Fusion Energy:
“Pipe Dream or Panacea”

Mike Mauel
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Energy Options & Paths to Climate Stabilization
Aspen, 9 July 2003

Fusion Energy:

~~"Pipe Dream or Panacea"~~

"Promise, Progress, and the Challenge Ahead"

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~ OUTLINE ~

Fusion Primer
Power Configurations
Progress
MFE Next Steps: Optimization and Burning Plasma
"Fast Track" 35 Year Plan to enable Commercial Power

References

- Rose and Clark: *Plasmas and Controlled Fusion* (1961)
- Sheffield: "The Physics of Magnetic Fusion Reactors," *RMP* (1994)
- Hawryluk: "Results from D-T Tokamak Confinement Experiments," *RMP* (1998)
- Example fusion resource development scenarios…
  - Schmidt, *et al.*, "U.S. Fusion Future," *Fus. Tech.* (2001)
  - Ongena and Van Oos, "Energy for future centuries. Will fusion be an inexhaustible, safe and clean energy source?" *Fus. Sci. and Tech.* (2002)
  - Report of the European Fusion "Fast Track", D. King, *et al.* (2001)
  - Report of the U.S. DOE FESAC "A [35 Year] Plan to Develop Fusion Energy" (2003)
- "The FIRE Place" **http://fire.pppl.gov/**
- Levitated Dipole Experiment **http://www.psfc.mit.edu/ldx/**

Why Fusion Energy Science?

- for fundamental plasma physics and critical plasma technologies
- for national defense
- for fusion energy…
  - 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 Research

- Tremendous progress in *understanding* how to confine & control high-temperature matter, e.g.
  - Suppression of some forms of turbulence
  - Control of some pressure-limiting instabilities
- First light achieved at NIF
- Negotiations well-along to start ITER construction: an international burning plasma experiment at the scale of a power plant. *The world's largest scientific partnership to develop carbon-free energy.*

Fusion Primer

- Fusion fuel cycles
- Elements of a fusion power source
- Two general approaches:
  - IFE: Fast implosion of high-density fuel pellets
  - MFE: Magnetic confinement of low-density plasma
  - *Several options exist for each approach. Configuration optimization is an exciting area of today's research.*

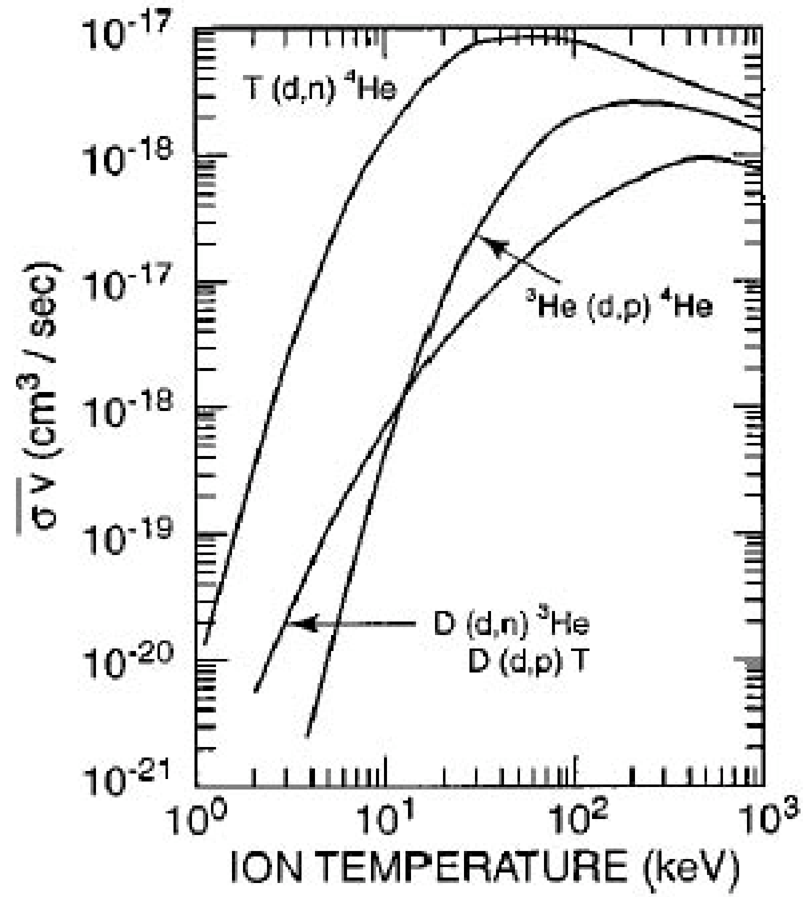
Fusion Reactions for Power

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

$$\mathrm{D} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He}\,(3.6\mathrm{MeV}) + \mathrm{H}\,(14.7\mathrm{MeV})$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{He}\,(0.82\mathrm{MeV}) + \mathrm{n}\,(2.45\mathrm{MeV})$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\,(1.01\mathrm{MeV}) + \mathrm{H}\,(3.02\mathrm{MeV})$$



- Coulomb barrier sets the fusion's high temperature: T > 15 keV (170,000,000 K) Fusion involves **high-temperature matter** called "plasma".
- 1 g of D yields 4 MW-days (1 g U^{235} yields 1 MW-day)
- 33 g D in every ton of water. *However, no T and ^{3}He resources exist on earth.*

D-T (^{6}Li) Fusion

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

Fast n

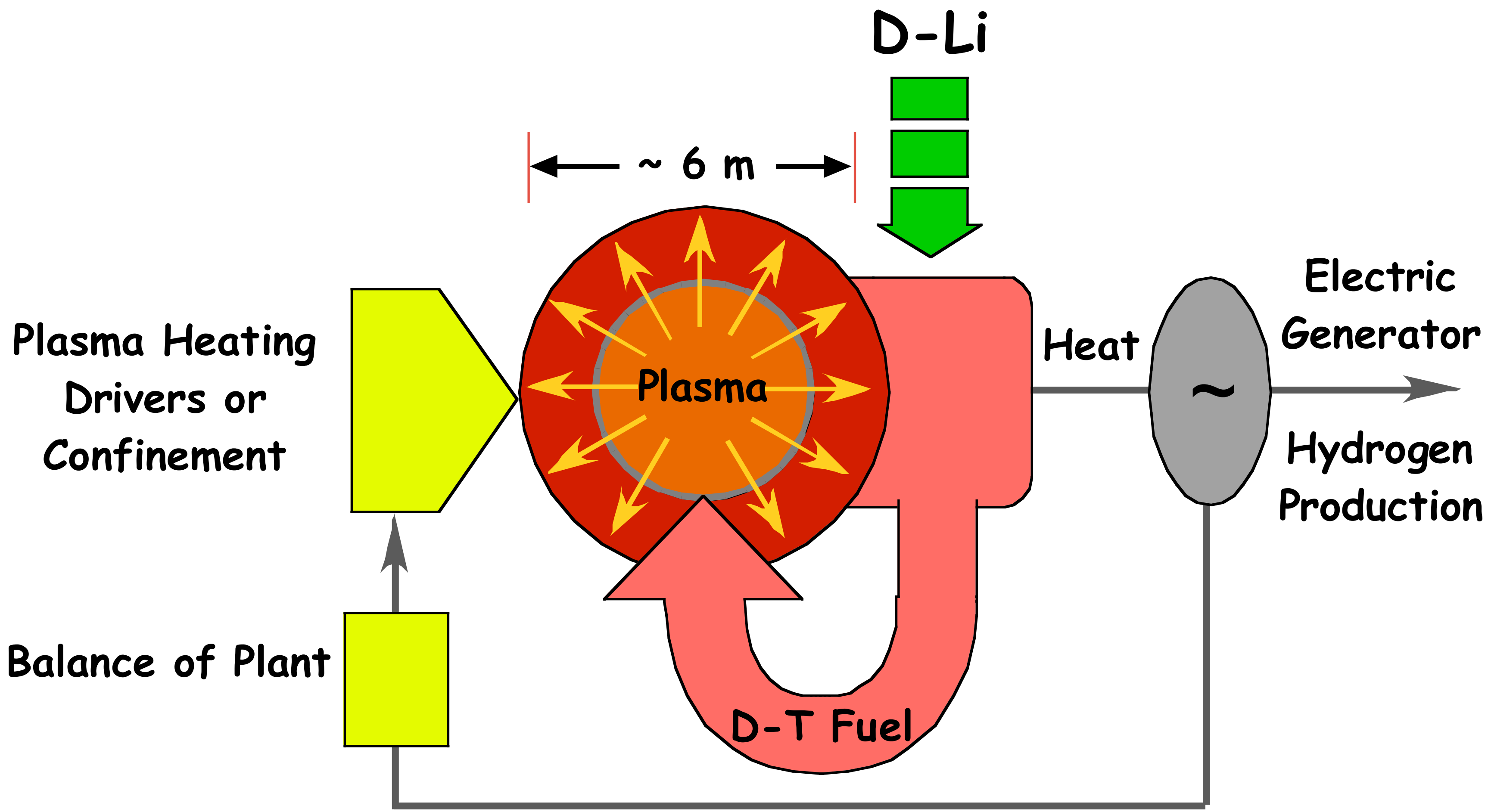
$$\left\{\begin{array}{lrl} Plasma: & \mathrm{D} + \mathrm{T} \rightarrow & {}^4\mathrm{He}\,(3.5\mathrm{MeV}) + \mathrm{n}\,(14.1\mathrm{MeV}) \\ Blanket: & {}^6\mathrm{Li} + \mathrm{n} \rightarrow & {}^4\mathrm{He}\,(2.05\mathrm{MeV}) + \mathrm{T}\,(2.73\mathrm{MeV}) \\ & f \times [{}^9\mathrm{Be}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

T

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

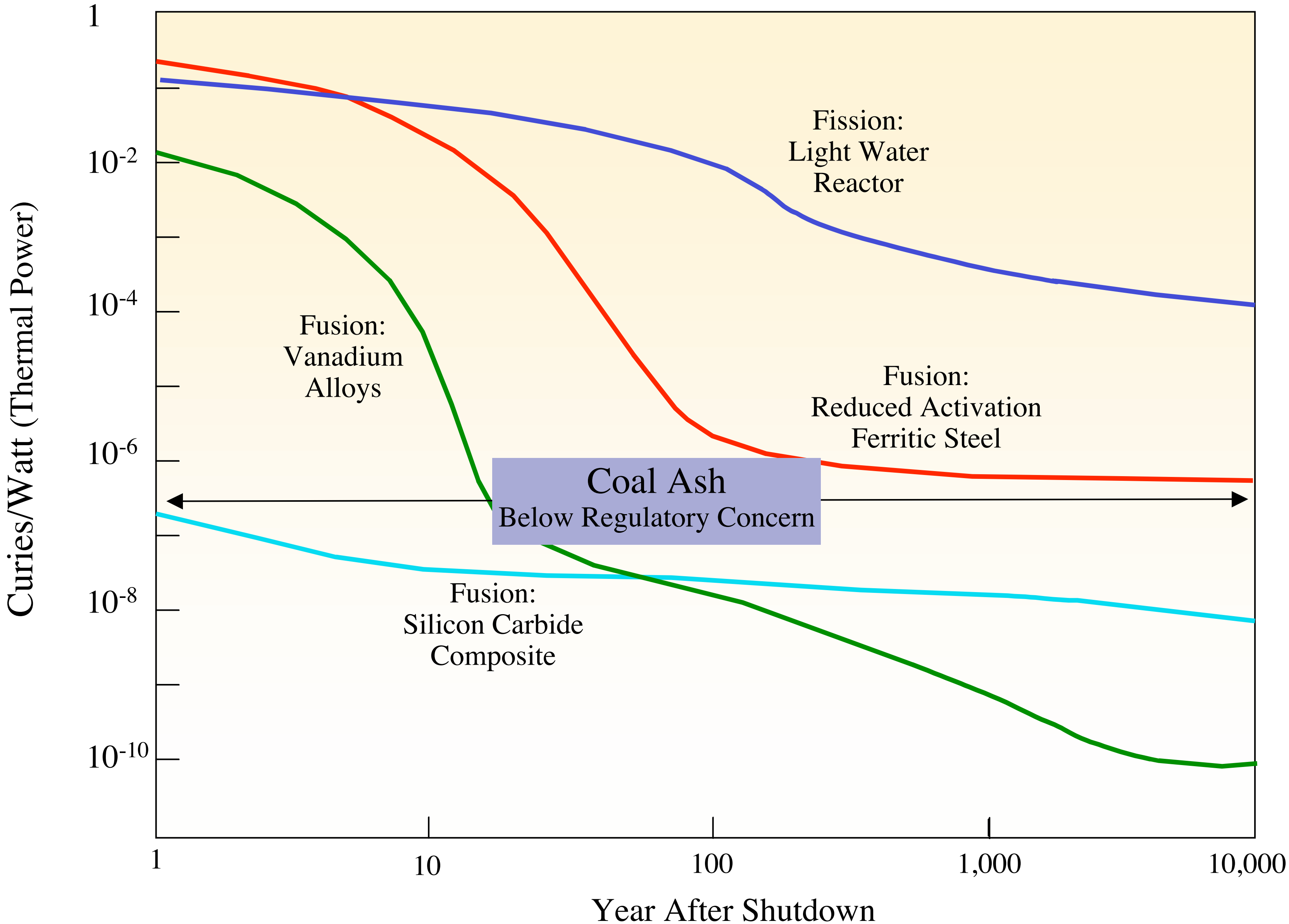
- Largest cross-section. Easiest fuel-cycle for fusion power production. Applicable for both MFE and IFE.
- ~ 80% of energy as fast neutrons (~ 1.5 m shielding)
  à the source of fusion’s technology & materials challenge.

