Discovery Research in Magnetic Fusion Energy

or

“How we learn about magnetic containment and the potential to reduce the cost of fusion energy with alternate configurations”

Mike Mauel
Columbia University
http://www.columbia.edu/~mem4/

National Undergraduate Fusion Fellowship Program
13 June 2014

The slides for this talk are online at:
http://www.apam.columbia.edu/mauel/mauel_pubs/NUF2014-DiscoveryMagFusion.pdf

Outline

- **Columbia University's plasma physics experiments**
- **Plasma containment depends upon the shape of the magnetic field**
  - What can we learn by changing magnetic topology? Examples…
  - Stellarator: optimizing the helical plasma torus
  - Spheromak: Magnetic self-organization
  - ➡ Levitated dipole: "simplest" axisymmetric magnetic confinement
- **Fusion energy needs discoveries to overcome challenges to economic viability**
  - Over 200 tokamaks and soon there will be ITER…
    We know a lot about the challenging economics of tokamak-based fusion energy
  - Discoveries are needed from creative new scientific investigations

(2004) SPIDER-MAN 2

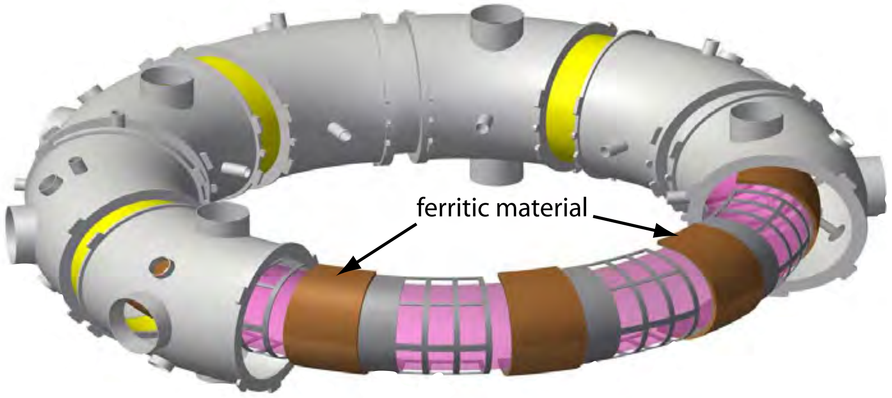
COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

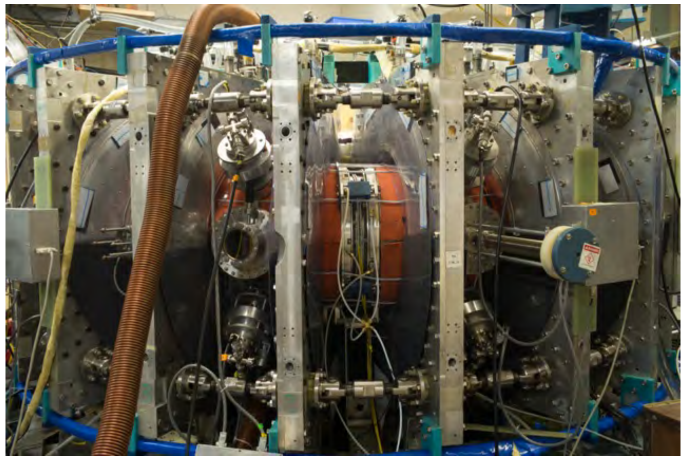
Columbia University Collaborator
Dr. Otto Octavius Stabilize Fusion in NYC…

Magnetized Plasma Physics Research at Columbia University

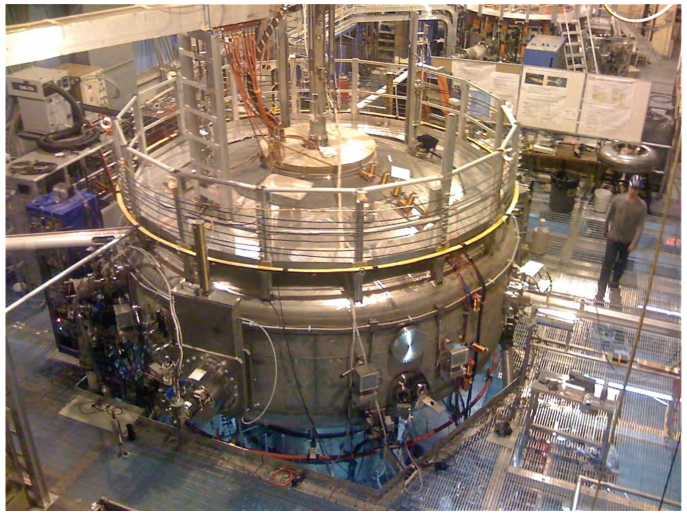
- CNT Stellarator

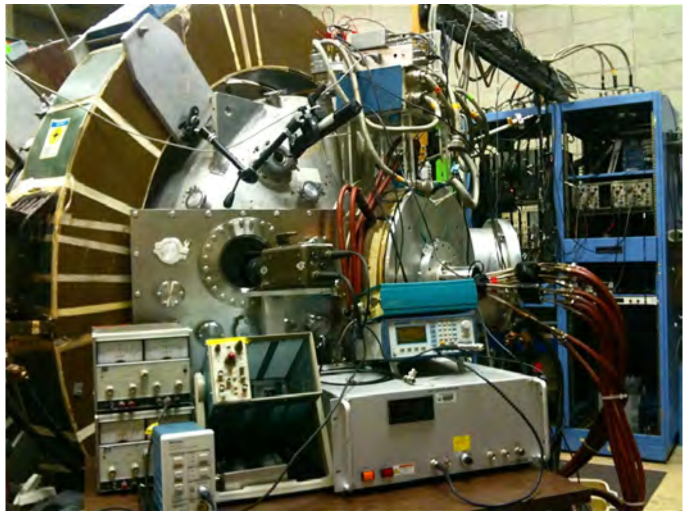
- HBT-EP Tokamak





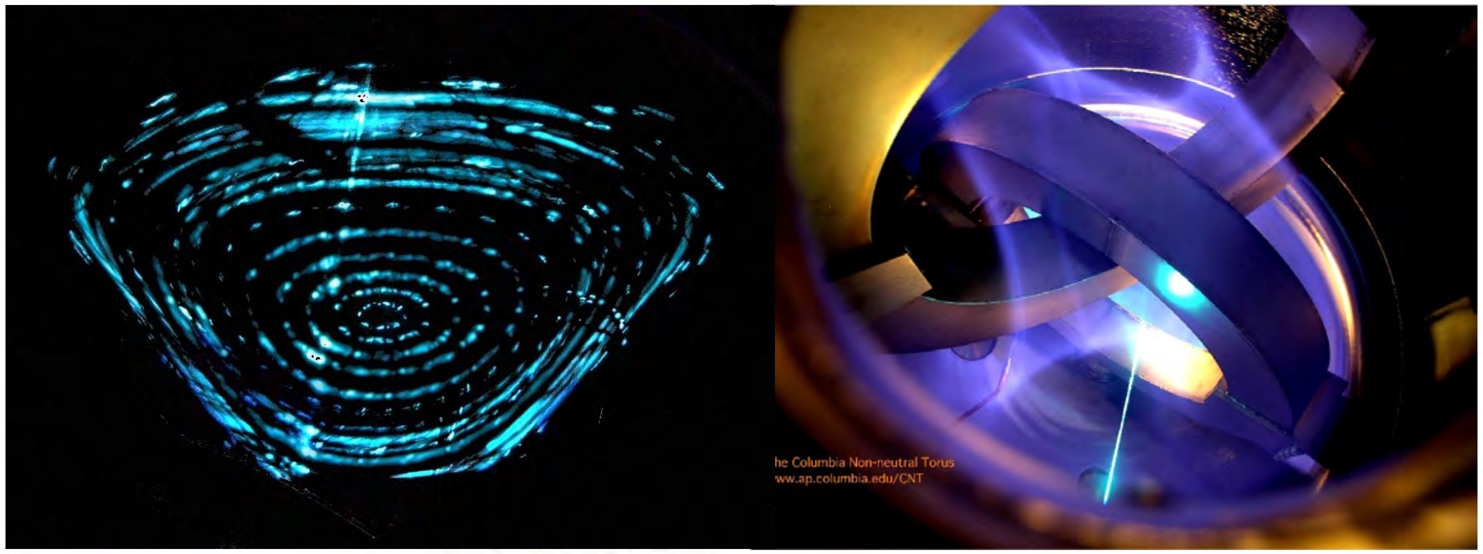
- CTX/LDX Dipole



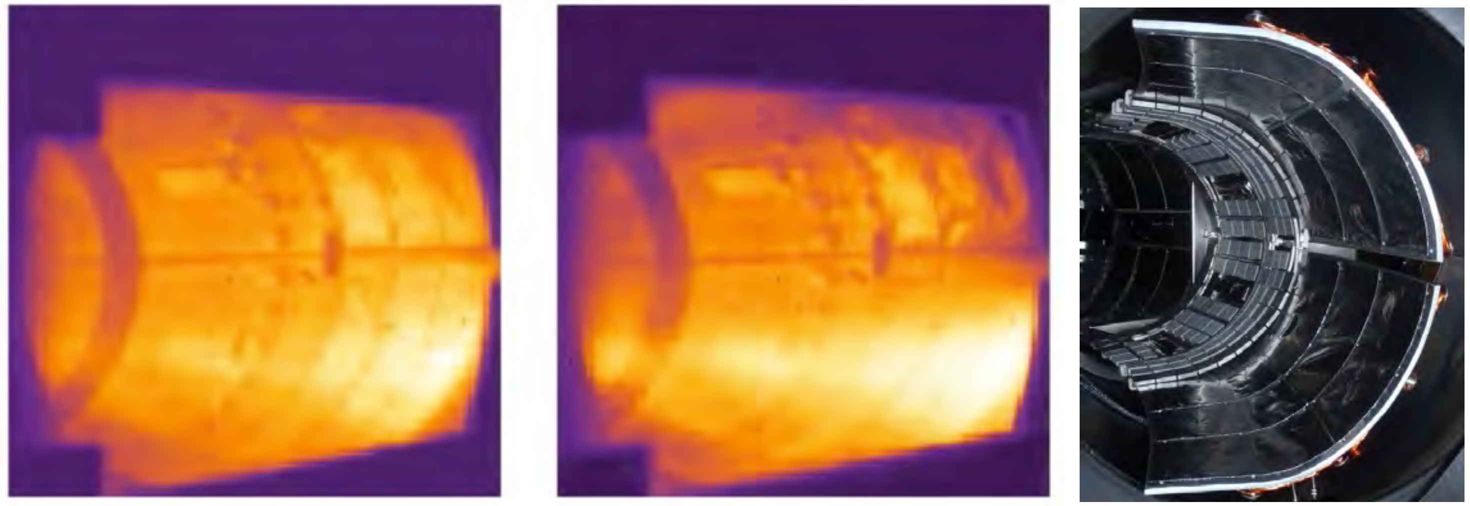


Magnetized Plasma Physics Research at Columbia University

- CNT Stellarator



- HBT-EP Tokamak



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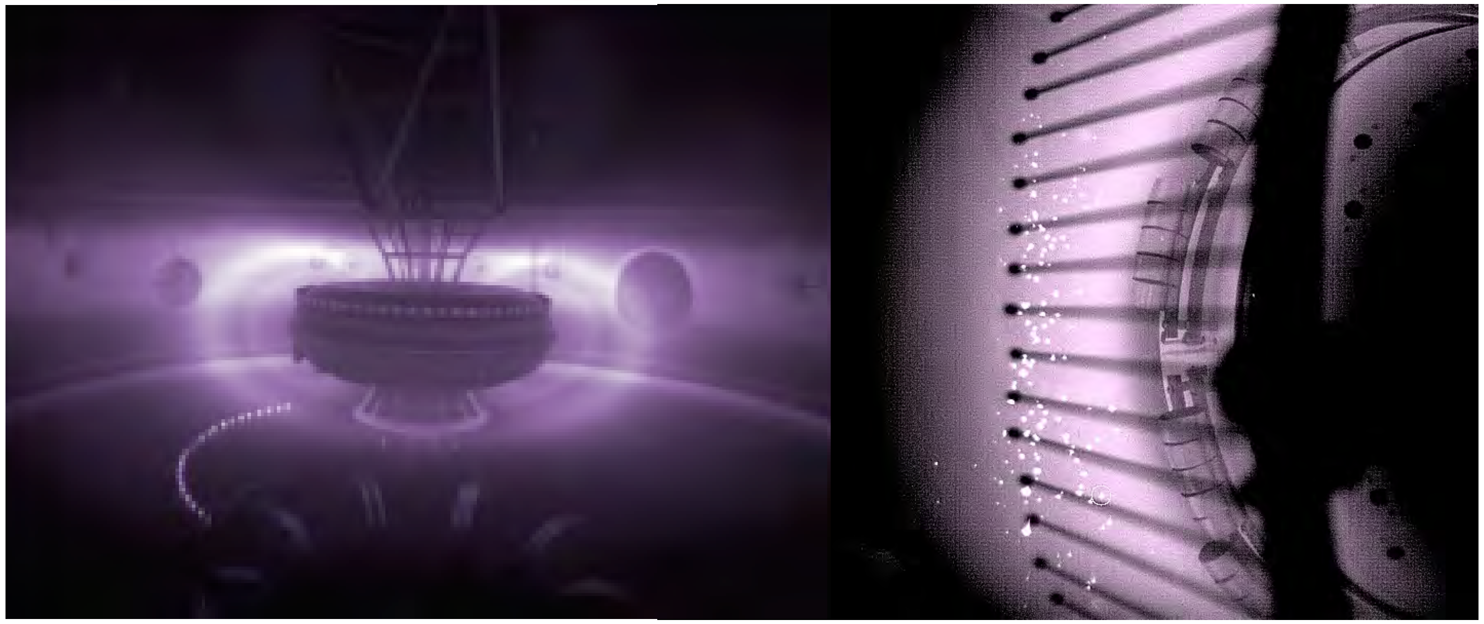


How Do Magnetic Fields Confine Ionized Matter?

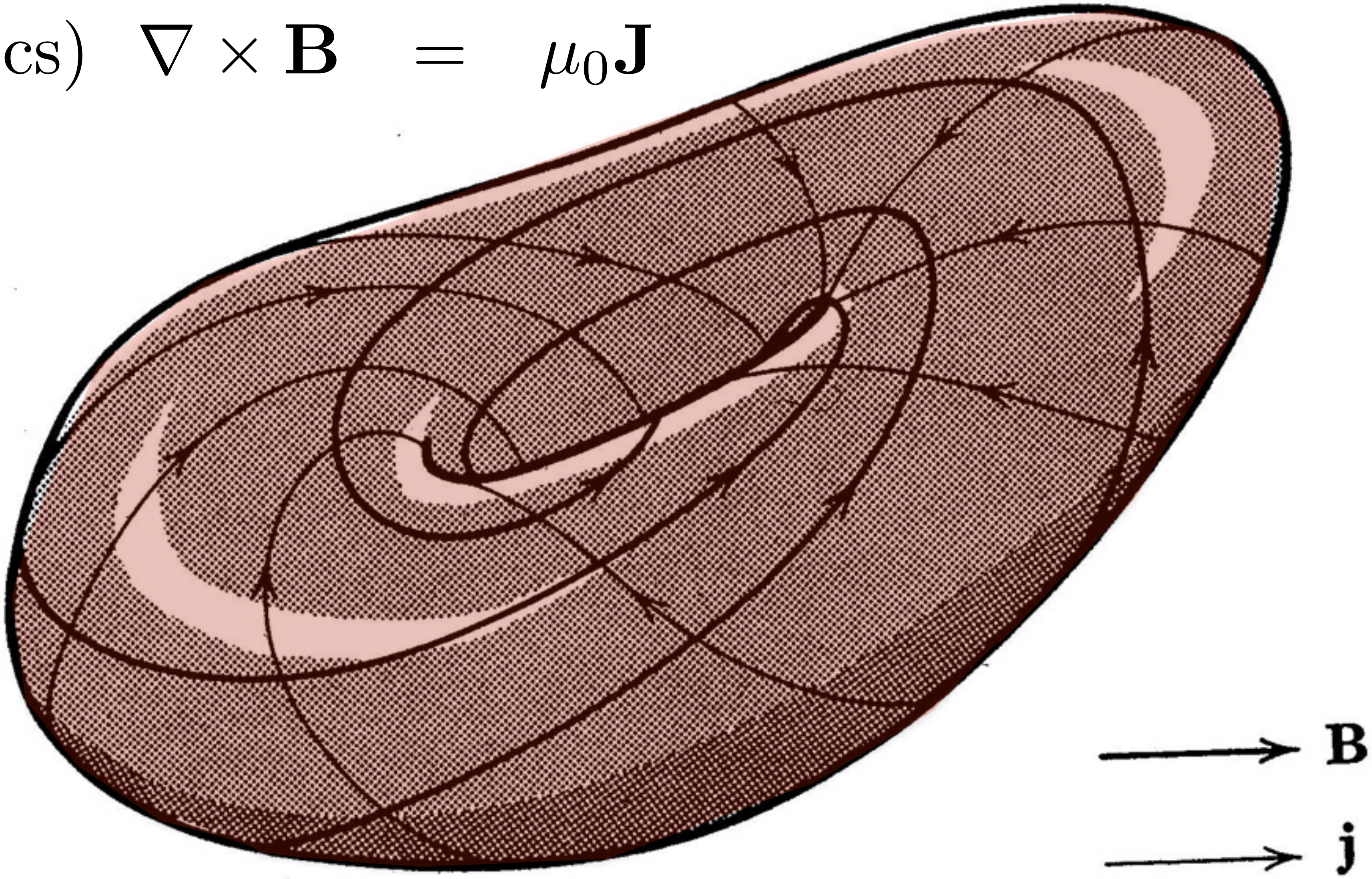
Equations of magnetic confinement…

$$\begin{aligned}
\text{(No monopoles)} \quad \nabla \cdot \mathbf{B} &= 0 \\
\text{(No charge accumulation)} \quad \nabla \cdot \mathbf{J} &= 0 \\
\text{(No unbalanced forces)} \quad 0 &= -\nabla P + \mathbf{J} \times \mathbf{B} \\
\text{(Magnetostatics)} \quad \nabla \times \mathbf{B} &= \mu_0 \mathbf{J}
\end{aligned}$$

Plasma Pressure

Plasma Current

Magnetic Torus



How Do Magnetic Fields Confine Ionized Matter?

Equations of magnetic confinement…

Plasma Pressure

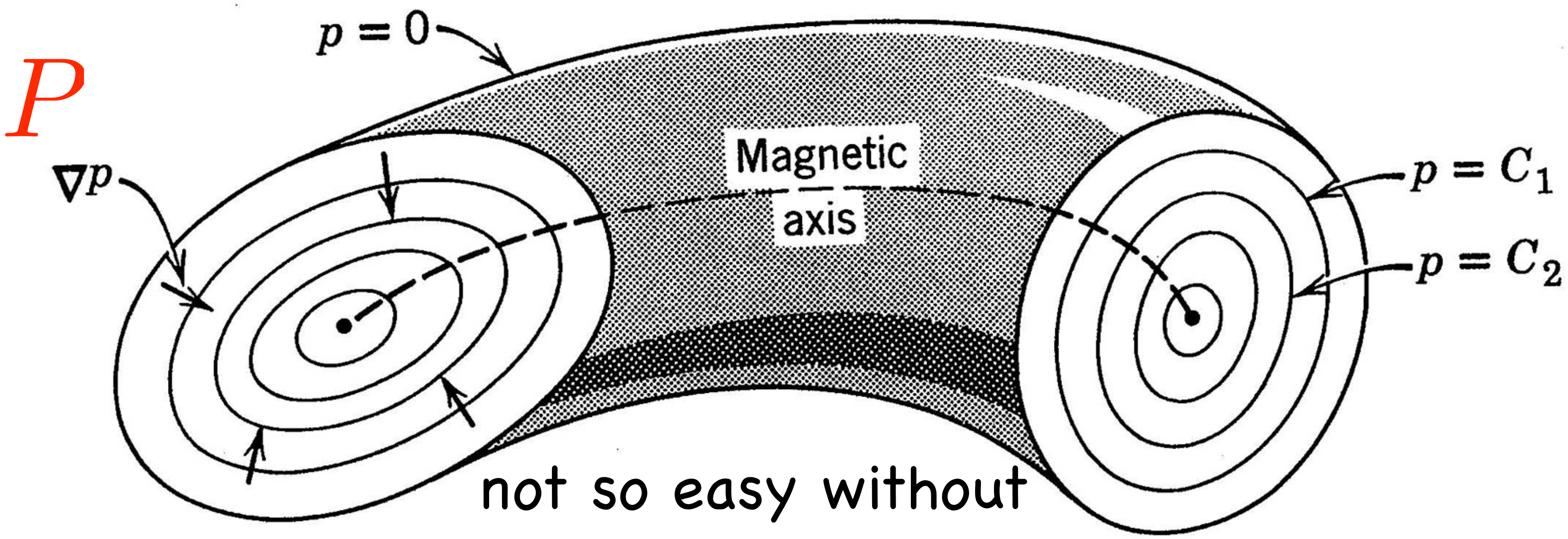
Plasma Current

$$\begin{aligned} \text{(No monopoles)} \quad \nabla \cdot \mathbf{B} &= 0 \\ \text{(No charge accumulation)} \quad \nabla \cdot \mathbf{J} &= 0 \\ \text{(No unbalanced forces)} \quad 0 &= -\nabla P + \mathbf{J} \times \mathbf{B} \\ \text{(Magnetostatics)} \quad \nabla \times \mathbf{B} &= \mu_0 \mathbf{J} \end{aligned}$$

Magnetic Torus

Surfaces of constant plasma pressure form nested tori

$$\begin{aligned} \mathbf{J} \times \mathbf{B} &= \nabla P \\ \mathbf{B} \cdot \nabla P &= 0 \\ \mathbf{J} \cdot \nabla P &= 0 \end{aligned}$$



not so easy without symmetry (chaotic fields)

Four Plasma Tori

- Axi-symmetric toroid with external poloidal currents (*fails*)

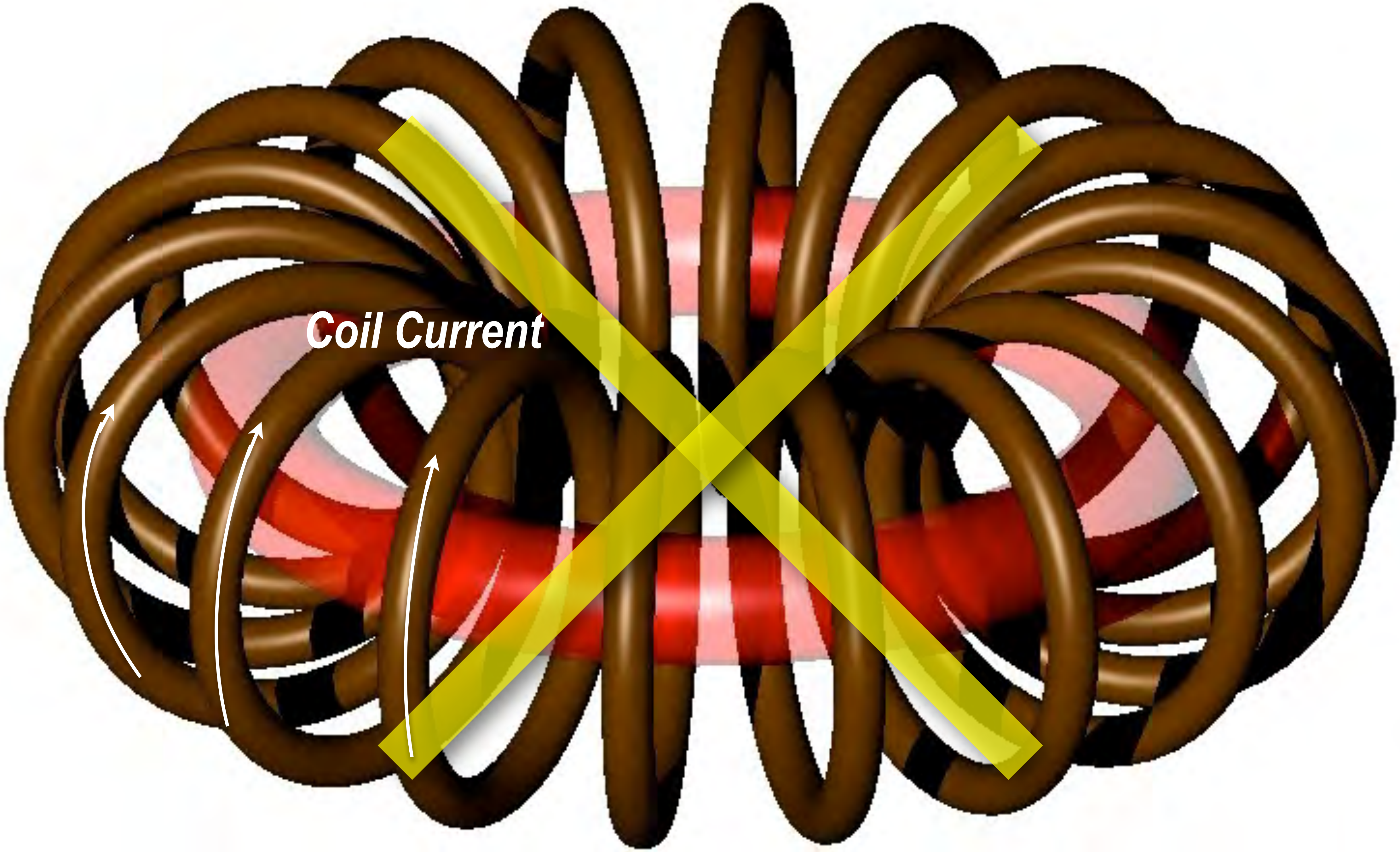
- Axi-symmetric toroid with internal toroidal current ("*levitated dipole*" *inside* the plasma)

- Axi-symmetric toroid with (mostly) external poloidal currents ***and*** (mostly) **plasma** toroidal current ("*tokamak*")

- Non-symmetric plasma torus with external helical coils ("*stellarator*")

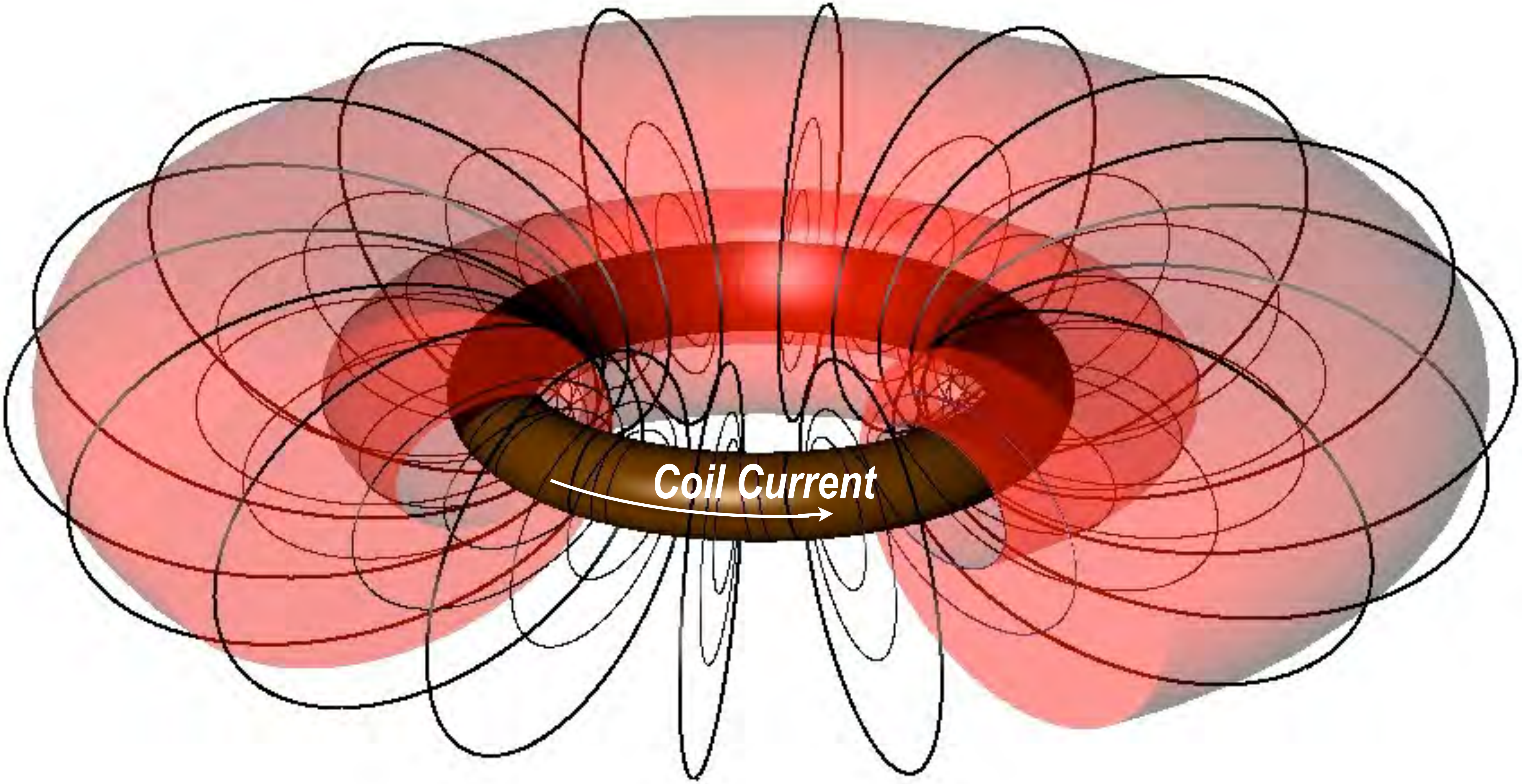
How to make a magnetic torus?

