The Development Path for Magnetic Fusion Energy

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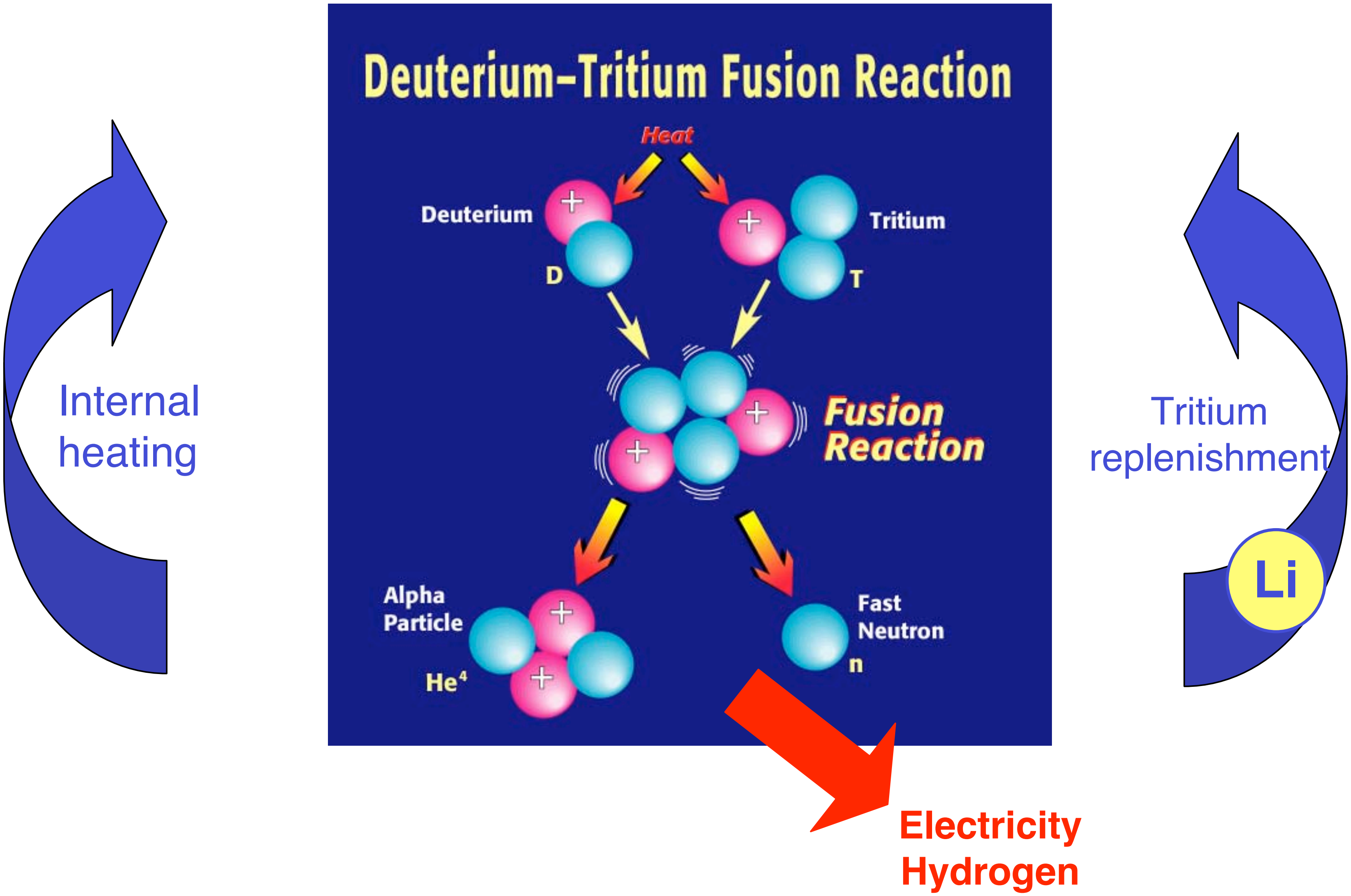
Global Climate and Energy Project Workshop on Fusion Energy

