Introduction to Magnetic Fusion Research

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National Undergraduate Fusion Fellowship Program
8 June 2000

Today is an Exciting Time for Fusion

- Tremendous progress in *understanding* how to confine & control high-temperature matter
- Experiments are extending the limits technology: *superconductivity, lasers, heat sources, advanced materials, systems control, and scientific computation,…*
- Operational "certification" achieved at National Ignition Facility (NIF) *(See Dan Clark's talks on Thur-Fri.)*
- International community to build ITER: the first burning plasma experiment at the scale of a power plant & *the world's largest energy science partnership.*

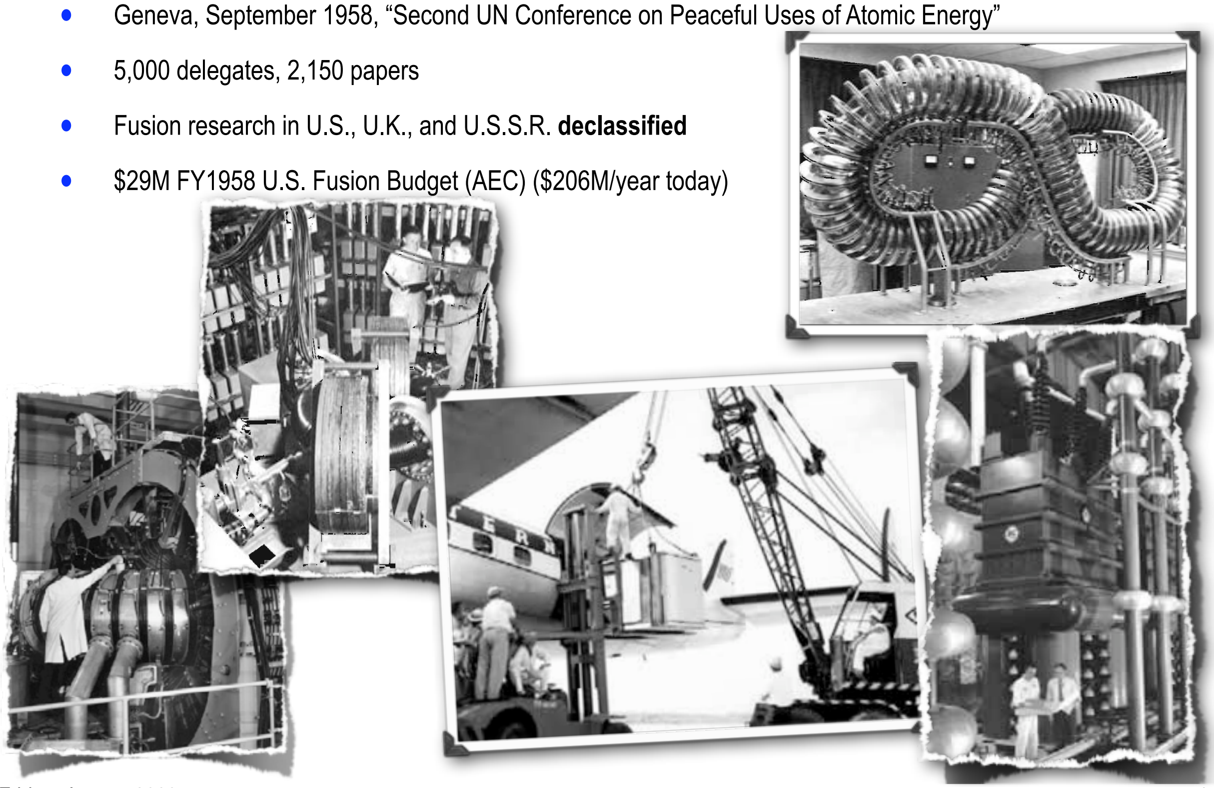
Happy Anniversary

NASA founded October 1, 1958

Discovery of the radiation belts
Explorer 1 (January 31, 1958) and
Explorer III (March 26, 1958)

Official Declassification of Controlled Thermonuclear Fusion Research

- Geneva, September 1958, “Second UN Conference on Peaceful Uses of Atomic Energy”
- 5,000 delegates, 2,150 papers
- Fusion research in U.S., U.K., and U.S.S.R. **declassified**
- $29M FY1958 U.S. Fusion Budget (AEC) ($206M/year today)



My Fusion Viewpoint

- Fusion energy science is still a "young" field
- Fusion energy is still "science-based" R&D
- Like other energy sources, fusion power plants have configuration options. *Future fusion power plants will probably look different from today's experiments.*
- Discoveries ahead!
- While fusion systems appear complicated and expensive, fusion has overwhelming advantages as a sustainable carbon-free energy source.

Magnetic Fusion Research
Outline

- Fusion primer
- Fusion: "**Green**" nuclear power
- Magnetic fusion energy primer
- ITER: Fusion at the scale of a power plant
- Columbia University's plasma physics experiments

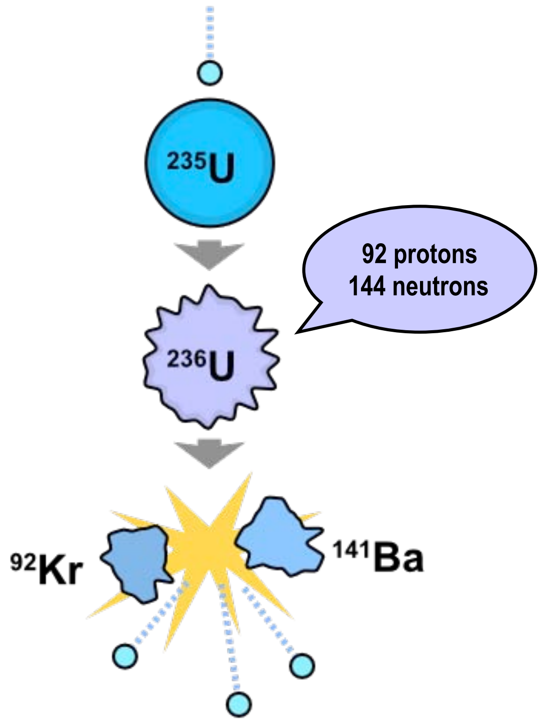
Forces of Nature

Gravity	*Tidal Energy*
Electromagnetic/ Molecular	*Combustion, Batteries, "Everyday" Energy and Chemistry*
Weak/Radiation	*Geothermal Energy*
Strong/Nuclear	*Fission, Fusion, and Solar (including wind, hydro, …)*

Chemical vs. Nuclear Energy Density

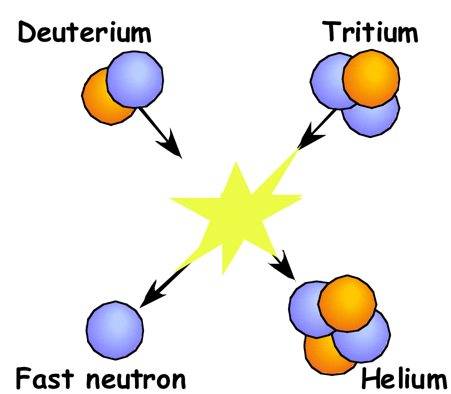
Why Fission is (Relatively) Easy to Do…

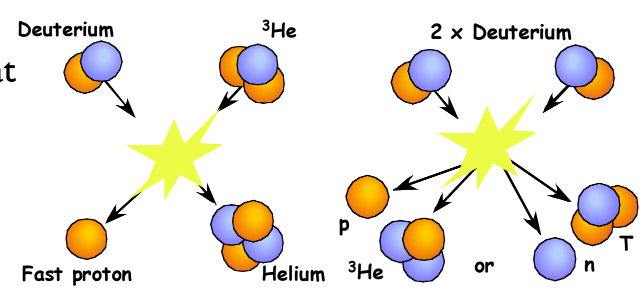
- Nuclear force is very-short ranged. Must get very close!
- Neutrons can easily split big, positively-charged nuclei…
- Because **neutrons are neutral!**
- Nucleons like to be paired (even numbers!) so certain nuclei are fissile: ^{233}U, ^{235}U, ^{239}Pu



Why Fusion is (Really, Really) Hard to Do…

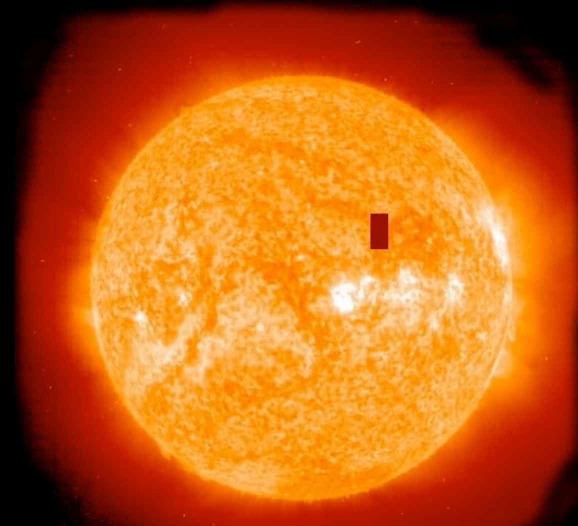
- Nuclear force is very-short ranged. Must get very close!
- Fusion requires close contact between light nuclei, like D, ^{3}He
- Difficult because all light nuclei are **positively charged!**
- Fusion energy occurs only at temperatures approaching 150,000,000 degrees!





Fusion in our Sun

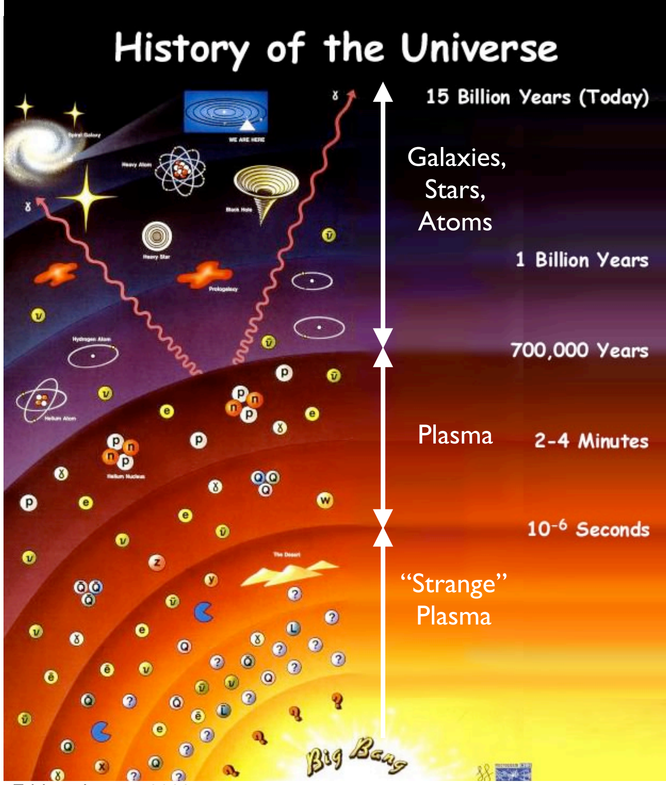
- 90% H, 9% He, 1% others
- Solar core: 15,000,000°
- (H + H) fusion rate limited by "Deuterium Bottleneck" or by high coulomb barrier in (H + C), (H + N) (Hans Bethe, Nobel 1967)
- Low power density (~1,000 W/m^3) with > 6 billion year burn-up time!



SOHO EUV Image Thursday 17 February 2005

Proton (hydrogen) fusion can not be used for a power plant. It's too slow!

100-300 s after the "Big-Bang": The Age of Fusion



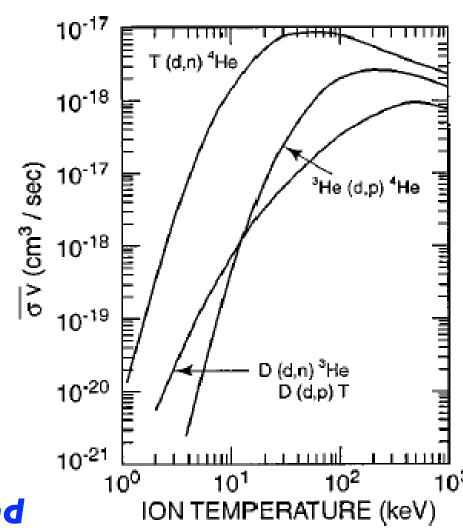
- At 100 sec, the universe cools to 1,000,000,000°
- Protons and neutrons fuse to Deuterium (heavy hydrogen). The whole universe is a "**burning plasma**"!
- D + D → ^{3}He + p
  D + D → T + p
  D + T → ^{4}He + n
  D + ^{3}He → ^{4}He + p
- At 300 sec, nearly all D has fused to ^{4}He . Universe cools and expands. Fortunately…

Deuterium (also ^{3}He and Lithium): Nature's Gift from the "Big Bang"!

- After the "Age of Fusion", the Universe consists of hydrogen (90%), ^{4}He (9%), D (0.02%), ^{3}He (0.01%) and a pinch of Li.
- Heavy elements, including uranium, created billions of years later in exploding stars.
- 1 g of D yields 4 MW-days (4 times 1 g U^{235})

Fusion Reactions for Earthly Power

$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He}\,(3.5\mathrm{MeV}) + \mathrm{n}\,(14.1\mathrm{MeV})$$
$$\mathrm{D} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He}\,(3.6\mathrm{MeV}) + \mathrm{H}\,(14.7\mathrm{MeV})$$
$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{He}\,(0.82\mathrm{MeV}) + \mathrm{n}\,(2.45\mathrm{MeV})$$
$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\,(1.01\mathrm{MeV}) + \mathrm{H}\,(3.02\mathrm{MeV})$$



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

- **Opens Friday!**
- **It is the near future. Astronaut Sam Bell is living on the far side of the moon, completing a three-year contract with Lunar Industries to mine Earth's primary source of energy, Helium-3. It is a lonely job, made harder by a broken satellite that allows no live communications home. Taped messages are all Sam can send and receive.**

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

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

Fast n

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

T

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

- D-T fusion has largest cross-section and lowest T ~ 170,000,000°.
- Tritium is created from ^{6}Li forming a **self-sufficient fuel cycle**. Practically no resource limit (10^{11} TW y D; 10^4(10^8) TW y ^{6}Li)!
- **Notice**: ~ 80% of energy as fast neutrons (~ 1.5 m shielding).
  ➠ the source of fusion's technology & materials challenge.

