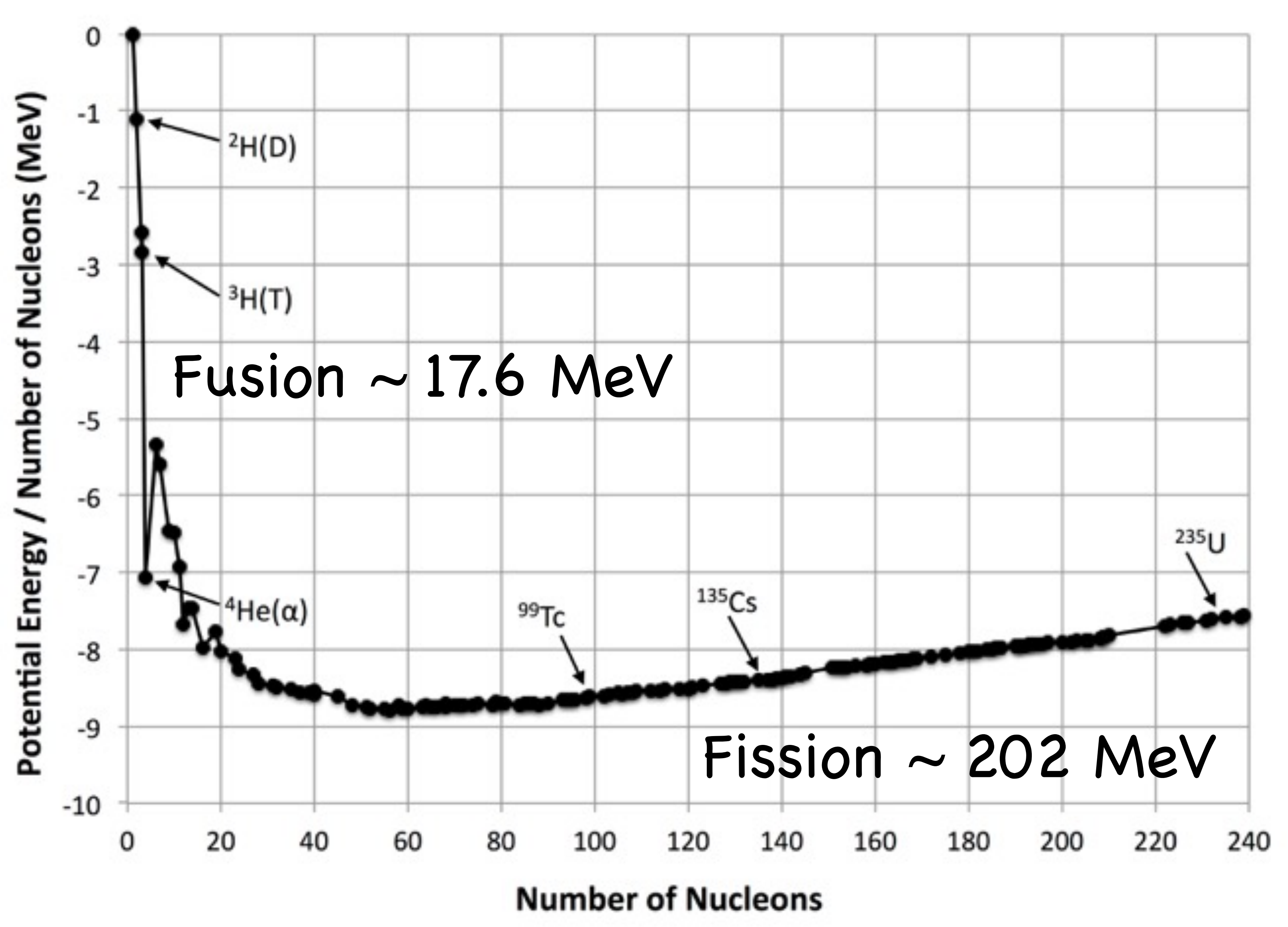
Introduction to Fusion



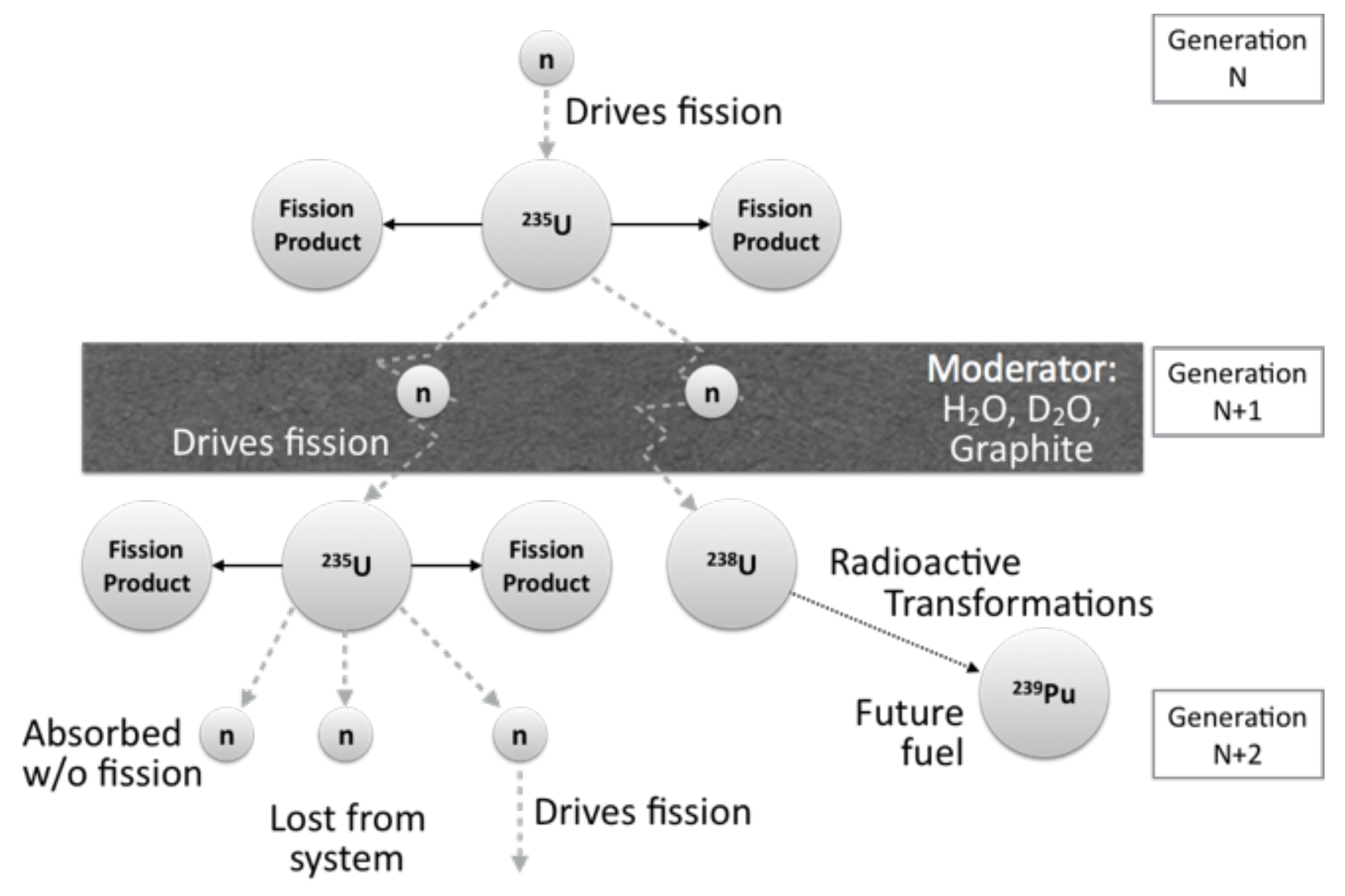
Fusion ~ 17.6 MeV

Fission ~ 202 MeV

Lise Meitner

Mass-energy (mc^2) of natural nuclei minus total mc^2 of protons and neutrons from which they are formed (~ 940 MeV each), divided by the number of nucleons

Fission Runs on a Chain Reaction

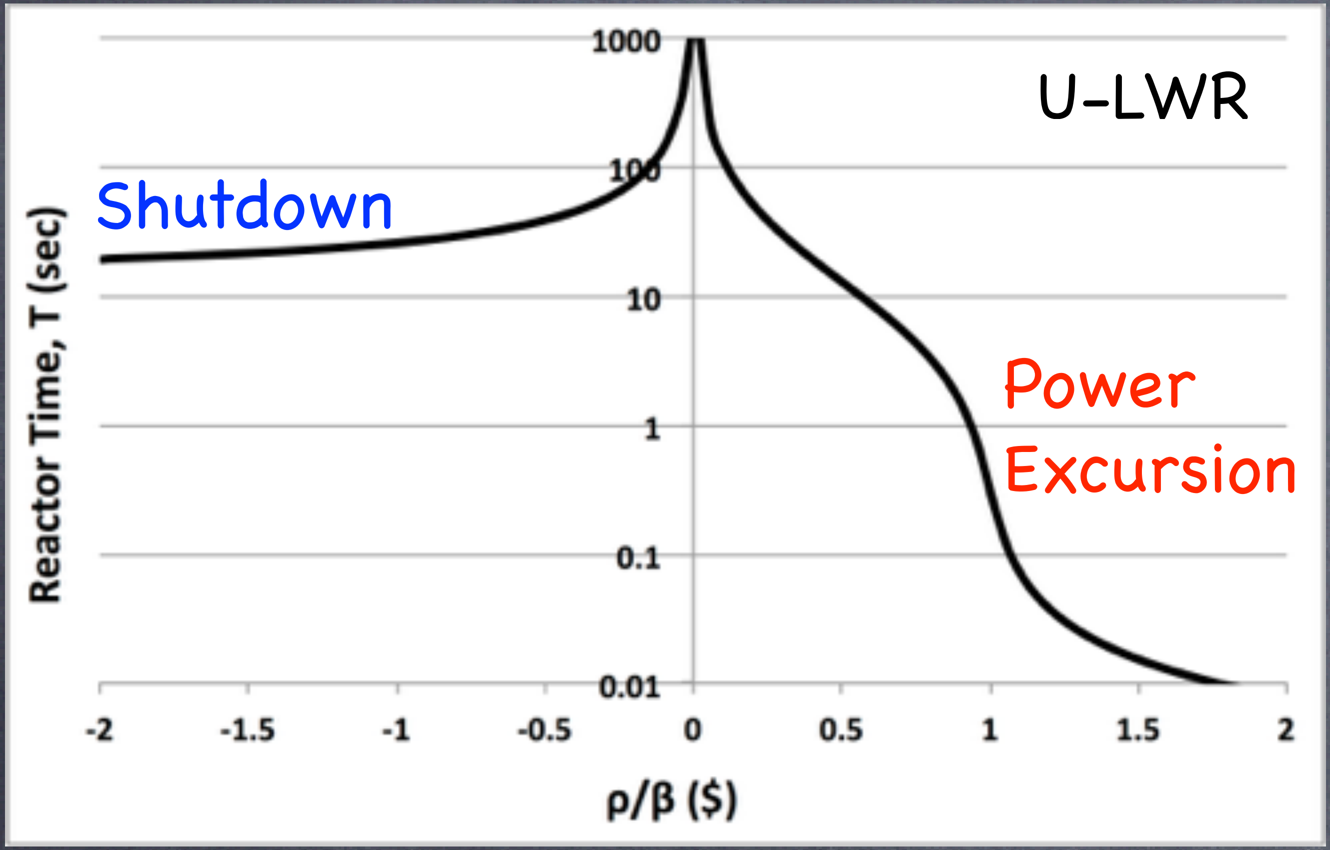


1 generation is about 50 μsec in a light water reactor.