FAILS TO CONFINE PARTICLES



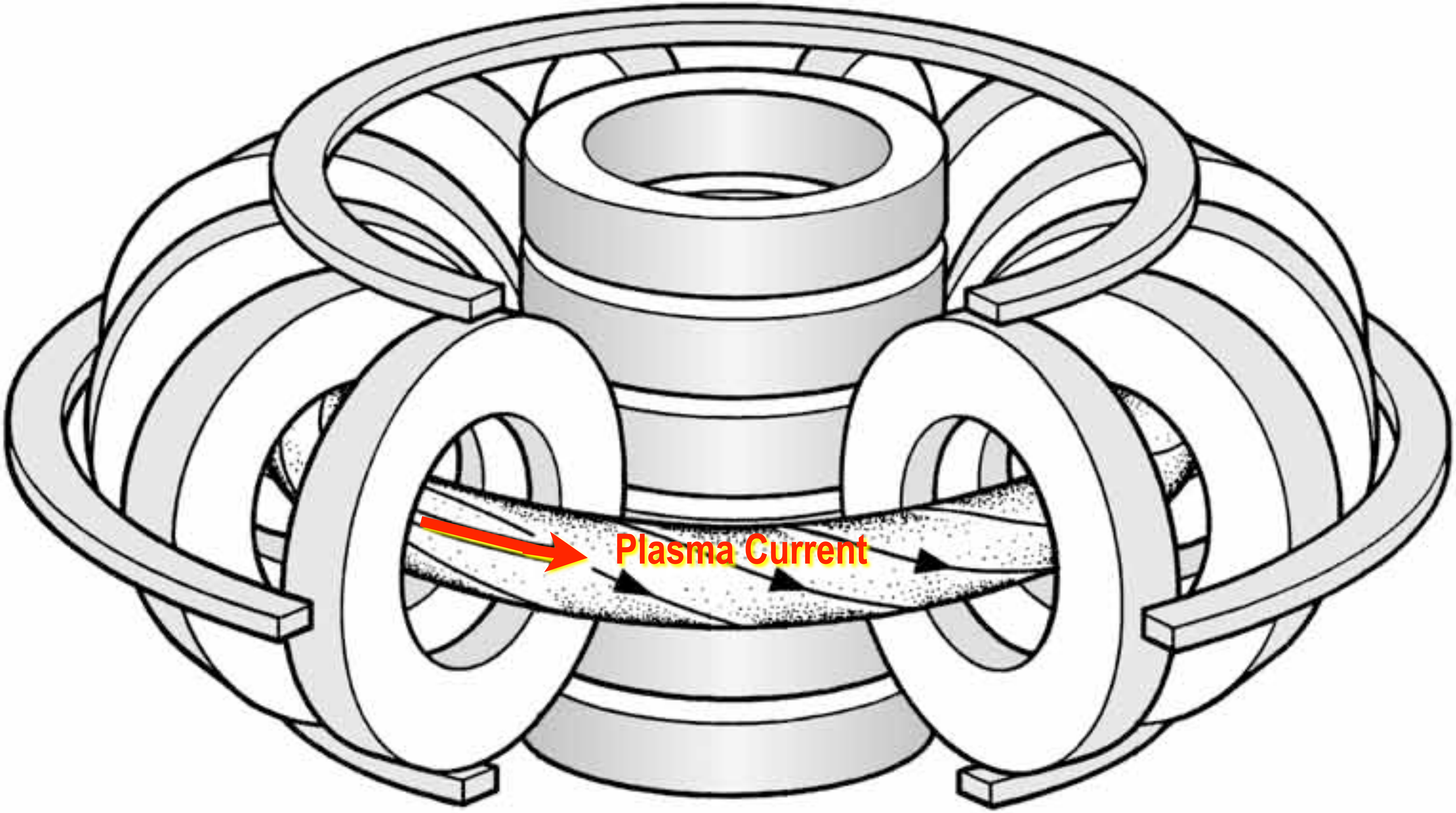
Toroidal Field from Poloidal Currents

How to make a magnetic torus?



Poloidal Field from Toroidal Currents

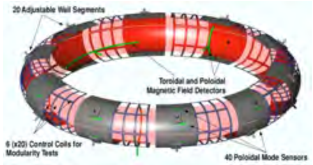
How to make a magnetic torus?



Combined Toroidal and Poloidal Field (Tokamak)

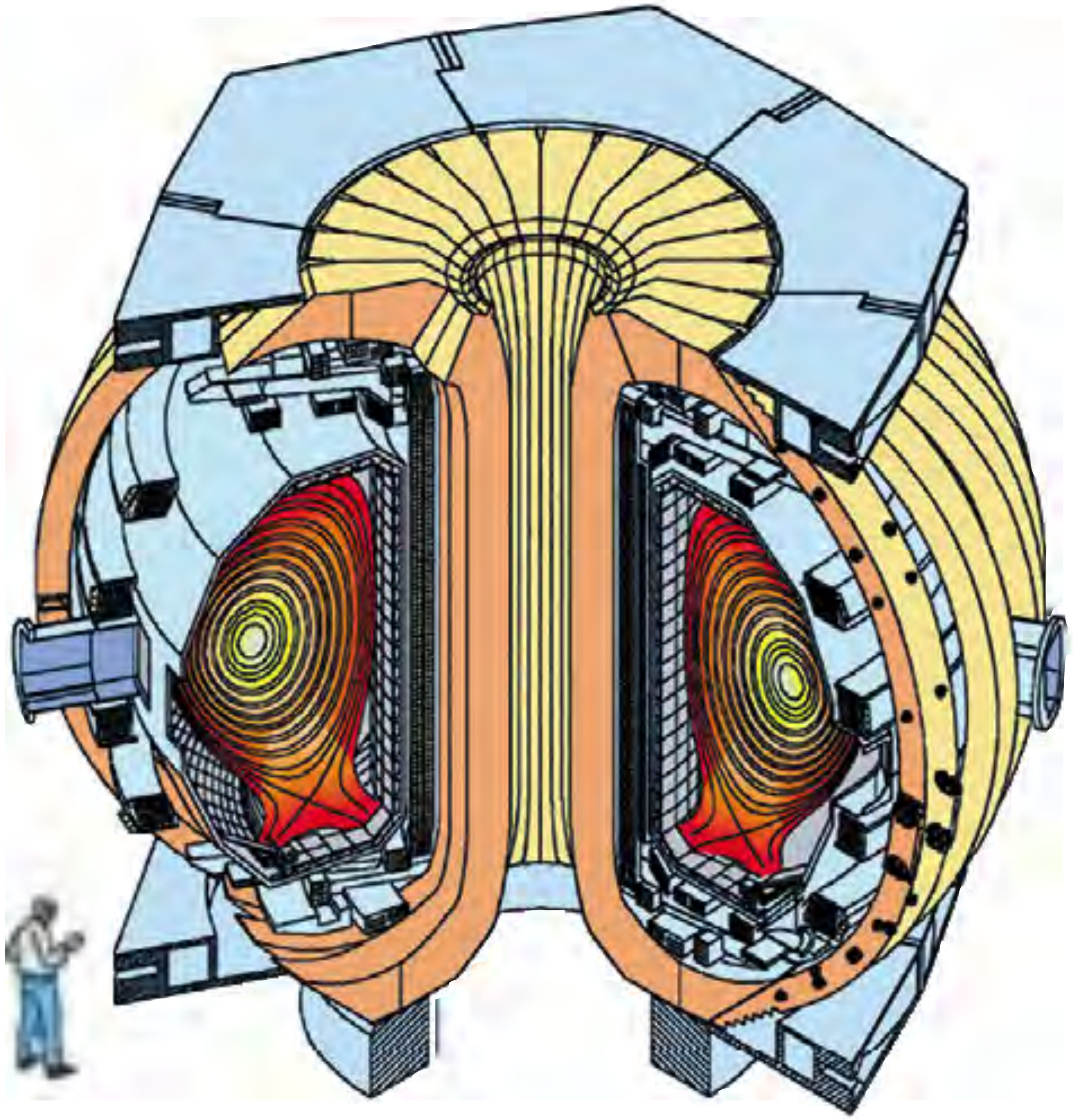
How to make a magnetic torus?

⊢ 1.8 m ⊣



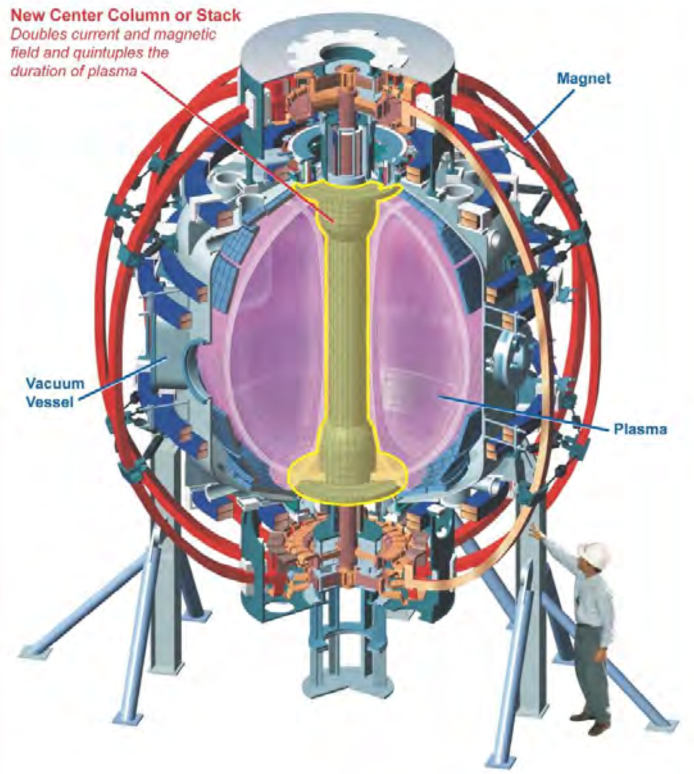
HBT-EP
Columbia University

⊢ 3.3 m ⊣



DIII-D
General Atomics

⊢ 1.7 m ⊣

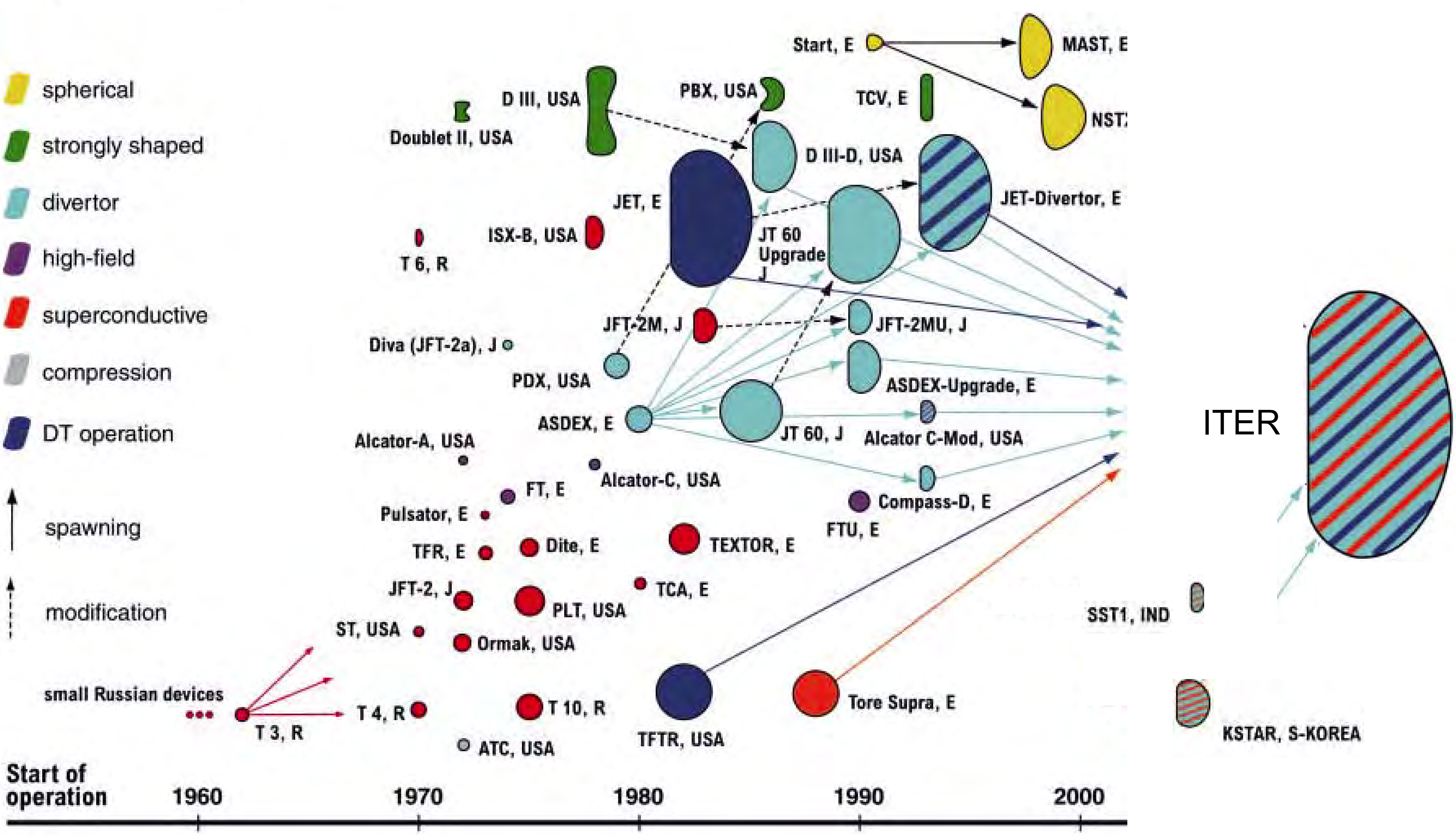


NSTX-U
PPPL

Combined Toroidal and Poloidal Field (Tokamak)

More than 200 Tokamaks

(*We know how tokamaks work relatively well.*)



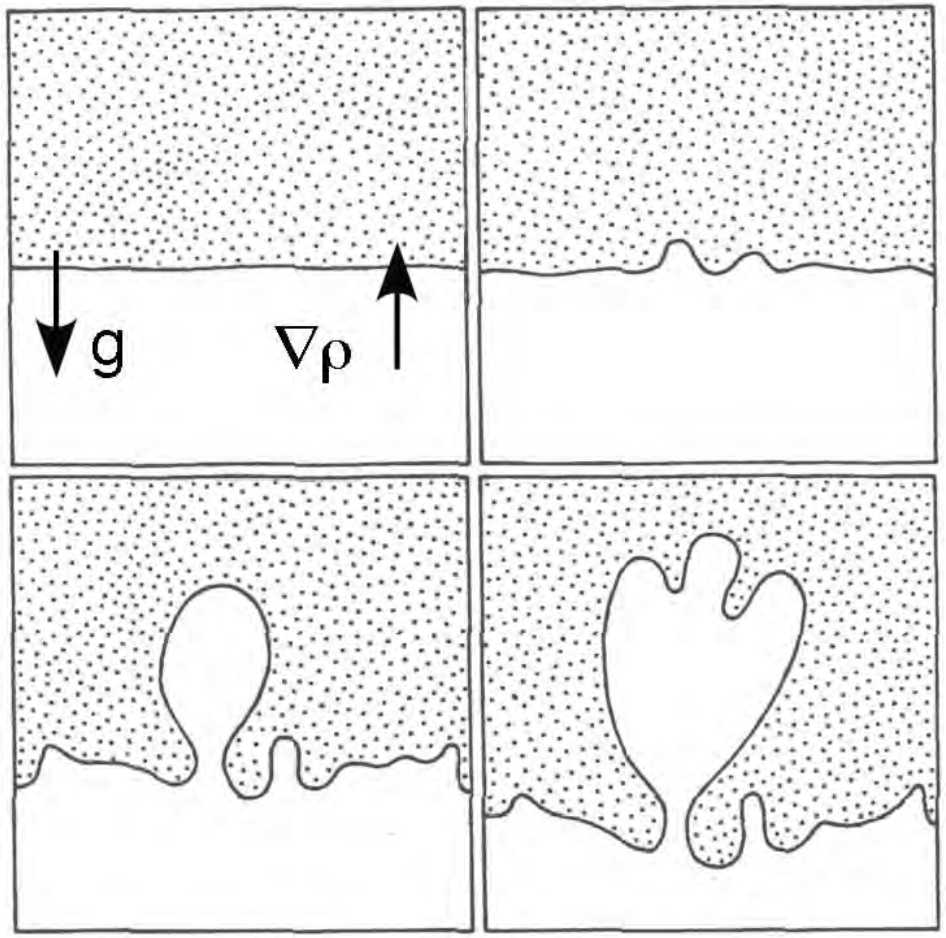
Mayor Tokamak Facilities

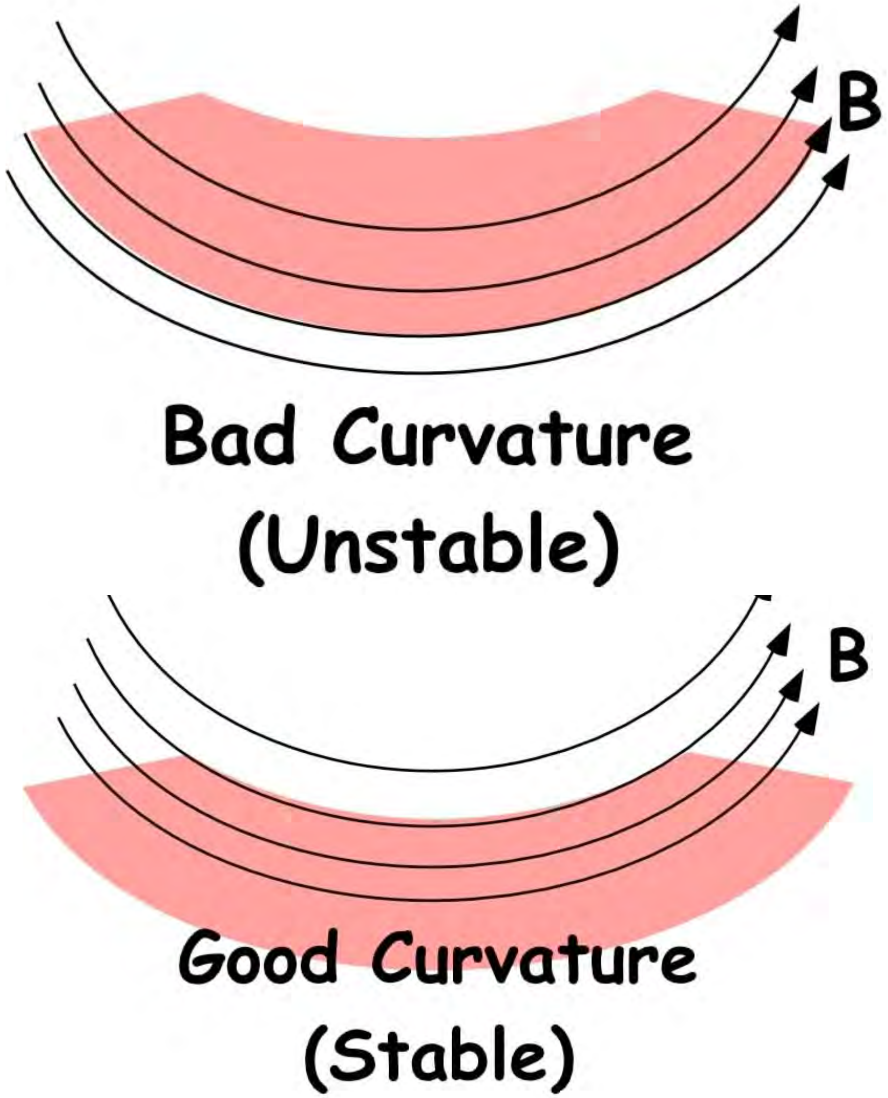
Magnetic Fusion Optimization Depends on Shape

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

Interchange Instability

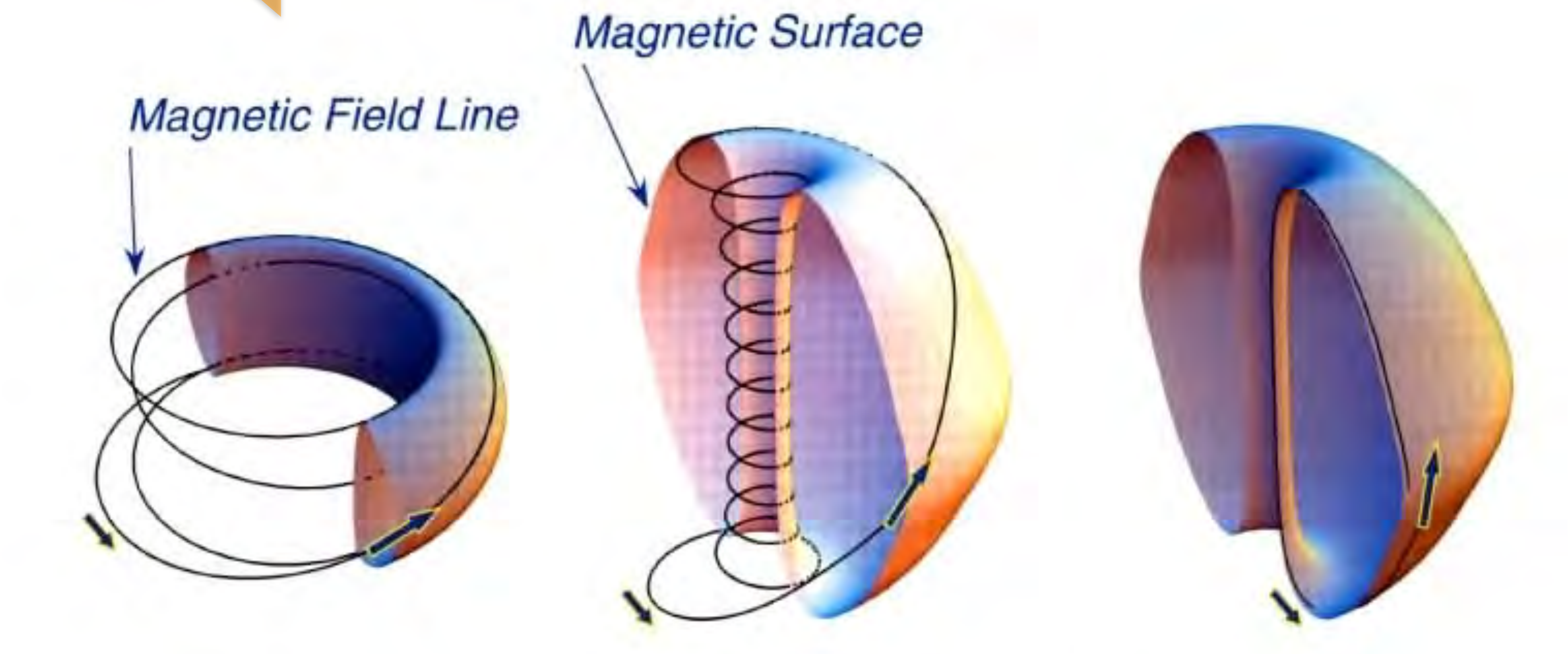
Bending Field ➠ Effective g





How to make a magnetic torus?