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

D-D (^{3}He) Fusion

6D

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

^{3}He T

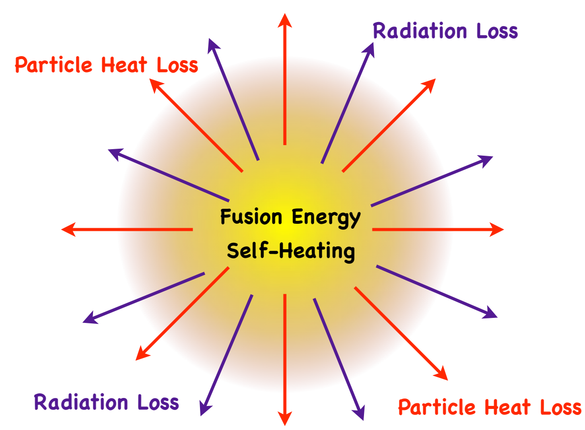
$$\approx 2\,(^4\text{He}) + 3H + e^- + n + \text{(41.5 MeV plasma)} + \text{(2.45 MeV blanket)}$$

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

Self-Sustained Fusion Burn

$$\frac{W_p}{\tau_E} + P_{rad} = (\text{Charged Particle Fusion Power})$$

- Lawson's condition
- τ_E is energy confinement time
- Only three reactions can be used within a thermonuclear fusion power plant: (i) D-D, (ii) D-T, (iii) D-He^3



$$
\begin{array}{lll}
(1a) & D + D \xrightarrow{50\%} & T(1.01\text{ MeV}) + p(3.02\text{ MeV}) \\
(1b) & \xrightarrow{50\%} & He^3(0.82\text{ MeV}) + n(2.45\text{ MeV}) \\
(2) & D + T \longrightarrow & He^4(3.5\text{ MeV}) + n(14.1\text{ MeV}) \\
(3) & D + He^3 \longrightarrow & He^4(3.6\text{ MeV}) + p(14.7\text{ MeV})
\end{array}
$$

Neutrons escape and heat surrounding blanket

Self-Sustained Fusion Burn

- Lawson's condition
- τ_E is energy confinement time
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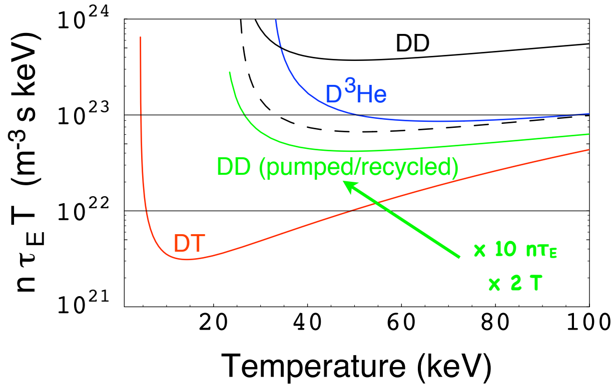

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(1a) & D + D & \xrightarrow{50\%} & T(1.01\ MeV) + p(3.02\ MeV) \\
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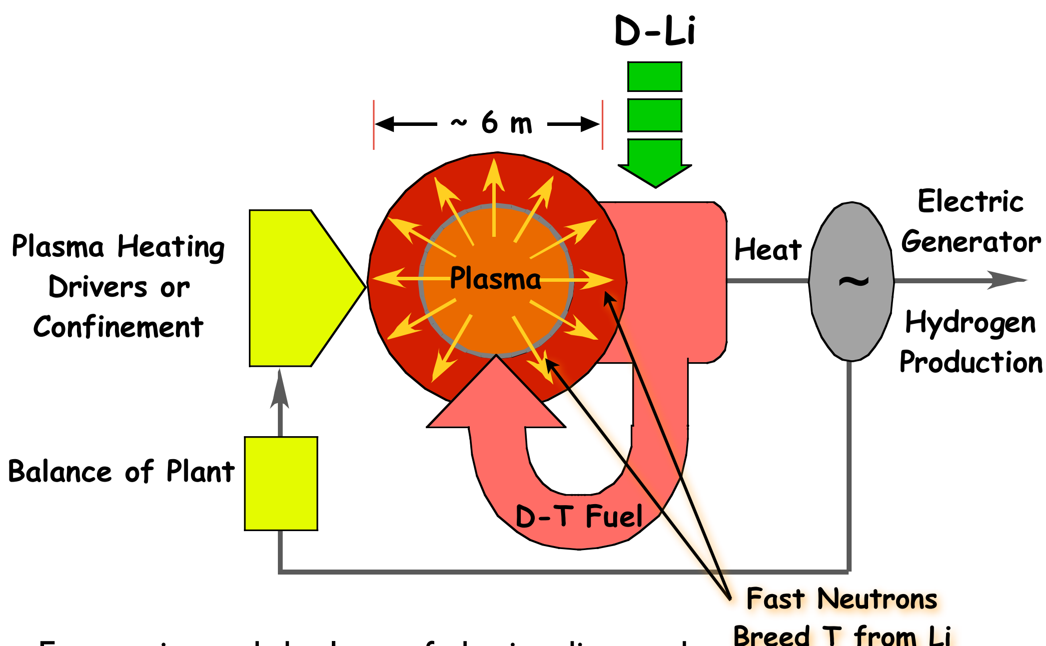
(3) & D + He^3 & \longrightarrow & He^4(3.6\ MeV) + p(14.7\ MeV)
\end{array}
$$

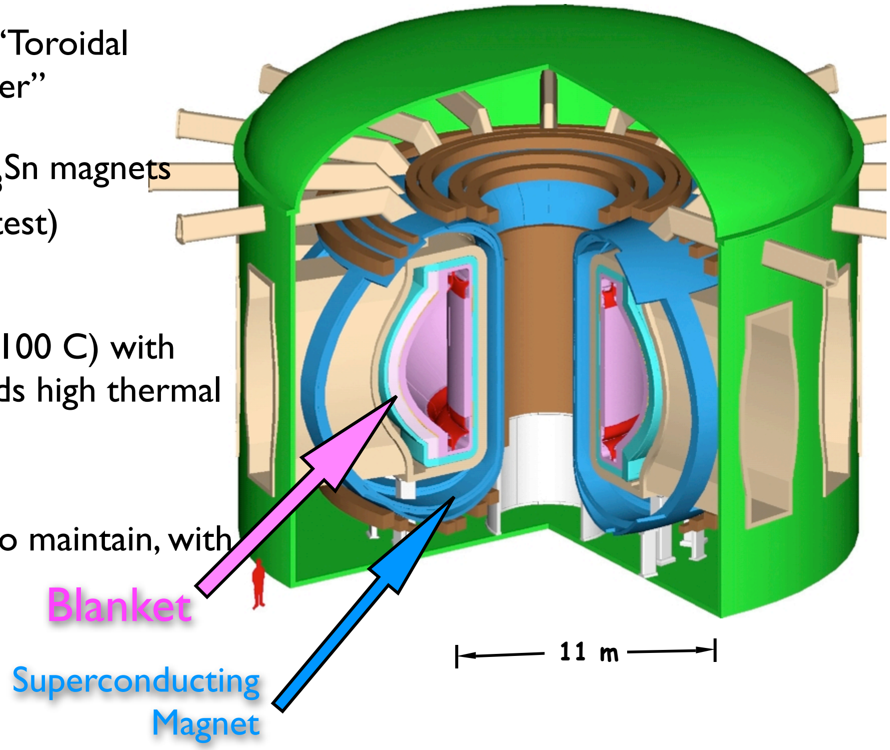
Elements of a D-T(Li) Fusion System



Economics and the laws of physics dictate the $\geq$ 6m scale of fusion power devices.
(**No** small **silver bullet!** nor small pilot-plant.)

Magnetic Containers are Toroidal

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



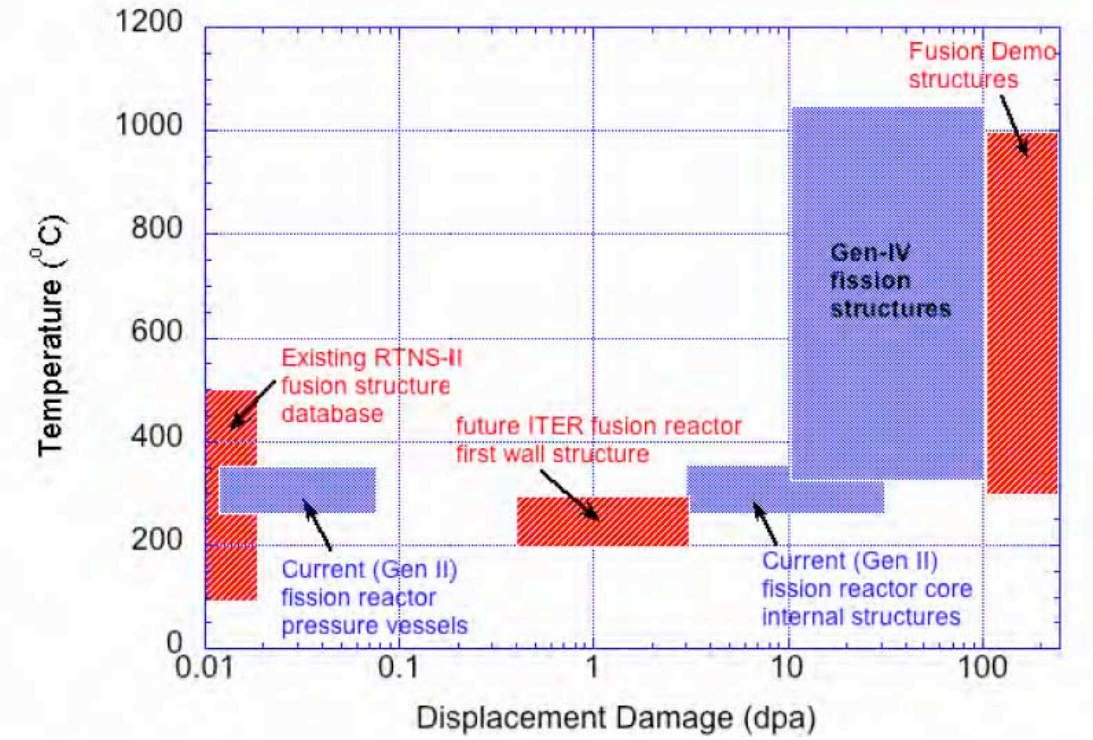
Can Fusion be "Green" Nuclear Power?

- No public evacuation plan. Low tritium inventory. Max offsite dose <1 rem; public and worker safety is assured in all events.
- No long term storage of radioactive material.
- While international inspection/monitoring will still be required, **fusion does not need any fertile/fissile material.**
- *Work still needed to demonstrate safety and environmental advantages of fusion…*

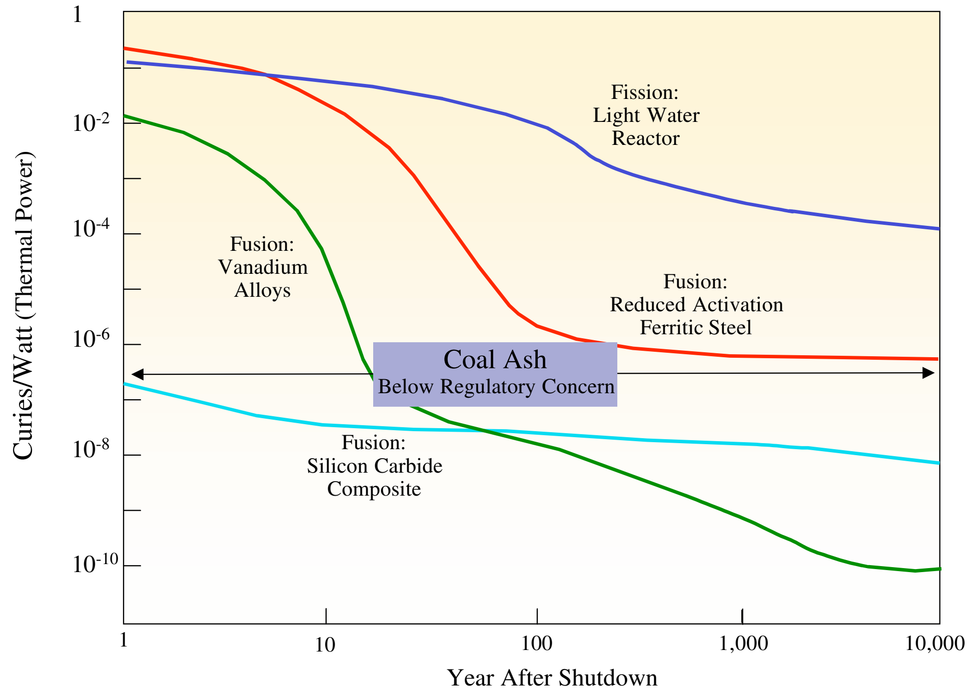
Fusion's Materials Challenge

- 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.
- **Good options exist**: Ferritic/martensitic steels, Vanadium alloys, Tungsten first wall, SiC/SiC composites, new nano-engineered materials, …

Significant Materials Challenges for Fusion and Gen-IV Fission



Attractive Low Activation Material Options for D-T Fusion



Two Approaches to Fusion Power

- Inertial Fusion Energy (IFE)
  - Fast implosion of high-density fuel capsules.

    Reaches ~ 200 Gbar from 25-35 fold radial convergence.
  - Several ~ 350 MJ (0.1 ton TNT) explosions per second.
- Magnetic Fusion Energy (MFE)
  - Strong magnetic pressure (100's atm) confine low-density (10's atm) plasma.
  - Particles confined within "toroidal magnetic bottle" for at least ~ 10 km and 100's of collisions per fusion event.
  - Fusion power density (~10 MW/m^3 and 20,000 × solar) allows plasma to be sustained for continuous power.

Two Approaches to Fusion Power

- Inertial Fusion Energy (IFE)
  - $n \sim 10^{30}\ m^{-3}$ $T \sim 20$ keV $\tau_E \sim 0.5$ nsec   ($n\,T\,\tau_E \sim 10^{22}$)
  - 30 times **more** particle density than diamond!

- Magnetic Fusion Energy (MFE)
  - $n \sim 10^{20}\ m^{-3}$ $T \sim 20$ keV $\tau_E \sim 5.0$ sec   ($n\,T\,\tau_E \sim 10^{22}$)
  - 250,000 times **less** particle density than air!

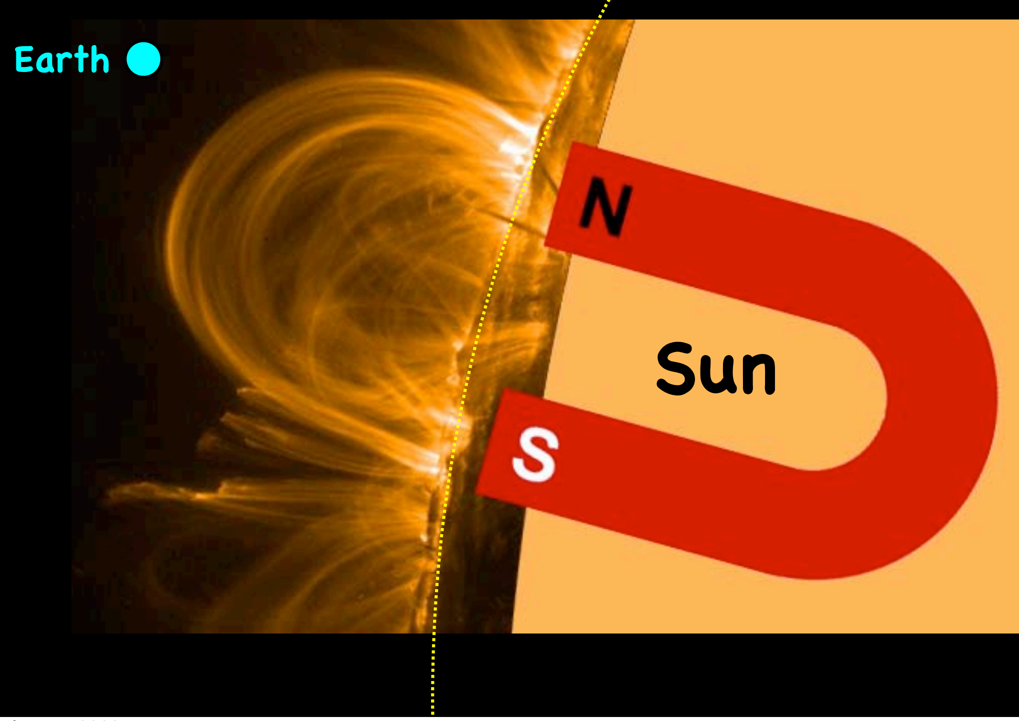
MFE is 10^{10} slower and less dense than IFE

MFE: Low Density Implies Long Mean-Free Path

- Coulomb collisions 100 times more frequent for D-T ions than for fusion events.
  (10,000 times more frequent for electrons!)
- Neutral charge-exchange cross-section is 30,000,000,000 times larger than fusion cross-section, so plasma must be fully-ionized and "thick", >2 m, to prevent gas penetration
- At 20 keV, mean-free-path for coulomb collisions about 10 km
- Magnetic confinement requires ion confinement for >1,000 km (620 miles!)

