Fusion Energy: Progress towards an Unlimited Energy Source

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5 June 2007

Today is an Exciting Time for Fusion

- Tremendous progress in *understanding* how to confine & control high-temperature matter
- Experiments are extending the limits technology: *superconductivity, lasers, heat sources, advanced materials, systems control, and computation,…*
- First light achieved at National Ignition Facility (NIF)
- International community to build ITER: the first burning plasma experiment at the scale of a power plant & *the world's largest energy science partnership.*

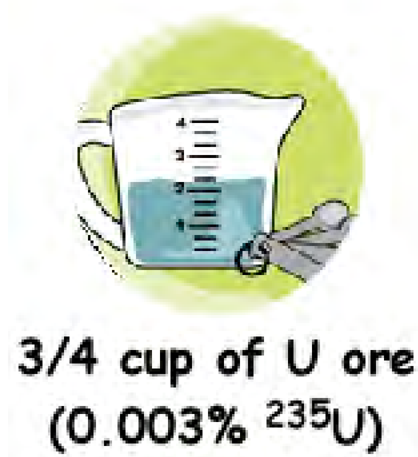
Outline

- Fusion Primer
- Can fusion be “**green**” nuclear power?
- Exciting Science and Experiments
- ITER: Fusion at the scale of a power plant
- Discussion and questions

“Forces” of Nature

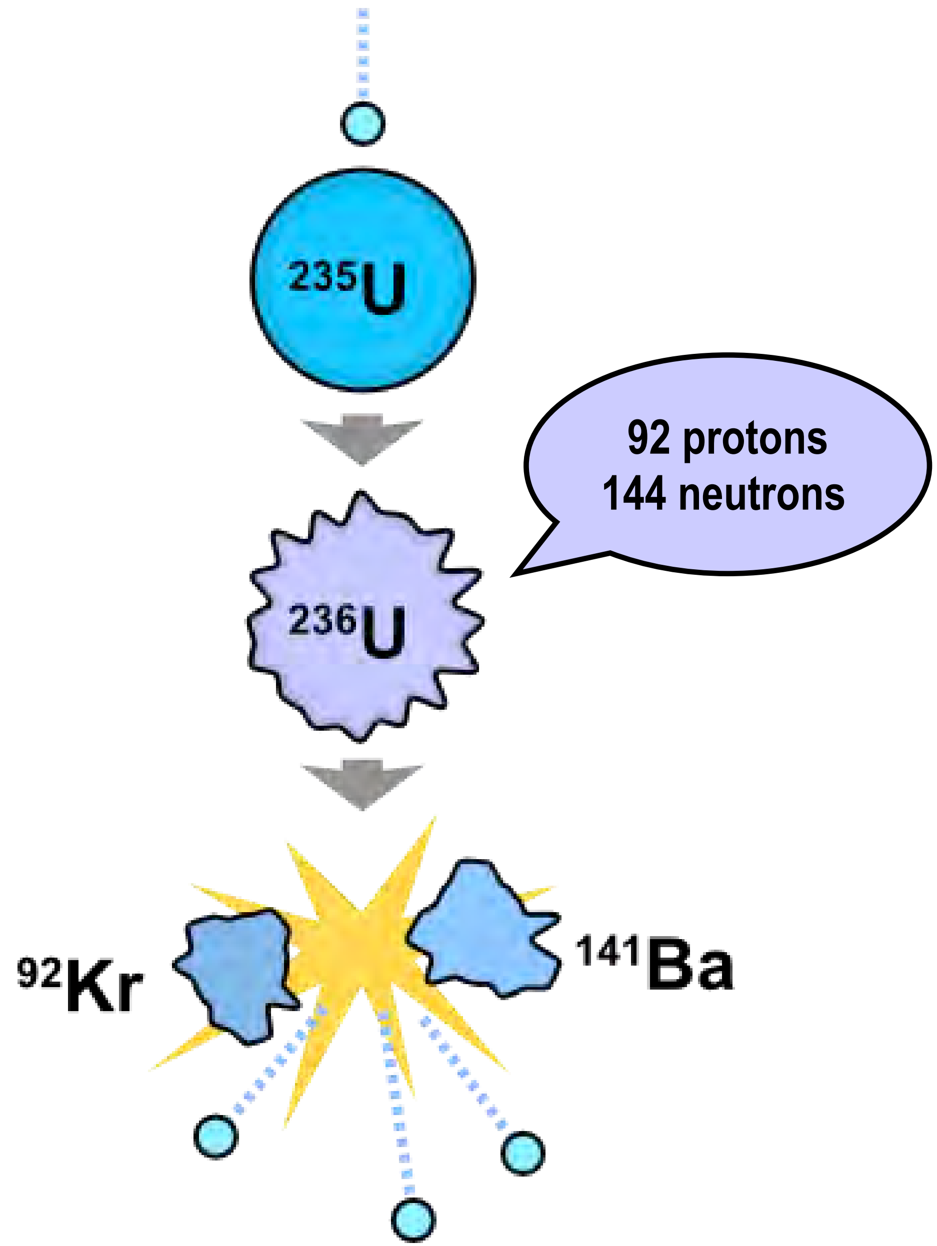
Gravity	*Tidal Energy*
Electromagnetic/ Molecular	*Combustion, Batteries, “Everyday” Energy and Chemistry*
Weak/Radiation	*Geothermal Energy*
Strong/Nuclear	*Fission, Fusion, and Solar (including wind, hydro, …)*

Chemical vs. Nuclear Energy Density



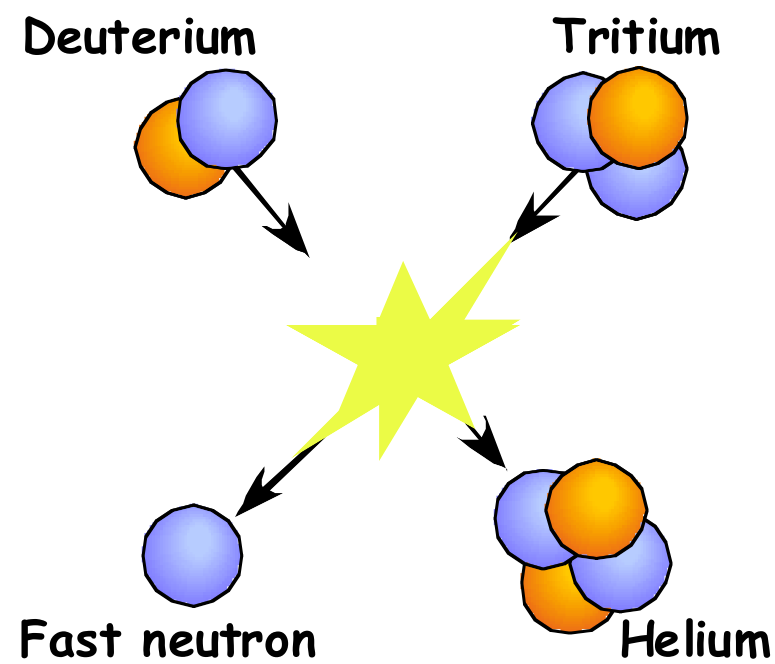
Why Fission is (Relatively) Easy to Do…

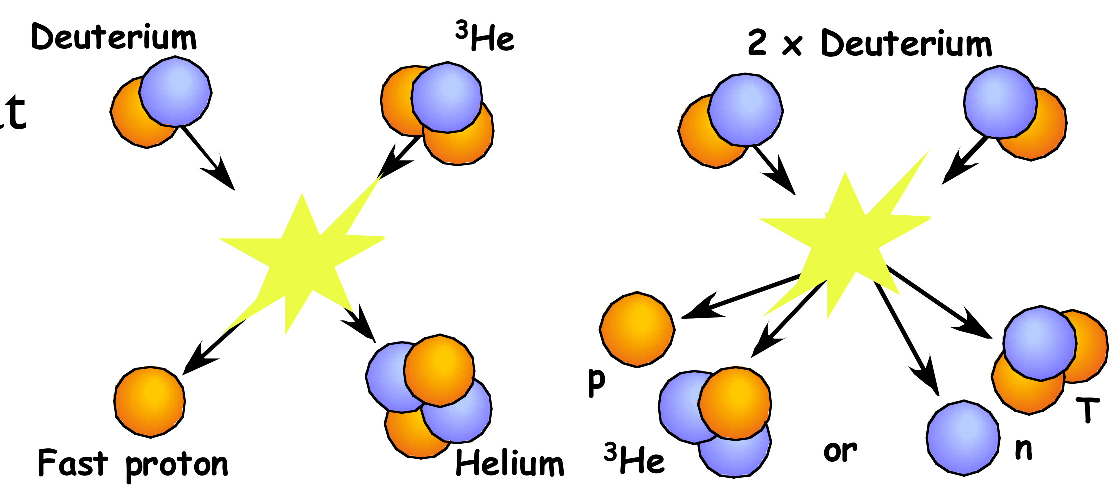
- Nuclear force is very-short ranged. Must get very close!
- Neutrons can easily split big, positively-charged nuclei…
- Because **neutrons are neutral!**
- Nucleons like to be paired (even numbers!) so certain nuclei are fissile: ^{233}U, ^{235}U, ^{239}Pu



Why Fusion is (Really, Really) Hard to Do…

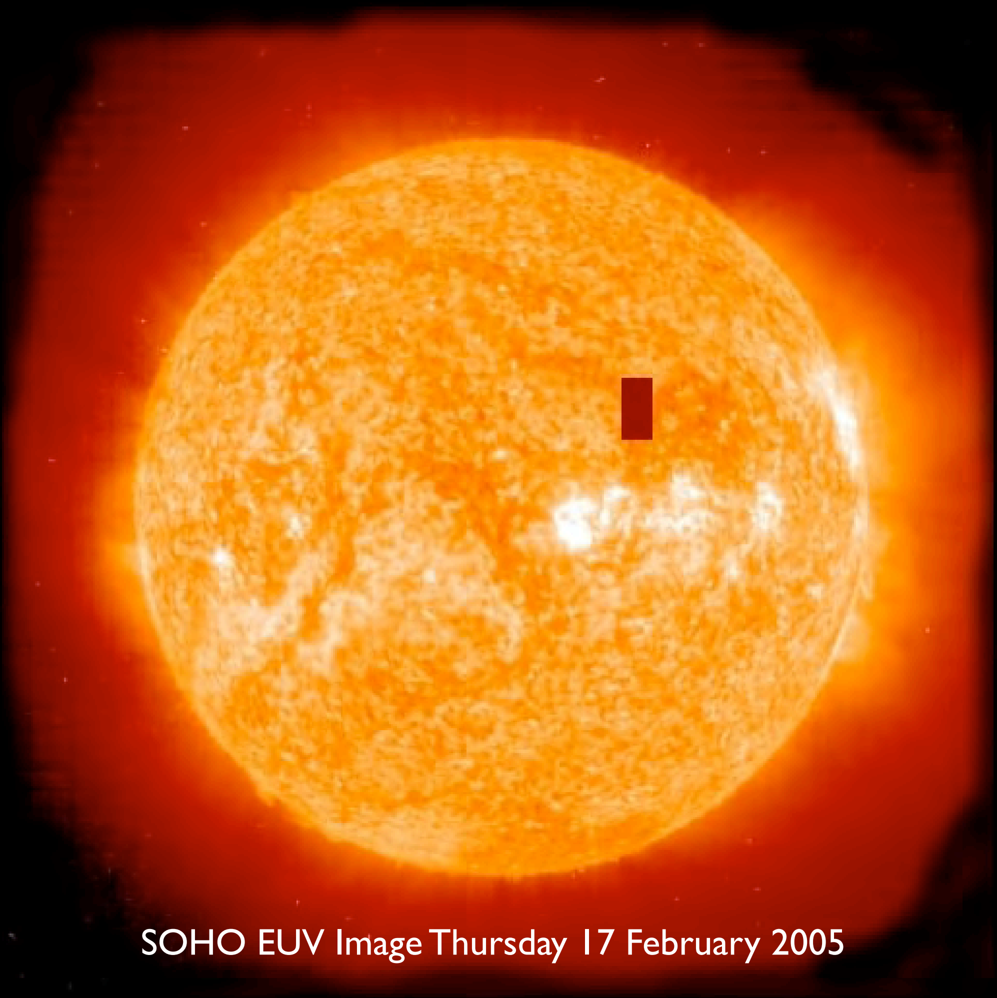
- Nuclear force is very-short ranged. Must get very close!
- Fusion requires close contact between light nuclei, like D, ^{3}He
- Difficult because all light nuclei are **positively charged!**
- Fusion energy occurs only at temperatures approaching 150,000,000 degrees!





Fusion in our Sun

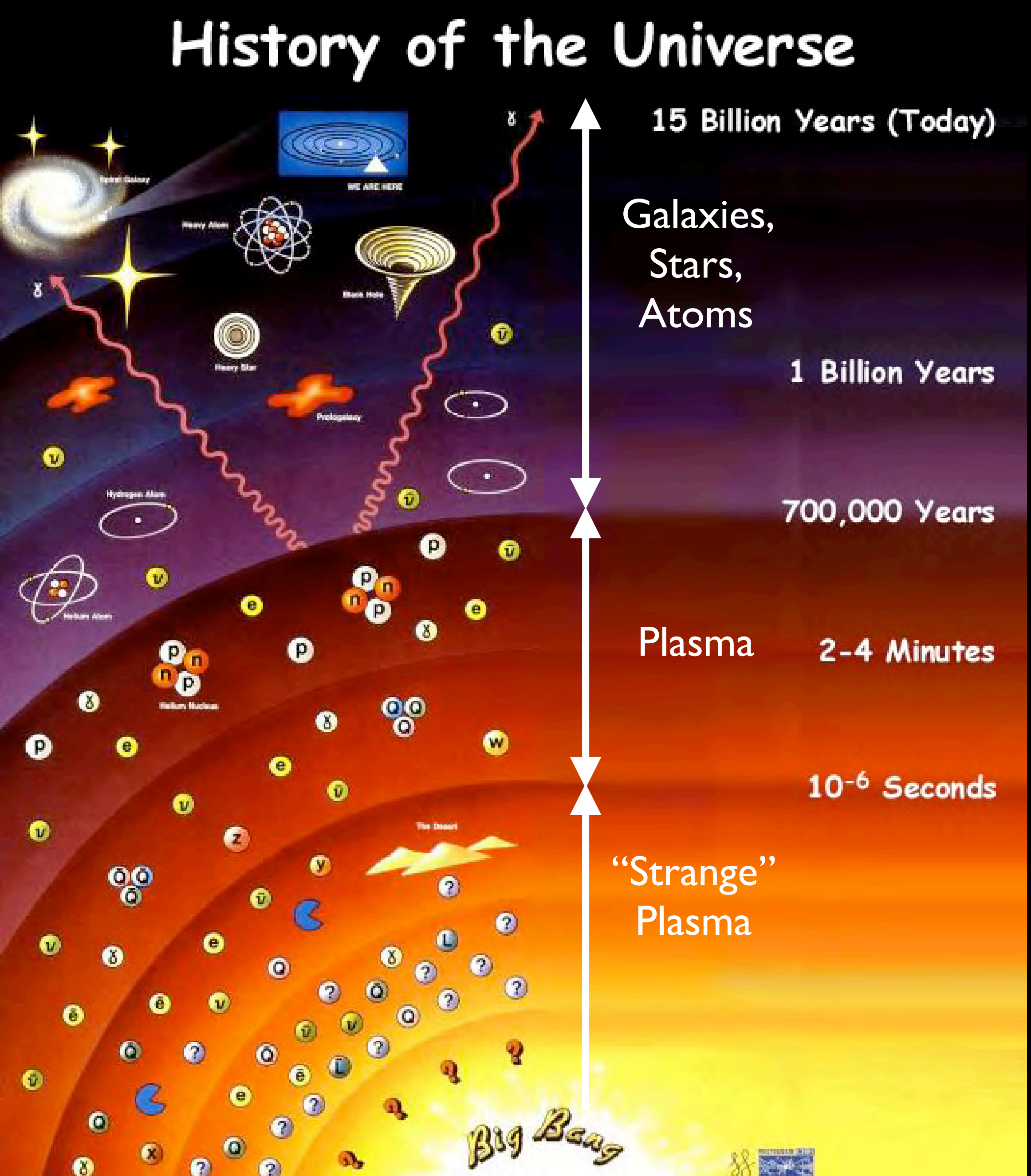
- 90% H, 9% He, 1% others
- Solar core: 15,000,000°
- (H + H) fusion rate limited by "Deuterium Bottleneck" or by high coulomb barrier in (H + C), (H + N) (Hans Bethe, Nobel 1967)
- Low power density (~1,000 W/m^3) with > 6 billion year burn-up time!



