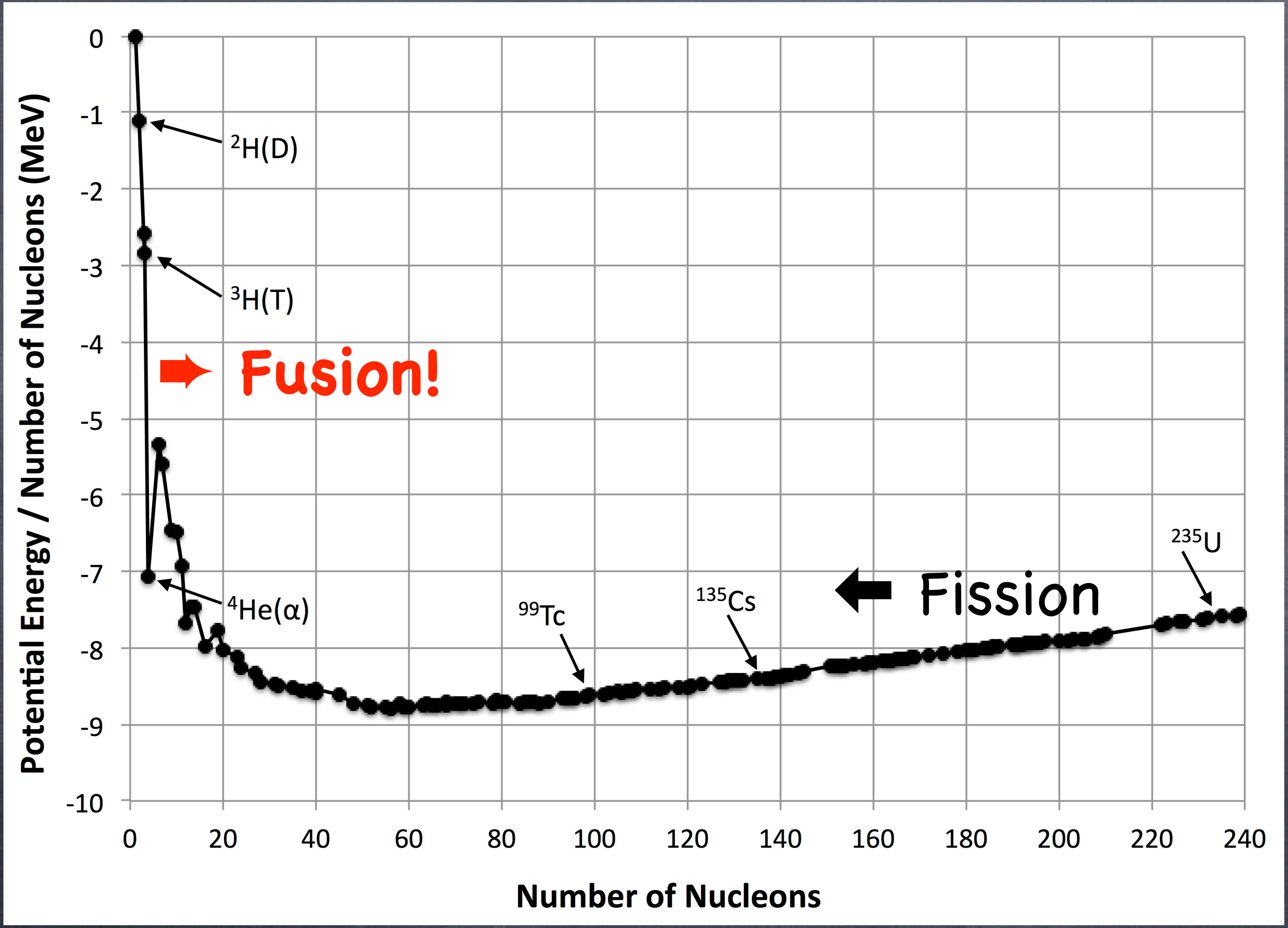
Introduction to Magnetic Fusion



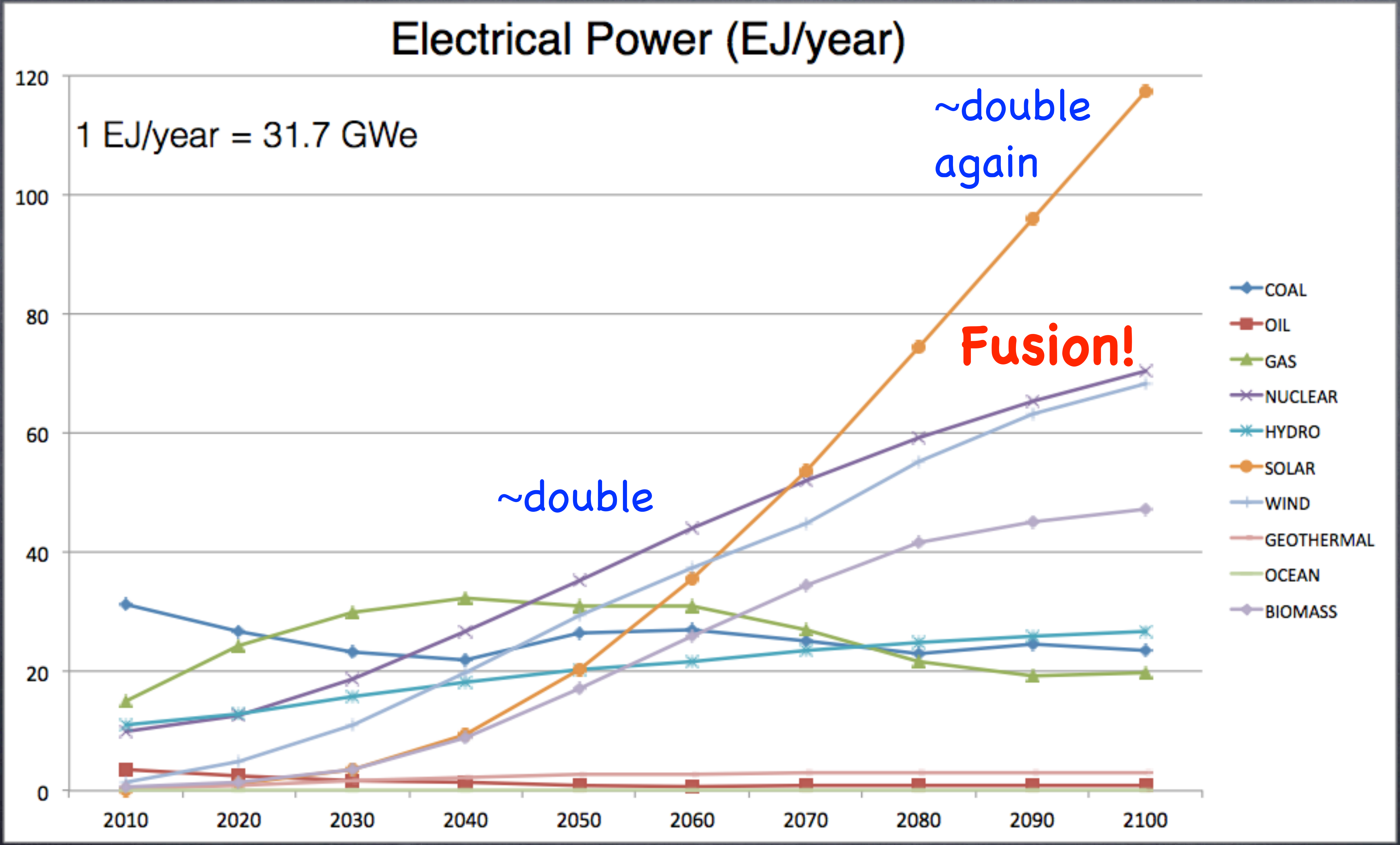
Potential energy in nucleus / # of nucleons

Why Use Fusion for Energy?

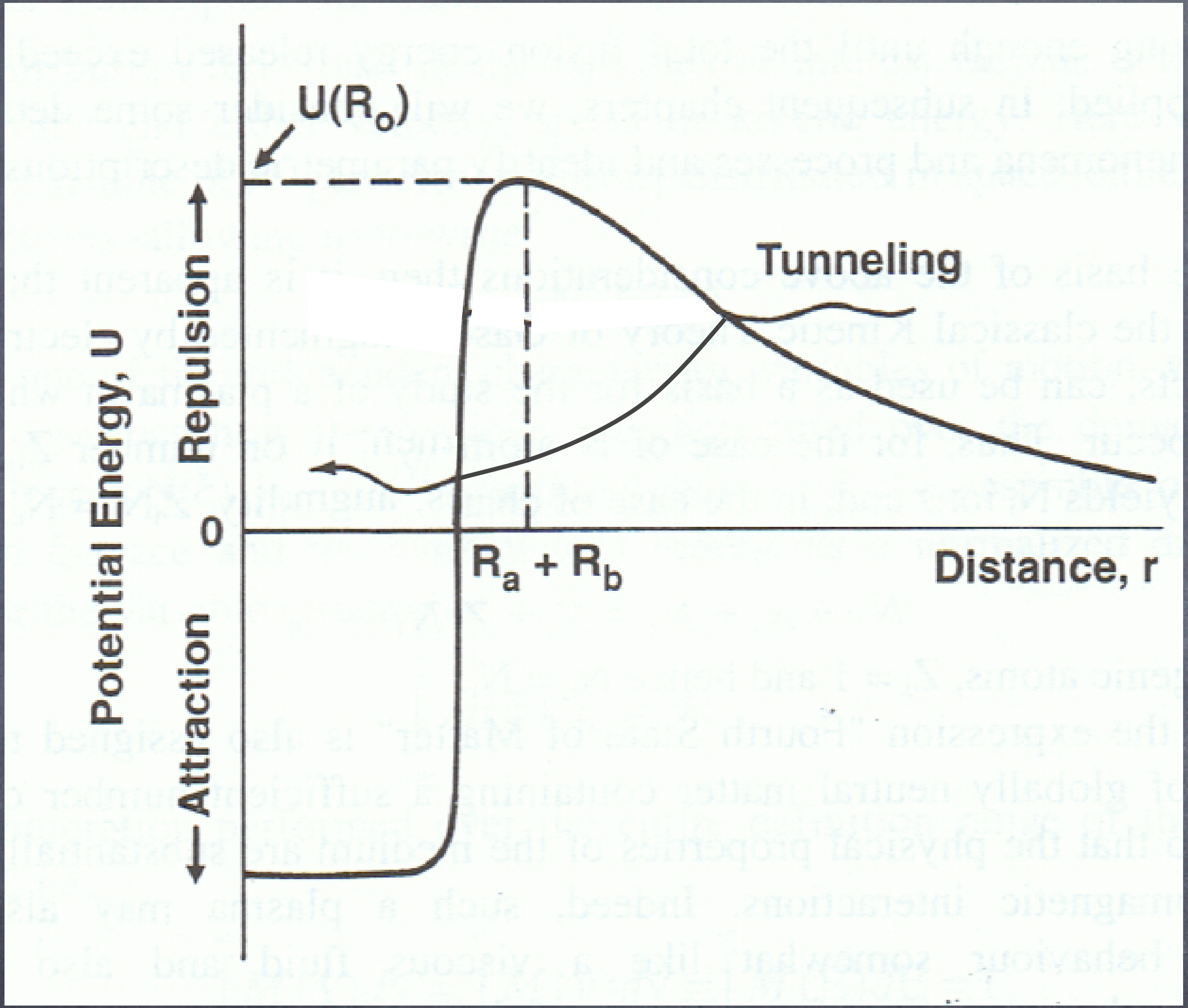
- Worldwide, very long term availability of low cost fuel.
- Negligible CO_2 production from operations.
- Fusion does not have fission's key issues:
  - No possibility of criticality accident or meltdown.
  - Short-lived radioactive waste.
  - Low risk of nuclear proliferation.
- Steady power source that does not require inter-seasonal energy storage (c.f., wind & solar at large scale)
- Little land use (c.f., biomass at large scale)
- No need to bury carbon dioxide
  (c.f., biomass, coal, gas require unprecedented CO_2 storage)