High q ← Increasing Toroidal Field ← Low q



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

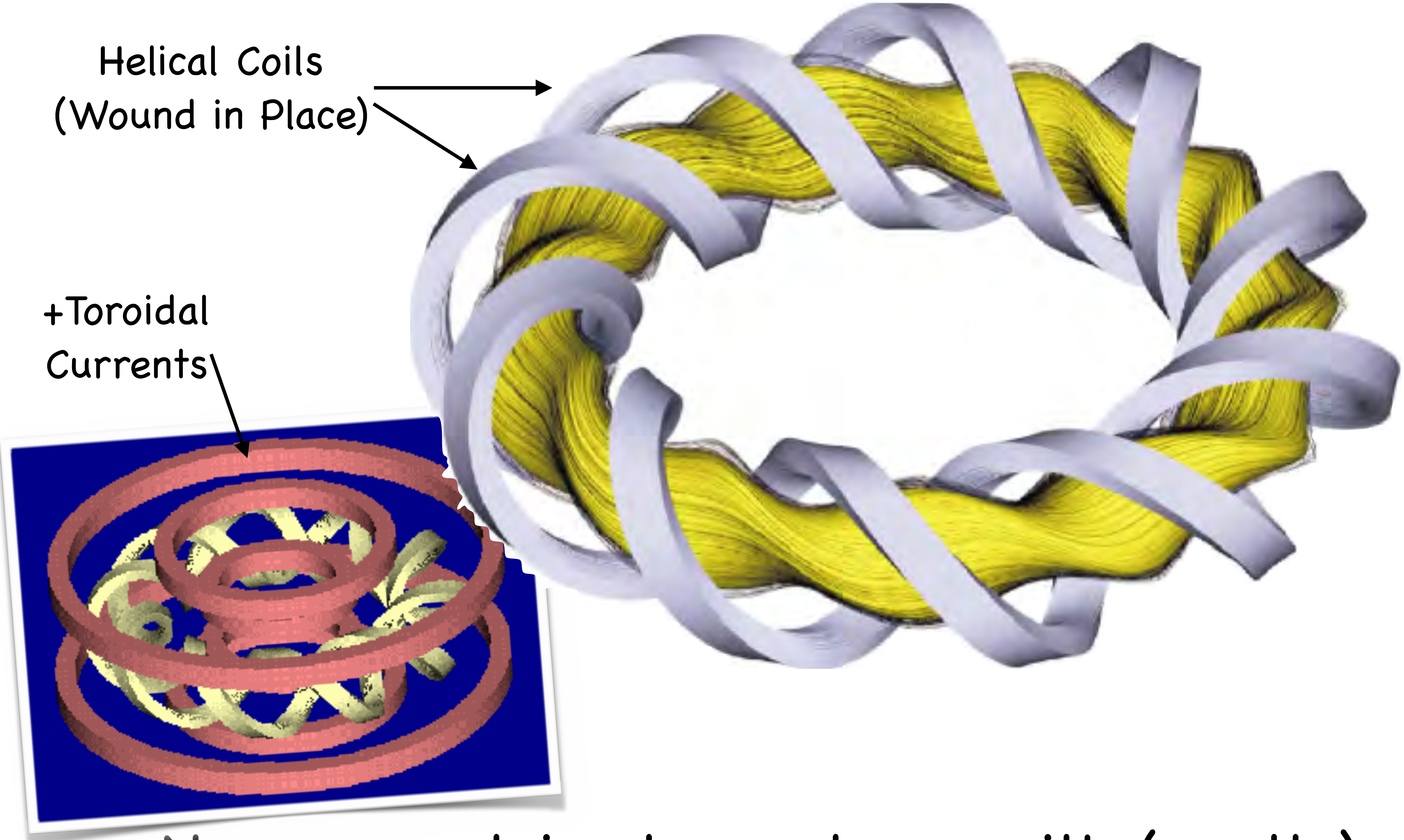
Tokamak Plasma (safety factor $q = 4$)

Spherical Torus Plasma (safety factor $q = 12$)

Spheromak Plasma (safety factor $q = 0.03$)

Combined Toroidal and Poloidal Field (Tokamak)

How to make a magnetic torus?



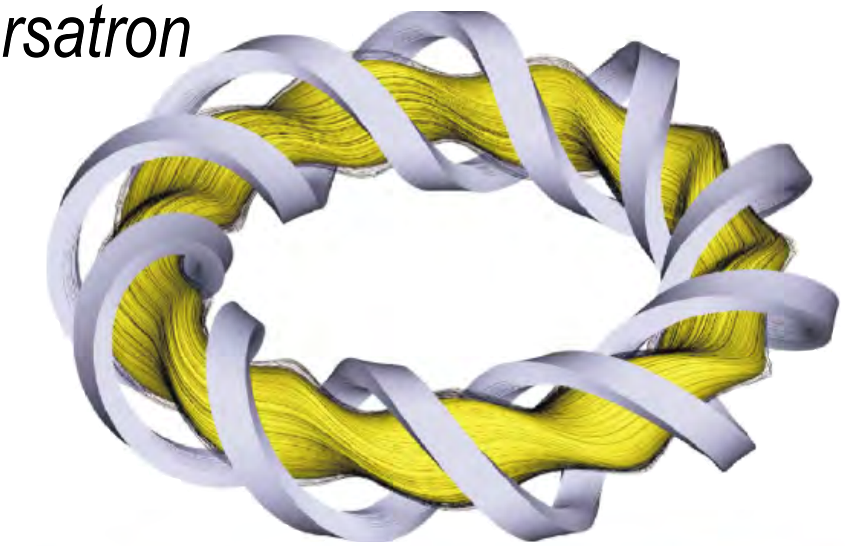
Helical Coils
(Wound in Place)

+Toroidal
Currents

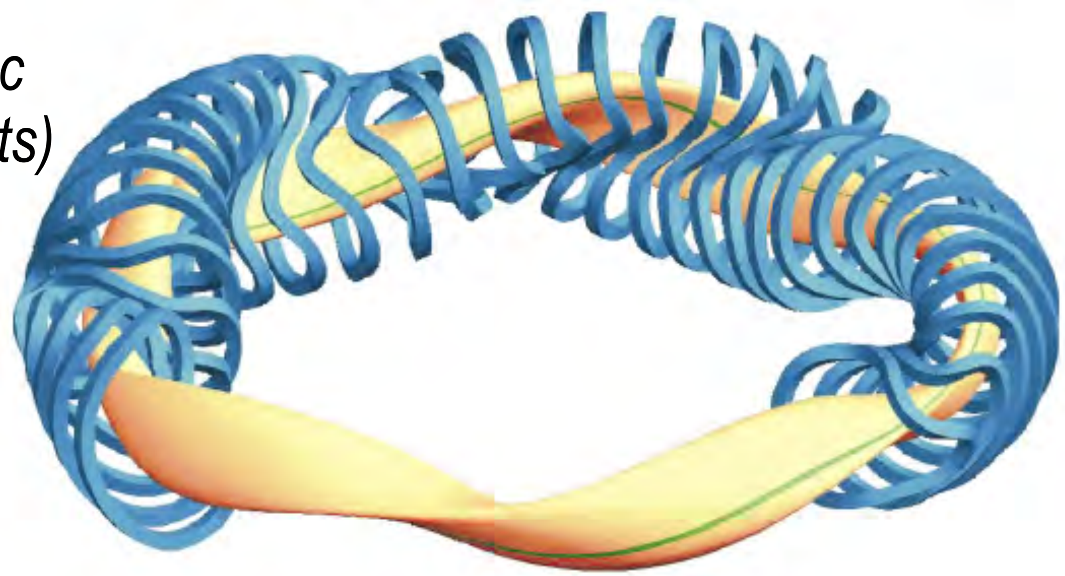
Non-symmetric plasma torus with (mostly) external helical currents (Stellarator)

How to make a magnetic torus?

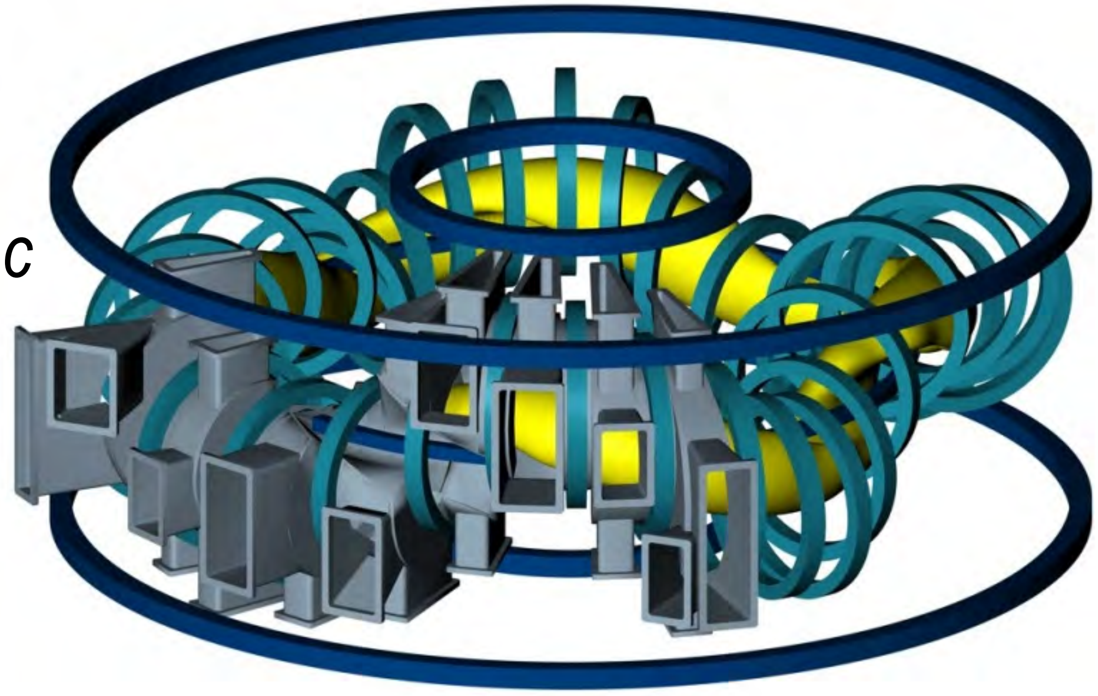
Torsatron

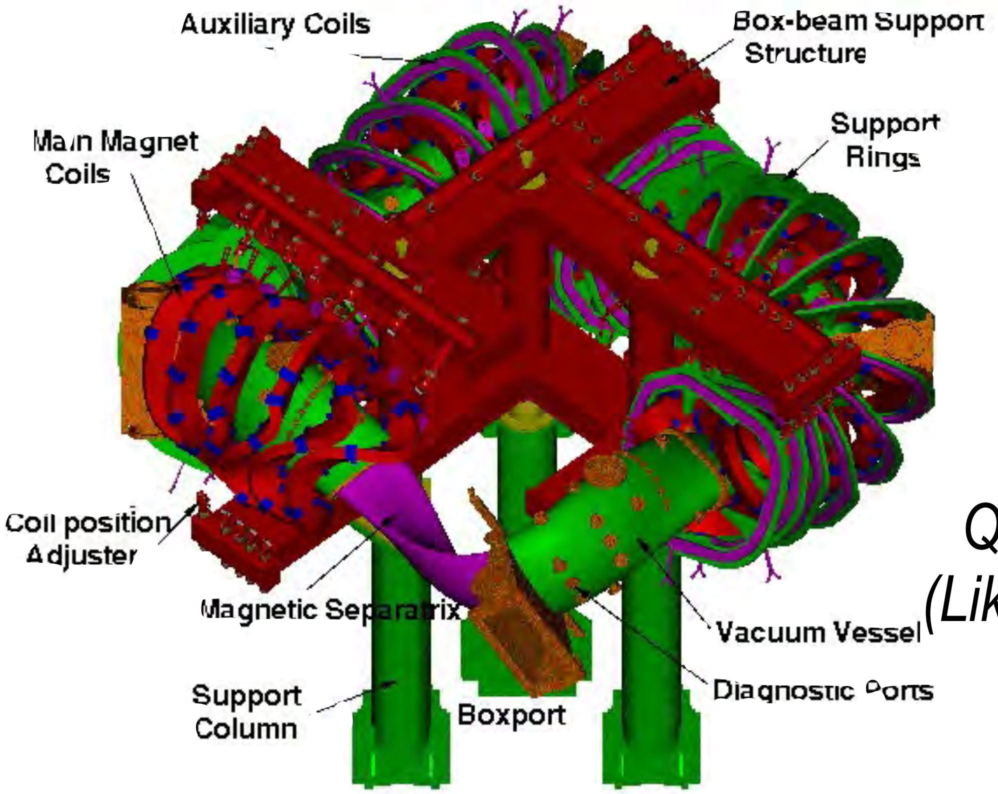


Quasi-Isodynamic
(no parallel currents)



Heliac





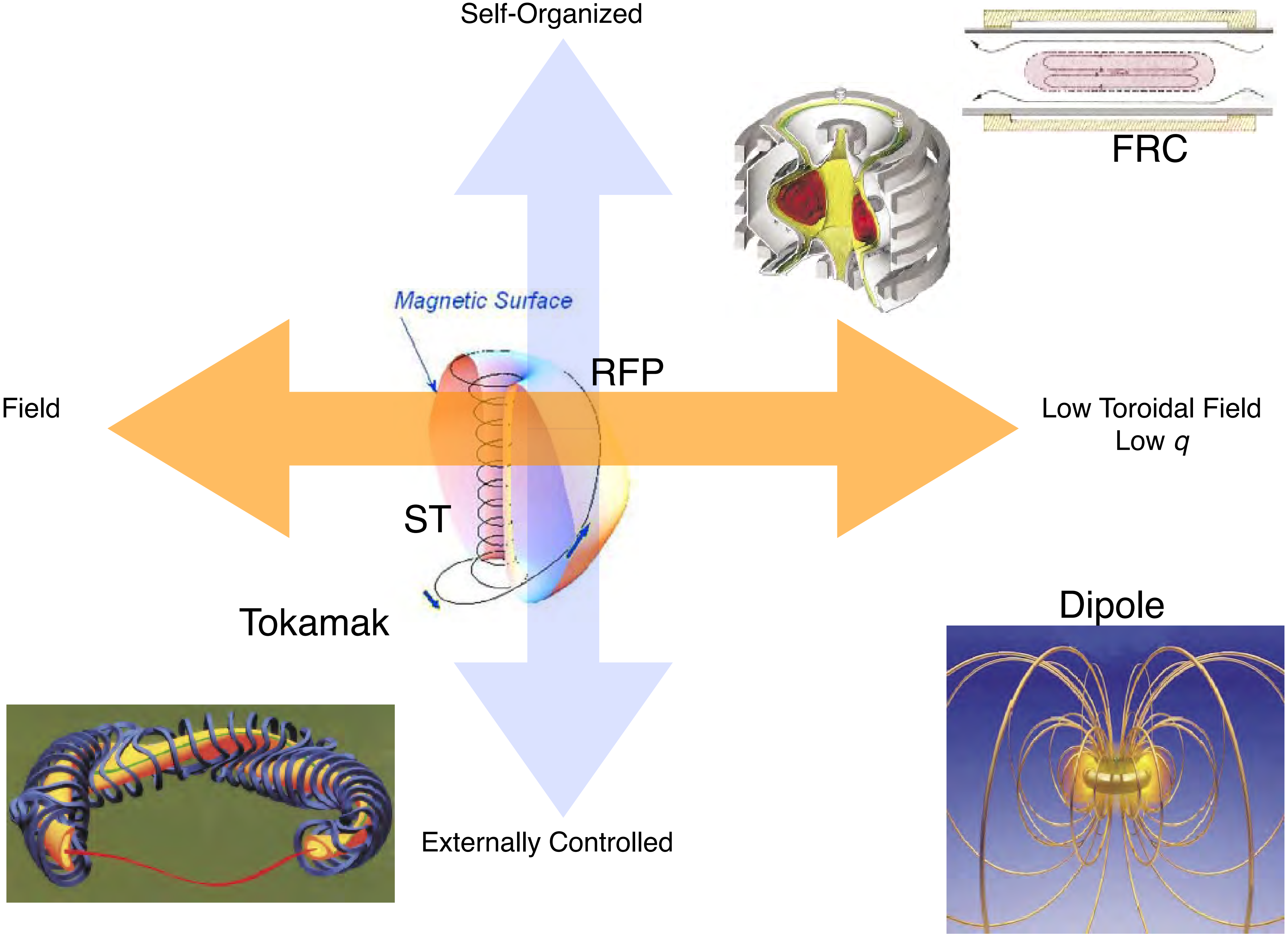
Quasi-Symmetry
(Like tokamak along
helical path)

Non-symmetric plasma torus with (mostly) external helical currents (Stellarator)

Why study different magnetic tori?

- ***Fundamental study***
  - Confinement science, heating, sustainment, heat flux to boundaries, fluctuations, instabilities, complex behaviors of high-temperature matter, magnetized “bright matter” throughout the universe, …
- ***Fusion energy***
  - Magnetic torus has to “work” and make fusion
  - Achieve fusion’s promise of safety and environmental attractiveness
  - Have economically viable applications (like high payload space power and propulsion, non-carbon electrical power on Earth, …)

Toroidal Magnetic Configurations



Self-Organized

High Toroidal Field
High q

Low Toroidal Field
Low q

Externally Controlled

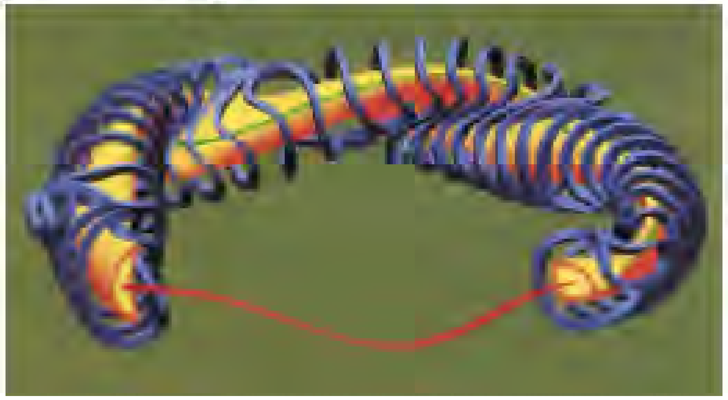
Different Configurations Test Complementary Regimes

Example: Helical Lines Nested Surfaces

Externally-Imposed Fields
$B_T/B_p >> 1;\ q > 1$

Self-Organized Fields
$B_T/B_p \leq 1;\ q < 1$

Stellarator Tokamak RFP **Spheromak**



(–) Large applied field ($B^2/2\mu_0 >> P$);
(++) Robustly stable magnetic topology;
(+) Does not require wall stabilization;
(++) Strong fields produce good confinement;
(++) Steady state;
(+) Relatively simple startup;
(– –) Coils link plasma;
(– –) Relatively low power density;
(–) Superconducting magnets;
(–) Divertor flux trapped within coils;
(–) Large aspect ratio, large size; ...

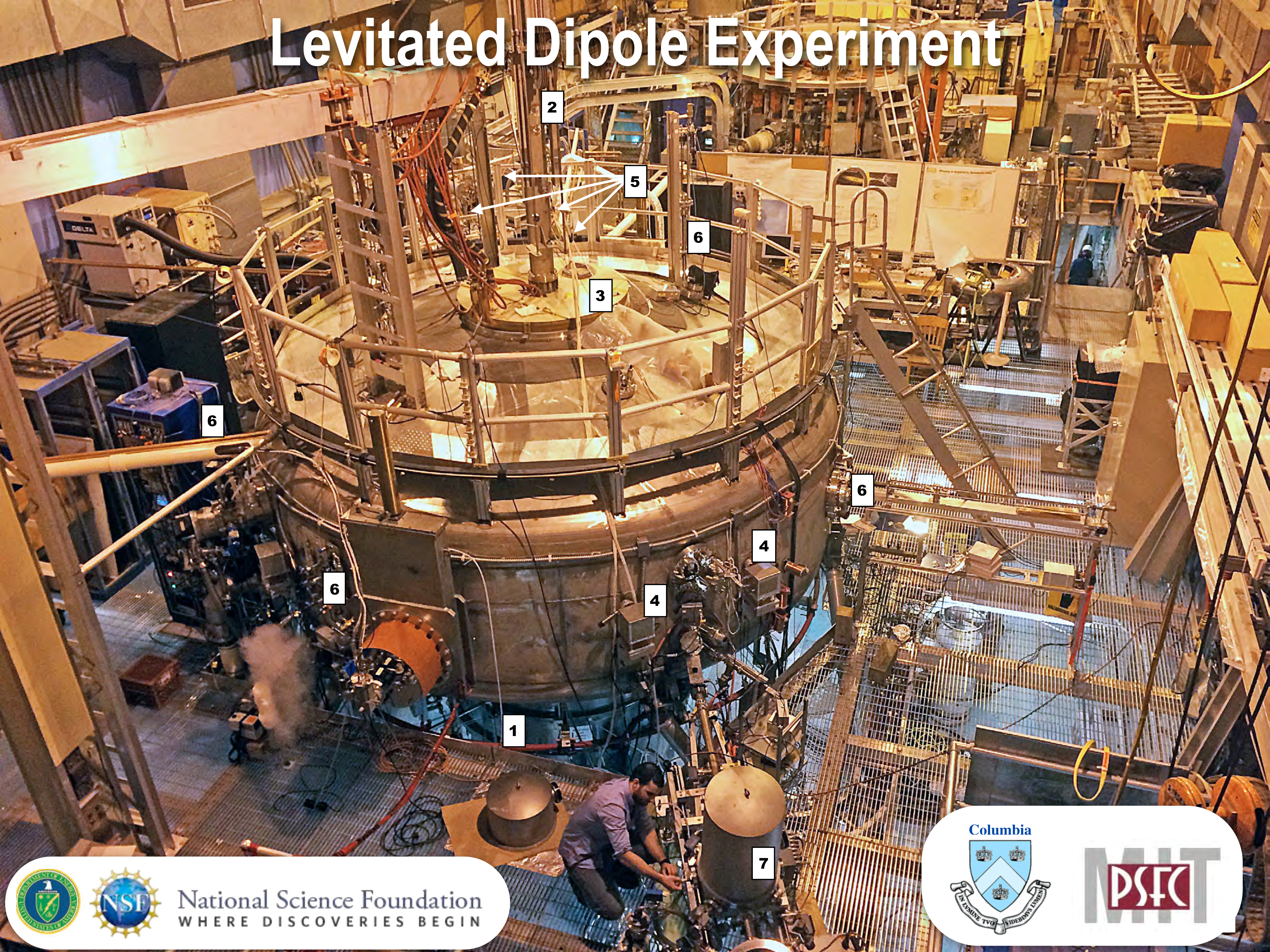
(++) Small applied field ($B^2/2\mu_0 \geq P$);
(– –) Magnetic topology requires sustaining significant plasma current;
(–) Requires wall stabilization;
(– –) Self-generated fields driven by magnetic turbulence;
(–) Relatively complex startup;
(++) Simple coils;
(++) Potentially high power density;
(+) Large divertor flux expansion;
(+) Small aspect ratio, small size; ...