SOHO EUV Image Thursday 17 February 2005

Proton (hydrogen) fusion can not be used for a power plant. It's too slow!

100-300 s after the "Big-Bang": The Age of Fusion



- At 100 sec, the universe cools to 1,000,000,000°
- Protons and neutrons fuse to Deuterium (heavy hydrogen). The whole universe is a "**burning plasma**"!
- $D + D \rightarrow {}^3He + p$
  $D + D \rightarrow T + p$
  $D + T \rightarrow {}^4He + n$
  $D + {}^3He \rightarrow {}^4He + p$
- At 300 sec, nearly all D has fused to ${}^4He$. Universe cools and expands. Fortunately…

Deuterium (and Lithium): Nature's Gift from the "Big Bang"!

- After the "Age of Fusion", the Universe consists of hydrogen (90%), ^4He (9%), D (0.02%), ^3He (0.01%) and a pinch of Li.
- Heavy elements, including uranium, created billions of years later in exploding stars.
- 1 g of D yields 4 MW-days (4 times 1 g U^{235})

Two Approaches to Fusion Power

- Inertial Fusion Energy (IFE)
  - Fast implosion of high-density fuel capsules.

    Reaches ~ 200 Gbar from 25-35 fold radial convergence.
  - Several ~ 350 MJ (0.1 ton TNT) explosions per second.
- Magnetic Fusion Energy (MFE)
  - Strong magnetic pressure (100's atm) confine low-density (10's atm) plasma.
  - Particles confined within "toroidal magnetic bottle" for at least ~ 10 km and 100's of collisions per fusion event.
  - Fusion power density (~10 MW/m^3 and 20,000 × solar) allows plasma to be sustained for continuous power.

Fusion Comparison

Solar Core	Early Universe	Magnetic Fusion	Inertial Fusion
$4H \rightarrow {}^4He + 2e^+$	$D + D \rightarrow {}^4He + \gamma$	$D + T \rightarrow {}^4He + n$	$D + T \rightarrow {}^4He + n$
15 million°	500 million°	200 million°	200 million°
1.6 kW/m^3	10^{11} MW/m^3	10MW/m^3	10^{15} MW/m^3

Very "Slow"	100 Seconds	Steady State	"Fast" < 1 ns

D-T (^{6}Li) Fusion: Easiest Fuel for Laboratory Power

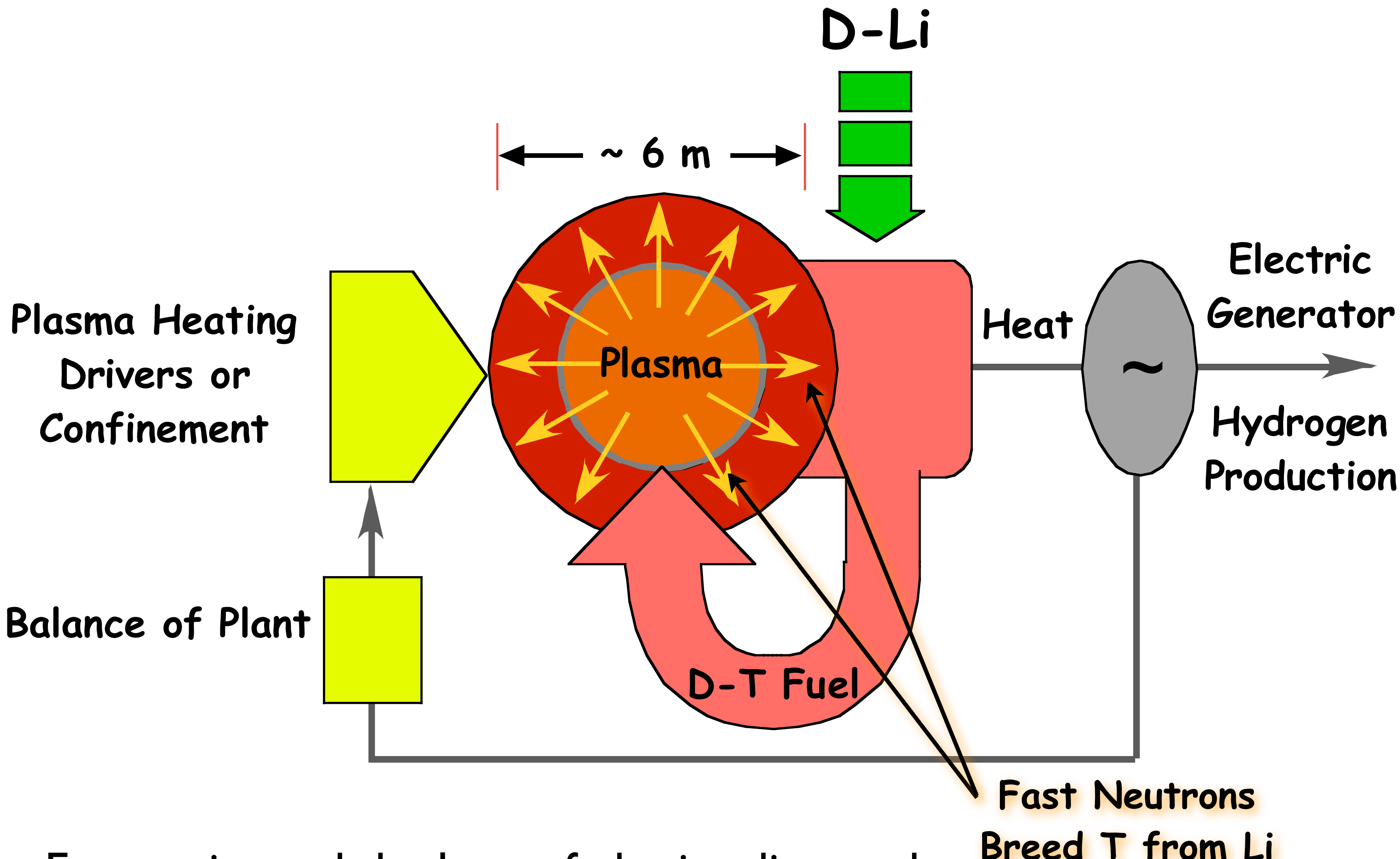
$$\text{D} + \textbf{T} \rightarrow {}^4\text{He}\ (3.5\ \text{MeV}) + \textbf{n}\ (14.1\ \text{MeV})$$

$$\textbf{n} + {}^6\text{Li} \rightarrow {}^4\text{He}\ (2.05\ \text{MeV}) + \textbf{T}\ (2.73\ \text{MeV})$$

- Tritium is created from ^{6}Li forming a **self-sufficient fuel cycle**. Practically no resource limit (10^{11} TW y D; 10^4(10^8) TW y ^{6}Li)!
- **Notice**: ~ 80% of energy as fast neutrons (~ 1.5 m shielding).

➠ the source of fusion's technology & materials challenge.

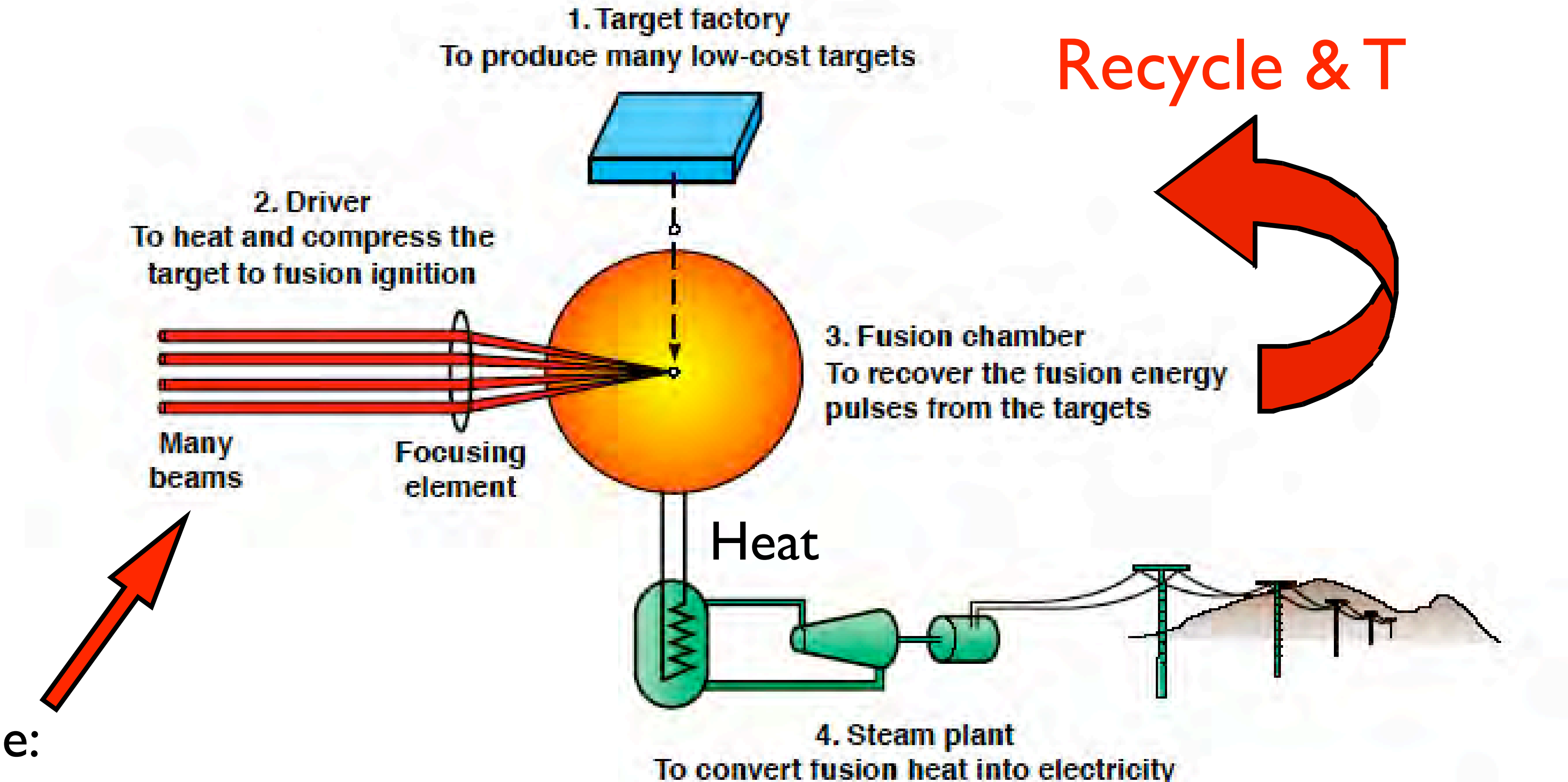
Elements of a D-T(Li) Fusion System



Economics and the laws of physics dictate the ≥ 6m scale of fusion power devices.
(**No** small **silver bullet!** nor small pilot-plant.)

IFE

< $0.50/capsule



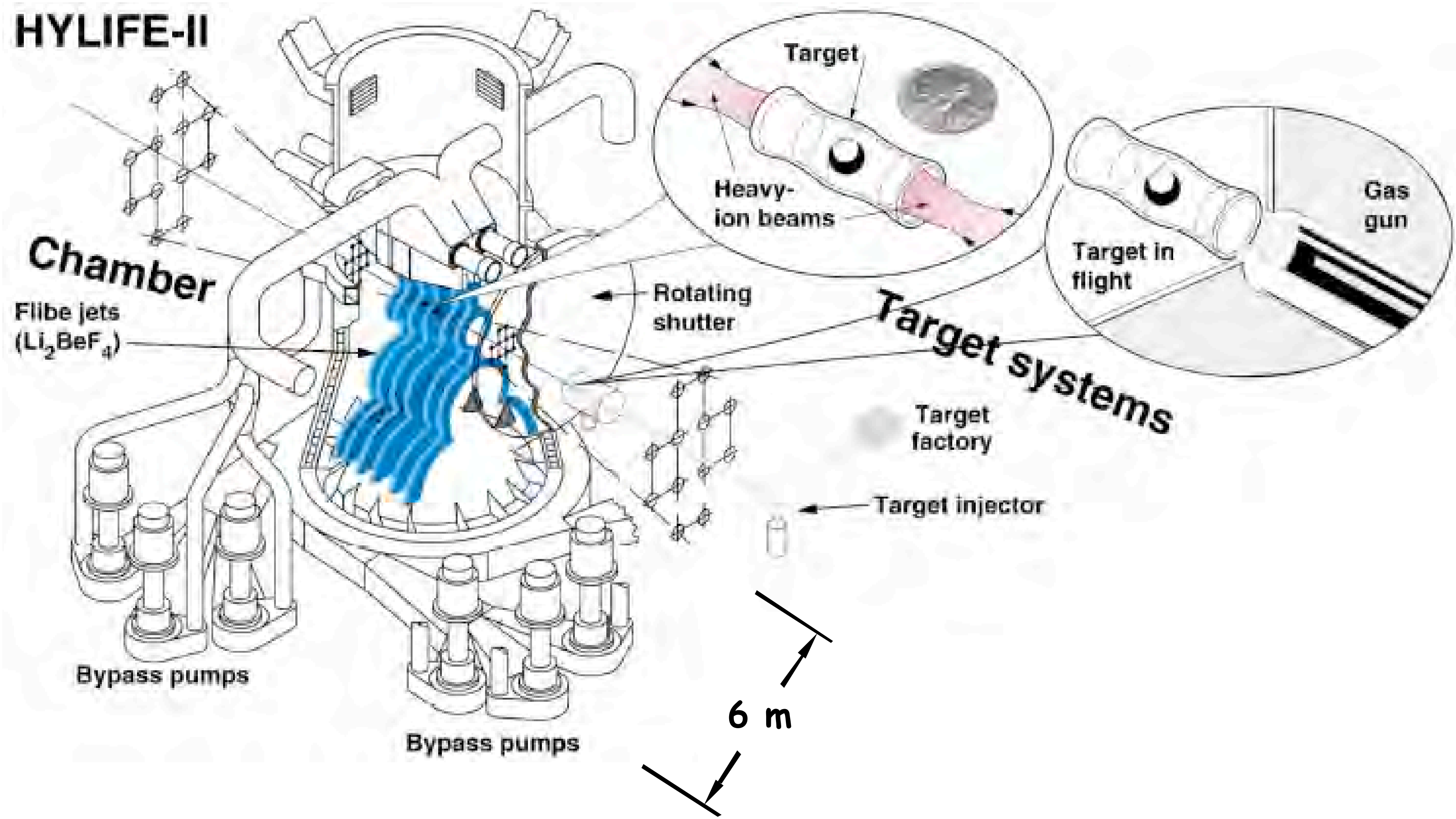
Example:

~ 100 beams (2.5 GeV Xe) ⇒ 5 MJ

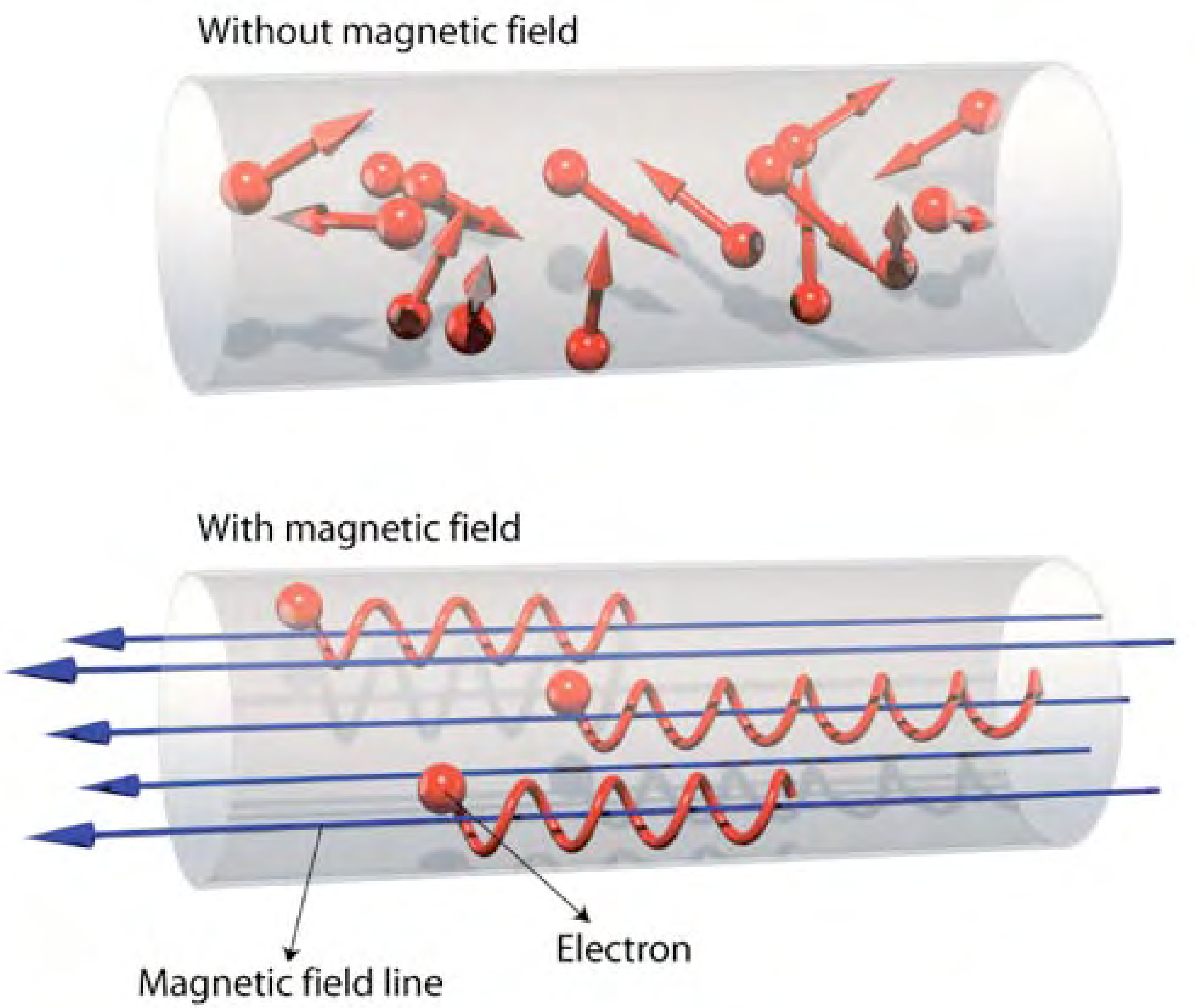
(About the length of SLAC ~2.5 km)

IFE Chamber

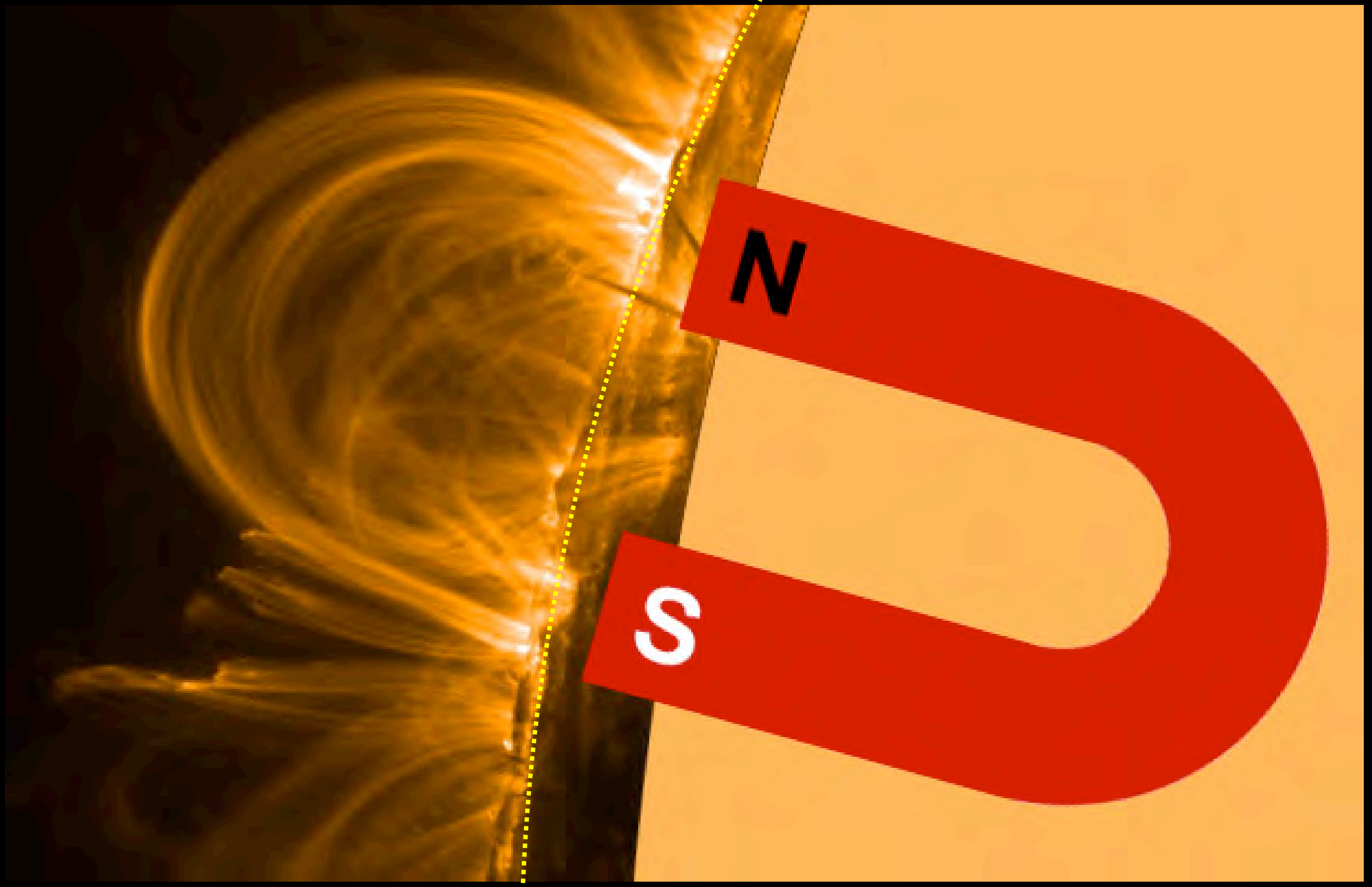
~100 beams



How Do Magnetic Fields Confine Ionized Matter?