$N_{Doubling} \approx 70$ / % increase per generation

Safety - Prompt Criticality: Chernobyl

- The controllability of fission systems depends on “delayed neutrons”
  - ≈ 15 second delay; 0.65% of total for uranium, 0.21% for plutonium

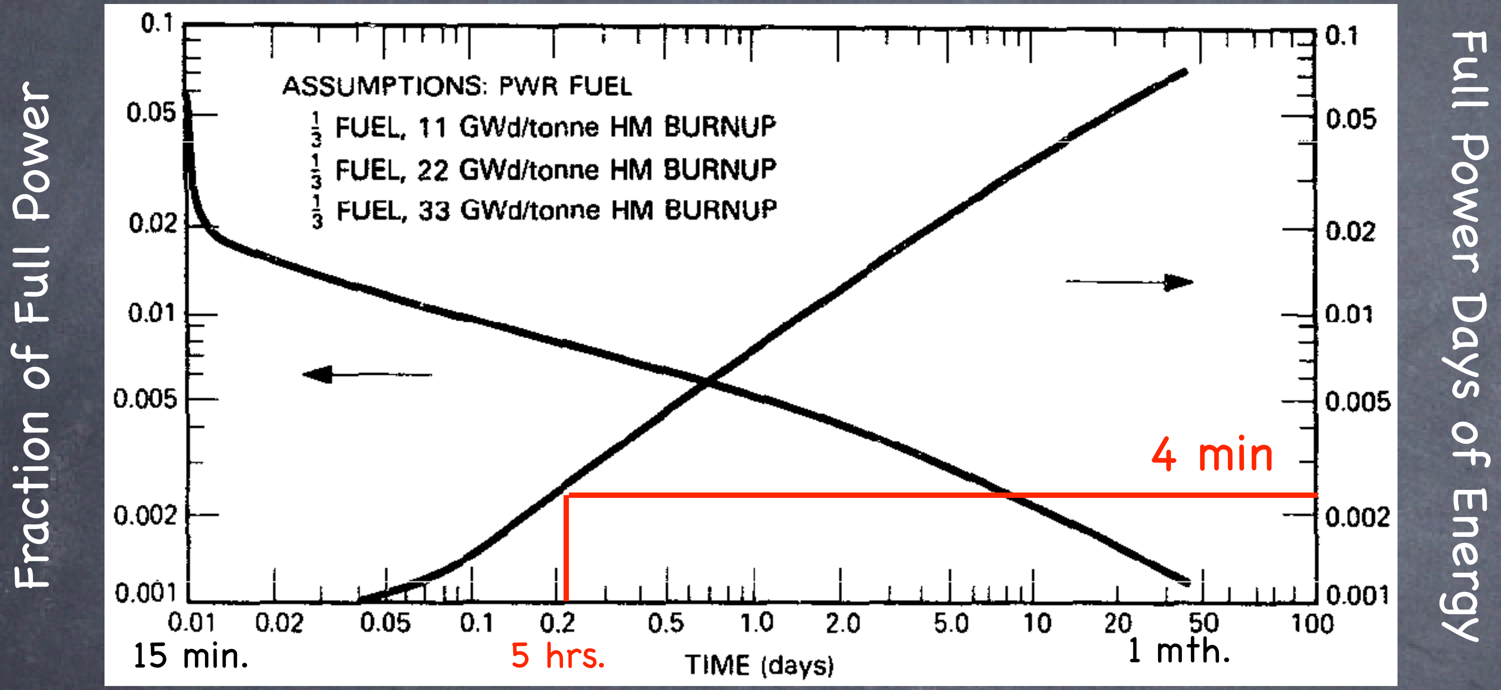


- β is delayed fraction
- ρ ≈ (Gen N+1 / Gen N) - 1, including all of the neutrons
- ρ/β is measured in $ (!)
- You really want to stay far below $1.00

- The Chernobyl reactor went “prompt critical” and reached at least 10x its normal operating power.
- Fusion systems have no equivalent of prompt criticality.

Safety - Meltdown: TMI & Fukushima

- The fission reaction turns off when the chain reaction is extinguished, but radioactive decay continues to produce heat.



Light Water Reactors have about 5 hours to meltdown with no flow of cooling water.

- It was the failure to remove this decay heat that resulted in the core meltdowns at Three Mile Island and Fukushima
- There isn't major decay heat in a fusion system.

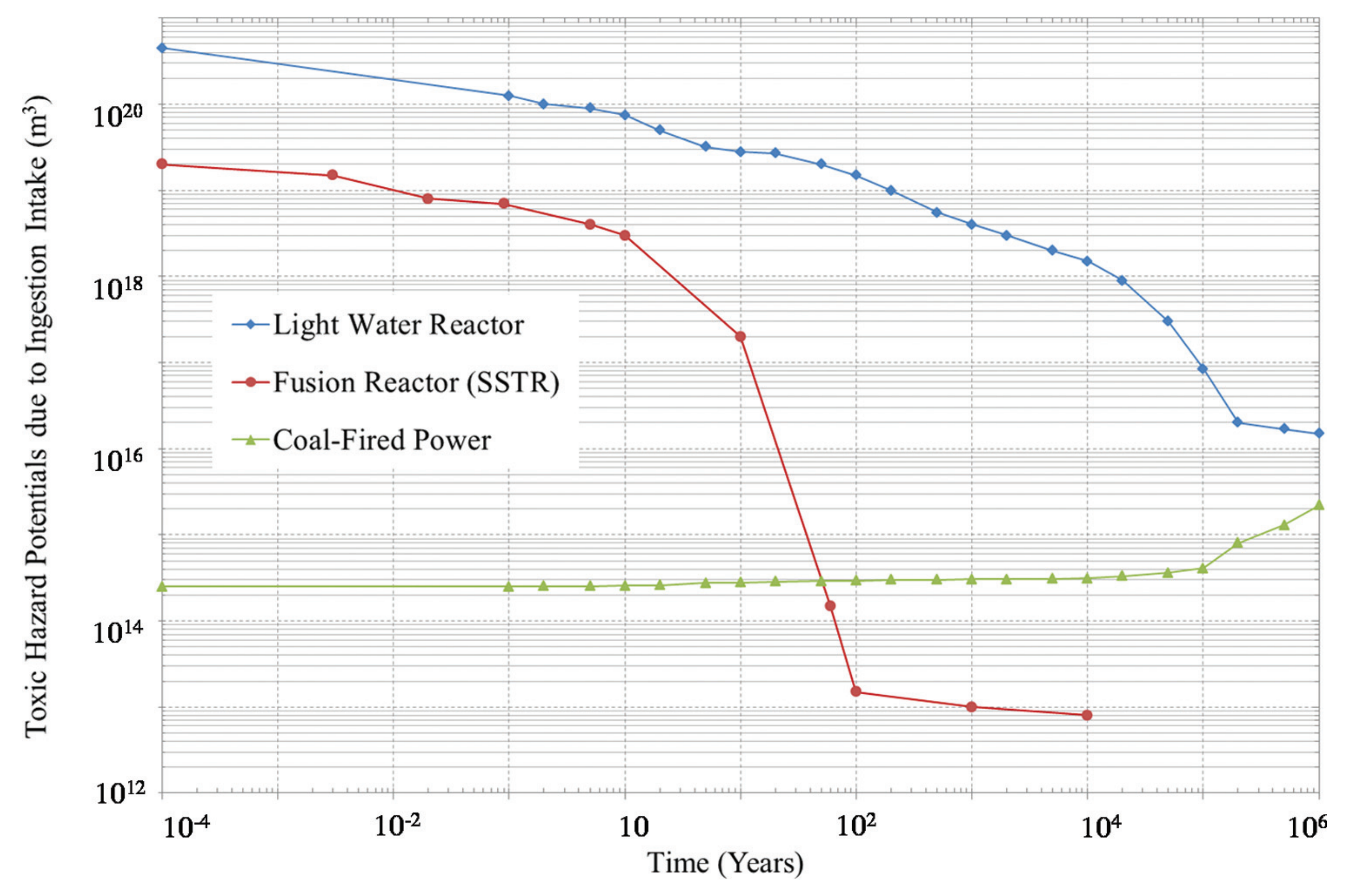
Waste

- The U.S. and most other countries exclusively use a "once-through" fuel cycle:
  - Mine, enrich, burn, store, (bury).
  - Waste carries risk of dirty bombs, Pu usable in weapons
    - Stored spent fuel is self-protecting for ≈ 100 years

- Leave fuel rods in cooling ponds for ≈ 5 yrs
- Transfer to dry casks
- 2 casks hold 1 year of fuel
- What about the long run? Radiotoxicity is very long-lived.
- Fast reactor waste has little Pu and minor actinides, but still long-lived fission products.

- Waste from fusion is much less long-lived.

Radioactivity from Fusion is Short-Lived



Biological Hazard Potential measured by how much water is needed to dilute all the materials to regulated safe drinking levels.

Fusion should require neither local evacuation plans nor geological storage of radioactive waste.

Centrifuges Make Proliferation Easier

- A facility sized for 1 power plant can make material for ~ 75 bombs/yr, starting from 4% enriched.

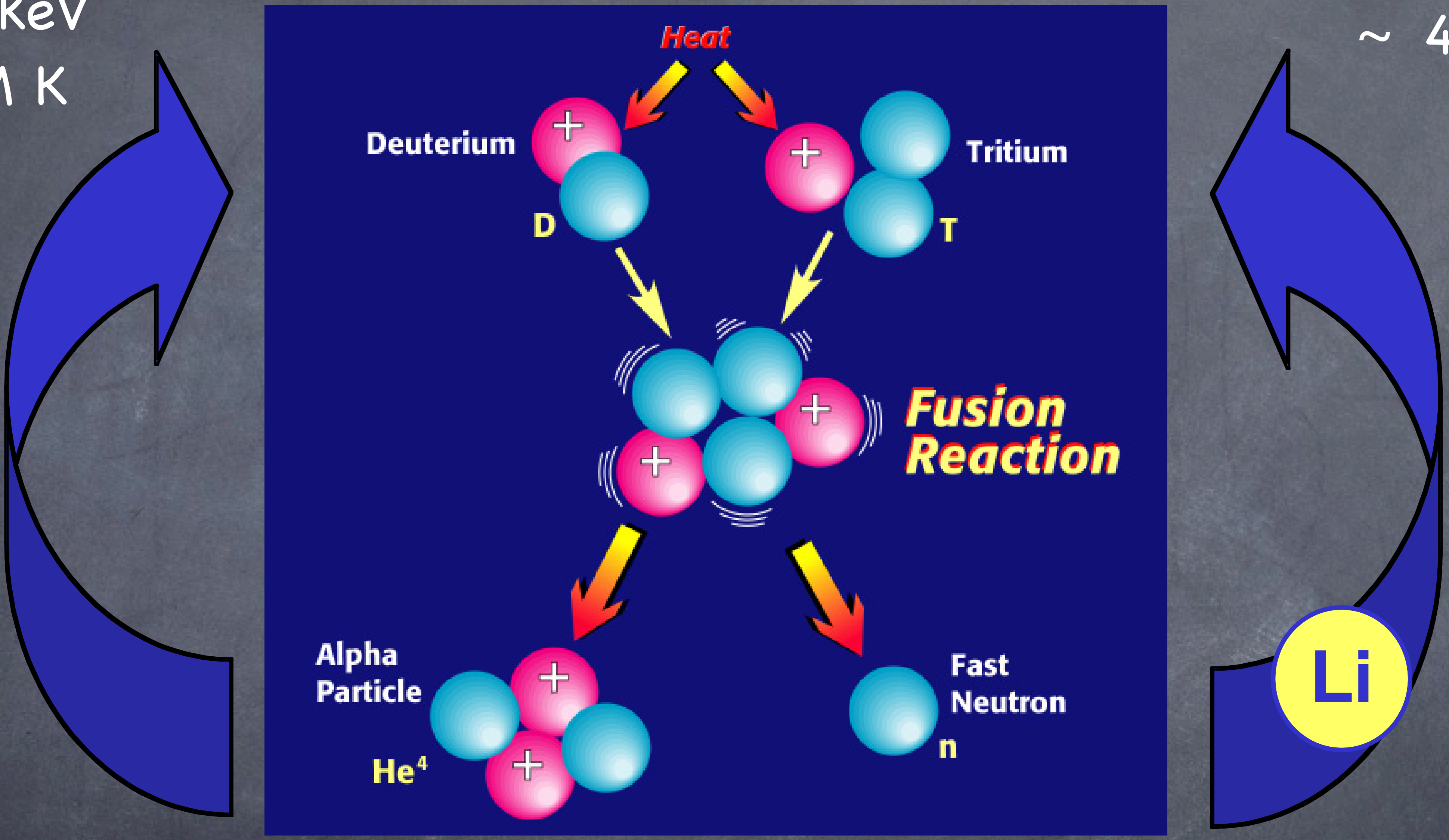
Nuclear Power and Fissile Material

	Fission Enrichment	**Fission Reprocessing**	**Fusion with safeguards**
Clandestine Facility	Centrifuge plant, 100 kW, 550 m^2 ~ 1 SQ/year	Can account spent fuel rods	Large size and power make detection easy.
Covert use of Declared Facility	Can assay degree of enrichment	1% “Material Unaccounted For” (MUF) Surveillance & Containment	Easy to detect presence of fertile material.
Breakout of Declared Facility	Rapid production in large centrifuge plant. (1-3 weeks to use)	Spent LWR fuel + reprocessing (1-3 months to use) MOX + FR fuel (1-3 weeks to use)	No fissile material at breakout; easy (?) to disable.

