Magnetic Fusion Energy:

Why, When, and How

California Institute of Technology
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by

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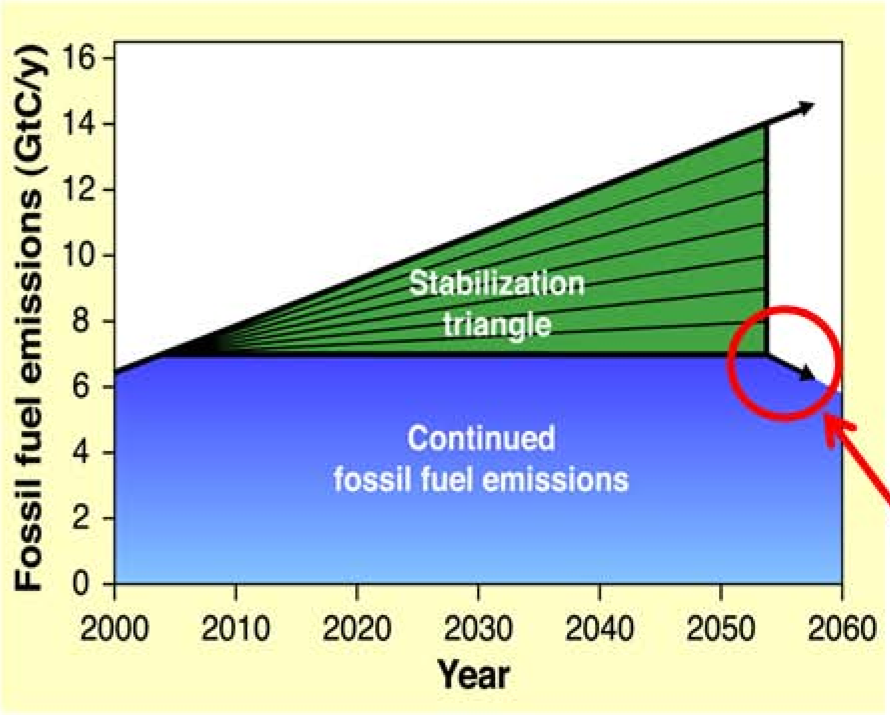
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Near-term Technologies Can and Must be Used to Stabilize CO_2 Emissions over the Next 50 Years



Improved Efficiency
Electricity from Natural Gas
Reduced Rate of Deforestation
CO_2 Sequestration
Nuclear Fission
Wind, Solar, Biomass

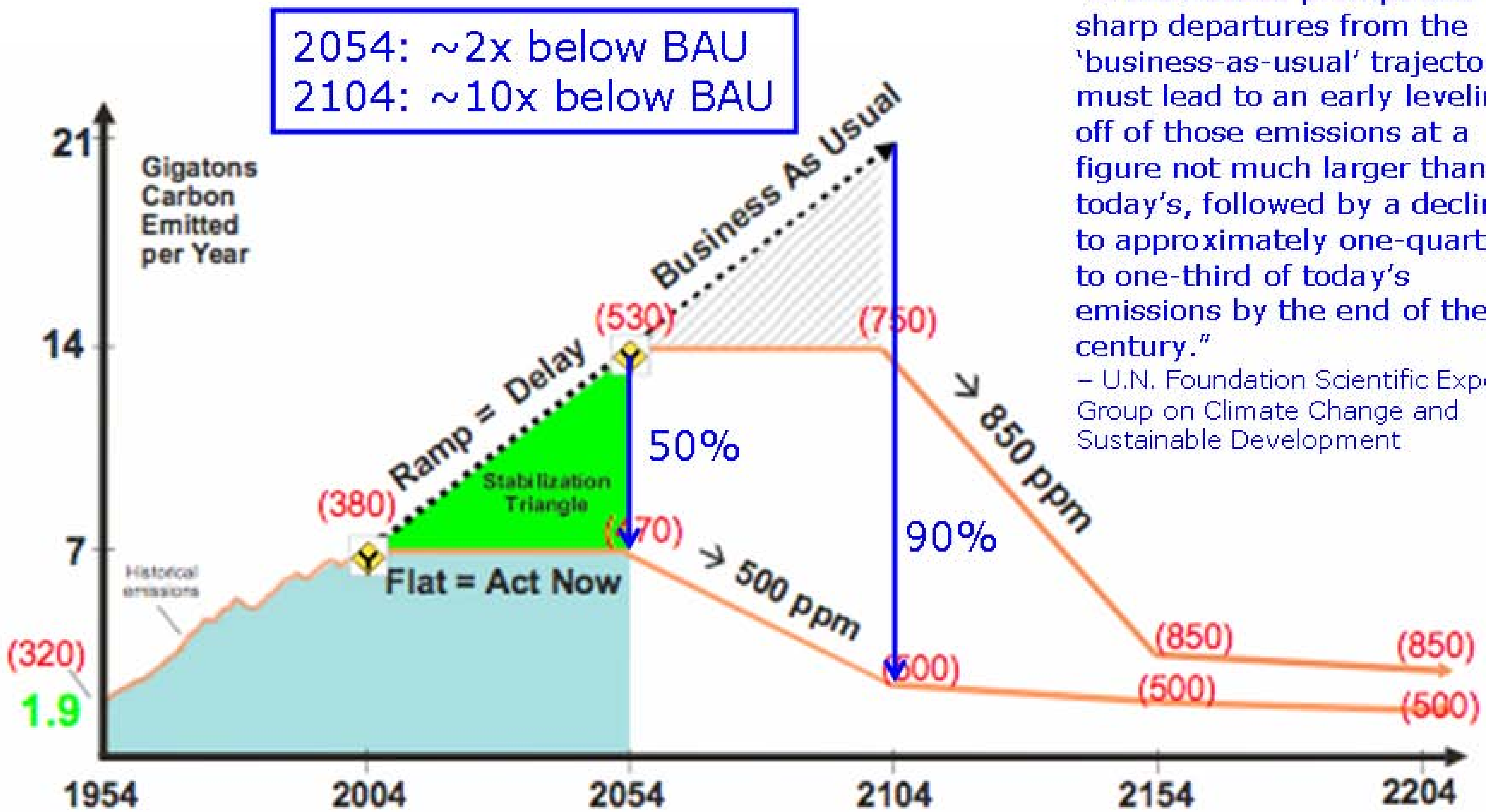
Pacala and Socolow, Science, 2004

Can near-term technologies address the whole, long-term problem?

Issues: Maximum annual capacity, total resources, environmental impact, proliferation, variability in space and time, land use.

Pacala and Socolow: "We agree that fundamental research is vital to develop the revolutionary mitigation strategies needed in the second half of this century and beyond."

The Climate Change Challenge has Near-Term and Long-Term Elements

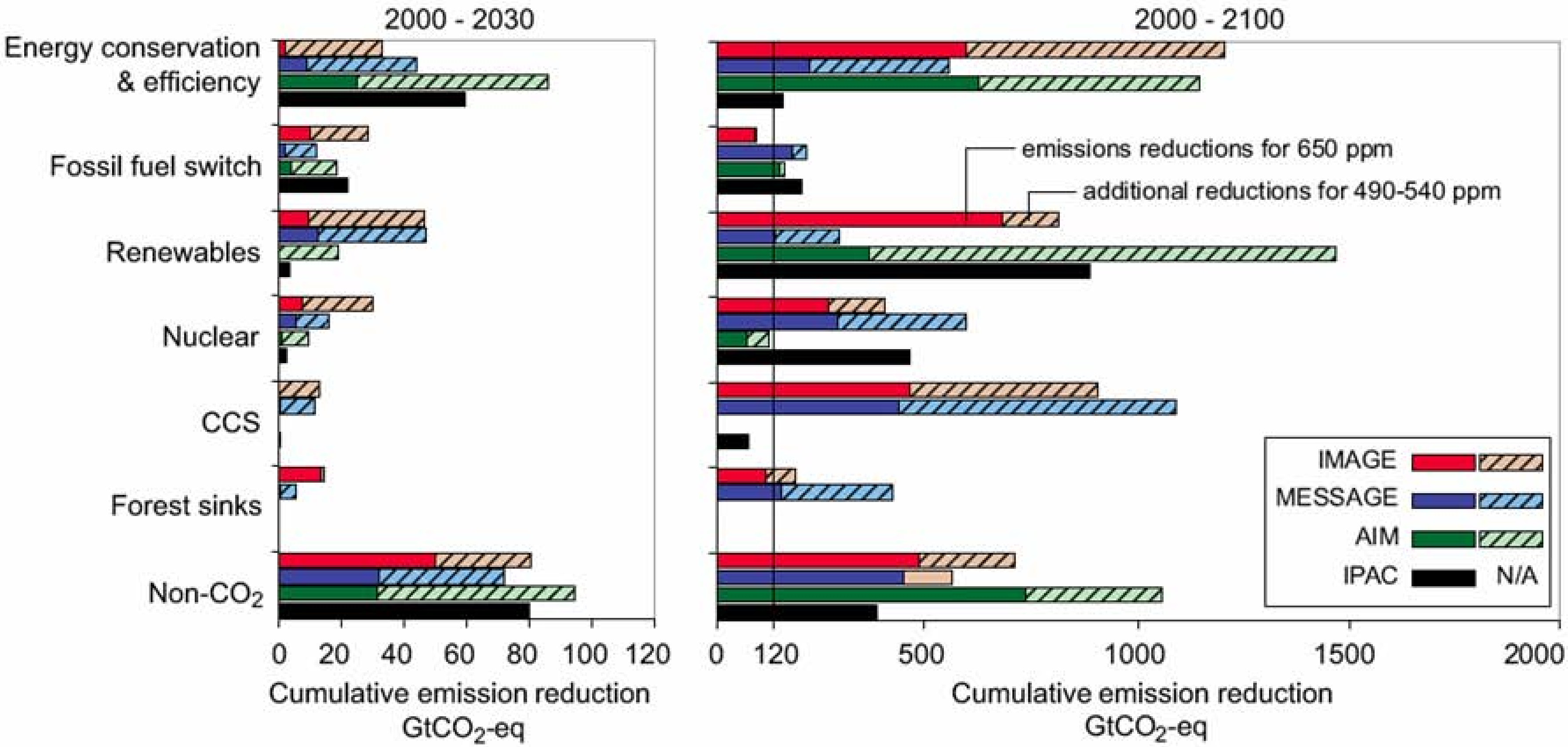


"... the needed prompt and sharp departures from the 'business-as-usual' trajectory must lead to an early leveling off of those emissions at a figure not much larger than today's, followed by a decline to approximately one-quarter to one-third of today's emissions by the end of the century."

– U.N. Foundation Scientific Expert Group on Climate Change and Sustainable Development

