Fusion Energy in a Non CO_2 Emitting Energy Portfolio

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Energy for a Future without Carbon Emission
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Abstract

Fusion has the potential to provide essentially inexhaustible, non-CO^2 emitting energy with low land-use costs and low nuclear materials risks. With a sustained and strong international research program, fusion development scenarios suggest several TW of fusion power could be available within the present century. This presentation will describe the scientific and technical issues facing fusion researchers in realizing the potential of fusion, highlight the recent advances and progress in fusion experiments, and overview international plans for the demonstration of fusion energy technology. Fusion energy involves high-temperature ionized gas, called plasma, that is heated to more than 170 million degrees so that isotopes of hydrogen can combine to create helium and release nuclear energy. The 33 g of natural deuterium present in every ton of water yields an energy-equivalent of more than 400 tons of oil. The challenge facing fusion scientists is two-fold: (1) the hot plasma must be suspended long enough for fusion reactions to occur, and (2) the fusion confinement device must be configured to be reliable and economically attractive. The most successful approach to date uses strong magnetic fields to create a toroidal magnetic bottle that allows the ionized gas to circulate for many 10's of km and to generate fusion energy at a power density that has already exceeded that produced in the sun by more than 40,000 times. Perhaps the most significant scientific advance in fusion research is the so-called "transport barrier". Plasma turbulence that normally mixes cold plasma (at the edge) with the confined hot plasma is suppressed spontaneously by the appearance of differential bands of plasma flow. Plasma created in this high-confinement mode could serve as the basis for the next-step burning plasma experiment, called ITER, that is being proposed to be built internationally to study fusion energy production at the scale of future power plants. An international "fast-track" to fusion energy has been proposed that coordinates research results from the ITER experiment with experiments to understand (1) material properties in the fusion environment, (2) techniques to sustain and control plasma configuration, and (3) the fundamental properties of high-temperature matter that is self-heated through fusion reactions.

Why Fusion Energy Science?

- Basic science and technology to understand the high-temperature plasma state of matter
- National defense
- Energy potential…
  - **Inexhaustible**: “unlimited” fuel and available to all nations; Low land-use costs
  - **Clean**: no greenhouse gases nor air pollution; Storage of short-lived radioactive components.
  - **Safe**: no catastrophic accidents; Low-risk for nuclear materials proliferation

Today is an Exciting Time for Fusion

- Tremendous progress in *understanding* how to confine & control high-temperature matter, e.g.
    - Increasing pressure by shaping magnetic fields
    - Suppression of some forms of turbulence
- First light achieved at NIF (inertial fusion)
- International commitment (a.k.a competition!) to build ITER: the first burning plasma experiment at the scale of a power plant and *the world's largest scientific partnership to develop carbon-free energy.*

Outline

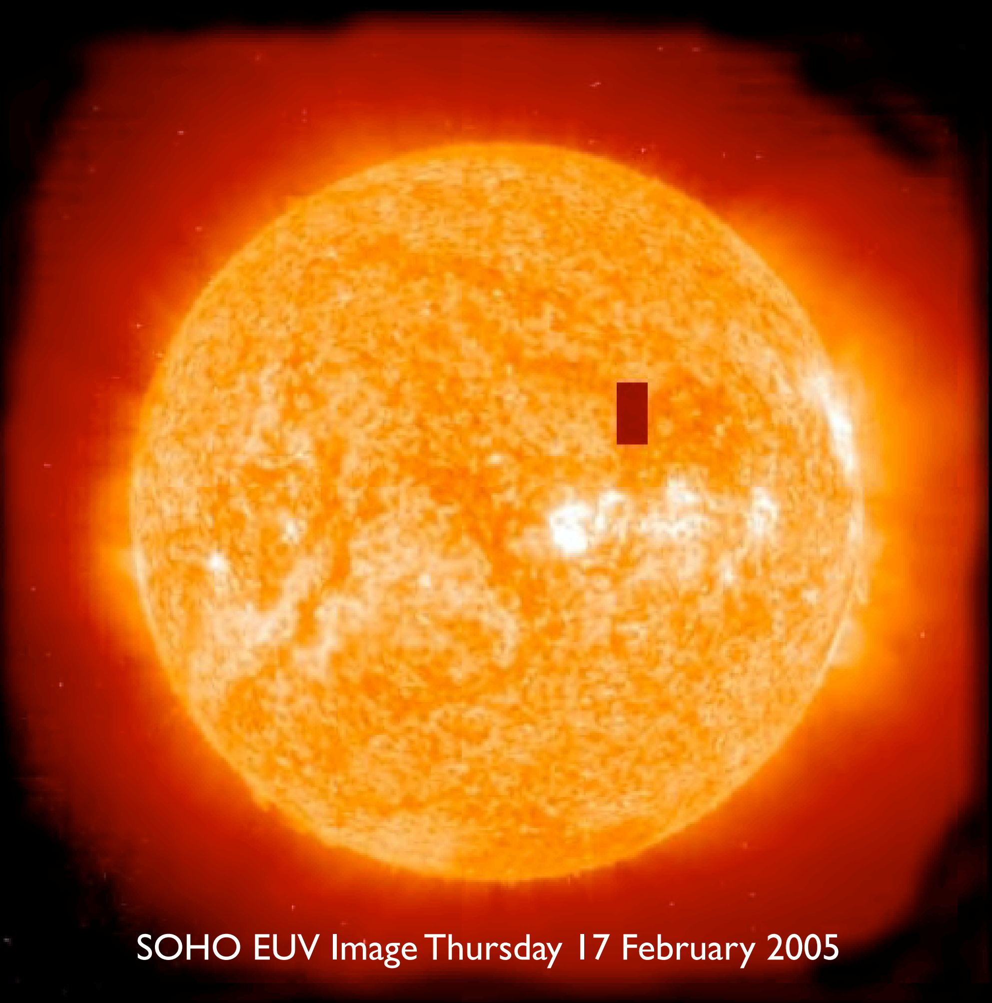
- Fusion Primer
- Power Configurations
- Progress
- Next steps in Magnetic Fusion Energy (MFE)
- International Plans for Fusion Power

Fusion Primer

- Fusion is the **joining** of two light nuclei into a heavier nucleus releasing tremendous energy.
- Fusion of a drop of water (1 g) into iron releases energy equivalent to 75 barrels of oil!
- The catch: Fusing nuclei have **positive** electrical charge and strongly repel each other.
- The easiest nuclei to fuse (at the lowest temperatures) have the smallest electrical charge:
  - **Hydrogen** ($Z = 1$): Requires temperature ≈200,000,000°
  - **Neon** ($Z = 10$): Requires temperature ≈10,000,000,000°

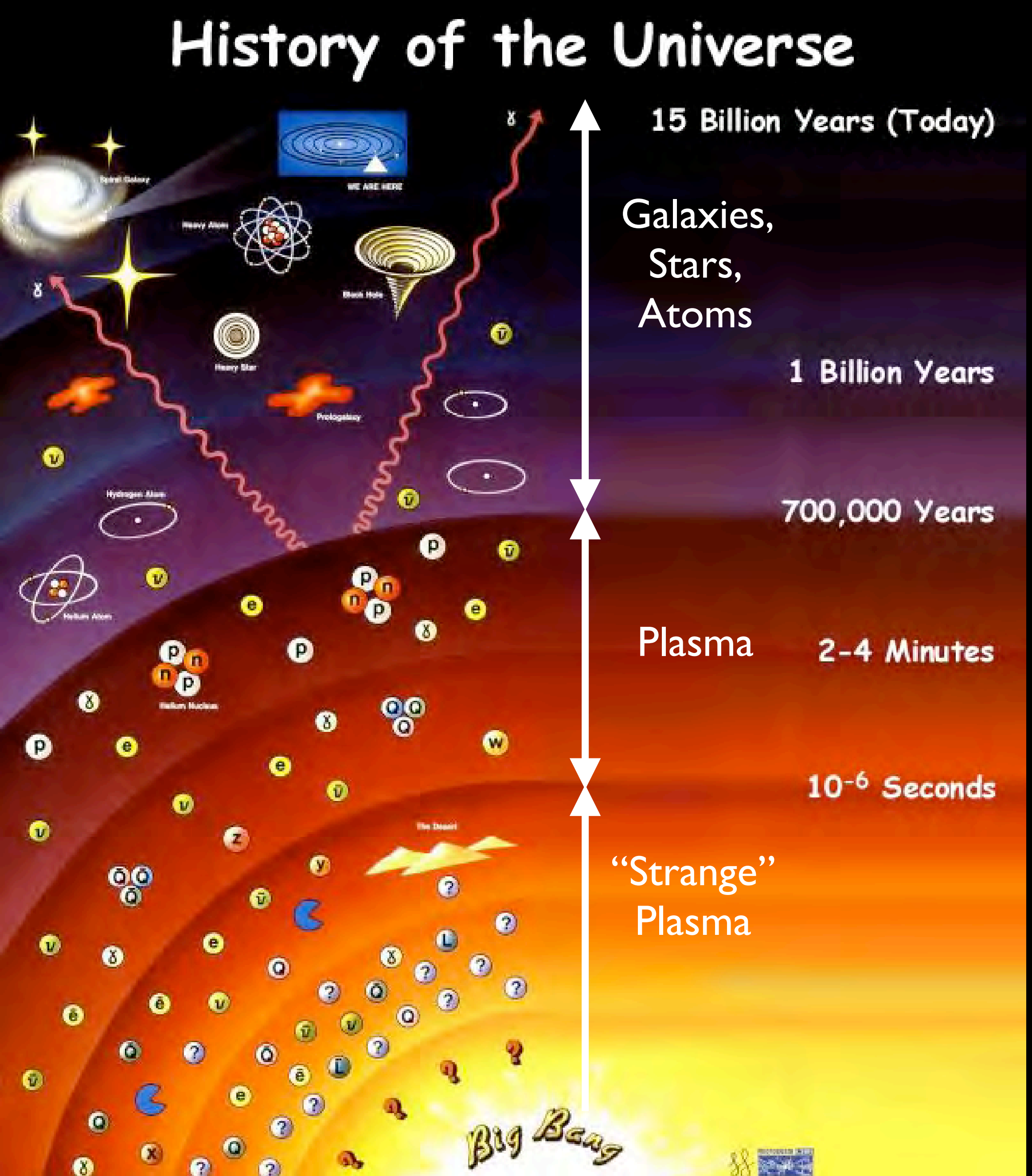
Fusion in our Sun

- 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: Nature's Gift from the "Big Bang"!

- After the "Age of Fusion", the Universe consists of hydrogen (90%), ^{4}He (9%), D (0.02%), ^{3}He (0.01%) and a pinch of Li.