Two Cycles Sustain DT Fusion

T ~ 14 keV
~ 160M K

~ 400g/day



heat

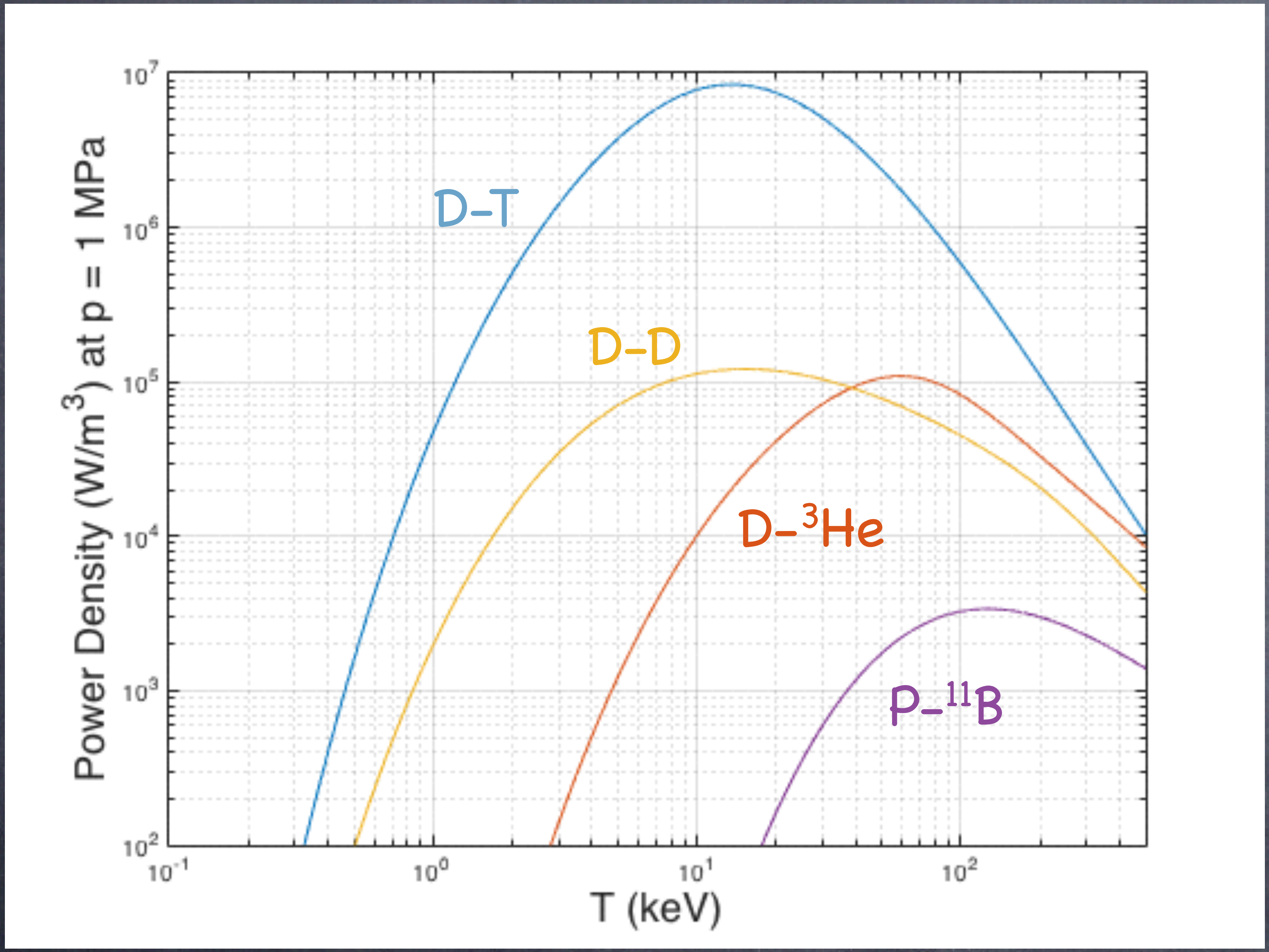
tritium

$D + T \Rightarrow \alpha\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV})$

$n + {}^{6}Li \Rightarrow \alpha + T + 4.8\ \mathrm{MeV}$

Fuel is plentiful & cheap D & ^{6}Li

Fusion Requires very High Temperatures because of Electrostatic Repulsion of Nuclei



α power density
= 1/5 fusion power density
≈ 1.7 10^6 W/m^3

Fuel energy density
= (3/2)nkT = (3/2)p
= 15 atm ≈ 1.5 10^6 J/m^3

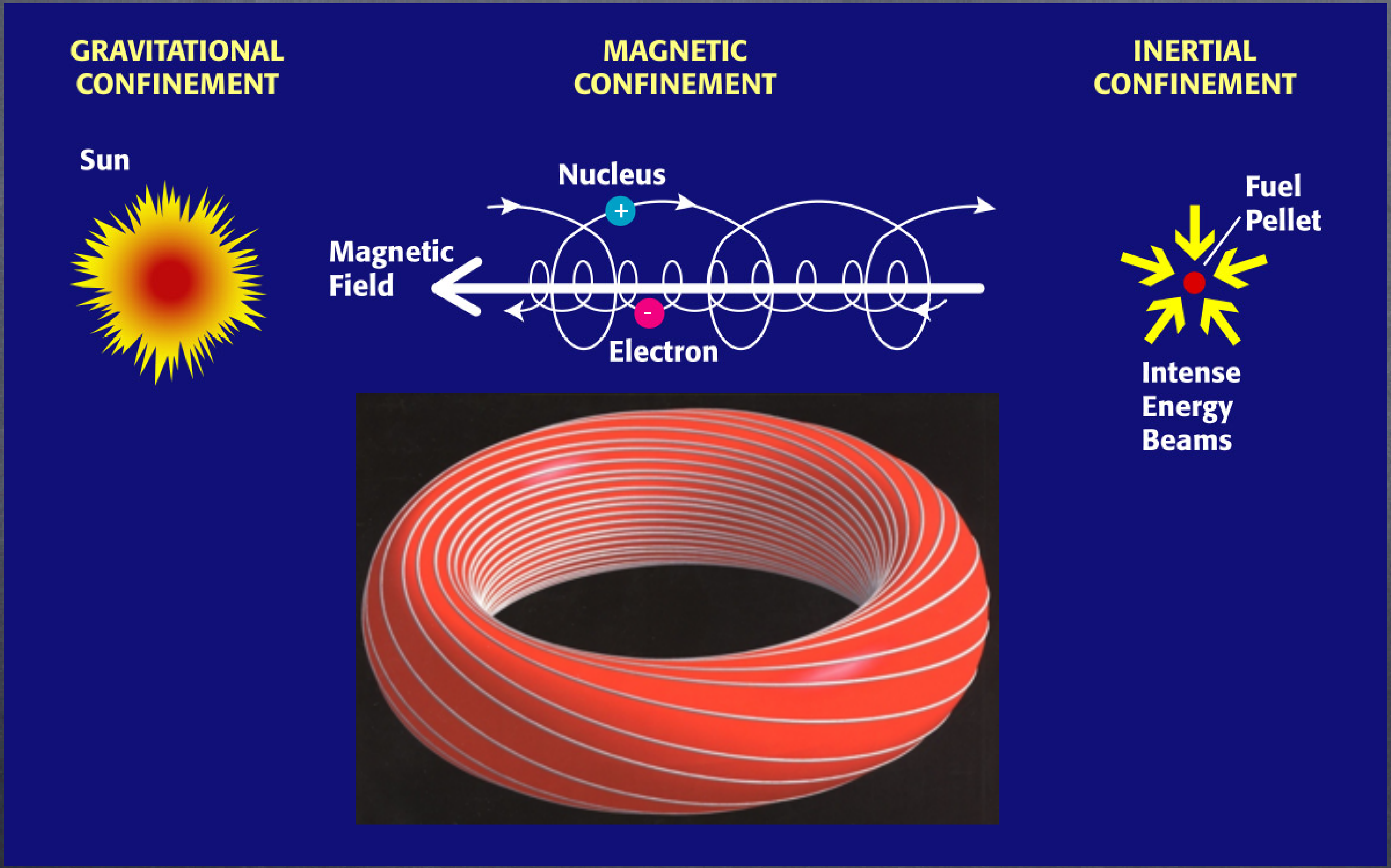
Need to "confine" power for ~ 1 sec for DT
At very (!) high T.

