Innovations and New Ideas in Magnetic Fusion Energy

or

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

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

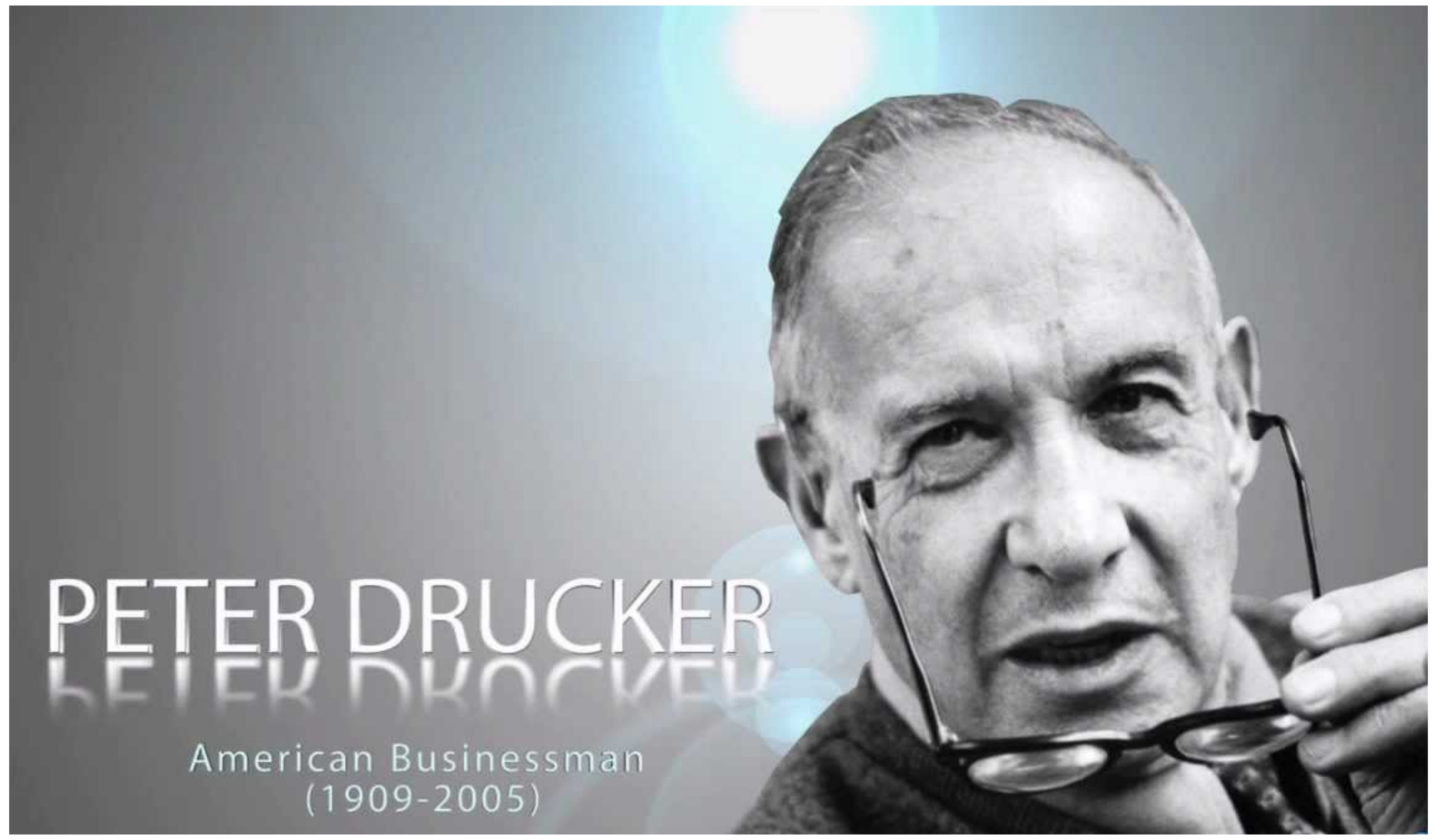
Science Undergraduate Laboratory Internship (SULI)
13 June 2017

The slides for this talk are online at:
http://www.apam.columbia.edu/mauel/mauel_pubs/NUF2017-InnovationsMagFusion.pdf

§Robert Gross, Columbia University, *Fusion Energy* (1984)

What is Innovation?

Innovation



Presidential Medal of Freedom (2002)

Peter Drucker "Founder of Modern Management" (*Harvard Business Review*, 2002):

Innovation is the specific function of entrepreneurship, whether in an existing business, a public service institution, or a new venture started by a lone individual in the family kitchen. It is the means by which the entrepreneur either creates new wealth-producing resources or endows existing resources with enhanced potential for creating wealth.

Innovations, New Ideas, Learning from Failures, and Entrepreneurship

- **Elon Musk:** “When Henry Ford made cheap, reliable cars, people said, ‘Nah, what’s wrong with a horse?’ That was a huge bet he made, and it worked.” (2003)

- **Steve Jobs:** “Innovation has nothing to do with how many R & D dollars you have. When Apple came up with the Mac, IBM was spending at least 100 times more on R & D. It’s not about money. It’s about the people you have, how you’re led, and how much you get it.” (1998)

- **Carl Sagan:** “But the fact that some geniuses were laughed at does not imply that all who are laughed at are geniuses. They laughed at Columbus, they laughed at Fulton, they laughed at the Wright Brothers. But they also laughed at Bozo the Clown.” (1979)

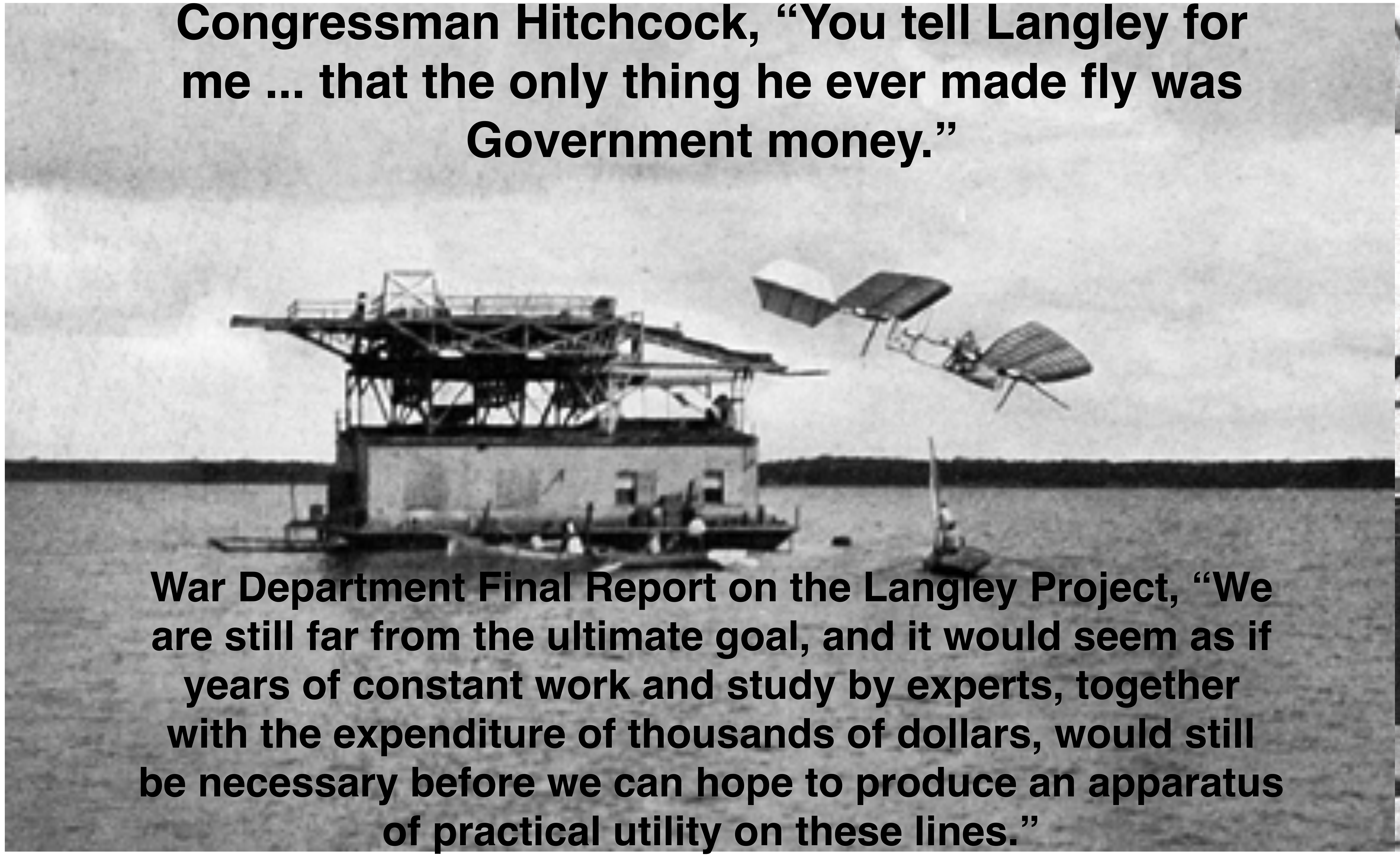
- **Thomas Edison:** “I can never find the things that work best until I know the things that don’t work.” (1908)

- **Orville Wright:** “If we worked on the assumption that what is accepted as true really is true, then there would be little hope for advance” (1903)

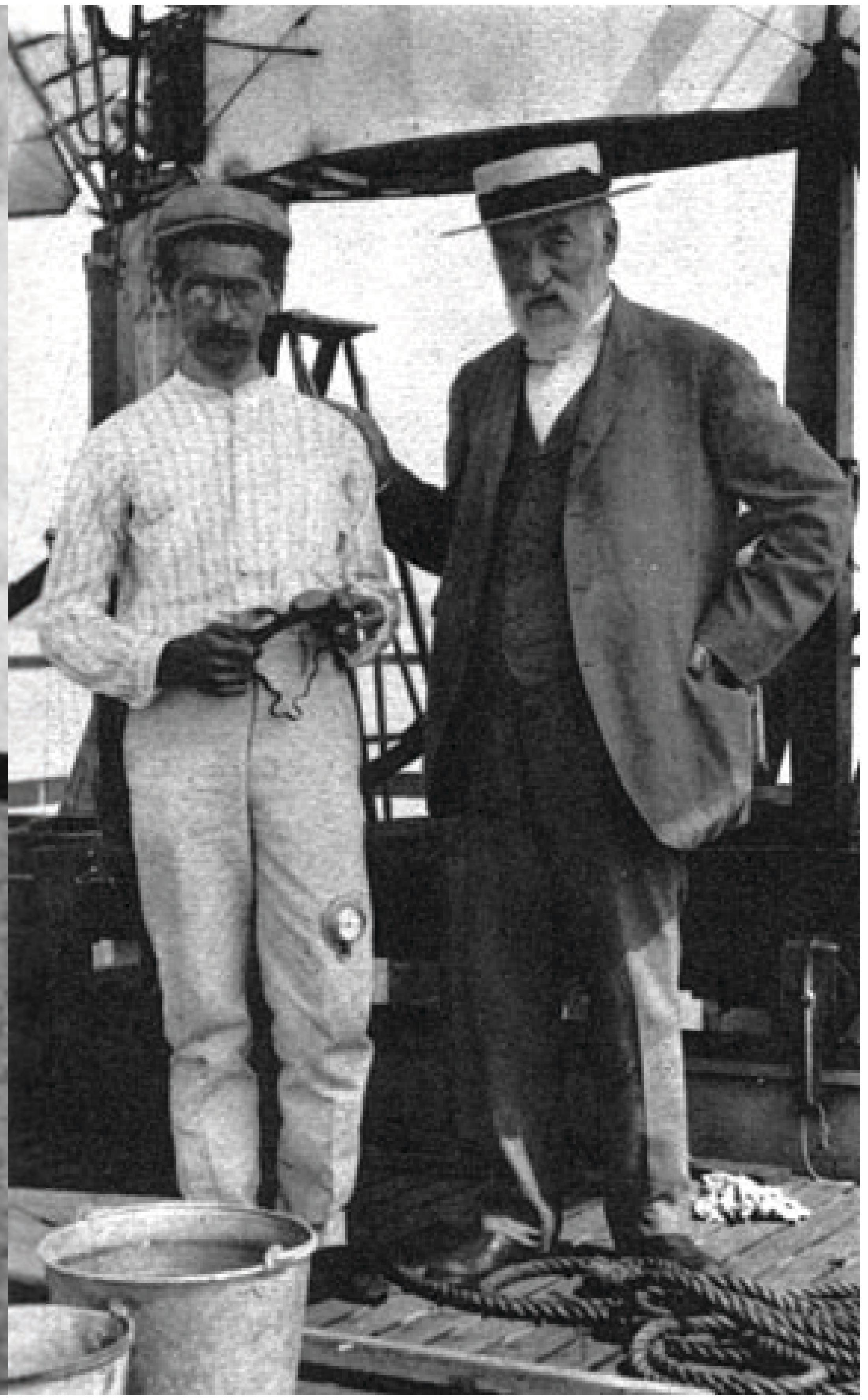
- **Wilbur Wright:** “In studying their failures we found many points of interest to us.” (1900)

“Langley’s Folly”

“Crash” program of human flight requested by President McKinley and well-funded by Smithsonian Institute and War Department



Failures on the Potomac: Oct. 7, 1903 and Dec. 8, 1903

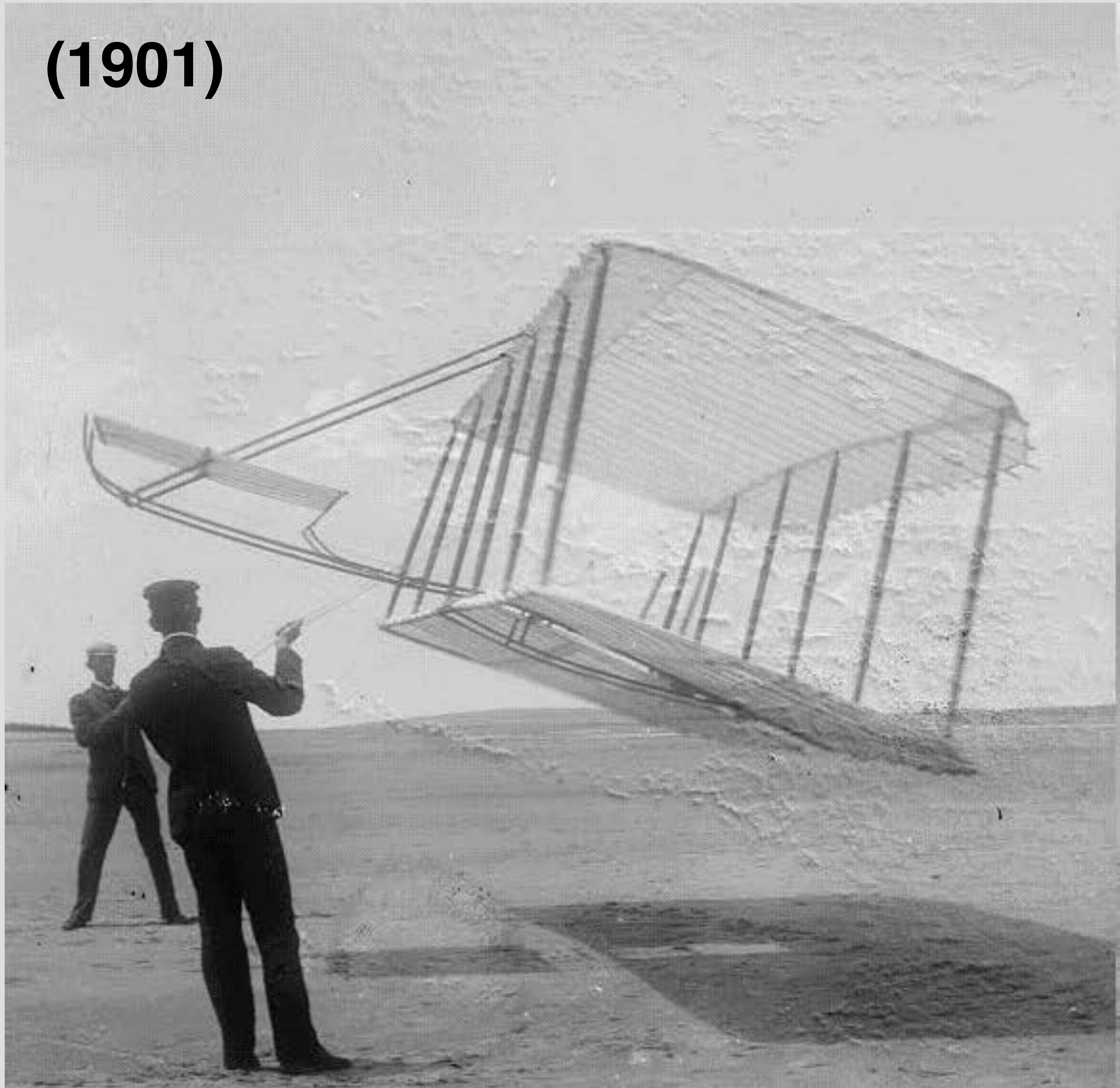


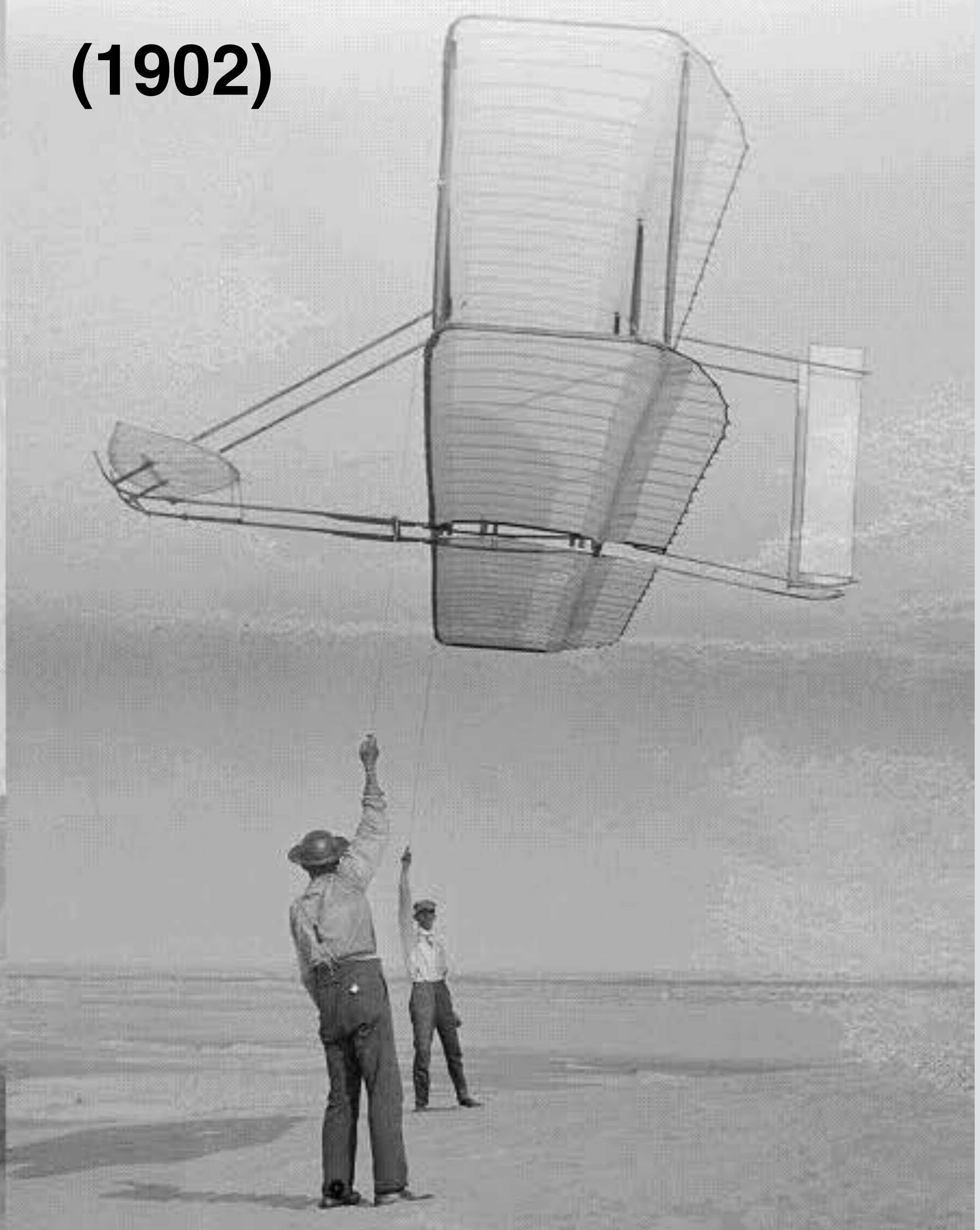
Charles Manly (pilot) & Samuel Langley aboard the Large Aerodrome-A (1903)


8 Days Later at Kitty Hawk…
Systematic engineering
“Steerable” & Capable of Take-off/Landing
Careful step-by-step validation
Privately funded (50 times less than Langley)

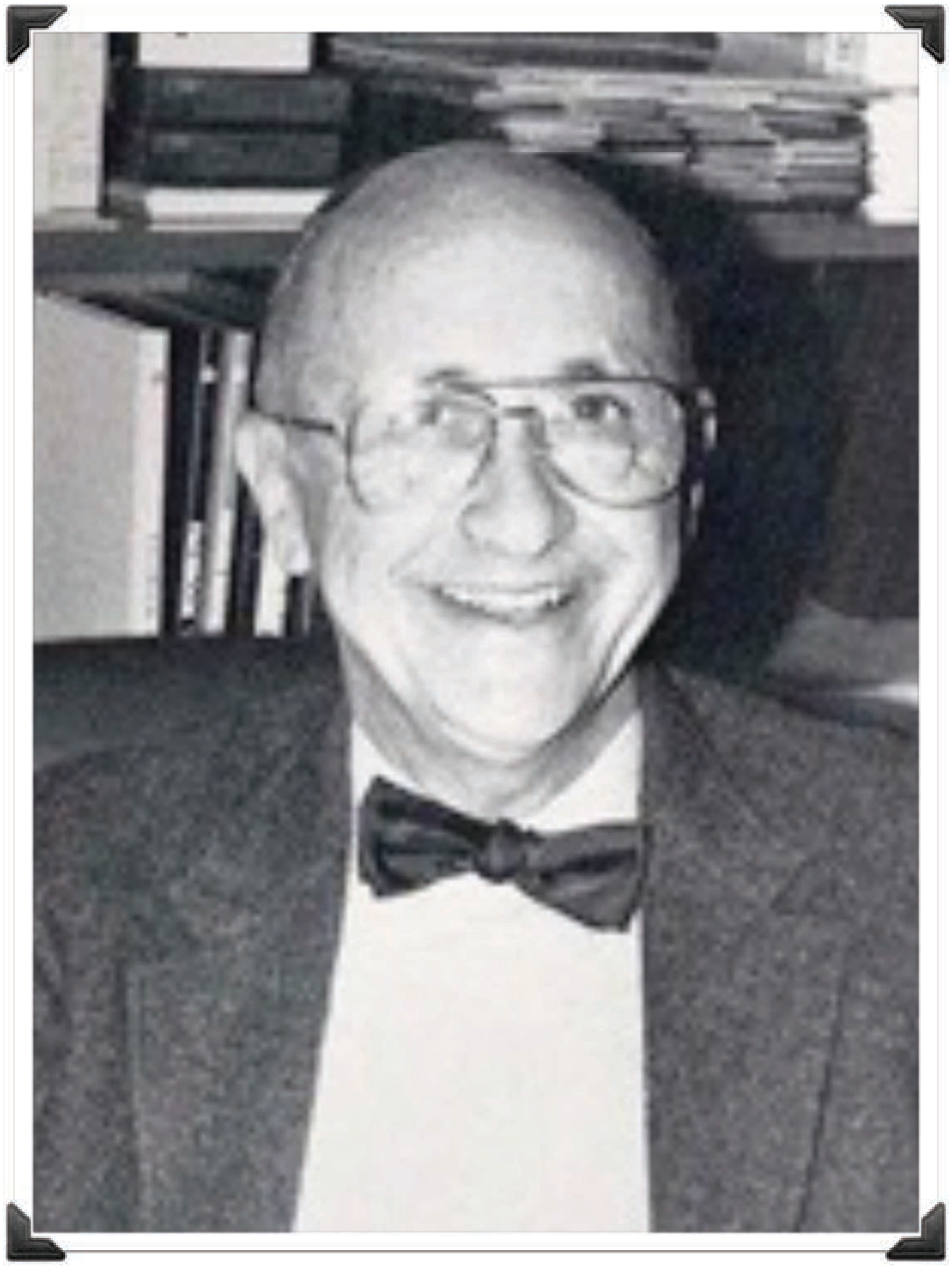

Wright Brother’s Wind Tunnel
> 200 Wing Shapes

Step-by-Step Tests of Predictive Understanding of Aerodynamics

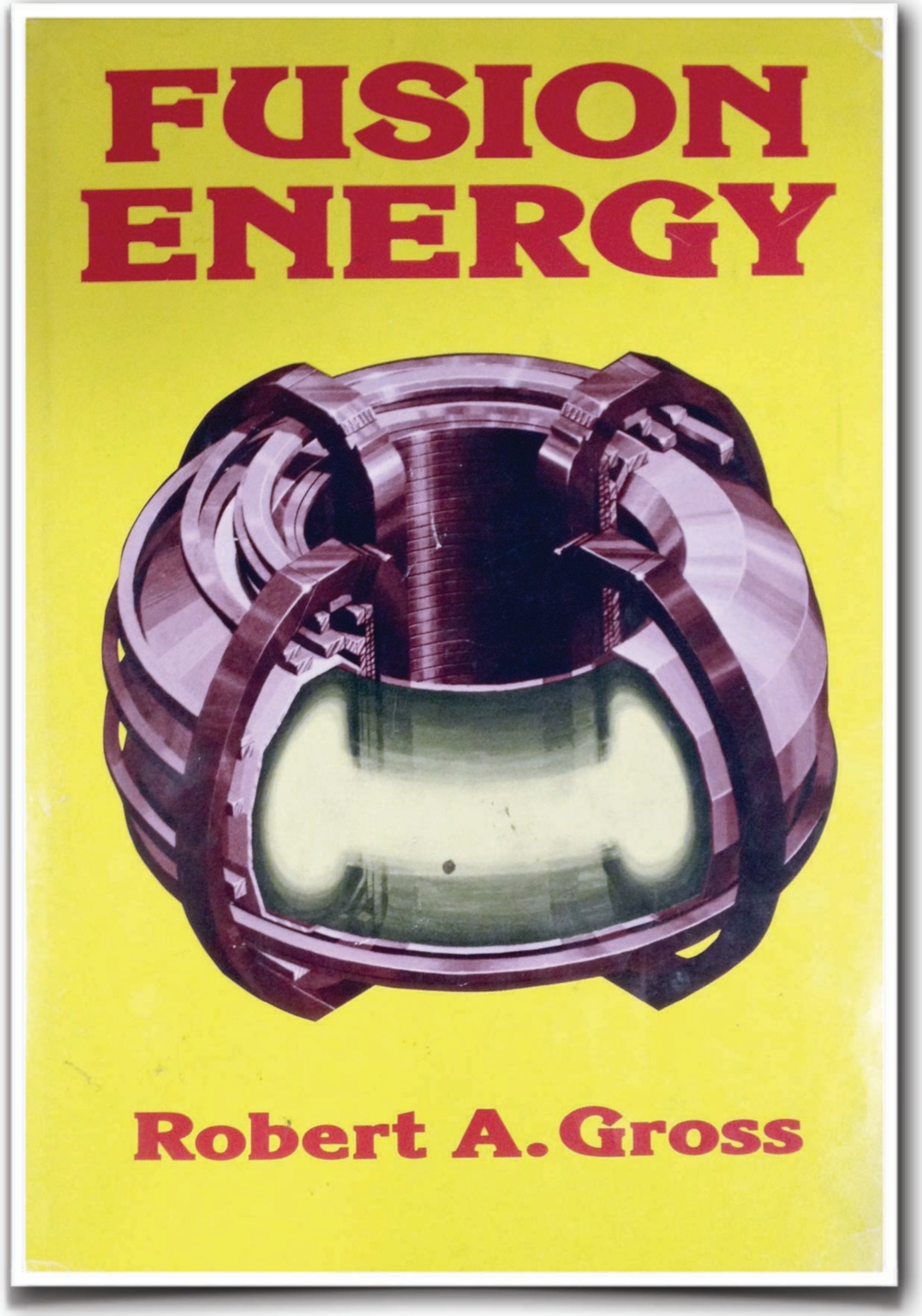




Innovation never stops…



Prof. Robert Gross
Columbia University
Fusion Energy
(1984)



Robert Gross, Columbia University, *Fusion Energy* (1984)

The Early Question was "Can fusion be done, and, if so how?"

During 60 years…

- Established the new fields of plasma physics, science, and engineering
- Over 200 tokamaks and many other plasma tori. (*We really know how to design tokamaks!*)
- Realistic (nearly "predictive") models and simulations for magnetic confinement.
- Repeatedly generated over 10 MW fusion power! (TFTR in 1994 and JET in 1997)
- Achieved net fusion gain > 1, "equivalent" (JT-60U in 1996)
- Superconducting magnets! (Tore Supra/WEST, LHD, EAST, K-Star, W7-X, …)
- Construction well underway: the first fusion experiment at ambitious scale of a power plant (ITER)
- …

Robert Gross, Columbia University, *Fusion Energy* (1984)

“Now, the challenge lies in whether fusion can be done in a reliable, an economical, and socially acceptable way…”

Building on 60 years of science and technical experience, fusion is focusing on …

Innovations, New Ideas, Learning from Failures, and Entrepreneurship

Fusion: the "Ultimate Energy Source"

Liquid CO_2 (1 ton @ 1500 psi) | Coal | Oil | LNG | Grass | H_2 (4500 psi)

3/4 cup of U ore
(0.003% ^{235}U)

16 FL OZ Water
(0.015% D/H)

The Overwhelming Potential of Fusion Power…

Drink Fusion!

The FUTURE of Power

Only 30 years away!

More Energy than…

1 Barrel of Oil

37,000 Laptop Batteries

1/4 Ton of Coal

1 Bale of Switchgrass

Nutrition Facts

Serving Size 16 FL OZ (474 ml)

Amount Per Serving

Calories 1,900,000,000

Total Carbon 0g

Total Waste 0g

Ingredients:

4,500,000,000,000,000,000,000 Deuterons

The Overwhelming Potential of Fusion Power is Attracting Innovators in Industry, Government Labs, and Universities today…

TRI ALPHA ENERGY
leading the way to the future...

tokamak energy
a faster way to fusion

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Princeton SATELLITE SYSTEMS

UC San Diego

LOCKHEED MARTIN

GENERAL ATOMICS

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Ucla

generalfusion

Columbia

AUBURN UNIVERSITY

UNIVERSITY of WASHINGTON

MIT PSFC

Los Alamos NATIONAL LABORATORY EST. 1943

Helion Energy

TEXAS

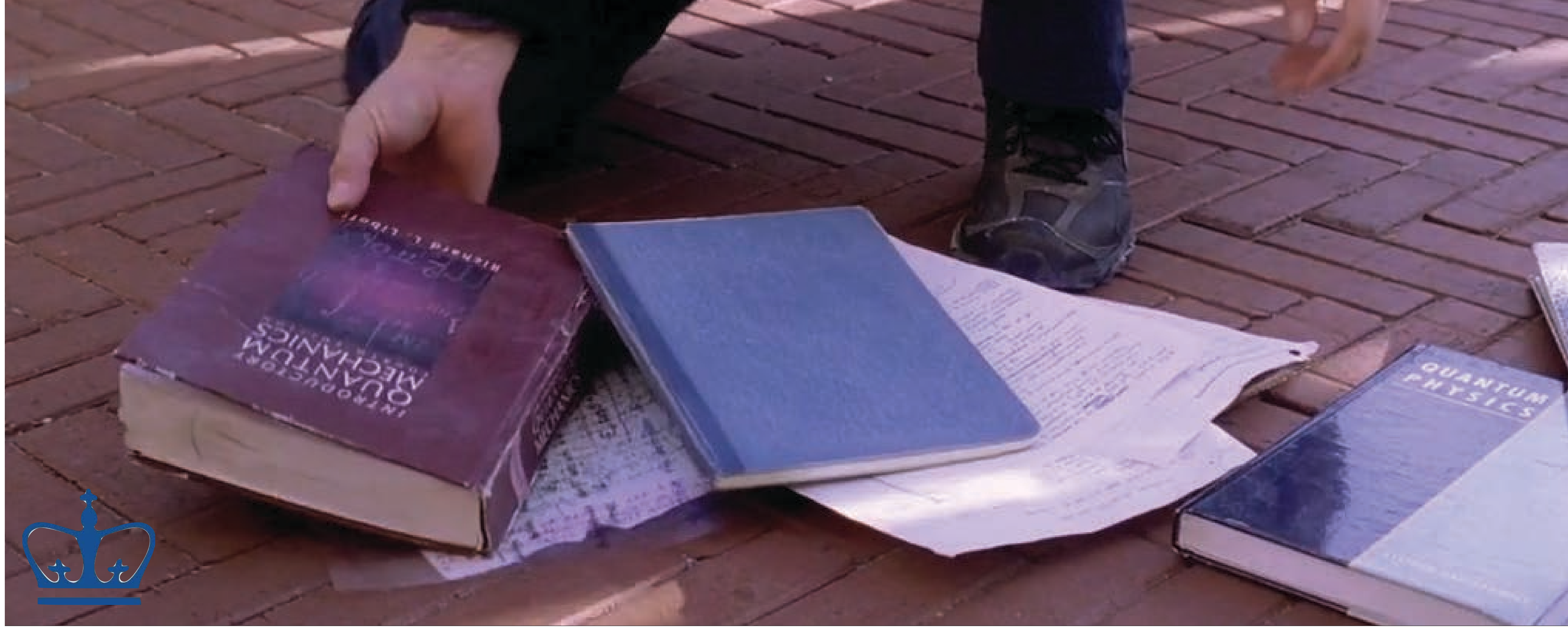
Outline

✓ Innovation

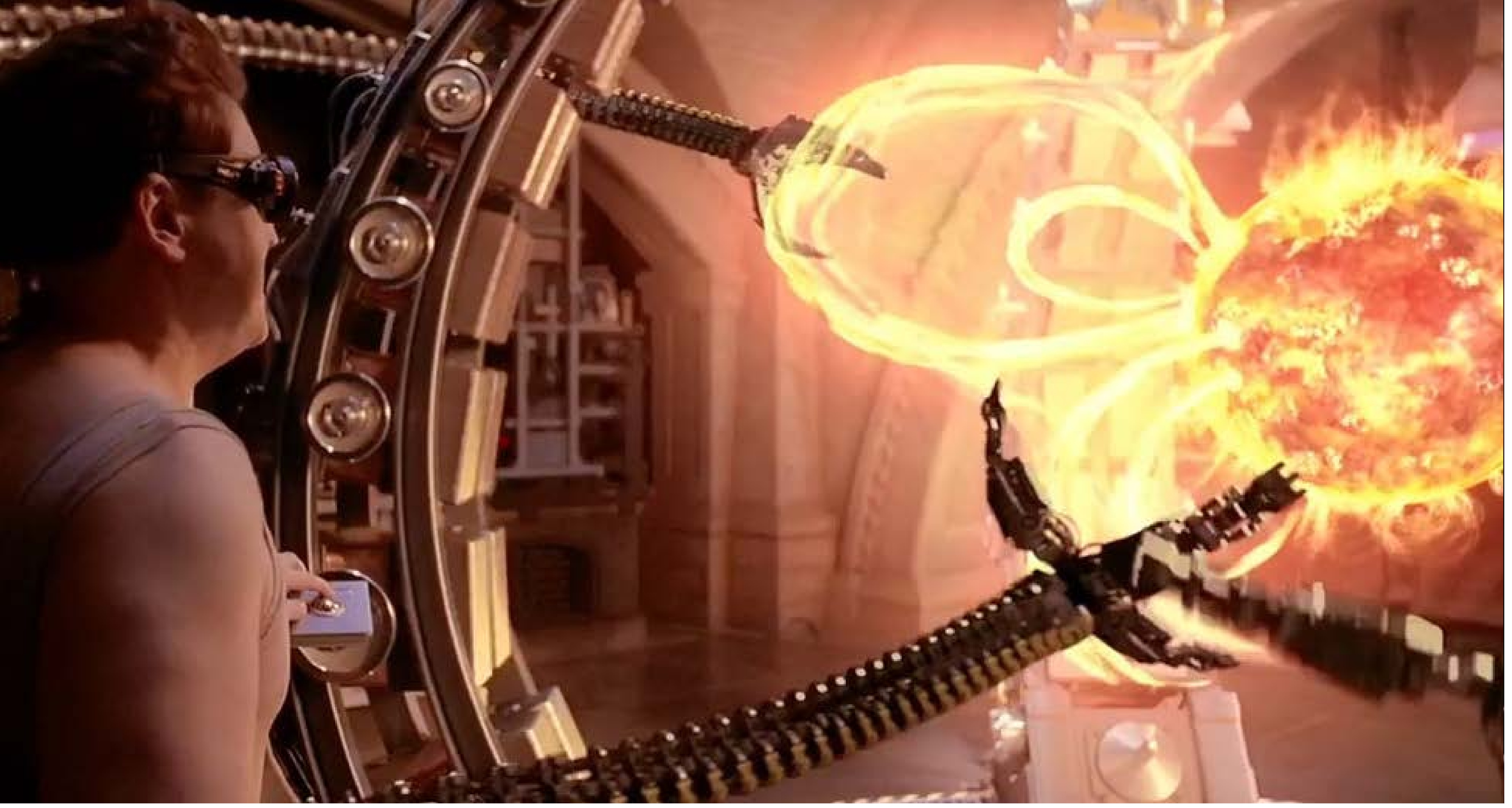
➡ Fusion experiments at Columbia University: active plasma control

- Many plasma tori: the great flexibility of magnetic plasma confinement
- How to design a tokamak
- Innovations to meet the challenges to fusion's economic potential
- Neutrons and the possibility for "advanced" fusion fuel
- (*Seriously*) Fusion hype and science fiction…


2004
SPIDER-MAN 2
sony.com/Spider-Man


INTRODUCTORY QUANTUM MECHANICS
QUANTUM PHYSICS


Control
Actuators
Tritium
($30,000/g)
0.1 BOE/g
OSCORP
INDUSTRIES
“A successful fusion reaction.
1,000 MW surplus.”




“We have a containment breach”


CORE TEMP
SYSTEM UNSTABLE

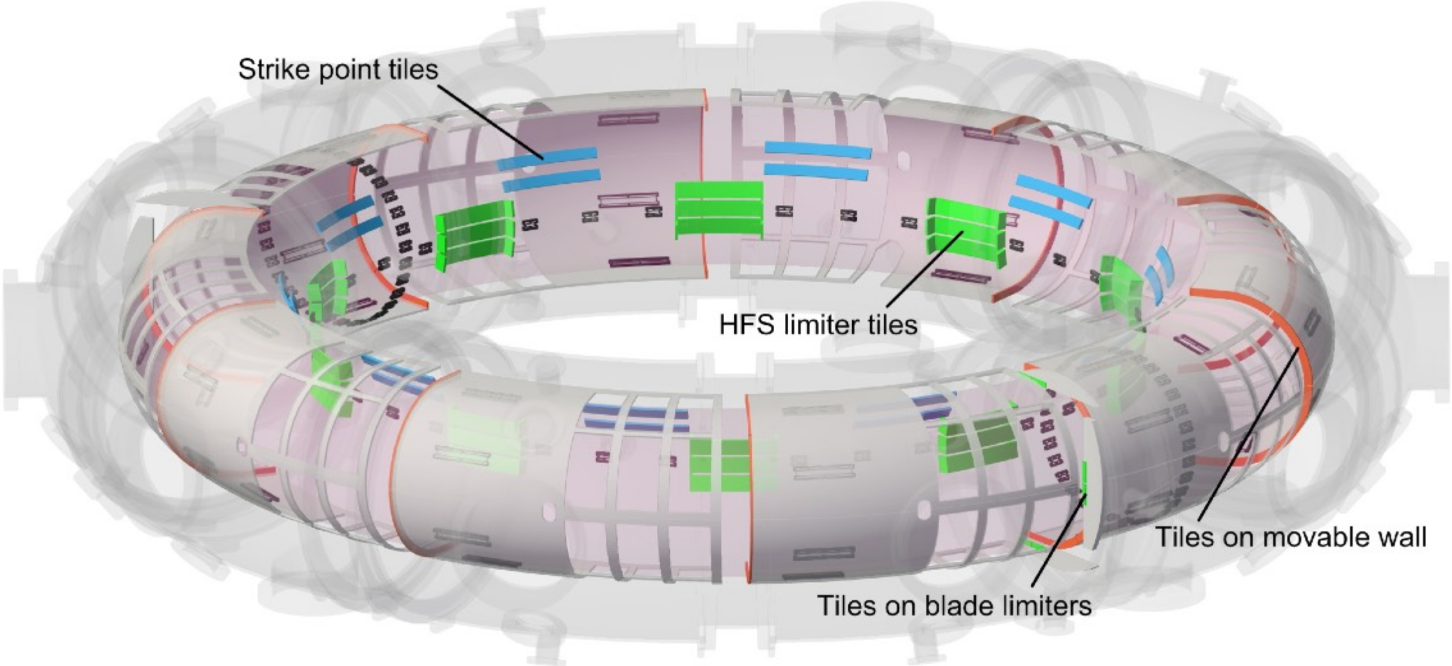

Plasma-wall interaction

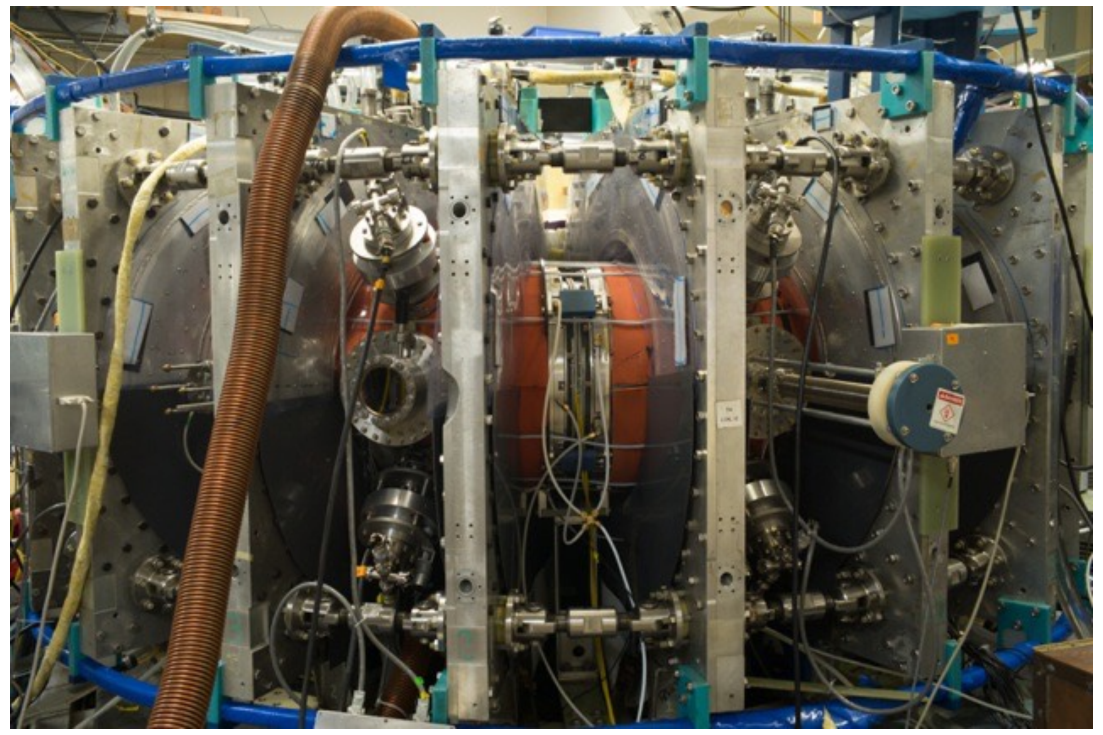
What’s wrong with this picture?