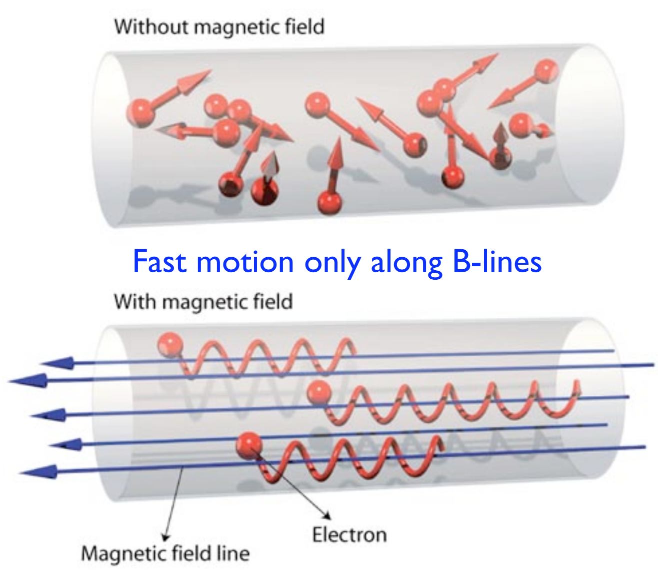
MFE plasma dynamics is nearly "collisionless"

Solar Magnetic Fields



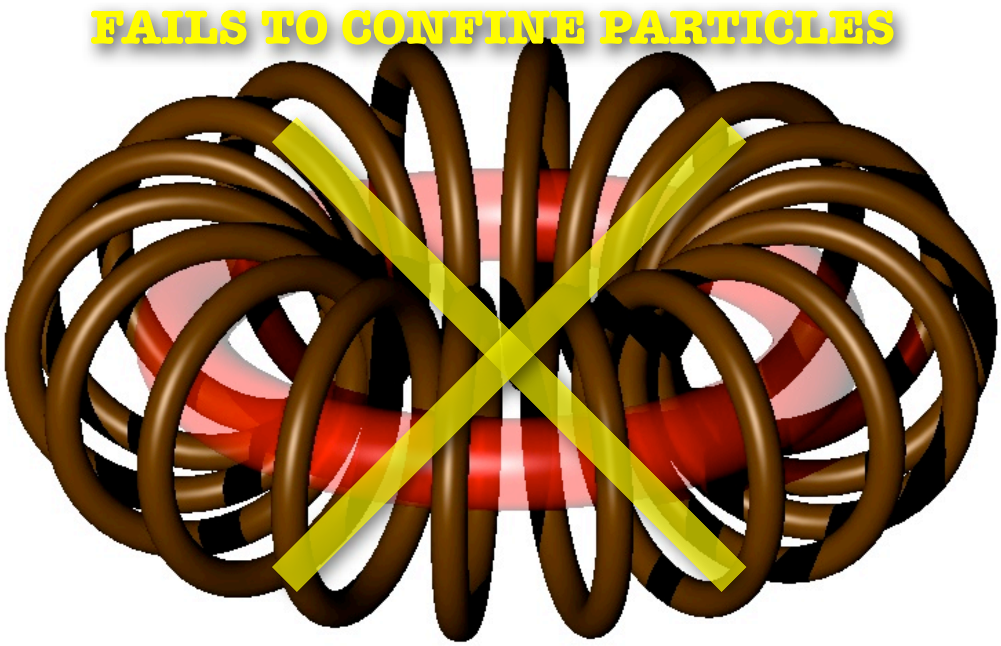
How Do Magnetic Fields Confine Ionized Matter?

$$\frac{d\mathbf{v}}{dt} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$



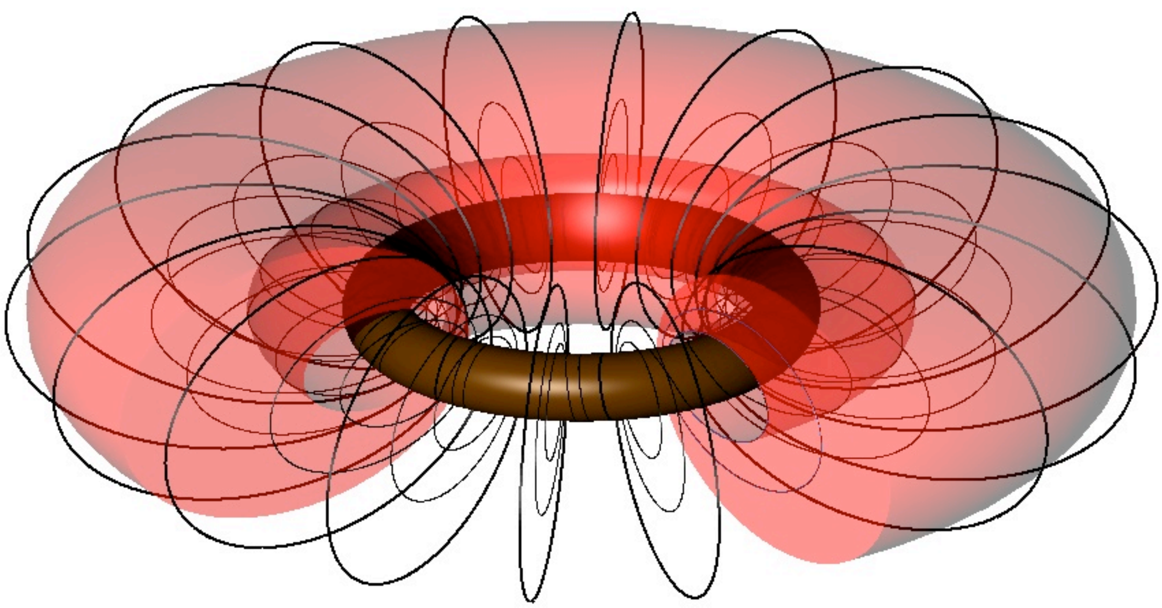
B = 2 T and T = 20 keV, then gyroradius ≈ 1cm
but must be confined along B-lines for hundreds of miles!!!

How to make a magnetic torus?



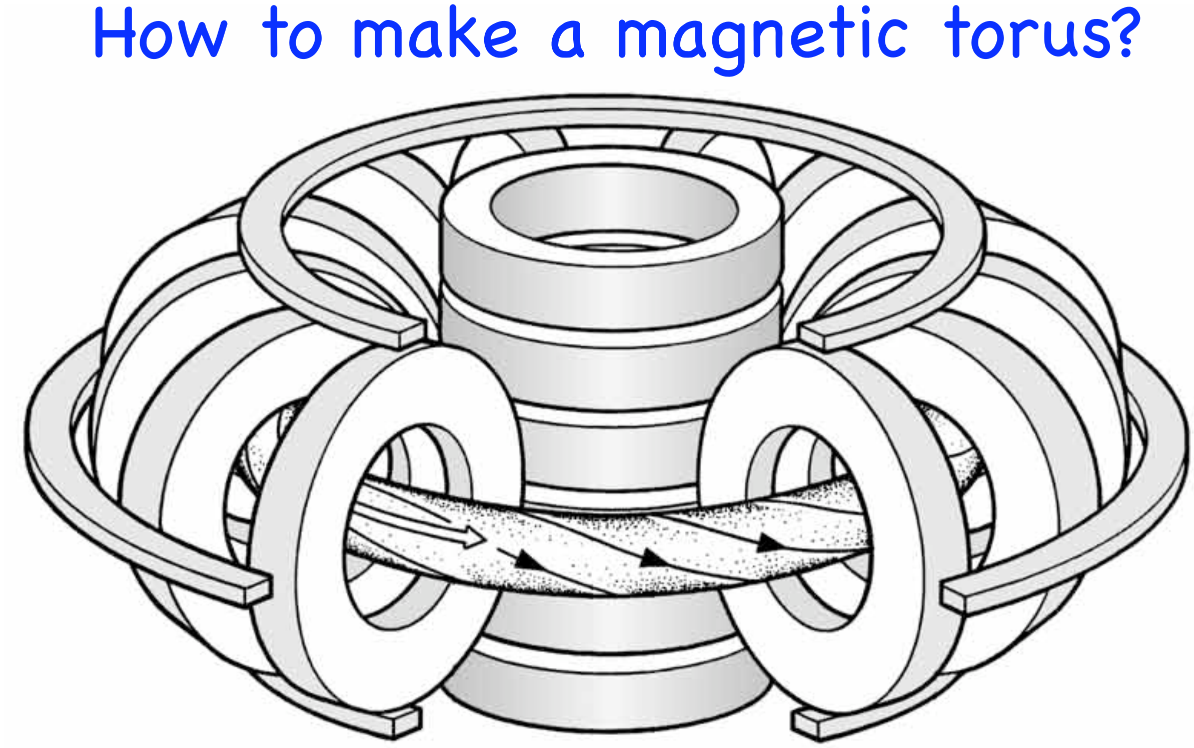
Toroidal Field from Poloidal Coils

How to make a magnetic torus?



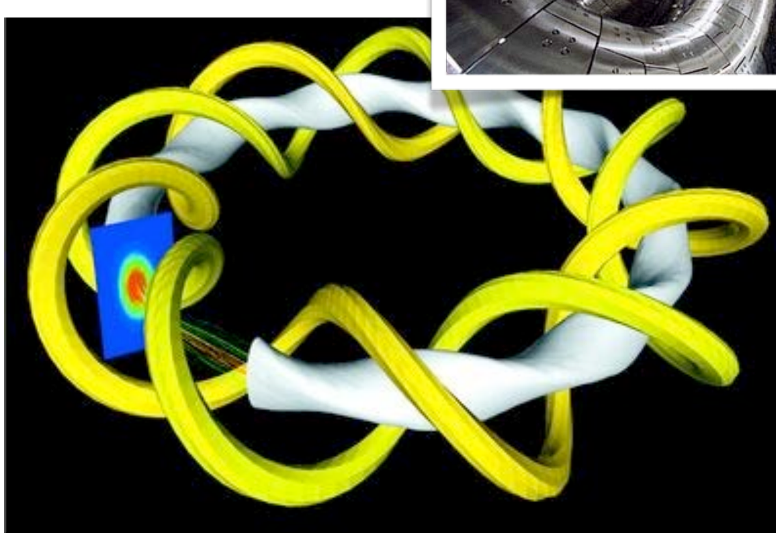
Poloidal Field from Toroidal Coils

How to make a magnetic torus?



Combined Toroidal and Poloidal Field (Tokamak)

How to make a magnetic torus?



Combined Toroidal and Poloidal Field (Stellarator)

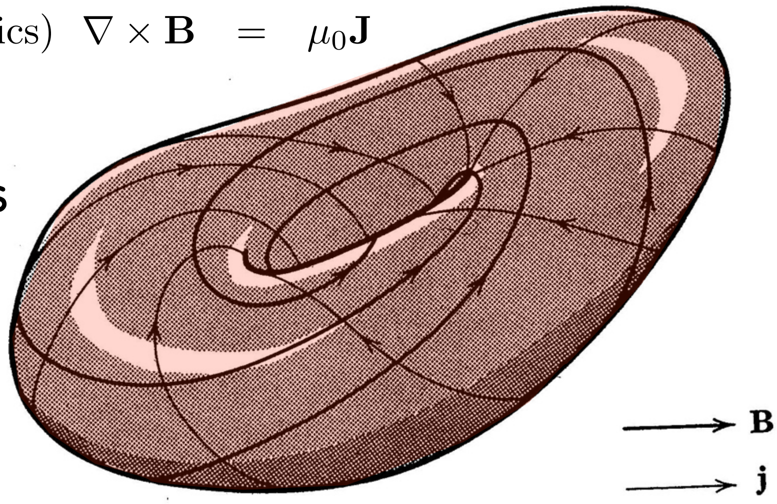
How Do Magnetic Fields Confine Ionized Matter?

Equations of magnetic confinement…

Plasma Pressure
Current

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

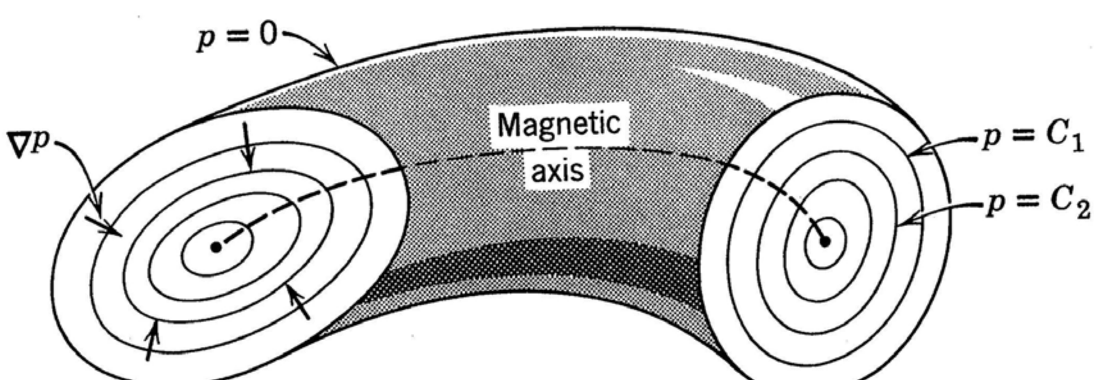
Magnetic Torus



How Do Magnetic Fields Confine Ionized Matter?