Confinement time
≡ energy ÷ power

1 eV = 11,600 K, 10 keV = 116M K

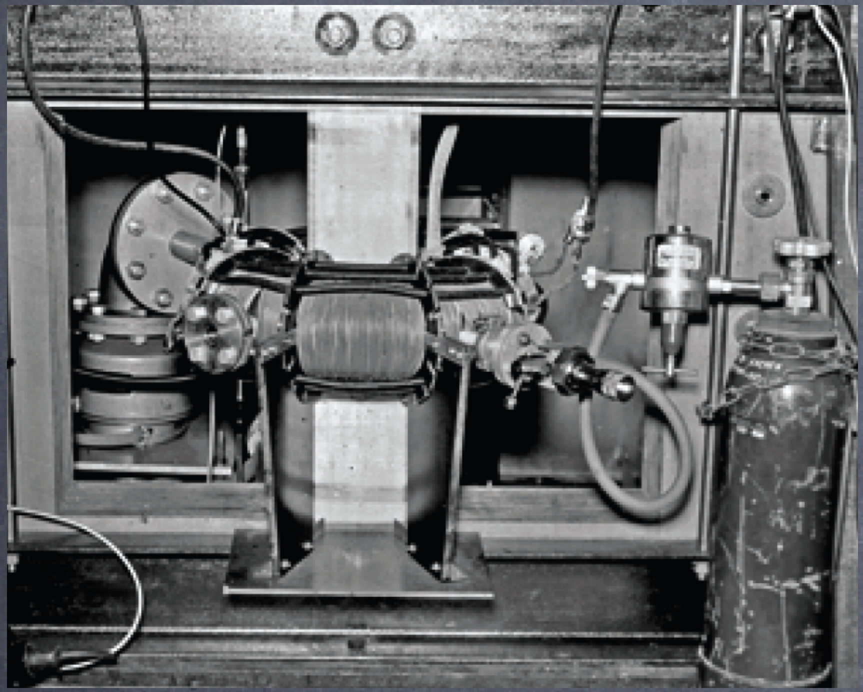
Fusion Fuel can be Confined Three Ways

Plasma ≡ ionized gas, occurs at T > 10,000 K



q ≡ toroidal transits per poloidal transit

First Issue is Macroscopic Stability

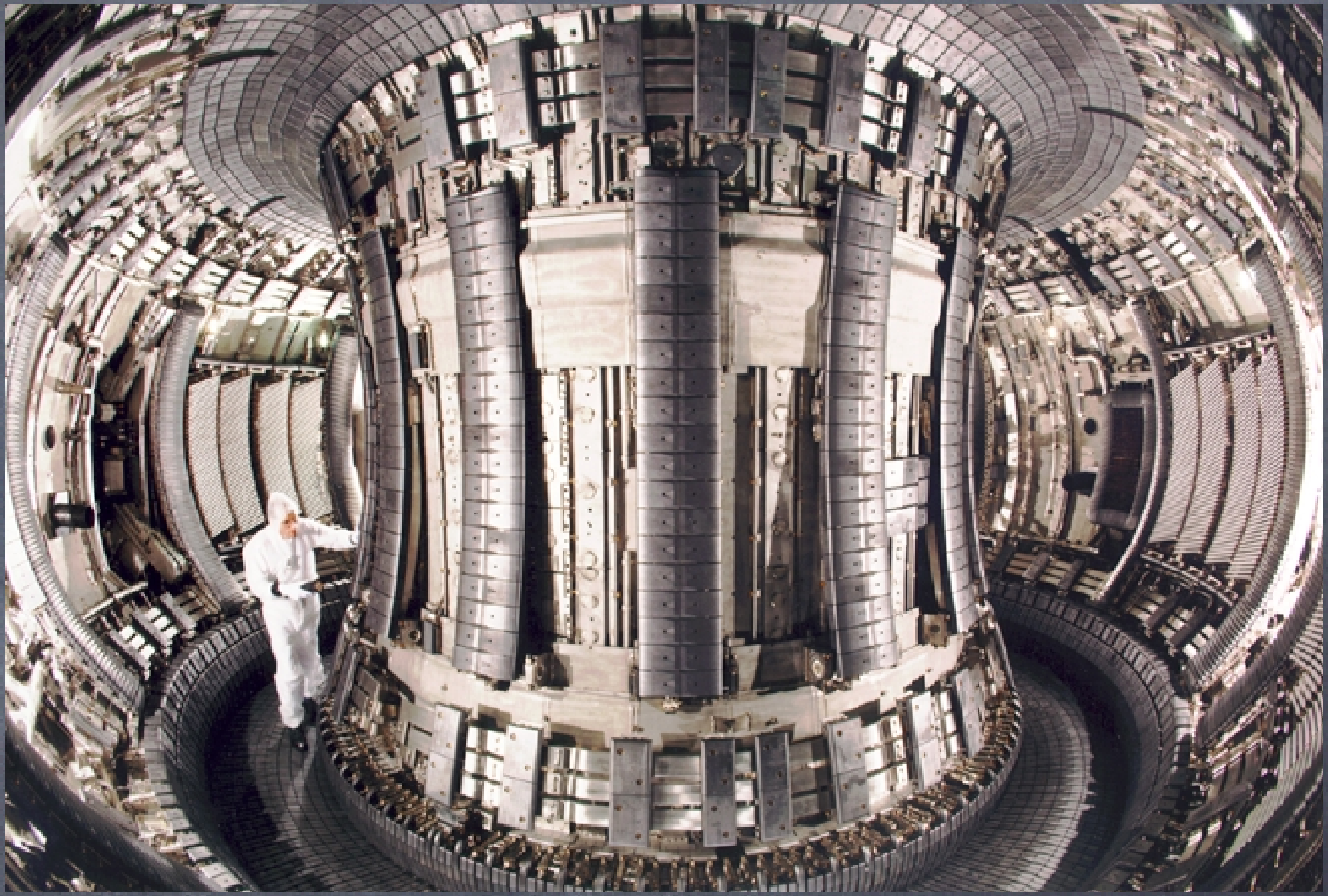


1957

First Experiments

"Perhapsatron" @LANL

Tore itself apart in μsecs



Joint European Torus

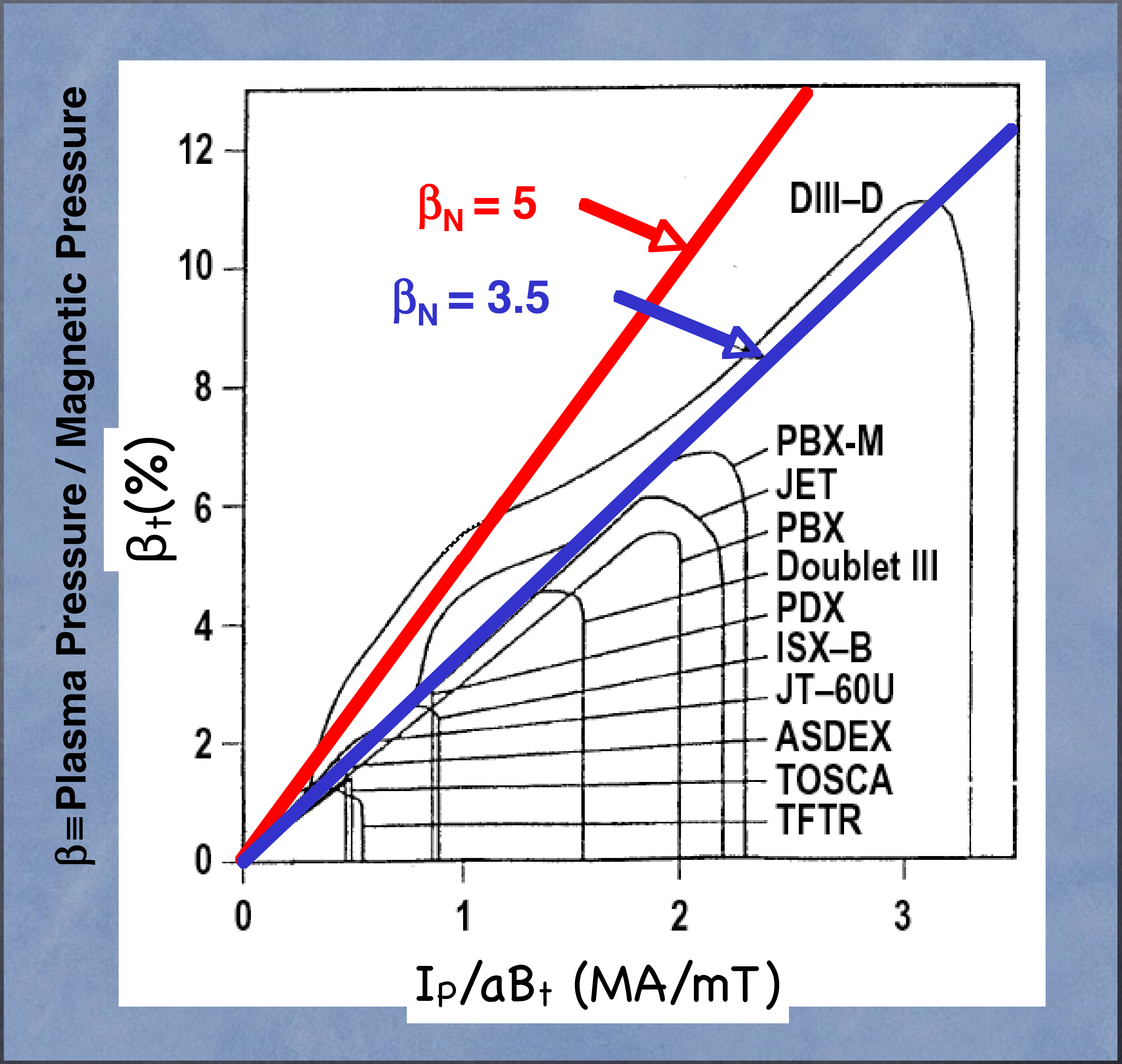
near Oxford, UK

Runs stably for 20 secs

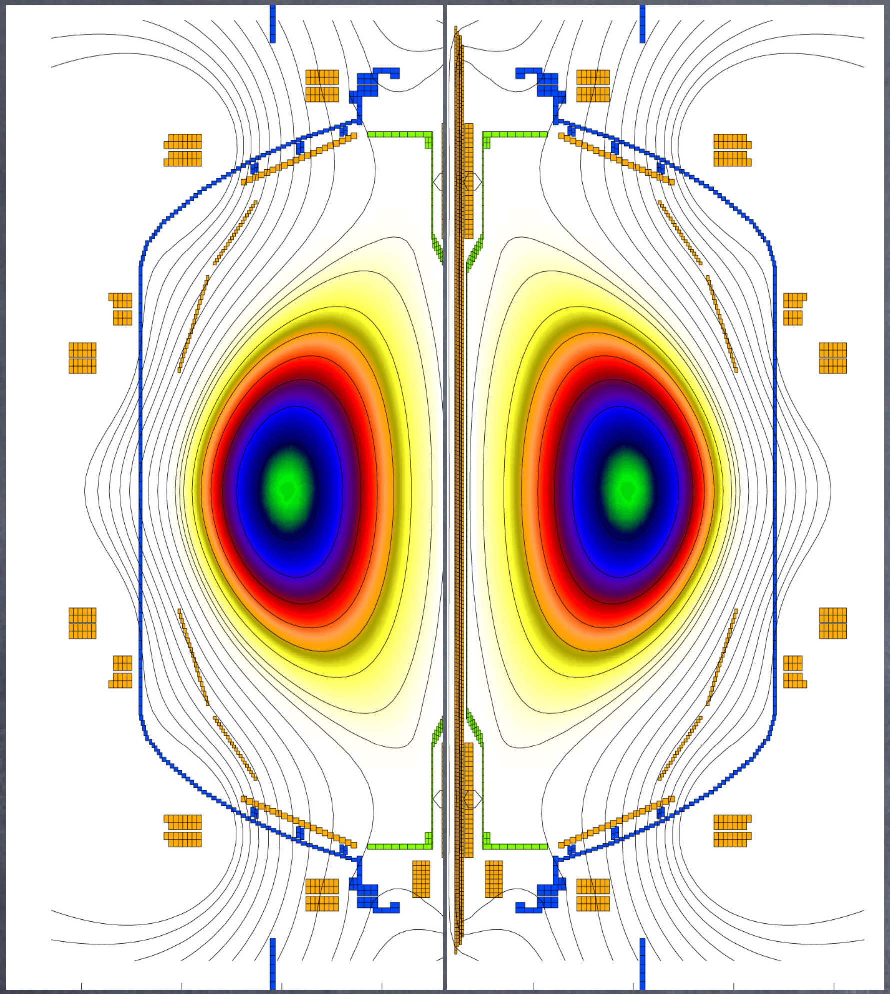
Need to Sustain High Plasma Pressure

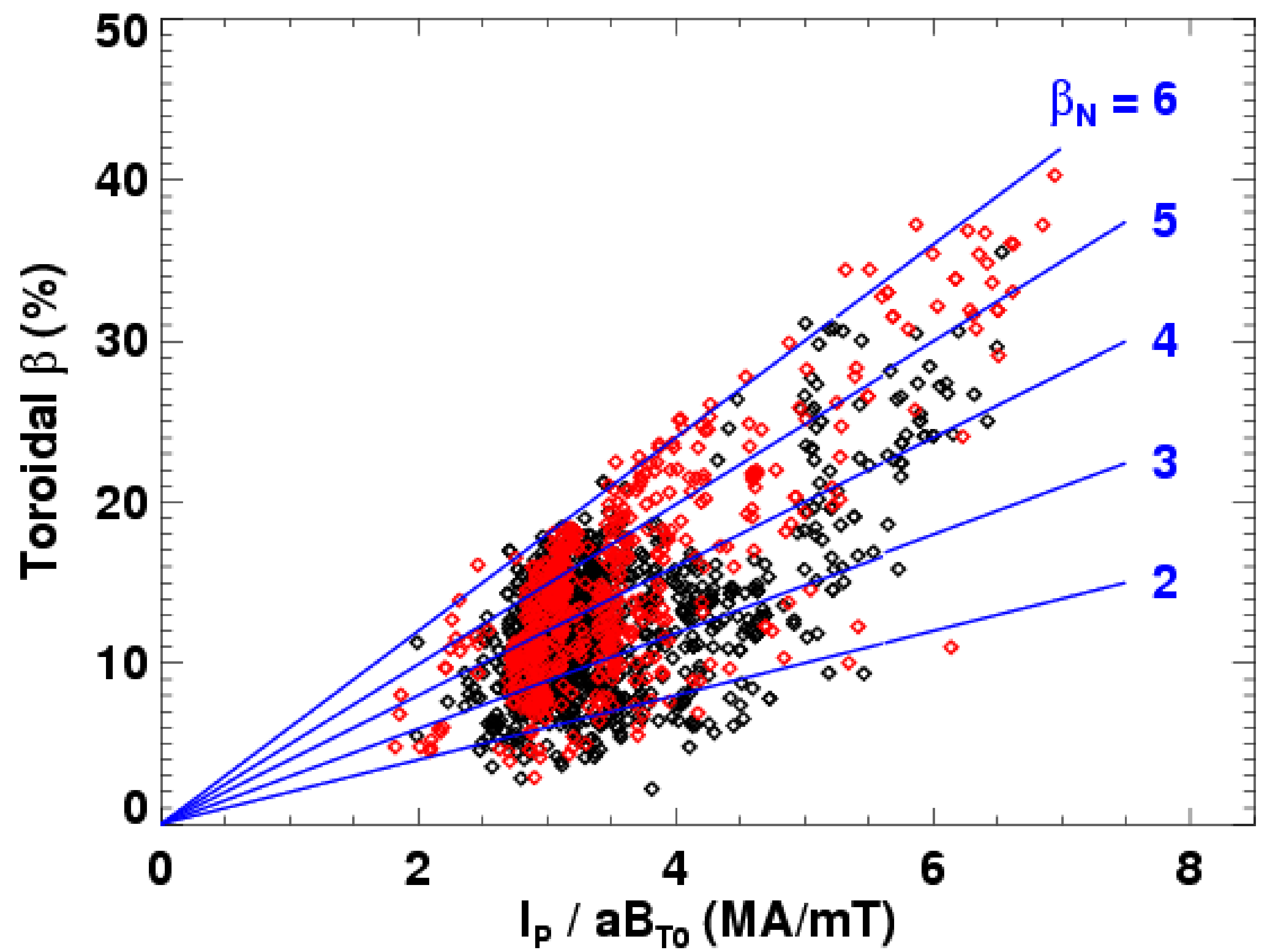
- β_t ≡ plasma pressure / magnetic pressure in toroidal B field, B_t.
- Data from many experiments have shown β_N up to the predicted range.
- Data from many experiments show current limits based on limits to $q(a) = q_a > 2\text{–}3$.
- This sets the basic outline of tokamak operating space.

$$\beta_N \equiv \frac{100\beta_t}{\left(I_P/10^6\right)/\left(aB_t\right)} = \frac{\beta_t(\%)}{I_P(MA)/\left(aB_t\right)}$$