Magnetized Plasma Physics Research at Columbia University

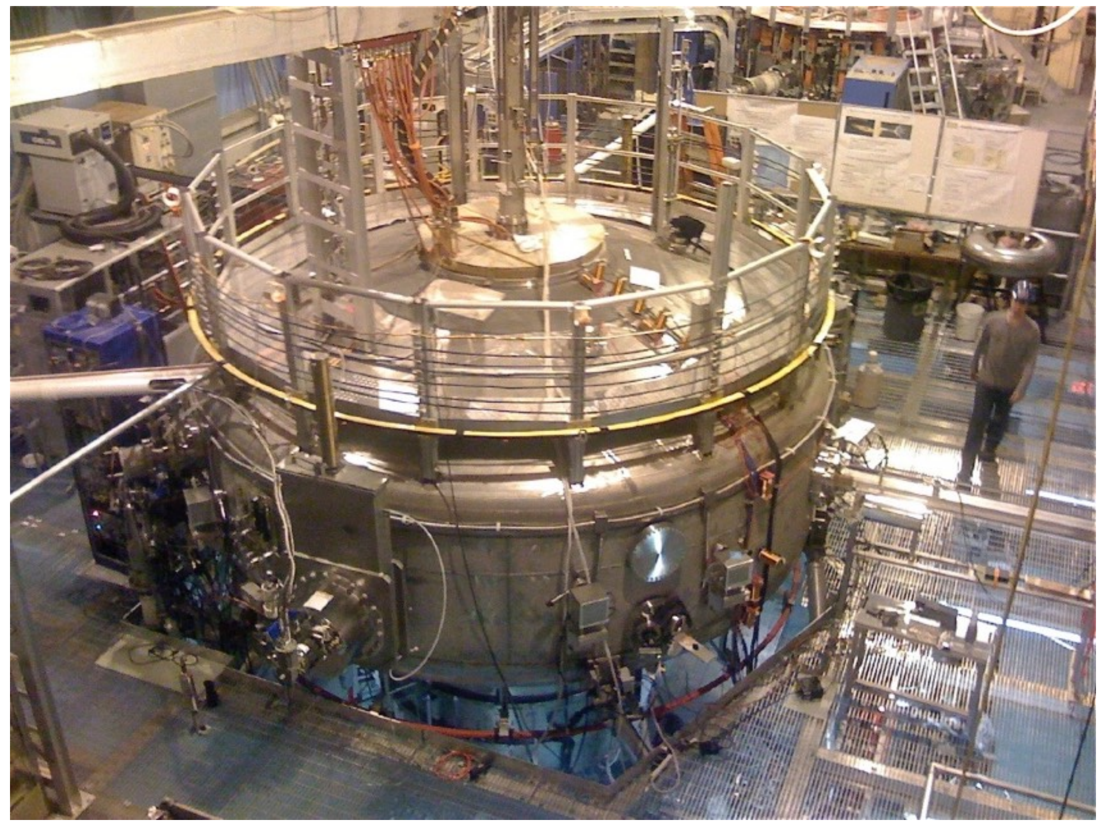
- CNT Stellarator

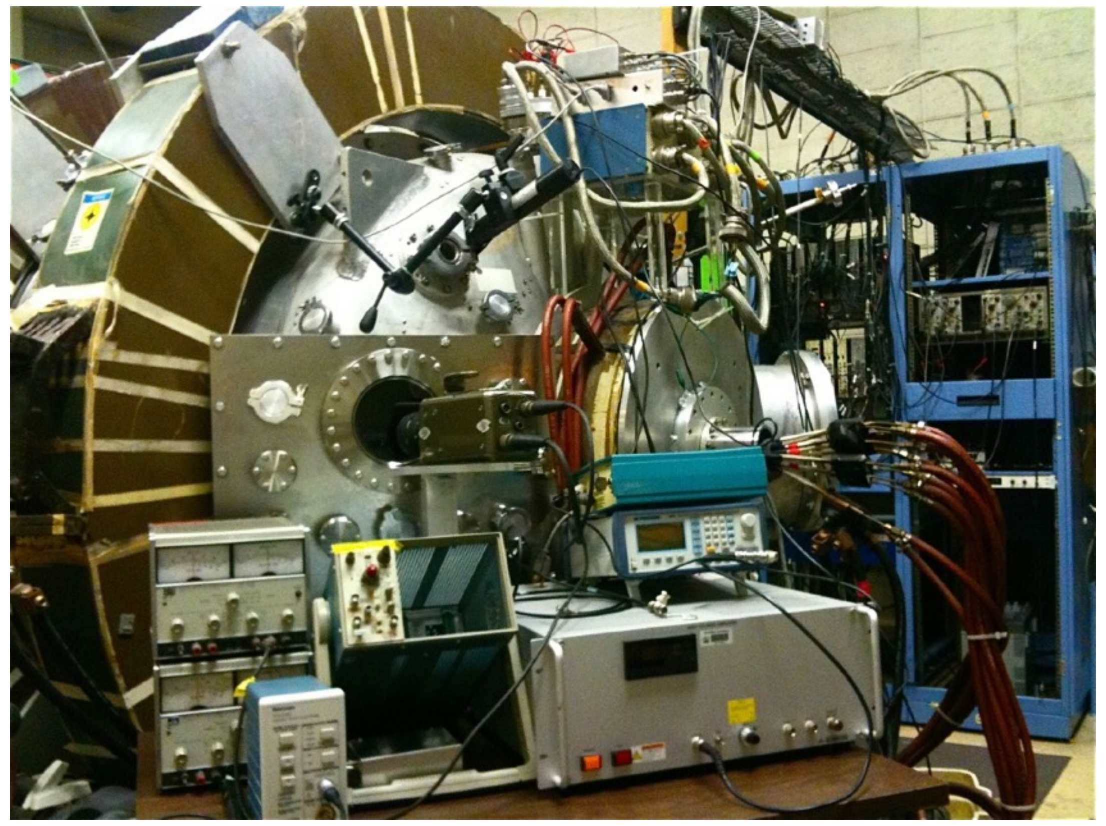
- HBT-EP Tokamak





- CTX Ring Current Trap





Magnetized Plasma Physics Research at Columbia University

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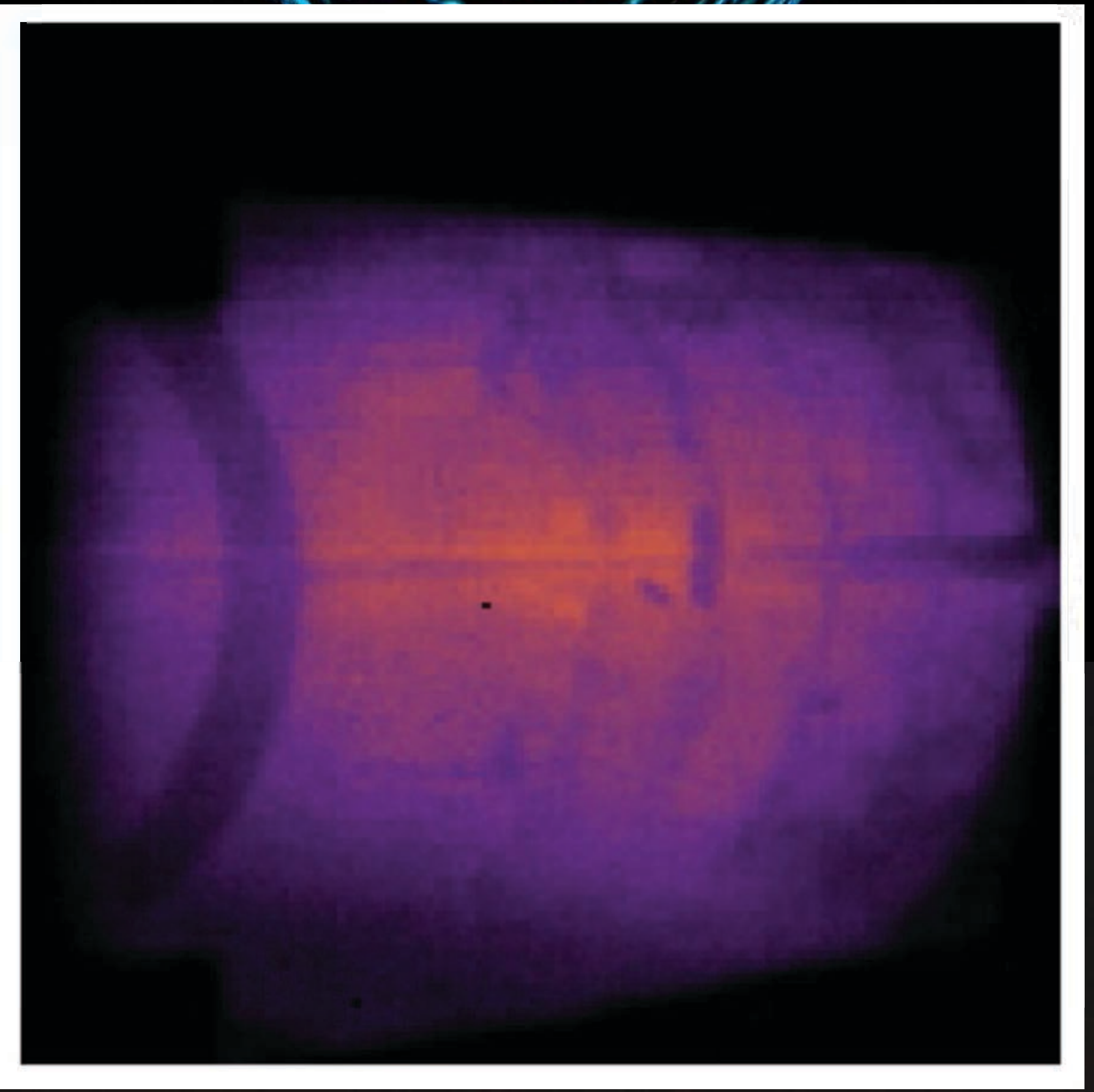
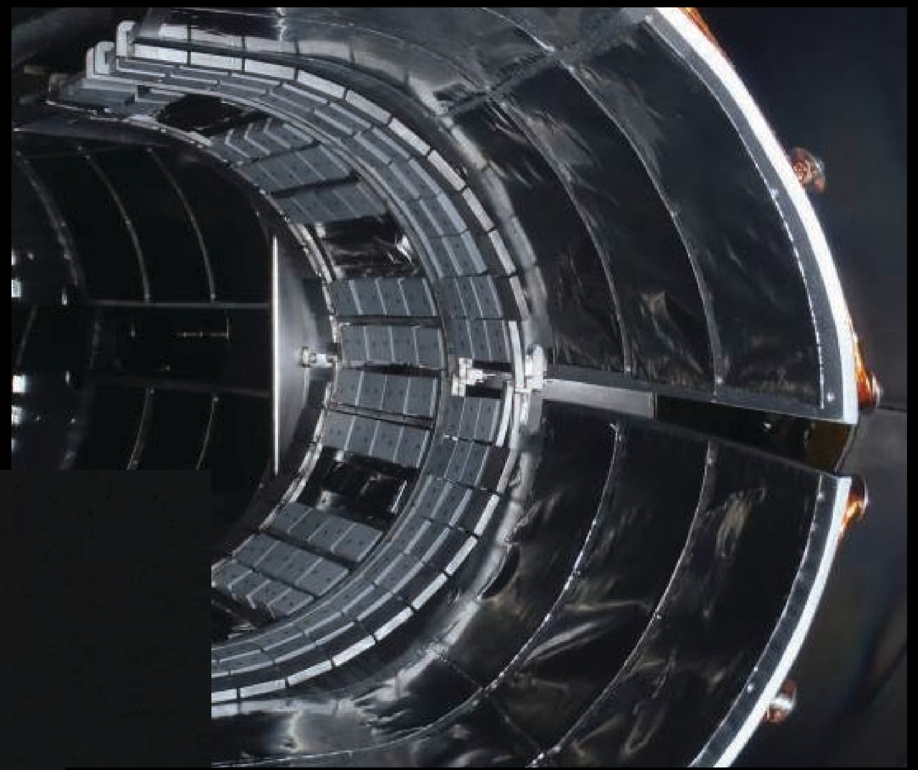
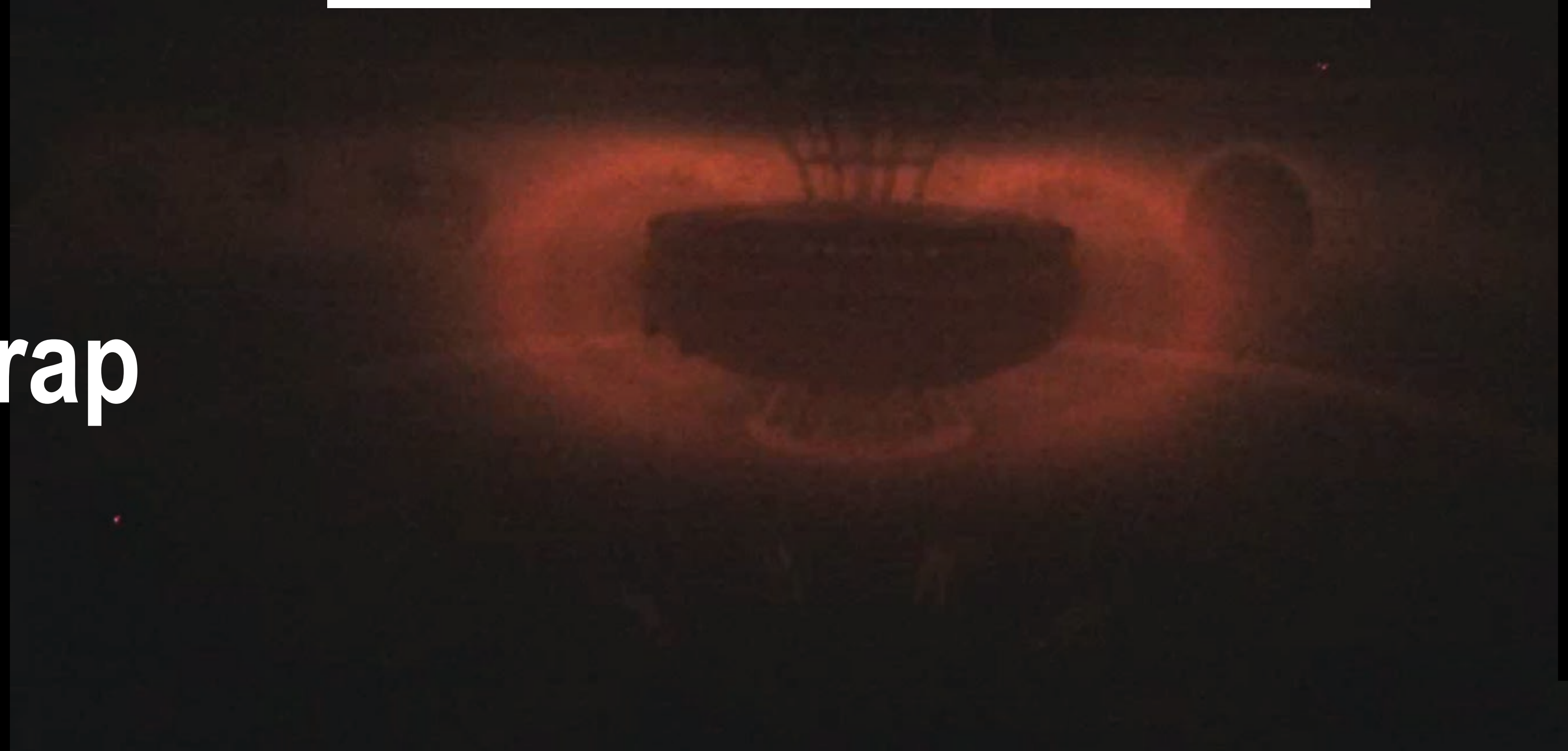
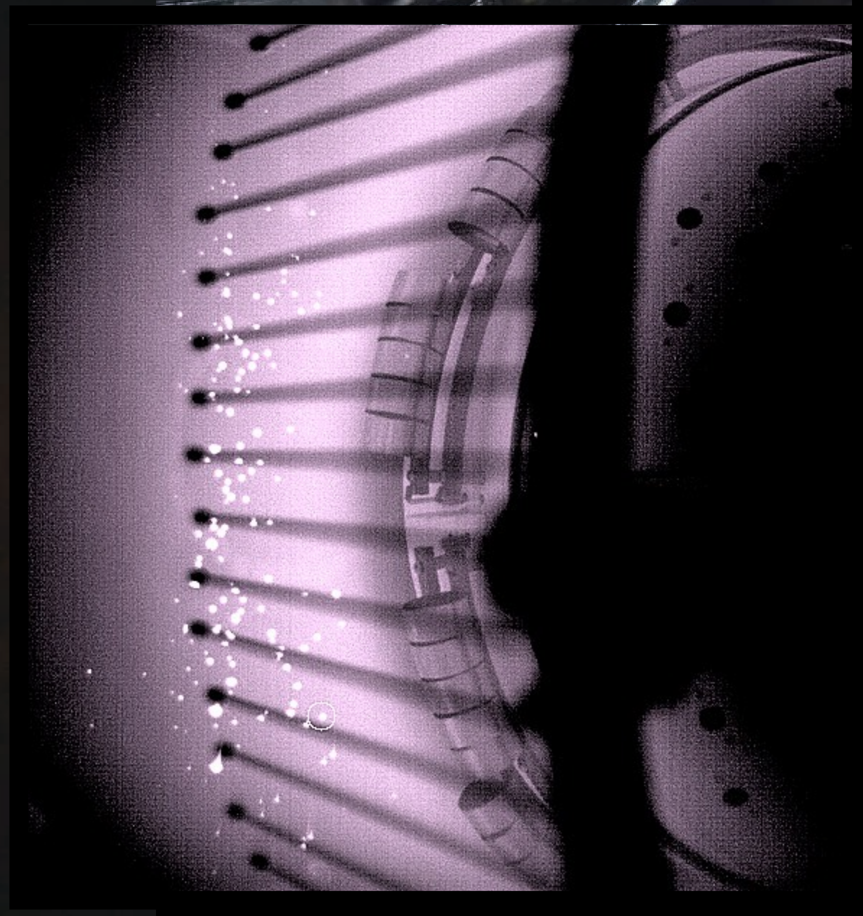
- CTX Current Ring Trap

Outline

- ✓ Innovation
- ✓ Fusion experiments at Columbia University: active plasma control
- ➡ Many plasma tori: the great flexibility of magnetic plasma confinement
- How to design a tokamak
- Innovations to meet the challenges to fusion's economic potential
- Neutrons and the possibility for "advanced" fusion fuel
- (*Seriously*) Fusion hype and science fiction…

How Do Magnetic Fields Confine Ionized Matter?

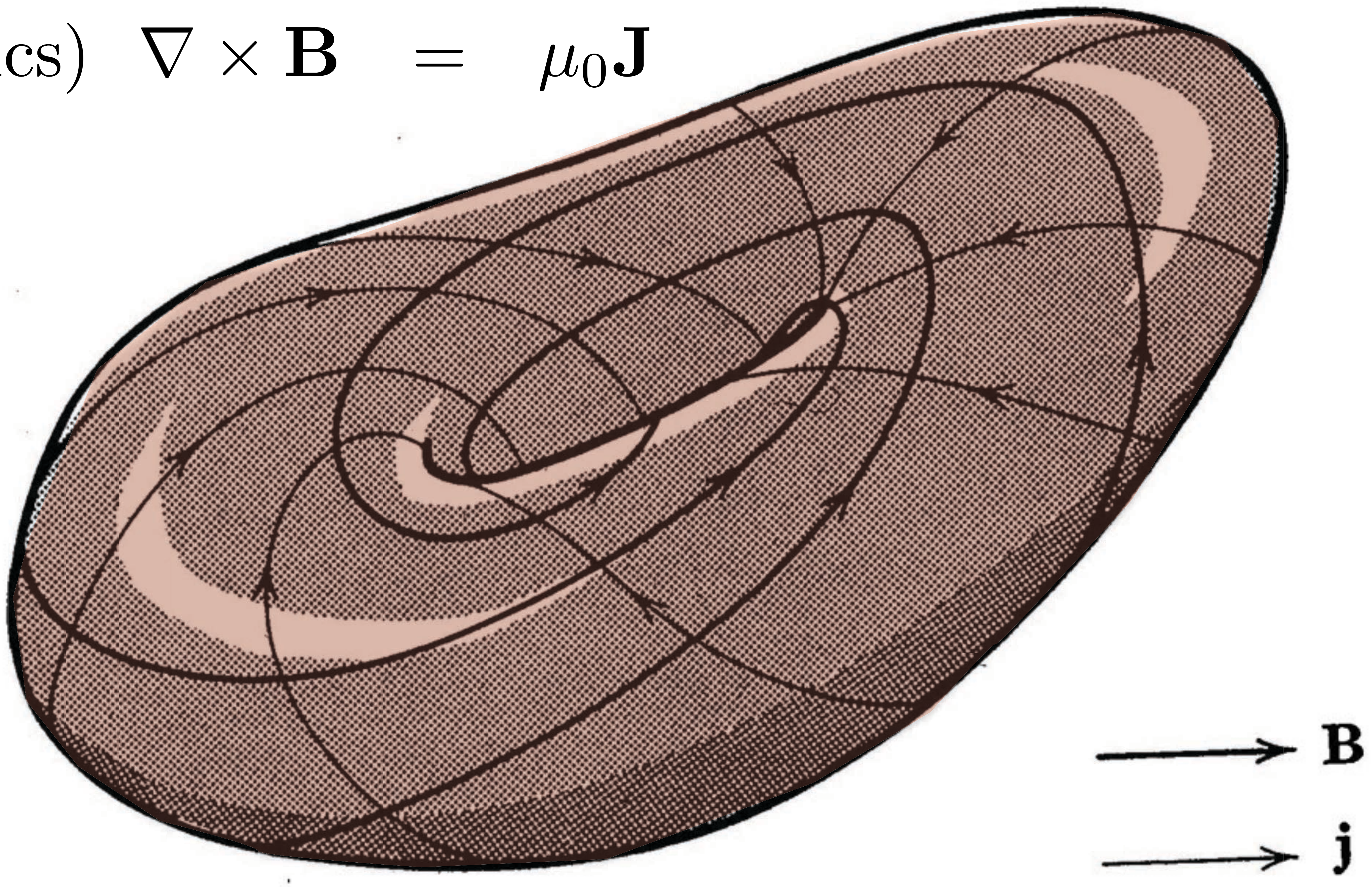
Equations of magnetic confinement…

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



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\end{aligned}$$

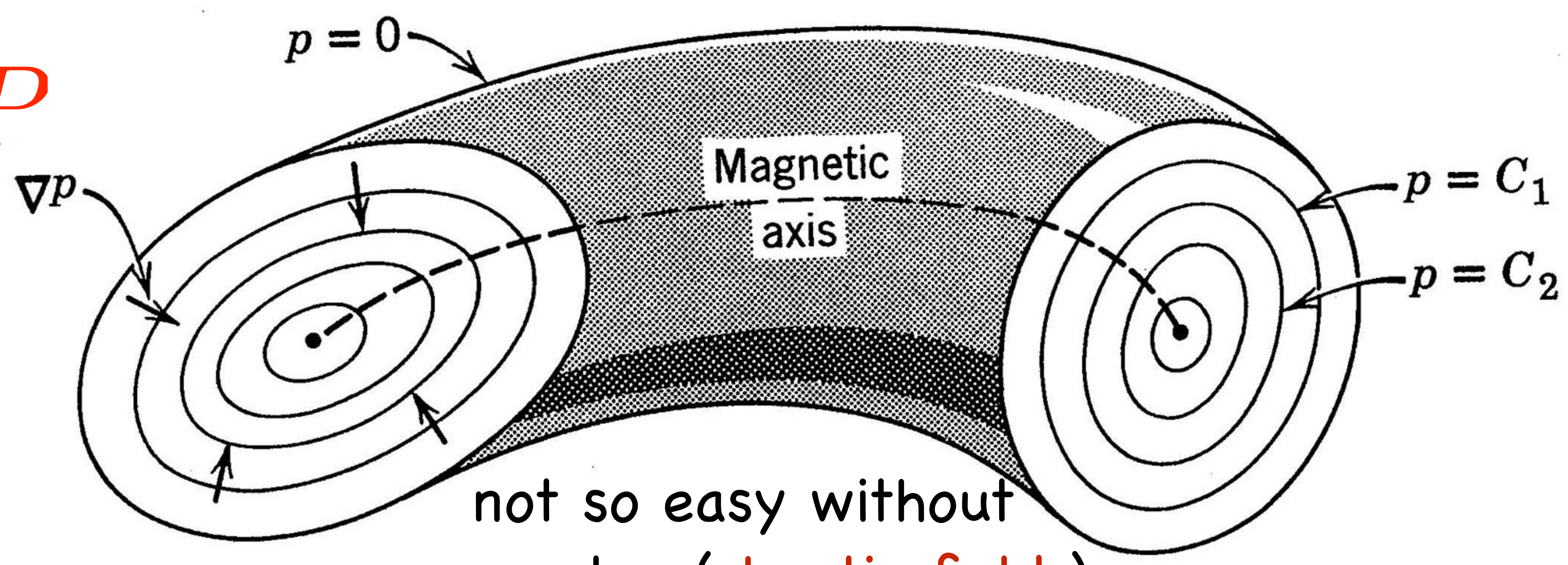
Plasma Pressure (P)

Plasma Current ($\mathbf{J}$)

Magnetic Torus

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

Surfaces of constant plasma pressure form nested tori



not so easy without symmetry (chaotic fields)

Design Options for a Plasma Torus

- Use strong electromagnets to generate **magnetic field** (**B**) and minimize **plasma current** (**J**)

  $$ Coils are Expensive

- Drive large **current** (**J**) through plasma and *self-generate* **magnetic field** (**B**)

  ≈≈ Plasma current instability

- Use *both* strong electromagnets and drive large plasma current

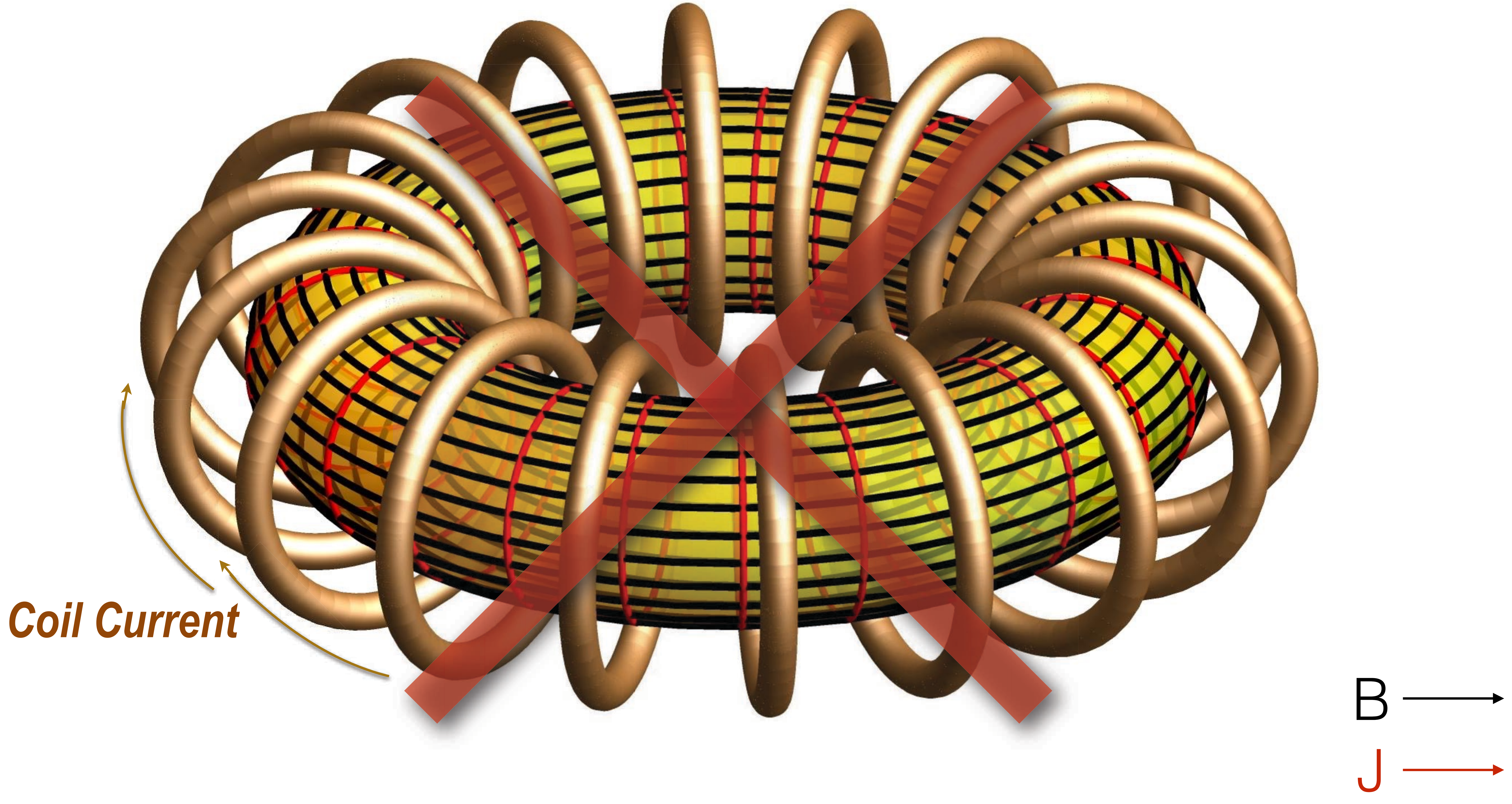
  $$ Coils and
  ≈≈ Plasma instability

Many Types of Plasma Tori

- Axially-**symmetric** torus with external poloidal currents (***fails***)
- Axially-**symmetric** torus with *internal toroidal current inside* the plasma ("*FRC*" and "*levitated current ring*")
- Axially-**symmetric** torus with combining external poloidal currents ***and*** internal toroidal current ("*tokamak*", "*RFP*", and "*spheromak*")
- ***Non-symmetric*** plasma torus w external helical coils ("*stellarator*")

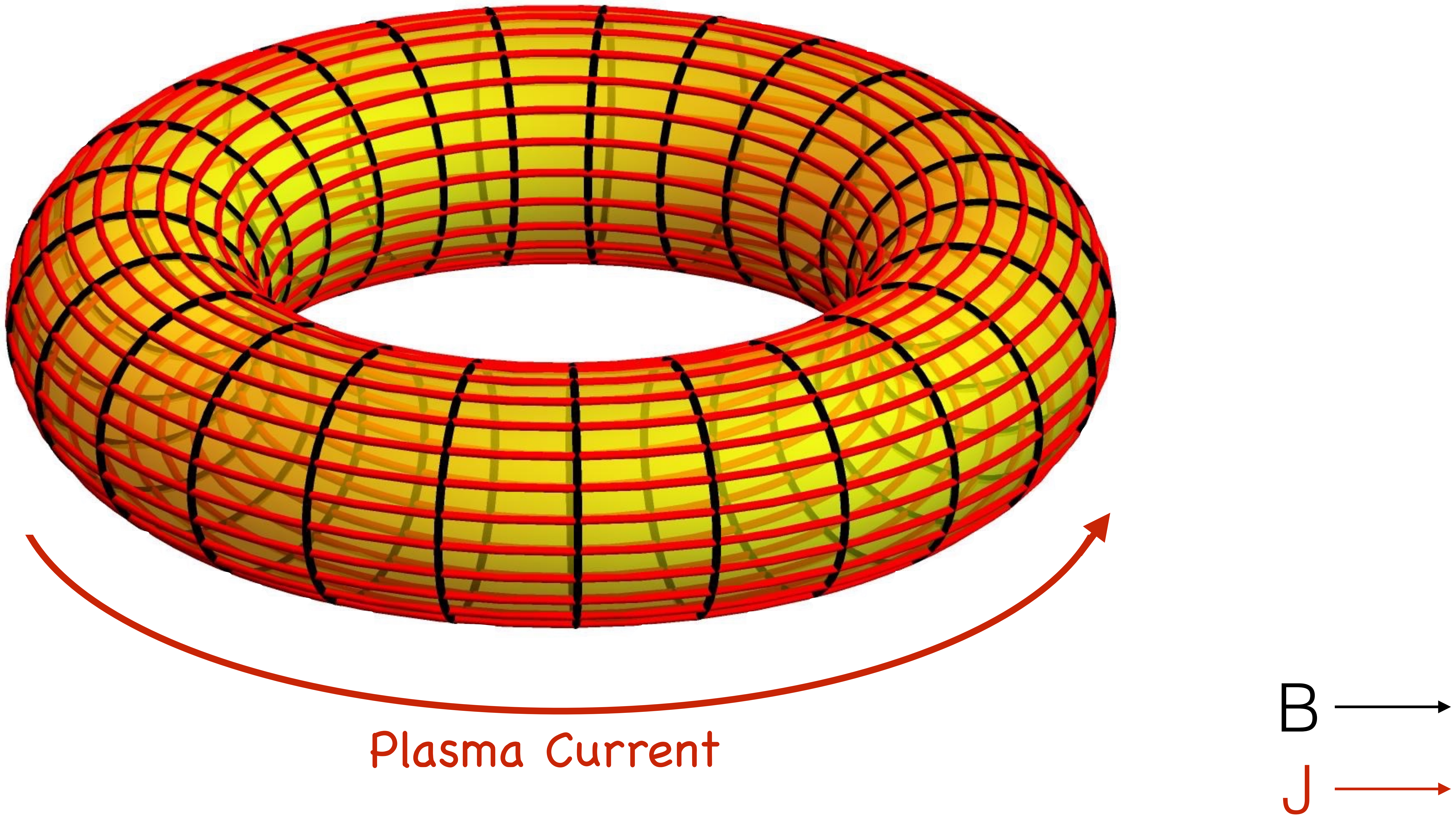
FAILS TO CONFINE PARTICLES

How to make a magnetic torus?



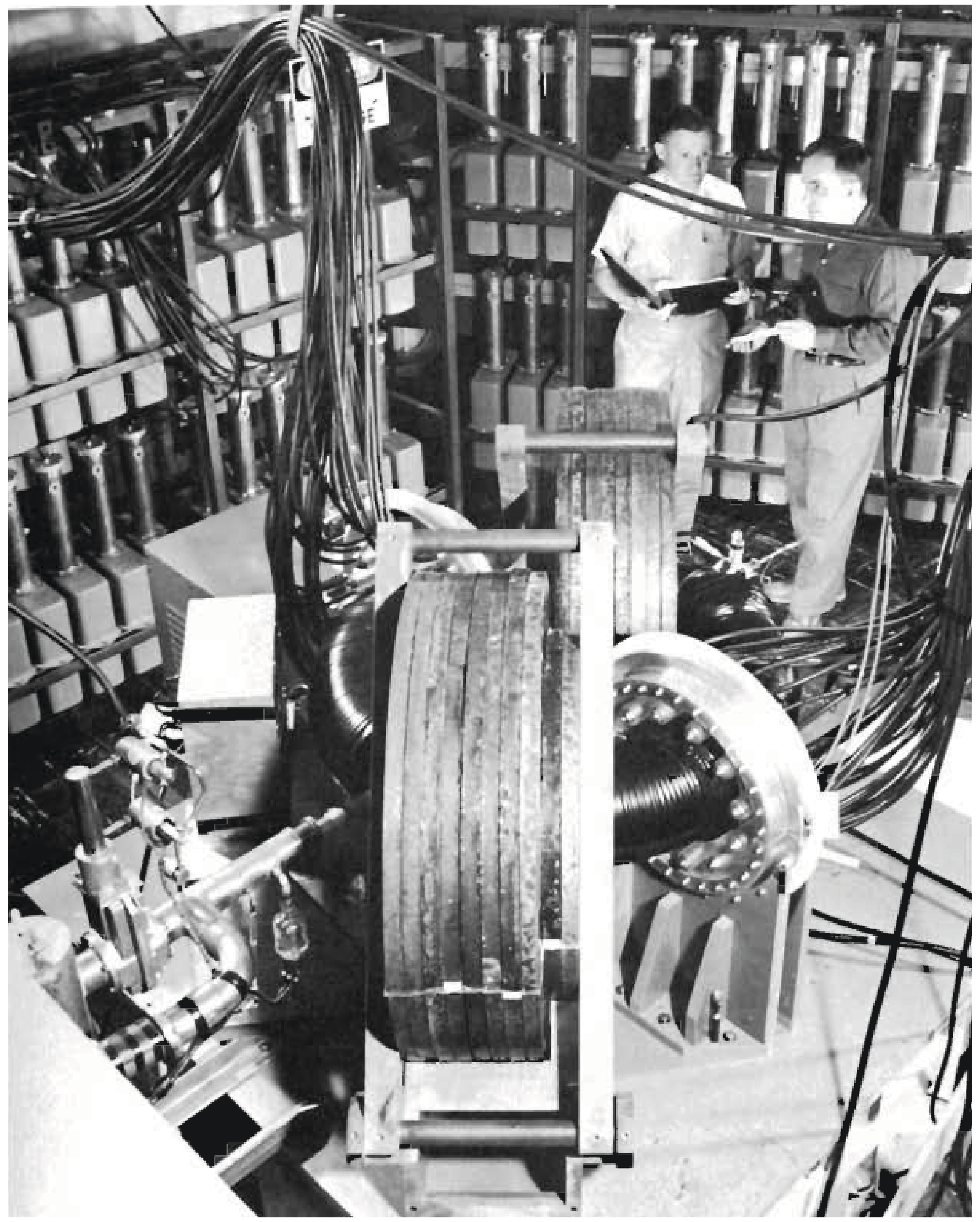
Toroidal Field from External Coils
(toroidal "theta-pinch")

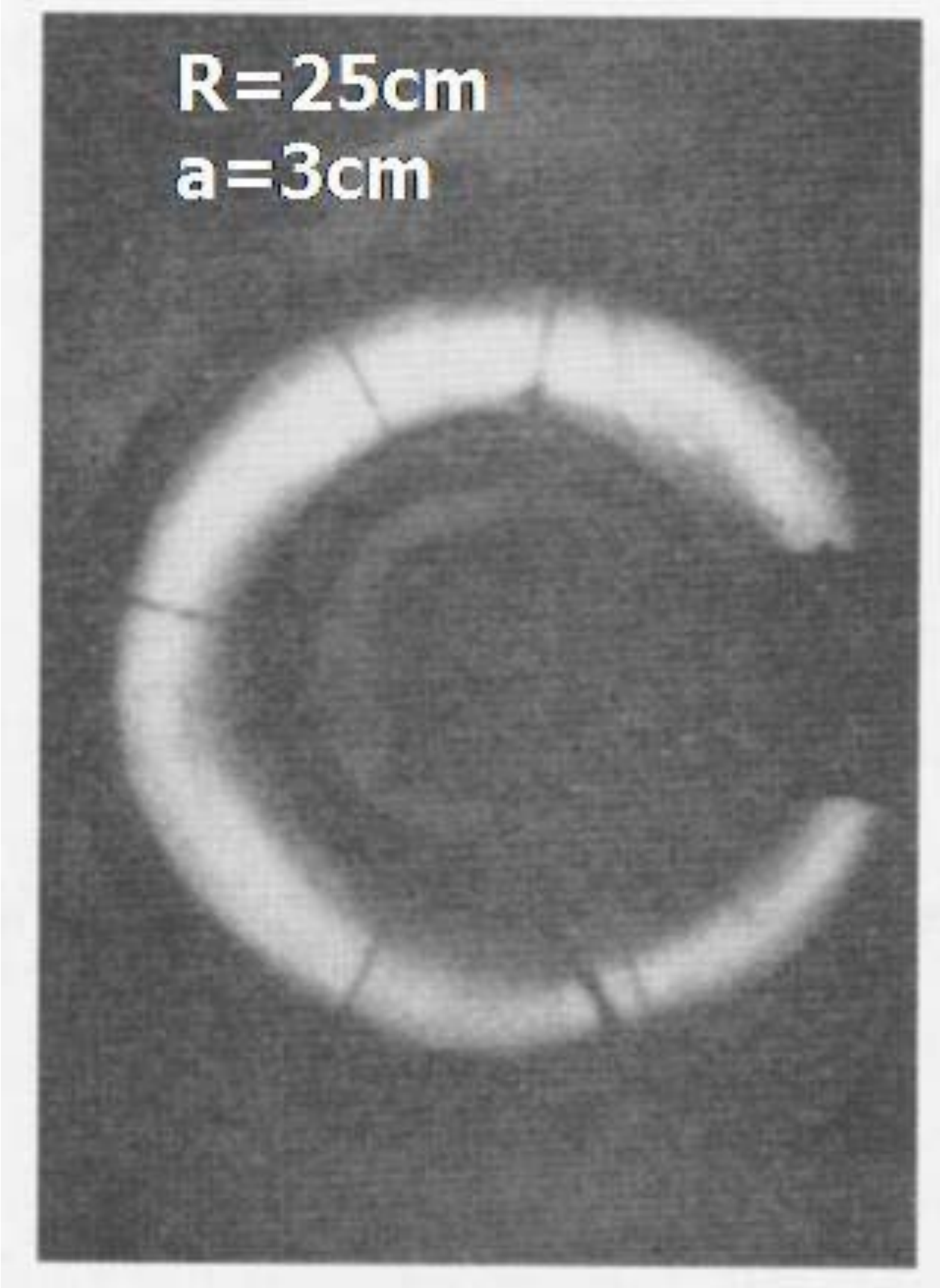
How to make a magnetic torus?