(with "personal" judgements of potential value)

Outline

- **Plasma containment depends upon the shape of the magnetic field**
  - What can we learn by changing magnetic topology? Examples…
  - Stellarator: optimizing the helical plasma torus
  - ➡ Levitated dipole: “simplest” axisymmetric magnetic confinement
  - Spheromak: Magnetic self-organization
- **Fusion energy needs discoveries to overcome challenges to economic viability**
  - Over 200 tokamaks and soon there will be ITER: what we know about the economics of tokamak-based fusion energy
  - Discoveries are needed from creative new scientific investigations
- **Columbia University’s plasma physics experiments**

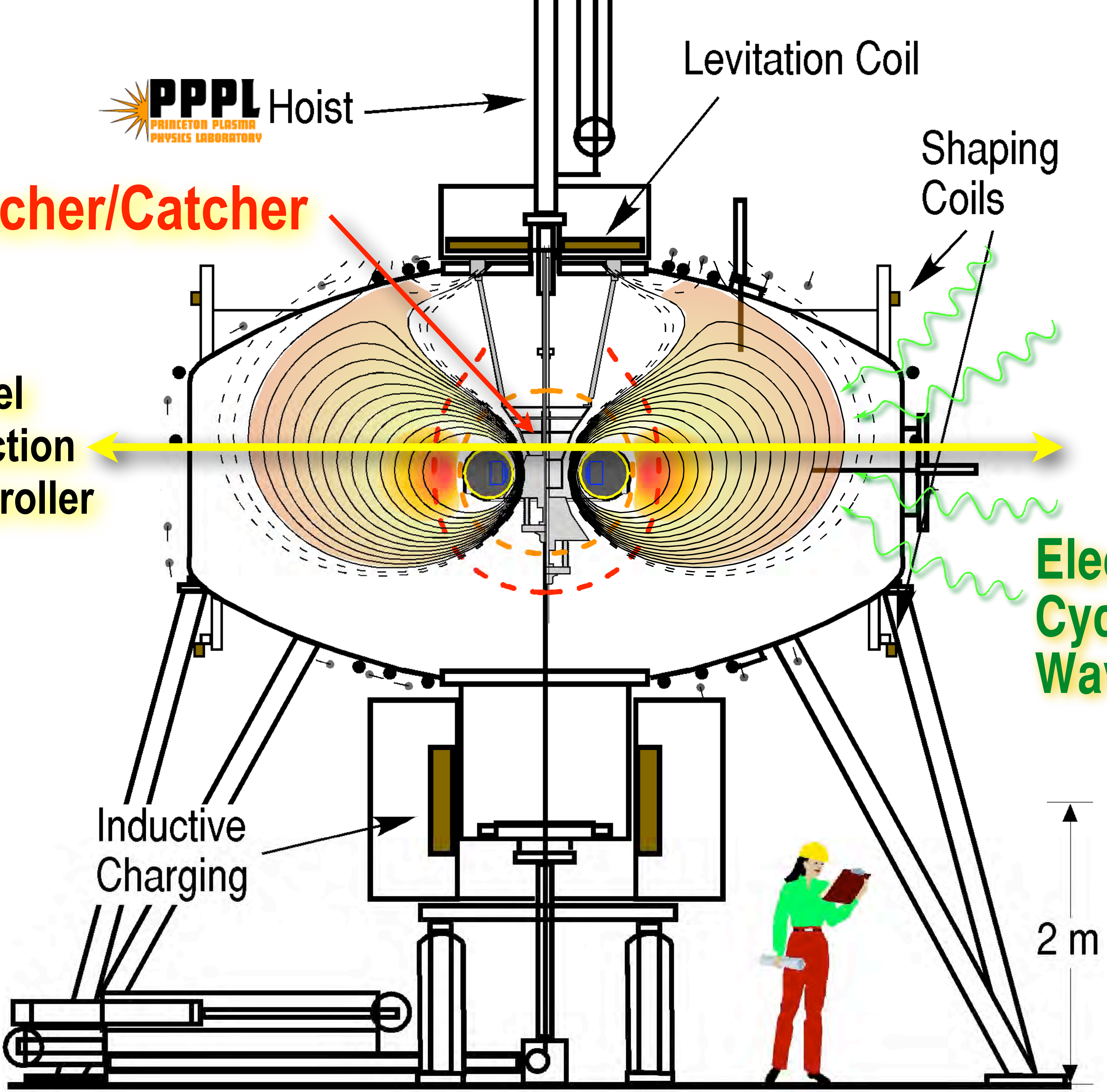
Levitated Dipole Experiment



National Science Foundation
WHERE DISCOVERIES BEGIN

Columbia

PSFC



PPPL PRINCETON PLASMA PHYSICS LABORATORY Hoist

Levitation Coil

Shaping Coils

Launcher/Catcher

8 Channel Laser Detection and RT Controller

Electron Cyclotron Waves

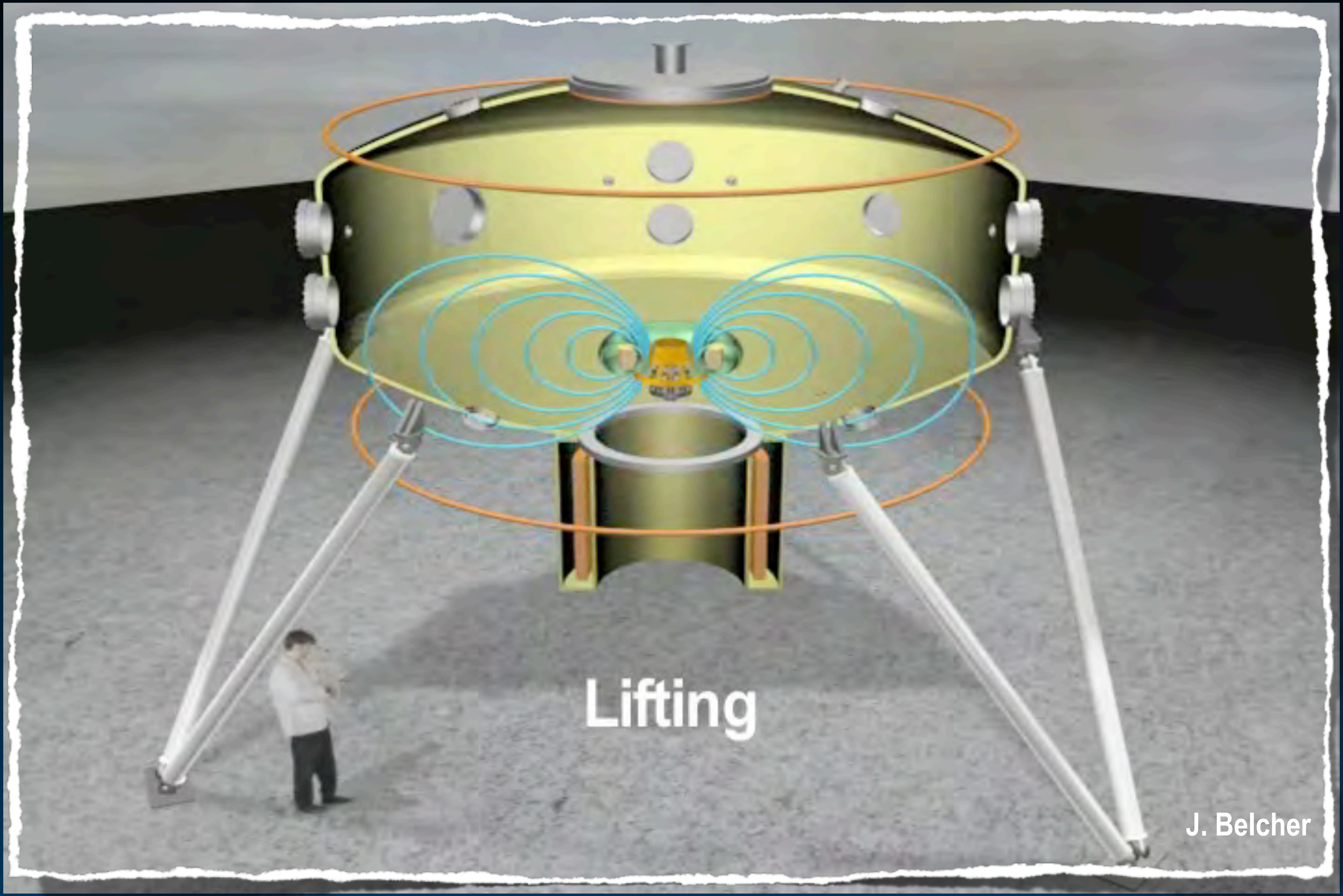
Inductive Charging

2 m

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

MIT MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lifting, Launching, Levitation, Experiments, Catching

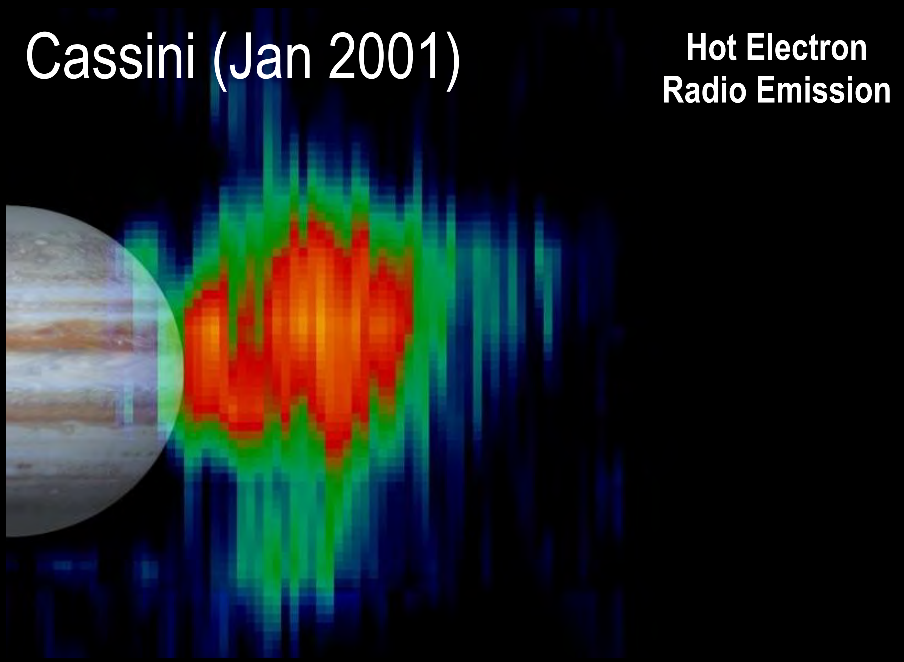


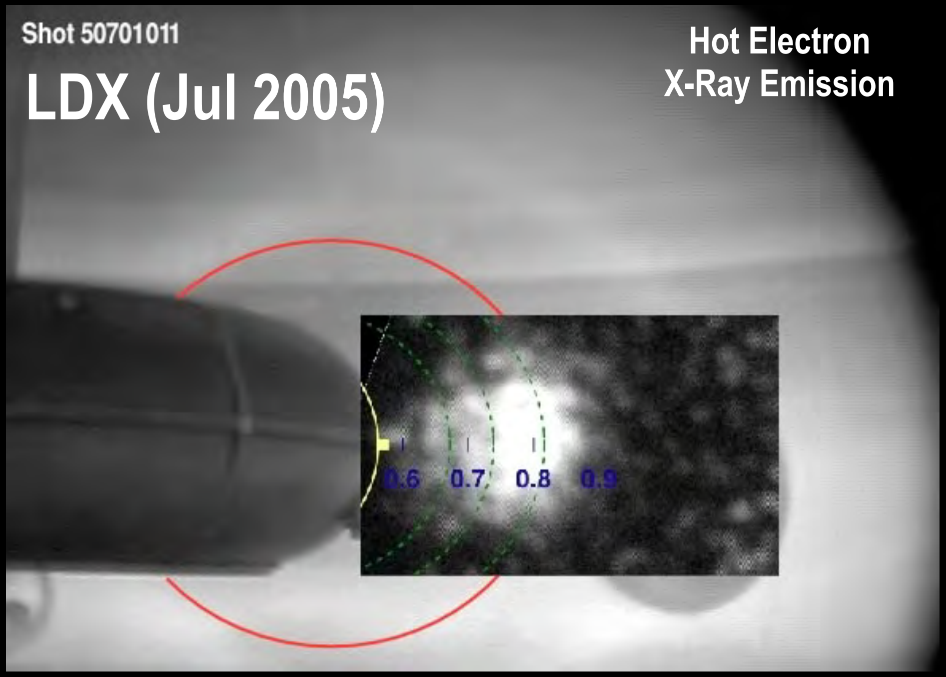
First Levitated Dipole Plasma Experiment

Discover a New Regime by Linking Space and Laboratory Science

- ***<u>Leveraging space physics to discover a new regime</u>*:** axisymmetric, steady-state, compressibility ($\omega^* \sim \omega_d$), $\beta \sim 1$, no field-aligned currents, shear-free, bounce-averaged gyrokinetics, wave-particle dynamics, …
- Magnetospheric configuration but not a "miniature magnetosphere"
  (*high β stability but without polar losses and field-aligned currents*)
- Toroidal magnetic confinement, but not a "miniature fusion reactor"
  (*controlled tests of transport, stability, and self-organization)*

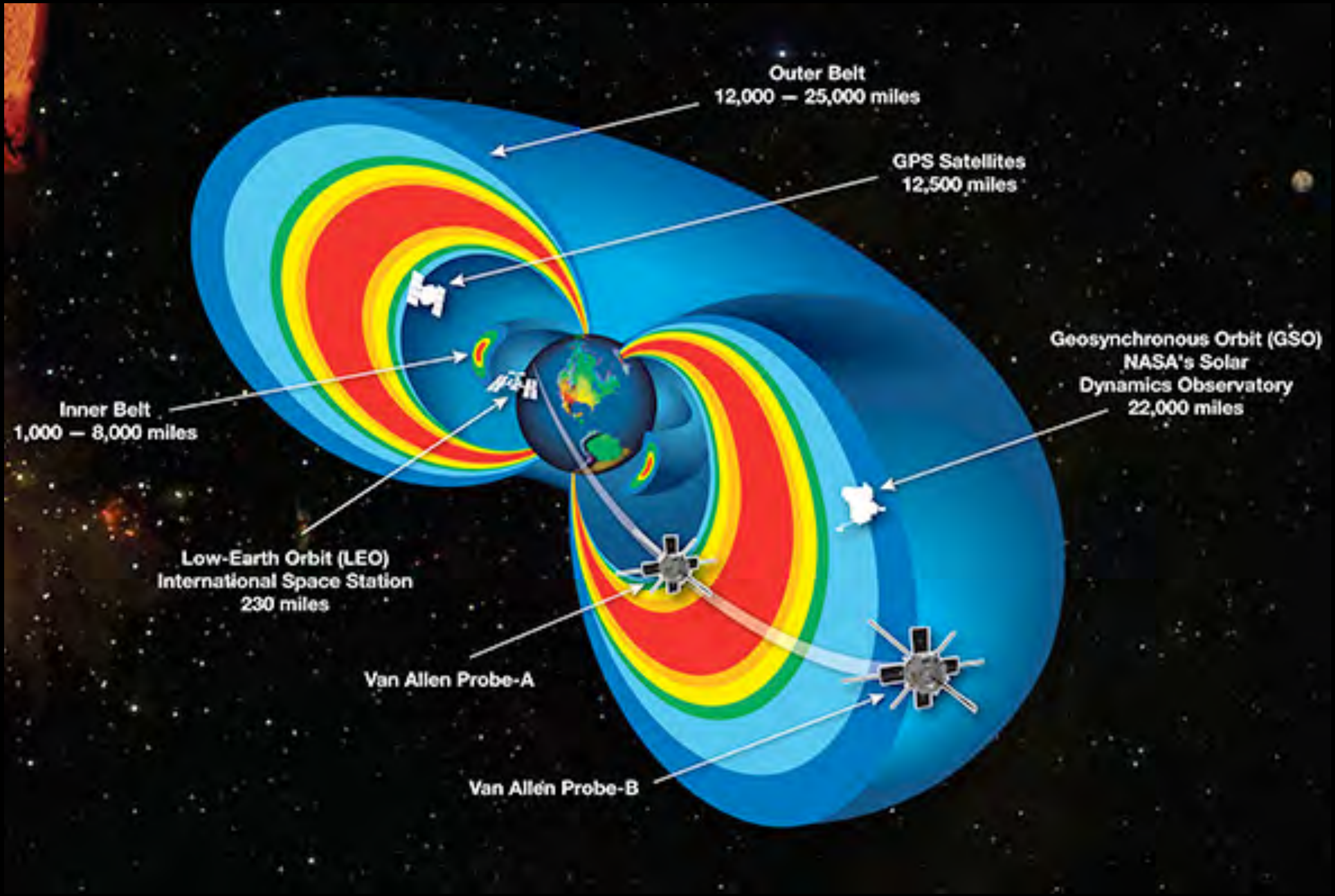
Fast Particles in Space and Lab





Our Space Environment is Complex and Highly Variable

With Concurrent Plasma Processes and Important Questions to Answer



Van Allen Probes (A&B) Launched August 2012

Discovered **New** 3rd Radiation Belt (2 MeV e^-) then annihilated by passage of interplanetary shock
ScienceExpress, Baker, *et al.*, 28 Feb 2013

INNER MAGNETOSPHERIC MODELING WITH THE RICE CONVECTION MODEL

FRANK TOFFOLETTO, STANISLAV SAZYKIN, ROBERT SPIRO and
RICHARD WOLF
Department of Physics and Astronomy, Rice University, Houston, TX 77005, U.S.A.

Semi-collisional Plasmasphere and Ring Current

TABLE I

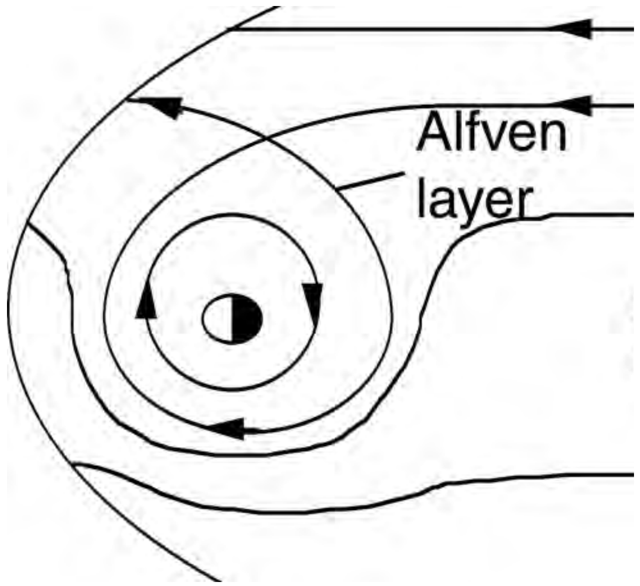
Comparison of equations of ideal MHD with those used in the RCM

Ideal MHD	RCM
$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho v) = 0$	$\boxed{(\frac{\partial}{\partial t} + \vec{v}_k(\lambda_k, \vec{x}, t)\cdot\nabla)\eta_k = S(\eta_k) - L(\eta_k)}$
$(\frac{\partial}{\partial t} + \vec{v}\cdot\nabla)(\rho\vec{v}) = \vec{j}\times\vec{B} - \nabla P$	$\vec{j}_k \times \vec{B} = \nabla P_k$
$(\frac{\partial}{\partial t} + \vec{v}\cdot\nabla)(P\rho^{-5/3}) = 0$	$P = \frac{2}{3}\sum_k \eta_k\lvert\lambda_k\rvert V^{-5/3}, \lambda_k = constant$
$\nabla\cdot\vec{B} = 0$	Part of the magnetic field model.
$\nabla\times\vec{B} = \mu_0\vec{j}$	Included in magnetic field, but $\vec{j} \neq \sum_k \vec{j}_k$.
$\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$	Included implicitly in mapping.
$\vec{E} + \vec{v}\times\vec{B} = 0$	$\boxed{\vec{E}\cdot\vec{B} = 0 \text{ and } \vec{E}_\perp + \vec{v}_k\times\vec{B} = \frac{\nabla W(\lambda k, \vec{x}, t)}{q_k}}$

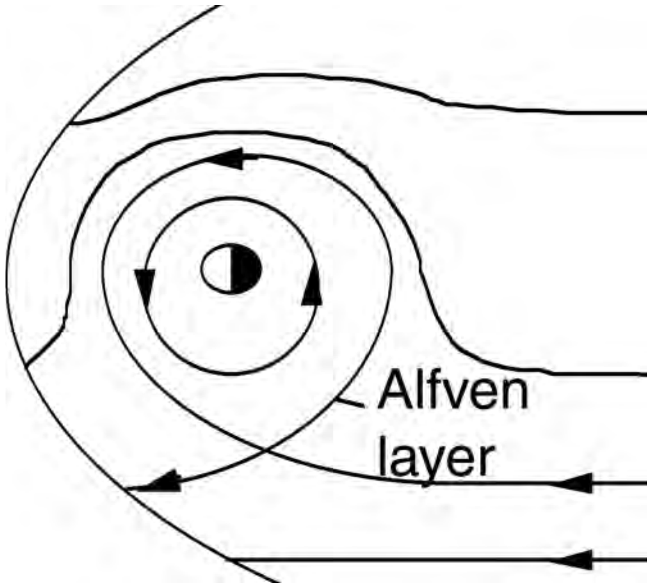
For each species and invariant energy λ, η is conserved along a drift path.
Specific Entropy

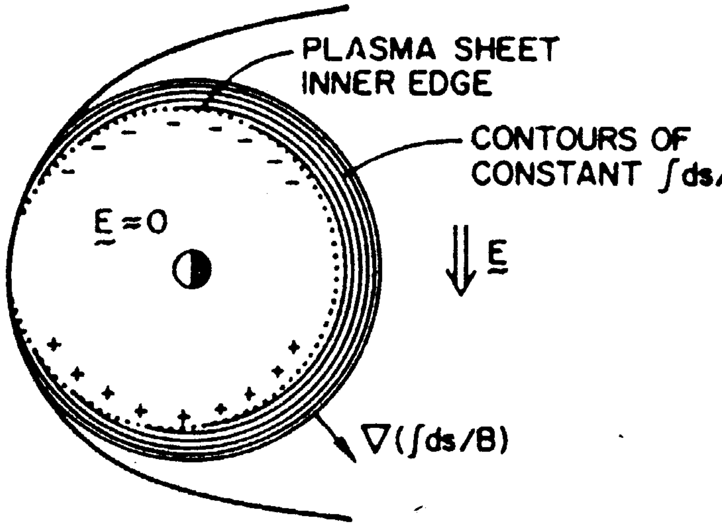
$$pV^\gamma = \frac{2}{3}\sum_s \lvert\lambda_s\rvert\eta_s$$

Ions



Electrons





Space Science Reviews **107:** 175–196, 2003.

Self-Organized Mixing: Dye Stirred in Glass

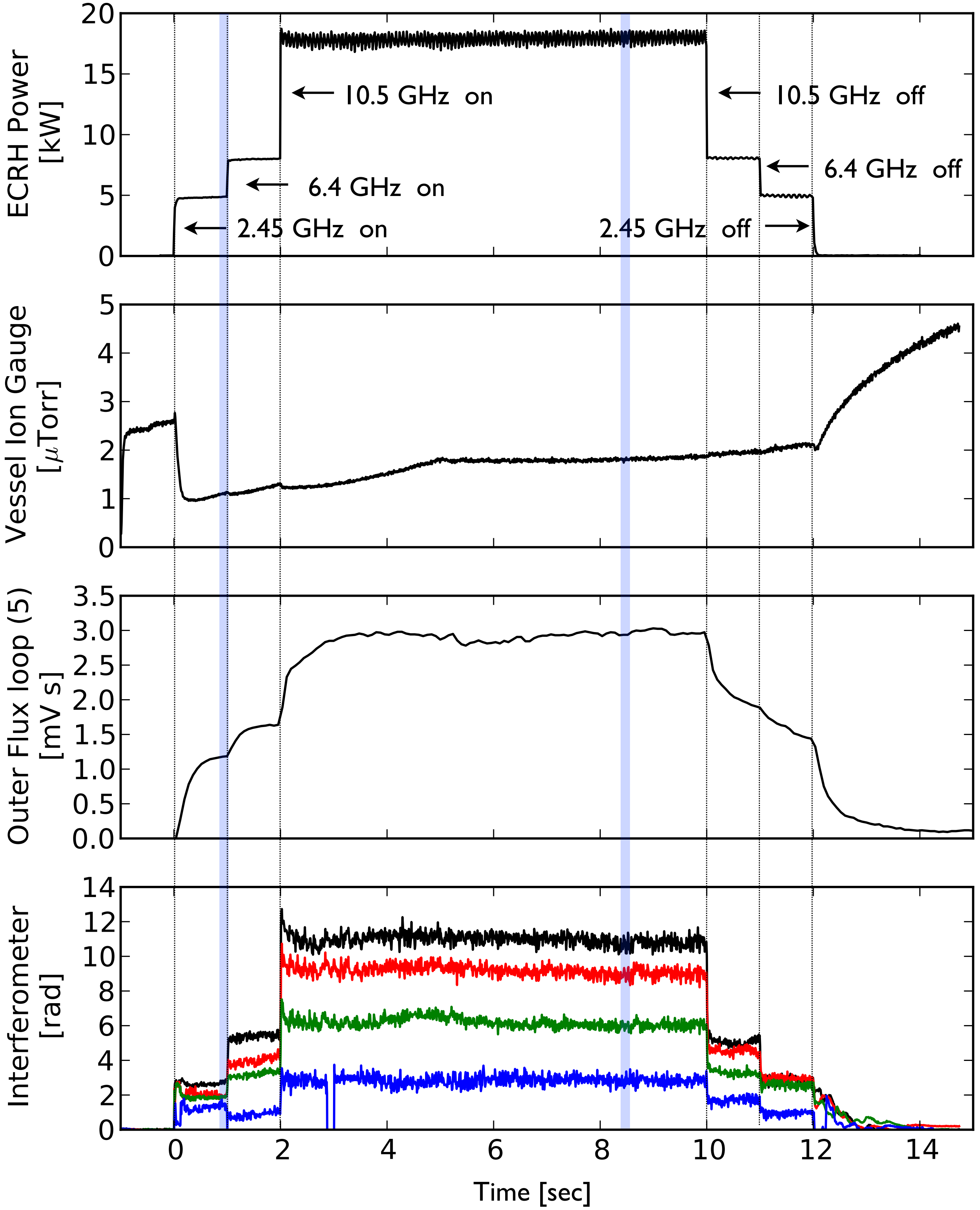
New Regime: High β, Turbulent Self-Organized, Steady-State

- 20 kW injected electron cyclotron waves
- Density proportional to injected power
- Plasma energy proportional to power
- Peak plasma density 10^{12} cm^{-3}
- Plasma energy 250 J (3 kA ring current)
- Peak β ~ 40% (100% achieved in RT-1)
- Classical fast particles 〈E_h〉 ~ 54 keV
- Peak 〈T_e〉 > 0.5 keV (thermal)

Sustained, dynamic, steady state …

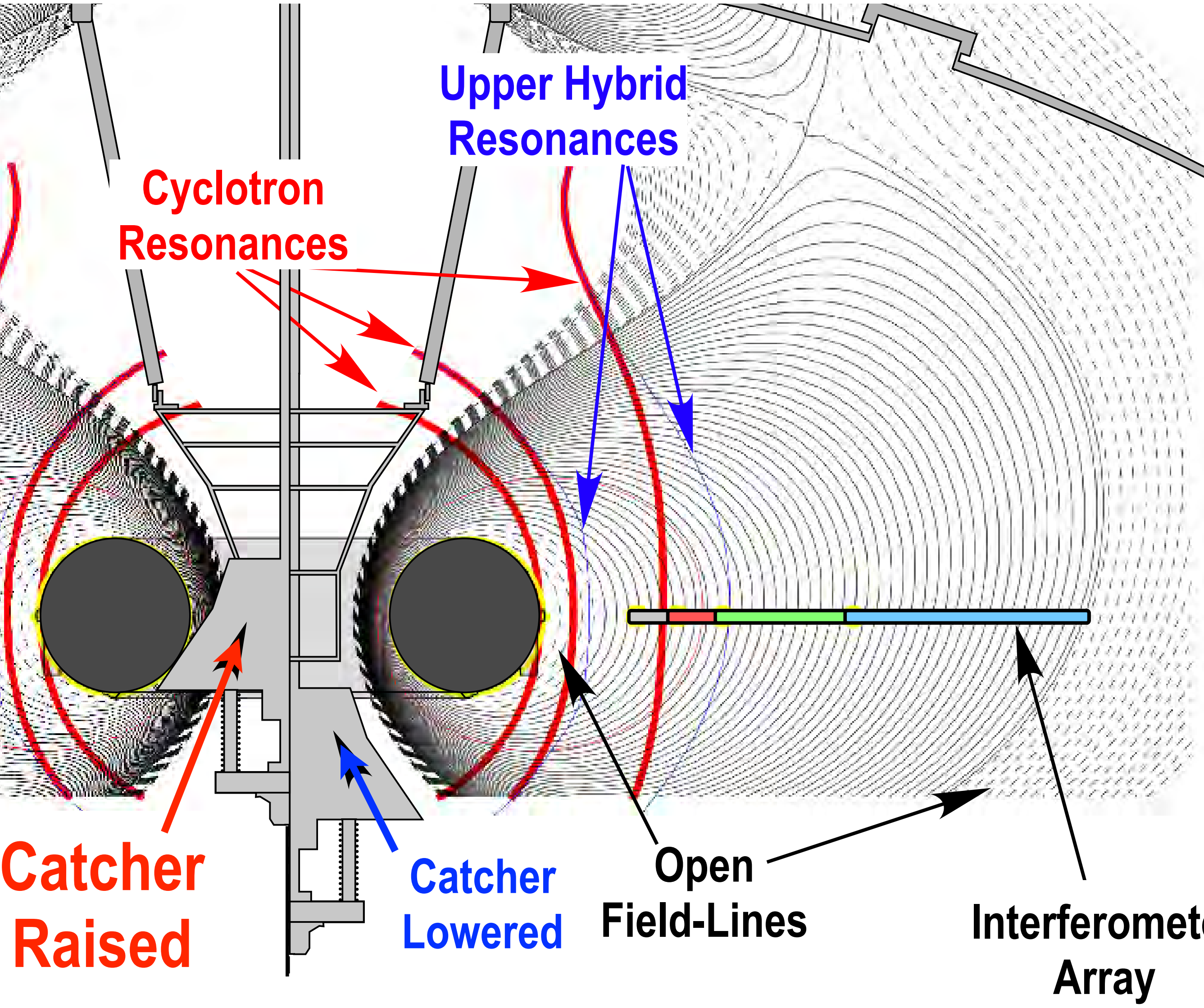
- ***Plasma density and electron pressure naturally approach "canonical" profile shape determined magnetic flux-tube volume, δV.***
- ***Density evolves at rates described by bounce-averaged gyrokinetic theory.***