(See Goldston, Bulletin of Atomic Scientists 2018, Why Fusion?)

Electricity to Double Twice This Century



Fusion is by Quantum Tunneling



Electrostatic repulsion

Strong-force attraction

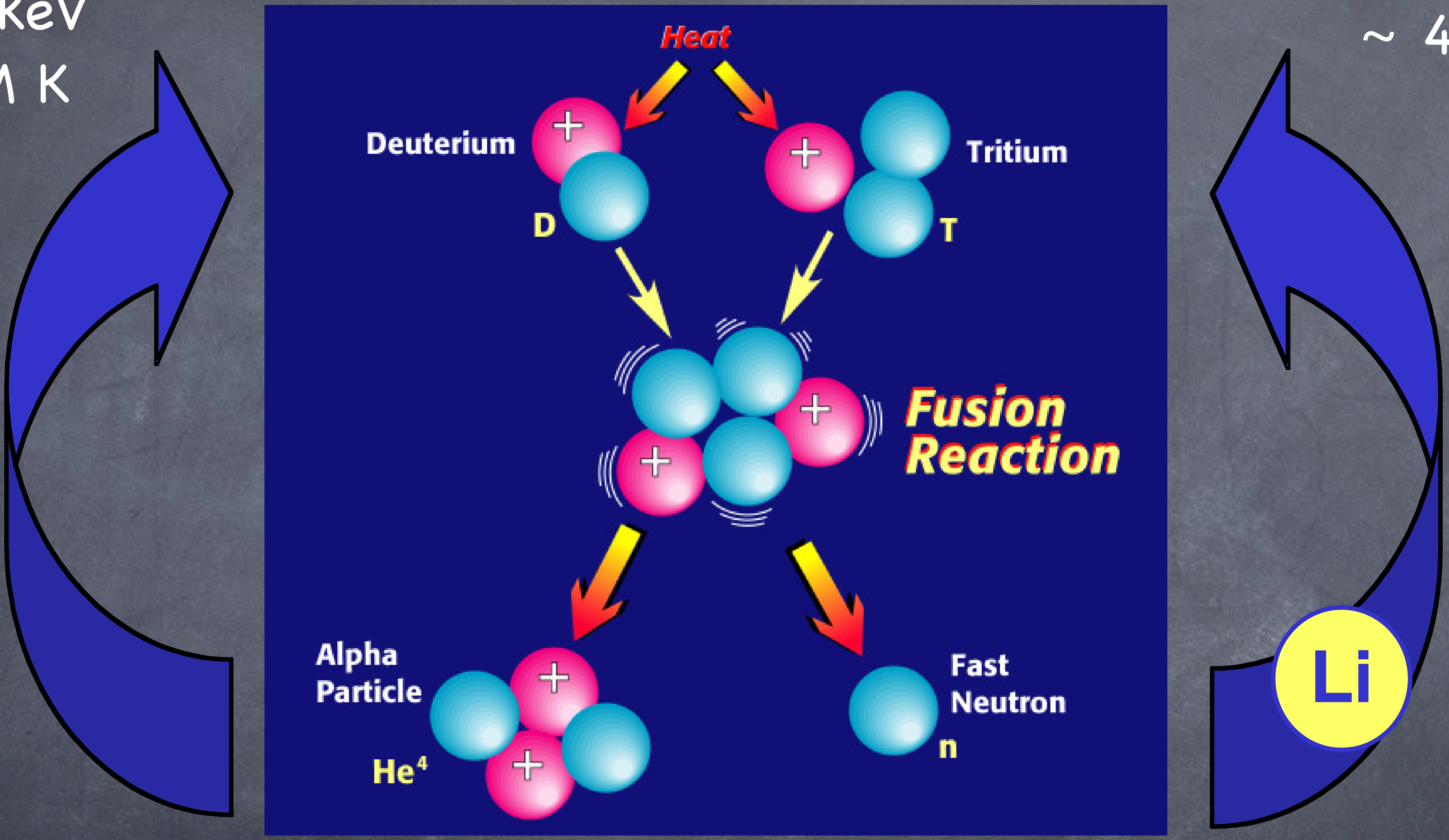
Low-Z nuclei fuse best.

