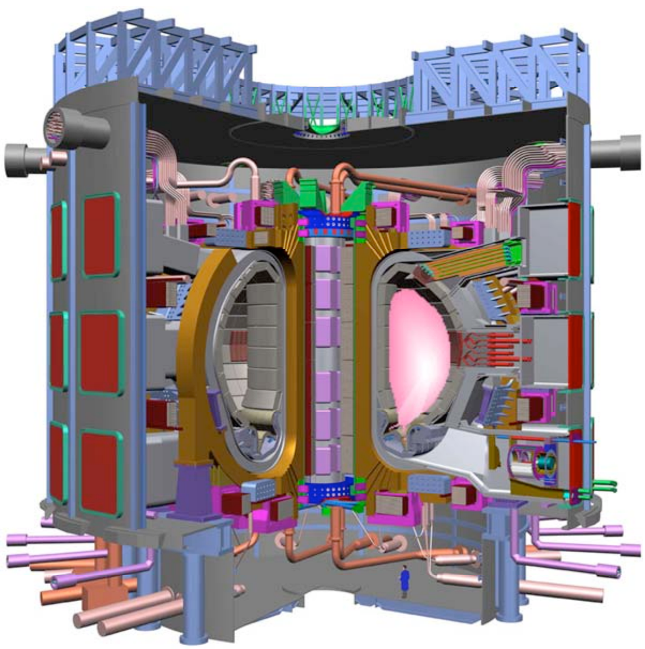
ITER Negotiations:
Europe, Japan, Russia, US, China, South Korea

- Two sites are now on the table:
  - Japan: Rokkasho, northeast corner of the main island
  - France: Cadarache, near Aix-en-Provence
- The financial numbers add up:
  - The Host pays 48%
  - The primary non-Host pays 12%
  - US, China, South Korea, Russia each pay 10%
- The key issues for resolution are:
  - Siting - how do we have a win/win?
  - Management of a major international construction project
  - Risk allocation



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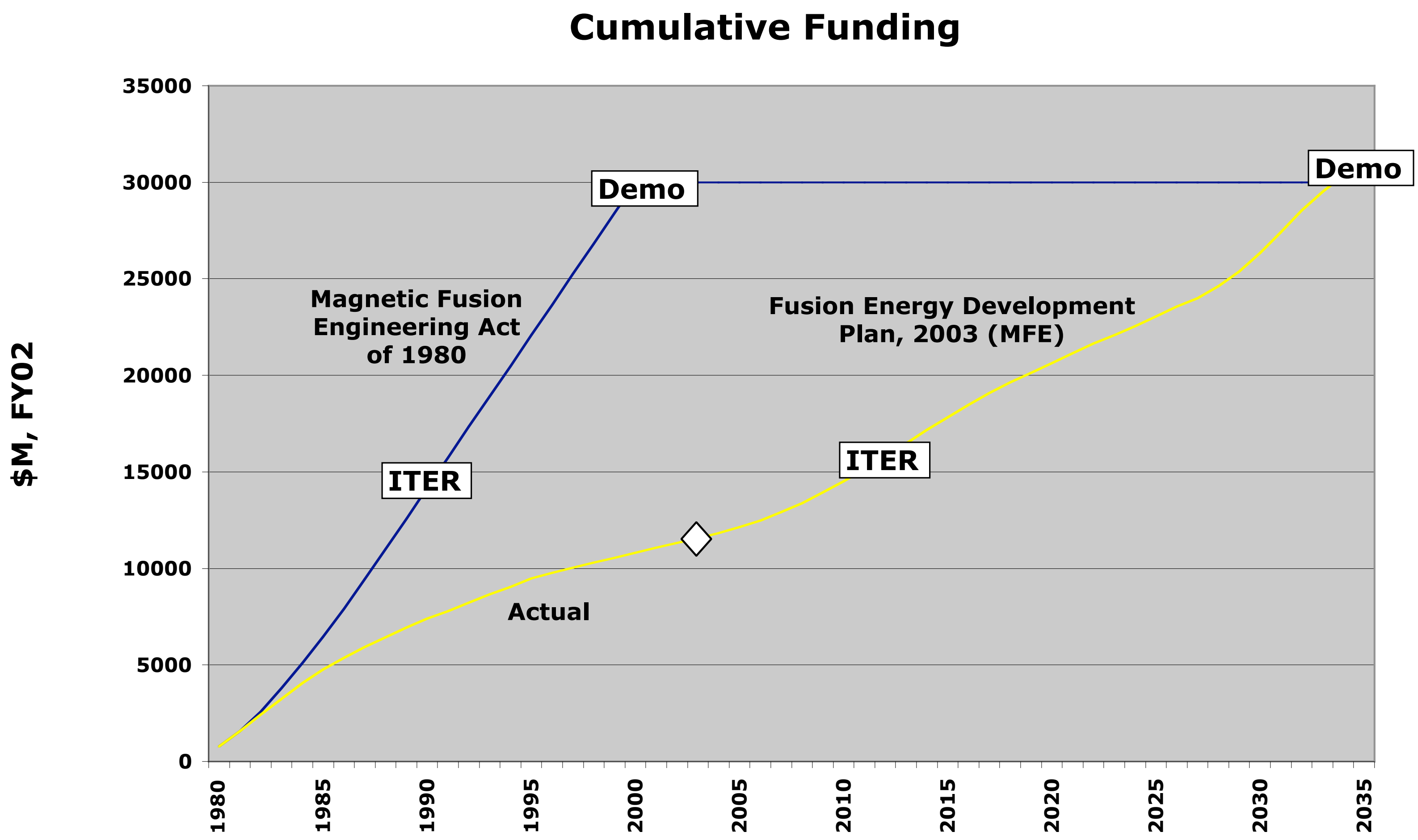
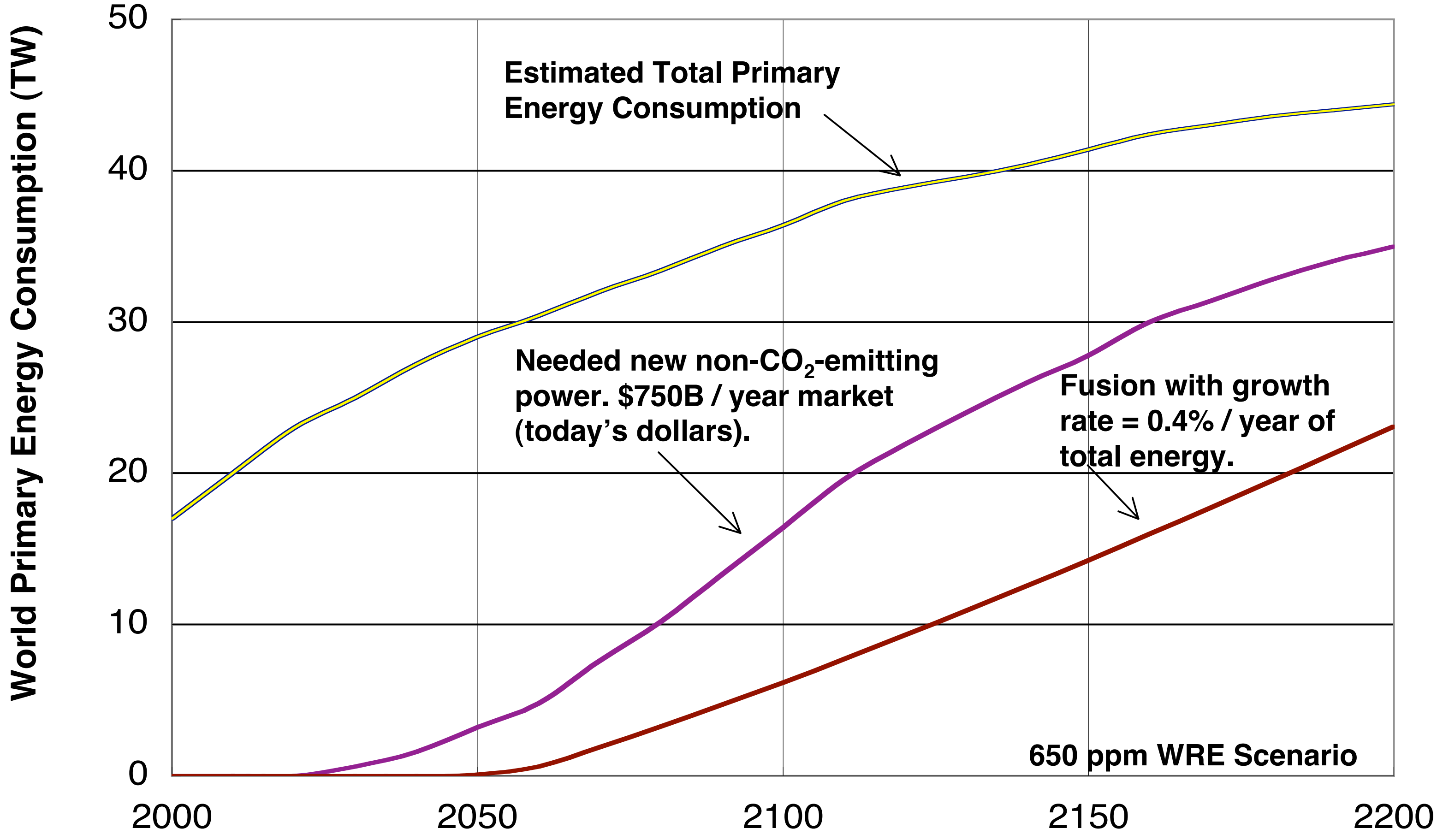
The Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980