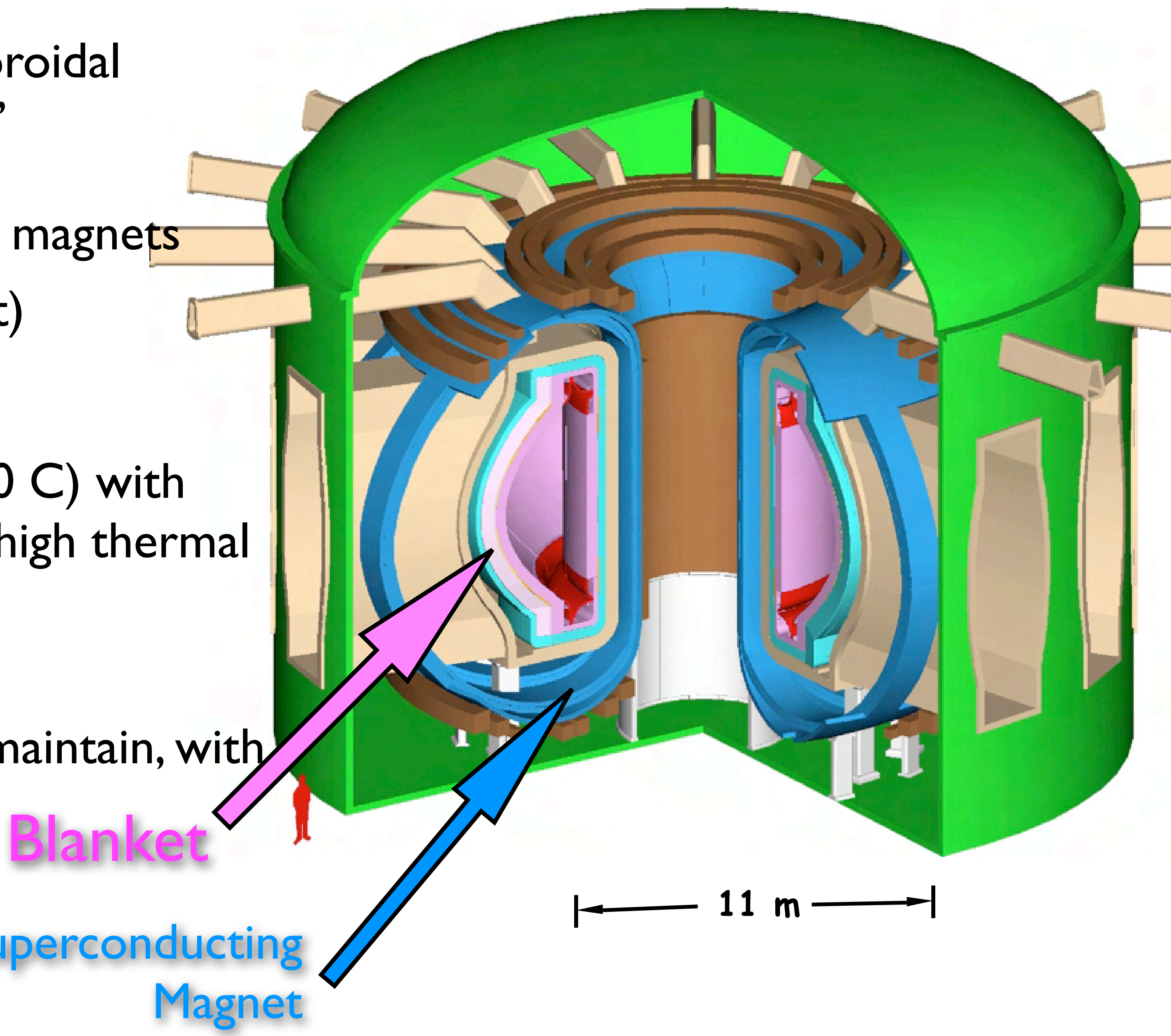


Solar Magnetic Fields



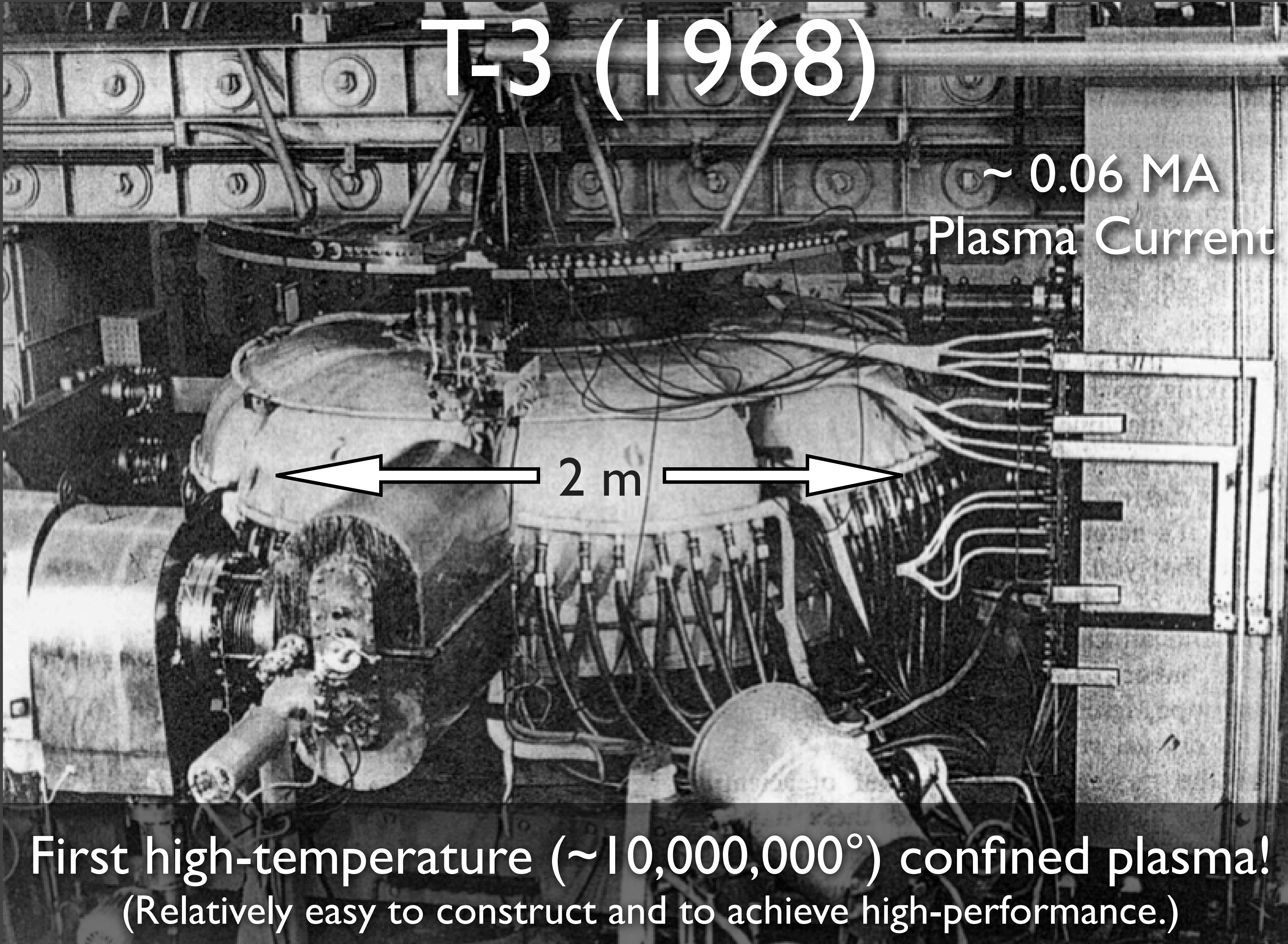
Magnetic Containers are Toroidal

- Tokamak means "Toroidal Magnetic Chamber"
- Steady state, Nb_3Sn magnets (Coldest ↔ Hottest)
- SiC blanket (~ 1,100 C) with PbLi coolant yields high thermal efficiency.
- Modular, "easy" to maintain, with 85% availability
- 1 GWe

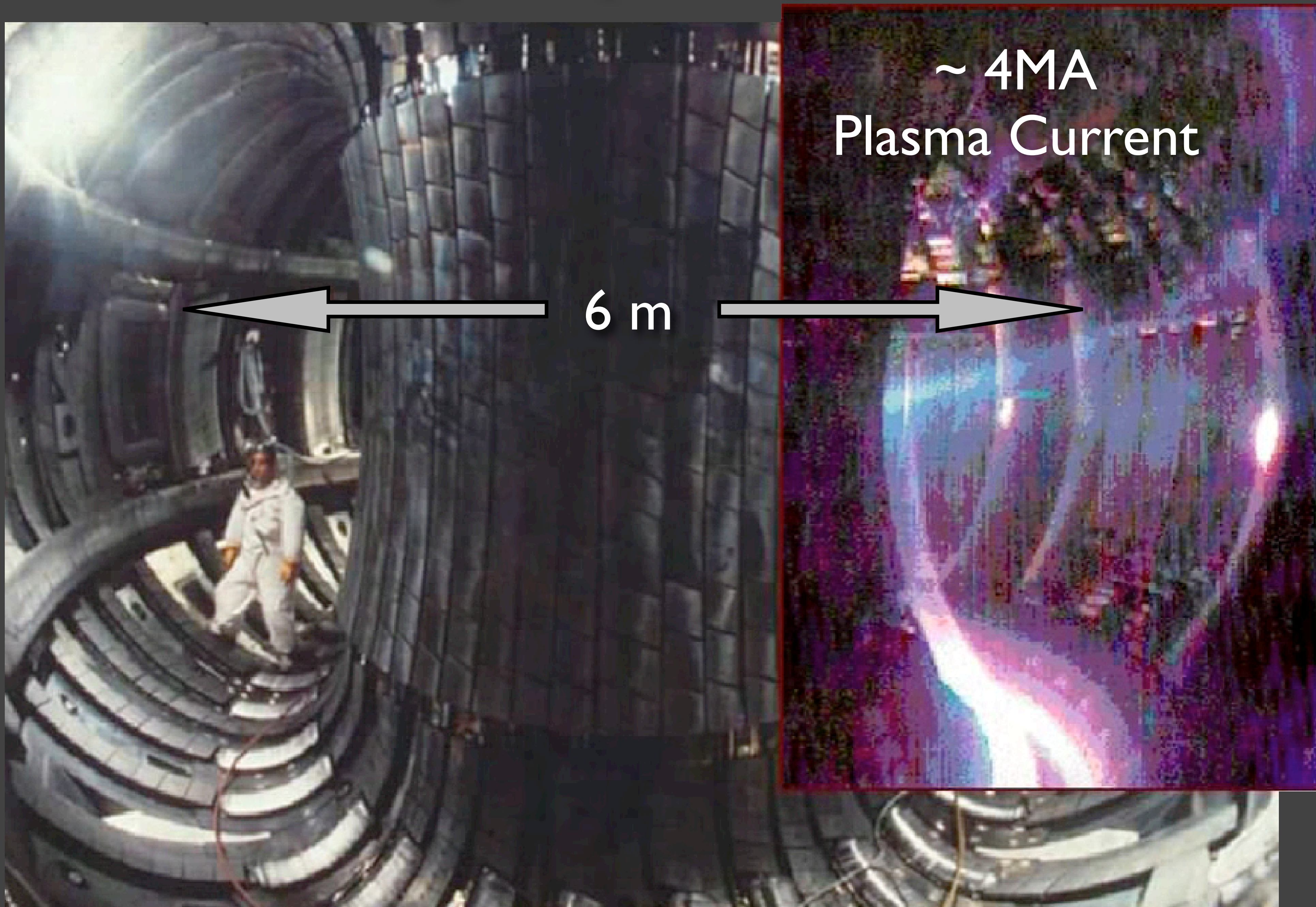


Can Fusion be "Green" Nuclear Power?

- No public evacuation plan. Low tritium inventory. Max offsite dose <1 rem; public and worker safety is assured in all events.
- No long term storage of radioactive material.
- While international inspection/monitoring will still be required, **fusion does not need any fertile/fissile material.**
- *Work still needed to demonstrate safety and environmental advantages of fusion…*

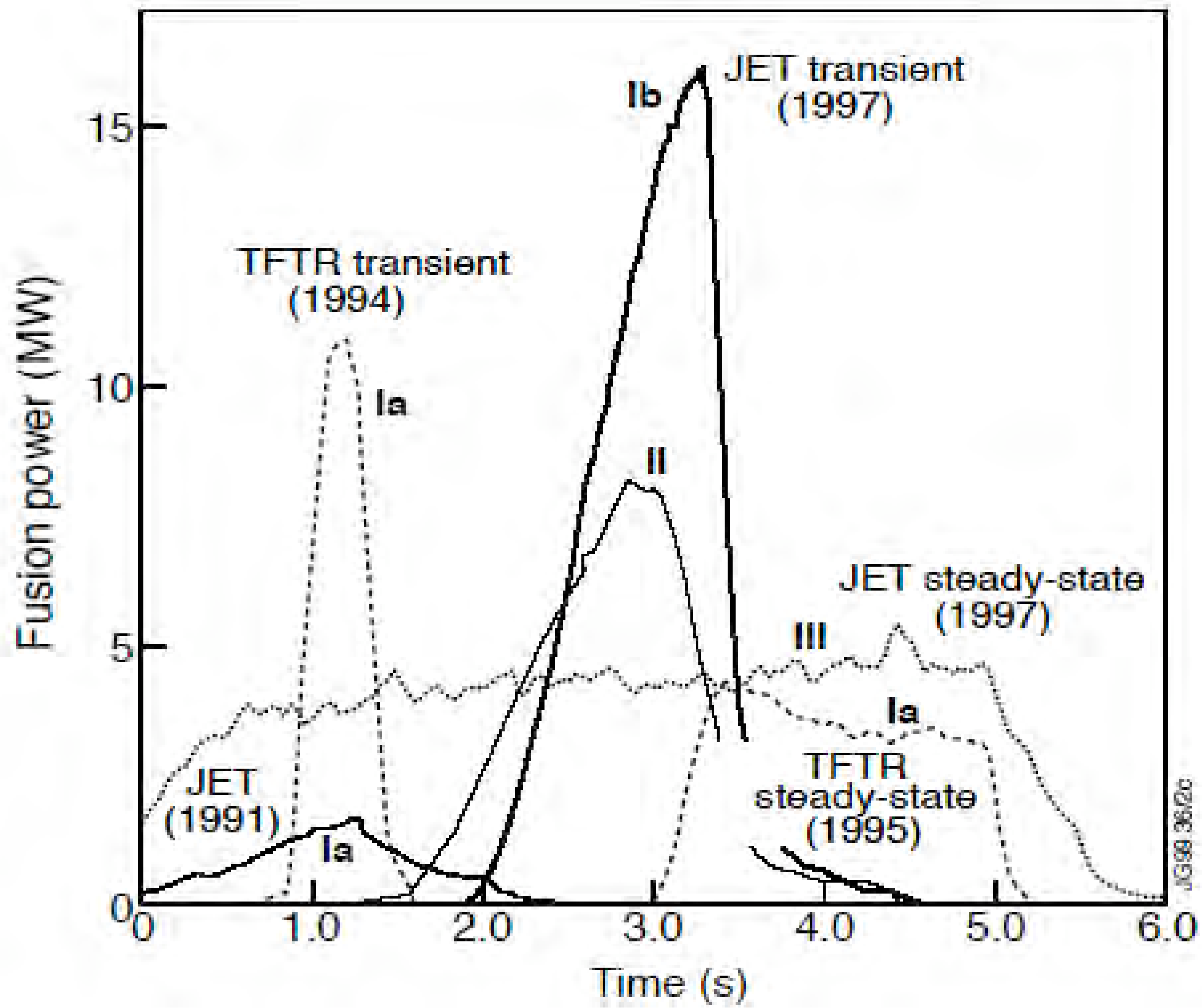

T-3 (1968)
~ 0.06 MA
Plasma Current
2 m
First high-temperature (~10,000,000°) confined plasma!
(Relatively easy to construct and to achieve high-performance.)

JET (1997)



Significant Fusion Power already Produced in the Lab

- ✓ 2.5 MW/m^3 achieved in TFTR!
- ✓ Establishes basic "scientific feasibility", *but power out < power in.*
- Fusion self-heating, characteristic of a "burning plasma", has yet to be explored.
- The technologies needed for net power must still be demonstrated.



Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines), in different regimes:

(Ia) Hot-Ion Mode in limiter plasma; (Ib) Hot-ion H-Mode;

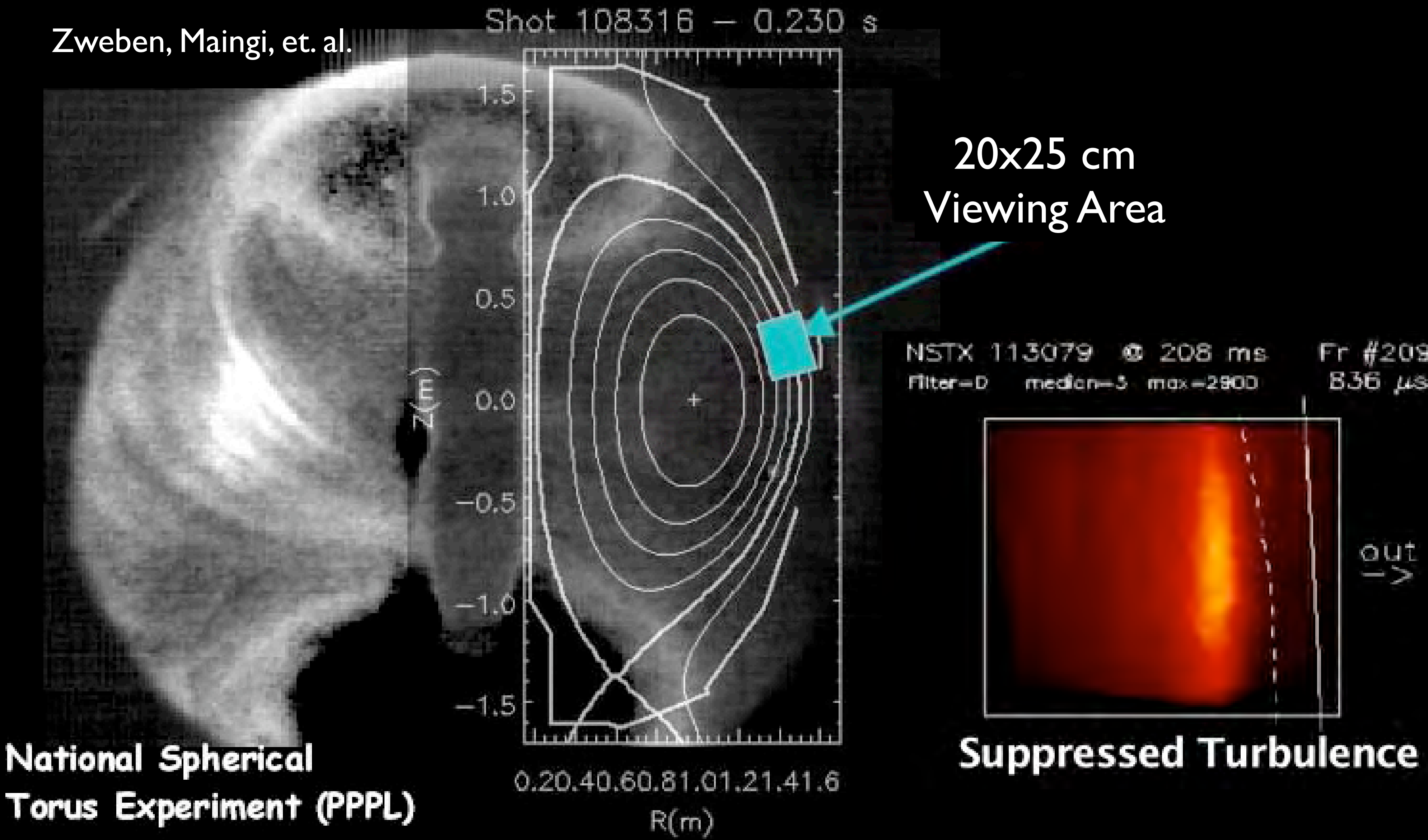
(II) Optimized shear; and (III) Steady-state ELMY-H Modes.