Poloidal Field from Plasma Current
(toroidal “z-pinch”)

How to make a magnetic torus?





Instability

Poloidal Field from Plasma Current
(toroidal "z-pinch")

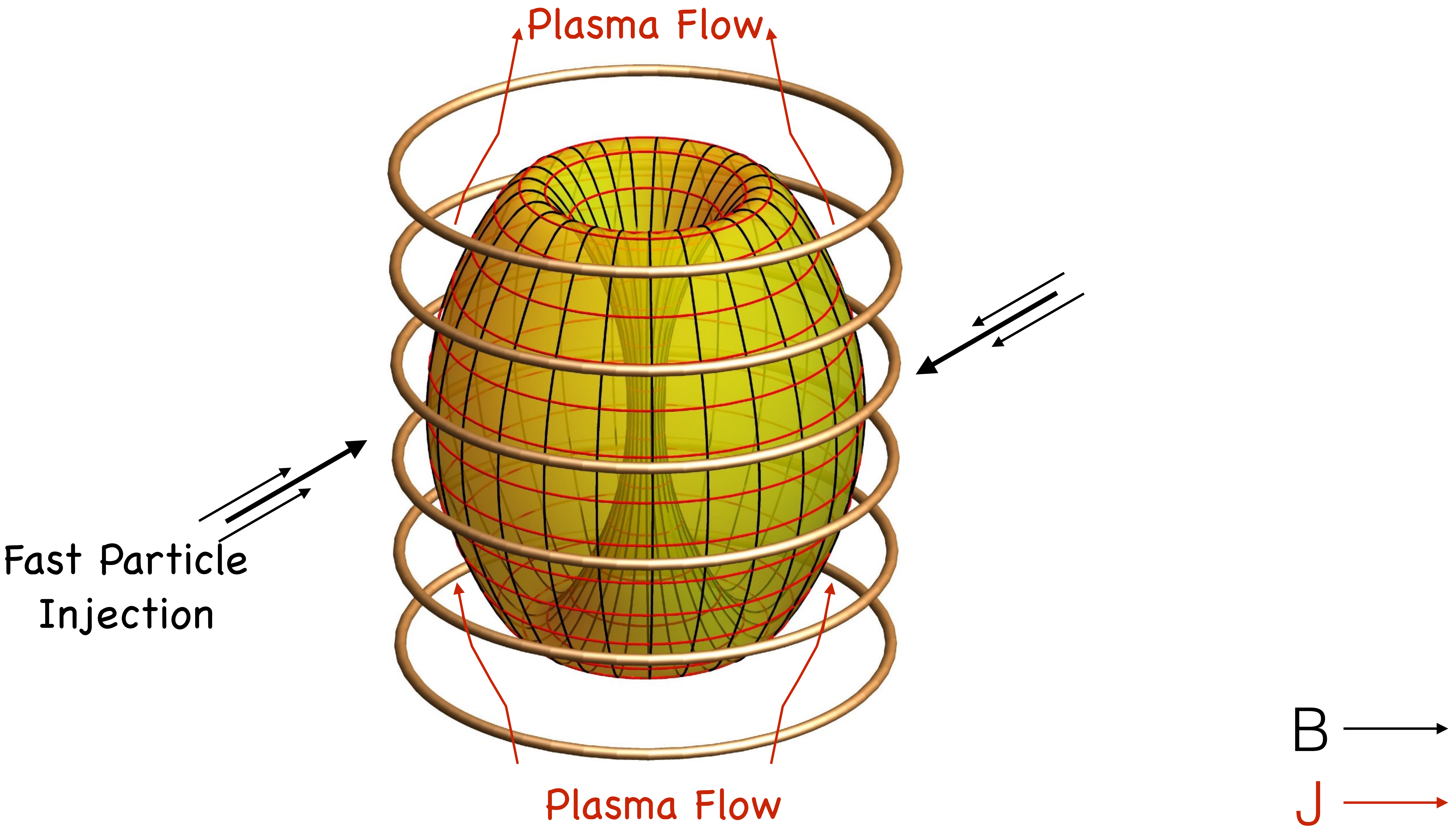
Stabilized with External Control

How to make a magnetic torus?

TRI ALPHA ENERGY
leading the way to the future...

PrincetonSATELLITE
SYSTEMS

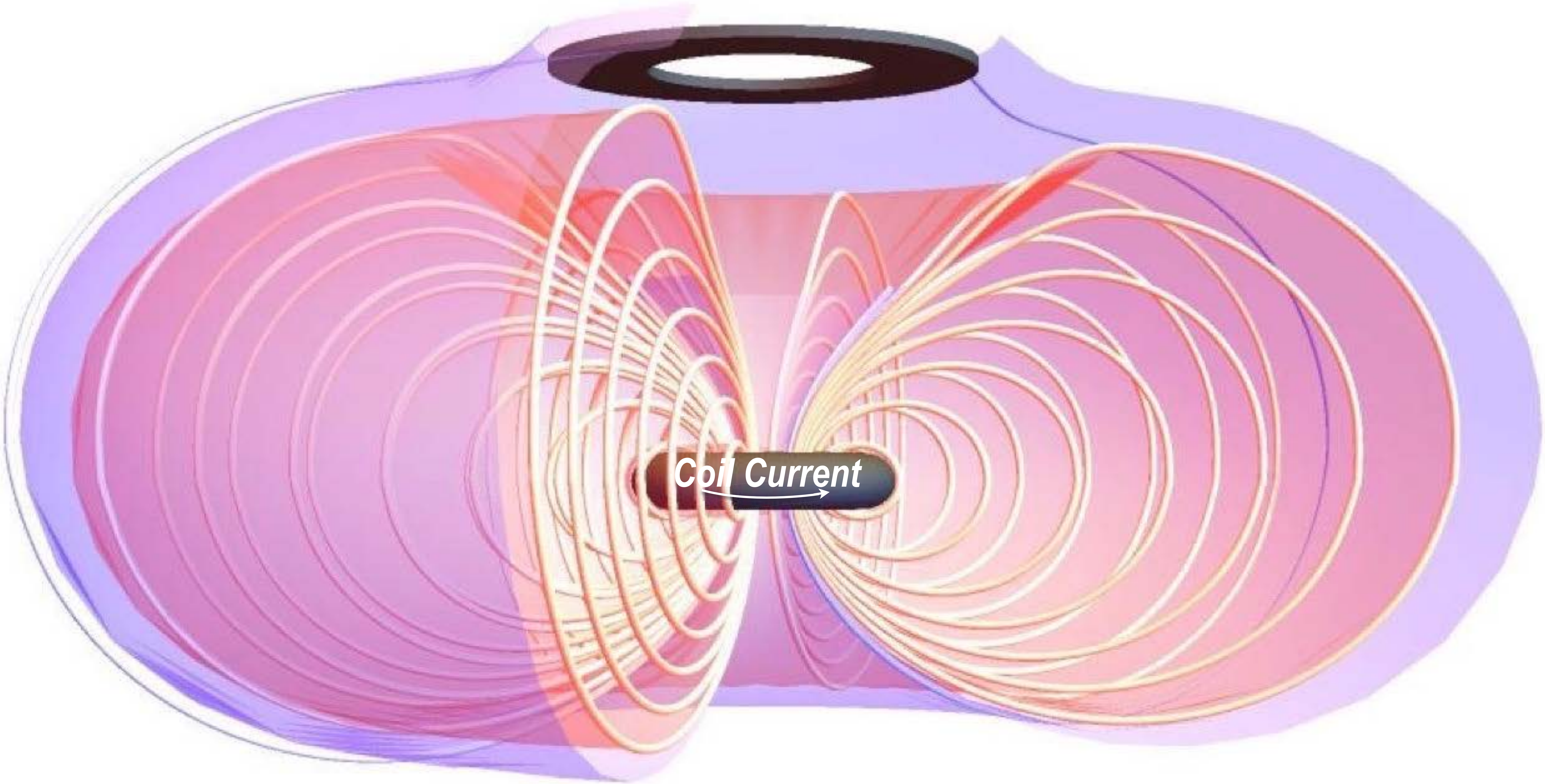
Helion Energy



Poloidal Field from Plasma Current
("Field Reversed Configuration" FRC)

Stable with Internal Coil

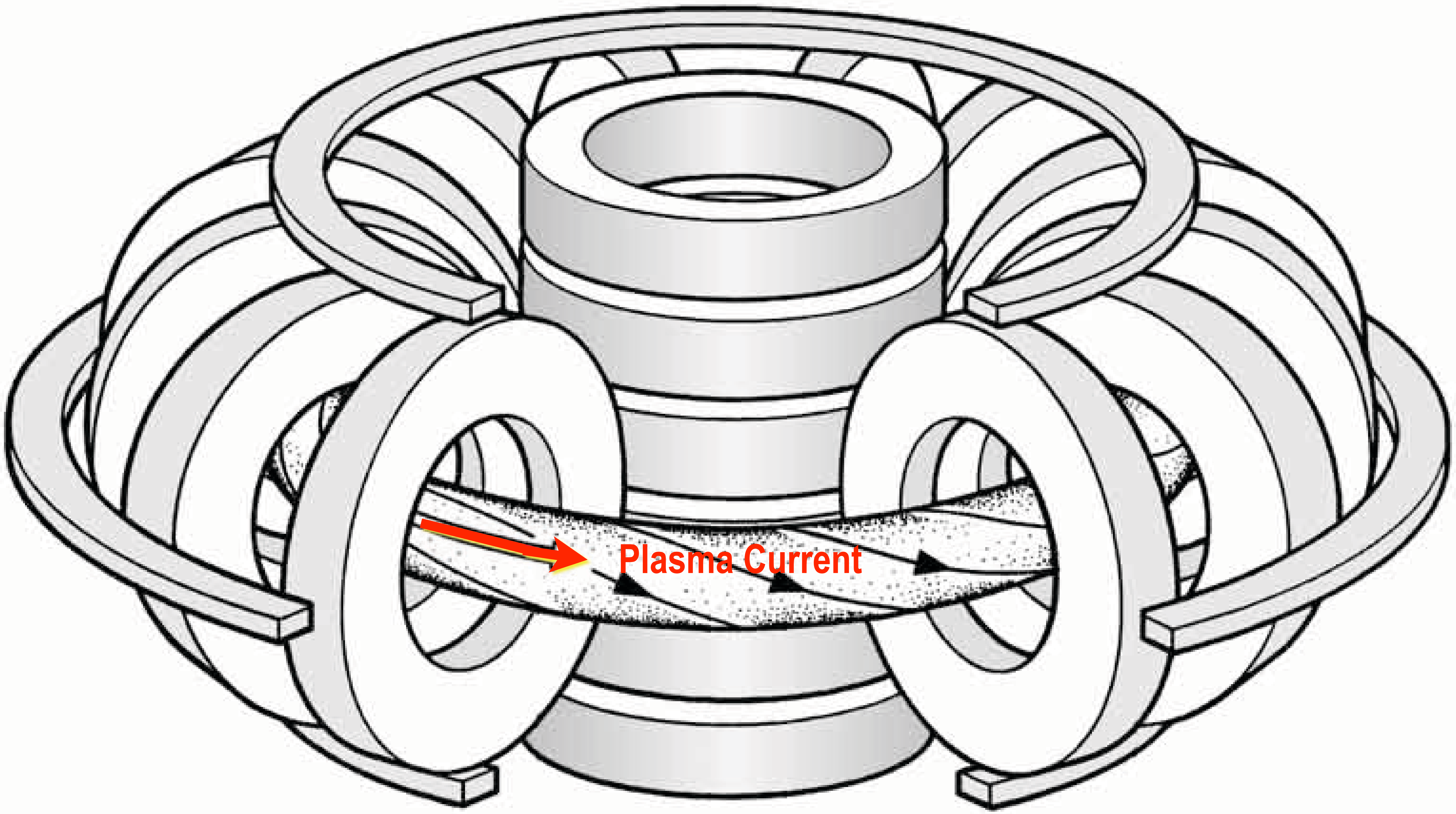
How to make a magnetic torus?



Poloidal Field from Floating Current Ring

(but how can a coil float within a plasma?)

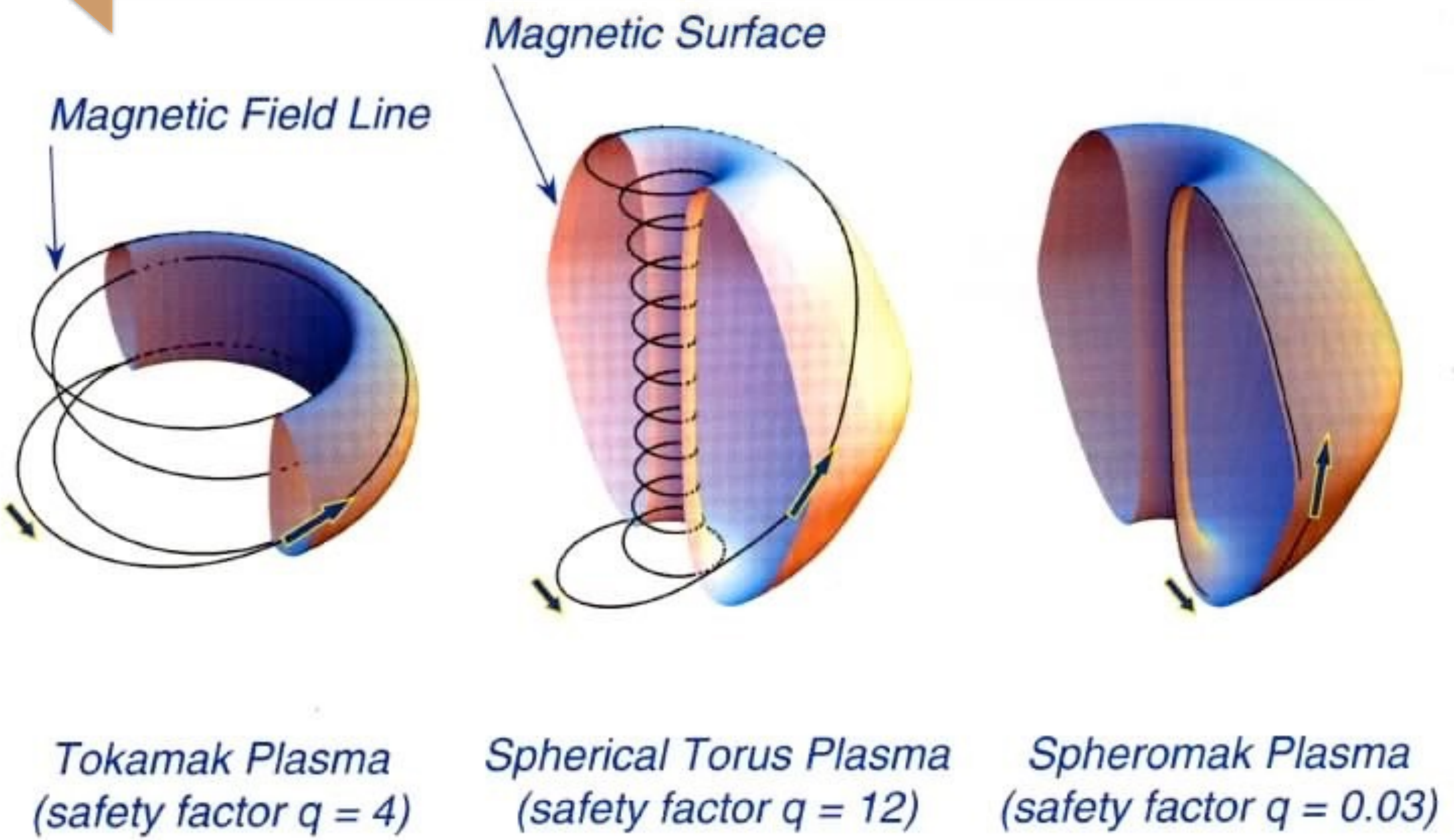
How to make a magnetic torus?



Combining External Magnets and Plasma Current (Tokamak)
Safety factor $q > 1$

How to make a magnetic torus?

High q ← **Increasing Toroidal Field** ← Low q



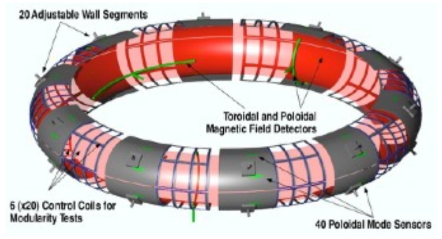
Combined Toroidal and Poloidal Field (Tokamak, RFP, Spheromak)

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

How to make a magnetic torus?

0.015 MA

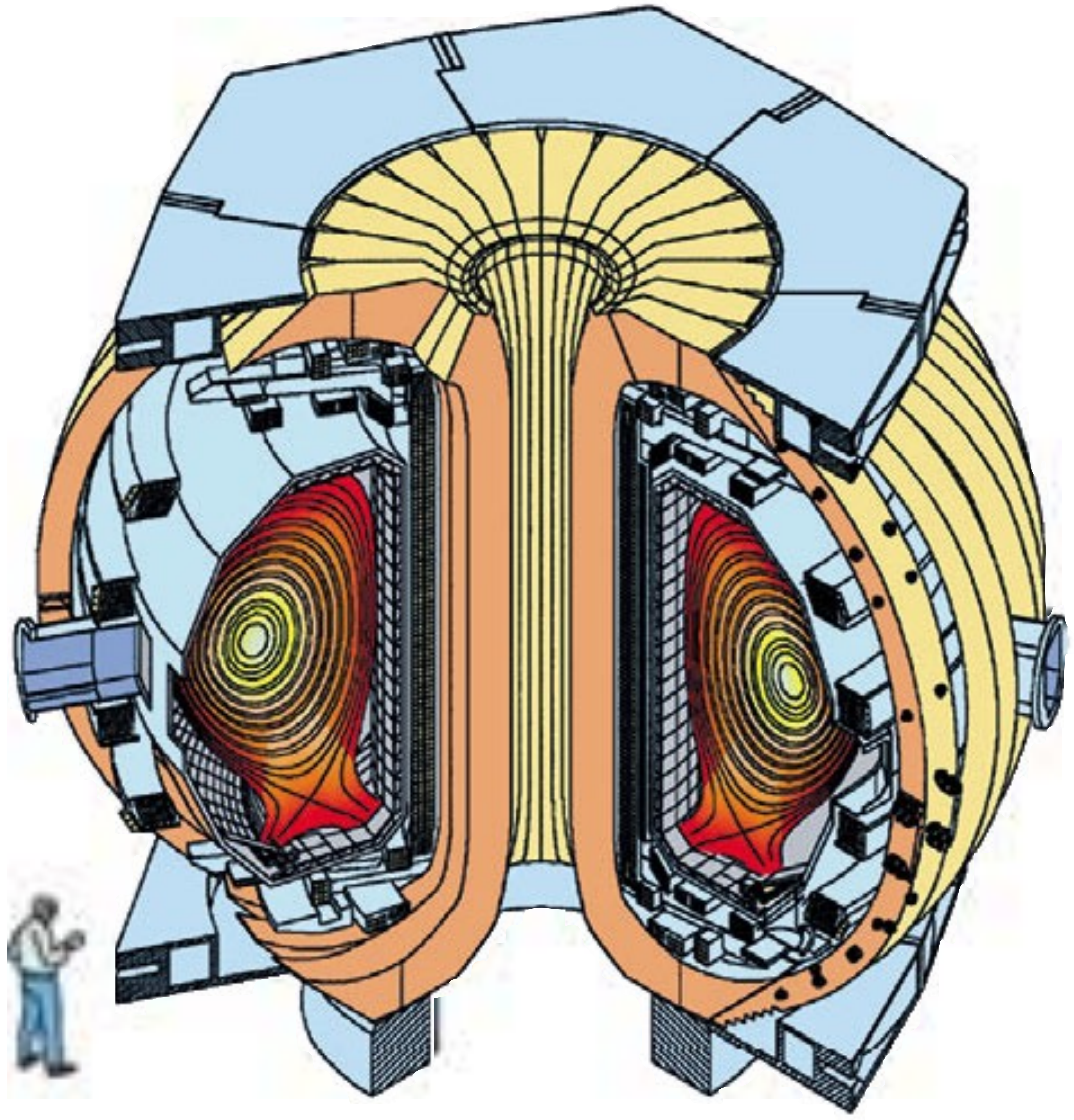
1.8 m



HBT-EP
Columbia University

1.0 MA

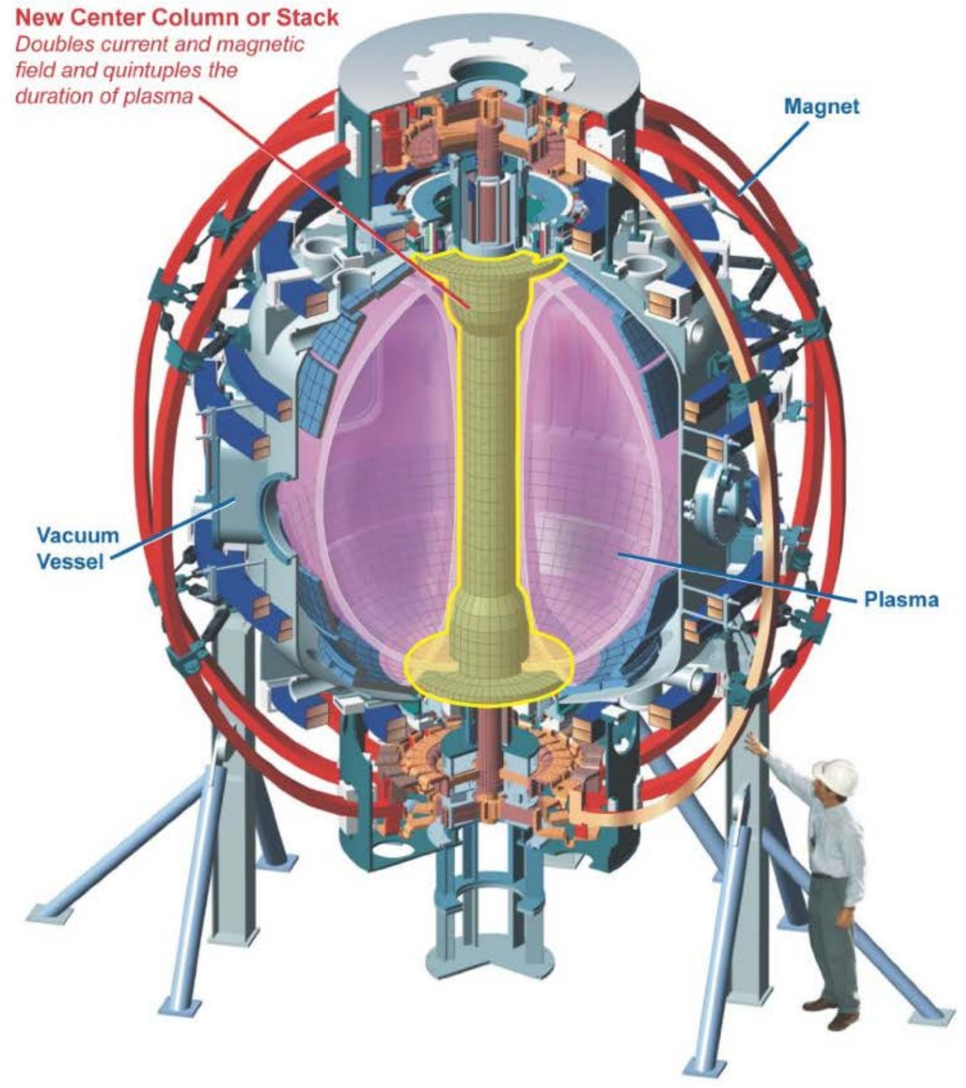
3.3 m



DIII-D
General Atomics

0.7 MA

1.7 m



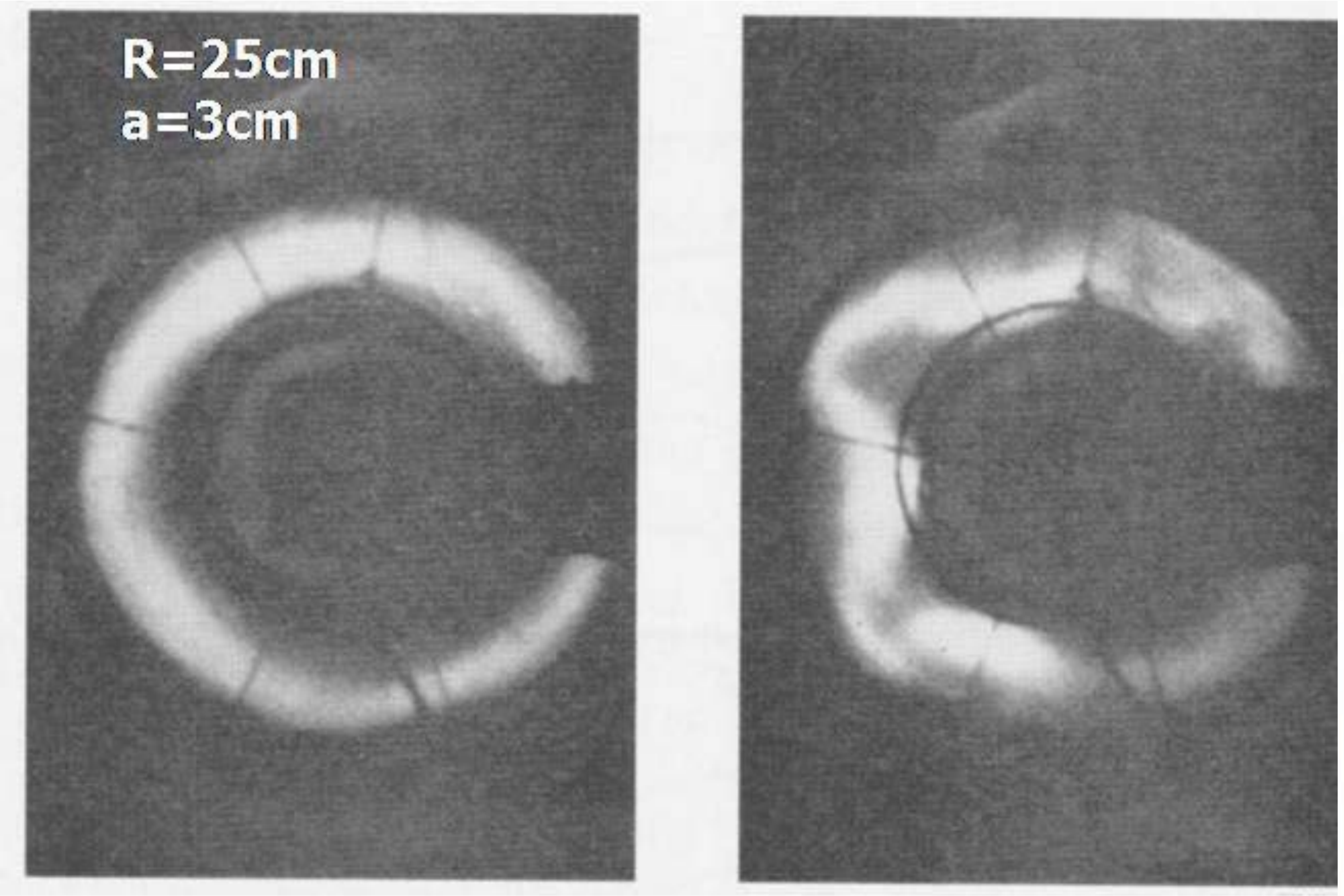
NSTX-U
PPPL

Combined Toroidal and Poloidal Field (Tokamak)

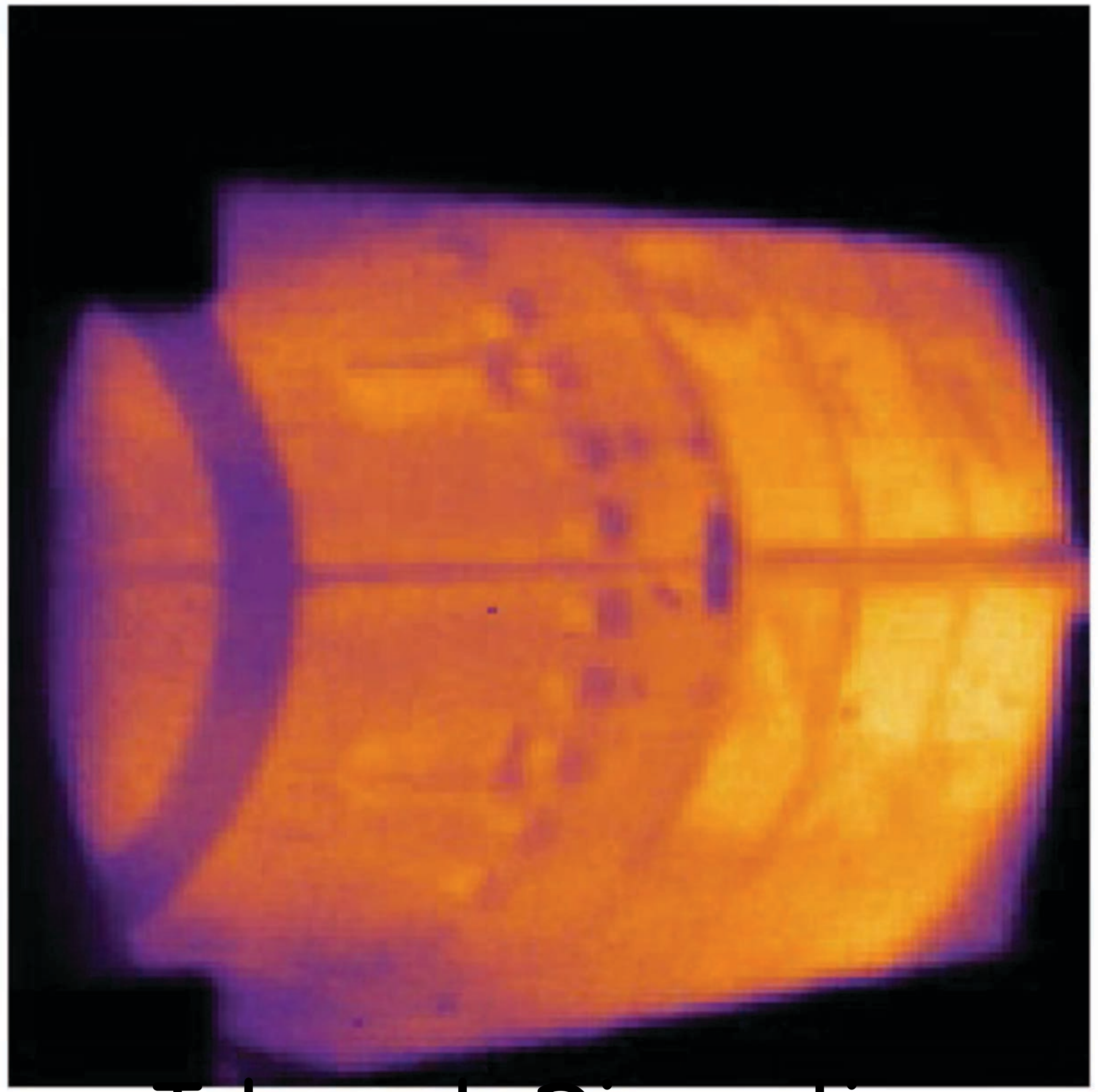
With **Toroidal Plasma Current**

Magnetic Fusion Optimization Depends on Shape and Plasma Current

Kink Instability of Large Plasma Current



Toroidal "z-pinch"

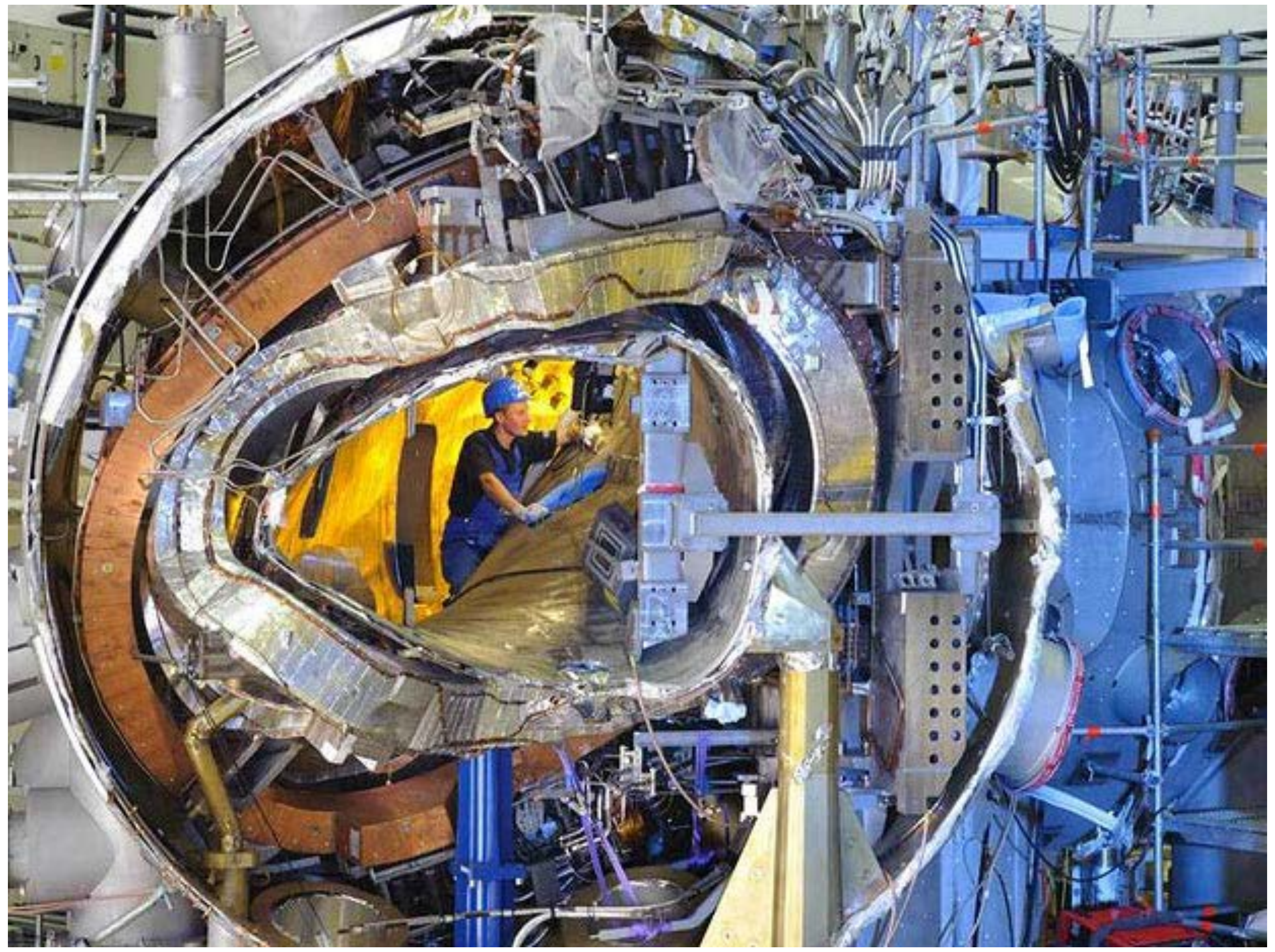


Tokamak Disruption

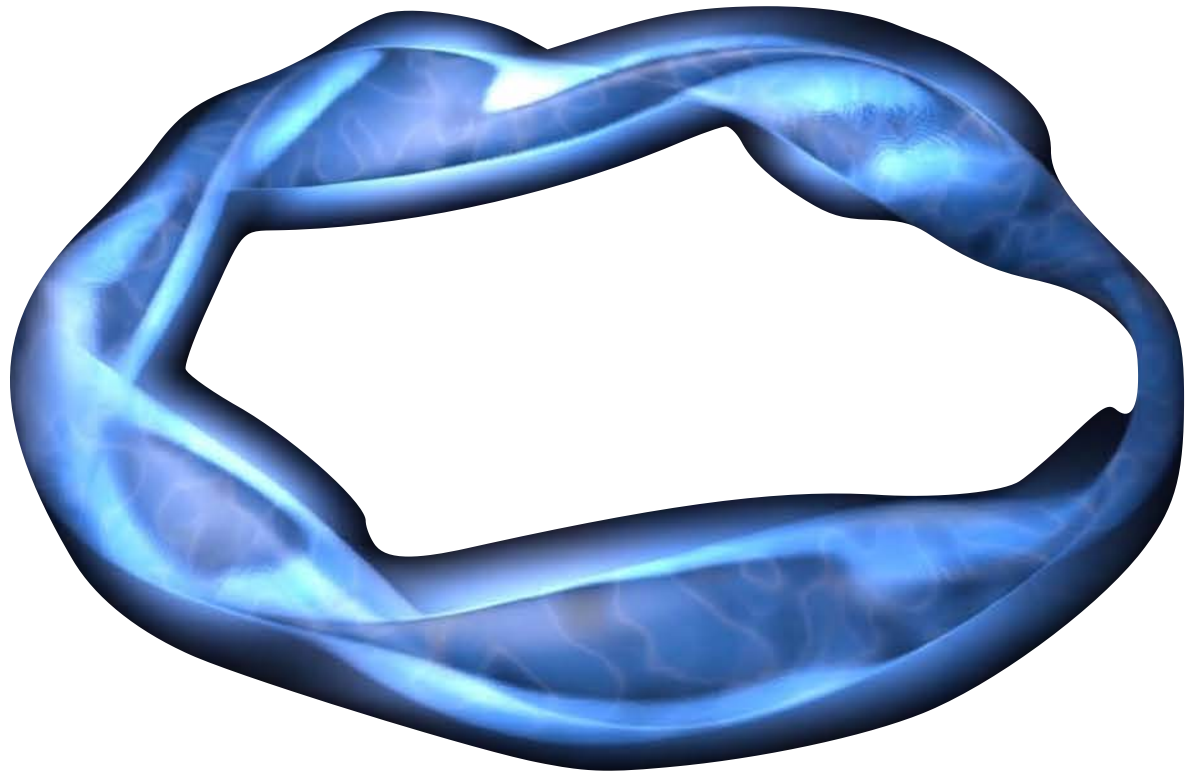
Fundamentally, the behavior of magnetically-confined plasma depends upon the **shape of** and **current within** the magnetic flux tube…

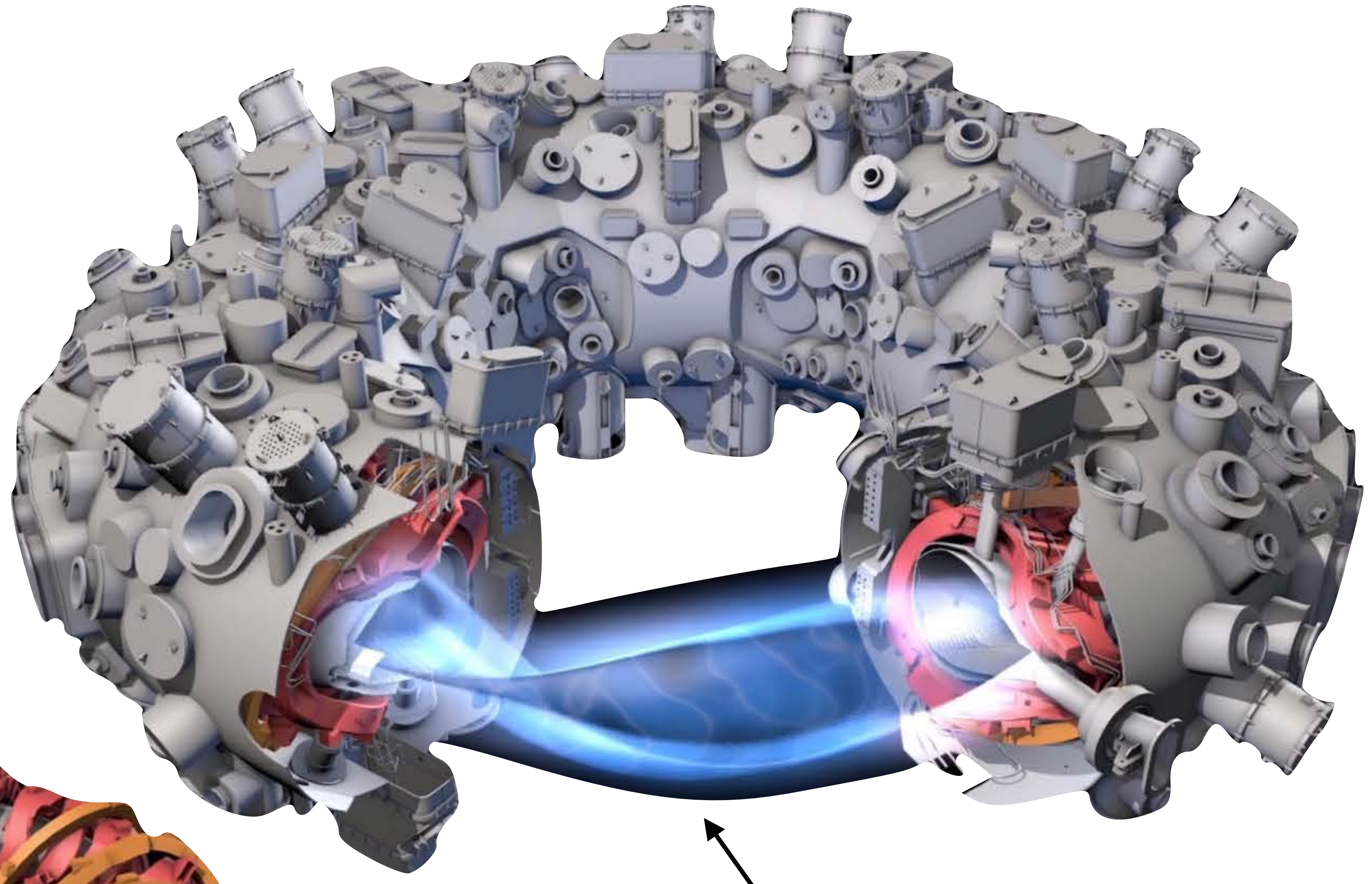
How to make a magnetic torus?