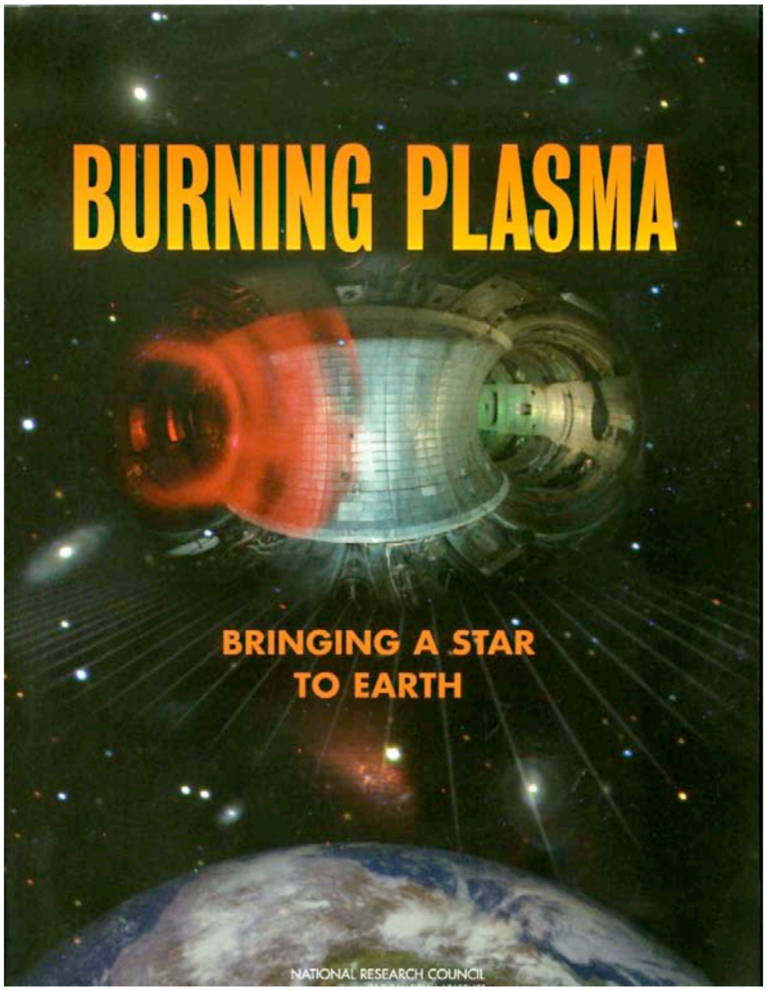
The pace of fusion energy development is set by funding.

The Value of Fusion-Produced Energy is 12,000x Greater than the Development Cost



Total value = $296T at $0.02 per kWhr thermal ($FY2002)

The National Academy Endorses both ITER and a Strong Domestic Fusion Program



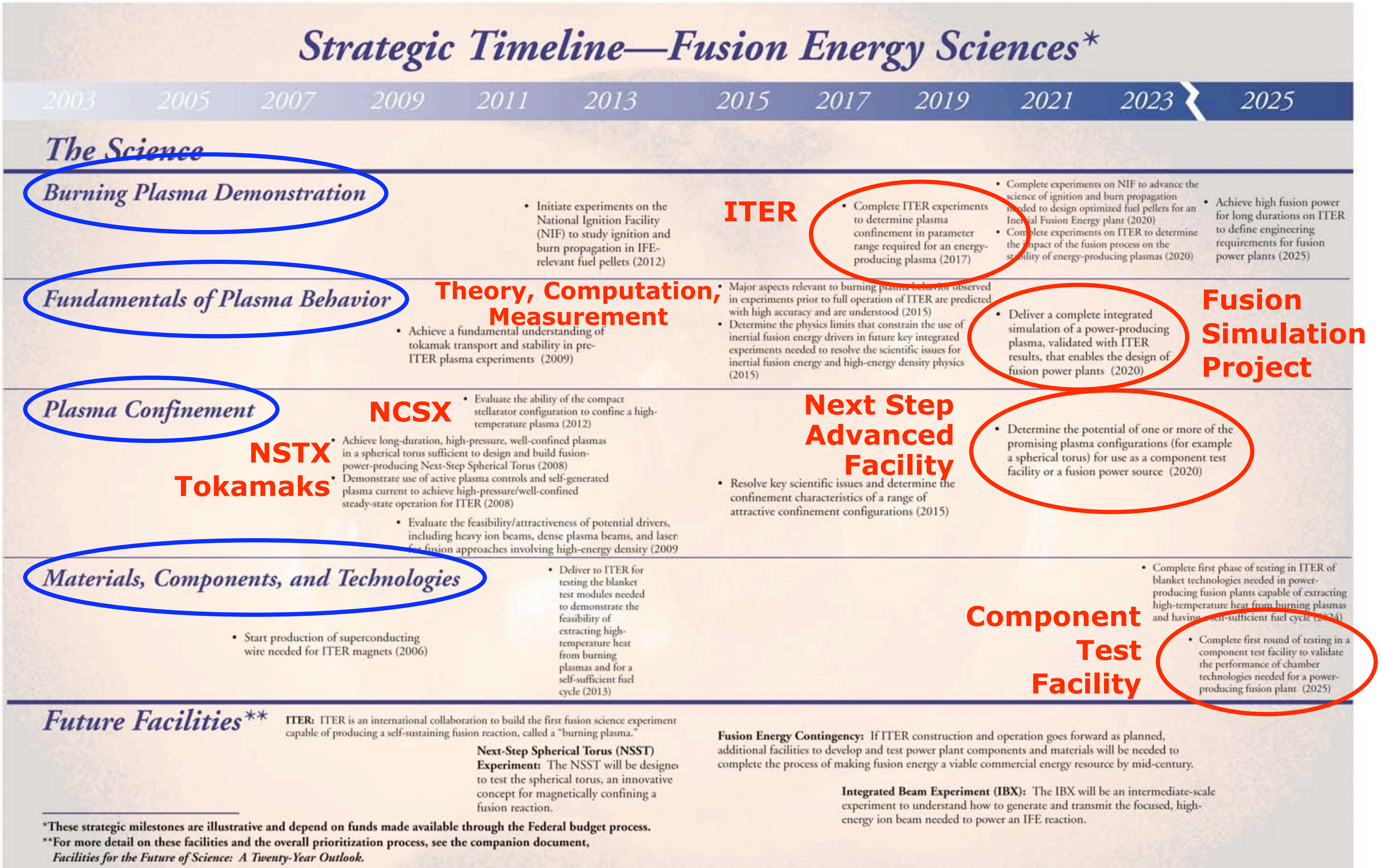
"A strategically balanced U.S. fusion program should be developed that includes U.S. participation in ITER, a strong domestic fusion science and technology portfolio, an integrated theory and simulation program, and support for plasma science. As the ITER project develops, a substantial augmentation in fusion science program funding will be required in addition to the direct financial commitment to ITER construction."