Fusion Science Research Today

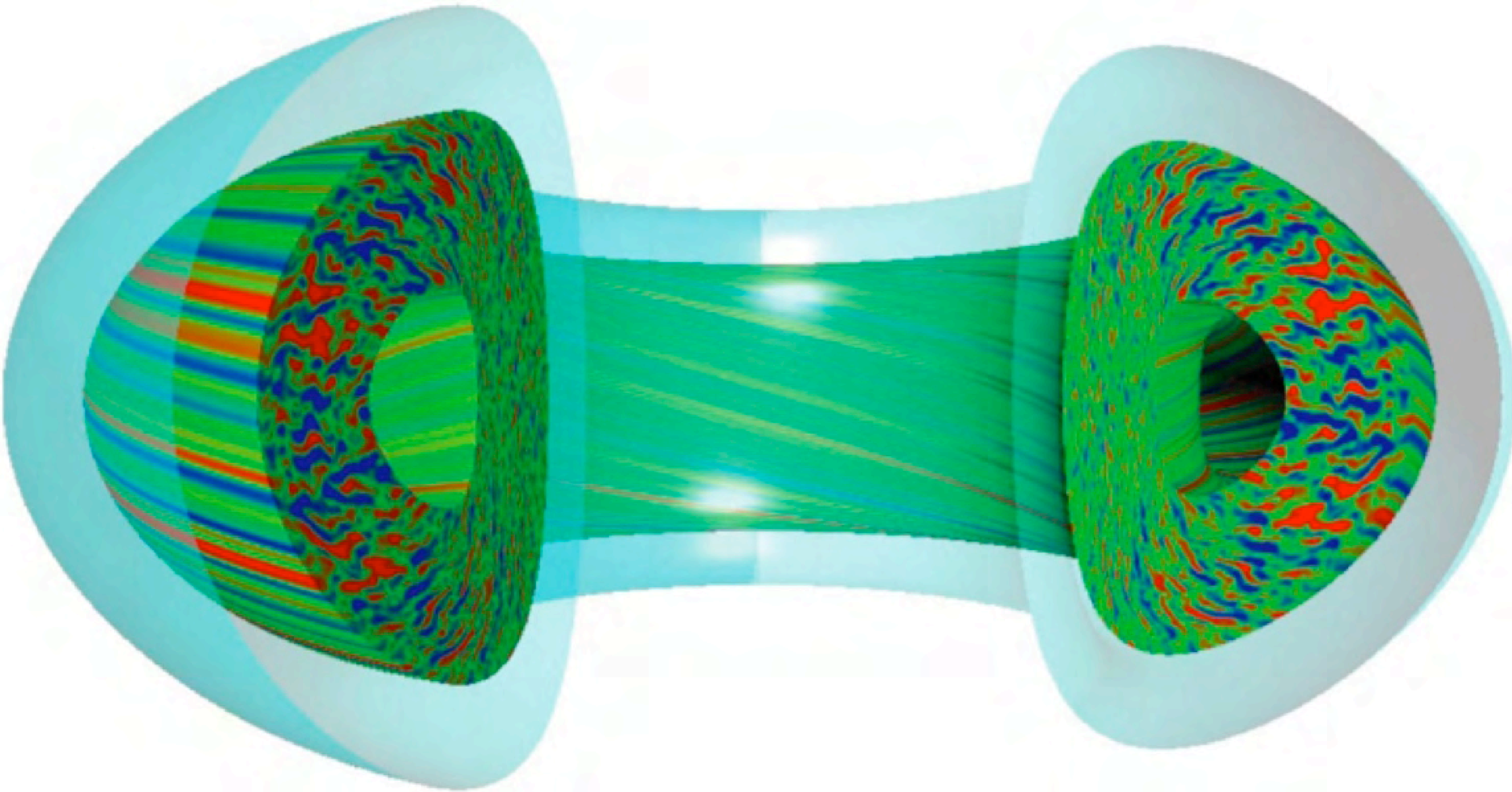
- Understand confined high-temperature matter
- Optimize and control the fusion configuration
- Answer pressing questions for ITER's "Burning Plasma" physics studies

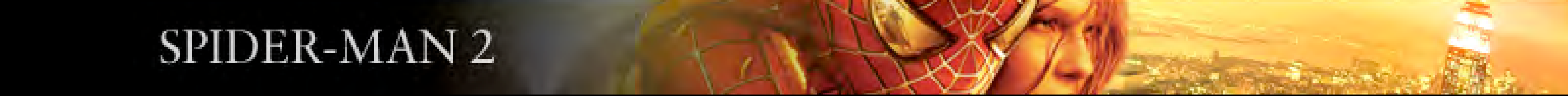
Viewing the Turbulence "Transport Barrier"

Zweben, Maingi, et. al.



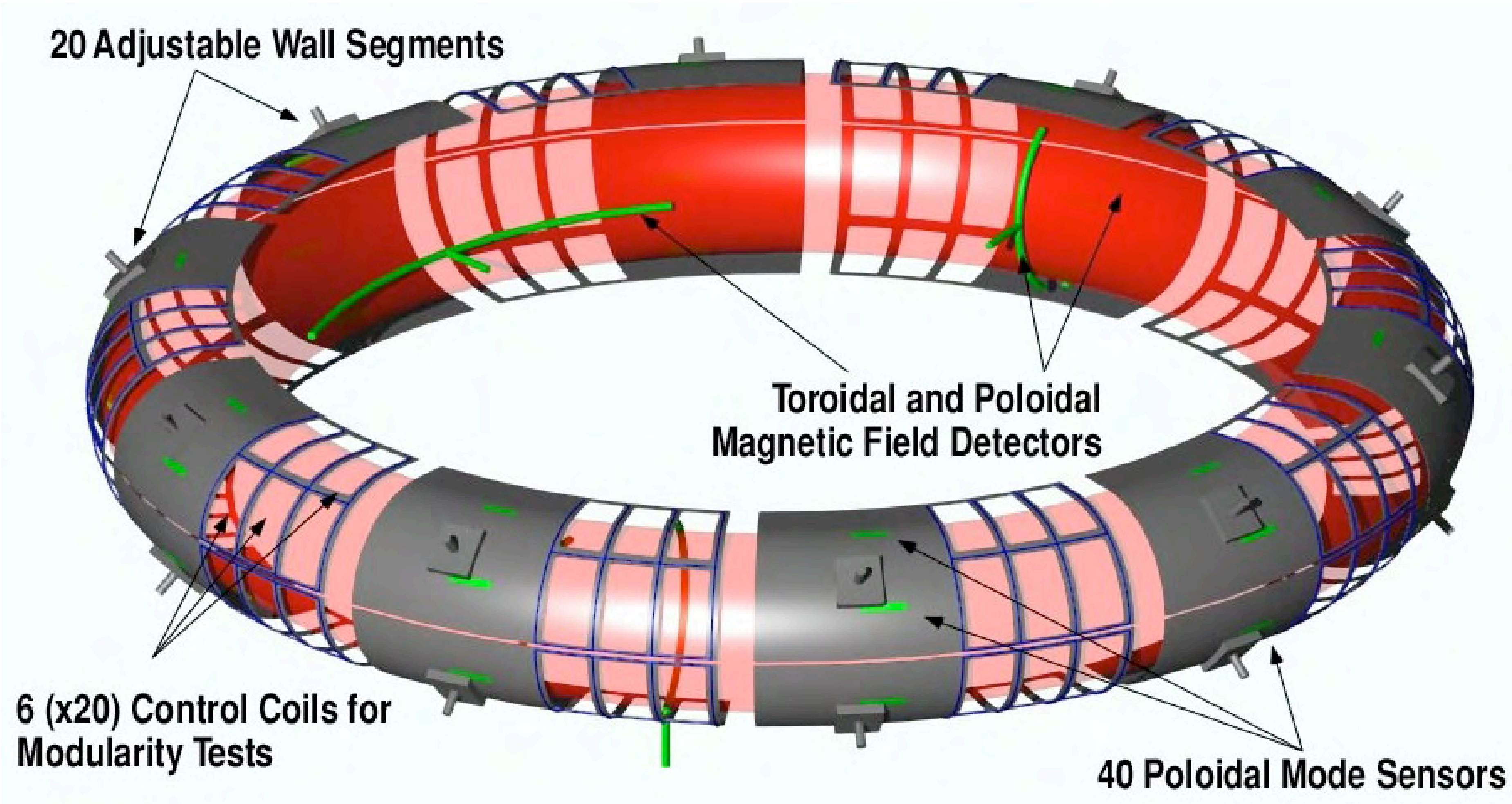
Measurement ⇔ Theory ⇔ Simulation





Dr. Otto Octavius Fails to Stabilize Fusion in NYC…

Magnetic Sensors and Controllers



Three Examples: Experiments to Understand and Test New Confinement Options…

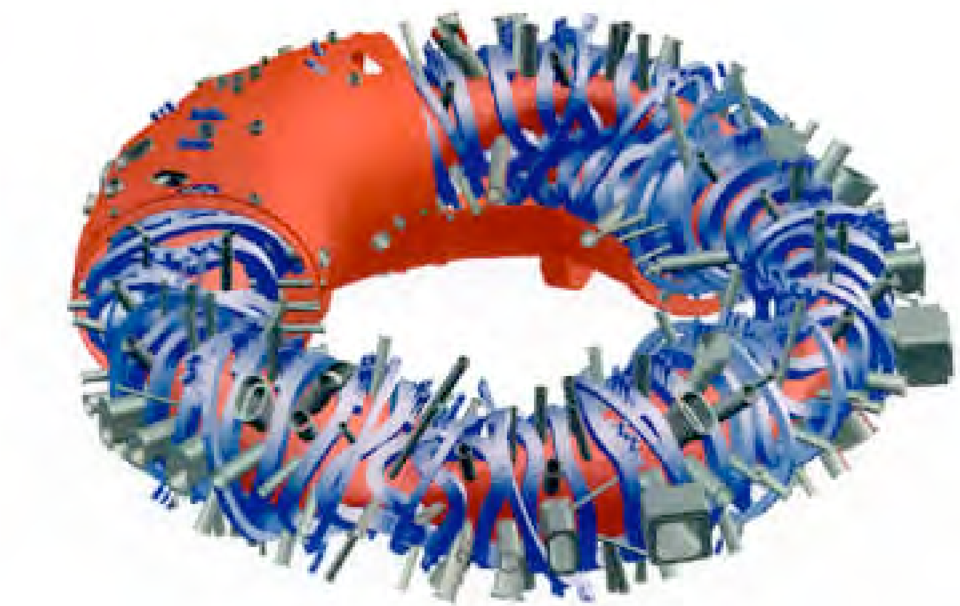
- **Japan**: Large Helical Device
- **Germany**: Twisted coils to confine without plasma current
- **USA**: Levitated dipole experiment to investigate "tritium-free" fusion

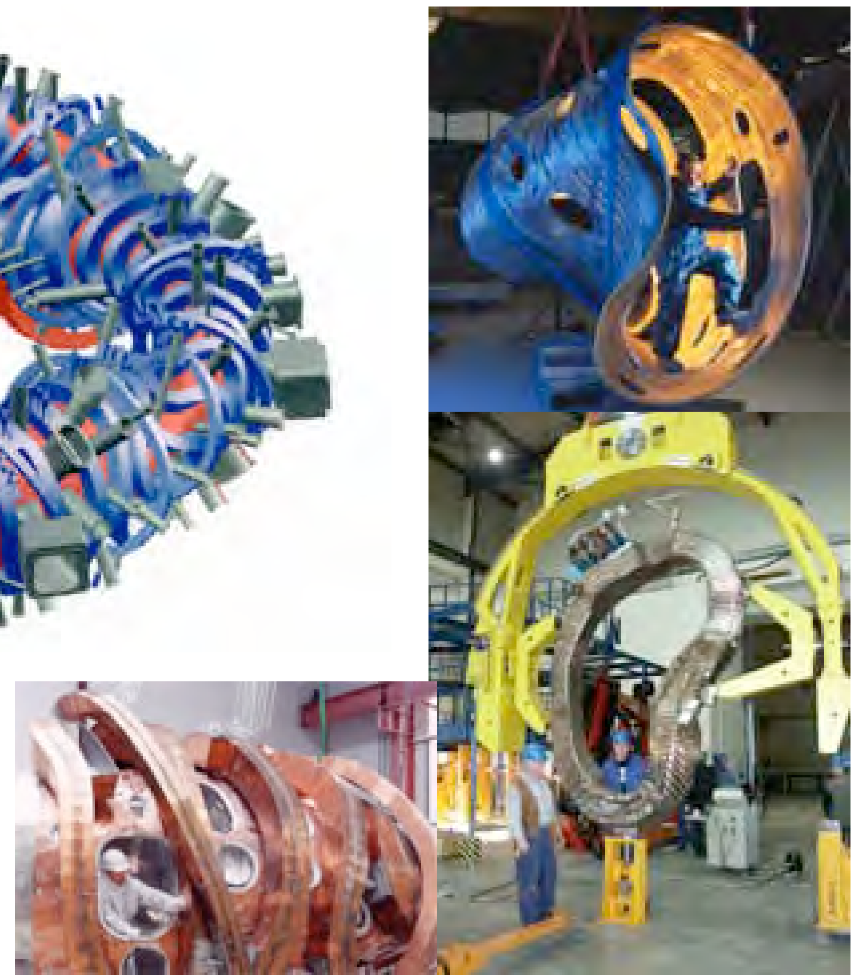
Large Helical Coil Device

(**Japan**) Large superconducting helical coils eliminates the need for plasma current drive and achieves steady plasma confinement.