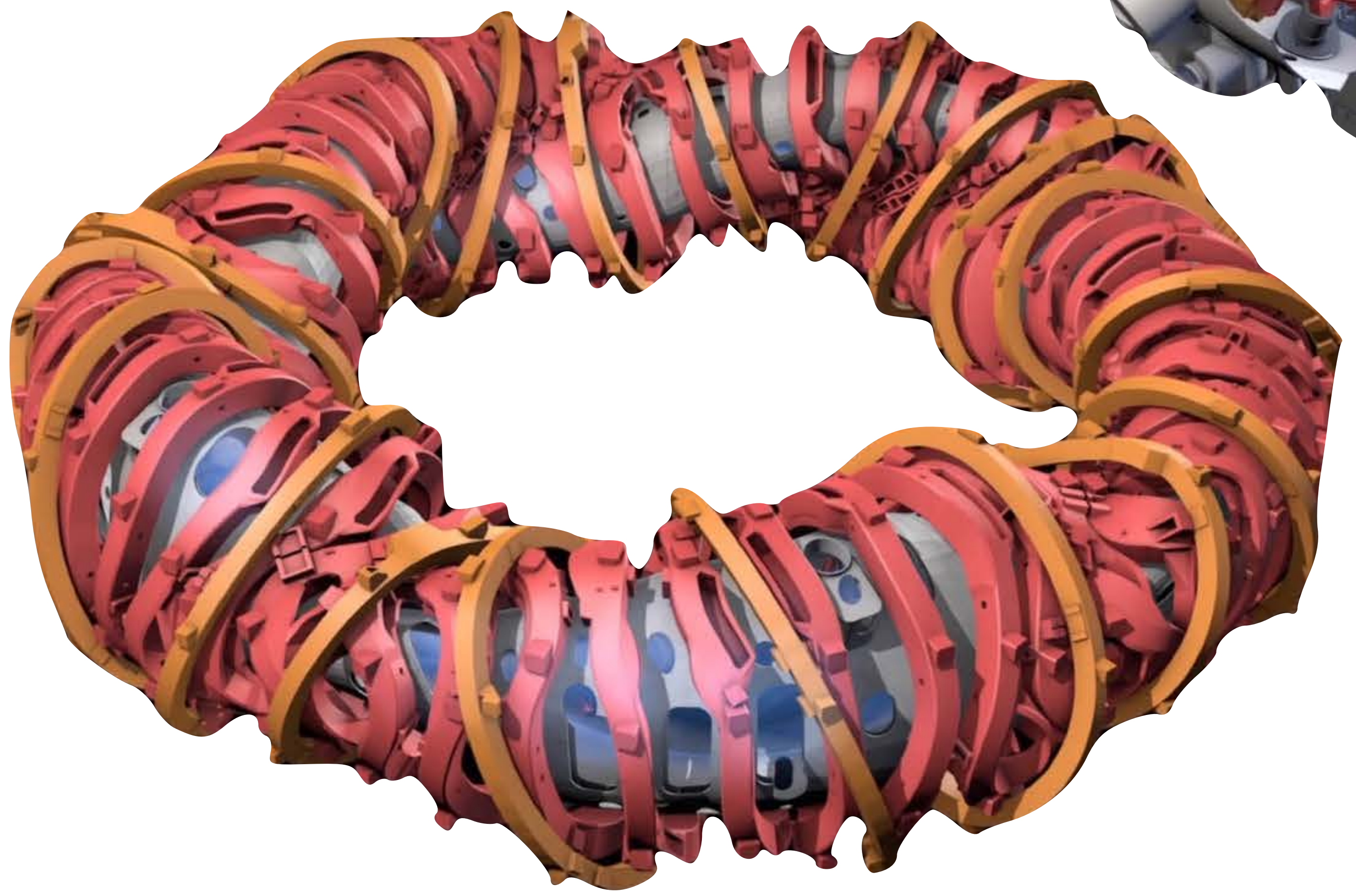
(with very small parallel current)

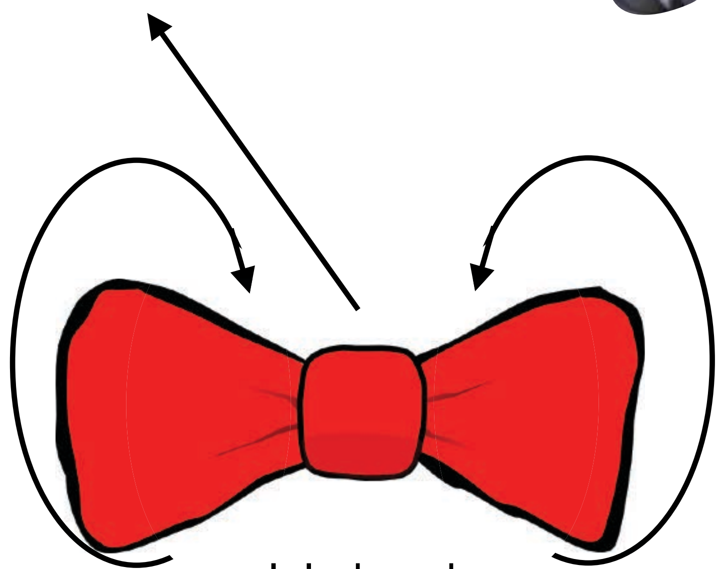


https://www.ipp.mpg.de/16900/w7x









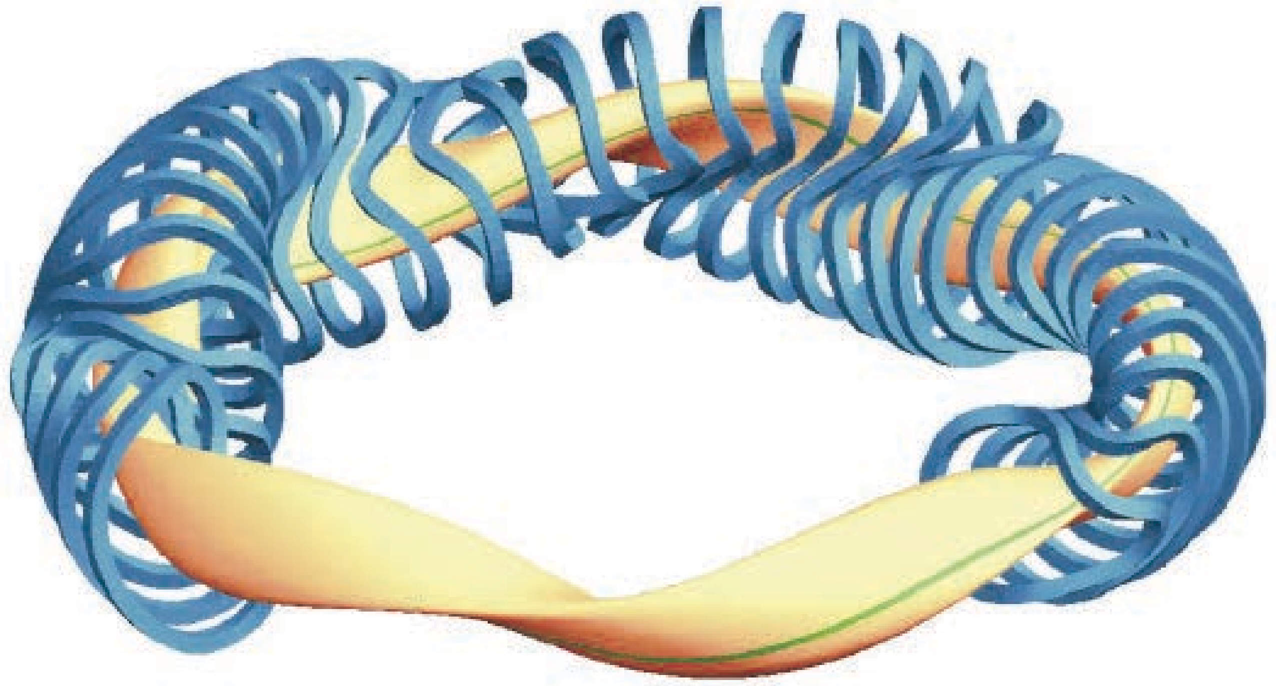
Non-symmetric plasma torus with (**mostly**) external “helical” magnets (Stellarator)

How to make a magnetic torus?

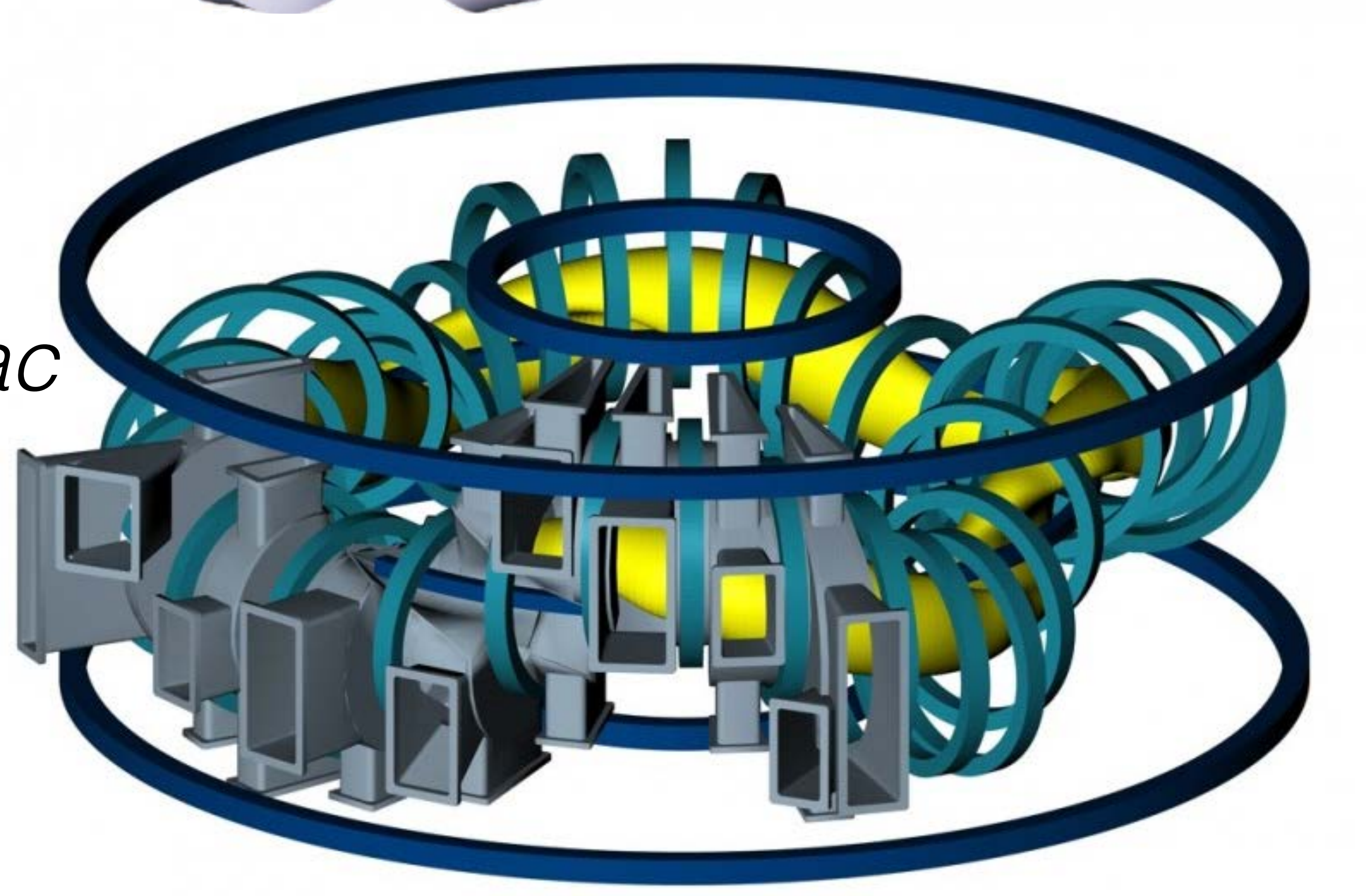
(with very small parallel current)

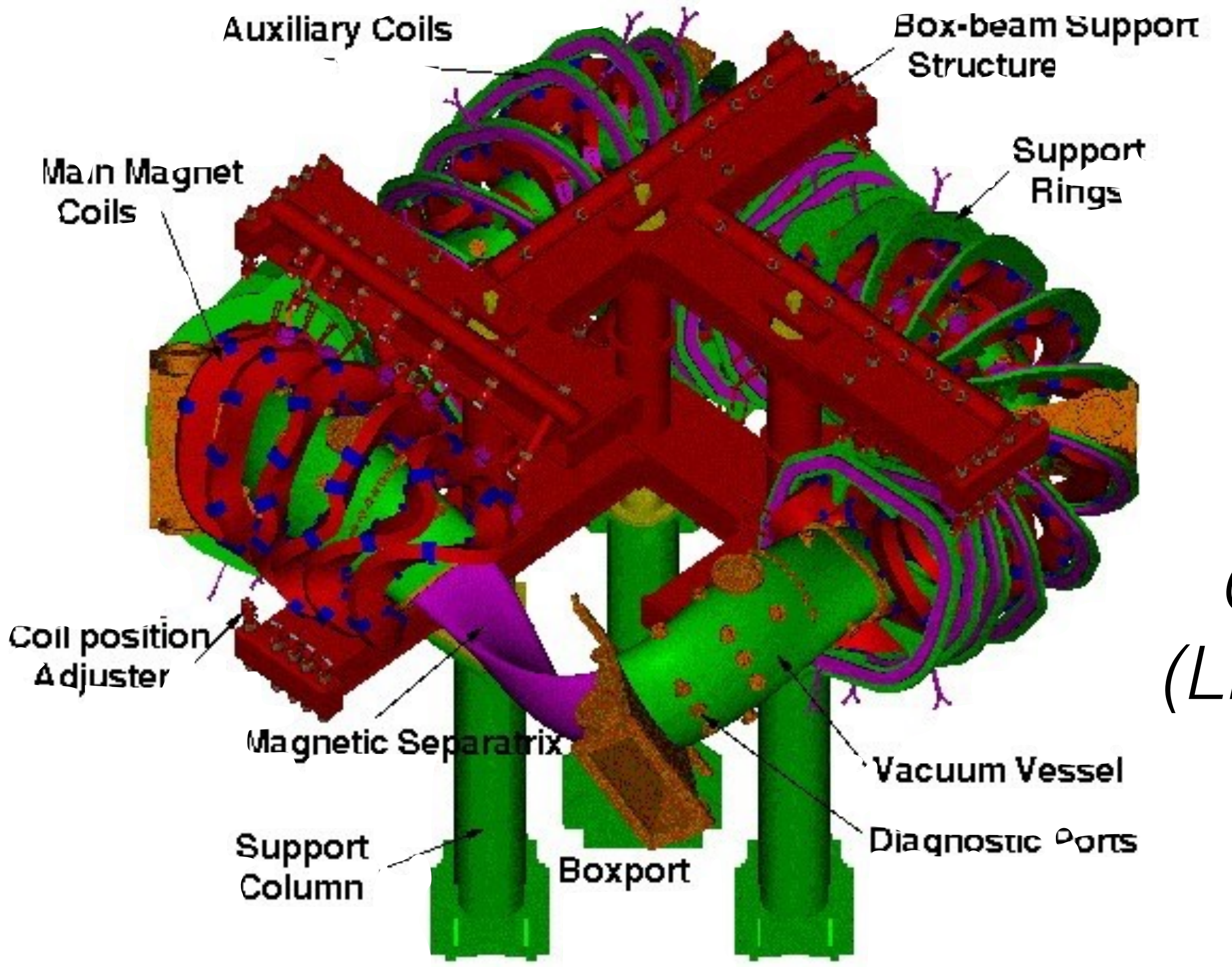
Torsatron

Quasi-Isodynamic
*(**almost** no parallel currents)*



Heliac





Quasi-Symmetry
(Like tokamak along helical path)

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

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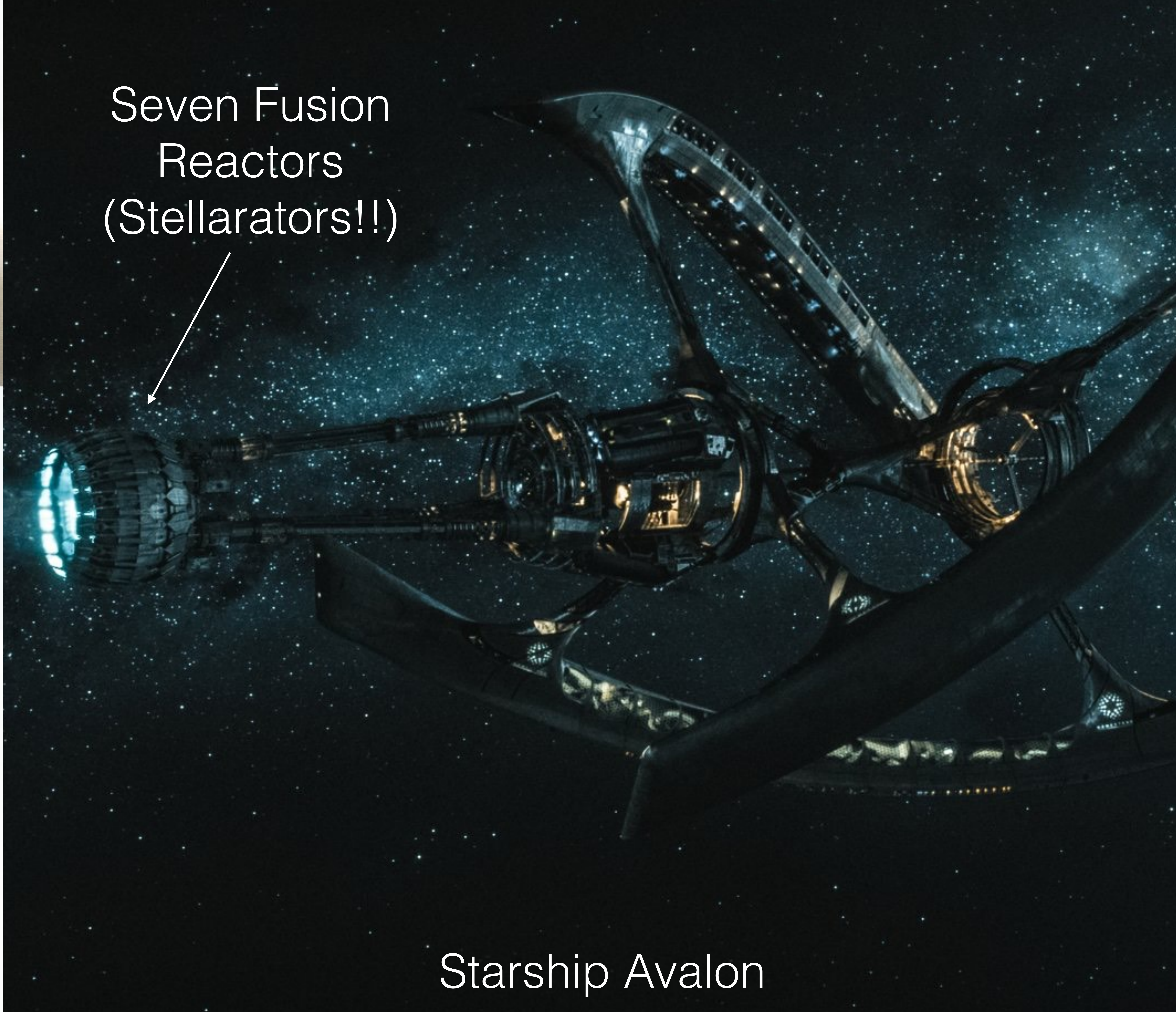
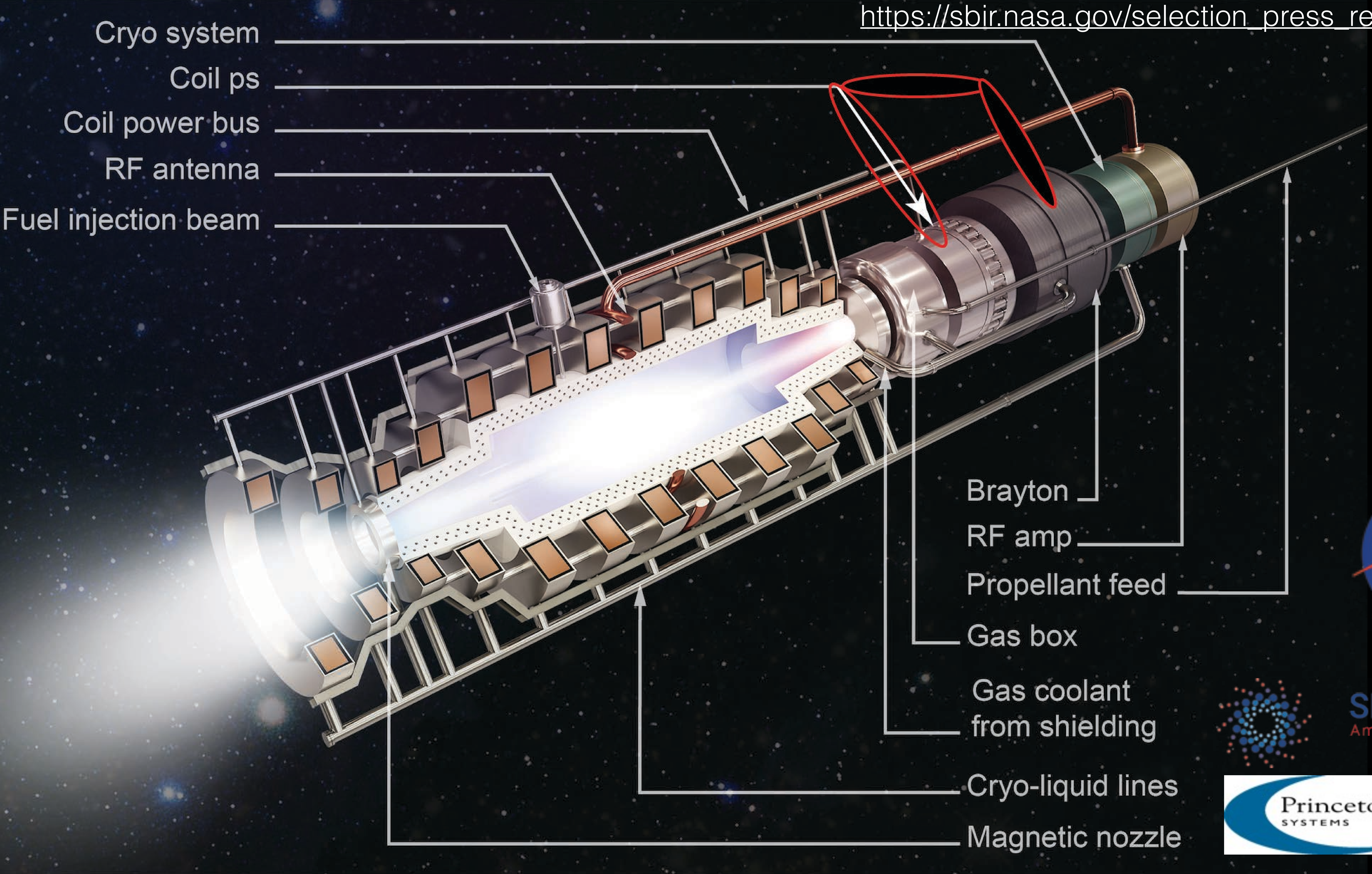
- Neutrons and the possibility for "advanced" fusion fuel
- ➡ (*Seriously*) Fusion hype and science fiction…

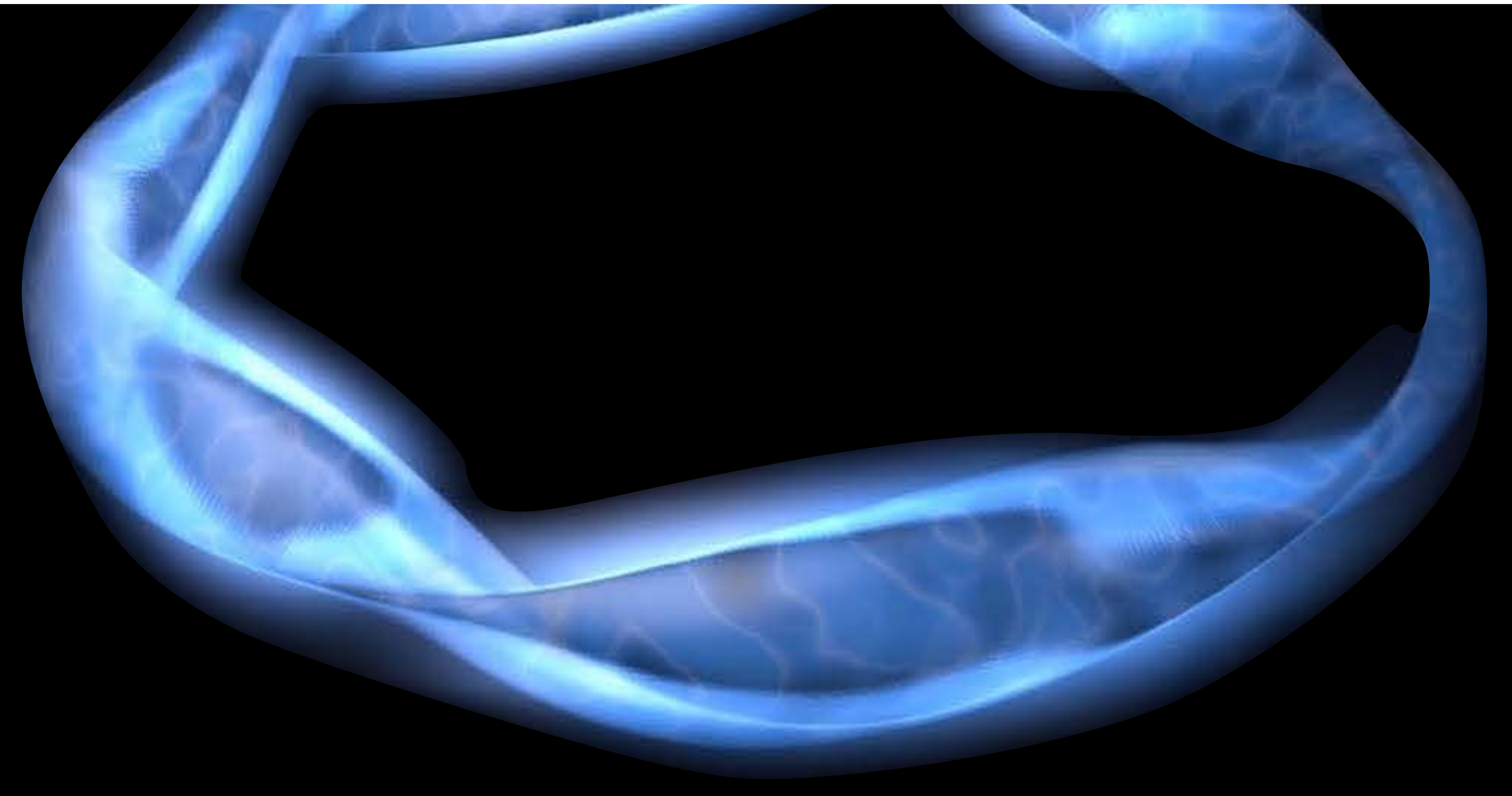

JENNIFER LAWRENCE
CHRIS PRATT
PASSENGERS
CHRISTMAS
IN 3D AND REALD 3D

2016


Seven Fusion Reactors (Stellarators!!)
Starship Avalon

https://sbir.nasa.gov/selection_press_rel/node/58010





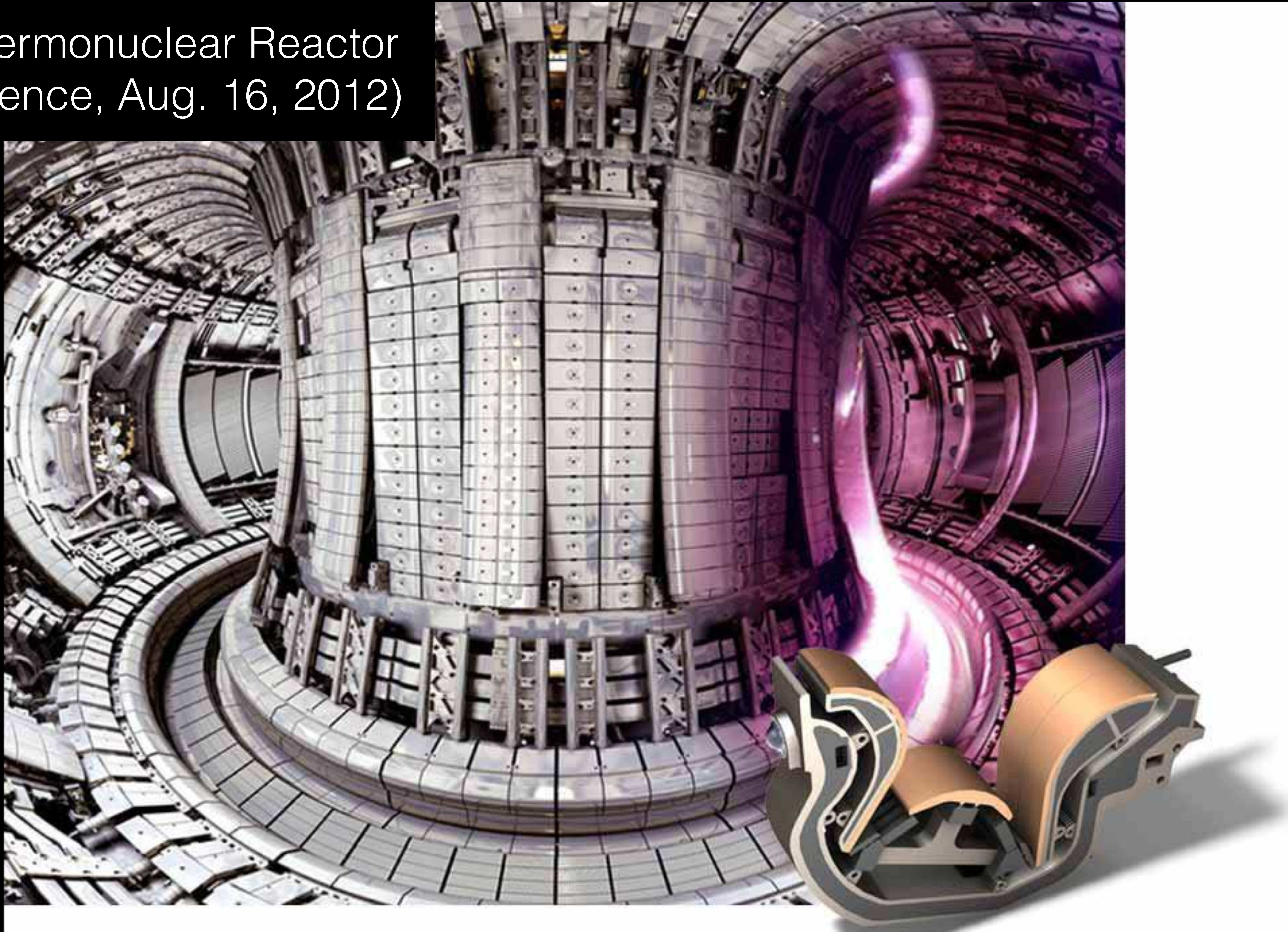
https://www.ipp.mpg.de/16900/w7x


Meteor Hole
Impurity Leak

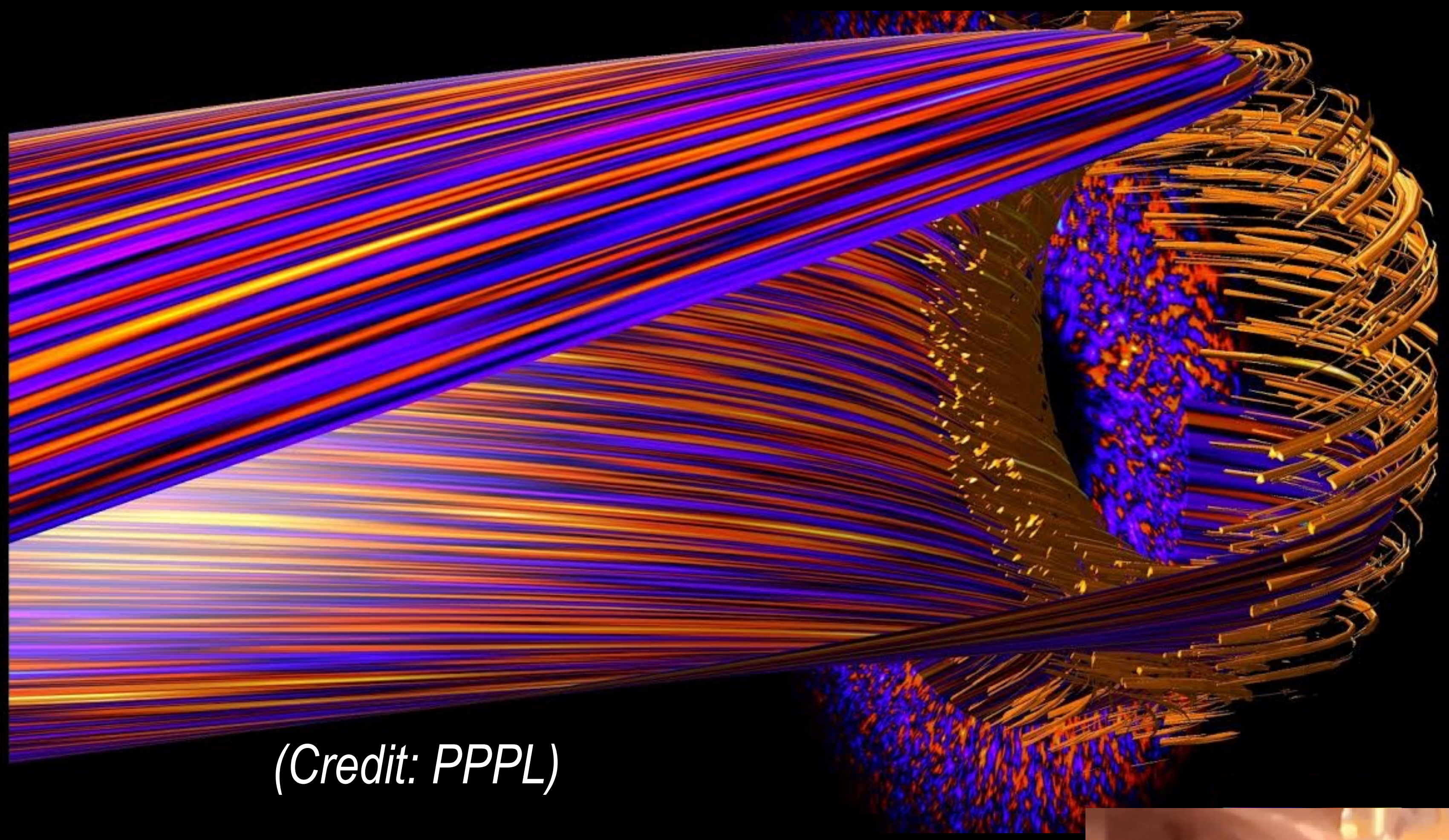

"Dirty" Plasma

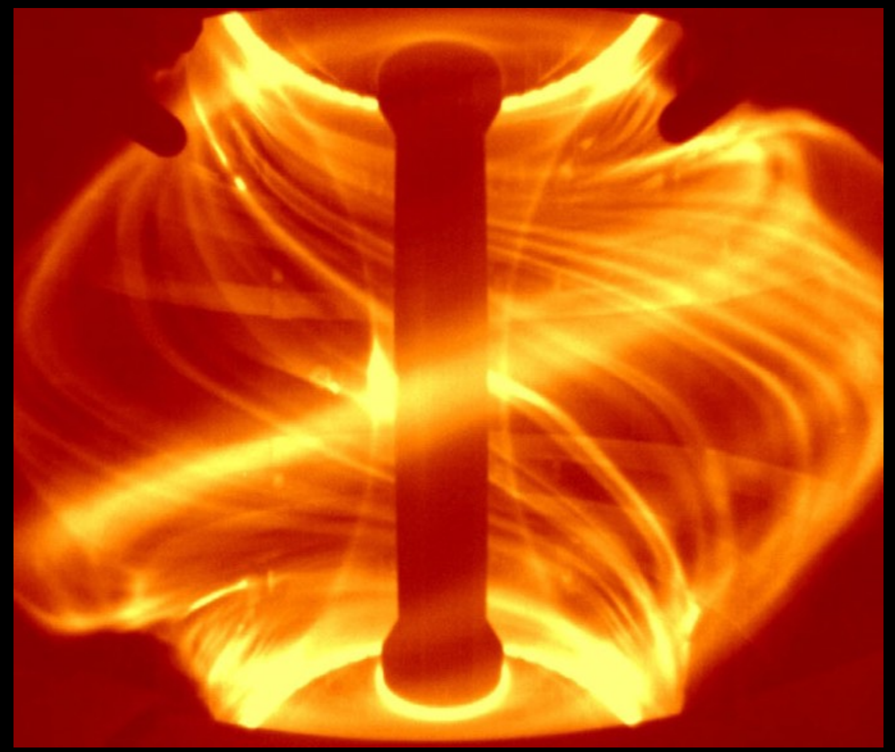

Divertor and
Plasma Exhaust

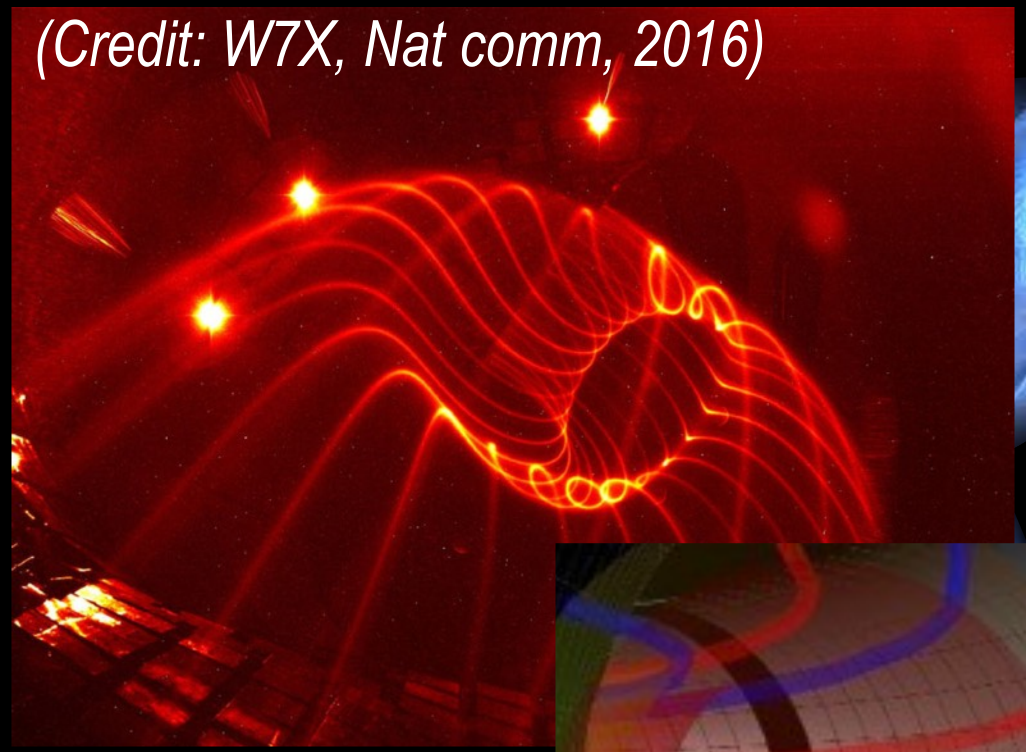
How to Line a Thermonuclear Reactor
Jim Heirbaut (Science, Aug. 16, 2012)

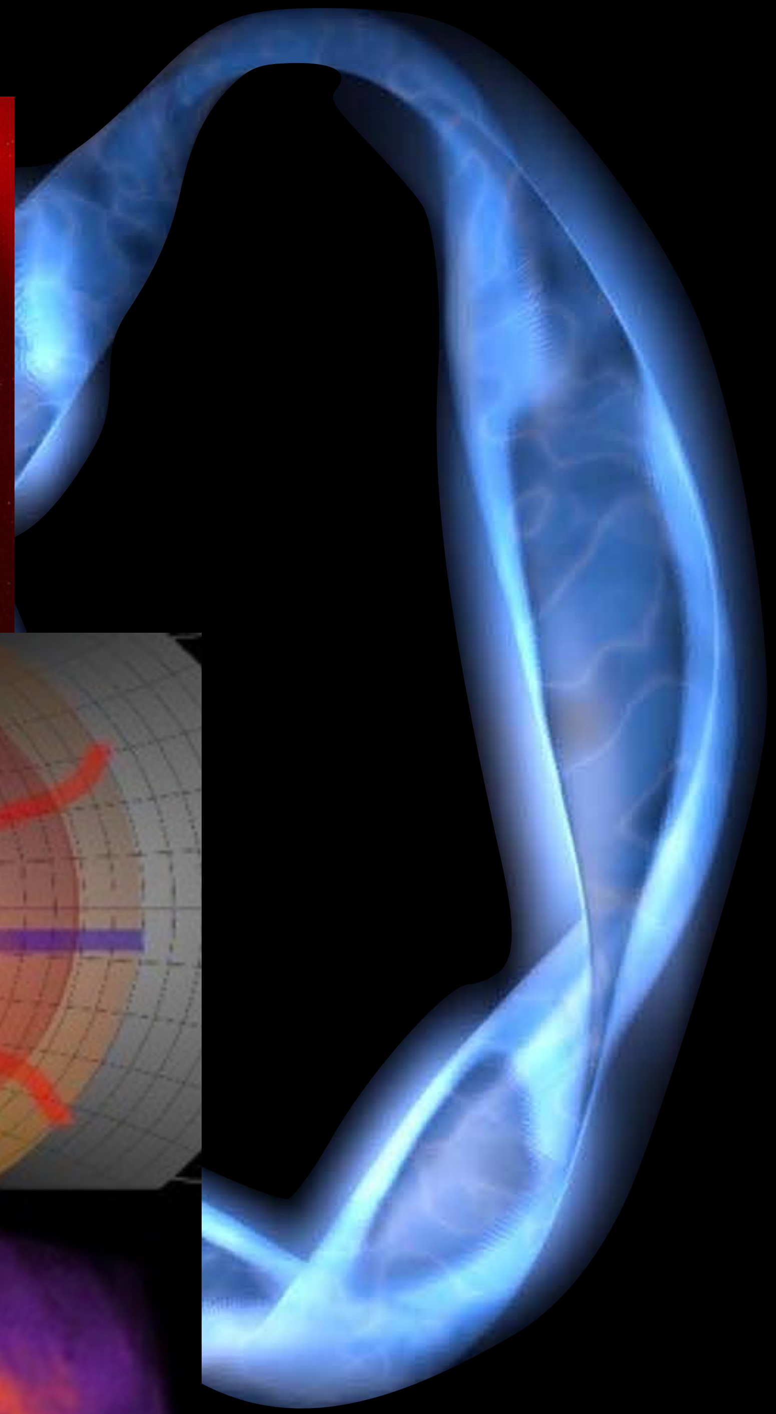


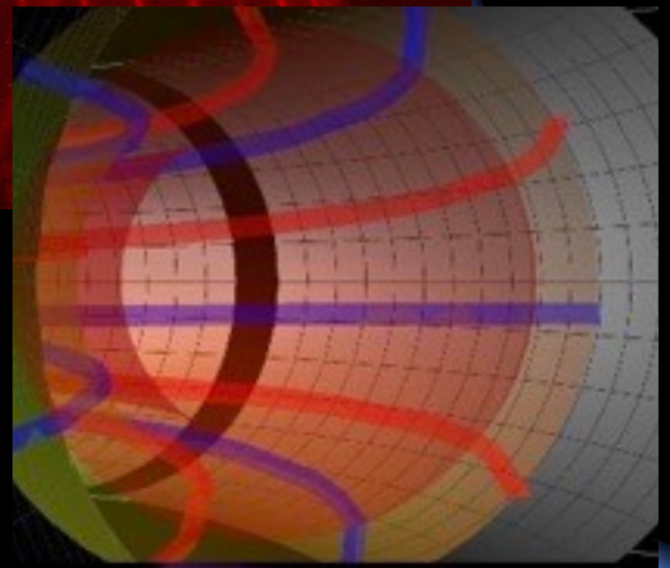
Great Flexibility in the Design of Magnetized Tubes of Plasma