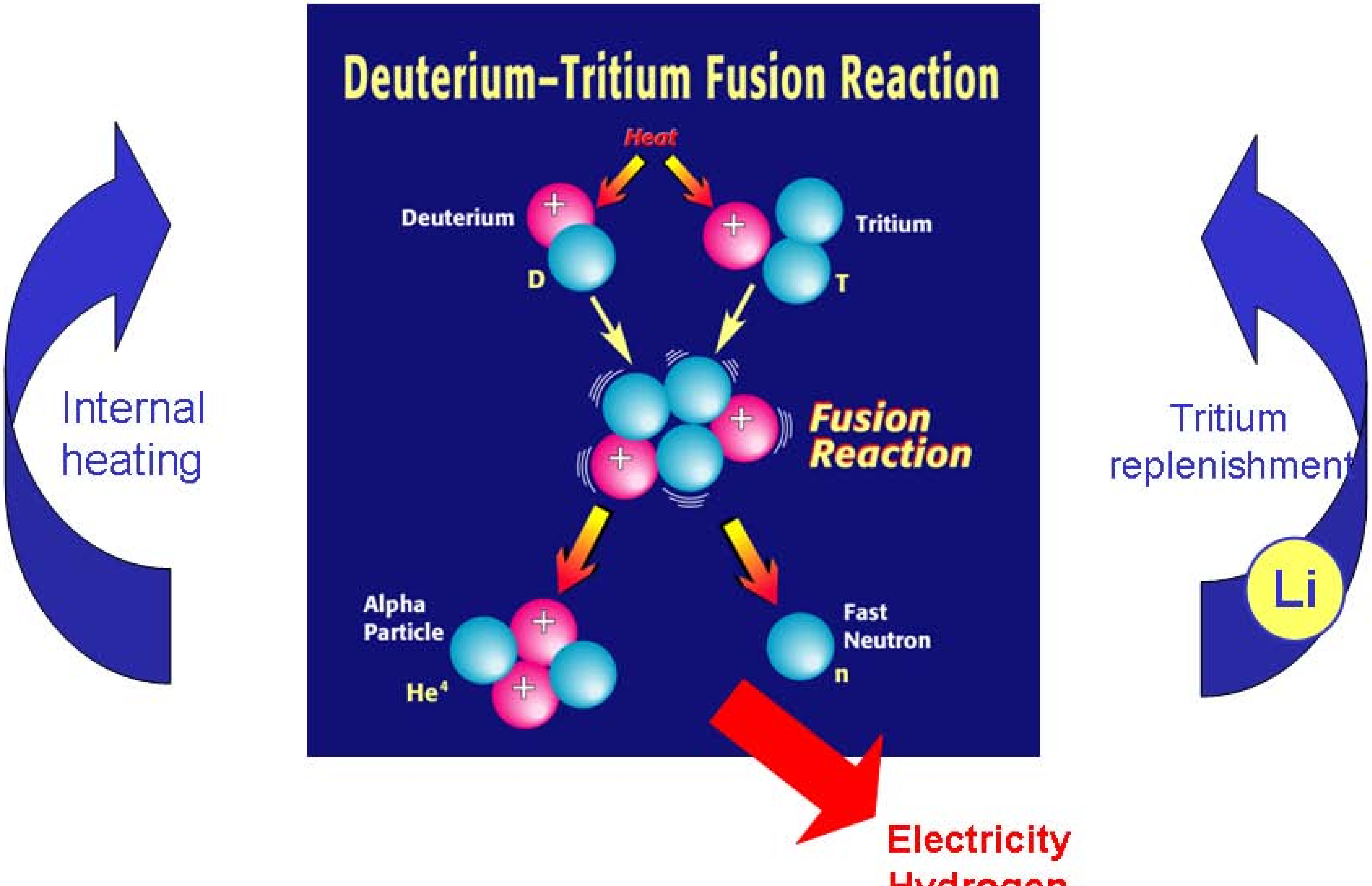
Rob Socolow

IPCC: 95% of the CO_2 Mitigation Required this Century Comes after 2030



IPCC Climate Change 2007: Mitigation of Climate Change

Fusion is an Attractive Long-Term Form of Nuclear Energy

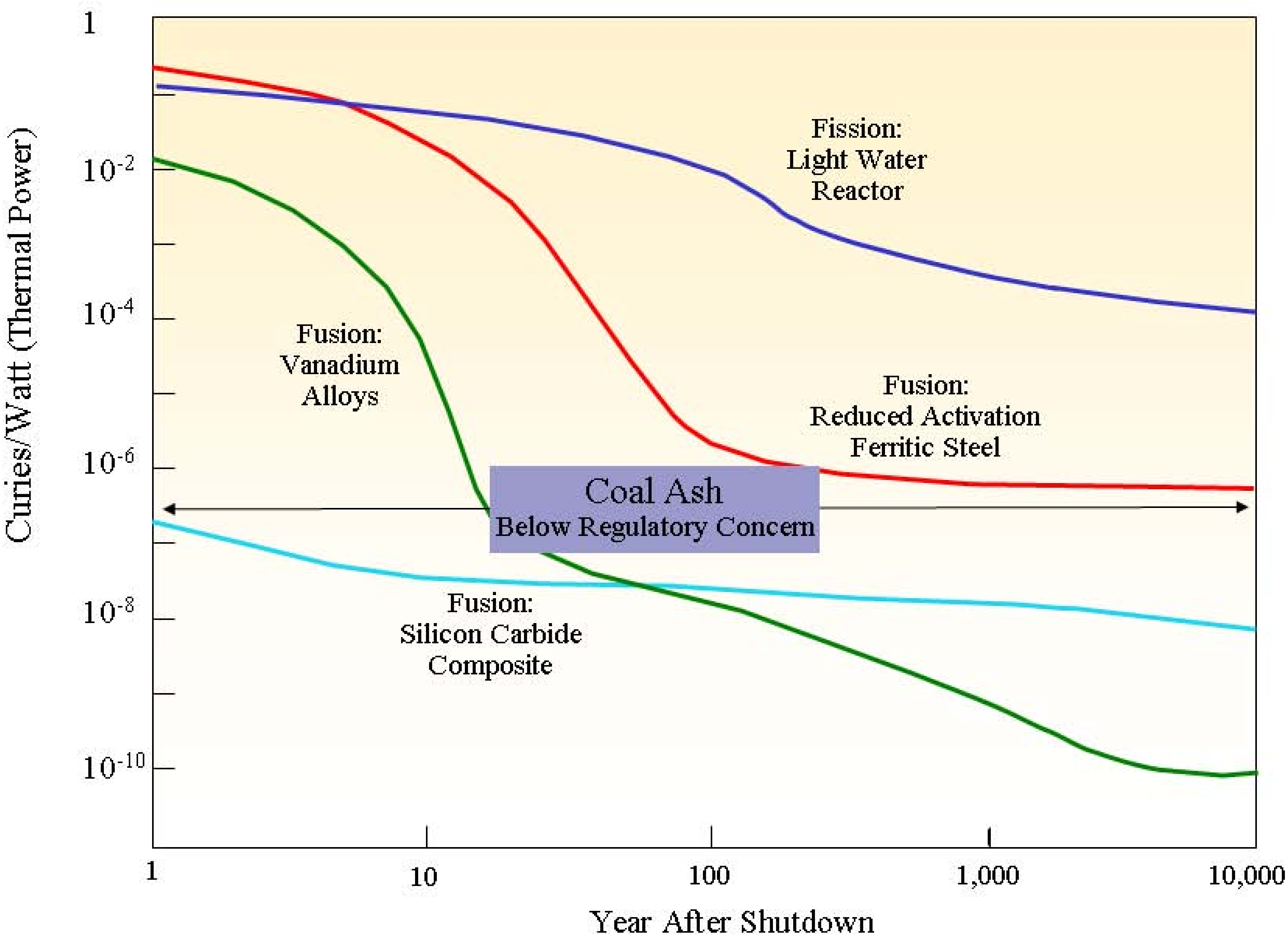


Fusion can be an Abundant, Safe and Reliable Energy Source

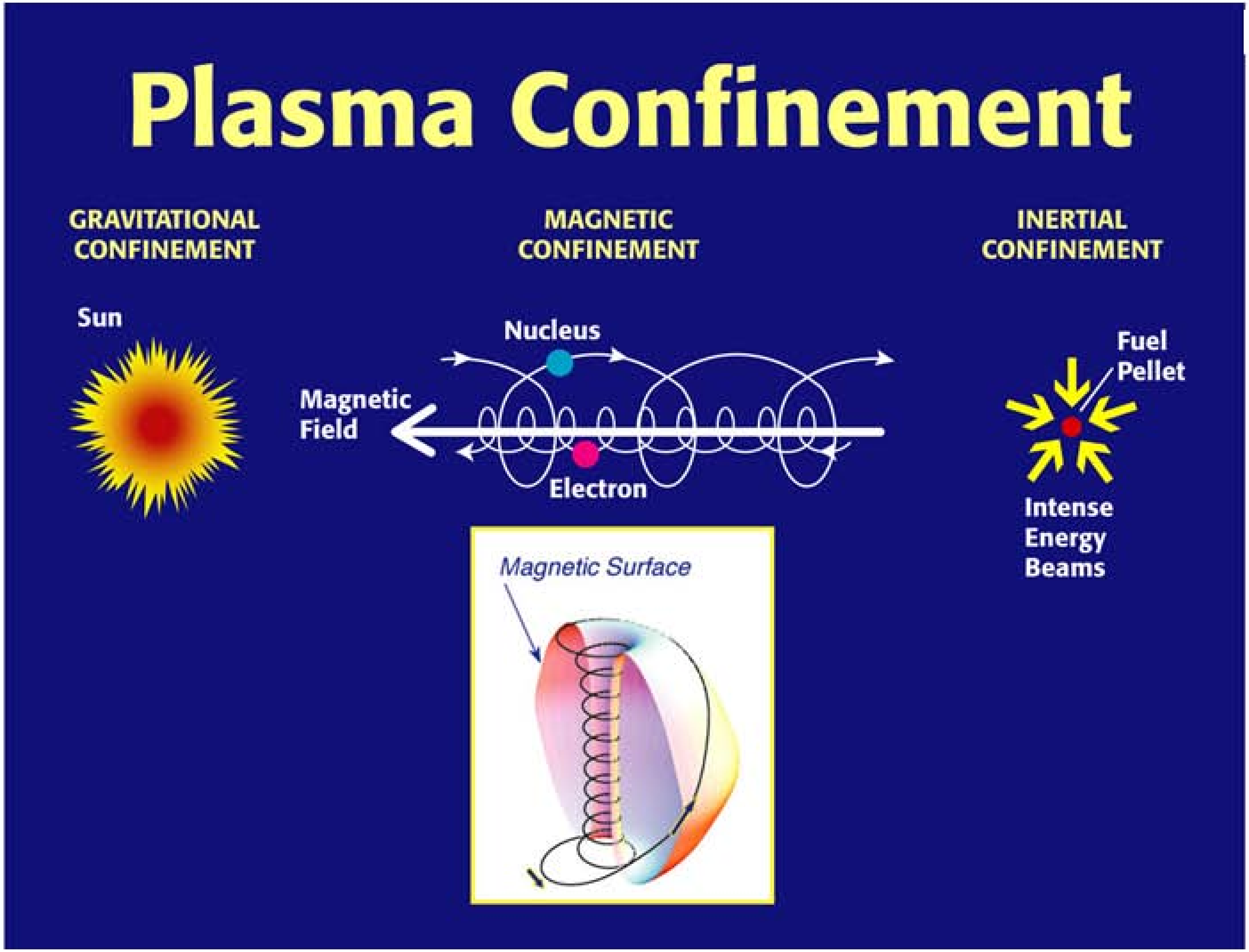
- **Worldwide, very long term availability of low cost fuel.**
  - No geopolitical instability due to competition for energy resources.
- **No acid rain nor CO_2 production.**
  - Reduced pollution and global climate change.
- **No possibility of runaway reaction or meltdown.**
  - No Chernobyl, no Three Mile Island, no evacuation plan.
- **Short-lived radioactive waste.**
  - No Yucca Mountain.
- **Low risk of nuclear proliferation.**
  - All nations can have the full fusion fuel cycle with minimal oversight.
- **Steady power source that can be located near markets.**
  - No need for large energy storage, local CO_2 sequestration, very long distance transmission, nor large land use.
- **Estimated to be cost-competitive with coal, fission.**

Complements nearer-term energy sources.

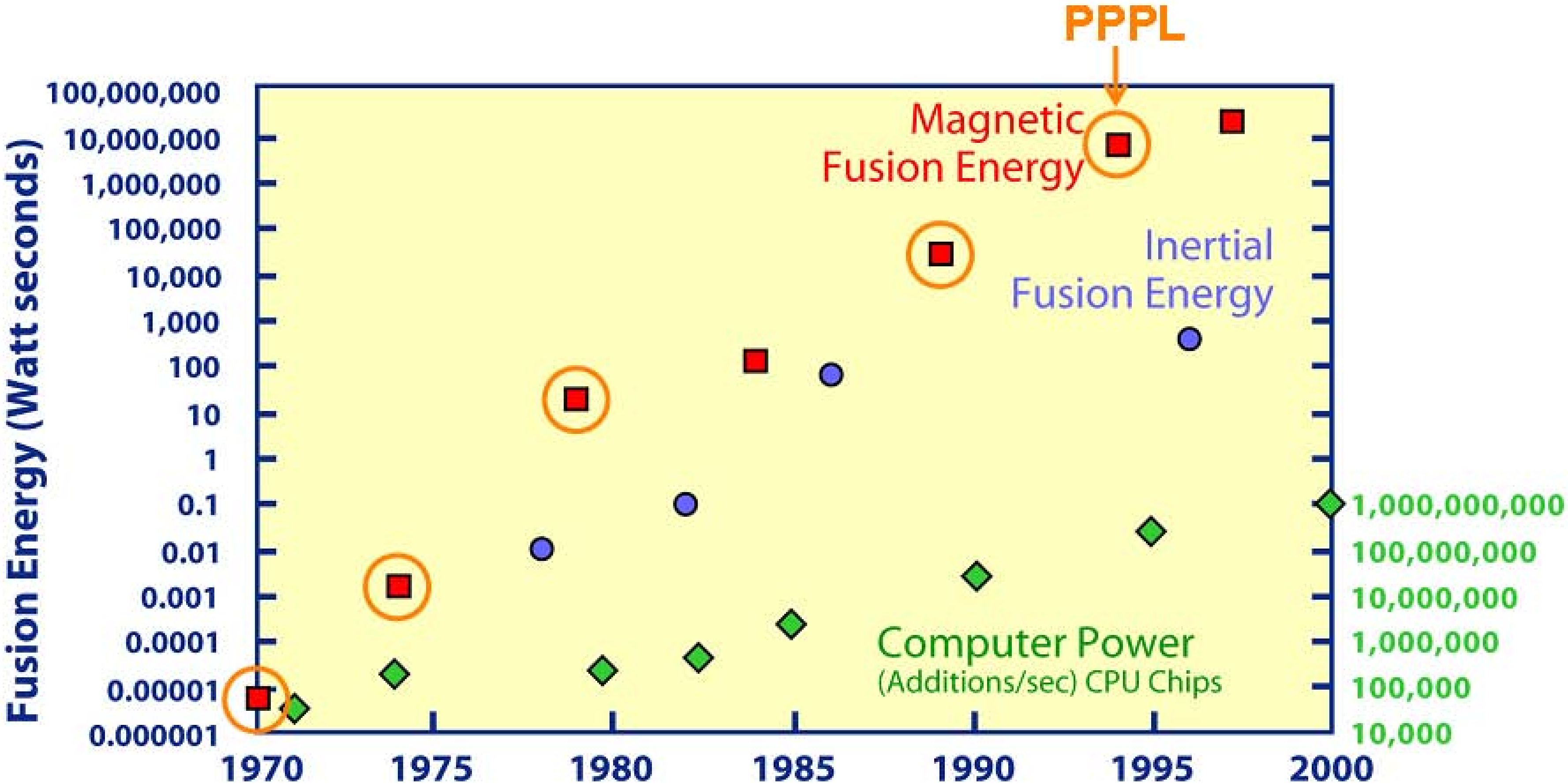
Fusion will not Require Geological Storage