They can get closer, and the barrier is weaker.

Two Cycles Sustain a Deuterium-Tritium Burn

T ~ 14 keV
~ 160M K

~ 400g/day



heat

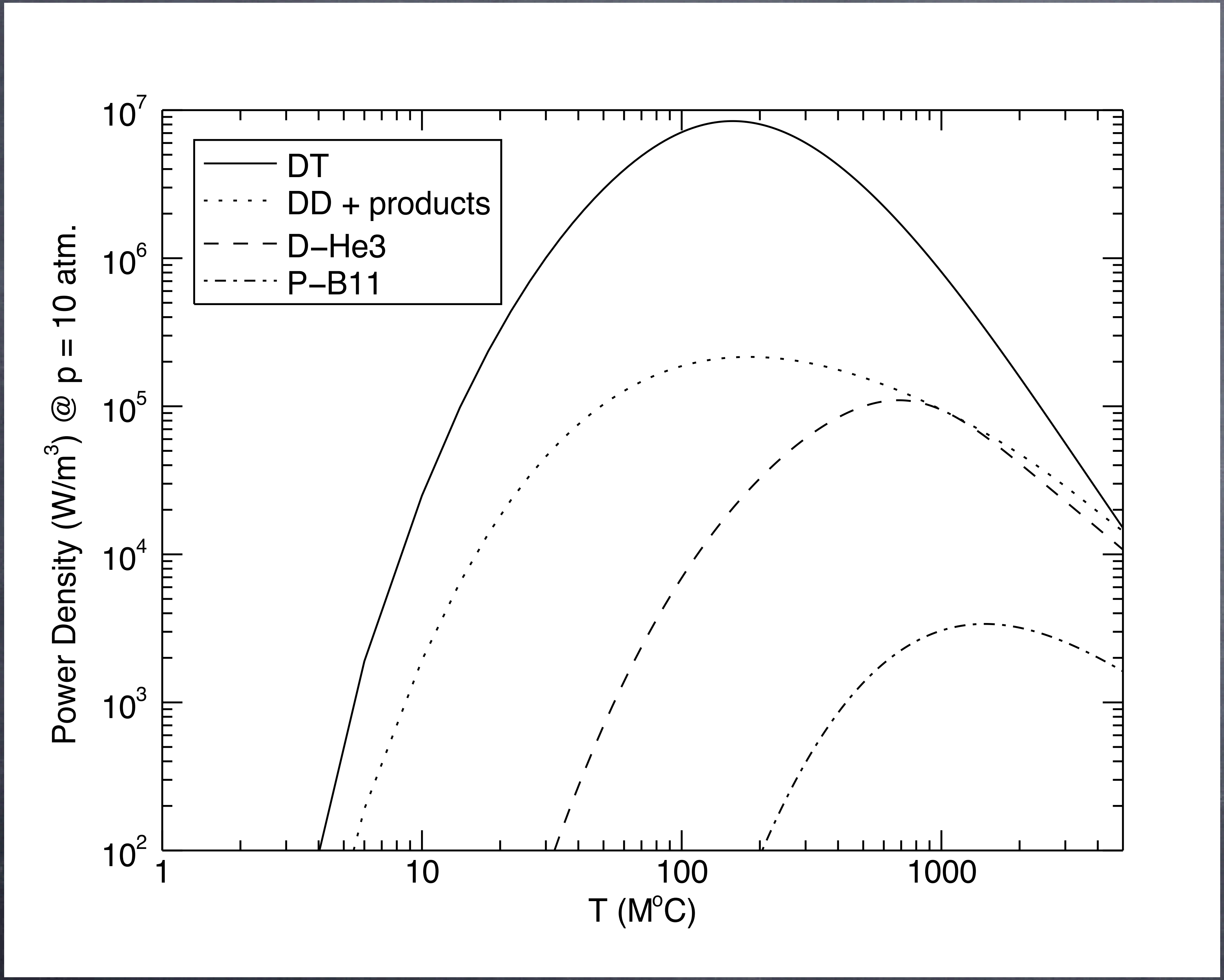
tritium

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

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

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

$$\text{Confinement time} \equiv \frac{\text{Energy density}}{\text{Power density}}$$

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

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

A Fusion Plasma Must be Very, Very Nearly Charge Neutral

- You need about $10^{20}/m^3$ ion density to get a useful power density. $e = 1.602\ 10^{-19}C$
- If no electrons, this is a charge density, $\rho = 16\ C/m^3$.
- $\vec{\nabla}\cdot\vec{E} = \rho/\varepsilon_0$; For a sphere, Gauss ⇒ $4\pi r^2 E_r = (4\pi/3) r^3 \rho/\varepsilon_0$
- $E_r = r16/(3\text{x}8.85\ 10^{-12}) = 6\ 10^{11}$V/m (for r = 1m)
- Cannot support macroscopic charge imbalance!

