Bringing the Stars to Earth:
The Path to Fusion Power

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Outline

- What is 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

Energy from the 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

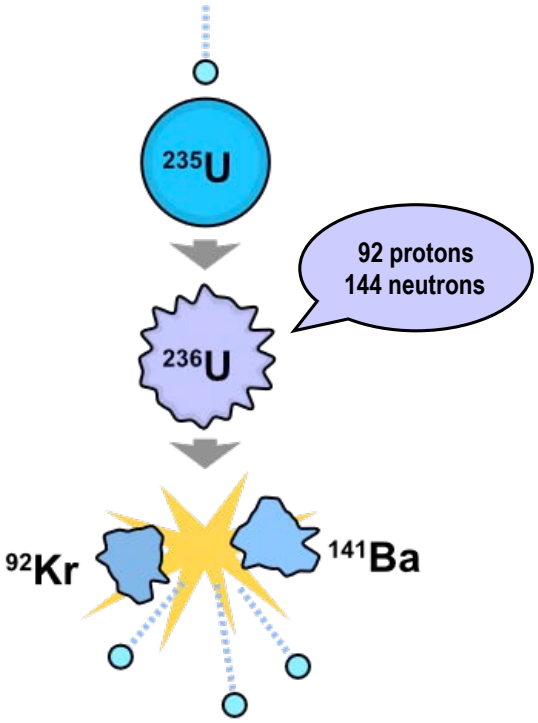
Liquid CO_2 (1 ton @ 1500 psi) | Coal | Oil | LNG | Grass | H_2 (4500 psi)

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

16 FL OZ Water (0.015% D/H)

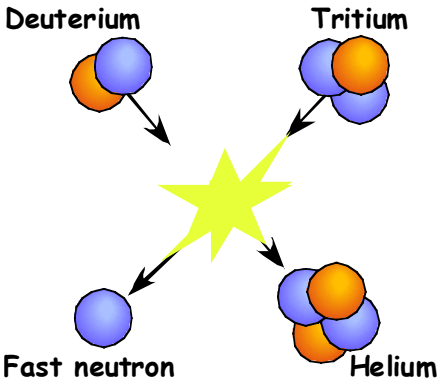
Why Fission is (Relatively) Easy to Do…

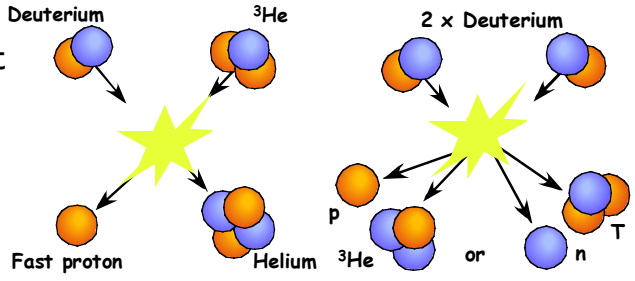
- Nuclear force is very-short ranged. Must get very close!
- Neutrons can easily split big, positively-charged nuclei…
- Because **neutrons are neutral!**
- Nucleons like to be paired (even numbers!) so certain nuclei are fissile: ^{233}U, ^{235}U, ^{239}Pu



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

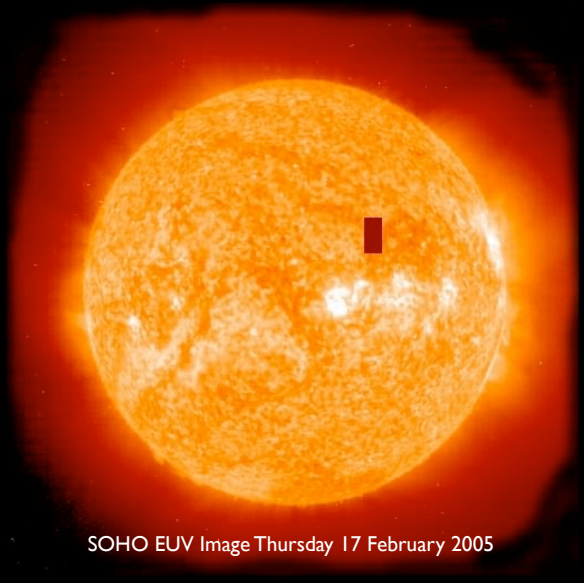
- Nuclear force is very-short ranged. Must get very close!
- Fusion requires close contact between light nuclei, like D, ^{3}He
- Difficult because all light nuclei are **positively charged!**
- Fusion energy occurs only at temperatures approaching 150,000,000 degrees!





Fusion in our Sun

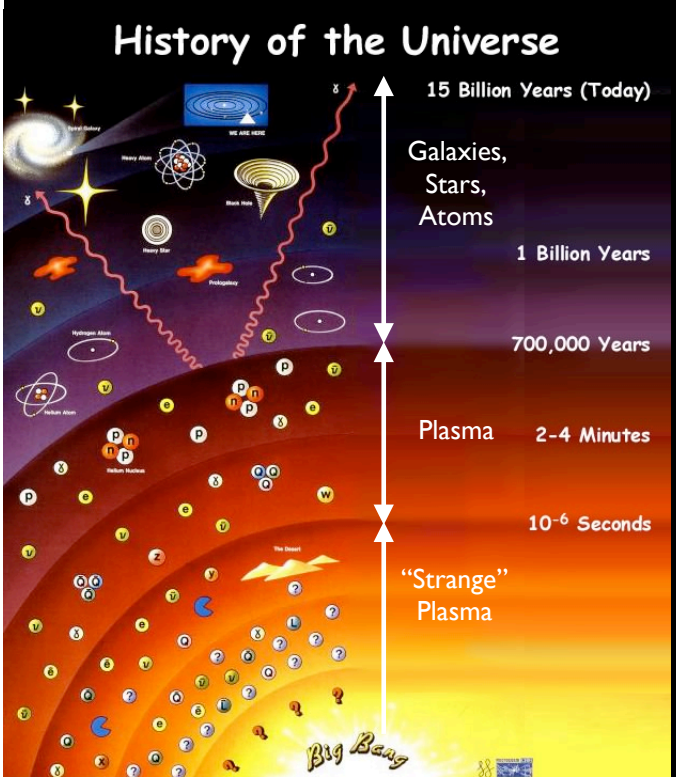
- 90% H, 9% He, 1% others
- Solar core: 15,000,000°
- (H + H) fusion rate limited by "Deuterium Bottleneck" or by high coulomb barrier in (H + C), (H + N) (Hans Bethe, Nobel 1967)
- Low power density (~1,000 W/m^3) with > 6 billion year burn-up time!



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



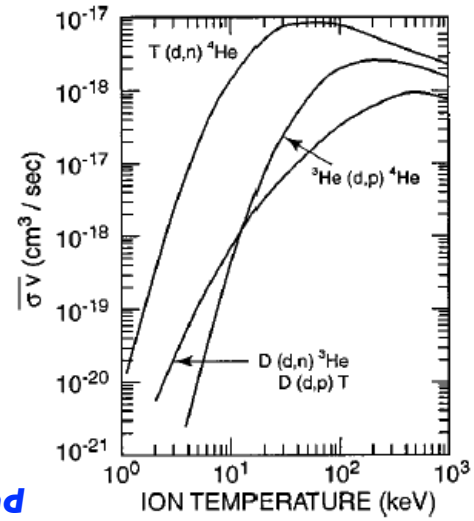
- At 100 sec, the universe cools to 1,000,000,000°
- Protons and neutrons fuse to Deuterium (heavy hydrogen). The whole universe is a "**burning plasma**"!
- D + D → ^{3}He + p
  D + D → T + p
  D + T → ^{4}He + n
  D + ^{3}He → ^{4}He + p
- At 300 sec, nearly all D has fused to ^{4}He . Universe cools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

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

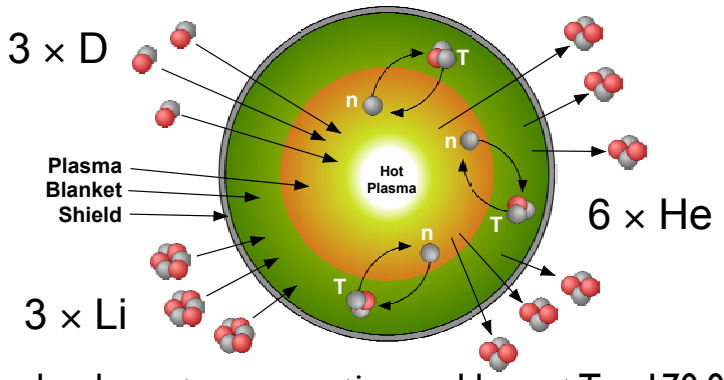


- Coulomb barrier sets the fusion's high temperature: T > 15 keV (170,000,000 K) Fusion involves **high-temperature matter** called "plasma".
- 33 g D in every ton of water, *but* ***no T and ^{3}He resources*** *exist on earth.*

- 2009 BAFTA "Best British Film" (Director: Duncan Jones, Son of David Bowie)
- 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

$$3D + 3(^6Li) \rightarrow 6(^4He) + 3n + (10.5\ \text{MeV plasma}) + (56.4\ \text{MeV blanket})$$

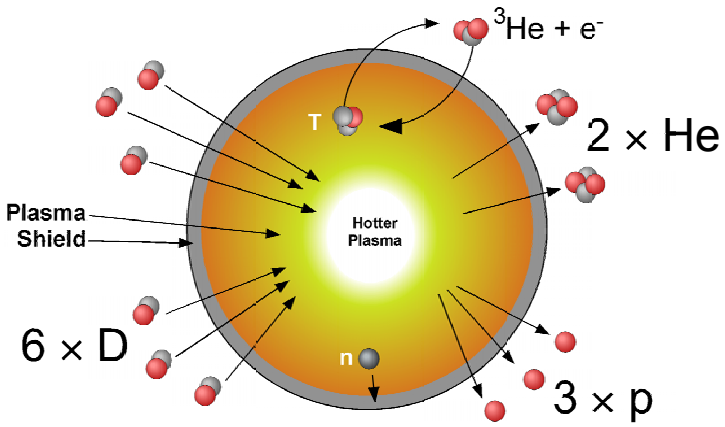


- D-T fusion has largest cross-section and lowest T ~ 170,000,000°.
- Tritium is created from ^{6}Li forming a **self-sufficient fuel cycle**. Practically no resource limit (10^{11} TW y D; $10^4(10^8)$ TW y ^{6}Li)!
- **Notice**: ~ 80% of energy as fast neutrons (~ 1.5 m shielding).
  ➠ the source of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

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

D-D (^{3}He) Fusion

$$6D \rightarrow 2(^4He) + 3H + e^- + n + (41.5 \text{ MeV plasma}) + (2.45 \text{ MeV shield})$$

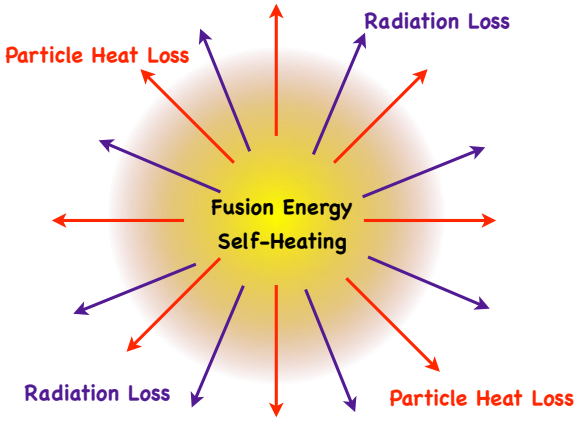


- Significantly reduced fast neutron flux!! Most energy to plasma and then first wall. Simplifies fusion component technologies.
- Next easiest fusion fuel cycle, but requires confinement ~25 times better than D-T(Li) **and** T extraction from plasma (*i.e.* only MFE).
- Equally challenging, but exciting,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



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

Neutrons escape and heat surrounding blanket

Self-Sustained Fusion Burn

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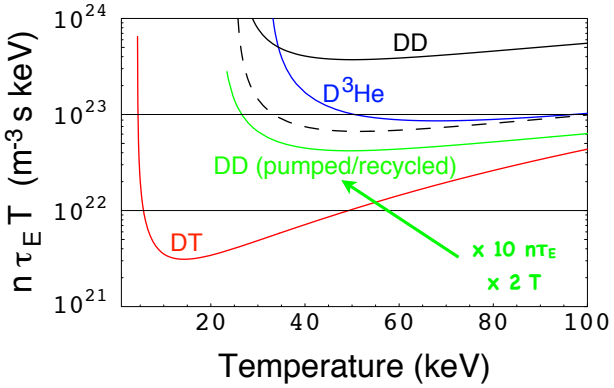

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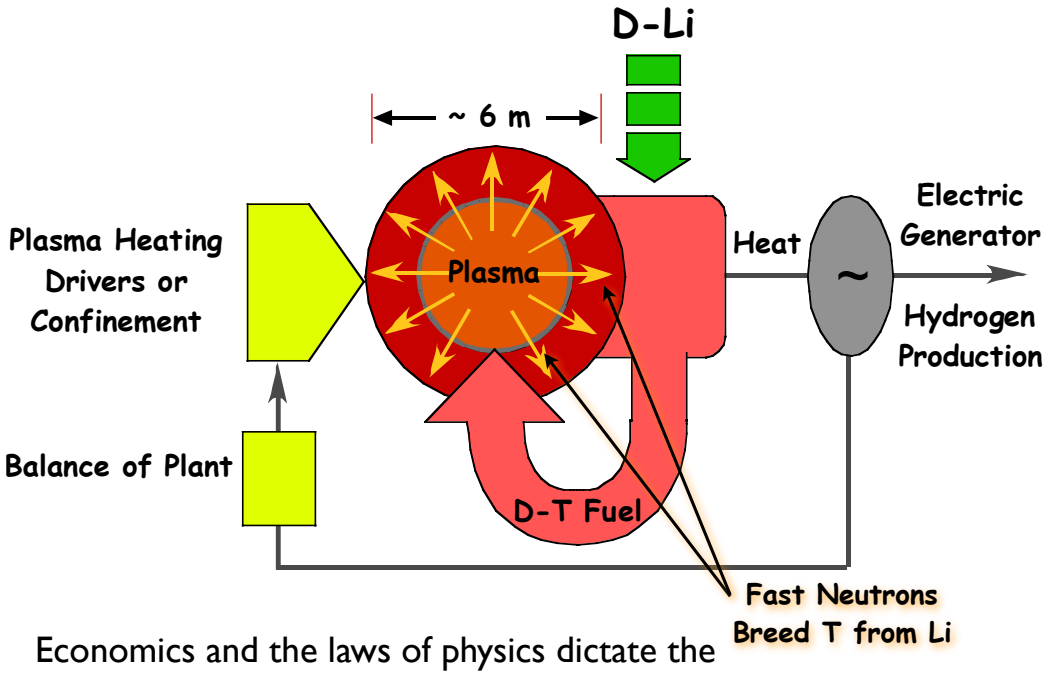
\end{aligned}
$$

Two Approaches to **Controlled** 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.

