Innovations and New Ideas 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
10 June 2015

The slides for this talk are online at:
http://www.apam.columbia.edu/mauel/mauel_pubs/NUF2015-DiscoveryMagFusion.pdf

Outline

- Columbia University's plasma physics experiments
- Many types of plasma tori: testing our predictive understanding
- Fusion energy needs innovation 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

- **Innovations and new ideas from creative new scientific investigations are the only way to address these challenges**

(2004) SPIDER-MAN 2

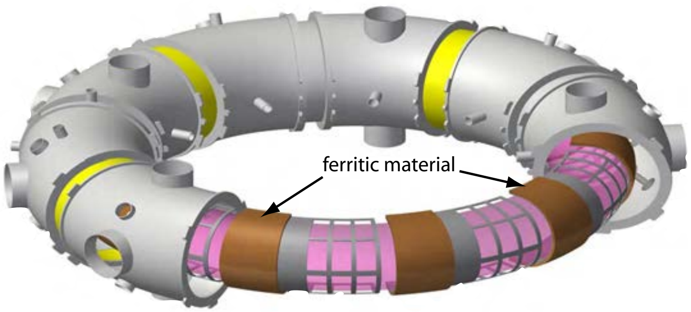
COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

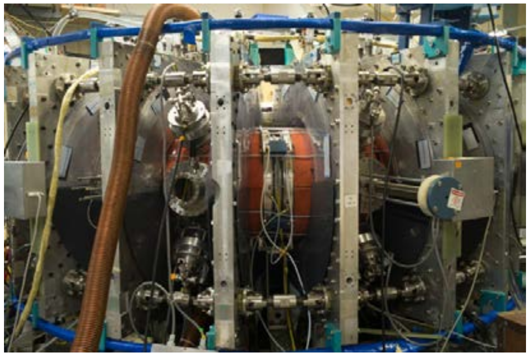
Columbia University Collaborator
Dr. Otto Octavius Stabilize Fusion in NYC…

Magnetized Plasma Physics Research at Columbia University

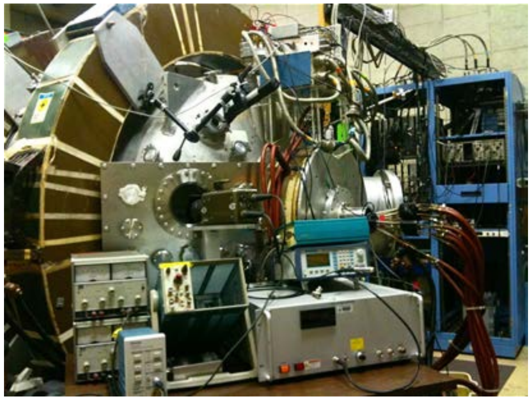
- CNT Stellarator

- HBT-EP Tokamak



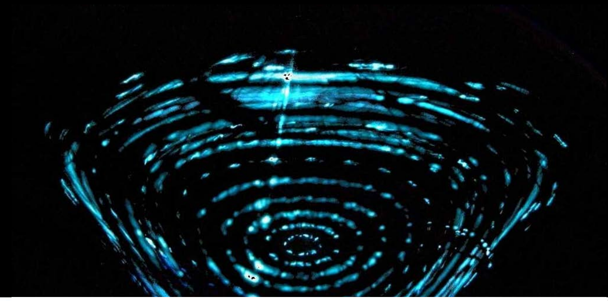


- CTX/LDX Dipoles

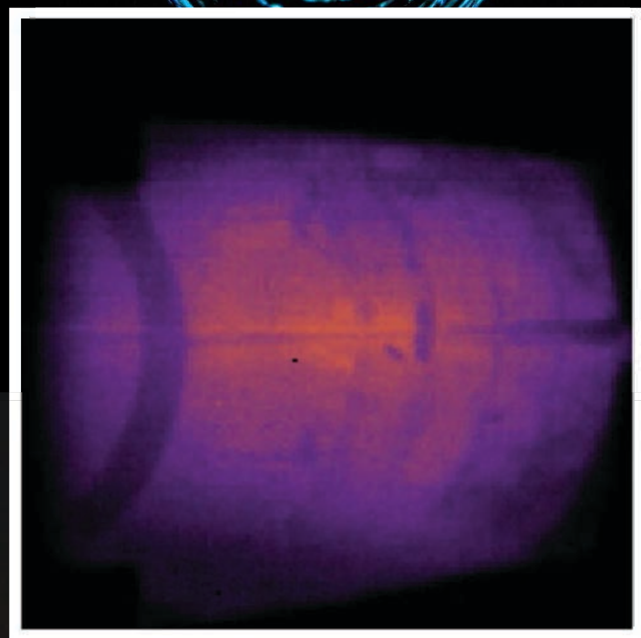


Magnetized Plasma Physics Research at Columbia University

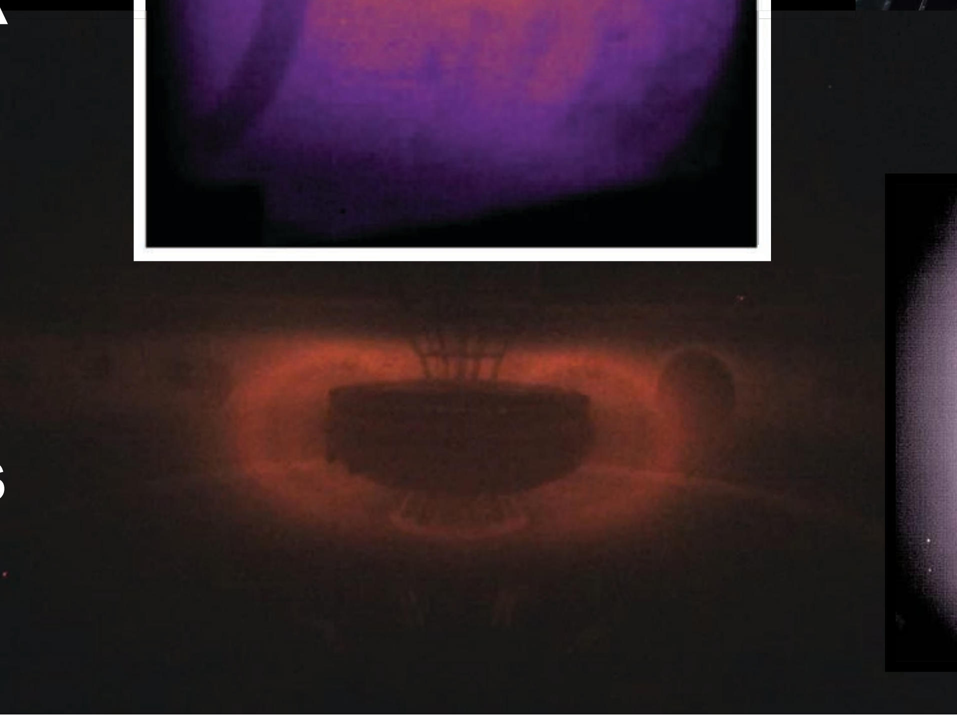
- **CNT Stellarator**

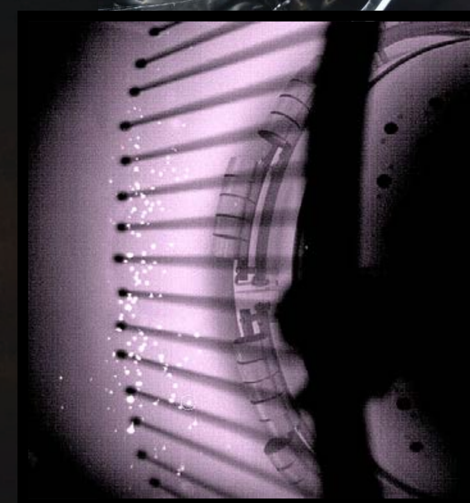


- **HBT-EP Tokamak**



- **CTX/LDX Dipoles**





How Do Magnetic Fields Confine Ionized Matter?

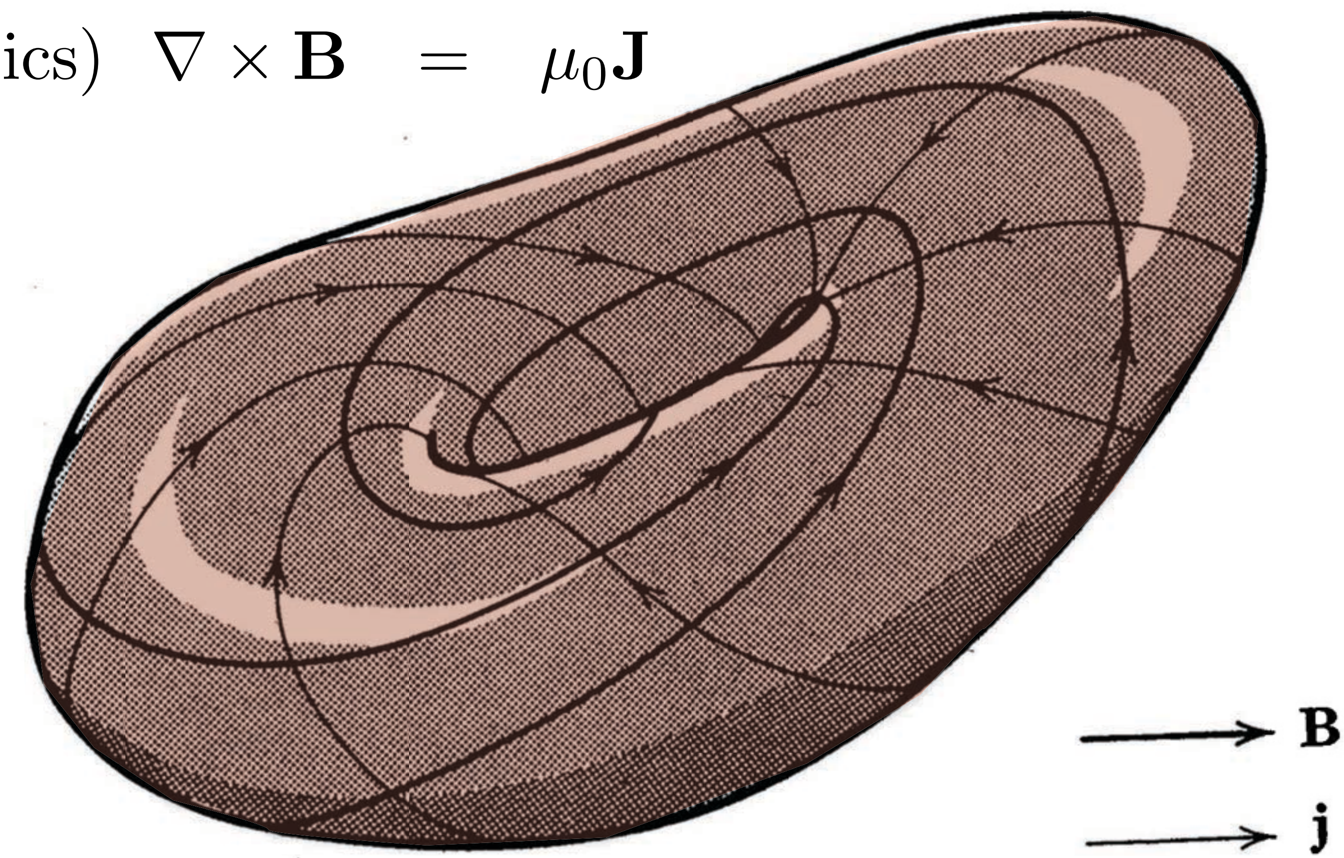
Equations of magnetic confinement...

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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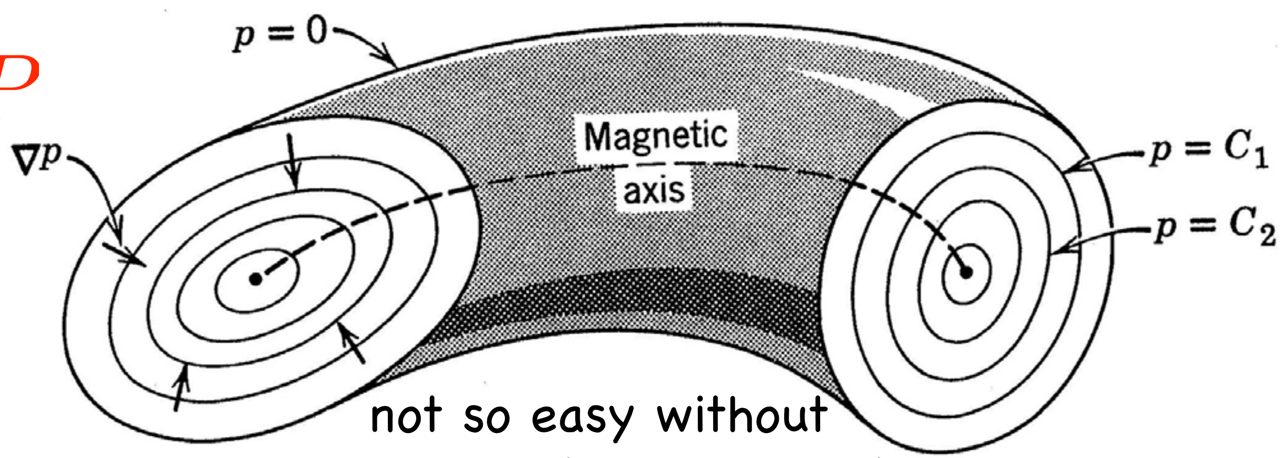
\text{(Magnetostatics)} \quad \nabla \times \mathbf{B} &= \mu_0 \mathbf{J}
\end{aligned}
$$

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)

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

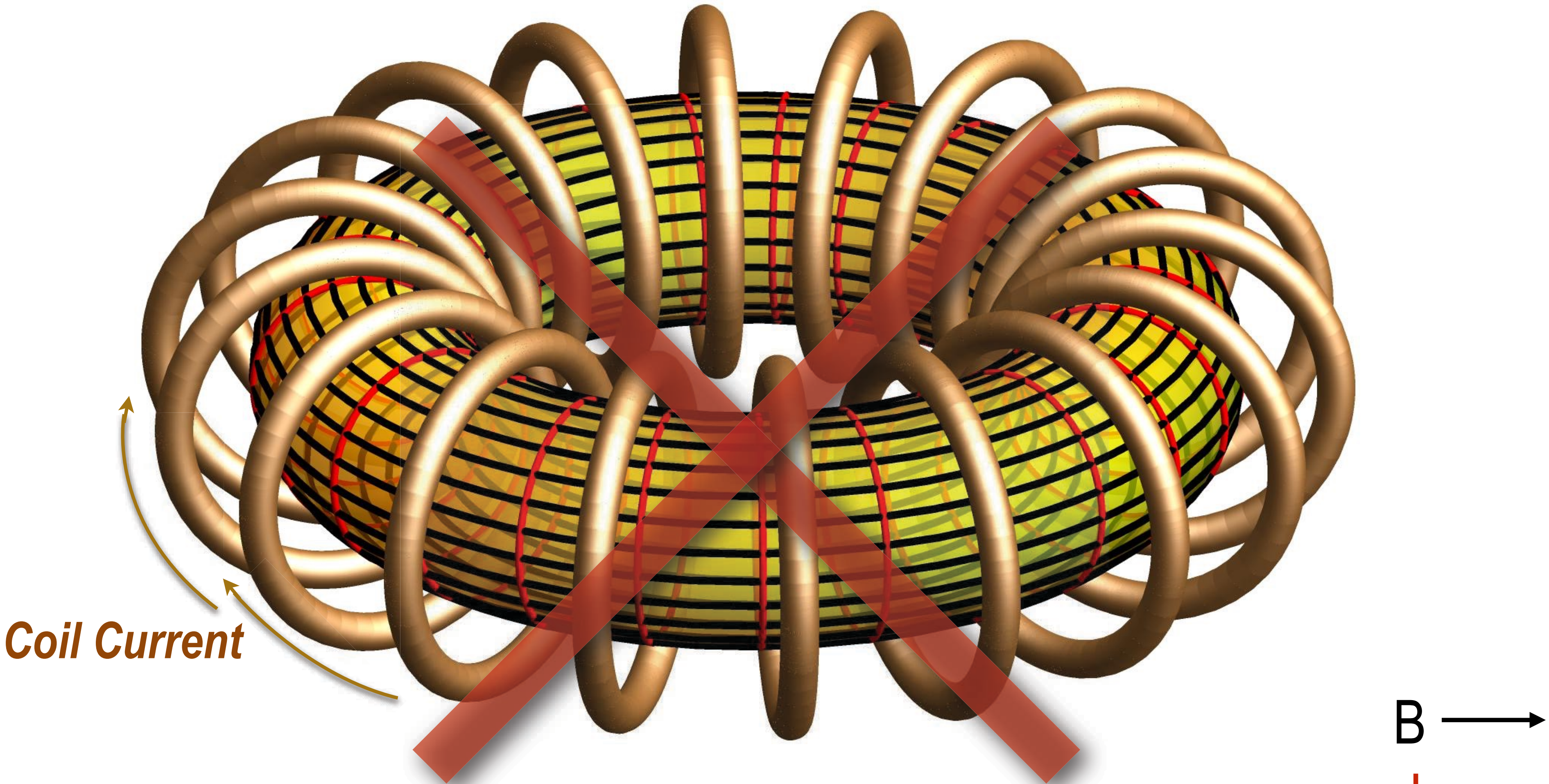
Many Types of Plasma Tori

Testing our Predictive Understanding of Magnetized Plasma

- Axially-**symmetric** torus with external poloidal currents (***fails***)
- Axially-**symmetric** torus with internal toroidal current *inside* the plasma ("*FRC*" and "*levitated dipole*")
- 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*")

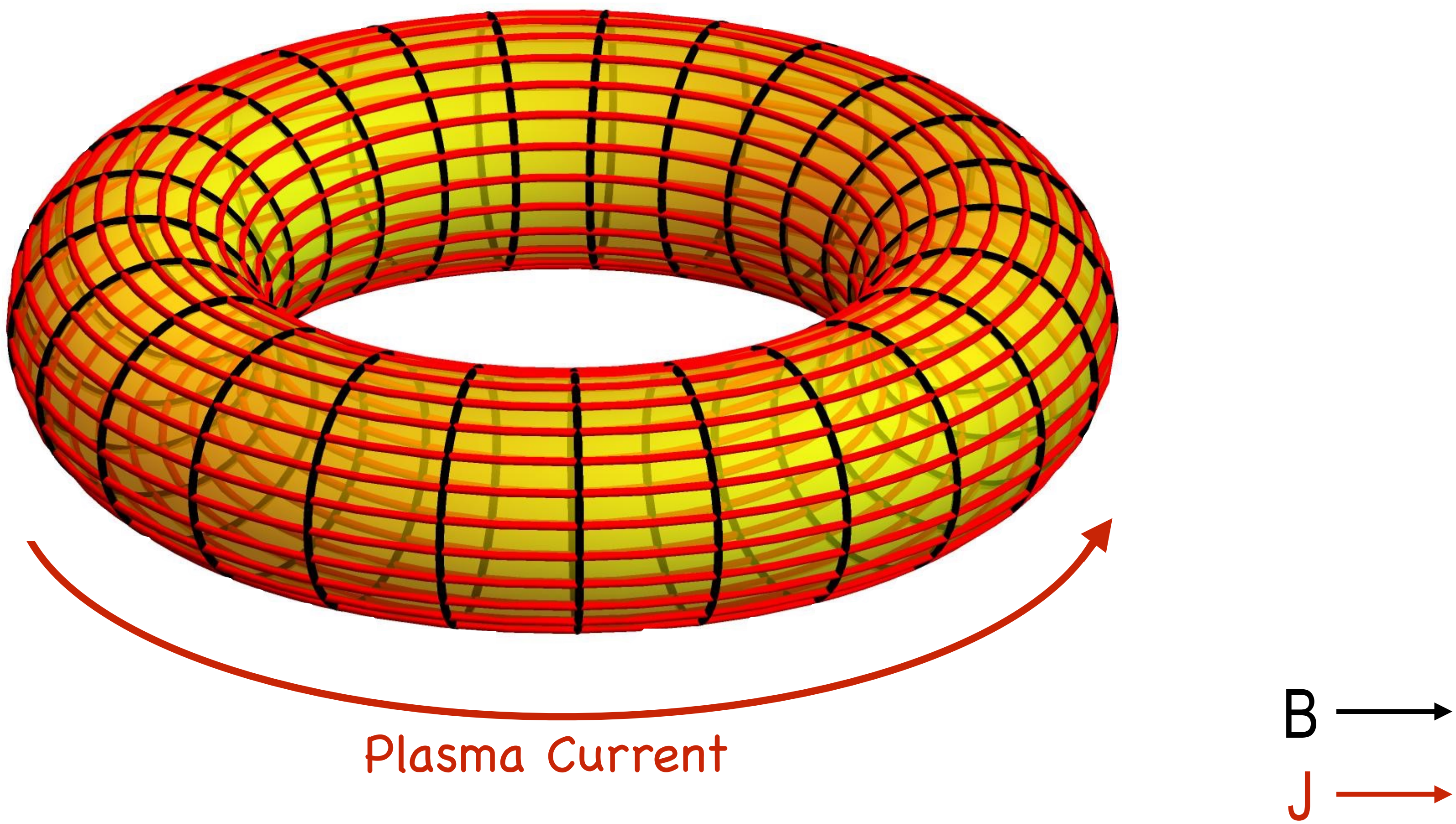
FAILS TO CONFINE PARTICLES

How to make a magnetic torus?