Magnetic Fields Confine Hot Plasmas

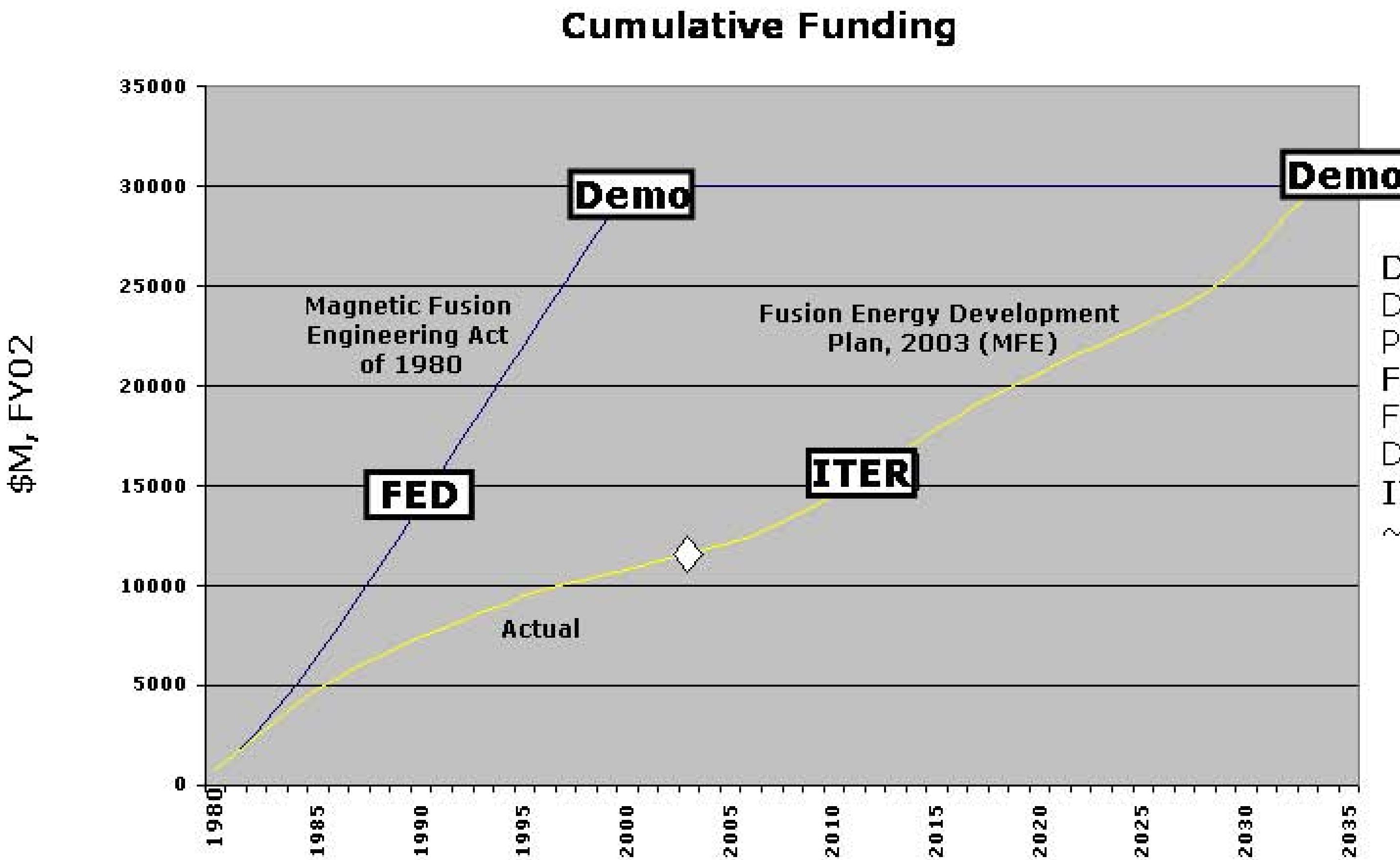


Fusion is Progressing Rapidly



ITER will produce over 200 GJ of heat per pulse from fusion, demonstrating the scientific and technological feasibility of magnetic fusion. NIF will produce over 2 MJ of fusion heat, demonstrating the scientific feasibility of inertial fusion.

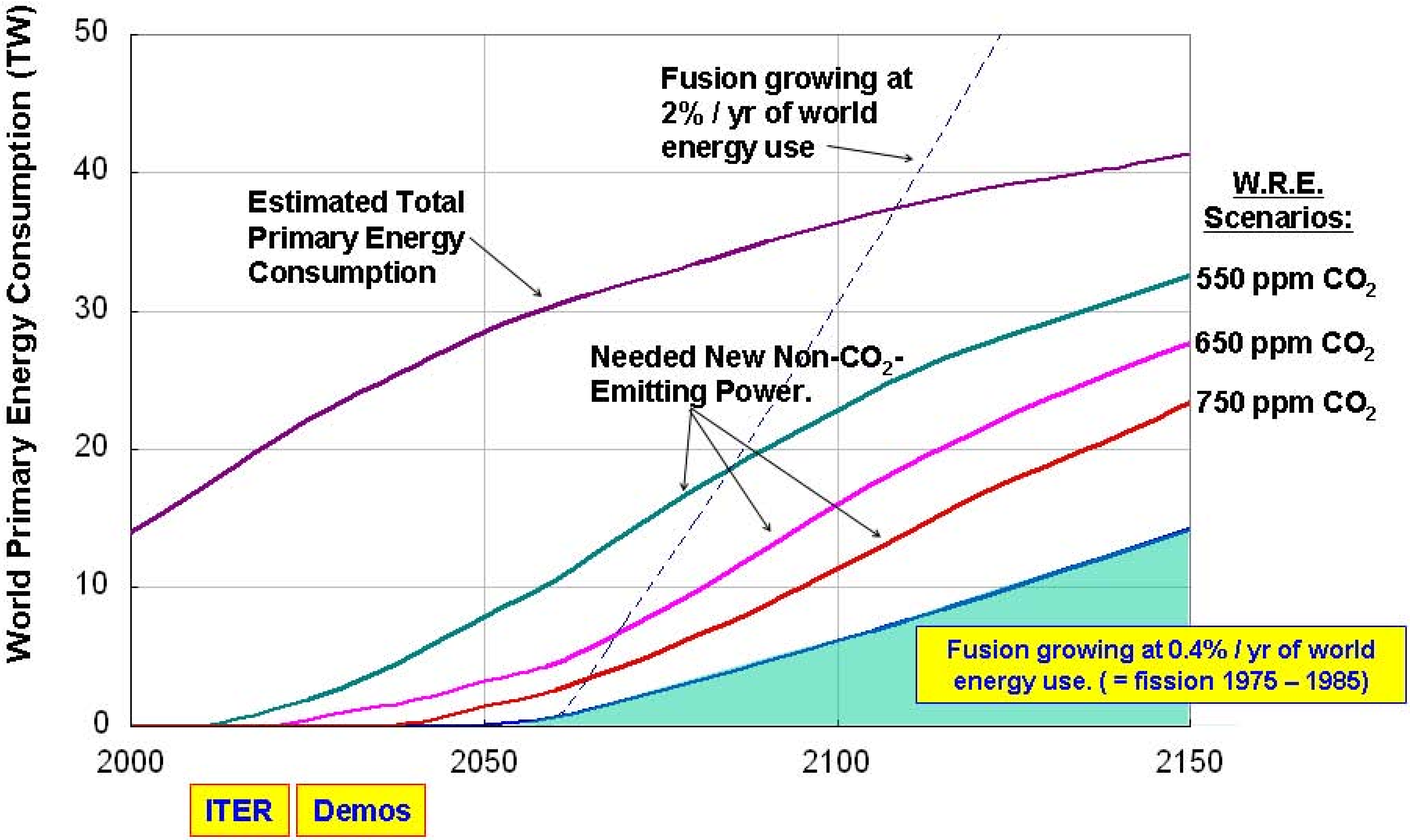
With Adequate Investment the U.S. can be Competitive in the Development of Fusion



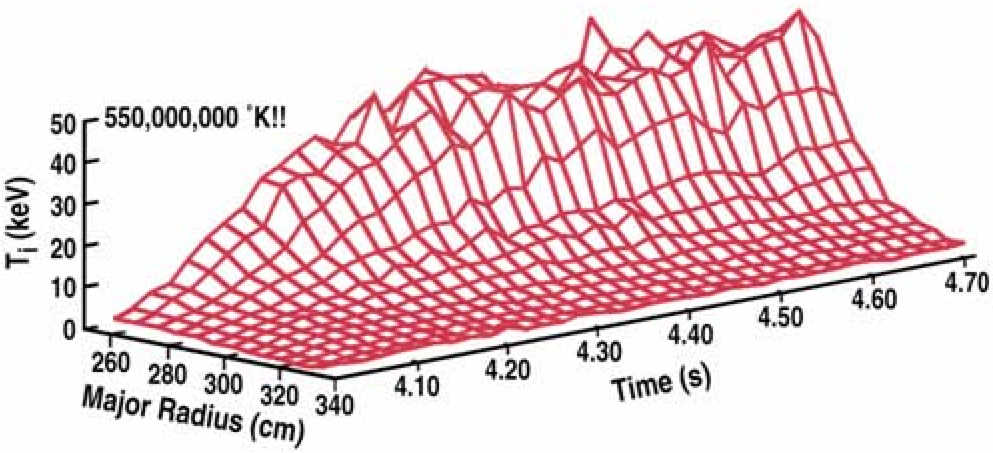
Demo: Demonstration Power Plant
FED: Fusion Engineering Device
ITER: "The Way" ~ FED

Because of the immense scale and impact of worldwide energy production, energy R&D like fusion is a good investment for society. Size of investment and time scale are prohibitive for private corporations.