Self-Organized, Steady-State Profiles at High β

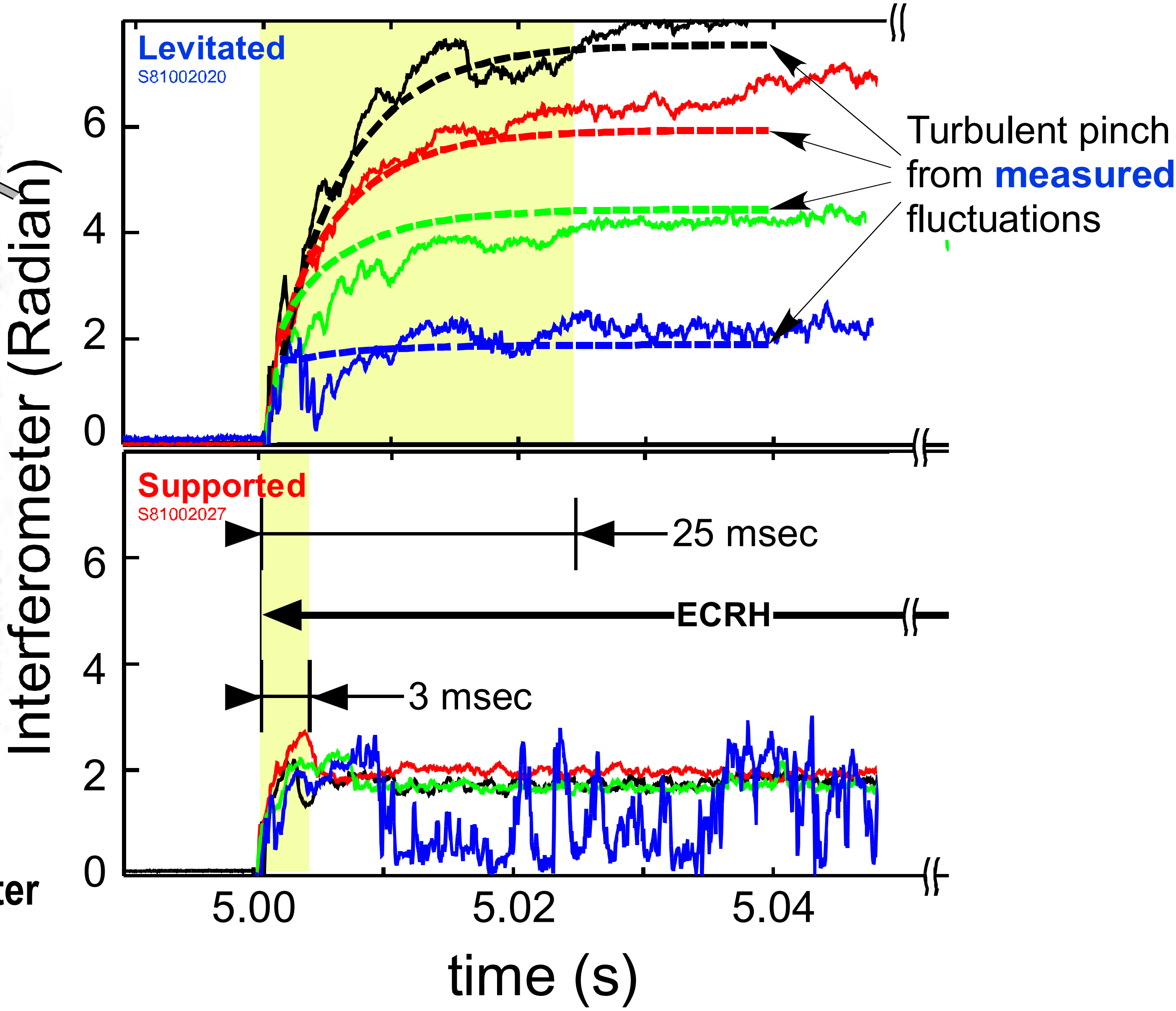


Quantitative Verification of Inward Turbulent Pinch

$$\frac{\partial(\bar{n}\delta V)}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D_{\psi} \frac{\partial(\bar{n}\delta V)}{\partial \psi}$$



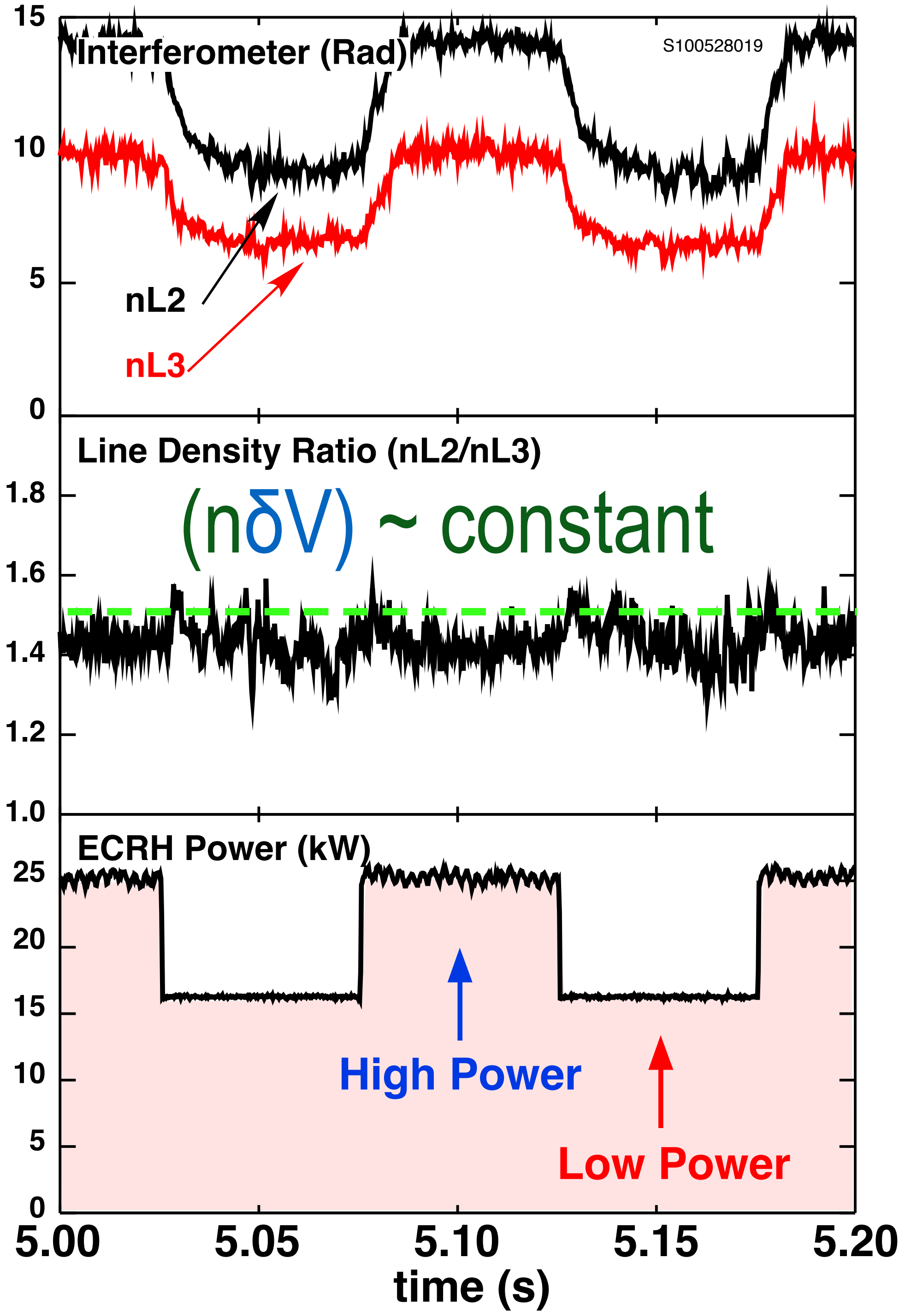
With levitated dipole, inward turbulent transport sets profile evolution

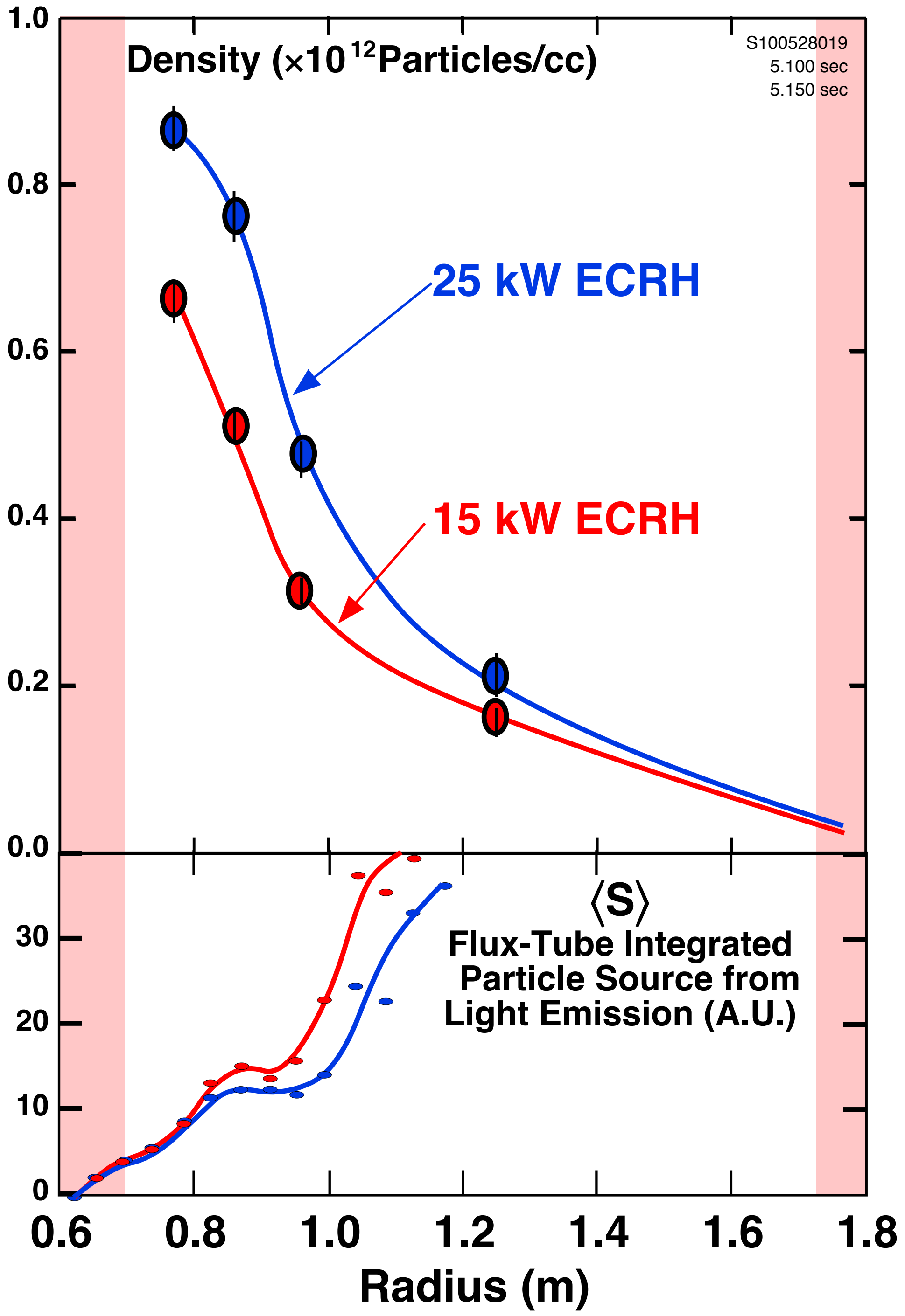


Alex Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nature Phys* **6**, 207 (2010).

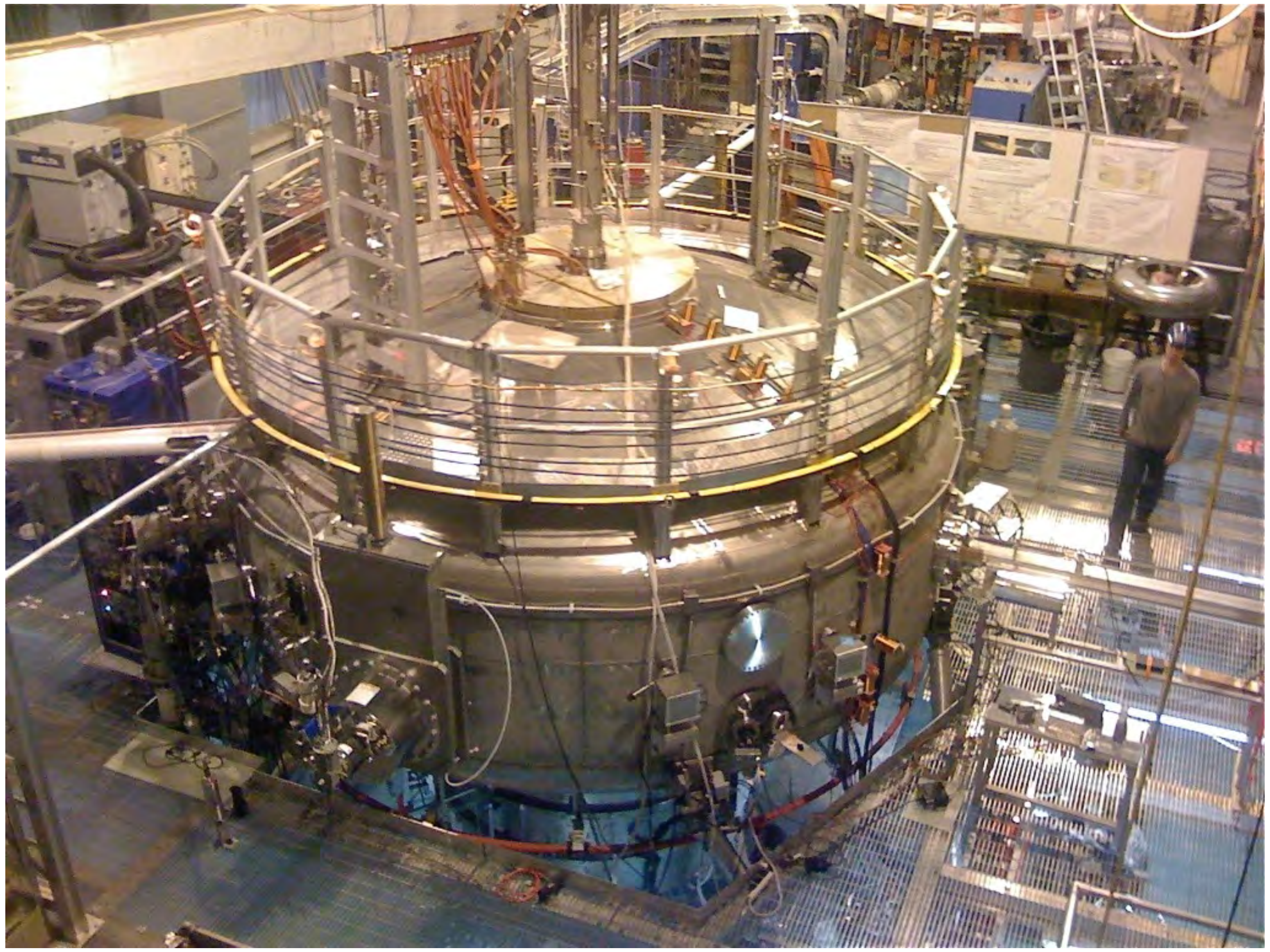
Heating or gas modulation demonstrates (**Robust**) inward pinch & **Natural** "canonical" profile

- Density increases with power (*T* ~ constant). Density **profile shape is unchanged** near ($n\delta V$) ~ constant.
- Gas source moves radially outward. **Inward pinch required** to increase central density.



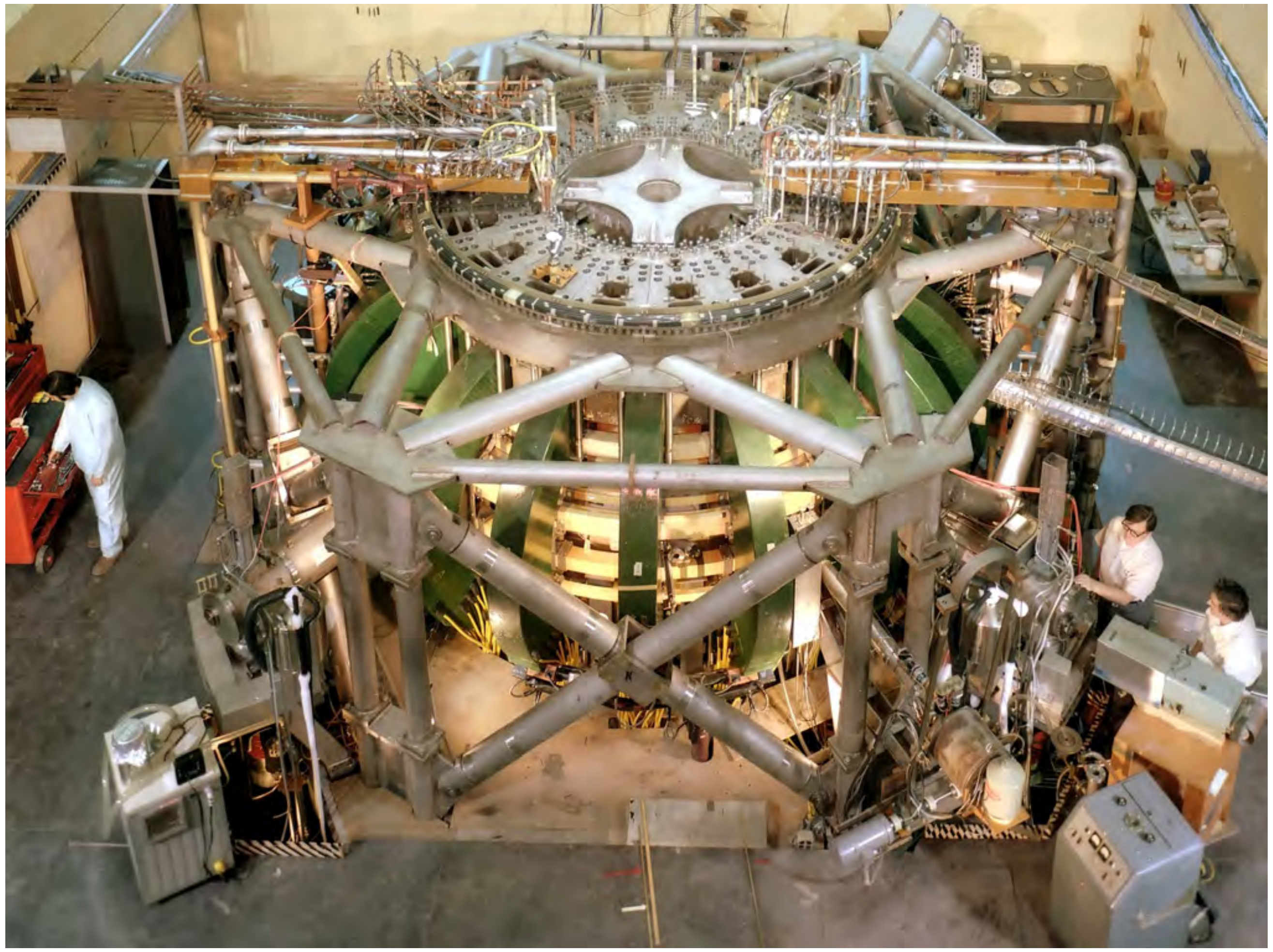


Turbulent Pinch is a Fundamental Process found in Toroidal Magnetic Systems Including Tokamaks and Planetary Magnetospheres (but, different…)



Levitated Dipole Experiment (LDX)

1.2 MA Superconducting Ring
Steady-State
25 kW ECRH
1 MW ICRF (unused)



Princeton Large Torus (PLT)

17 MA Copper Toroid
1 sec pulses
750 kW Ohmic
75 kW LHCD
2.5 MW NBI & 5 MW ICRF

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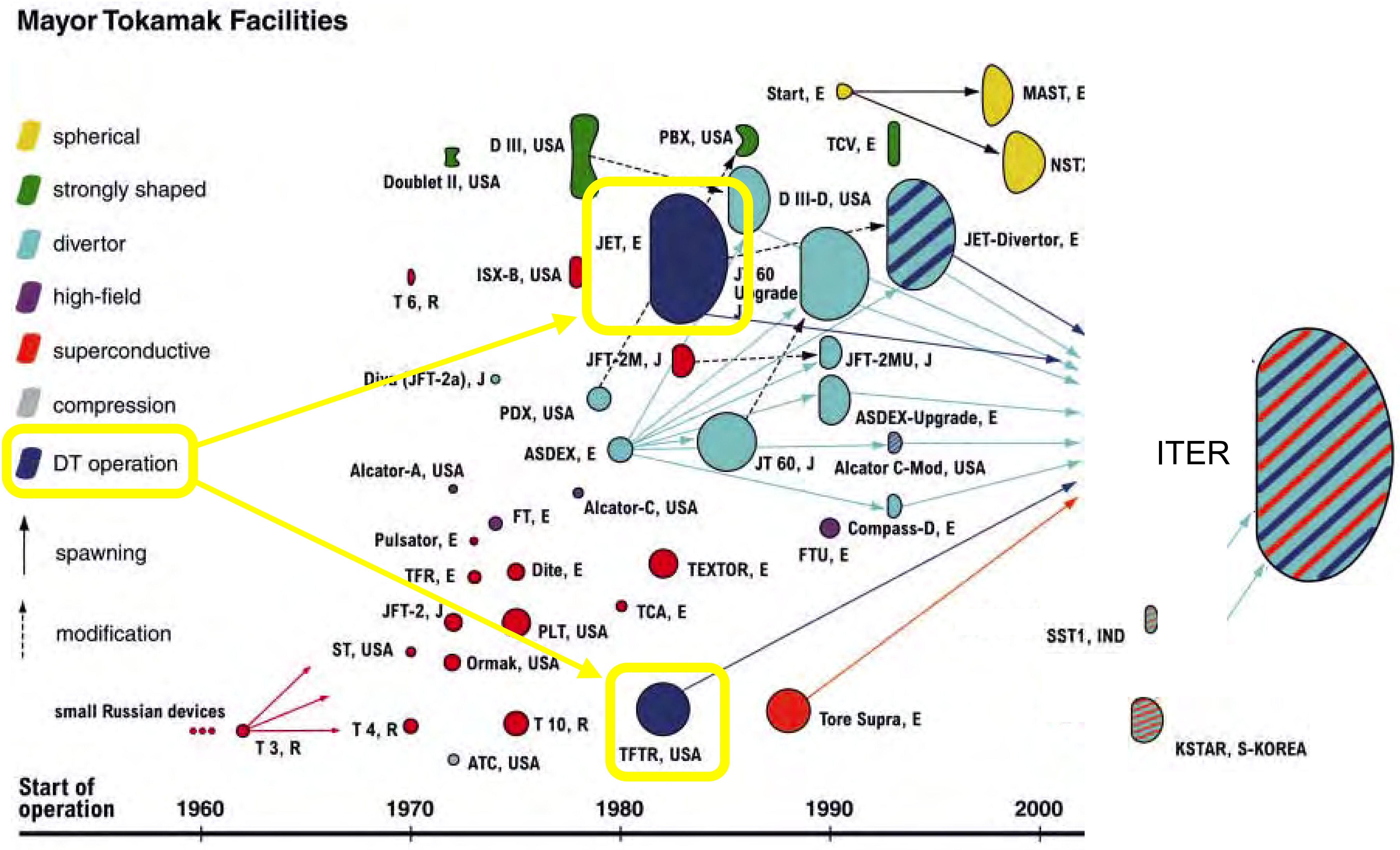
  - ➡ Discoveries are needed from creative new scientific investigations
- **Columbia University’s plasma physics experiments**

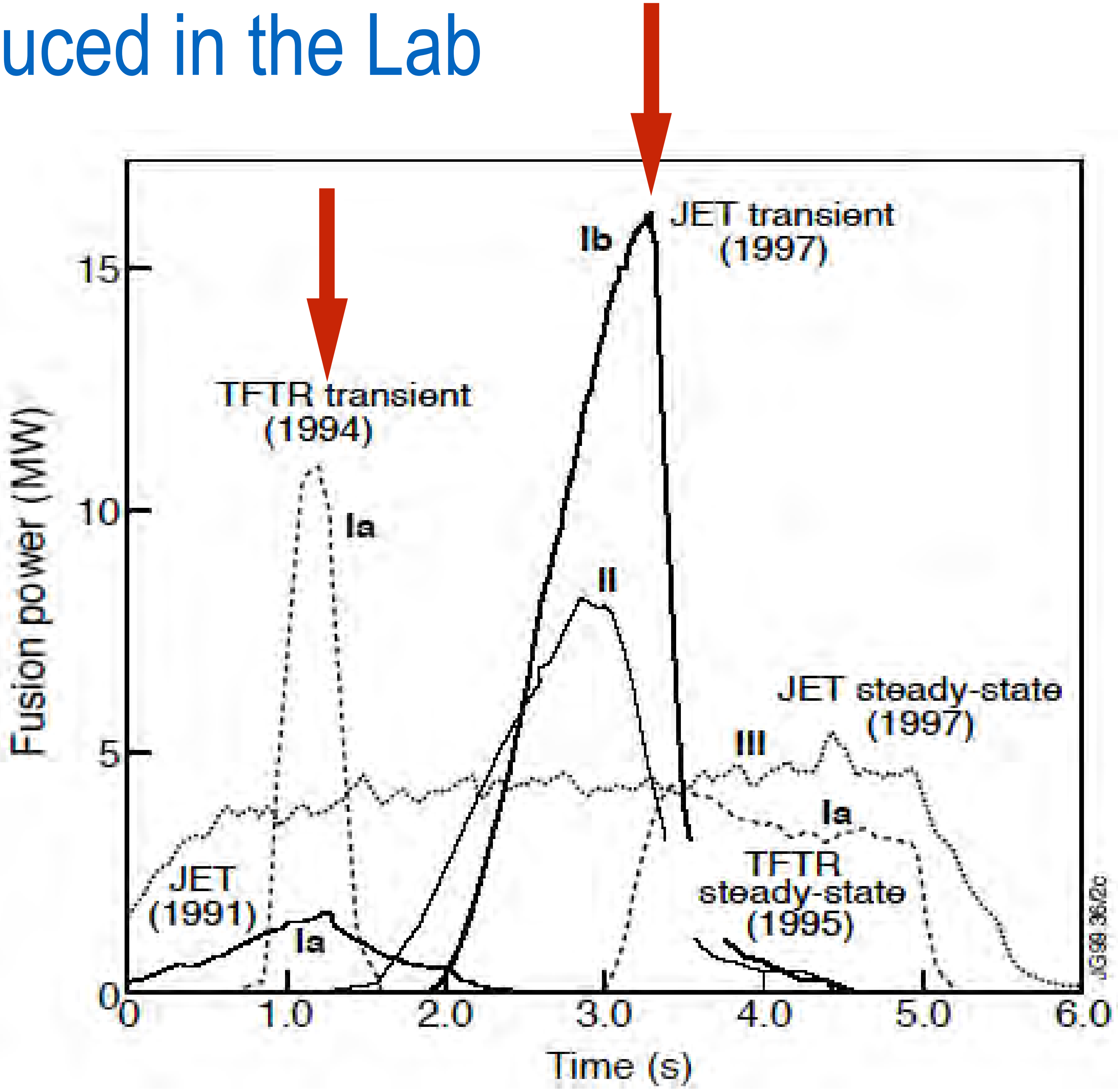
More than 200 Tokamaks

(*We know how tokamaks work relatively well.*)



Significant Fusion Power already Produced in the Lab

- ✓ 2.5 MW/m3 achieved in TFTR!
- ✓ Establishes basic “scientific feasibility”, but power out < power in.
- ◉ Control instabilities, disruptions & transients
- ◉ Fusion self-heating, characteristic of a “burning plasma”, has yet to be explored.
- ◉ Steady state, maintainability, high-availability still T.B.D.
- ◉ The technologies needed for net power still T.B.D.