- 1 g of D yields 4 MW-days (4 times 1 g U^{235})

- 4.5 g of D in every barrel of water!
(1 barrel H_20 ⇒ 400 barrels of Oil)

Tritium (^3H) and ^3He are Even More Reactive than Deuterium (^2H)

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

$$D + \mathbf{{}^3He} \rightarrow {}^4He\ (3.6\ MeV) + p\ (14.7\ MeV)$$

- However, *no T and ^3He resources exist on earth!*
- Tritium must be created either from
  - Splitting Lithium with neutrons (easiest) or
  - Deuterium fusion (harder)

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

$$\mathrm{D} + {}^6\mathrm{Li} + f \times [{}^9\mathrm{Be}] \ (\text{with } f \ll 1)$$

Fast n

$$\begin{aligned} &\textit{Plasma}: & \mathrm{D} + \mathrm{T} &\rightarrow {}^4\mathrm{He}\,(3.5\mathrm{MeV}) + \mathrm{n}\,(14.1\mathrm{MeV}) \\ &\textit{Blanket}: & {}^6\mathrm{Li} + \mathrm{n} &\rightarrow {}^4\mathrm{He}\,(2.05\mathrm{MeV}) + \mathrm{T}\,(2.73\mathrm{MeV}) \\ & & f \times [{}^9\mathrm{Be} + \mathrm{n} &\rightarrow 2\,({}^4\mathrm{He}) + 2\mathrm{n} - 1.57\mathrm{MeV}] \end{aligned}$$

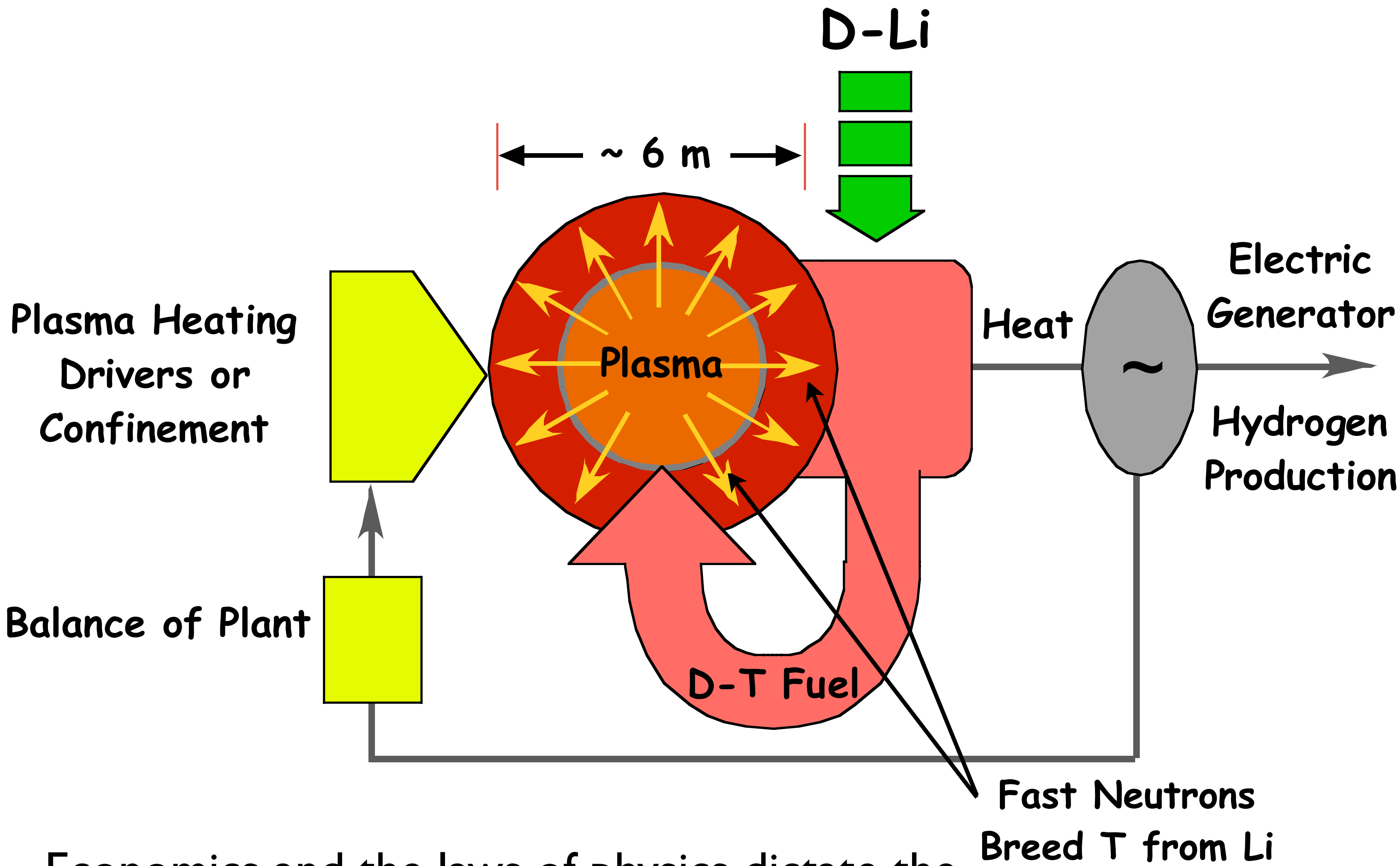
T

$$\approx 2\,({}^4\mathrm{He}) + (3.5 \text{ MeV plasma}) + (18.8 \text{ MeV blanket})$$

- D-T fusion has largest cross-section and lowest T ~ 170,000,000°.
- 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.)

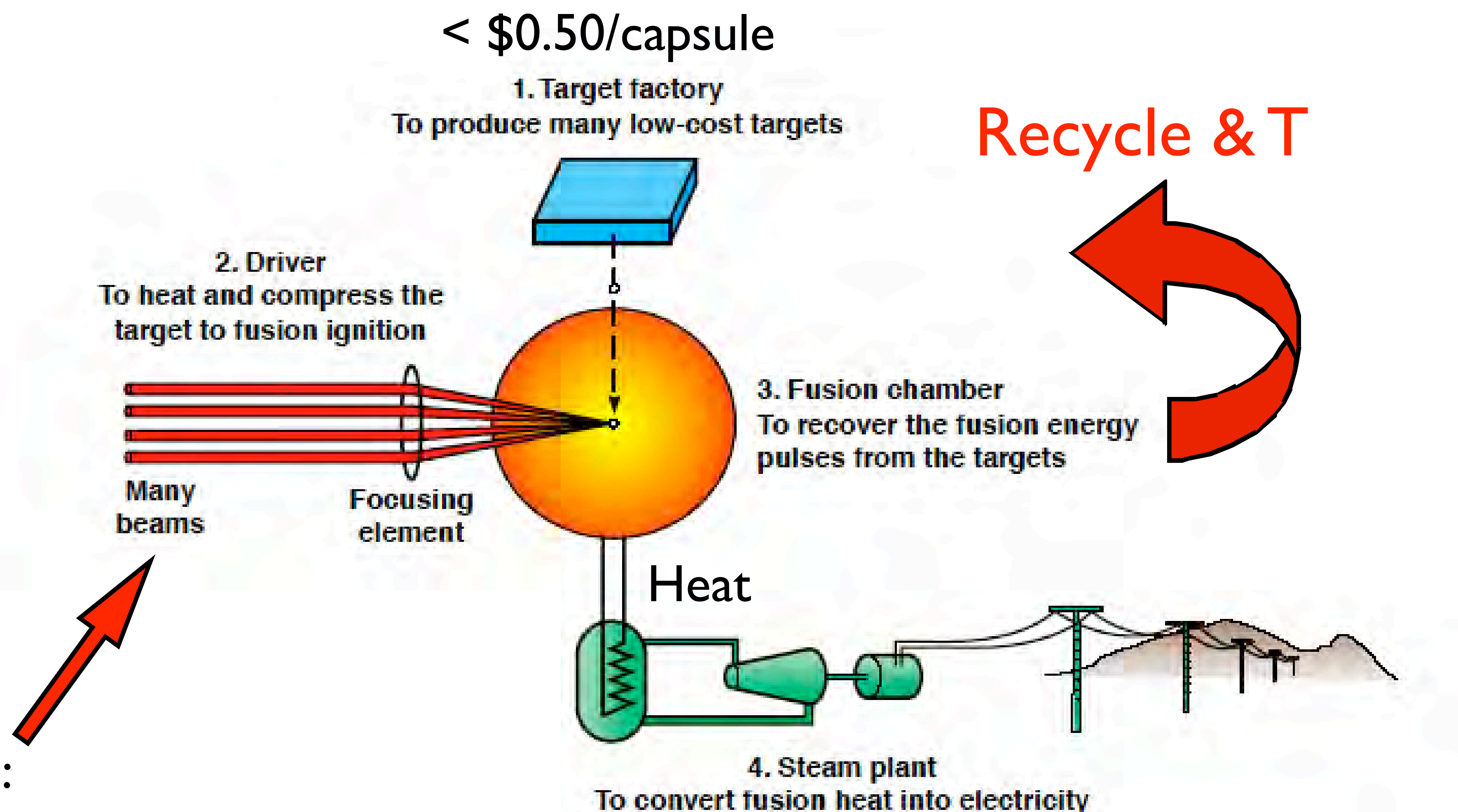
Two Approaches to Fusion Power

Each has R&D Paths with Plausible Technologies leading to Attractive & Economical Energy

- Inertial Fusion Energy (IFE)
  - Fast implosion of high-density D-T 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.