National Research Council, Burning Plasma Report, 2003

President Bush on Fusion (2/6/03)

DOE Science 20-Year Strategic Plan

Defines the U.S. Strategy for Fusion Energy Sciences



DOE Science 20-Year Strategic Plan

Defines the U.S. Strategy for Fusion Energy Sciences

Strategic Timeline—Fusion Energy Sciences*

2003 | 2005 | 2007 | 2009 | 2011 | 2013 | 2015 | 2017 | 2019 | 2021 | 2023 | 2025

The Science

Burning Plasma Demonstration

- Initiate experiments on the National Ignition Facility (NIF) to study ignition and burn propagation in IFE-relevant fuel pellets (2012)
- Complete ITER experiments to determine plasma confinement in parameter range required for an energy-producing plasma (2017)
- Complete experiments on NIF to advance the science of ignition and burn propagation needed to design optimized fuel pellets for an Inertial Fusion Energy plant (2020)
- Complete experiments on ITER to determine the impact of the fusion process on the stability of energy-producing plasmas (2020)
- Achieve high fusion power for long durations on ITER to define engineering requirements for fusion power plants (2025)

Fundamentals of Plasma Behavior

Theory, Computation, Measurement

- Achieve a fundamental understanding of tokamak transport and stability in pre-ITER plasma experiments (2009)
- Major aspects relevant to burning plasma behavior observed in experiments prior to full operation of ITER are predicted with high accuracy and are understood (2015)
- Determine the physics limits that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high-energy density physics (2015)
- Deliver a complete integrated simulation of a power-producing plasma, validated with ITER results, that enables the design of fusion power plants (2020)

Fusion Simulation Project

Plasma Confinement

- Evaluate the ability of the compact stellarator configuration to confine a high-temperature plasma (2012)
- Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus sufficient to design and build fusion-power-producing Next-Step Spherical Torus (2008)
- Demonstrate use of active plasma controls and self-generated plasma current to achieve high-pressure/well-confined steady-state operation for ITER (2008)
- Evaluate the feasibility/attractiveness of potential drivers, including heavy ion beams, dense plasma beams, and laser for fusion approaches involving high-energy density (2009
- Resolve key scientific issues and determine the confinement characteristics of a range of attractive confinement configurations (2015)
- Determine the potential of one or more of the promising plasma configurations (for example a spherical torus) for use as a component test facility or a fusion power source (2020)

Materials, Components, and Technologies

- Start production of superconducting wire needed for ITER magnets (2006)
- Deliver to ITER for testing the blanket test modules needed to demonstrate the feasibility of extracting high-temperature heat from burning plasmas and for a self-sufficient fuel cycle (2013)
- Complete first phase of testing in ITER of blanket technologies needed in power-producing fusion plants capable of extracting high-temperature heat from burning plasmas and having a self-sufficient fuel cycle (2024)
- Complete first round of testing in a component test facility to validate the performance of chamber technologies needed for a power-producing fusion plant (2025)

Future Facilities**

ITER: ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a "burning plasma."

Next-Step Spherical Torus (NSST) Experiment: The NSST will be designe to test the spherical torus, an innovative concept for magnetically confining a fusion reaction.

Fusion Energy Contingency: If ITER construction and operation goes forward as planned, additional facilities to develop and test power plant components and materials will be needed to complete the process of making fusion energy a viable commercial energy resource by mid-century.

Integrated Beam Experiment (IBX): The IBX will be an intermediate-scale experiment to understand how to generate and transmit the focused, high-energy ion beam needed to power an IFE reaction.

*These strategic milestones are illustrative and depend on funds made available through the Federal budget process.
**For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.*

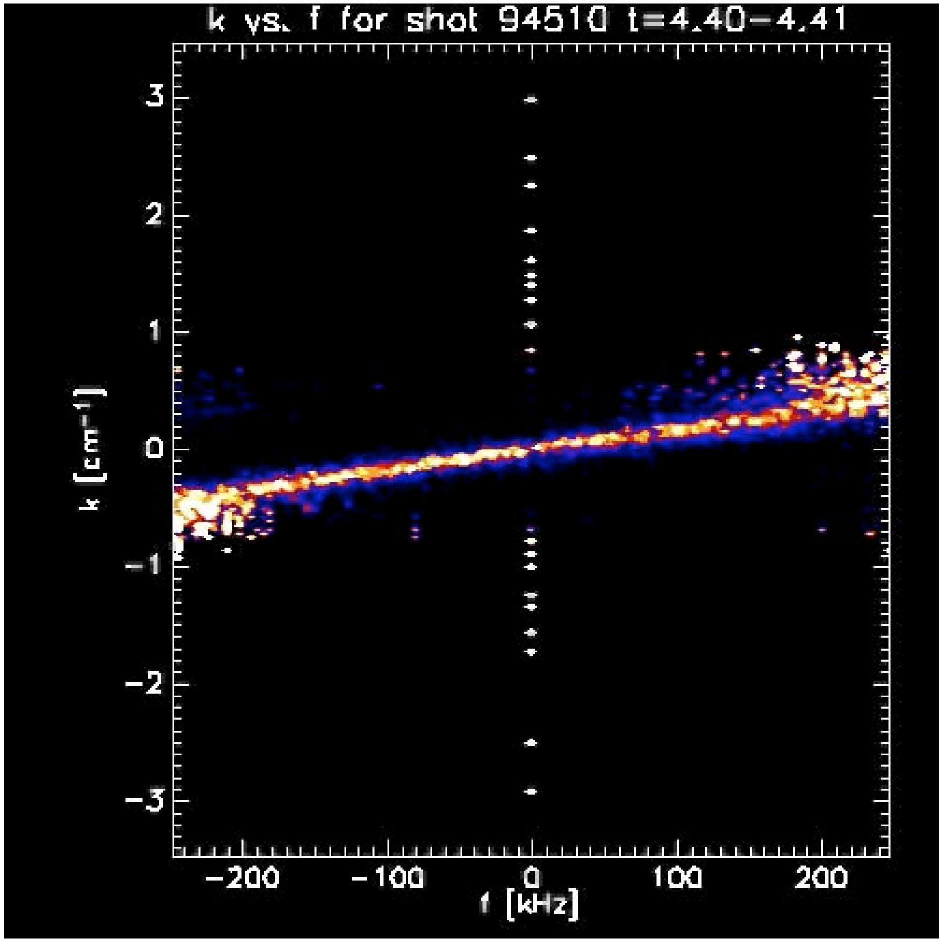
Simulation of Microwave Reflection From Plasma Turbulence