Elements of a D-T(Li) Fusion System



...plus component decommissioning.

Attractive Low-Activation Material Options for D-T Fusion



Other fuel cycles are possible, but *more challenging*, e.g.

D-D (^{3}He) Fusion

$$\overbrace{\begin{array}{lrl} Plasma: & D + D \rightarrow & {}^3He\,(0.82\text{MeV}) + n\,(2.45\text{MeV}) \\ & D + D \rightarrow & T\,(1.01\text{MeV}) + H\,(3.02\text{MeV}) \\ & 2 \times [D + {}^3He \rightarrow & {}^4He\,(3.6\text{MeV}) + H\,(14.7\text{MeV})] \\ & T \rightarrow & \text{extract to long-term storage} \\ 12.3\ years: & T \rightarrow & {}^3He + e^- + (0.019\text{MeV}) \end{array}}^{6D}$$

^{3}He T

$$\approx 2\,({}^4\text{He}) + 3H + e^- + n + (41.5\text{ MeV plasma}) + (2.45\text{ MeV blanket})$$

- Significantly reduced fast neutron flux!! Most energy to plasma and then first wall. Simplifies fusion component technologies.
- Next easiest fusion fuel cycle, but requires confinement ~25 times better than D-T(Li) **and** T extraction (only for MFE).
- Equally challenging, but exciting, D-D options exist for IFE.

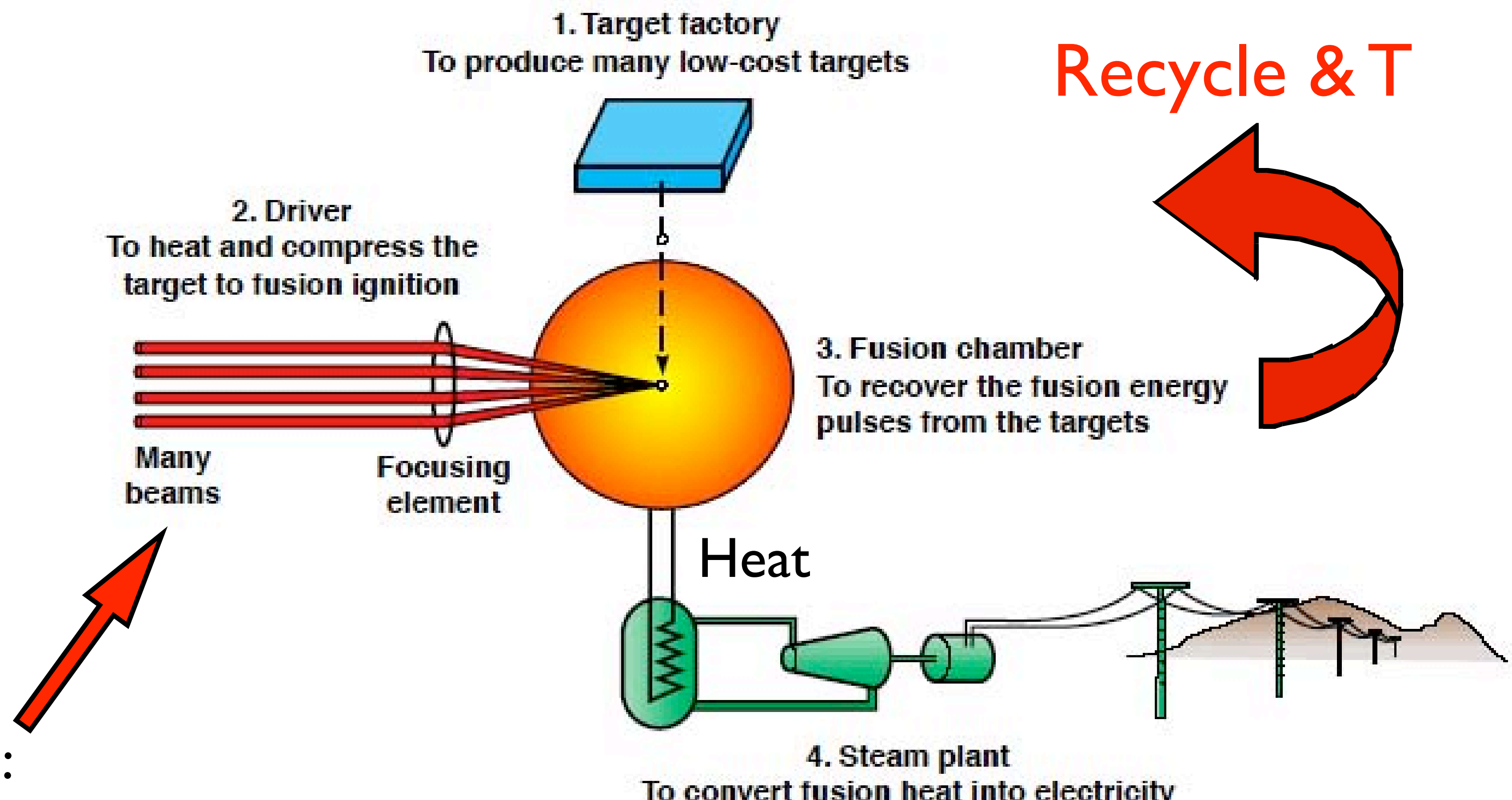
Two Approaches to Fusion Power

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) self-sustained plasma continuously.
  - 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) > 40,000 × solar

IFE

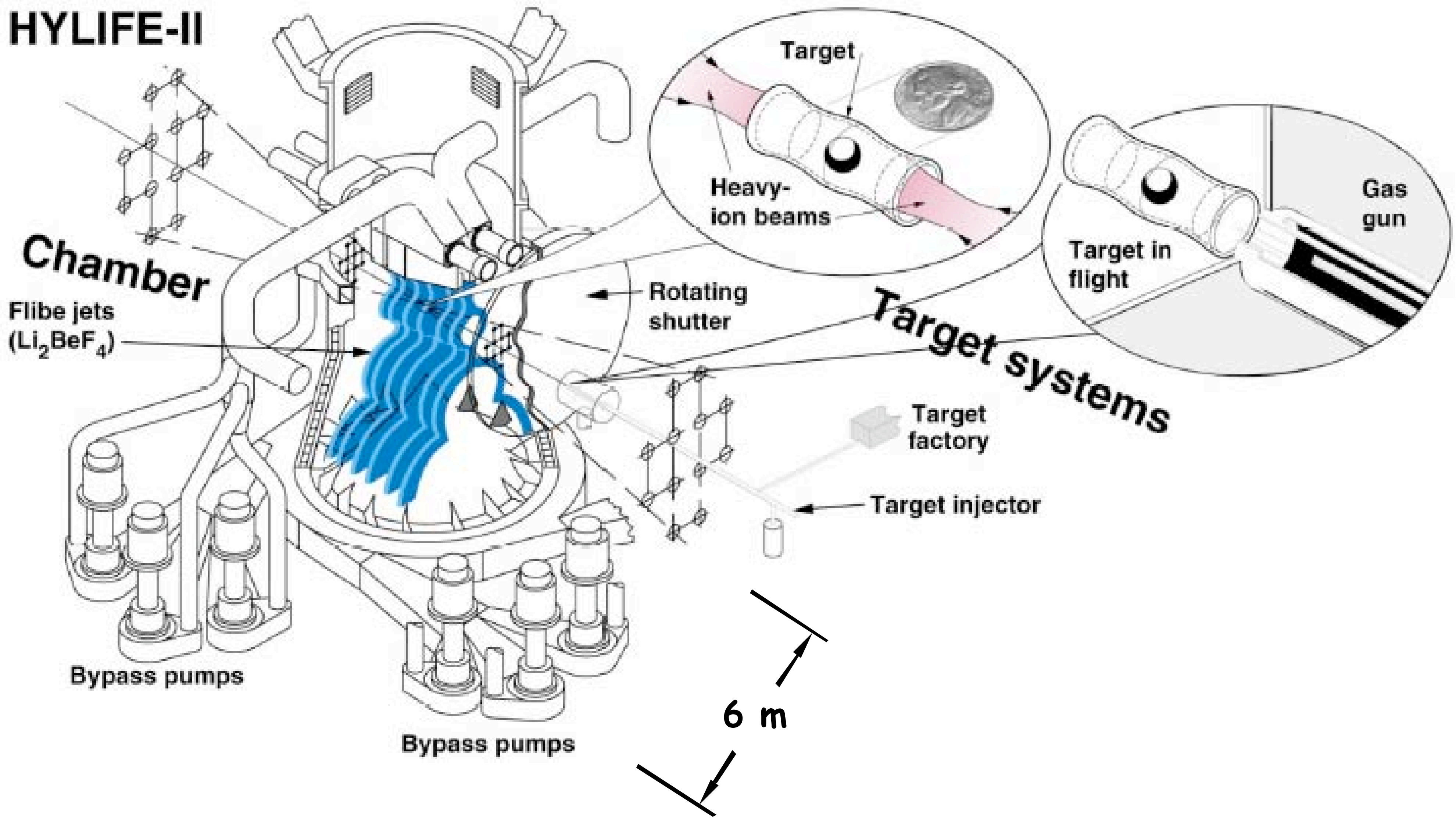
< $0.50/capsule



Example:
~ 100 beams (2.5 GeV Xe) ⇒ 5 MJ
(About the length of SLAC ~2.5 km)