Configuration Optimization

"Twisted coils" achieve good confinement without plasma current and without driven plasma controls. *New experiments…*

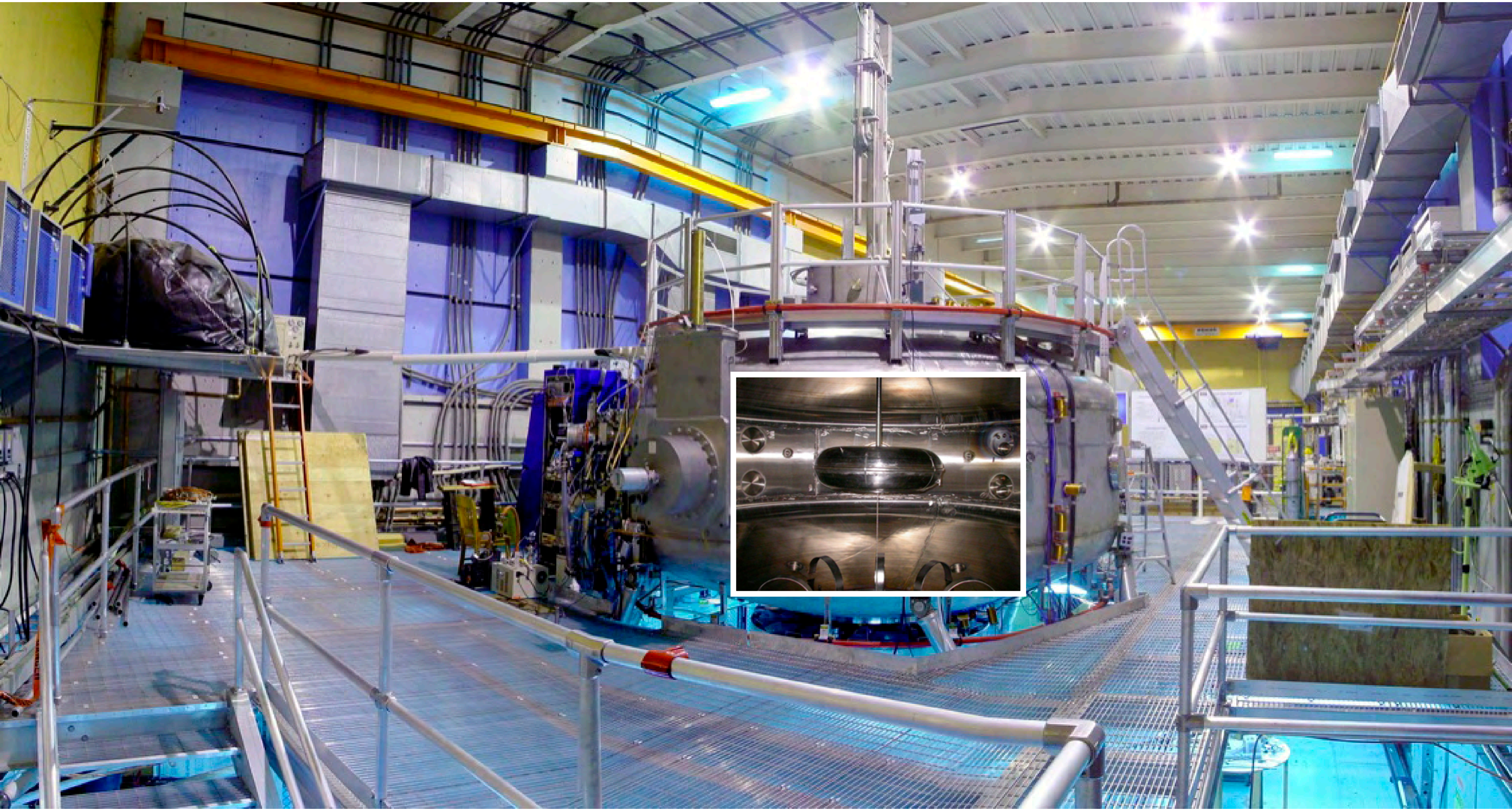


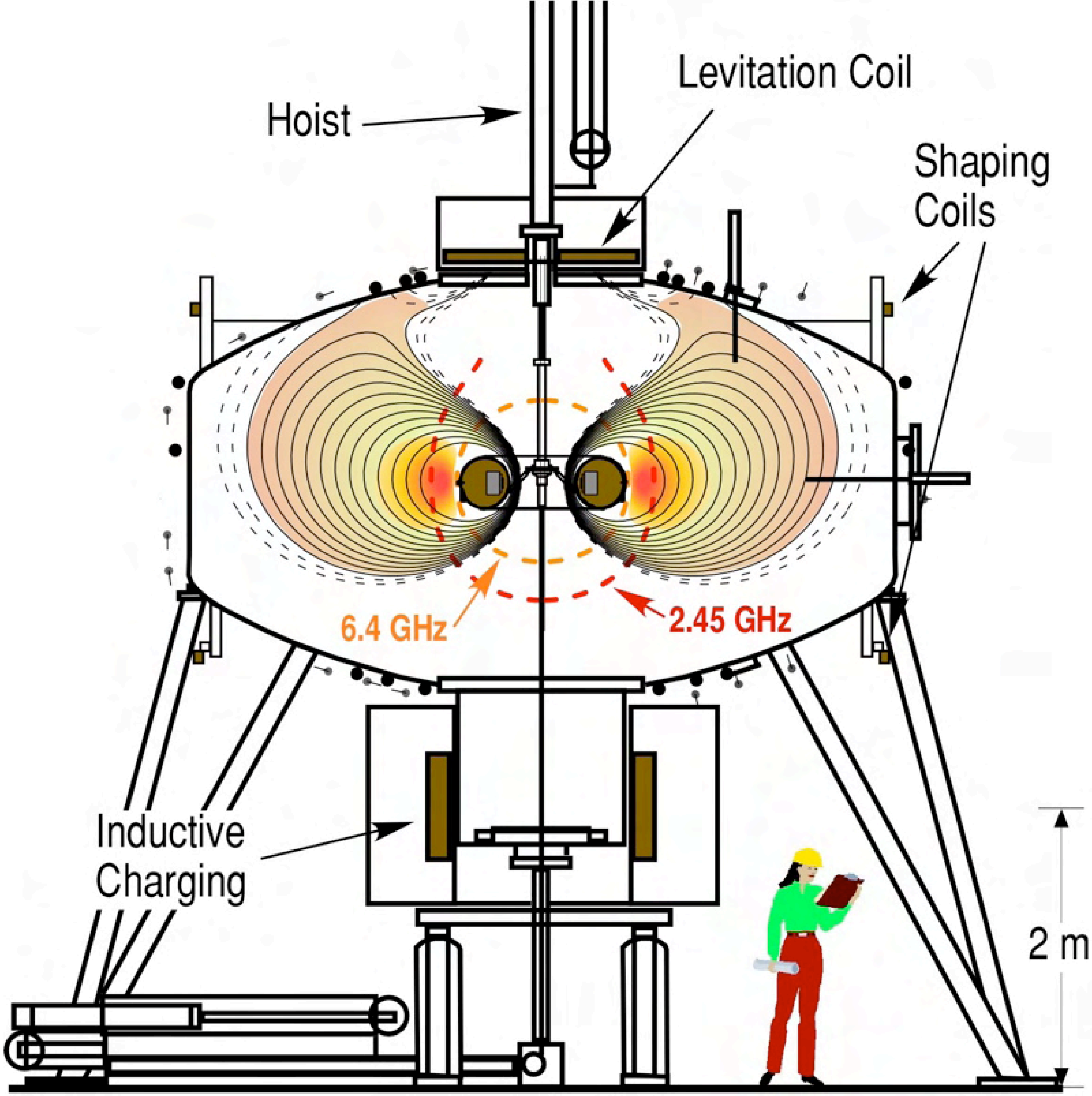


Now under construction…

Levitated Dipole Experiment

MIT-Columbia University

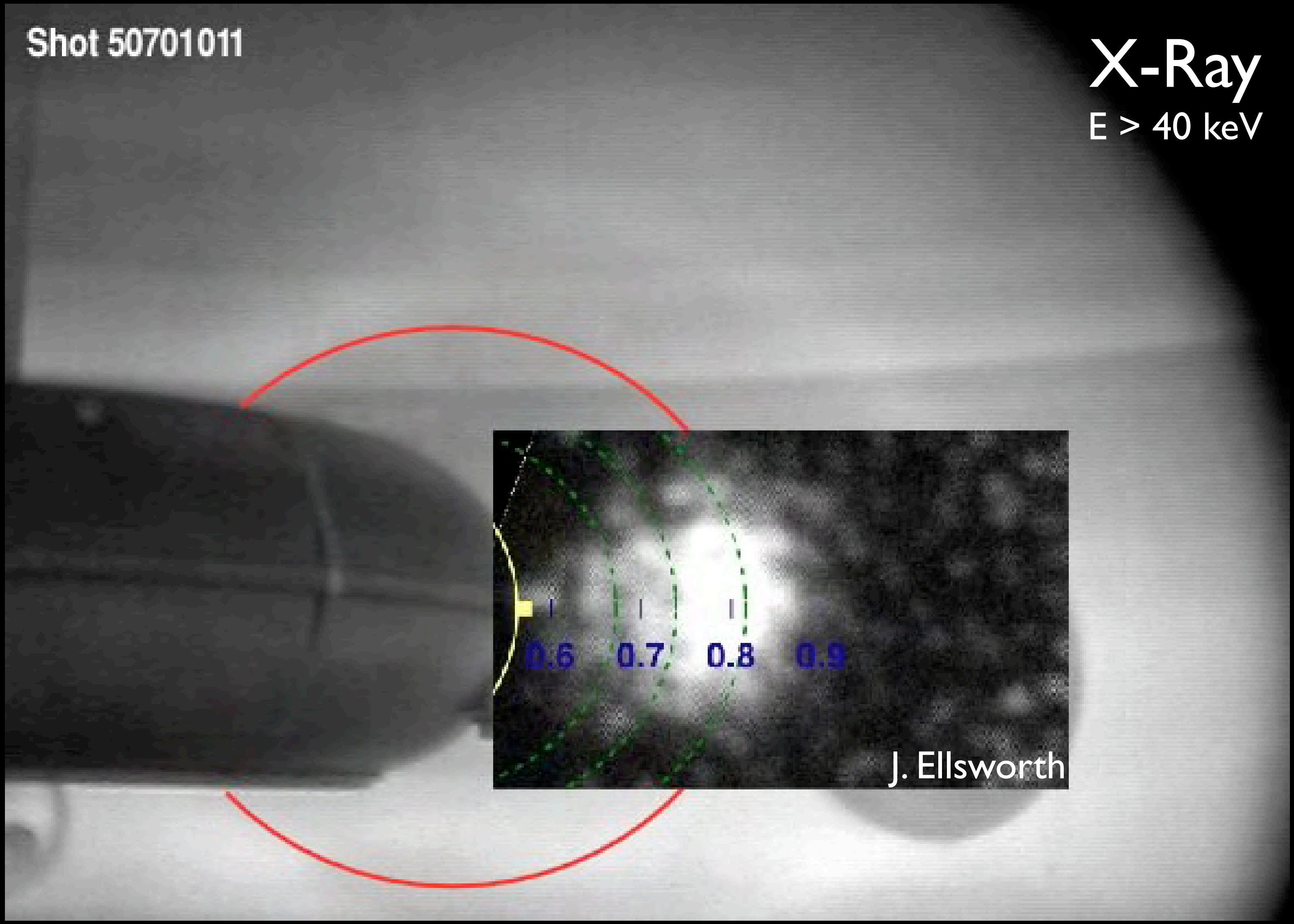




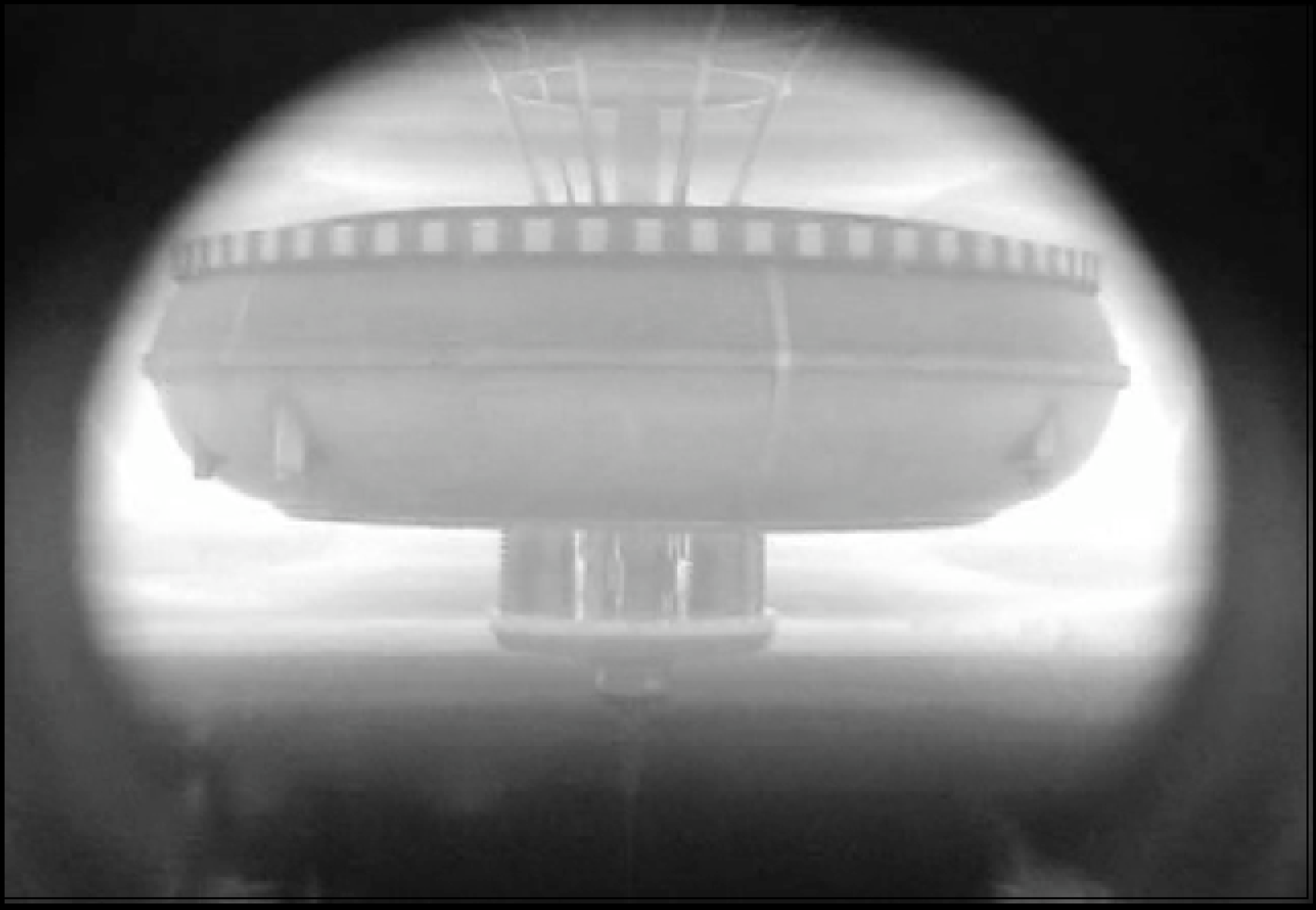
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Characterizing the High-β Plasma