IFE



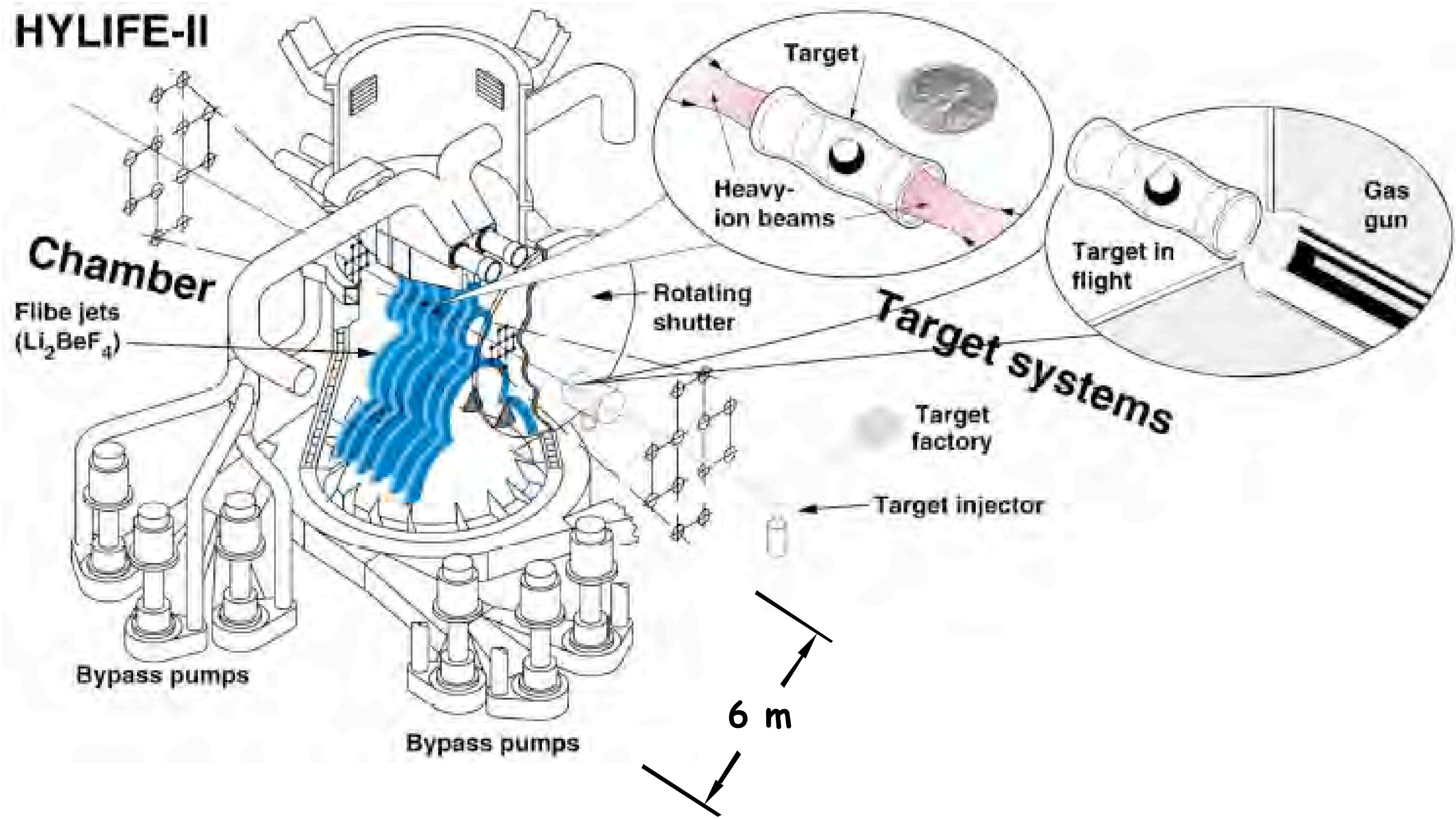
Example:

~ 100 beams (2.5 GeV Xe) ⇒ 5 MJ

(About the length of SLAC ~2.5 km)

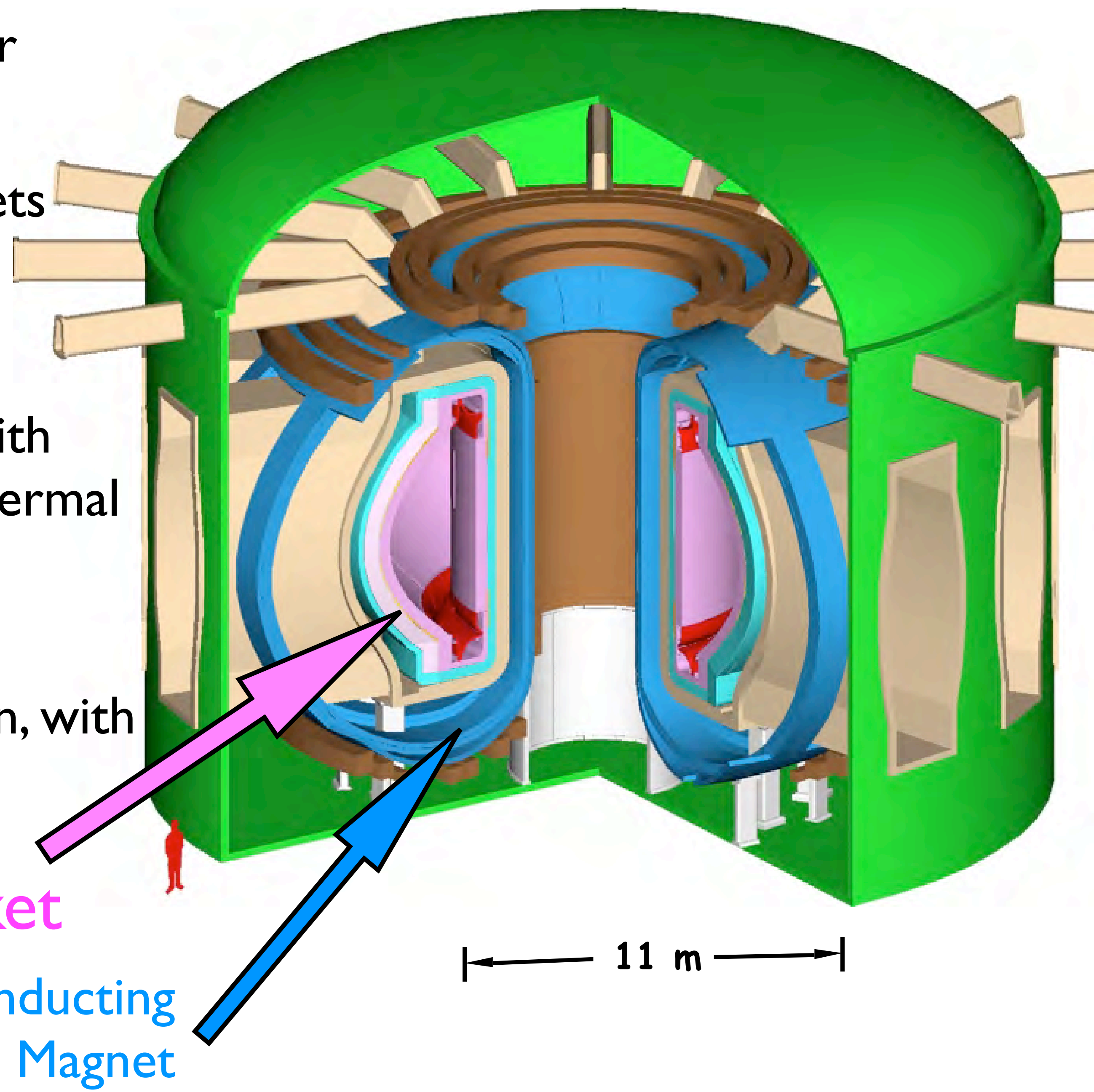
IFE Chamber

~100 beams



MFE

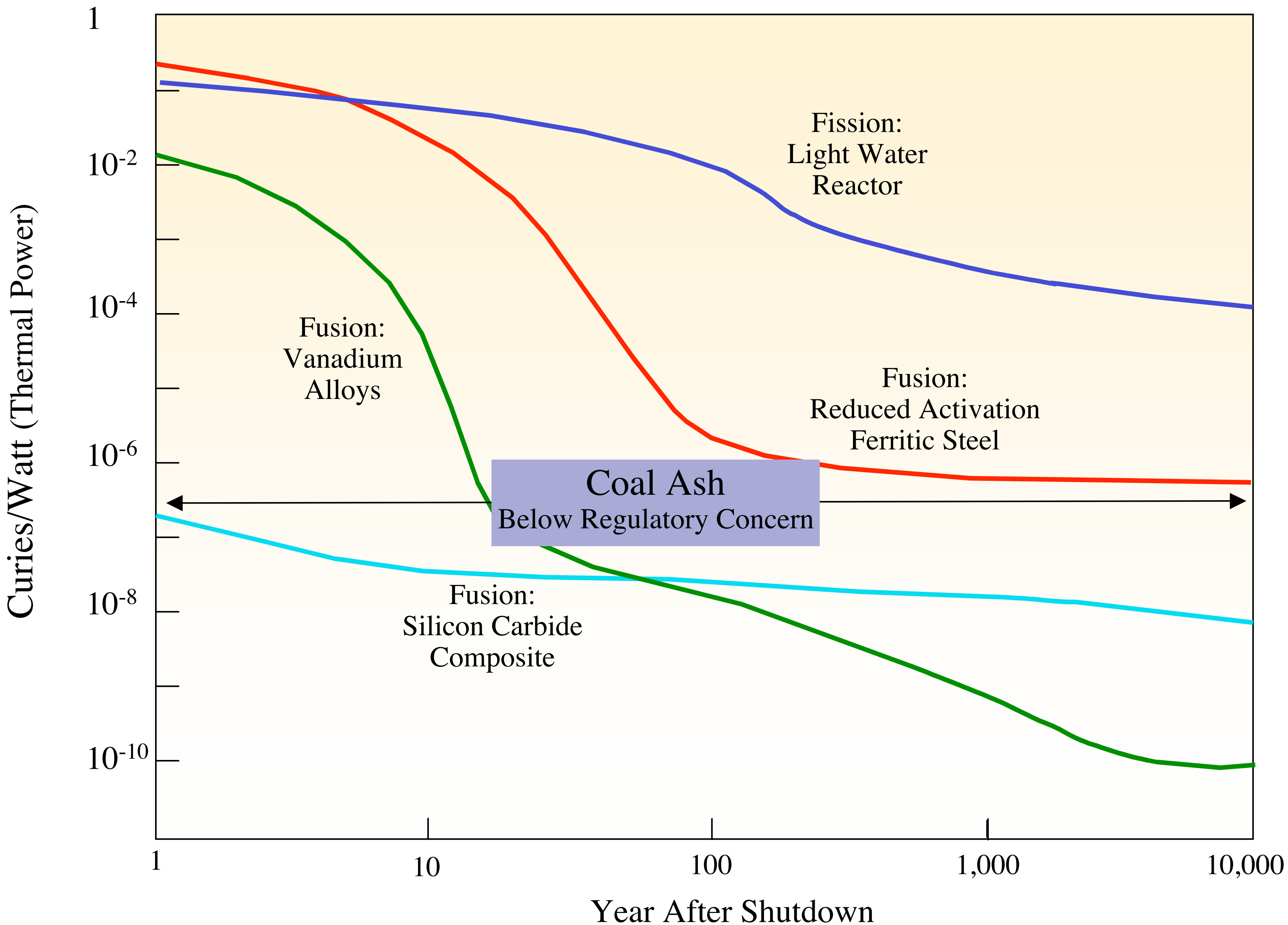
- Toroidal magnetic chamber
- Steady state, Nb_3Sn magnets (Coldest ↔ Hottest)
- SiC blanket (~ 1,100 C) with PbLi coolant yields high thermal efficiency.
- Modular, "easy" to maintain, with 85% availability
- 1 GWe



Fusion's Materials Challenge

- Unlike fission, the by-products of fusion are not inherently radioactive. Fusion has low proliferation risks.
- When fabricated from low activation materials, fusion does not produce long-lived radioactive waste.
- Fusion's **materials challenge** is to develop long-life, high-strength materials with high neutron-irradiated fracture toughness and good helium swelling resistance.
- **Good options exist**: Ferritic/martensitic steels, Vanadium alloys, and SiC/SiC composites