May 1, 2006

Fusion is an Attractive Long-term Form of Nuclear Energy

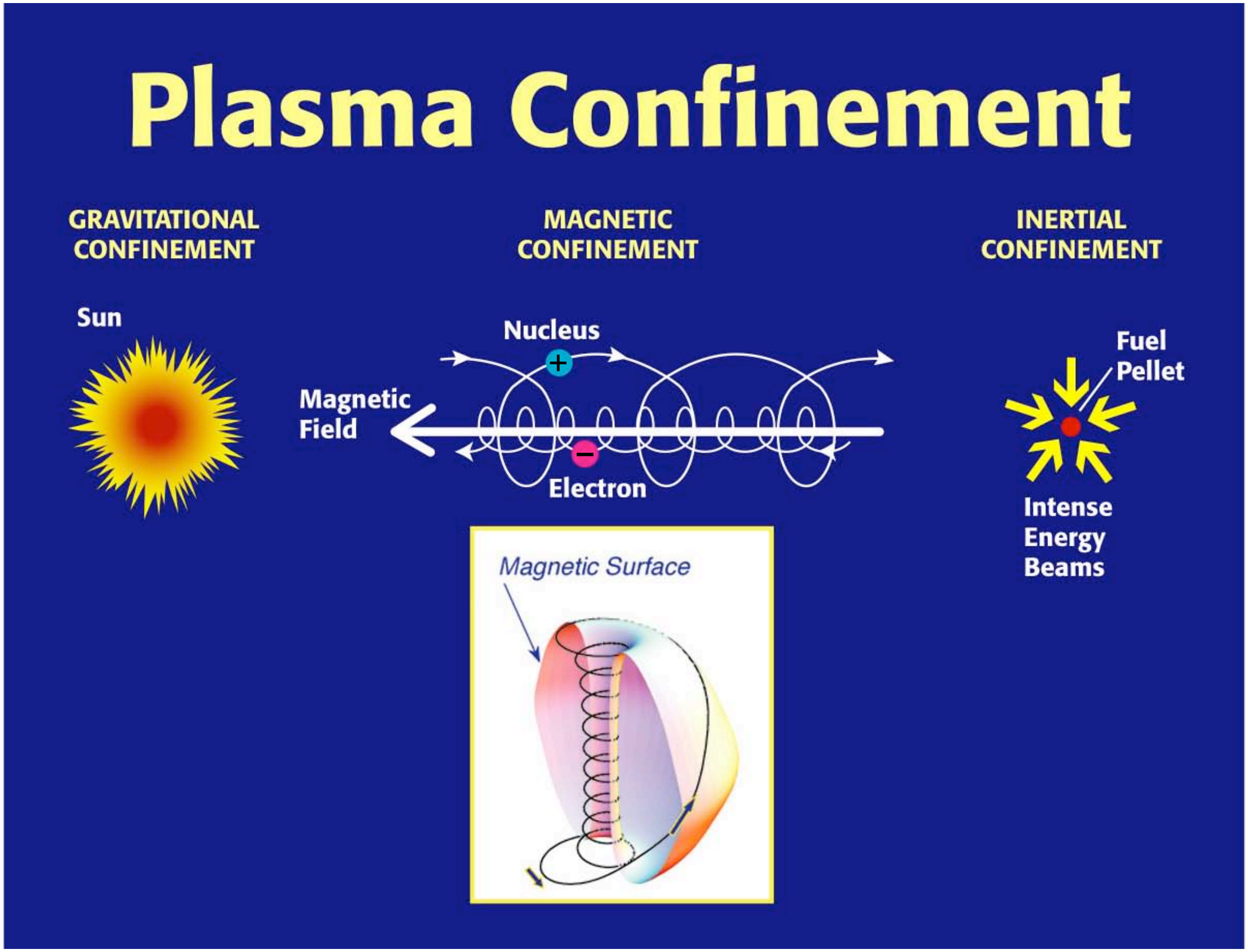


Fusion can be an Abundant, Safe and Reliable Energy Source

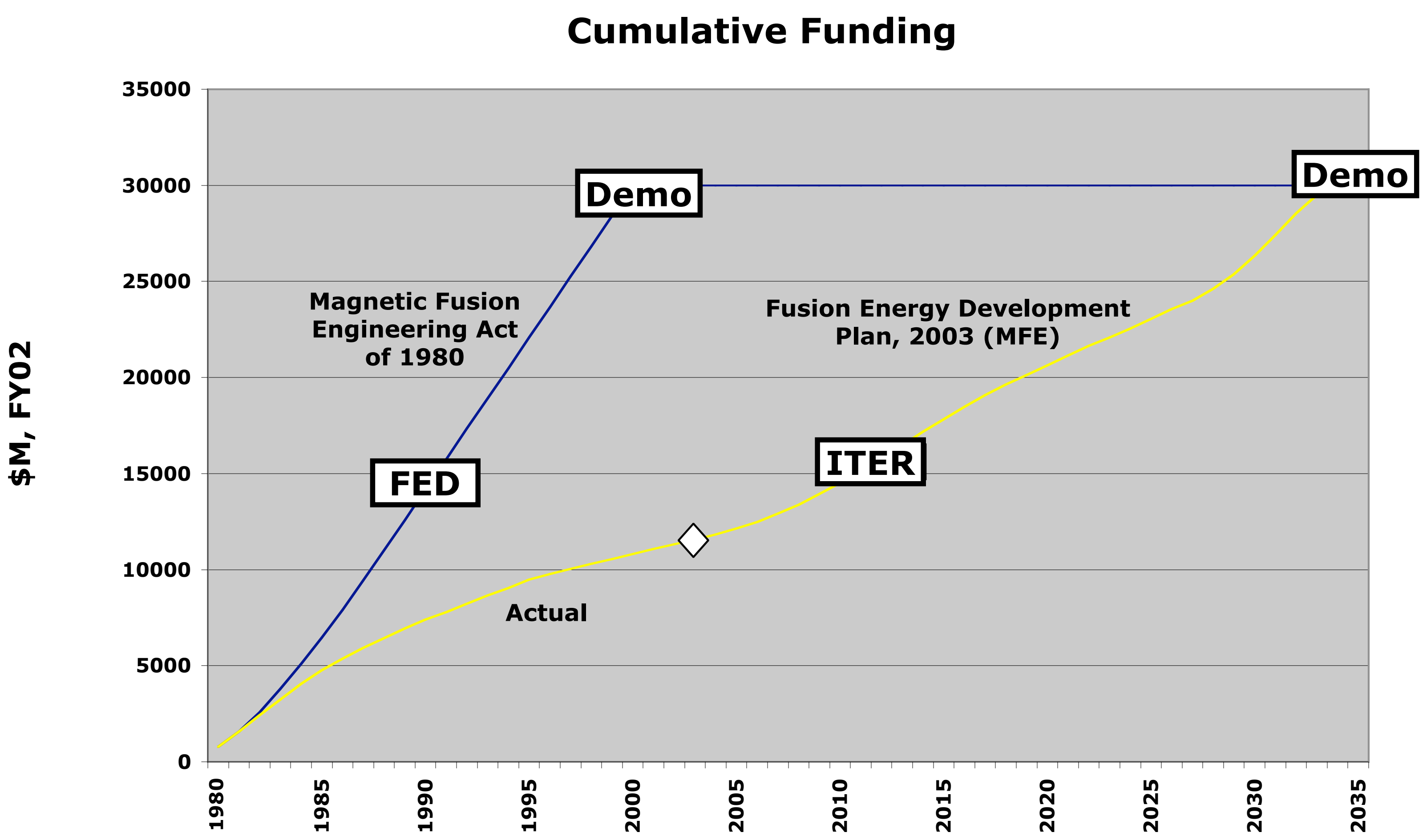
- **Worldwide long-term availability of low-cost fuel.**
- **No acid rain or CO_2 production.**
- **No possibility of runaway reaction or meltdown.**
- **Short-lived radioactive waste.**
- **Low risk of nuclear proliferation.**
- **Steady power source, without need for large land use, large energy storage, very long distance transmission, nor local CO_2 sequestration.**
- **Estimated to be cost-competitive with coal, fission.**

Complements nearer-term energy sources.

