Introduction to Magnetic Fusion Research

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The slides for this talk are online at:
http://www.apam.columbia.edu/mauel/mauel_pubs/NUF2011_IntroMagFusion.pdf

Outline

- What is fusion?
- Can fusion be "**green**" nuclear power?
- What is magnetic fusion research today?
- ITER: Fusion at the scale of a power plant
- Columbia University's plasma physics experiments

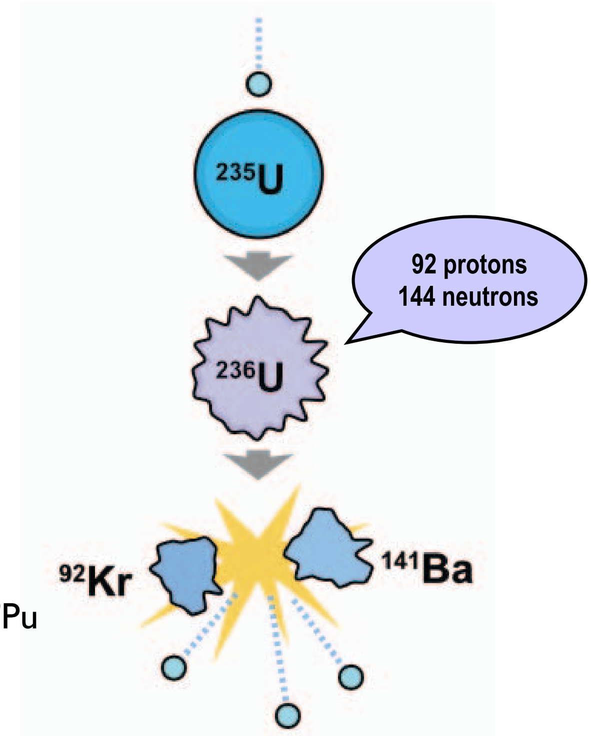
Energy from the Forces of Nature

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

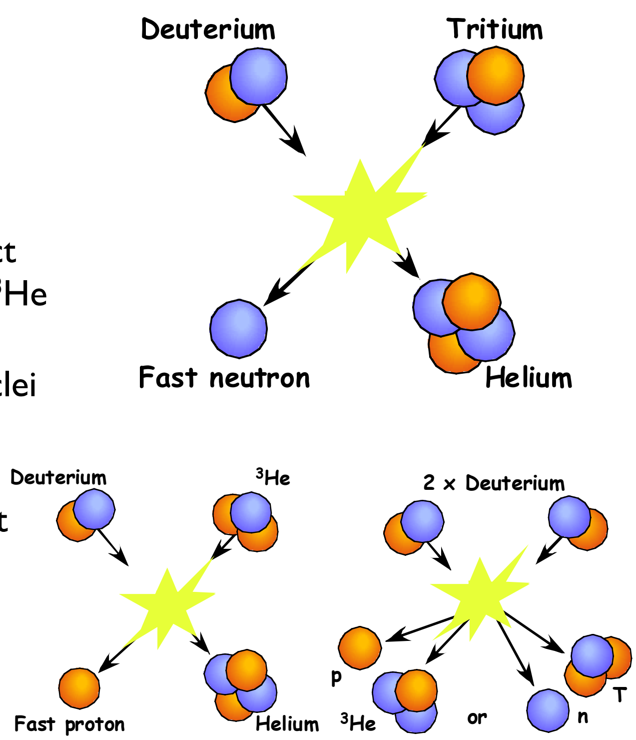
Why Fission is (Relatively) Easy to Do…

- 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



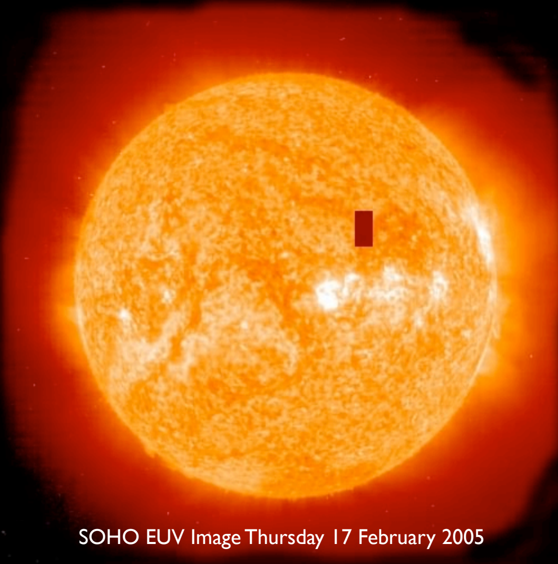
Why Fusion is (Really, Really) Hard to Do…

- 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

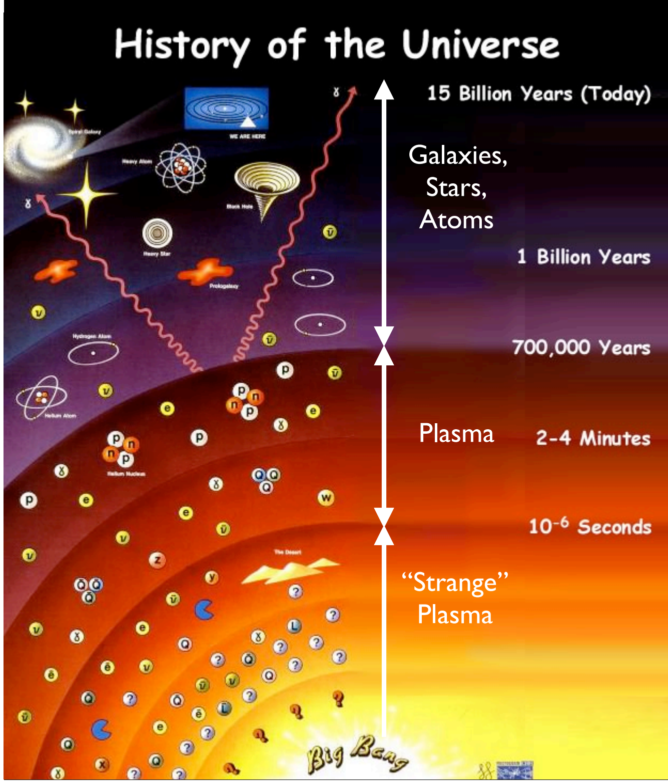
- 90% H, 9% He, 1% others
- Solar core: 15,000,000°
- (H + H) fusion rate limited by "Deuterium Bottleneck" or by high coulomb barrier in heavy stars (H + C), (H + N) (Hans Bethe, Nobel 1967)
- Low power density (~1,000 W/m^3) with > 6 billion year burn-up time!



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**"!
- $D + D \rightarrow {}^3He + p$
  $D + D \rightarrow T + p$
  $D + T \rightarrow {}^4He + n$
  $D + {}^3He \rightarrow {}^4He + p$
- At 300 sec, nearly all D has fused to ^4He . Universe cools and expands. Fortunately…

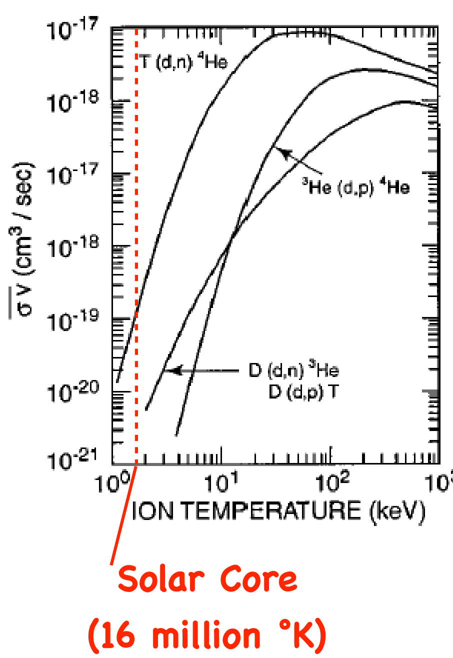
Deuterium (also ^{3}He and Lithium): Nature's Gift from the "Big Bang"!

- 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

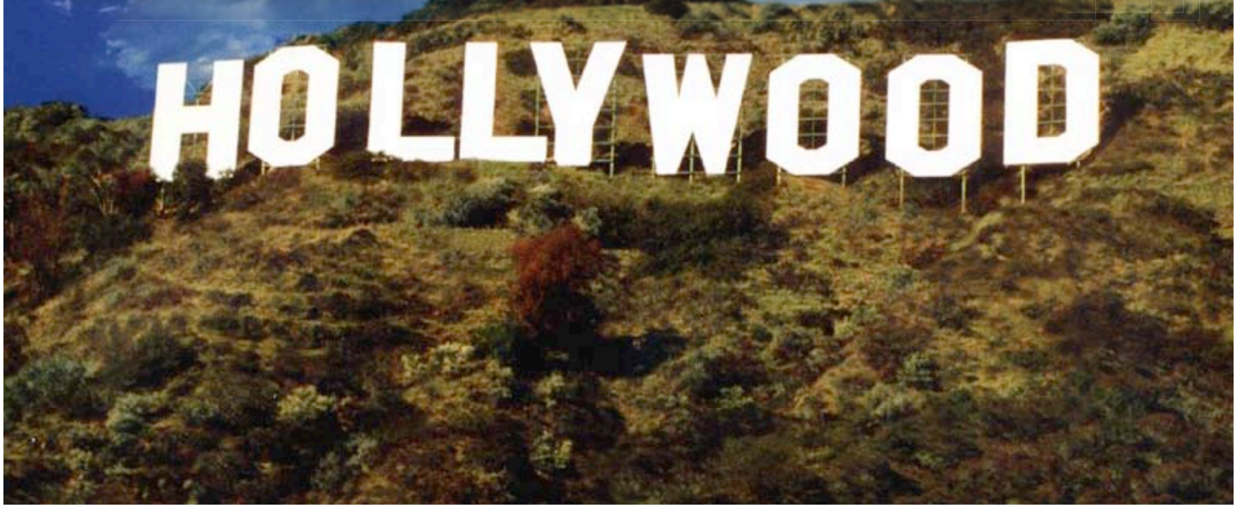
$$\mathrm{D} + \mathrm{T} \rightarrow {}^4\mathrm{He}\,(3.5\mathrm{MeV}) + \mathrm{n}\,(14.1\mathrm{MeV})$$
$$\mathrm{D} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He}\,(3.6\mathrm{MeV}) + \mathrm{H}\,(14.7\mathrm{MeV})$$
$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{He}\,(0.82\mathrm{MeV}) + \mathrm{n}\,(2.45\mathrm{MeV})$$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

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



Three Movies:

- Mining fusion fuel (*sci-fi*)
- Controlling fusion instabilities (*action*)
- Environmental destruction from energy (*doc*)

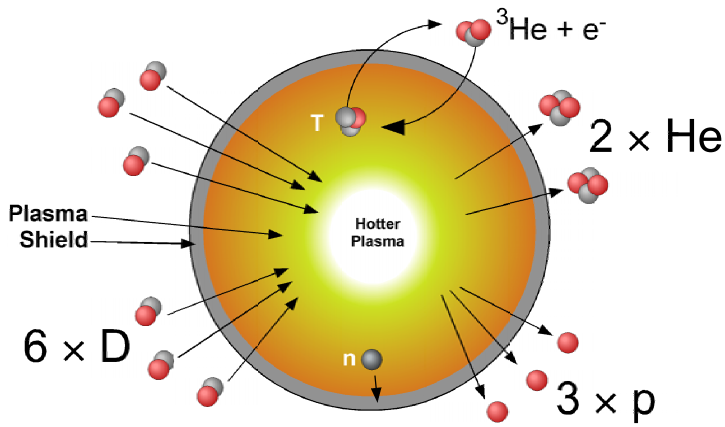


- 2009 BAFTA "Best British Film" (Director: Duncan Jones, Son of David Bowie)
- It is the near future. Astronaut Sam Bell is living on the far side of the moon, completing a three-year contract with Lunar Industries to mine Earth's primary source of energy, Helium-3. It is a lonely job, made harder by a broken satellite that allows no live communications home. Taped messages are all Sam can send and receive.

Least complicated fusion fuel cycles are variants of D-D, but *plasma confinement more demanding*, e.g.