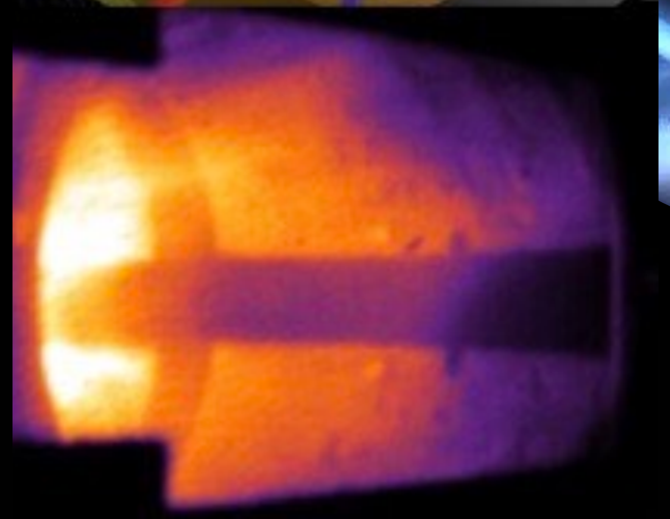

(Credit: PPPL)

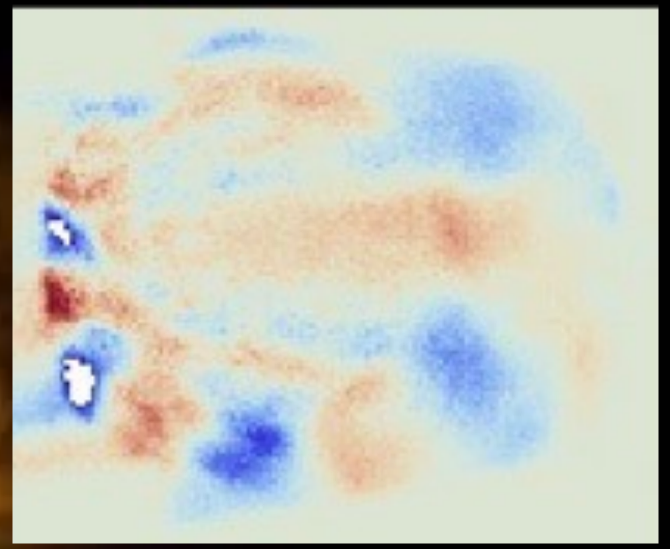

(Credit: Culham)


(Credit: W7X, Nat comm, 2016)

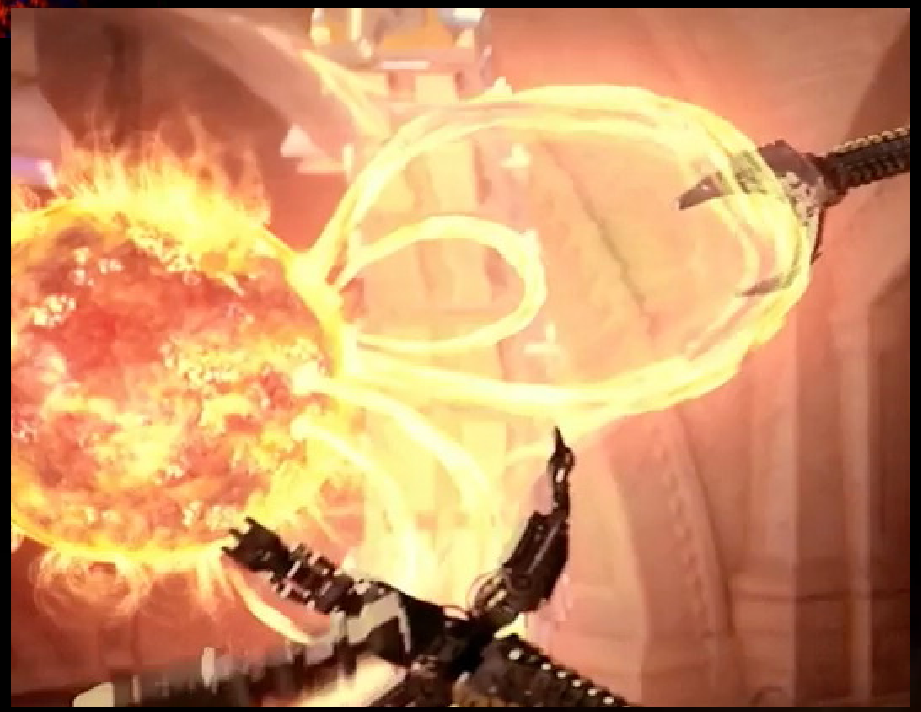


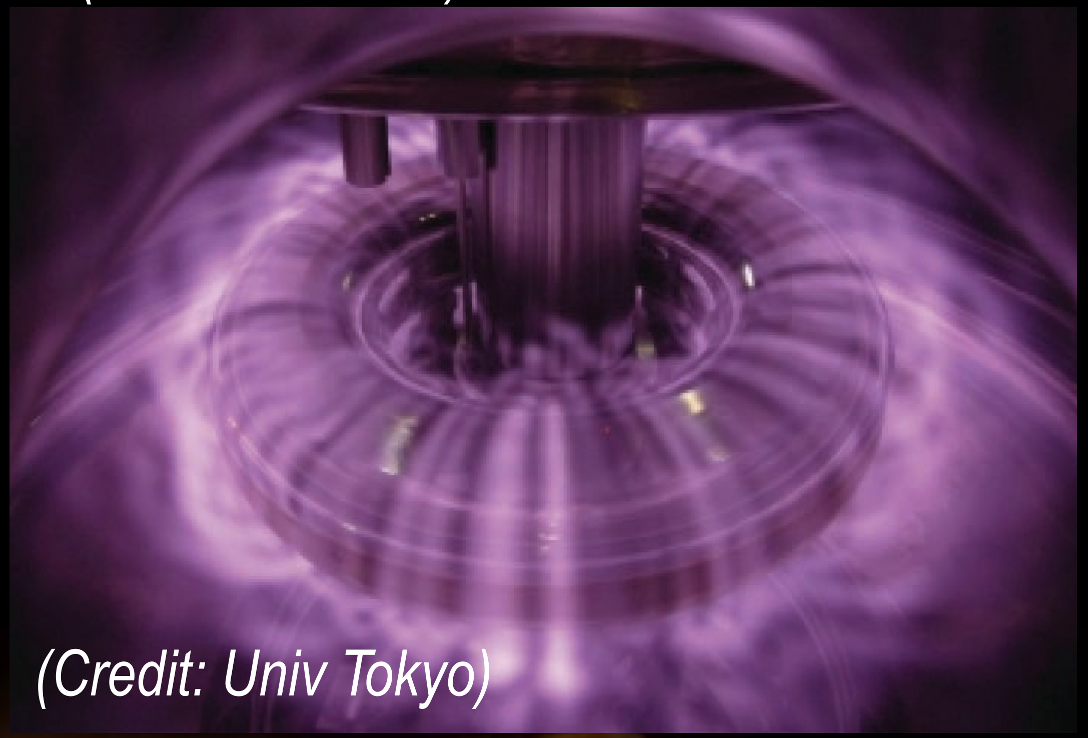







(Credit: NASA ISS)


(Credit: Spider-Man 2)


(Credit: Univ Tokyo)


(Credit: NASA Goddard SDO)

Outline

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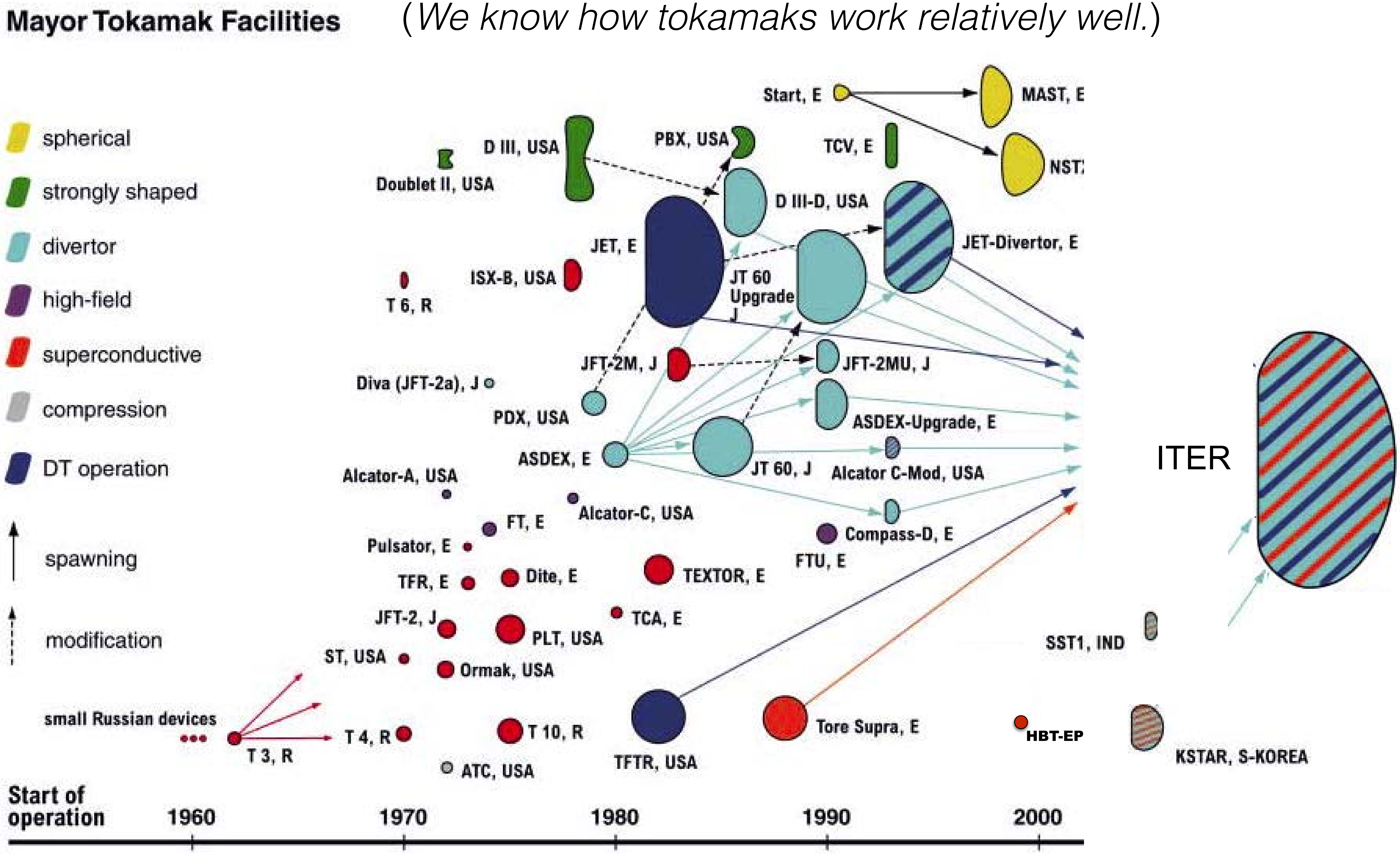
- Innovations to meet the challenges to fusion’s economic potential
- Neutrons and the possibility for “advanced” fusion fuel
- (*Seriously*) Fusion hype and science fiction…

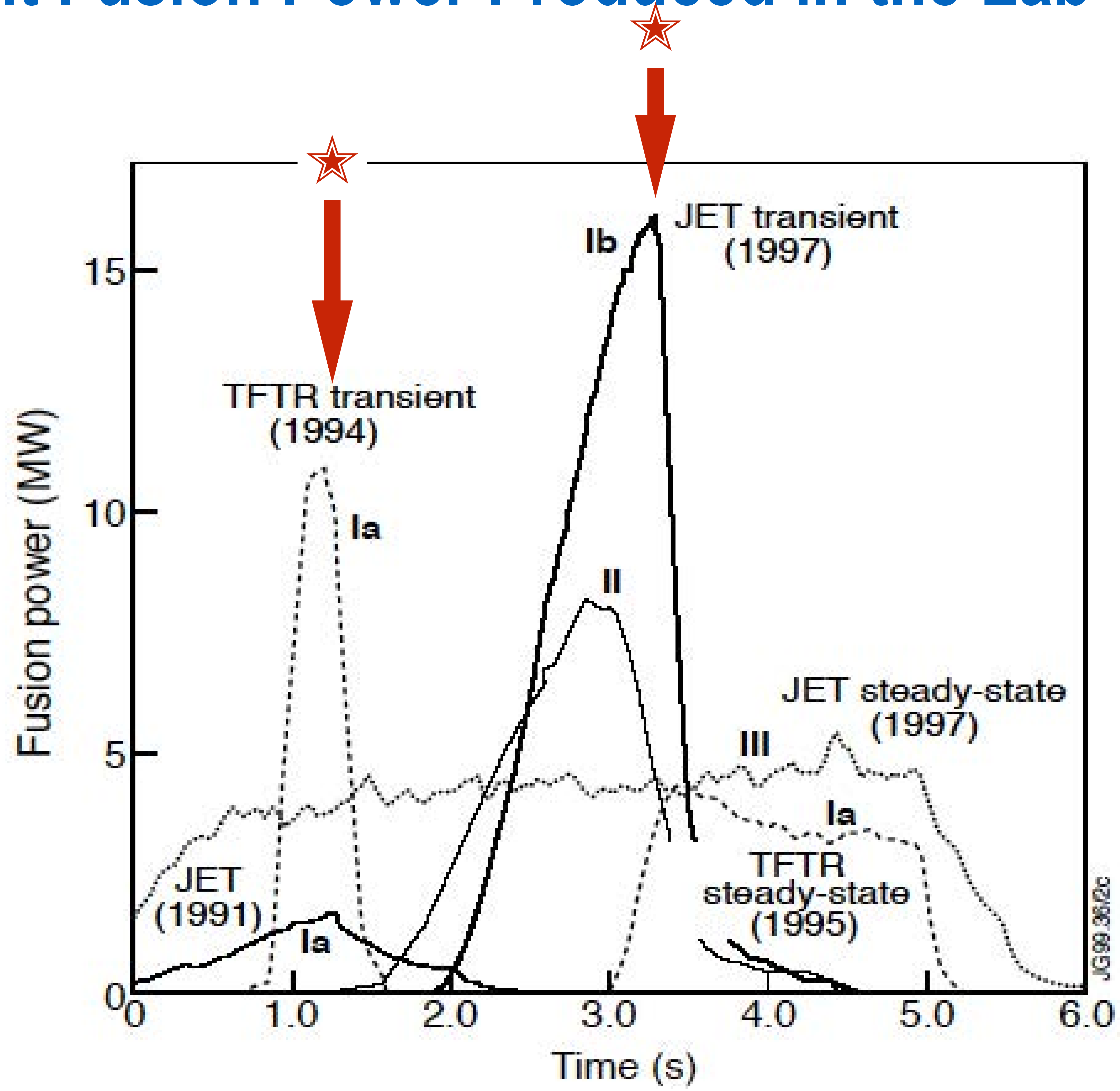
More than 200 Tokamaks

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



20 Years Ago: Significant Fusion Power 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", to be explored in ITER.
- ★ Control instabilities, disruptions & transients still T.B.D.
- ◉ Steady state, maintainability, high-availability still T.B.D.
- ◉ The technologies needed for net power still T.B.D.

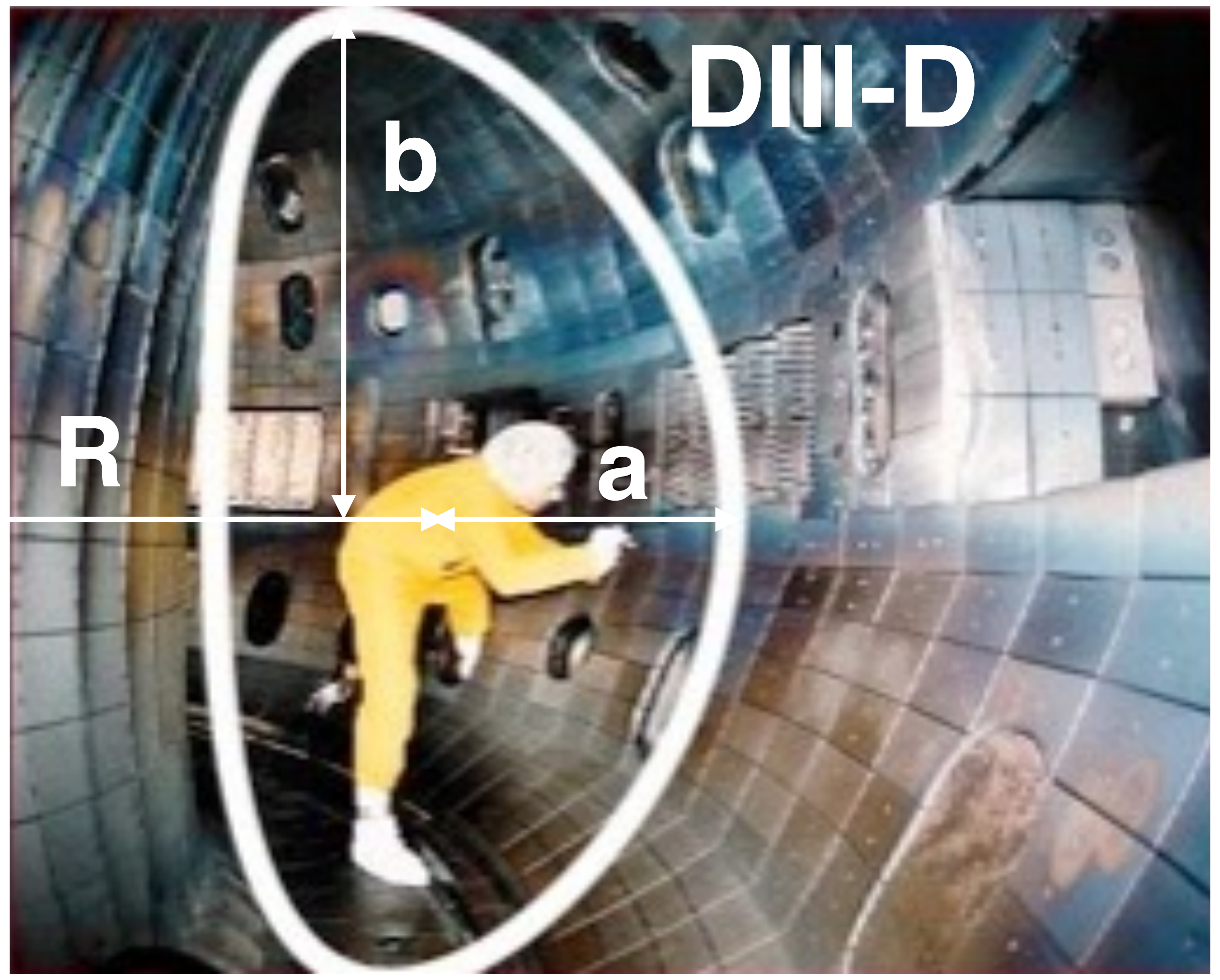


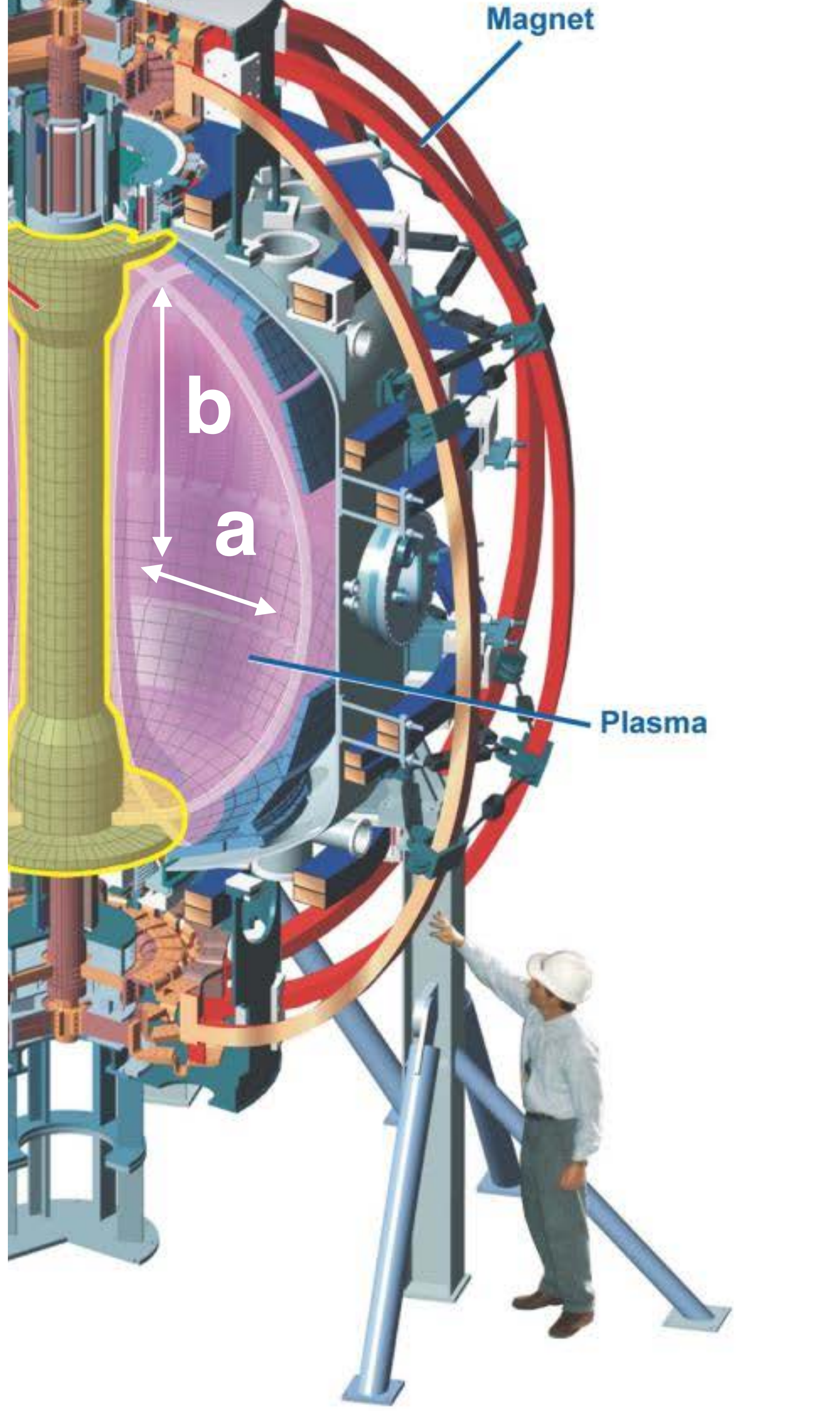
Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines), in different regimes:

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

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

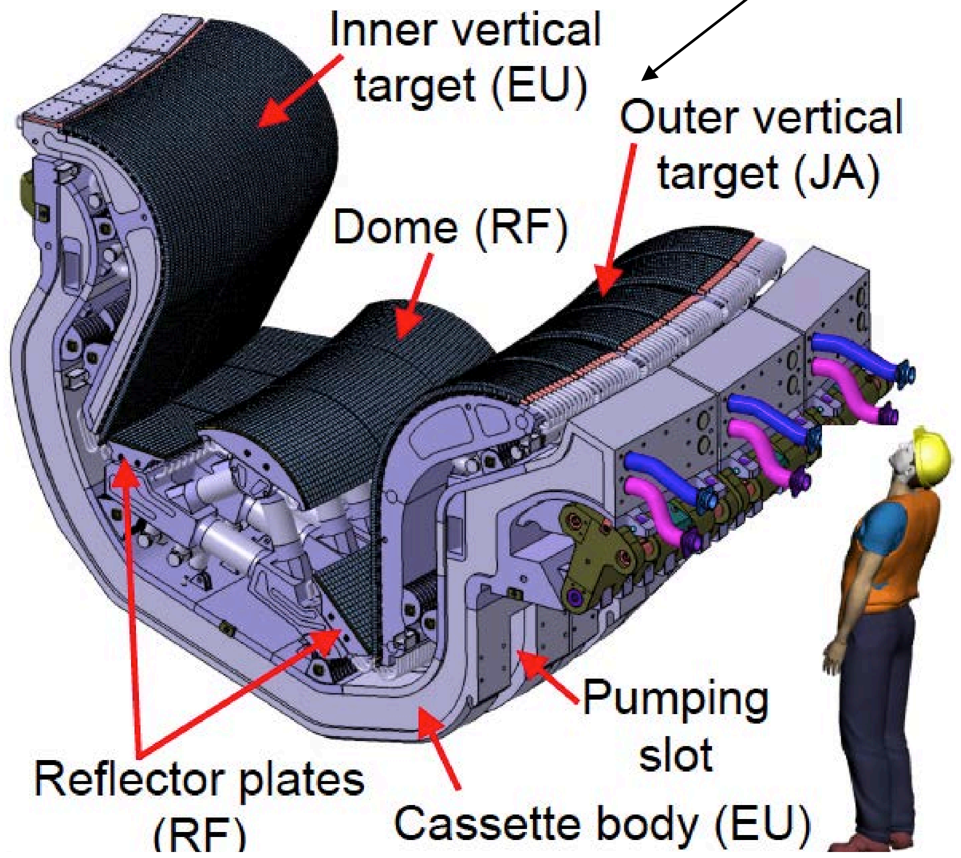
How to Design a Tokamak





- **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)



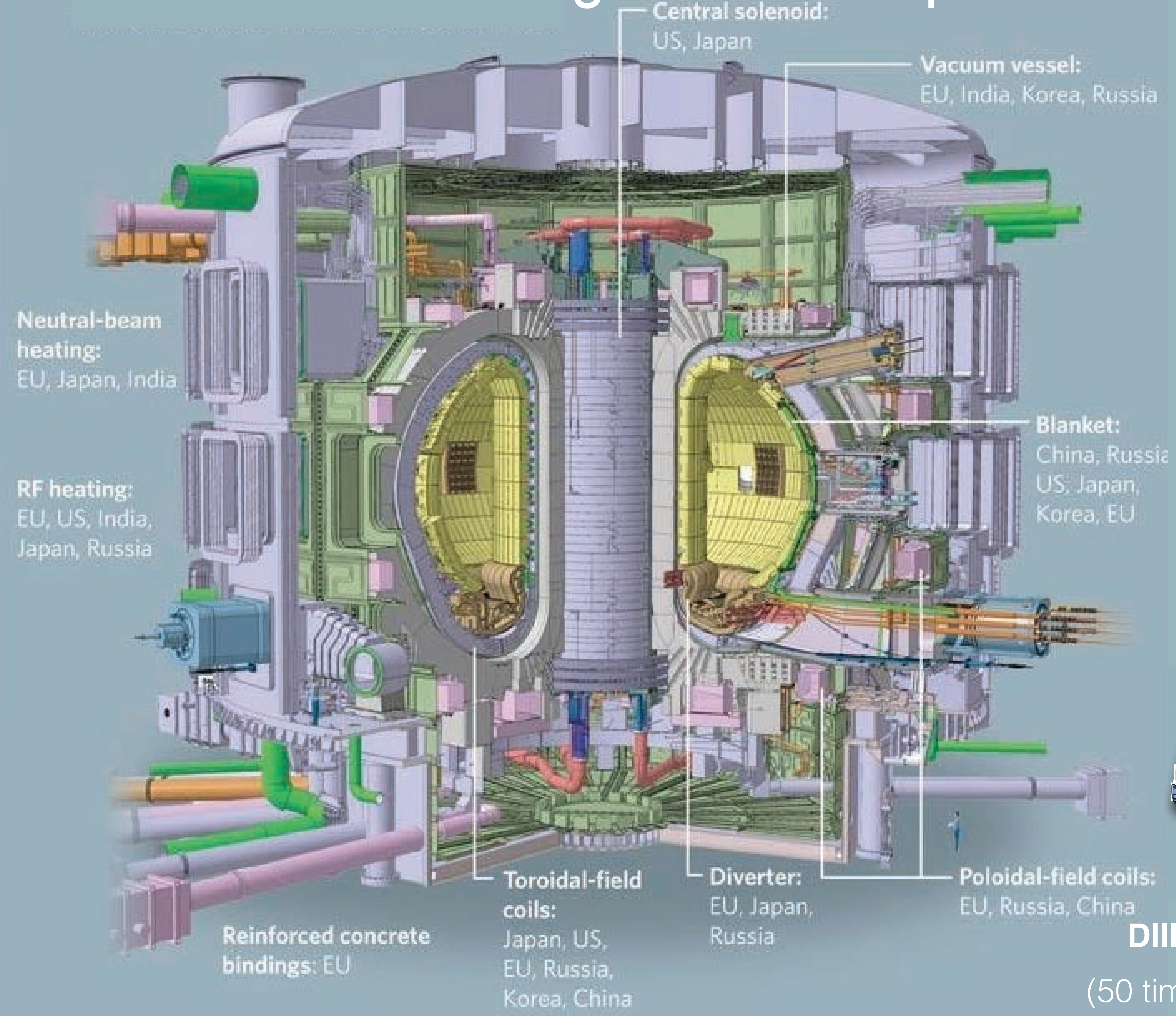
ITER: The International Burning Plasma Experiment
(April, 2017)

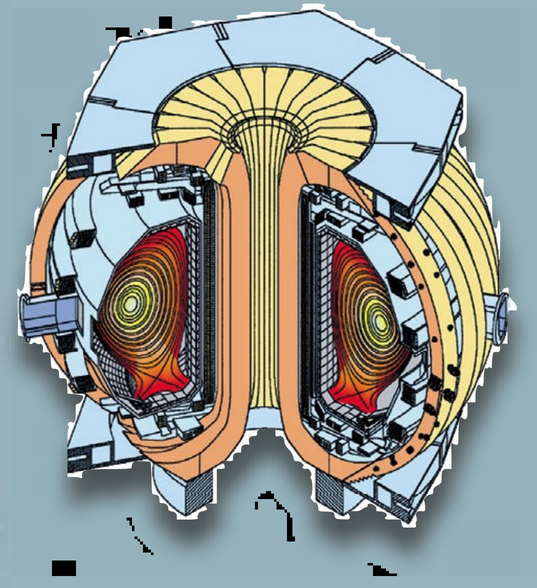
ITER: The International Burning Plasma Experiment

Important fusion science experiment, but without low-activation fusion materials, tritium breeding, …

~ 500 MW
10 minute pulses

23,000 tonne
51 GJ
Expensive





DIII-D ⇒ ITER ÷ 3.7

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

Outline

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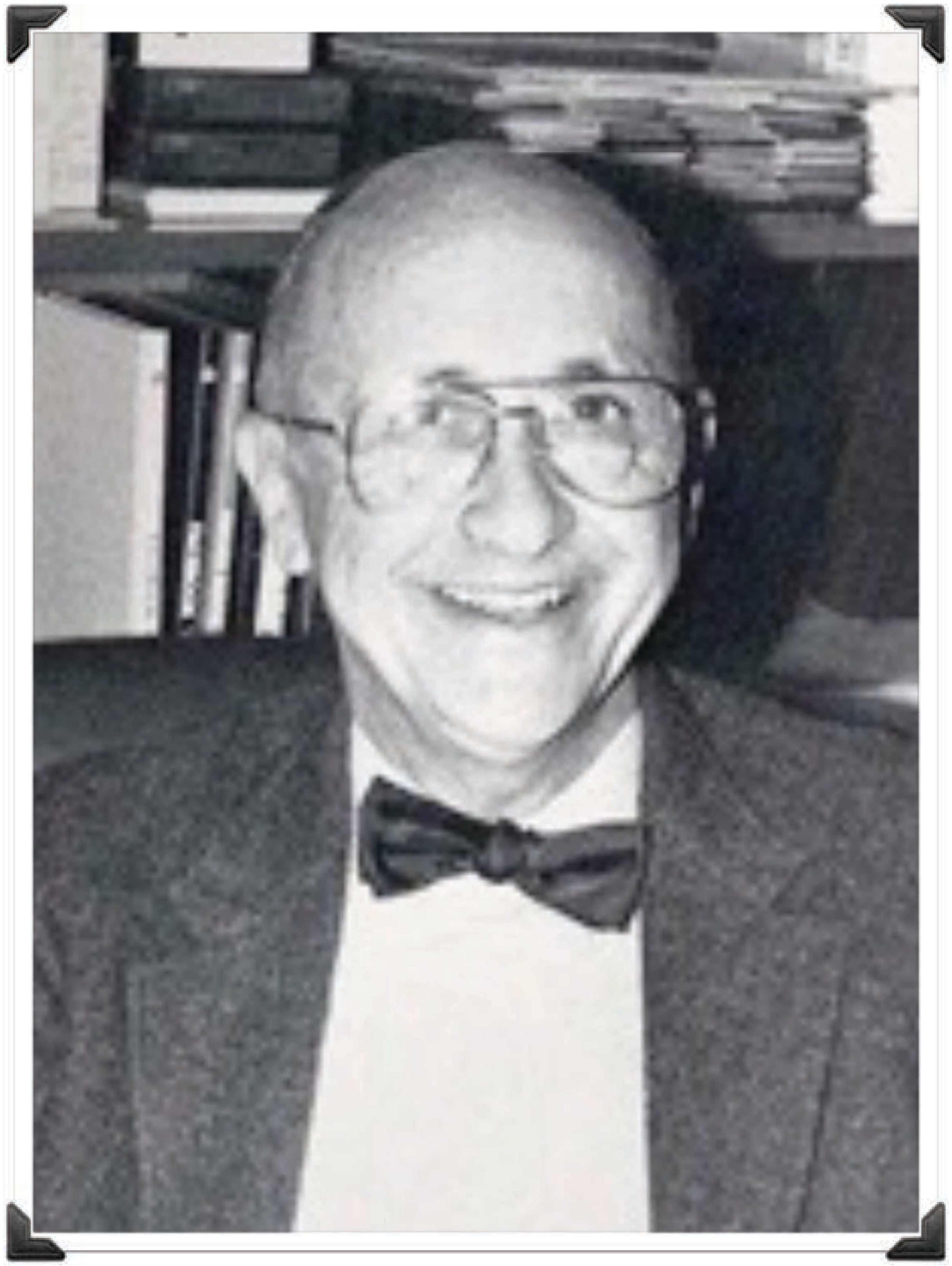
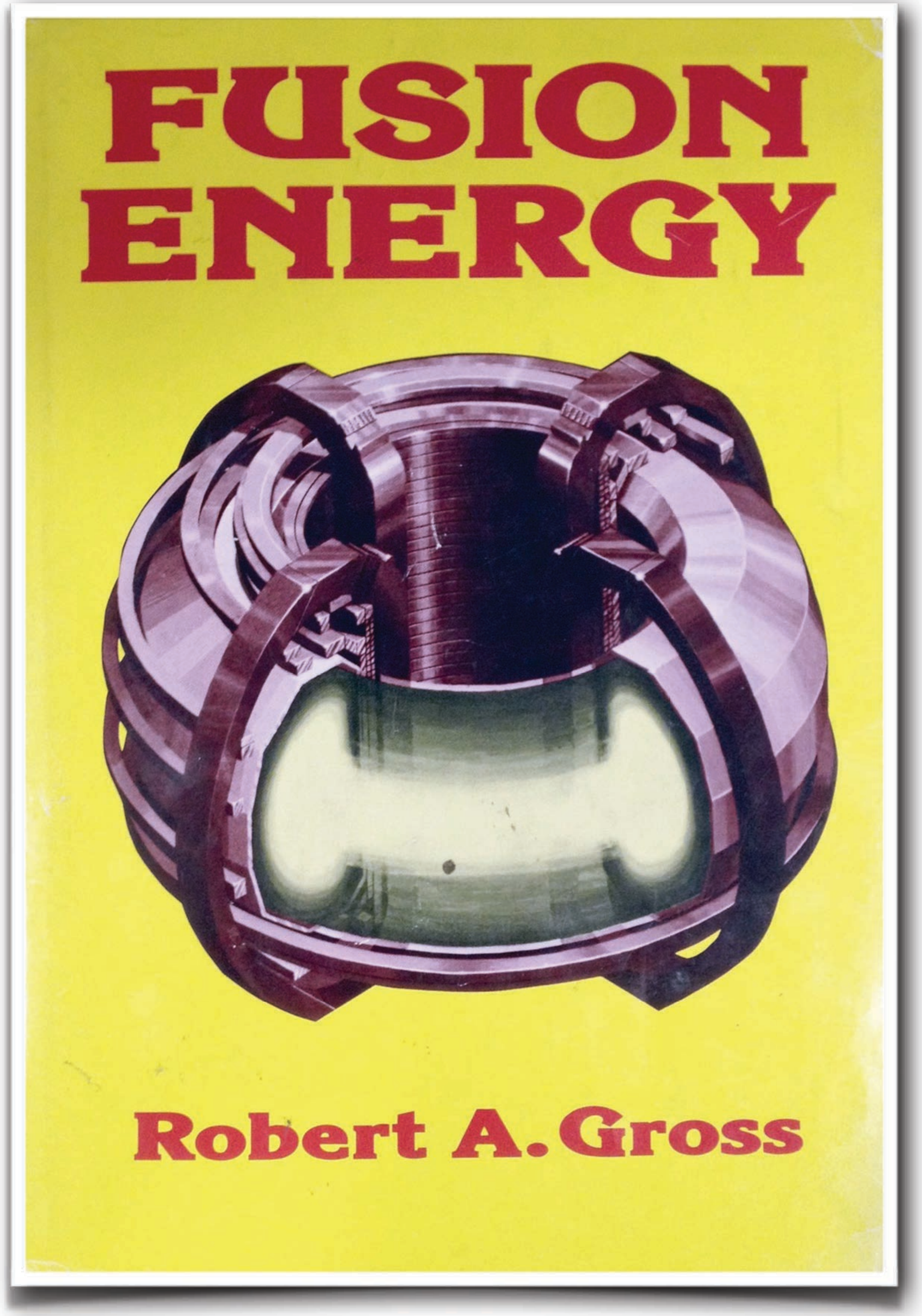
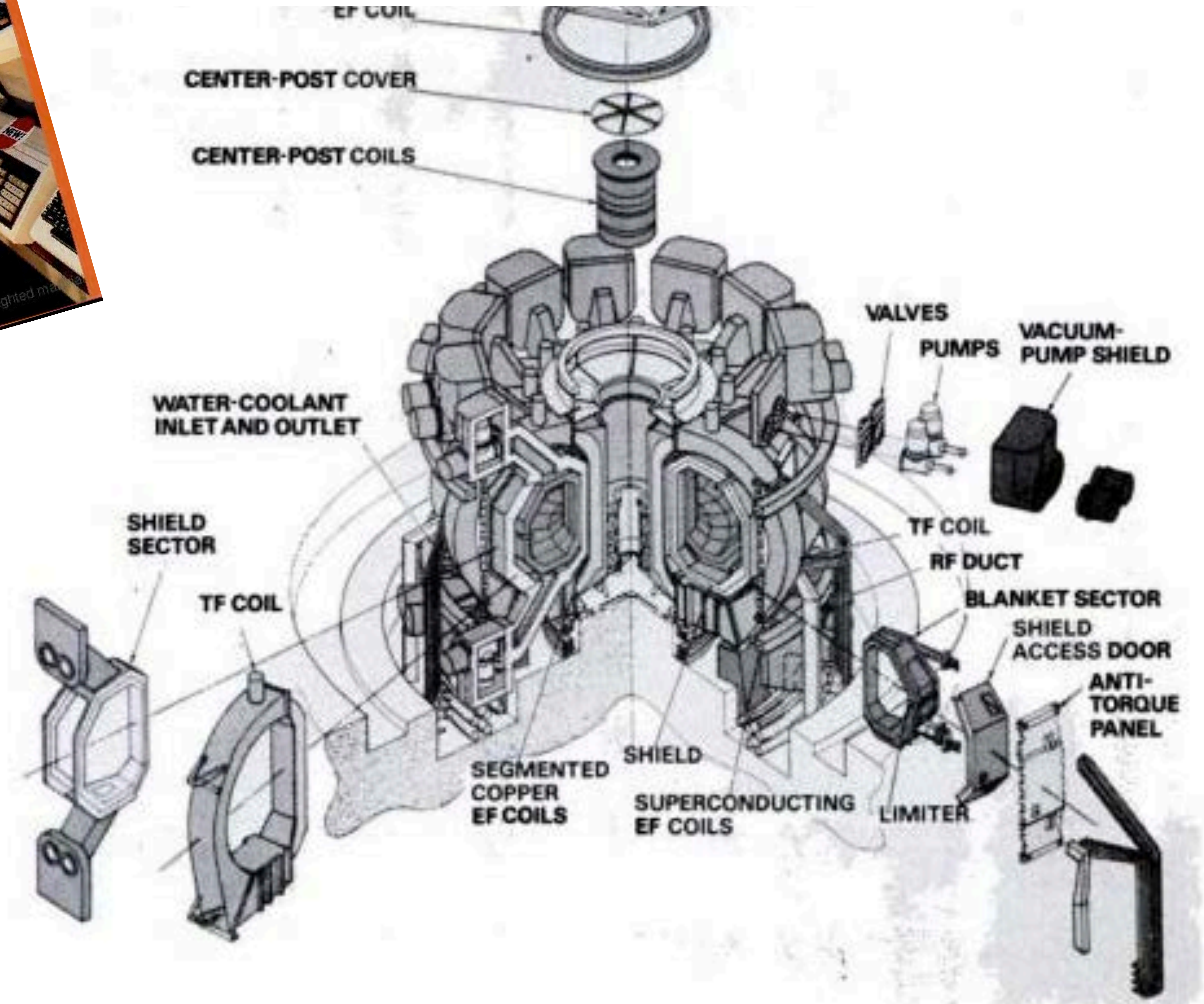


Prof. Robert Gross
Columbia University
Fusion Energy
(1984)



Science (November 1981)

By ARTHUR FISHER



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 determination.

The Starfire reactor shown here in cross section is based on the so-called tokamak design, one of the most promising yet

mode typical of some other concepts. The DOE study suggests that the design could be cost-competitive with nuclear-fission plants and coal-fired electric power systems at the turn of the century.