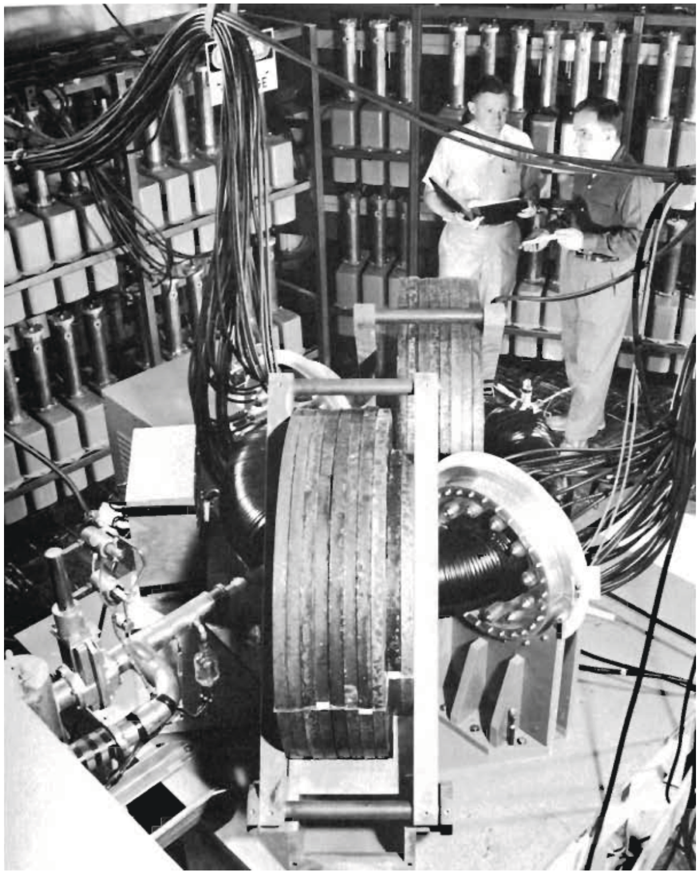
Toroidal Field from External Coils
(toroidal "theta-pinch")

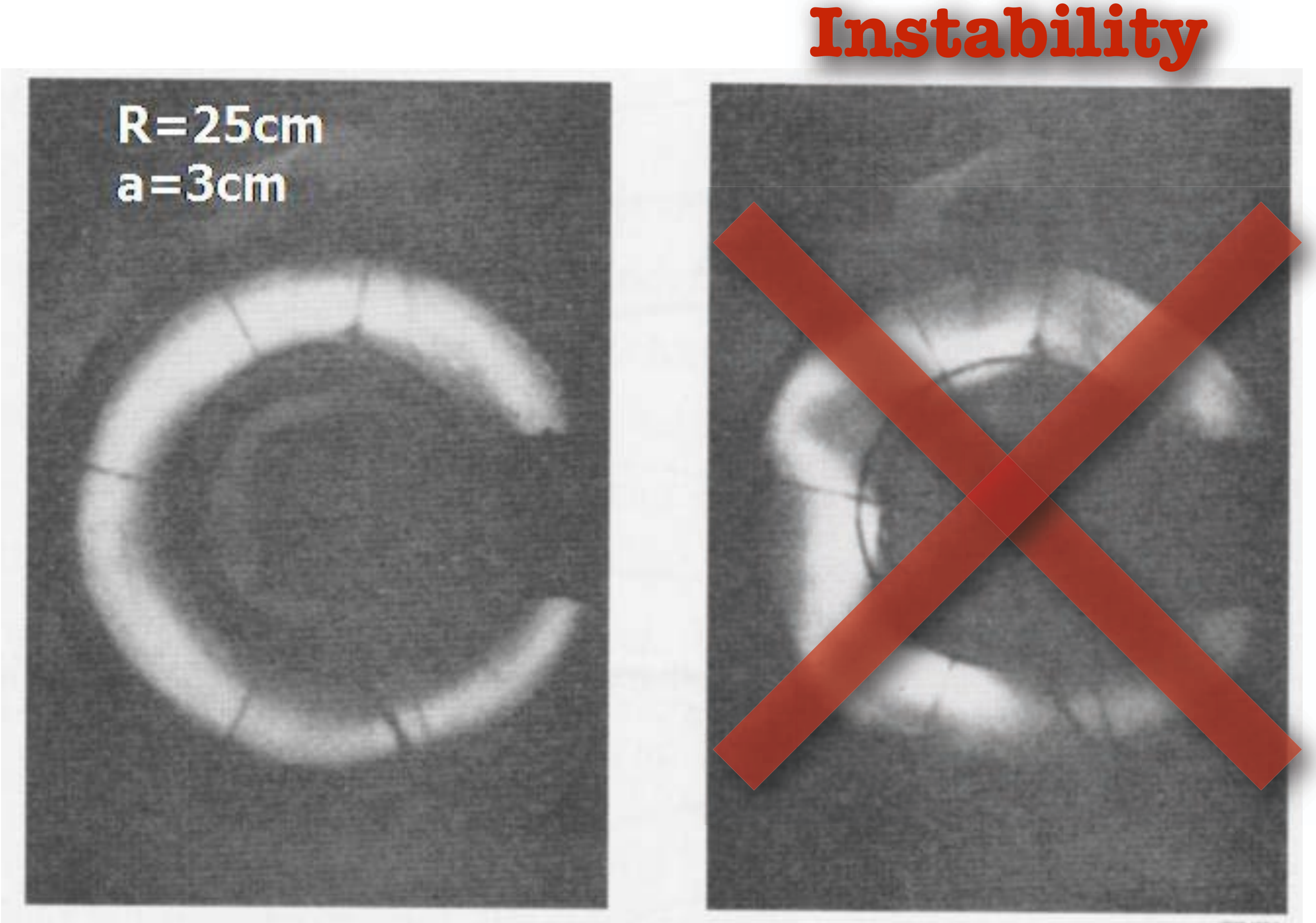
How to make a magnetic torus?



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

How to make a magnetic torus?

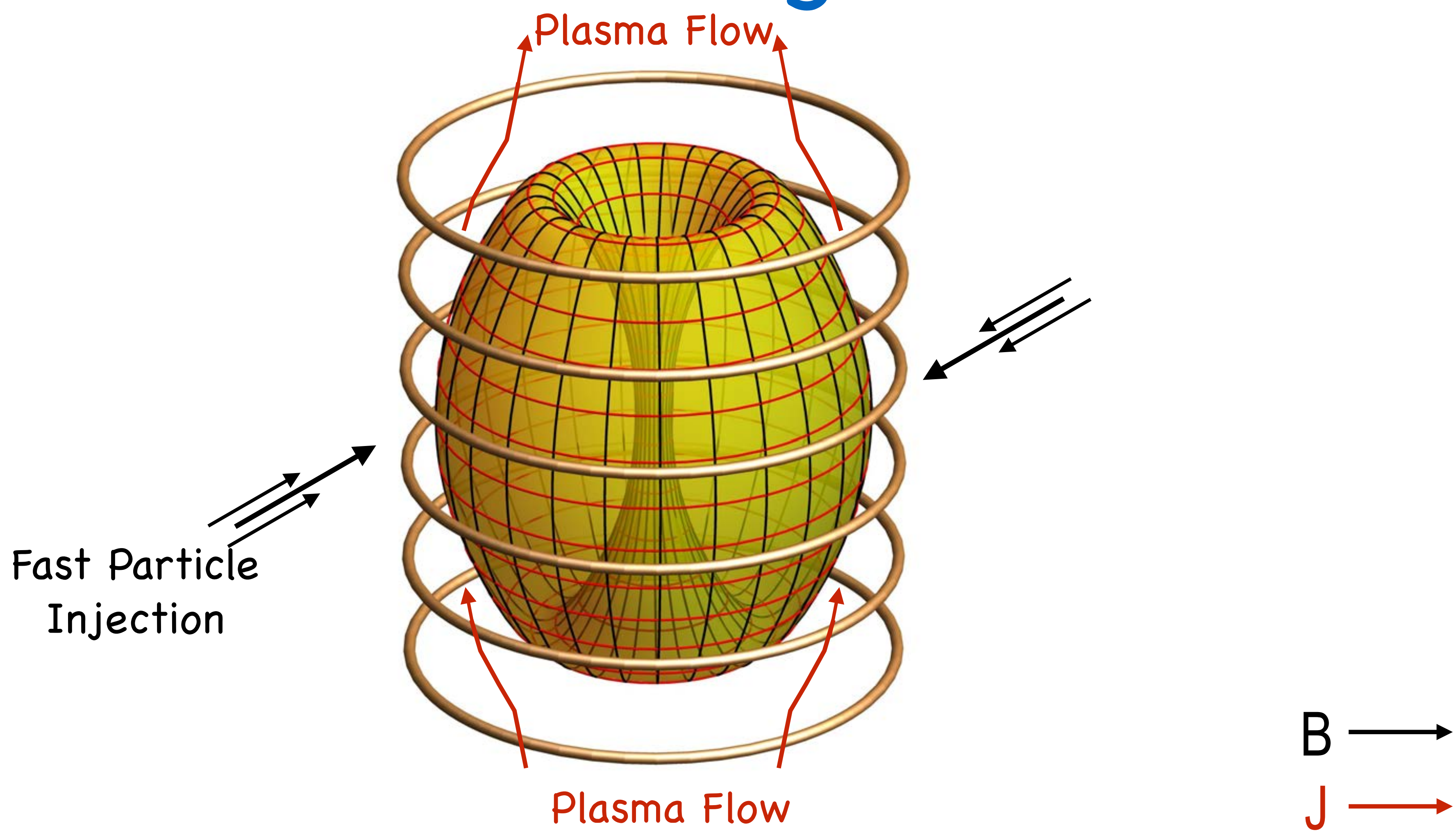




Poloidal Field from Plasma Current
(toroidal "z-pinch")

Stabilized with External Control

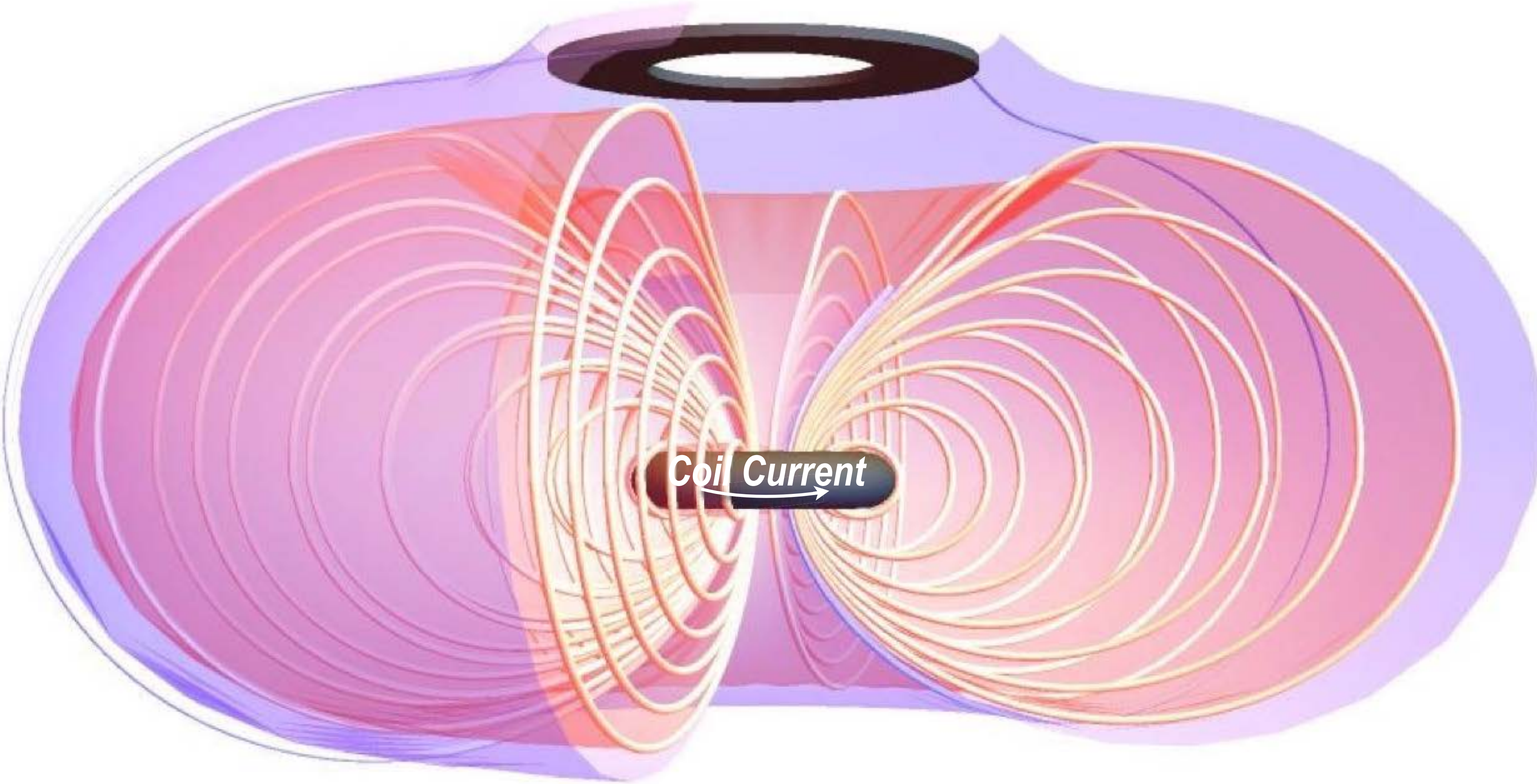
How to make a magnetic torus?



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

Stable with Internal Coil

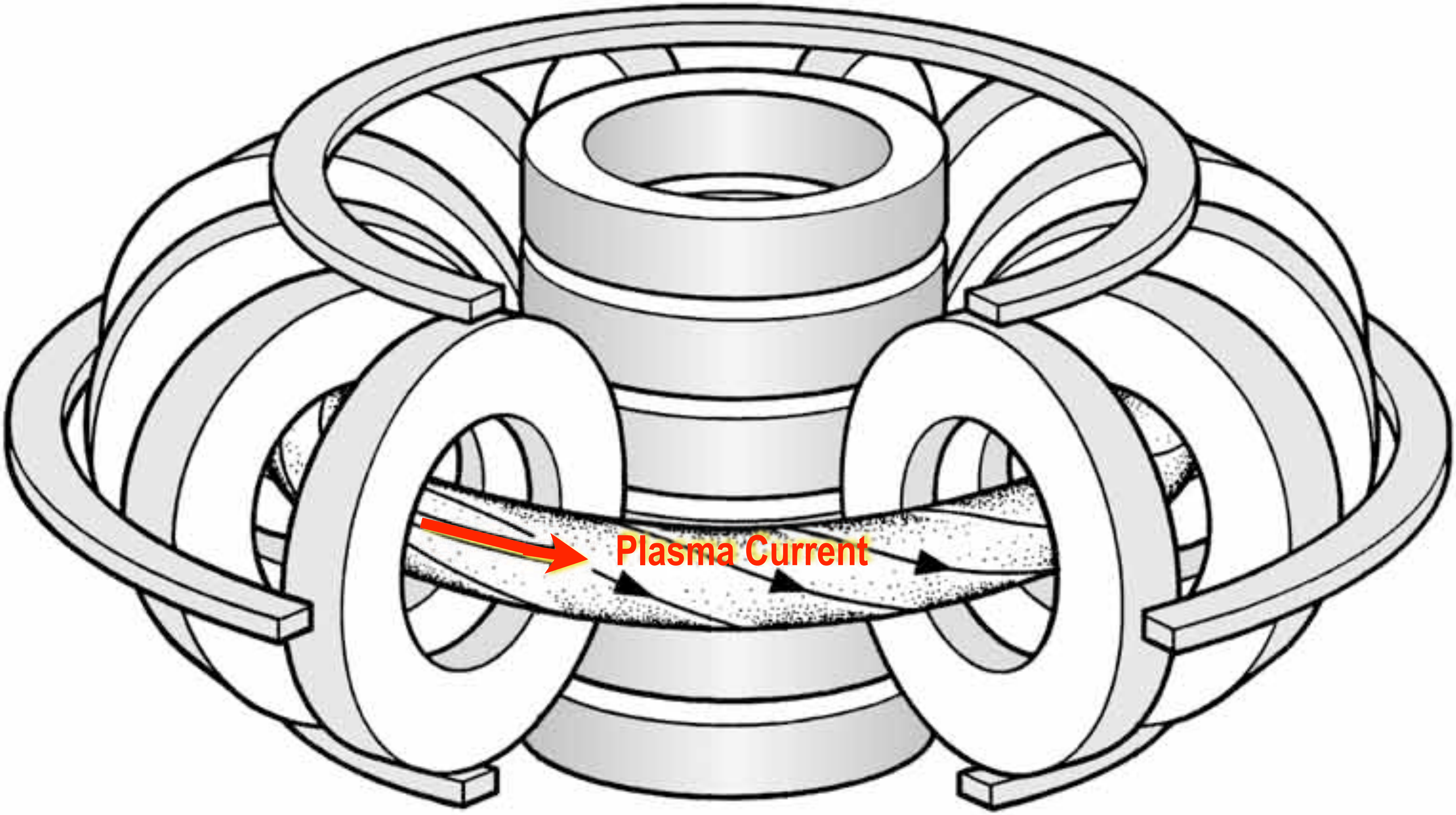
How to make a magnetic torus?



Poloidal Field from Floating Dipole Magnet

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

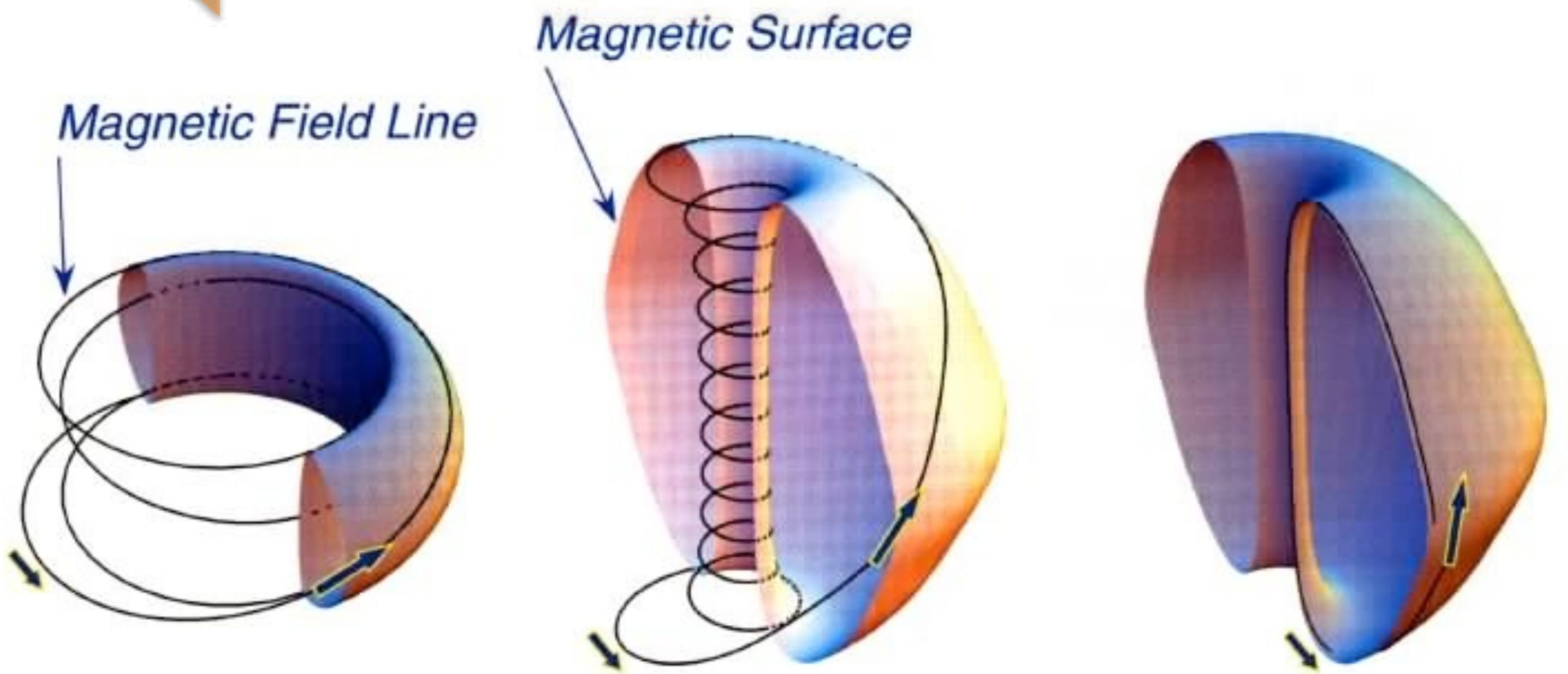
How to make a magnetic torus?



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

How to make a magnetic torus?