D-D (^{3}He) Fusion

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

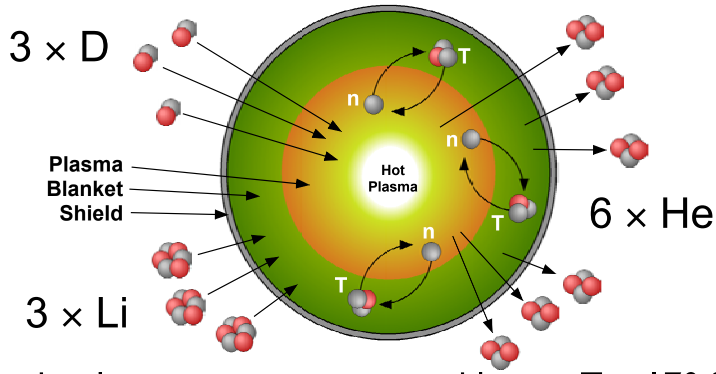


- Significantly reduced fast neutron flux!! Most energy to plasma and then first wall. Simplifies fusion component technologies.
- Next easiest fusion fuel cycle, but requires confinement ~25 times better than D-T(Li) **and** T extraction from plasma (*i.e.* only MFE).
- Other challenging, but plausible,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

D-T (^{6}Li) Fusion:

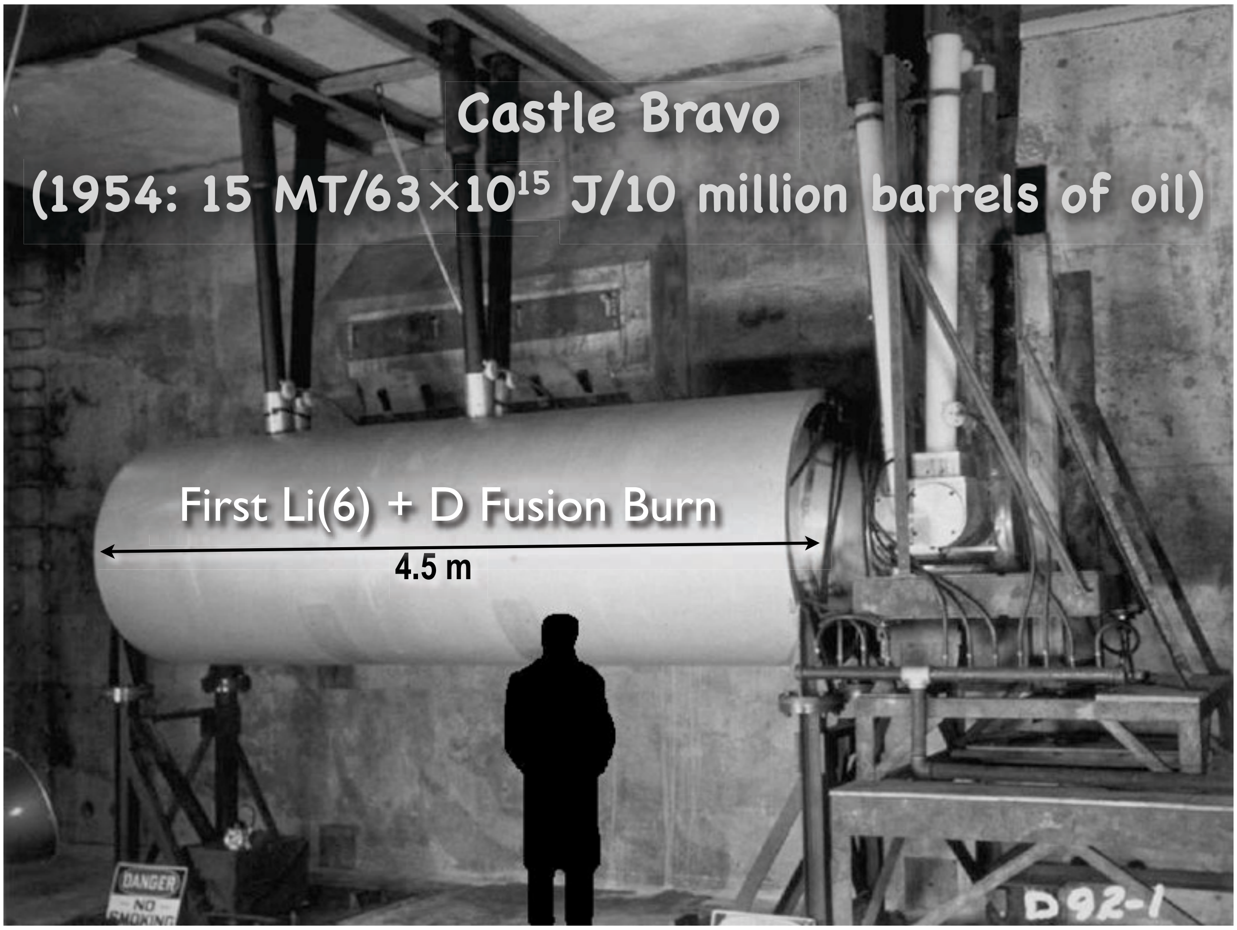
"Most Reactive Fuel" for Earthly Fusion

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



- 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).

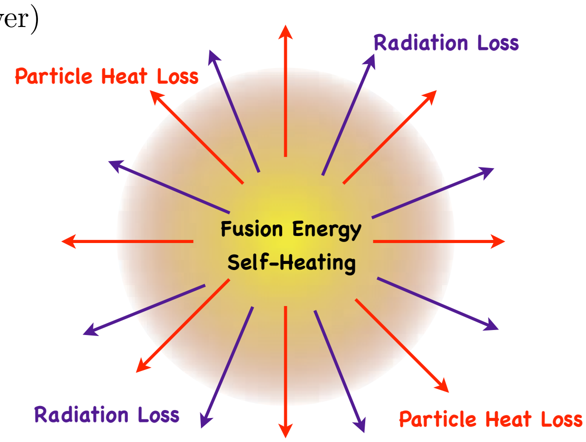
  ➠ the source of fusion's technology & materials challenge.



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
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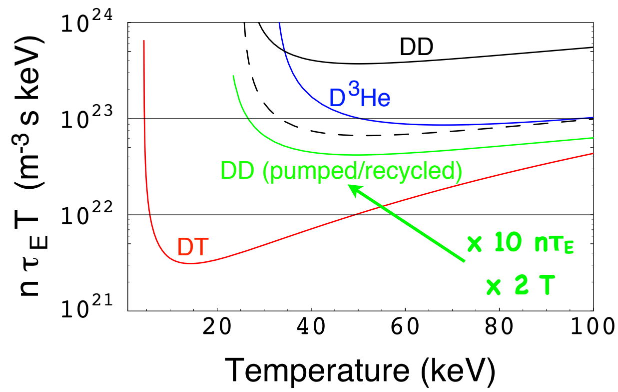

$$
\begin{array}{lll}
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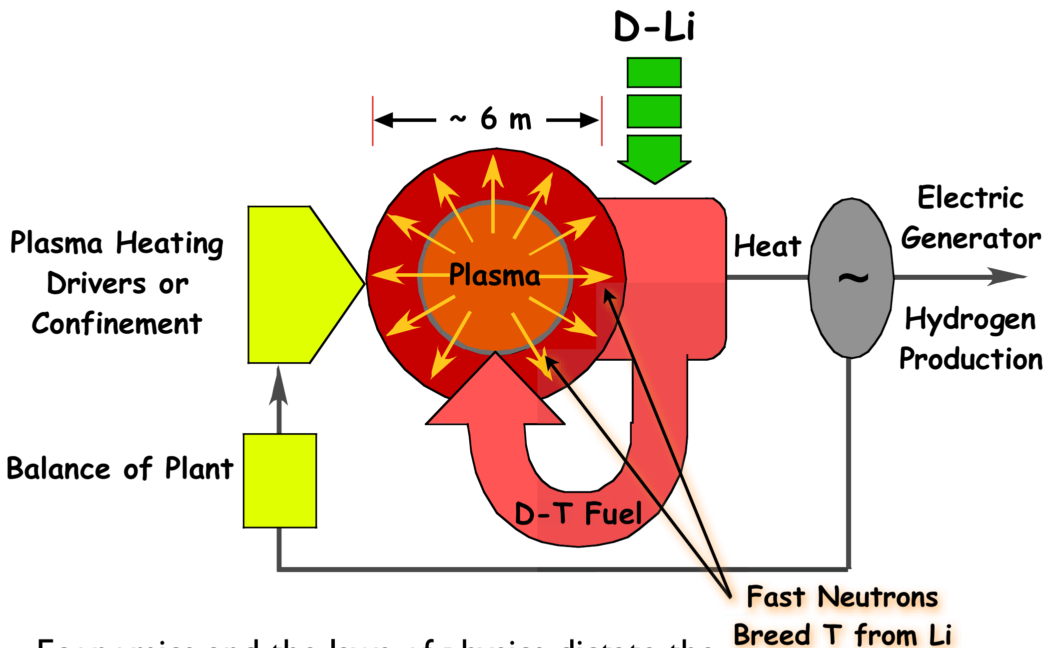
(3) & D + He^3 \longrightarrow & He^4(3.6\,\text{MeV}) + p(14.7\,\text{MeV})
\end{array}
$$

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.