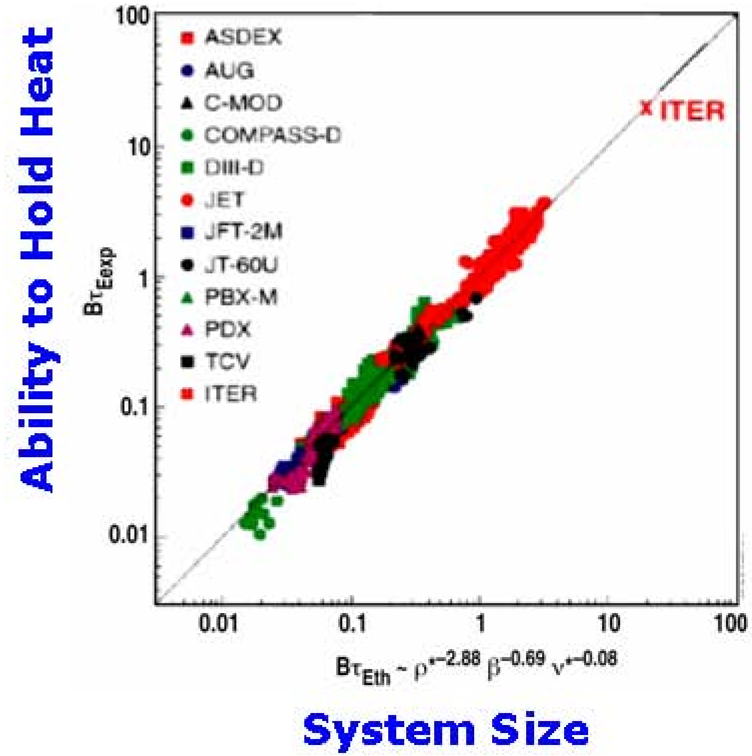
Fusion Has the Potential to be an Important Element in Addressing Climate Change in the Second Half of this Century and Beyond



U.S. R&D has Contributed Strongly to the Science and Technology Basis for ITER



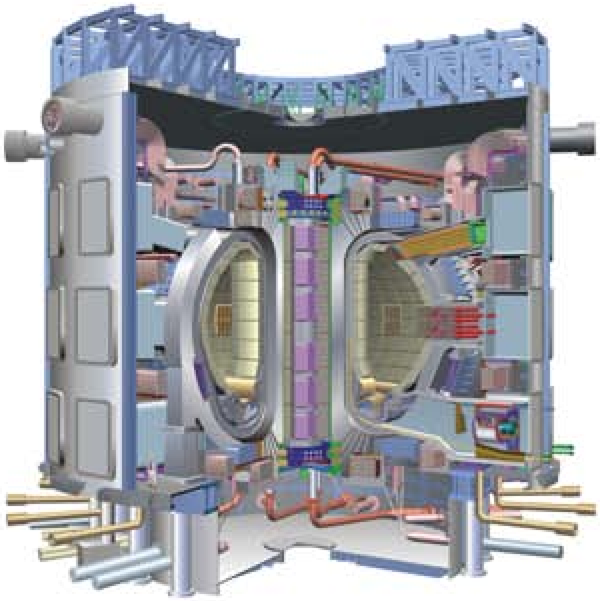
Temperatures have already been achieved in excess of what is needed for ITER. Science and technology for plasma heating are well developed.



Data from experiments worldwide, supported by advanced computation, indicate that ITER will achieve its design performance.

The ITER Agreement was Signed Nov. 21, 2006

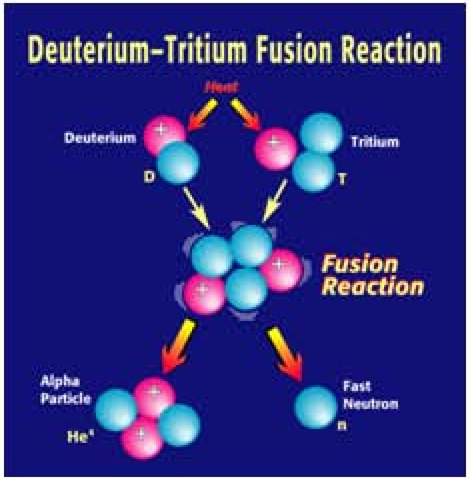
China, Europe, India, Japan, Russia, South Korea, U.S.



- **Over half the world's population is represented in ITER.**
  - **A strong international scientific consensus that magnetic fusion can be an important new non-CO_2-emitting power source.**
- **The negotiations over site and payment were successful.**
  - **Europe pays 45.4% – spending 1/5 of this in Japanese industry (!).**
  - **Each of the other six participants (including U.S.) pays 9.1%.**
  - **Europe pays for one-half of a set of additional fusion R&D facilities to be located in Japan, valued at 16% of ITER.**

ITER will Demonstrate the Scientific and Technological Feasibility of Fusion Power; Further S&T is Needed to Make Fusion Practical

- ITER is truly a dramatic step. For the first time the fusion fuel will be sustained at high temperature by the fusion reactions themselves.
  - **Today:** *10 MW(th) for 1 second with gain ~1*
  - **ITER:** *500 MW(th) for >400 seconds with gain >10*



- Many of the technologies used in ITER will be the same as those required in a power plant.

- Further plasmas science and fusion technology development are needed.
  - **Demo:** *2500 MW(th) continuous with gain >25, in a device of similar size and field as ITER*

  ⇒ Higher power density

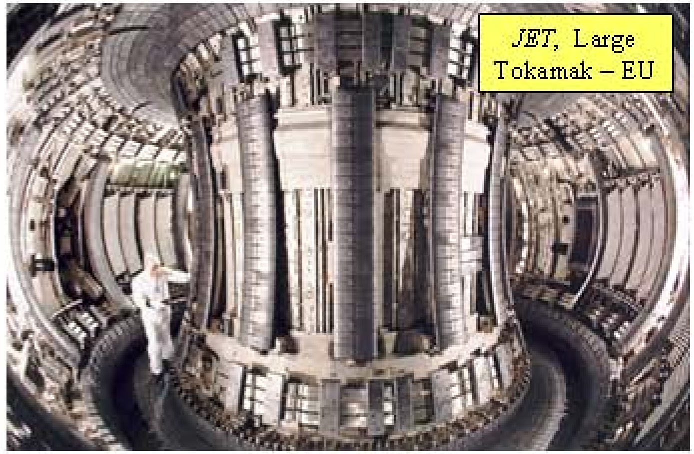
  ⇒ Efficient continuous operation

  ⇒ Robust plasma facing components

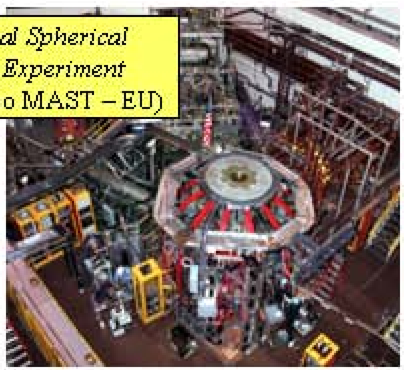
  ⇒ Long lived, low-activation structure

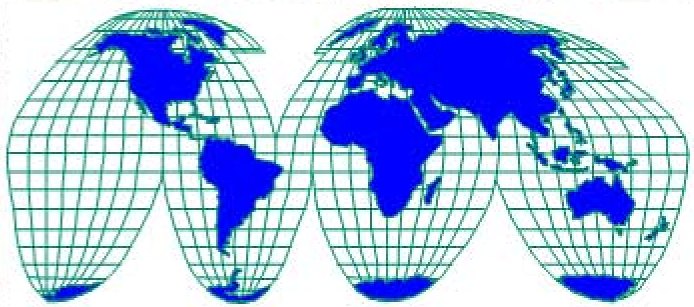
Magnetic Fusion Research is a Worldwide Activity, Optimizing the Plasma Configuration


C-Mod, Tokamak MIT


JET, Large Tokamak – EU


W7-X, Large Superconducting Stellarator – EU

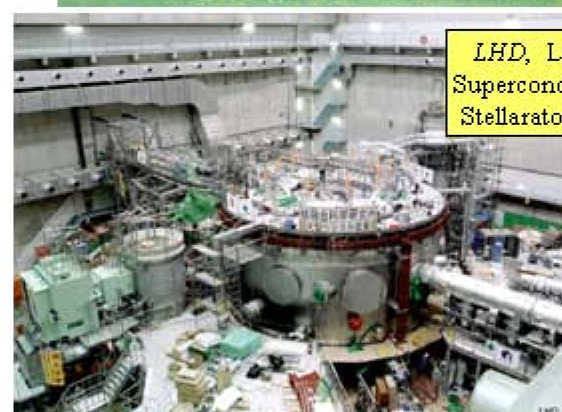

National Spherical Torus Experiment PPPL (also MAST – EU)



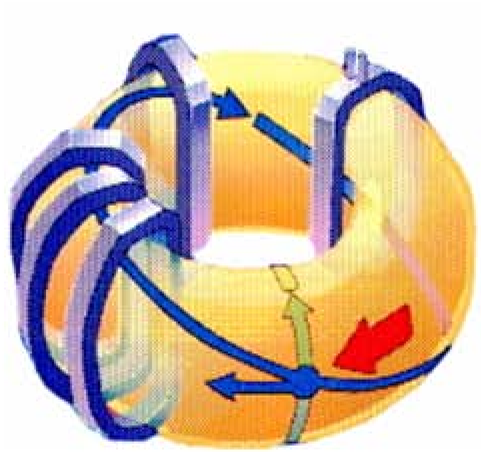

EAST, SST-1, *KSTAR* Superconducting Tokamaks, – China, India, Korea


DIII-D, Tokamak General Atomics

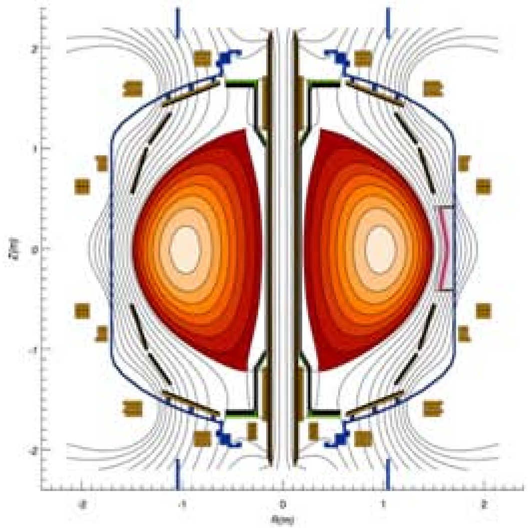

JT-60U, Large Tokamak– JA


LHD, Large Superconducting Stellarator – JA

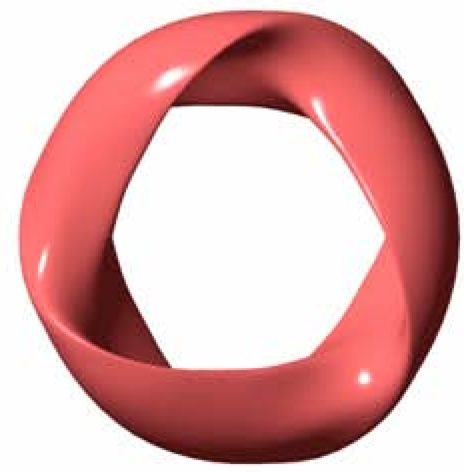
Research is Needed in ITER, and in Parallel with ITER for Practical Fusion



Advanced Tokamak
Active instability control and driven continuous operation.



Spherical Torus
High fusion power at given size and magnetic field.



Compact Stellarator
Passive stability and efficient continuous operation.

Practical fusion requires high fusion power and compact efficient continuous operation.
This research positions the U.S. to be competitive in fusion.

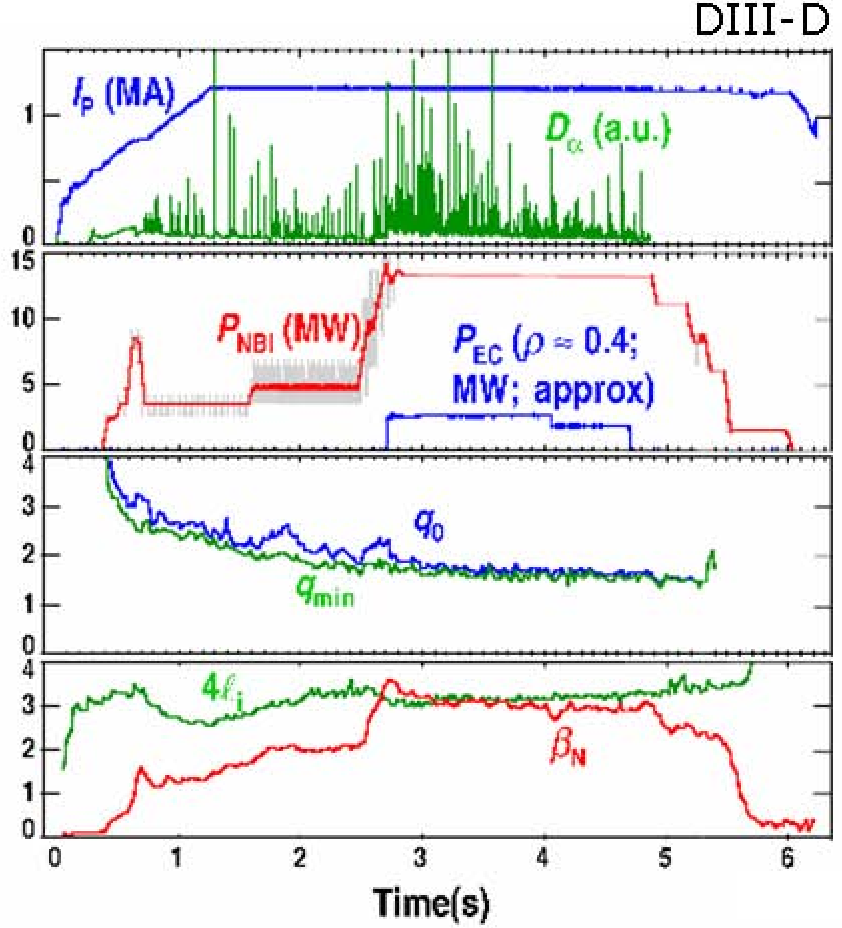
The "Advanced Tokamak" is a Potential Route to Continuous High Power and Gain

Control of Edge Localized Modes to limit damage to plasma facing surfaces.