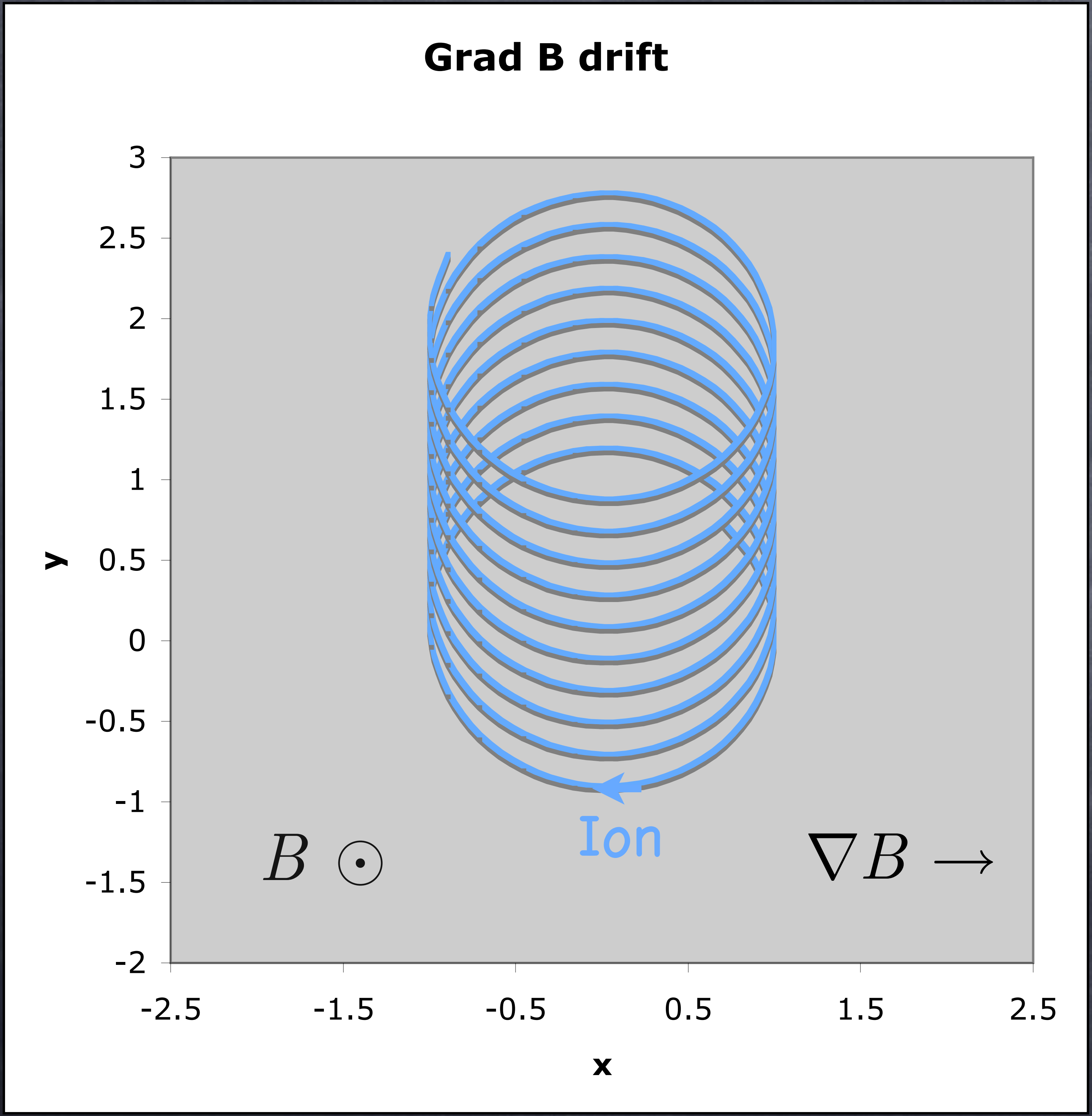
Very Low Aspect Ratio Allows Very High β_t

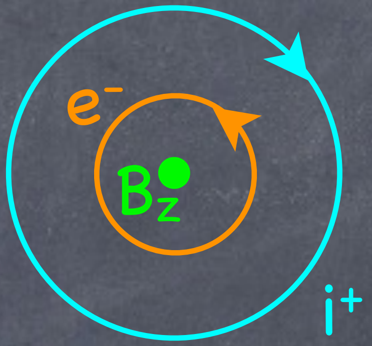




- Careful though, low R/a leaves little room for center column... affects coil technology, reduces B_{T0}
- High triangularity is also favorable for stability.

Next Issue is Confinement



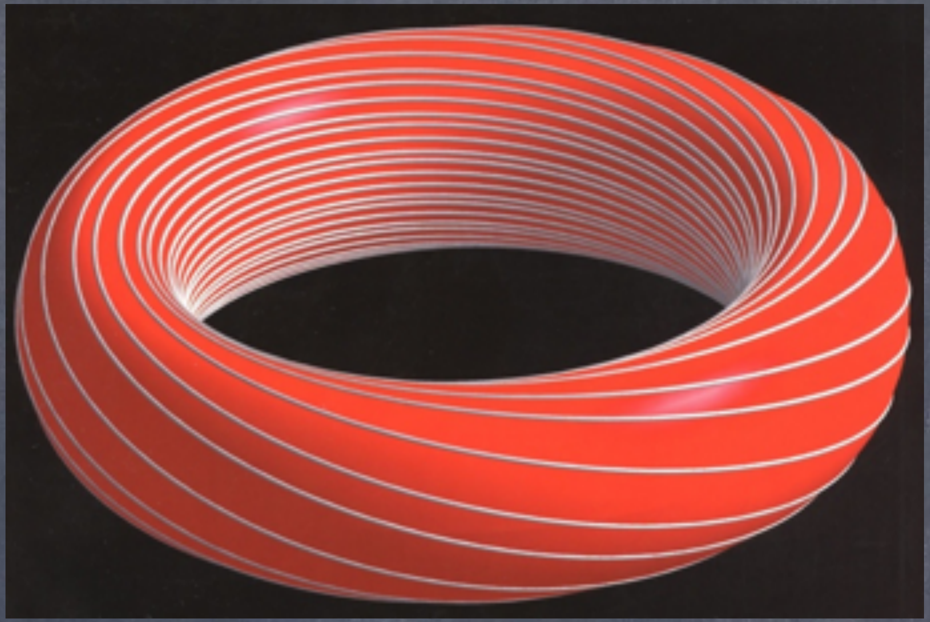


Larmor orbits, radius = r_L

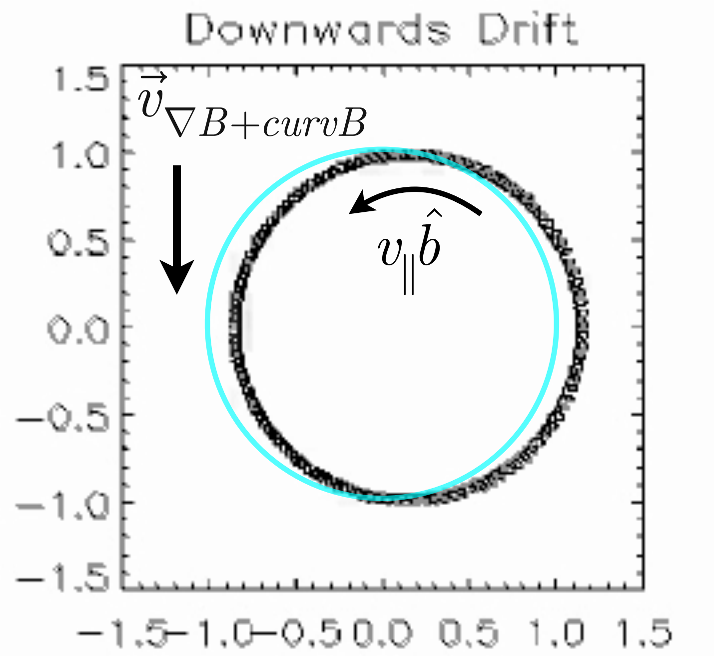
Magnetic Twist (= Transform) Confines Orbits

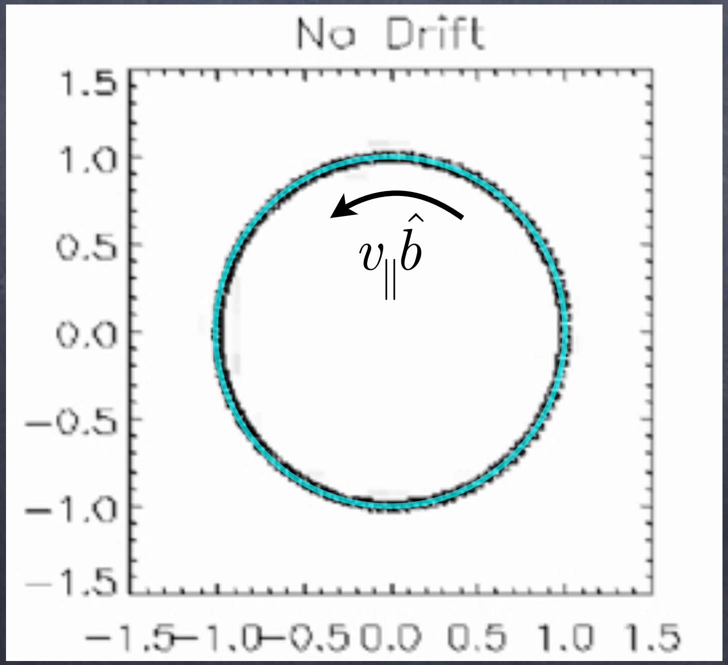
$B \propto 1/R$

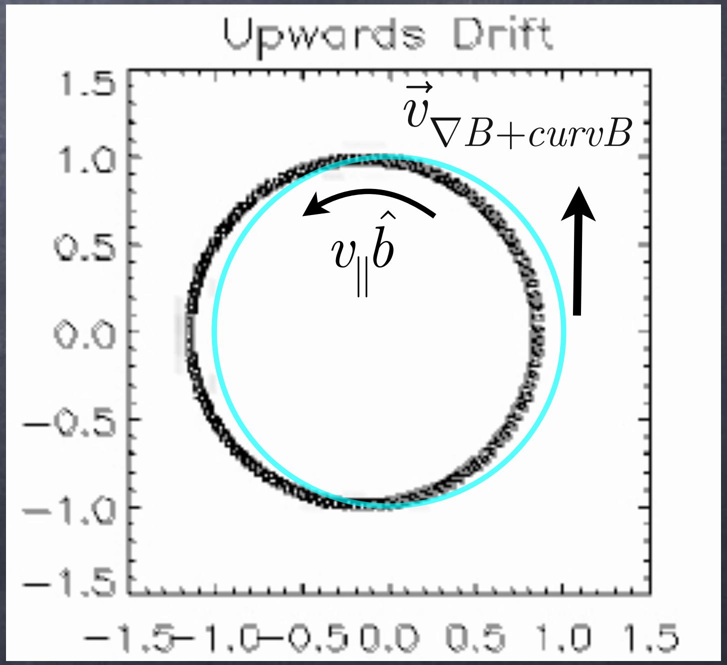
$$q \equiv \frac{long-way\ transits}{short-way\ transits}$$