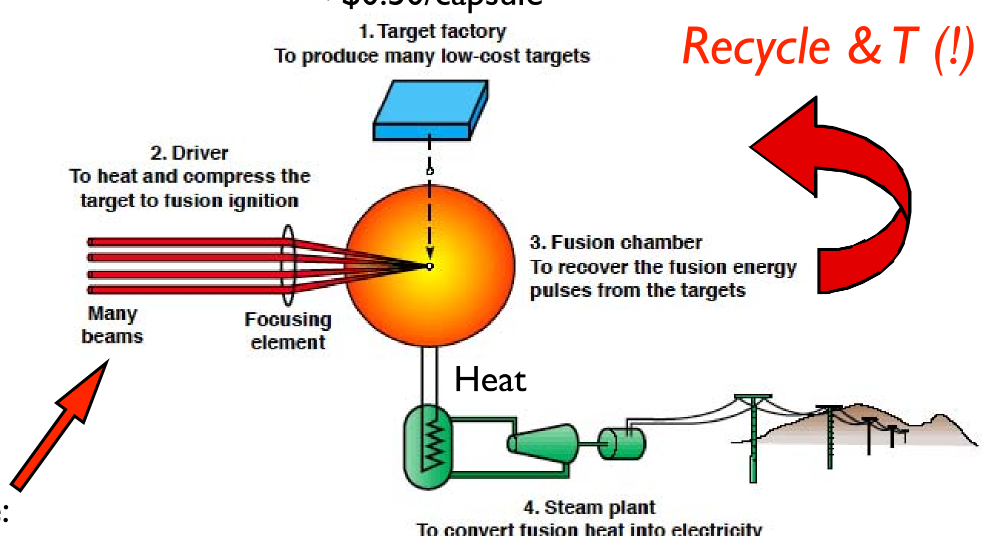
Elements of a D-T(Li) Fusion System



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

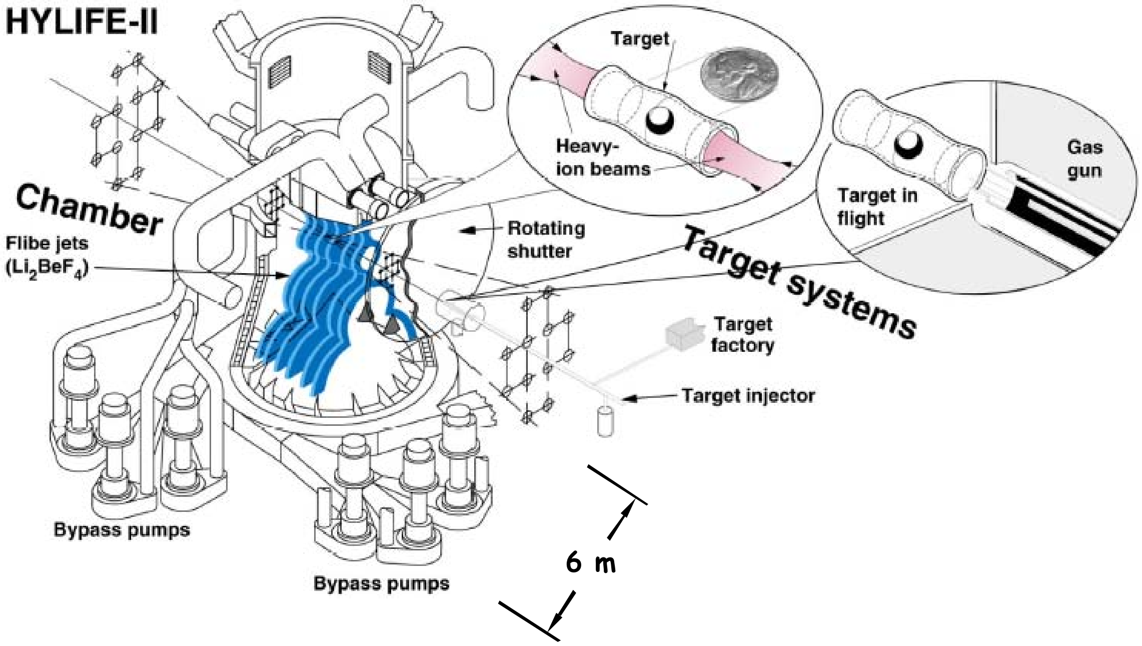


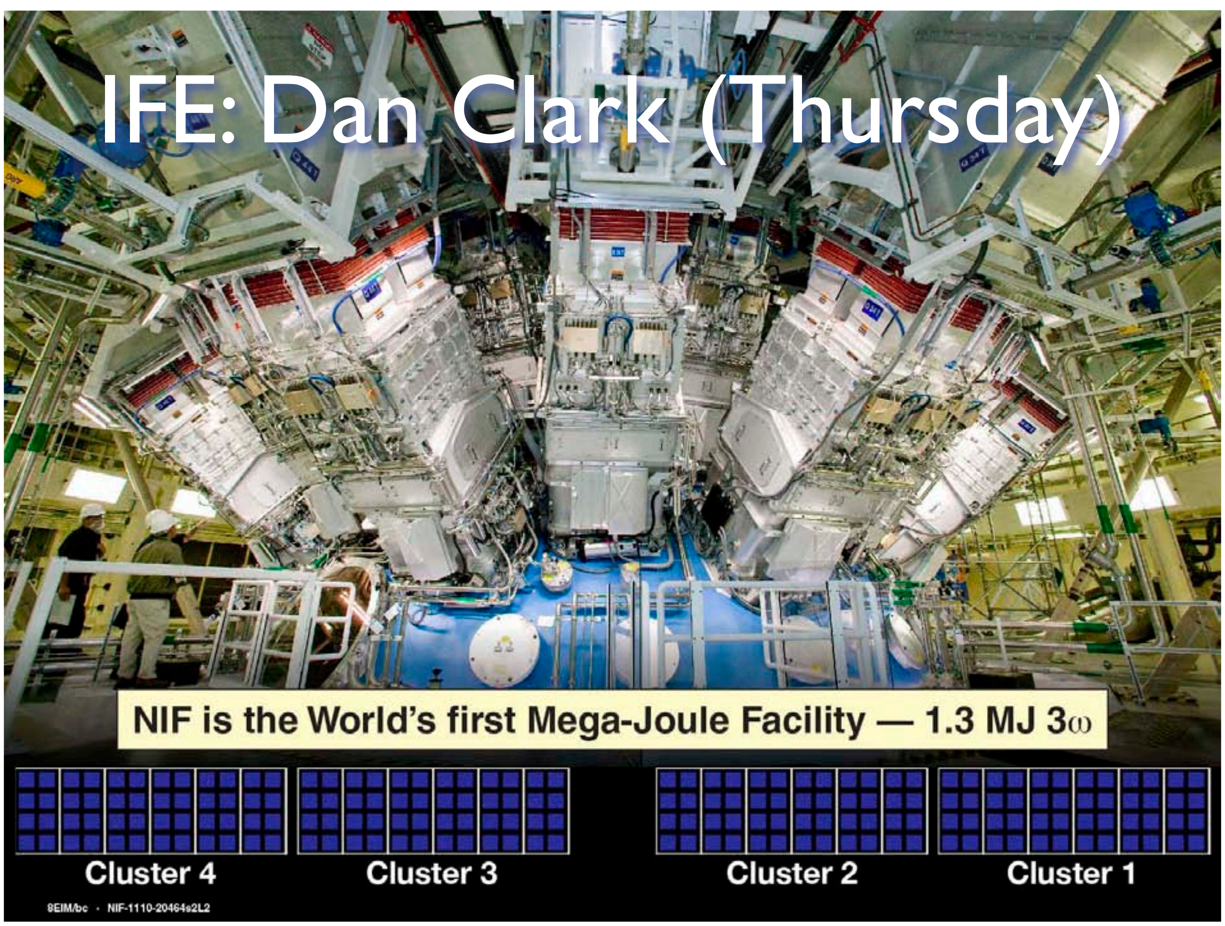
Example:
~ 100 beams (2.5 GeV Xe) ⇒ 5 MJ

(About the length of SLAC ~2.5 km)

IFE Chamber

~100 beams





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!

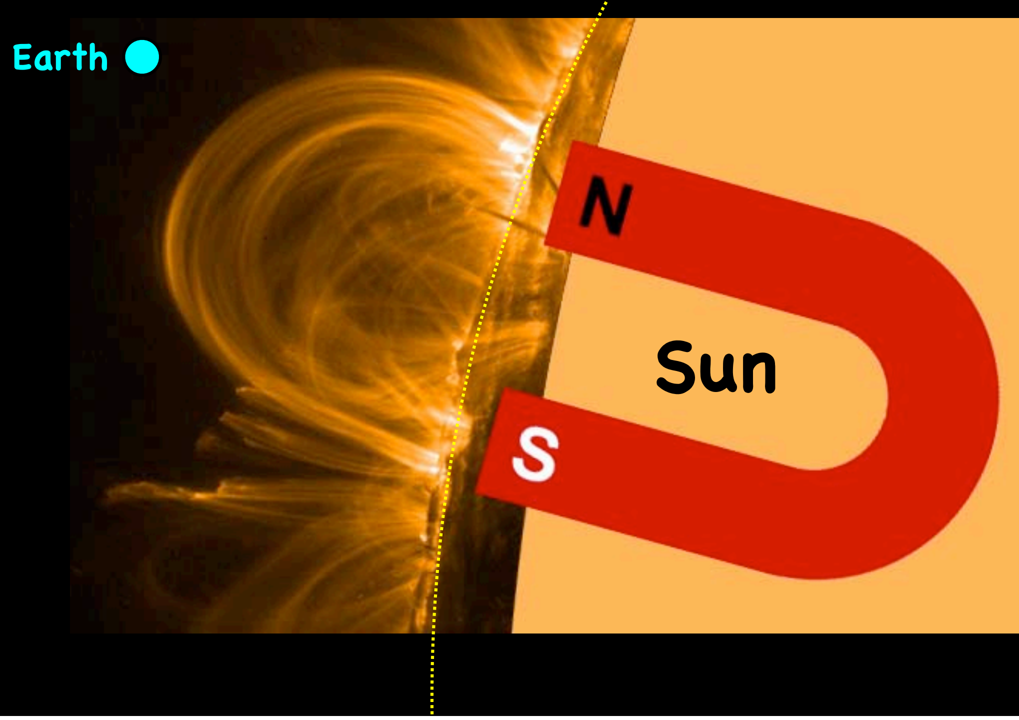
MFE is 10^{10} slower and less dense than IFE

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"

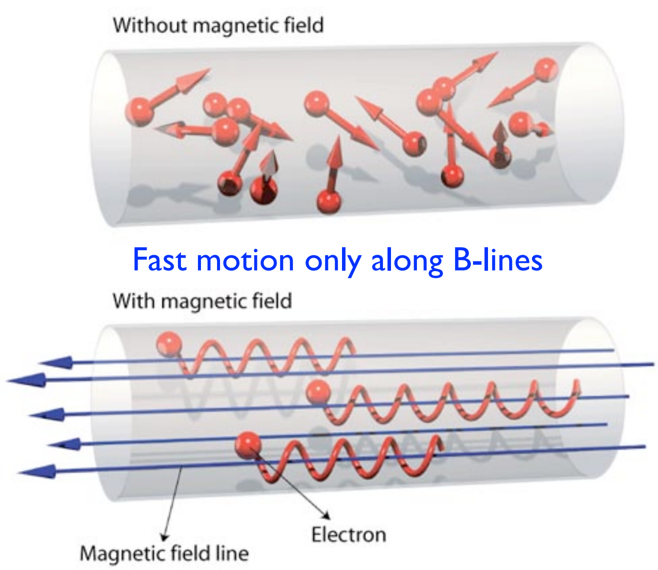
Solar Magnetic Fields



How Do Magnetic Fields Confine Ionized Matter?

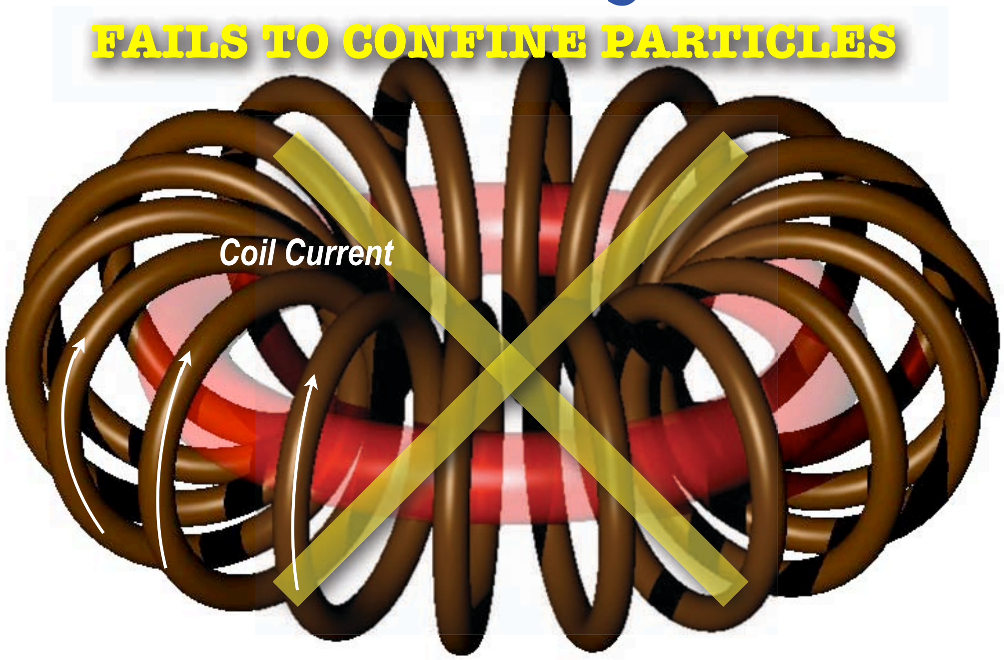
$$\frac{d\mathbf{v}}{dt} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$

Fast motion in *all* directions



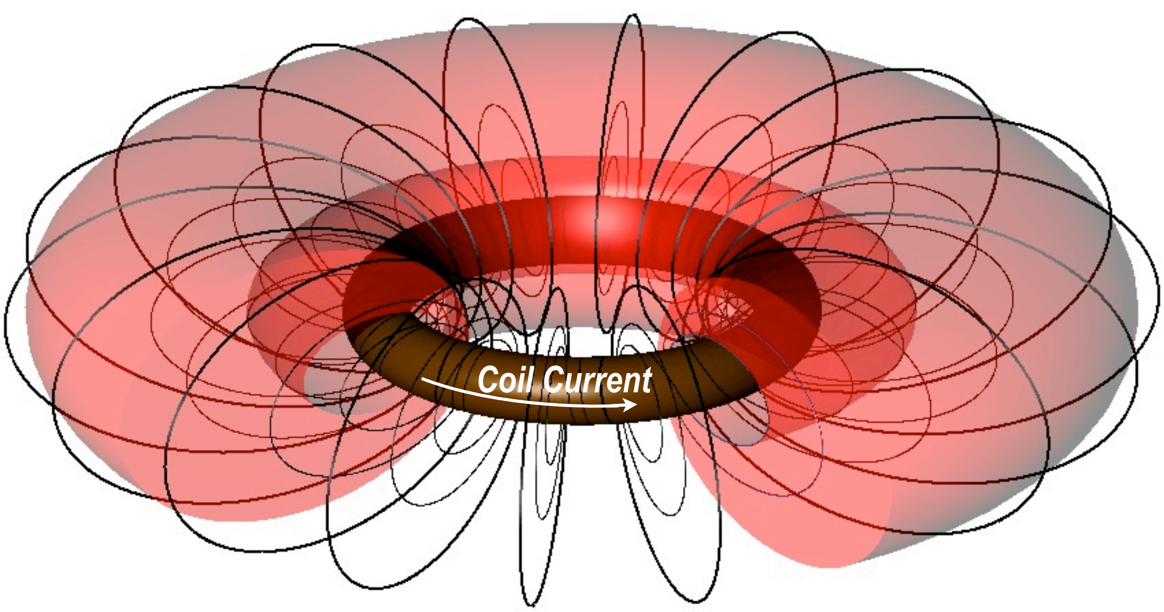
B = 2 T and T = 20 keV, then gyroradius ≈ 1cm
but must be confined along B-lines for hundreds of miles!!!

How to make a magnetic torus?



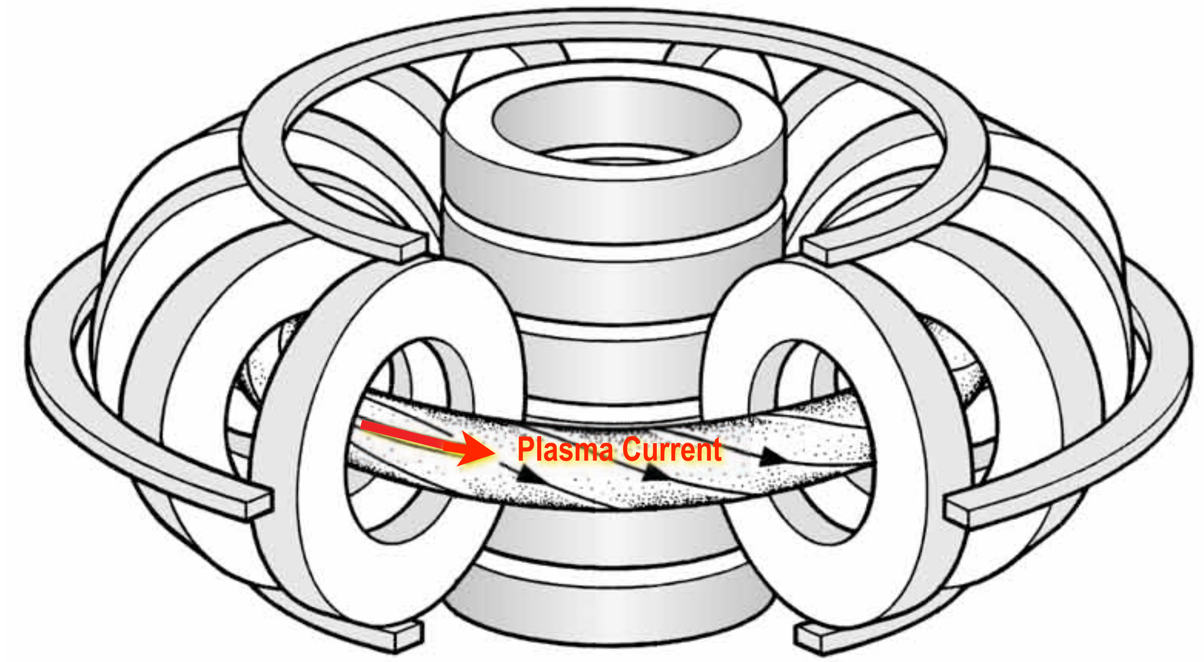
Toroidal Field from Poloidal Coils

How to make a magnetic torus?