High q ← Increasing Toroidal Field ← Low q



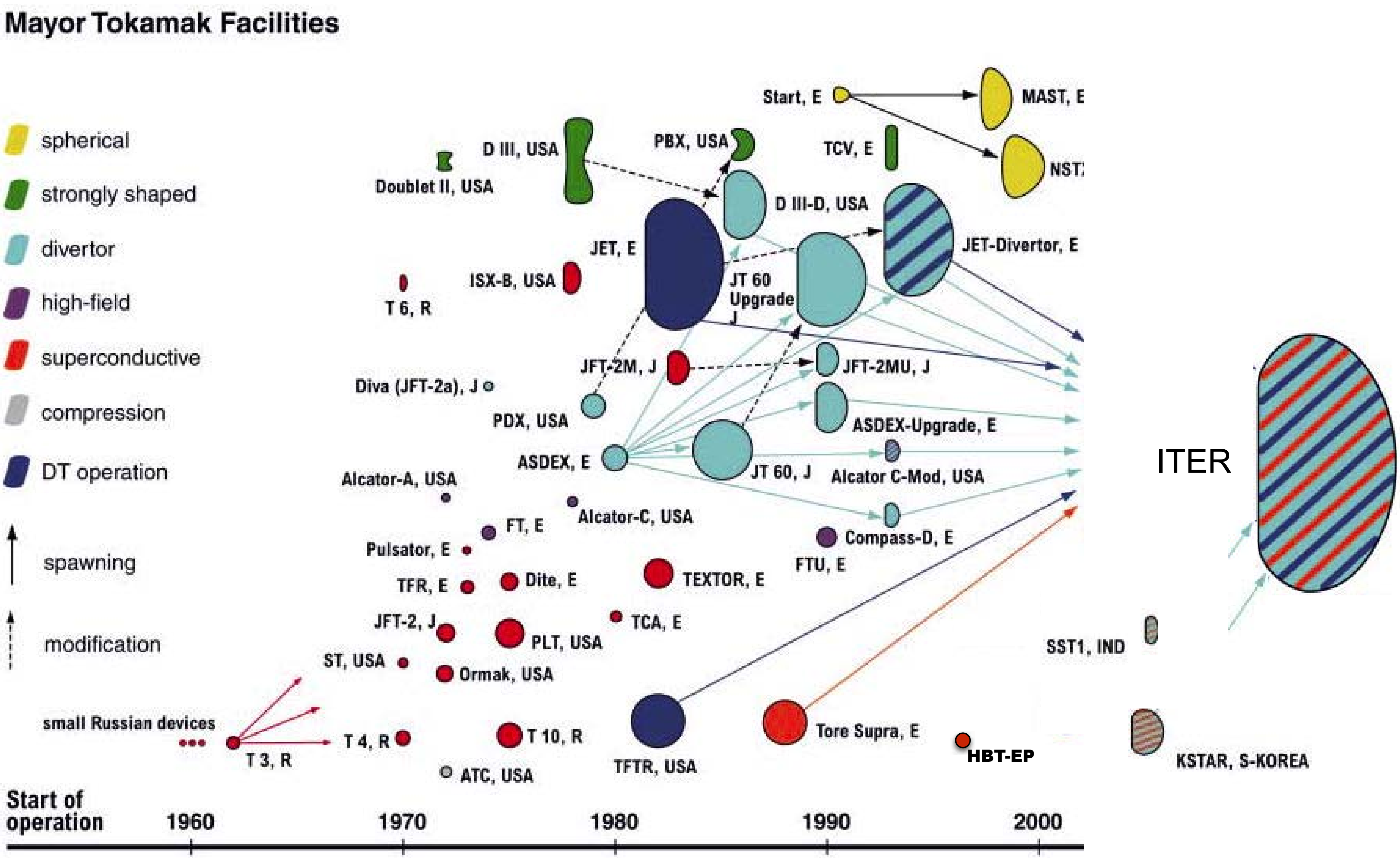
Fundamentally, the behavior of magnetically-confined plasma depends upon the shape of the magnetic flux tube...

Tokamak Plasma	Spherical Torus Plasma	Spheromak Plasma
(safety factor $q = 4$)	(safety factor $q = 12$)	(safety factor $q = 0.03$)

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

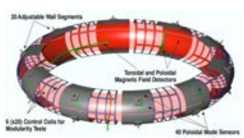
More than 200 Tokamaks

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



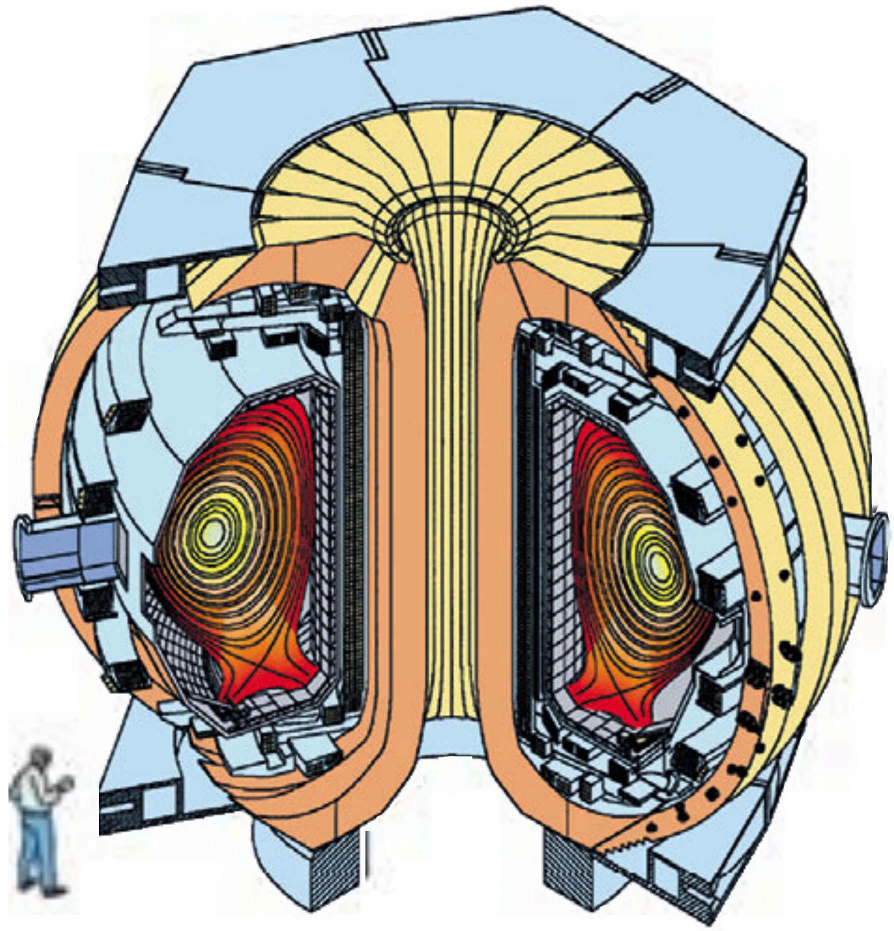
How to make a magnetic torus?

⊢1.8 m⊣



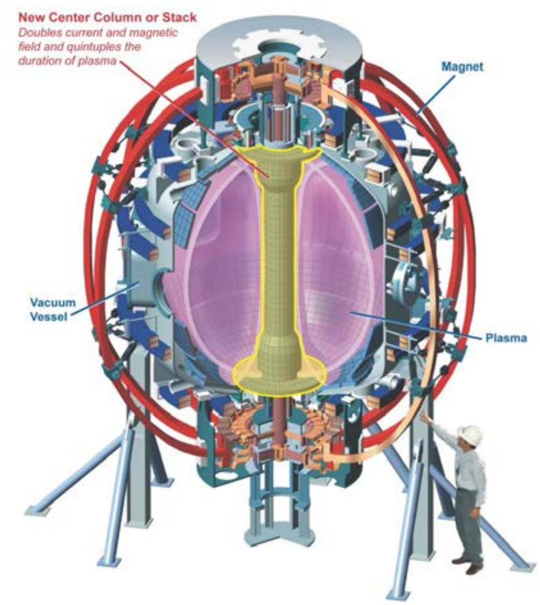
HBT-EP
Columbia University

⊢ 3.3 m ⊣



DIII-D
General Atomics

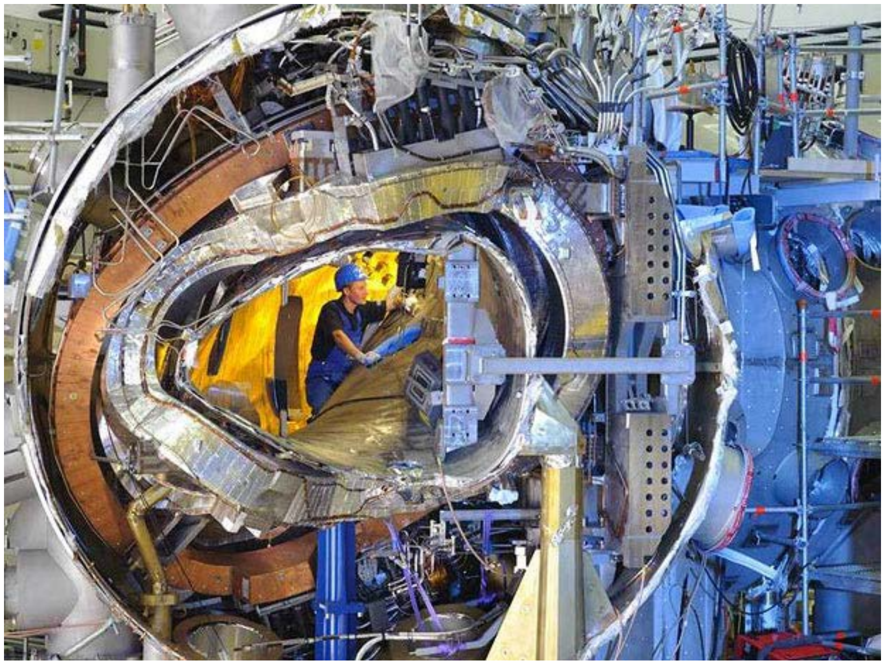
⊢1.7 m⊣



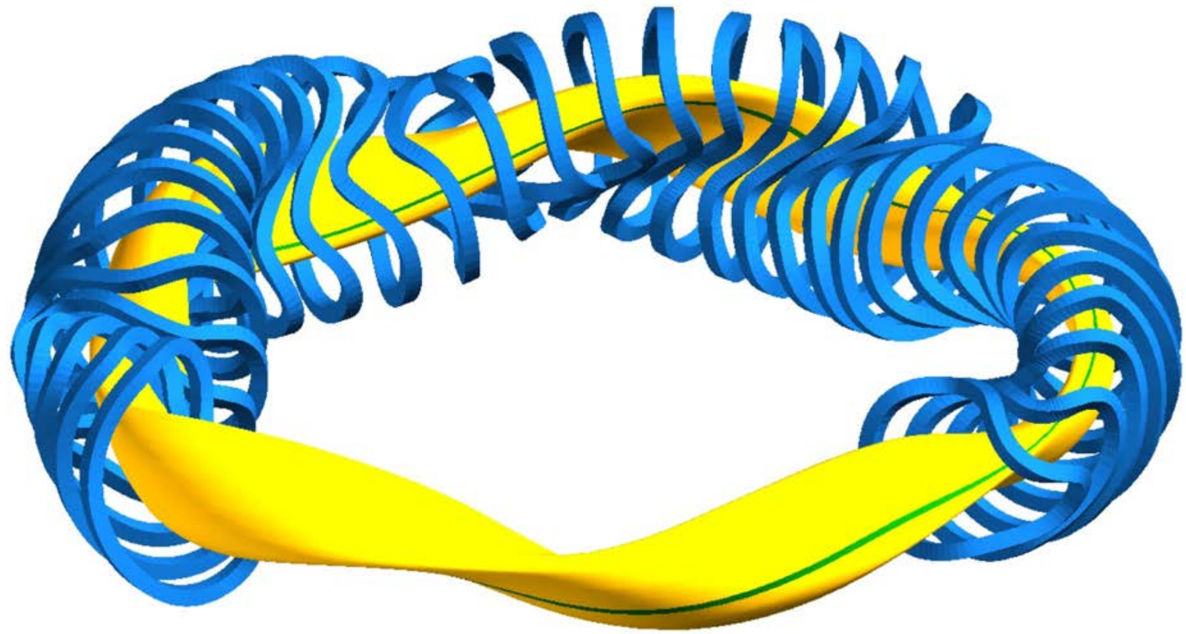
NSTX-U
PPPL

Combined Toroidal and Poloidal Field (Tokamak)

How to make a magnetic torus?



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

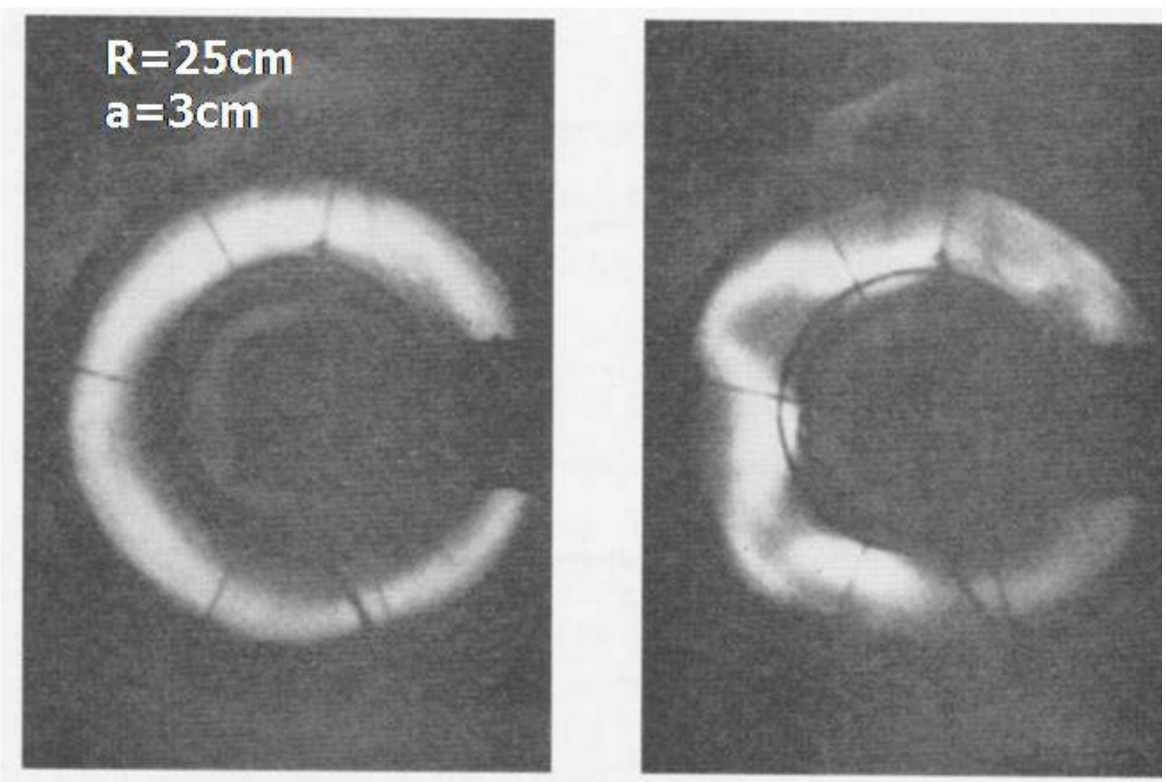


Non-symmetric plasma torus with (**mostly**) external "helical" magnets (Stellarator)

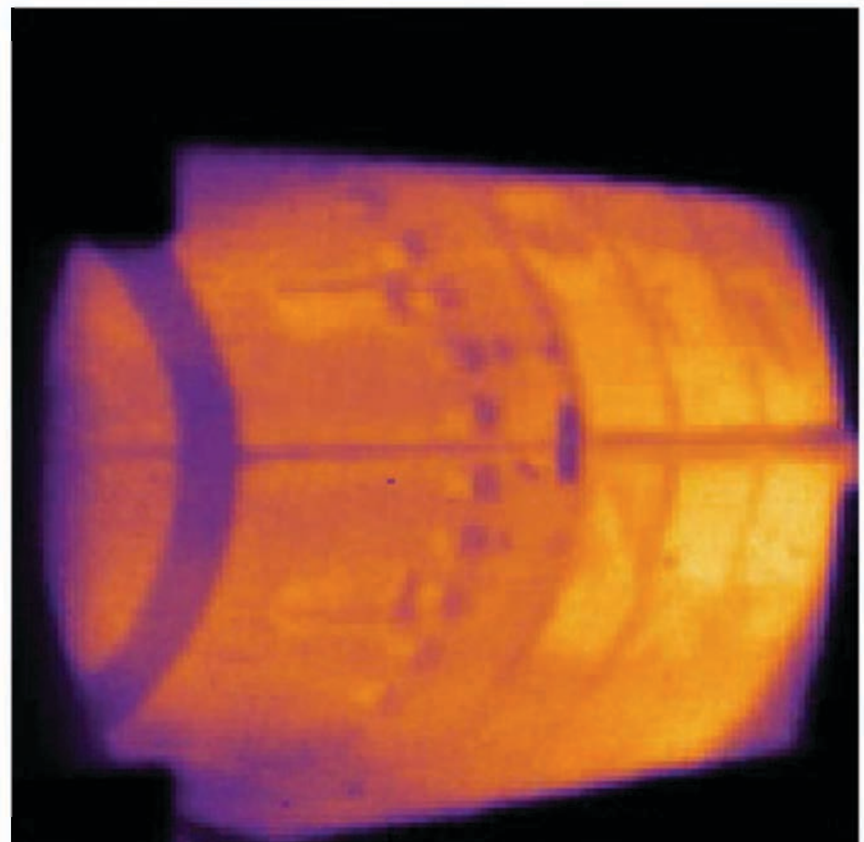
Magnetic Fusion Optimization Depends on Shape and Plasma Current

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

Kink Instability of Large Plasma Current



Toroidal "z-pinch"

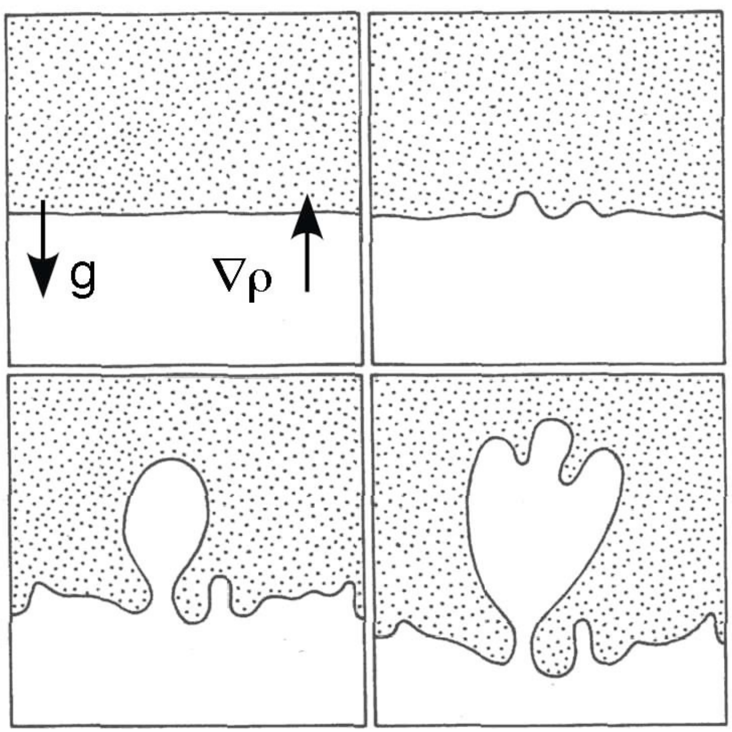


Tokamak Disruption

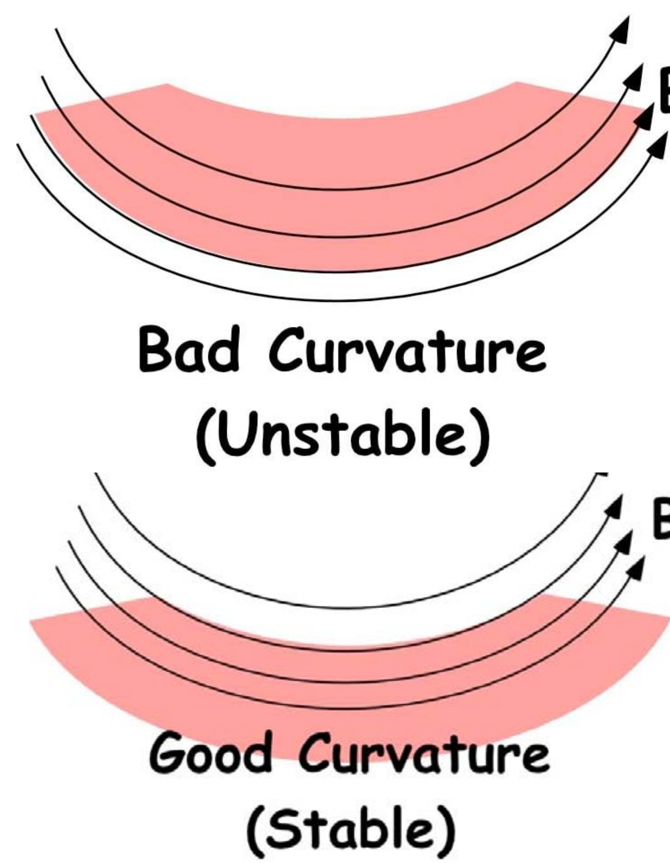
Magnetic Fusion Optimization Depends on Shape and Plasma Current

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

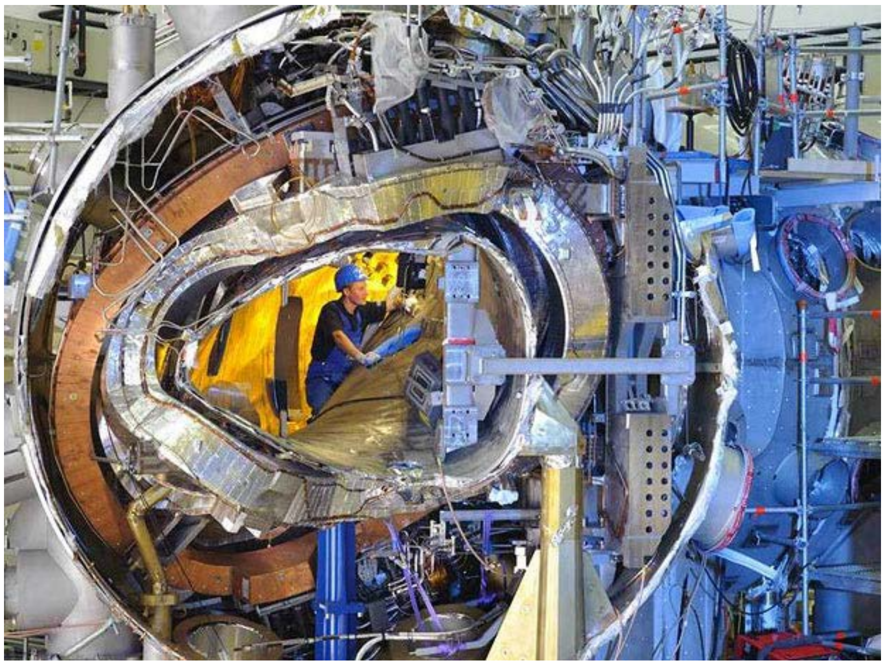
Interchange Instability



Bending Field ➠ Effective g



How to make a magnetic torus?