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

Surfaces of constant plasma pressure form nested tori

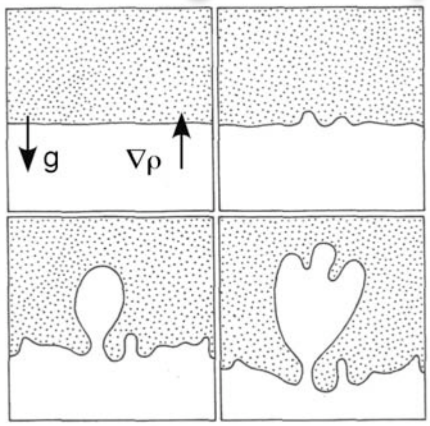


Magnetic Torus

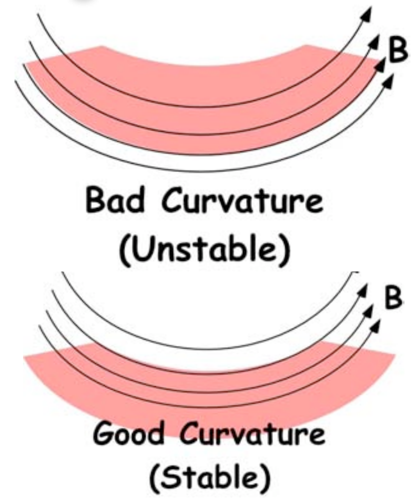
MFE Configuration Optimization Depends on Shape

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

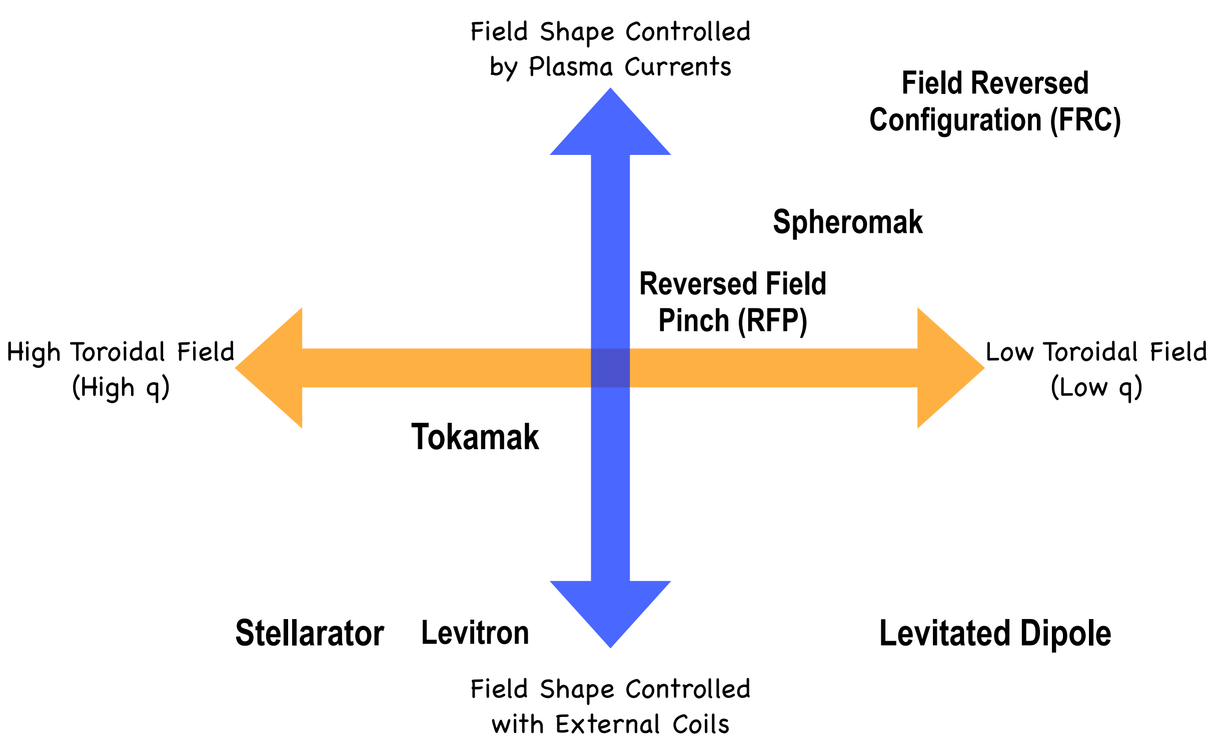
Interchange Instability



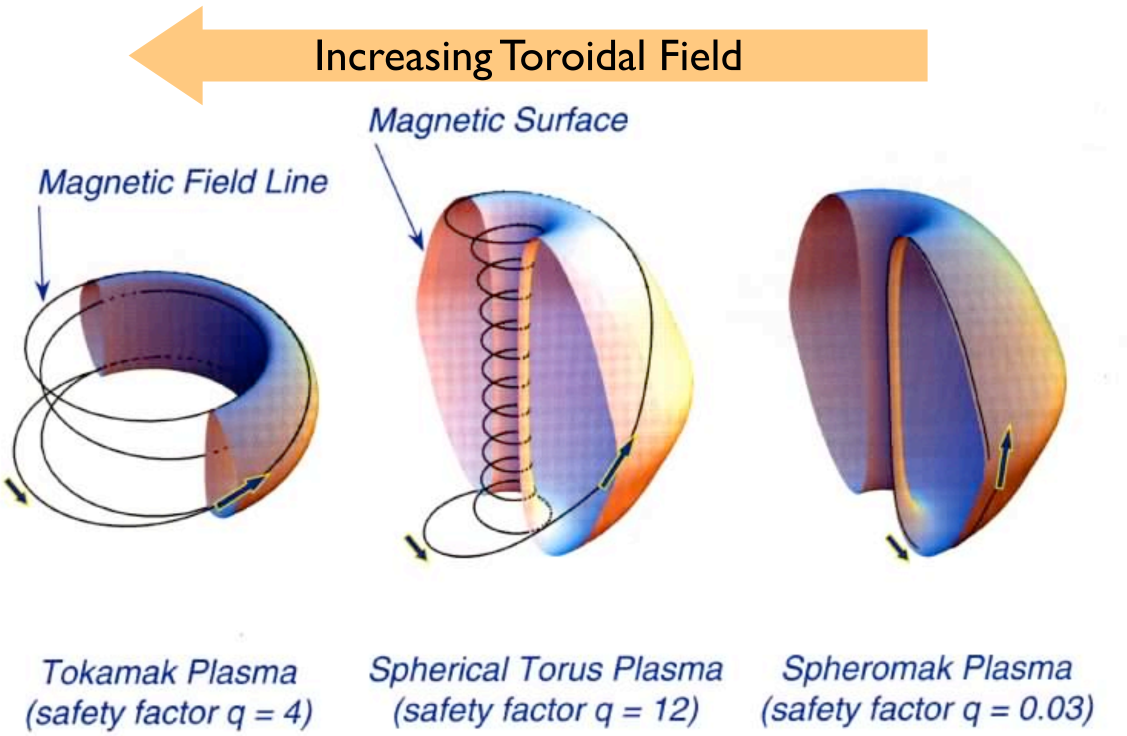
Bending Field ➠ Effective g

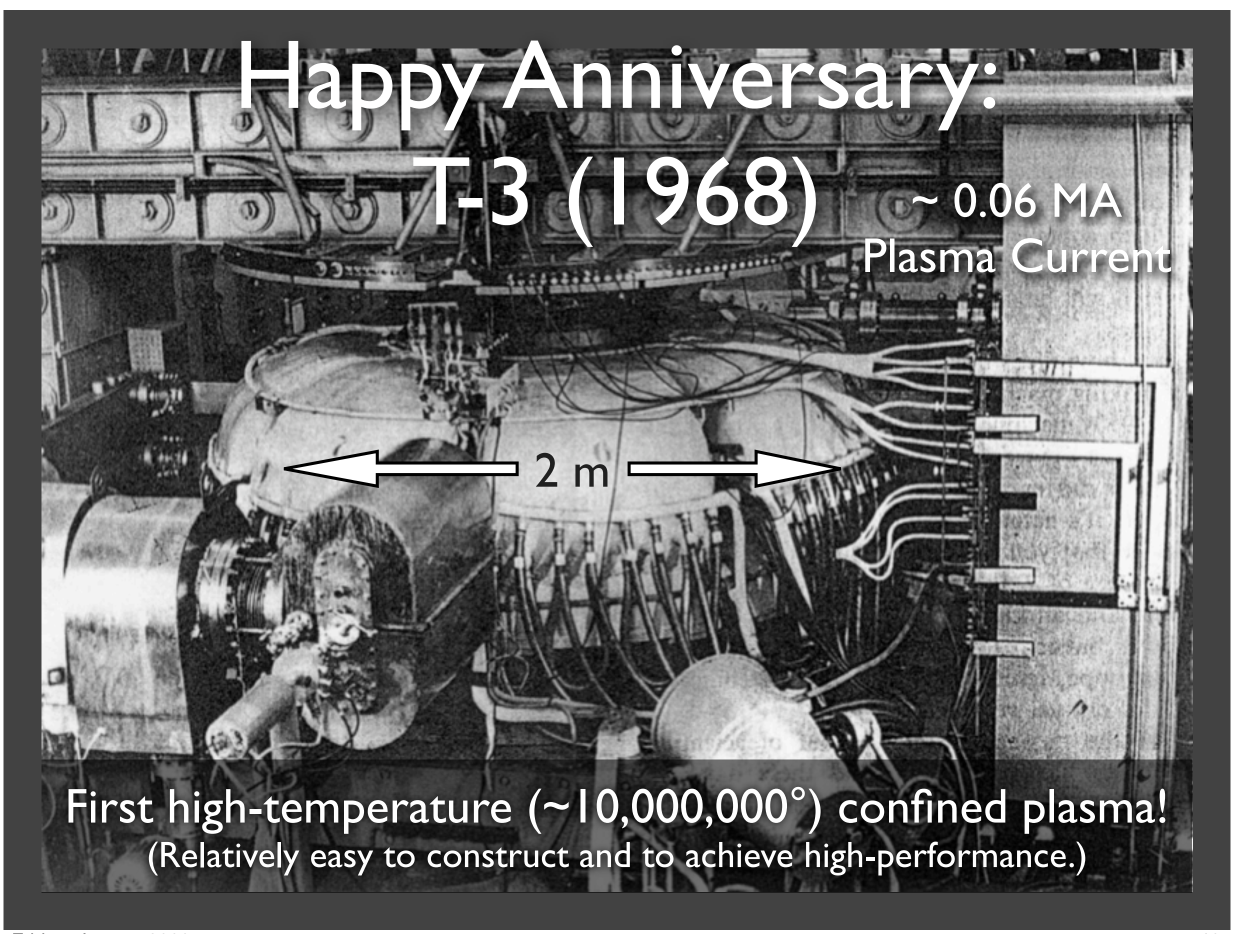


Many Toroidal Shapes Confine Plasma

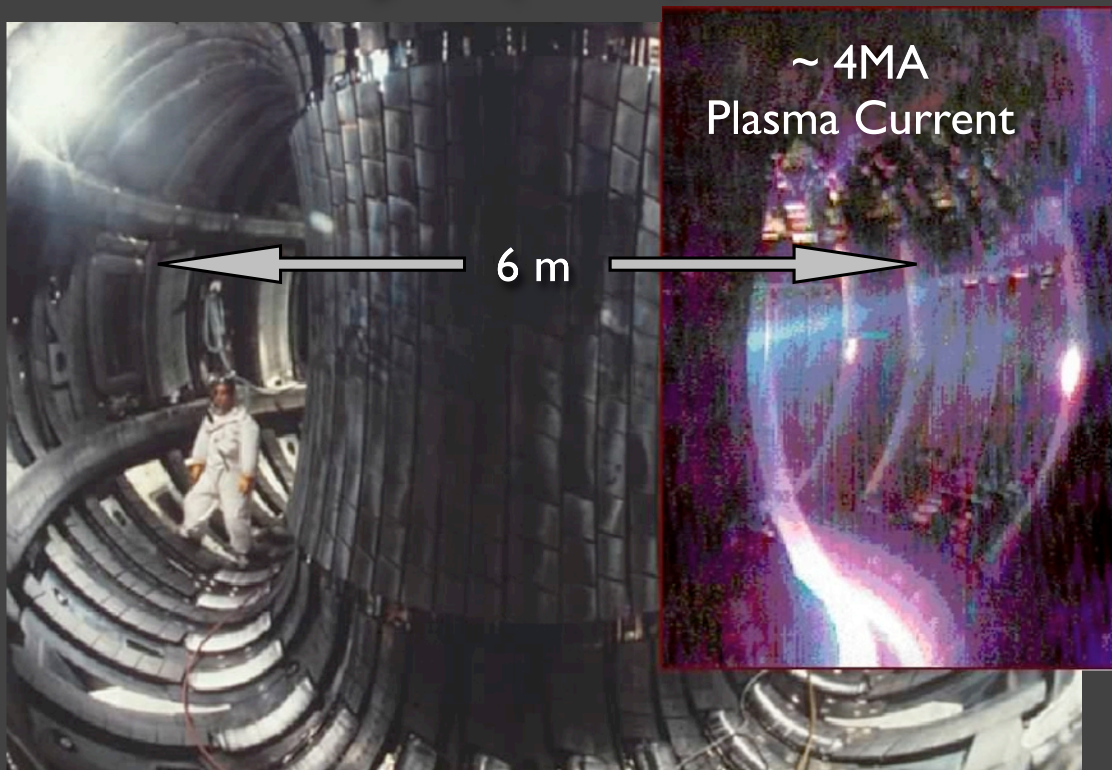


MFE Example:
“Shape” Change with Toroidal FIeld

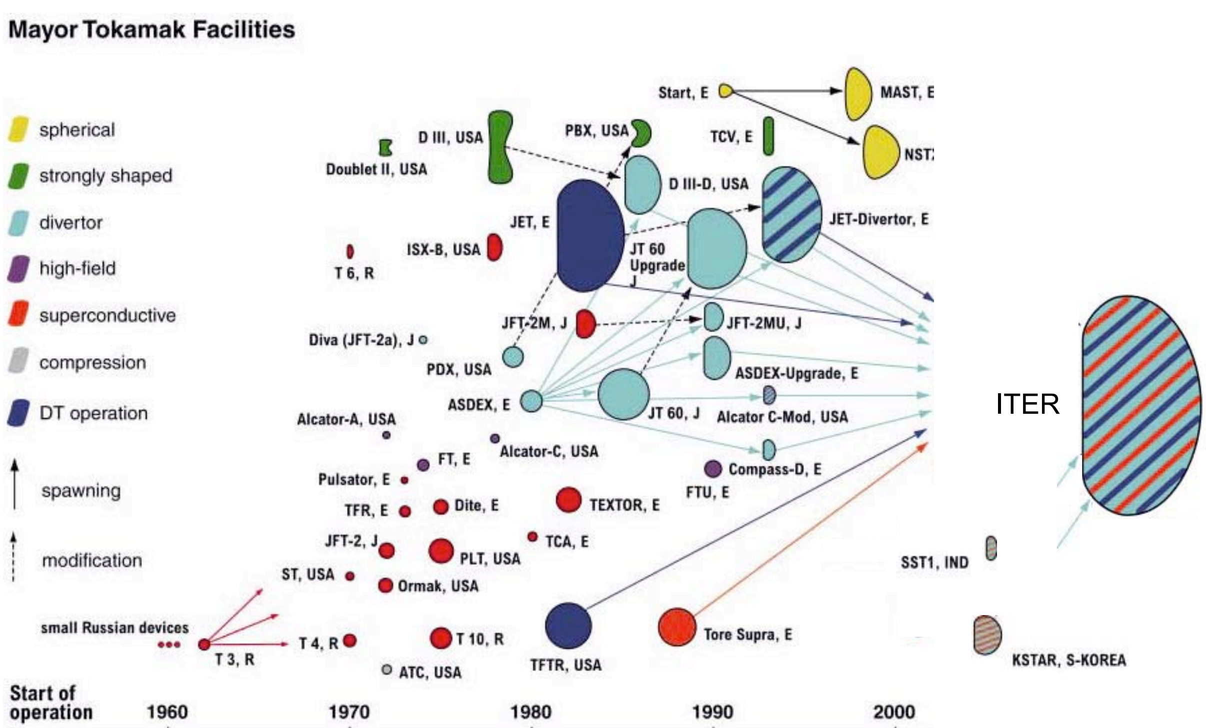




JET (1997)