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;

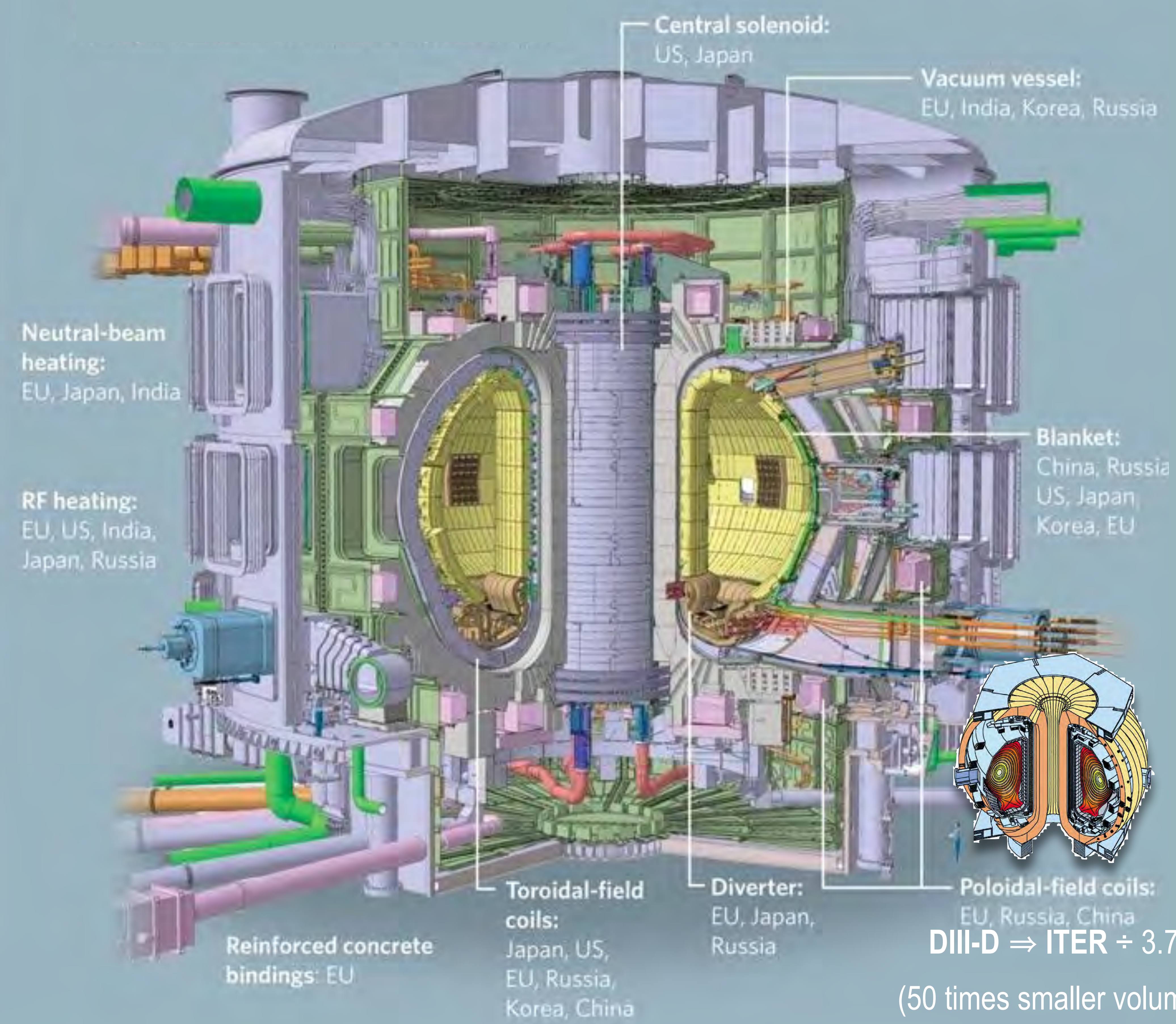
(II) Optimized shear; and (III) Steady-state ELMY-H Modes.

ITER: The International Burning Plasma Experiment

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

~ 500 MW
10 minute pulses

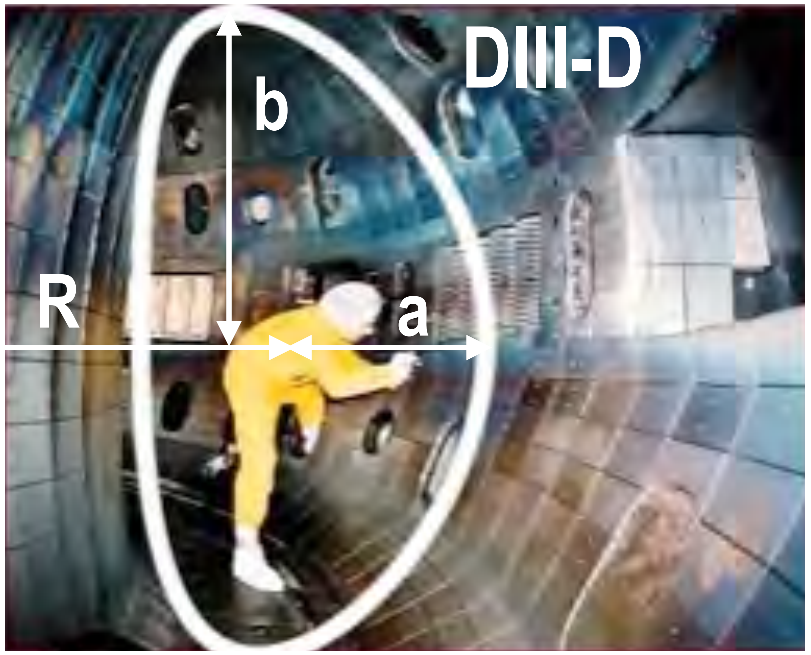
23,000 tonne
51 GJ
>30B $US (?)



DIII-D ⇒ ITER ÷ 3.7

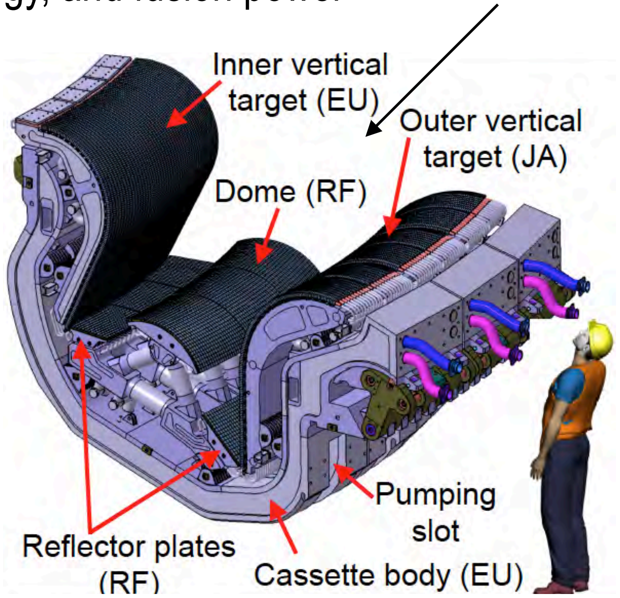
(50 times smaller volume)
(400 times smaller energy)

How to Design a Tokamak



- **Choose the shape** of the magnetic plasma torus
  - aspect ratio, $\varepsilon = a/R \sim 0.16$
  - elongation (shape), $\kappa = b/a \sim 1.8$
  - Safety factor, $q \sim 3$
- **Select operating parameters** based on experience (*high as possible*)
  - normalized plasma beta, $\beta_N \sim 1.8$ (kink stability)
  - normalized plasma density, $n_G \sim 0.85$ (resistive stability)
- **Select plasma temperature**, (a B), β, and plasma current
  - $T \sim 0.6 \times I_p$; choose $T \sim 9$ keV $\Rightarrow I_p = 15$ MA and $(a\,B) = 10$ m · T, and $\beta \sim 2.5\%$
- **Select magnetic field in superconductor (11.8 T)** and **shielding (1.4 m)**, determines size, plasma density, energy, and fusion power
  - R = 6.2 m, B = 5.3 T, $n = 10^{20}$ m^{-3}, 400 MW fusion power, 350 MJ plasma energy, **50 GJ** magnet energy, **0.9 GJ** plasma current energy (*enough to melt half ton of steel*)
- **Check plasma energy confinement** needed to achieve desired fusion gain, Q ≡ (Power Out)/(Power In) ~ 10
  - $\tau_E \sim 3.7$ sec requiring only 40 MW of injected power (gyroBohm: **Yes!!**) and 120 MW power to divertor
- **Check divertor cooling (must be less than 10 MW/m^2, ÷ 6 of surface of sun!)** maybe? / maybe not?
- **Check design** and determine whether or not first wall survives plasma disruptions, ELMS, loss-of-control, …
- **Check design** and determine whether or not we can build it considering strength of materials, superconducting magnet technology, **neutron radiation damage**, **current drive efficiency**, …
- **Figure out how to be tritium self-sufficient and become an affordable energy source…**

54 Divertor Segments
(9 tons each)

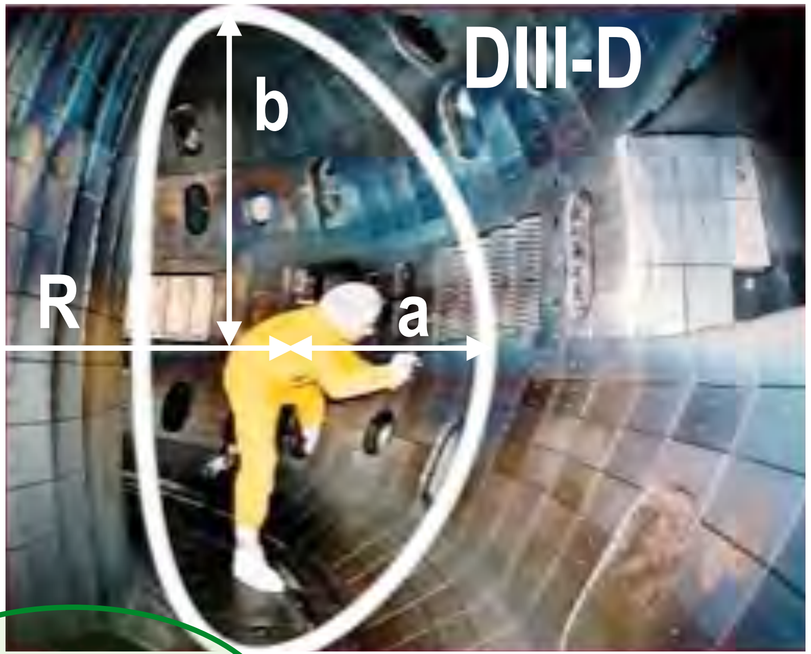


How to Design a Tokamak

Better

- **Choose the shape** of the magnetic plasma torus
  - aspect ratio, ε = a/R ~ 0.16
  - elongation (shape), κ = b/a ~ 1.8
  - Safety factor, q ~ 3

Optimize Shape



- **Select operating parameters** based on experience (*high as possible*)
  - normalized plasma beta, β_N ~ 1.8 (kink stability)
  - normalized plasma density, n_G ~ 0.85 (resistive stability)

Control Instability

- **Select plasma temperature**, (a B), β, and plasma current
  - T ~ 0.6 × I_p ; choose T ~ 9 keV ⇒ I_p = 15 MA and (a B) = 10 m · T, and β ~ 2.5%
- **Select magnetic field in superconductor (11.8 T)** and **shielding (1.4 m)**, determines size, plasma density, energy, and fusion power
  - R = 6.2 m, B = 5.3 T, n = 10^{20} m^{-3}, 400 MW fusion power, 350 MJ plasma energy, **50 GJ** magnet energy, **0.9 GJ** plasma current energy (*enough to melt half ton of steel*)

Better Magnets

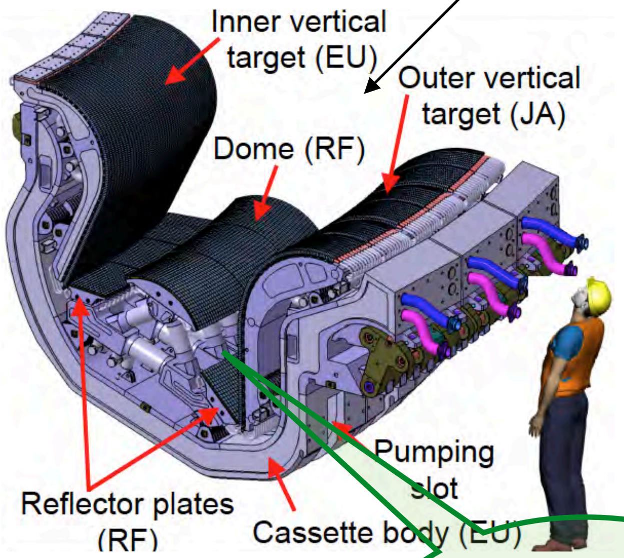
- **Check plasma energy confinement** needed to achieve desired fusion gain, Q ≡ (Power Out)/(Power In) ~ 10
  - τ_E ~ 3.7 sec requiring only 40 MW of injected power (gyroBohm: **Yes!!**) and 120 MW power to divertor

Improve Confinement

- **Check divertor cooling (must be less than 10 MW/m^2, ÷ 6 of surface of sun!)** maybe? / maybe not?
- **Check design** and determine whether or not first wall survives plasma disruptions, ELMS, loss-of-control, …
- **Check design** and determine whether or not we can build it considering strength of materials, superconducting magnet technology, neutron radiation damage, **current drive efficiency**, …
- **Figure out how to be tritium self-sufficient and become an affordable energy source…**

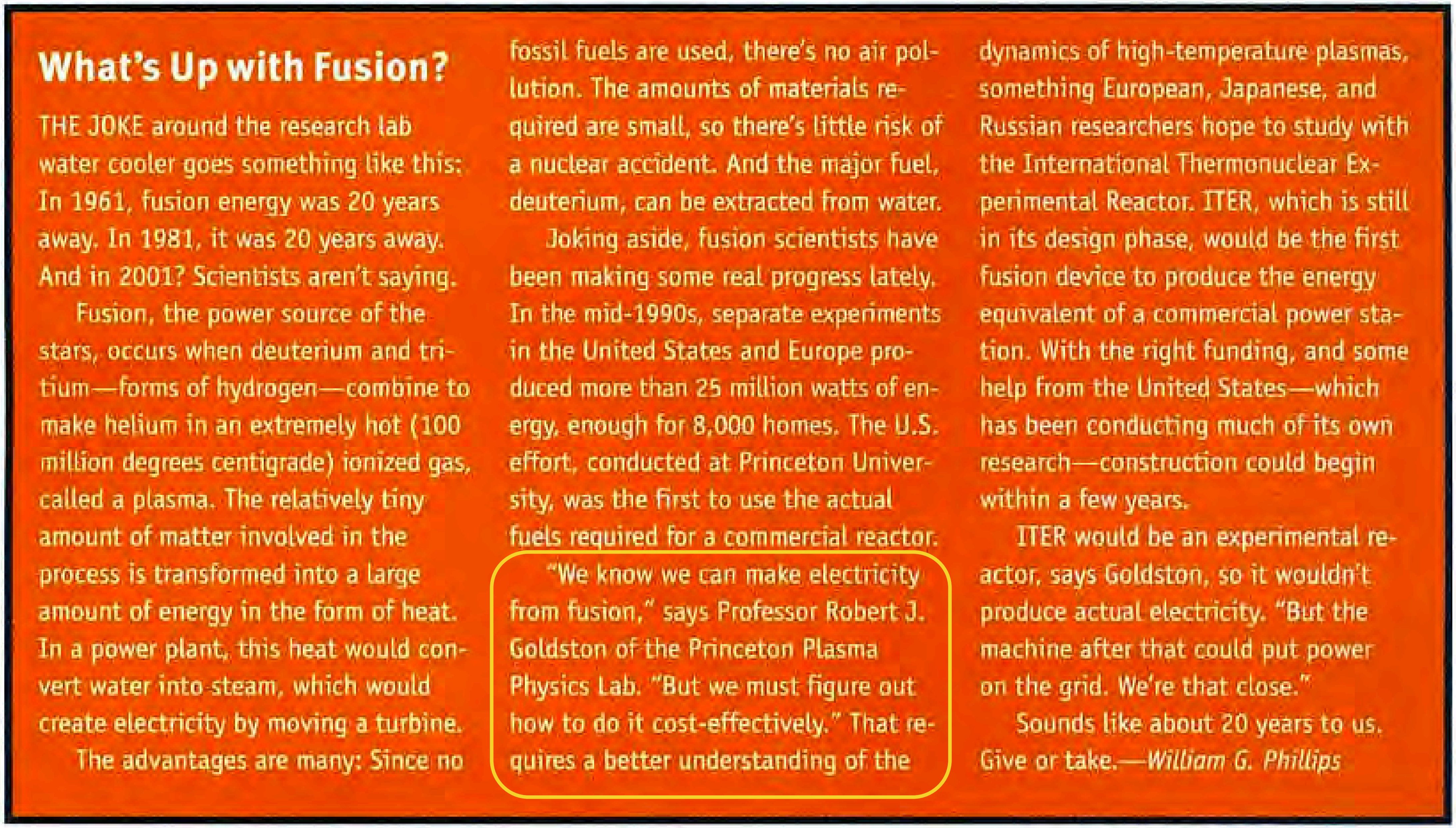
Advanced Fuels

54 Divertor Segments (9 tons each)



Spread the Heat

Popular Science (May 2001)



What's Up with Fusion?

THE JOKE around the research lab water cooler goes something like this: In 1961, fusion energy was 20 years away. In 1981, it was 20 years away. And in 2001? Scientists aren't saying.

Fusion, the power source of the stars, occurs when deuterium and tritium—forms of hydrogen—combine to make helium in an extremely hot (100 million degrees centigrade) ionized gas, called a plasma. The relatively tiny amount of matter involved in the process is transformed into a large amount of energy in the form of heat. In a power plant, this heat would convert water into steam, which would create electricity by moving a turbine.

The advantages are many: Since no fossil fuels are used, there's no air pollution. The amounts of materials required are small, so there's little risk of a nuclear accident. And the major fuel, deuterium, can be extracted from water.

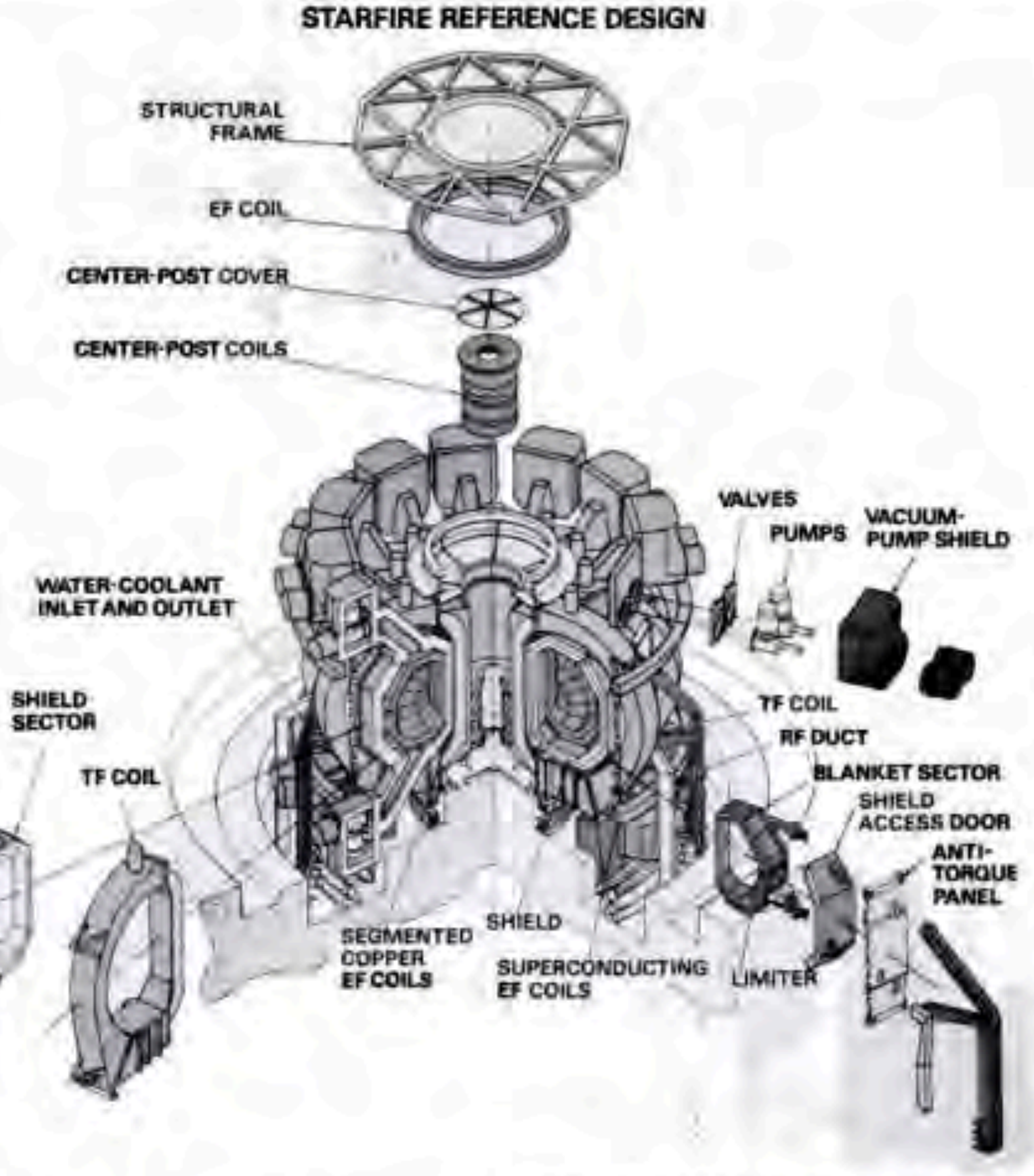
Joking aside, fusion scientists have been making some real progress lately. In the mid-1990s, separate experiments in the United States and Europe produced more than 25 million watts of energy, enough for 8,000 homes. The U.S. effort, conducted at Princeton University, was the first to use the actual fuels required for a commercial reactor.

"We know we can make electricity from fusion," says Professor Robert J. Goldston of the Princeton Plasma Physics Lab. "But we must figure out how to do it cost-effectively." That requires a better understanding of the dynamics of high-temperature plasmas, something European, Japanese, and Russian researchers hope to study with the International Thermonuclear Experimental Reactor. ITER, which is still in its design phase, would be the first fusion device to produce the energy equivalent of a commercial power station. With the right funding, and some help from the United States—which has been conducting much of its own research—construction could begin within a few years.

ITER would be an experimental reactor, says Goldston, so it wouldn't produce actual electricity. "But the machine after that could put power on the grid. We're that close."

Sounds like about 20 years to us. Give or take.—*William G. Phillips*

Popular Science (November 1981)


STARFIRE REFERENCE DESIGN

Starfire fusion reactor

You're looking at the most detailed design to date of a year-2000 commercial fusion power reactor. Dubbed Starfire, it is the result of a two-year, $2 million study prepared for the Department of Energy by Argonne National Laboratory, McDonnell Douglas Astronautics Co., and a variety of electric utilities and other private companies.