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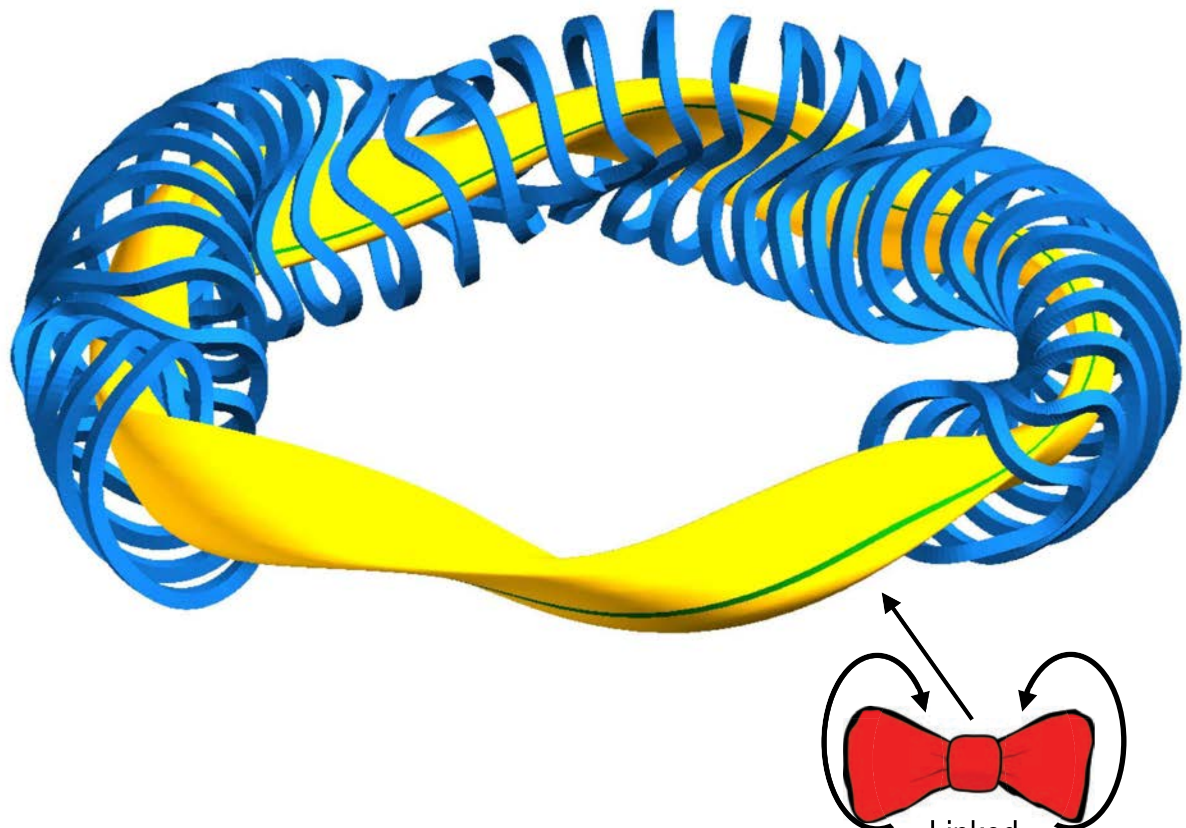
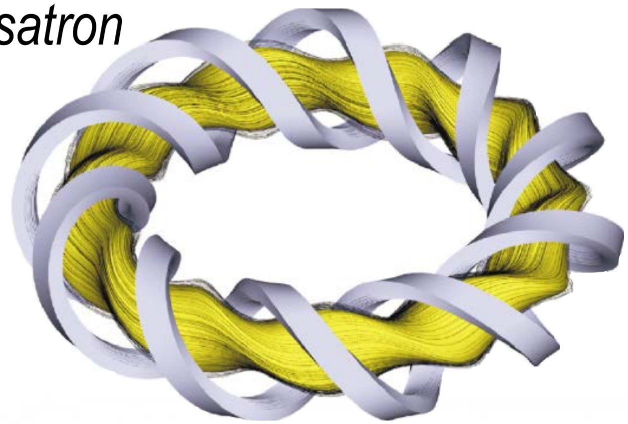


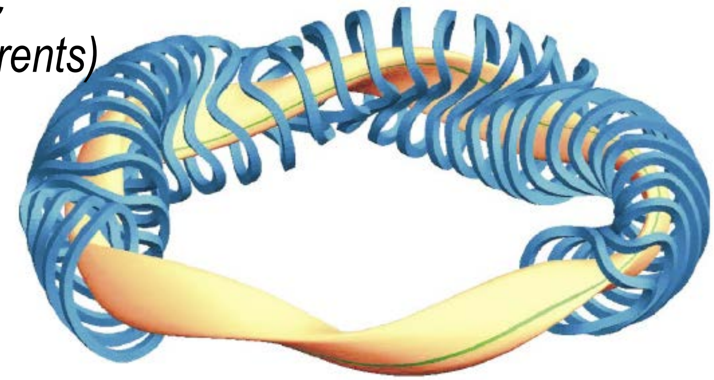
Non-symmetric plasma torus with (**mostly**) external "helical" magnets (Stellarator)

How to make a magnetic torus?

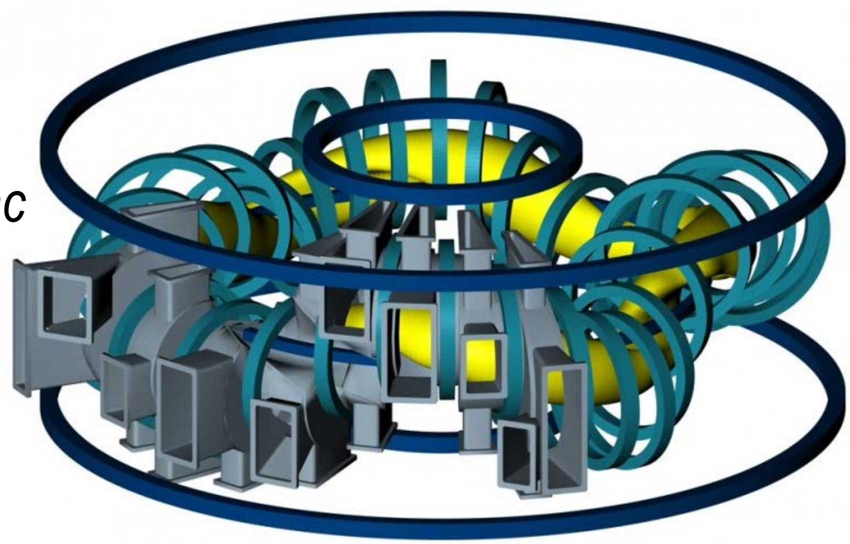
Torsatron

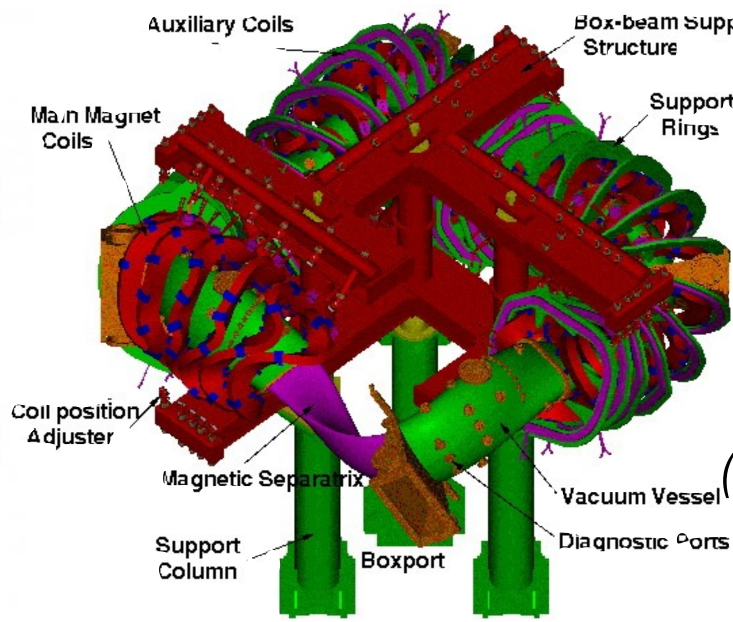


Quasi-Isodynamic
*(**almost** no parallel currents)*



Heliac





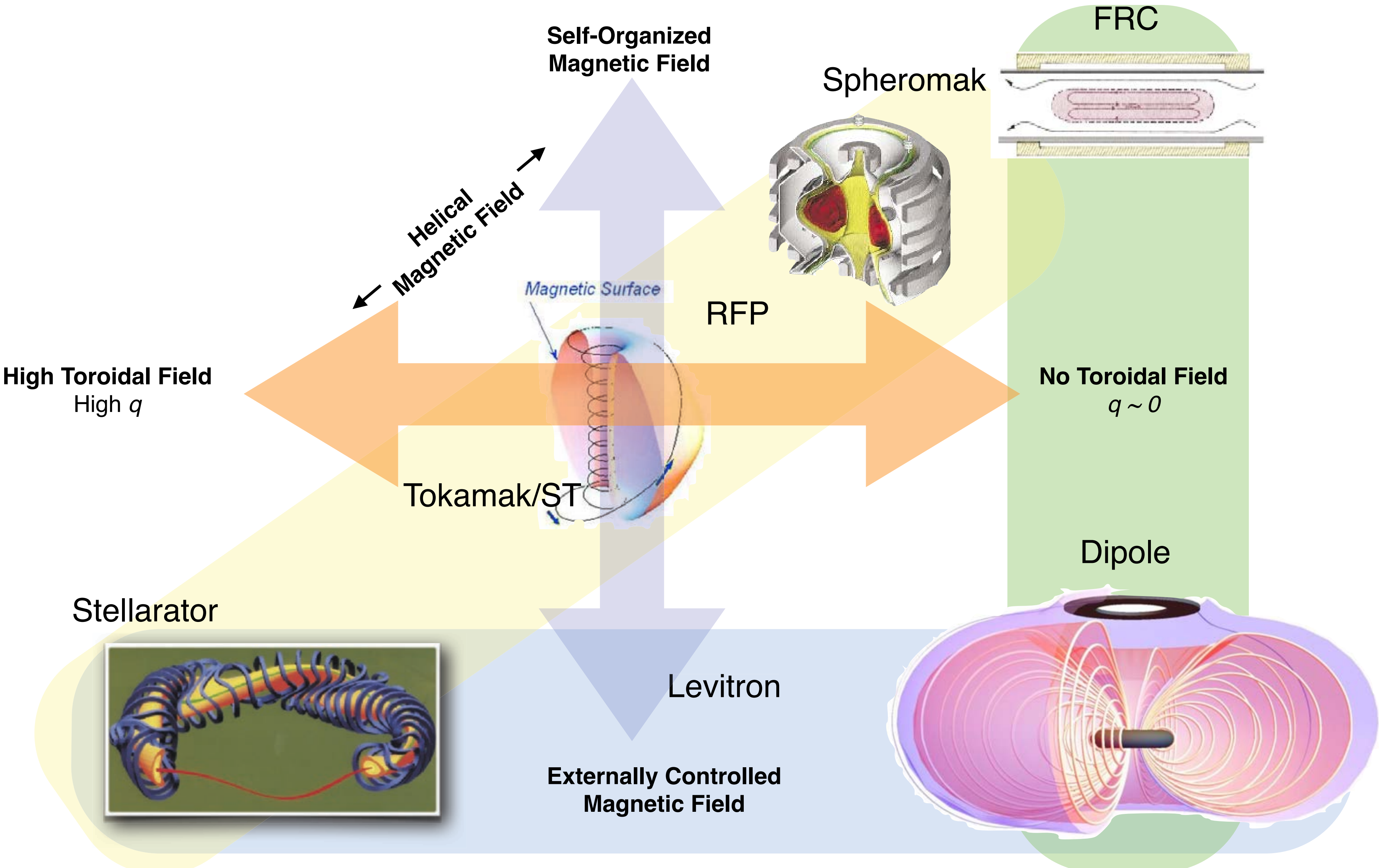
Quasi-Symmetry
(Like tokamak along helical path)

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

Why study different magnetic tori?

- ***Fundamental study***
  - Develop a **predictive science** of confinement, heating, sustainment, heat flux to boundaries, fluctuations, instabilities, …
  - Laboratory study of **"bright matter"** found throughout the universe, …
- ***Fusion energy***
  - Torus has to confine plasma at high pressure and …
  - Generate fusion power reliability (**no uncontrolled instabilities**!)
  - Achieve fusion's promise of safety and environmental attractiveness
  - **Economic viability** (like clean cost-competitive electrical power on Earth, high payload space power and propulsion, …)

Plasma Toroidal Configurations



Outline

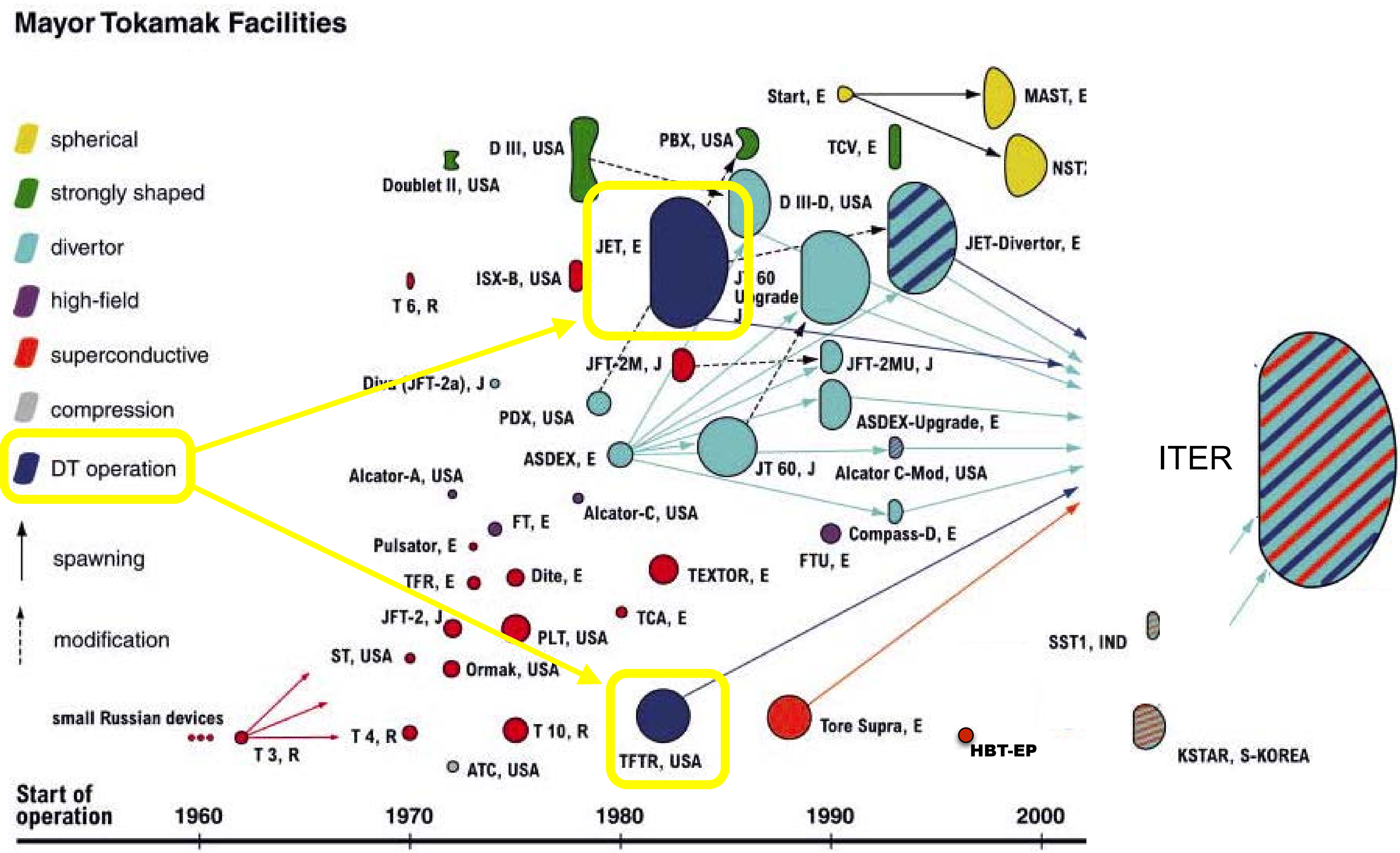
- Columbia University’s plasma physics experiments
- Many types of plasma tori: testing our predictive understanding
- Fusion energy needs innovation to overcome challenges to economic viability

  Over 200 tokamaks and *soon there will be ITER*…
  We know a lot about the challenging economics of tokamak-based fusion energy

- **Innovations and new ideas from creative new scientific investigations are the only way to address these challenges**

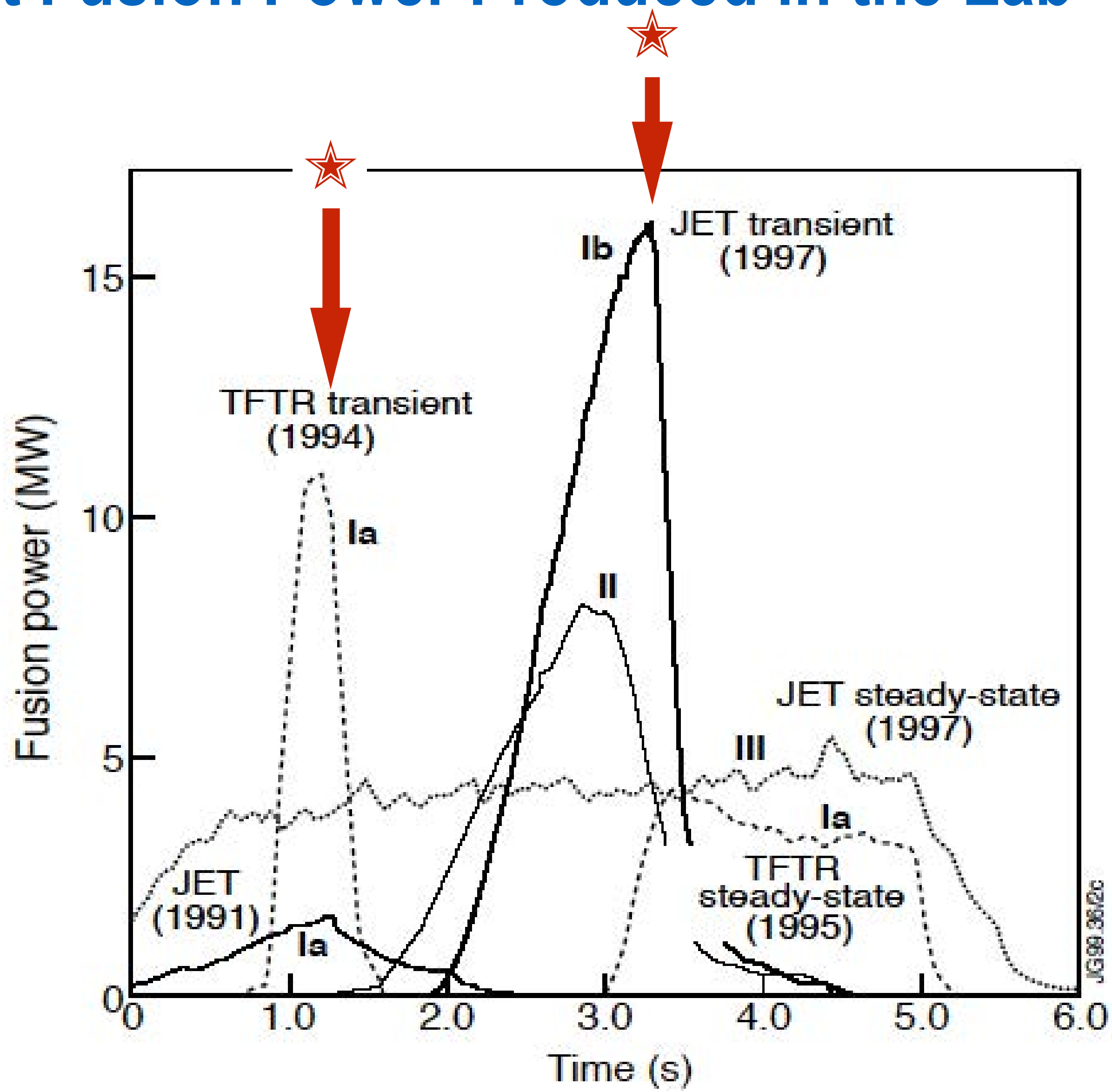
More than 200 Tokamaks

(*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.