External current drive, aided by internal "bootstrap current" to maximize efficiency, needed to sustain steady state.

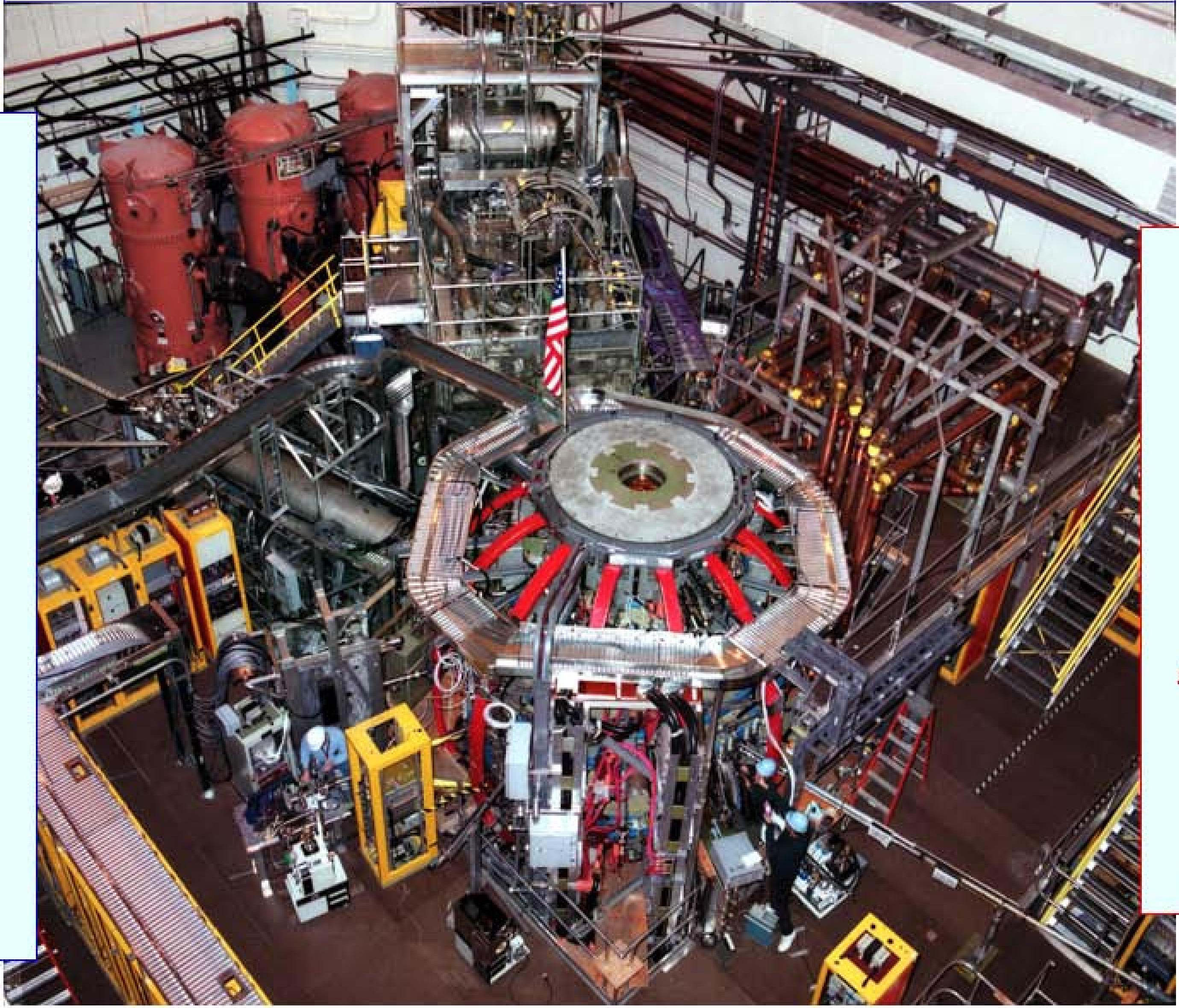
Operation at higher plasma pressure for higher fusion power, using rotation and mode feedback control.

Elimination of plasma current termination events, called disruptions.



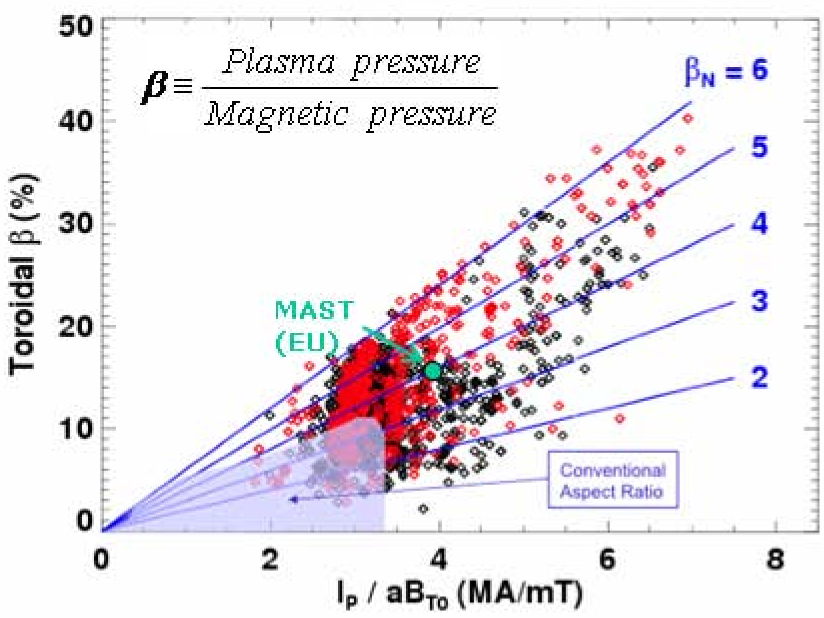
National Spherical Torus Experiment

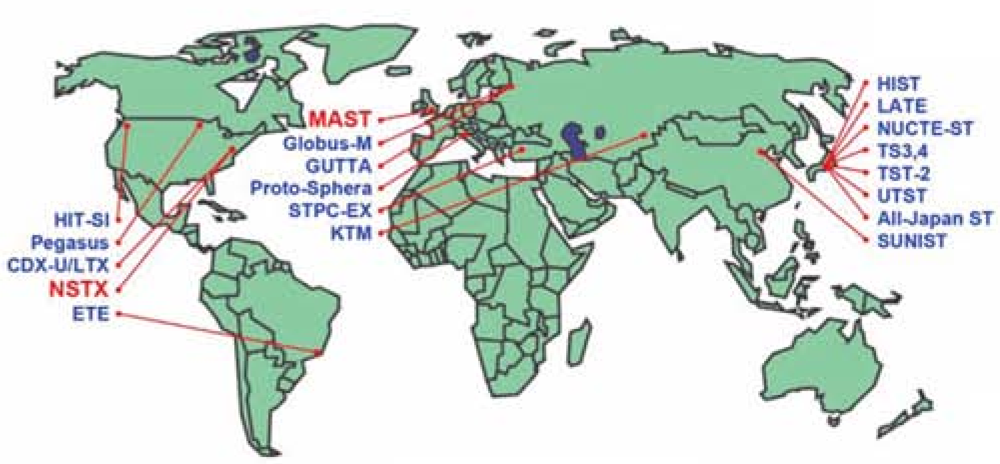
ANL
College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAERI
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

The National Spherical Torus Experiment is Leading the World in High β Research

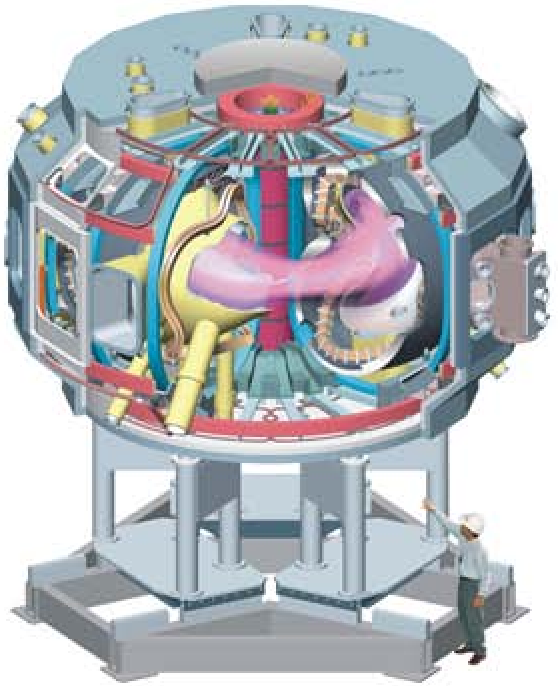




- **NSTX has achieved the highest β.**
- **NSTX has the most powerful plasma heating systems.**
- **NSTX has the most sophisticated instability control tools.**
- **NSTX has the most advanced plasma measurement tools.**

High β is needed for high-power fusion systems.

NCSX will Assess the World's Leading Stellarator Concept for Fusion Energy



National Compact Stellarator Experiment

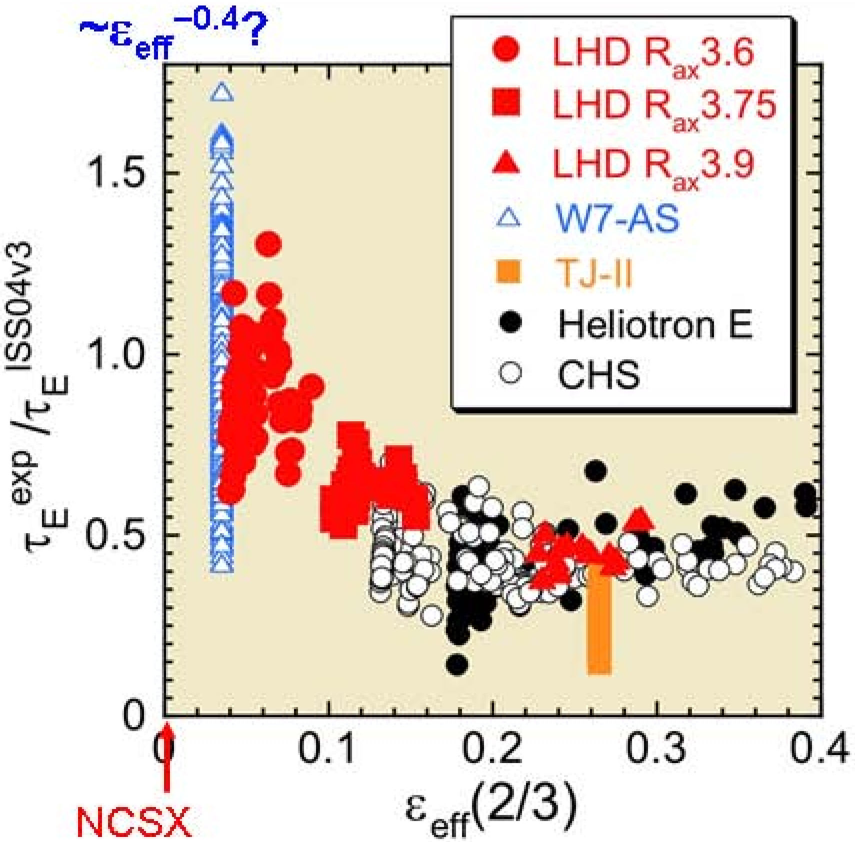
R = 1.42m <a> = 0.33m

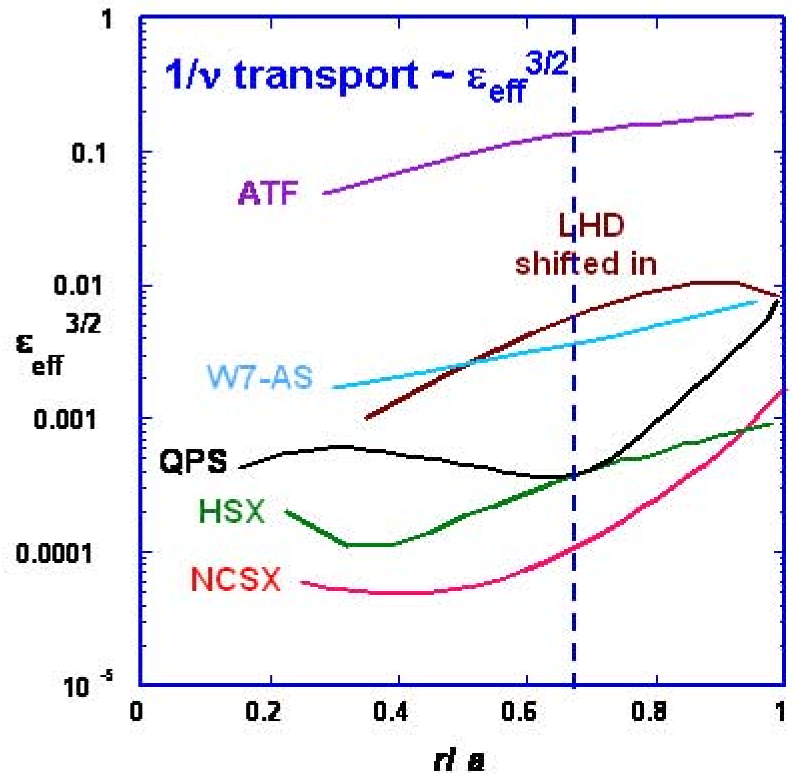
B_t = 2 T, I_p < 350 kA

- **Optimized Design**
  - A unique design that is much more compact than foreign stellarator designs, with higher β than equivalent advanced tokamak.
  - No need for current drive for steady state, can operate at high density for high efficiency.
  - Passively stable to internal and external modes, with no need for rotation drive or feedback control.
  - No disruptions.
- **Optimization Process**
  - Numerically optimized based on global stability, unique tokamak-like quasi-axisymmetry, and buildability.
  - Massively parallel computing studied over 500k configurations.