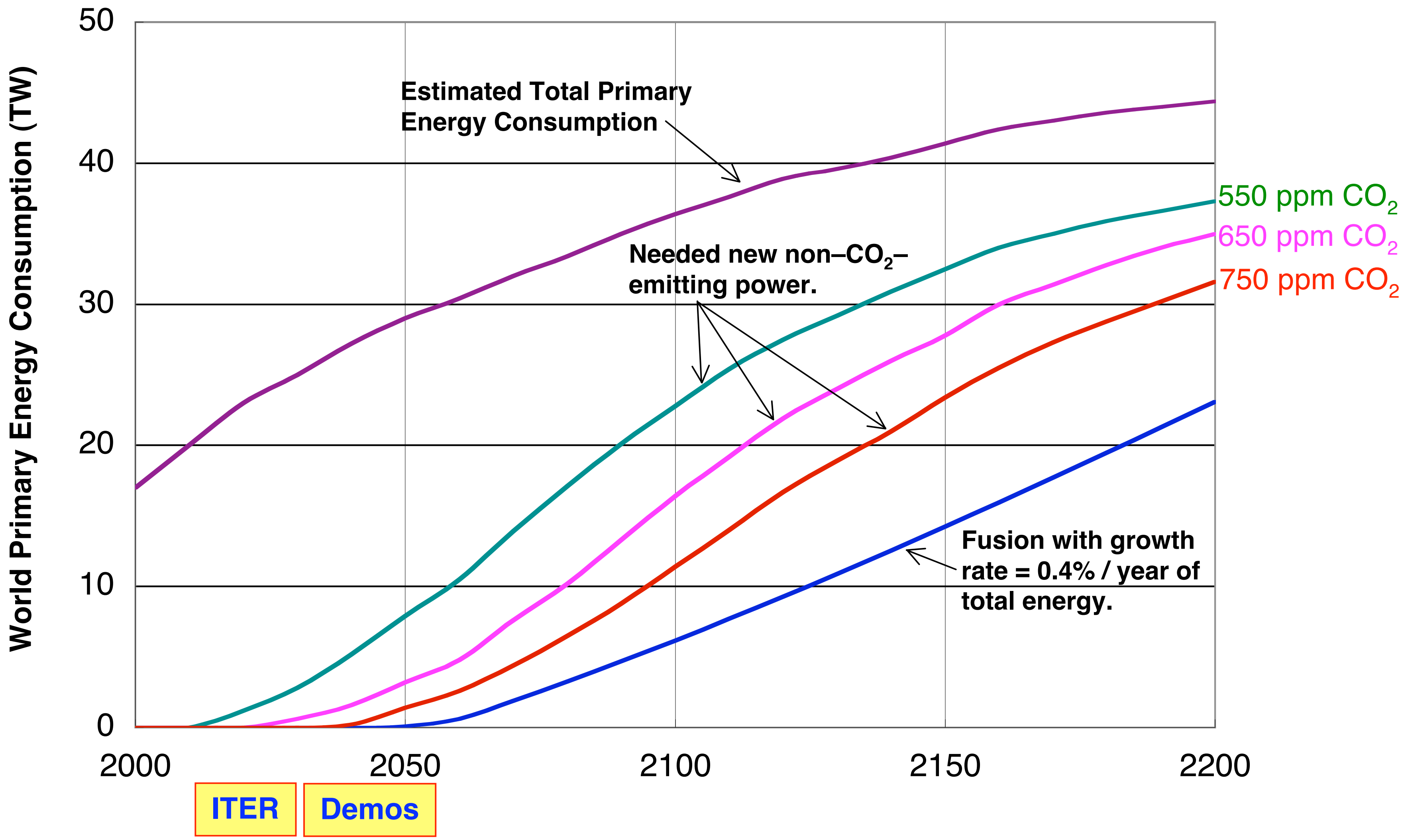
Magnetic Fields Confine Hot Plasmas



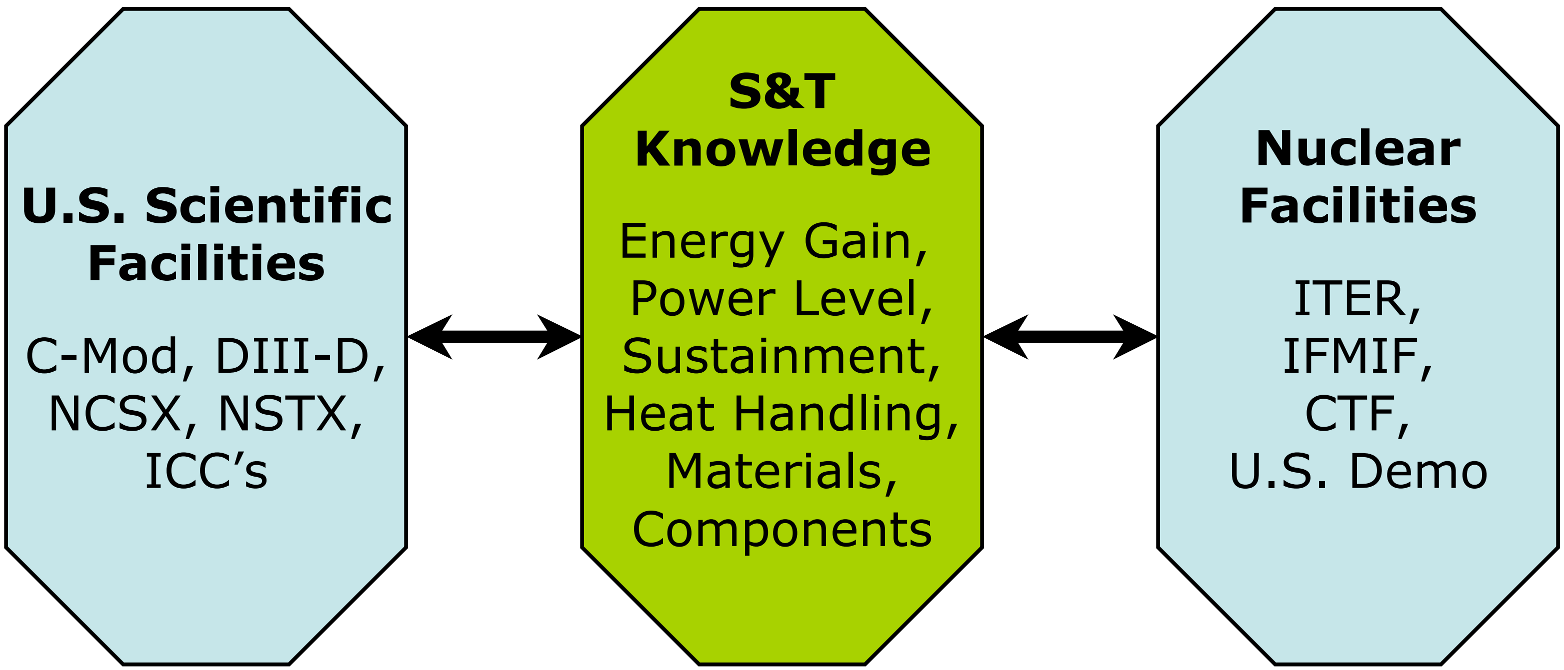
When Can we Have Fusion Energy?



Fusion can be an Important Element in Addressing Climate Change



The U.S. Fusion Program is Structured Around Developing the Knowledge Base for Practical Fusion Energy



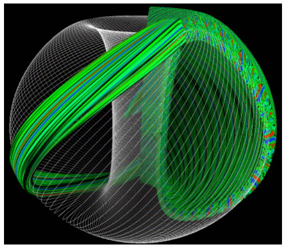
Critical, world-leading contributions to fusion knowledge

Scientific and technological knowledge embodied in simulation codes

Steps to demonstrate the practicality of commercial fusion power

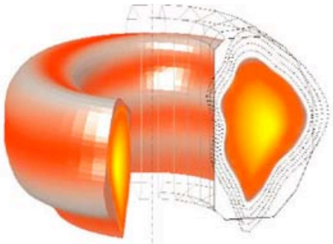
Fusion Knowledge: Advances and Goals - I

- **Energy Gain**
  - Internal heating by fusion must largely sustain the high plasma temperature against turbulent heat loss, giving high gain ≡ fusion heat production / input power.
  - Advanced simulations and experiment support the projection that ITER will demonstrate gain > 10.
  - *Demo must achieve gain of 25.*



Turbulence Calculation

- **Power Level**
  - Fusion power must be maximized for given cost.
  - Plasma shaping and active field control allow higher plasma pressure per magnetic field, so higher power level. Theory and experiment: ITER will produce > 500 MW.
  - *Demo must achieve 2500 MW at ITER size and field.*



Instability Control

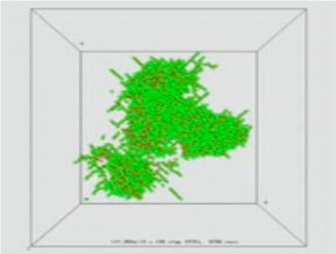
- **Sustainment**
  - High fusion output power must be produced steadily, with low external power for sustainment.
  - Self-sustaining plasma currents have been discovered, and compact configurations have been invented that do not require external drive. ITER: 400 – 3000 seconds.
  - *Demo must operate continuously.*

Sustained Configuration

Fusion Knowledge: Advances and Goals - II

- **Heat Handling**
  - Fusion vessel must be able to handle sustained high heat loads, maximum off-normal events.
  - Means are being developed to spread heat in space and time, to handle ITER heat loads.
  - *Demo must handle 5x higher heat loads.*
- **Materials**
  - Materials are needed that can handle high fluence of energetic neutrons, with reduced activation.
  - New reduced-activation ferritic steels, evolved from fission, are promising.
  - *A materials irradiation facility will be needed to develop materials to handle 14 MeV neutrons.*
- **Components**
  - Fusion systems require large, high tech components that operate reliably.
  - ITER R&D has already demonstrated magnets at about half power plant scale.
  - *A component test facility will be needed to qualify nuclear components for Demo.*

Tungsten Brush



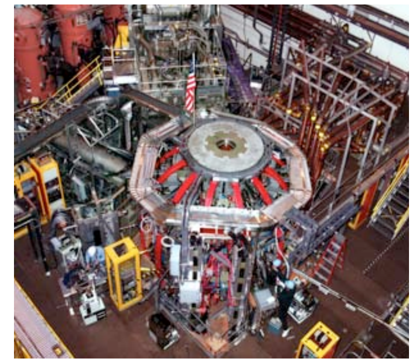
Neutronics Calculation

ITER R&D Magnet

U.S. Facilities Provide Critical, World-Leading Contributions to the Knowledge Base for Fusion

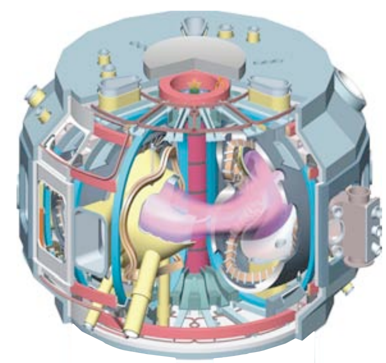
Alcator C-Mod:
ITER-like magnetic field, plasma density and geometry. Lower-Hybrid current drive.