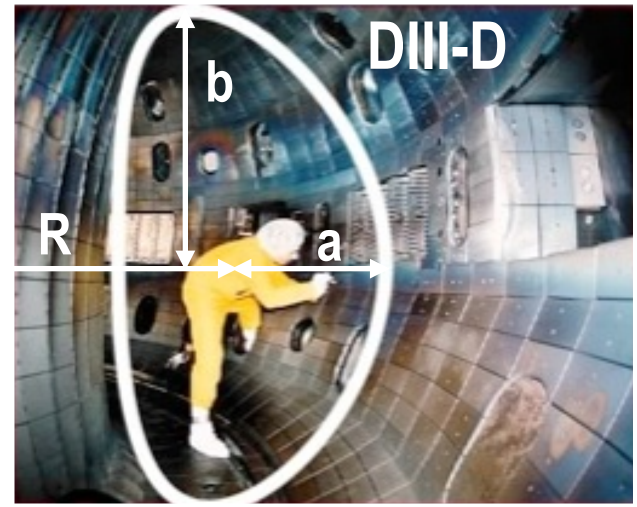
Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines), in different regimes:

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

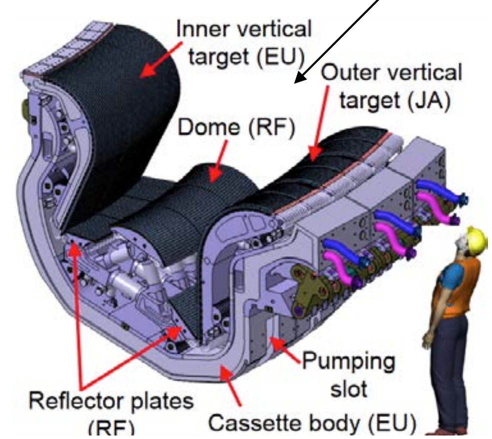
(II) Optimized shear; and (III) Steady-state ELMY-H Modes.

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…**



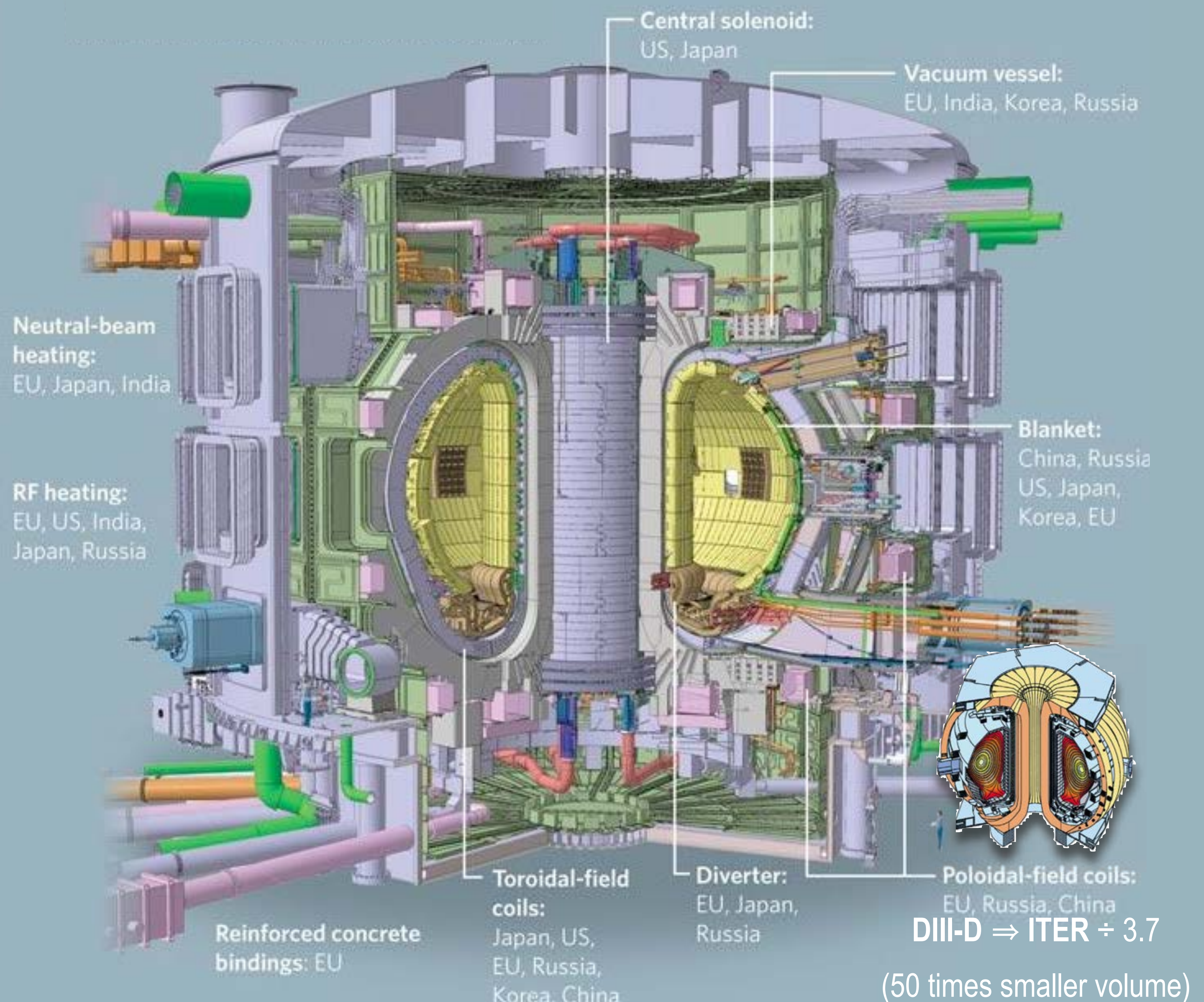
54 Divertor Segments (9 tons each)



ITER: The International Burning Plasma Experiment

ITER: The International Burning Plasma Experiment

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



DIII-D ⇒ ITER ÷ 3.7

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

~ 500 MW
10 minute pulses

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

NATURE | COMMENT

Nuclear physics: Pull together for fusion

Bernard Bigot

09 June 2015

ITER director-general Bernard Bigot explains how he will strengthen leadership and management to refocus the project's aim of harnessing nuclear fusion.

Nature **522**, 149–151 (11 June 2015) doi:10.1038/522149a

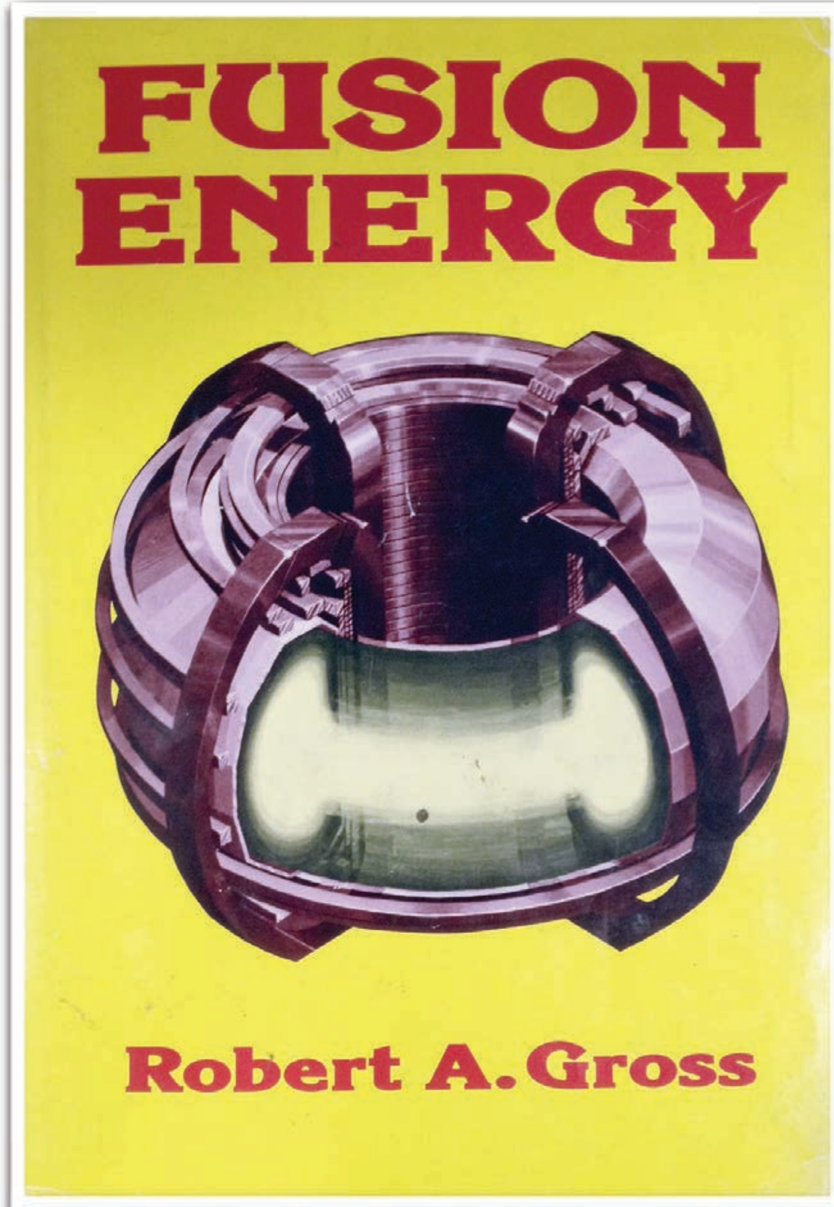
http://www.nature.com/nature

Before the end of this year, I am expected to submit, along with all stakeholders, an updated, robust and reliable schedule … and a cost and risk analysis. With renewed management and a streamlined organization, we are **now ready to prepare for the assembly and commissioning phase**, the step before fusion switches on.

Further delays and costs are inevitable. ITER will meet these challenges if it has the unanimous political support of the seven members, on the basis of the long-term value of fusion technology.

All of us at ITER have a huge, historic responsibility. **The project may be the last chance we have this century to demonstrate that fusion is manageable.**

Prof. Robert Gross
Columbia University
Fusion Energy
(1984)



"Fusion has proved to be a very difficult challenge.

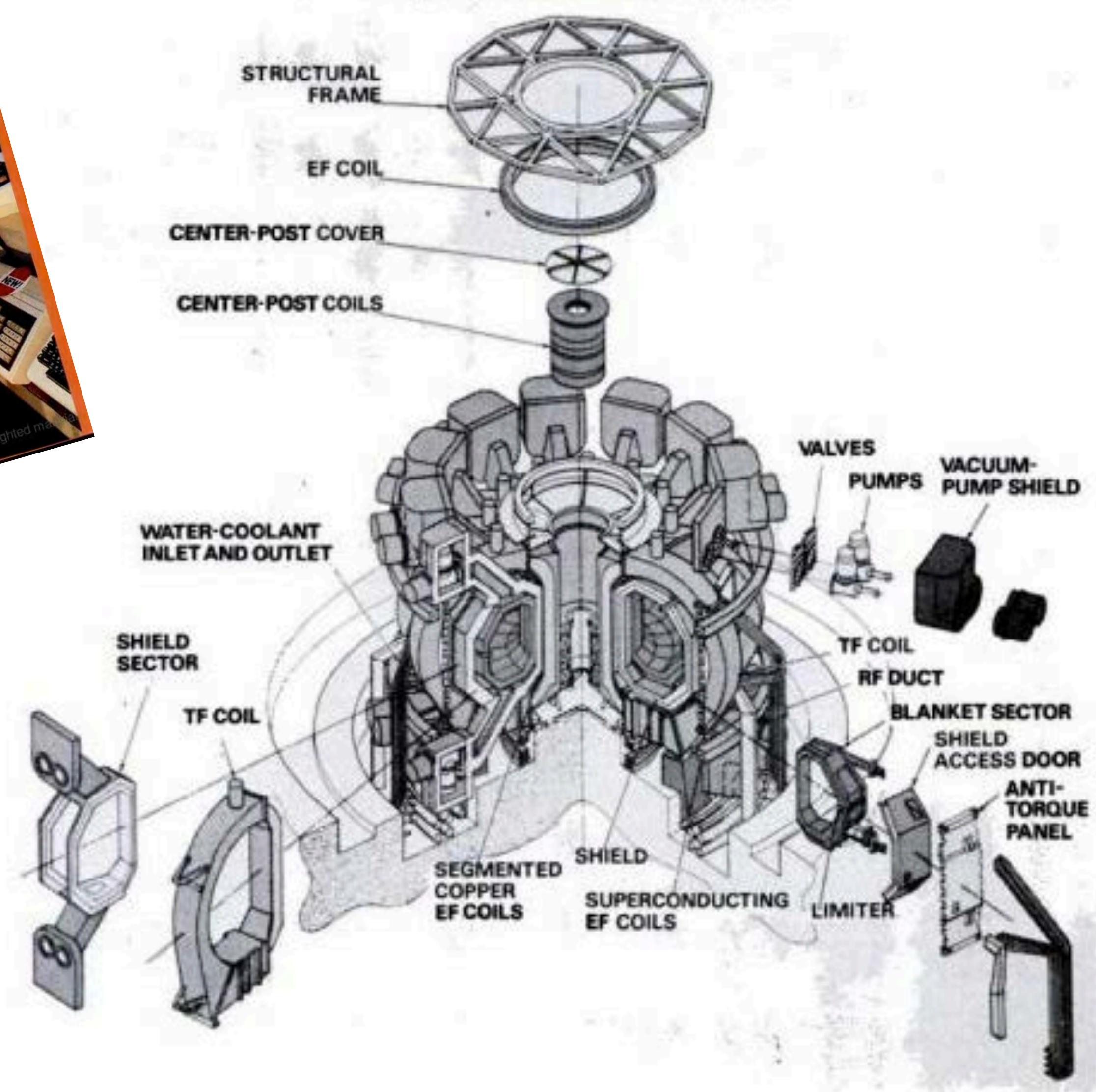
The early question was—Can fusion be done, and, if so how? …

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

Popular Science (November 1981)

nary step toward that determ
eactor shown
d on the so-ca
f the most pr
ıentally [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

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-

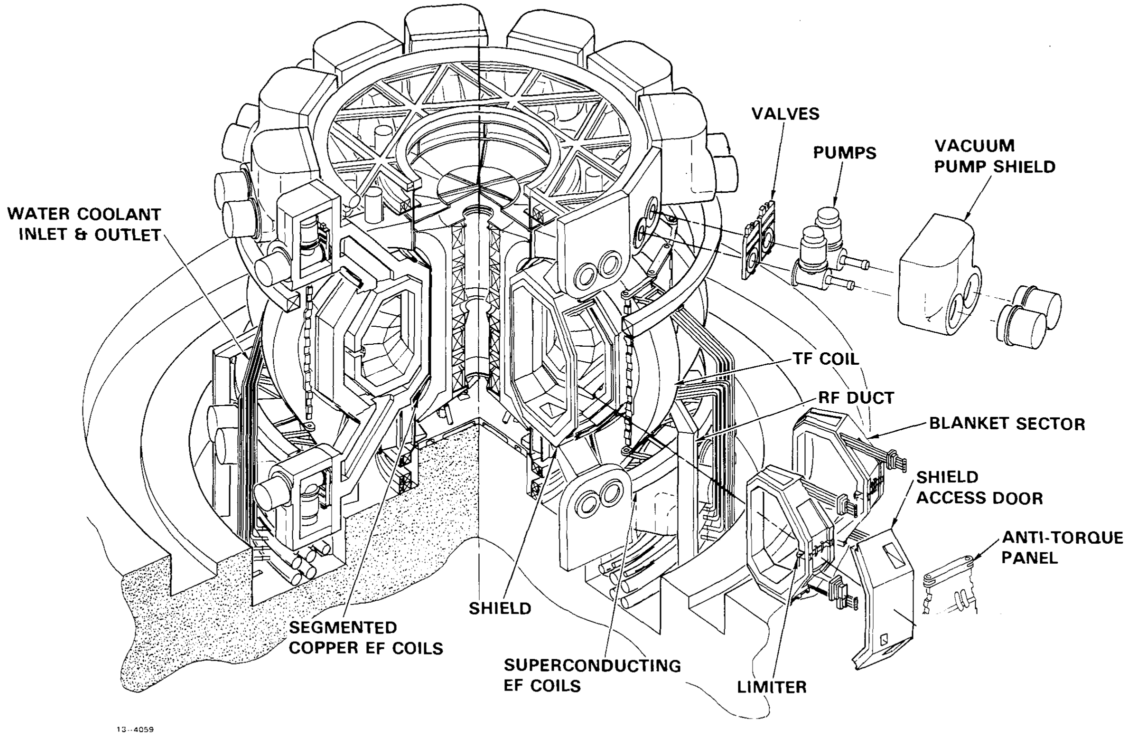
Scissor-wing tested

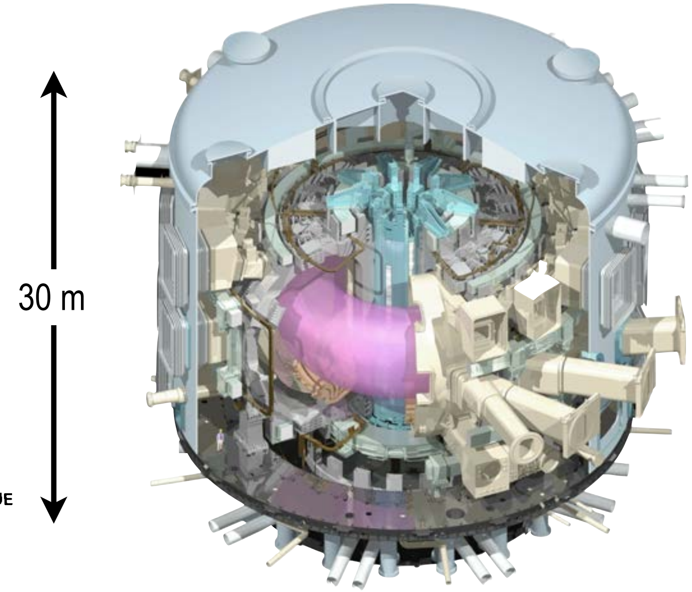
The latest step in the prog
incredible AD-1 is pictu
NASA'S unique scissor-wing
flown successfully with its
maximum, 60-degree obliq
Flight tests at Dryden Flight R
ter by pilot Tom McMurty hav
craft can skew its wing at an
from 30 to 60 degrees and stil
maneuvers required of it.

The object of the bizarre de
omy [PS, Oct. '78]. At low spe
ing takeoffs and landings, a
transport of the future woul
wing perpendicular to the bo
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





(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
P_e (MW)	1200	≈ 140
Cost ($M)	6,800	> 30,000 (?)