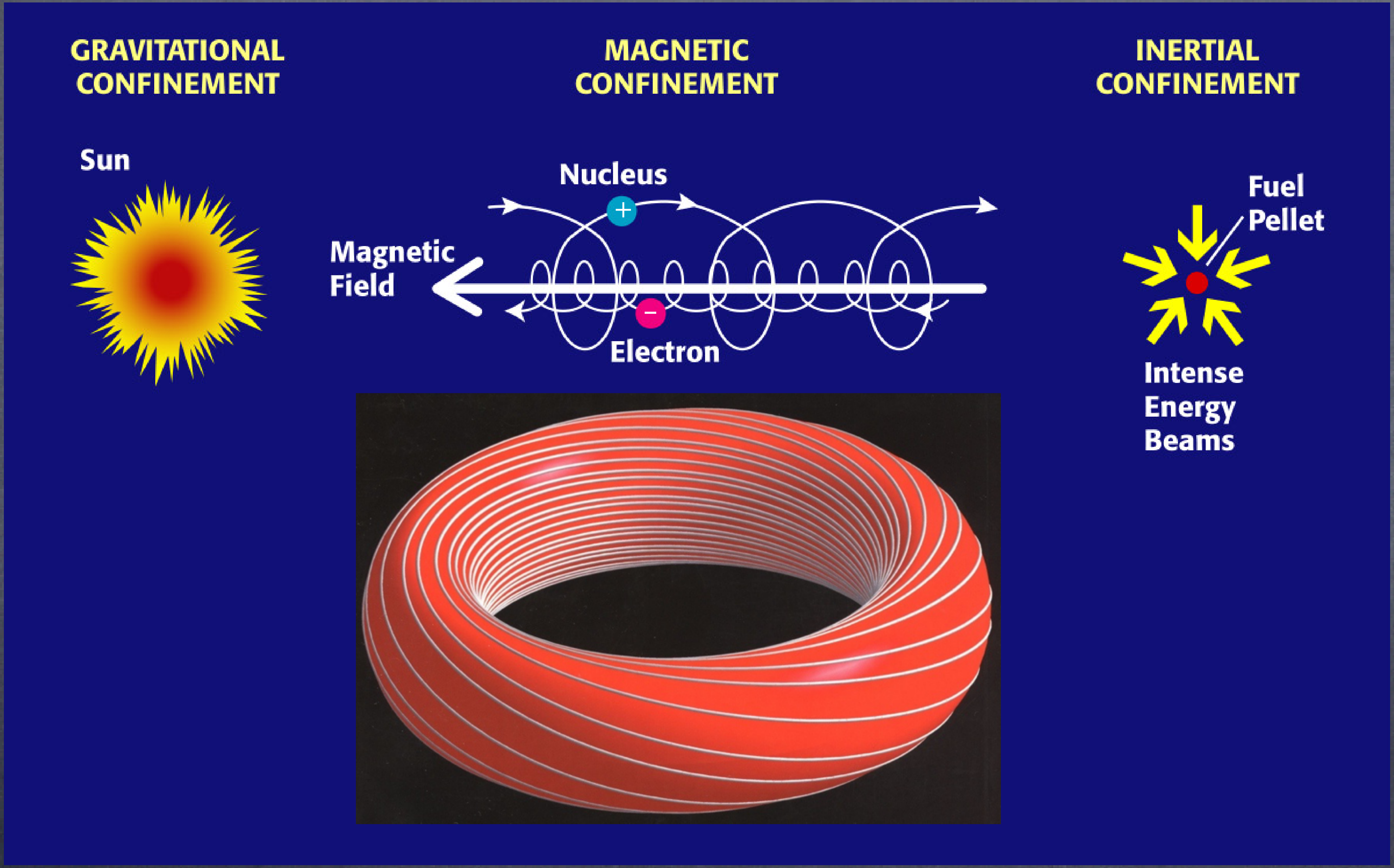
$$n_e = \sum_i n_i Z_i = n_D + n_T + \sum_{imp} n_j Z_j$$

$$Z_{eff} \equiv \frac{1}{n_e} \sum_i n_i Z_i^2$$

- Impurities (including He fusion product) waste plasma pressure on themselves and on Z_j electrons.