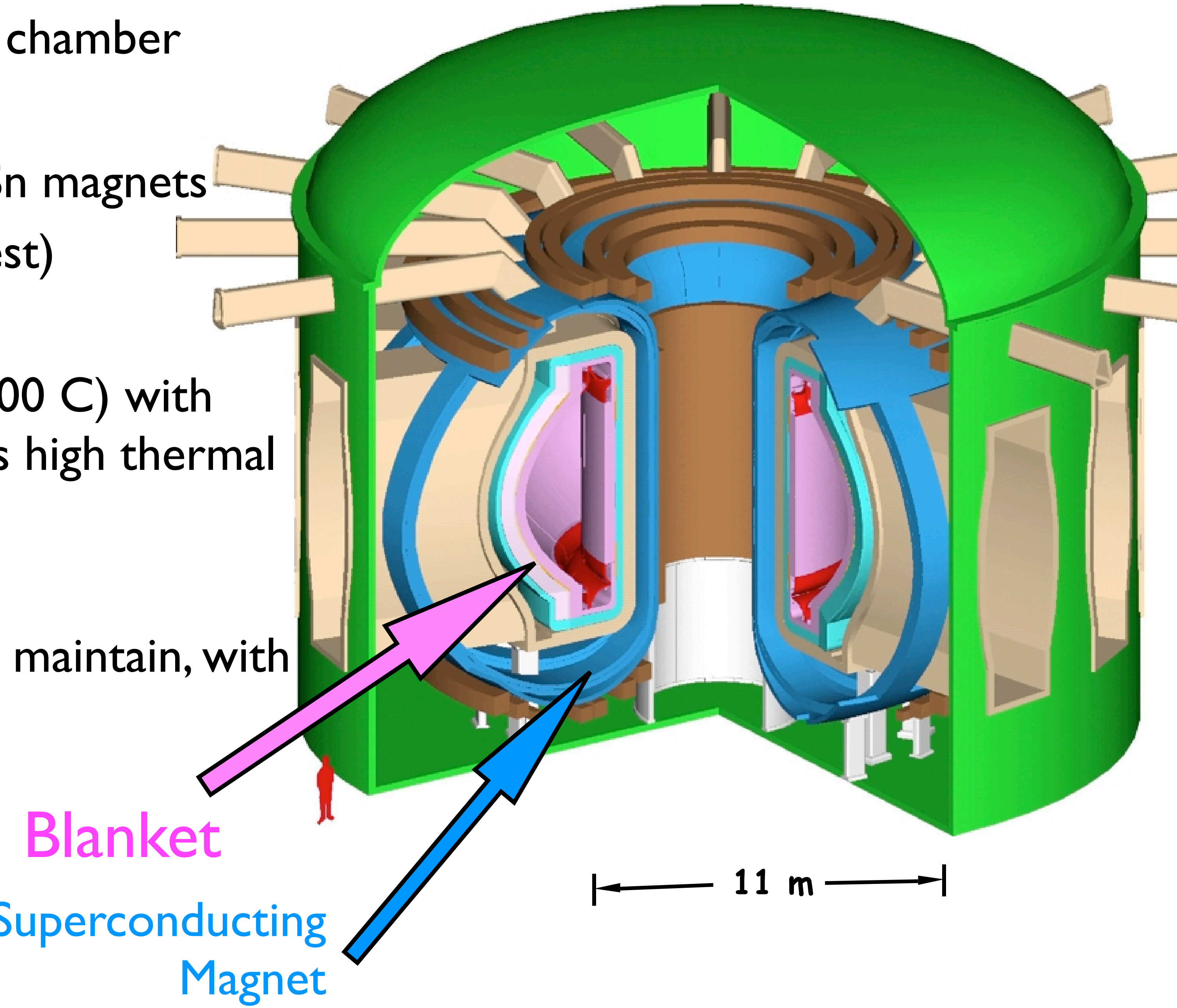
IFE Chamber

~100 beams



MFE

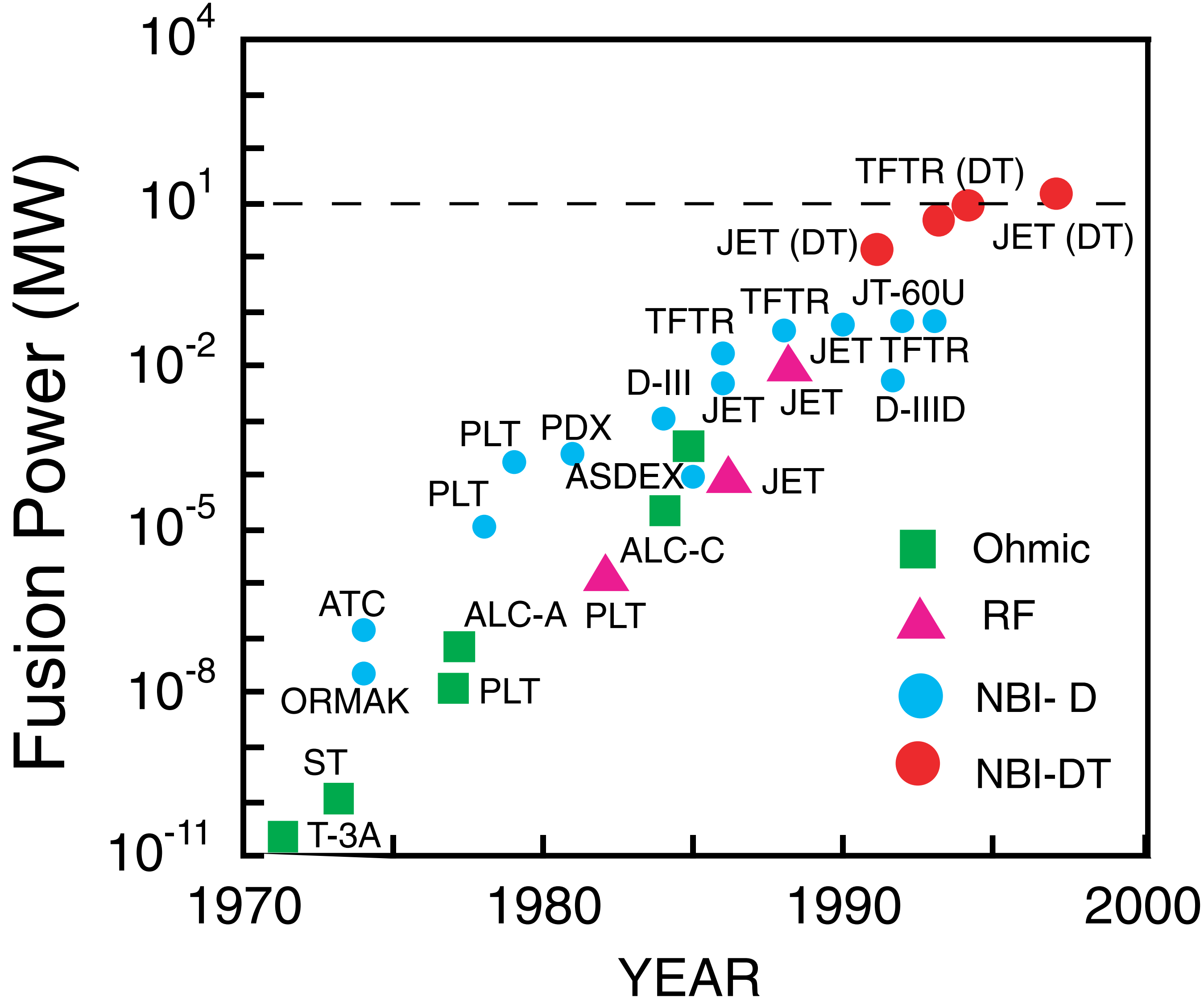
- Toroidal magnetic chamber
- Steady state, Nb_3Sn magnets (Coldest ↔ Hottest)
- SiC blanket (~ 1,100 C) with PbLi coolant yields high thermal efficiency.
- Modular, "easy" to maintain, with 85% availability
- 1 GWe



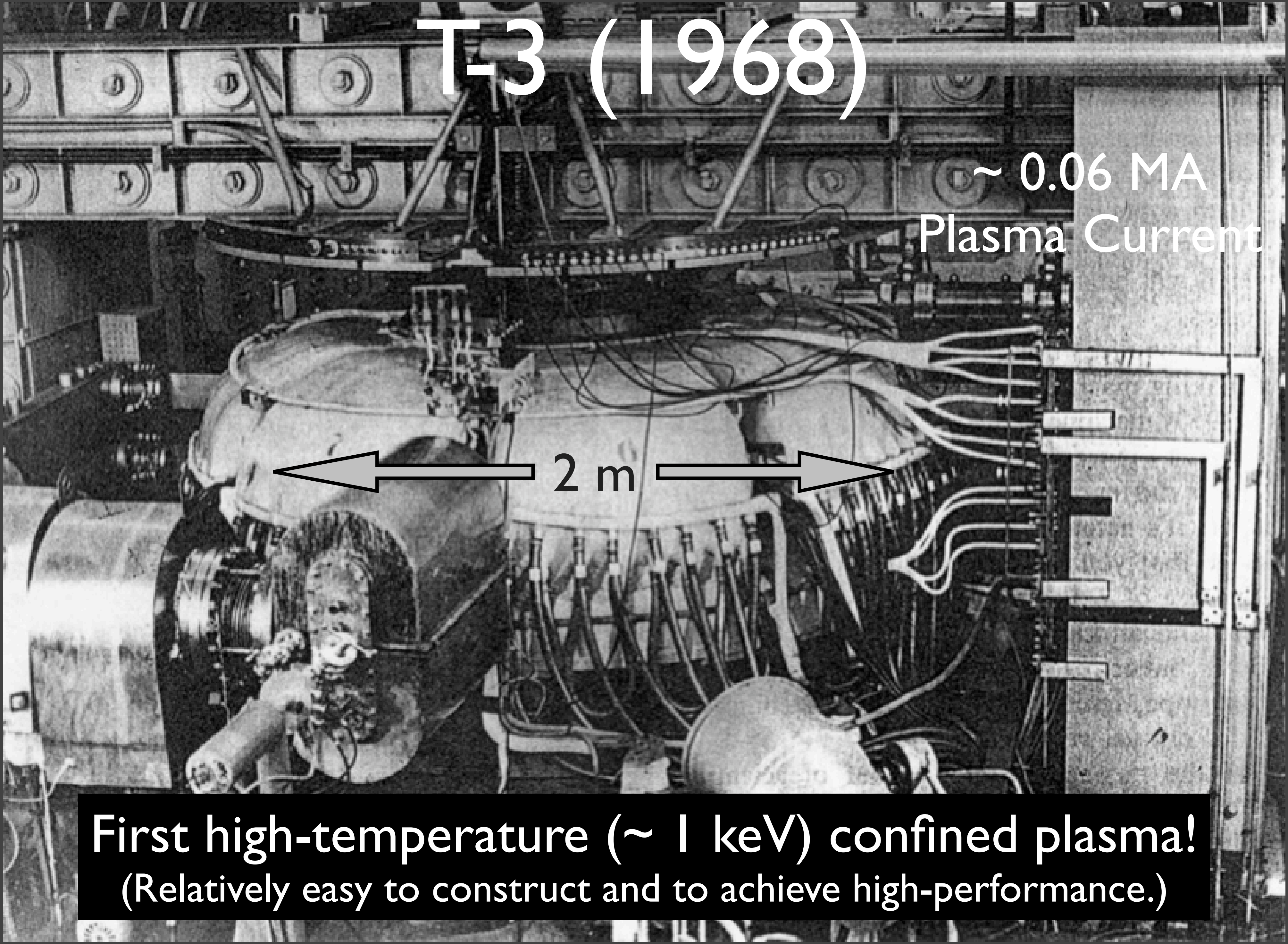
Fusion Progress

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

Huge Advance in Fusion Parameters and Know-How



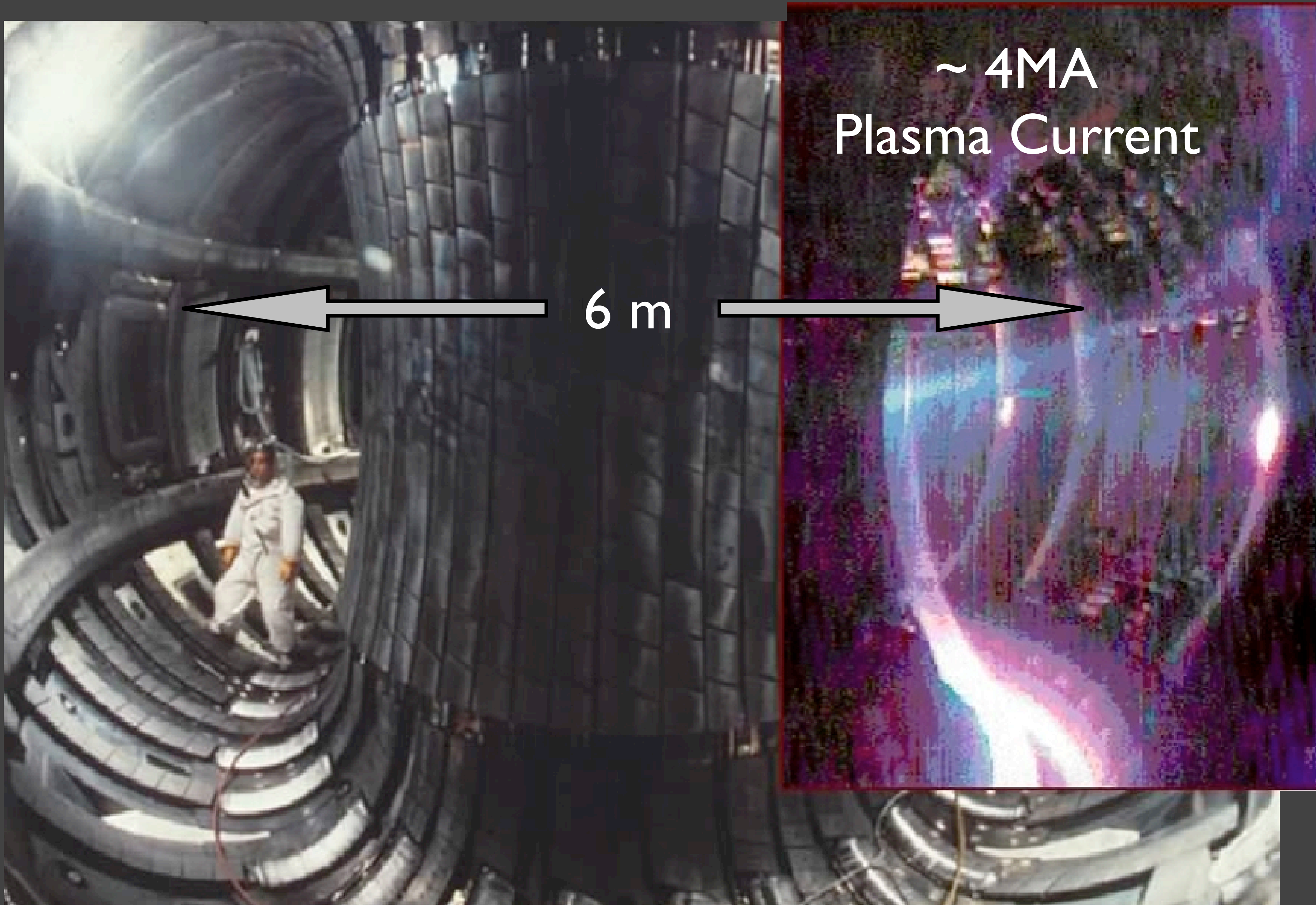
T-3 (1968)



First high-temperature (~ 1 keV) confined plasma!