Starfire = $5.7/W$_e$

(per equivalent Watt)

$ITER ~ 35 × $Starfire

ITER is an experiment
Not a Power Plant

Advances in renewable energy technology have made the issue of fusion's cost unavoidable

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

	Capital Cost	1985	2014
Fission:	$\$5.5/W_e$	43 GWy (96 units)	91 GWy (94 units)
Solar PV:	$\$3.9/W_e$	0.0011	2.1 GWy
Solar Thermal:	$\$5.1/W_e$		
Onshore Wind:	$\$2.2/W_e$	0.0007	21 GWy
Offshore Wind:	$\$6.2/W_e$		

- *Sometime in the future*, fusion energy research must show cost competitiveness and "economic viability"

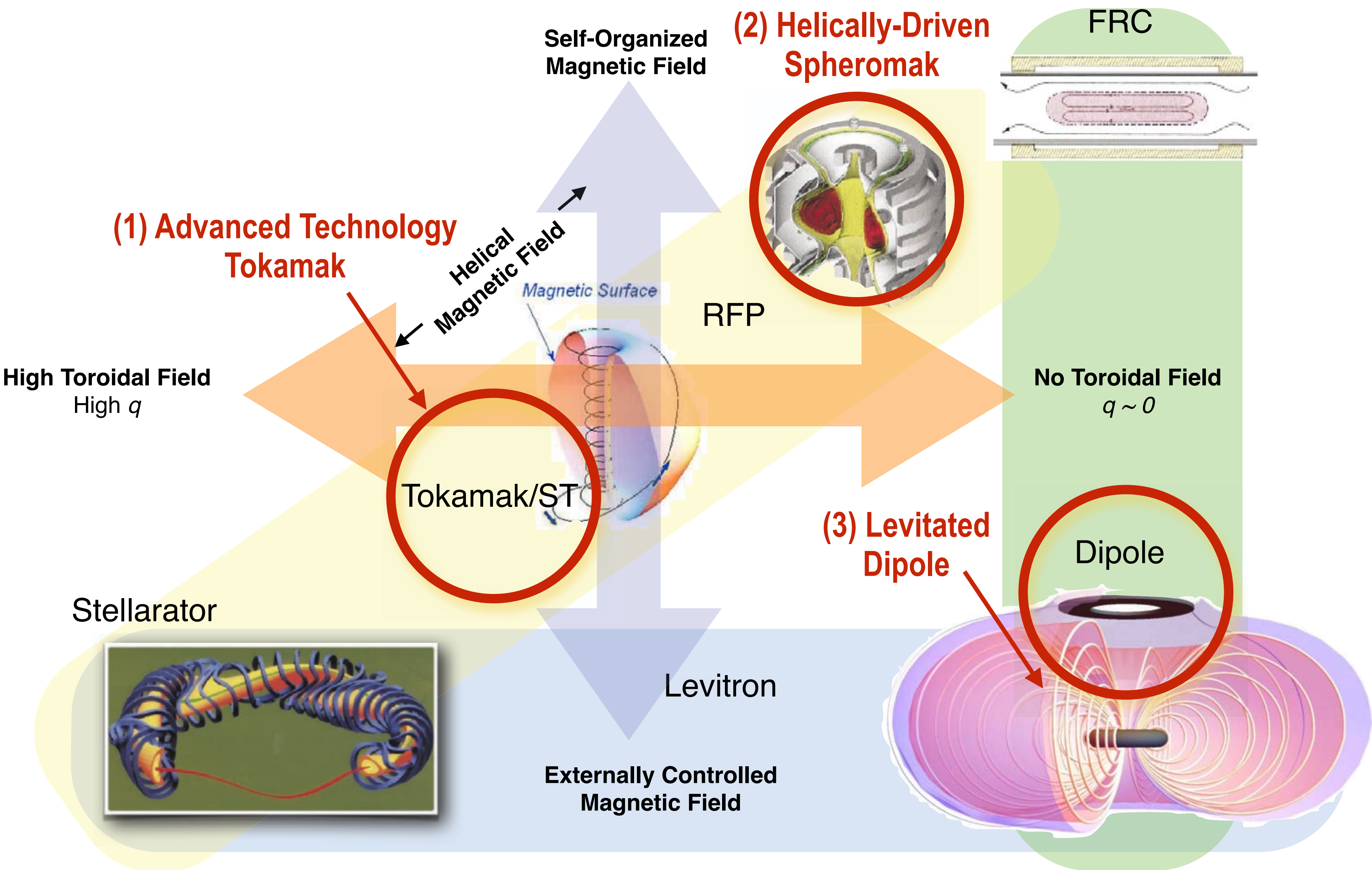
Outline

- Columbia University's plasma physics experiments
- Many types of plasma tori: testing our predictive understanding
- Fusion energy needs innovation 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

- **Innovations and new ideas from creative new scientific investigations are the only way to address these challenges**

Three Examples of Fusion Innovation



How to Design a Tokamak

Better

- **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, $q \sim 3$

Optimize Shape

- **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)

Control Instability

- **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 $\beta \sim 2.5\%$

Better Magnets

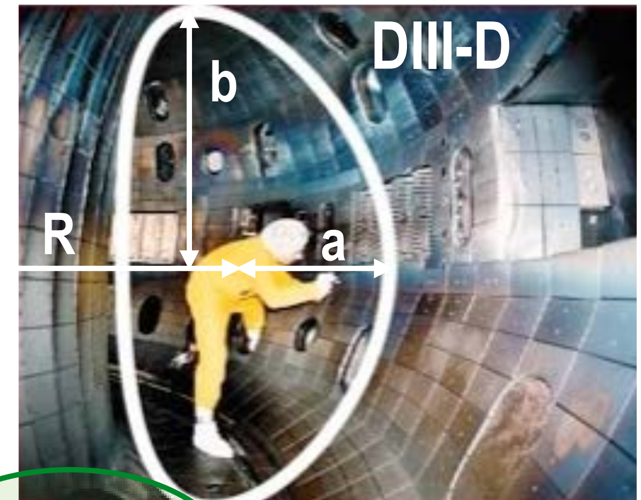
- **Select magnetic field in superconductor (11.8 T)** and **shielding (1.4 m)**, determines size, plasma density, energy, and fusion power
  - R = 6.2 m, B = 5.3 T, $n = 10^{20}$ m^{-3}, 400 MW fusion power, 350 MJ plasma energy, **50 GJ** magnet energy, **0.9 GJ** plasma current energy (*enough to melt half ton of steel*)

Improve Confinement

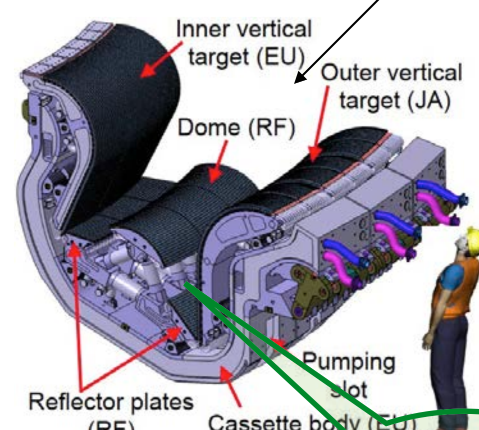
- **Check plasma energy confinement** needed to achieve desired fusion gain, Q = (Power Out)/(Power In) ~ 10
  - $\tau_E \sim 3.7$ sec requiring only 40 MW of injected power (gyroBohm: **Yes!!**) and 120 MW power to divertor
- **Check divertor cooling (must be less than 10 MW/m^2**, **÷ 6 of surface 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…**

Advanced Fuels Liquid Blankets

Spread the Heat



54 Divertor Segments (9 tons each)

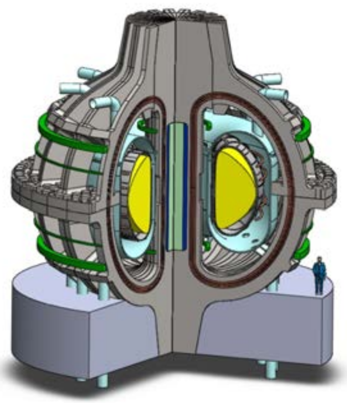


(1) Advanced Technology Tokamak

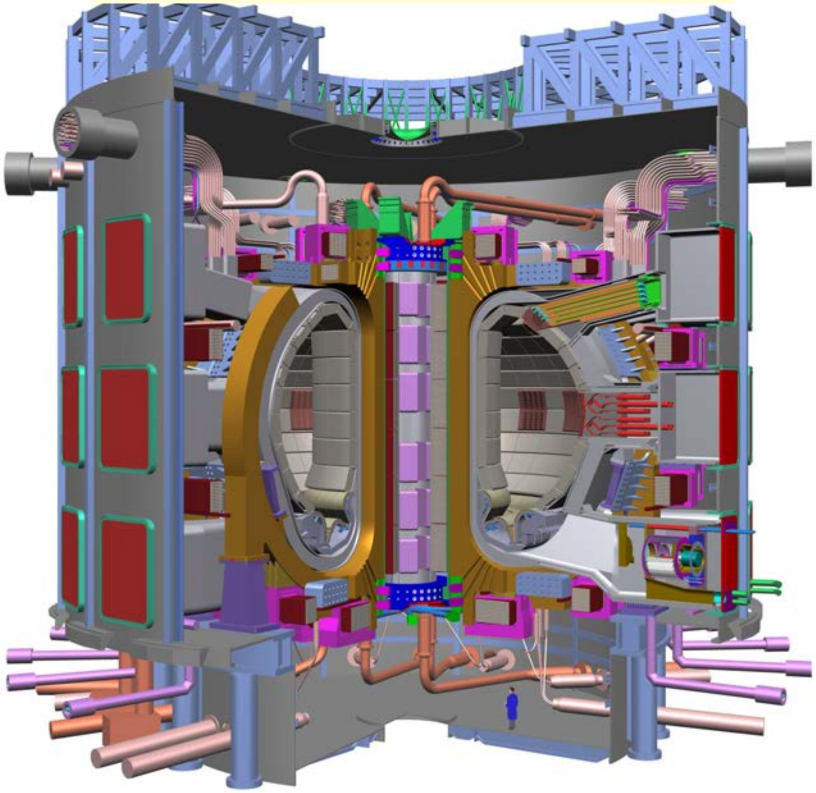
Prof. Dennis Whyte's Lecture (Monday)

- ***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

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

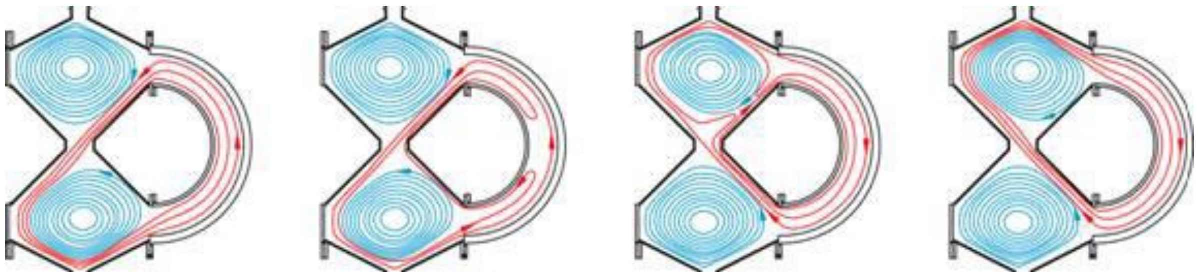


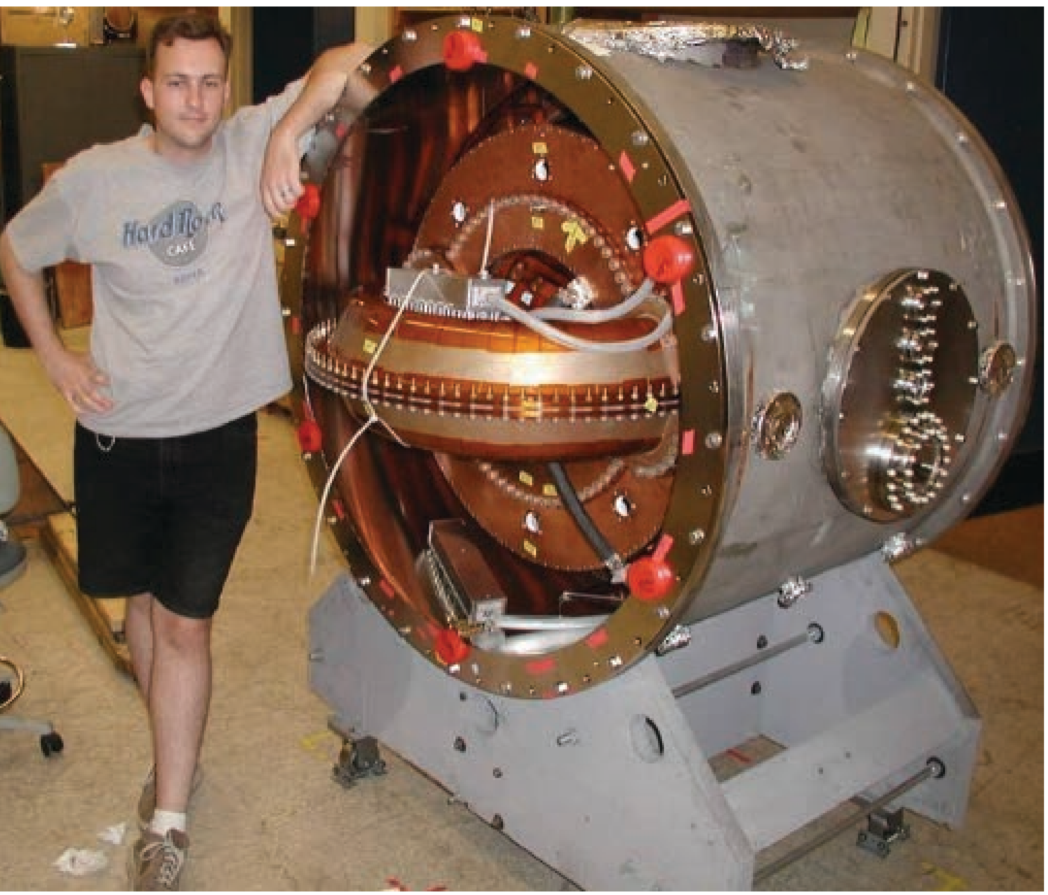
Fusion power: 500 MW
Q = 10
B= 5.3 T

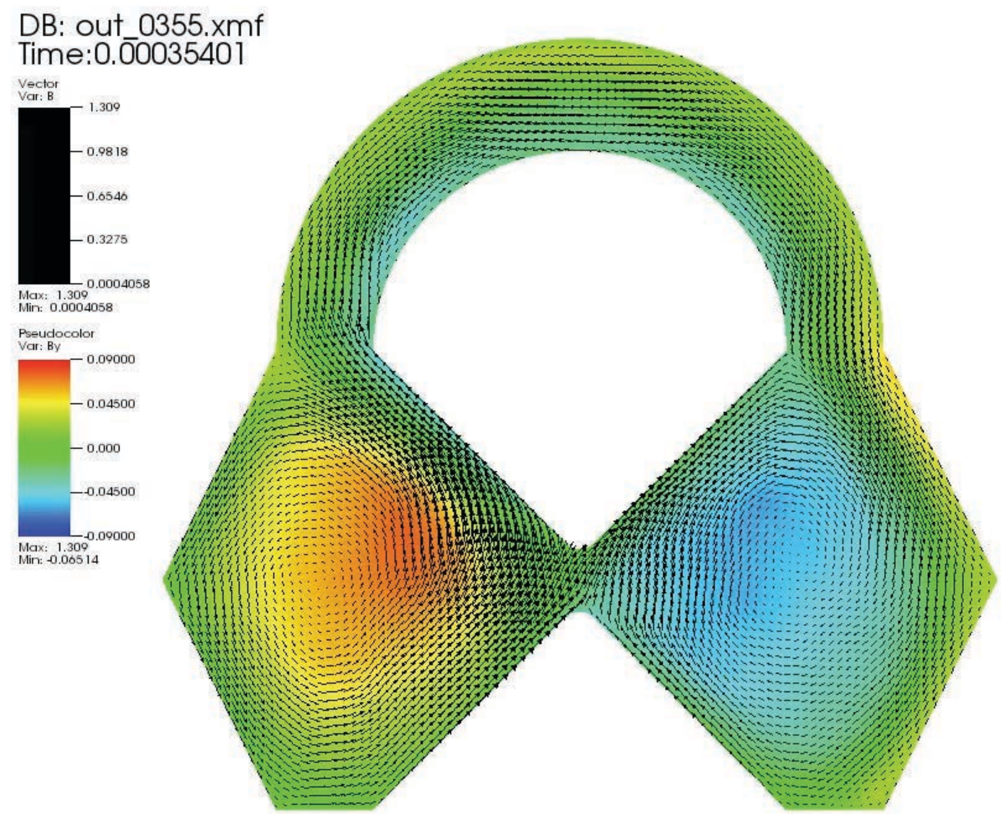


(2) Helically-Driven Spheromak

(University of Washington)



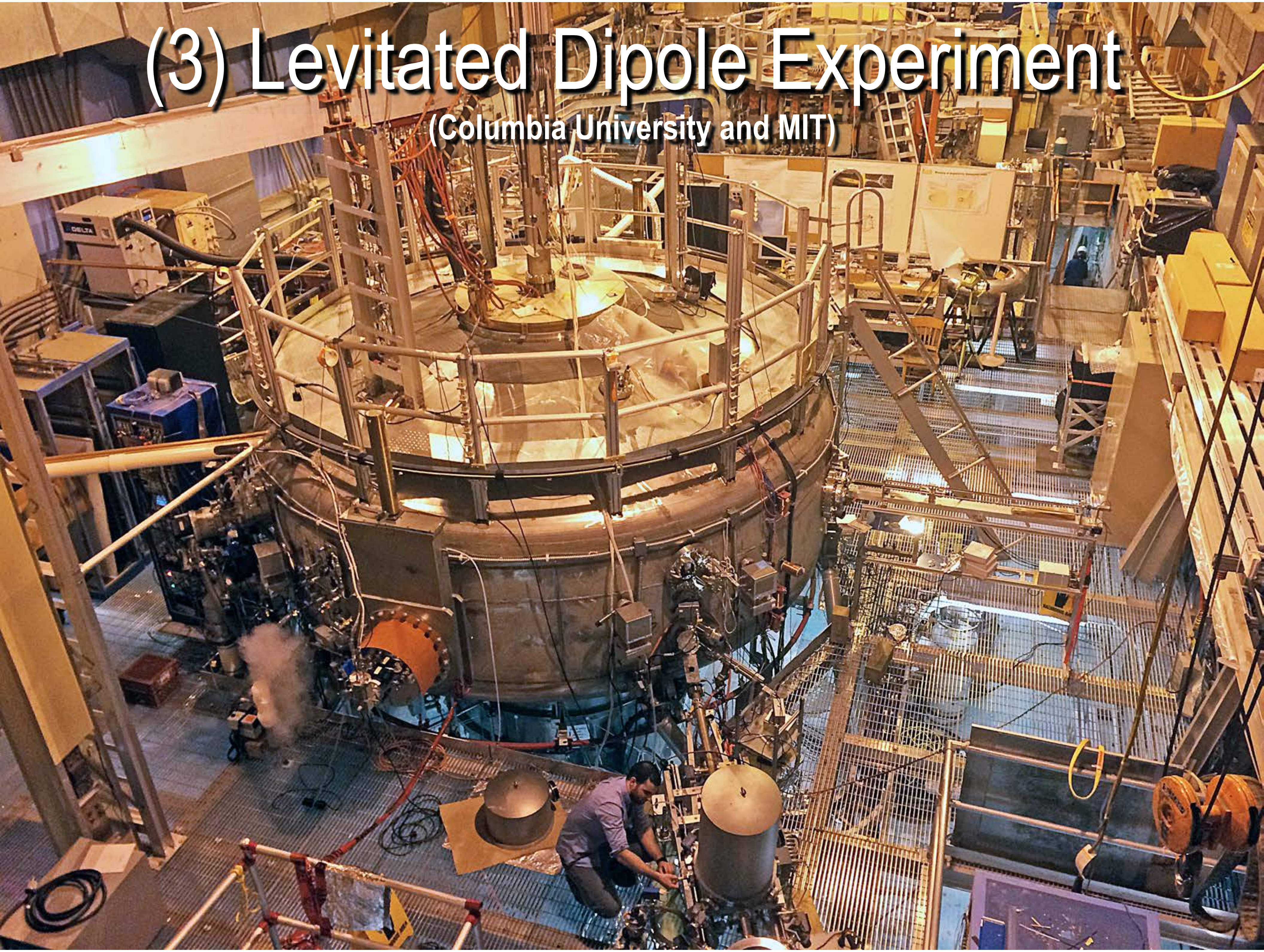




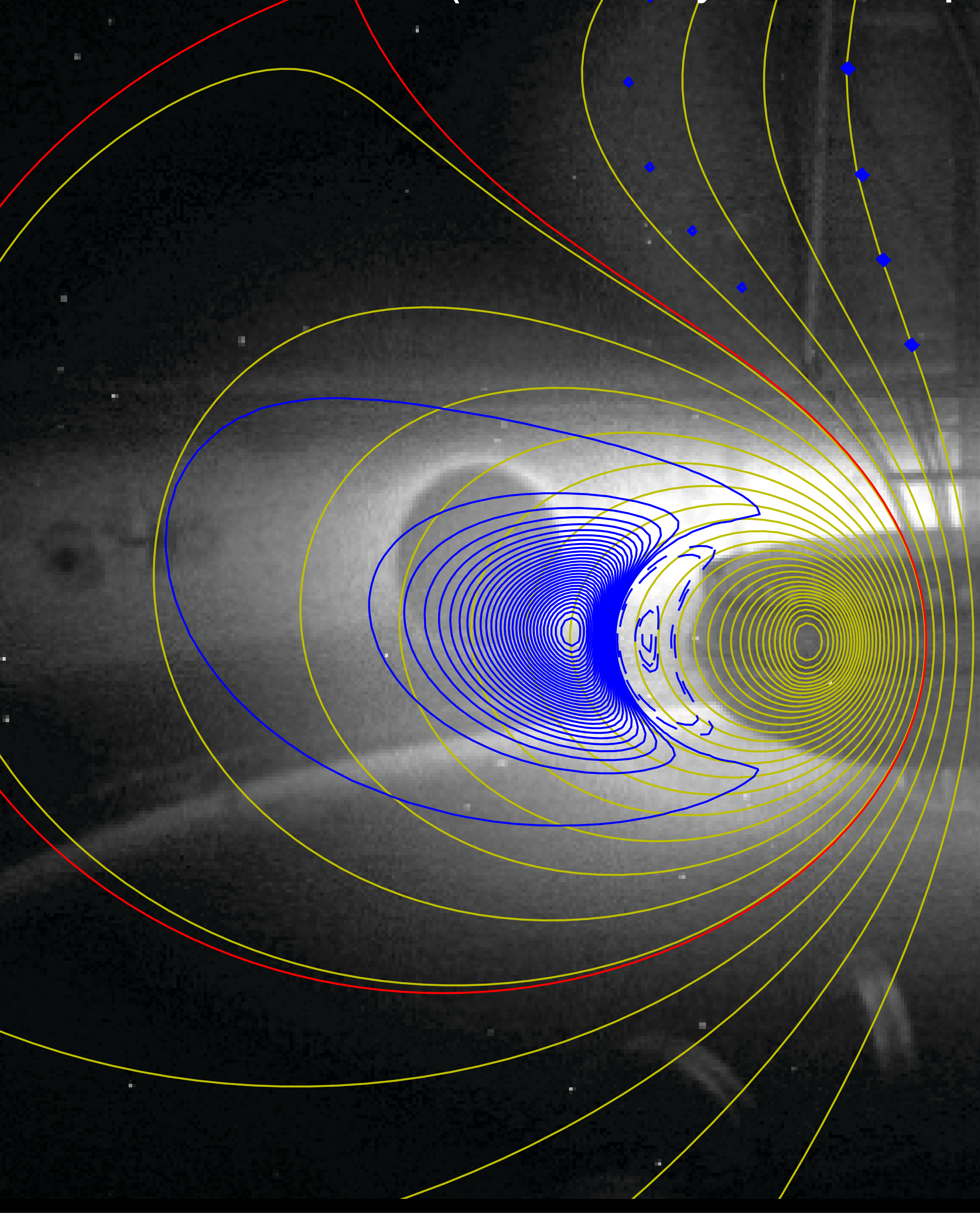
Jarboe, *et al.*, *Fus. Sci. and Tech.*, **66**, 369 (2014)