NSTX:
High plasma pressure per magnetic field. Broadens basis for ITER science issues.



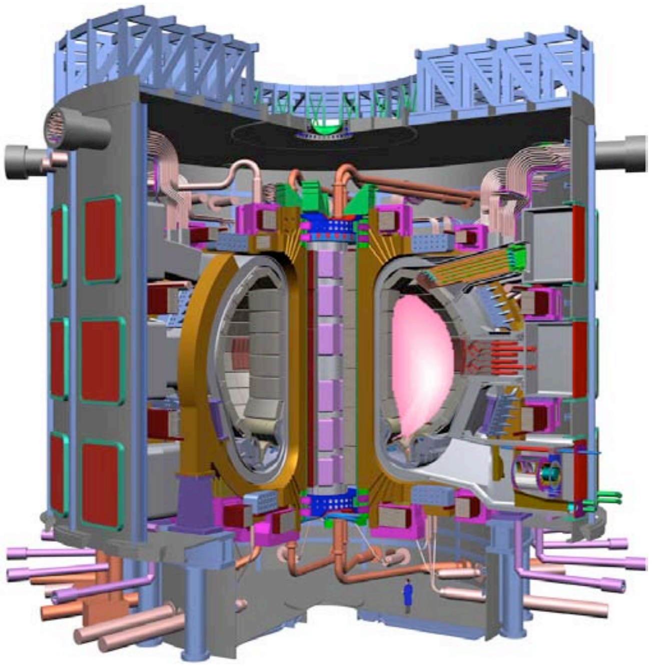
DIII-D:
Flexible plasma shape, instability feedback control, Electron Cyclotron current drive.

NCSX:
World-leading compact 3-D geometry. Steady-state without current drive, stable without feedback control.



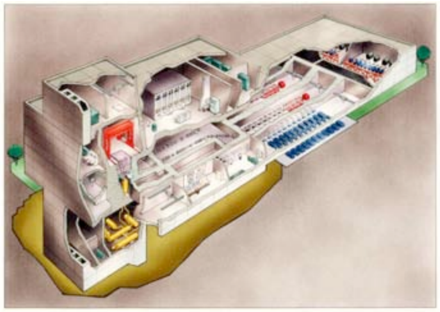
A range of smaller Innovative Confinement Concept experiments investigates alternative, and in some cases simpler, geometries for high plasma pressure (fusion power) and steady state.

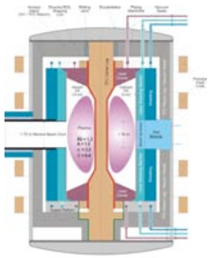
Nuclear Facilities will be Needed to Demonstrate the Practicality of Commercial Fusion Energy



ITER will produce 500 MW of fusion power for over 400 seconds, demonstrating the scientific and technological feasibility of fusion. *Seven-party international partnership.*

An ion-beam based Fusion Materials Irradiation Facility will qualify material samples with 14 MeV neutrons in half-liter volume. *Japan-Europe design, prototyping.*





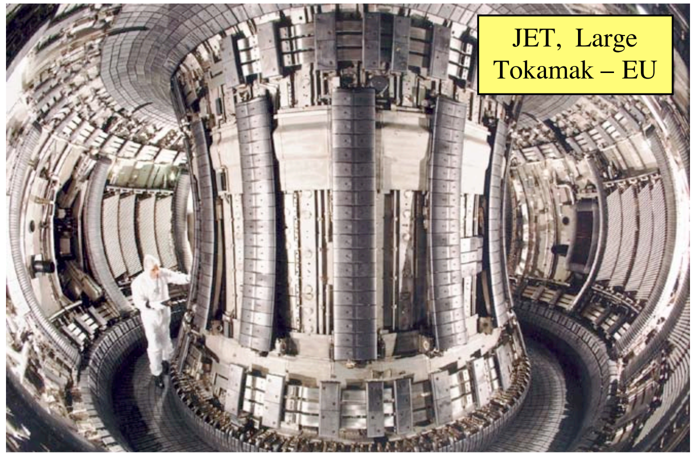
A compact Component Test Facility will qualify nuclear components for Demo: lithium-bearing blankets (interactions between structure, coolant and breeder), heat handling, auxiliary systems. *Opportunity for U.S. leadership.*

Simulation Codes will Make Possible the Step to a Commercially Attractive U.S. Demo

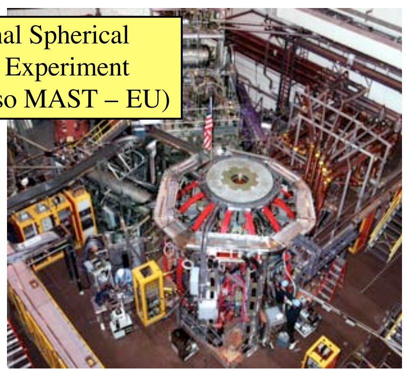
- **Knowledge gained from experiment and theory is embodied in advanced simulation codes.**
  - **Gain:** Gyro-kinetic turbulence simulations.
  - **Power density:** Macroscopic stability with advanced fluid models.
  - **Pulse length:** 3-D geometry and advanced current drive codes.
  - **Heat loads:** Simulations of plasma edge, high heat-flux components.
  - **Reliable operation:** Simulations of materials in 14 MeV neutron environment; interactions between structure, coolant and breeder.
- **Integration across codes leads to greater fidelity, *e.g.,***
  - Gyrokinetic effects in fluid models of macroscopic stability.
  - Macrostability, gyrokinetic and 3-D effects at plasma edge.
  - Effects of current drive on 3-D stability.
- **Experimental results from ITER, combined with results from scientific facilities and other nuclear facilities, will allow simulation and design of a competitive U.S. Demo.**

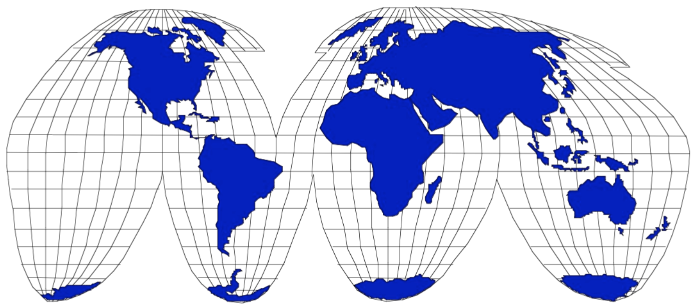
Magnetic Fusion Research is a Worldwide Activity: Optimizing the Configuration for Fusion