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

JET (1997)



Fusion Power Production

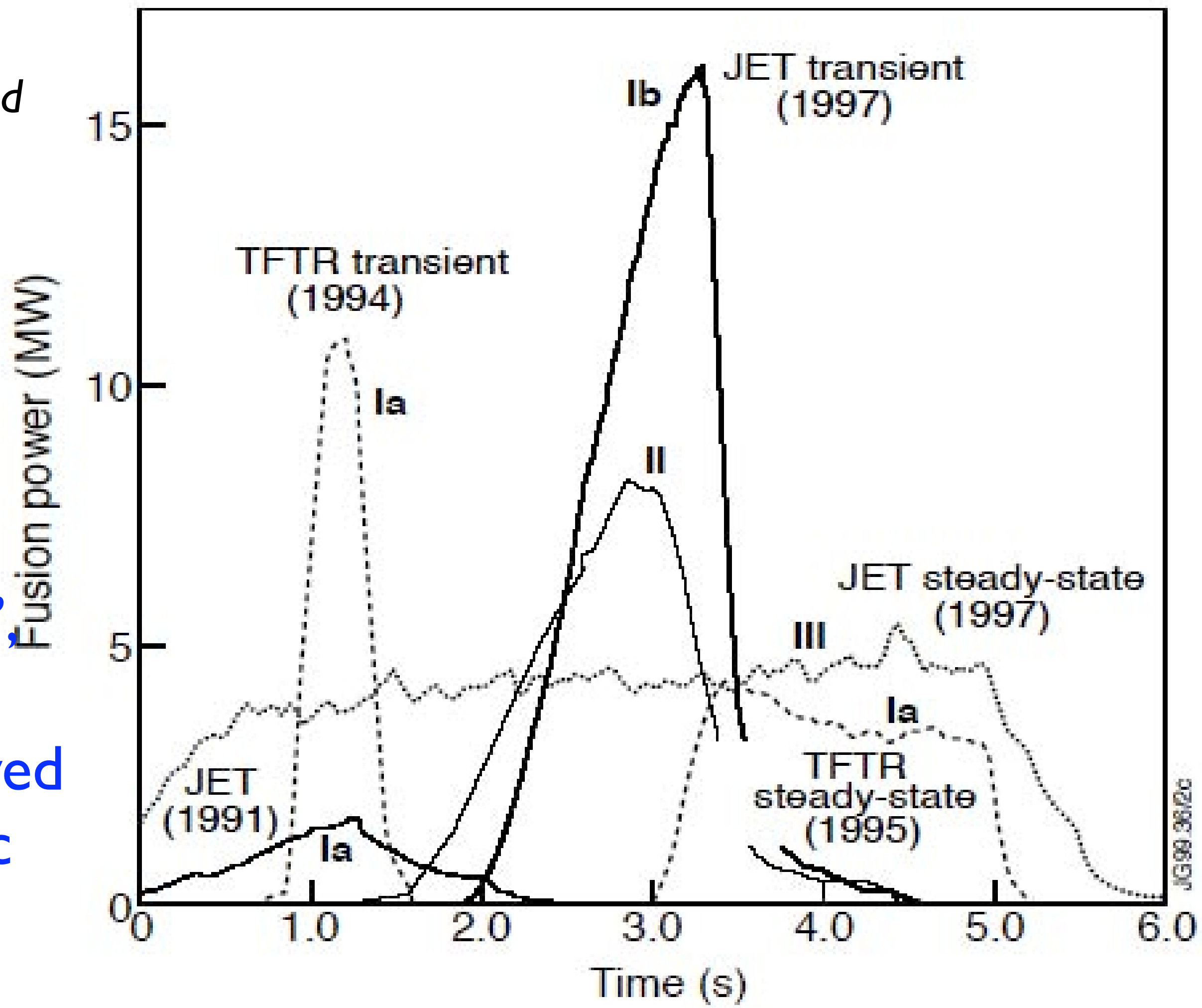
Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines), in different regimes:

(Ia) Hot-Ion Mode in limiter plasma

(Ib) Hot-ion H-Mode,

(II) Optimized shear and

(III) Steady-state ELMY-H Modes.



Establishes "scientific feasibility", *but* fusion power ≈ injected power. We have not yet observed fusion self-heating characteristic of a "burning plasma" nor developed the technologies needed for net power production

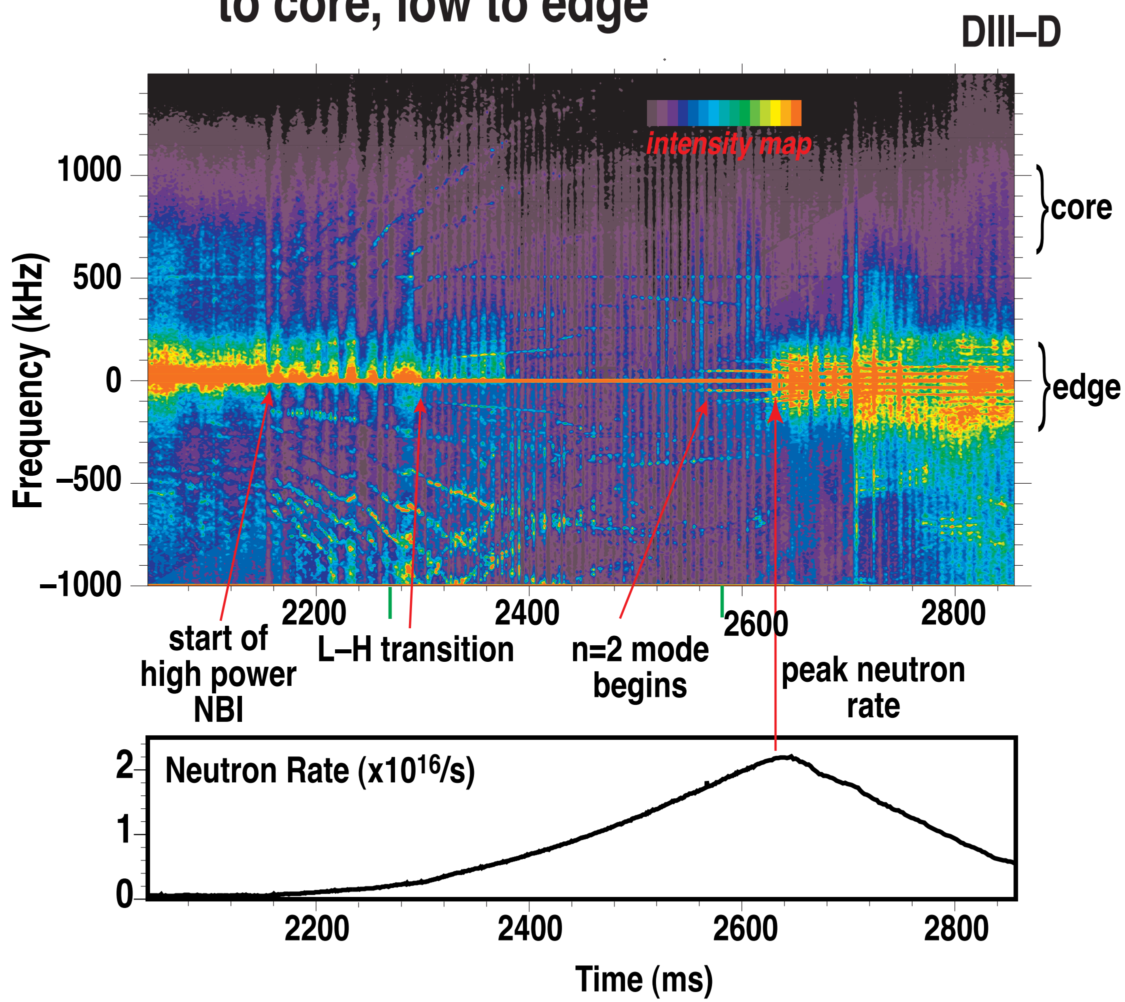
Understanding Plasma Confinement

- MHD stability at high plasma pressure
- High-power electromagnetic wave injection and heating
- Plasma-surface interactions, radiation, recombination, and particle flows
- *Suppression of plasma turbulence with flow*
- …

Example Research Advance: Controlling Turbulent Instability

Color contour map of fluctuation intensity as function of time from FIR scattering data

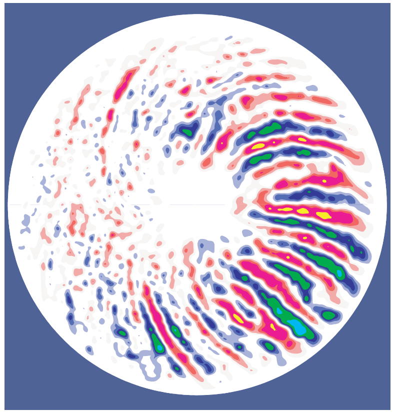
– **Higher frequencies correspond to core, low to edge**



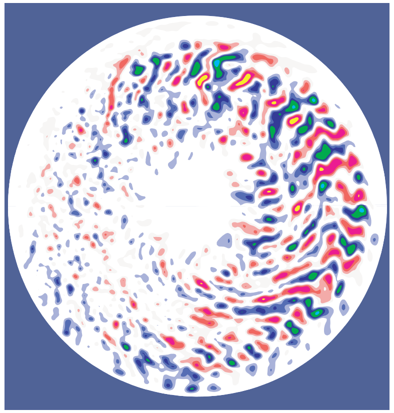
Measurement ⇔ Theory

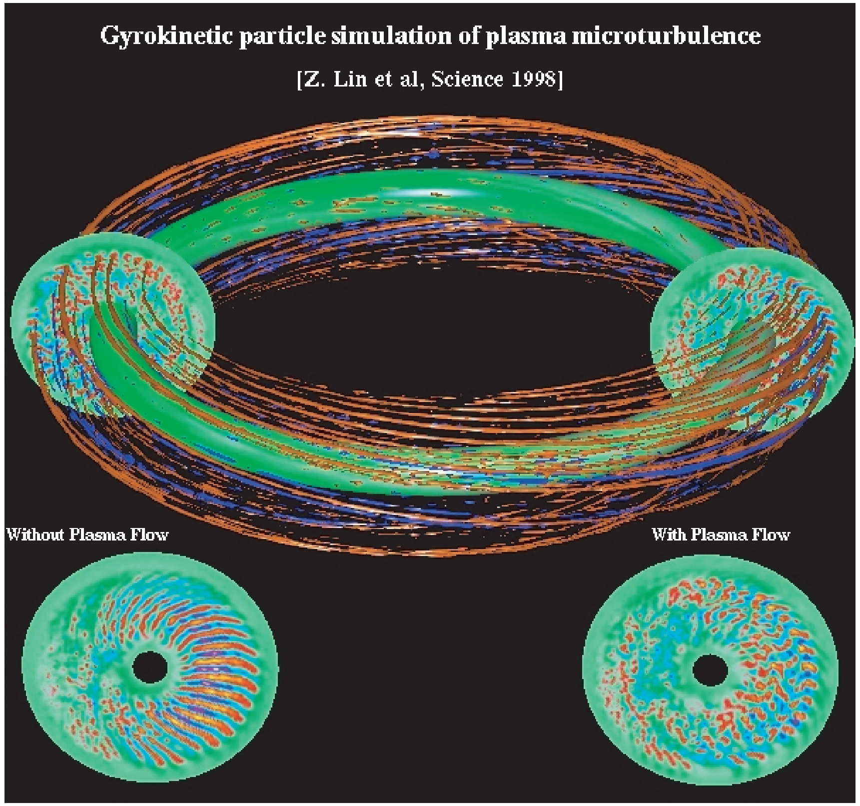
- Recent advance: Small scale sheared poloidal flows can shear apart radial eddies, reducing their radial step size and the transport by an order of magnitude

Without sheared flows



With sheared flows





Answers to the 7 AGCI Questions for Fusion

1. Practically no resource limit (10^{11} TW y D; 10^4(10^8) TW y ^{6}Li)
2. Fully-developed fusion economy could supply many 10's TW electricity and hydrogen. (Likely with advancing new materials.)
3. So far only a ~ 10's MW s produced in pulsed research devices. (Net power production requires next-step device.)
4. Fusion R&D must *significantly accelerate* for 2050 deployment. International 35 year "Fast Track" to "commercial demonstration" exists. (U.S. share ~ $25B.) Challenges: configuration choice, burn physics, & low-activation **materials** and components.
5. One or few ~ GWe power plants possible by 2050. Aggressive (~ 2-4% growth) scenarios suggest several TW by 2100.
6. Practically no limit once fusion technology has been established.
7. The laws of physics dictate the (relatively large) scale of fusion power devices. (**No** small **silver bullet!** nor small pilot-plant.)