(3) Levitated Dipole Experiment

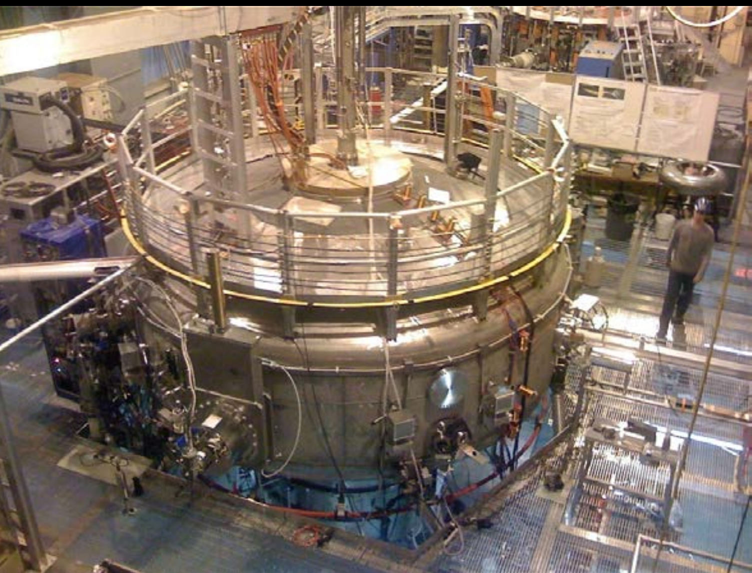
(Columbia University and MIT)

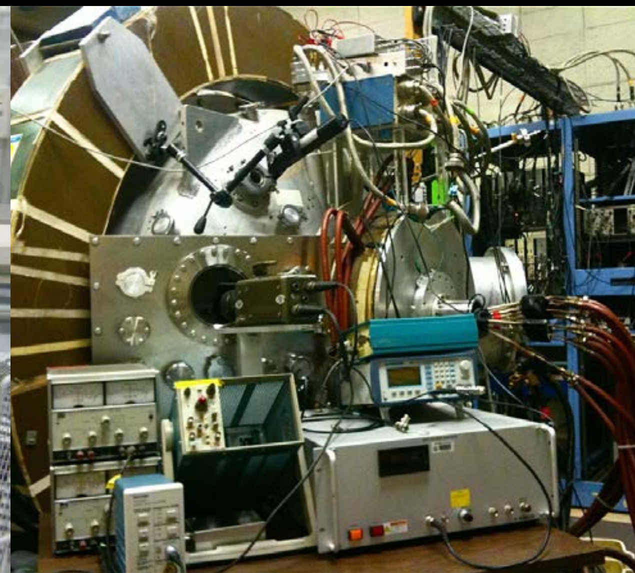


High β, Steady State, Self-Organized, Very-Large Plasma Torus
(and a very small superconducting coil)



Laboratory Magnetospheres: Facilities for Space-Relevant Physics Experiments

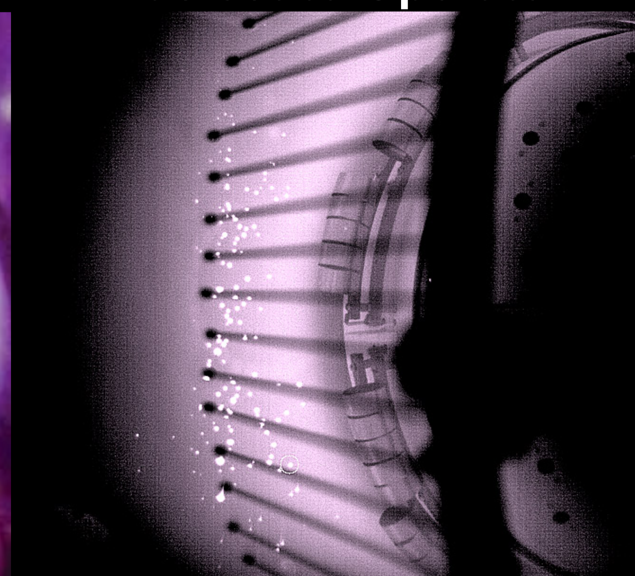




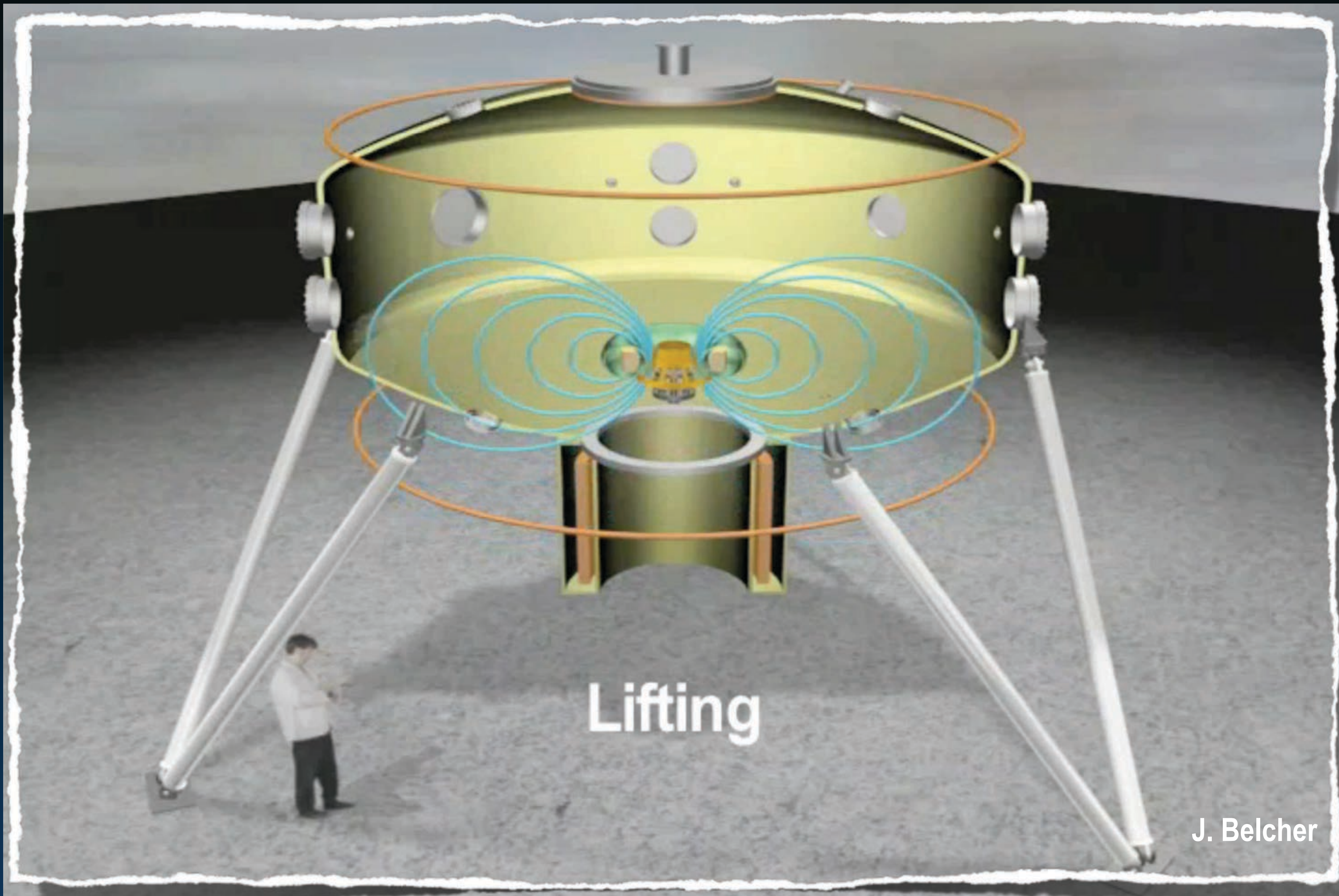
LDX (MIT)
Largest Size

RT-1 (U Tokyo)
Highest Power and β

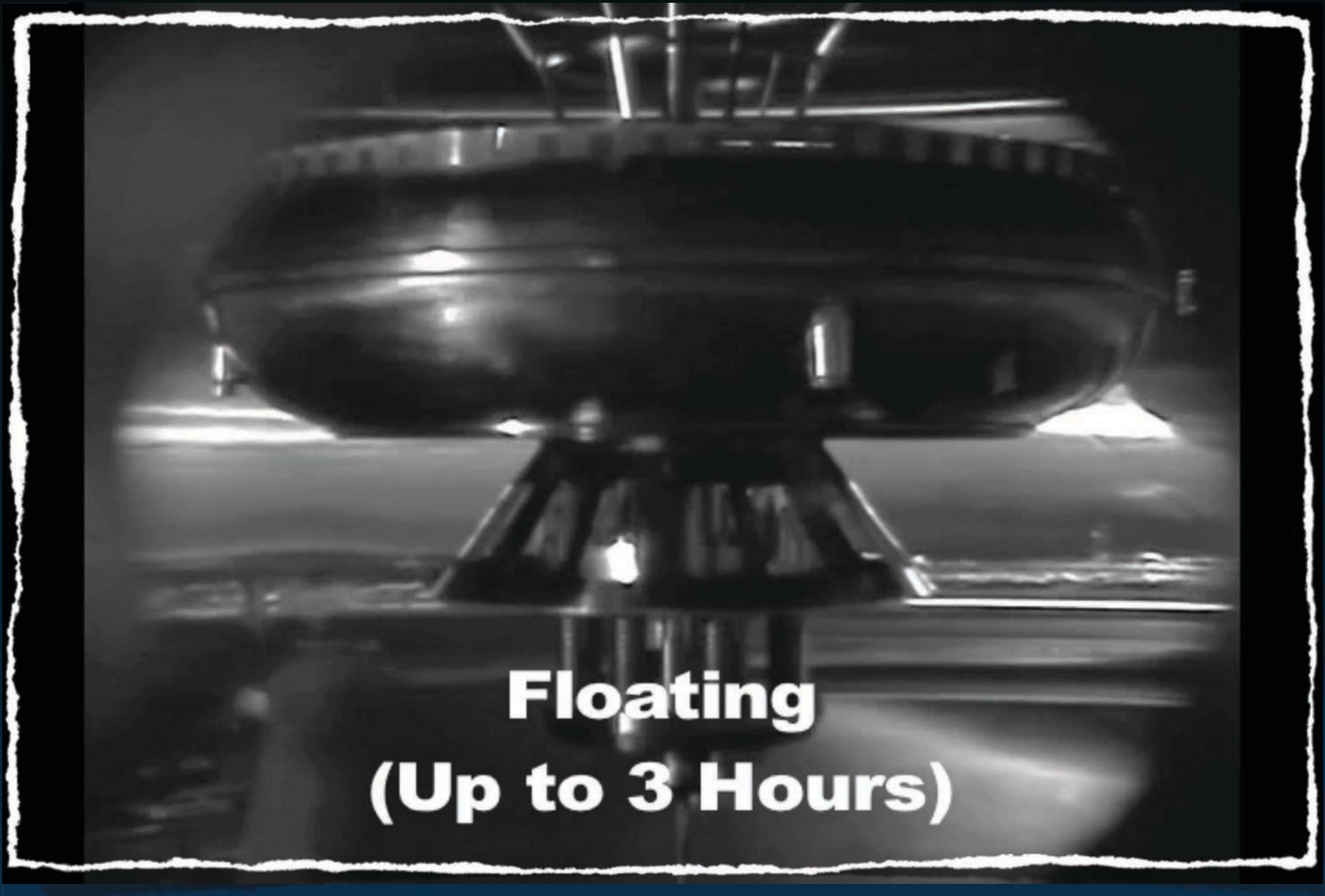
CTX (Columbia)
Easiest to Operate



Lifting, Launching, Levitation, Experiments, Catching

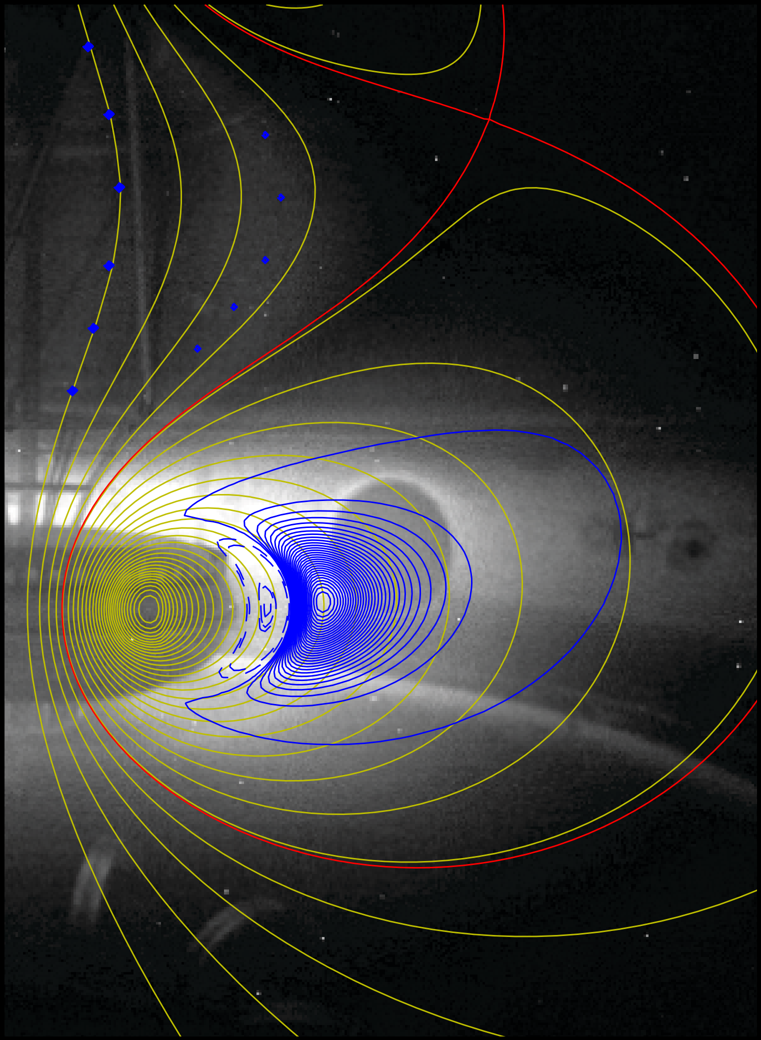


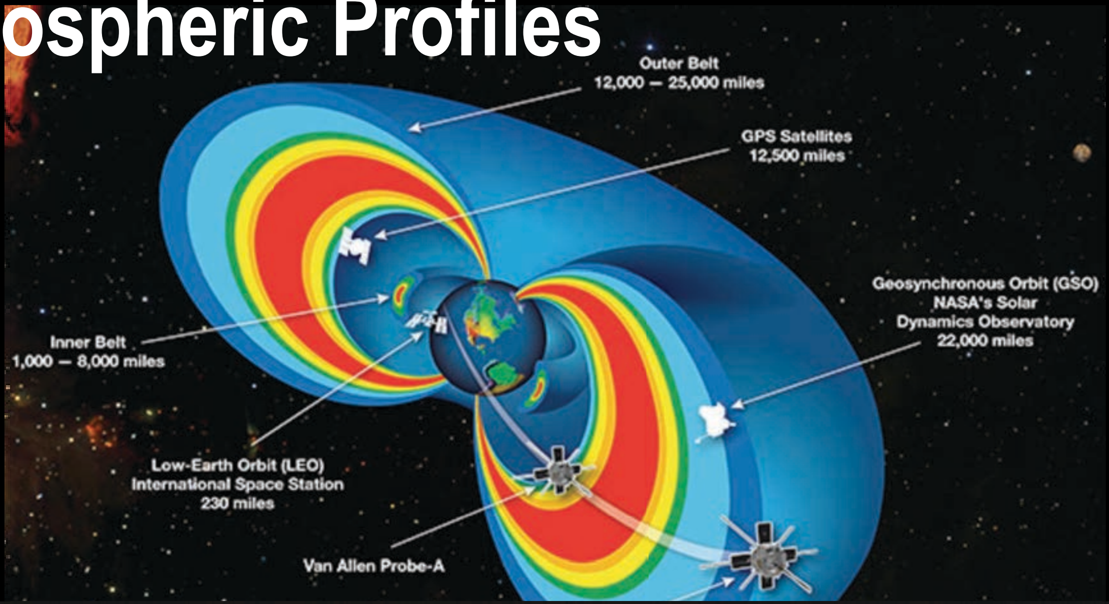
First Levitated Dipole Plasma Experiment



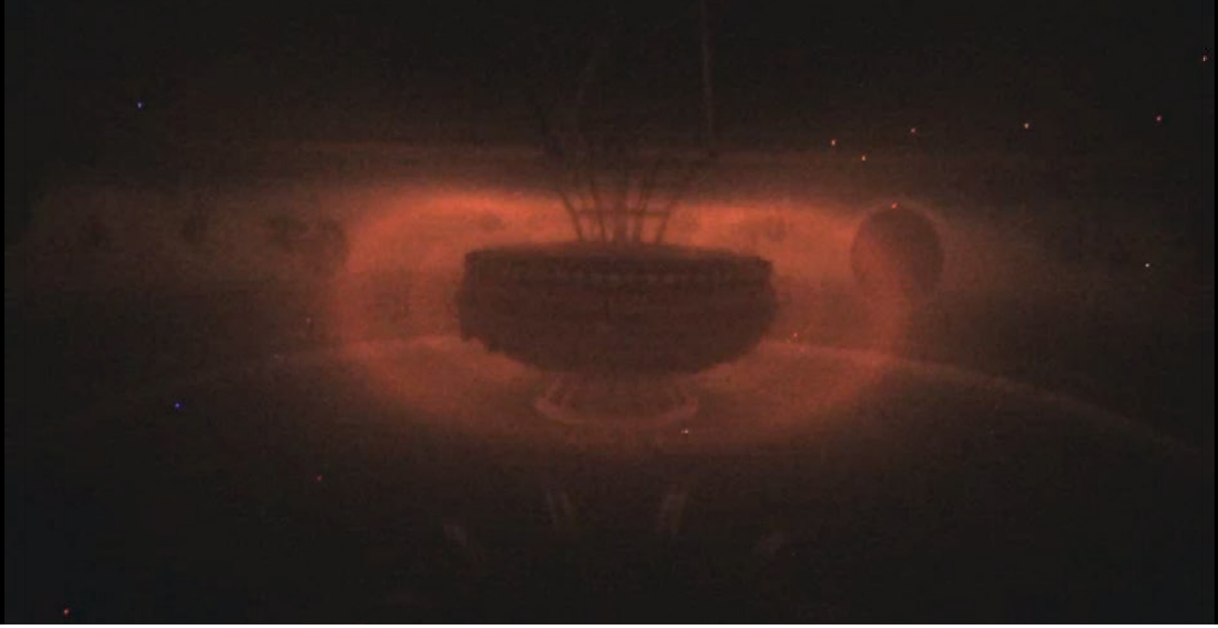
Levitated Magnet Achieves Extreme Plasma Beta and Magnetospheric Profiles