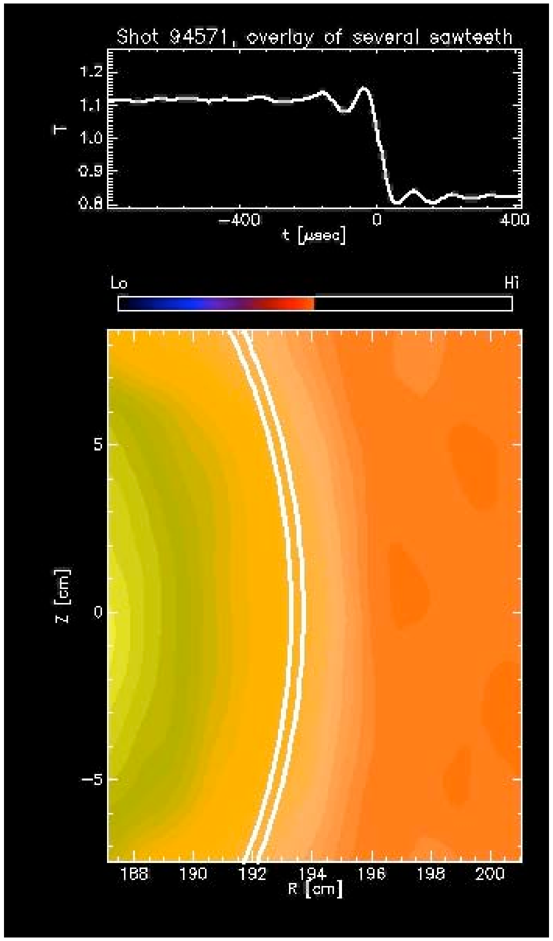
Z. Lin, GTC simulation

G.J. Kramer, E. Valeo, R. Nazikian, Full Wave simulation

S. Klasky, I. Zatz, Visualization

Advanced Plasma Diagnostics in Action





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Collaboration with UC Davis at TEXTOR in Germany

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NCSX

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NSTX Tokamaks

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Next Step Advanced Facility

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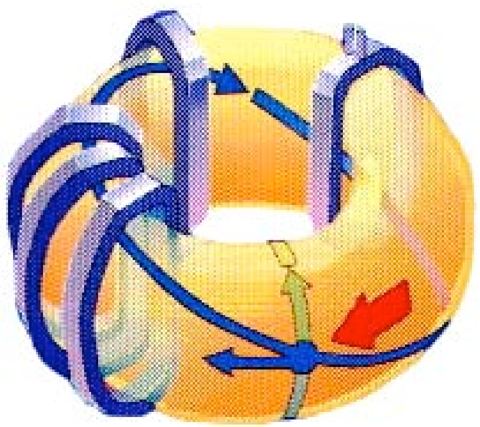
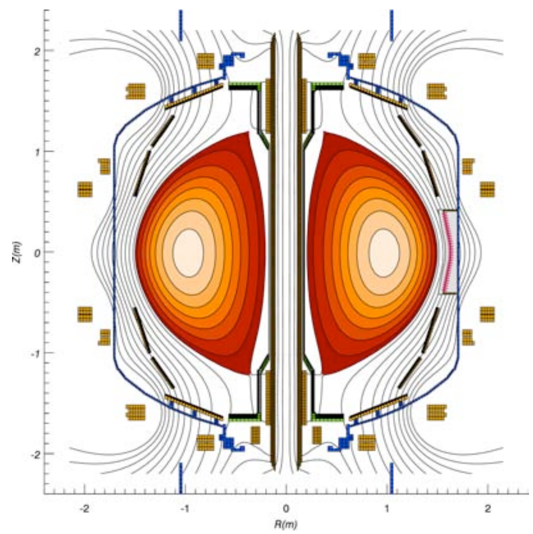
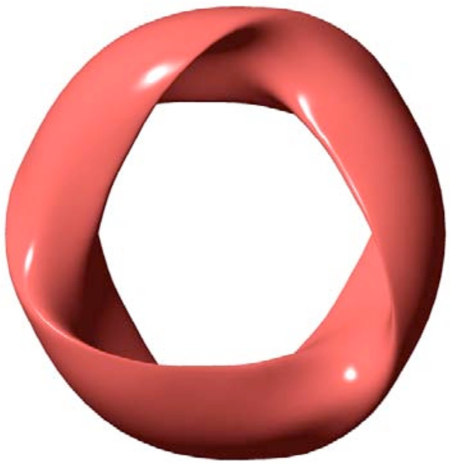
PPPL is Engaged in Fusion Plasma Science across a Breadth of Configurations



Advanced Tokamak
Active instability control and driven steady-state.



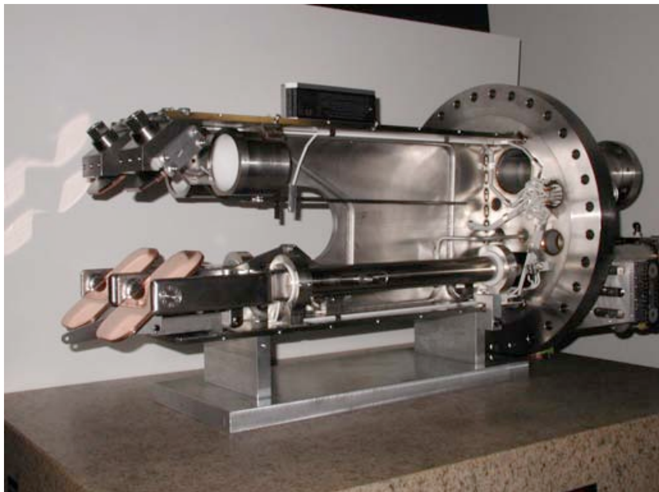
Spherical Torus
High plasma pressure at low magnetic field.



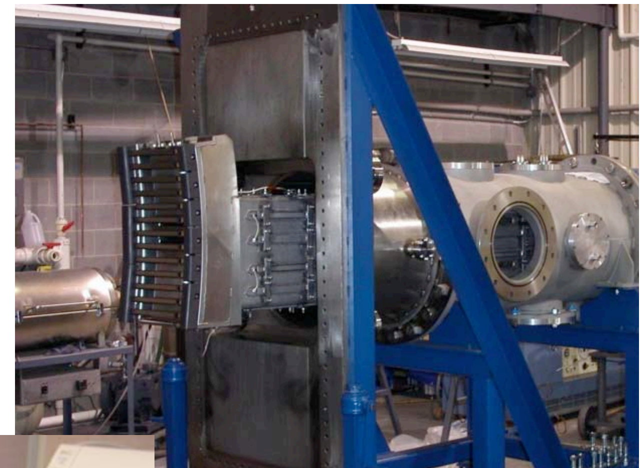
Compact Stellarator
Passive stability and steady-state operation.

Understanding that spans configurations is the deepest. Combine U.S. innovation with ITER for practical fusion.