$\Rightarrow$



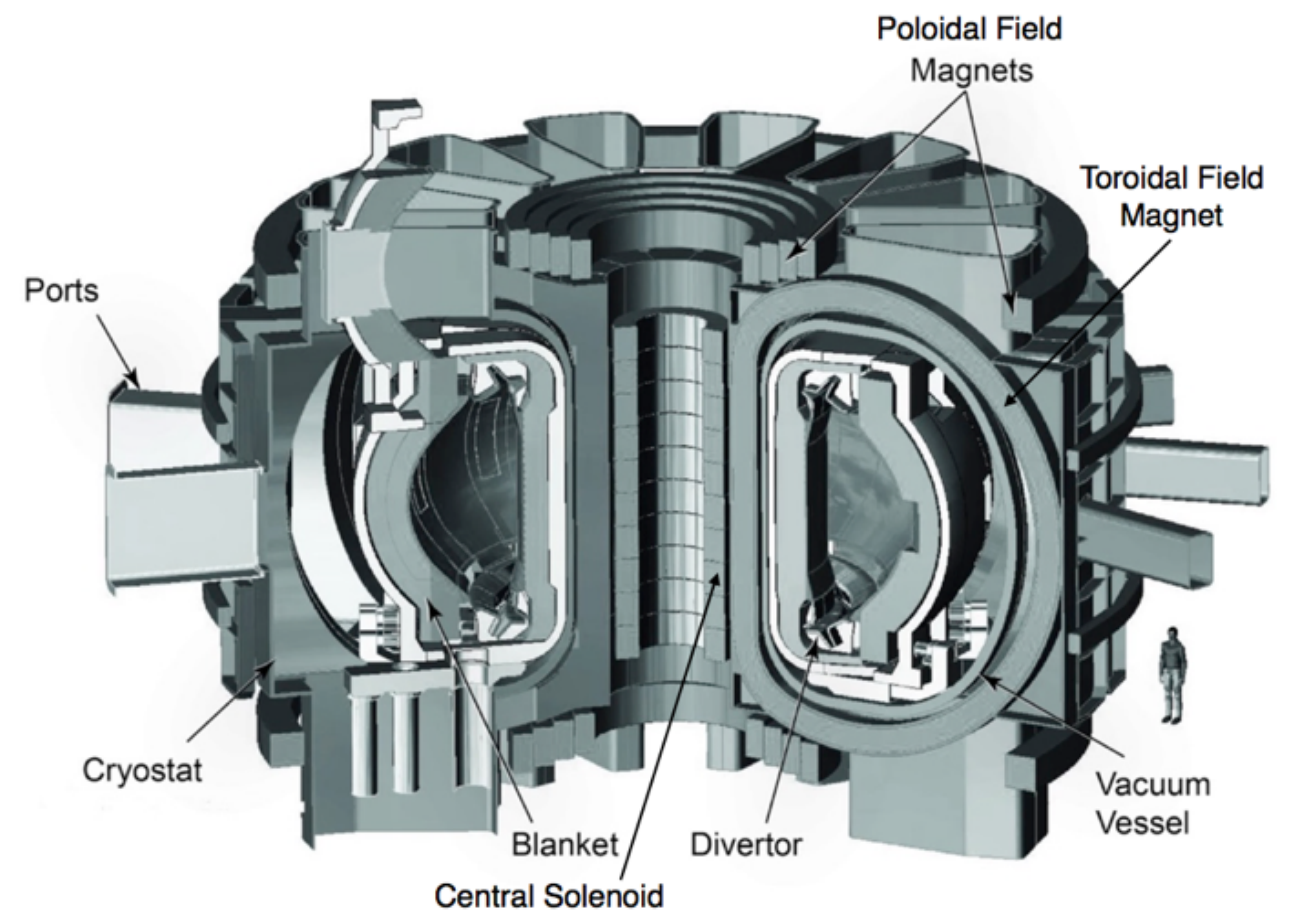




— Magnetic field

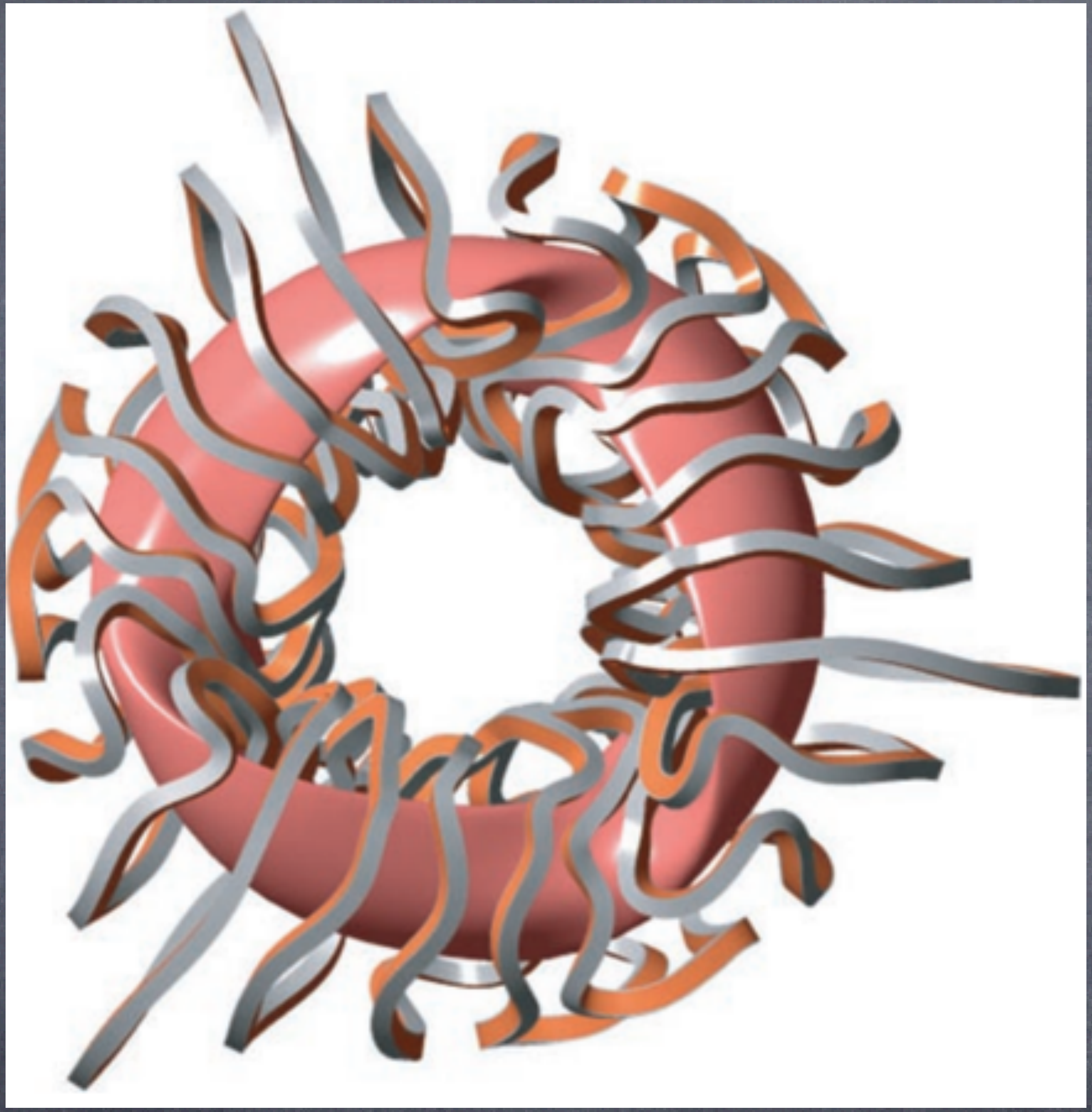
$\delta r \sim \pm q r_L \cos\theta$

Concept for a Tokamak Fusion Pilot Plant



Gets magnetic twist with plasma current

Stellarators Get Twist Differently



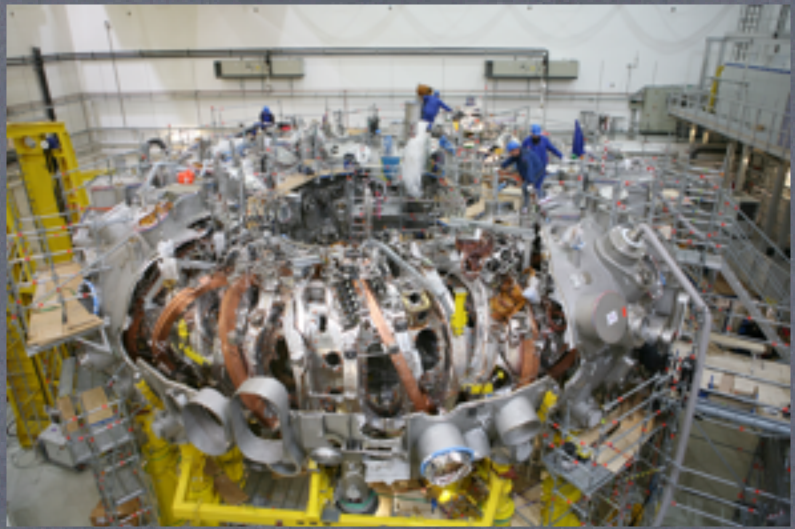
The twisting plasma “pulls” the field lines with it.

Fusion Research is International

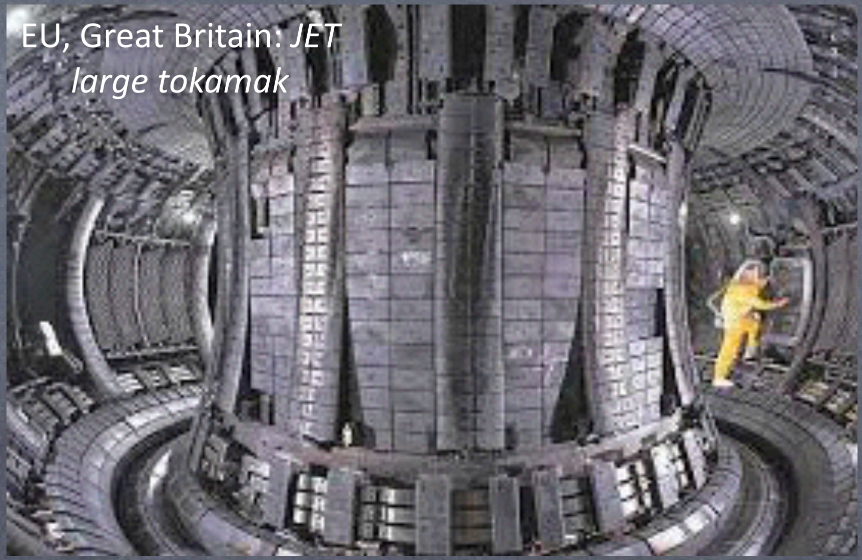
USA, Princeton: *NSTX-U*
low aspect ratio tokamak

EU, Germany: *ASDEX-U*
medium-size tokamak

EU, Germany: W7X
superconducting stellarator



USA, San Diego: DIII-D
medium-size tokamak

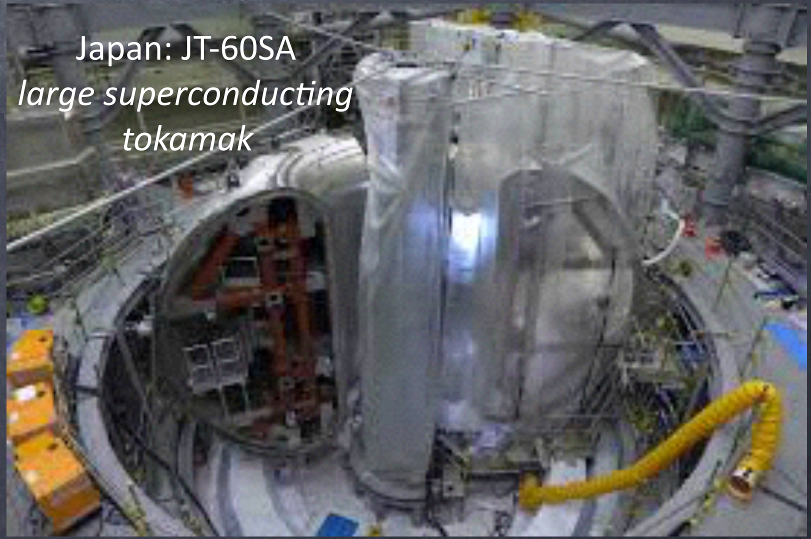


EU, Great Britain: *JET*
large tokamak

Japan: LHD
superconducting stellarator

China: *EAST*
superconducting tokamak

Korea: KSTAR
superconducting tokamak



Japan: JT-60SA
large superconducting tokamak

The Plasma Energy is due to a Balance Between Heating and Losses

- Local power density balance (in the core) for steady operation

$$\frac{d}{dt}U_{th} = \frac{3}{2}\frac{d}{dt}\left(n_e + \sum_i n_i\right)T = 0 = n_D n_T \left\langle \sigma v \right\rangle_{DT} E_\alpha + p_{aux} - \frac{\frac{3}{2}\left(n_e + \sum_i n_i\right)T}{\tau_E^{transport}} - p_{rad,core}$$

T and E_α are in Joules, U is energy density, Joules/m^3, p is power density, Watts/m^3

- ⍰ heating is in the core and core E-M radiation short-circuits magnetic confinement of heat.
- Here we assume 100% efficiency of α particle heating.

Plasma Gain, Q_p, Depends on nT⍰$_E^{transport}$ $(1-f_{rad,core})$

$$p_a + p_{aux} = p_{loss} \equiv U_{th} \,/\, \tau_E^{transport} + p_{rad,core}; \quad f_{rad,core} \equiv p_{rad,core} \big/ p_{loss}$$

$$p_{loss} - p_{rad,core} = p_{loss}\left(1 - f_{rad,core}\right) = U_{th} \,/\, \tau_E^{transport}$$

$$p_{loss} = \frac{\frac{3}{2}\left(n_e + \sum_i n_i\right)T}{\tau_E^{transport}\left(1 - f_{rad,core}\right)}$$

$$f_\alpha \equiv \frac{p_\alpha}{p_{loss}} = \frac{n_D n_T T^2 \left(\frac{\langle \sigma v \rangle_{DT}}{T^2}\right) E_\alpha}{\dfrac{\frac{3}{2}\left(n_e + \sum_i n_i\right)T}{\tau_E^{transport}\left(1 - f_{rad,core}\right)}}$$

$\propto$ nT⍰$_E^{transport}$ $(1-f_{rad,core})$

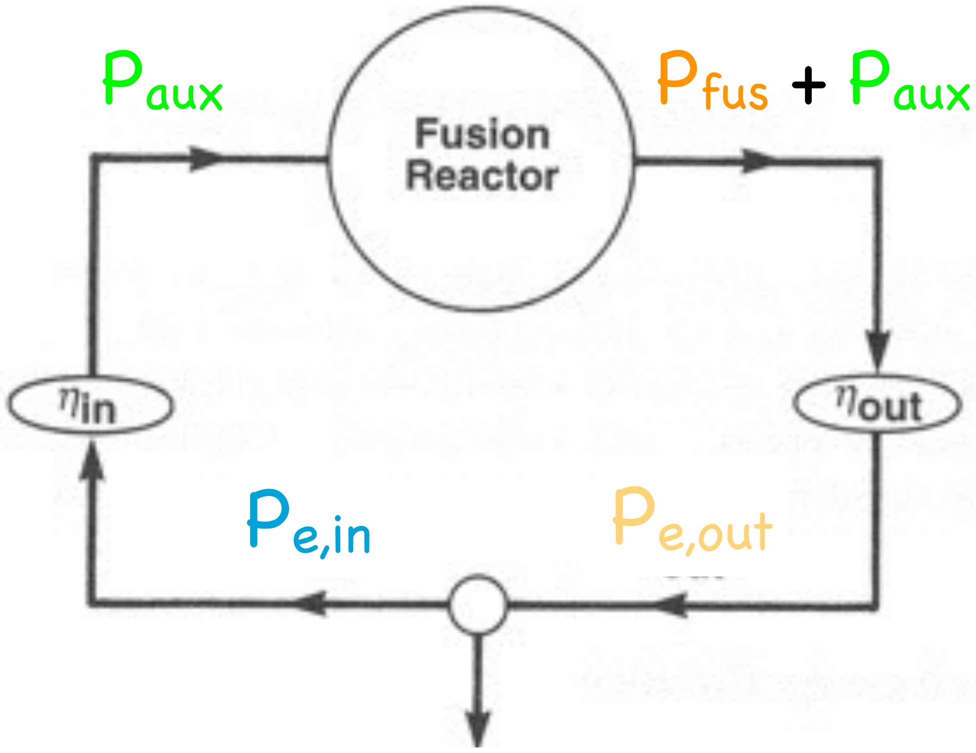
Fusion “triple product”