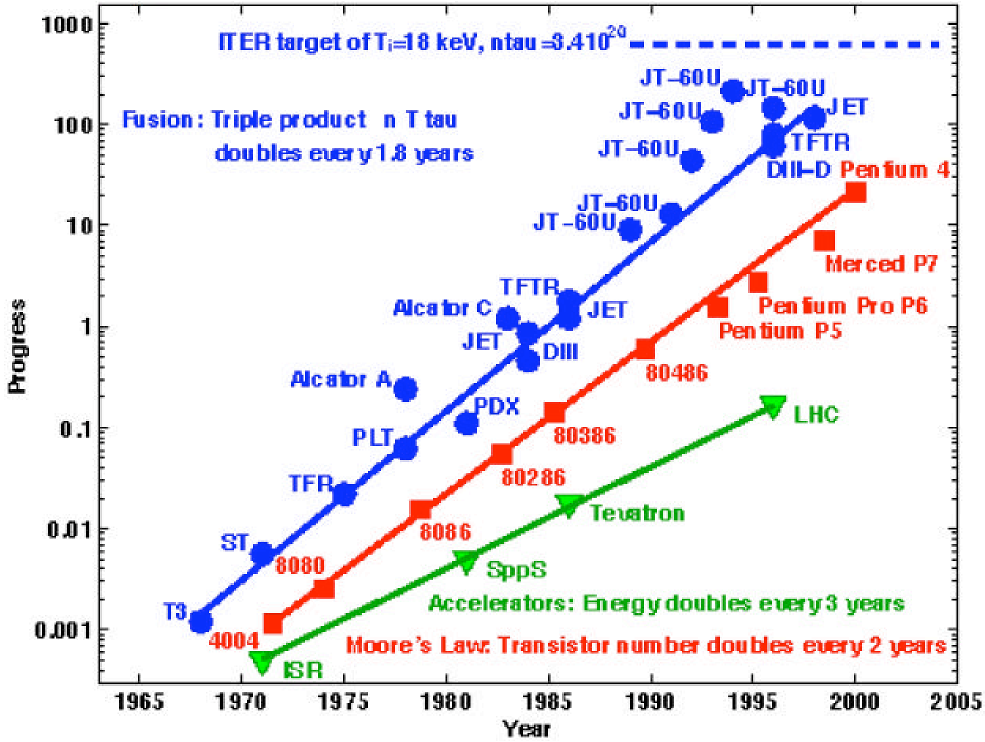


Over 100 Tokamaks



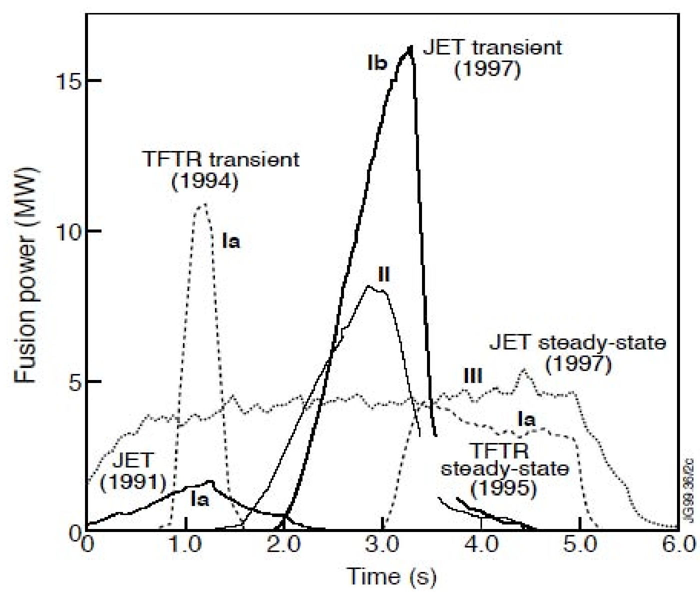
Rapid Progress

(through larger size)



Significant Fusion Power already Produced in the Lab

- ✓ 2.5 MW/m^3 achieved in TFTR!
- ✓ Establishes basic "scientific feasibility", *but power out < power in.*
- ◉ Fusion self-heating, characteristic of a "burning plasma", has yet to be explored.
- ◉ The technologies needed for net power must still be demonstrated.



Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines), in different regimes:
(Ia) Hot-Ion Mode in limiter plasma; (Ib) Hot-ion H-Mode;
(II) Optimized shear; and (III) Steady-state ELMY-H Modes.

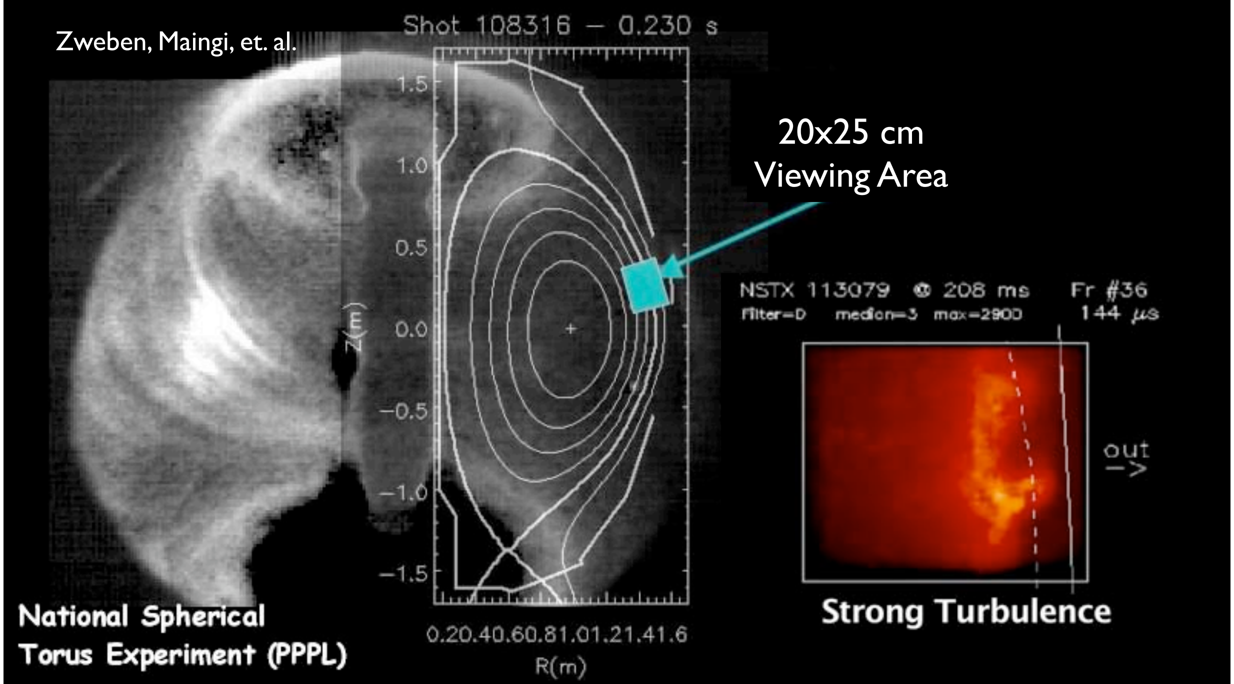
MFE Research Requires Understanding Plasma Physics and Motivates Plasma Physics

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

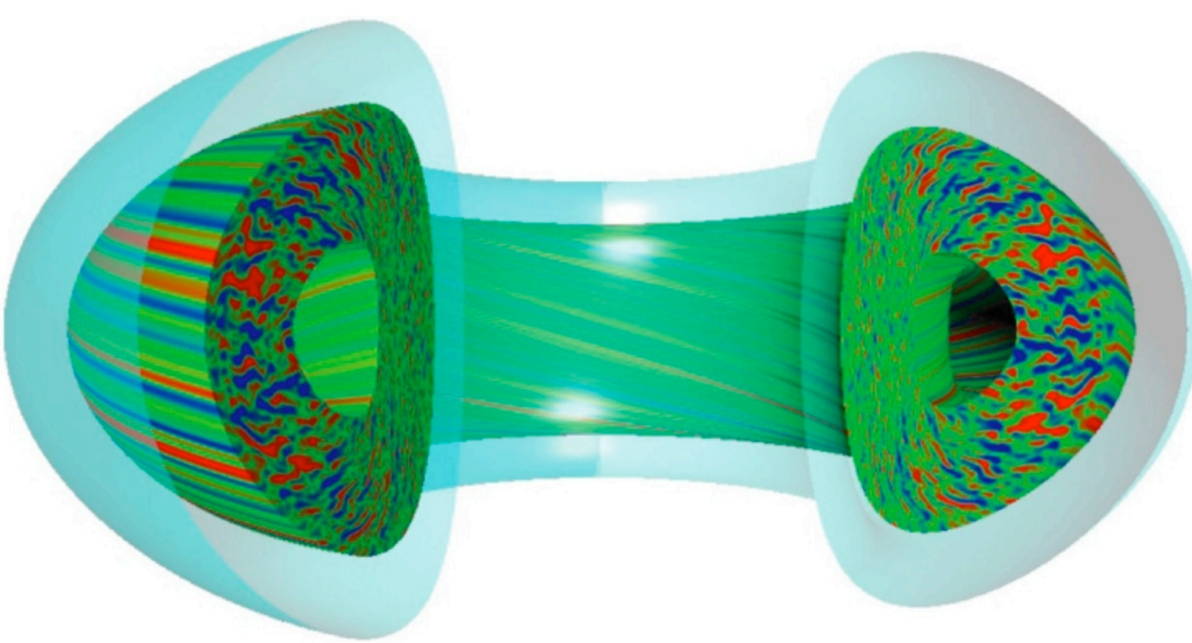
Three Examples

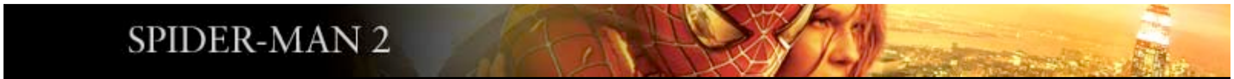
- Turbulence and fluctuations and transport
- Plasma control of instabilities
- Shape variation of magnetic confinement

Viewing the Turbulence "Transport Barrier"



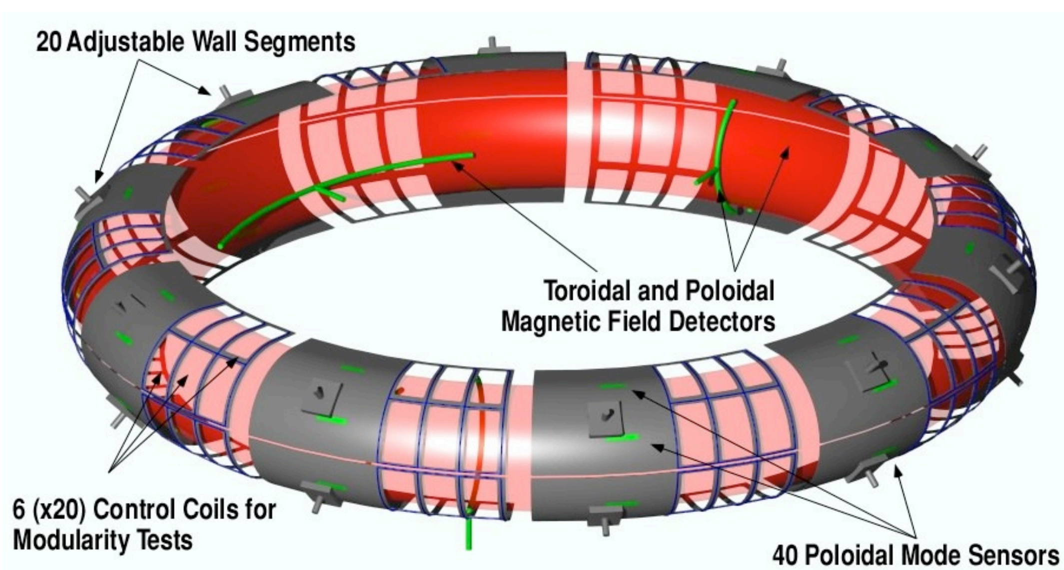
Measurement ⇔ Theory ⇔ Simulation





Dr. Otto Octavius Fails to Stabilize Fusion in NYC…

HBT-EP Succeeds to Stabilize Plasmas in NYC!