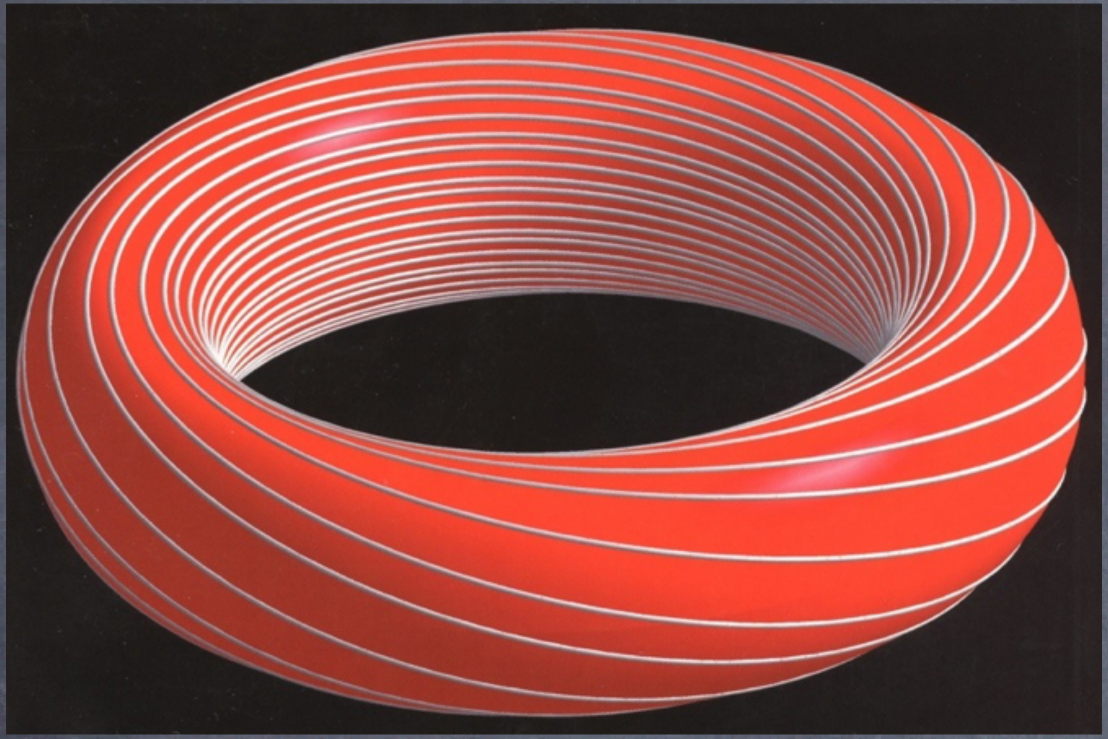
Fusion Fuel can be Confined Three Ways

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



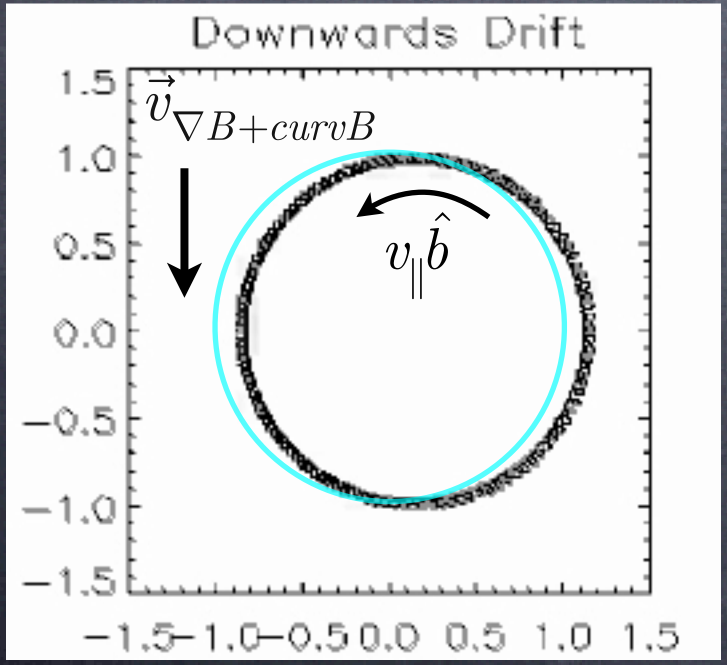
We focus in this lecture on magnetic confinement.

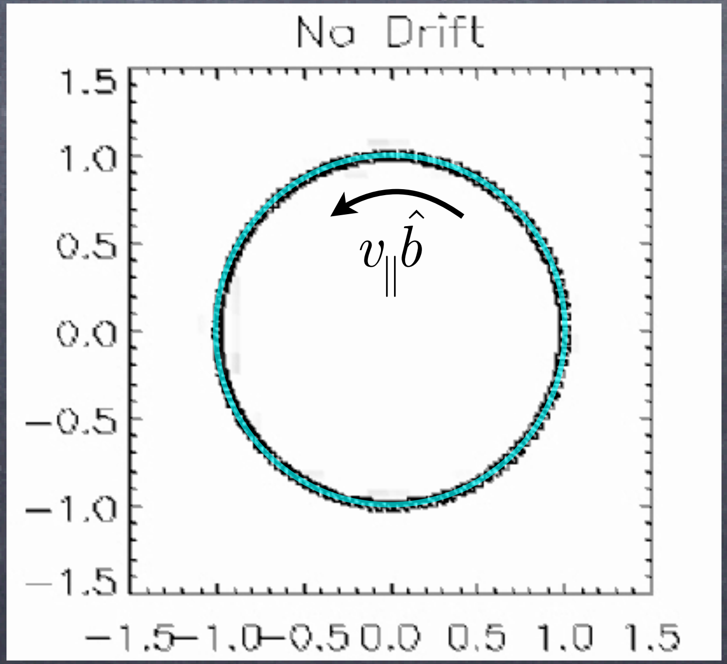
Toroidal Plasmas Need Twist

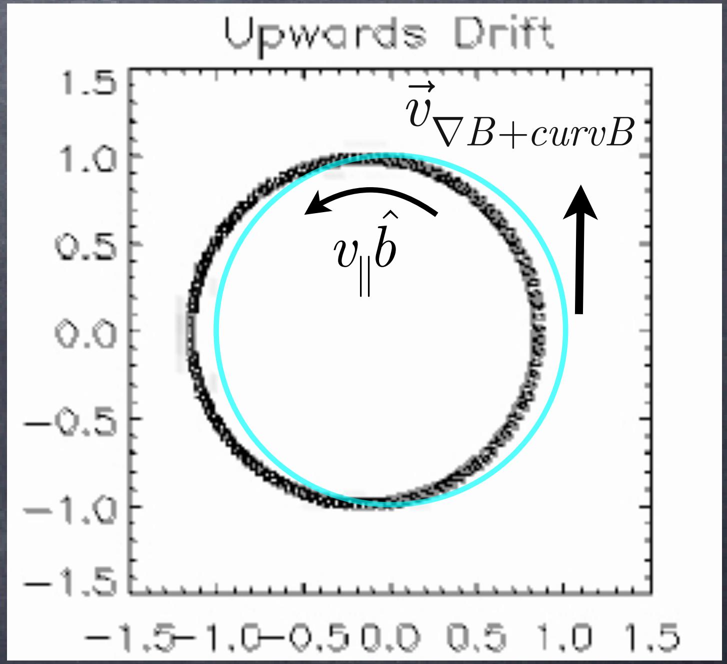


Particles follow field lines but also drift vertically.