LDX Plasma



International Thermonuclear Experimental Reactor

Europe, Japan, U.S., Russia, South Korea, China, India
http://www.iter.org/

2006 Global Energy Prize

Evgeniy Velikhov

Yoshikawa Masaji

Robert Aymar

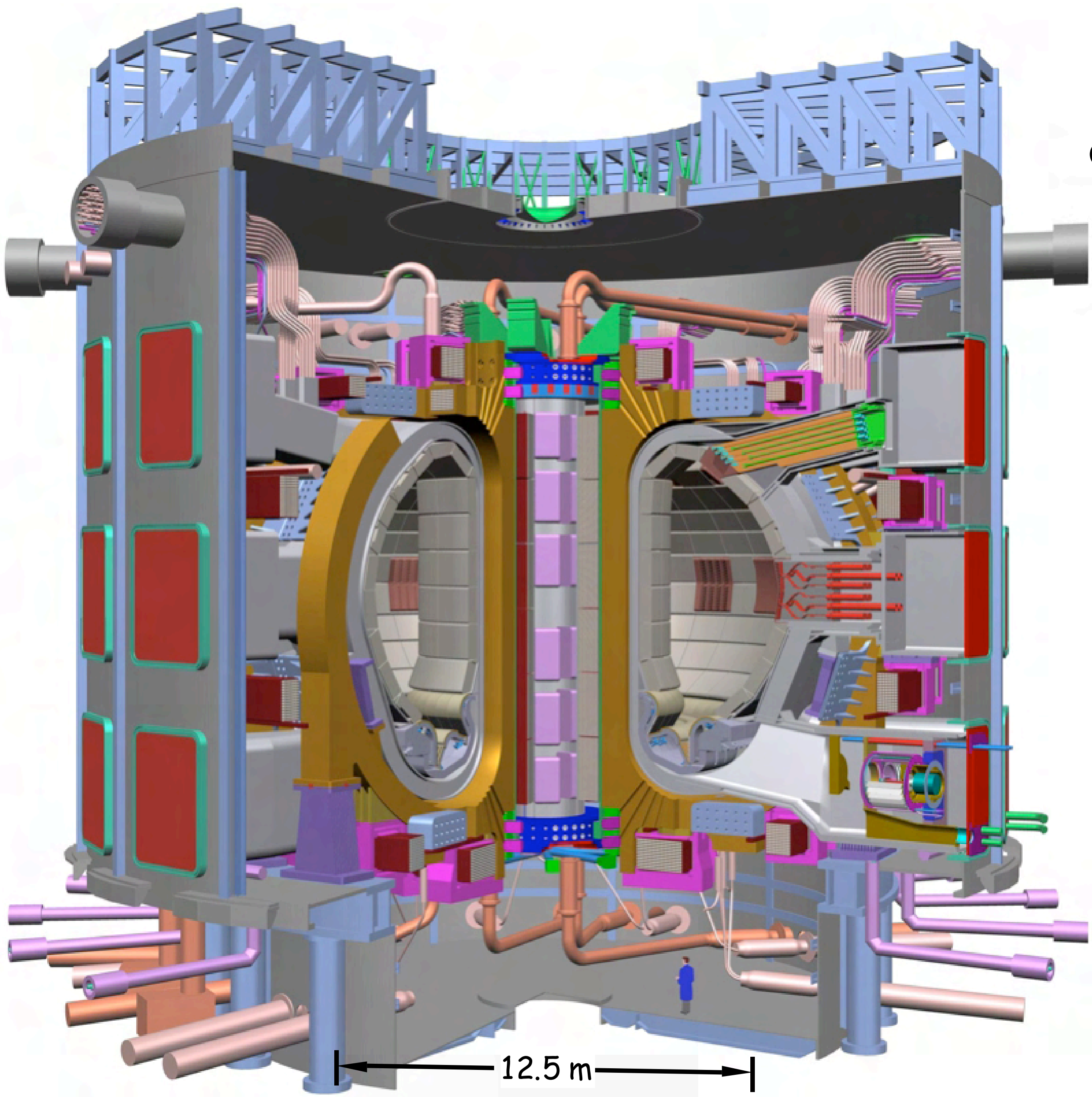
For the development of scientific and engineering foundation for building the International Thermonuclear Experimental Reactor (ITER) Project

ITER Agreement Signed
November 21, 2006

Burning Plasma Experiment

- Demonstrate and study strong fusion self-heating in near steady-state conditions:
  - Strongly self-heating:
    - 500 MegaWatts; Fusion power gain ~ 10
    - ~ 70 % self-heating by fusion alpha particles
  - Near steady state:
    - 300 to > 3000 seconds; Many characteristic physics time scales
    - Technology testing
    - Power plant scale
- Numerous scientific experiments and technology tests.
- Demonstrate the **technical feasibility** of fusion power.

ITER: The International Burning Plasma Experiment



World-wide effort:
Europe, Japan, Russia, U.S.,
China, South Korea, India …

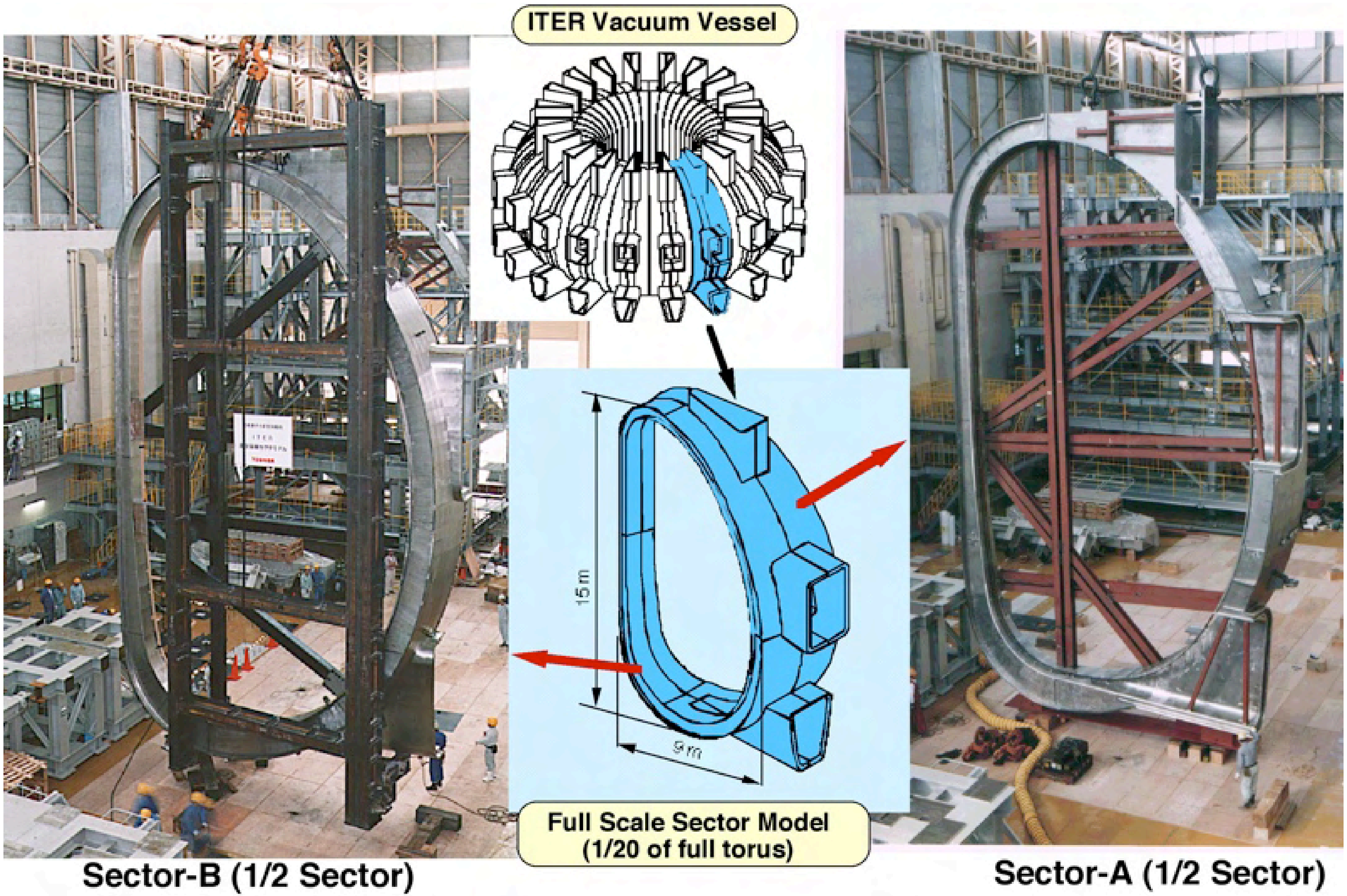
Physics

Technology
Testing

Built at fusion power scale, but without low-activation fusion materials

18,000 tonne (about US$11B)

Benefits from Comprehensive Component R&D

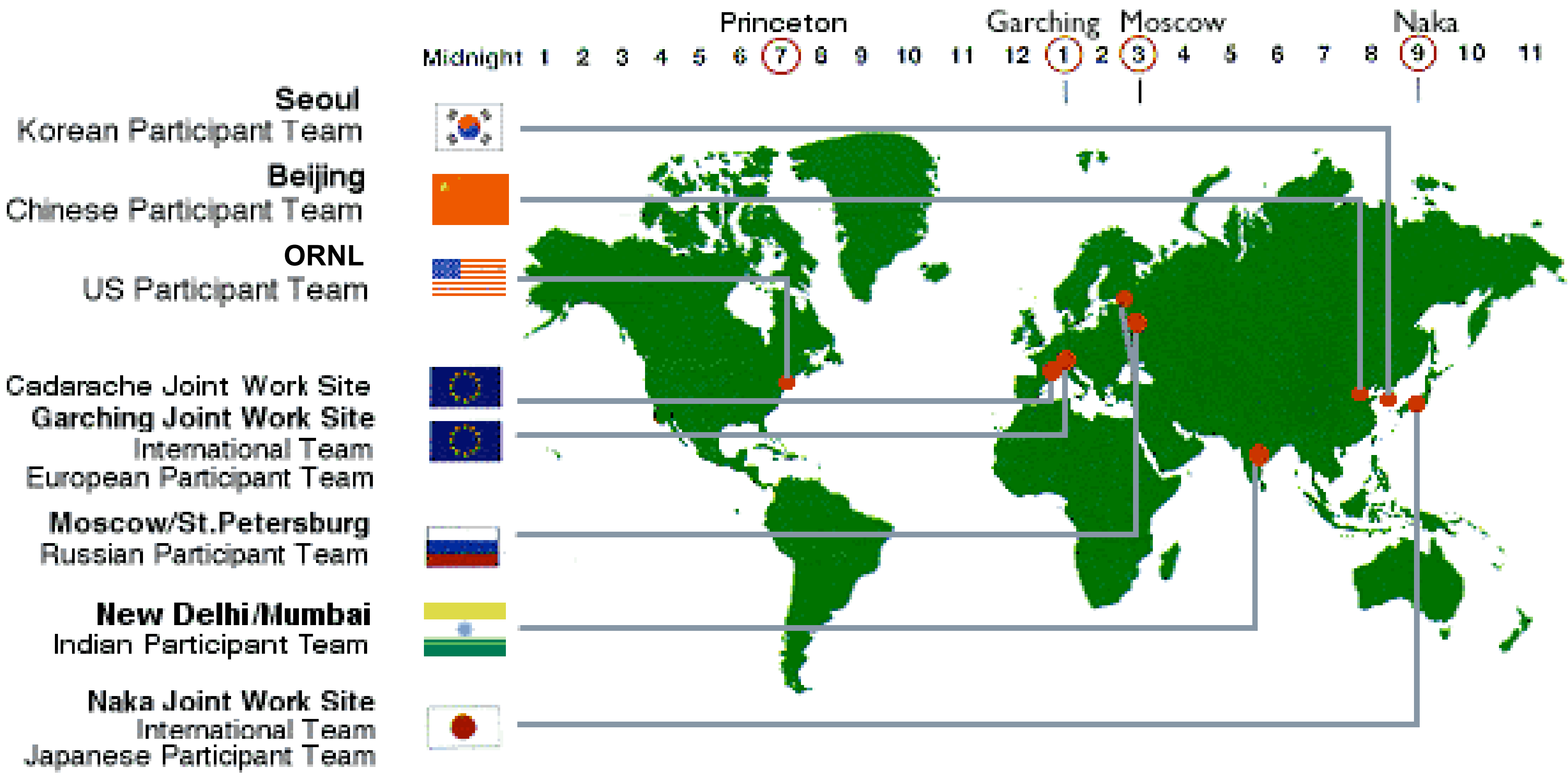


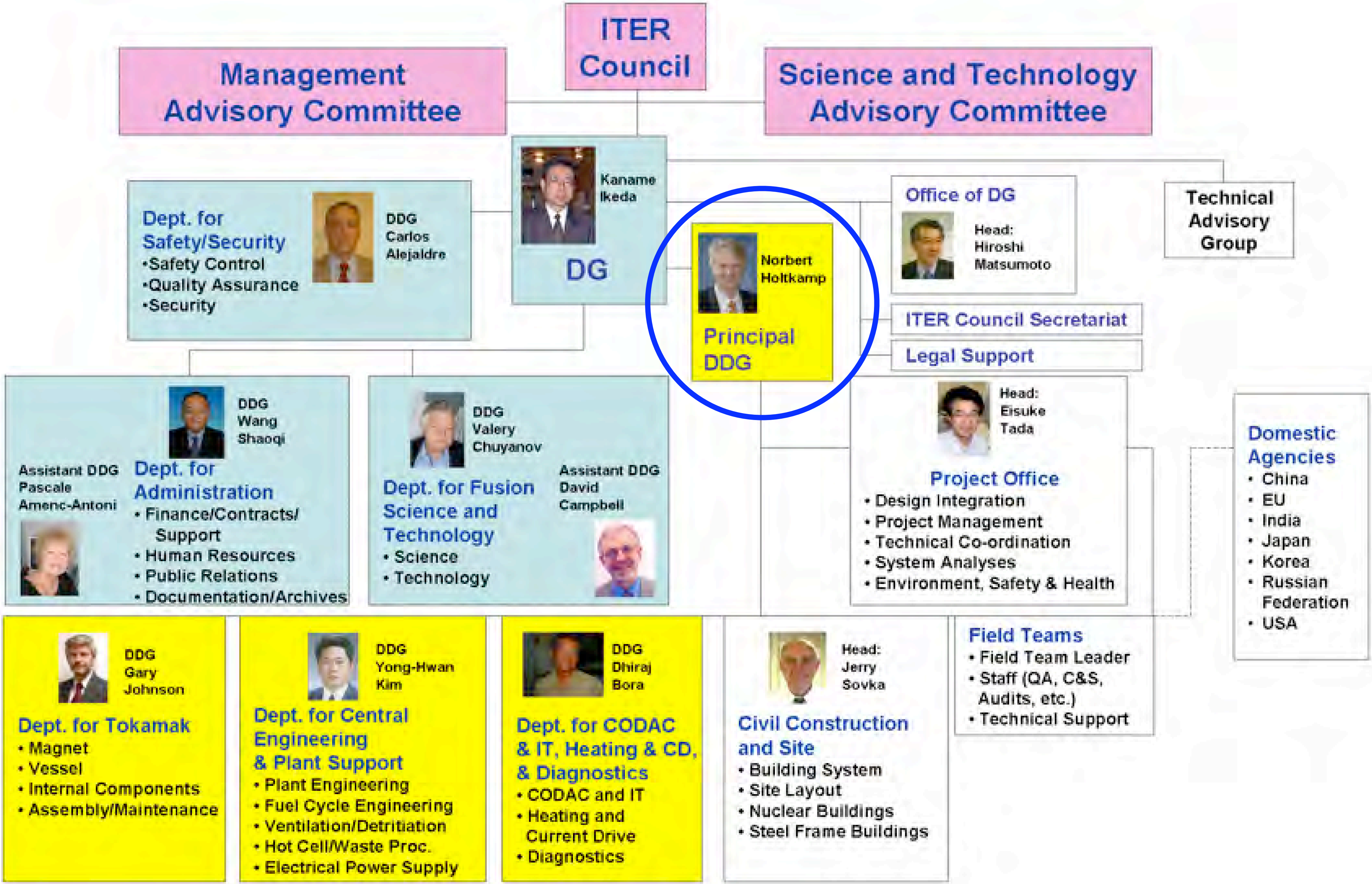
View of full-scale sector model of ITER vacuum vessel completec
in September 1997 with dimensional accuracy of ± 3 mm