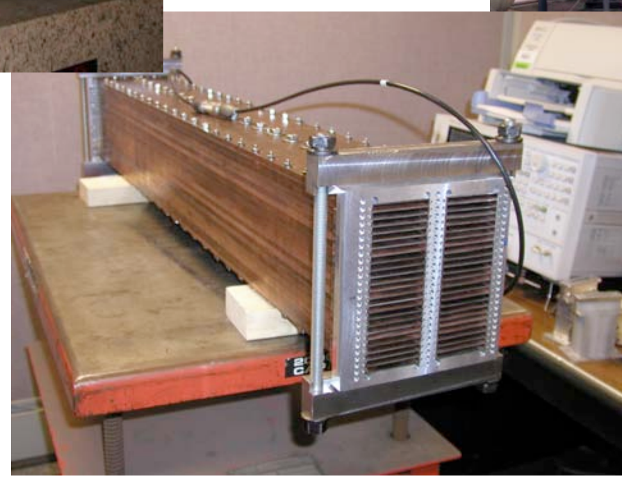
PPPL is Developing Plasma Control Techniques through Off-Site Tokamak Research



Electron Cyclotron Launcher at DIII-D



Ion Cyclotron Launcher at JET



Lower Hybrid Launcher at C-MOD

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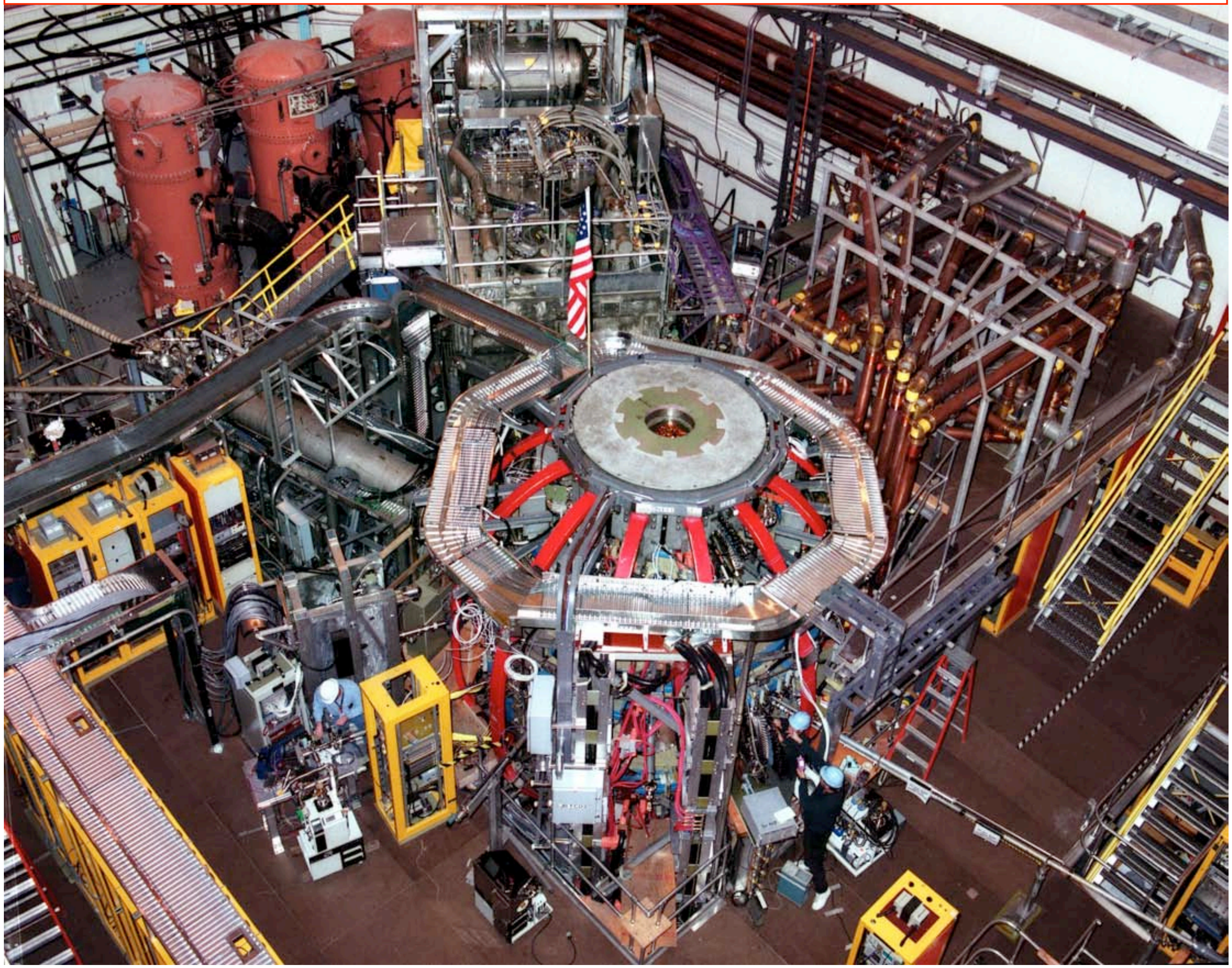
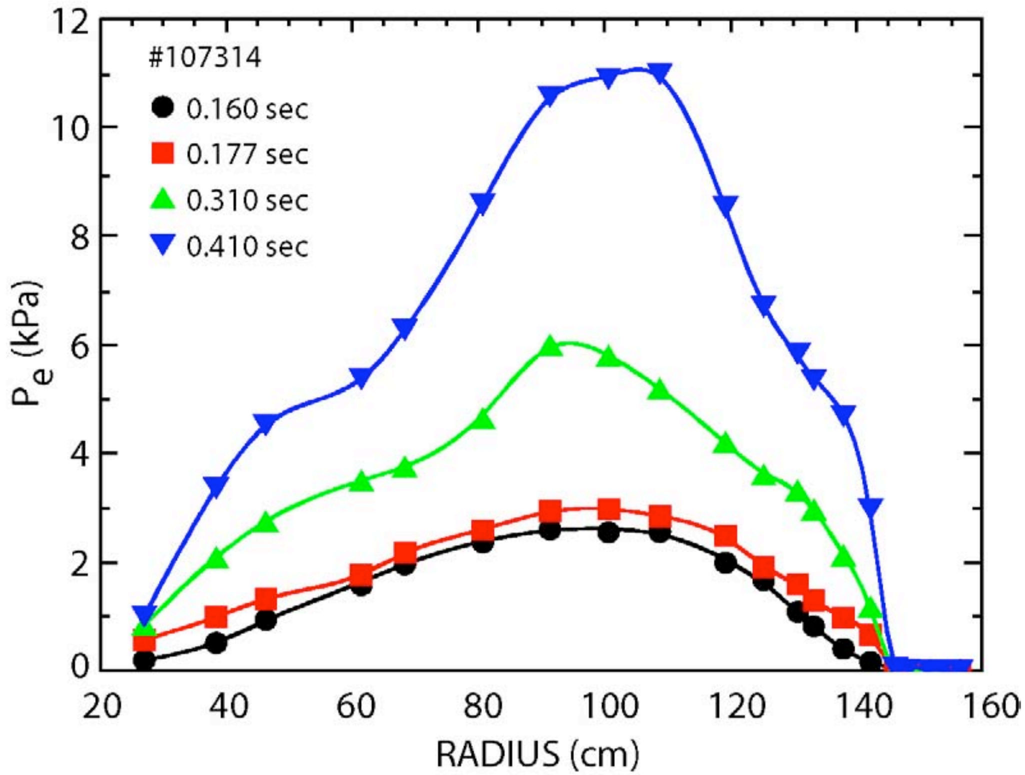
National Spherical Torus Experiment