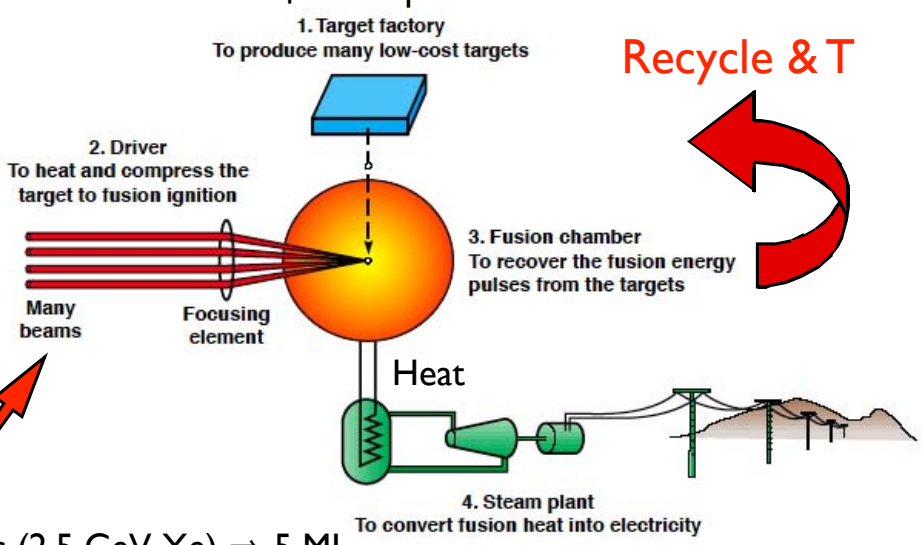
Elements of a D-T(Li) Fusion System



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

IFE

< $0.50/capsule

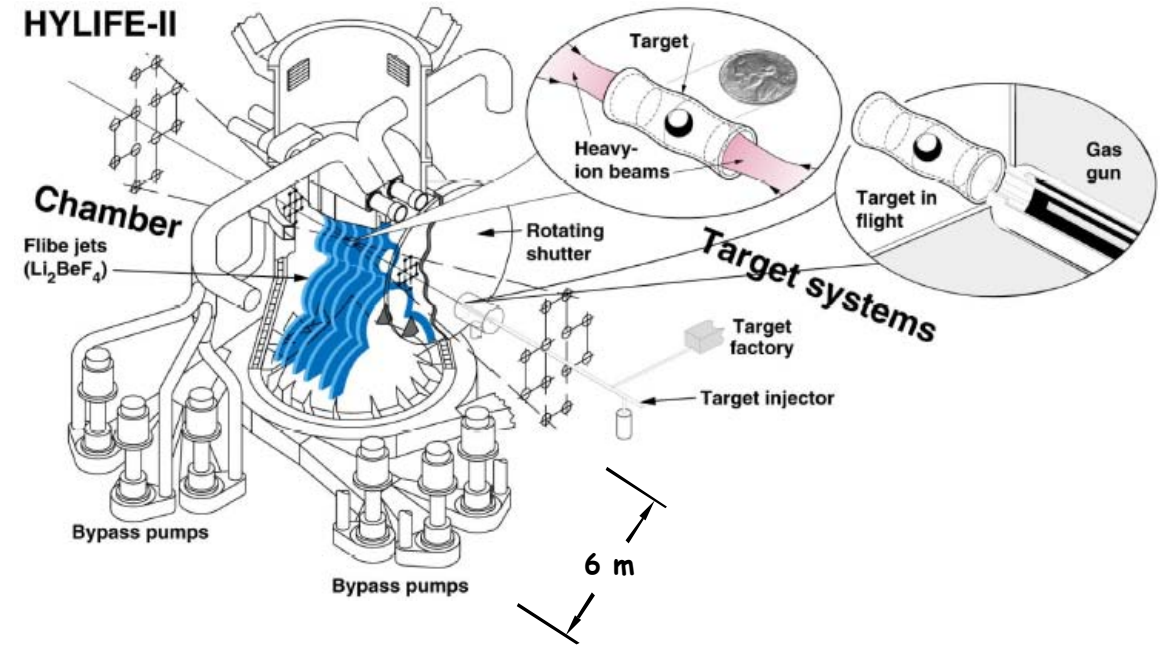


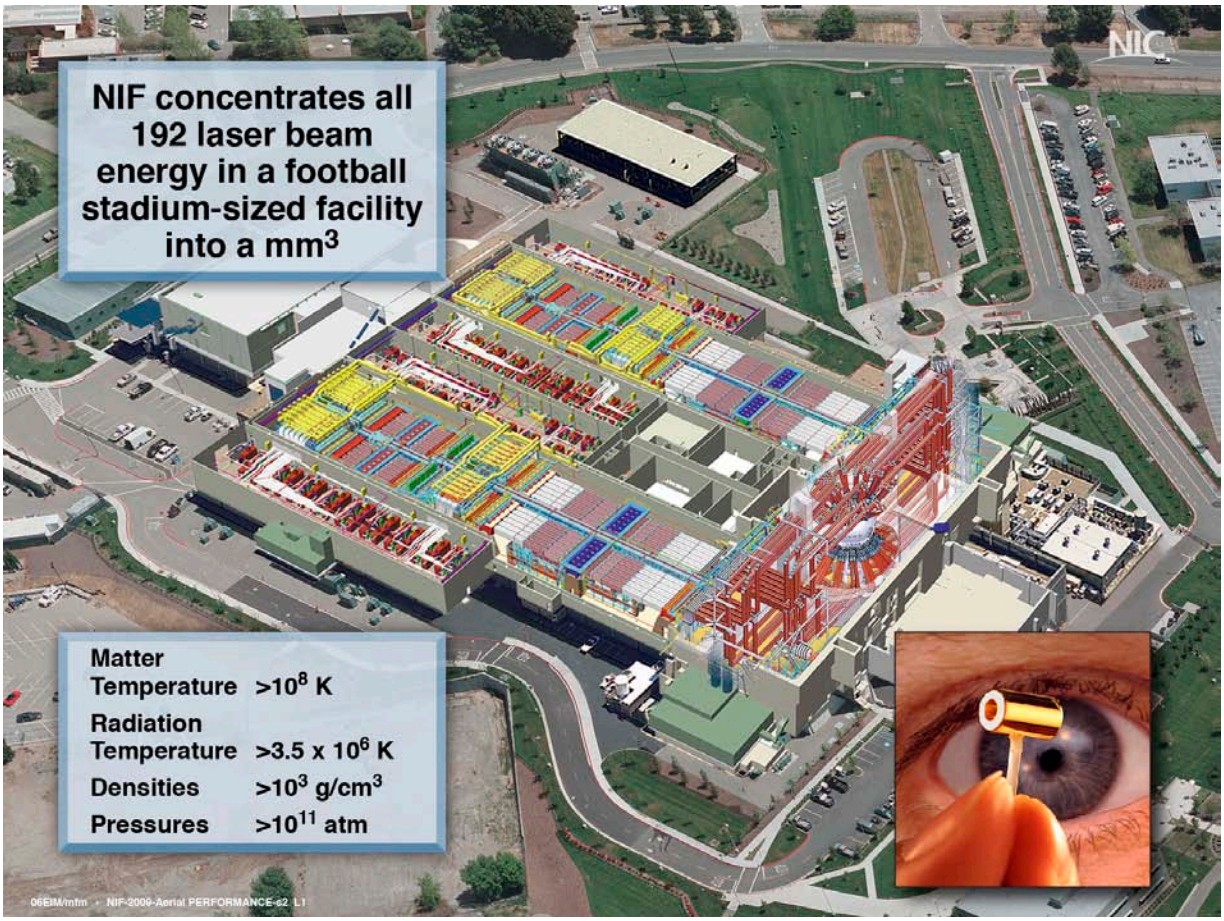
Example:
~ 100 beams (2.5 GeV Xe) ⇒ 5 MJ

(About the length of SLAC ~2.5 km)