Poloidal Field from Toroidal Coil

How to make a magnetic torus?



Combined Toroidal and Poloidal Field (Tokamak)

How to make a magnetic torus?

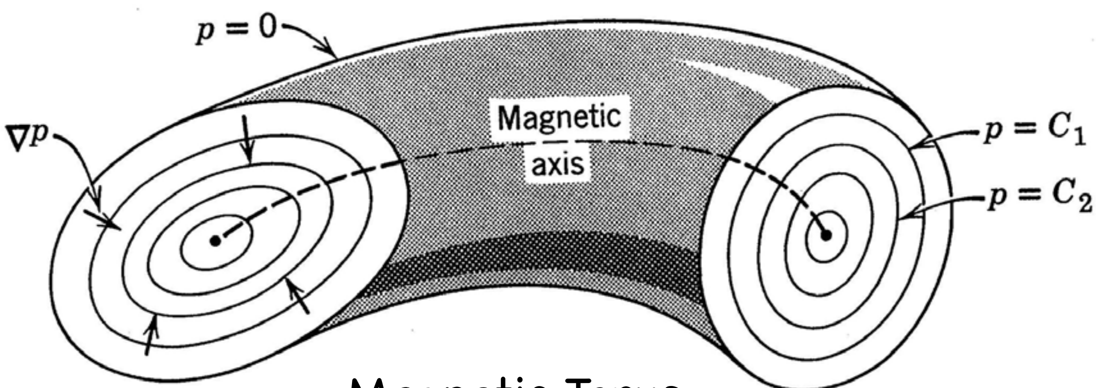
Twisted Coils (!)

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



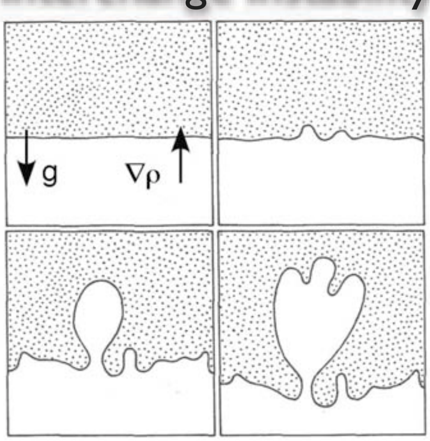
Magnetic Torus

Jill Foley: Next lecture...

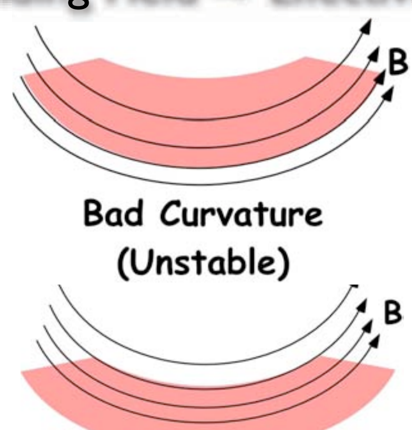
MFE Configuration Optimization Depends on Shape

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

Interchange Instability

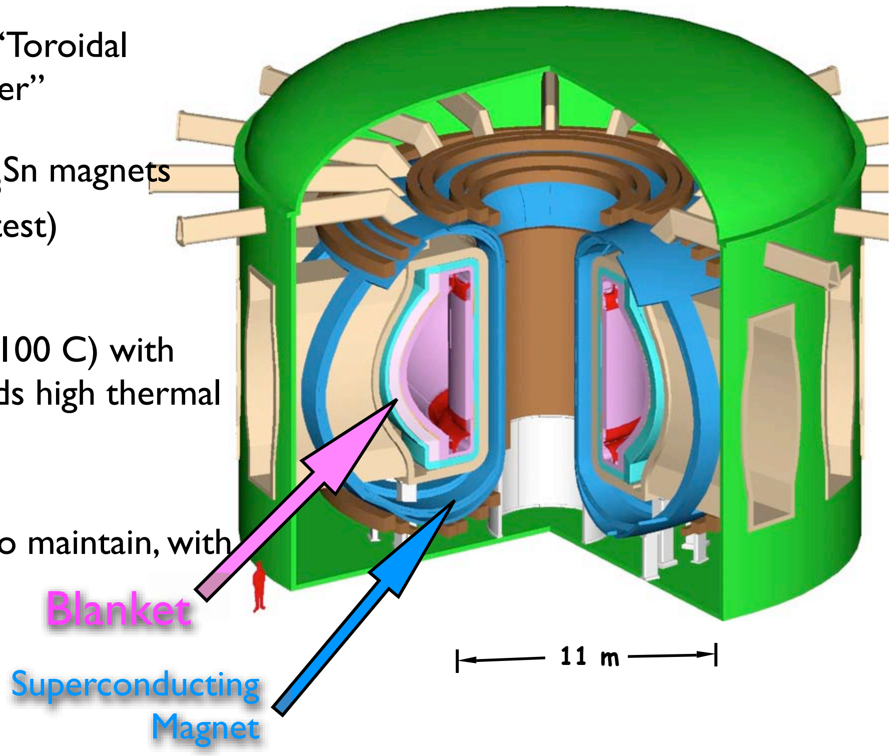


Bending Field ➠ Effective g



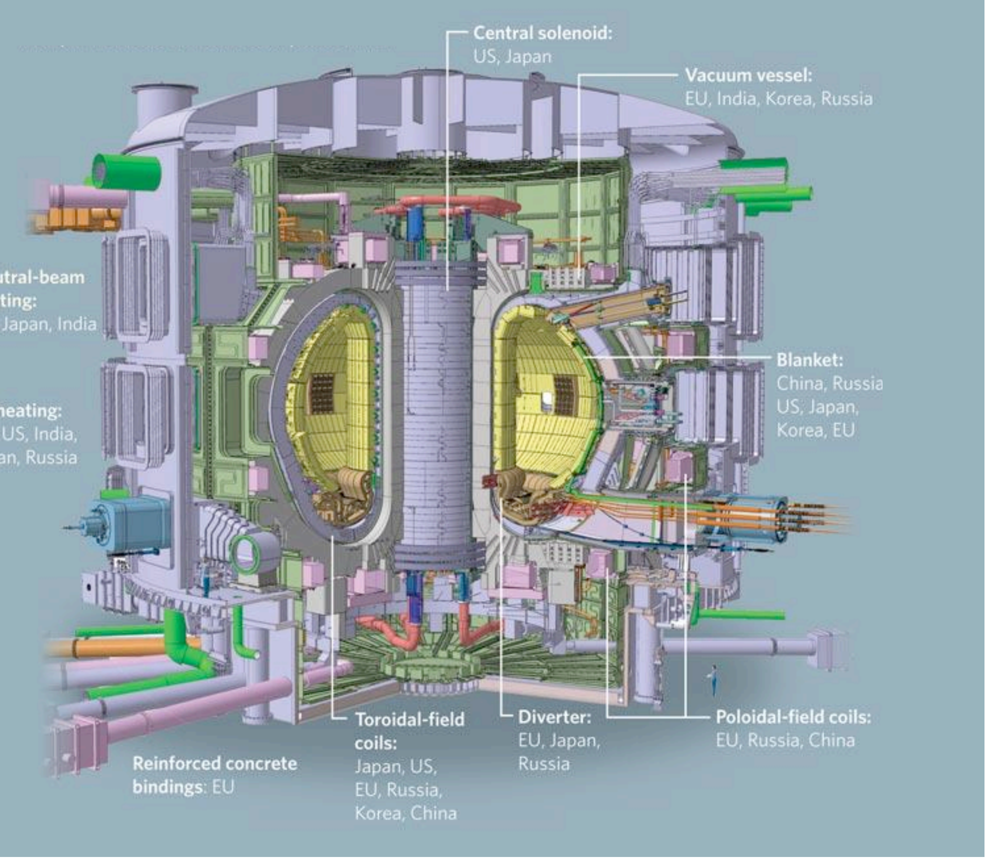
Magnetic Fusion Reactors are Toroidal

- 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



ITER: The International Burning Plasma Experiment

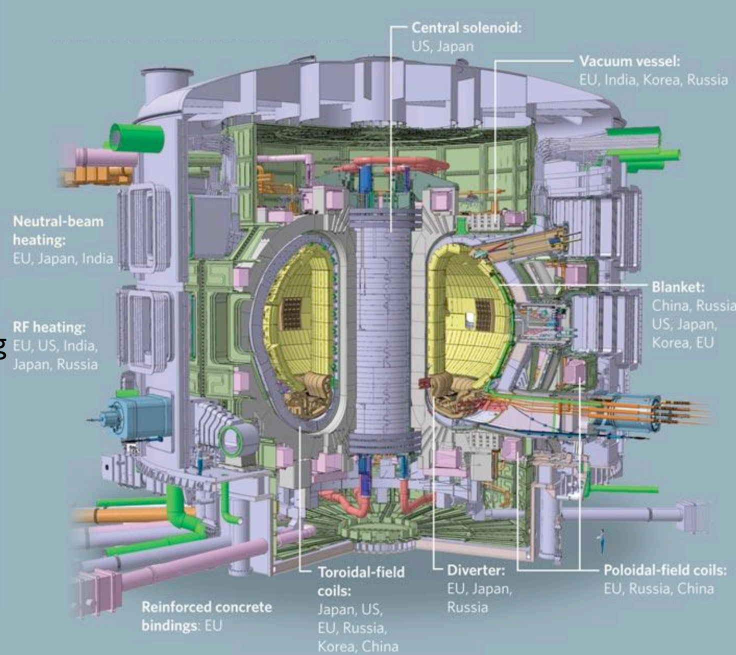
23,000 tonne
22B $US



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

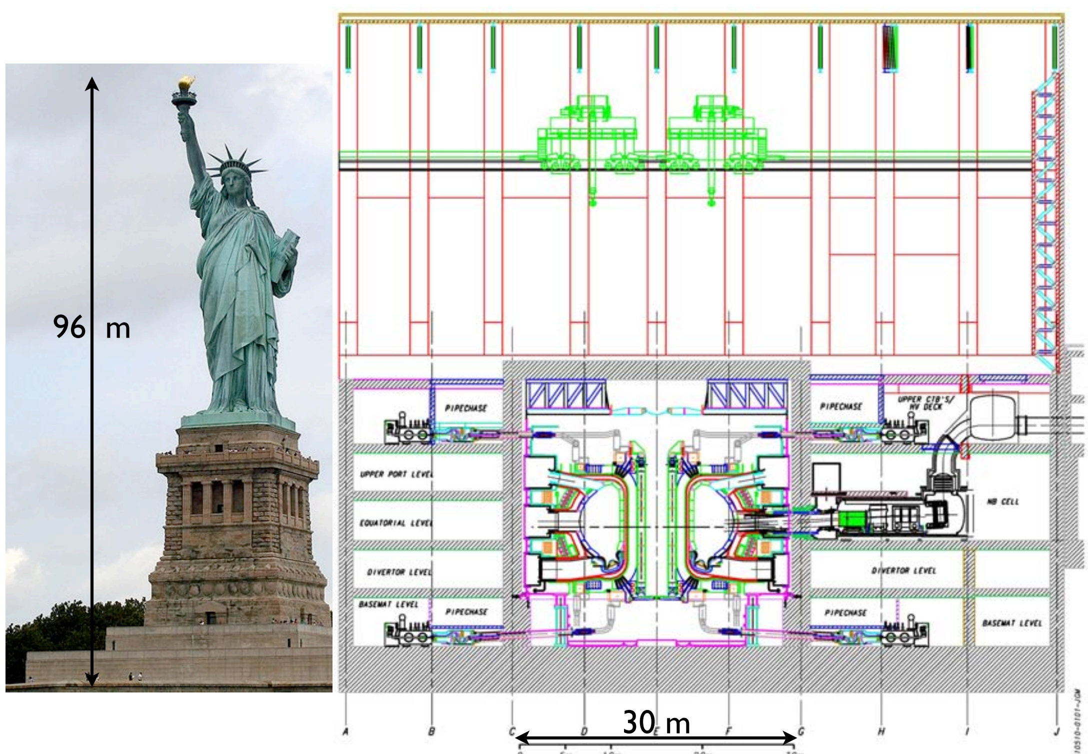
ITER: The International Burning Plasma Experiment

- Culmination of 50 years of magnetic fusion research
- 500 MW fusion power for seven minute pulses
- EU, Japan, Russia, China, S Korea, India, USA
- 50 GJ magnetic energy: the largest superconducting magnet system ever
- At 22B US$: the most ambitious international science project ever
- 23,000 tons (tokamak only); 360,000 tons entire experimental hall.