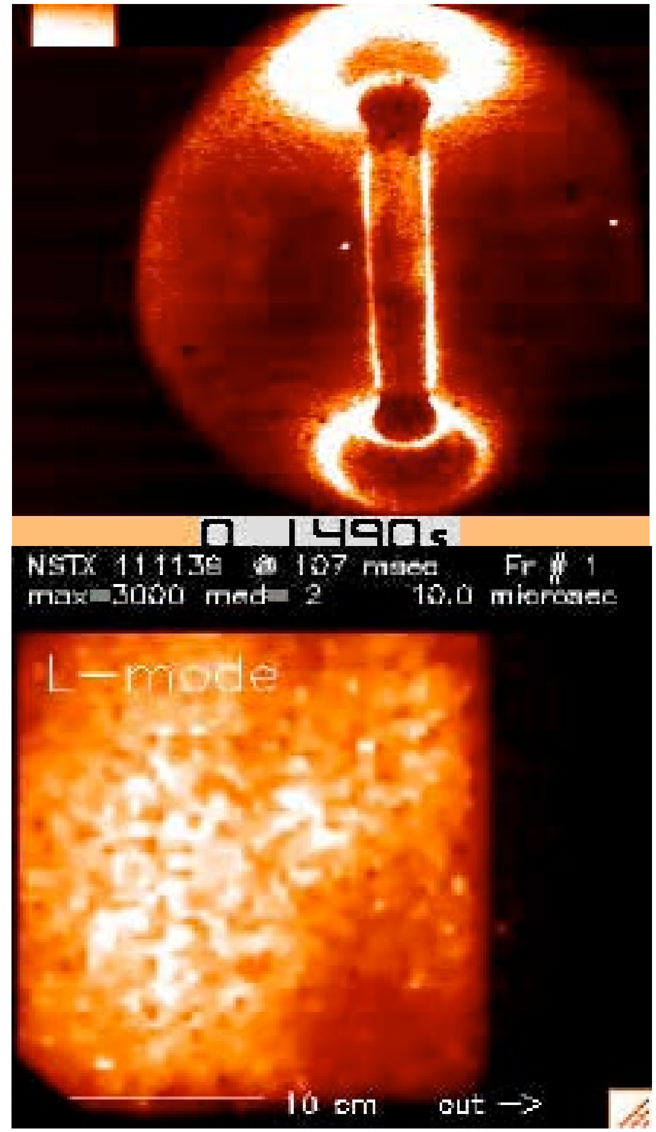


Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Garching
IPP, Jülich
U Quebec

Collaboration is Central to NSTX Science and Management

Very Steep Pressure Gradients are Observed near Edge of Plasma in H-mode





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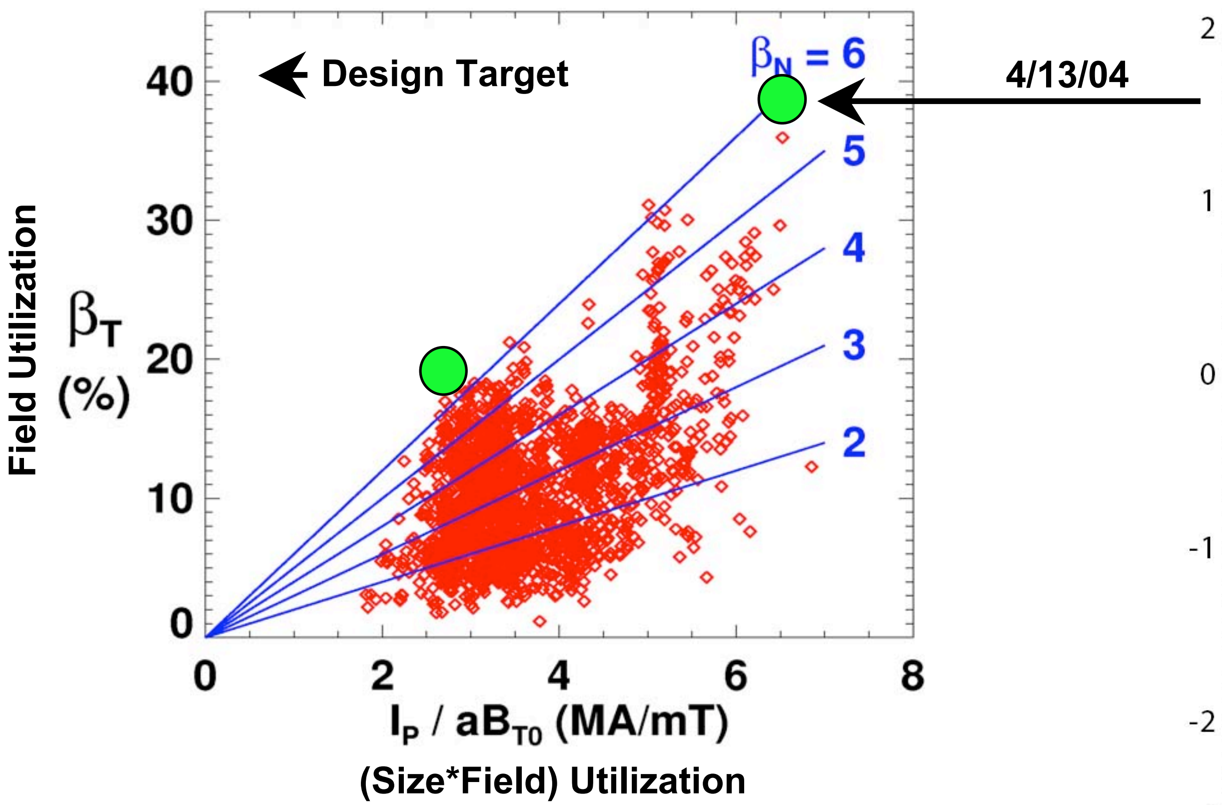
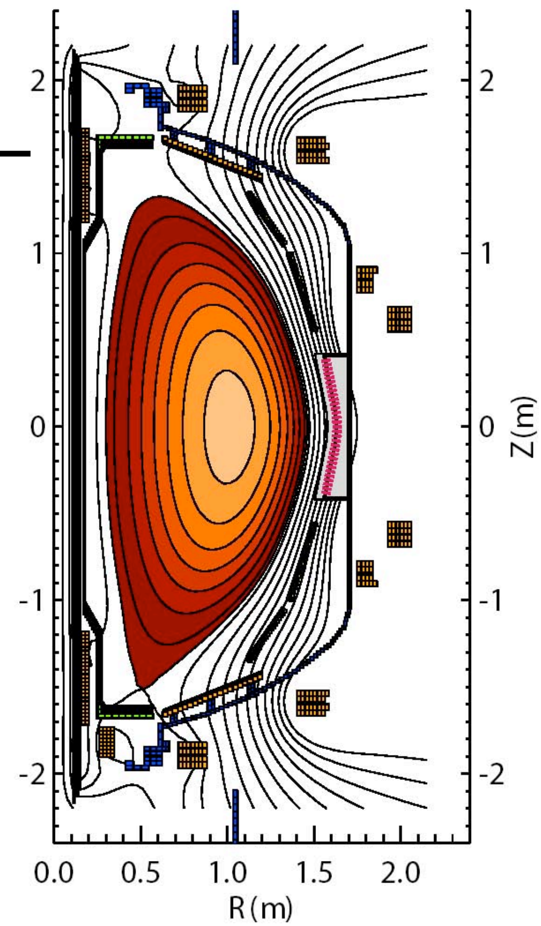
β_T ~ 38% Achieved: Goal is 40%