Looking at the whole plasma:

$$Q_p \equiv \frac{5P_\alpha}{P_{aux}} = \frac{5P_\alpha}{P_{loss} - P_\alpha} = \frac{5F_\alpha}{1 - F_\alpha} \quad \textit{takes off as } F_\alpha \to 1$$

- Q_p = 10 in ITER has $T_{i0} \approx 20$ keV, $n_{e0} \approx 10^{20}/m^3$, $\tau_E \approx 4$sec; $n_{e0}T_{i0}$⍰$_E \approx 8\ 10^{21}$ keV sec / m^3

Engineering Gain, Q_{eng}, Depends on Plasma Gain and Electrical Efficiencies



$$P_{e,net} = P_{e,out} - P_{e,in}$$

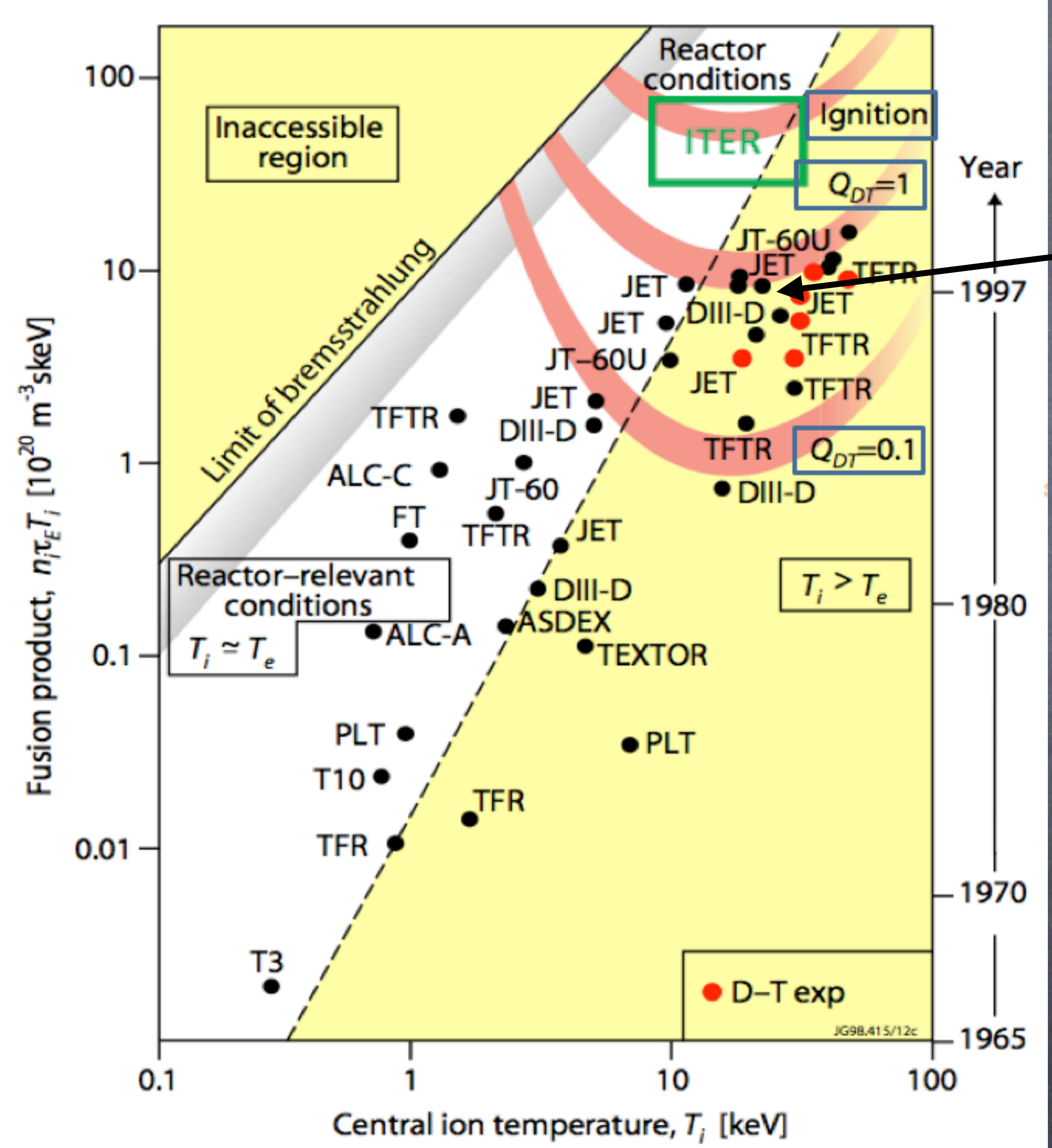
Fig. 8.1: Depiction of energy components associated with a general fusion power plant.

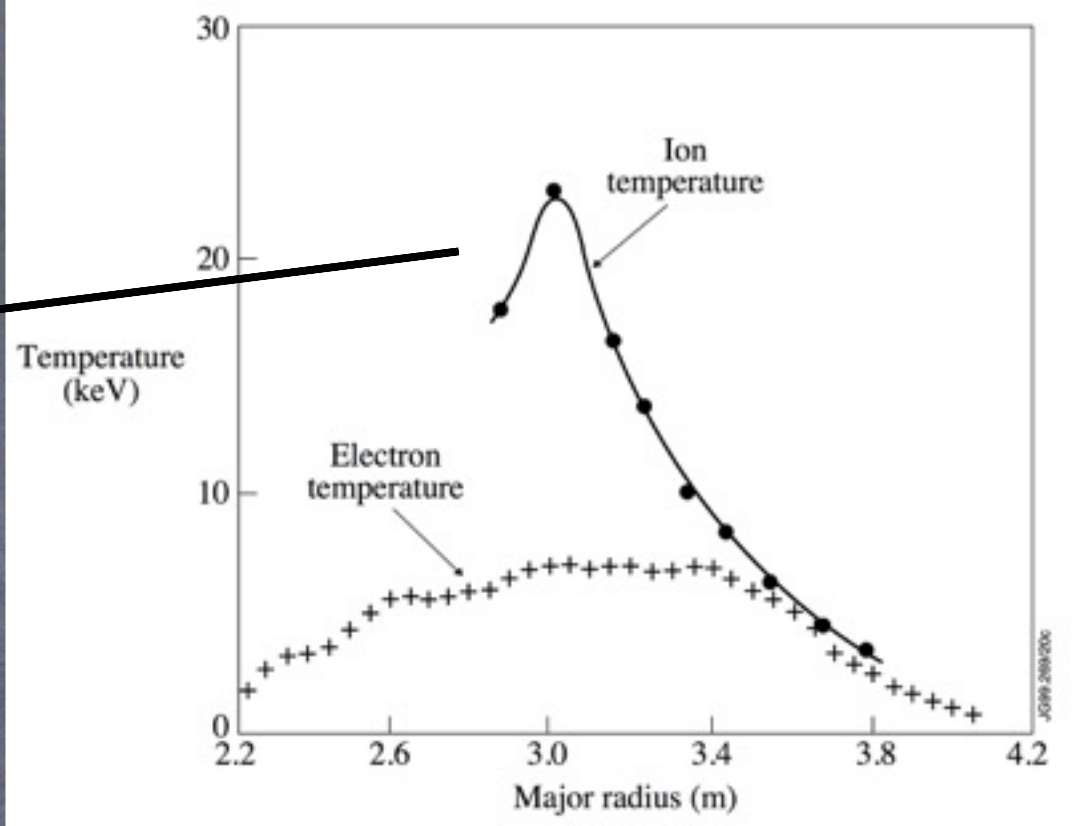
(These are Powers in Watts, not power densities in Watts/m^3.)

$$P_{e,net} = P_{e,out} - P_{e,in}; \quad P_{e,out} = \eta_{out}\left(P_{fus} + P_{aux}\right); \quad P_{e,in} = P_{aux}/\eta_{in}$$

$$Q_{eng} \equiv \frac{P_{e,out}}{P_{e,in}} = \frac{\eta_{out}(P_{fus} + P_{aux})}{P_{aux}\ /\ \eta_{in} + \ldots} \approx \eta_{in}\eta_{out}(Q_p + 1) \approx 0.3 \cdot 0.4(Q_p + 1)$$

Fusion "Triple Product" has Grown Dramatically

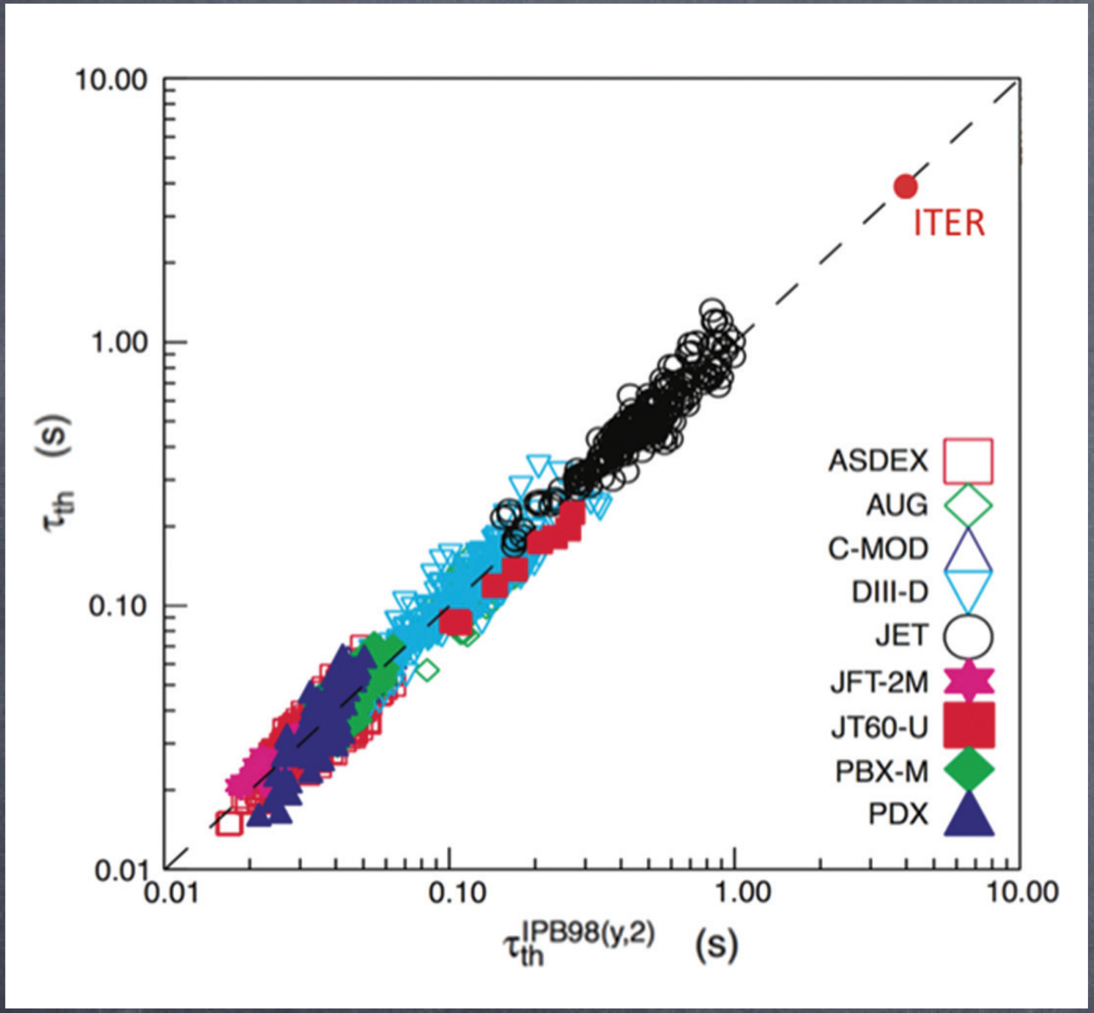




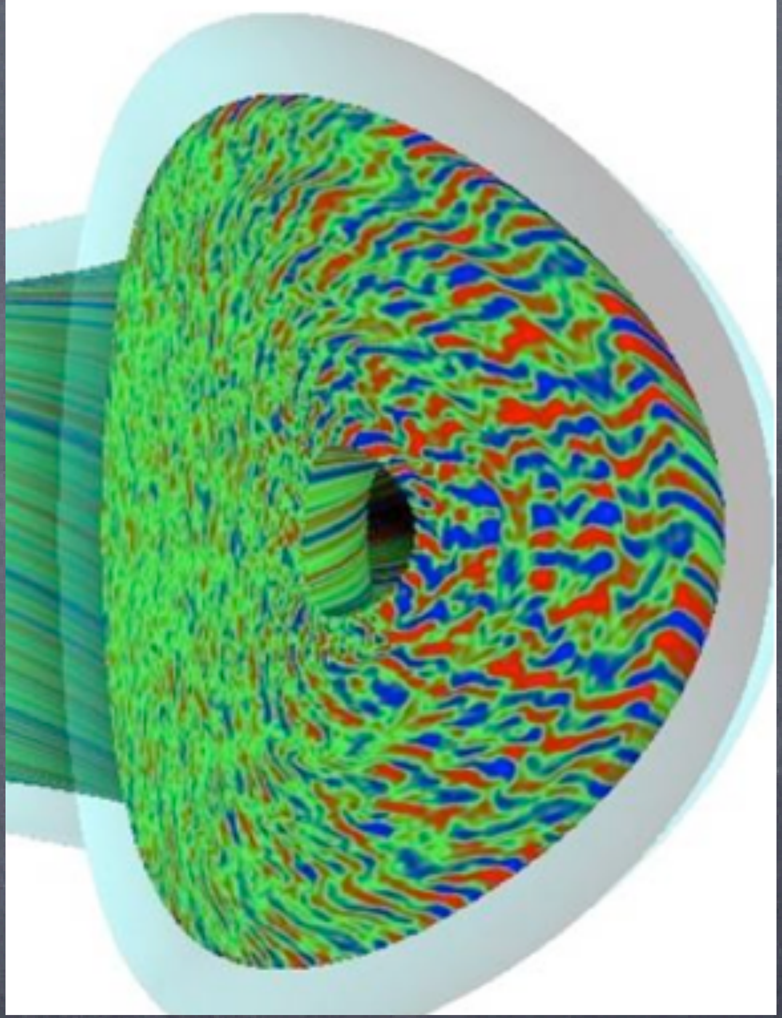
We should be able to attain self-sustained plasmas.