MFE Next Steps (~ next decade)

- Complete configuration optimization
- Burning plasma physics

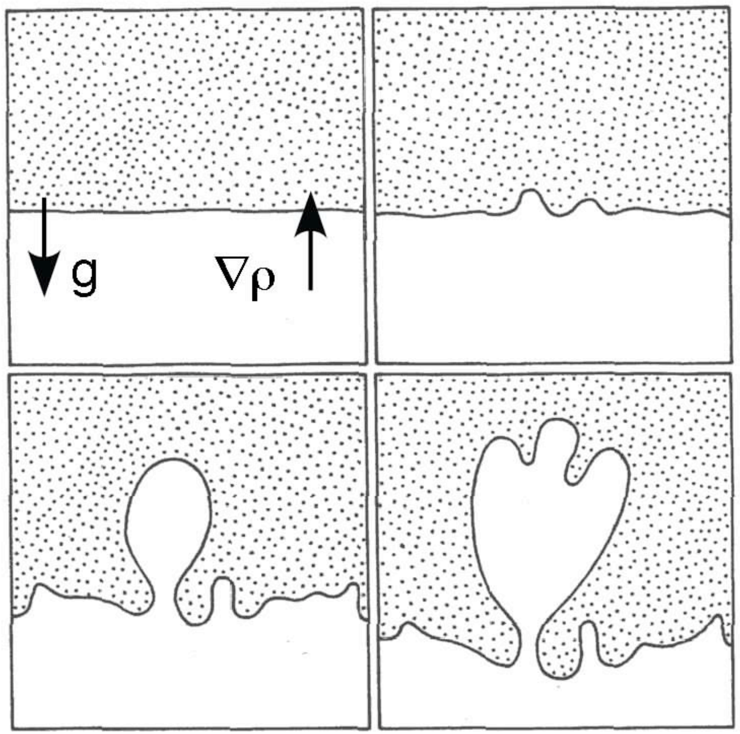
Configuration Optimization

- 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

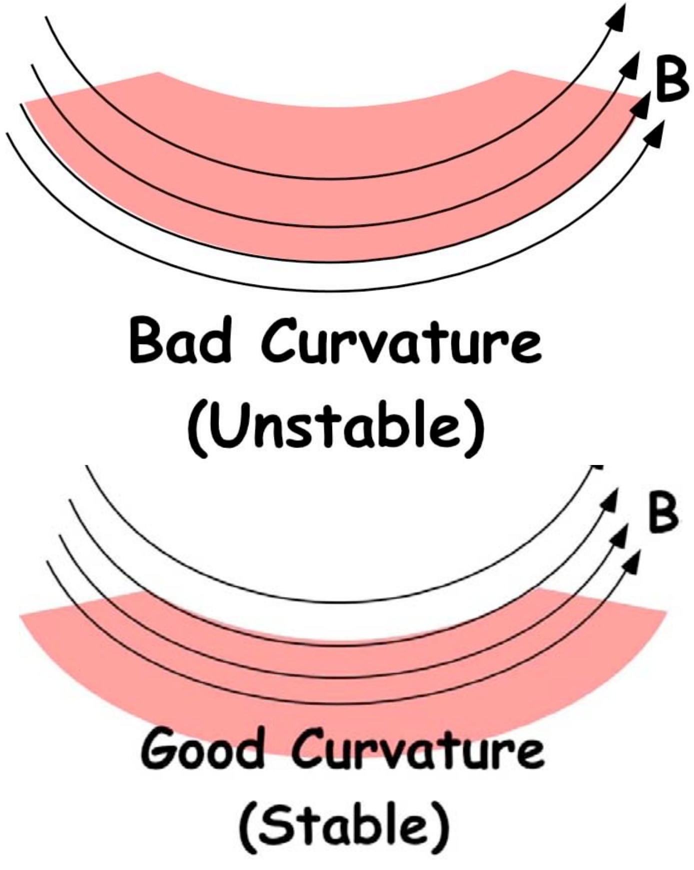
MFE Configuration Optimization

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

Interchange Instability

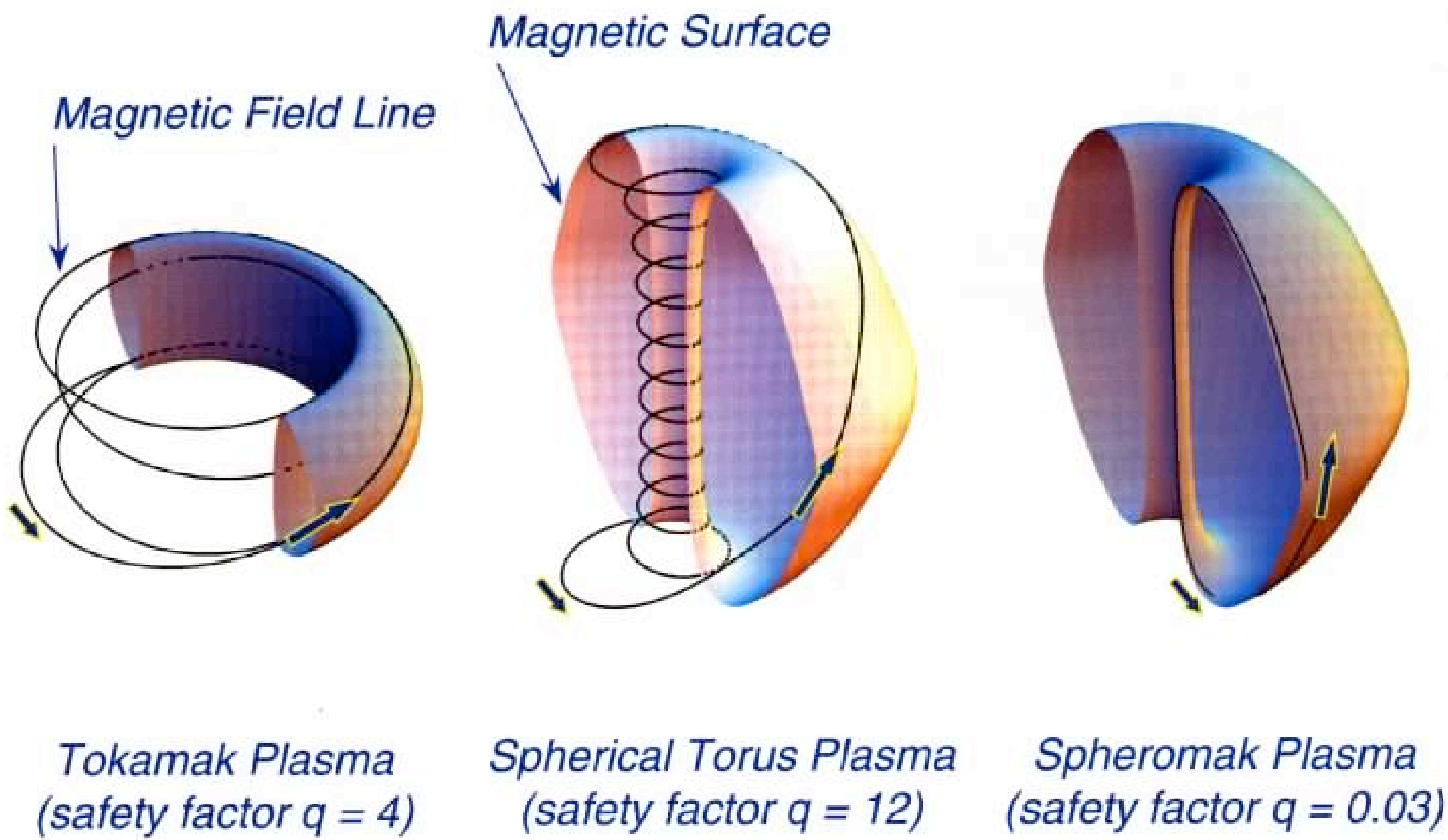


Bending Field à Effective g

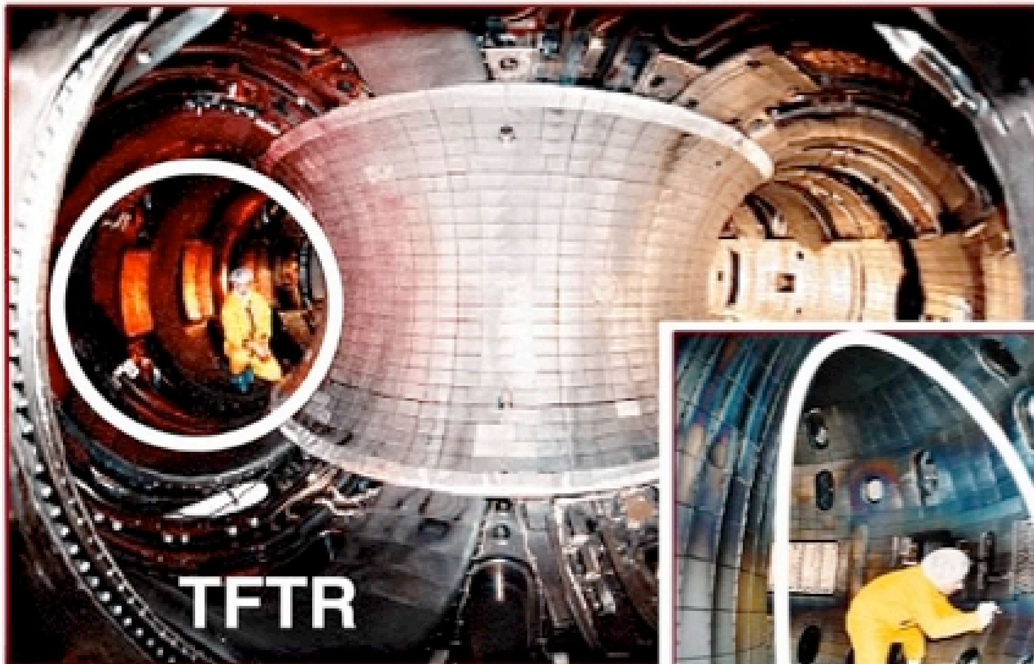


MFE Configuration Optimization

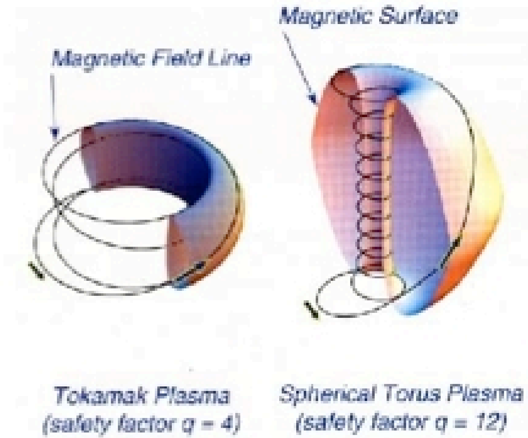
Fundamentally, the behavior of magnetically-confined plasma depends upon the shape of the magnetic flux tube…



Higher Pressure Through Shaping



DIII-D

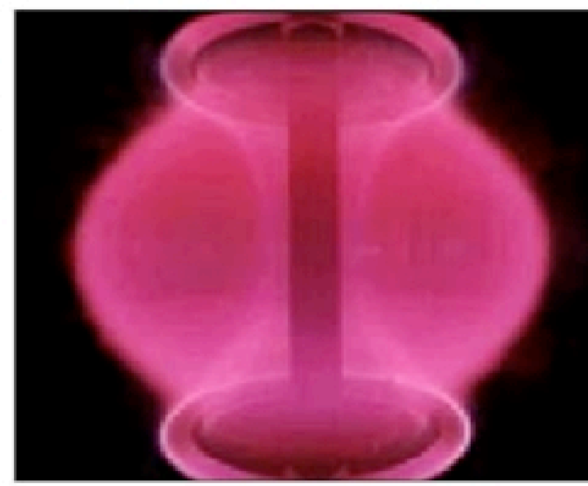


R/a = 2.9 :: 2.7 :: 1.3

β/χ = 0.03 :: 0.5 :: 1.8

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

START

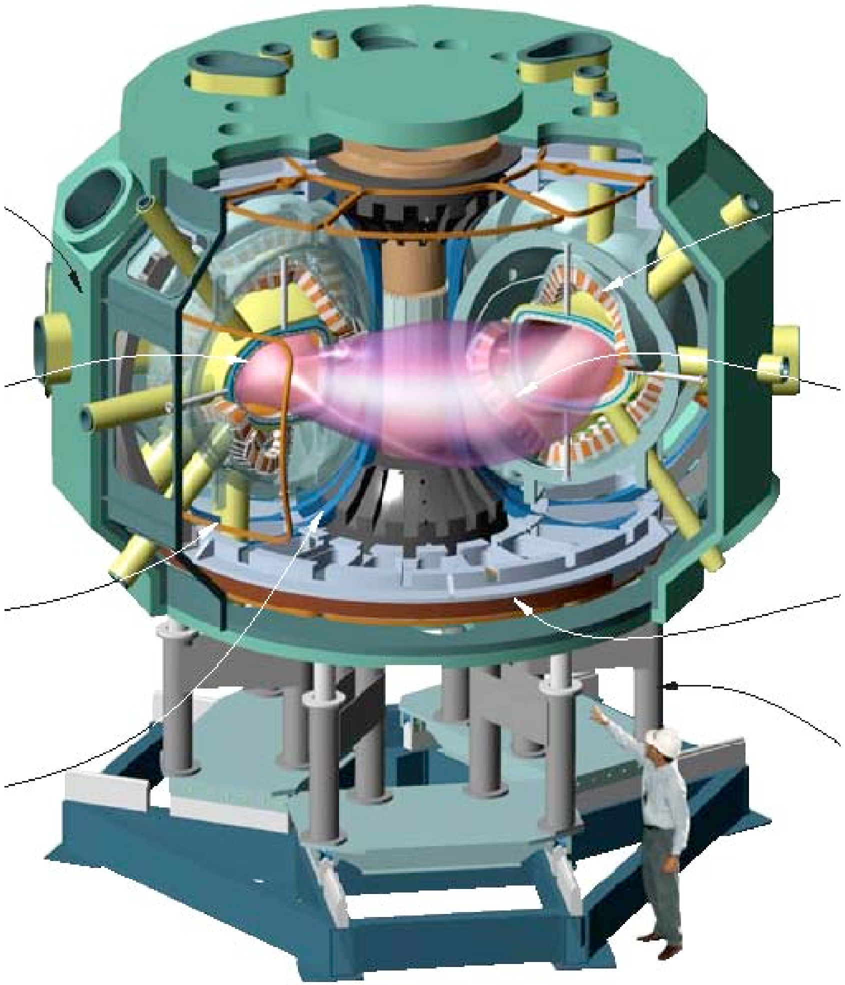


A plasma in the START experiment.