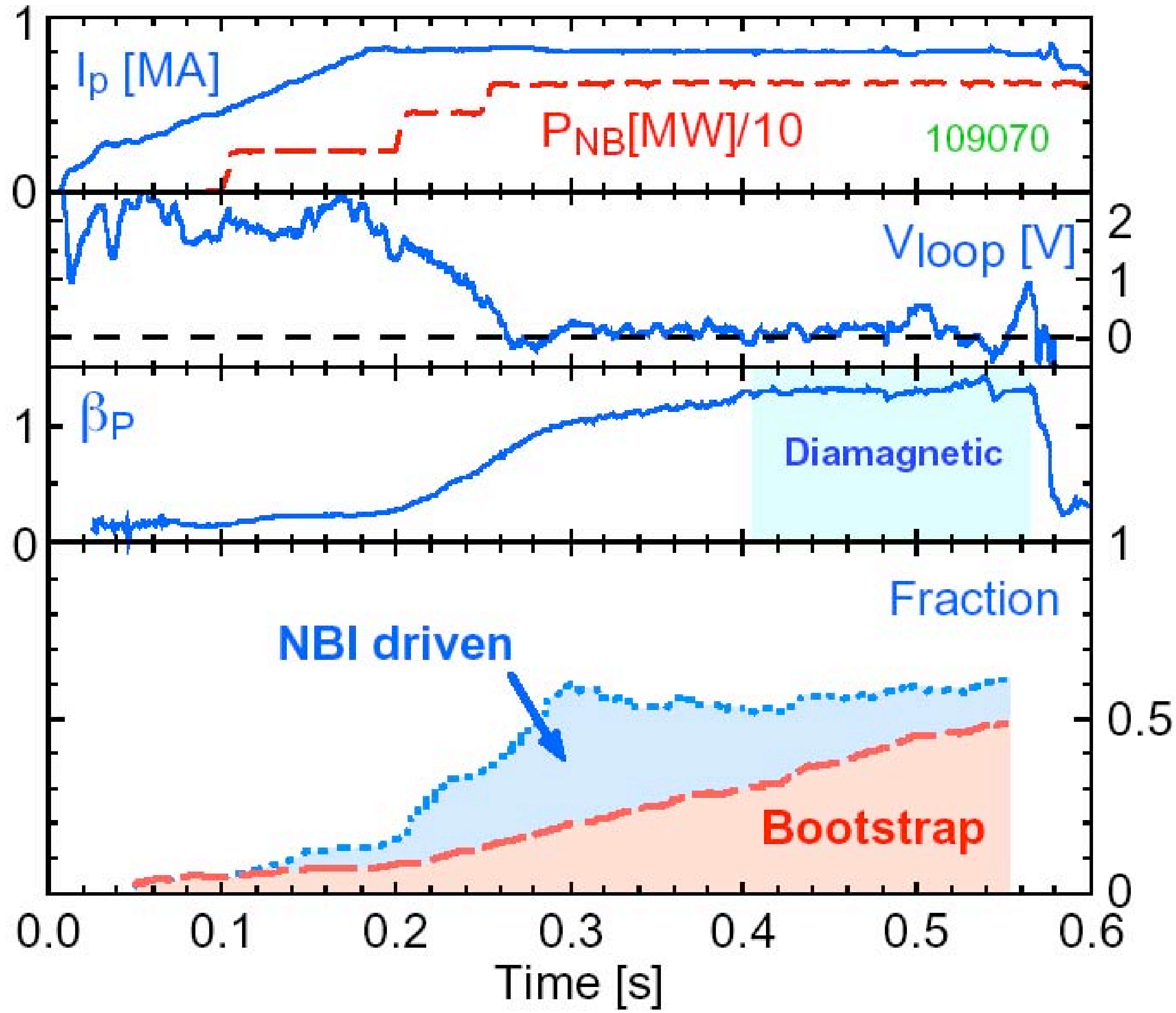


The next stage on NSTX is to demonstrate sustained operation.

A Major Challenge for Tokamaks & ST's: Sustained Operation

Most of the plasma current *must* be supplied through the self-sustained bootstrap current, while operating well above the no-wall beta limit.

Can be tested in ITER in conditions relevant to tokamak and ST.



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Compact Stellarators Offer a Different Twist on Plasma Confinement

Goals:

- **Steady-state, disruption-free high β plasma operation, without current or rotation drive for stable, steady operation at high power and high gain.**
- **Low R/a for high power / size.**

Through 3-dimensional Shaping:

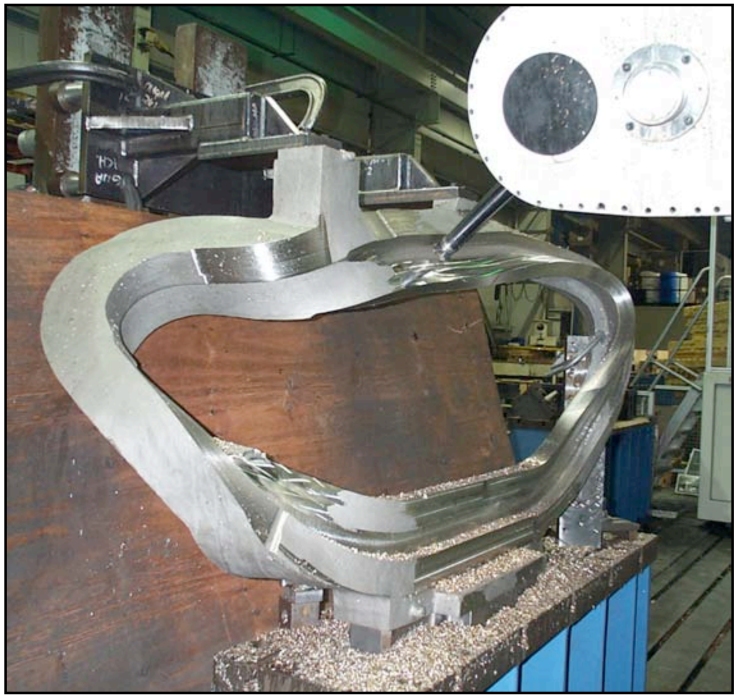
- **Massively parallel computing to maximize stability, buildability and quasi-symmetry / transport**
- **Quasi-axisymmetry builds on tokamak data base.**

Auburn U., Columbia U., LLNL, NYU, ORNL, PPPL, SNL-A, U. Texas, UCSD, U. Wisconsin

Australia, Austria, Japan, Germany, Russia, Spain, Switzerland, Ukraine

NCSX Manufacturing Accomplishments

Successful Prototypes of Key Components



Modular Coil Winding Form
Energy Industries of Ohio
Independence, Ohio

Vacuum Vessel Prototype
Major Tool and Machine
Indianapolis, Indiana

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Procurements later this summer.

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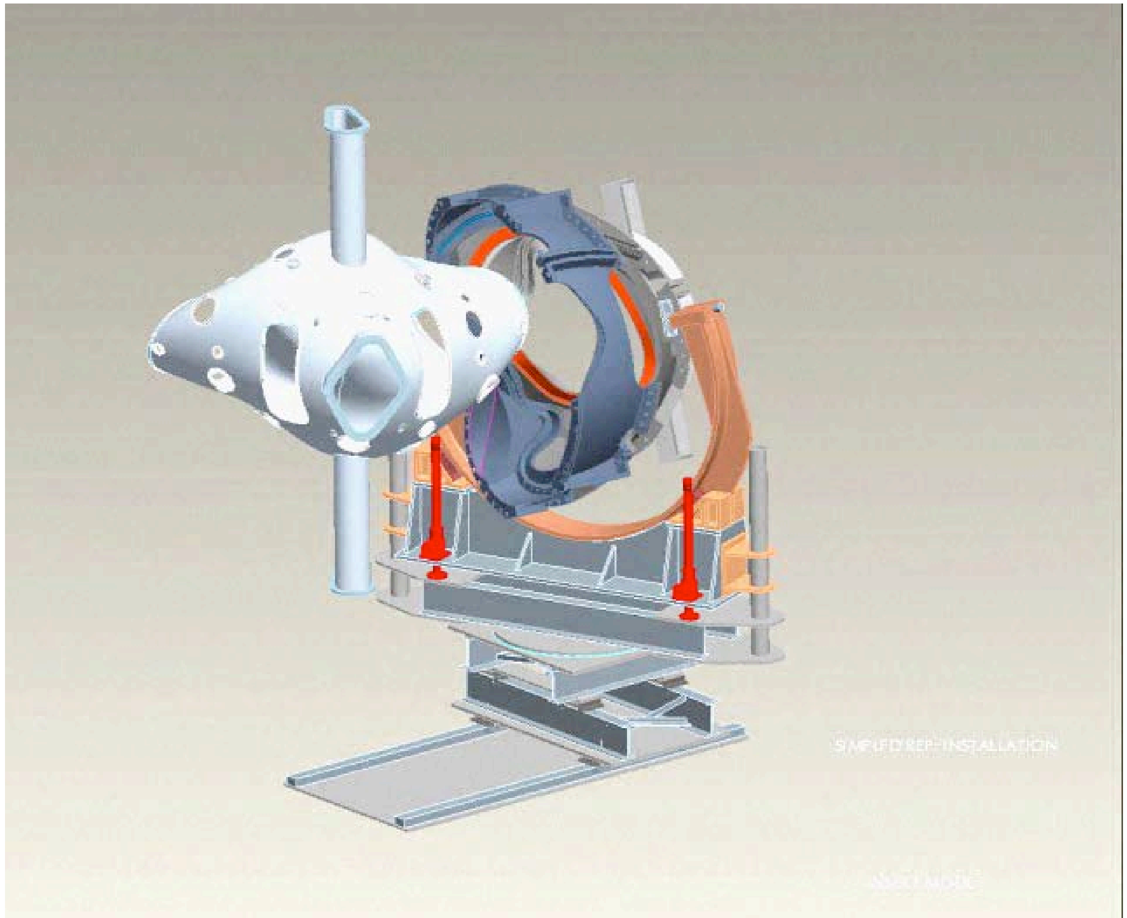
NCSX Design is Coming Together Nicely: A Joint PPPL-ORNL Effort