IFE Chamber

~100 beams





Laser Bay
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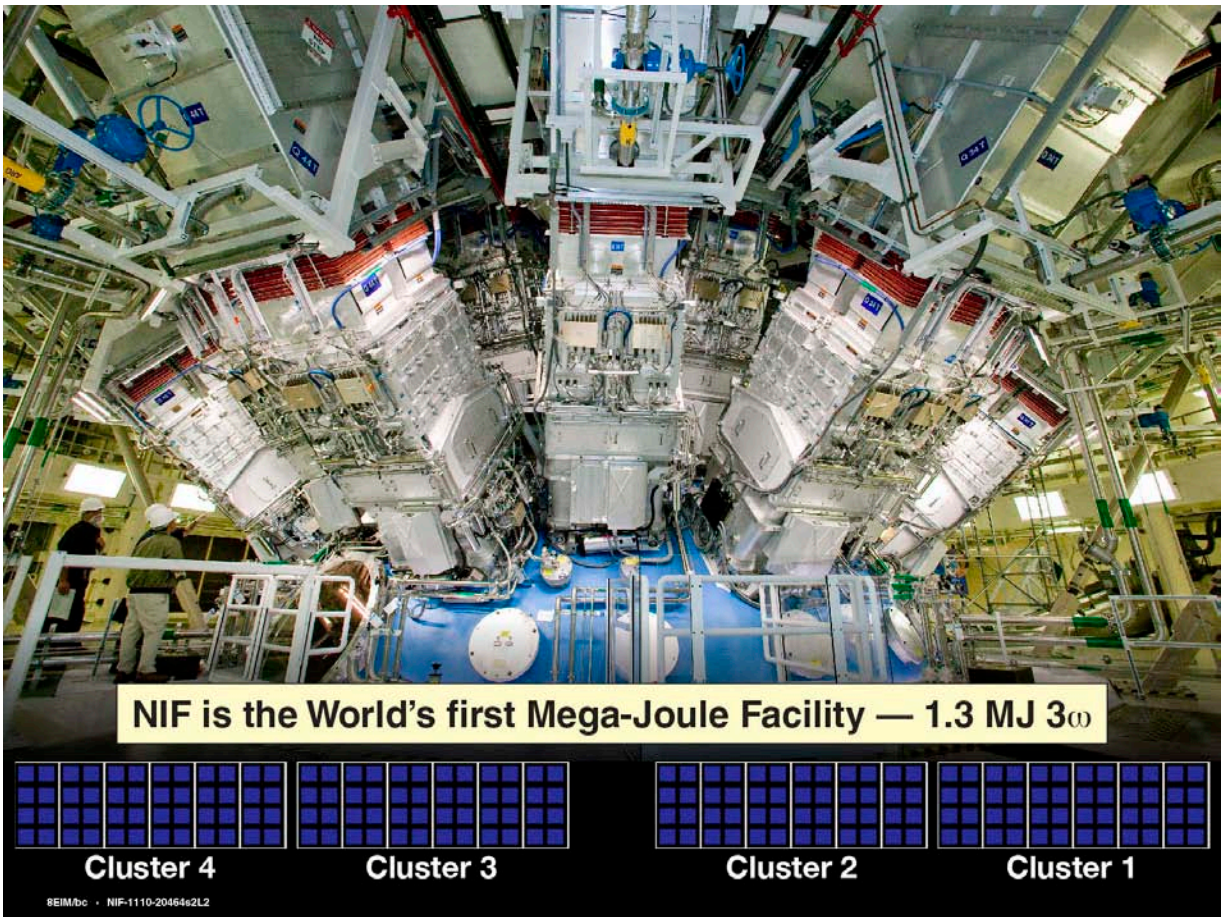
NIF is the World's first Mega-Joule Facility — 1.3 MJ 3ω
Cluster 4
Cluster 3
Cluster 2
Cluster 1
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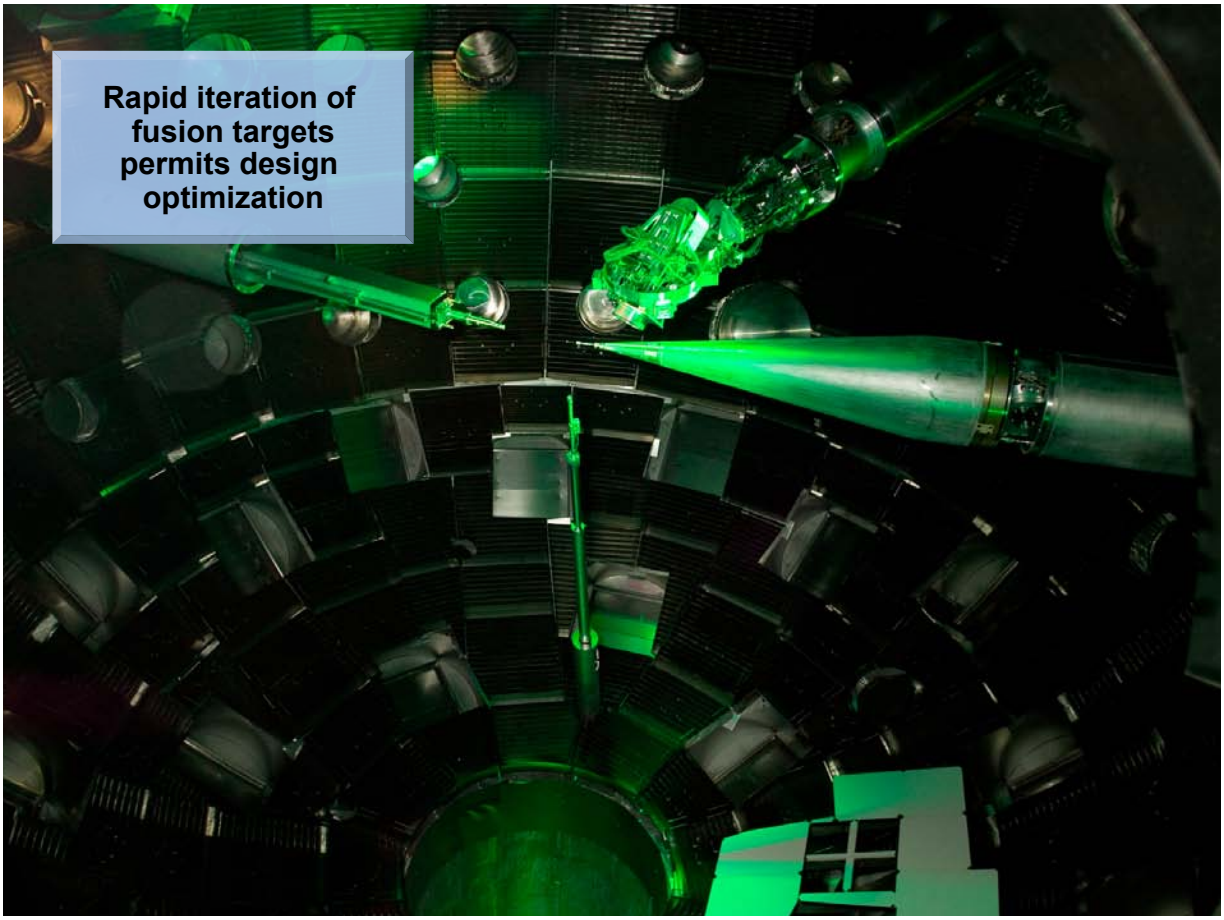


Two Approaches to Fusion Power

- 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!

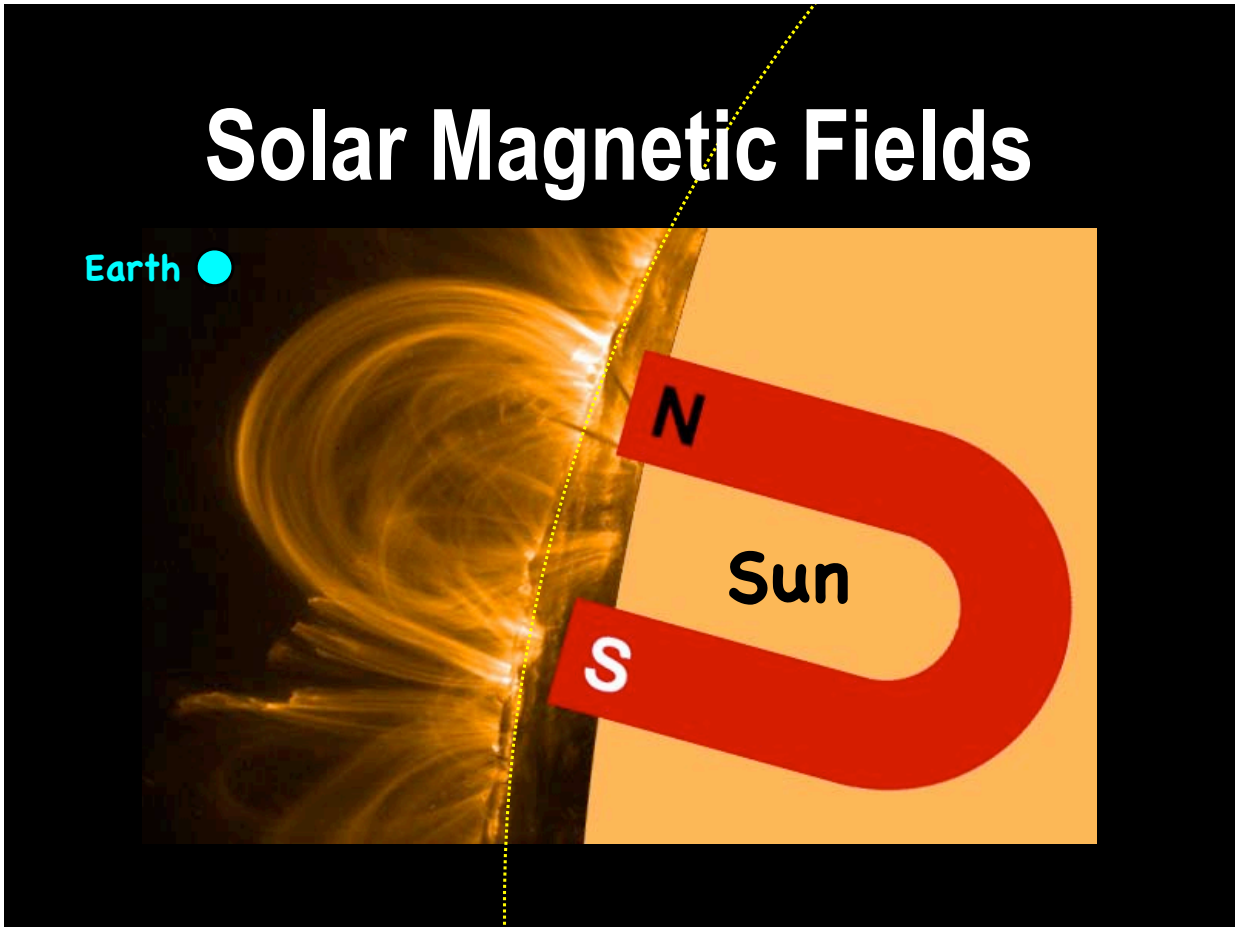
- Magnetic Fusion Energy (MFE)
  - $n \sim 10^{20}$ m^{-3} $T \sim 20$ keV $\tau_E \sim 5.0$ sec $(n\,T\,\tau_E \sim 10^{22})$
  - 250,000 times **less** particle density than air!

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!)

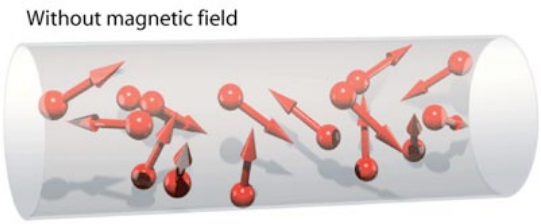
MFE plasma dynamics is nearly "collisionless"



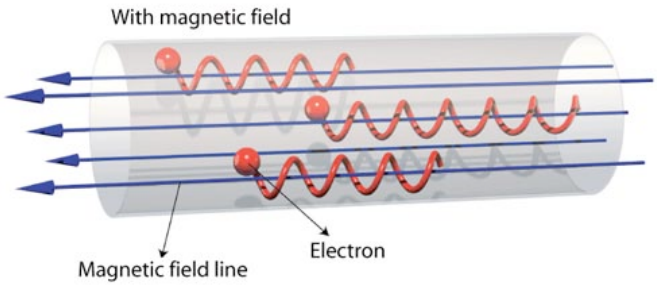
How Do Magnetic Fields Confine Ionized Matter?

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

Fast motion in *all* directions



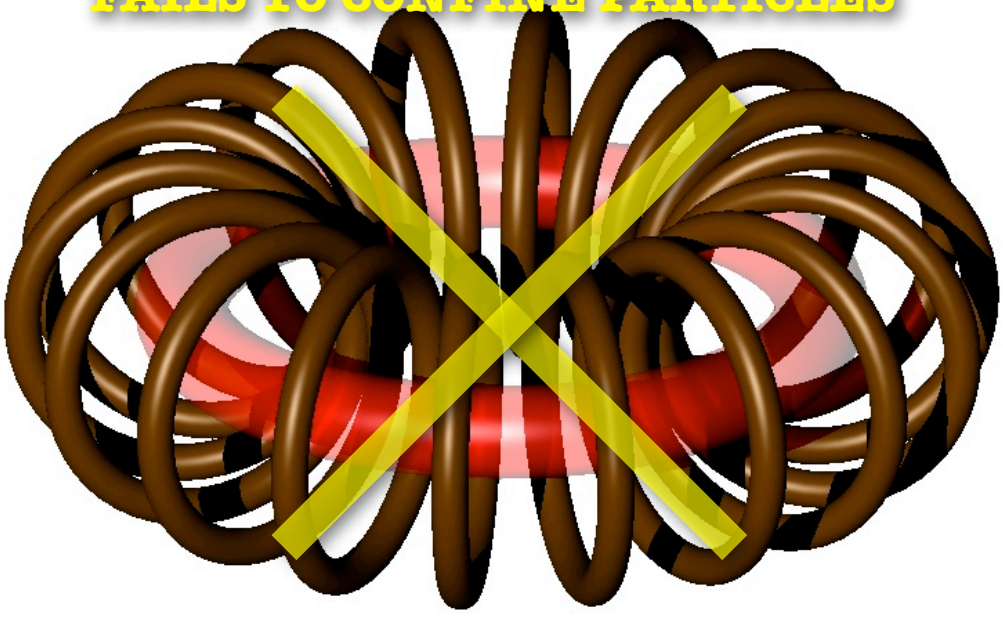
Fast motion only along B-lines



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

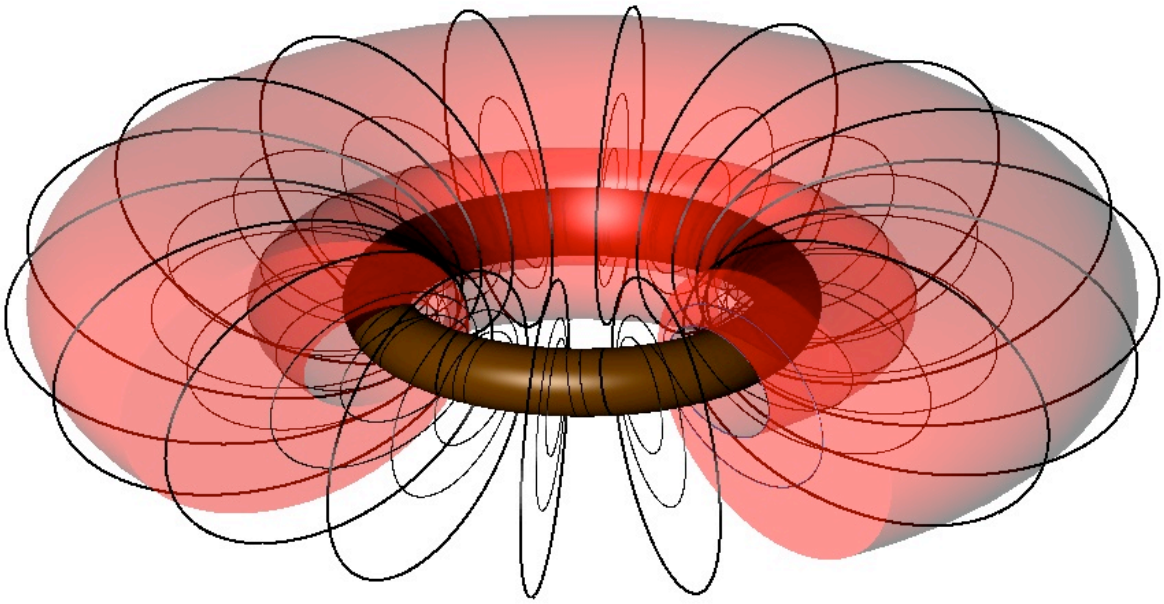
How to make a magnetic torus?