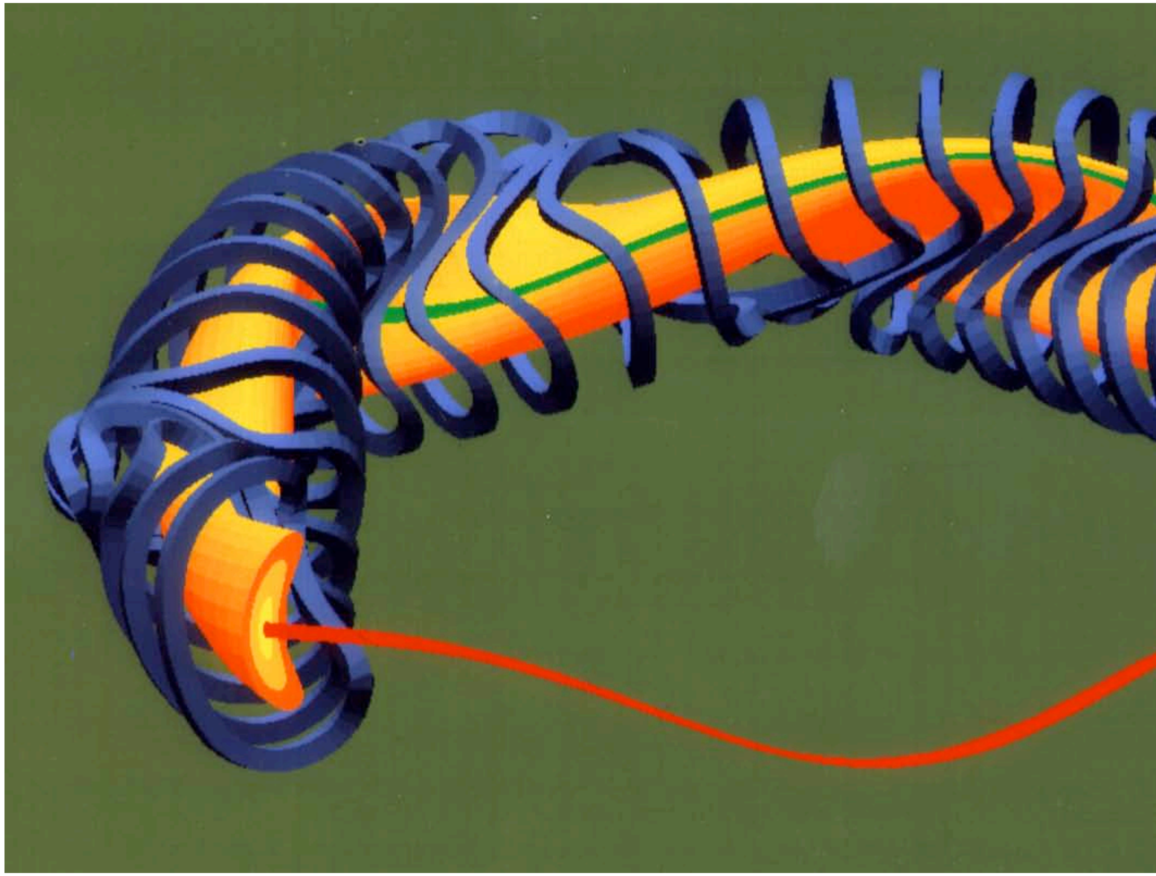
$\langle\beta\rangle$ = 38%

Configuration Optimization

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



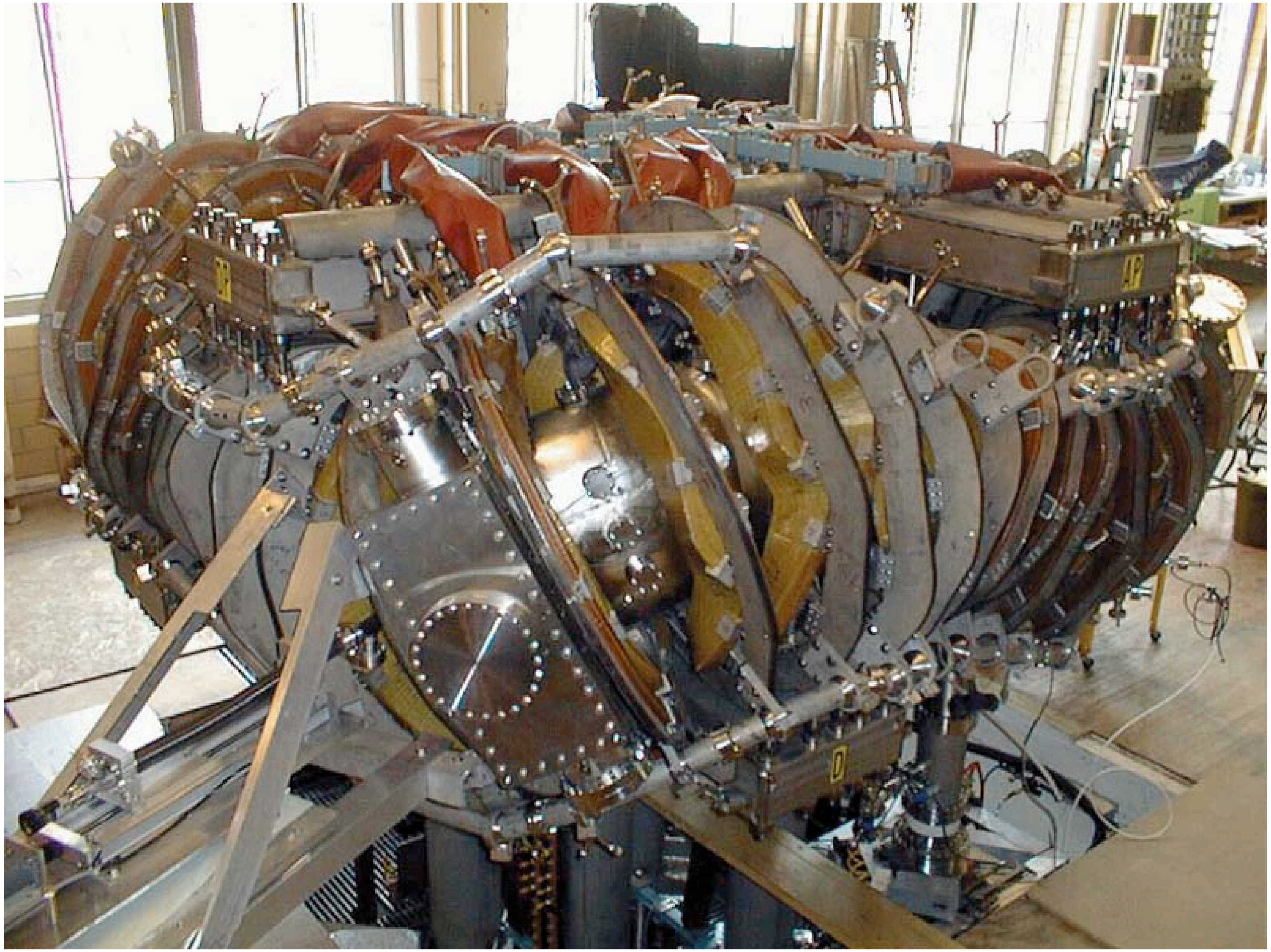
(**U.S.**) Compact, high-pressure plasma with Cu coils