Scissor-wing tested

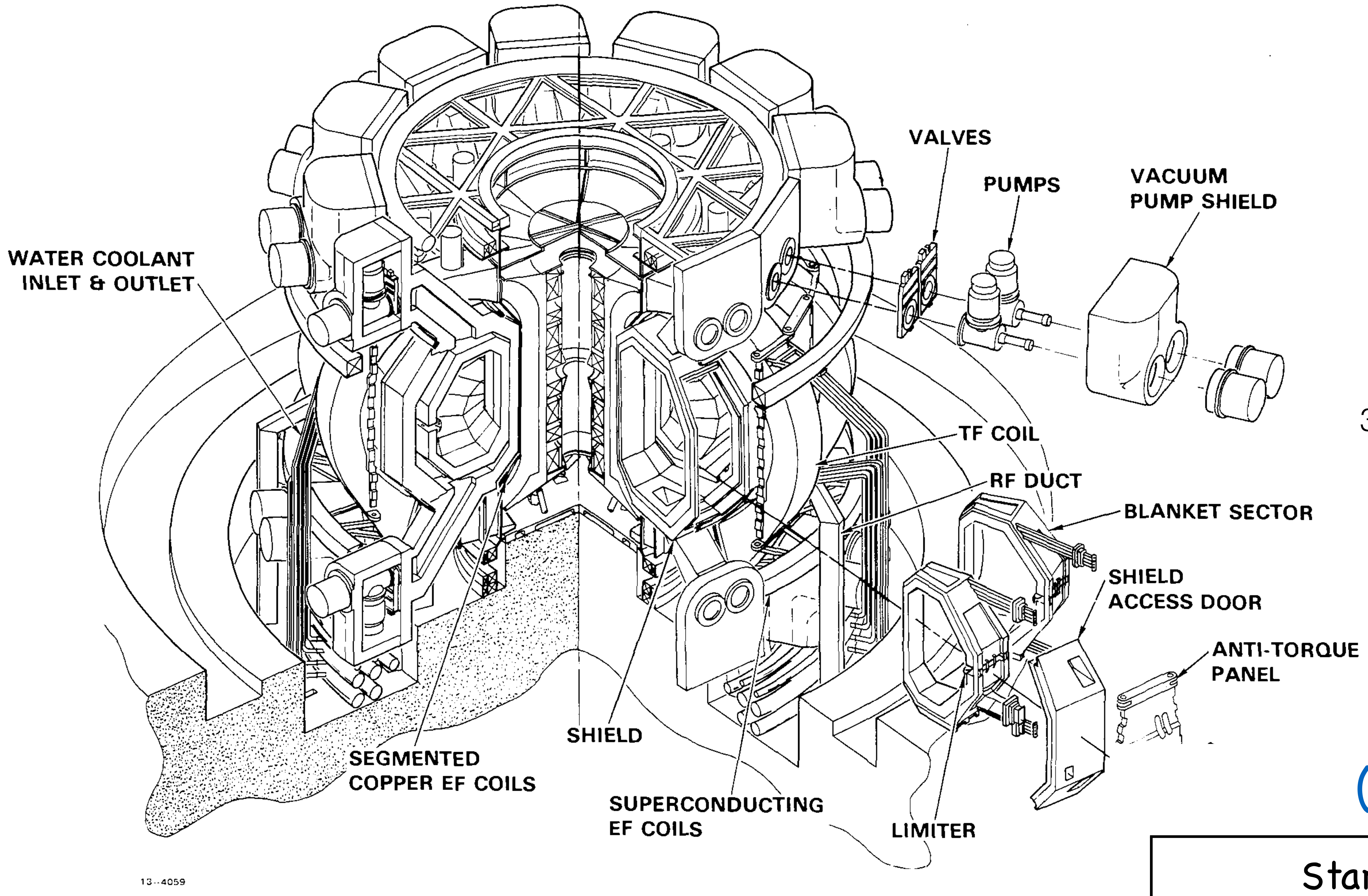
The latest step in the progress of the incredible AD-1 is pictured below. NASA'S unique scissor-wing aircraft has flown successfully with its wing at the maximum, 60-degree oblique position. Flight tests at Dryden Flight Research Center by pilot Tom McMurty have shown the craft can skew its wing at angles ranging from 30 to 60 degrees and still perform the maneuvers required of it.

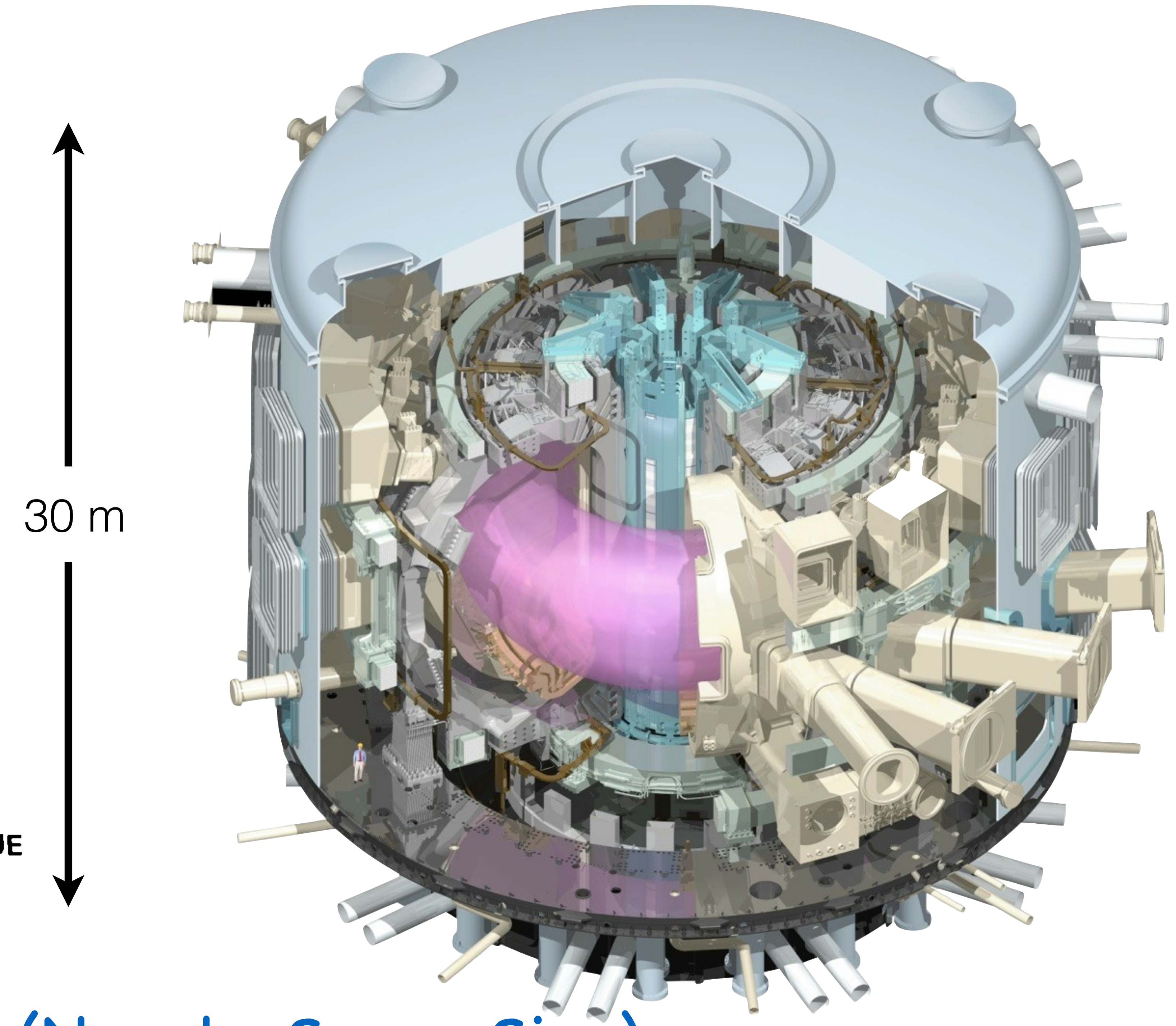
The object of the bizarre design is economy [PS, Oct. '78]. At low speeds and during takeoffs and landings, a scissor-wing transport of the future would fly with the wing perpendicular to the body, as in conventional aircraft. But by skewing the wing during transonic and supersonic flight, the plane would decrease aerodynamic drag and thus require less power—and less fuel.

Tennis turmoil

Four years ago I wrote about the introduction of the Prince tennis racket, a revolutionary design with an oversized head [PS, March '77]. Those who play tennis know that the Prince has been followed by a host of "big-head" competitors. In my sto-

Continued





(Nearly Same Size)

	Starfire (1981)	ITER (> 2027)
R, a (m)	7.0, 1.9	6.2, 2.0
I_p (MA)	10.1	15
B (T)	5.8	5.3
W_{mag} (GJ)	55	51
Tokamak (tonne)	24,000	23,000
Fusion Power (MW)	≈ 3510	≈ 500

ITER is an experiment
Not a Power Plant

How to Design a Better Tokamak

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Optimize Shape

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Control Instability

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Better Magnets

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Improve Confinement

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  - $\tau_E \sim 3.7$ sec requiring only 40 MW of injected power (gyroBohm: **Yes!!**) and 120 MW power to divertor

Spread the Heat

- **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, …
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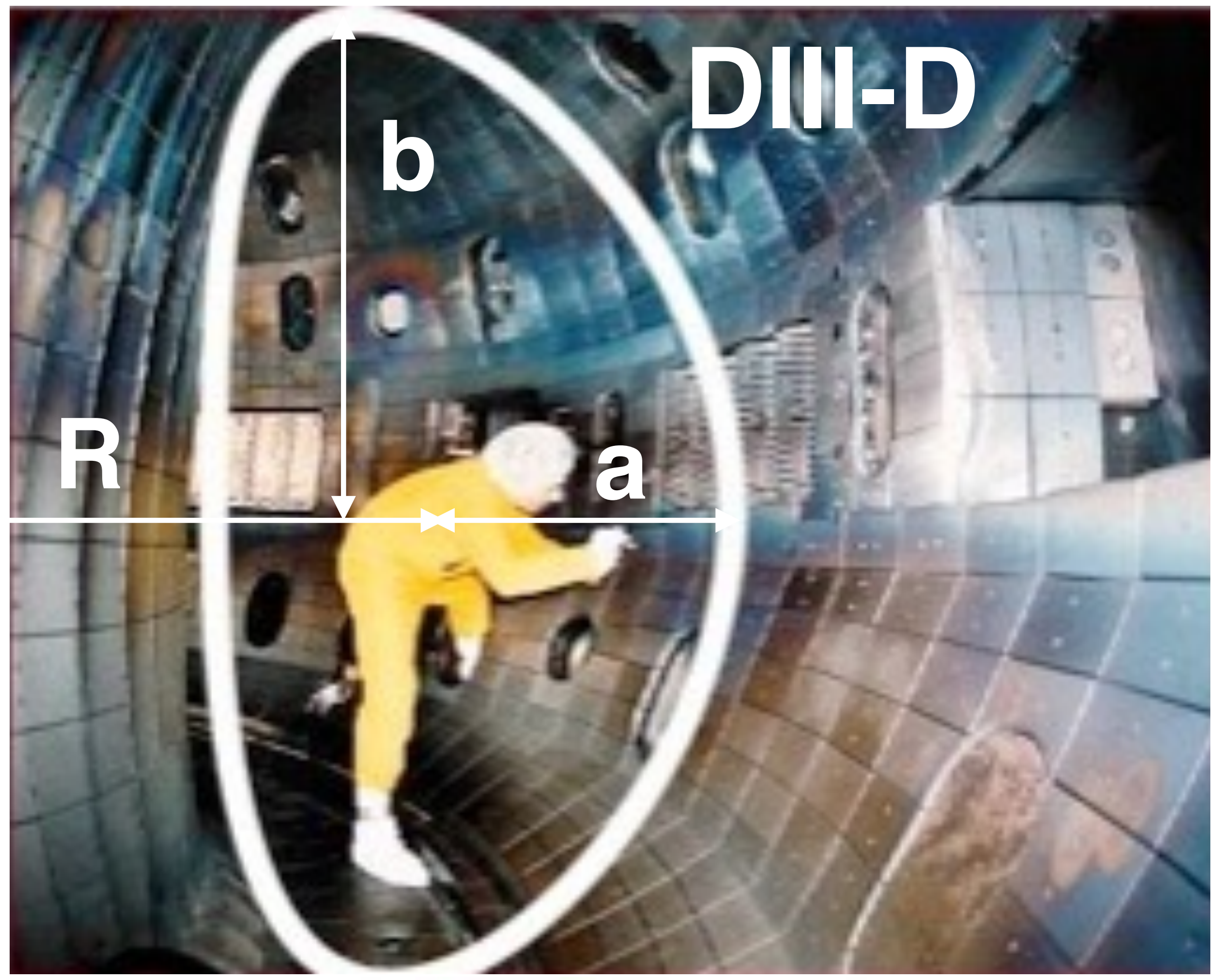
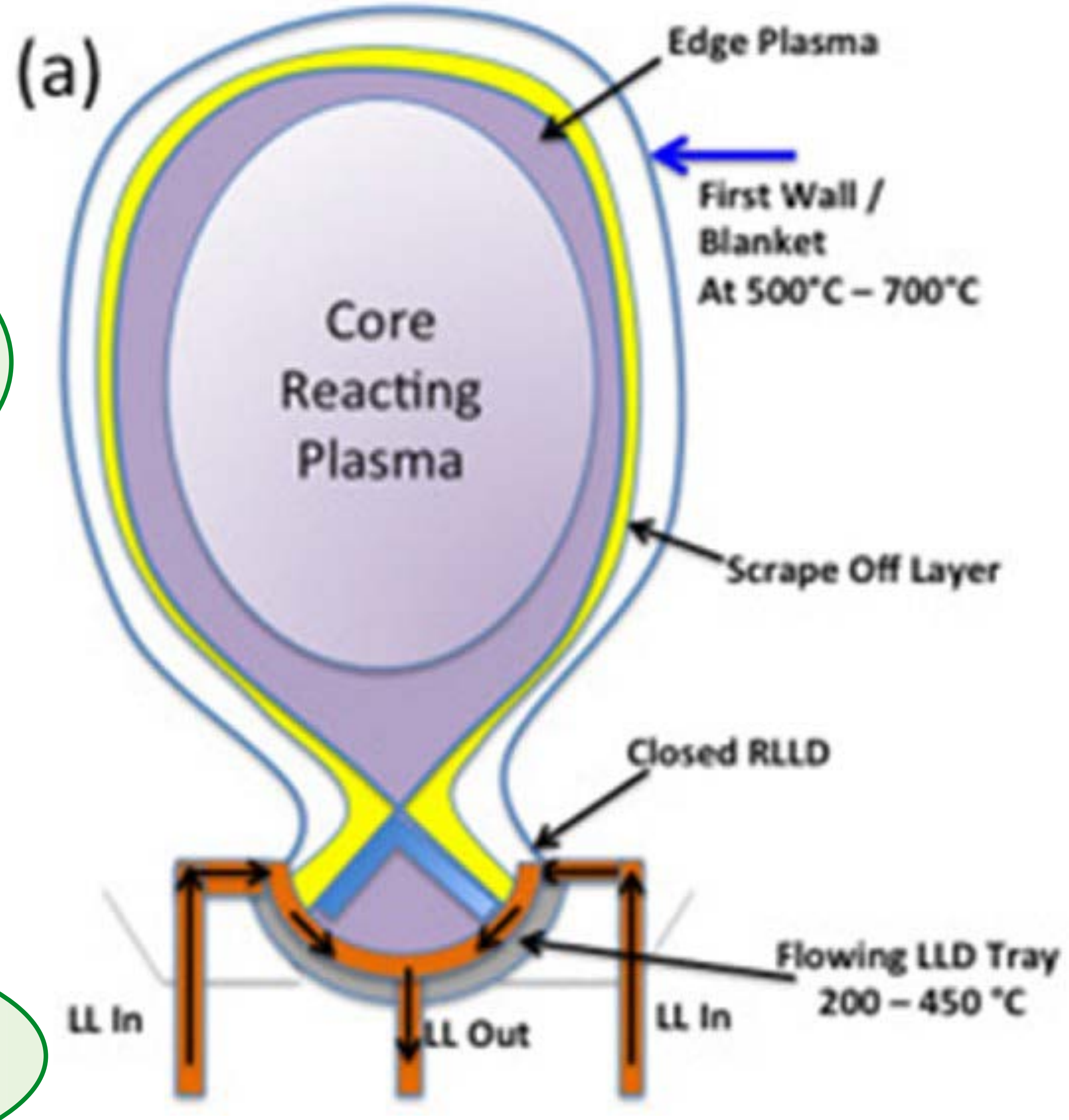
Advanced Fuels Liquid Blankets



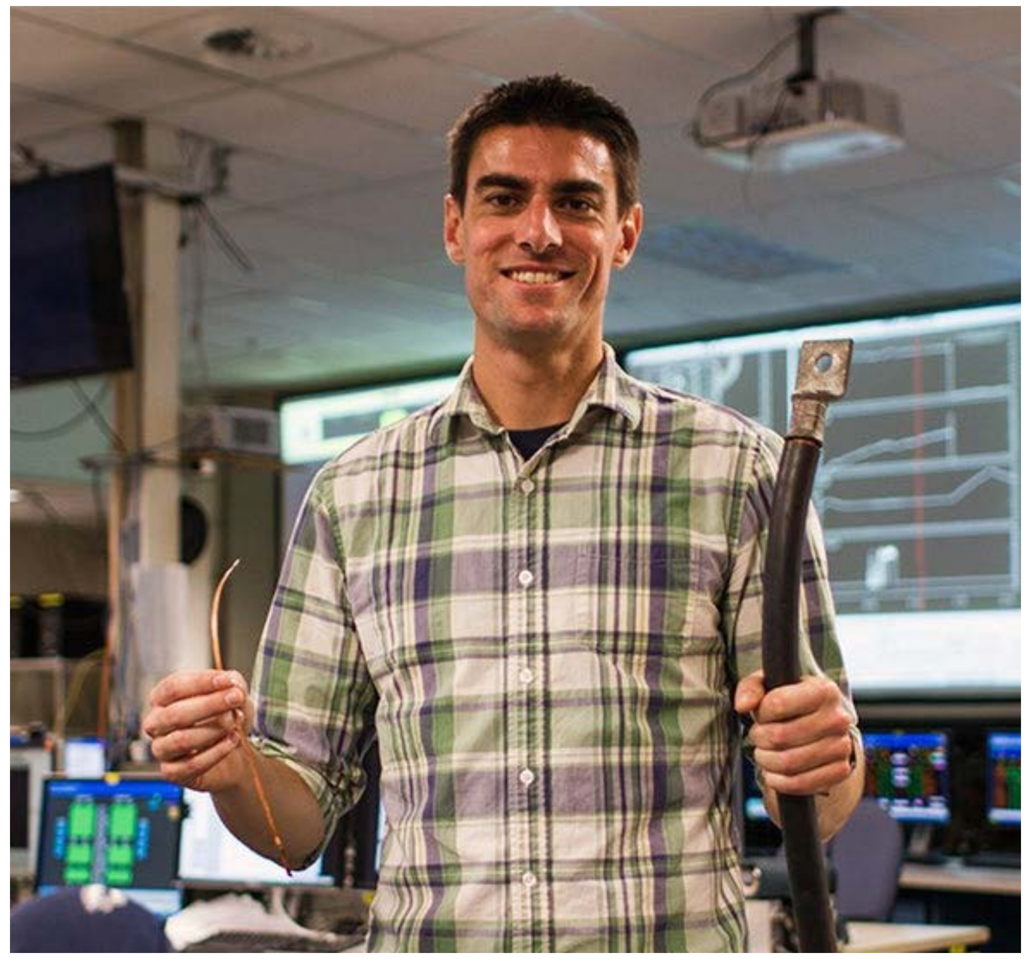


Ono, et al. 2013 Nucl. Fusion **53** 113030

(1) Advanced Technology Tokamak

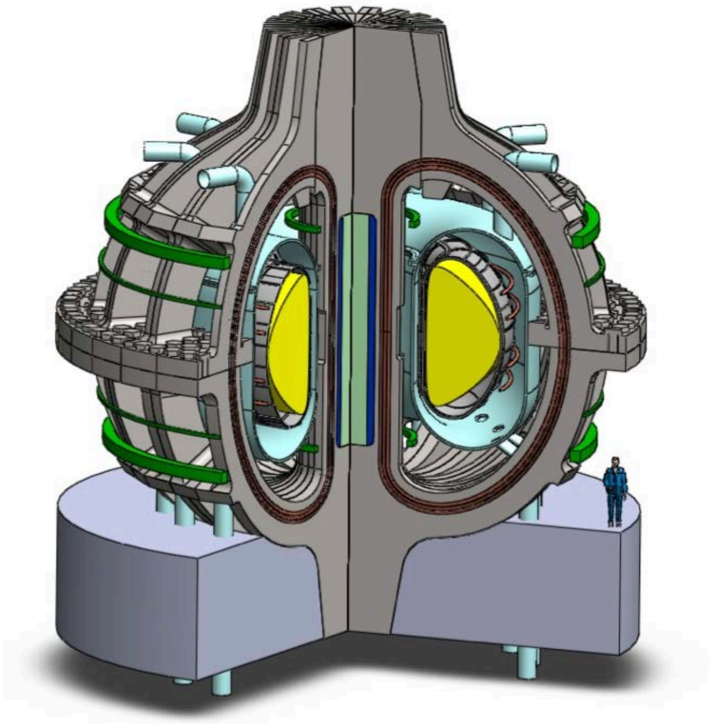
- ***New*** YBCO higher-field superconductor magnets
- ***New*** demountable design for easy maintenance
- ***New*** radio wave launcher for efficient current drive
- ***New*** “super divertor” to radiate escaping particle flux
- ***New*** molten-salt Li breeding blanket

$$a \times B \approx I_p \approx \text{constant}$$

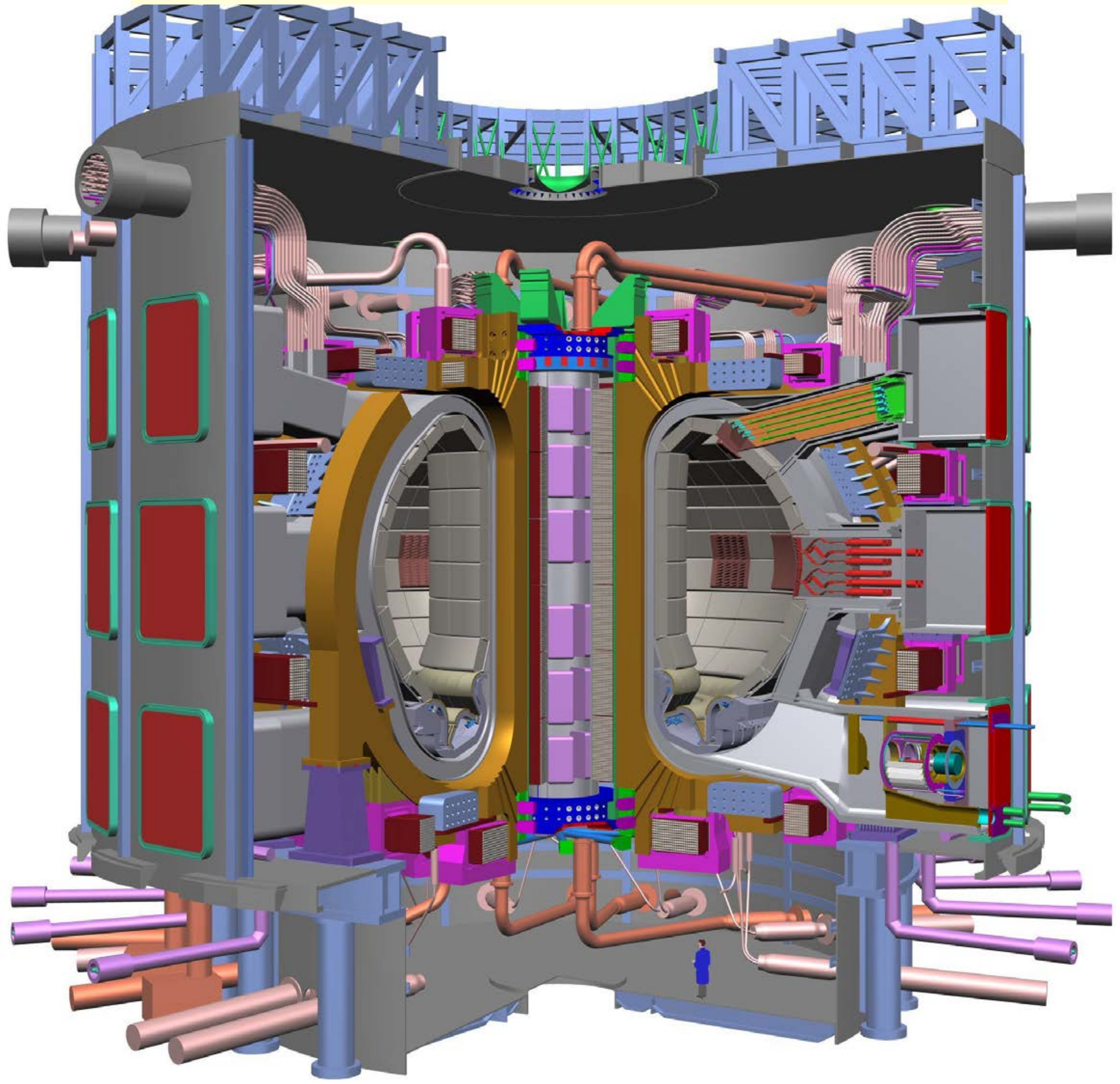


MIT's Brandon Sorbom holds REBCO superconducting tapes (left), which are the enabling technology behind the ARC reactor (*Credit: MIT ARC team*)

Fusion power: 500 MW
Q > 10
B = 9.2 T

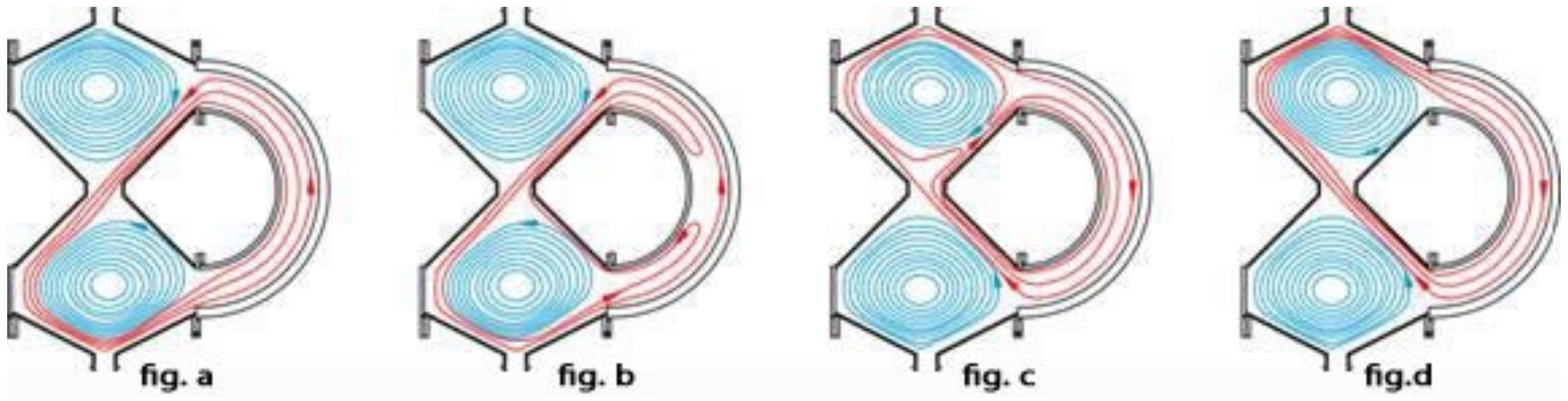


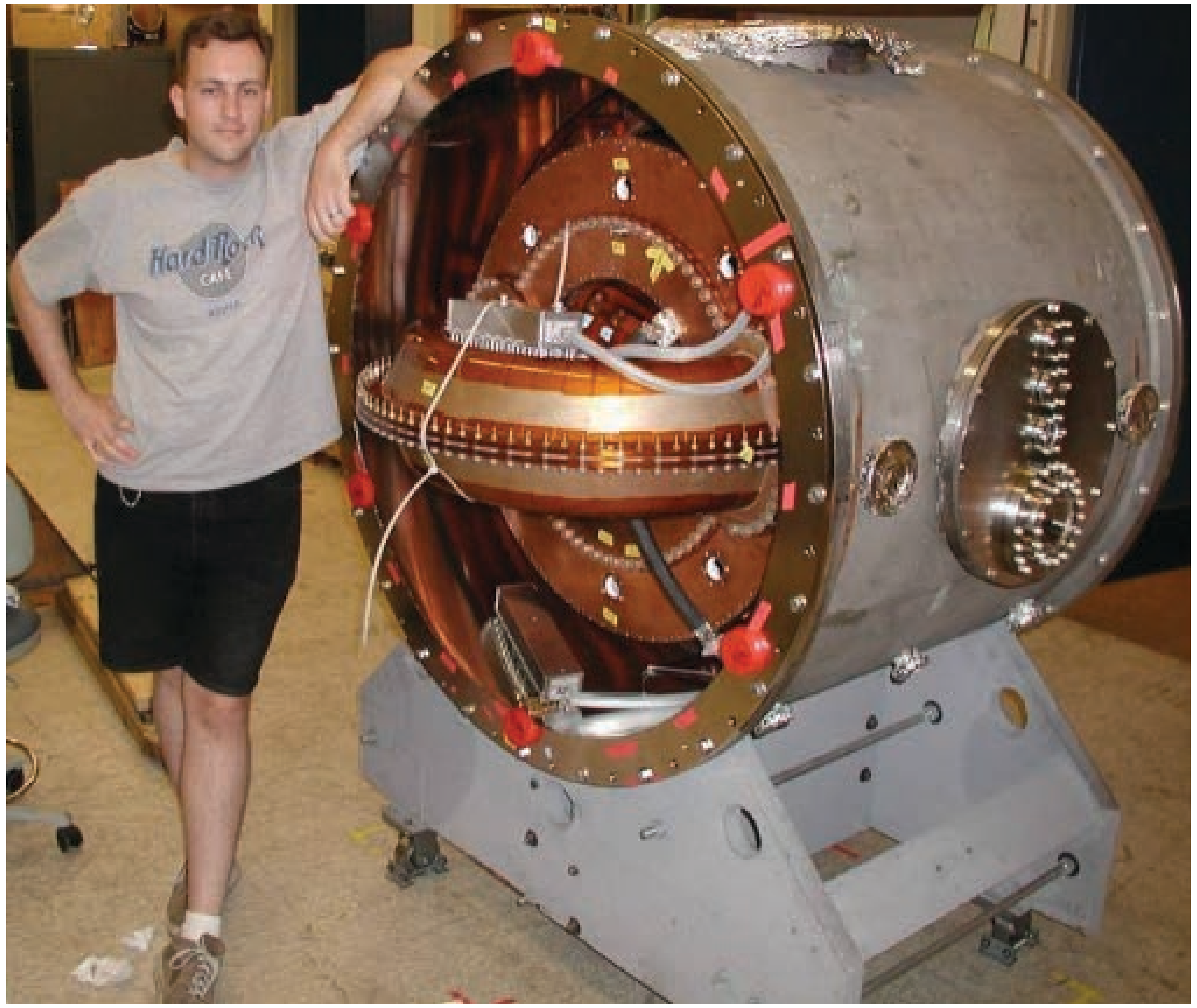
Fusion power: 500 MW
Q = 10
B= 5.3 T

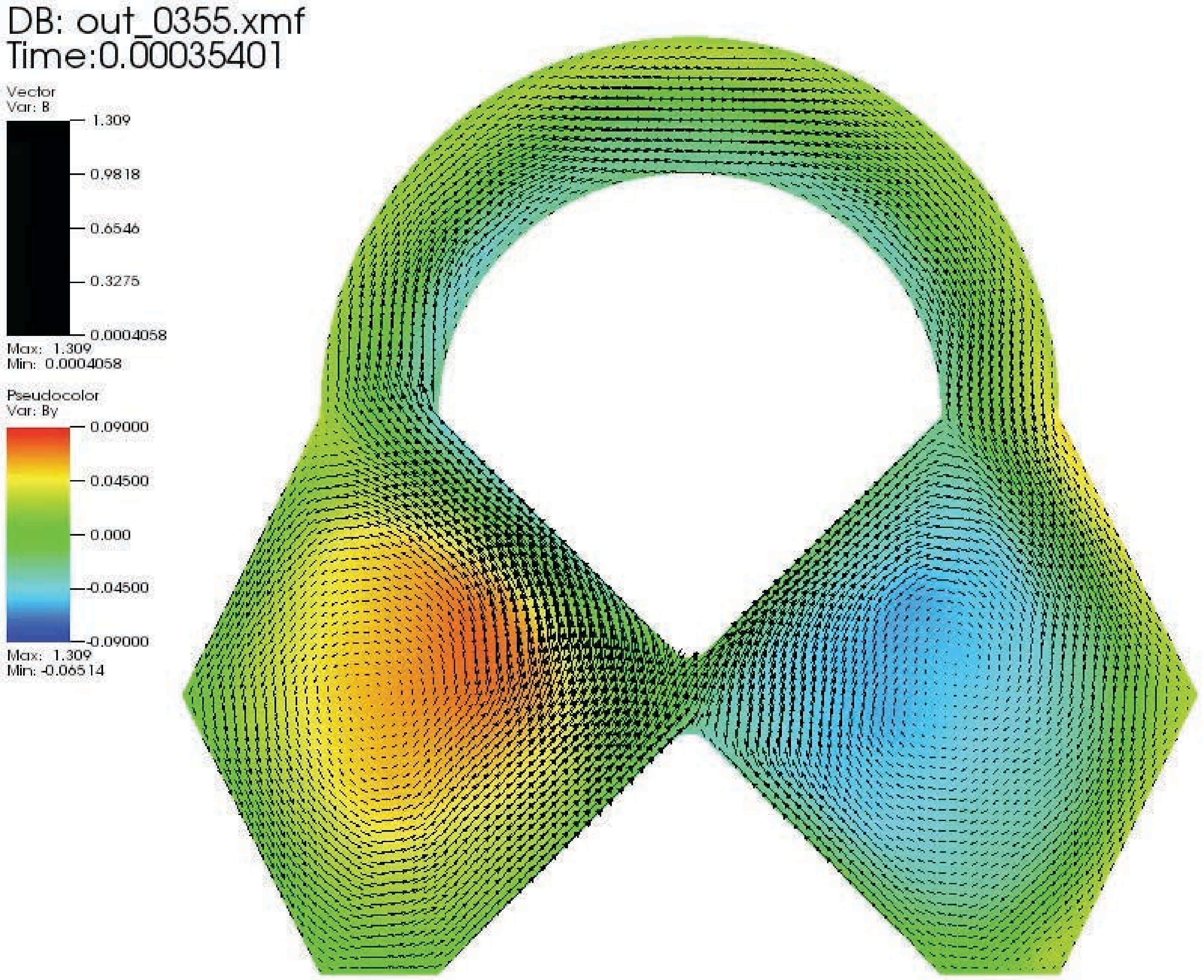


(University of Washington)

(2) Helically-Driven Spheromak







Jarboe, *et al.*, *Fus. Sci. and Tech.*, **66**, 369 (2014)

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D-T Fusion's Materials Challenge

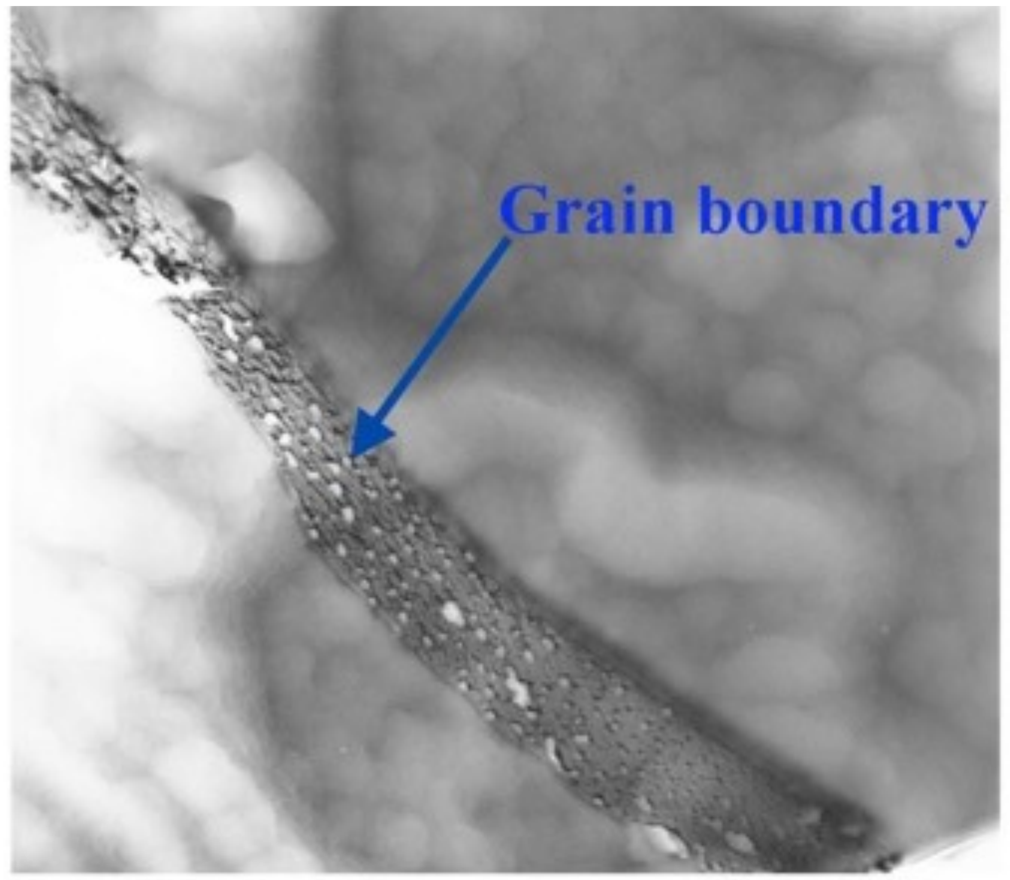
- (**Good news!**) When fabricated from low activation materials, fusion will **not** produce long-lived radioactive by-products.
- Fusion's materials challenge is to develop long-life, high-strength materials with high neutron-irradiated fracture toughness, good helium swelling resistance, and low tritium retention.
- Options exist (but much research required): Ferritic/martensitic steels, Vanadium alloys, Tungsten first wall, SiC/SiC composites, new nano-engineered materials, …

D-T Fusion's Materials Challenge

Swelling

"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**."