Practical fusion systems must be compact and operate efficiently in steady state.

Confinement Improves with Symmetry
NCSX is Most Symmetric Stellarator Design

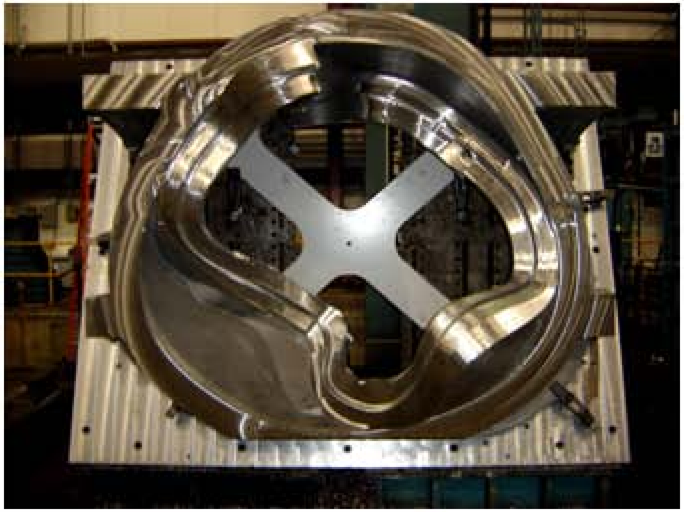




- New global confinement scaling study for stellarators (ISS04v3) found strong dependence on ripple magnitude (ε_{eff}).
- NCSX designed for the lowest ripple of all configurations.

NCSX Manufactured in Industry and at PPPL

Coil winding form
All 18 delivered.

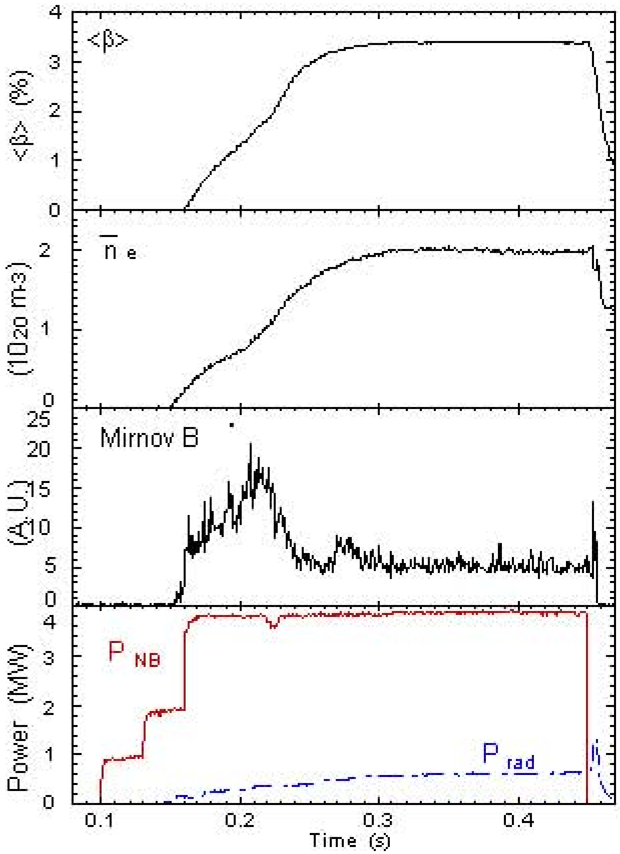


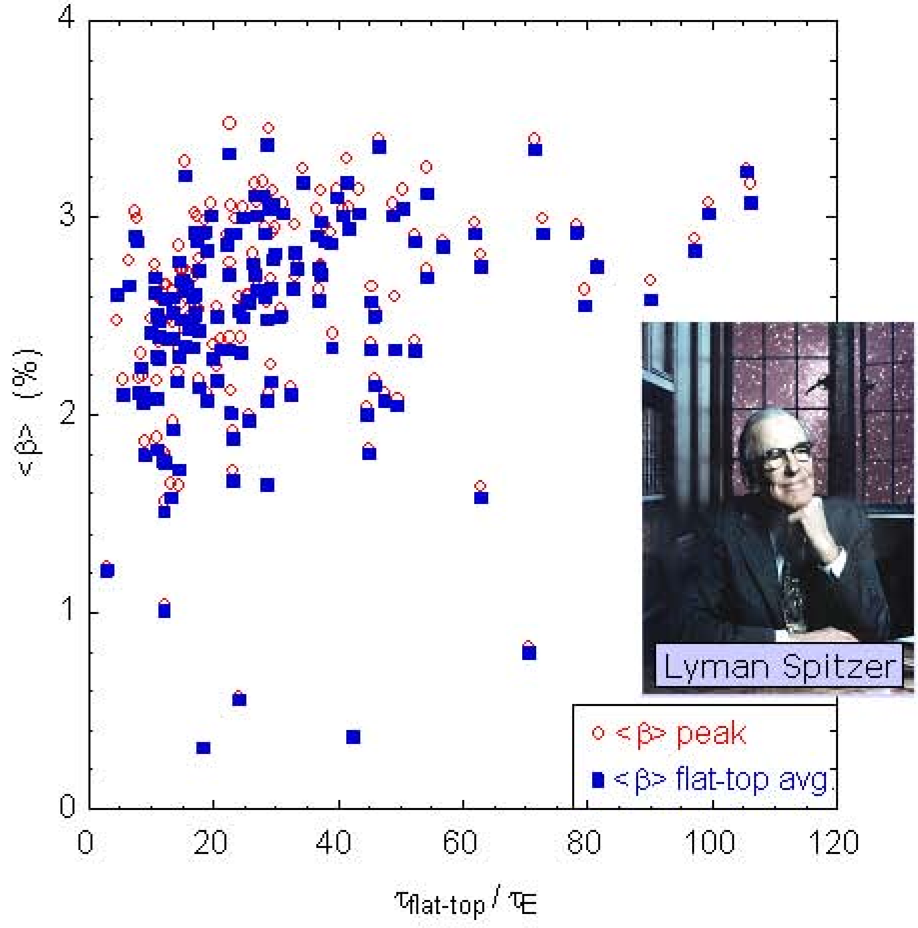
Vacuum vessel
All 3 sectors delivered.

Coil-winding facility
16 of 18 wound.

Stellarators make Steady, Quiescent Plasmas

W7-AS
(EU)





1 hour on Large Helical Device (JA)
W7-X (EU) will also run very long pulses.
Neither device has the compactness of NCSX.

Fusion Materials Requirements

- **Heat flux at divertor**
  - 10 – 40 MW/m^2, peak "normal operation"
  - Up to 50 MJ/m^2, transiently
  - ~ 500 MW total surface heat load
- **Particle flux at divertor**
  - D-T fuel particles: 10^{23} – 10^{24} $m^{-2}s^{-1}$ @ 1 – 1000 eV

    Must not retain significant significant tritium
  - He^{+2} fusion product: 10^{22} – 10^{23} $m^{-2}s^{-1}$ @ 10 – 1000 eV
  - Impurity ions: ~1% of D-T
- **Neutron flux to first wall structural components**
  - 2 – 5 MW/m^2
- **Required Lifetime**
  - 2 – 5 full-power years

Candidate Plasma-Facing Materials

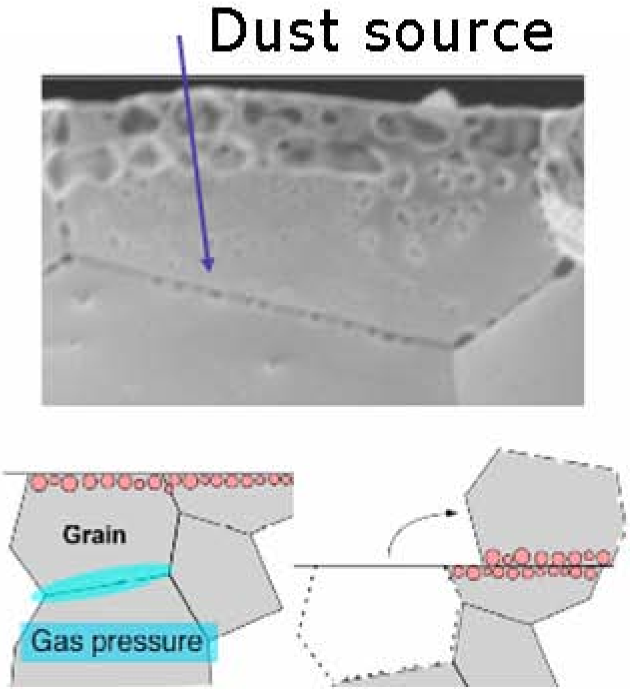
Elements – Solid

- **Tungsten**
- **Beryllium**
- **Carbon**

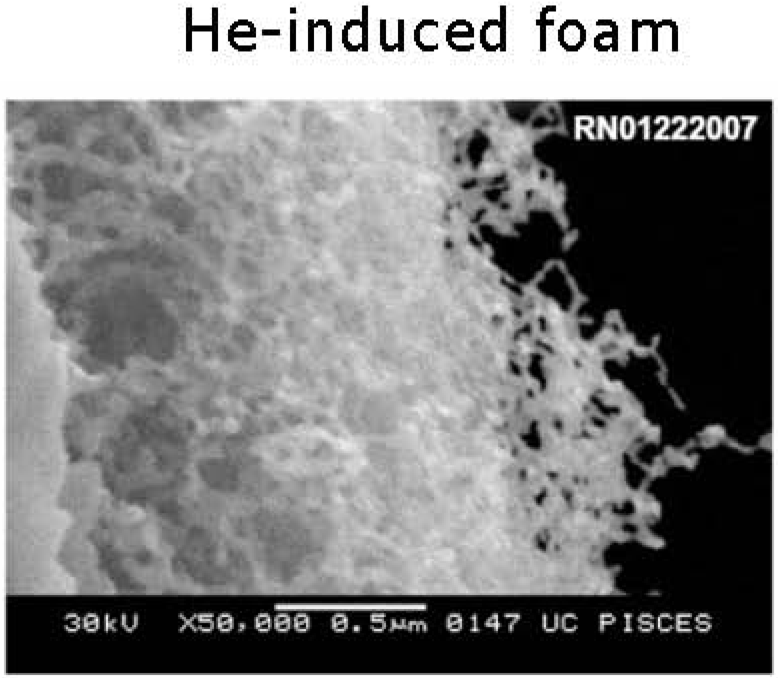
Elements – Liquid

- **Lithium**
- **Gallium**
- **Tin**

Tungsten has Very Low Sputtering due to Plasma Bombardment, but...



Nagoya University



UCSD

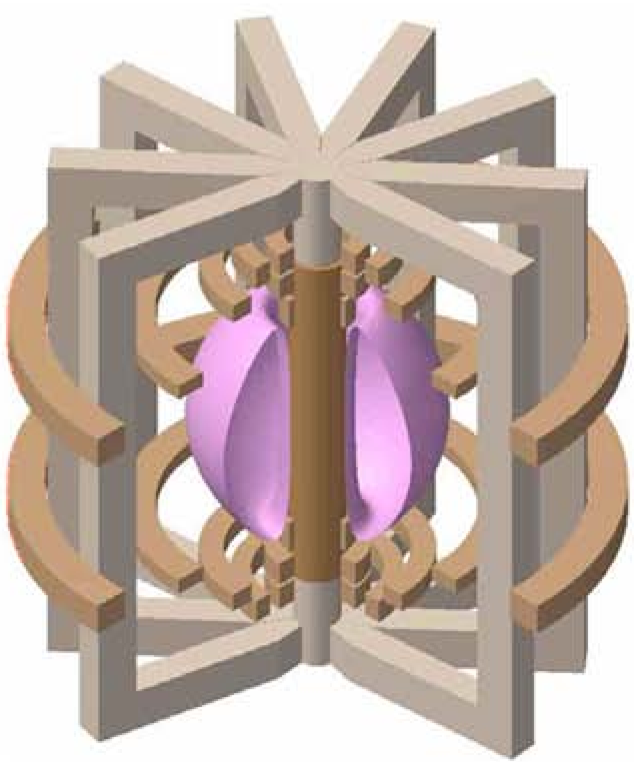
Melting at transient events is a potential problem.
At high power and fluence, dust and foam are concerns. T retention?
Tungsten radiates very strongly from the plasma core.