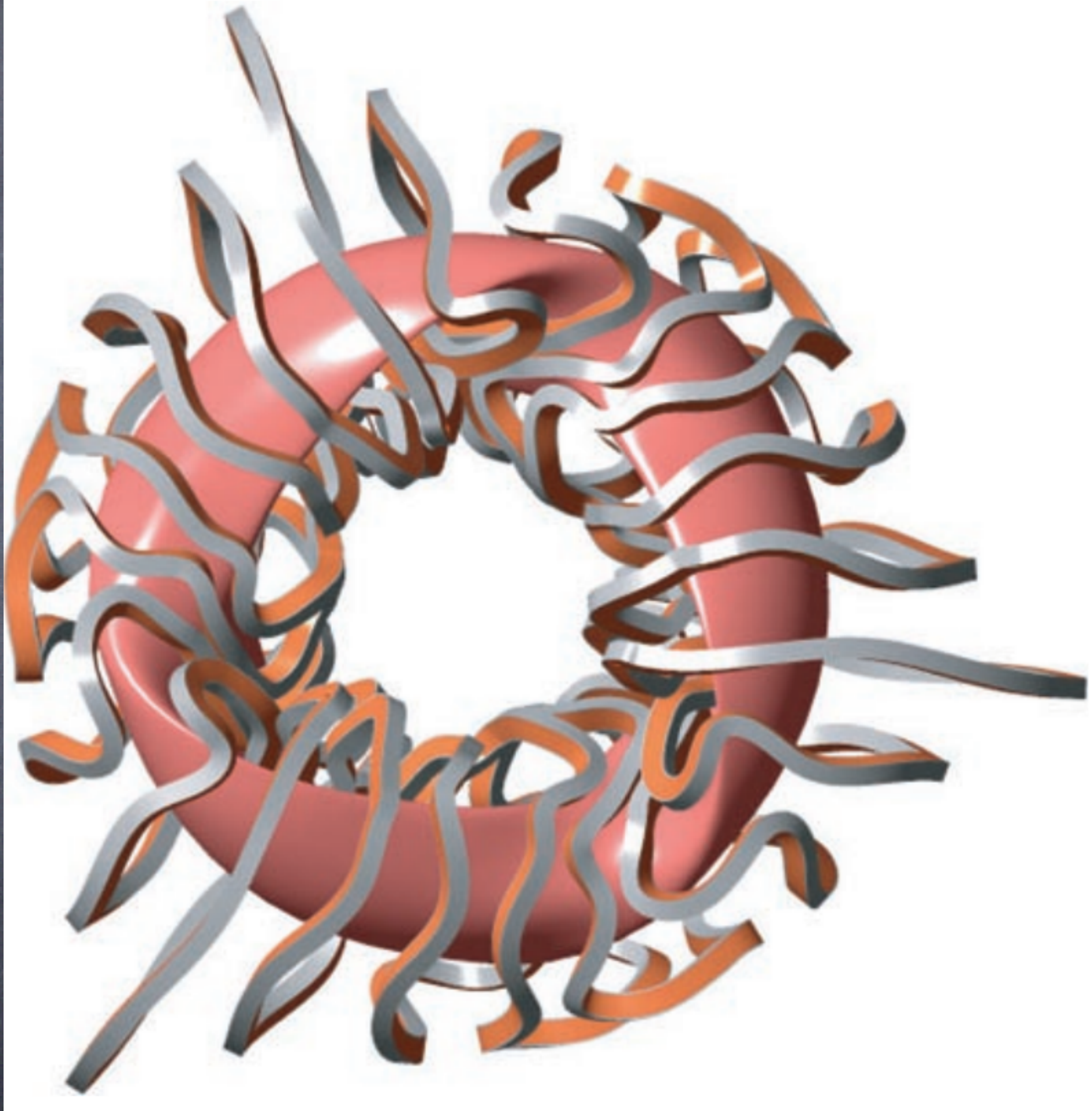
Twisting the field lines cancels drifts.