(**German**) Robustly stable plasma with superconducting coils

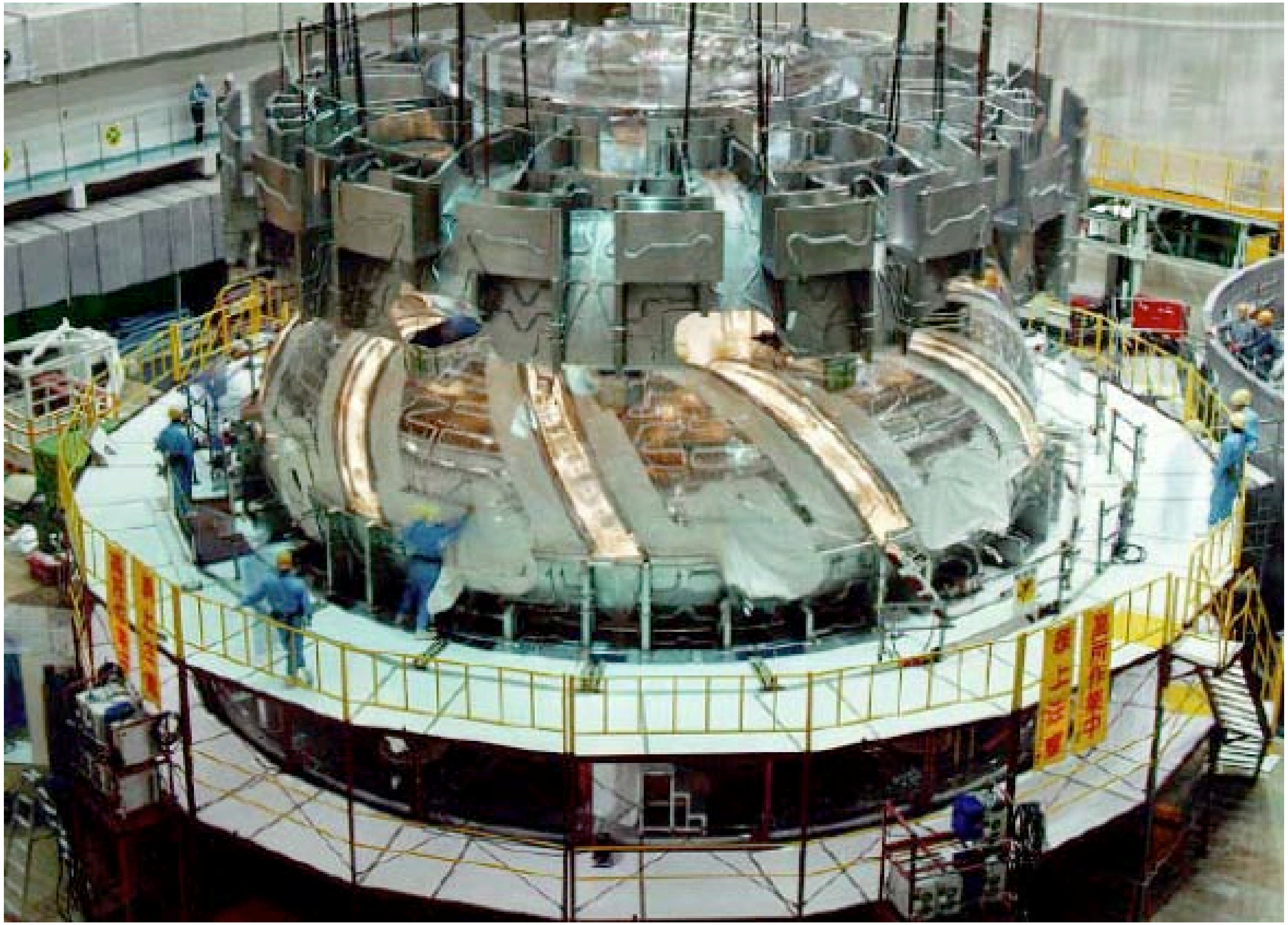
Configuration Optimization

(**University of Wisconsin**) Helical symmetry…

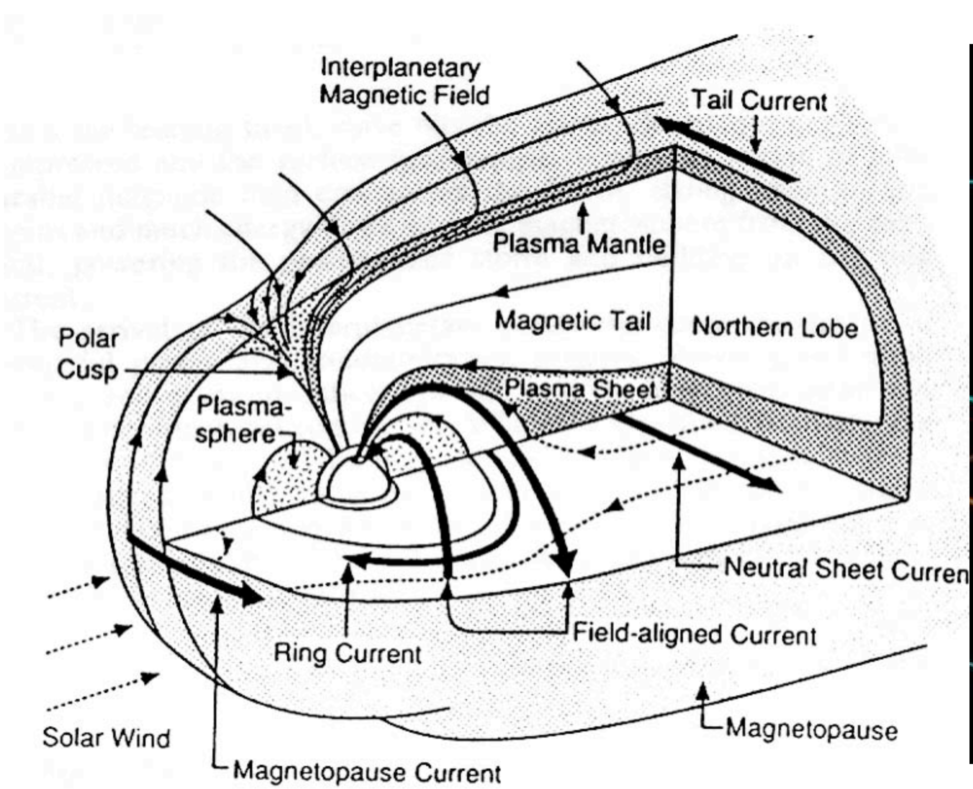


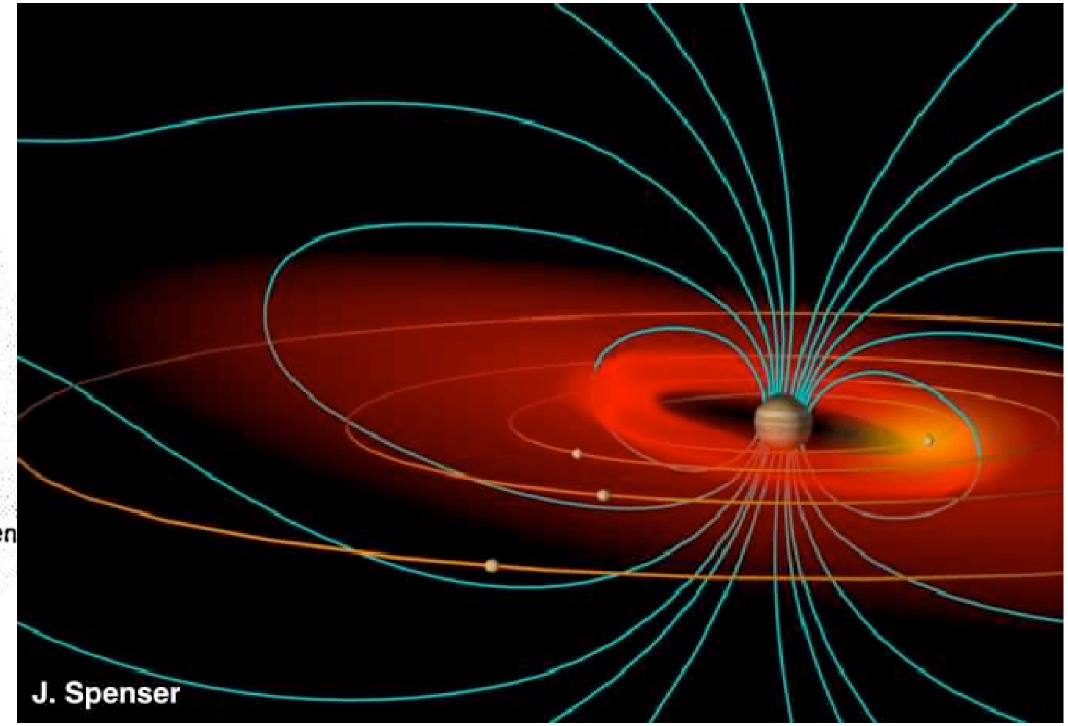
Configuration Optimization

(**Japan**) Large superconducting helical coils…



Learning from Nature's Way to Confine High-Pressure Plasma





Steady Plasma Circulation

High Pressure Confinement

Other fuel cycles are possible, but *more challenging*, e.g.

D-D (^{3}He) Fusion

$$\overbrace{\begin{array}{lrcl} Plasma: & D + D & \rightarrow & {}^3\mathrm{He}\,(0.82\mathrm{MeV}) + \mathrm{n}\,(2.45\mathrm{MeV}) \\ & D + D & \rightarrow & \mathrm{T}\,(1.01\mathrm{MeV}) + \mathrm{H}\,(3.02\mathrm{MeV}) \\ & 2 \times [D + {}^3\mathrm{He} & \rightarrow & {}^4\mathrm{He}\,(3.6\mathrm{MeV}) + \mathrm{H}\,(14.7\mathrm{MeV})] \\ & \mathrm{T} & \rightarrow & \text{extract to long-term storage} \\ 12.3\ years: & \mathrm{T} & \rightarrow & {}^3\mathrm{He} + e^- + (0.019\mathrm{MeV}) \end{array}}^{6D}$$

^{3}He

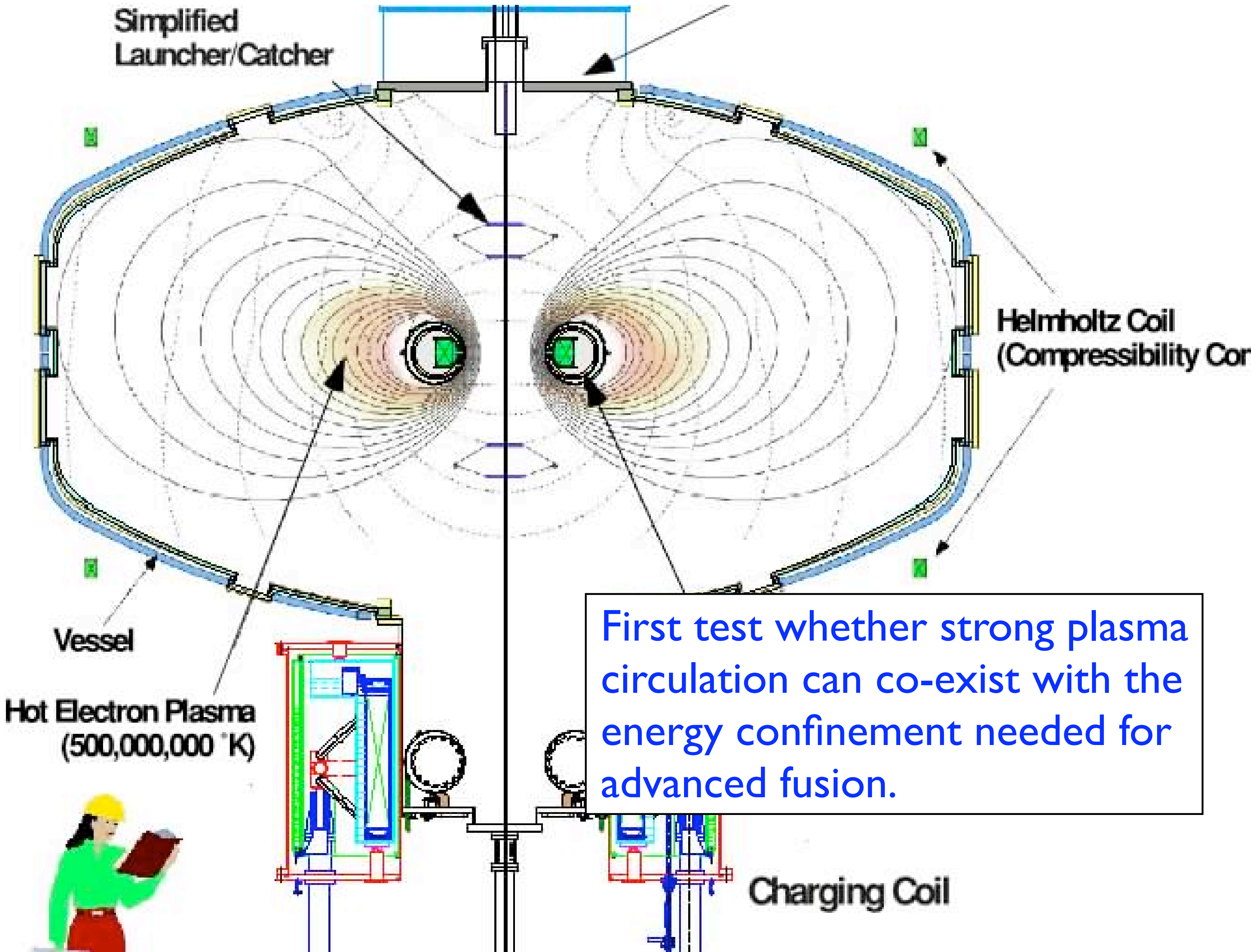
T

$$\approx 2\,({}^4\mathrm{He}) + 3H + e^- +$$

Can we extract T without extracting energy?

- Significantly reduced f... d then first wall. Simplifies fusion component technologies.
- Next easiest fusion fuel cycle, but requires confinement ~25 times better than D-T(Li) **and** T extraction (only for MFE).
- Equally challenging, but exciting, D-D options exist for IFE.

Levitated Dipole Experiment

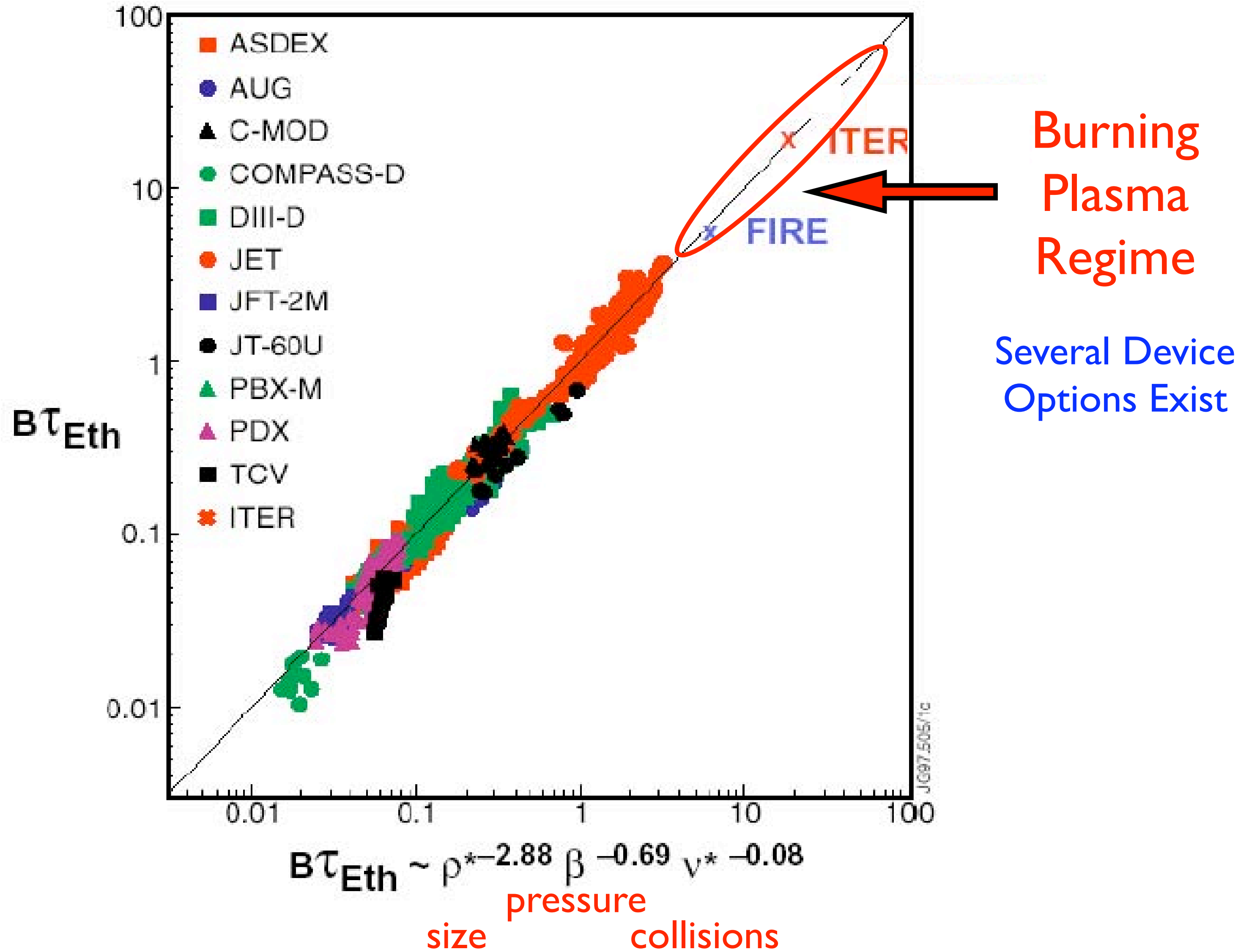


First test whether strong plasma circulation can co-exist with the energy confinement needed for advanced fusion.