C-Mod, Tokamak MIT

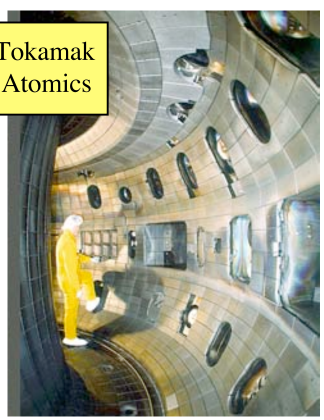

JET, Large Tokamak – EU

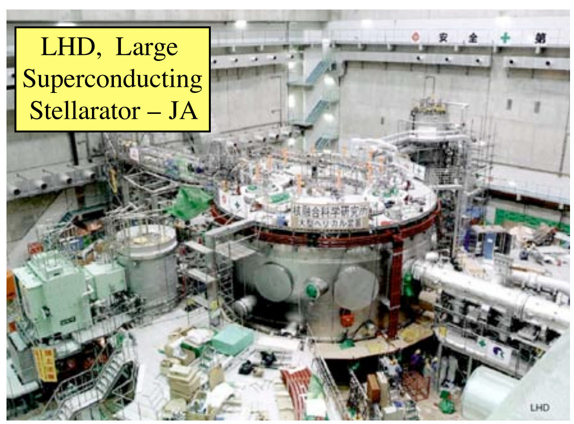

W7-X, Large Superconducting Stellarator – EU

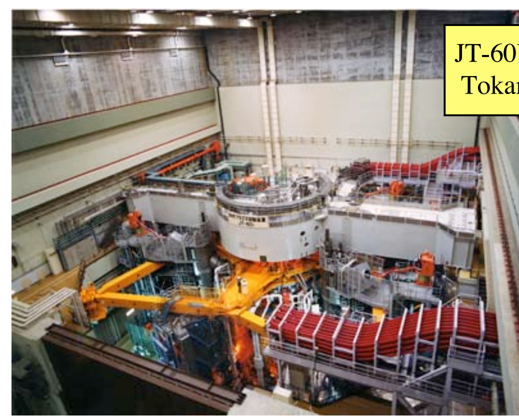

National Spherical Torus Experiment PPPL (also MAST – EU)



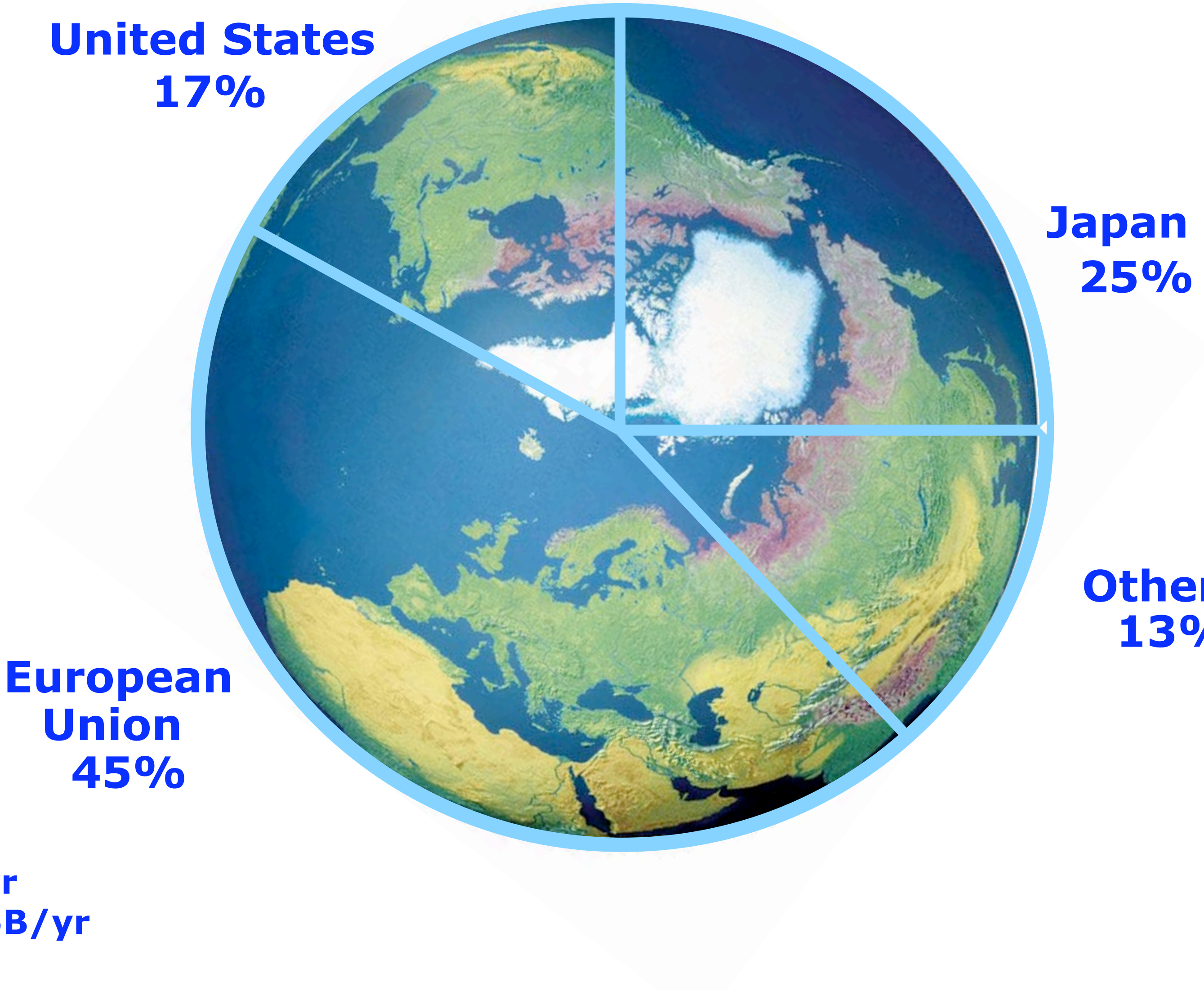

KSTAR, EAST, SST-1 Superconducting Tokamaks, – Korea, China, India


DIII-D, Tokamak General Atomics


LHD, Large Superconducting Stellarator – JA


JT-60U, Large Tokamak– JA

The U.S. is about 1/6 of the World Magnetic Fusion Effort



US: $260M/yr
World: ~$1.5B/yr
(FY 2005)

China is Making Dramatic Advances in Fusion

EAST will be on line in August

Superconducting magnets

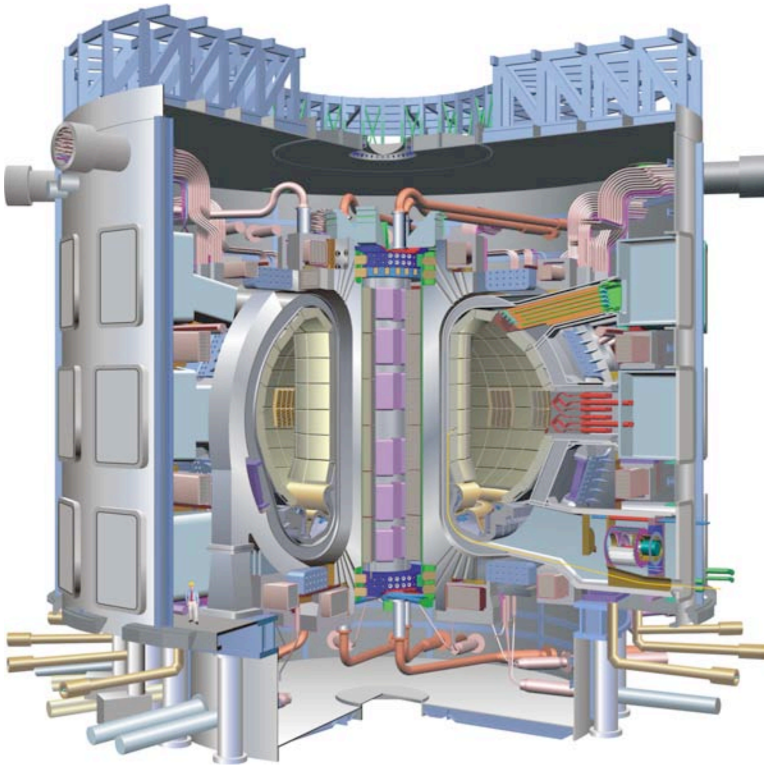
Magnet facility

Inside vessel

ITER Negotiations:

China, Europe, India, Japan, Russia, South Korea, U.S.