Liquid Lithium is Attractive as a Plasma-Facing Material

FTU, Italy
Capillary Porous System (CPS)

- Successful tests in TFTR, T-11, FTU, CDX-U, NSTX
- Reduces recycling, improves confinement.
- E-beam test to 25 MW/m^2 continuous operation.
- Plasma gun test to 15 MJ/m^2 off-normal load.
- Direct route to tritium removal, no dust.

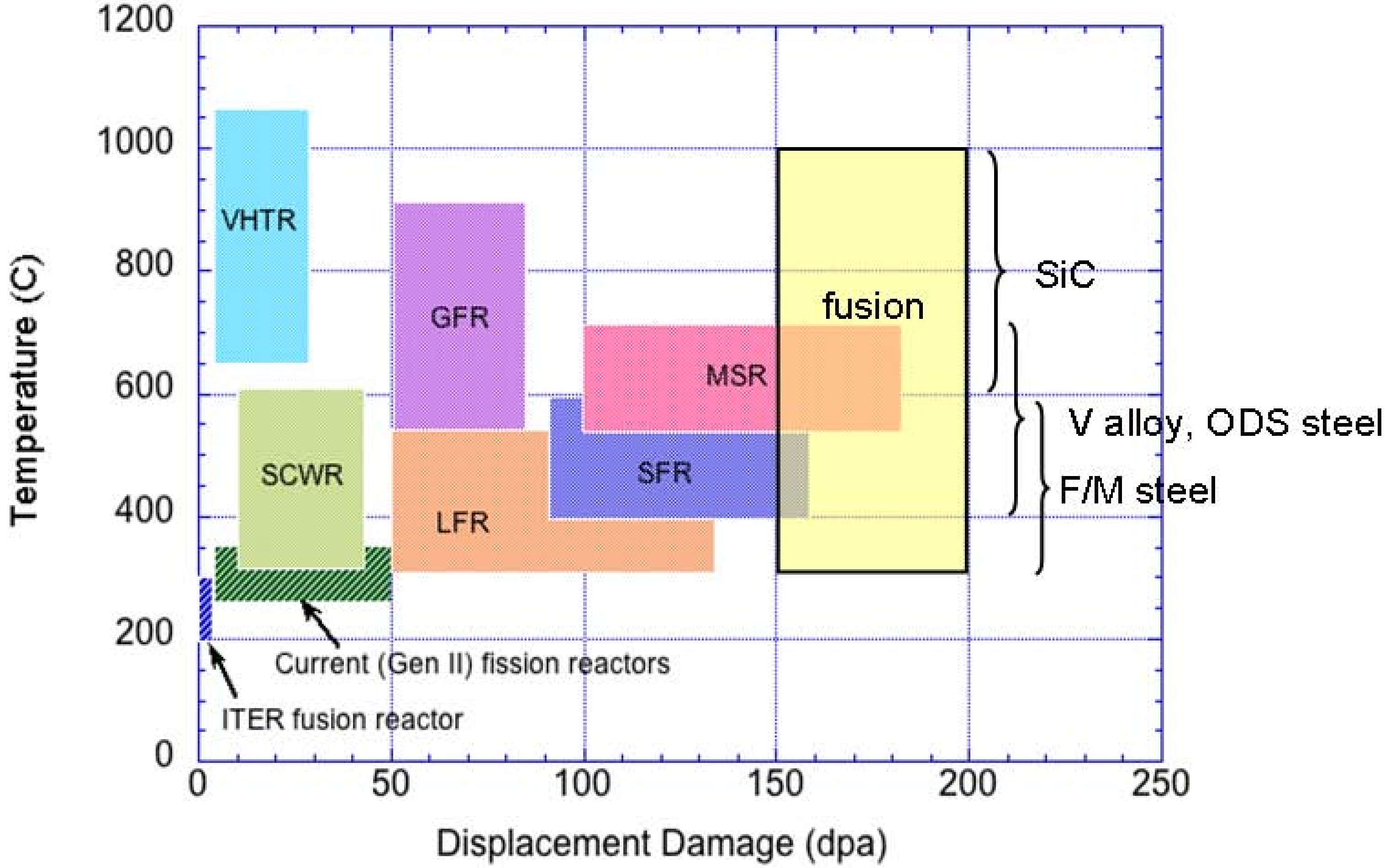
National High-power advanced Torus eXperiment



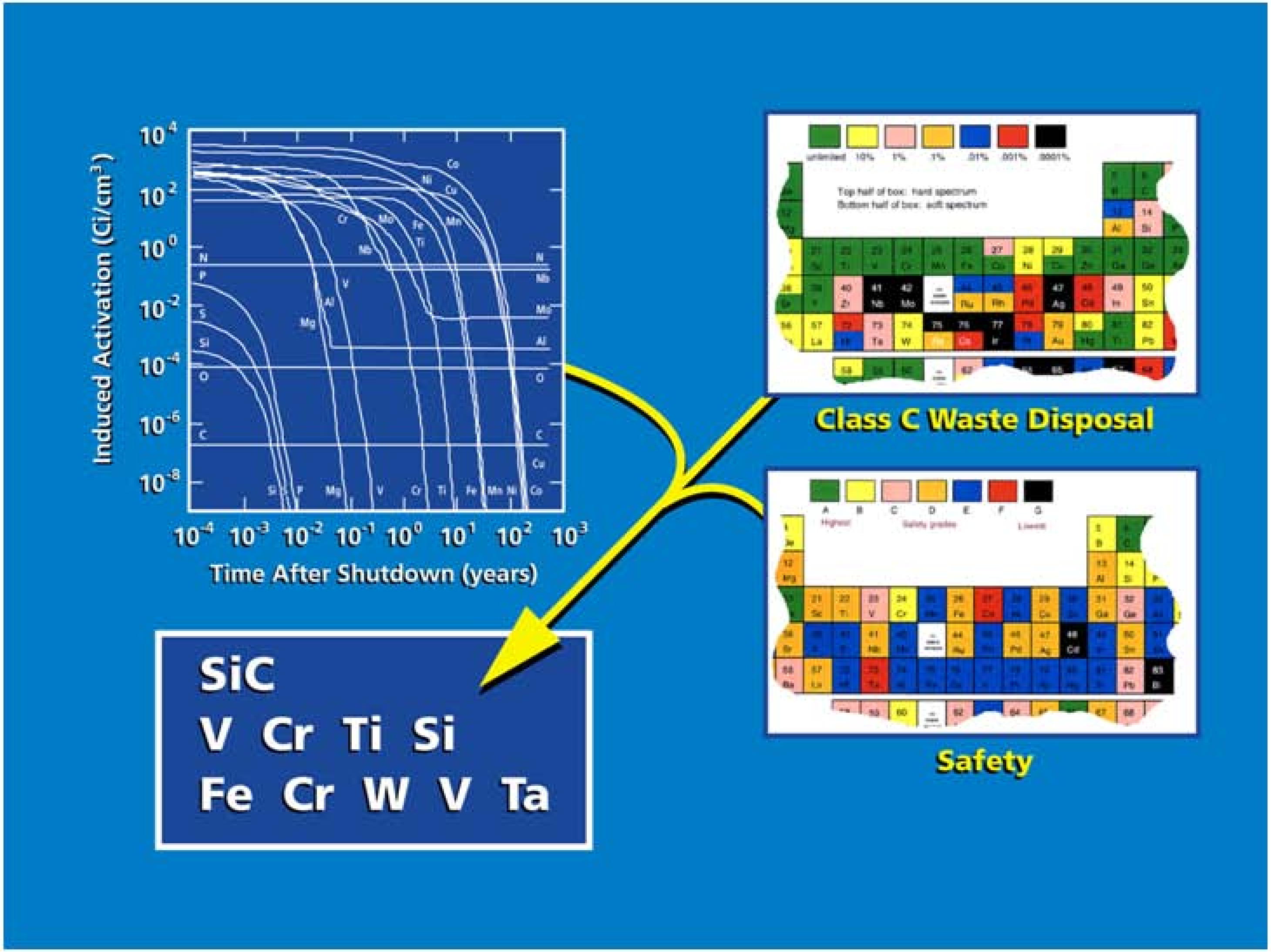
- Next key issues for Demo
  - Handling high heat flux
  - Avoiding tritium retention
- NHTX features
  - High power, small size
  - High temperature first wall
  - Long pulses, high duty factor
  - Solid, liquid divertor tests
  - Tritium capability
- No existing or planned device worldwide has these capabilities
  - Provides U.S. leadership
- Part of U.S. deliberation on next steps in parallel with ITER

To integrate a fusion-relevant plasma-material interface with stable sustained high-performance plasma operation.

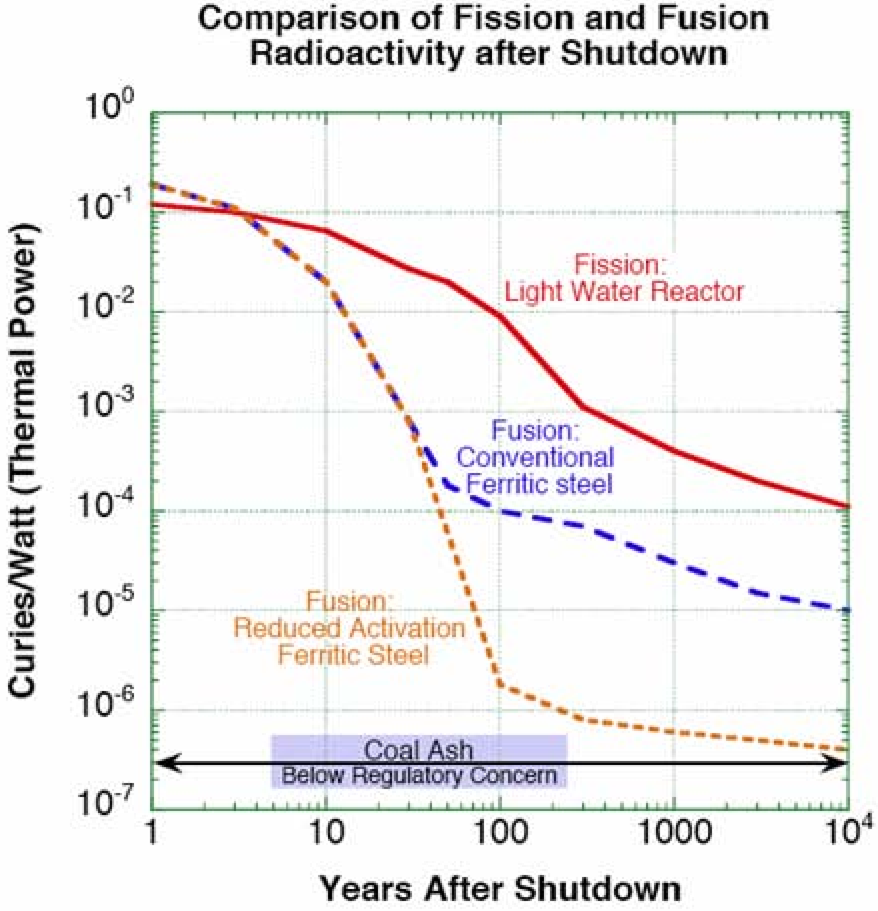
Comparison of Gen IV and Fusion Structural Materials Environments