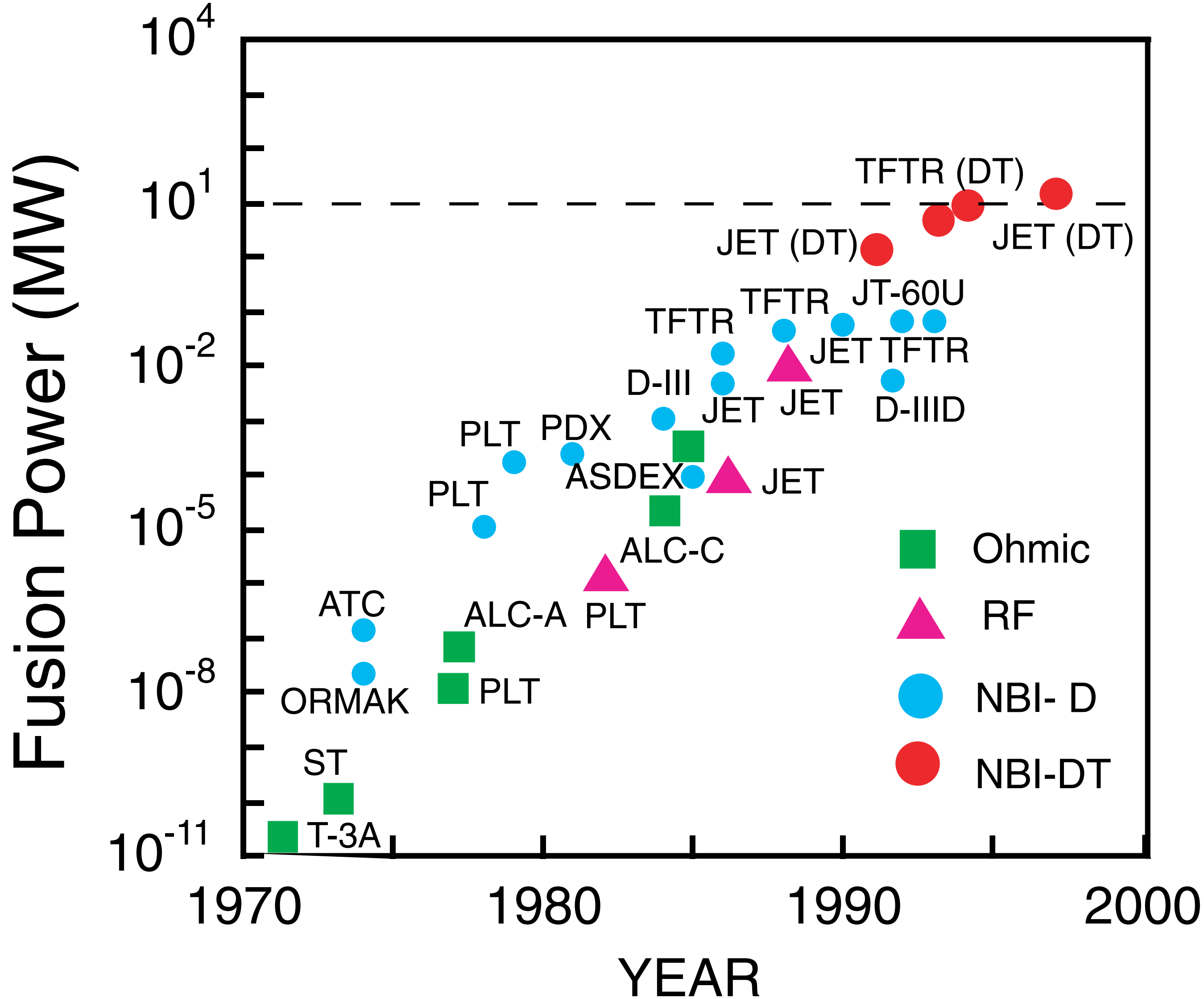
Attractive Low Activation Material Options for D-T Fusion



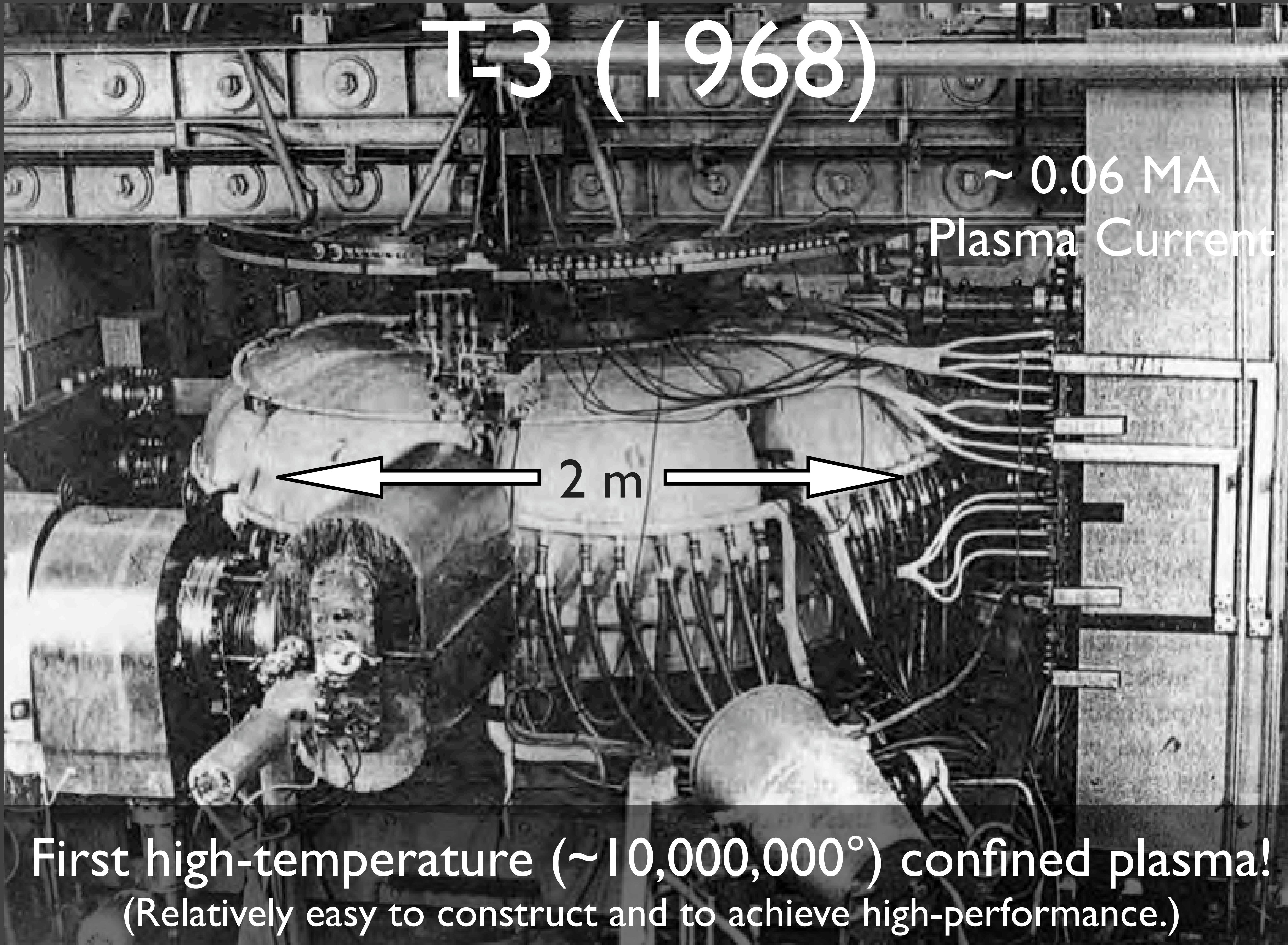
Fusion Progress

- From the beginning, a world-wide effort
- Tremendous progress in *understanding* high-temperature confined plasma in the fusion regime
- Over 15 MW fusion power has been generated in the laboratory, establishing "scientific feasibility"

Huge Advance in Fusion Parameters and Know-How



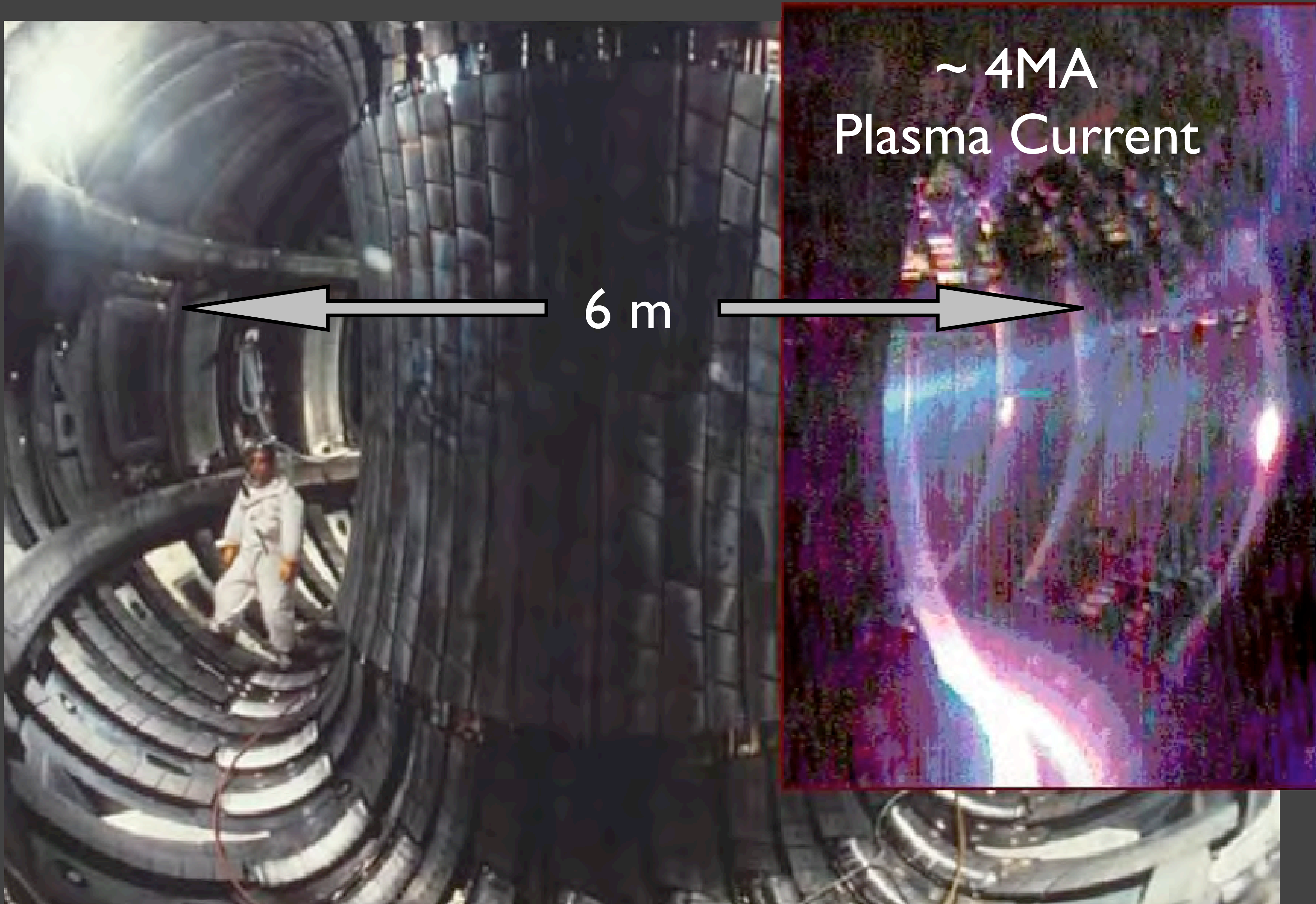
T-3 (1968)



First high-temperature (~10,000,000°) confined plasma!