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NCSX Coil Facility Installed in TFTR Test Cell

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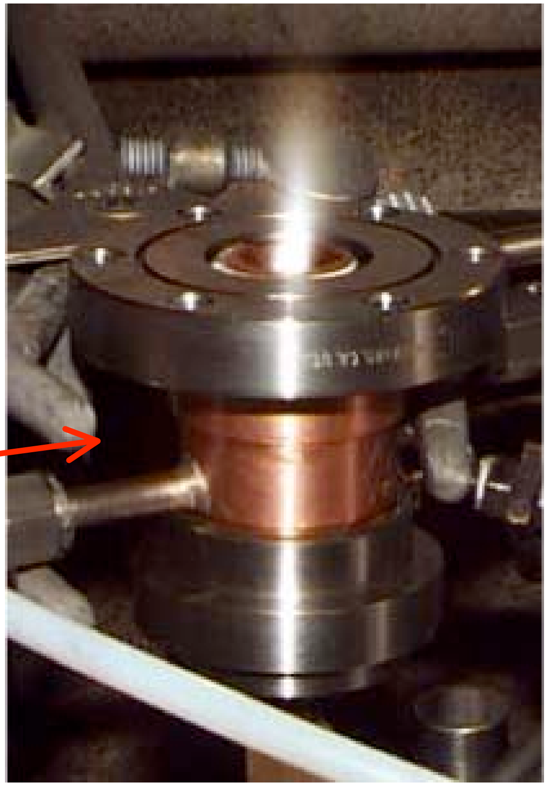
Fusion Research has Multiple Spillover Benefits

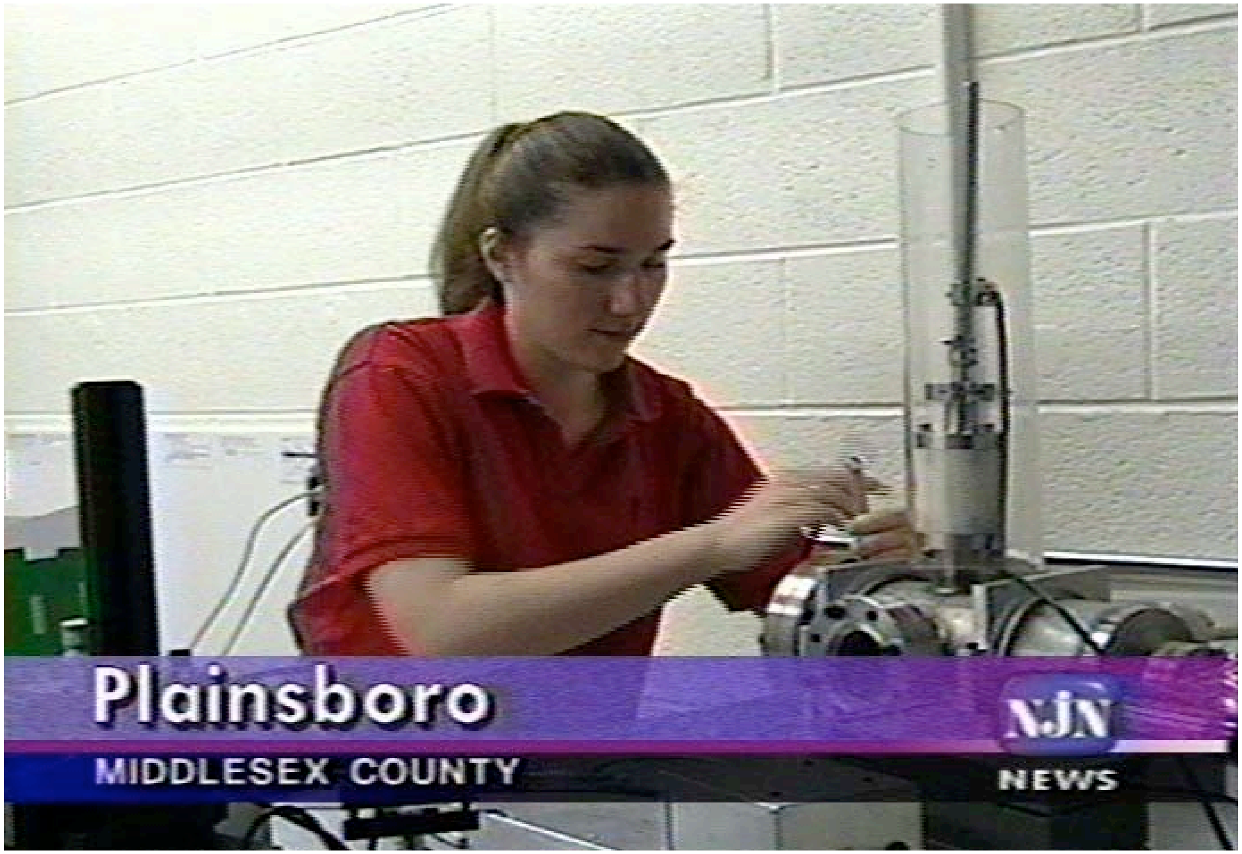


- **Plasma Processing of Chips and Circuits**
  - **Plasmas are used to etch features on modern computer chips.**
- **Coatings and Films**
  - **Plasmas provide hardened surfaces and corrosion resistance.**
- **Plasma Electronics**
  - **Fusion scientists are working to improve plasmas for wide-screen TV.**
- **Clean and Efficient Engines**
  - **Plasmatron fuel reformer for higher efficiency and cleaner exhaust.**
- **Waste Processing**
  - **Plasmas can be used to destroy toxic waste.**
- **Superconducting Sytems**
  - **Superconducting magnets for MRI and energy transmission.**
- **Scientific Advances**
  - **Most of the visible universe is plasma. Fusion science contributes to understanding near-Earth space, the sun, and the galaxies.**

Fusion Research Contributes to an Educated Workforce

- 54 Universities Nationwide Participate in Fusion Research
  - 50 Ph.D. Students are produced each year
  - Many continue in fusion research, but others contribute to many other fields of science and technology

- Each of the major fusion groups also has a strong educational outreach program. These programs reach K-12 students, their teachers and undergraduate students.



Fusion is an Important Part of the Nation's Energy Future

- **Fusion can be a very attractive domestic energy source.**
- **Fusion can be developed on a reasonable time scale, at a reasonable cost.**
- **Only the Federal Government can make the investment.**
- **Progress has been dramatic, but it is paced by funding.**
- **Princeton has a very exciting program in fusion research and in the science of plasmas.**

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