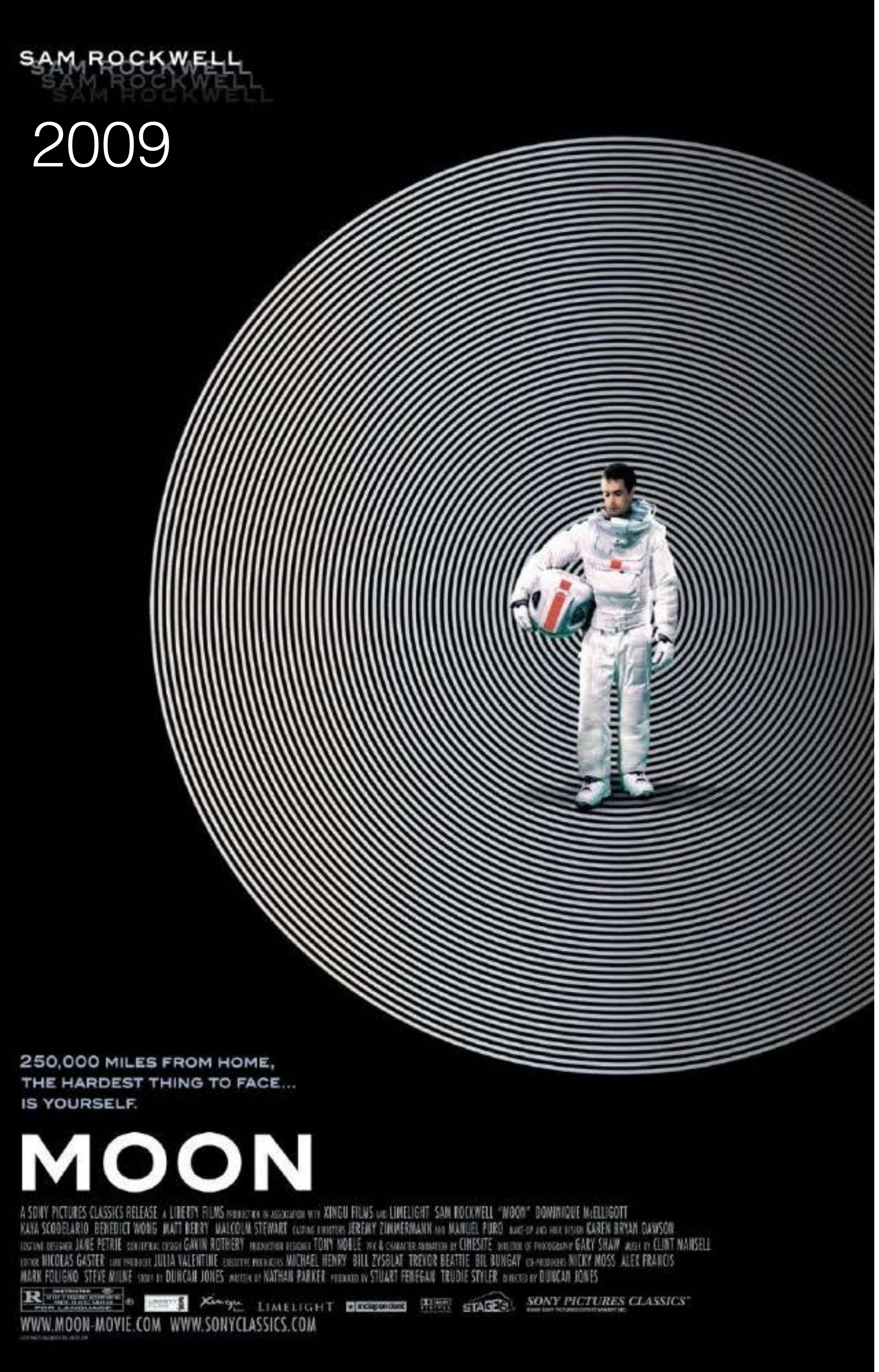
Advanced materials for fusion technology

Steven J. Zinkle

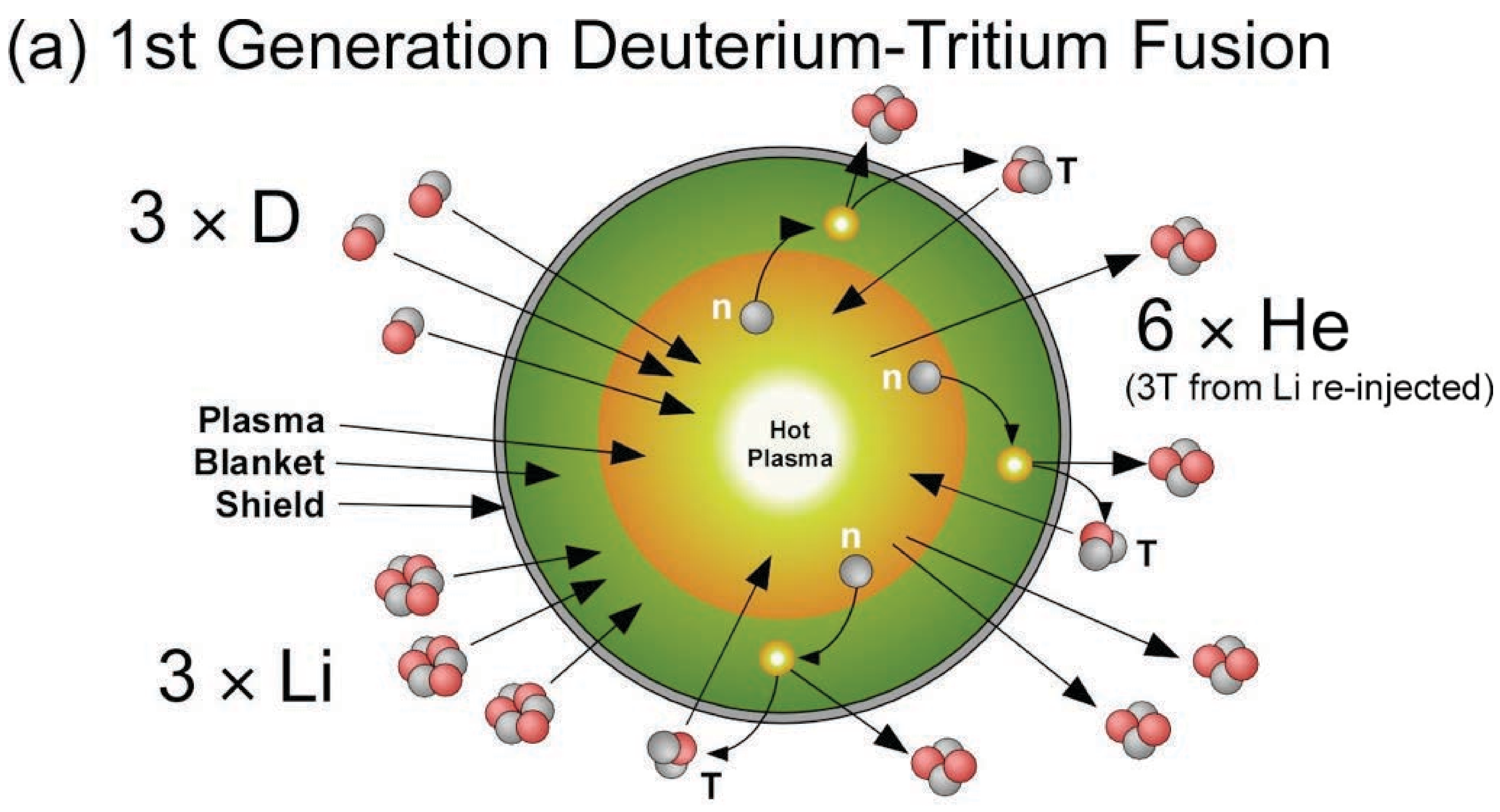
Fusion Engineering and Design, **74** (2005) p. 31-40

Mining for Fusion Fuel: ^{3}He

2009

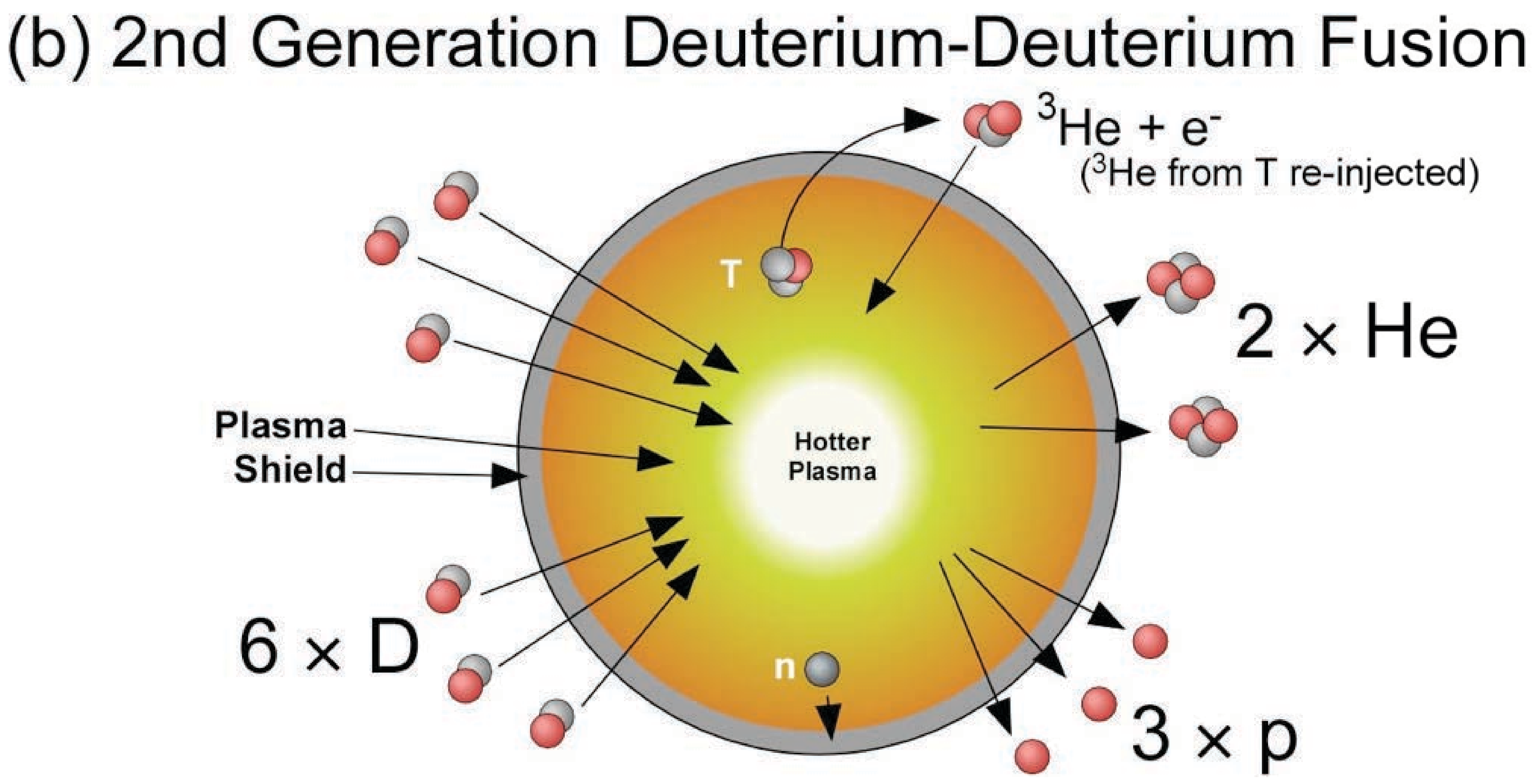


Two Pathways to Fusion Power



Problem: Fast Neutrons

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

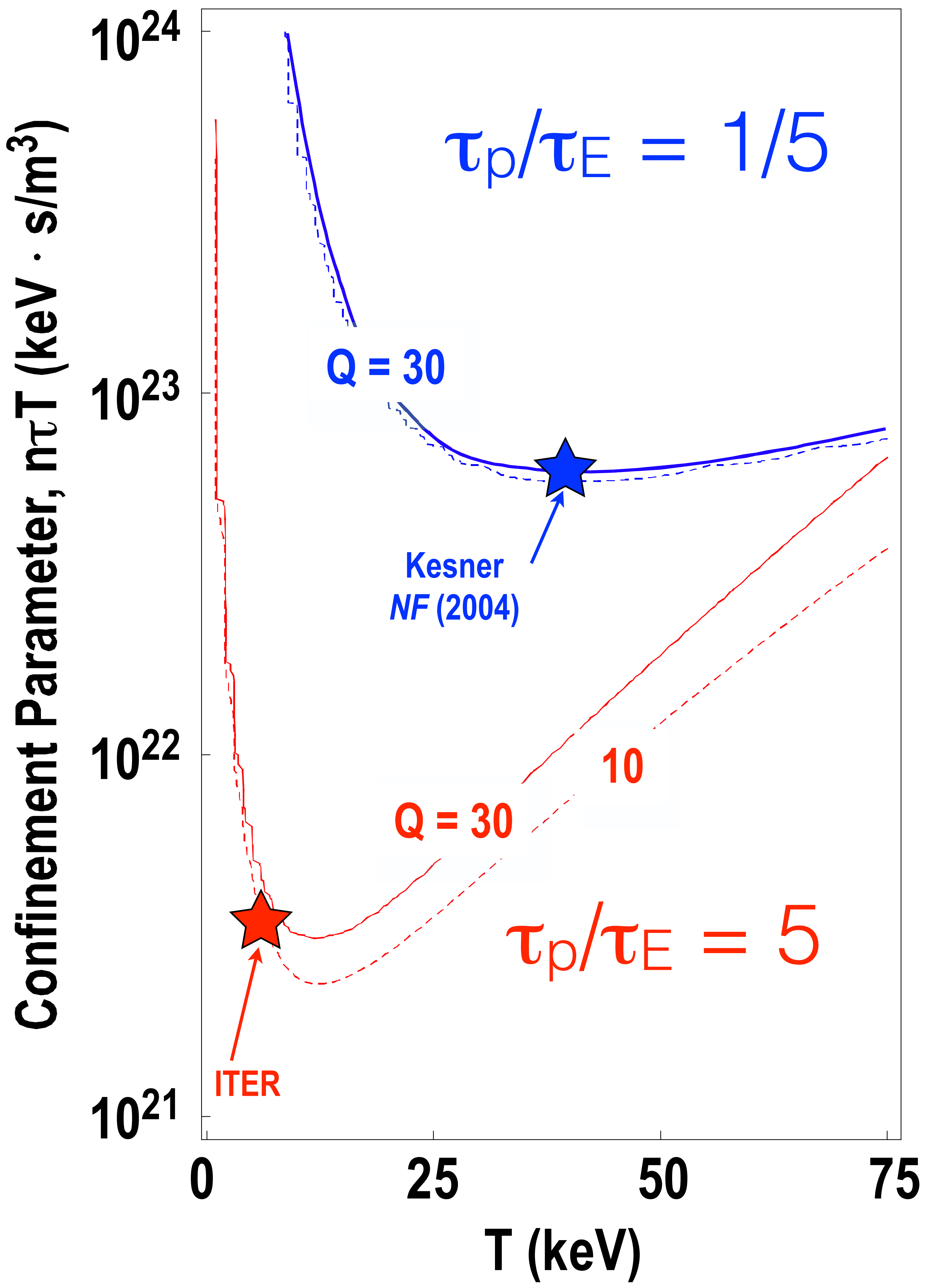


Problem: High plasma confinement

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

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

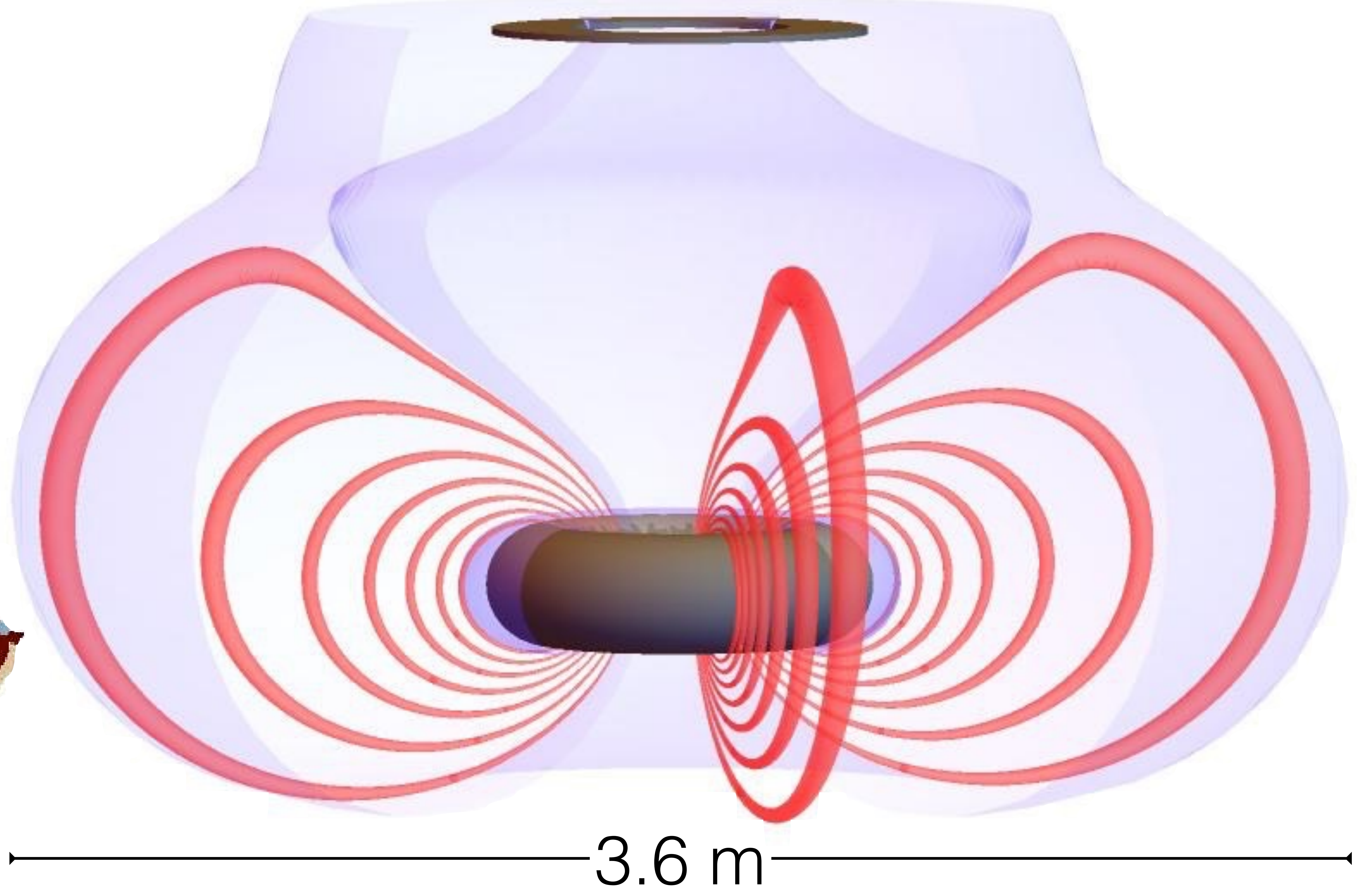
- Sheffield, Zinkle, Sawan (2002-06)
- No tritium breeding blankets
- No 14 MeV neutrons
- No structural materials problem
- Requires $\tau_p/\tau_E < 1$
- Requires 35 keV and *much higher plasma pressure*
- Requires 10 fold confinement improvement
- Requires stronger, higher-field superconducting magnets



Current Ring Traps: Designed for Maximum Flux Tube Expansion

a.k.a. "Laboratory Magnetospheres"

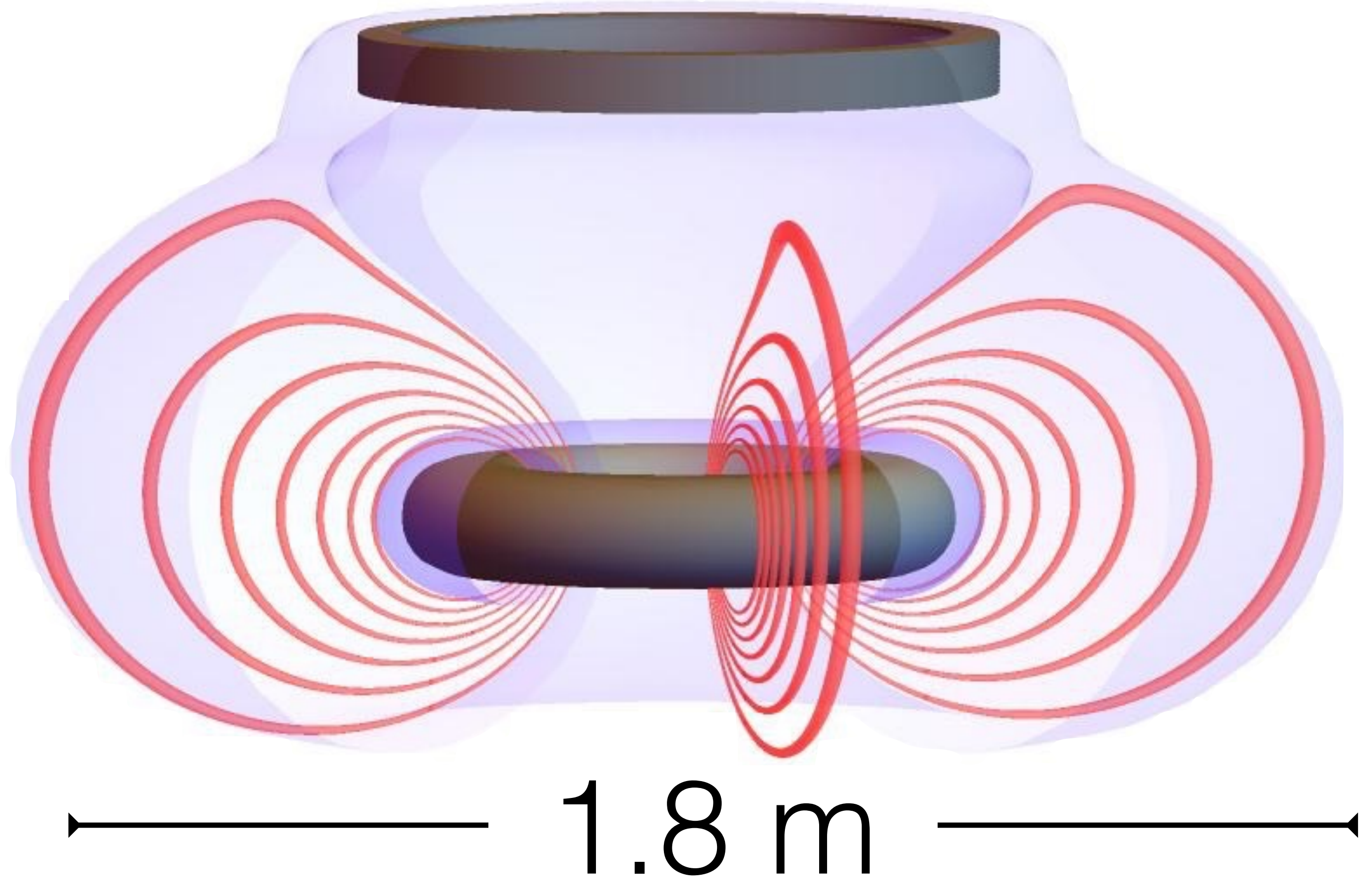
$$V = \int \frac{dl}{B} \propto L^4$$



Levitated Dipole Experiment (LDX)

Flux Tube Expansion:

δV(out)/δV(in) = 100

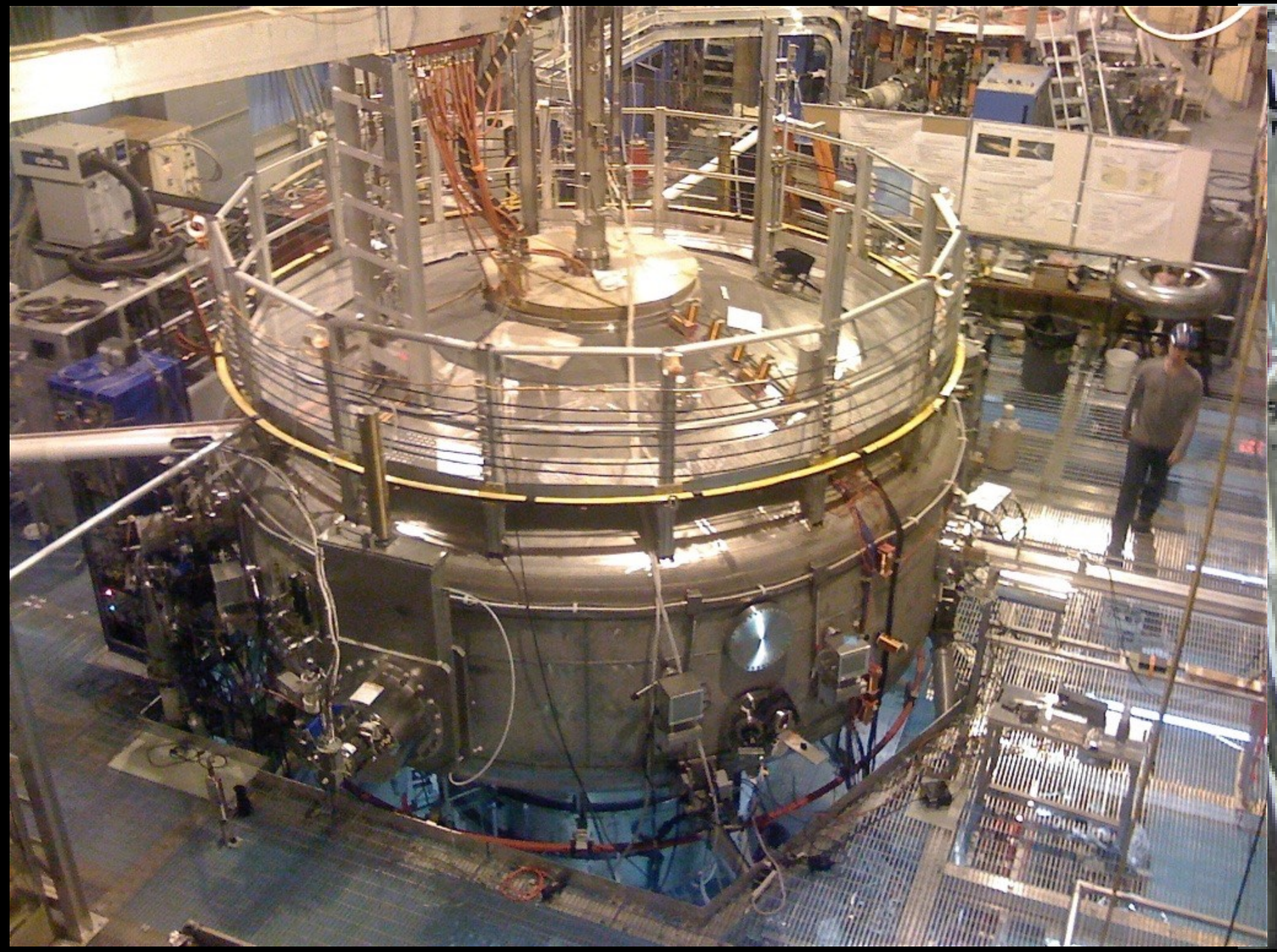


Ring Trap 1 (RT-1)

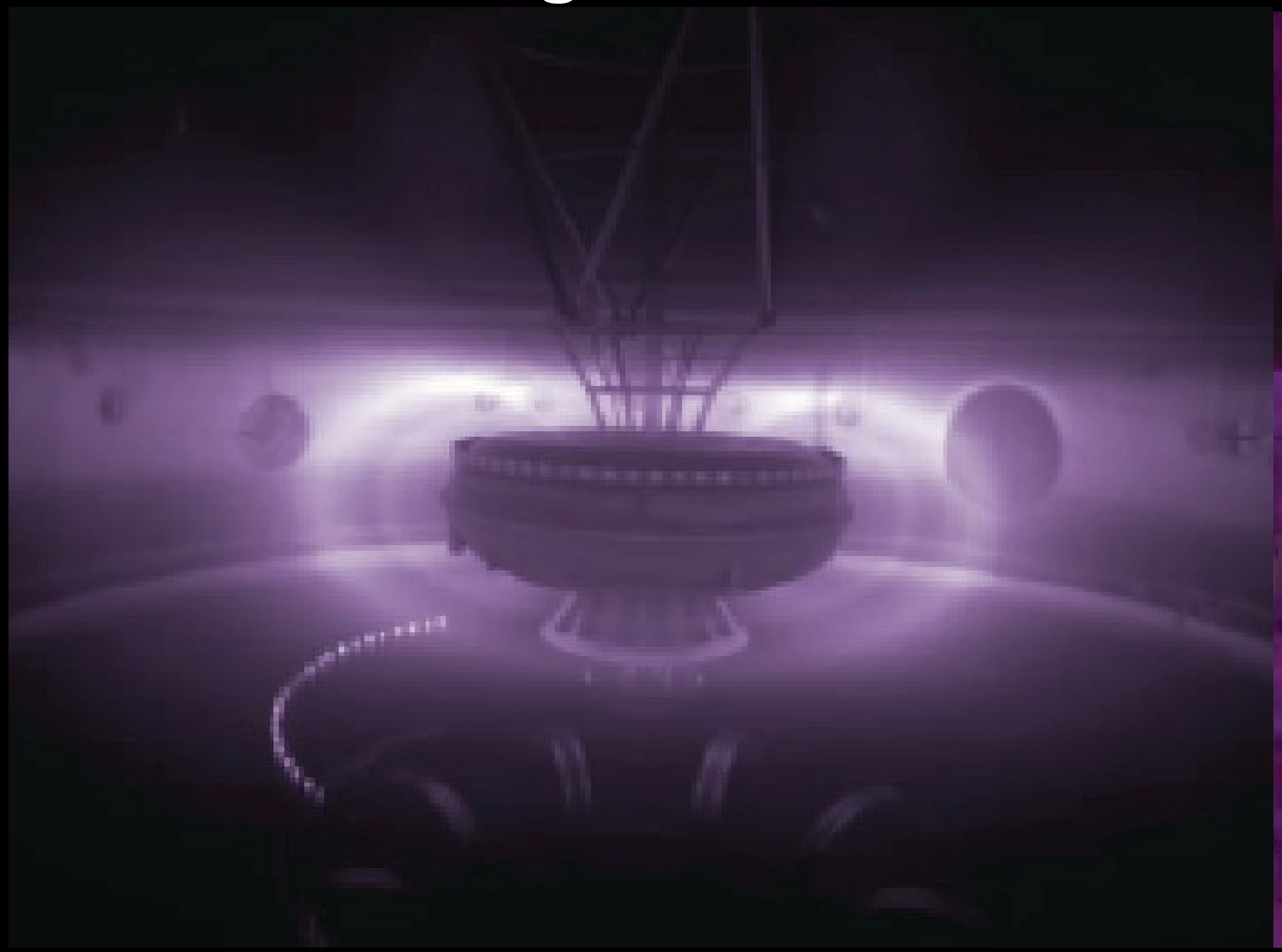
Flux Tube Expansion:

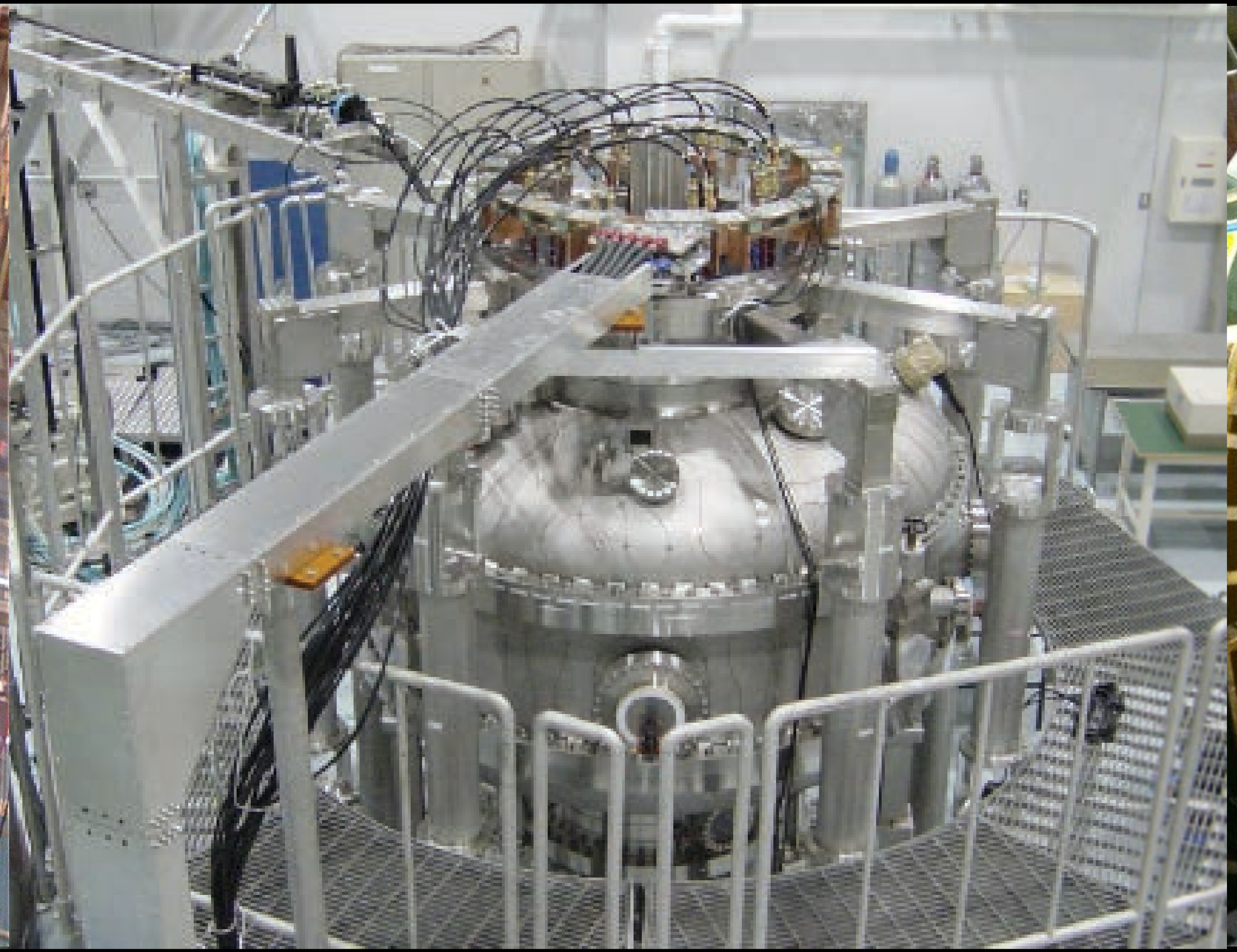
δV(out)/δV(in) = 40

“Laboratory Magnetospheres”
Facilities Connecting Space and Laboratory Plasma Physics

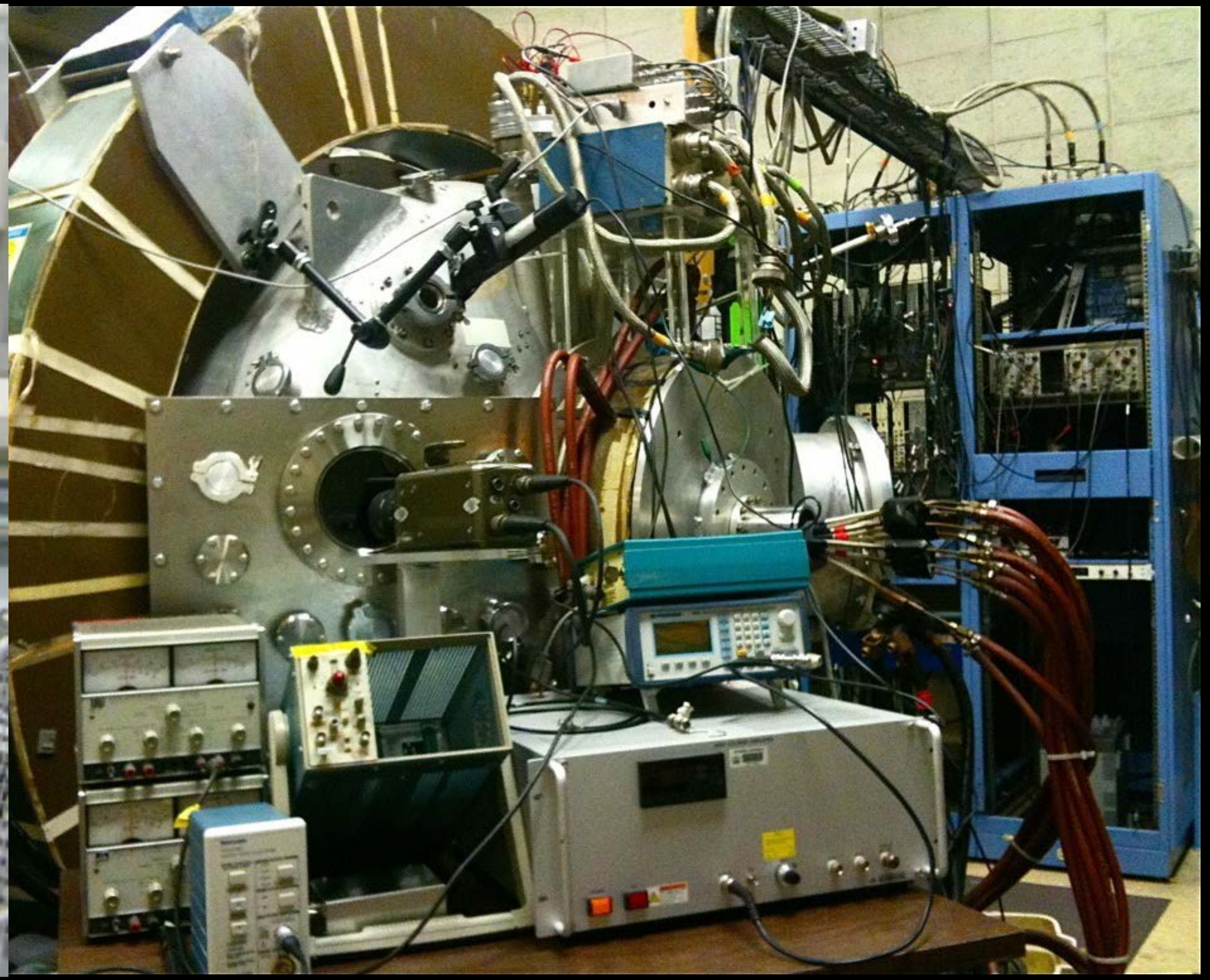


LDX (MIT)
Largest Size

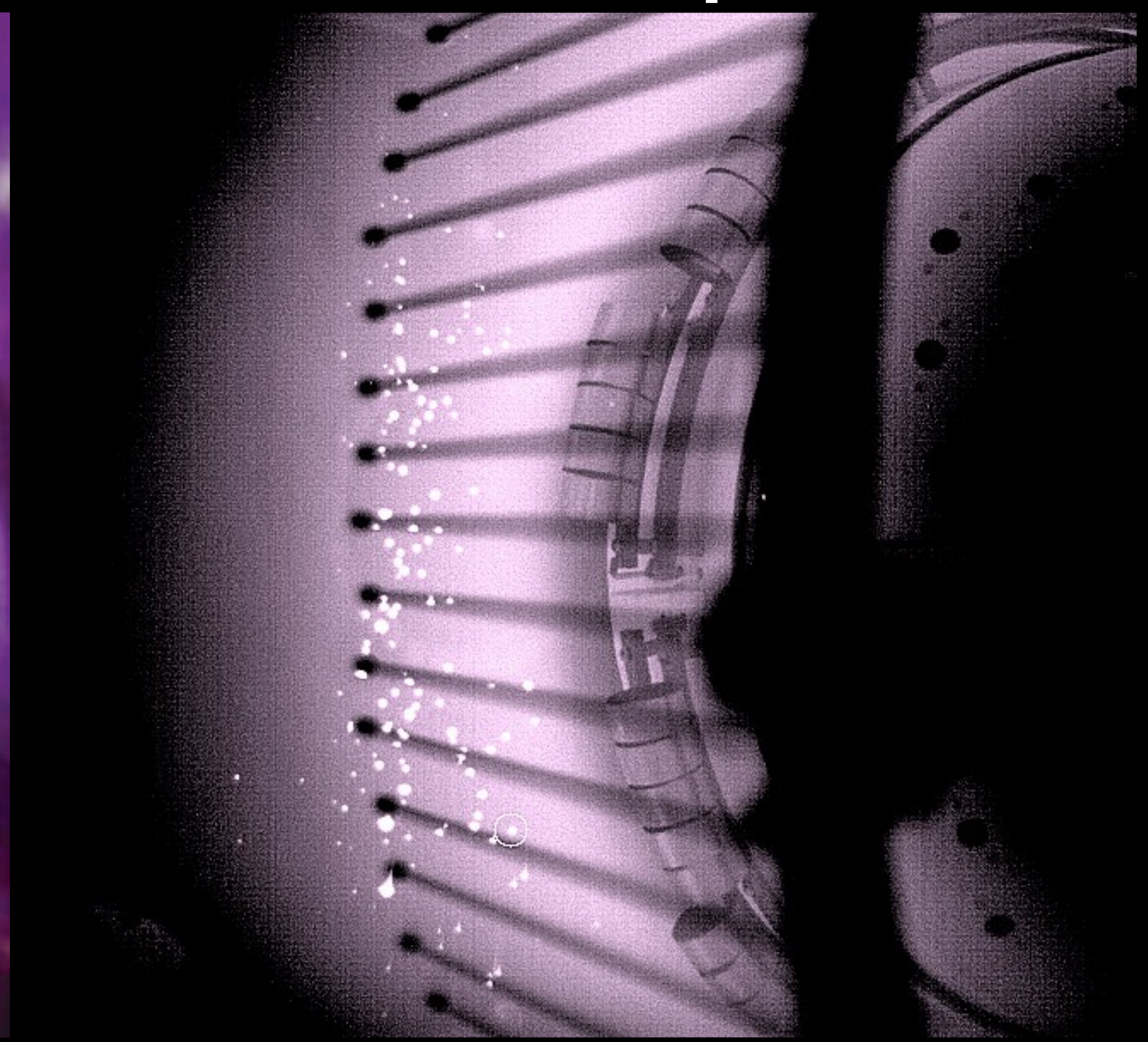




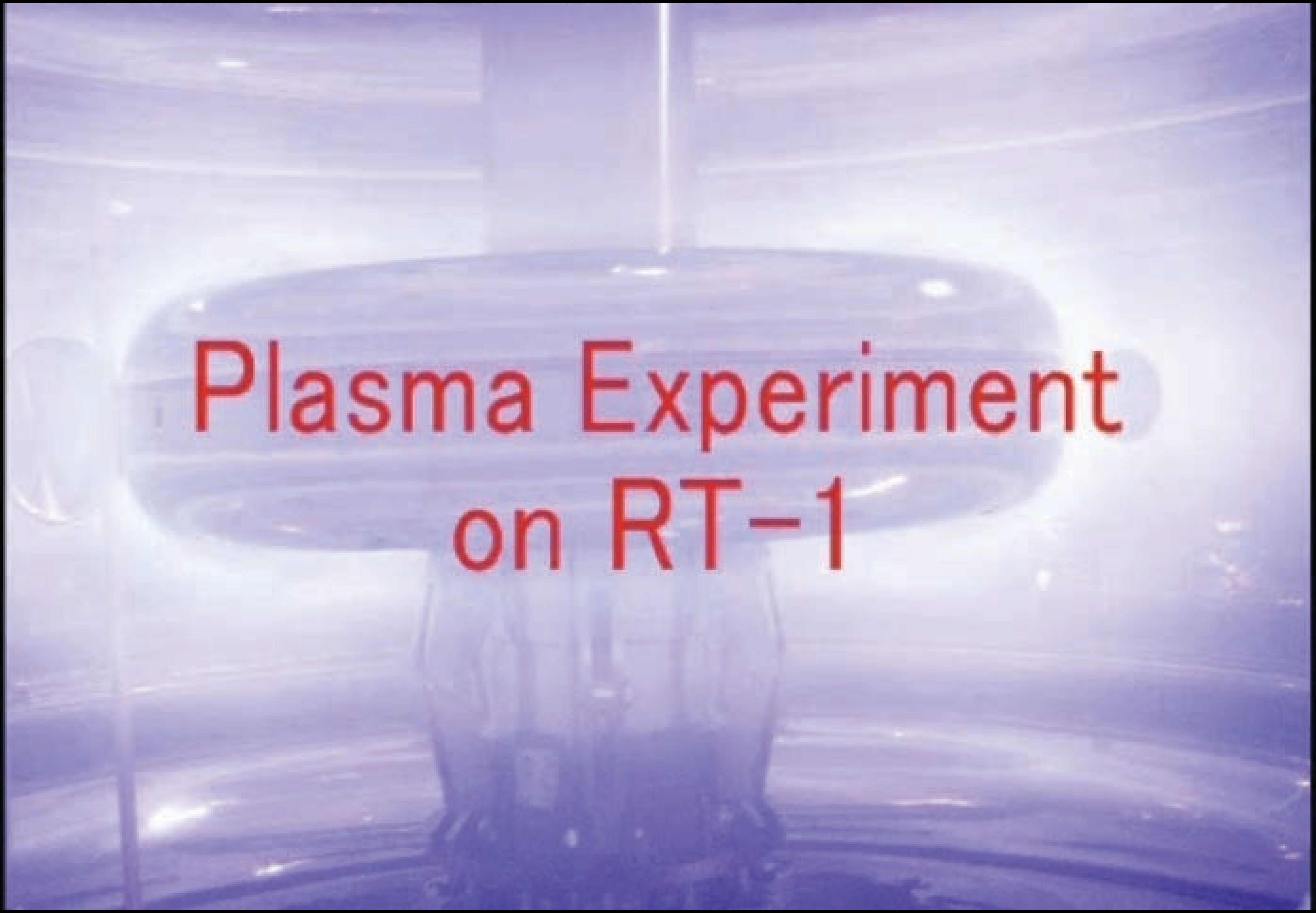
RT-1 (U Tokyo)
Highest Power and β



CTX (Columbia)
Easiest to Operate

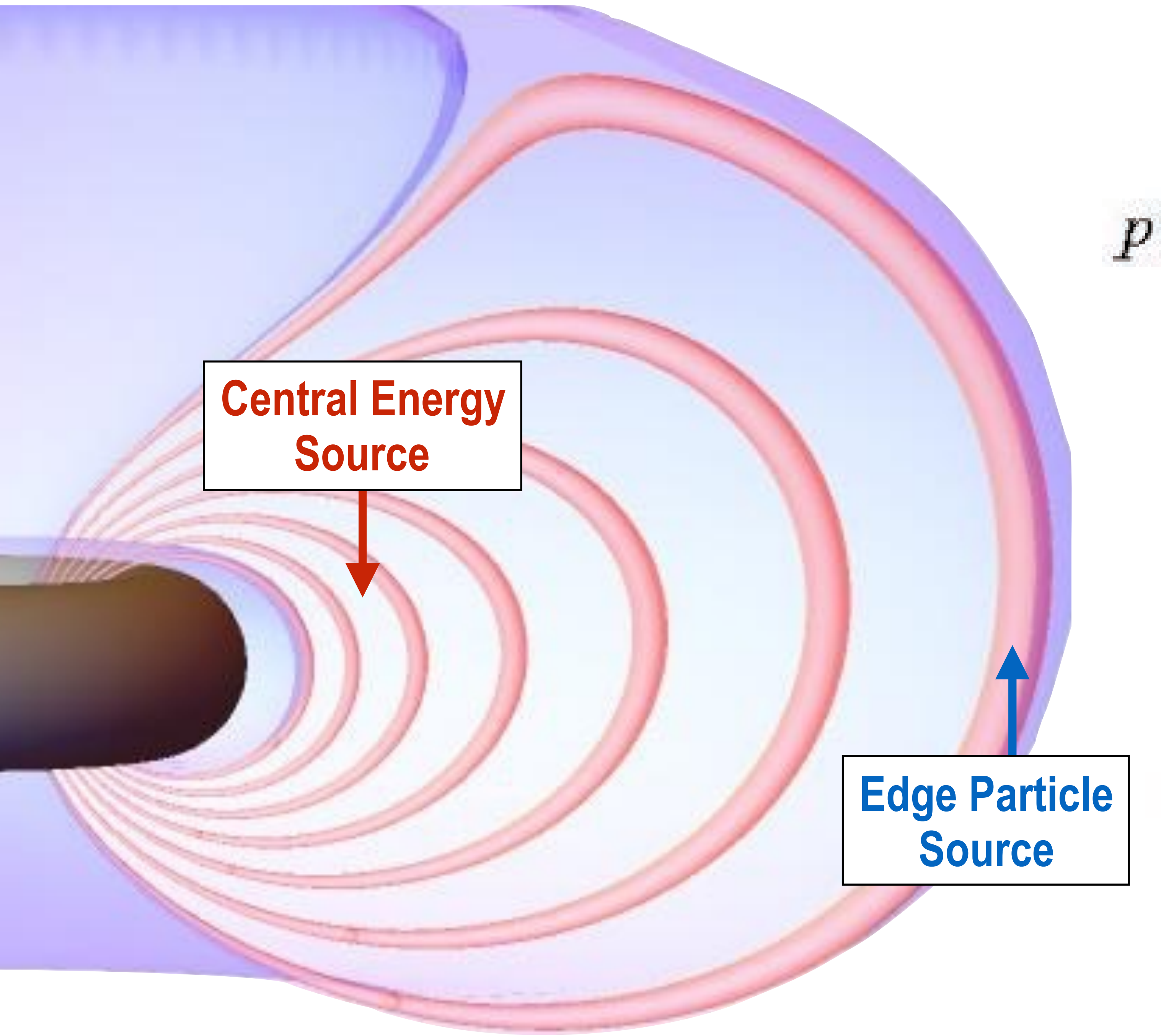


Launching/Catching Superconducting Ring



Solar wind drives radial diffusion in planetary magnetospheres, *but in the lab*…