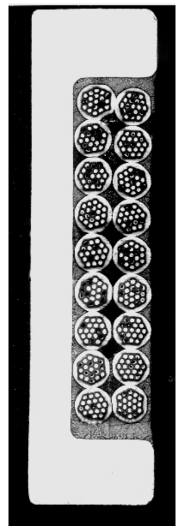
http://www.iter.org/

ITER is the Biggest Fusion Experiment

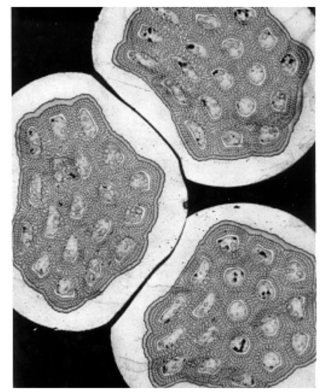


Nb3Sn (Niobium Tin)

- Discovered in **1954**
- 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
- In April **2008,** a record non-copper current density was achieved at 0.26 MA/cm^2 at 12 T and 4.2 K
- **Ceramic (brittle)**
- **T_c = 18.3 °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!**

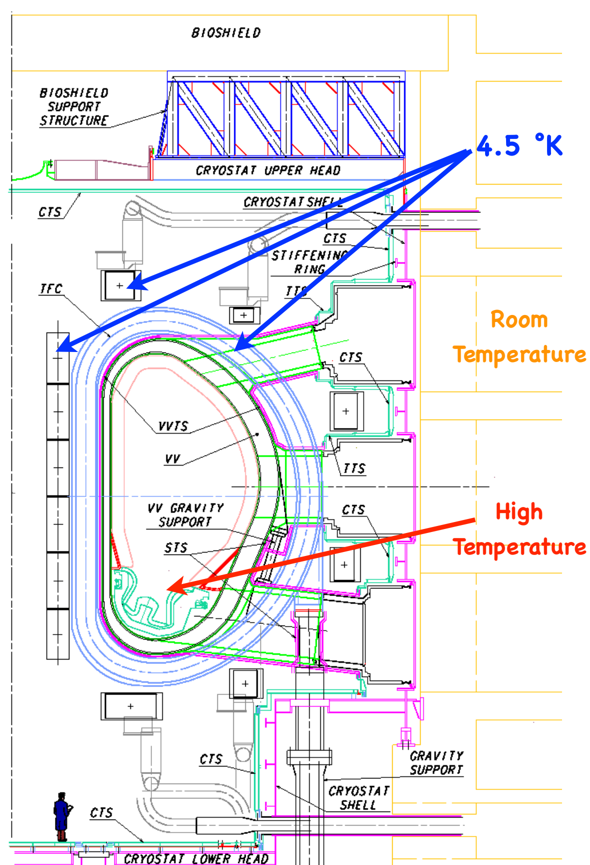


LDX Conductor in Soldered Cable

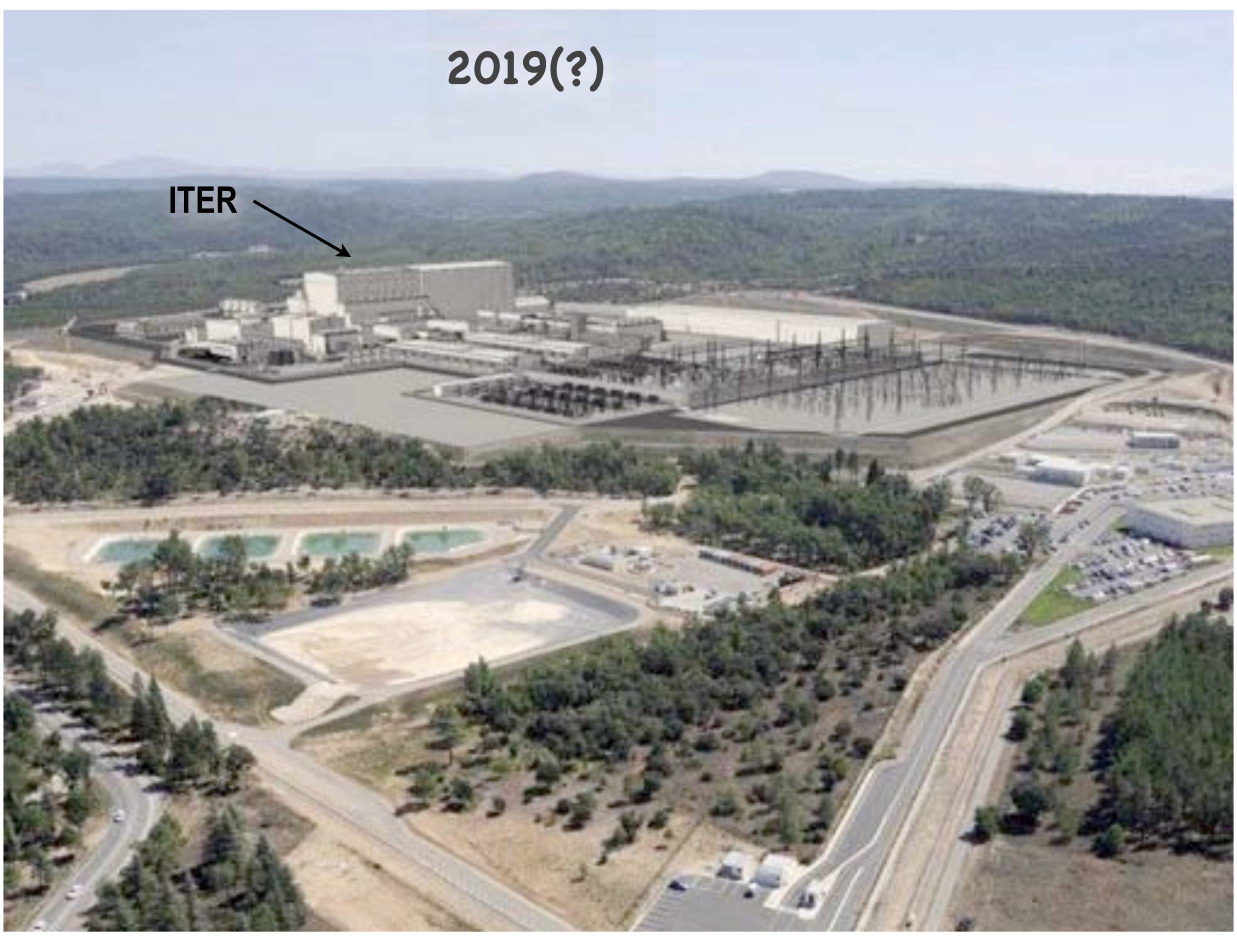


Cryostat and Thermal Shields/Supports

- In all cases the thermal shields consist of stainless steel panels that are cooled by helium gas with 80K inlet temperature.
- The cooling lines remove the heat load intercepted from the warm surfaces.
- The cold structures, operating around 4K face the TS surfaces.
- The conductive heat loads from all thermal shields are limited to small losses through their supports.




Early this year...


2019(?)
ITER

ITER is the Focus of Magnetic Fusion Today

- Huge cost and complexity requires the world's best and brightest.
- International agreement insures international commitment. Fusion scientists must make ITER "work".
- Many physics, technology, and control issues provide opportunities for innovation and discovery.
- Planning for research "after ITER" will likely happen *after* ITER produces its first results (IMHO).

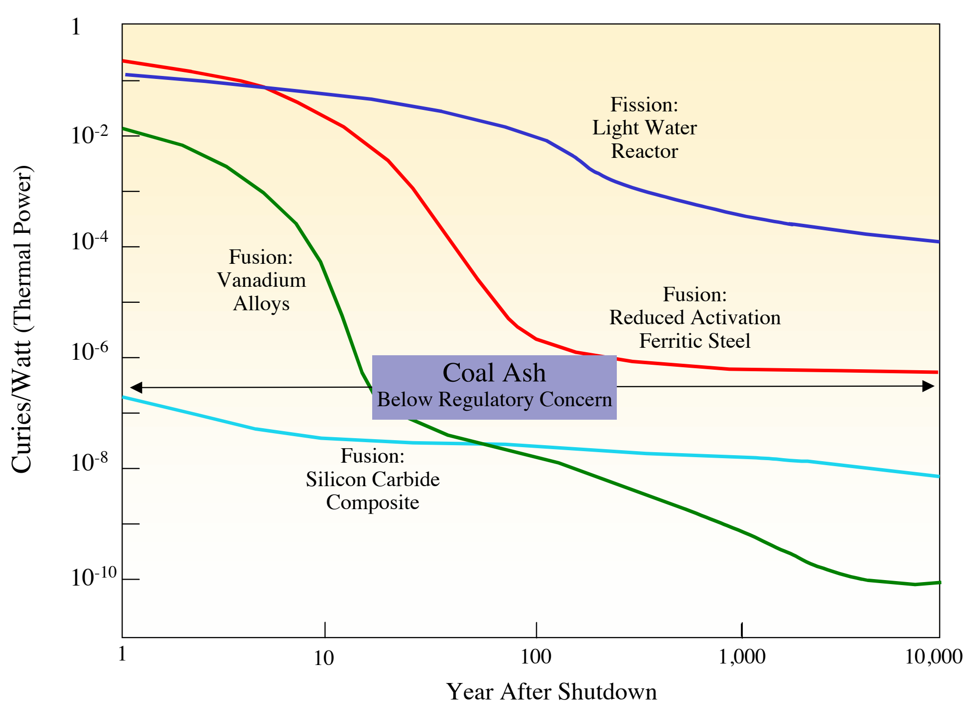
Can Fusion be "Green" Nuclear Power?

- 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.**
- *We need to demonstrate the safety and environmental advantages of fusion…*

D-T Fusion's Materials Challenge

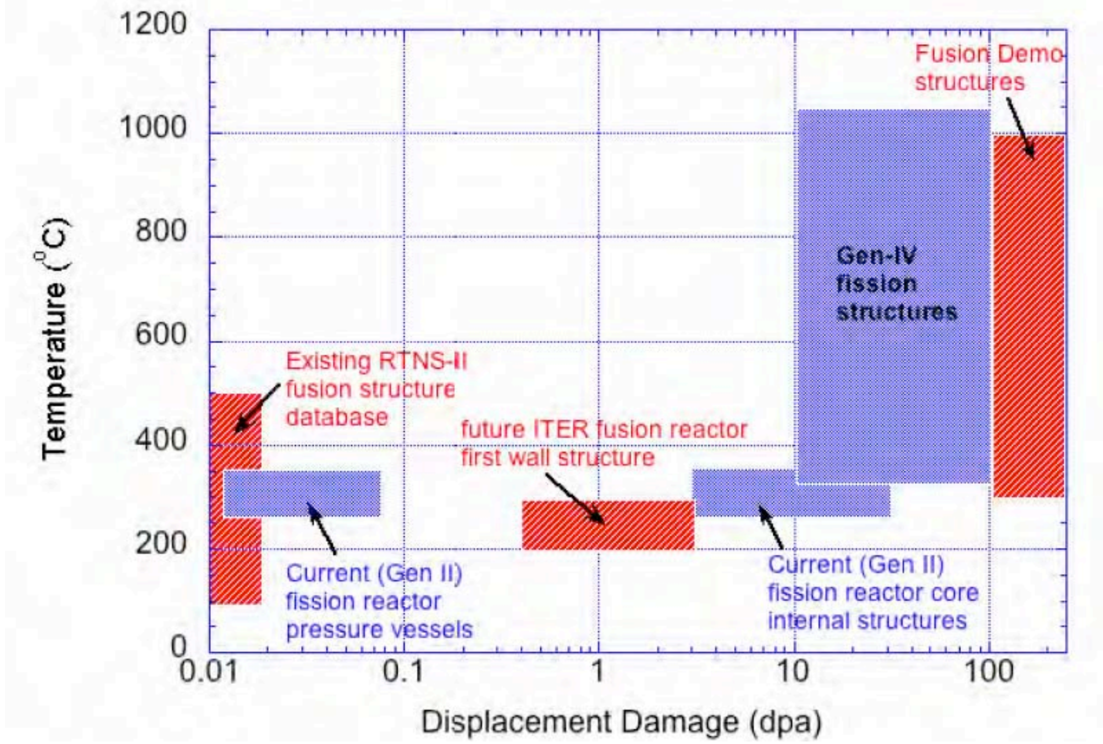
- When fabricated from low activation materials, fusion will not produce long-lived radioactive by-products.
- Fusion's **materials challenge** is to develop long-life, high-strength materials with high neutron-irradiated fracture toughness, good helium swelling resistance, and low tritium retention.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