Columbia University
In the City of New York

International Thermonuclear Experimental Reactor

Europe, Japan, U.S., Russia, South Korea, China, India
http://www.iter.org/

2006 Global Energy Prize

Evgeniy Velikhov

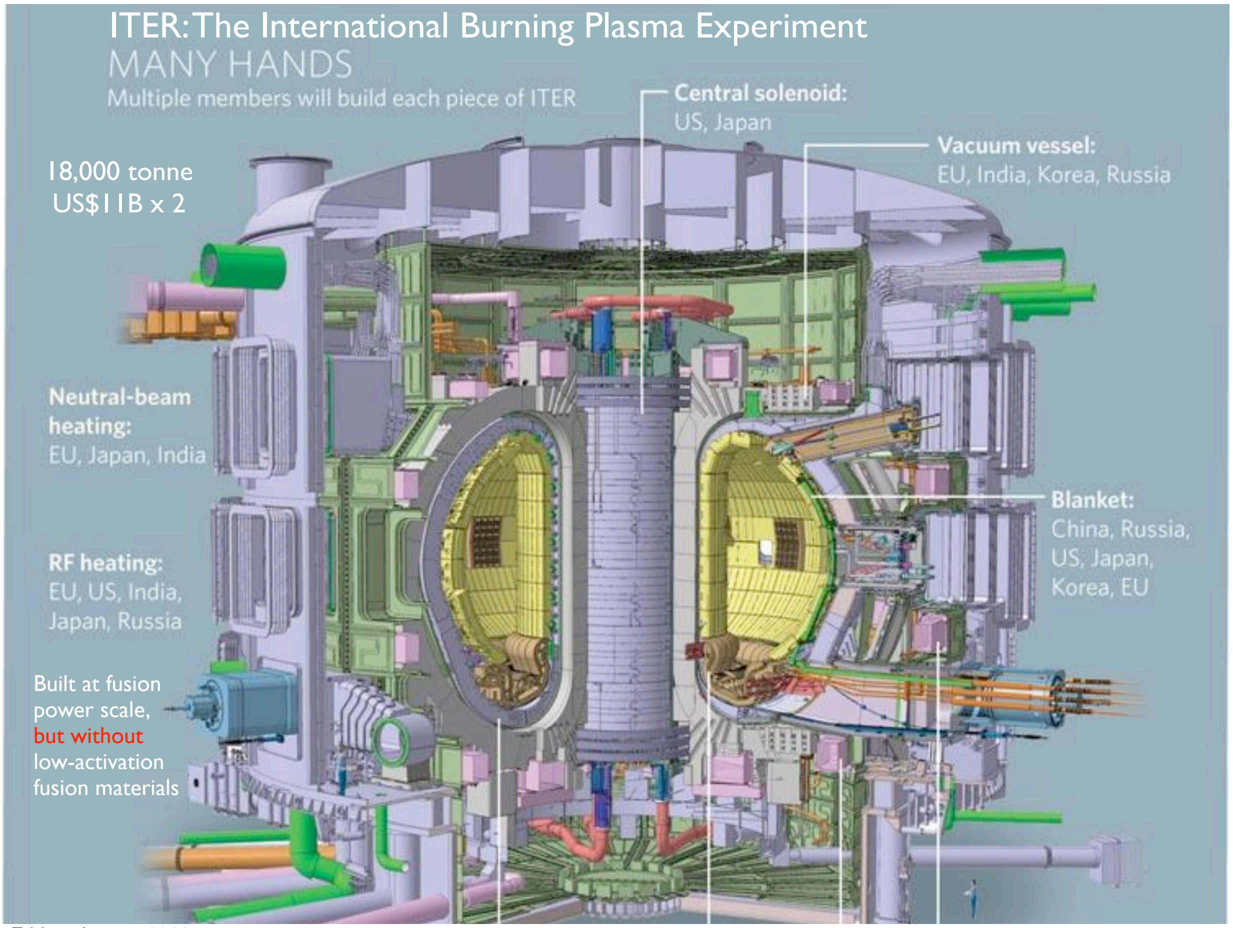
Yoshikawa Masaji

Robert Aymar

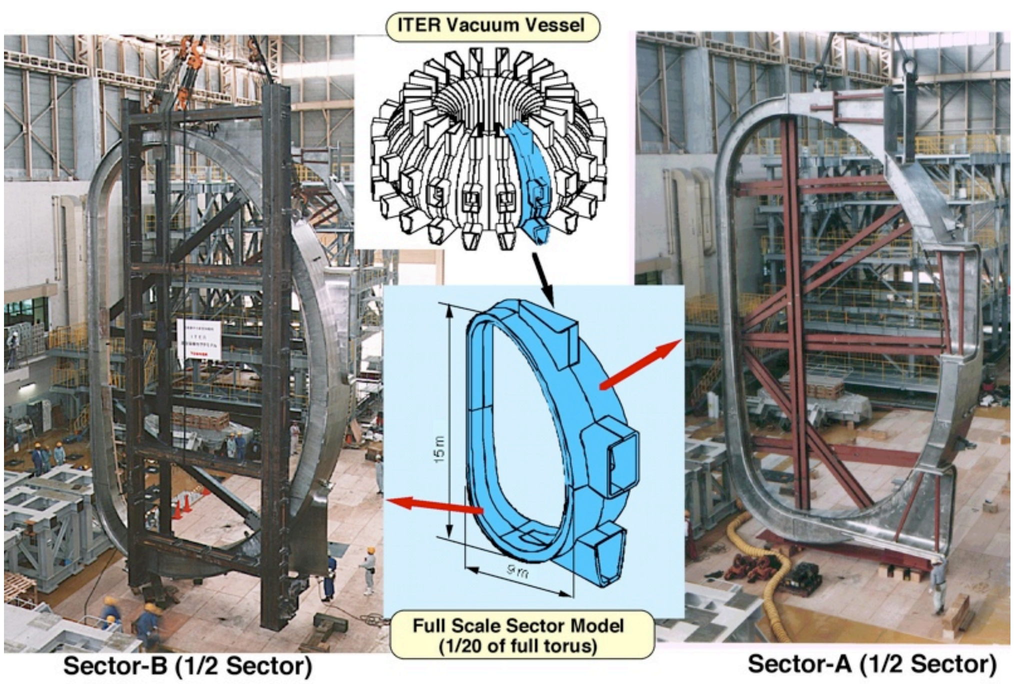
For the development of scientific and engineering foundation for building the International Thermonuclear Experimental Reactor (ITER) Project

Burning Plasma Experiment

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



Benefits from Comprehensive Component R&D

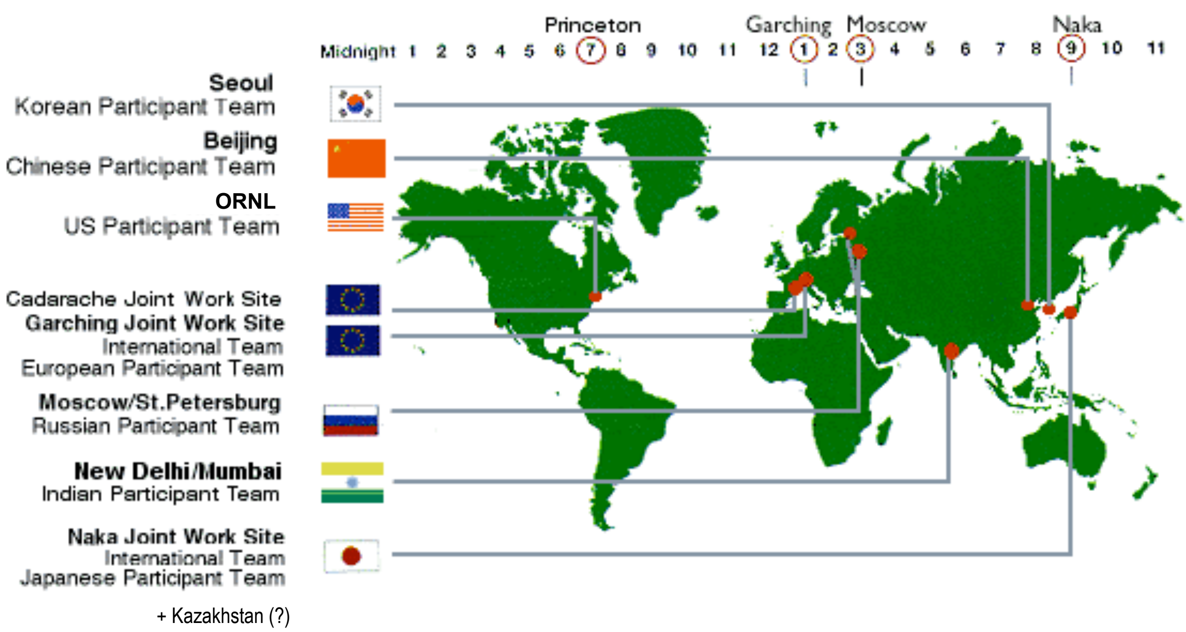


View of full-scale sector model of ITER vacuum vessel completec in September 1997 with dimensional accuracy of ± 3 mm

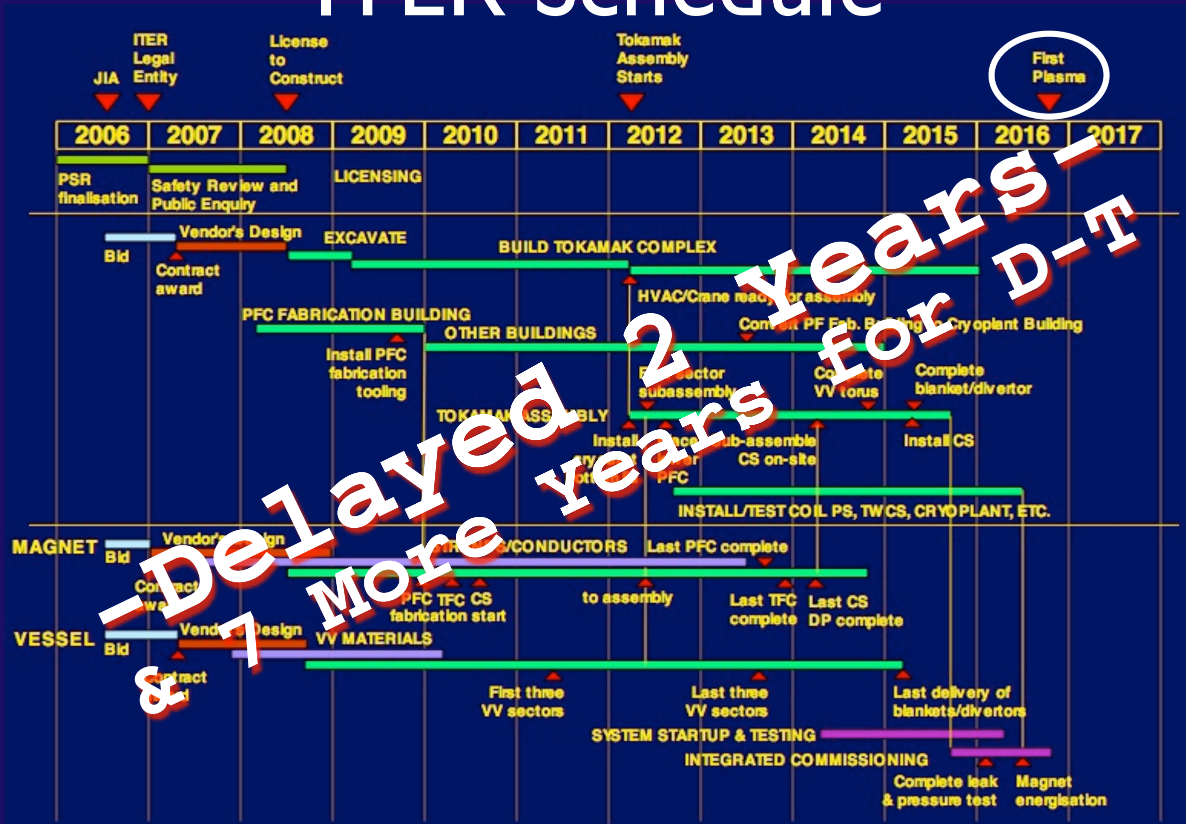
Benefits from Comprehensive Component R&D

Largest High-Field Superconducting Magnet is World: 640 MJ and 13T!

Coordinating an International Team



ITER Schedule



John Holdren's AAAS Presidential Lecture (February 2007)

Four Key S&T Challenges

- Meeting the basic needs of the poor
- Managing competition for land, soil, water, and the net productivity of the planet
- Mastering the energy-economy-environment dilemma
- Moving toward a nuclear-weapon-free world

And the biggest challenge:

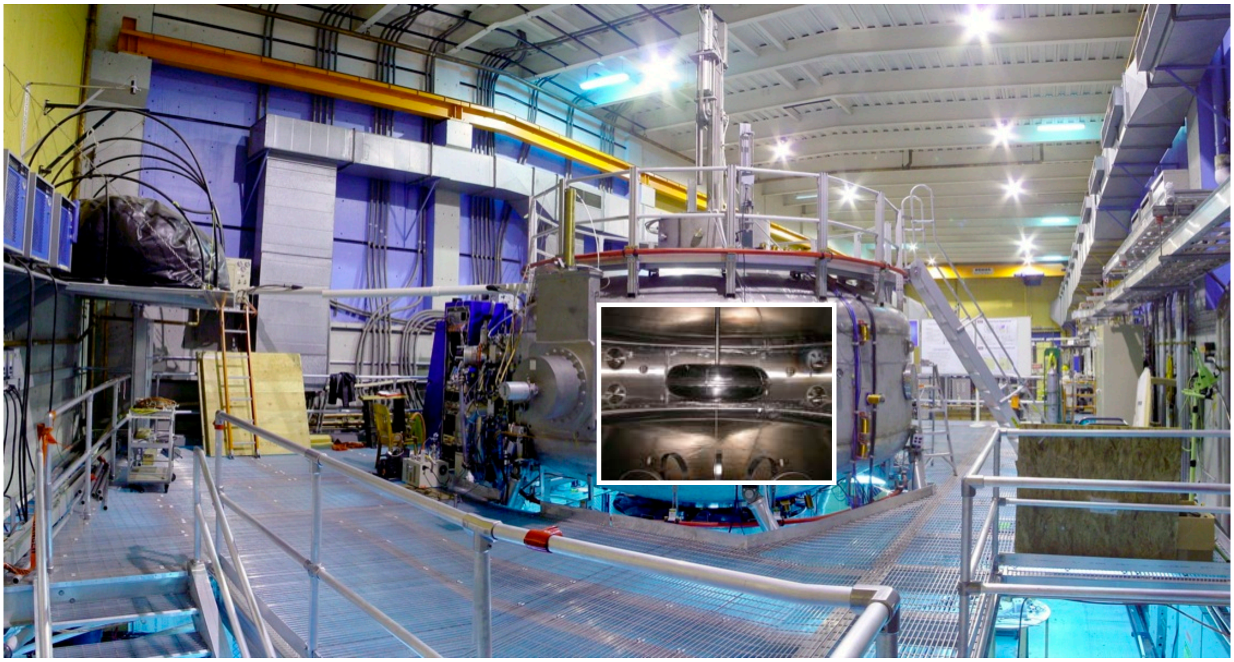
"Providing the affordable energy needed to create and sustain prosperity without wrecking the global climate with carbon dioxide emitted by fossil-fuel burning."

Experimentation at Columbia University

- ➡ HBT-EP: Active control of plasma instabilities and the magnetic boundary of a high-beta tokamak
- DIII-D: Collaboration to control MHD instabilities
- NSTX: Collaboration to control MHD instabilities
- ➡ CNT: Low-aspect ratio stellarator for non-neutral and positronic plasma
- ➡ LDX: Levitated superconducting dipole using the physics of space plasma to benefit fusion
- CTX: Nonlinear convective mixing, turbulence cascade in two-dimensional interchange motion
- CLM: Understanding drift-wave turbulence

Levitated Dipole Experiment

MIT-Columbia University



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

D-D (^{3}He) Fusion

$$6D$$

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

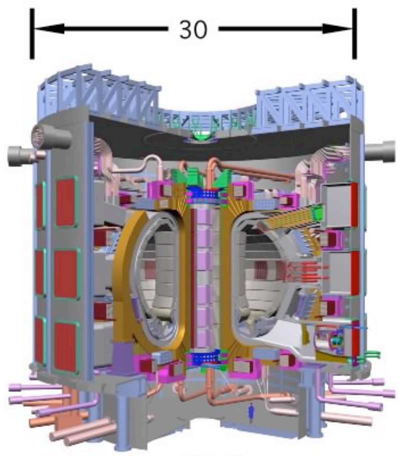
^{3}He T

$\approx 2\,(^4He) + 3H + e^-$ ...

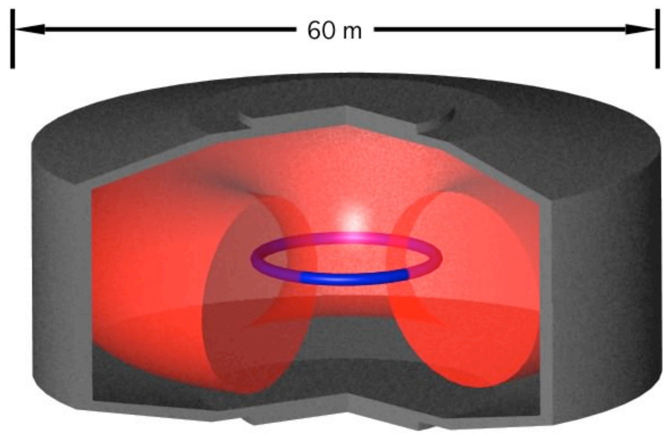
Can we extract T without extracting energy?