Confinement is (More or Less) Predictable

Energy Confinement Time



Regression Fit

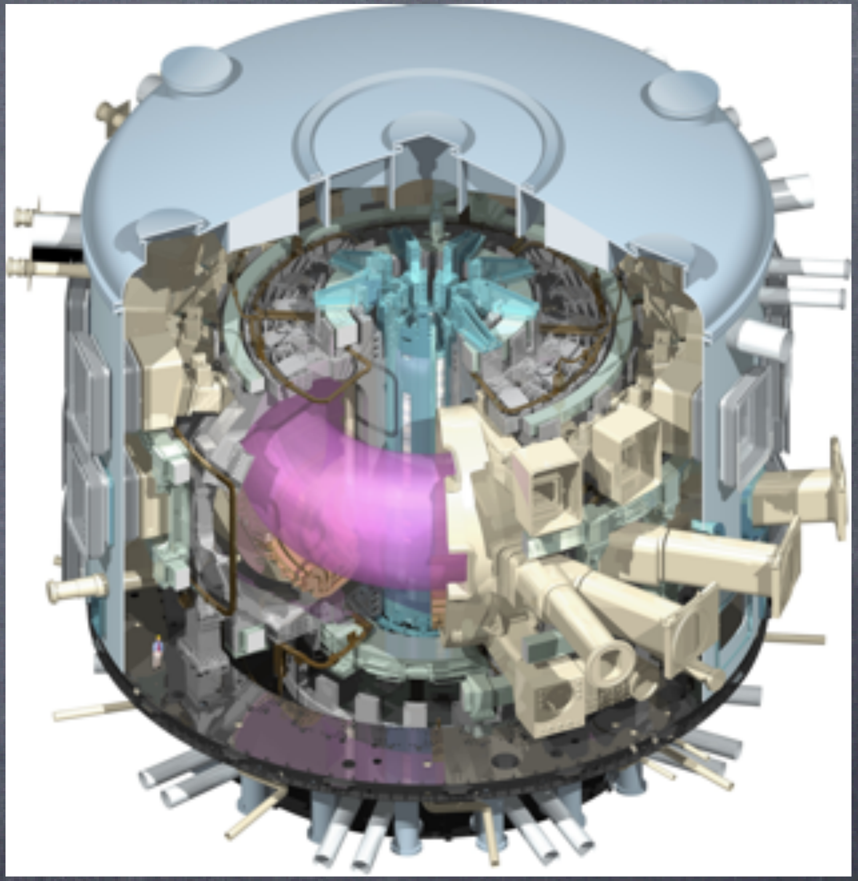


Turbulence Simulation

... but there can always be surprises...

International Thermonuclear Experimental Reactor

An Agreement to Construct ITER was Signed in 2006
China, Europe, India, Japan, Russia, South Korea, U.S.
over 1/2 of the world's population



- Europe pays 5/11 – spending 1/5 of this in Japanese industry (!).
- Europe pays for one-half of a set of additional fusion R&D facilities – located in Japan, valued at 16% of ITER.
- Each of the other six participants (including U.S.) pays 1/11.

ITER Construction is Underway

Aerial View

Tokamak Building

Coil Winding Facility

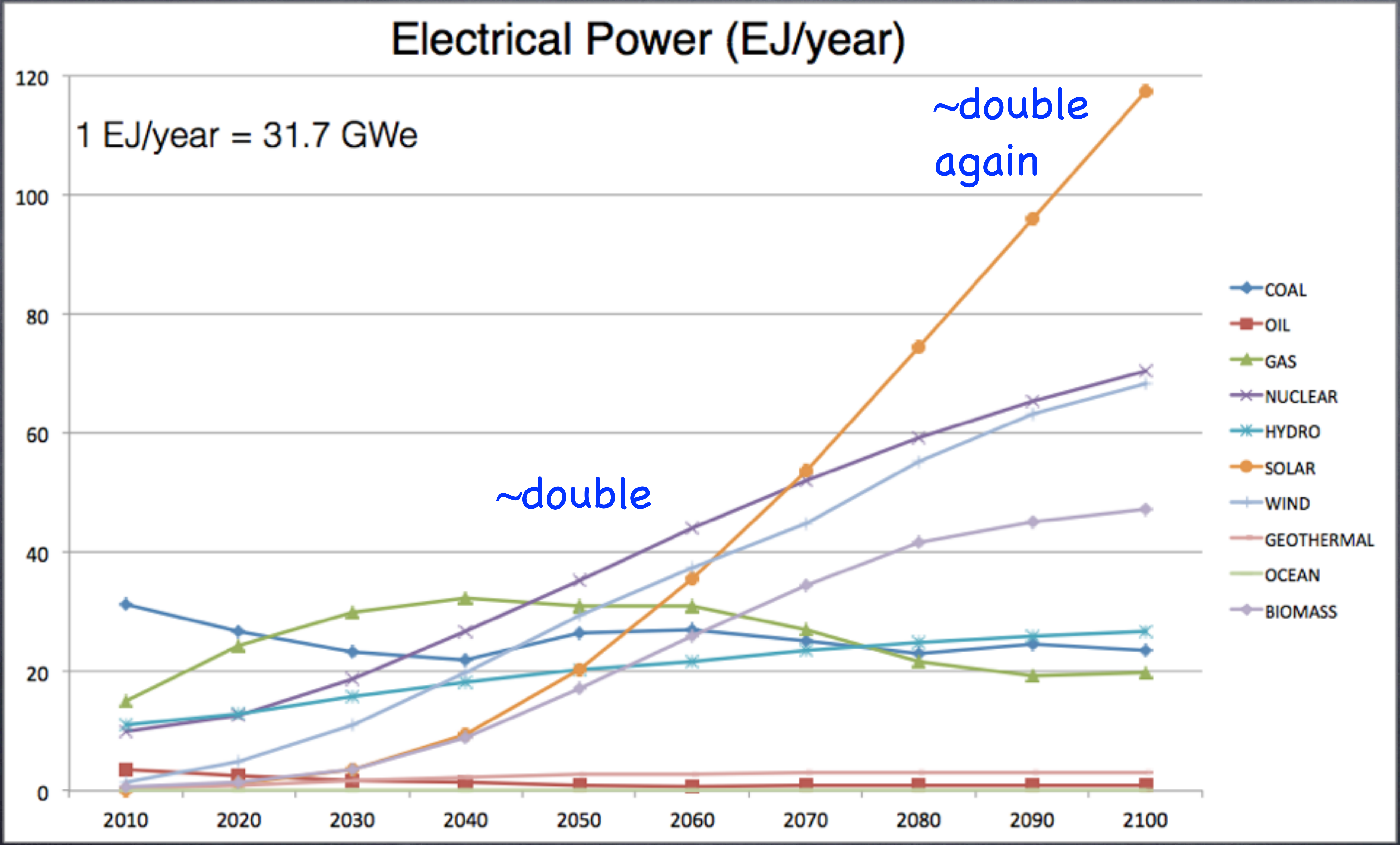
Assembly Hall, ITER STAC

Why Use Fusion for Energy?

- Worldwide, very long term availability of low cost fuel.
- Fusion does not have fission's key issues:
  - No possibility of prompt criticality or meltdown.
  - Short-lived radioactive waste.
  - Low risk of nuclear proliferation.
- Steady power source that can be located near markets. (c.f., wind, solar; order unity backup power or storage, at scale)
- Little land use (c.f., biomass competition with agriculture, at scale)
- No need to bury carbon dioxide (c.f., biomass, coal, gas require immense CO_2 storage, at scale)

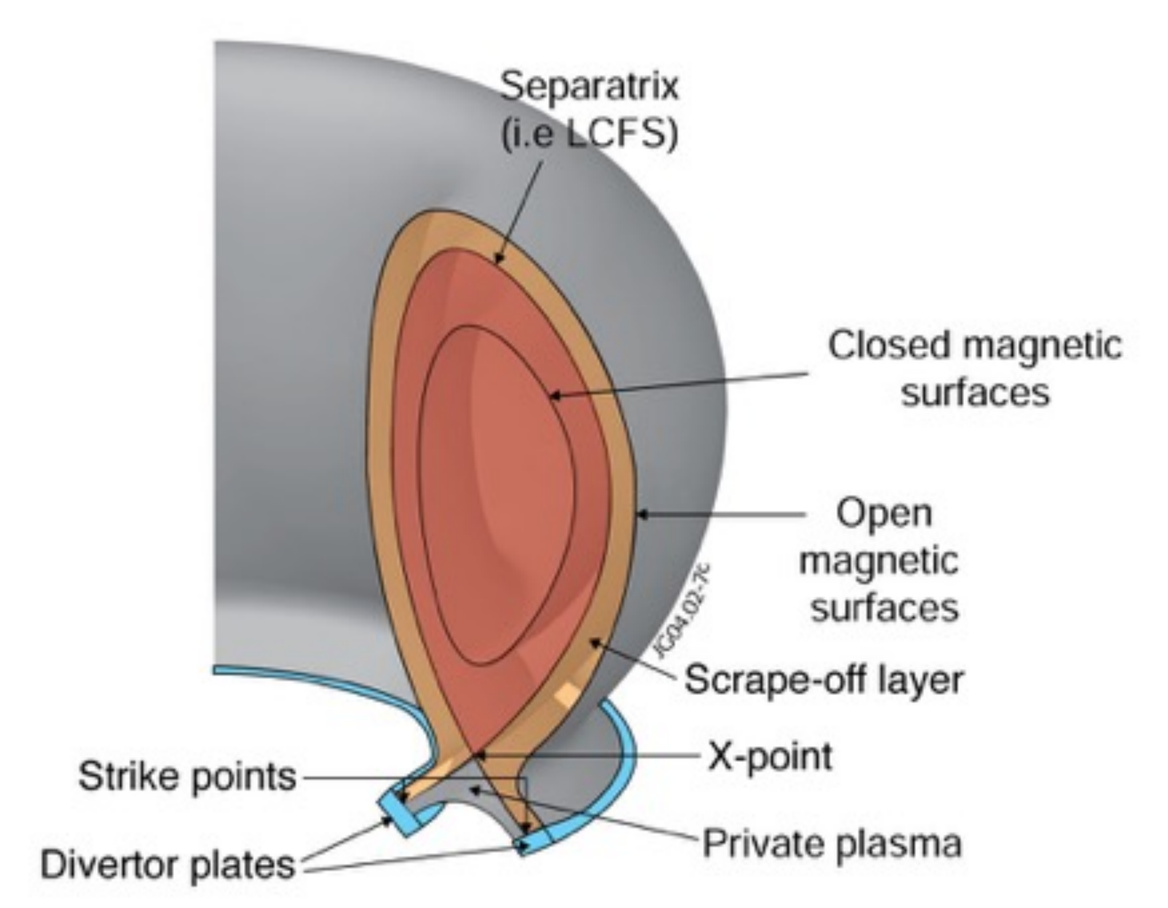
Cost?

Electricity Needs Double Twice by 2100



Science & Technology Challenges Remain

- A lot of progress has been made in:
  - Macroscopic stability
  - Energy confinement
  - Heating & current drive
  - But there is more to do.



- An area of opportunity:
  - High temperature superconducting magnets

- The biggest risks:
  - Power efflux
  - Materials and blanket