FAILS TO CONFINE PARTICLES



Toroidal Field from Poloidal Coils

How to make a magnetic torus?



Poloidal Field from Toroidal Coils

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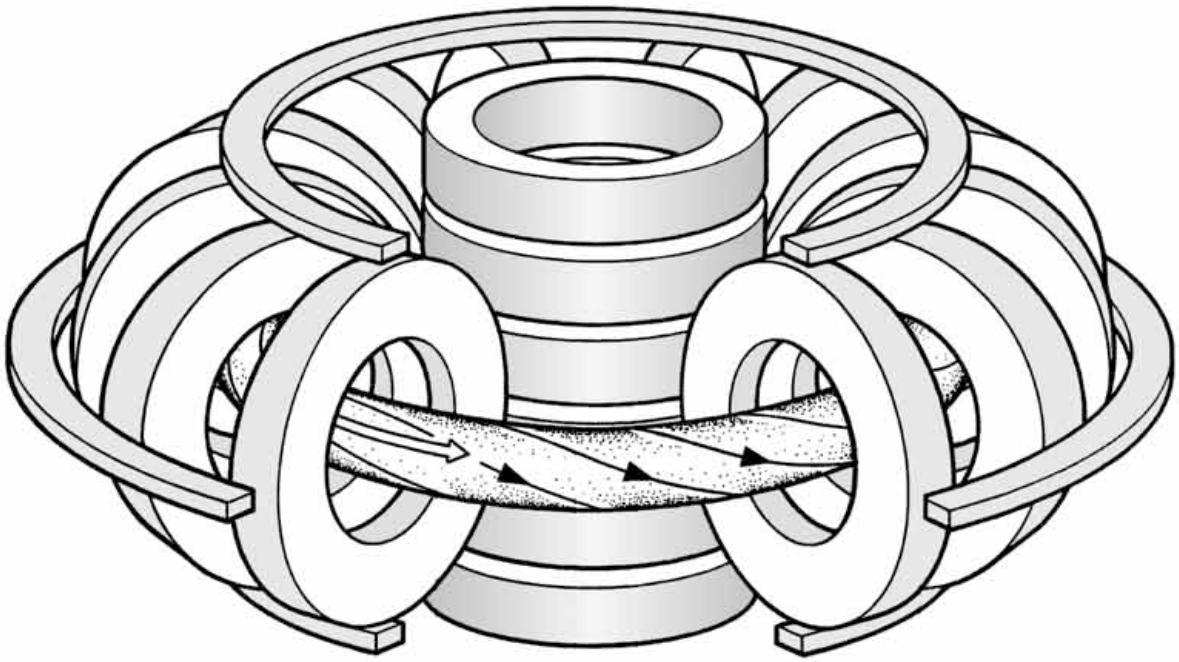
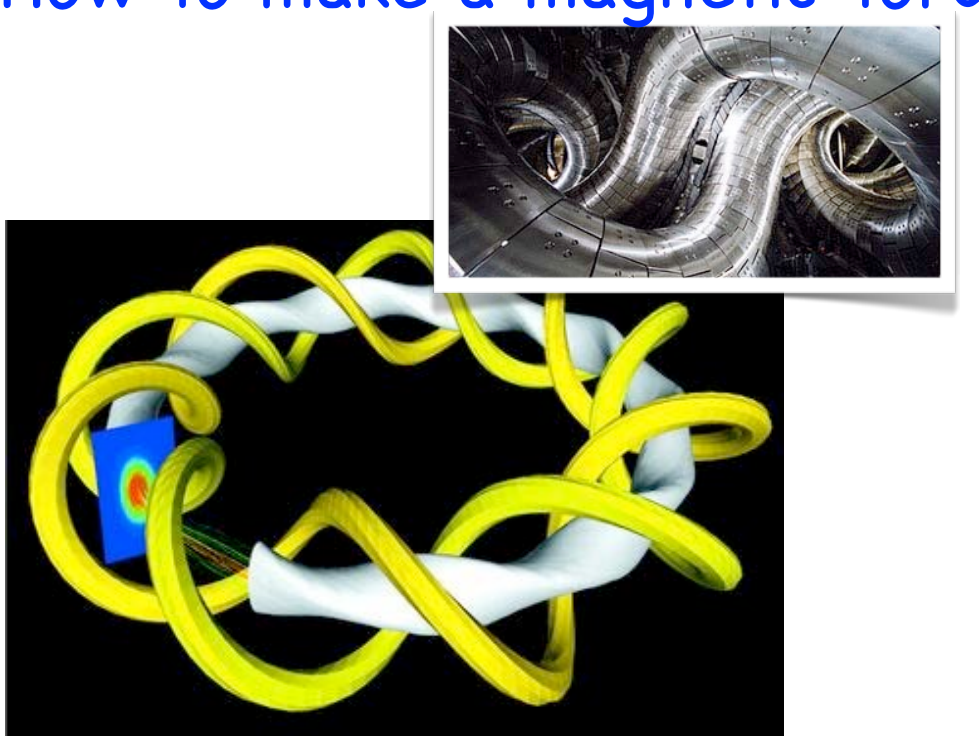


Combined Toroidal and Poloidal Field (Tokamak)

How to make a magnetic torus?

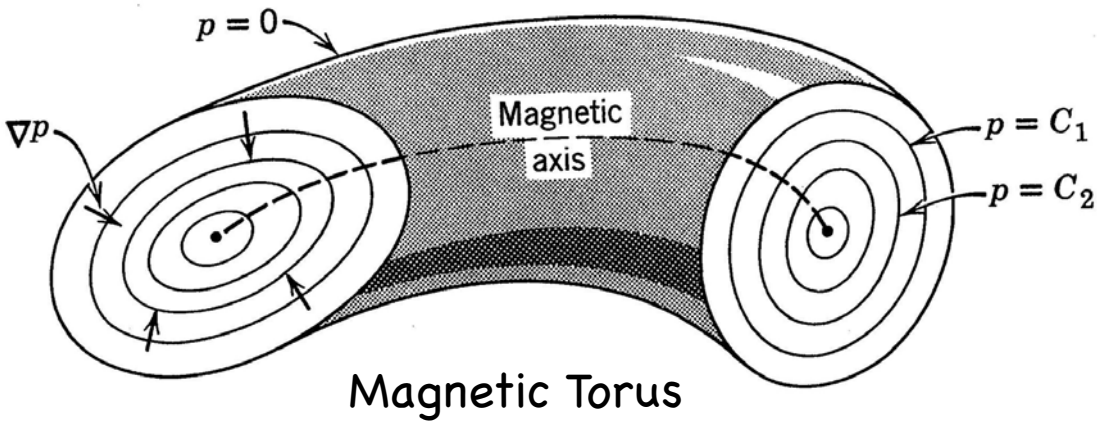


Combined Toroidal and Poloidal Field (Stellarator)

How Do Magnetic Fields Confine Ionized Matter?

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

Surfaces of constant plasma pressure form nested tori

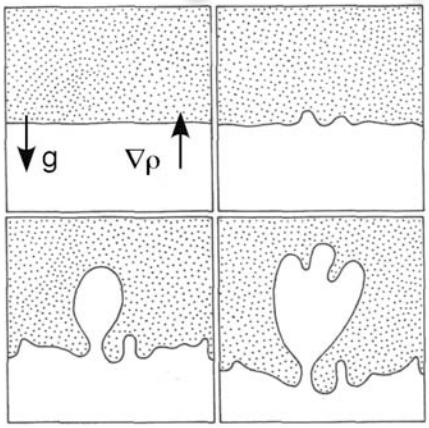


Magnetic Torus

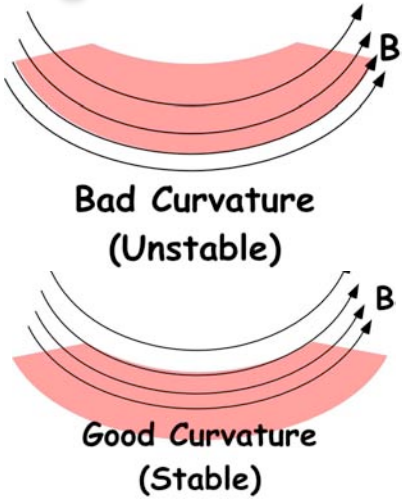
MFE Configuration Optimization Depends on Shape

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

Interchange Instability

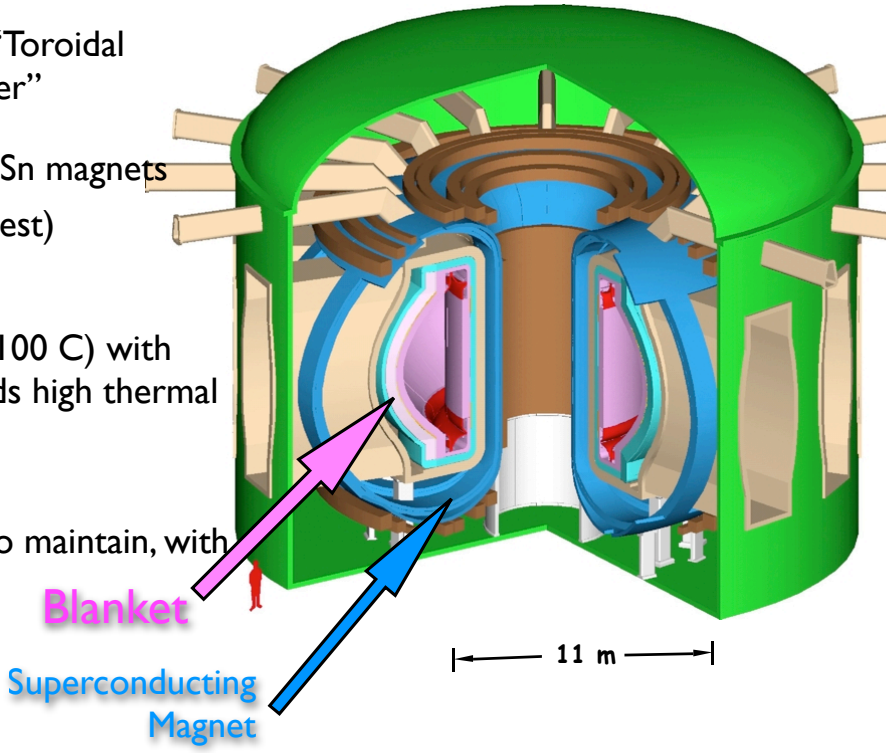


Bending Field ➠ Effective g



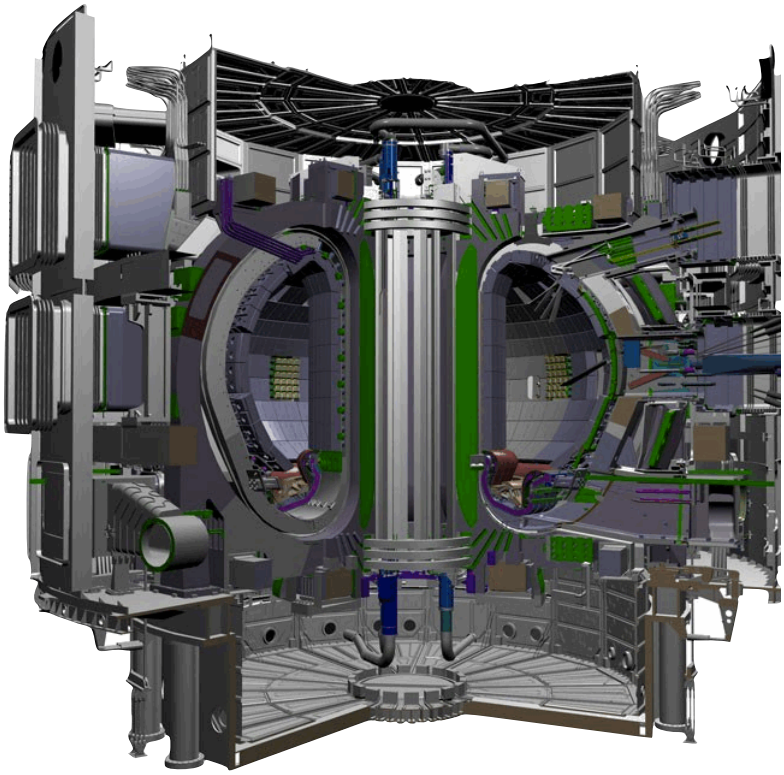
Magnetic Containers are Toroidal

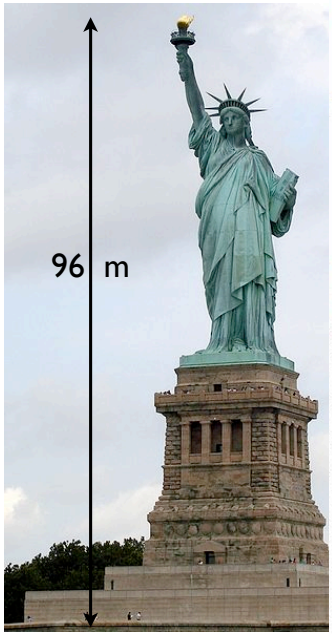
- Tokamak means "Toroidal Magnetic Chamber"
- Steady state, Nb_3Sn magnets (Coldest ↔ Hottest)
- SiC blanket (~ 1,100 C) with PbLi coolant yields high thermal efficiency.
- Modular, "easy" to maintain, with 85% availability
- 1 GWe