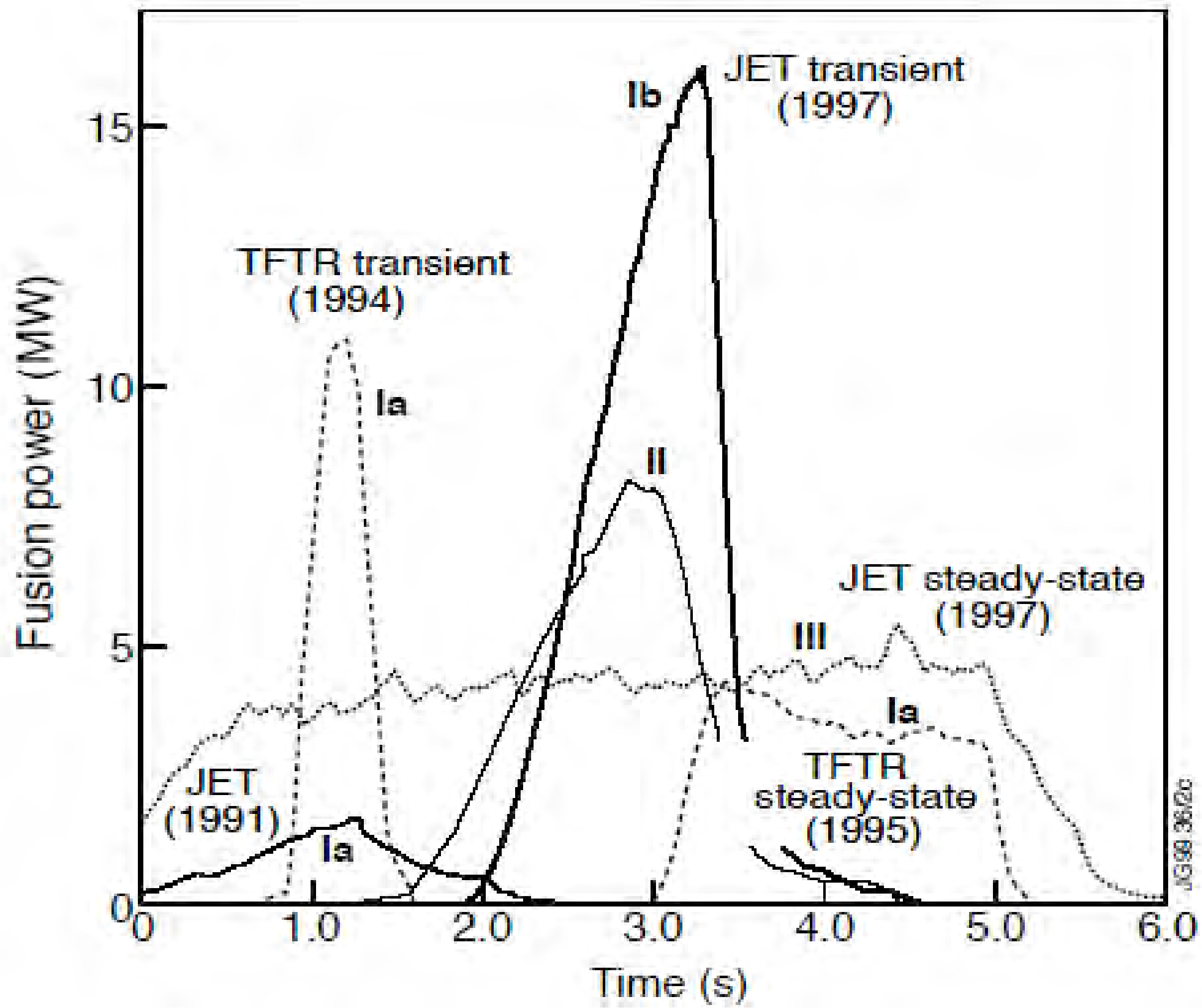
(Relatively easy to construct and to achieve high-performance.)

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
- Apply our developing knowledge-base to optimize the fusion configuration
- Move towards "Burning Plasma" physics studies

Understanding Matter in the High-Temperature Plasma State

- High-power EM wave injection, heating and current drive, energetic particle interactions…
- Plasma-surface interactions, radiation, recombination, and mass flow in plasmas…
- How does magnetic field structure impact confinement?
  ➡ *Achieving plasma stability at high pressure through "optimization of magnetic shape"*
- How does turbulence cause heat, particles, and momentum to escape?
  ➡ *Suppression of plasma turbulence: the "Transport Barrier"*

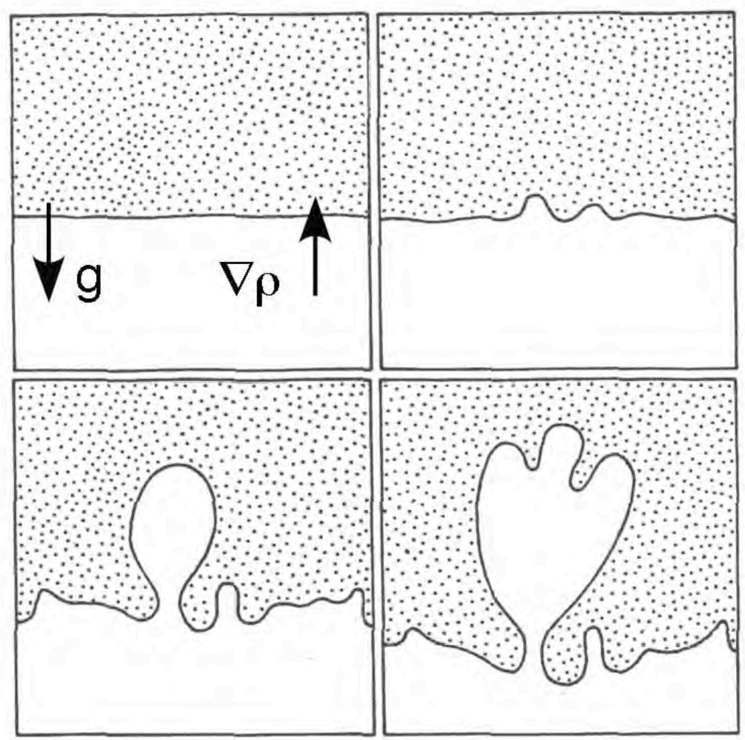
Configuration Optimization

- The major research activity for fusion (both MFE and IFE) leading to fusion's scientific and technical knowledge base.
- Small and medium-sized research devices often at universities.
- A source of innovation and discovery
- Significant practical results, for example:
    - Increased power density
    - Steady-state and reduced re-circulating power
    - Reduced driver energies
    - Improved reliability and control

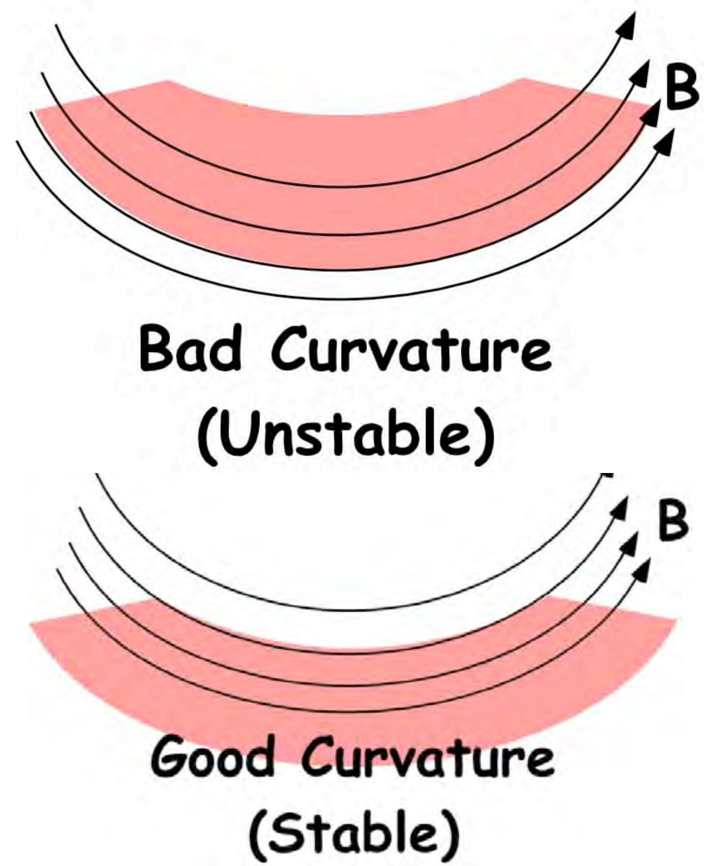
Example: MFE Configuration Optimization

Fundamentally, the behavior of magnetically-confined plasma depends upon the **shape** of the magnetic flux tube…