- **The site, Director General and Construction Manager have been selected:**
  - Cadarache, France, near Aix-en-Provence.
  - Kaname Ikeda; JA Ambassador to Croatia, nuclear engineer with experience in large-scale international projects.
  - Norbert Holtkamp: Built the accelerator for SNS.



- **The finances add up:**
  - Europe pays 45.4% – spending 1/5 of this in Japanese industry (!).
  - Each of the other six pays 9.1%.
  - Europe pays for 1/2 of "broader approach" additional fusion facilities in Japan, valued at 16% of ITER.
  - More than 1/2 of the world in ITER.

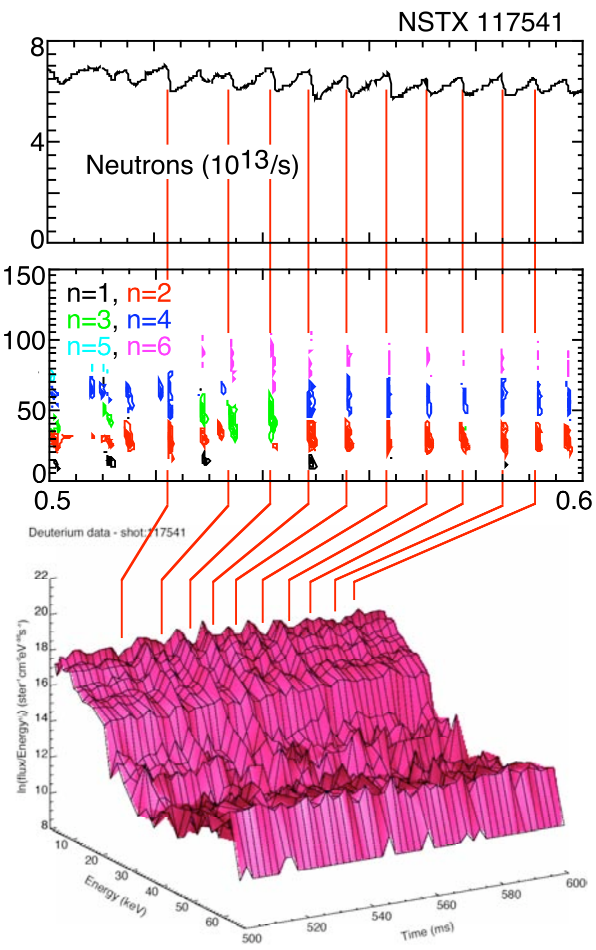
ITER will Test Magnetic Fusion Science at Power Plant Scale

- **Energy Gain:** Study – *for the first time* – self-sustained internal plasma heating by energetic helium fusion products.
  Extend the study of turbulent heat loss to much larger plasmas, providing a strong test of how turbulent structure size varies with system size.

- **Power level:** Extend the understanding of plasma pressure limits to much larger size systems, where particle trajectories are smaller compared with the plasma.

- **Sustainment:** Study external sustainment of plasma electrical currents at high temperature.

These results can be extrapolated via advanced computing to related magnetic configurations.



External heating in current experiments.

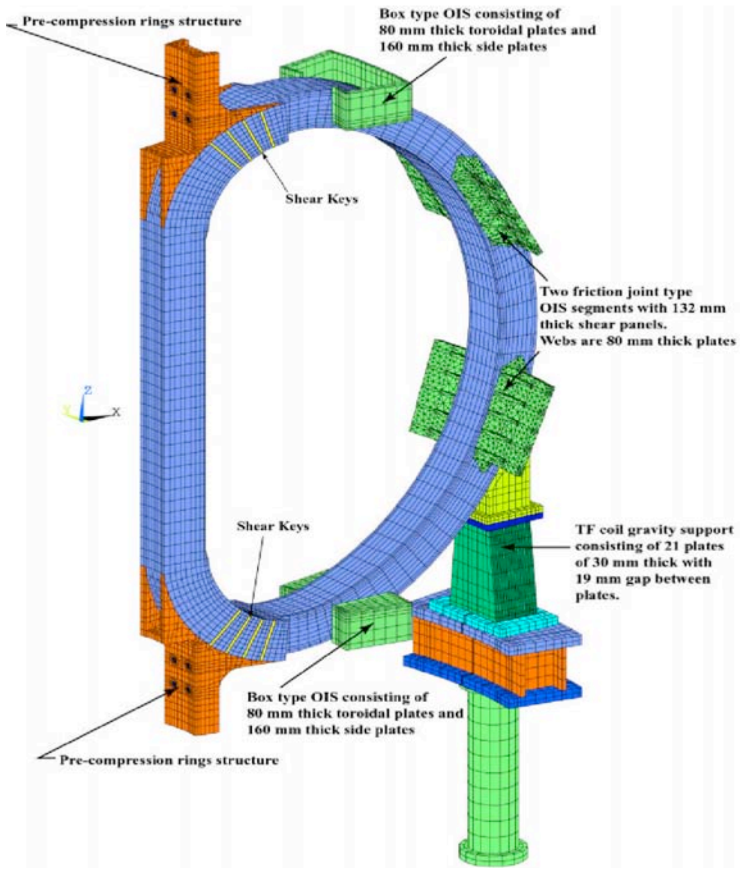
ITER will Test Fusion Technologies at Power Plant Scale

- **Plasma Vessel Components**
  - 5 MW/m^2 steady heat flux
  - 20% duty factor during operation

- **Nuclear Components**
  - Initial test of tritium replenishment by lithium-bearing modules in vessel wall.

- **Superconducting Magnets**
  - Power plant size and field, 40 GJ

These technologies are applicable to all configurations.