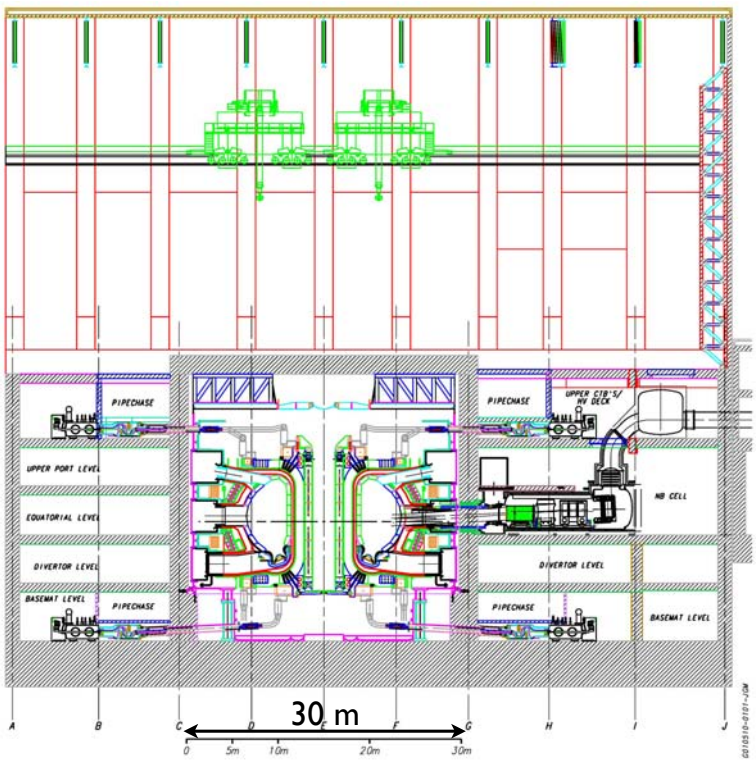


http://www.iter.org/

- Culmination of 50 years of magnetic fusion research
- 500 MW fusion power for 7 min pulses
- EU, Japan, Russia, China, S Korea, India, USA
- At 22B US$ (14B US$ official), the most ambitious international science project ever
- 23,000 tons (tokamak only), or $1M/ton

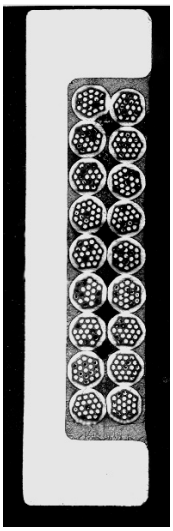




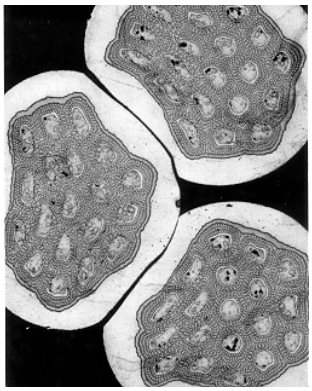


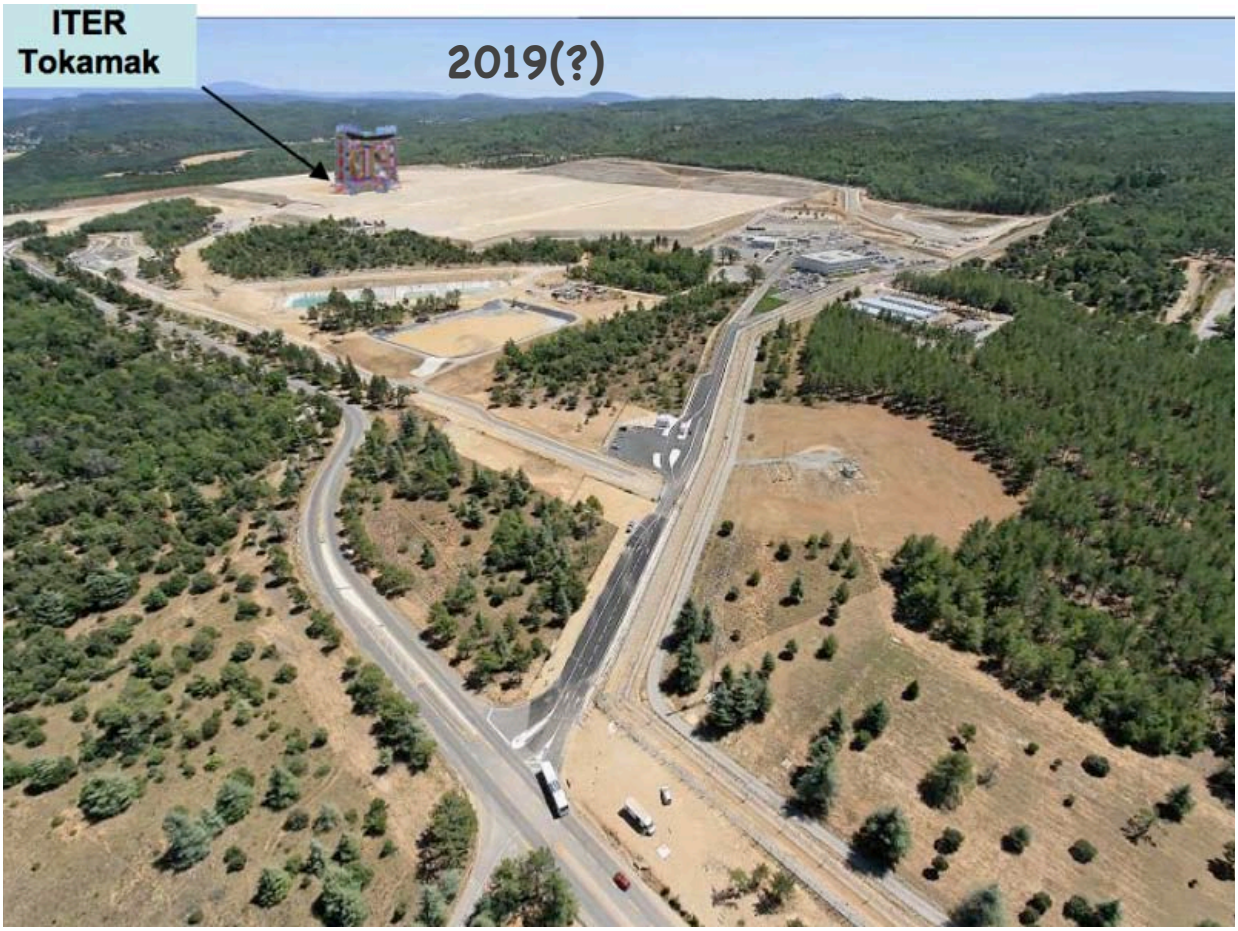
Nb_3Sn (Niobium Tin)

- Discovered in 1954
- Ceramic (brittle)
- In 1961, niobium-tin exhibits superconductivity at large currents and strong magnetic fields, becoming the first known material to support the high currents and fields necessary for high-field magnets
- Tc = 18.3 °K
- In April 2008 a record non-copper current density was achieved at 0.26 MA/cm^2 at 12 T and 4.2 K
- The strands necessary for the ITER TF coils have a total length of 150,000 km and would encircle the earth more than three times!



LDX Conductor in Soldered Cable





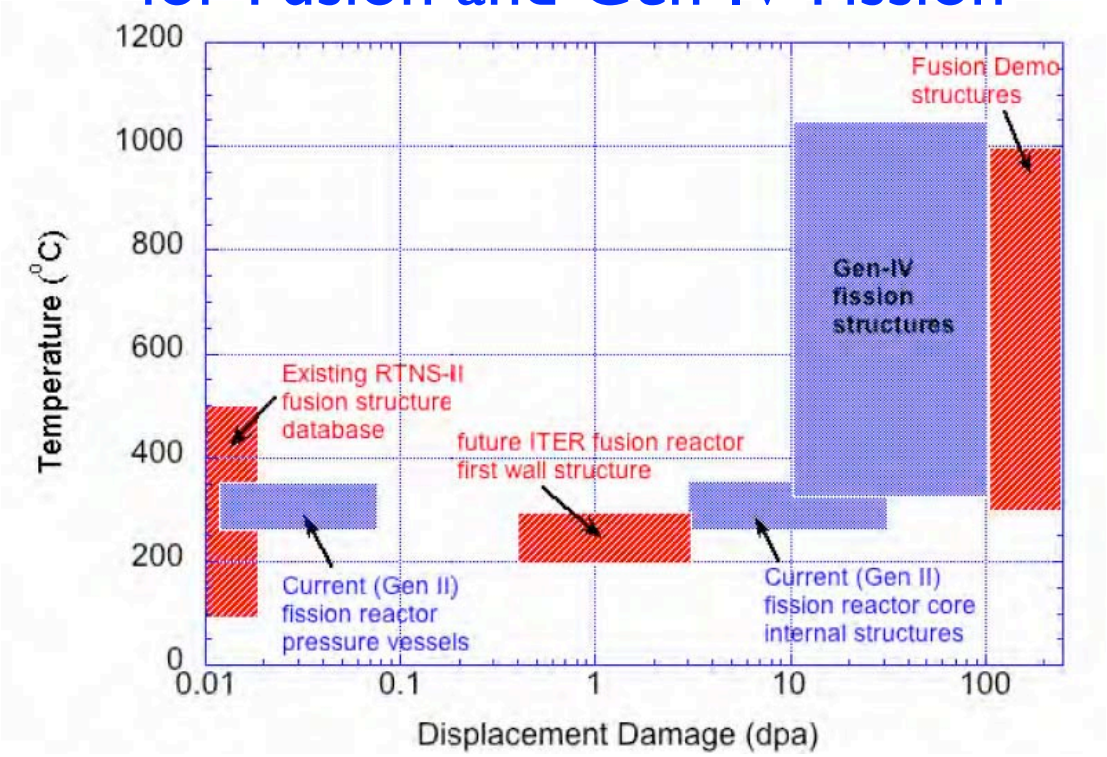
Can Fusion be "Green" Nuclear Power?

- 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, …

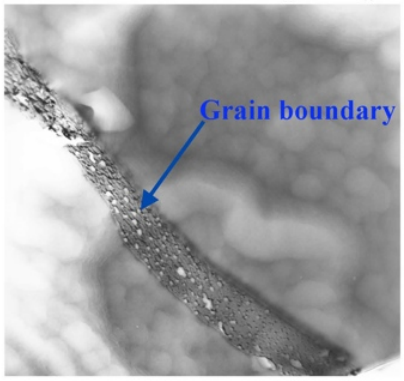
Significant Materials Challenges for Fusion and Gen-IV Fission



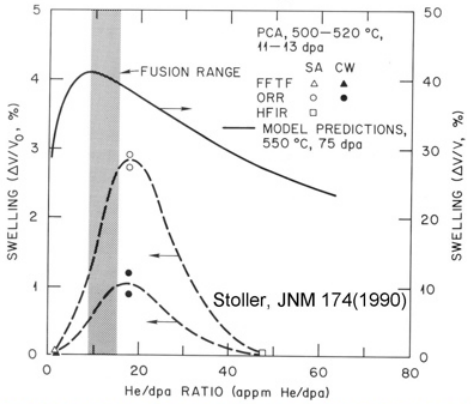
Stainless Steels May Not be Compatible with D-T Fusion

- He generation can alter the microstructural evolution path of irradiated materials (pronounced effects typically occur for >100 appm He)
  - Cavity formation (matrix and grain boundaries)
  - Precipitate and dislocation loop formation

He bubbles on grain boundaries can cause severe embrittlement at high temperatures