Interchange Instability



Bending Field ➠ Effective g



MFE Configuration Optimization

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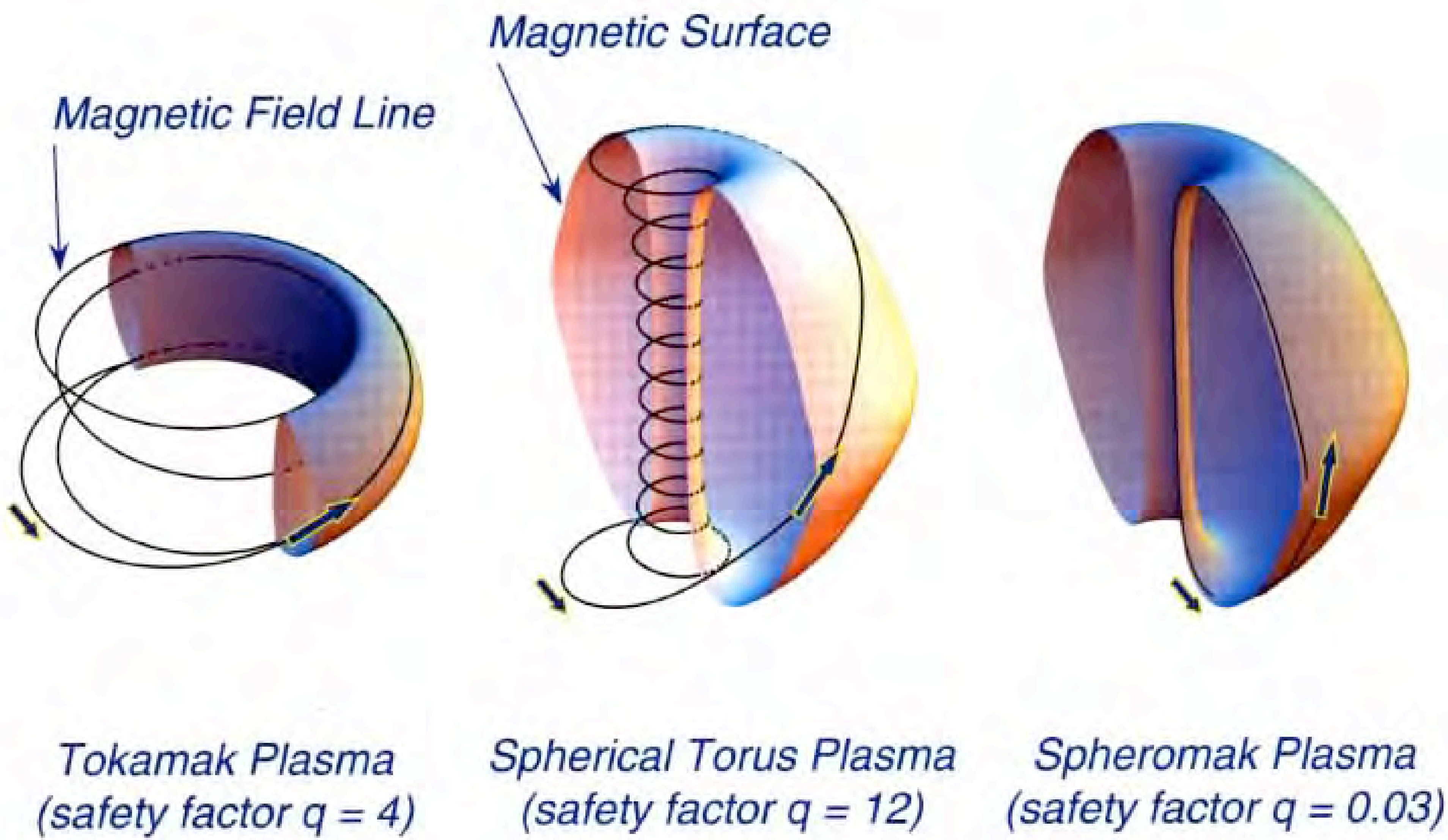
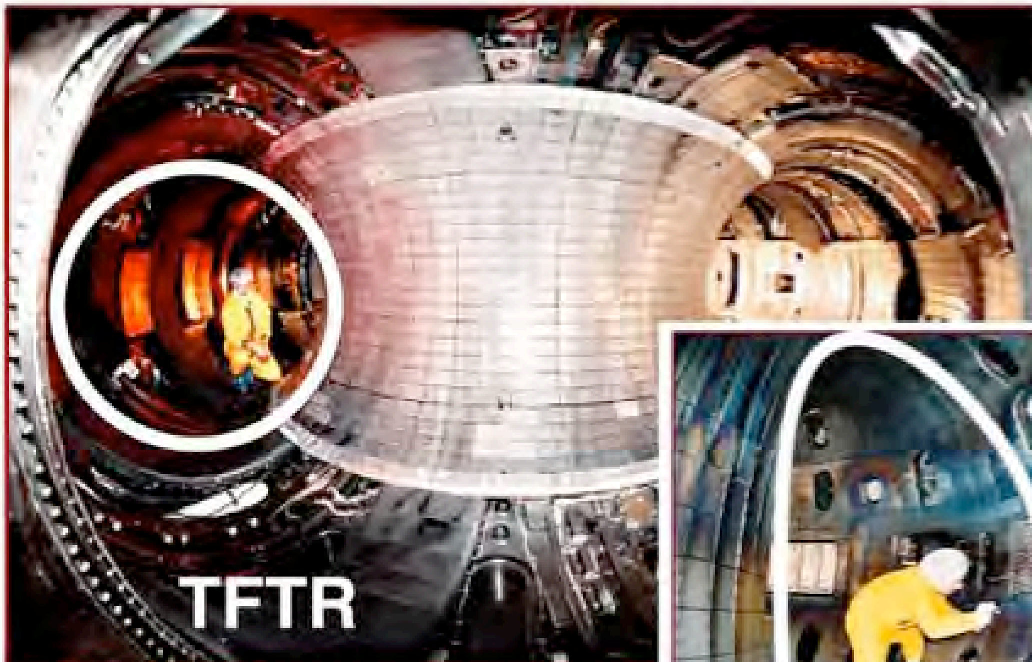
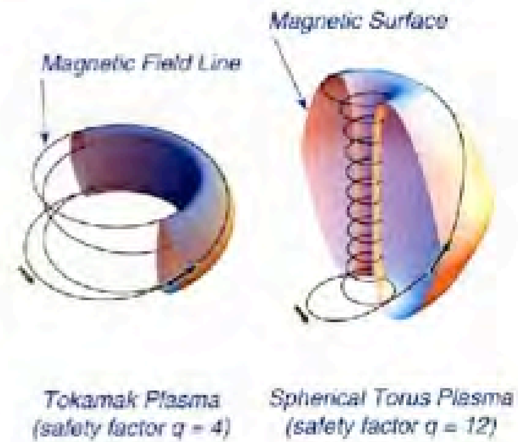


Magnetic Field Shaping Allows Higher Pressure



DIII-D



START

A plasma in the START experiment.

$\langle\beta\rangle = 38\%$

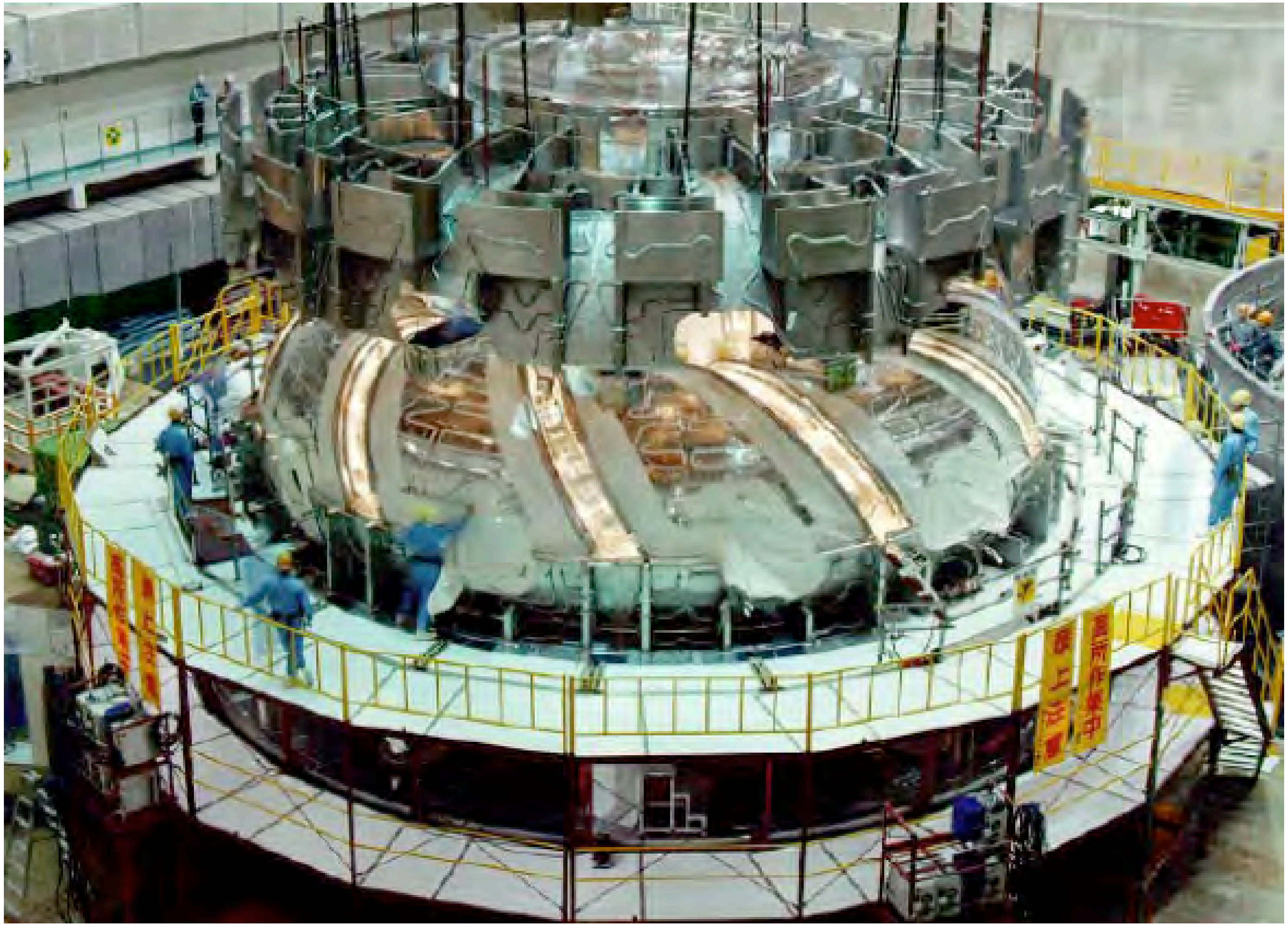
R/a = 2.9 :: 2.7 :: 1.3

β/χ = 0.03 :: 0.5 :: 1.8

(But, current drive is more difficult at low R/a.)