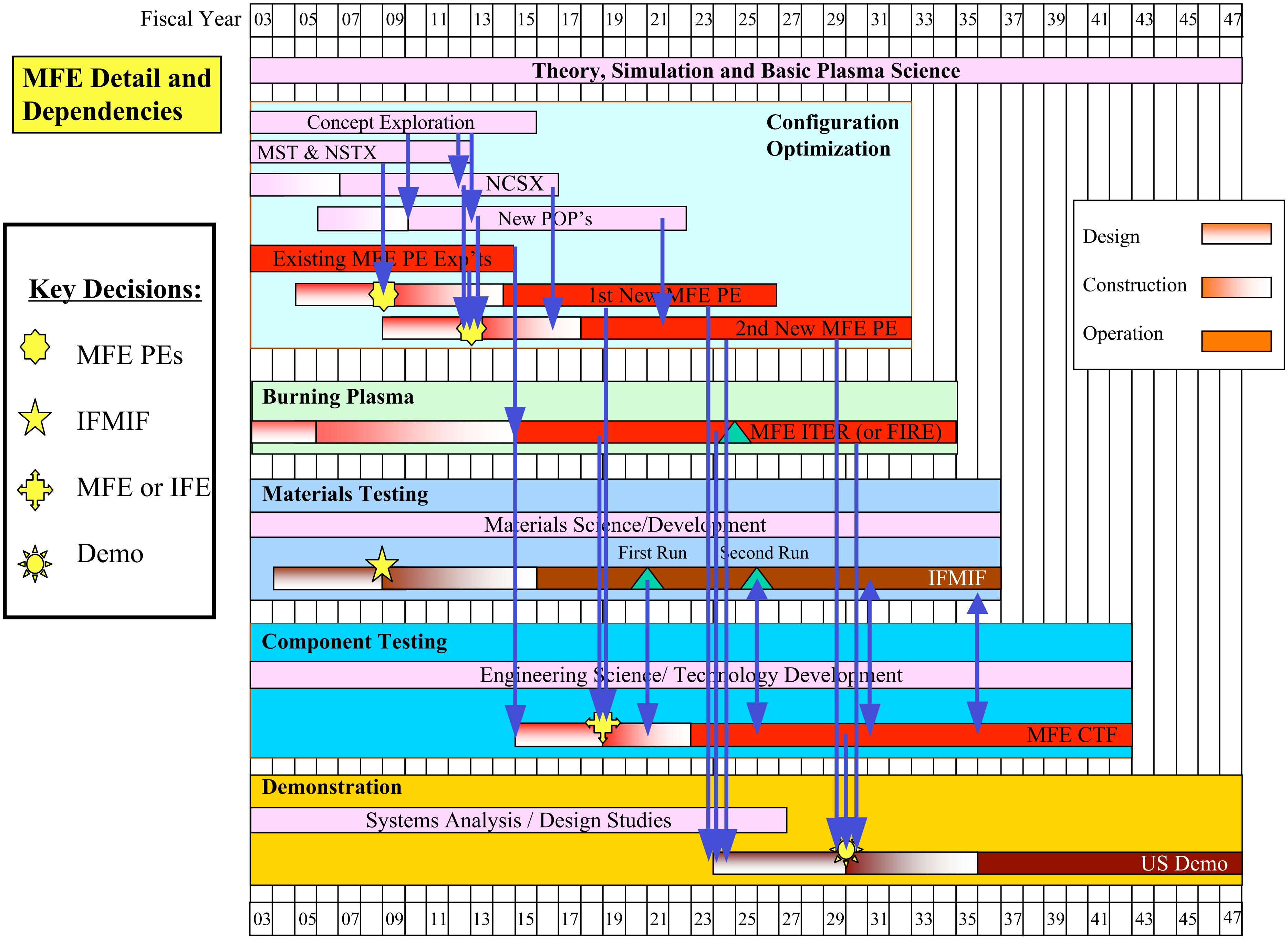


ITER Toroidal Field Coil

Principles of the FESAC Development Path

The goal of the plan is operation of a US demonstration power plant (Demo), which will enable the commercialization of fusion energy. The target date is about 35 years. Early in its operation the Demo will show net electric power production, and ultimately it will demonstrate the commercial practicality of fusion power.

The plan recognizes that difficult scientific and technological questions remain for fusion development. A diversified research portfolio is required for both the science and technology of fusion, because this gives a robust path to the successful development of an economically competitive and environmentally attractive energy source. In particular both Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE) portfolios are pursued because they present major opportunities for moving forward with fusion energy and they face largely independent scientific and technological challenges.



MFE Detail and Dependencies
Fiscal Year
03 05 07 09 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47
Theory, Simulation and Basic Plasma Science
Configuration Optimization
Concept Exploration
MST & NSTX
NCSX
New POP's
Existing MFE PE Exp'ts
1st New MFE PE
2nd New MFE PE
Burning Plasma
MFE ITER (or FIRE)
Materials Testing
Materials Science/Development
First Run
Second Run
IFMIF
Component Testing
Engineering Science/ Technology Development
MFE CTF
Demonstration
Systems Analysis / Design Studies
US Demo
Design
Construction
Operation
Key Decisions:
MFE PEs
IFMIF
MFE or IFE
Demo

Stages of Nuclear Technology Testing in Fusion Facilities

	Fusion "Break-in"	Design Concept & Performance Verification	Component Engineering Development & Reliability Growth
Stage:	**I**	**II**	**III**
Required Fluence (MW-y/m^2)	**~ 0.3**	**1 - 3**	**> 4 - 6**
Size of Test Article	**Sub-Modules**	**Modules**	**Modules / Sectors**
	• Initial exploration of performance in a fusion environment • Calibrate non-fusion tests • Effects of rapid changes in properties in early life • Initial check of codes and data • Develop experimental techniques and test instrumentation • Narrow material combination and design concepts • 10-20 test campaigns, each is 1-2 weeks	• Tests for basic functions and phenomena (tritium release / recovery, etc.), interactions of materials, configurations • Verify performance beyond beginning of life and until changes in properties become small (changes are substantial up to ~ 1-2 $MW \cdot y/m^2$) • Data on initial failure modes and effects • Establish **engineering feasibility** of blankets (satisfy basic functions & performance, 10 to 20% of lifetime) • Select 2 or 3 concepts for further development	• Identify failure modes and effects • Iterative design / test / fail / analyze / improve programs aimed at improving reliability and safety • Failure rate data: Develop a data base sufficient to predict mean-time-between-failure with sufficient confidence • Obtain data to predict mean-time-to-replace (MTTR) for both planned outage and random failure • Develop a data base to predict overall availability of FNT components in DEMO

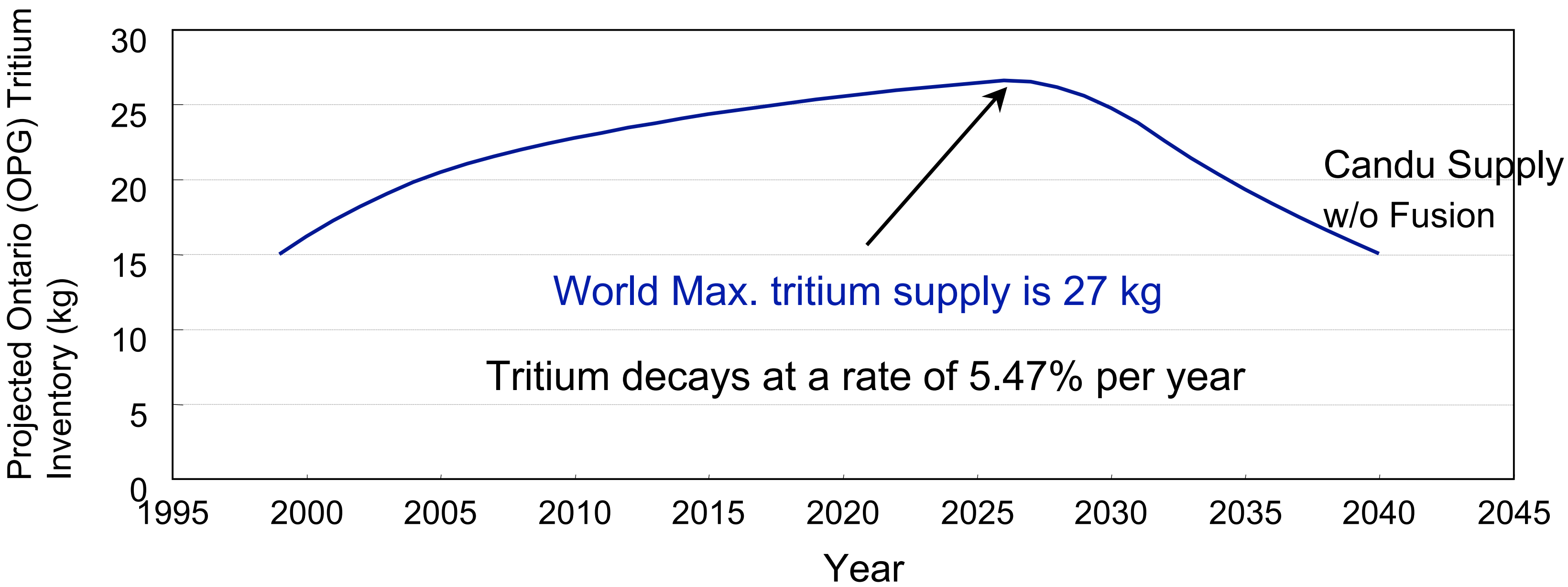
Demo

What is a CTF?

- The idea of CTF is a small size, low fusion power driven DT plasma-based device in which Fusion Nuclear Technology experiments can be performed in the relevant fusion environment at the smallest possible scale, cost, and risk. It must allow quick access for all components.
  - Small-size, low fusion power can be obtained in a low-Q plasma device such as a tokamak, ST or possibly gas dynamic trap.