Good News:
Low Activation Material Options for D-T Fusion



Bad News:

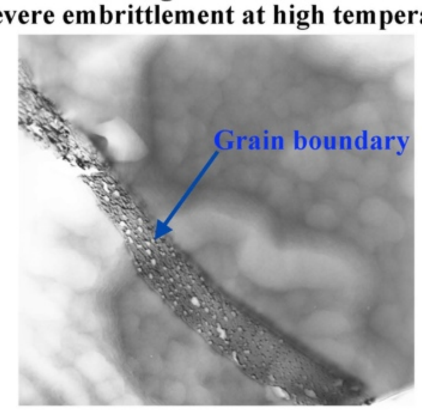
Significant Materials Challenges for Fusion and Gen-IV Fission



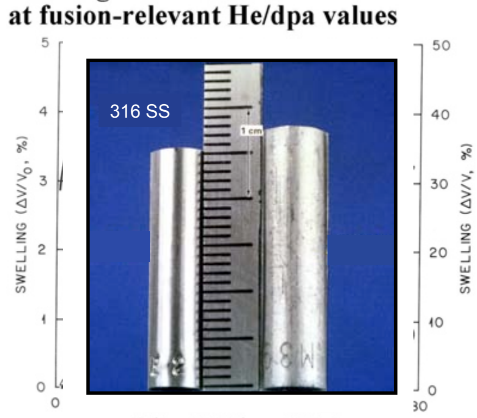
(Non-Magnetic) Stainless Steels probably **not** be Compatible with D-T Fusion

- **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

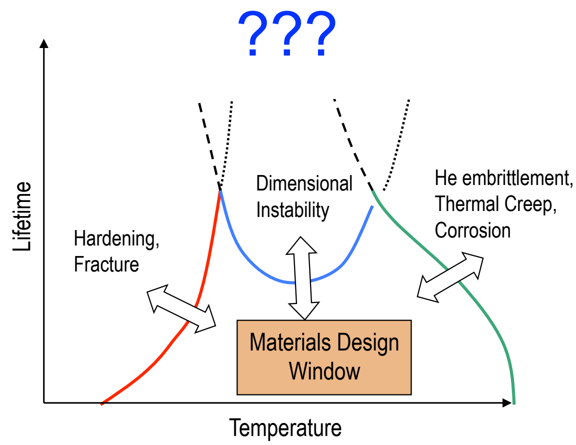


Management of He transmutation products (matrix trapping at engineered 2nd phases) is a key factor for fusion materials

D-T Fusion Material Limits

- Displacement damage and He coupled with stress results in microstructure and property changes.

- Low temperatures (< 0.4 T_m):
  - Hardening + He embrittlement
  - Loss of ductility
  - Loss of fracture resistance
- Intermediate temperatures (0.3 < T_m < 0.6):
  - Swelling + He
  - Irradiation creep + He
- At high temperatures (> 0.4 T_m):
  - Thermal creep
  - He embrittlement
  - Fatigue and creep-fatigue, crack growth
  - Corrosion, oxidation and impurity embrittlement



How big is Fusion's Design Window?

S. Zinkle (8/2010)

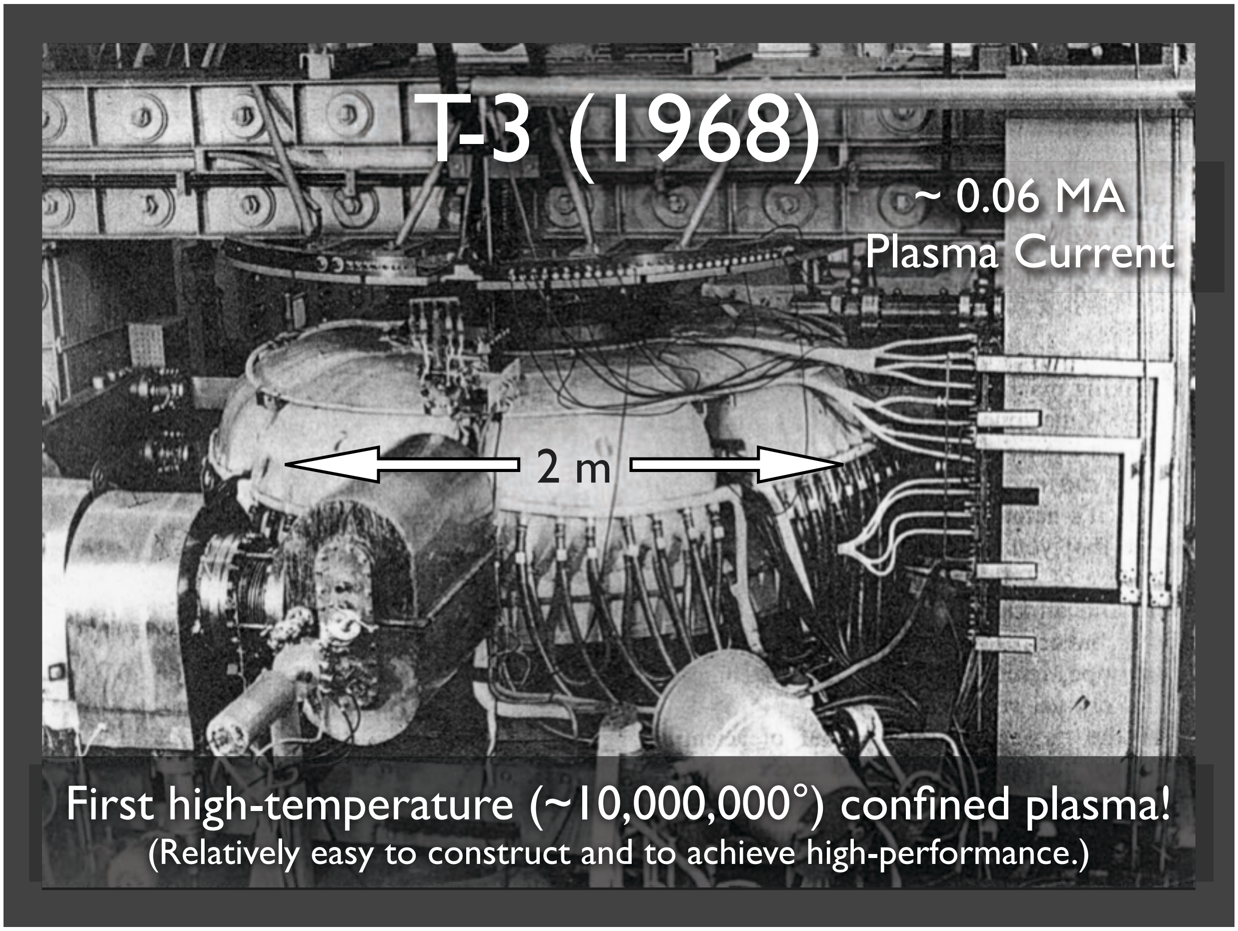
Magnetic Fusion Research Today

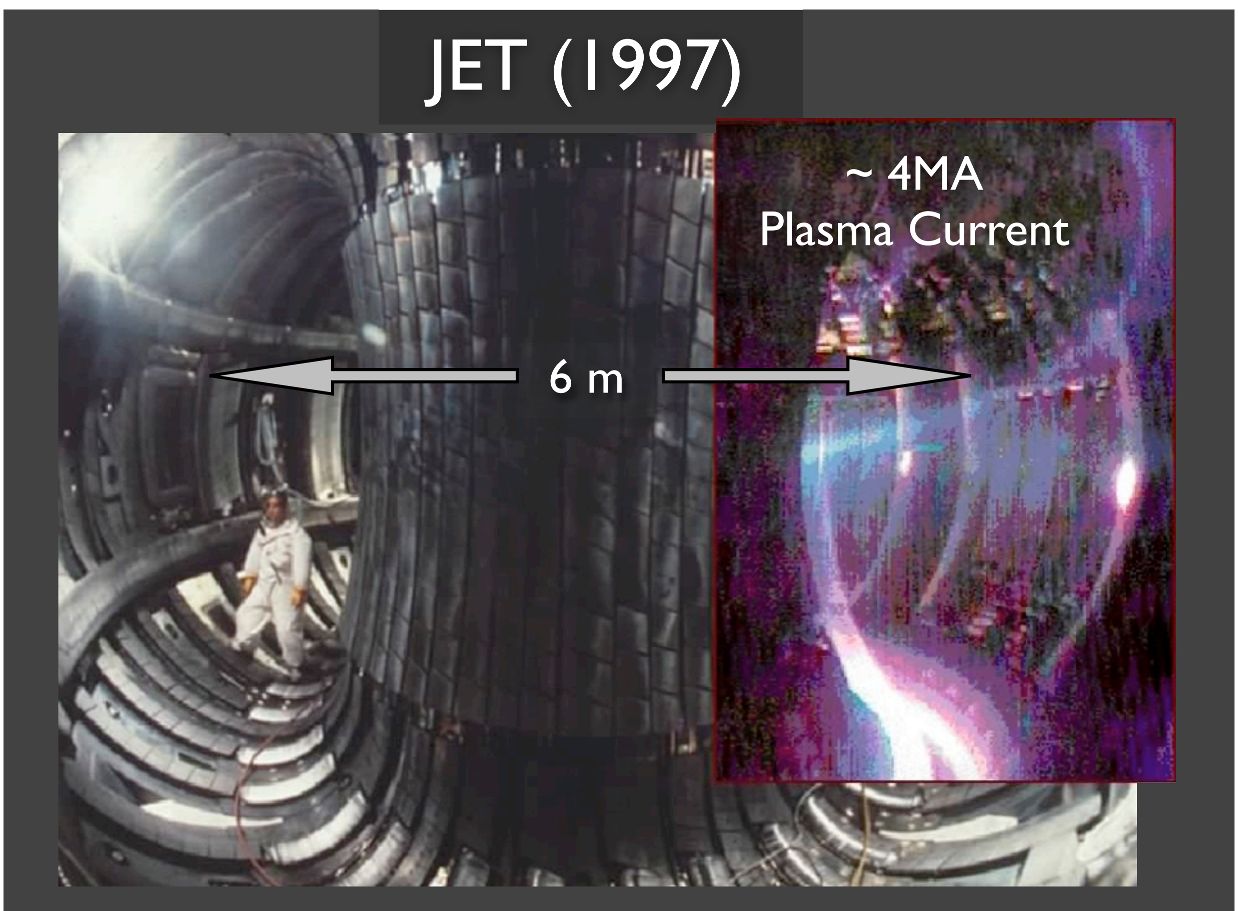
✓ Hot plasma confinement is sufficient for D-T fusion power

✓ Fluctuation-induced transport significantly reduced at high power flux: the "H-Mode"

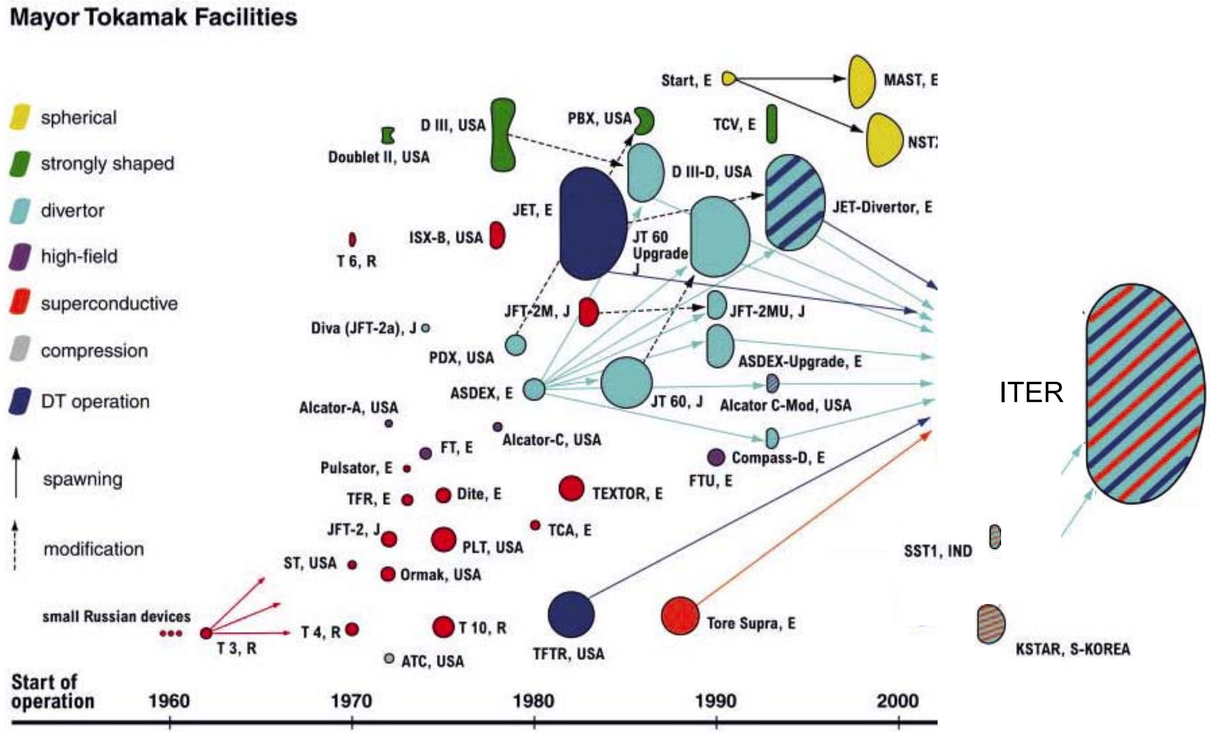
➡ Controlling plasma instabilities …

➡ Achieving steady-state…


T-3 (1968)
~ 0.06 MA
Plasma Current
2 m
First high-temperature (~10,000,000°) confined plasma!
(Relatively easy to construct and to achieve high-performance.)