Fusion—the process of melding light elements, such as isotopes of hydrogen, to make heavier elements with an enor-

nary step toward that determ
reactor shown
d on the so-ca
f the most pr
nentally (PS, D
oversimplify, a tokamak is
shaped chamber that confine
hot ionized gas, the thermo
until it can be heated to the e
temperatures needed for fus
The Starfire design would ge
tricity steadily, rather than
mode typical of some other c
DOE study suggests that the
be cost-competitive with nu
plants and coal-fired electric
tems at the turn of the centu

Scissor-wing tested

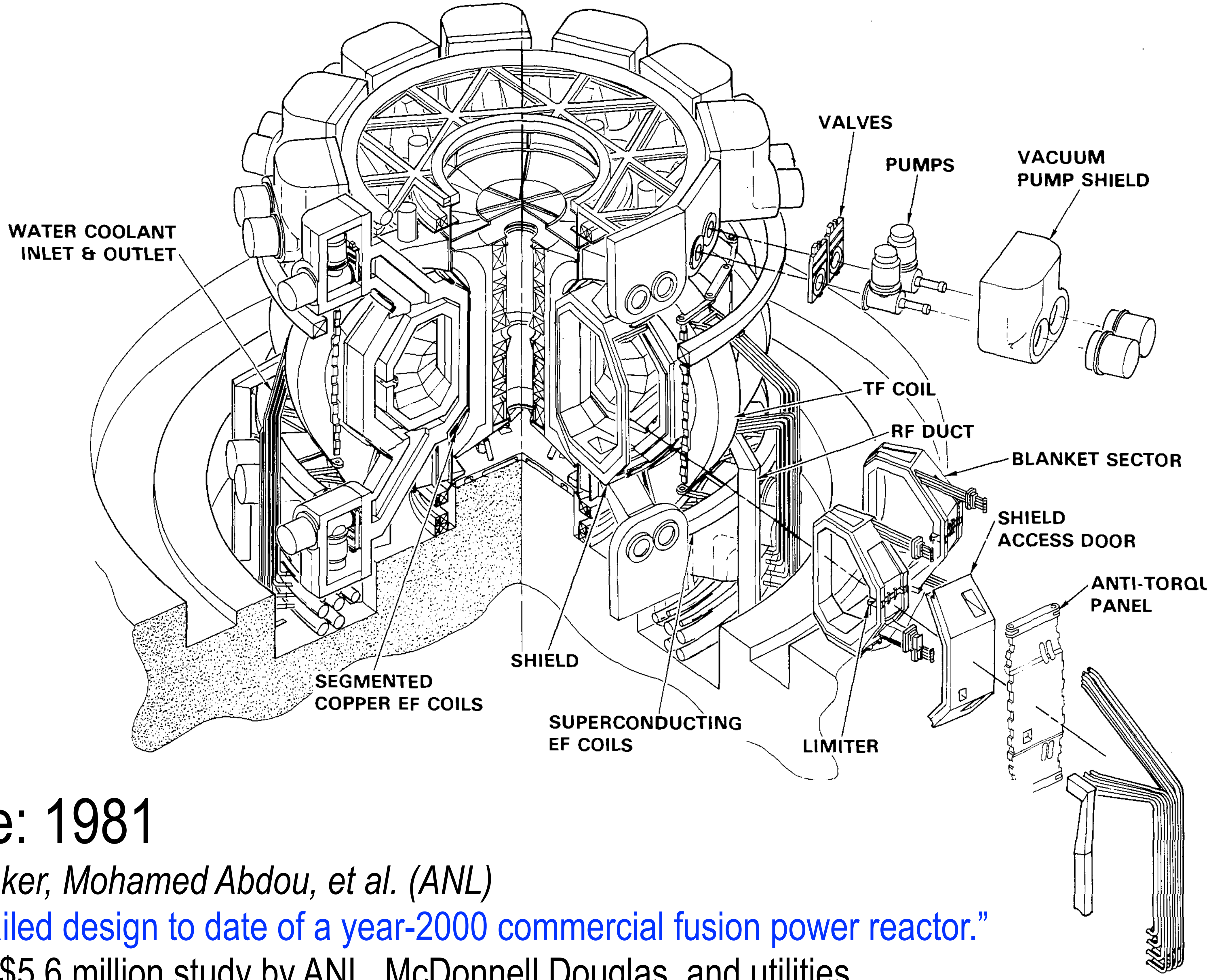
The latest step in the prog
incredible AD-1 is pictu
NASA'S unique scissor-wing
flown successfully with its
maximum, 60-degree obliq
Flight tests at Dryden Flight R
ter by pilot Tom McMurty hav
craft can skew its wing at an
from 30 to 60 degrees and stil
maneuvers required of it.

The object of the bizarre de
omy [PS, Oct. '78]. At low spe
ing takeoffs and landings, a
transport of the future would
wing perpendicular to the bod
ventional aircraft. But by
wing during transonic and
flight, the plane would decre
namic drag and thus require
and less fuel.

Tennis turmoil

Four years ago I wrote about
tion of the Prince tennis rack
tionary design with an oversiz
March '77]. Those who play
that the Prince has been fo
host of "big-head" competito

Starfire Represented Optimism of early 1980’s

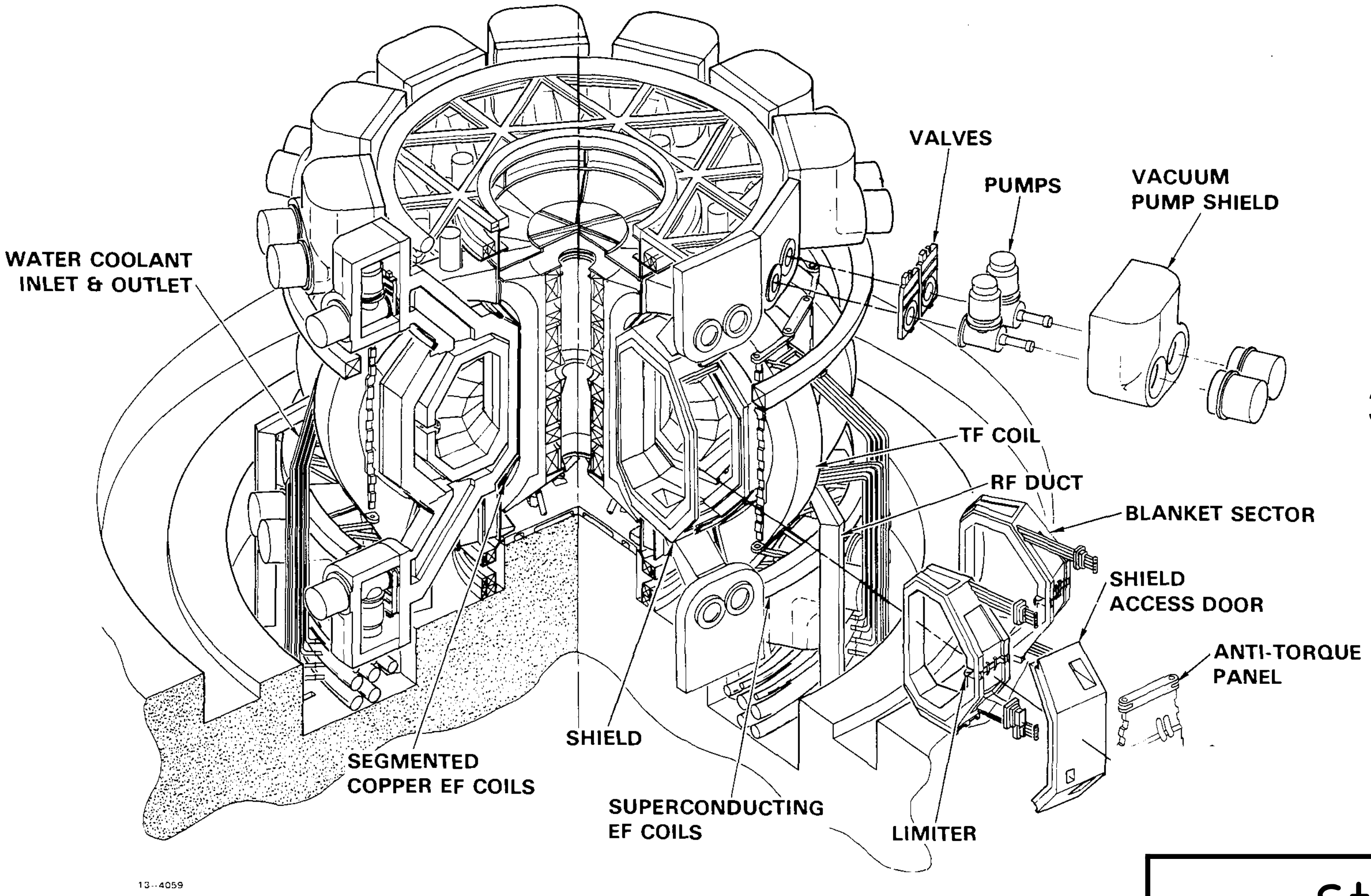


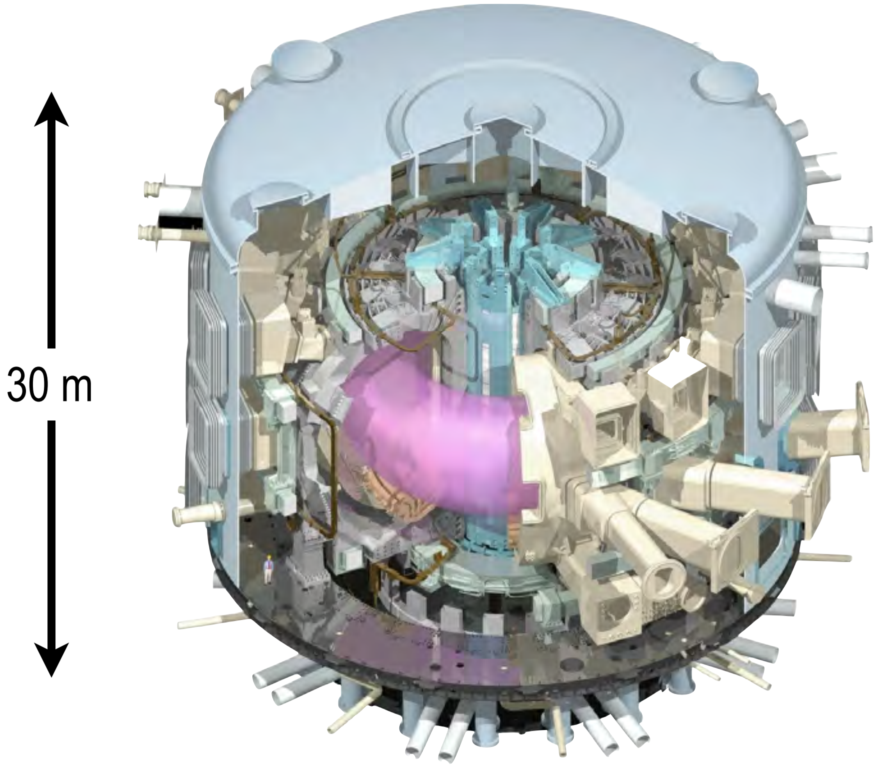
Starfire: 1981

Charlie Baker, Mohamed Abdou, et al. (ANL)

“Most detailed design to date of a year-2000 commercial fusion power reactor.”

Two-year, $5.6 million study by ANL, McDonnell Douglas, and utilities

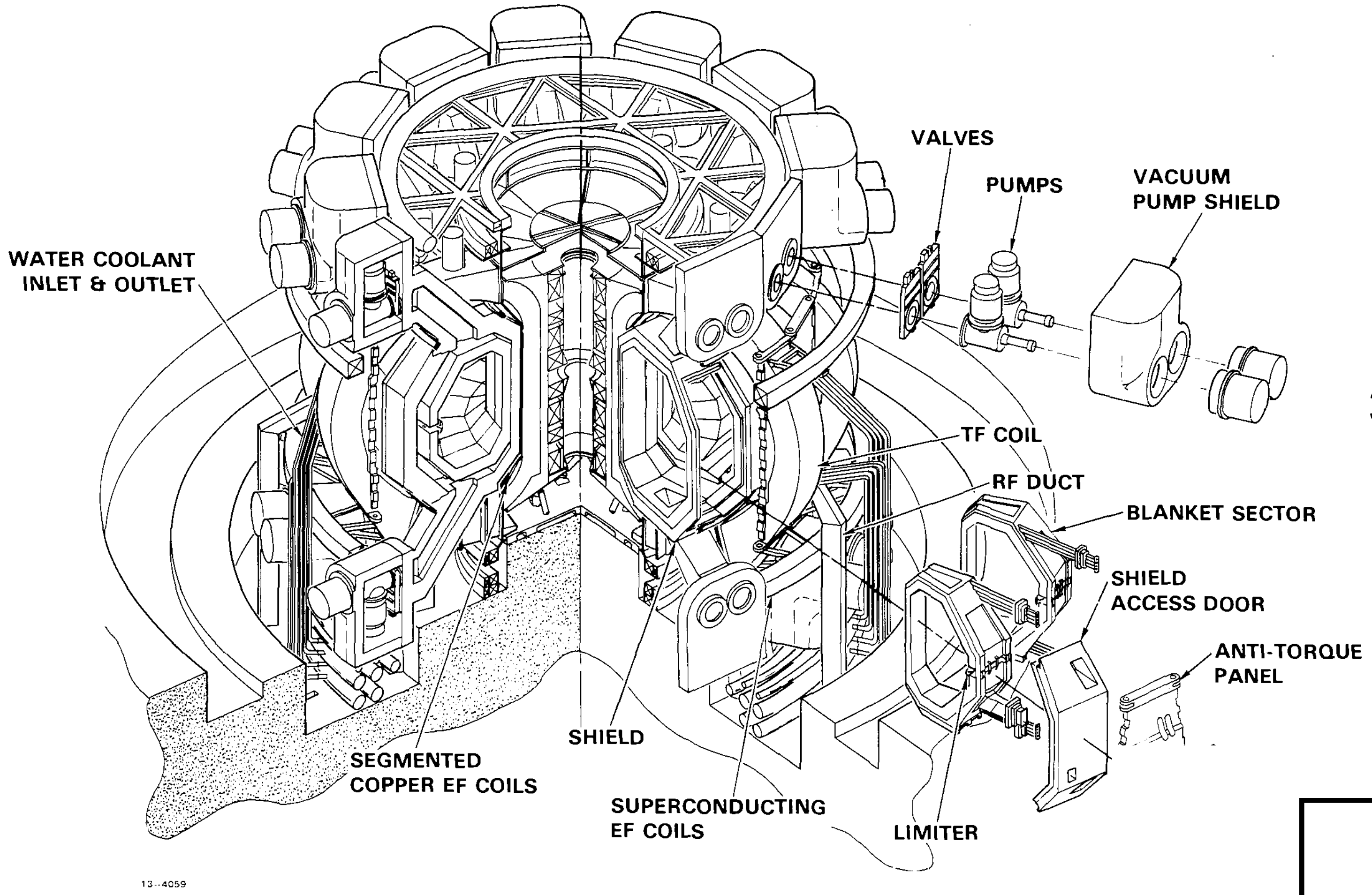


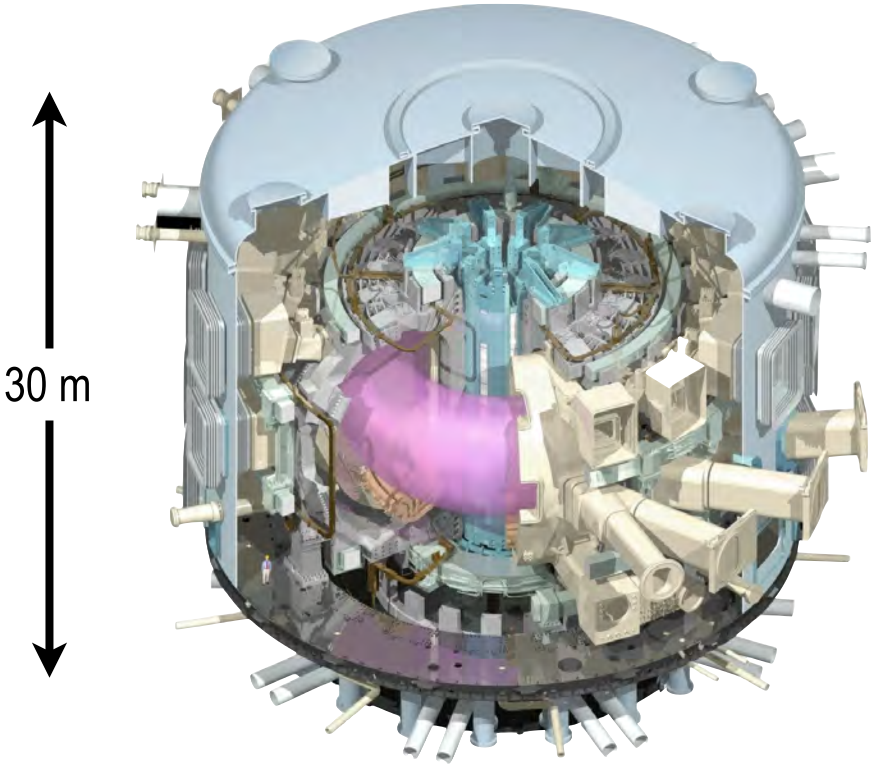


	Starfire (1981)	ITER (> 2027)
R, a (m)	7.0, 1.9	6.2, 2.0
I	10.1	15
B (T)	5.8	5.3
Duration	continuous	6000 x 7 min
P	3510	410
P	1200	−250
W	55	51
Tokamak (tonne)	24,000	23,000
Cost ($M)	6,800	> 30,000

Starfire = $\$5.7/W_e$

ITER ≥ 35 × Starfire





	Starfire (1981)	ITER (> 2027)
β	6.7, 7.3	2.5, 1.8
τ	3.6, 5.5	3.7, 1.0
n (10	1.0, 1.1	1.0, 0.85
T (keV)	24	9
λsol (mm)	100	~ 1
Max Flux (MW/m	4	> 20
Neutrons (MW/m	3.6	0.6
Material	Low-Activation SS	B-doped 316L

Today's 1st frontier for fusion…

"to demonstrate the scientific and technological **feasibility** of fusion energy for peaceful purposes"

Today's 2nd frontier for fusion…

"the challenge is whether fusion can be done in a reliable, an economical, and socially acceptable way"

ITER and advances in Alternate Energy Technology have made the issue of fusion’s cost unavoidable

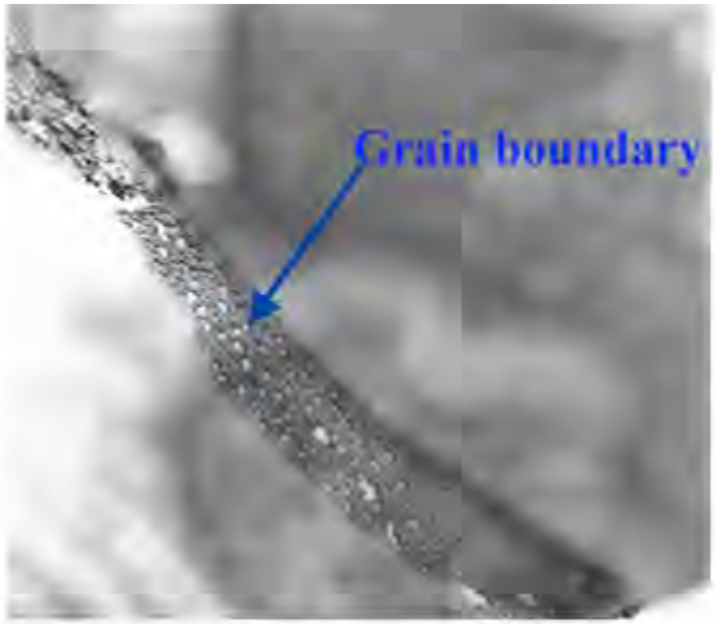
- EIA (April 2013) Utility-scale Cost and Generation:

	Capital Cost	1984	2013
Fission:	$5.5/W	37 GWy (96 units)	88 GWy (104 units)
Solar PV:	$3.9/W	0	2.5 GWy
Solar Thermal:	$5.1/W		
Onshore Wind:	$2.2/W	0	16 GWy
Offshore Wind:	$6.2/W		

- Fusion research must address “economic viability” and show cost competitiveness
- Holdren (*Science*, 1978): “Fusion, like solar energy, is not one possibility but many… The most attractive forms of fusion may require greater investment of time and money, but they are real reasons for wanting fusion at all.”

D-T Fusion’s Materials Challenge

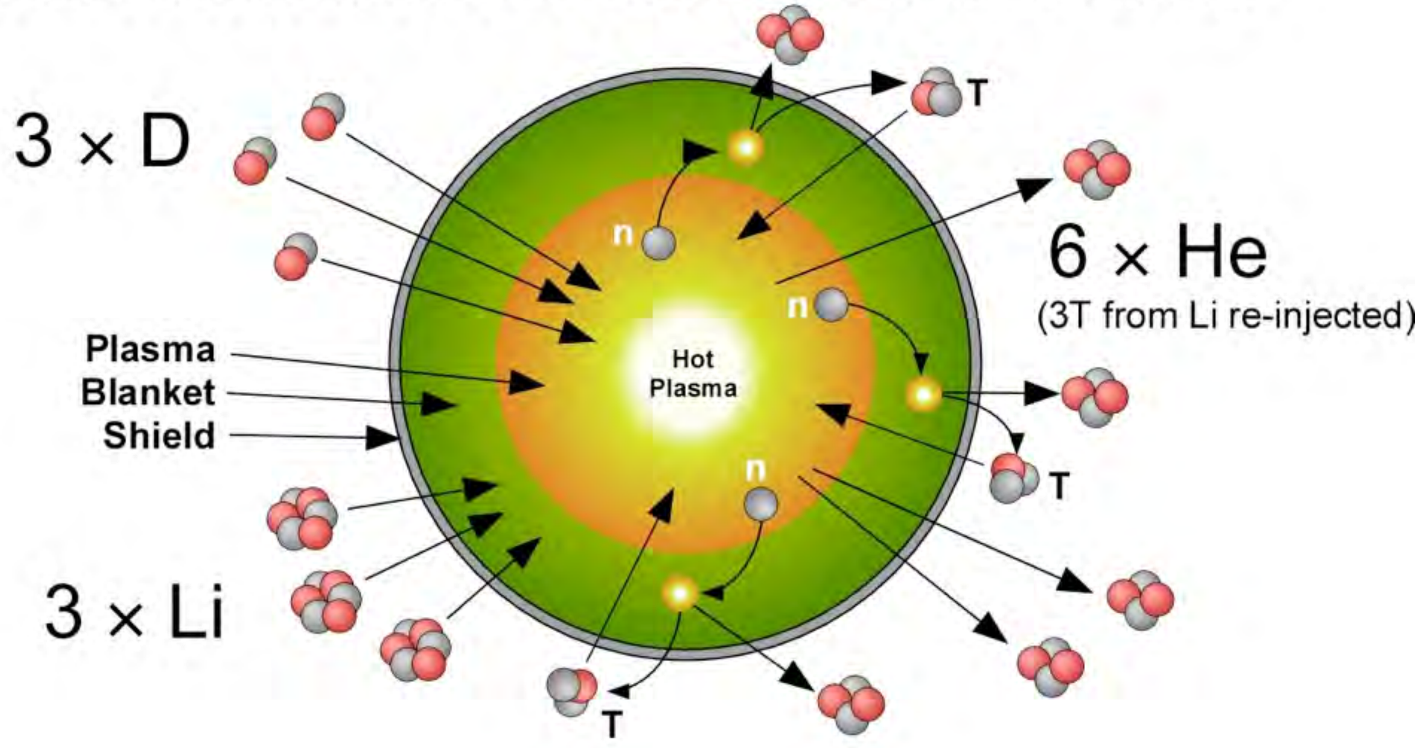
“The development challenges for these materials systems pale by comparison to that for fusion materials, which is arguably **the greatest structural materials development challenge in history**. The combination of high temperatures, high radiation damage levels, intense production of transmutant elements (in particular, H and He) and high thermomechanical loads that produce significant primary and secondary stresses and time-dependent strains requires very high-performance materials for fusion energy systems. In contrast to first generation (late 1950s) demonstration fission reactor plants, where the maximum damage level achieved by any structural material was on the order of **one displacement per atom (dpa)**, the structural materials in the first demonstration fusion reactor will be expected to satisfactorily operate up to damage levels approaching **100 dpa or higher**.”