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

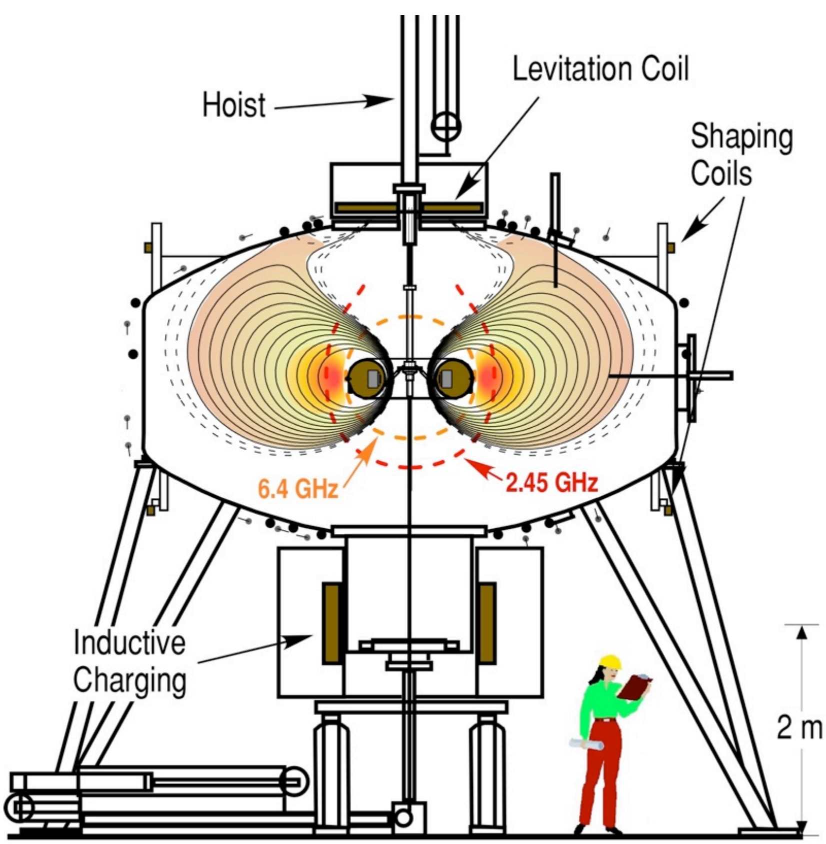
Something Different: Testing a New Approach to Fusion and Laboratory Plasma Confinement



ITER
500-700 MW
D-T Fusion

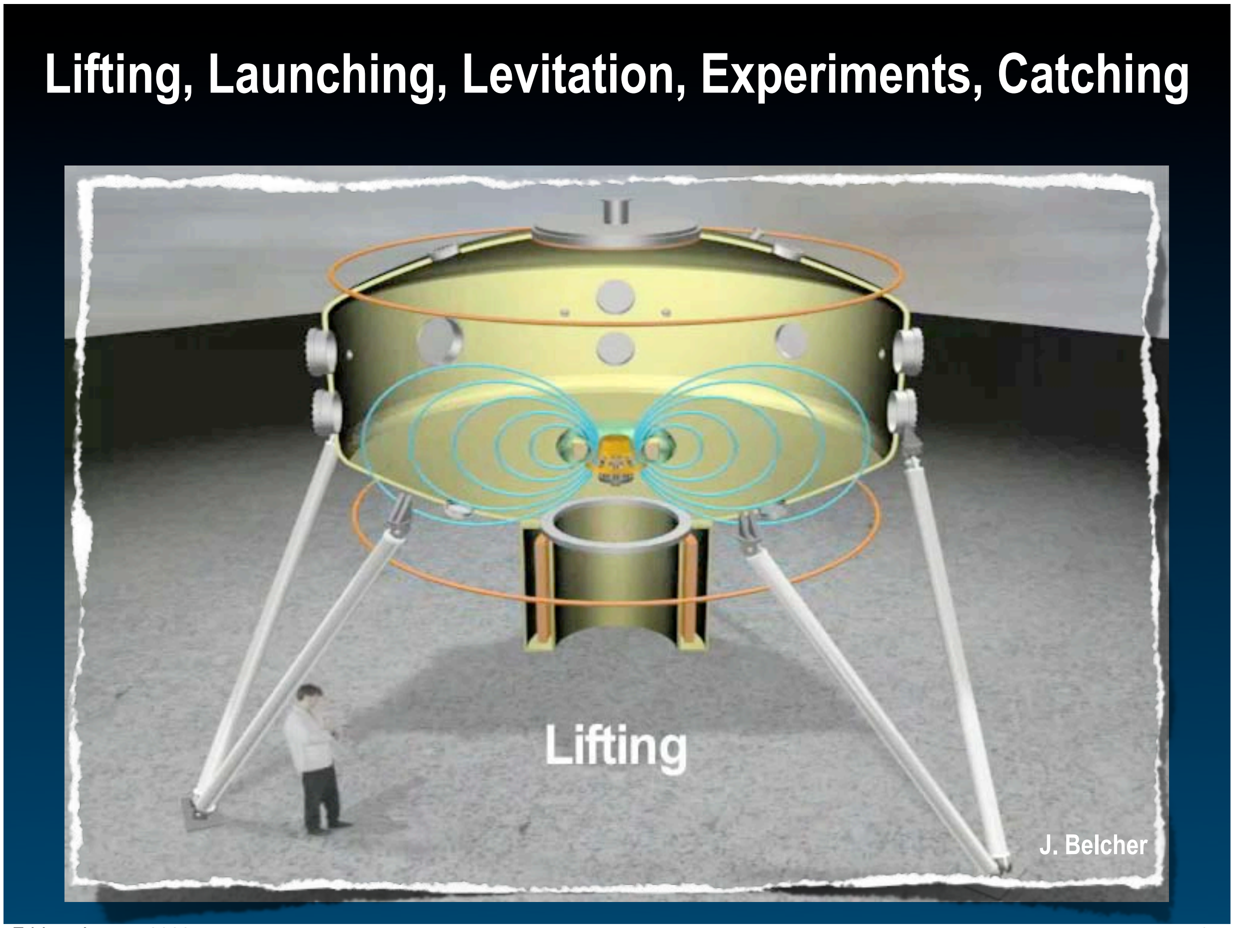


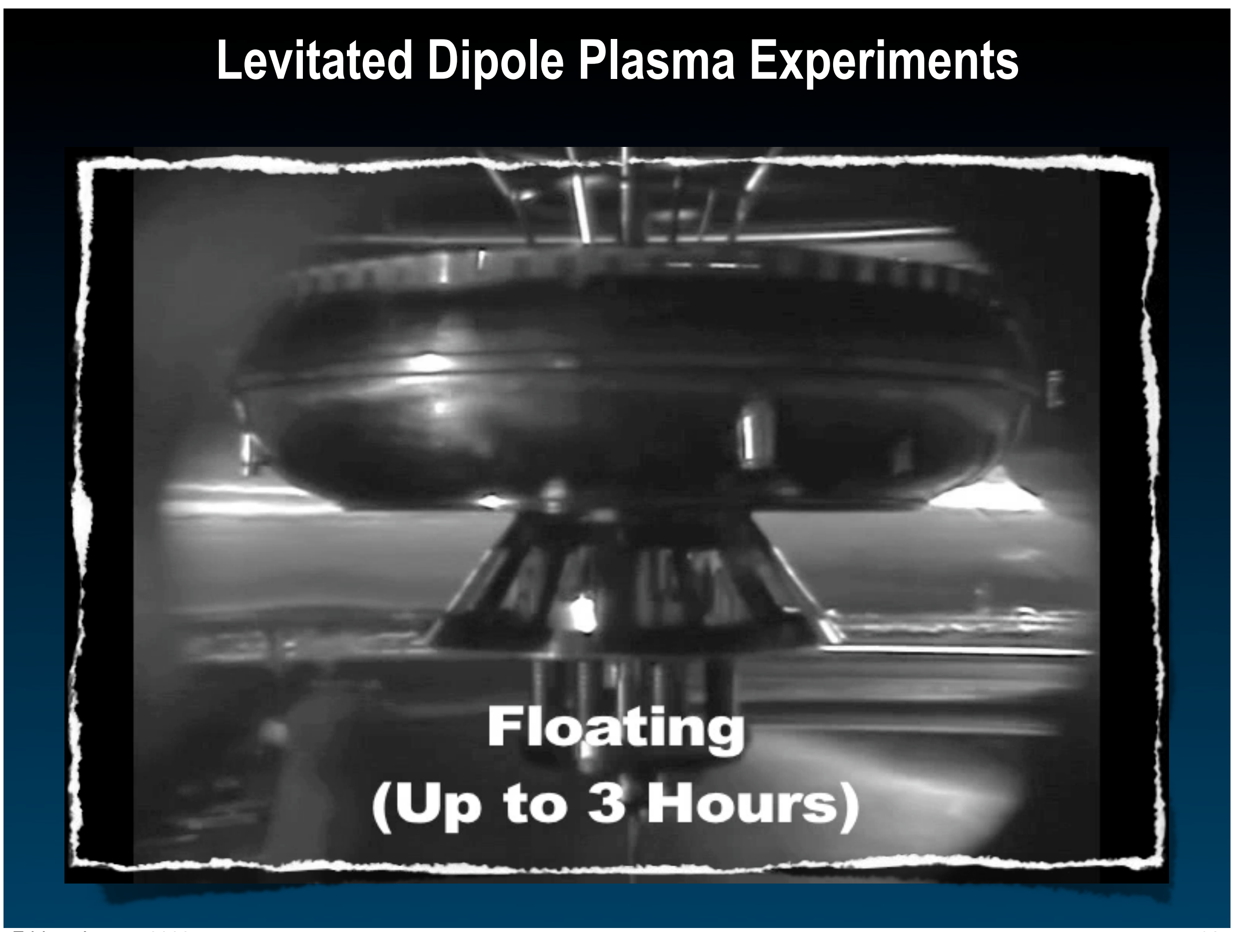
Levitated Dipole
600 MW
D-D(^{3}He) Fusion



Columbia University
in the City of New York

Massachusetts Institute of Technology

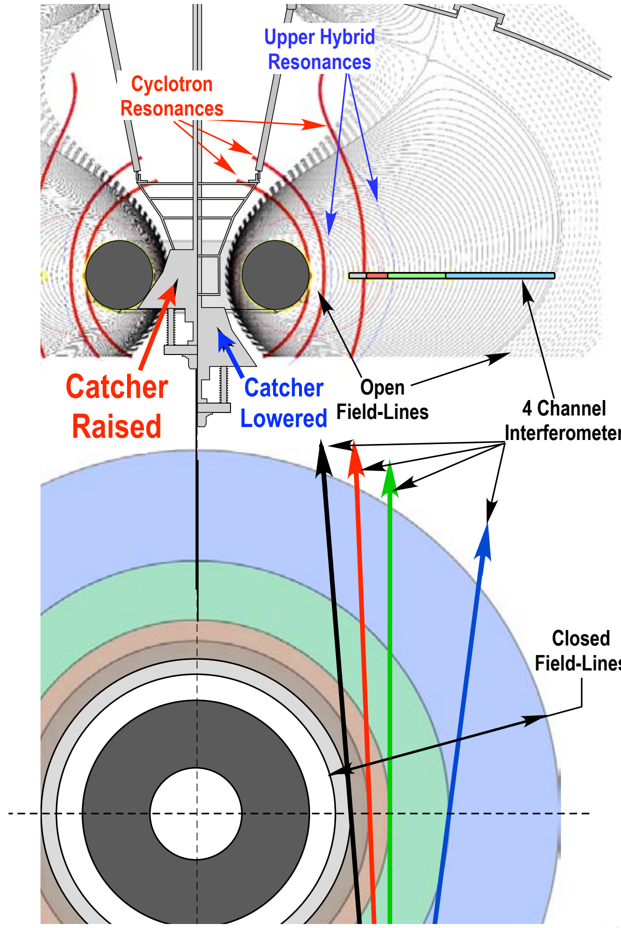

Lifting, Launching, Levitation, Experiments, Catching
Lifting
J. Belcher


Levitated Dipole Plasma Experiments
Floating
(Up to 3 Hours)

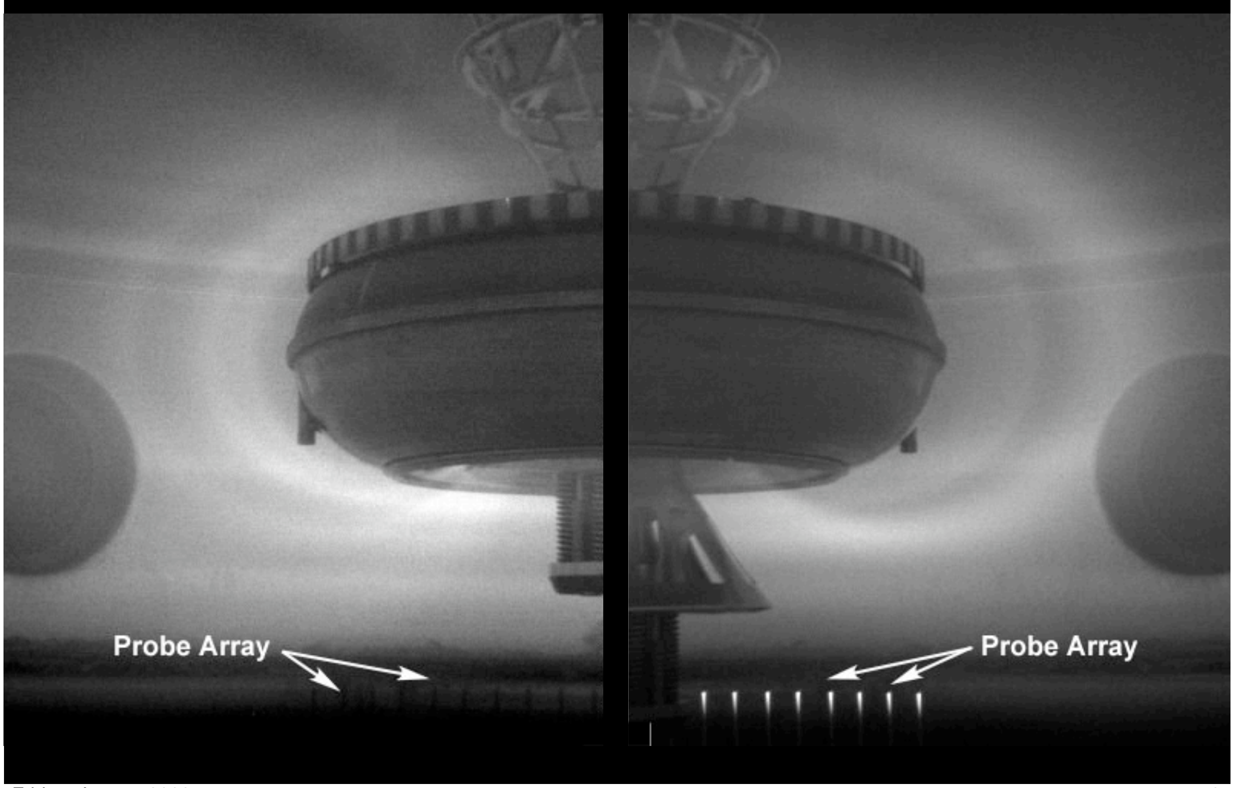
Density Profile with/ without Levitation

- *Procedure*:
  - Adjust levitation coil to produce equivalent magnetic geometry
  - Investigate multiple-frequency ECRH heating
- *Observe*: Evolution of density profile with 4 channel interferometer
- *Compare*: Density profile evolution with supported and levitated dipole

Alex Boxer, MIT PhD, (2008)