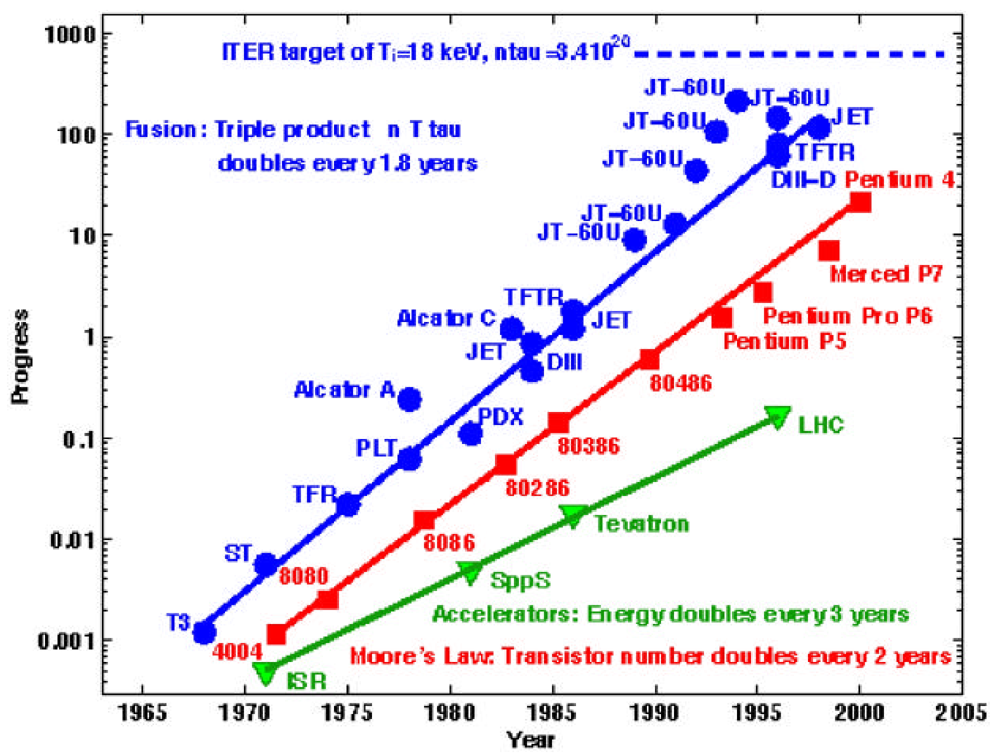

JET (1997)
~ 4MA
Plasma Current
6 m

Over 100 Tokamaks



Rapid Progress

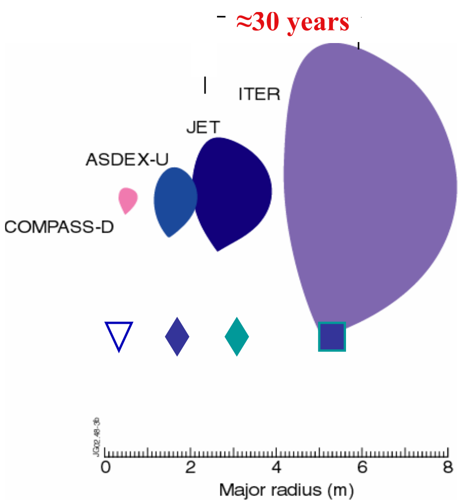
(through larger size)



Fusion Progress: Confinement & Size

$$nT\tau_E = 6.3 \times 10^{-6} \left(\frac{\beta}{\chi}\right) \times B^2 a^2$$

Confinement Size



$$nT\tau_E = \frac{n^2 V}{(f_\alpha + 1/Q)\, P_{fus} - P_{brem} - P_{rad}}$$

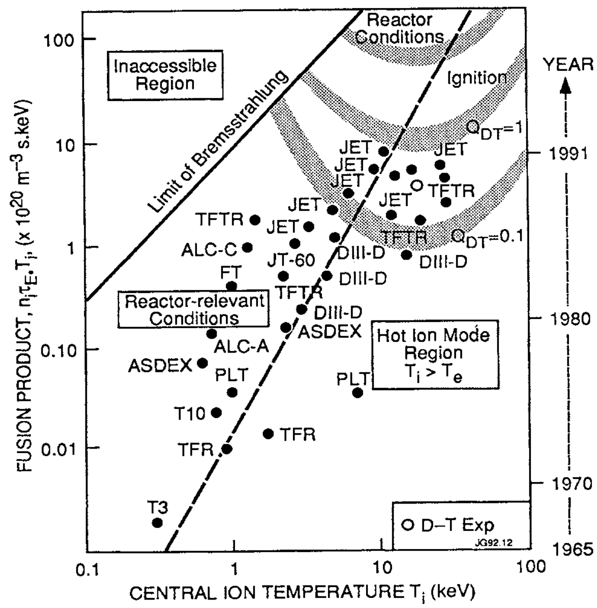


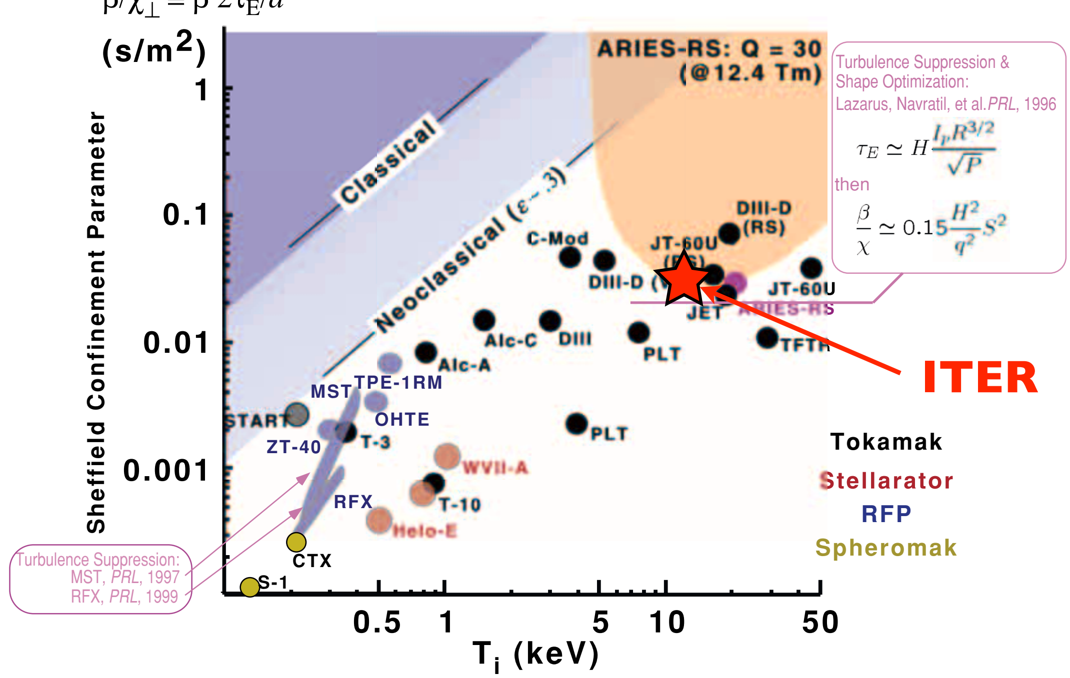
FIG. 31. Performance of tokamaks, JET Team, 1992.

Rev. Mod. Phys., Vol. 66, No. 3, July 1994

Simple Fusion Power Conditions

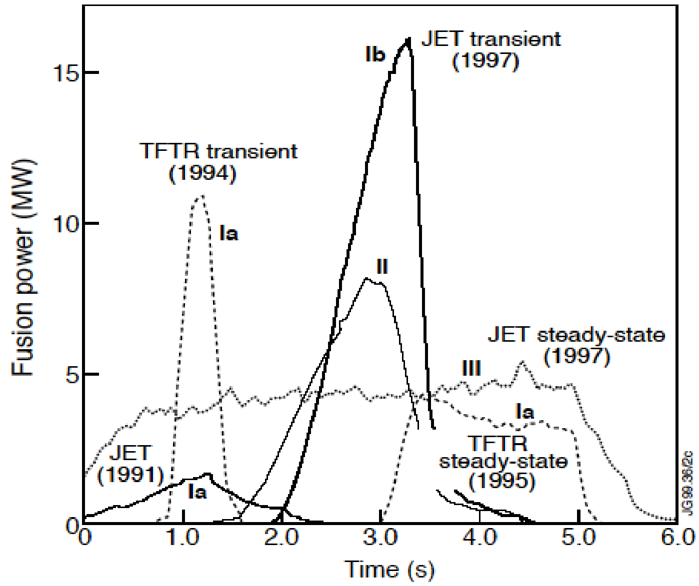
$$nT\tau_E = 6.3 \times 10^{-6} \left(\frac{\beta}{\chi}\right) \times B^2 a^2$$

$\beta/\chi_\perp \equiv \beta\, 2\tau_E/a^2$



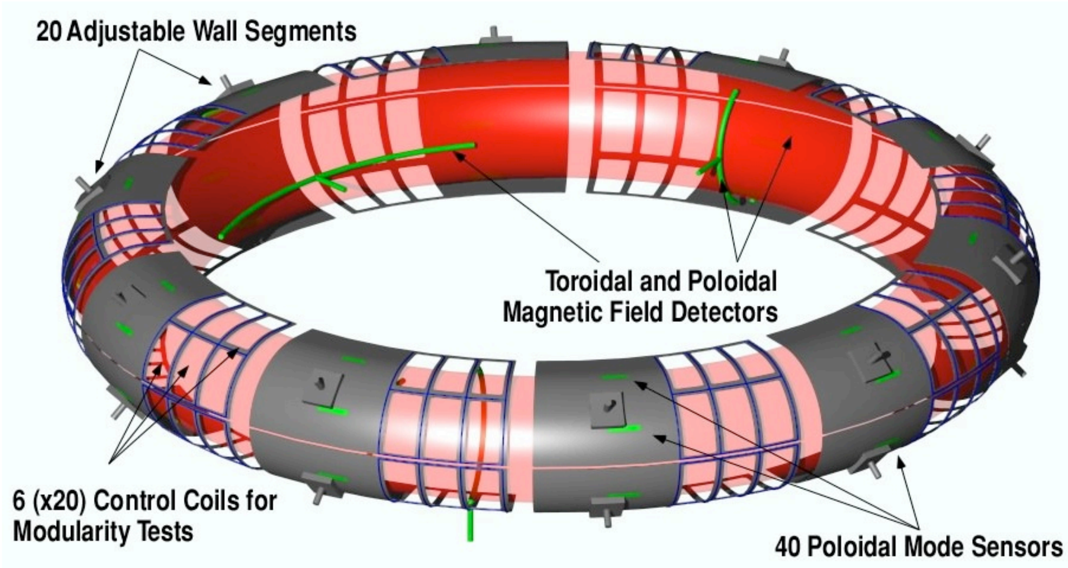
Significant Fusion Power already Produced in the Lab

- ✓ 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.