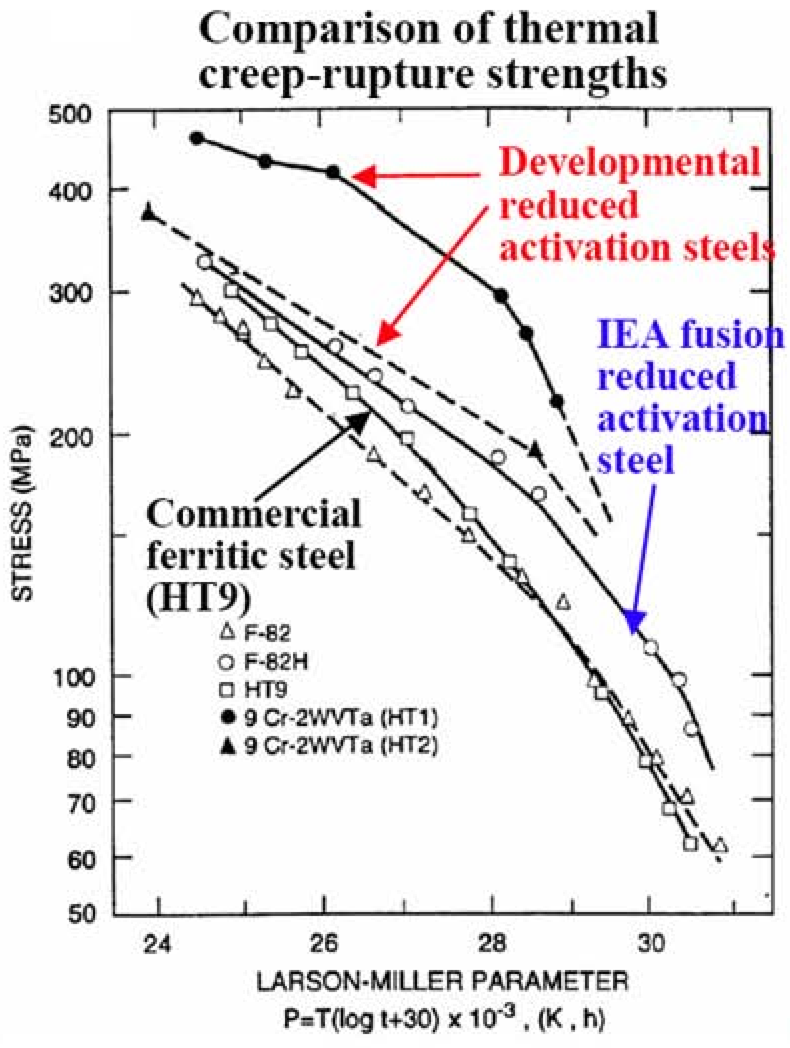


Low-Activation Structural Materials for Fusion

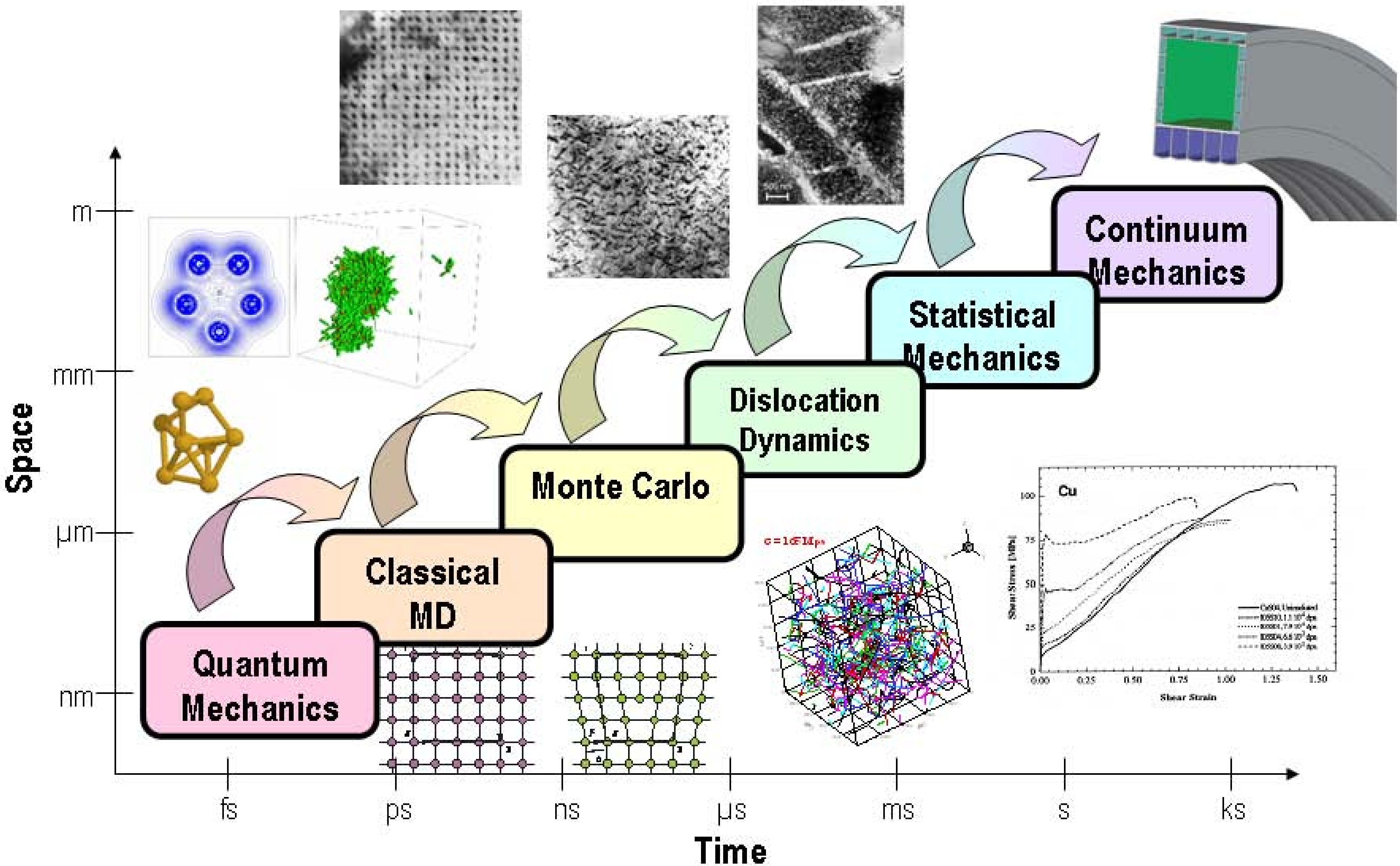


Steels with Reduced Radioactivity & Improved Properties Developed for Fusion

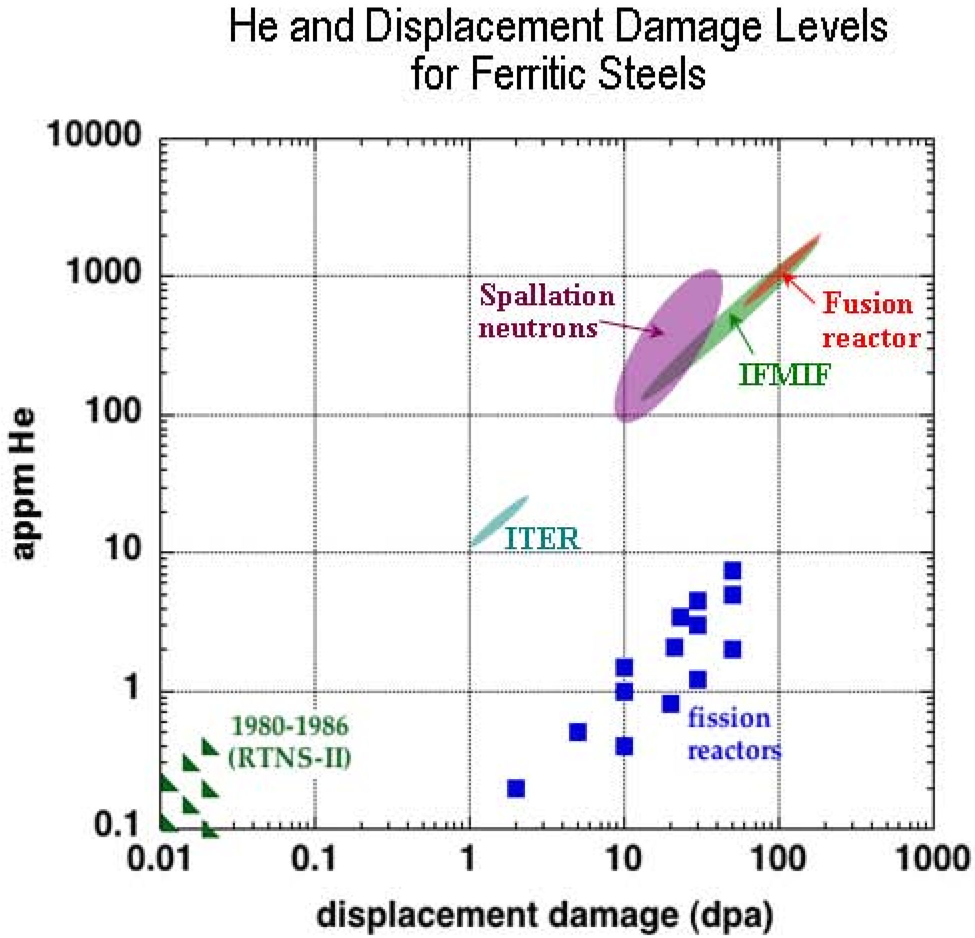


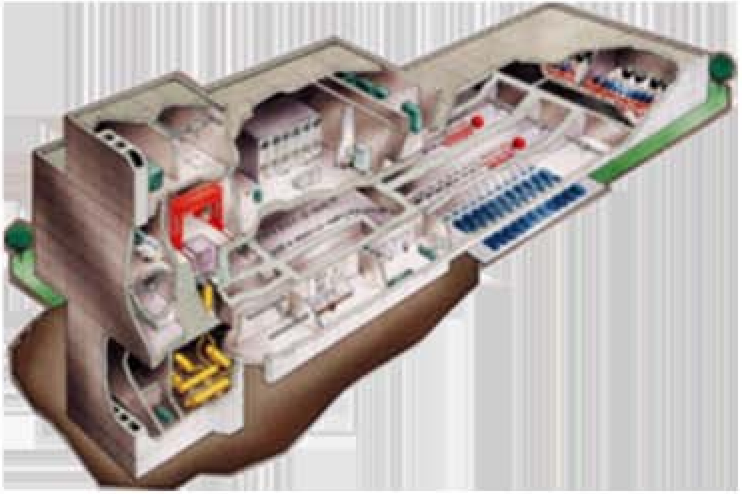


Multiscale Computational Modeling is an Indispensable Tool for Materials Development



Fusion Neutron Spectrum Results in High He to DPA Ratio

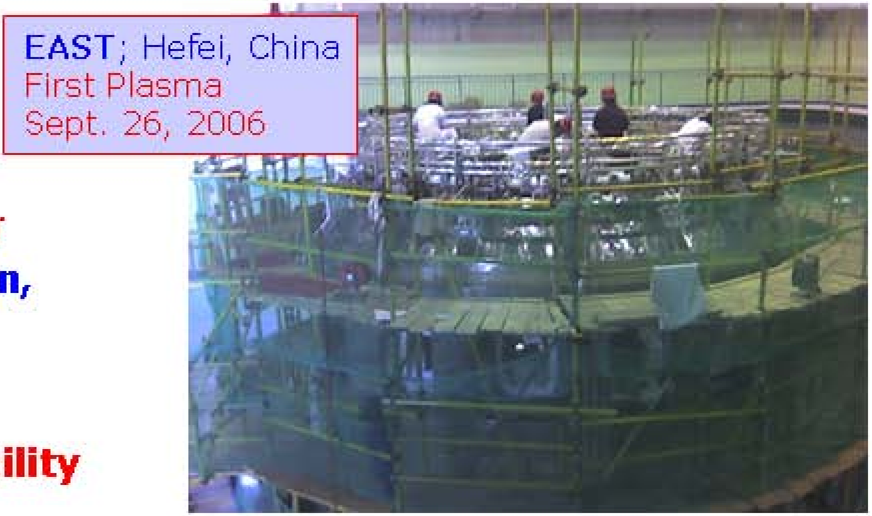




Neutron source to verify materials performance for design, construction, licensing and safe operation of Demo.

Fusion R&D is Being Pursued Aggressively Abroad

- **Five Major New Plasma Confinement Experiments Abroad**
  - China, Europe, India, South Korea, Japan + Europe located in Japan
  - Each is more costly than anything built in the U.S. in decades.
- **A Major New Fusion Computational Center**
  - Just for Japan + Europe, just for fusion, located in Japan
- **Engineering Design and Prototyping for a New Fusion Materials Irradiation Facility**
  - Japan + Europe located 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.
  - Many fewer young American scientists in fusion.



Fusion Energy Can be a Critical U.S. Technology

- **Fusion is an attractive, long-term form of nuclear energy.**
  - Fusion can have a significant impact on climate change
  - 95% of CO_2 mitigation this century is needed after 2030
- **Progress has been dramatic, and ITER is the next major step.**
  - ITER will demonstrate the scientific and technological feasibility of magnetic fusion energy.
- **Significant plasma physics and materials challenges remain.**
  - High Power Density
  - Continuous Operation
  - Robust Plasma - Facing Components
  - Low - Activation Structural Materials