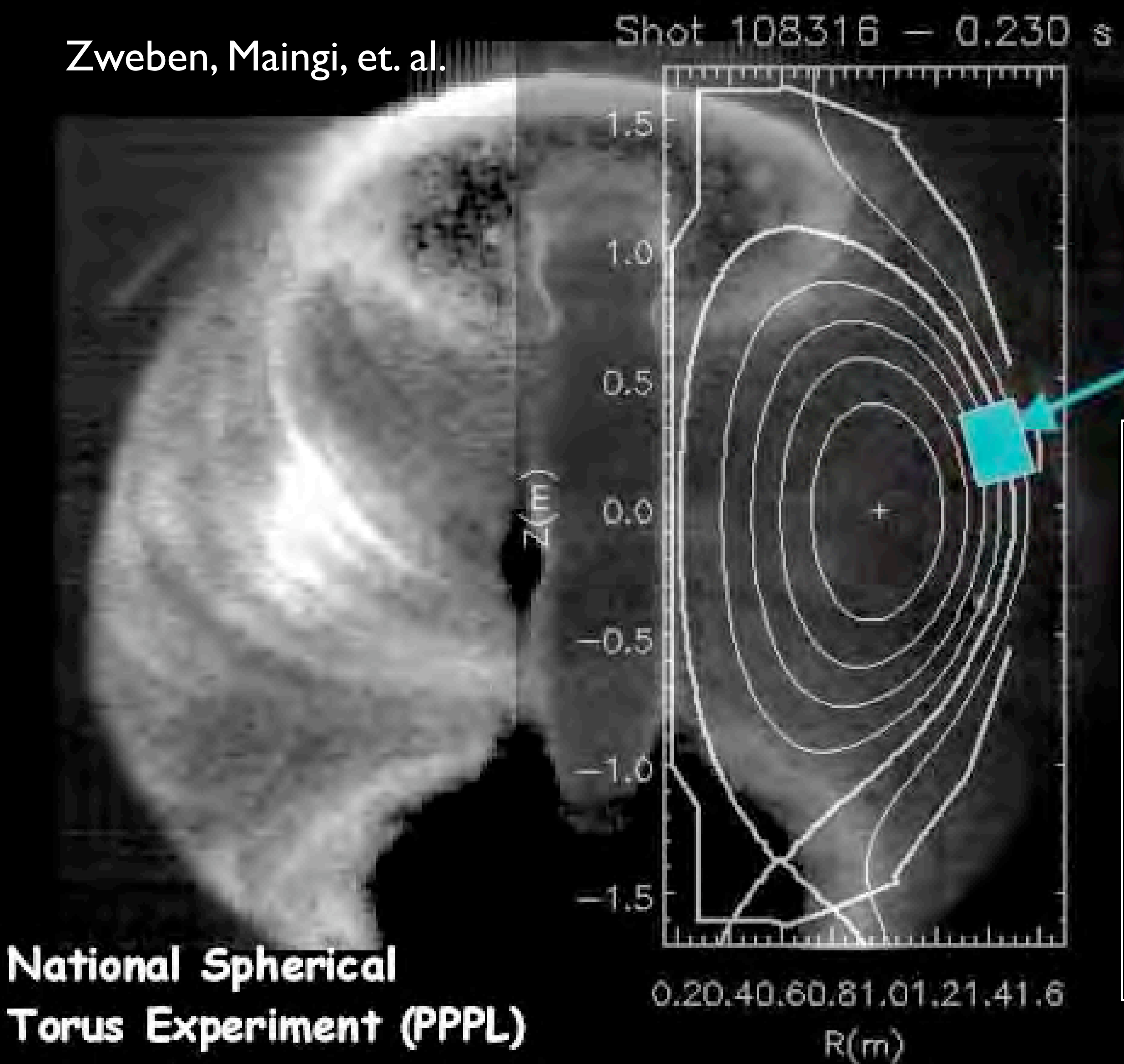
Optimization with Helical Coils

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

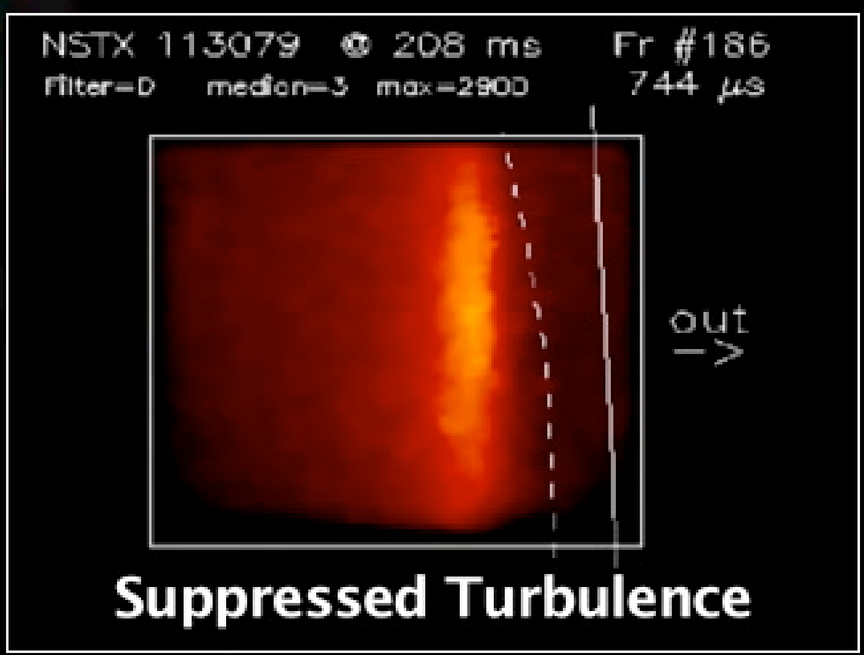


Viewing the Turbulence "Transport Barrier"

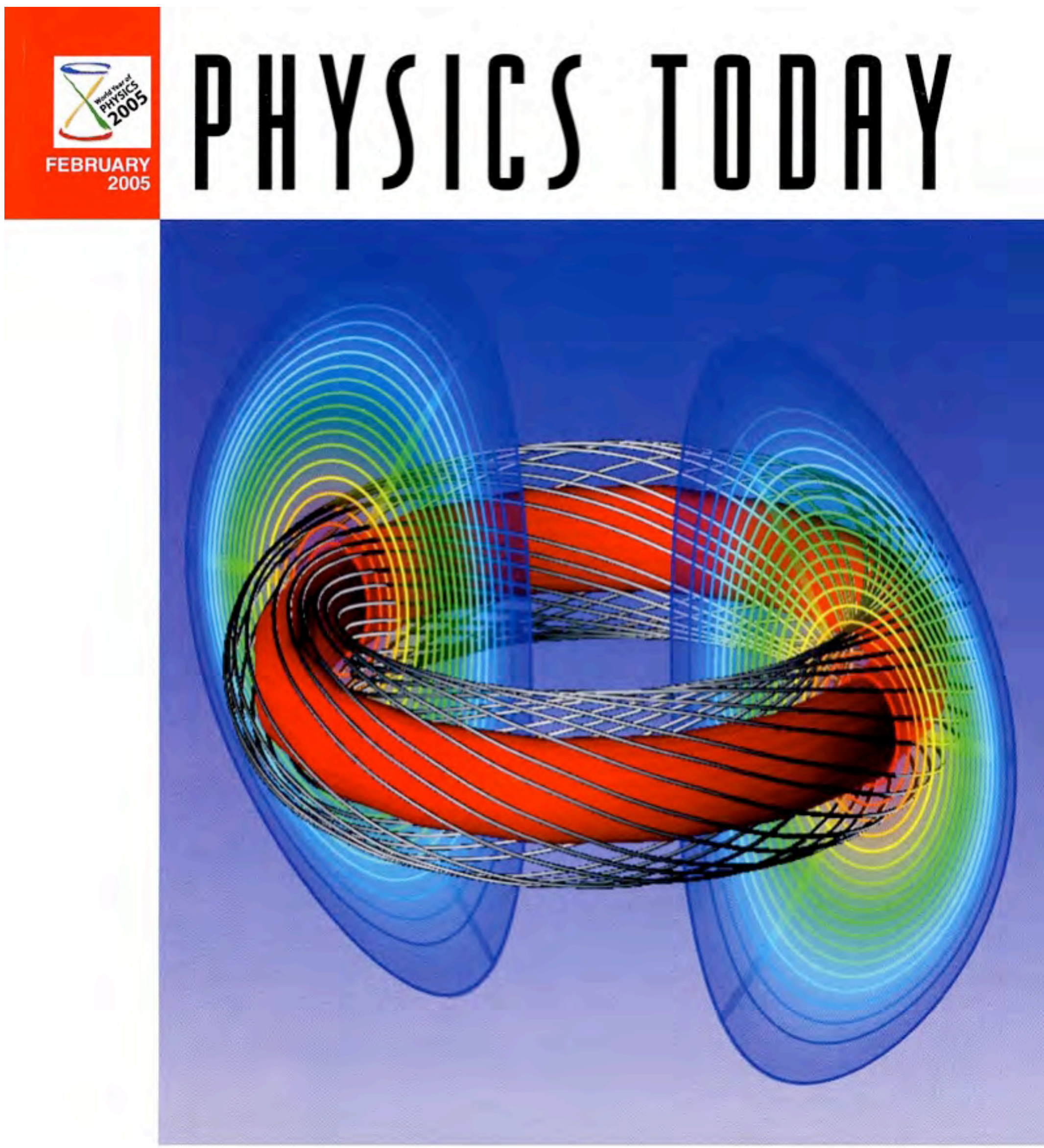
Zweben, Maingi, et. al.