Central heating excites instability that drives Centrally-Peaked Pressure and Density as the Final State of Turbulent Self-Organization



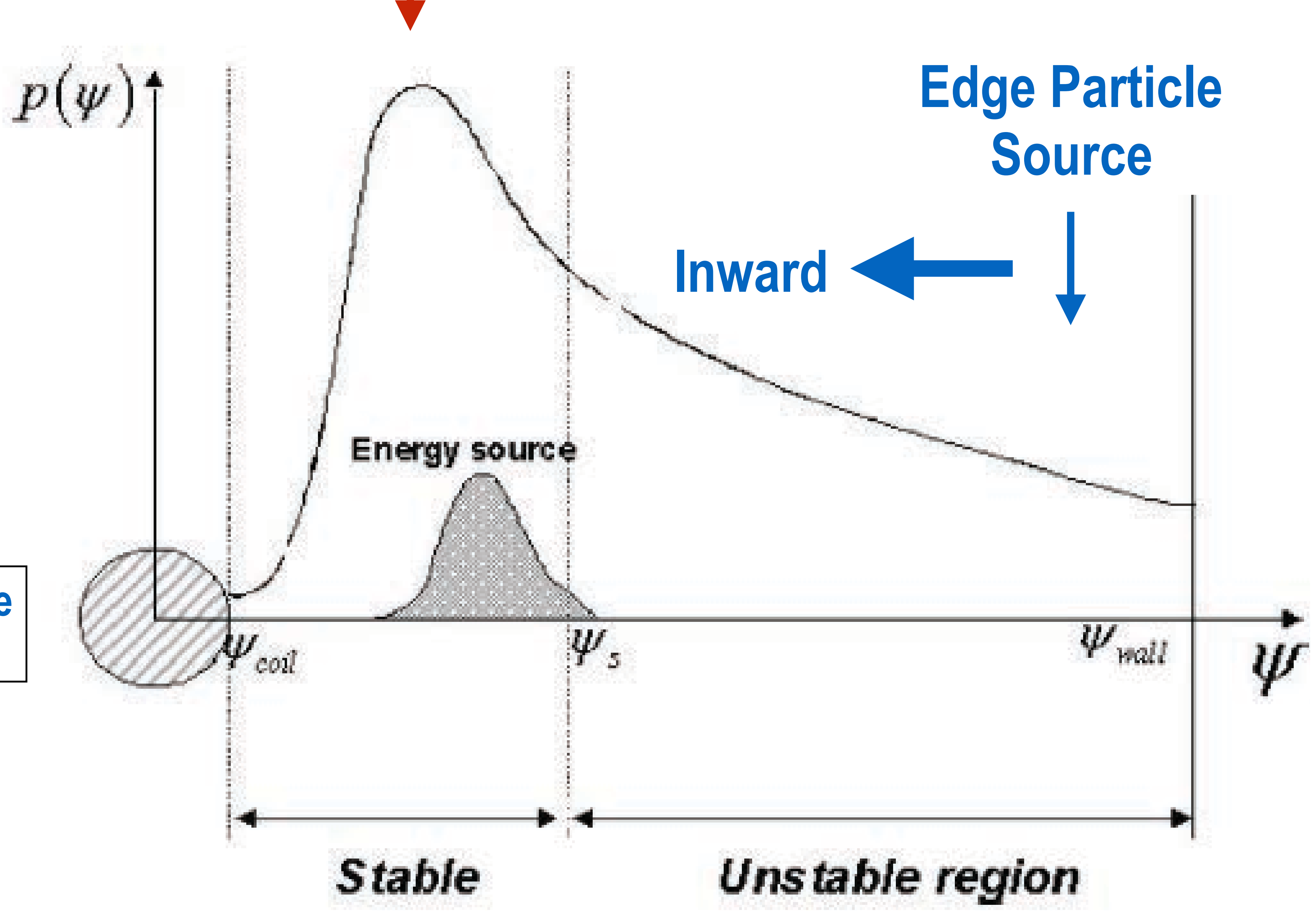


FIG. 1. The LDX schematic profile.

Quasilinear MHD Interchange Turbulence

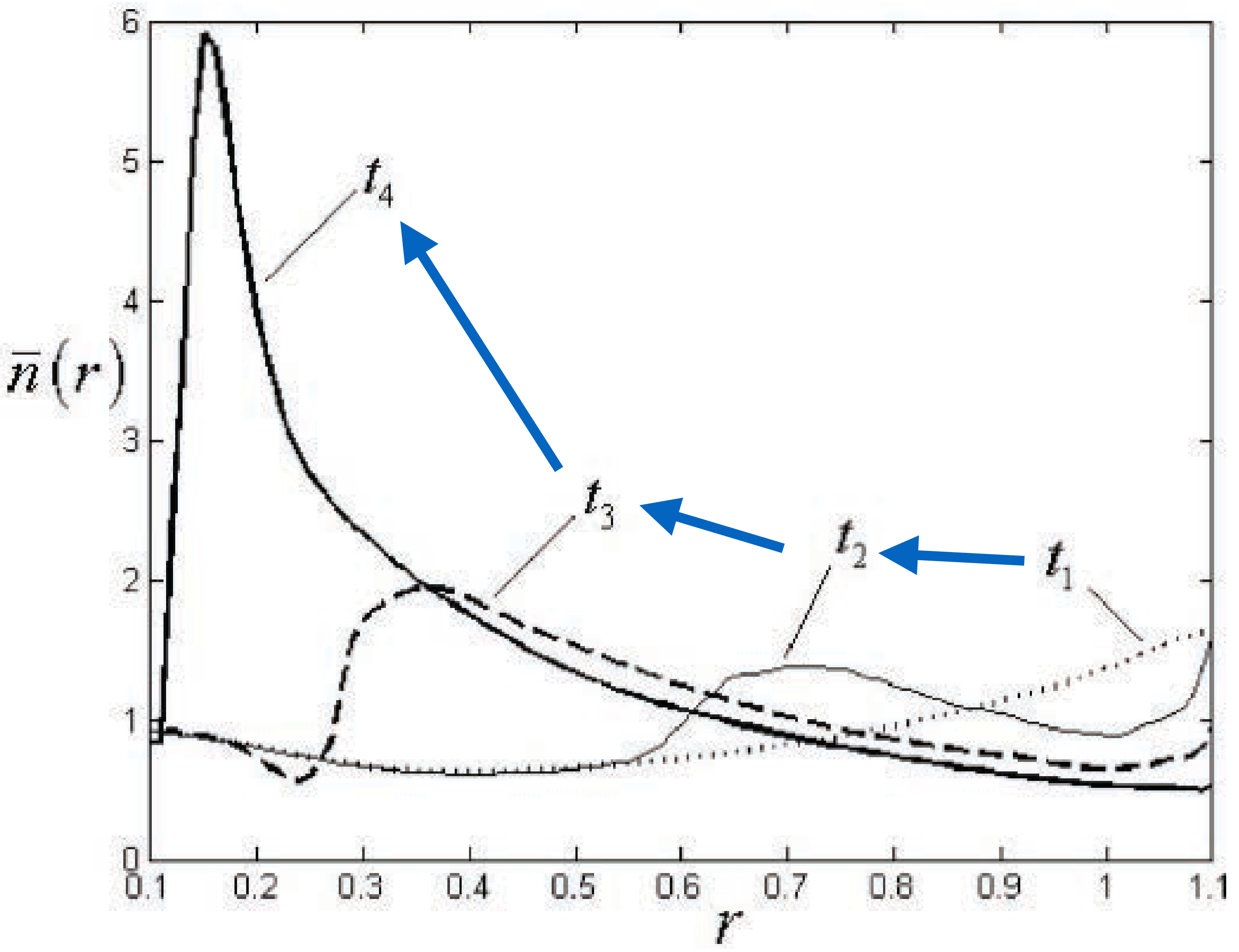


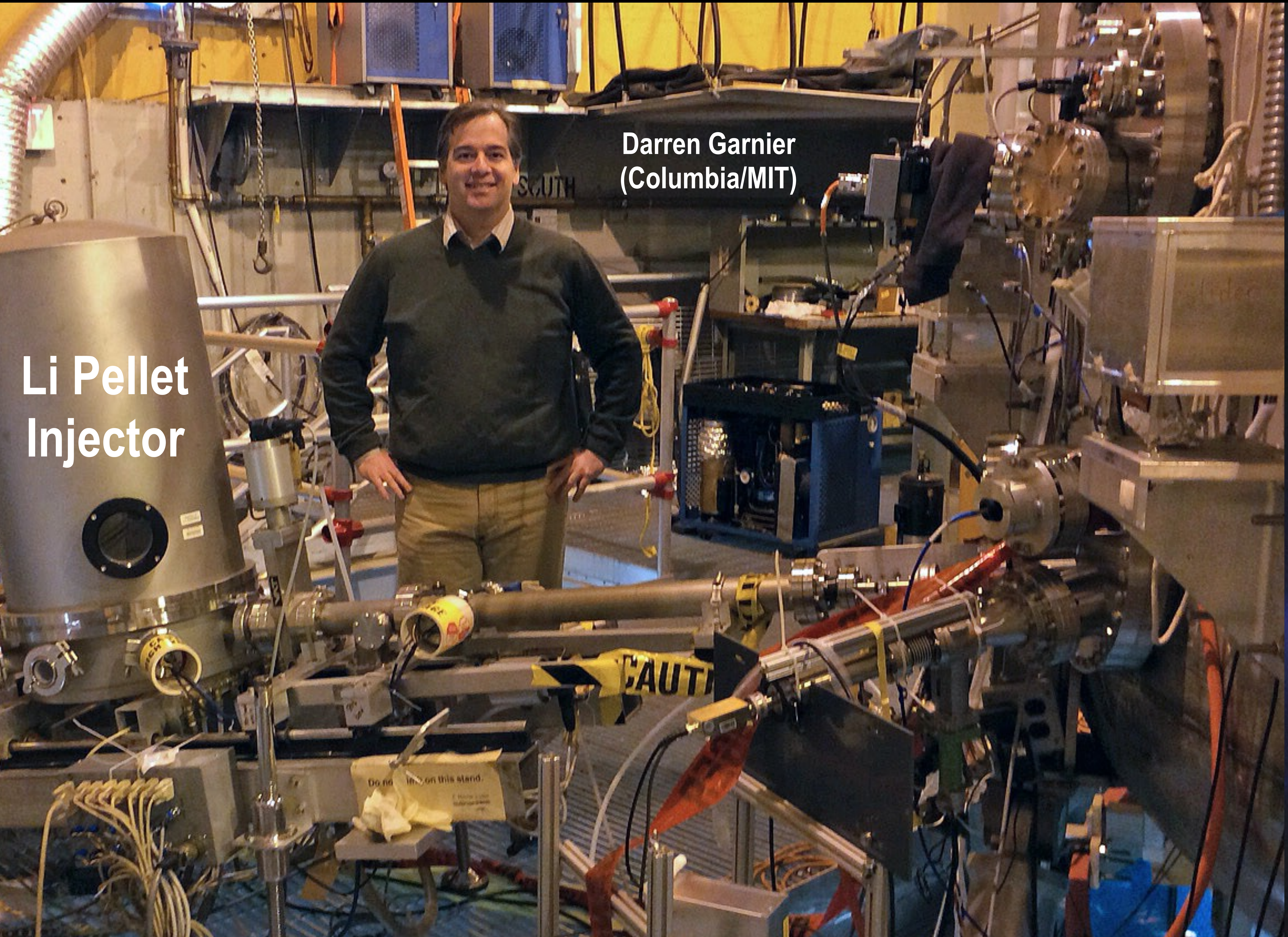
FIG. 5. The snapshots of the "self-organizations" process. Time t_1: before an instability is excited; t_2-t_4: different stages of self-organization.

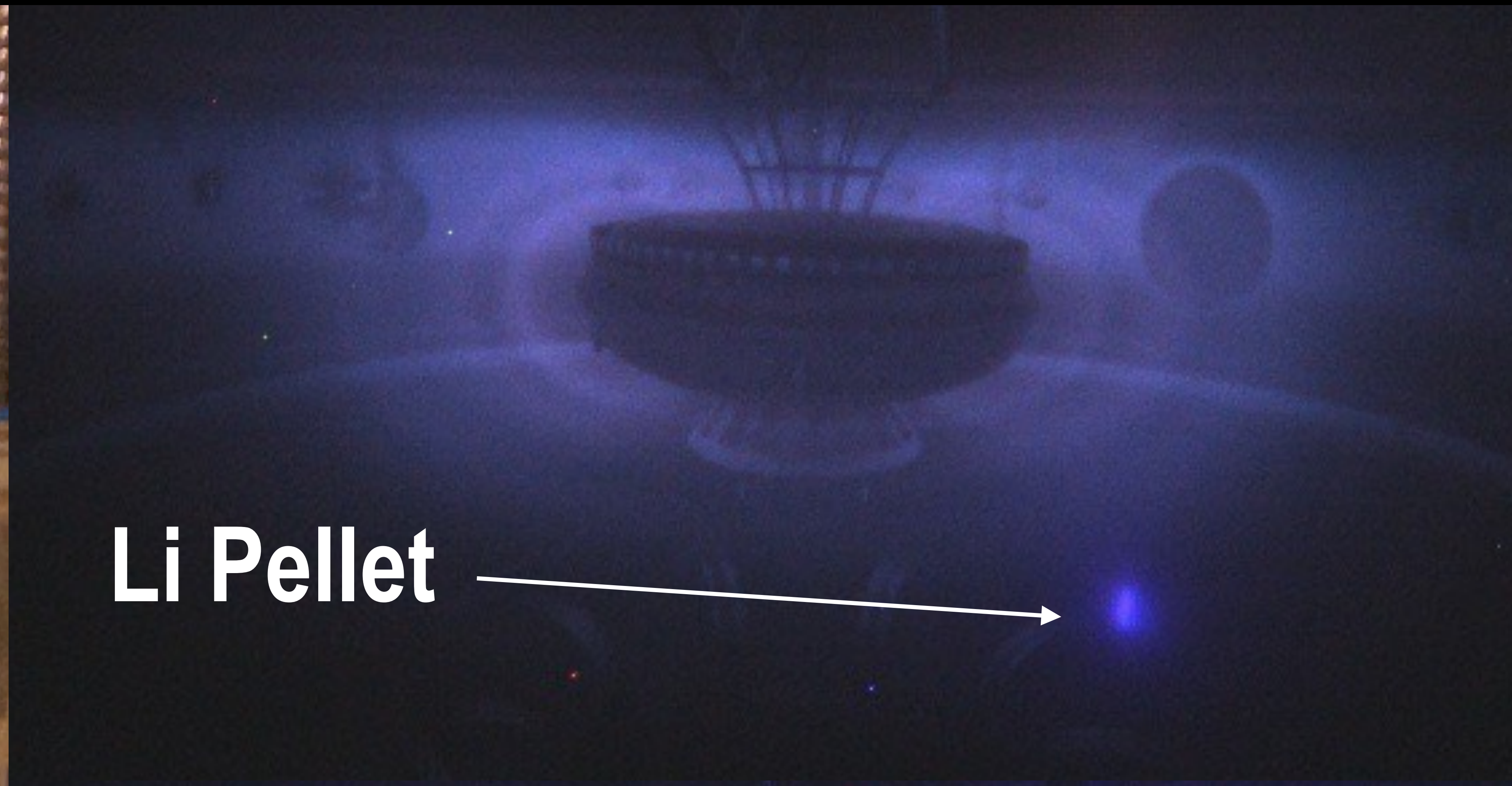
Alexie Kouznetsov (PhD MIT/Freidberg), *et al*, "Quasilinear theory of interchange modes in a closed field line configuration," *Phys Plasmas*, **14**, 102501 (2007)

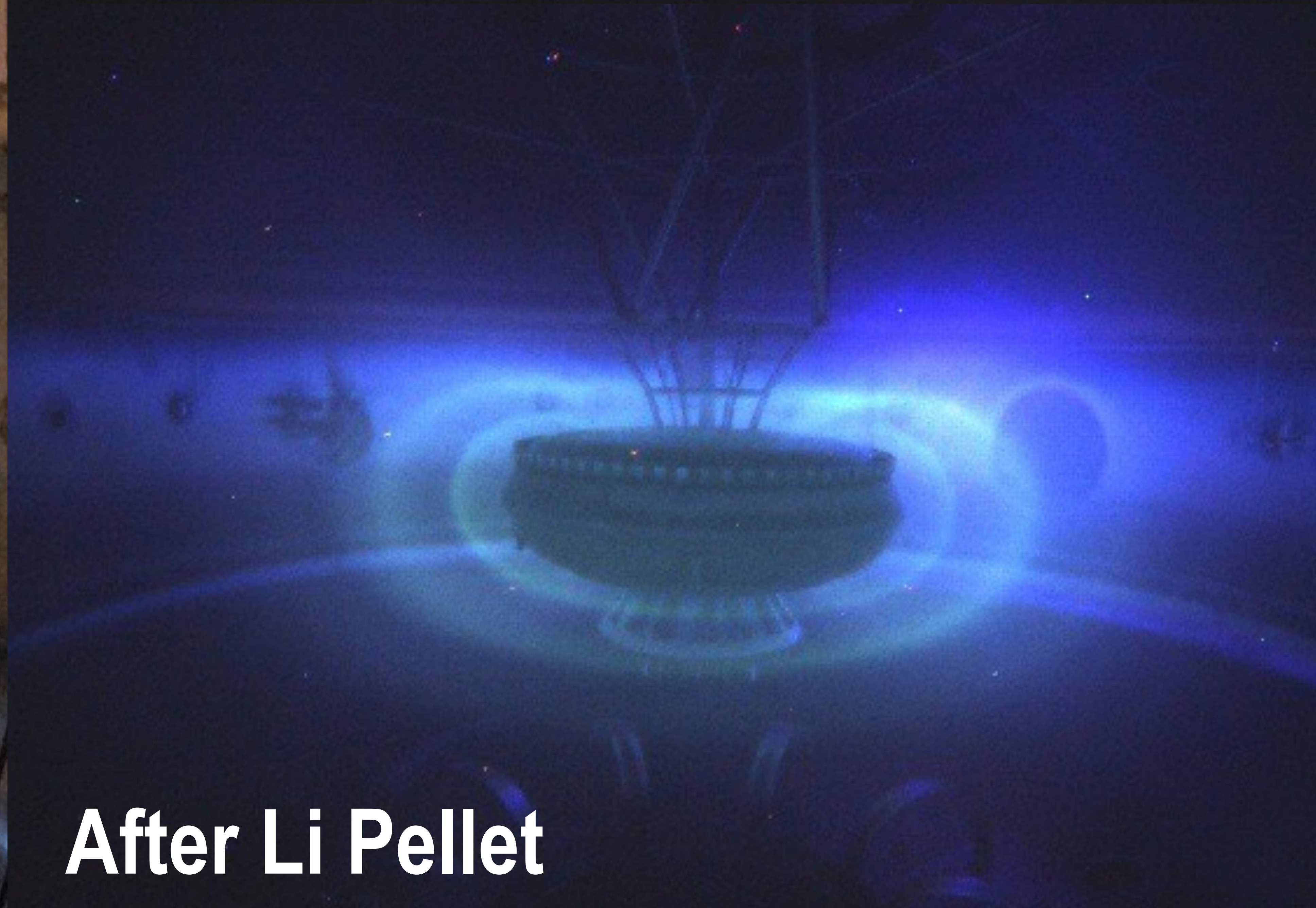
John Tonge (PhD UCLA/Dawson), *et al.*, "Kinetic simulations of the stability of a plasma confined by the magnetic field of a current rod," *Phys Plasmas* **10**, 3475 (2003).

Self-Organized Mixing: Dye Stirred in Glass

High Speed Pellet Injection Cools Core & Creates Internal Fueling and *Reverses* the Direction of Particle Diffusion

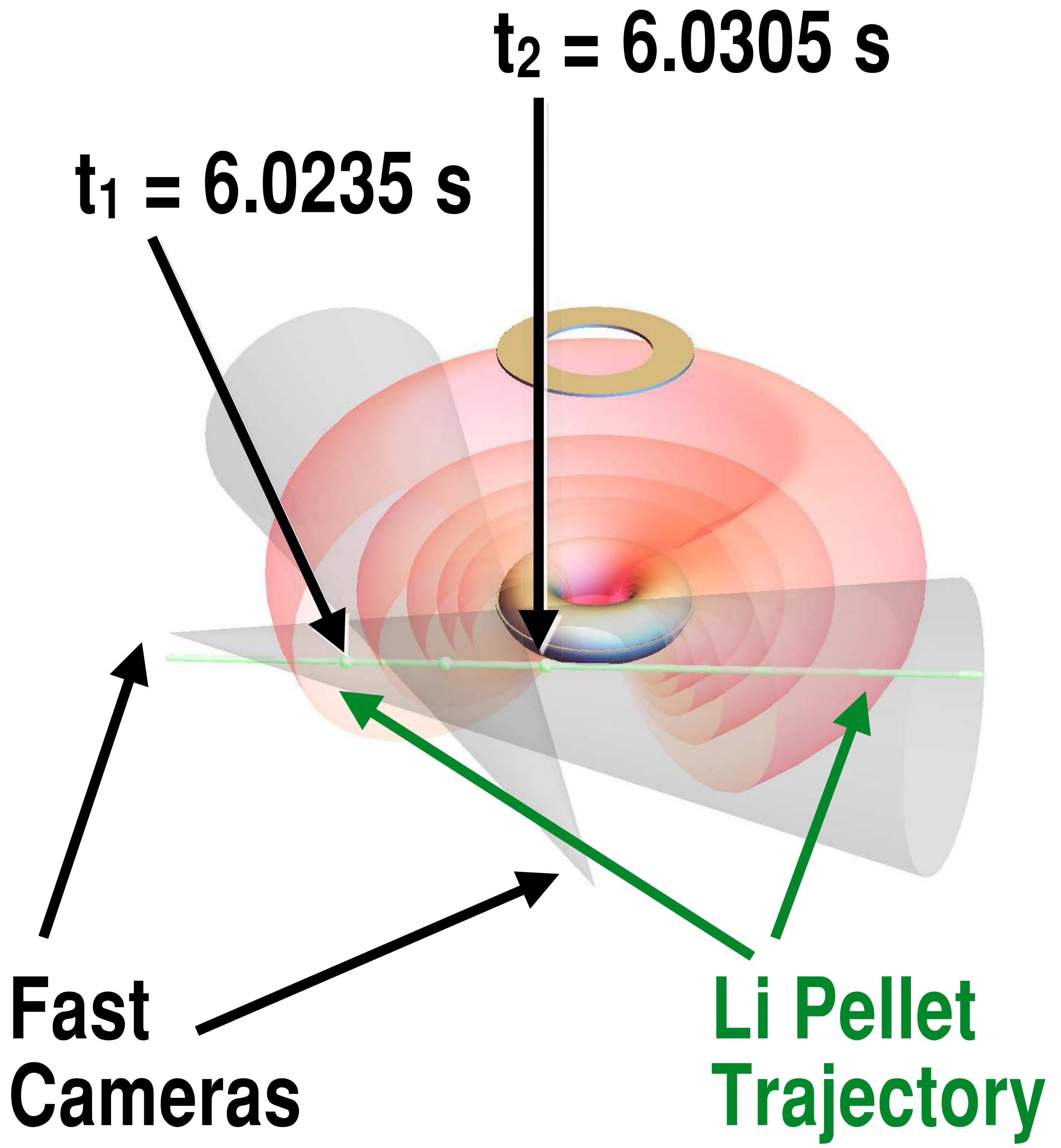




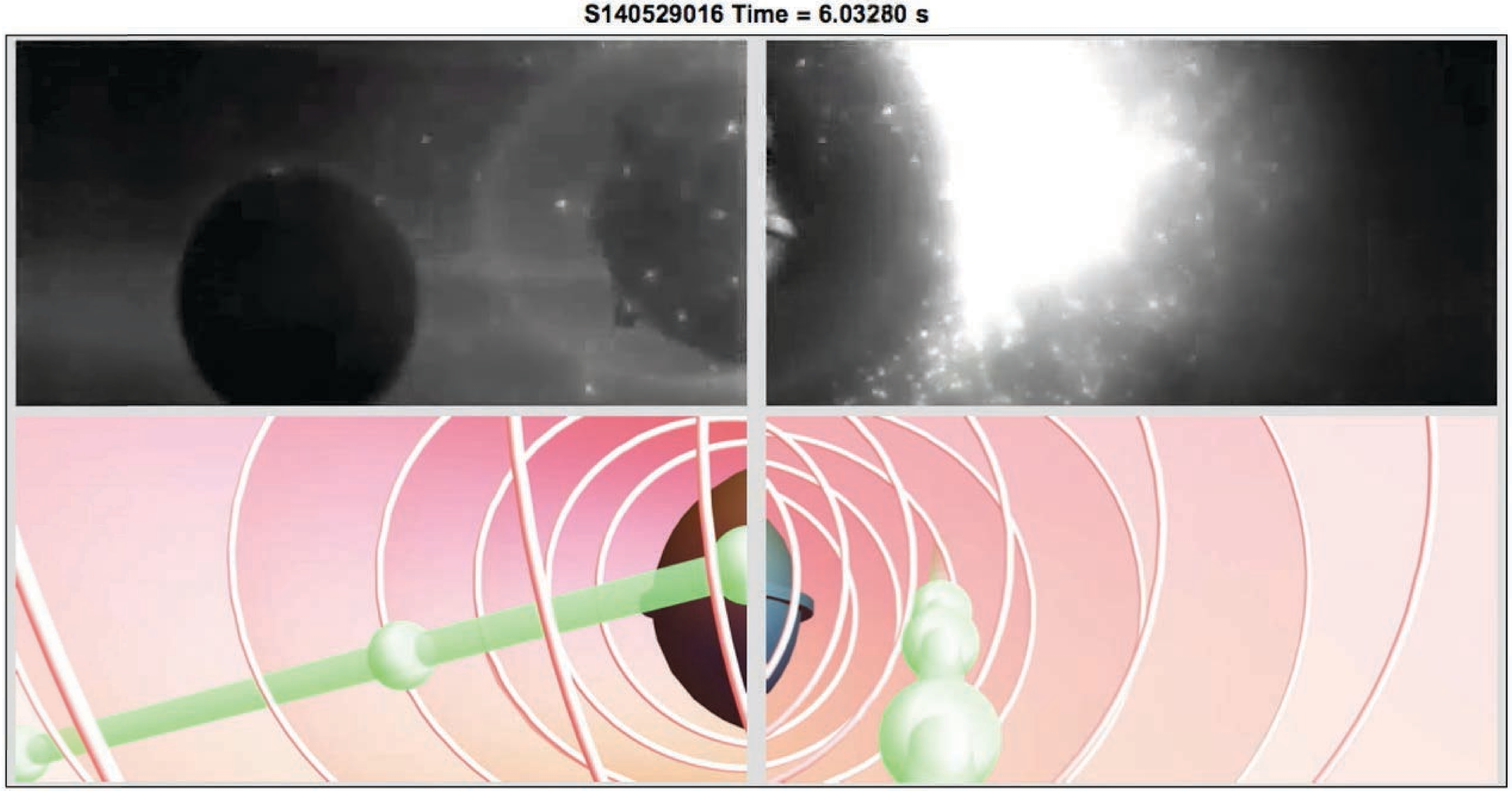


Li Pellet Injection Provides Internal Particle Source and Cools Plasma Core

1 mm^3



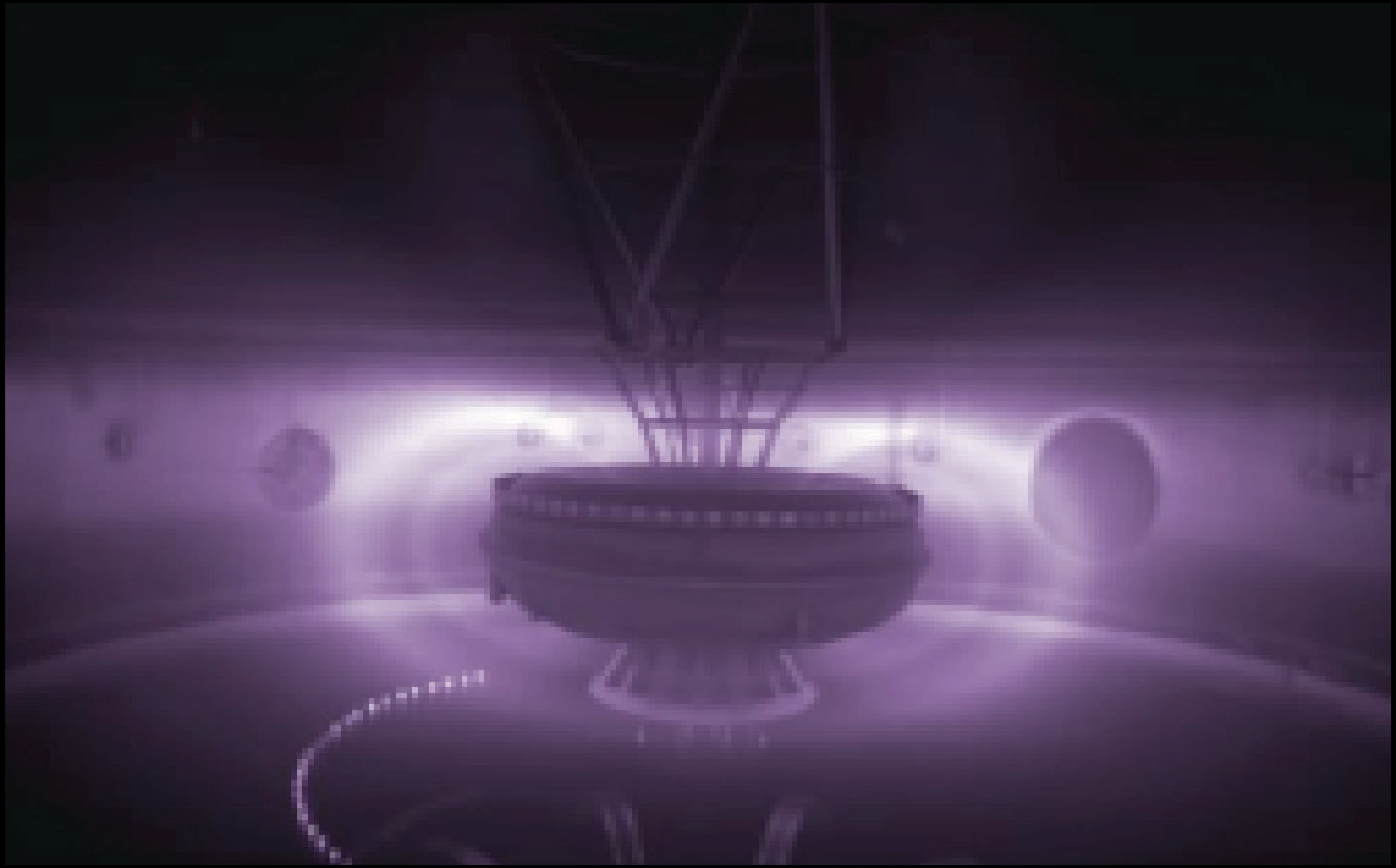
×5 Peak Density
×3 Electrons
÷3 Energy

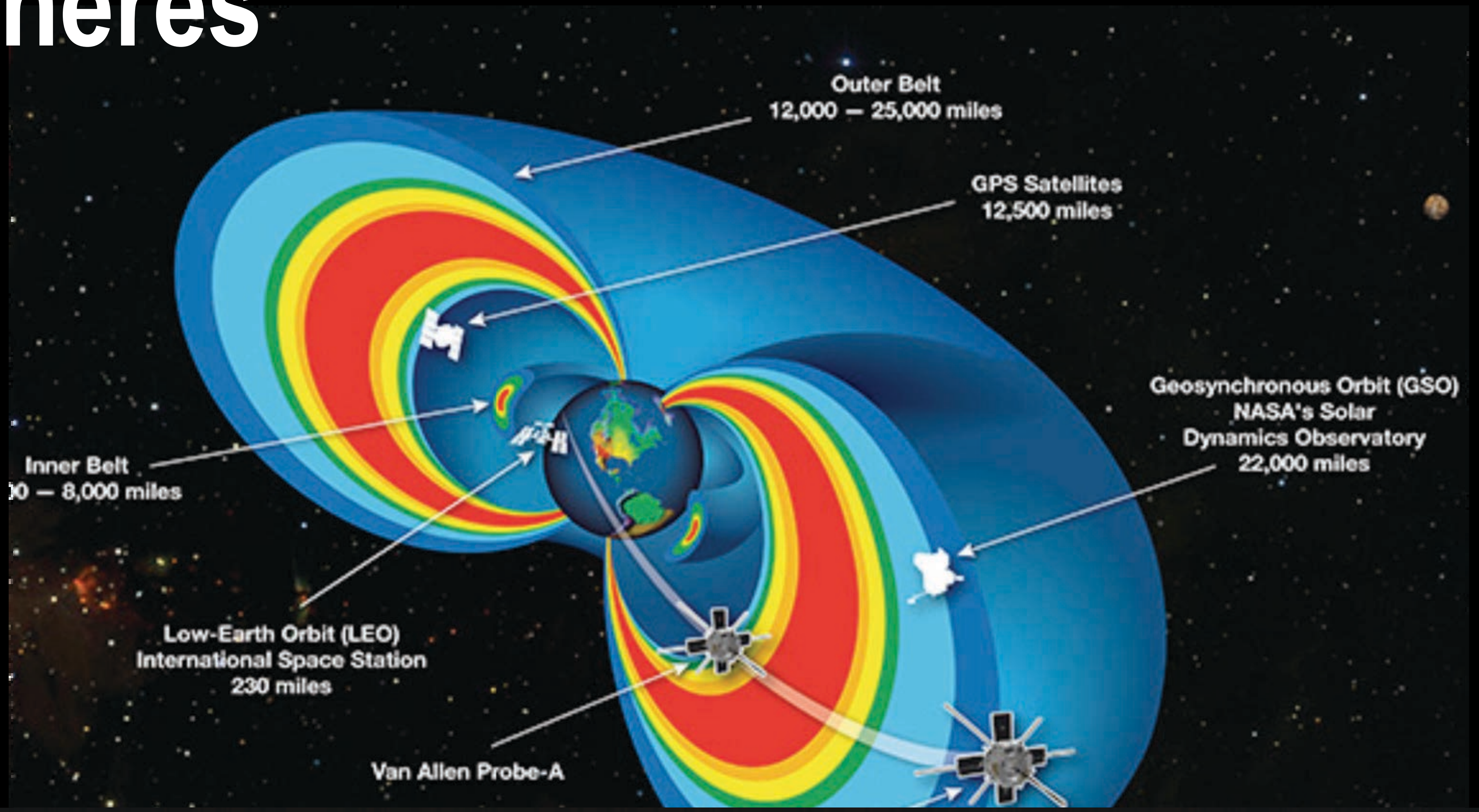


19 ms records pellet traveling at 175 m/s

Levitated Current Rings Confine Extreme Plasma Pressure as Found Naturally in Magnetospheres

Big Plasma - Small Magnet





Nature's way to confined plasma

Outline

✓ Innovation

✓ Fusion experiments at Columbia University: active plasma control

✓ Many plasma tori: the great flexibility of magnetic plasma confinement

✓ How to design a tokamak

✓ Innovations to meet the challenges to fusion's economic potential

✓ Neutrons and the possibility for "advanced" fusion fuel

✓ (*Seriously*) Fusion hype and science fiction…

Robert Gross, Columbia University, *Fusion Energy* (1984)

Summary

The Early Question was "Can fusion be done, and, if so how?"

- Established the new fields of plasma physics, science, and engineering
- Over 200 tokamaks and many other plasma tori. (We really know how to design tokamaks!)
- Realistic (nearly "predictive") models and simulations for magnetic confinement.
- Repeatedly generated over 10 MW fusion power (TFTR in 1994 and JET in 1997)
- Achieved net fusion gain "equivalent" (JT-60U in 1996)
- Construction well underway: the first fusion experiment at ambitious scale of a power plant (ITER)

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

- Building on 60 years of science and technical experience, fusion is focusing on …

➡ **Innovations, New Ideas, Learning from Failures, and Entrepreneurship**

(*Seriously*) Fusion hype and science fiction...

Plasma control

(2004)

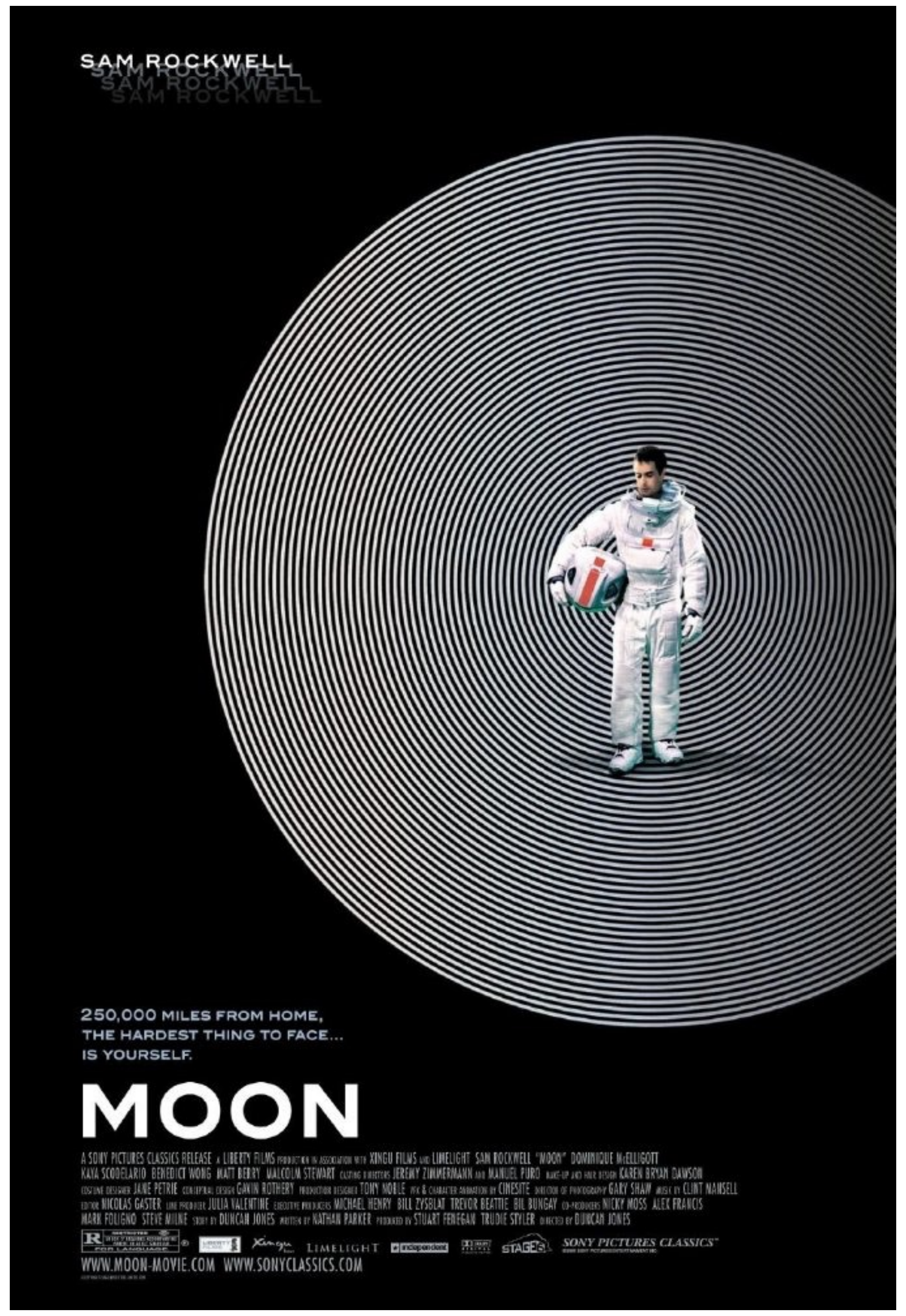
Helical Flux Tubes
Impurity Control
Fusion Rockets

(2016)

Smaller Fusion

(2008)

Advanced Fuels



(2009)