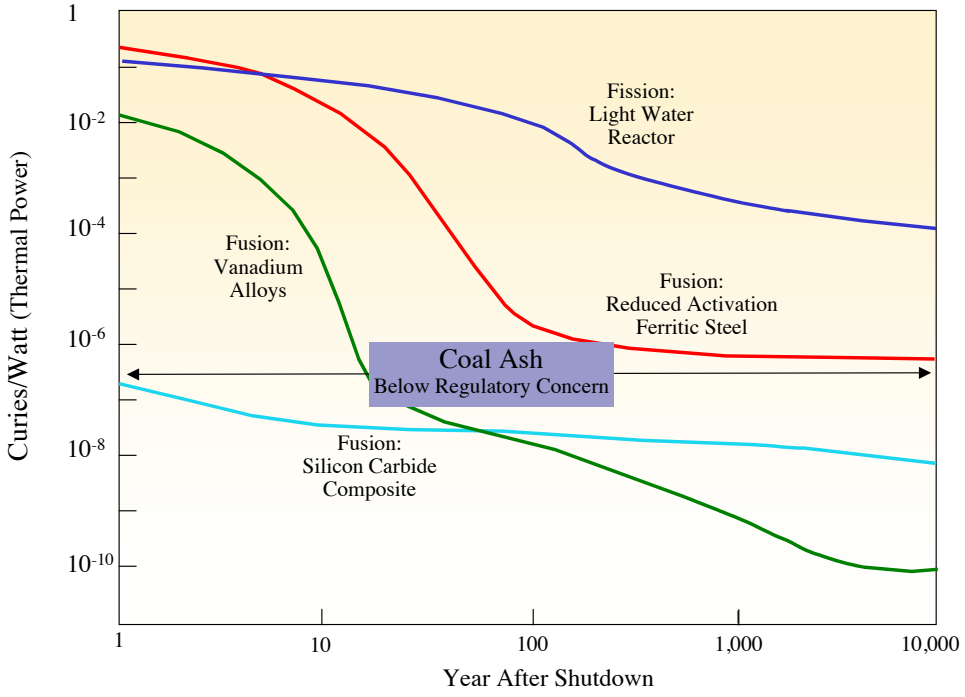


Swelling in stainless steel is maximized at fusion-relevant He/dpa values

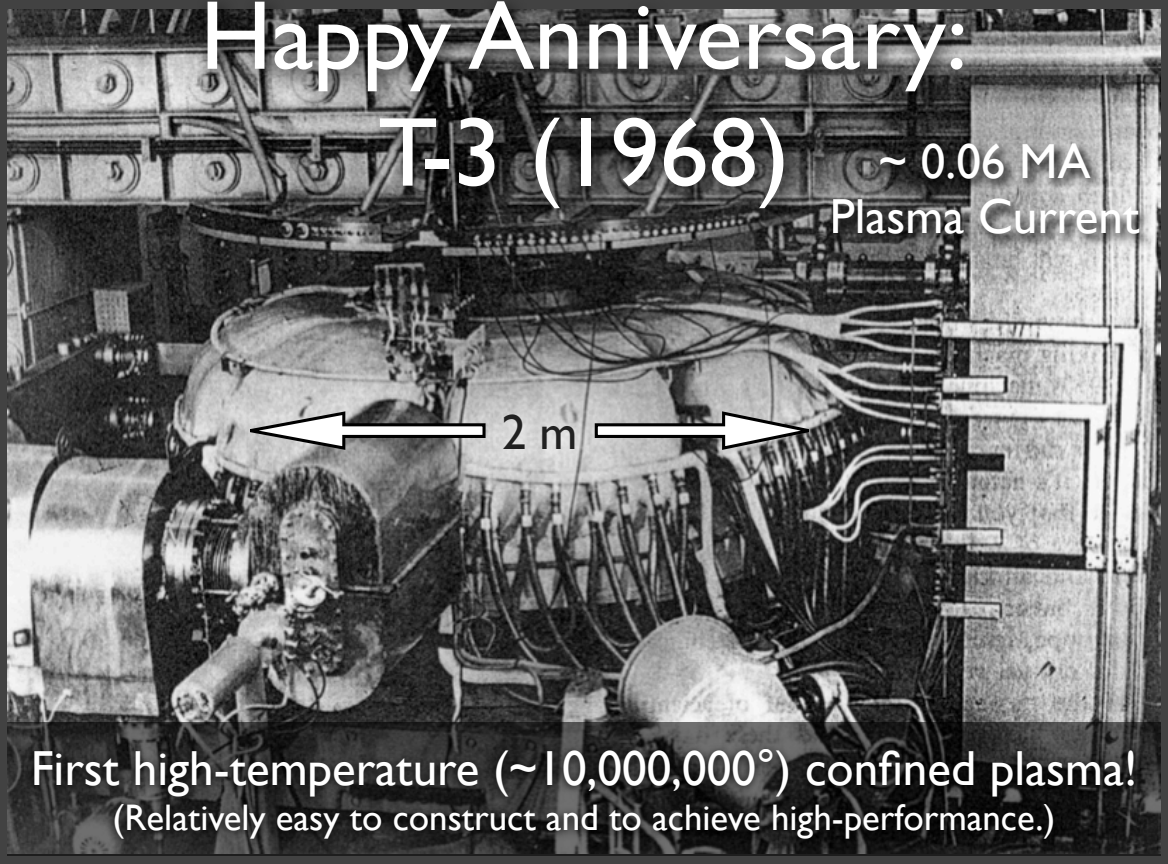


Management of He transmutation products (matrix trapping at engineered 2nd phases) is a key factor for fusion materials

Attractive Low Activation Material Options for D-T Fusion

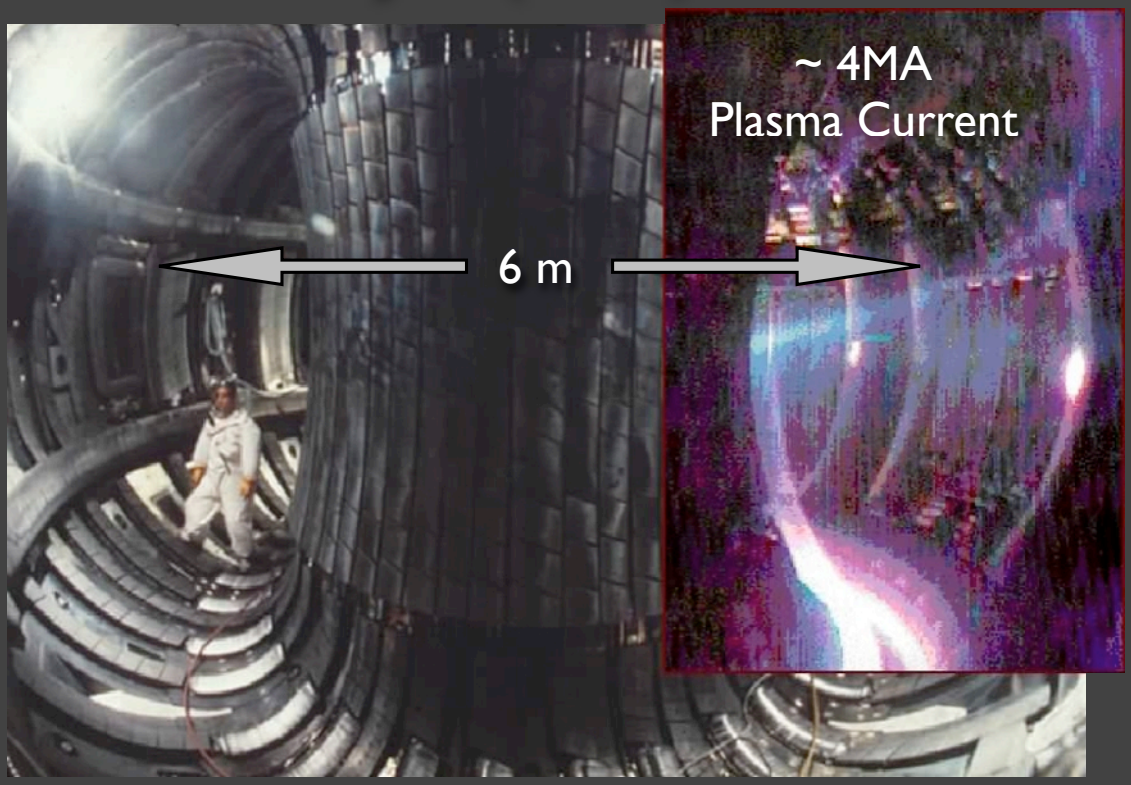


Happy Anniversary: T-3 (1968)

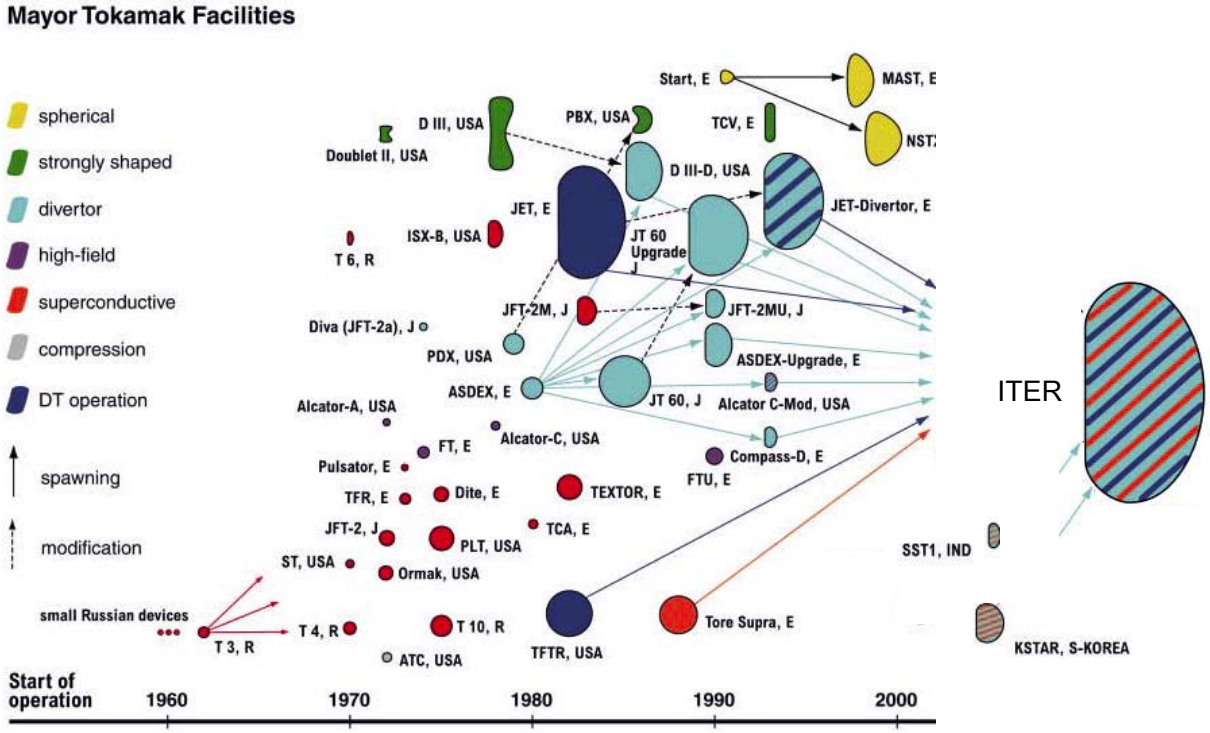


First high-temperature (~10,000,000°) confined plasma!
(Relatively easy to construct and to achieve high-performance.)

JET (1997)

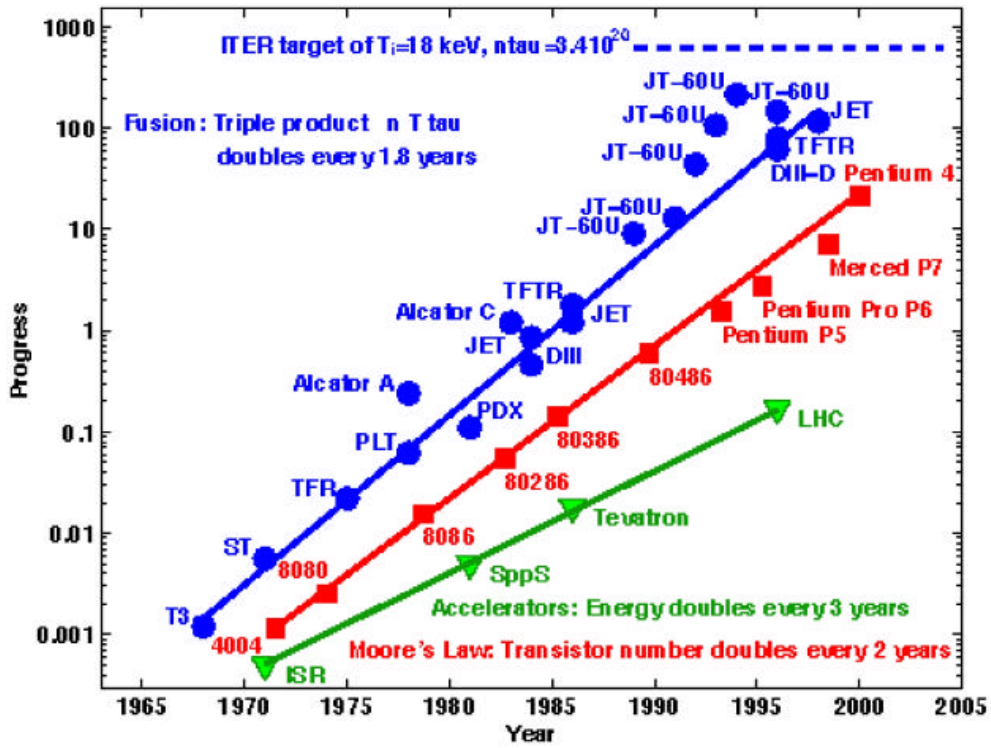


Over 100 Tokamaks



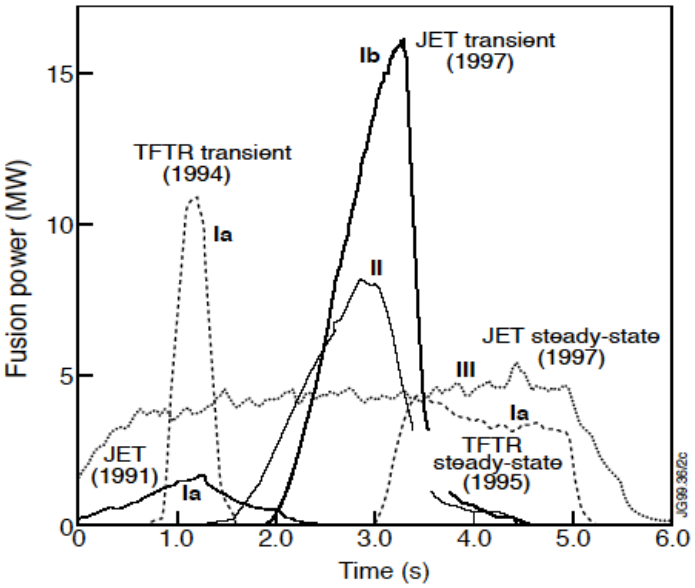
Rapid Progress

(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.