Advanced materials for fusion technology
Steven J. Zinkle
Fusion Engineering and Design, **74** (2005) p. 31-40

Two Pathways to Fusion

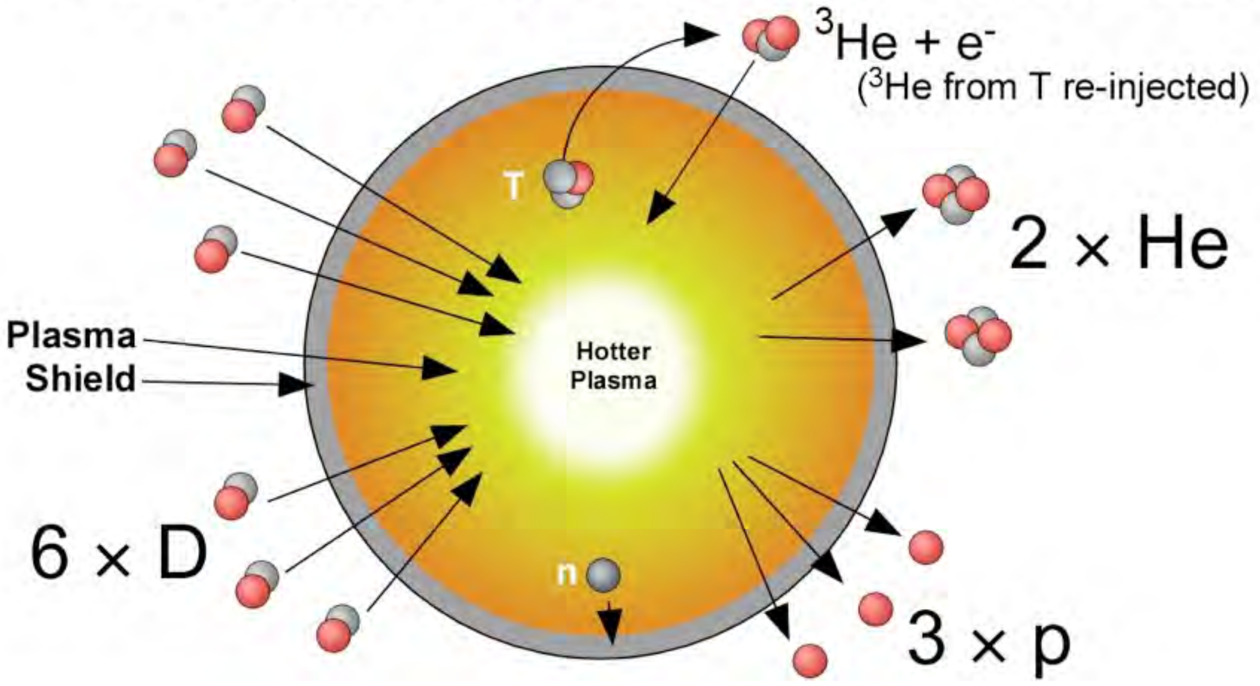
(a) 1st Generation Deuterium-Tritium Fusion



Problem: Fast Neutrons

- Develop materials that withstand > 40 dpa/FPY & 10 He appm/DPA
- Develop T breeding components
- ➡ Advance plasma confinement/ control to reduce cost

(b) 2nd Generation Deuterium-Deuterium Fusion

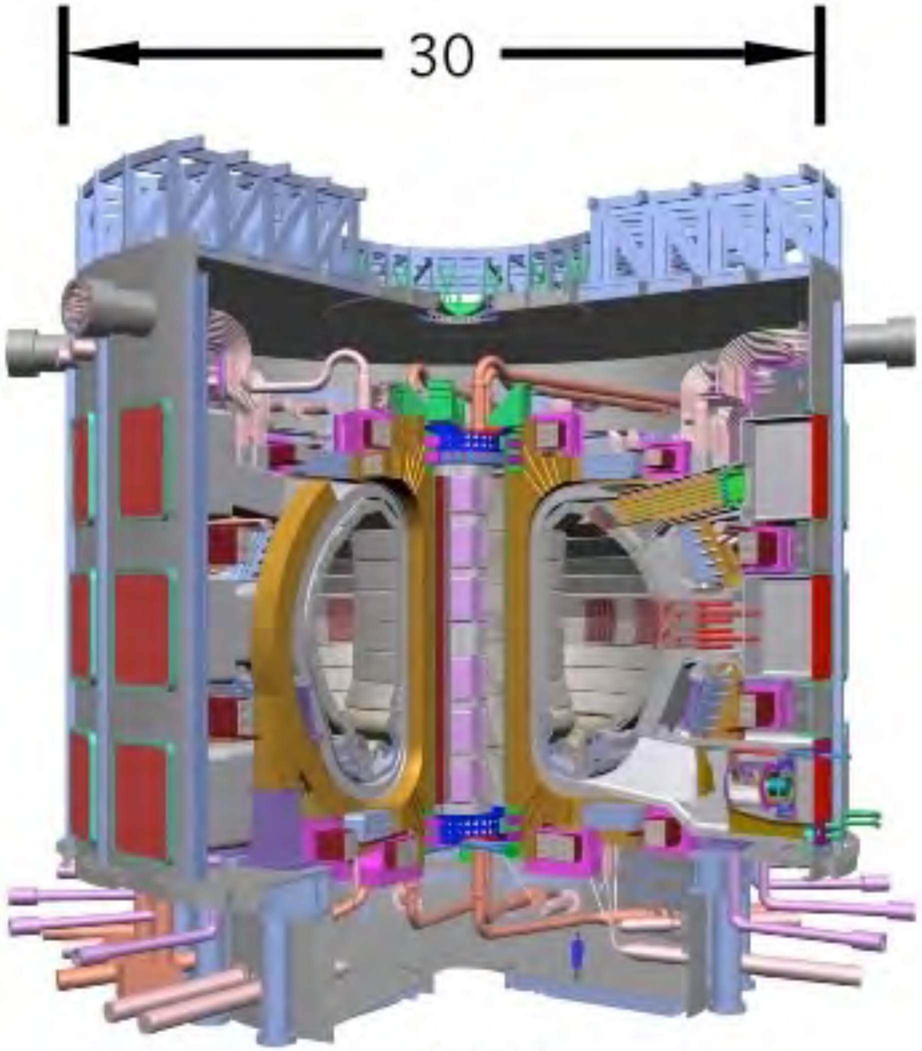


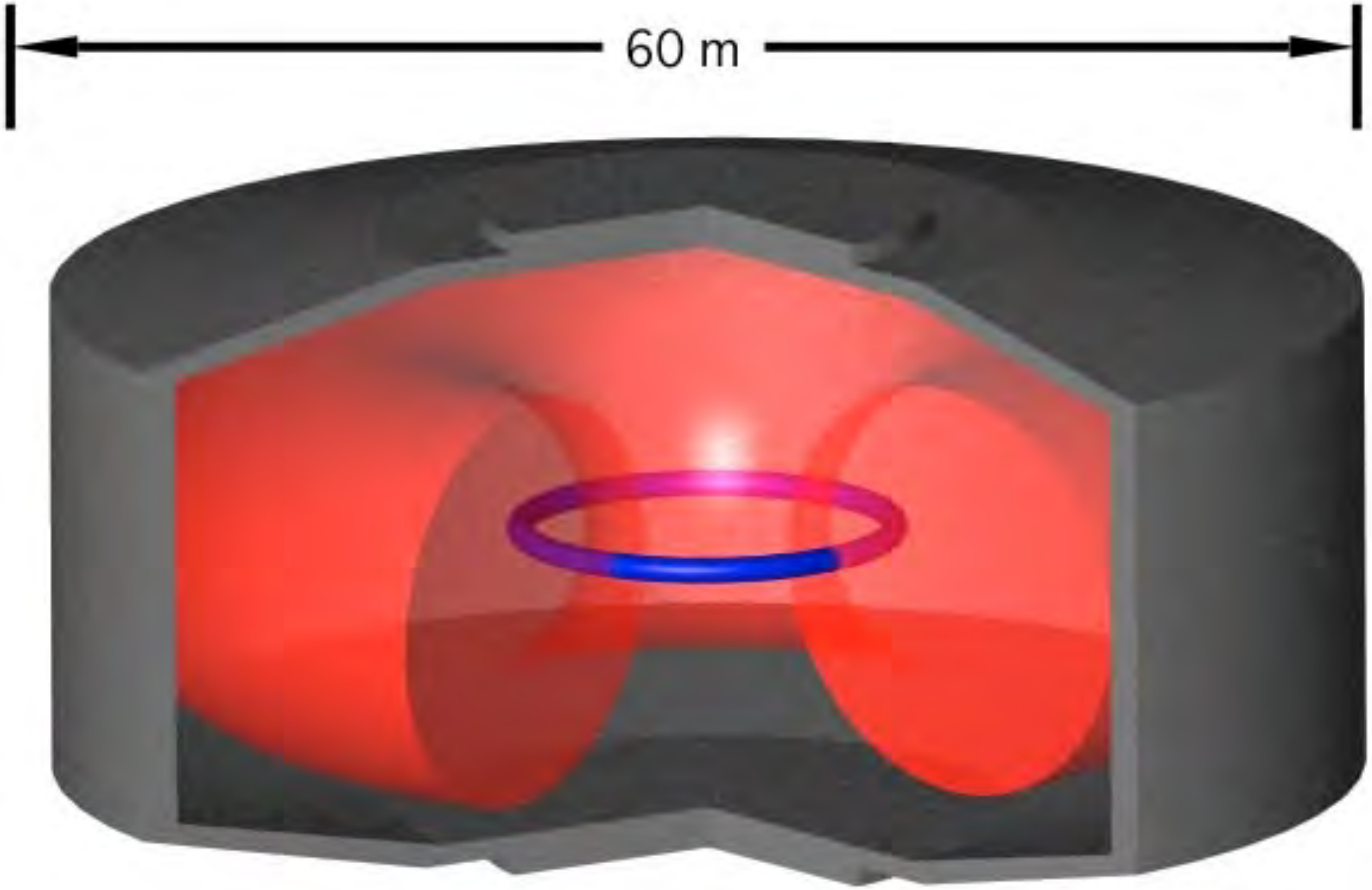
Problem: High plasma confinement

- Develop high field, high T_c superconductors
- ➡ Advance plasma confinement to achieve $\tau_p/\tau_E < 1$ at high beta

Levitated Dipole may Make Possible Tritium Suppressed Fusion

Dipole T-suppressed fusion is an **alternate technology pathway** that avoids the need to develop **breeding blankets** and **structural materials compatible with 14 MeV neutrons**.





ITER
500-700 MW
D-T Fusion

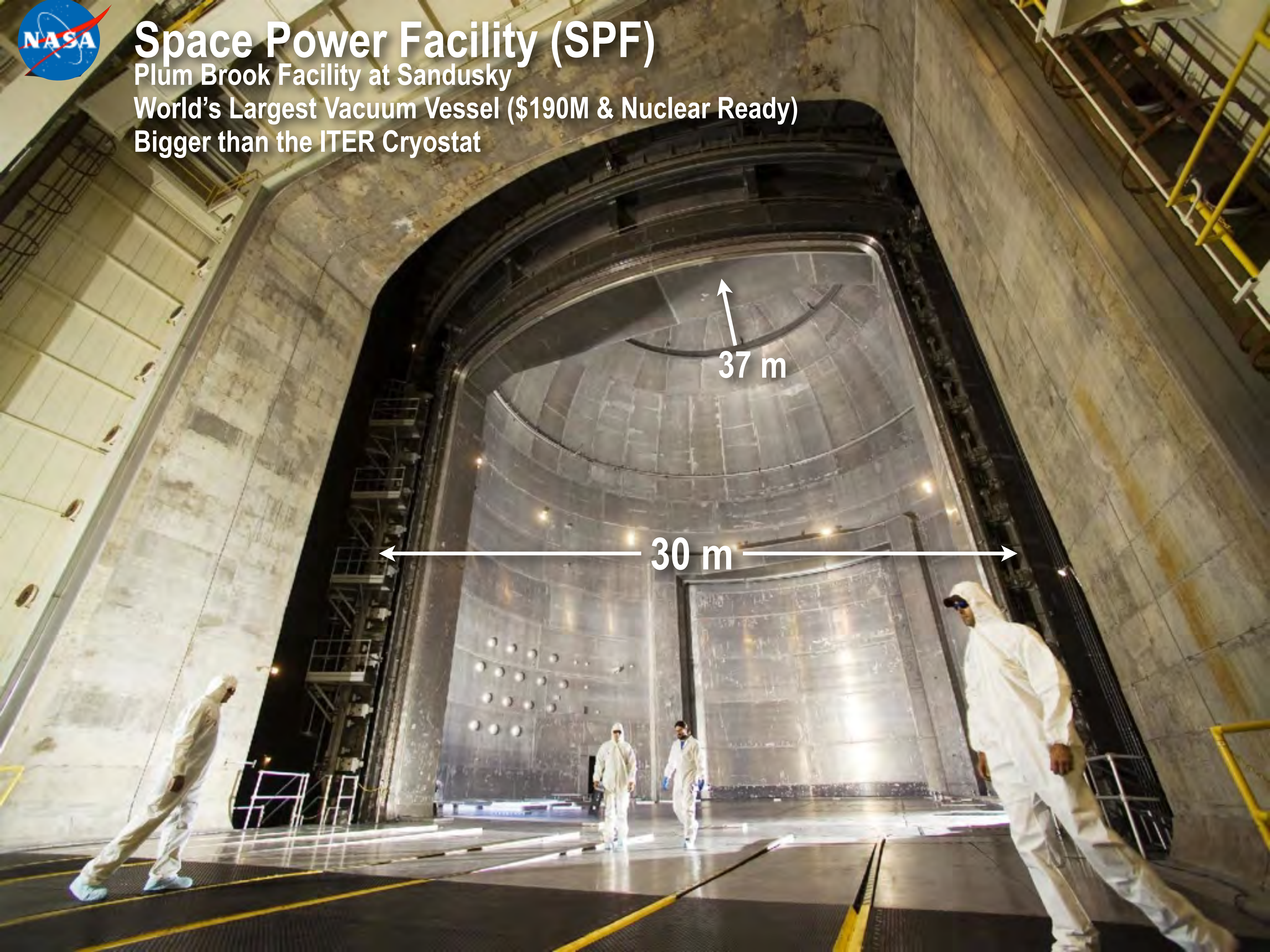
51 GJ	W_B	31 GJ
0.3GJ	W_p	3 GJ
>400 MW	14 MeV Power	14 MW

Levitated Dipole
600 MW
D-D(^{3}He) Fusion

Kesner, et al., NF (2004)

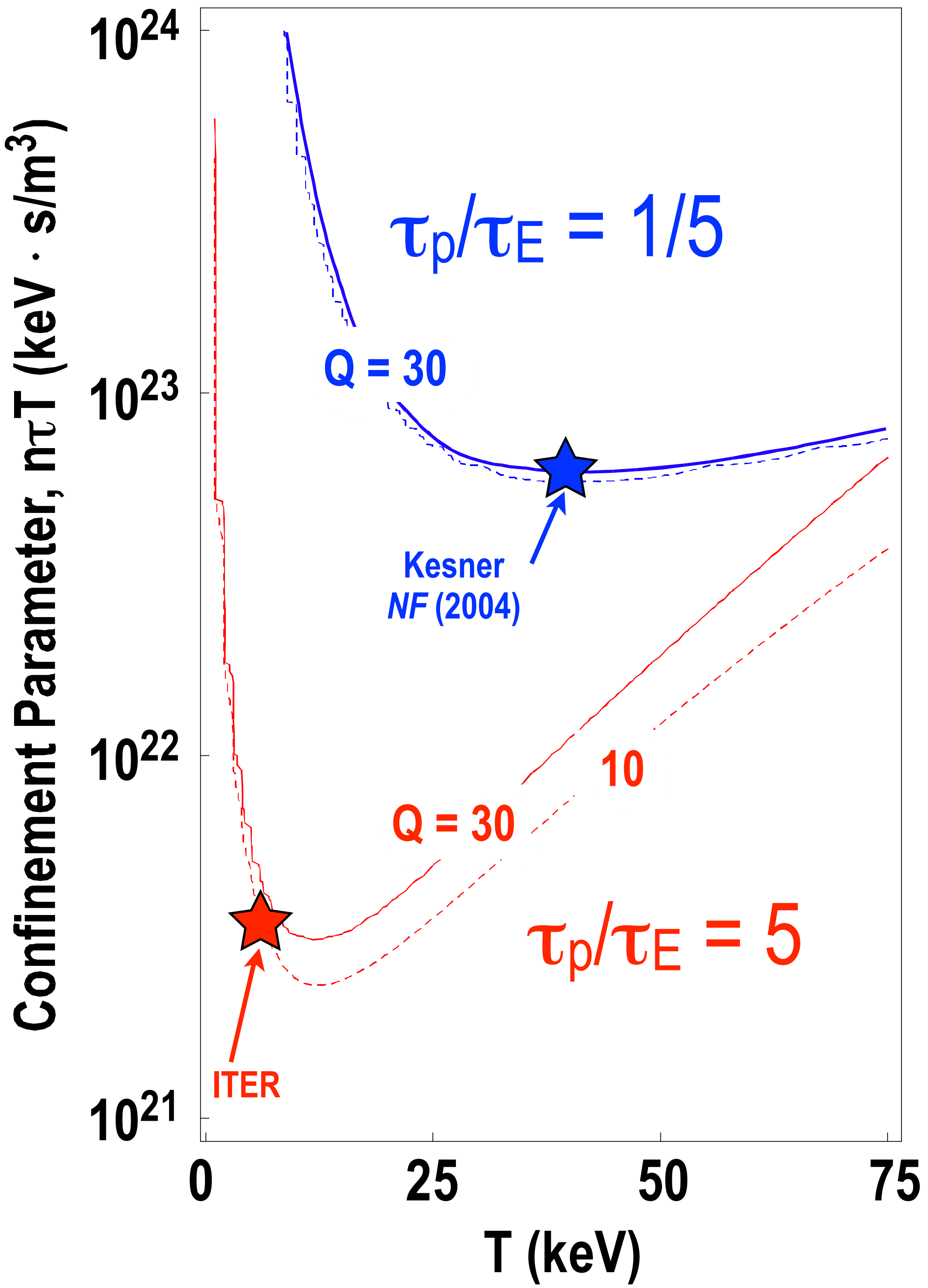
Space Power Facility (SPF)

Plum Brook Facility at Sandusky
World’s Largest Vacuum Vessel ($190M & Nuclear Ready)
Bigger than the ITER Cryostat



Turbulent Pinch in a Levitated Dipole may Make Possible Tritium Suppressed Fusion

- Sheffield, Zinkle, Sawan (2002-06)
- No tritium breeding blankets
- No 14 MeV neutrons
- No structural materials problem
- Requires $\tau_p/\tau_E < 1$
- Requires 35 keV
- Requires 10 fold confinement improvement
- Requires stronger, higher-field superconducting magnets



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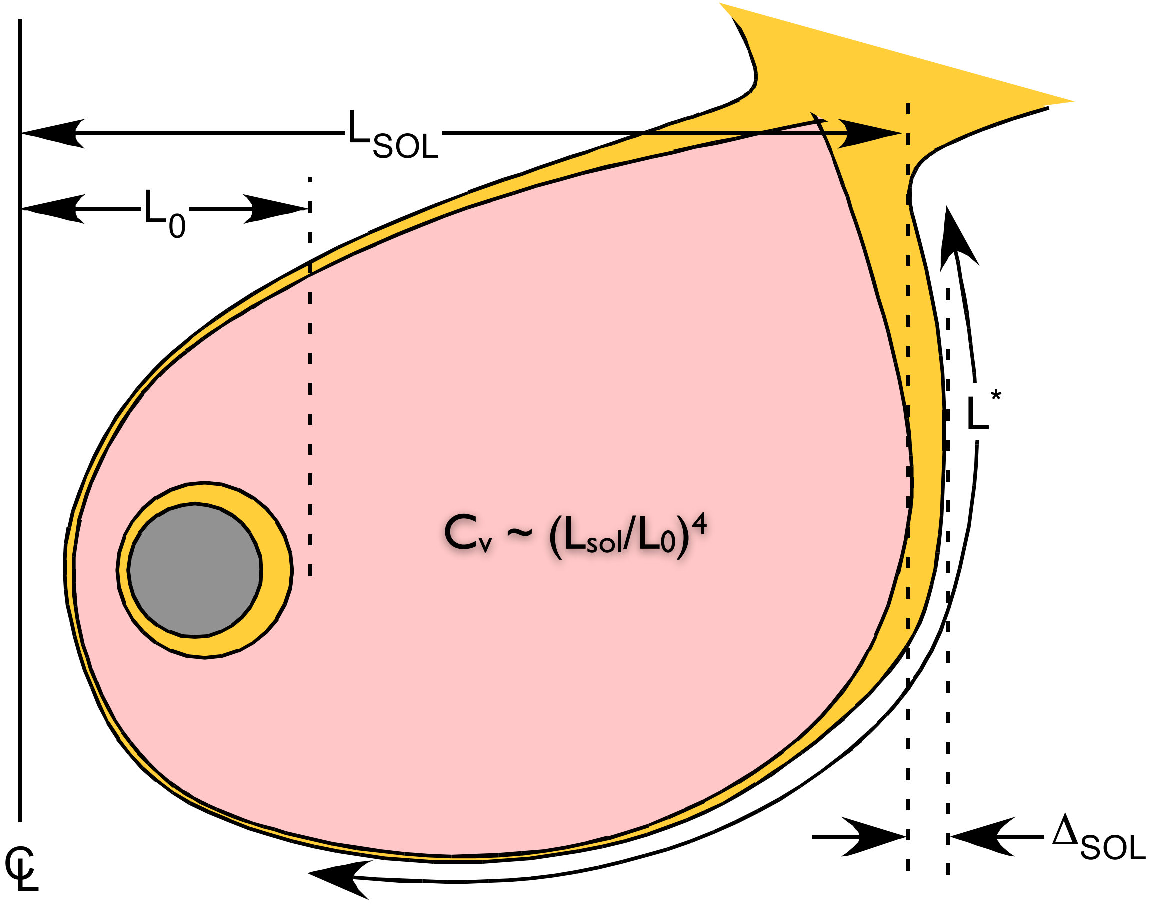
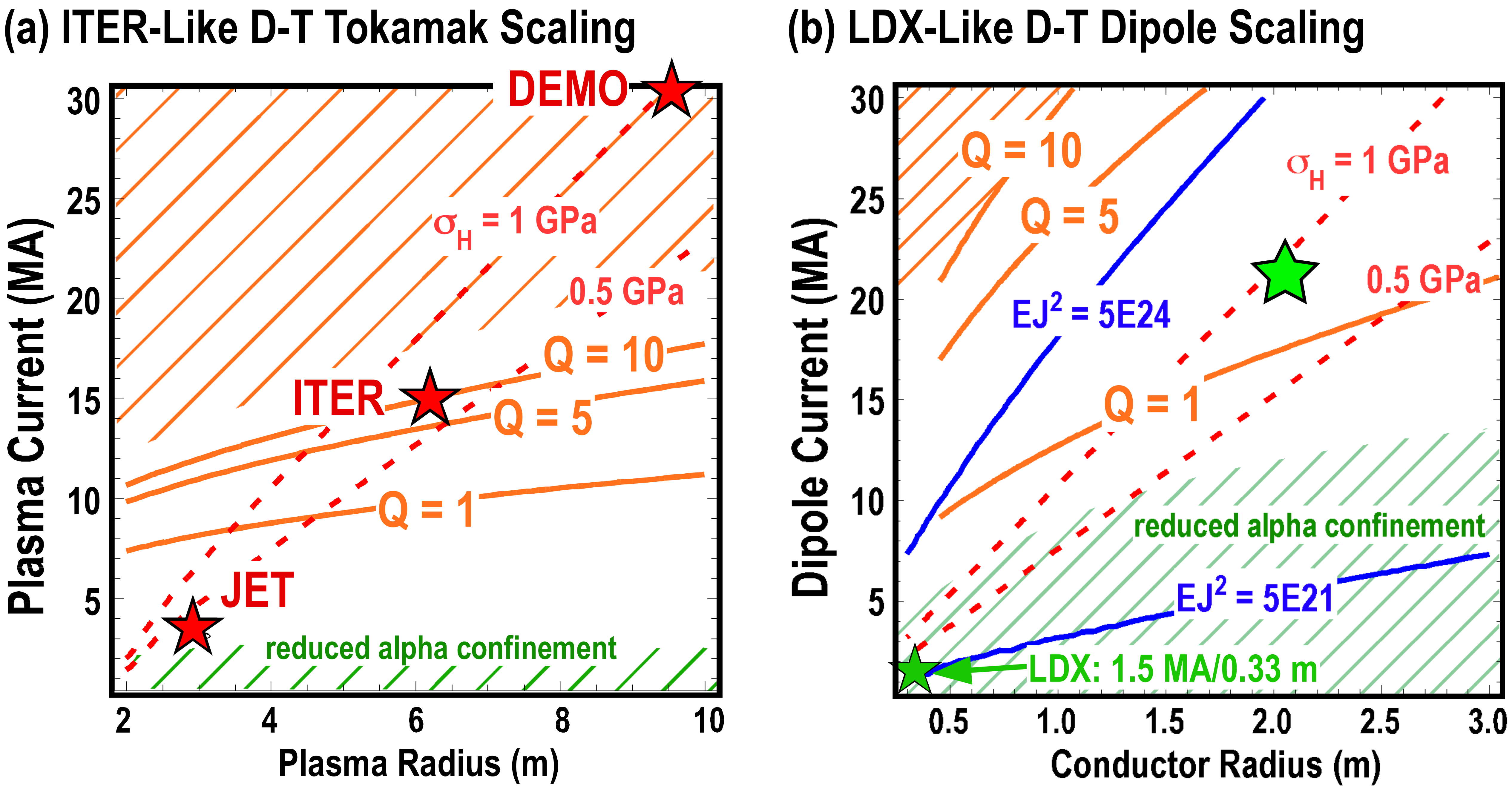
(N, $P\delta V^\gamma$) ~ constant implies peaked density and pressure profiles (**if $\gamma > 1$**)



Adiabatic mixing implies
core parameters determined by edge &
compressibility:

$$\tau_e/\tau_p \sim (4\gamma-3)C_v^{\gamma-1} > 50$$

Dipole Proof of Performance Scaled from LDX to fit in NASA's SPF



Fusion Gain - Magnet Stress - Quench Safety Parameter - Alpha Confinement

Summary

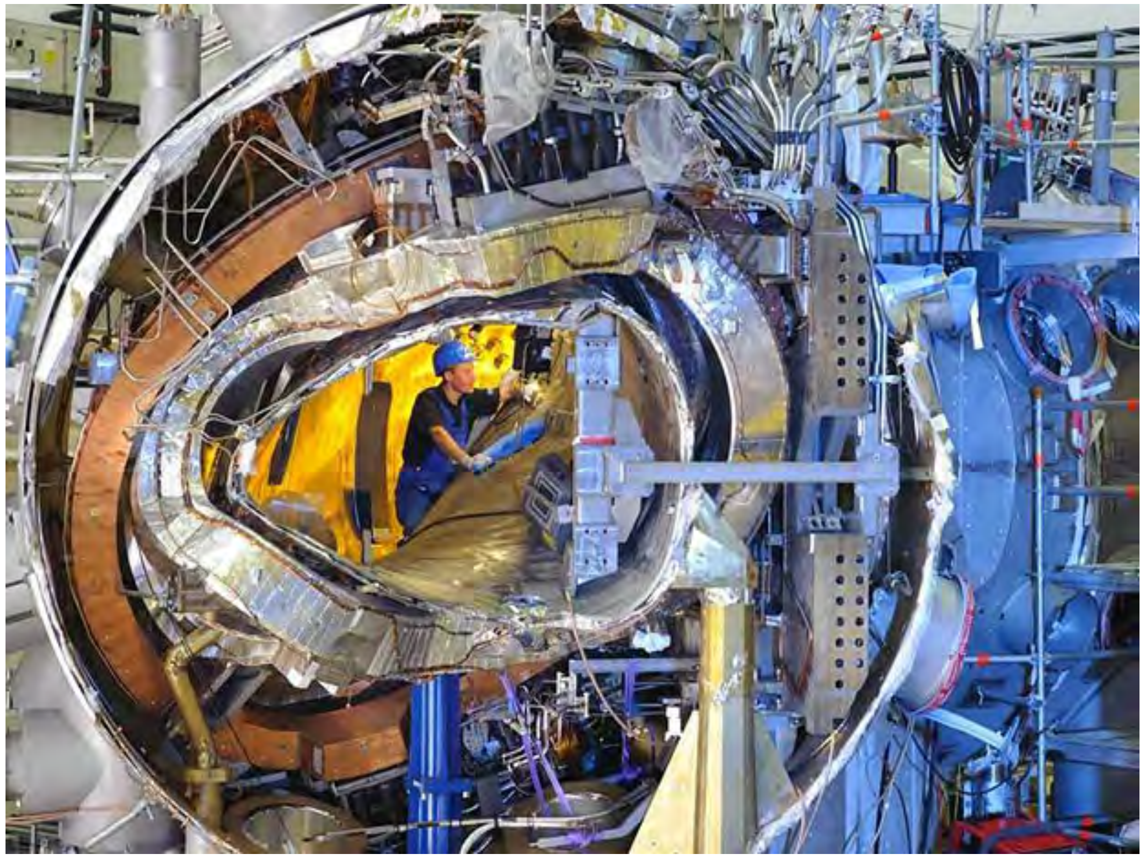
- **Plasma containment *and the success of fusion energy research* requires understanding how best to shape the magnetized plasma torus**
- **Fusion researchers must make discoveries to overcome challenges to economic viability**

IEEE SPECTRUM

Fusion Stellarator Starts Up

Alternate design to ITER might ultimately be better for generating electricity

By Alexander Hellemans
Posted 21 May 2014 | 19:44 GMT



Slate

An Interview With Linus Torvalds, Creator of Linux

By Dylan Love

BUSINESS INSIDER
ANALYZING THE TOP NEWS STORIES ACROSS THE WEB
JUNE 9 2014 10:00 AM

But ITER? With a huge, complex, expensive piece of hardware that you'll have one (or eventually just a handful) of? Yeah, I'm going to go out on a limb and say that there's a lot of red tape and politics and bureaucracy, to the point where collaboration is going to be really hard. A lot of committees... ***There's a lot of people hoping for a simpler, smaller, and yes, more scalable solution.***