Benefits from Comprehensive Component R&D

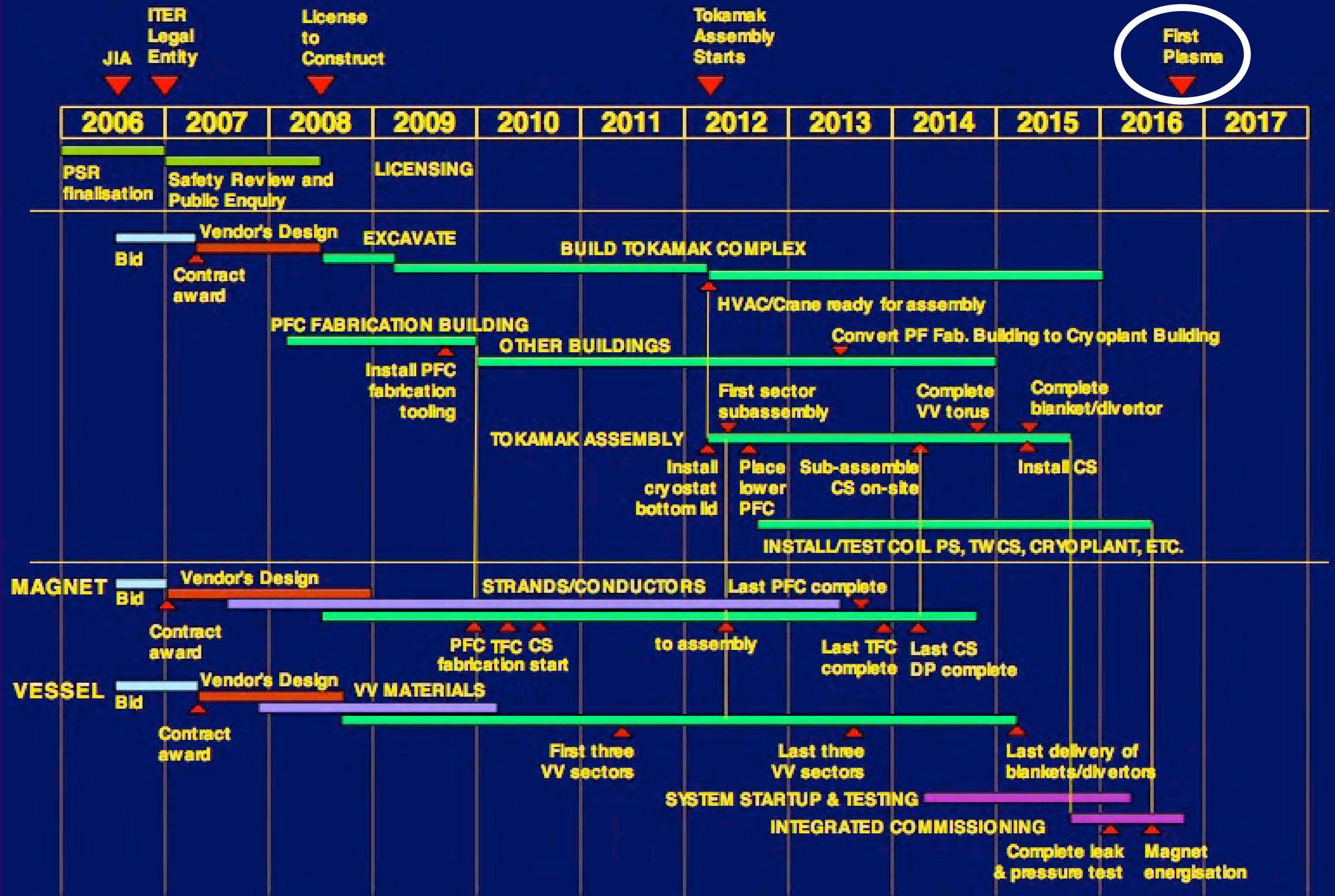
Largest High-Field Superconducting Magnet is World: 640 MJ and 13T!

Coordinating an International Team




ITER Council
Management Advisory Committee
Science and Technology Advisory Committee
Kaname Ikeda
DG
Technical Advisory Group
Dept. for Safety/Security
•Safety Control
•Quality Assurance
•Security
DDG Carlos Alejaldre
Norbert Holtkamp
Principal DDG
Office of DG
Head: Hiroshi Matsumoto
ITER Council Secretariat
Legal Support
Assistant DDG Pascale Amenc-Antoni
DDG Wang Shaoqi
Dept. for Administration
• Finance/Contracts/ Support
• Human Resources
• Public Relations
• Documentation/Archives
DDG Valery Chuyanov
Dept. for Fusion Science and Technology
• Science
• Technology
Assistant DDG David Campbell
Head: Eisuke Tada
Project Office
• Design Integration
• Project Management
• Technical Co-ordination
• System Analyses
• Environment, Safety & Health
Domestic Agencies
• China
• EU
• India
• Japan
• Korea
• Russian Federation
• USA
DDG Gary Johnson
Dept. for Tokamak
• Magnet
• Vessel
• Internal Components
• Assembly/Maintenance
DDG Yong-Hwan Kim
Dept. for Central Engineering & Plant Support
• Plant Engineering
• Fuel Cycle Engineering
• Ventilation/Detritiation
• Hot Cell/Waste Proc.
• Electrical Power Supply
DDG Dhiraj Bora
Dept. for CODAC & IT, Heating & CD, & Diagnostics
• CODAC and IT
• Heating and Current Drive
• Diagnostics
Head: Jerry Sovka
Civil Construction and Site
• Building System
• Site Layout
• Nuclear Buildings
• Steel Frame Buildings
Field Teams
• Field Team Leader
• Staff (QA, C&S, Audits, etc.)
• Technical Support

ITER Schedule



John Holdren's AAAS Presidential Lecture (February 2007)

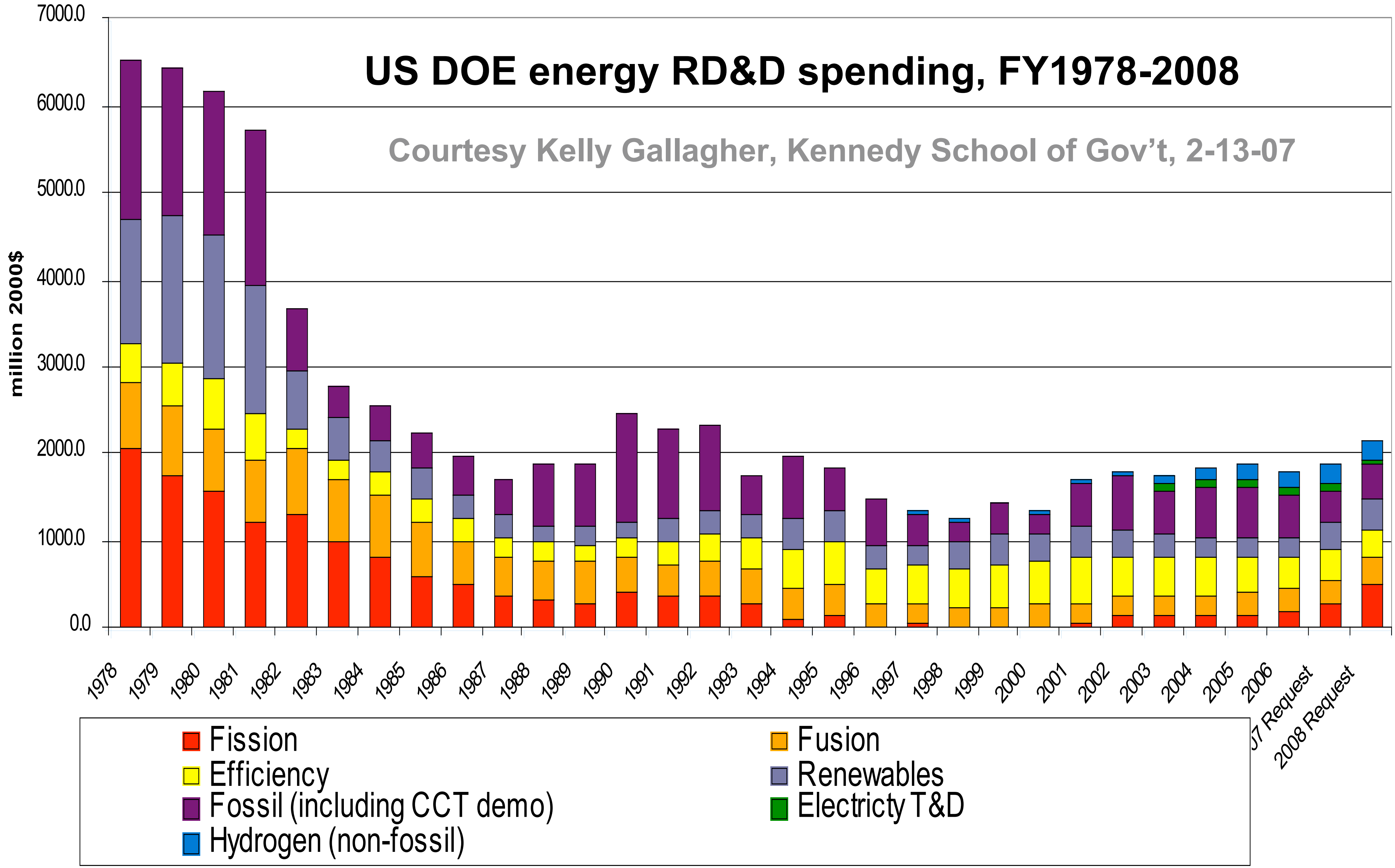
Four Key S&T Challenges

- Meeting the basic needs of the poor
- Managing competition for land, soil, water, and the net productivity of the planet
- Mastering the energy-economy-environment dilemma
- Moving toward a nuclear-weapon-free world

And the biggest challenge:

"Providing the affordable energy needed to create and sustain prosperity without wrecking the global climate with carbon dioxide emitted by fossil-fuel burning."

U.S. Energy R&D (30 y)



U.S. Energy R&D (PCAST97)

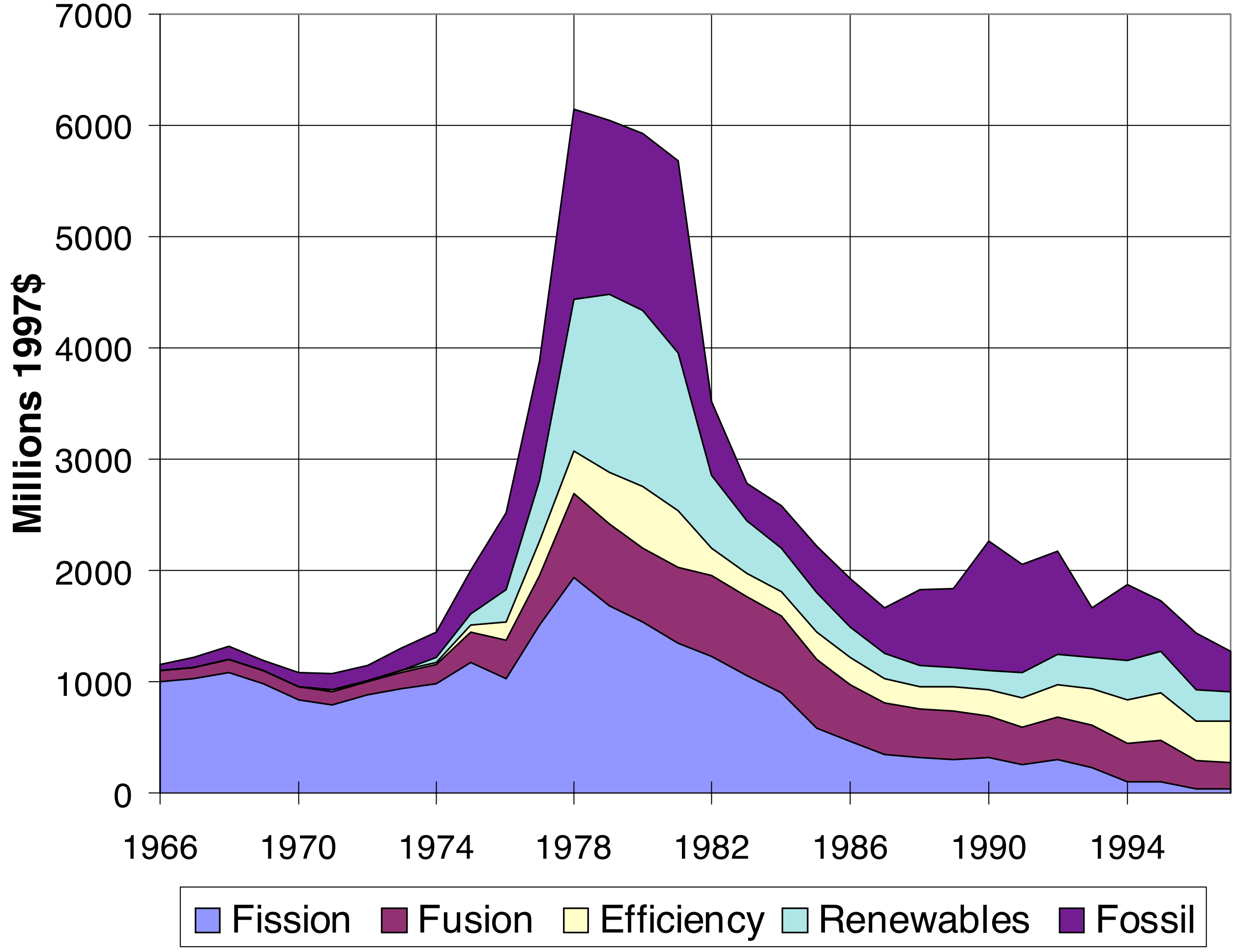


Figure 2.7: Energy technology R&D budget authority of DOE and predecessor agencies, 1966 to 1997. Source: DOE.

Summary

- Fusion promises nearly unlimited carbon-free energy.
- Tremendous progress has been made both in understanding and in fusion parameters.
- Attractive and economical fusion power plants exist (*on paper!*) that require aggressive R&D programs.
- With the construction of NIF and the world-wide effort to construct ITER, there is a great opportunity to accelerate fusion research.
- Successful R&D and aggressive implementation will allow fusion to contribute to world energy needs.