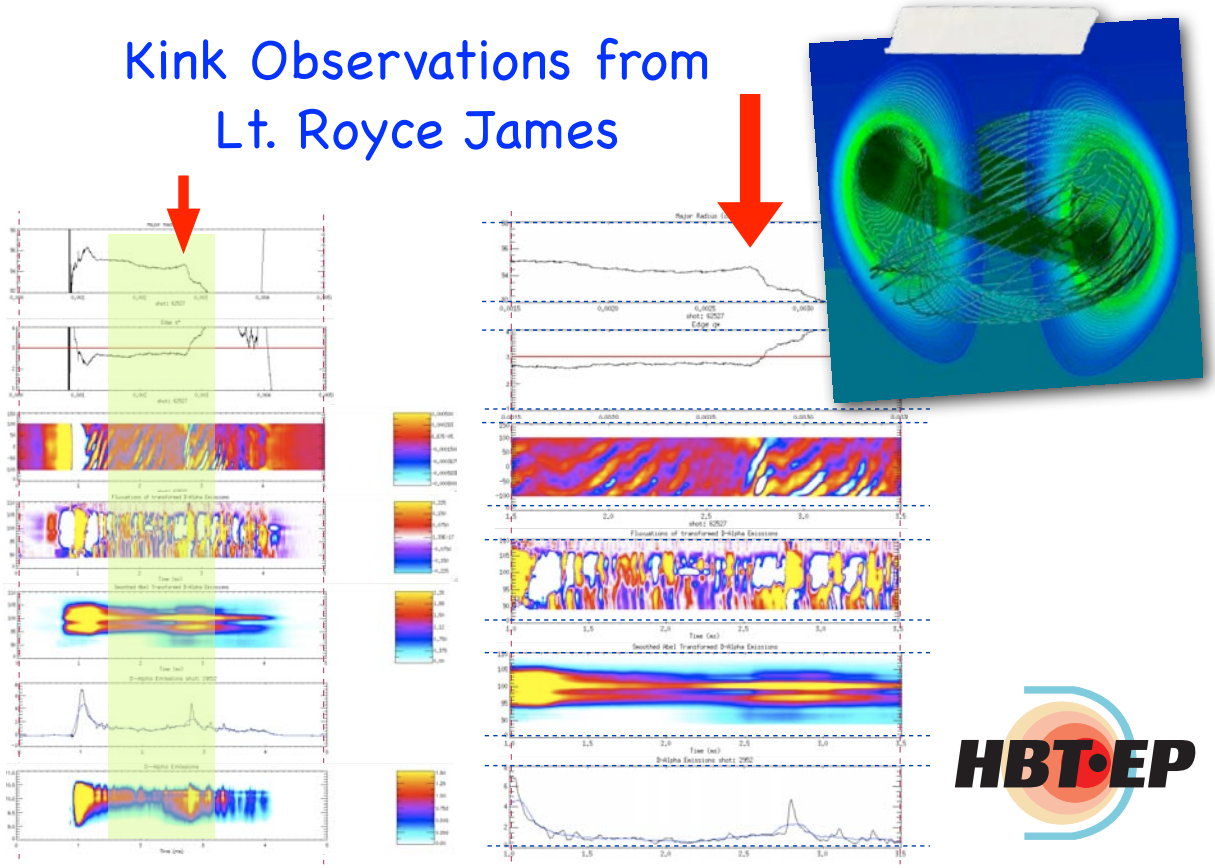


Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines), in different regimes:

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

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

Kink Observations from Lt. Royce James



HBT·EP

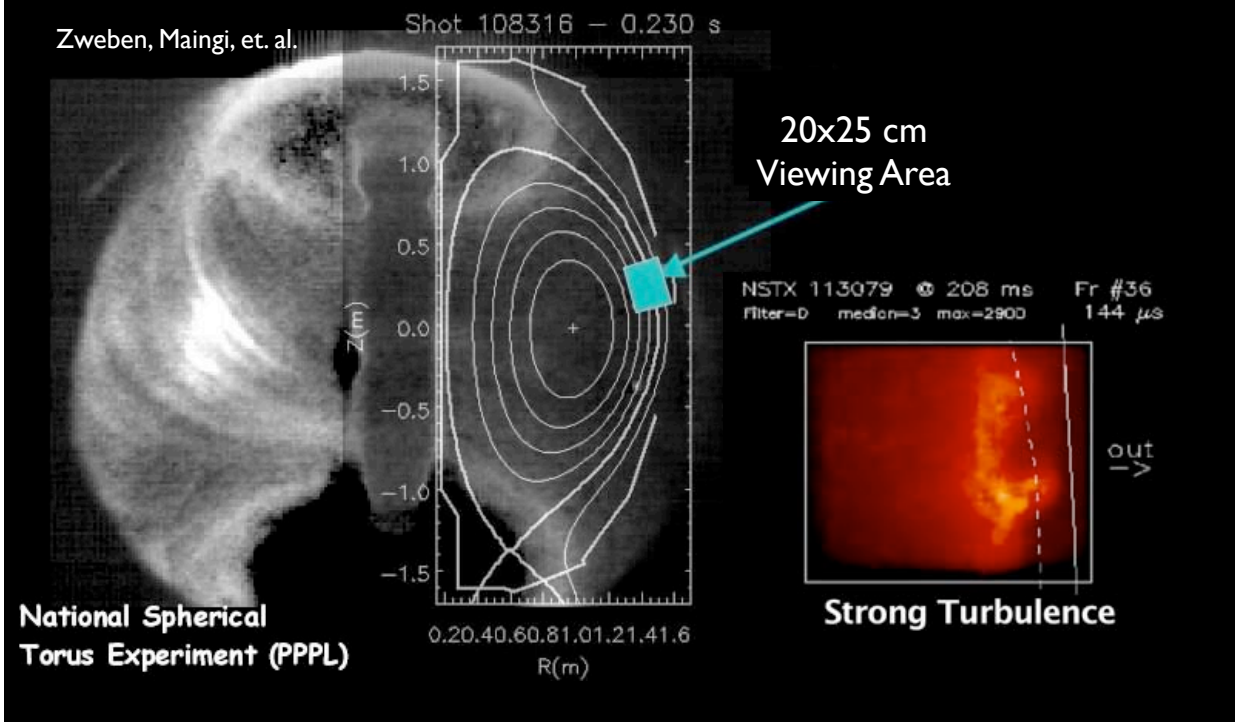
Fusion Science Research Today

- Understand confined high-temperature matter
- "Optimize" and control the fusion configuration

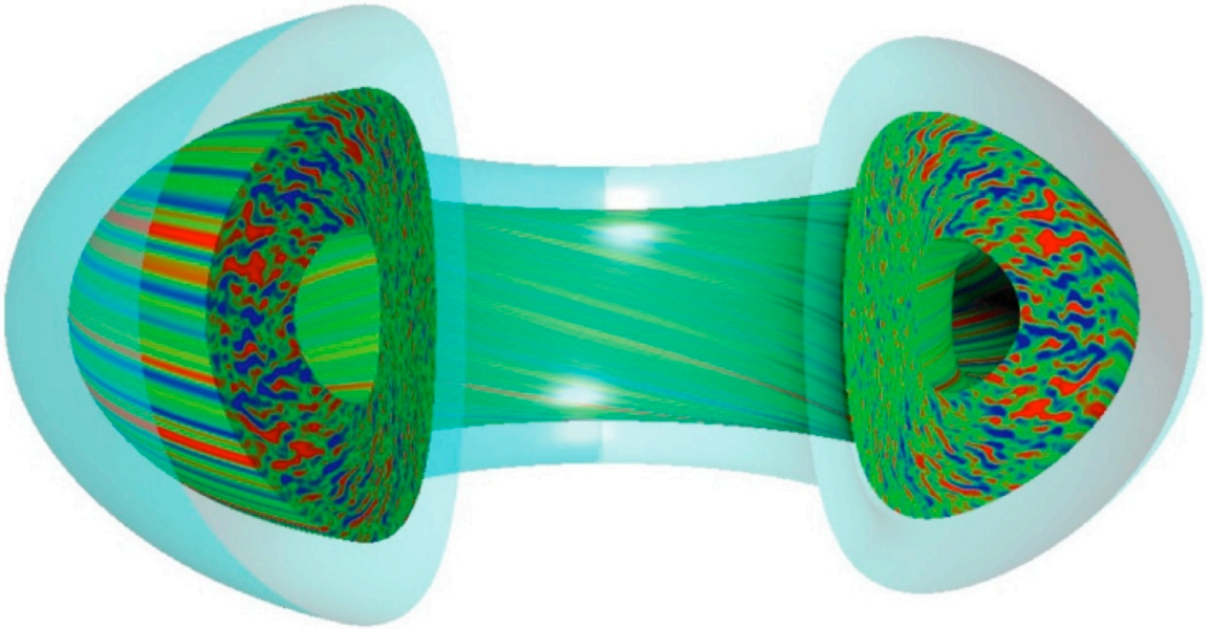
➡ Explore and understand "Burning Plasma" dynamics using ITER and fundamental physics

➡ Develop the modern engineered materials required for advanced nuclear power systems.

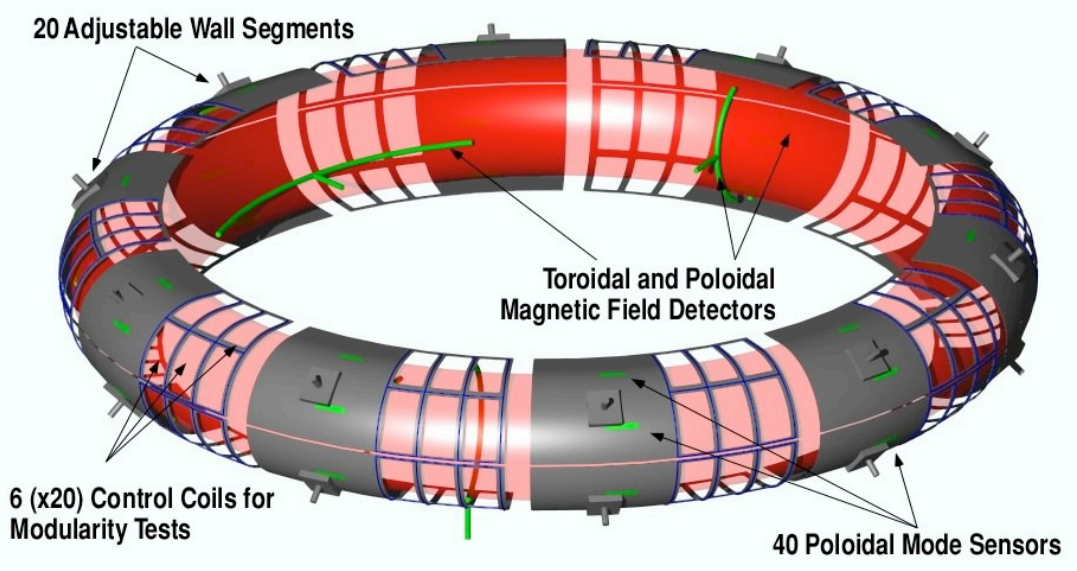
Viewing the Turbulence "Transport Barrier"