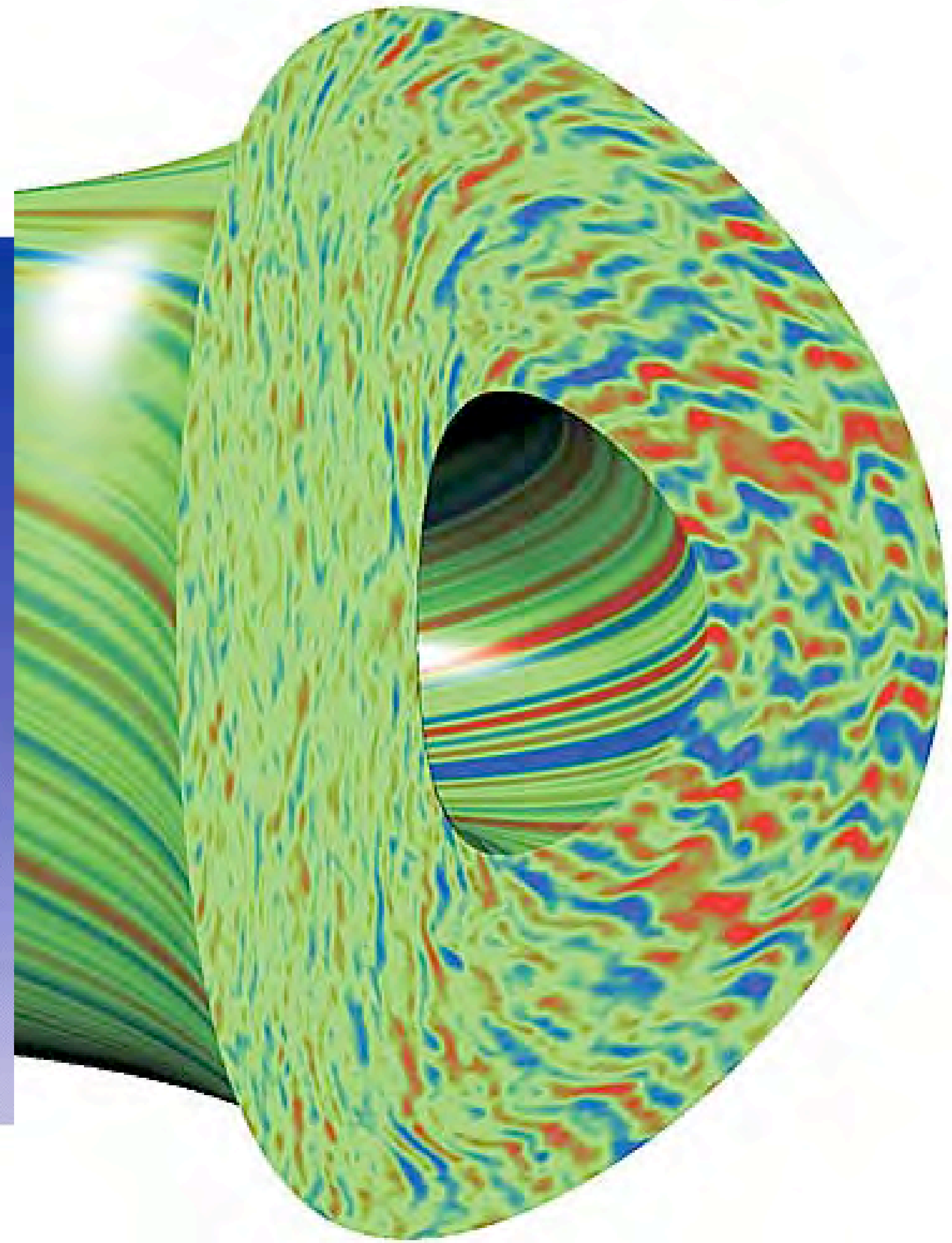
20x25 cm
Viewing Area



Measurement ⇔ Theory ⇔ Simulation



Toward simulating
confined plasmas

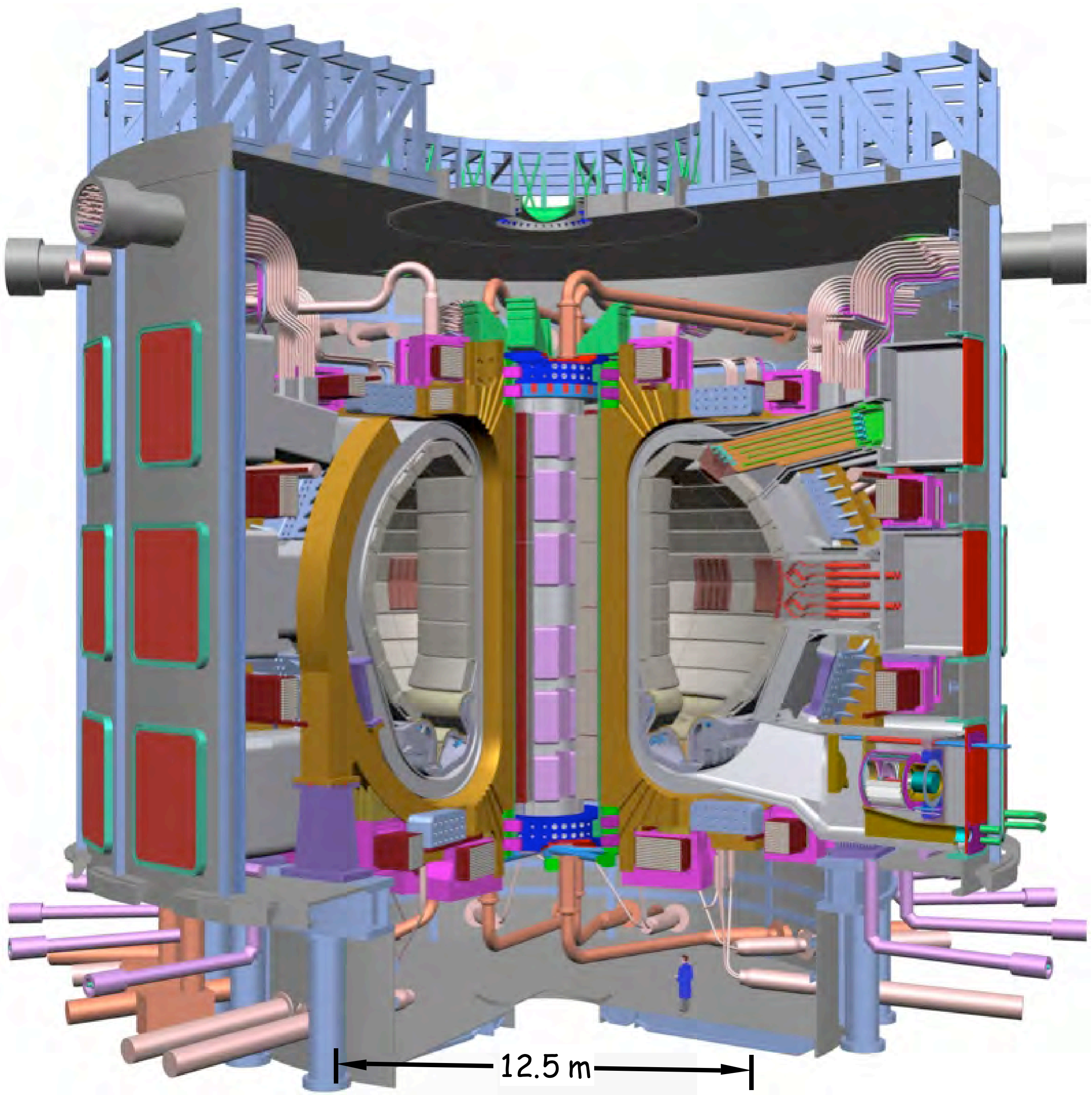


Don Batchelor (ORNL)

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, …

Physics

Technology
Testing

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

Where to put ITER?

Cadarache, France

Rokkasho, Japan

International Development of Fusion as a Source of Carbon-Free Energy

- Fusion research today is focused to answer important and broad questions of basic and applied science.
- However, our international partners desire more rapid development of fusion as a carbon-free energy option.
- Fusion is scientifically ready to explore "burning plasma" regime at the power-plant size-scale.
- Fully-developed fusion economy could supply many 10's TW electricity and hydrogen and meet goals for 21st century provided…
  - One or few ~ GWe power plants deployed by ≈2050.
  - Aggressive (~ 2-4% growth) scenarios suggest several TW by 2100.
- Practically "limitless" once fusion technology has been established.

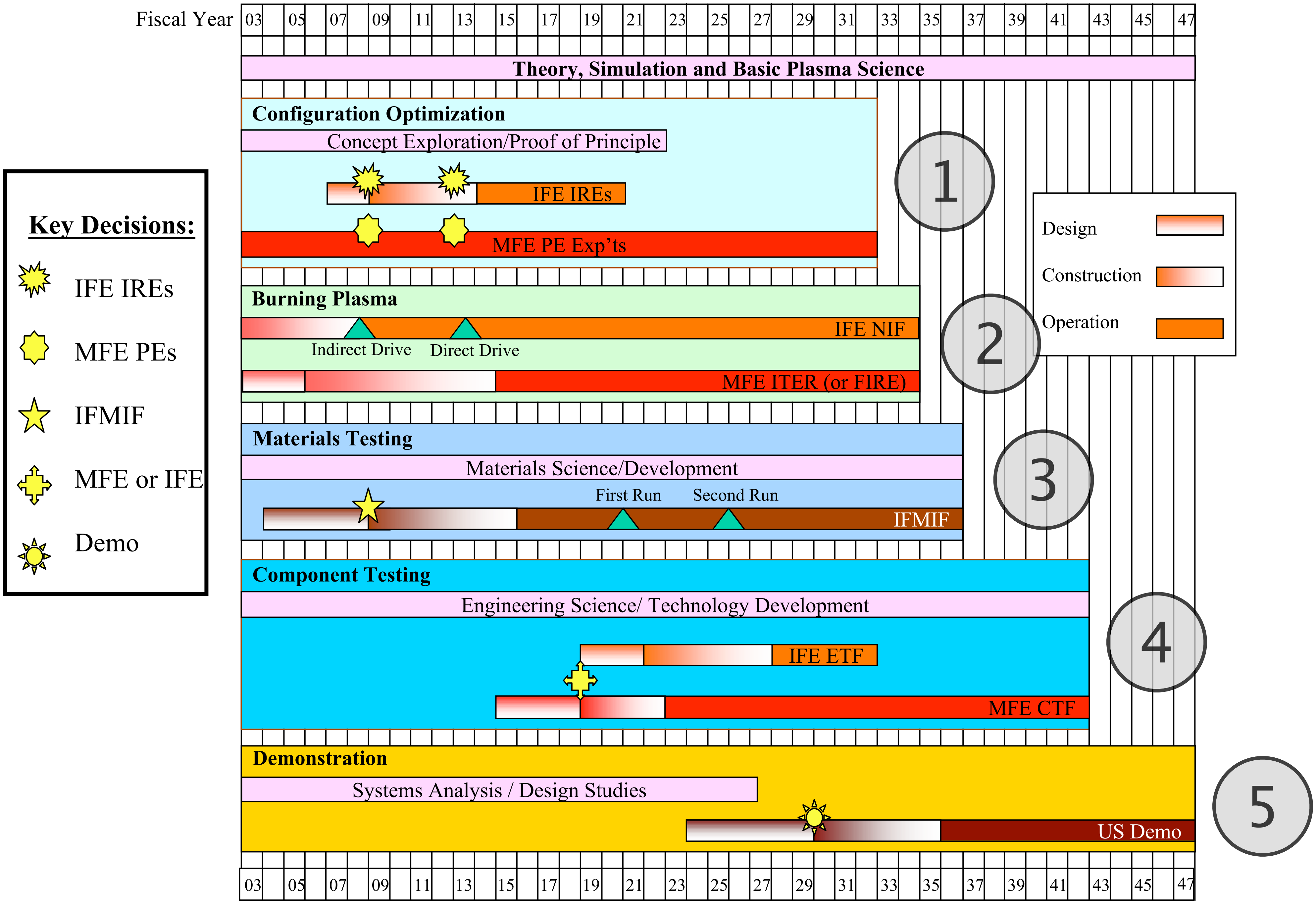
International Viewpoint: Fusion **can** be a Source of Carbon-Free Energy *This Century*

- Fusion R&D must *significantly accelerate* for a 2050 first commercial deployment.
- International 35 year "Fast Track" to "commercial demonstration" exists. (U.S. share ~ $25B.)
- Challenges: configuration choice, burn physics, and low-activation materials and components.

International Fast-Track to Fusion

- EU King Report (Nov. 2001):
  - Initiate and coordinate ITER and IFMIF (International Fusion Materials Irradiation Facility)
  - Expand mission of "DEMO" (limited component testing)
  - Shorten time to first fusion commercial development, ~ 35 years
- US FESAC Analysis (Mar. 2003):
  - 35 year target for operation of a US demonstration power plant (DEMO) that generates net electricity and demonstrates commercial practicality of fusion power.
  - Recognizes outstanding and difficult scientific and technological questions remain for fusion development. Strengthens IFE and MFE configuration optimization for next 15 years.
  - Leverages large international effort (ITER & IFMIF) and NAS program.

Detailed 5-Part Scenario & Decisions



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 a burning plasma experiment, there is a great opportunity to accelerate fusion research.
- Successful R&D and aggressive implementation would allow fusion to contribute many TW's by 2100.

References

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