Burning Plasma Experiment

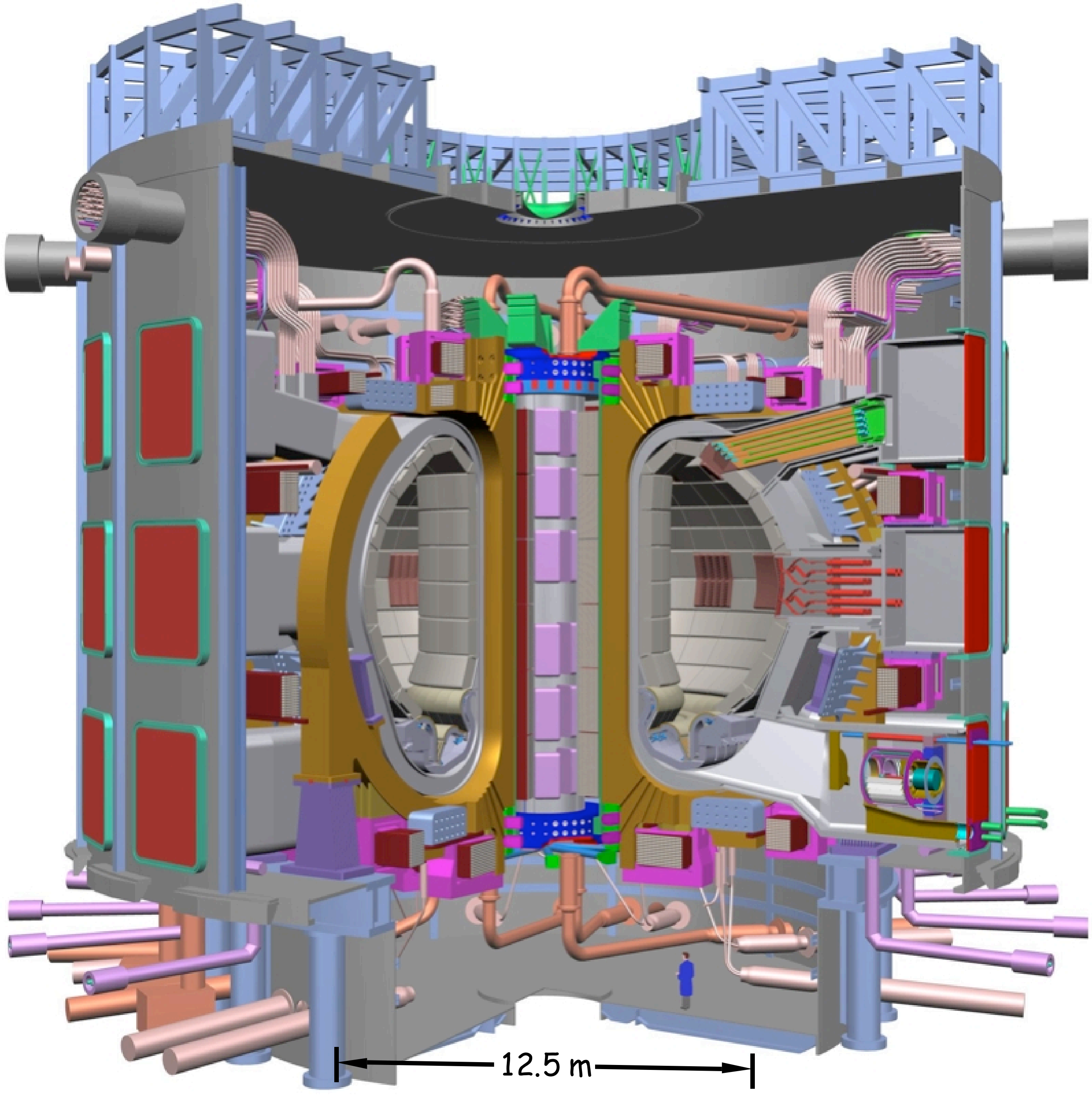
- Demonstrate and study strong fusion self-heating in near steady-state conditions:
    - Strongly self-heating:
        - 500 MegaWatts; Fusion power gain ~ 10
        - ~ 70 % self-heating by fusion alpha particles
    - Near steady state:
        - 300 to > 3000 seconds; Many characteristic physics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

Burning Plasma Regime is Reasonable Extrapolation from World's Database



Several Device Options Exist

ITER: The International Burning Plasma Experiment



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

Physics

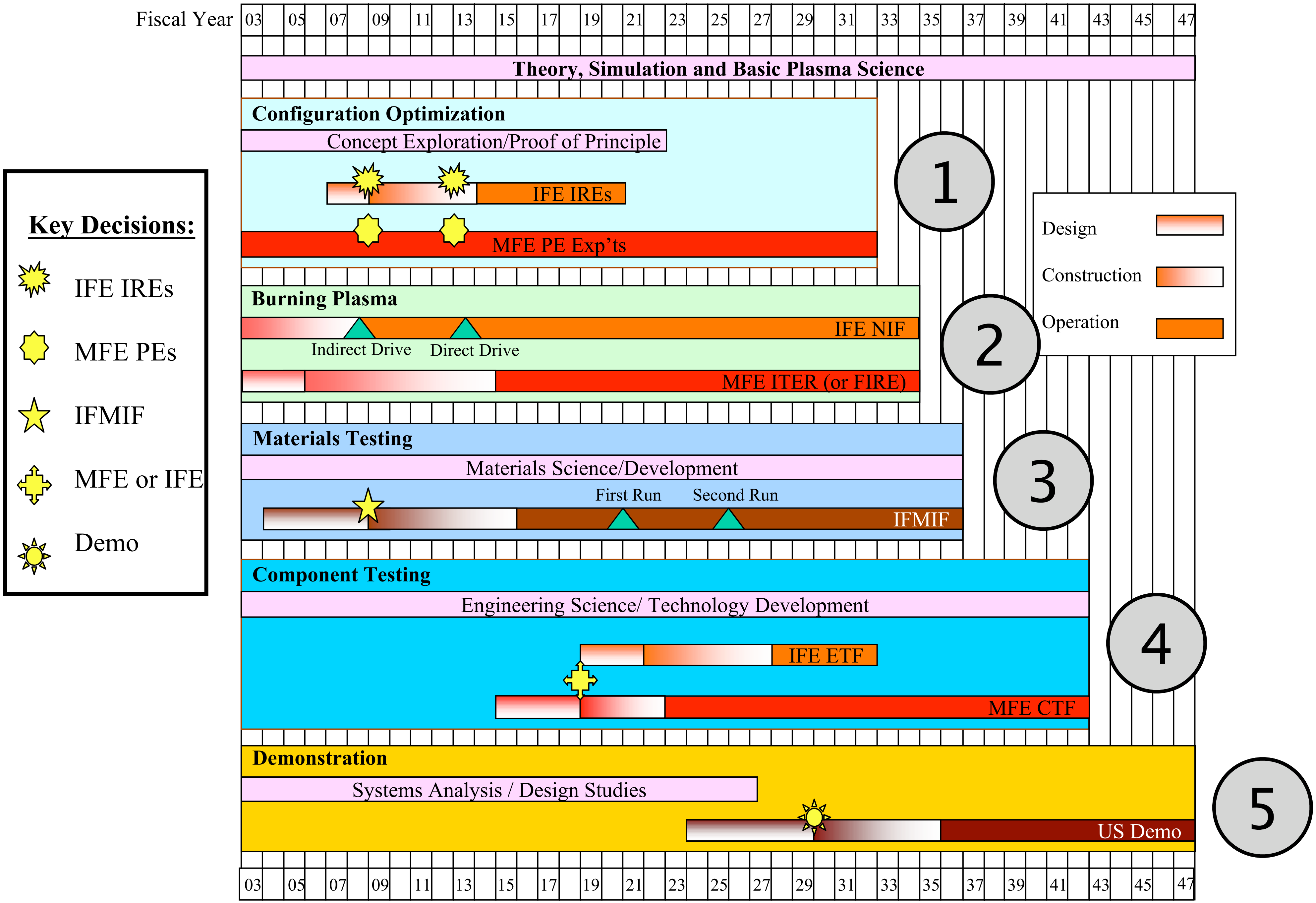
Technology Testing

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

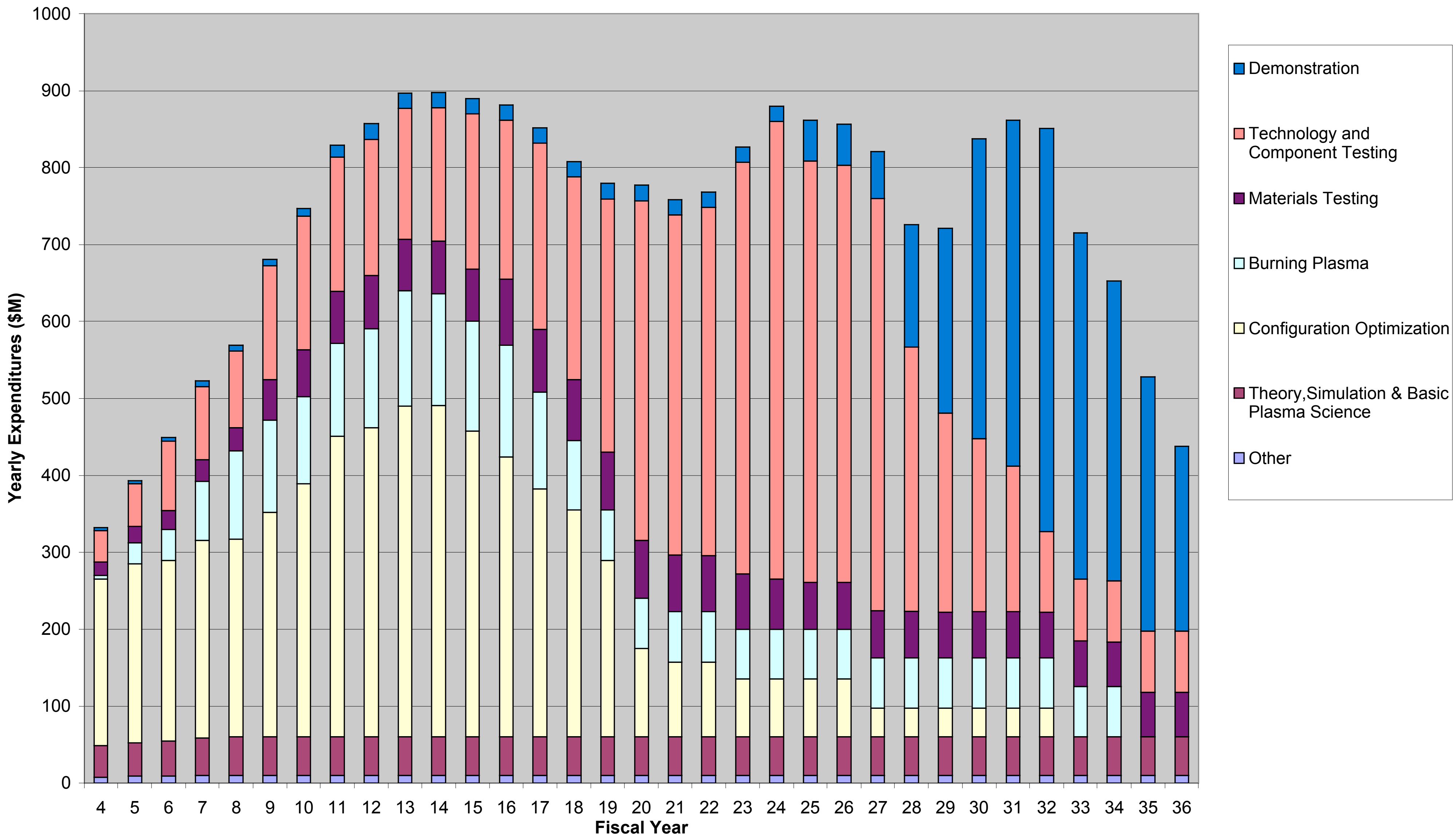
International Fast-Track to Fusion

- 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 fusion commercial development, ~ 35 years
- US FESAC Plan (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 and NAS program.

Detailed 5-Part Plan & Decisions



Double US Fusion Budget over the Next Five Years.
With Positive Decisions, Return Fusion Funding ~ 1980 Levels



Total U.S. Cost: ~ $24B ($FY2002) ⇒ more than half-way done!

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.