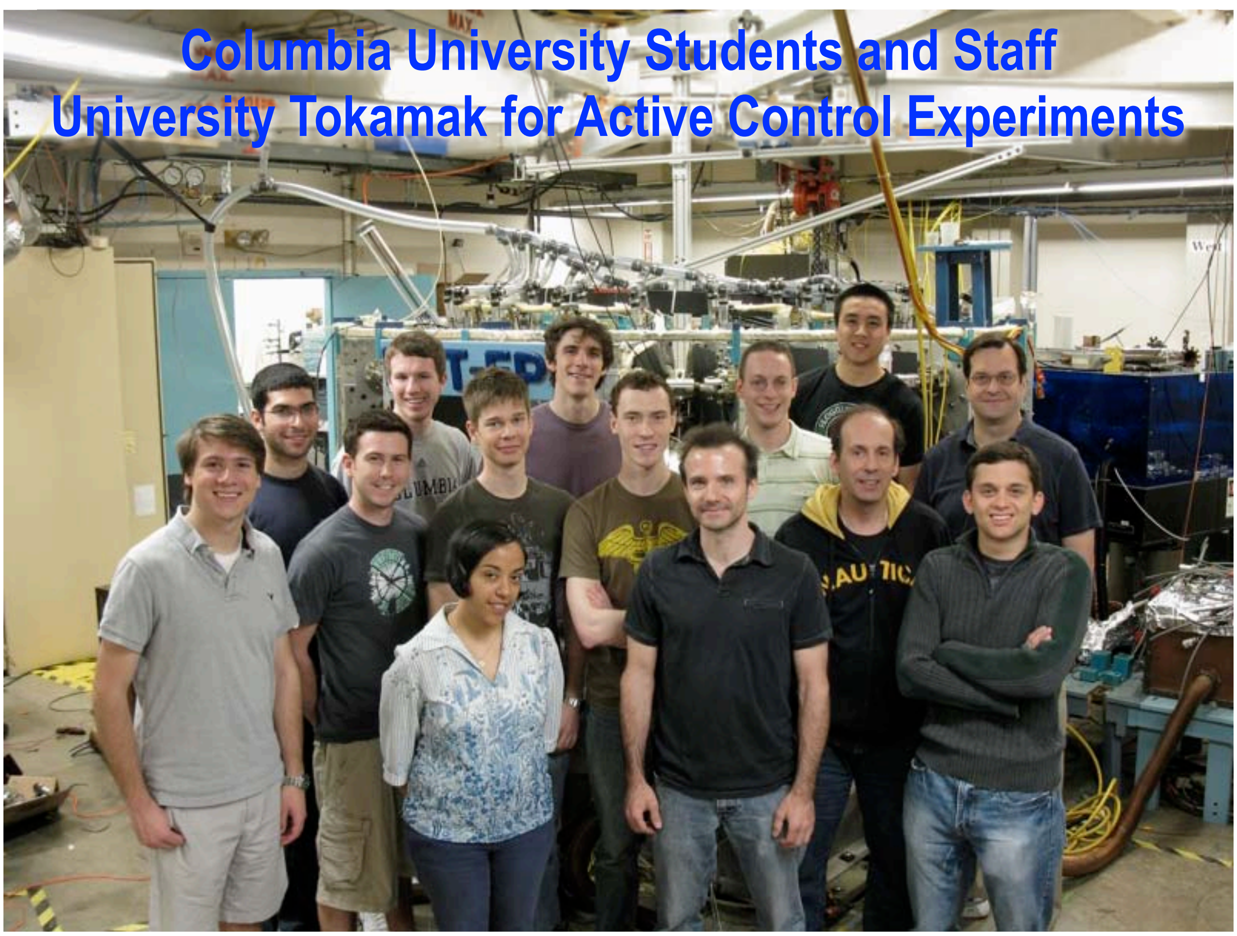


Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines), in different regimes:
(Ia) Hot-Ion Mode in limiter plasma; (Ib) Hot-ion H-Mode;
(II) Optimized shear; and (III) Steady-state ELMY-H Modes.

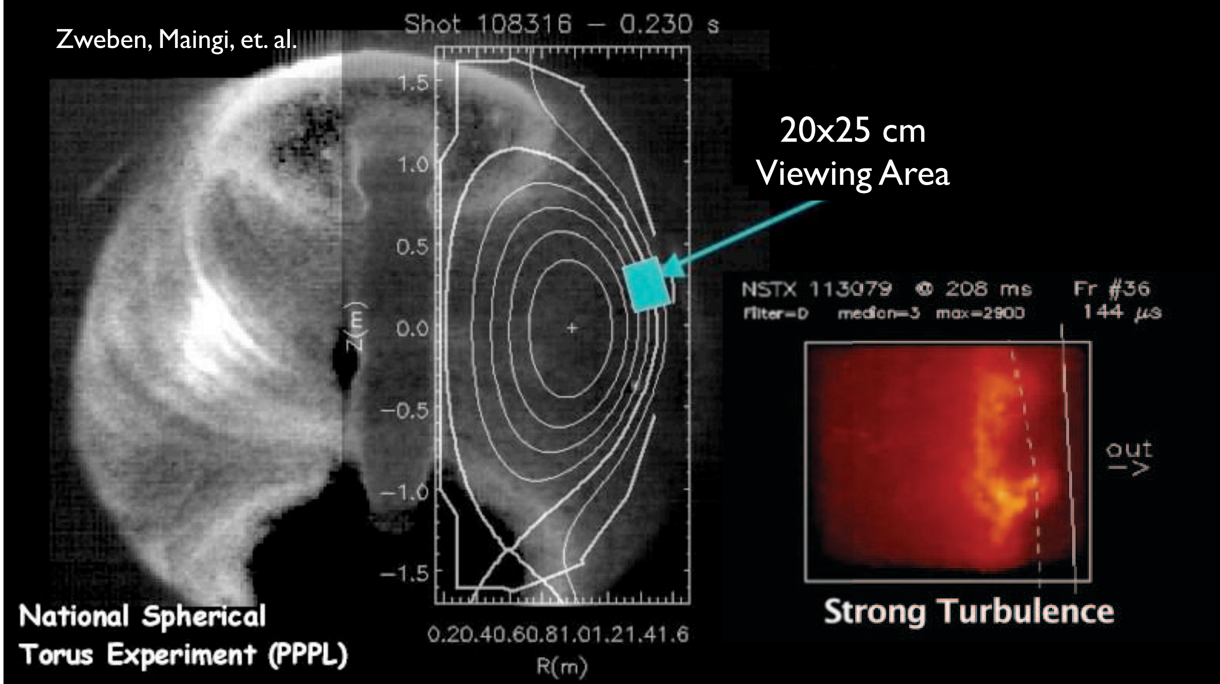
HBT-EP Stabilizes Plasmas in NYC!



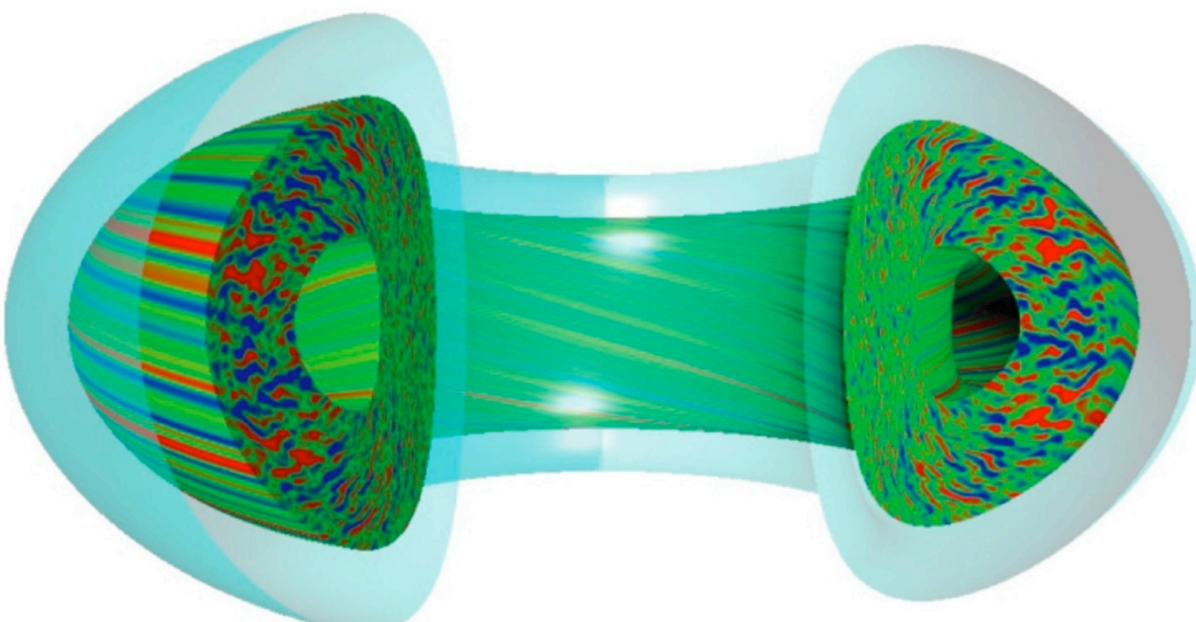
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK



H-Mode:
Viewing the Turbulence “Transport Barrier”



Measurement ⇔ Theory ⇔ Simulation



Bill Dorland: Tomorrow
Nikolai Gorelenkov: Thursday

International Thermonuclear Experimental Reactor

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

Burning Plasma Experiment by 2026 (?)

- Non-nuclear (H and He) experiments by 2019-21 (?)
- Beginning 2026 (?)…
  Demonstrate/study 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/technology tests (superconductors!)
- Demonstrate the **technical feasibility** of fusion power.

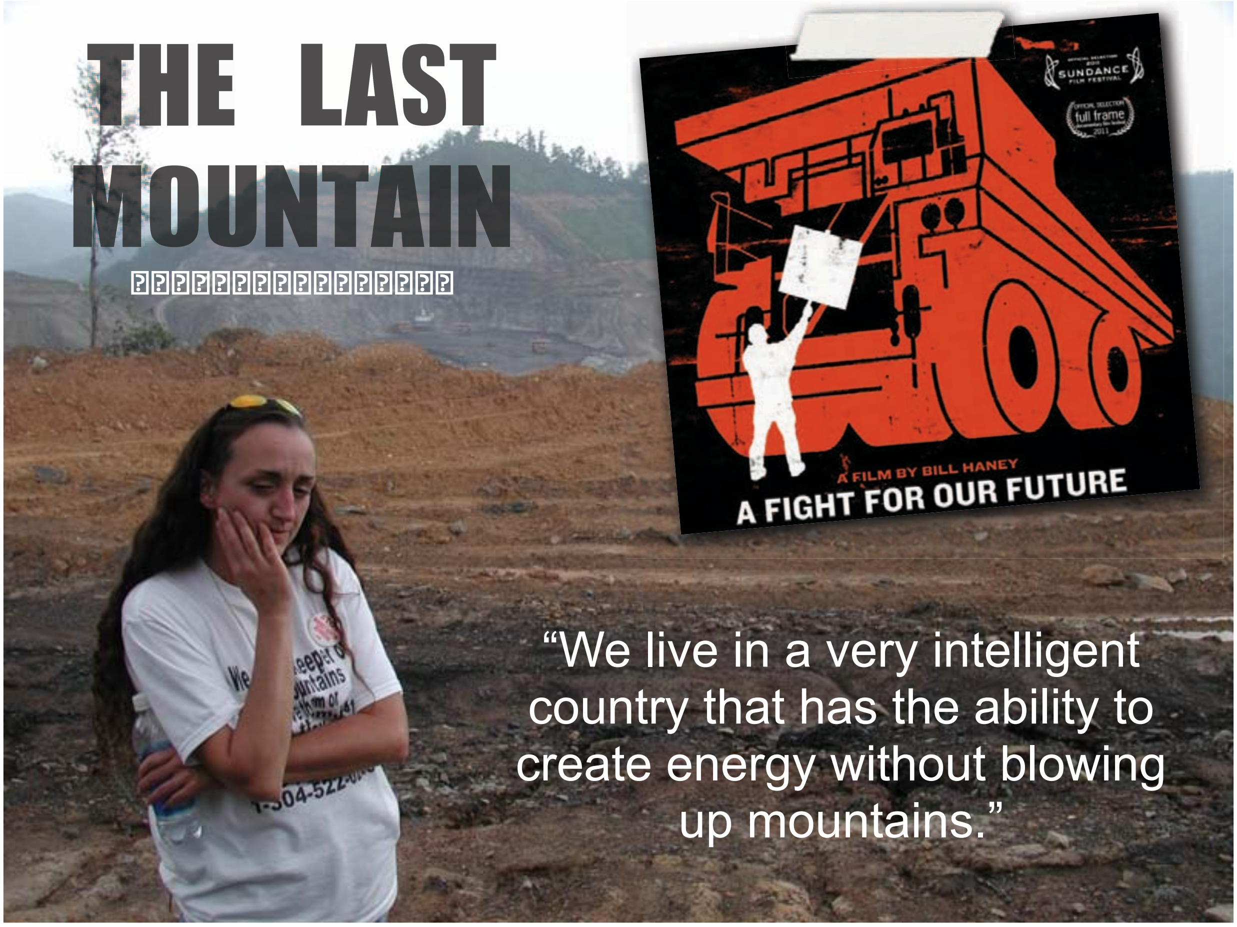
John Holdren's AAAS Presidential Lecture (February 2007)

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."


THE LAST MOUNTAIN
SUNDANCE
full frame
A FILM BY BILL HANEY
A FIGHT FOR OUR FUTURE
“We live in a very intelligent country that has the ability to create energy without blowing up mountains.”


Deep Horizon 5 million bbls
(April-July, 2010)

Summary

- Fusion promises nearly unlimited carbon-free energy.
- Tremendous progress has been made both in understanding and achieving fusion parameters.
- With the NIF operating and the world committed to construct ITER, **we now have the opportunity to demonstrate controlled fusion energy in the laboratory.**
- Huge challenges must be overcome to make fusion practical:
  advanced materials for D-T fusion and/or
  advanced confinement for D-D(^{3}He) fusion
- The world needs a successful fusion R&D program that will allow fusion to provide a long term energy solution.