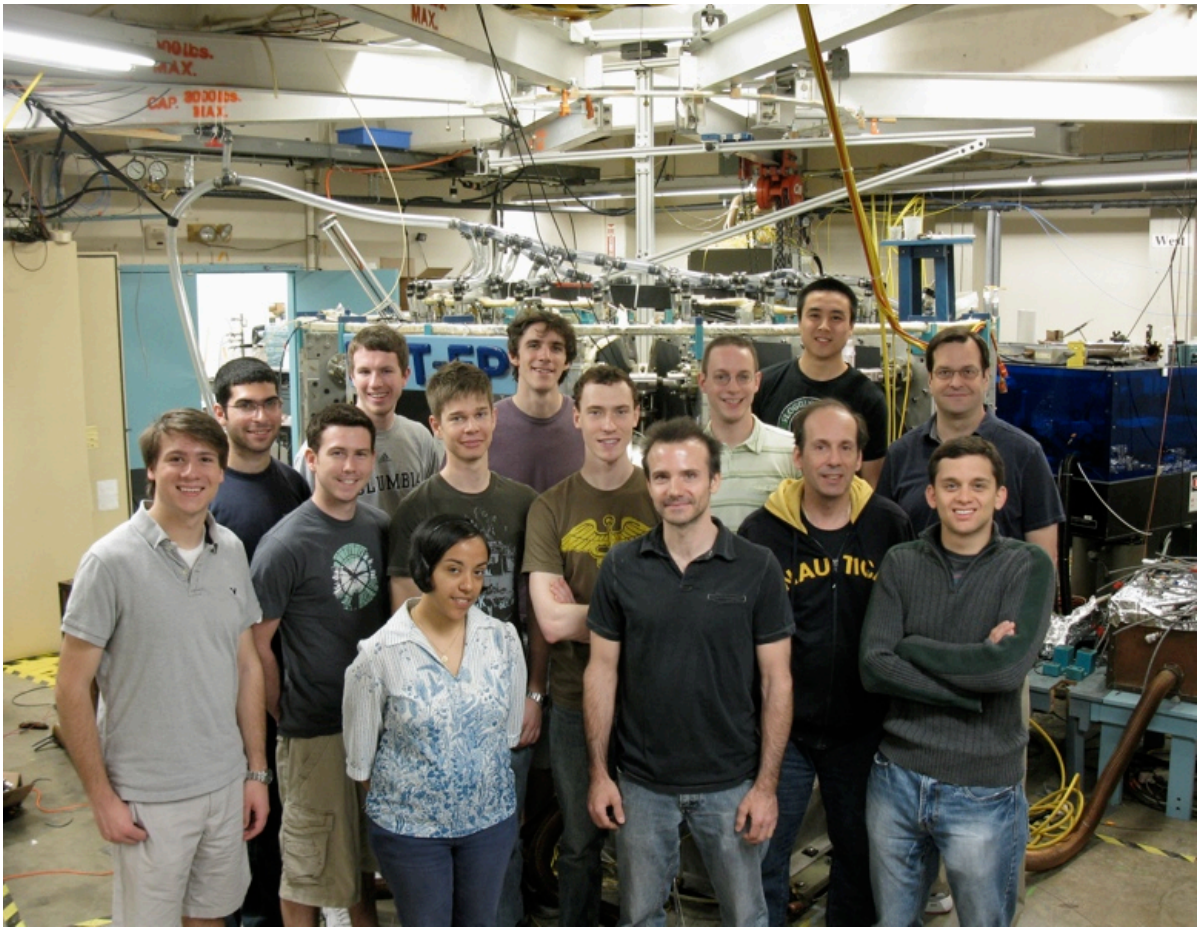
Measurement ⇔ Theory ⇔ Simulation



HBT-EP Stabilizes Plasmas in NYC!



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK



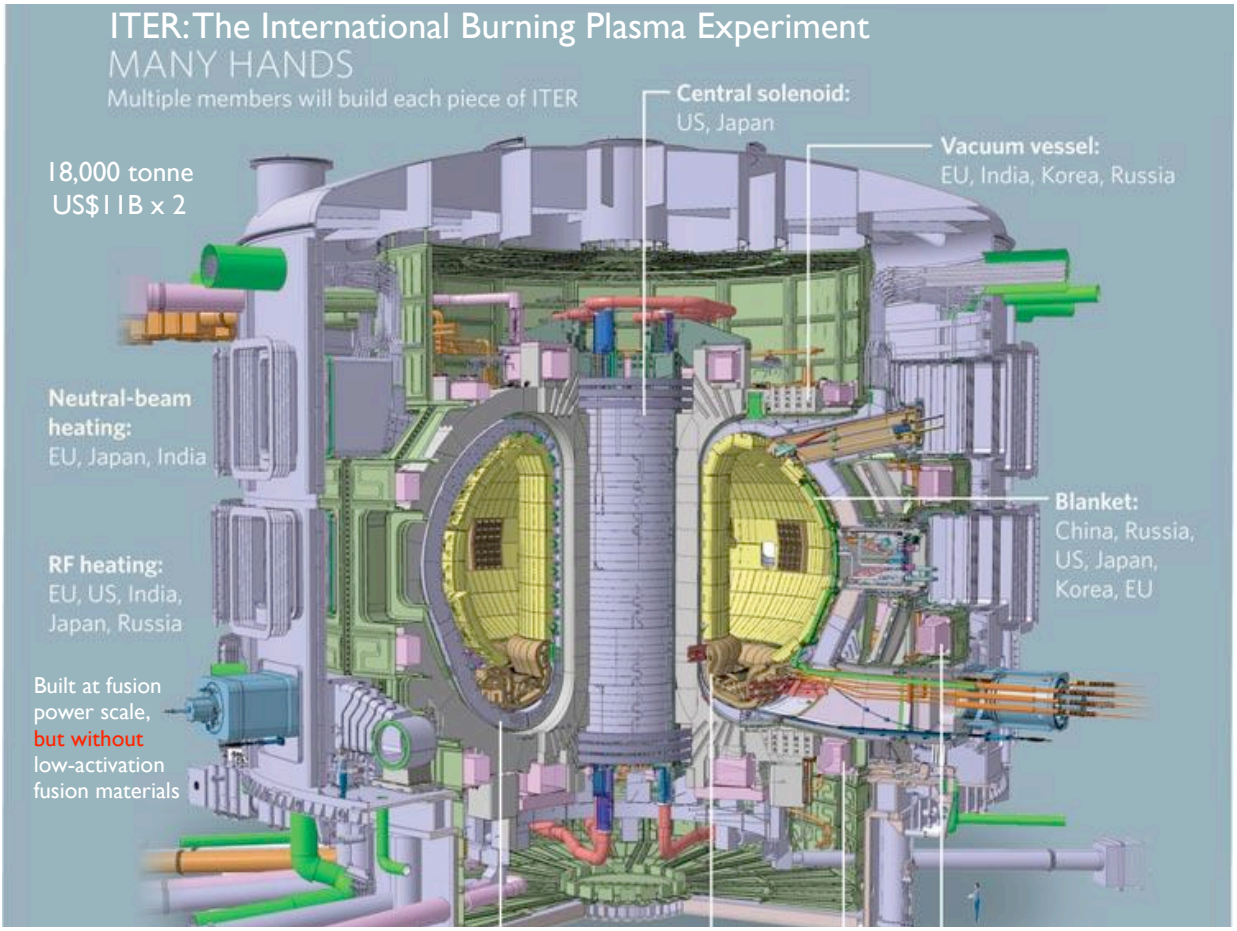
Columbia Fusion Researchers after Brooklyn Half-Marathon

International Thermonuclear Experimental Reactor

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

Burning Plasma Experiment

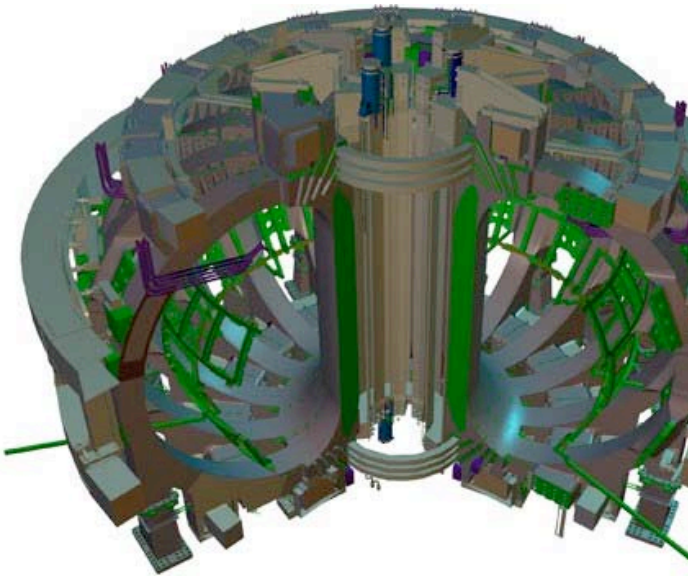
- Demonstrate and study strong fusion self-heating in near steady-state conditions:
  - Strongly self-heating:
    - 500 MegaWatts; Fusion power gain ~ 10
    - ~ 70 % self-heating by fusion alpha particles
  - Near steady state:
    - 300 to > 3000 seconds; Many characteristic physics time scales
 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



Description of ITER Magnets

(http://www.iter.org/mach/magnets)

- The superconducting material for both the Central Solenoid and the Toroidal Field coils is designed to achieve operation at high magnetic field (13 Tesla), and is a special alloy made of Niobium and Tin (Nb3Sn).
- The Poloidal Field coils and the Correction coils use a different, Niobium-Titanium (NbTi) alloy.
- In order to achieve superconductivity, all coils are cooled with supercritical Helium in the range of 4 Kelvin (-269°C).
- The ITER TF coils are designed to have a total magnetic energy of **41 gigajoules** and a maximum magnetic field of 11.8 tesla.



Benefits from Comprehensive Component R&D

Largest High-Field Superconducting Magnet is World: 0.64 GJ and 13T!

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."

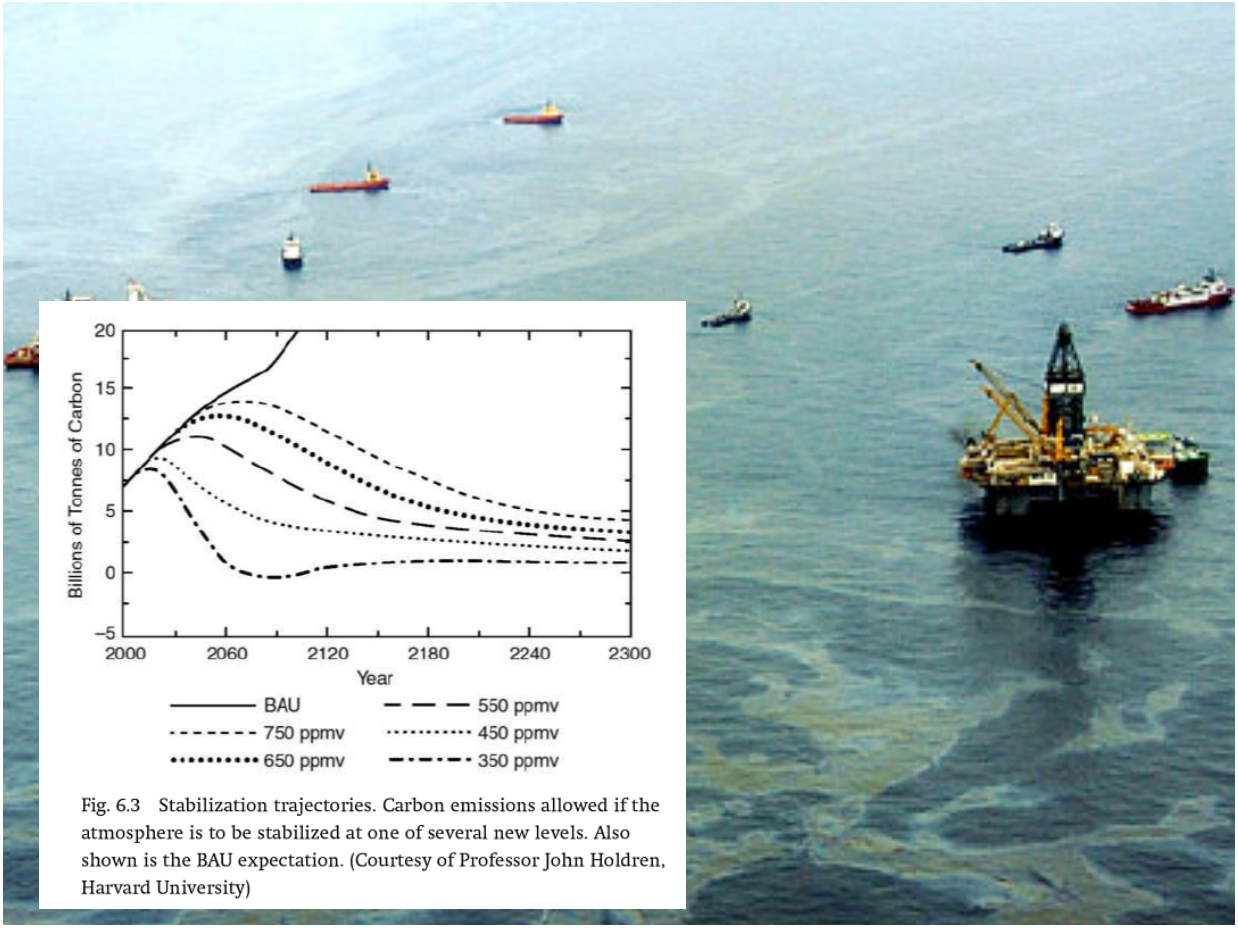


Fig. 6.3 Stabilization trajectories. Carbon emissions allowed if the atmosphere is to be stabilized at one of several new levels. Also shown is the BAU expectation. (Courtesy of Professor John Holdren, Harvard University)

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

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 fusion research.
- Successful R&D and aggressive implementation will allow fusion to contribute to world energy needs.