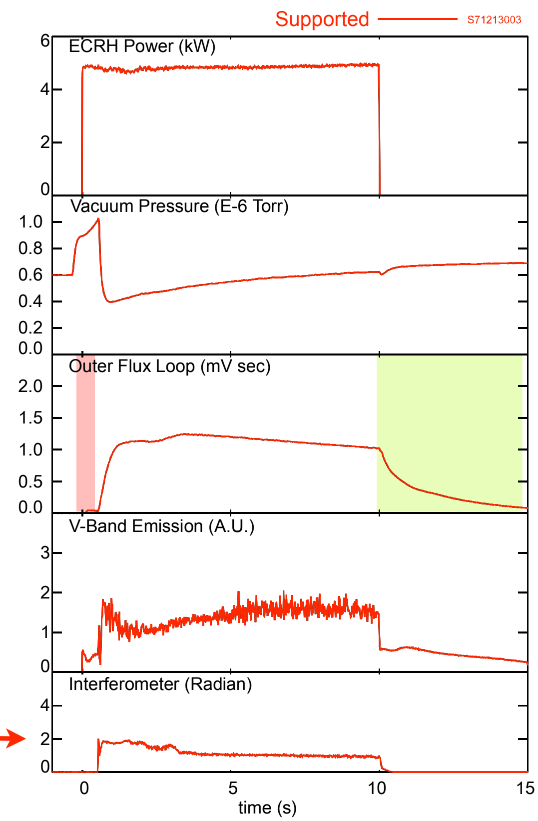
Compare Supported vs. Levitated



Plasma Confined by a Supported Dipole

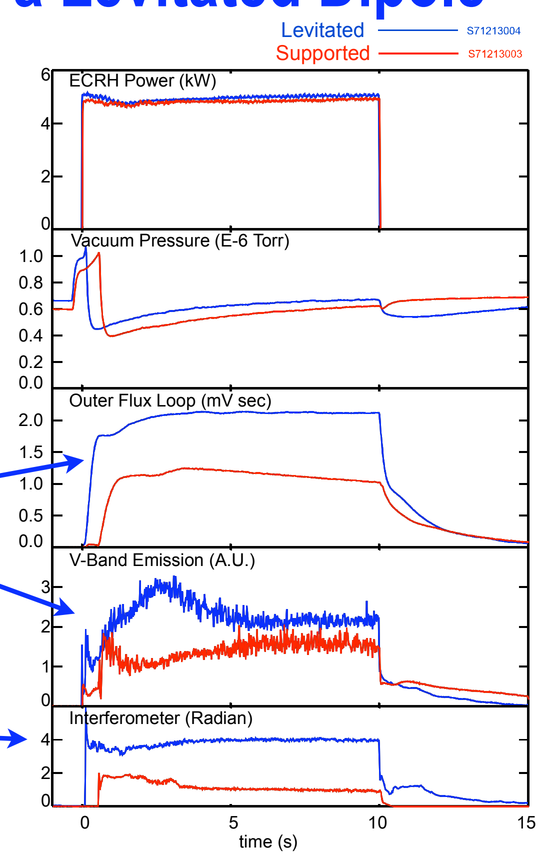
- 5 kW ECRH power
- D_2 pressure ~ 10^{-6} Torr
- Fast electron instability, ~ 0.5 s
- Ip ~ 1.3 kA or 150 J
- Cyclotron emission (V-band) shows fast-electrons
- Long, low-density "afterglow" with fast electrons

➡ **1×10^{13} cm^{-2} line density**

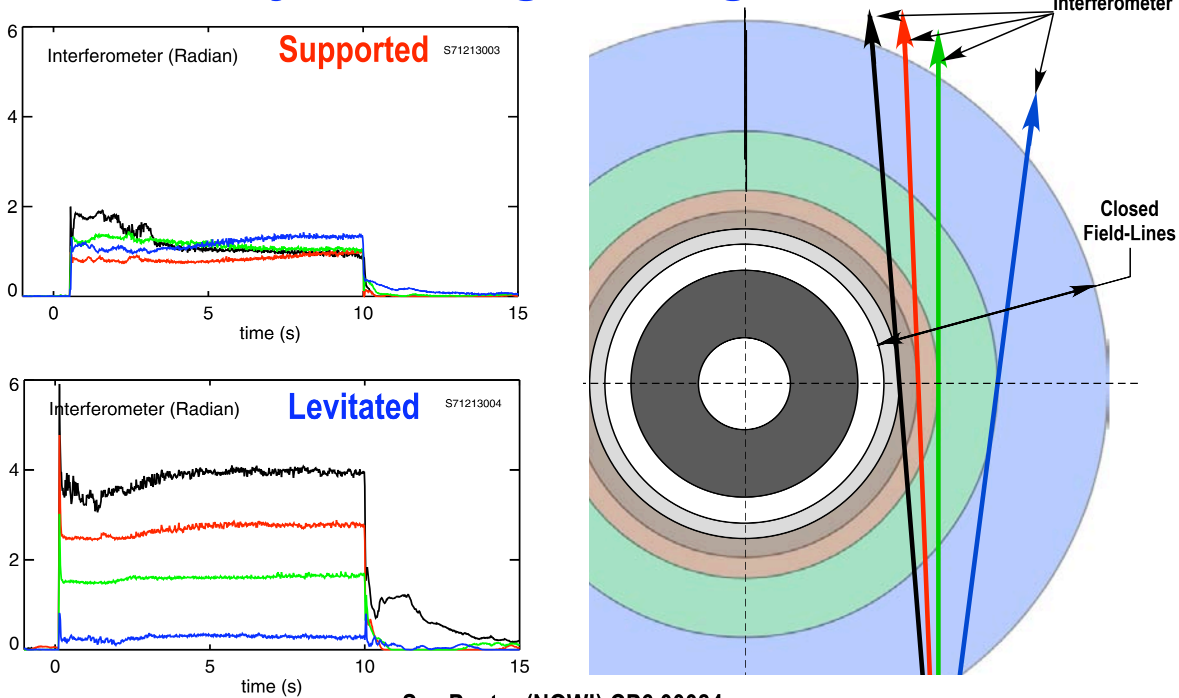


Plasma Confined by a Levitated Dipole

- Reduced fast electron instability
- 2 x Diamagnetic flux
- Increased ratio of diamagnetism-to-cyclotron emission indicates **higher thermal pressure**.
- Long, higher-density "afterglow" shows improved confinement.
- **3 x line density**

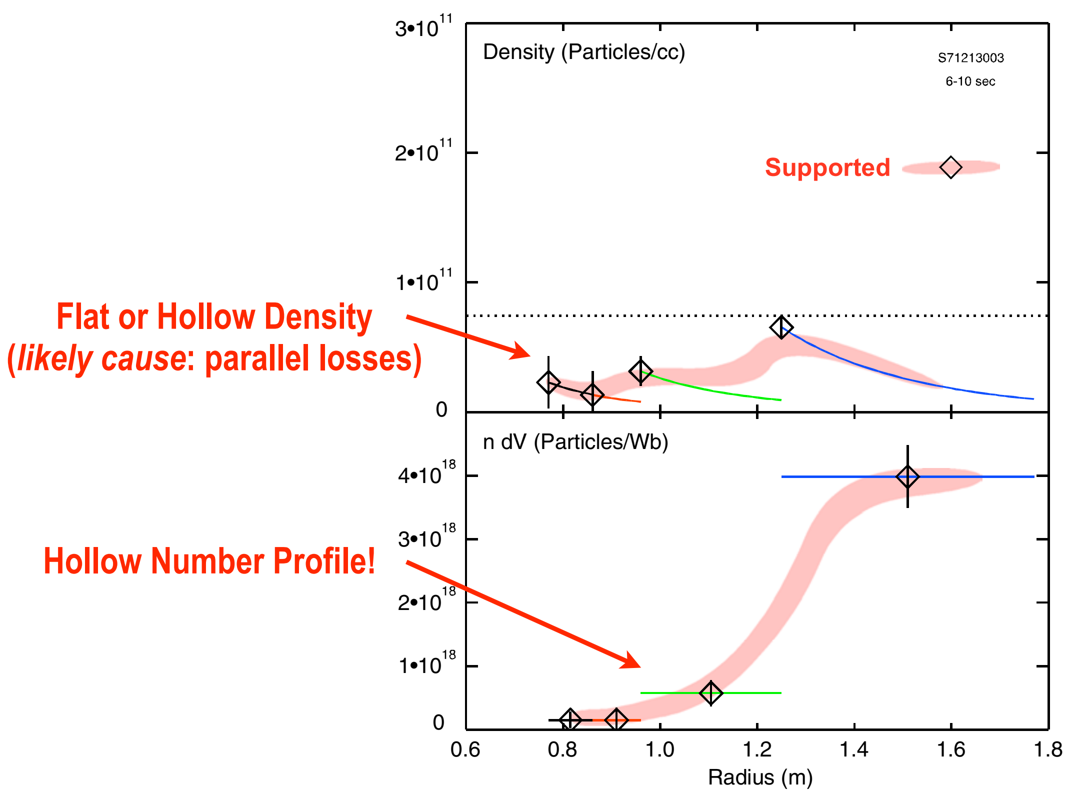


Multi-Cord Interferometer Shows Strong Density Peaking During Levitation



See Poster (NOW!) CP6.00084:
Boxer, et al., "Evidence of ``Natural" Density Profiles in a Dipole-Confined Plasma"

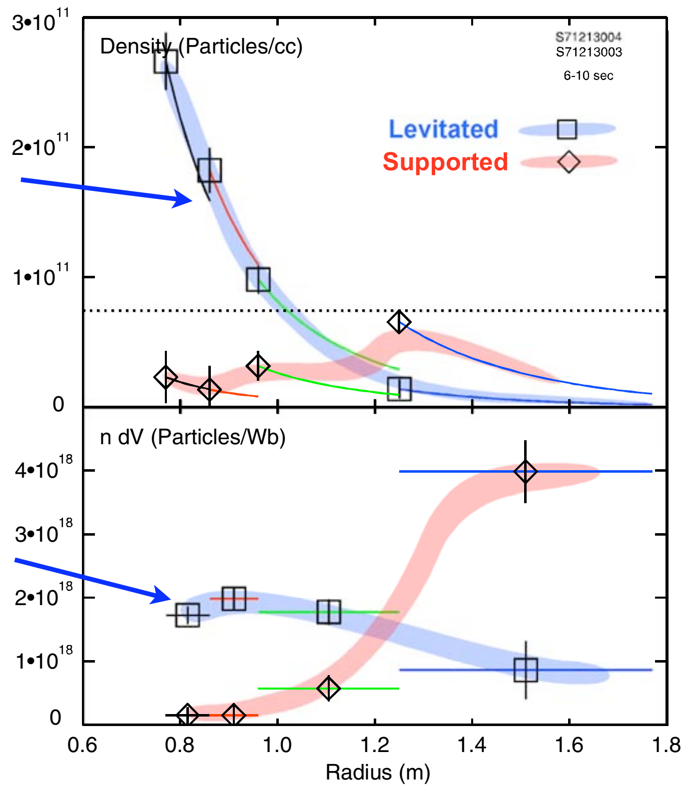
Inversion of Chord Measurements



Inversion of Chord Measurements

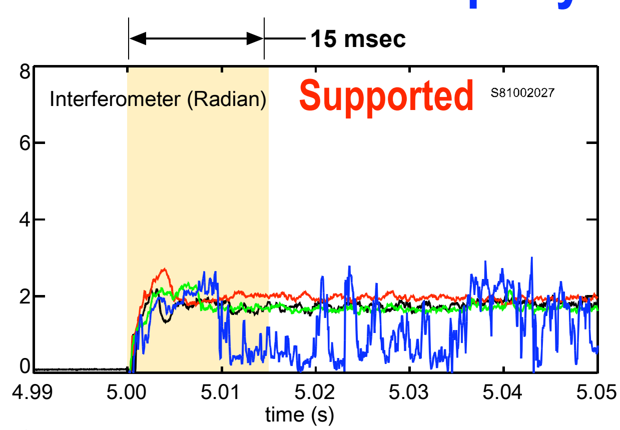
Strongly Peaked Density!

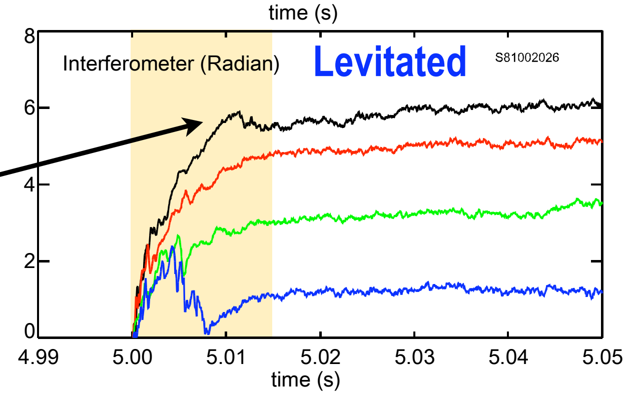
Uniform Number Profile!



Naturally Peaked Profiles Established Rapidly

- Initially (~ 4 msec), density rises equally for supported and levitated discharges
- Only when levitated, central density continues to increase
- Natural profiles are created in less than 15 msec!

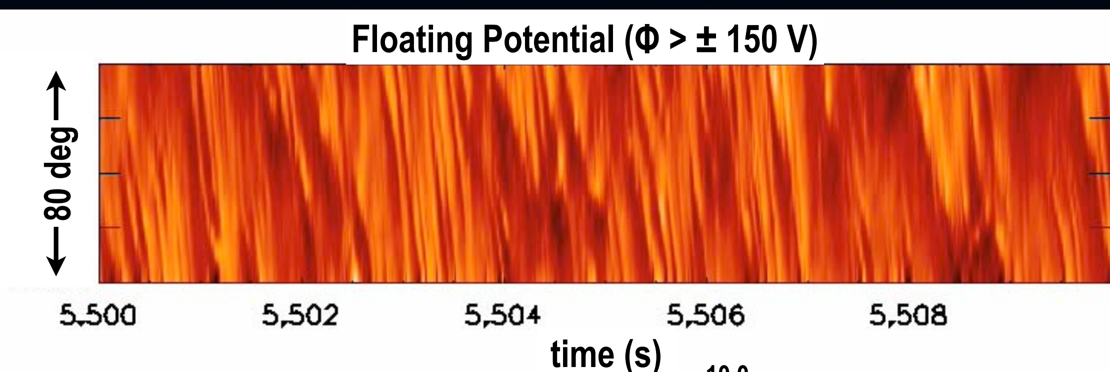




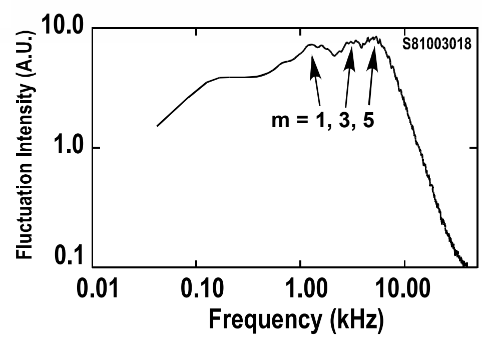
Floating Potential Probe Array

- Edge floating potential oscillations
- 4 deg spacing @ 1 m radius
- 24 probes
- Very long data records for excellent statistics!!

Floating Potential Probe Array



15 kW High-β Discharge
$\omega \sim \Omega\, m = \Omega R\, k$, with
$\Omega/2\pi \sim 1$ kHz



Summary

- Fusion promises nearly unlimited carbon-free energy.
- Tremendous progress has been made both in understanding and in fusion parameters.
- Attractive and economical fusion power plants exist (*on paper!*) that require aggressive R&D programs, *especially advanced materials!*
- With the construction of NIF and the world-wide effort to construct ITER, there is a great opportunity to ~~accelerate~~ levitate fusion research.
- Successful R&D and aggressive implementation will allow fusion to contribute to world energy needs.