Big Plasma - Small Magnet



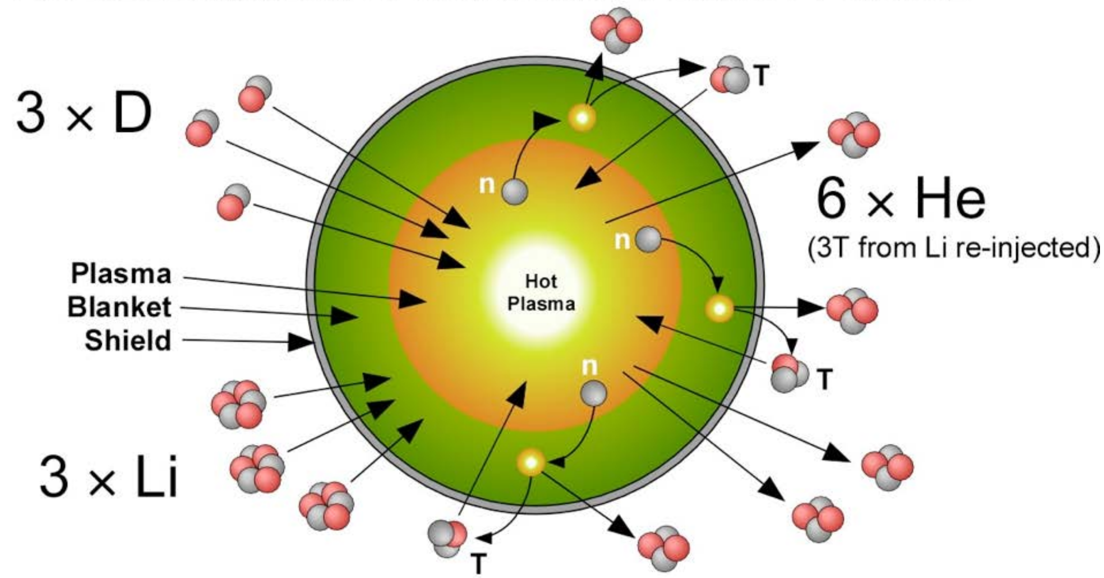


Nature's way to confined plasma



Two Pathways to Fusion

(a) 1st Generation Deuterium-Tritium Fusion

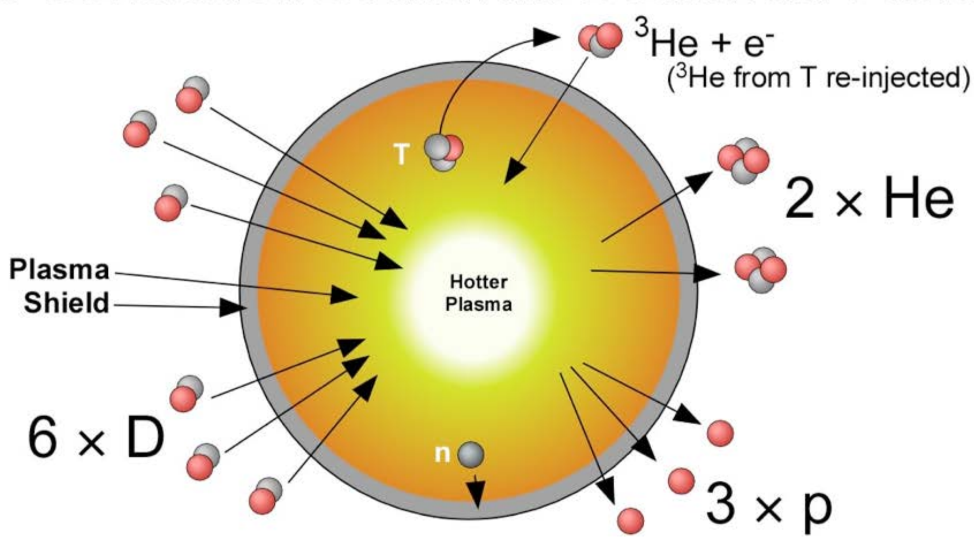


Problem: Fast Neutrons

- Develop materials that withstand > 40 dpa/FPY & 10 He appm/DPA
- Develop T breeding components

➡ Goal: Advance plasma confinement to reduce cost & control instabilities

(b) 2nd Generation Deuterium-Deuterium Fusion



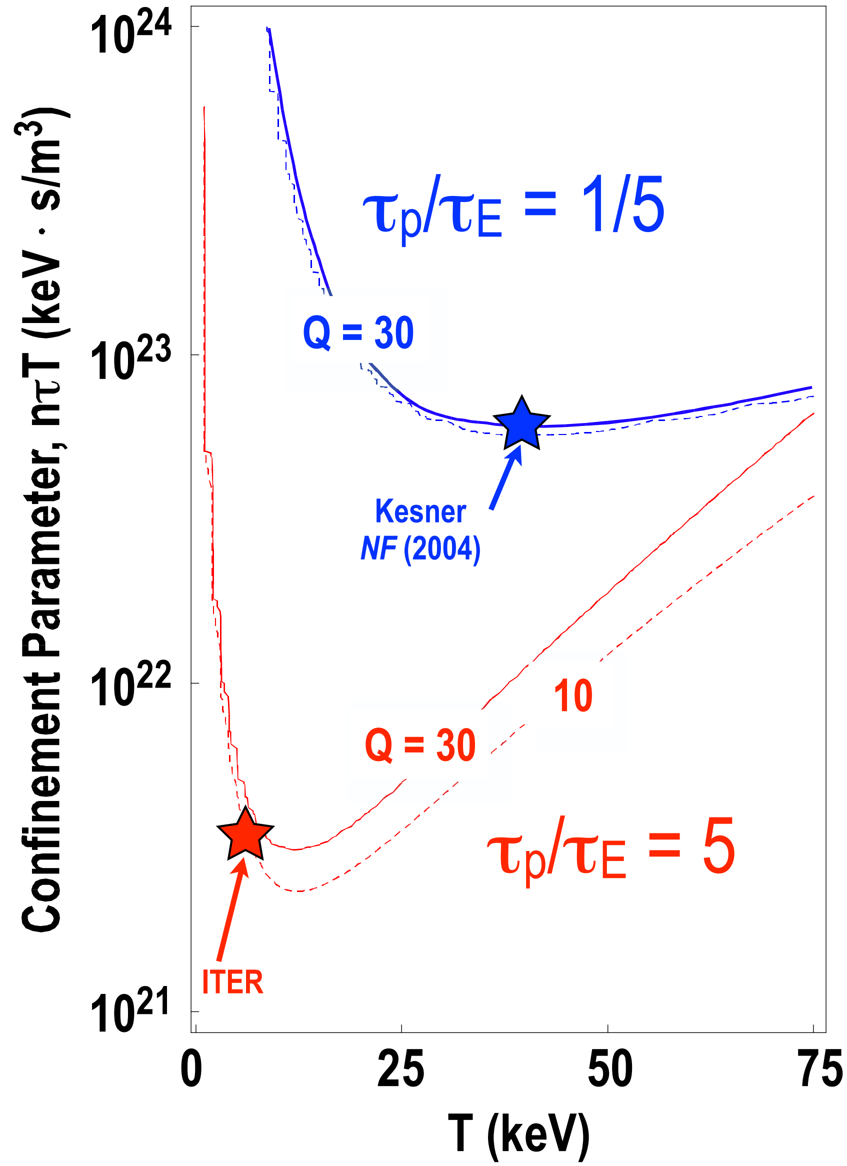
Problem: High plasma confinement

- 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
- Requires 10 fold confinement improvement
- Requires stronger, higher-field superconducting magnets



Innovations and New Ideas are Important to Science/Tech R&D

- **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)

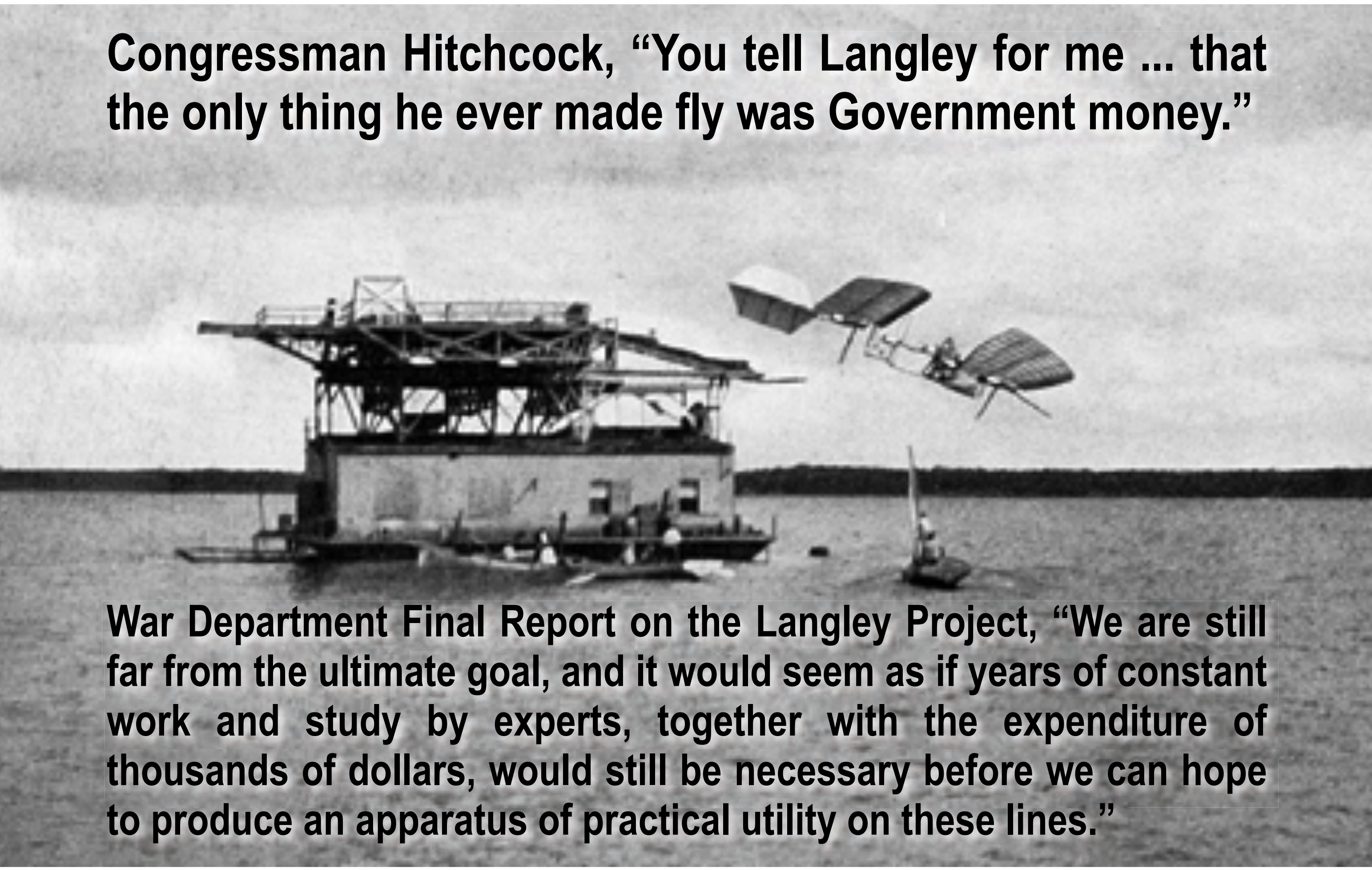
- **Carl Sagan:** “But the fact that some geniuses were laughed at does not imply that all who are laughed at are geniuses. They laughed at Columbus, they laughed at Fulton, they laughed at the Wright Brothers. But they also laughed at Bozo the Clown.” (1979)

- **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)

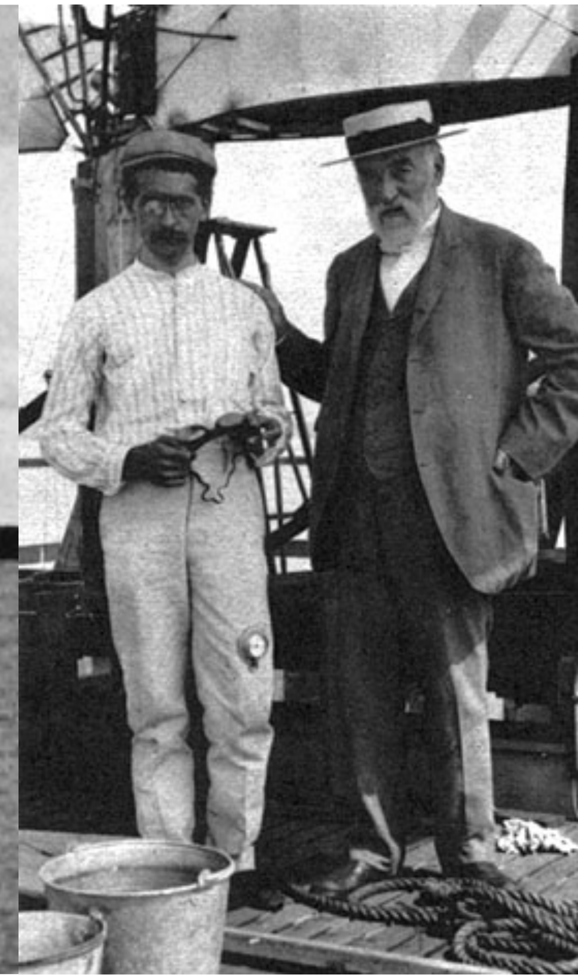
- **Wilbur Wright:** “In studying their failures we found many points of interest to us.” (1900)

“Langley’s Folly”

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

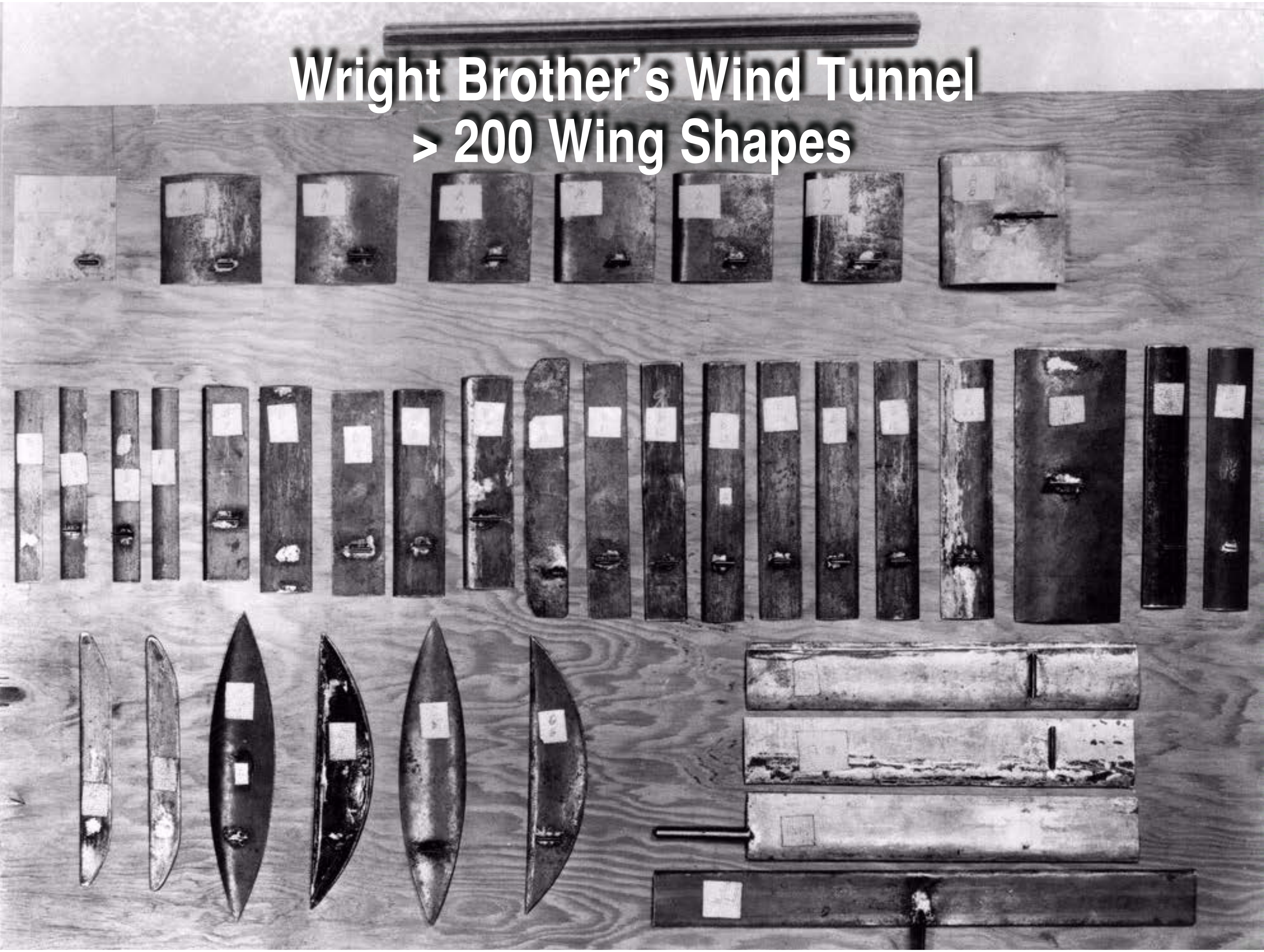


Failures on the Potomac: Oct. 7, 1903 and Dec. 8, 1903



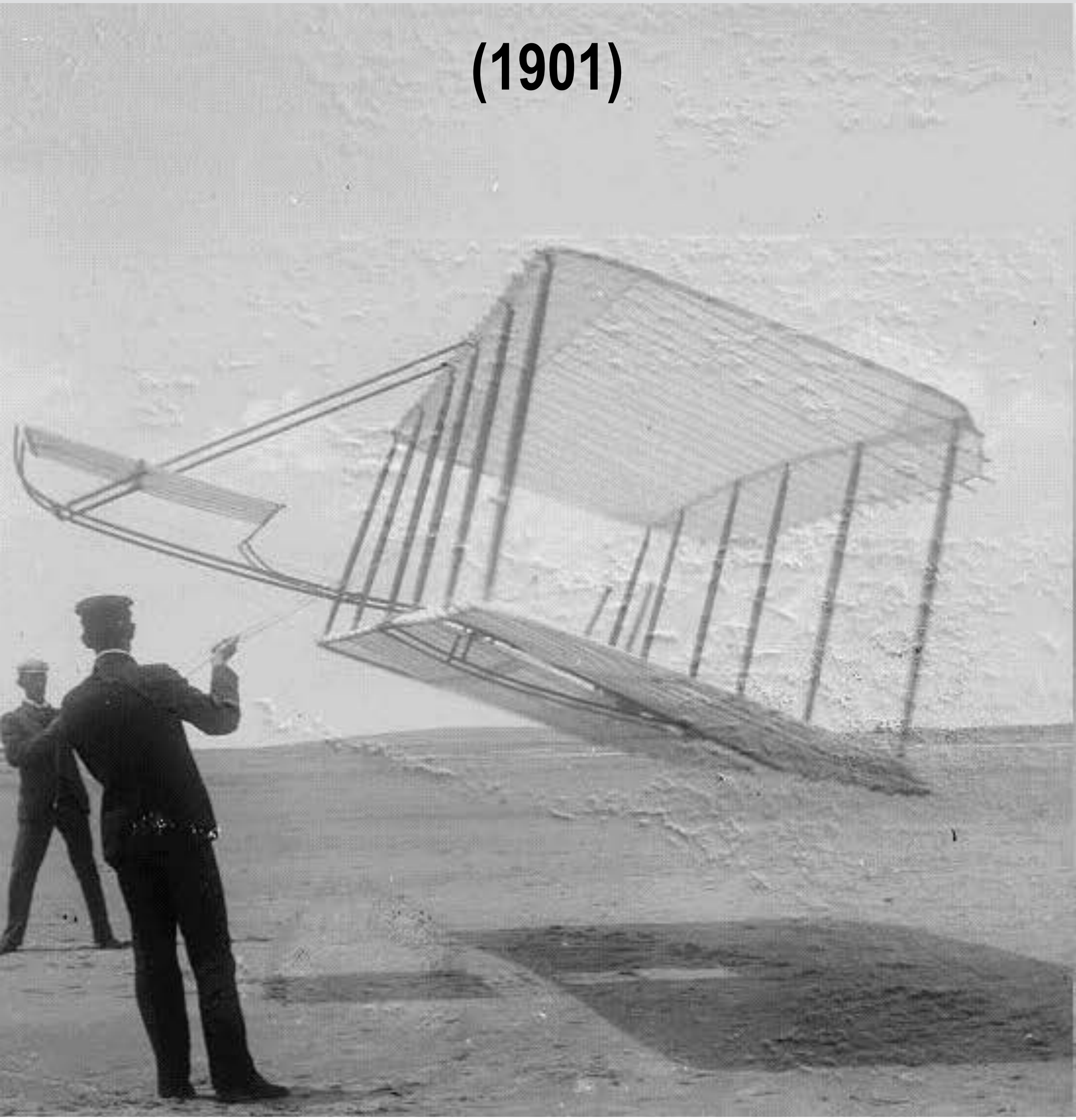
Charles Manly (pilot) & Samuel Langley aboard the Large Aerodrome-A (1903)


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 & Low-Cost Validation

Testing their Predictive Understanding of Aerodynamics



(1901)

(1902)

Fusion Science Innovation:
It's what fusion scientists do!

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

tokamak energy
a faster way to fusion

PPPL PRINCETON PLASMA PHYSICS LABORATORY

UC San Diego

LOCKHEED MARTIN

GENERAL ATOMICS

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Columbia
IN LVMINE TVO VIDEBIMVS LVMEN

AUBURN UNIVERSITY

MIT PSFC

generalfusion

UNIVERSITY of WASHINGTON

Los Alamos
NATIONAL LABORATORY
EST. 1943

Helion Energy

Ucla

TEXAS

Progress results when we learn from every new idea!

Summary

- Columbia University's plasma physics experiments
- Many types of plasma tori: testing our predictive understanding
- Fusion energy needs innovation 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

- **Innovations and new ideas from creative new scientific investigations are the only way to address these challenges**