- This is a faster, much less expensive, less risky approach than testing in a large device which will be strongly limited by tritium consumption as full breeding and tritium purging is achieved, and which will have a very large blanket to be replaced in multiple tests.

Projected Tritium Supply Impacts Blanket Testing



- ITER will burn ~15 kg T and provide ~5 weeks of Demo neutron fluence.
- A fission reactor can produce a few kg of tritium per year, at $200M/kg.
- A DT facility burns tritium at a rate of:

2.7 kg/week per 2500 MW of fusion power

*You will need to stop any test and replace the blanket if 1kg of tritium is not regenerated. At 3% loss this is **12 weeks** for Demo – an unacceptable period to change out **~1000 m^2** of blanket. For a 100 MW CTF the period is **6 years** and the area is **~50m^2**.*

DOE-SC 20-Year Strategic Plan

Fits Together Fusion Science and Energy Seamlessly

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)

ITER

- 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

Tokamaks

- 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)

Fusion Simulation Project

- Deliver a complete integrated simulation of a power-producing plasma, validated with ITER results, that enables the design of fusion power plants (2020)

Plasma Confinement

NCSX

- Evaluate the ability of the compact stellarator configuration to confine a high-temperature plasma (2012)

NSTX

- 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 lasers 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)

Next-Step Advanced Facility

- 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)

Component Test Facility

- 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 designed 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.

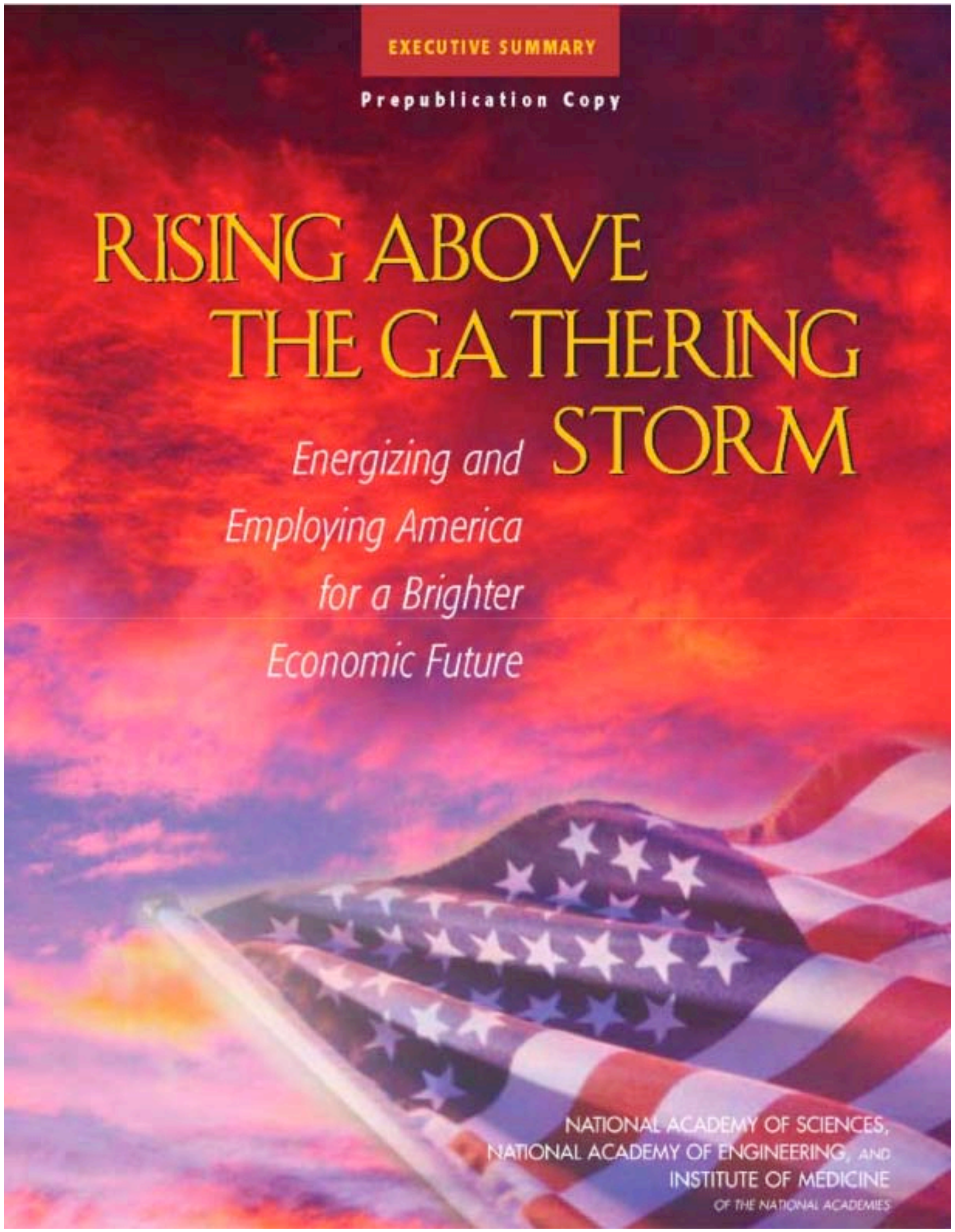
***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**
****For more detail on these facilities and the overall prioritization process, see the companion document, *Facilities for the Future of Science: A Twenty-Year Outlook.***

Conclusions - I

The U.S. fusion energy sciences program is ***still suffering from the severe budget cuts of the mid-1990's and the loss of a clear national commitment to develop fusion energy.*** The result is that despite the exciting scientific advances of the last decade it is becoming difficult to retain technical expertise in key areas. ***The President's fusion initiative has the potential to reverse this trend, and indeed to motivate a new cadre of young people not only to enter fusion energy research, but also to participate in the physical sciences broadly.*** With the addition of the funding recommended here, an exciting, focused and realistic program can be implemented to make fusion energy available on a practical time scale. On the contrary, ***delay in starting this plan will cause the loss of key needed expertise and result in disproportionate delay in reaching the goal.***

Other Nations are Leveraging ITER Strongly

- **Major New Plasma Confinement Experiments**
  - China, South Korea, India, Europe, Japan/Europe in Japan
  - Each is more costly than anything built in the U.S. in decades.
- **Major Fusion Computational Center**
  - Japan/Europe in Japan
  - Next generation beyond Japan's Earth Simulator
- **Engineering Design / Validation Activity for Fusion Materials Irradiation Facility**
  - Japan/Europe in Japan
  - Critical for testing of materials for fusion systems.
- **A new Generation of Fusion Scientists and Engineers is being Trained Abroad.**
  - China plans to have 1000 graduate students in fusion.



"Having reviewed trends in the United States and abroad, the committee is deeply concerned that the scientific and technical building blocks of our economic leadership are eroding at a time when many other nations are gathering strength. … we are worried about the future prosperity of the United States."

"The committee identified two key challenges that are tightly coupled to scientific and engineering prowess: creating high-quality jobs for Americans and responding to the nation's need for clean, affordable, and reliable energy."

Conclusions - II

Establishing a program now to develop fusion energy on a practical time scale will maximize the capitalization on the burning plasma investments in NIF and ITER, and ultimately will position the U.S. to export rather than import fusion energy systems. Failure to do so will relegate the U.S. to a second or third tier role in the development of fusion energy. Europe and Japan, which have much stronger fusion energy development programs than the U.S., and which are vying to host ITER, will be much better positioned to market fusion energy systems than the U.S. – unless aggressive action is taken now.

It is the judgment of the Panel that the plan presented here can lead to the operation of a demonstration fusion power plant in about 35 years, enabling the commercialization of attractive fusion power by mid-century as envisioned by President Bush.