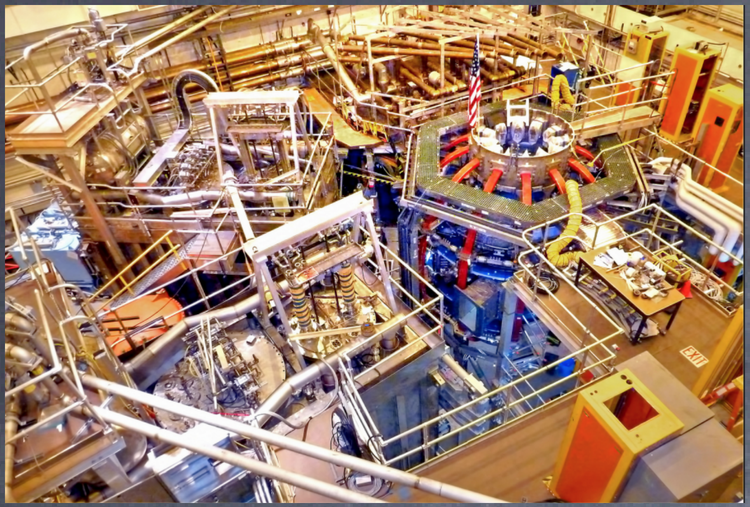


Stellarators Get Twist Differently

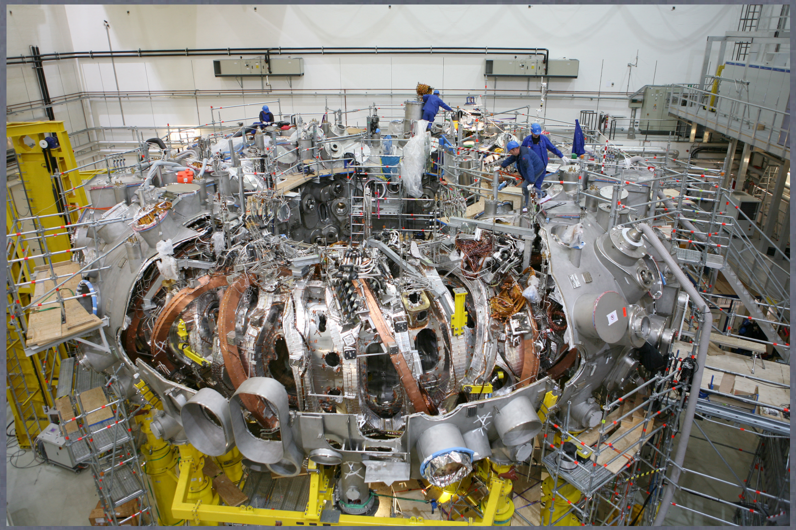


The twisting plasma “pulls” the field lines with it.

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

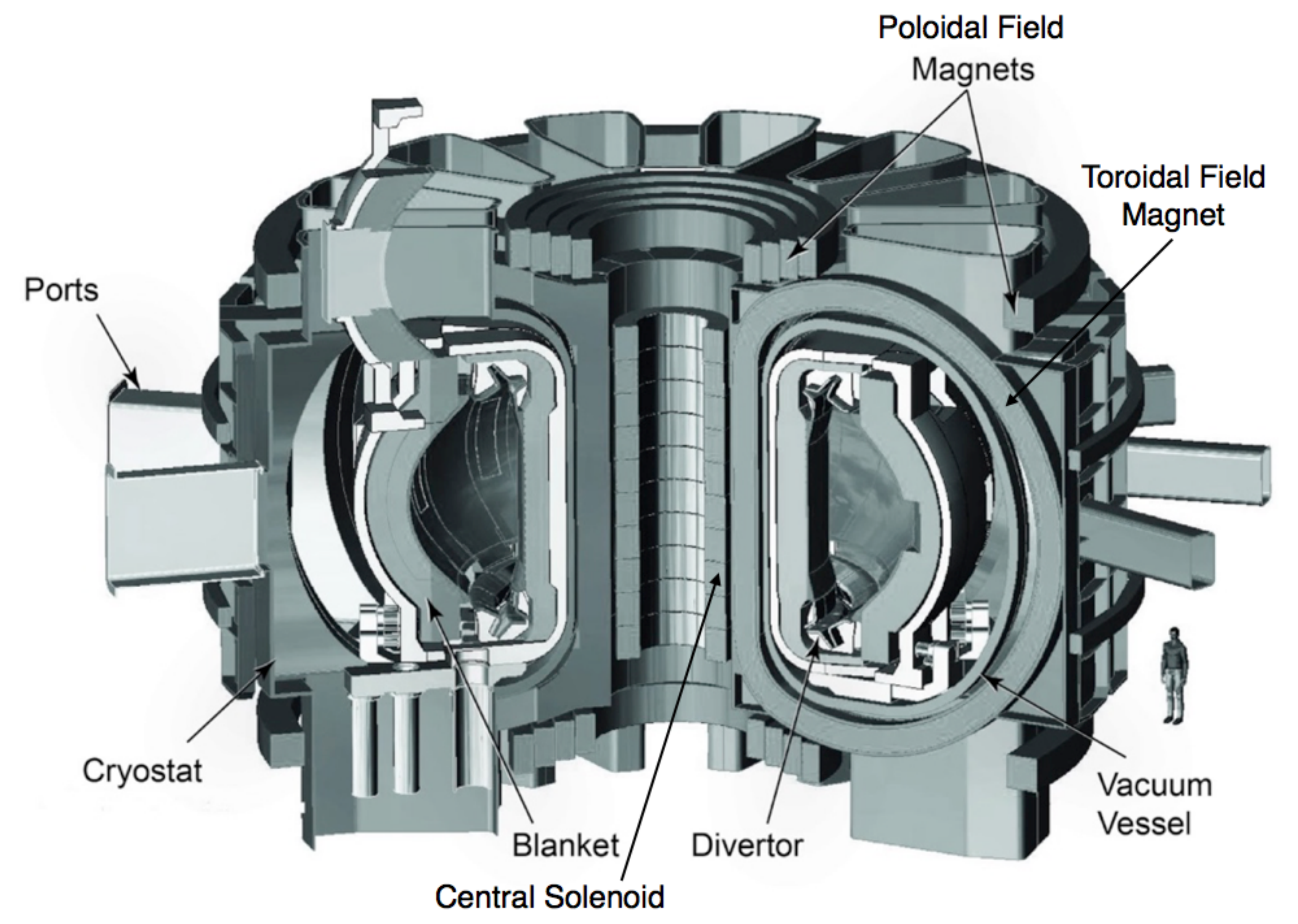

China: *EAST*
superconducting tokamak


Korea: KSTAR
superconducting tokamak


Japan: JT-60SA
large superconducting tokamak

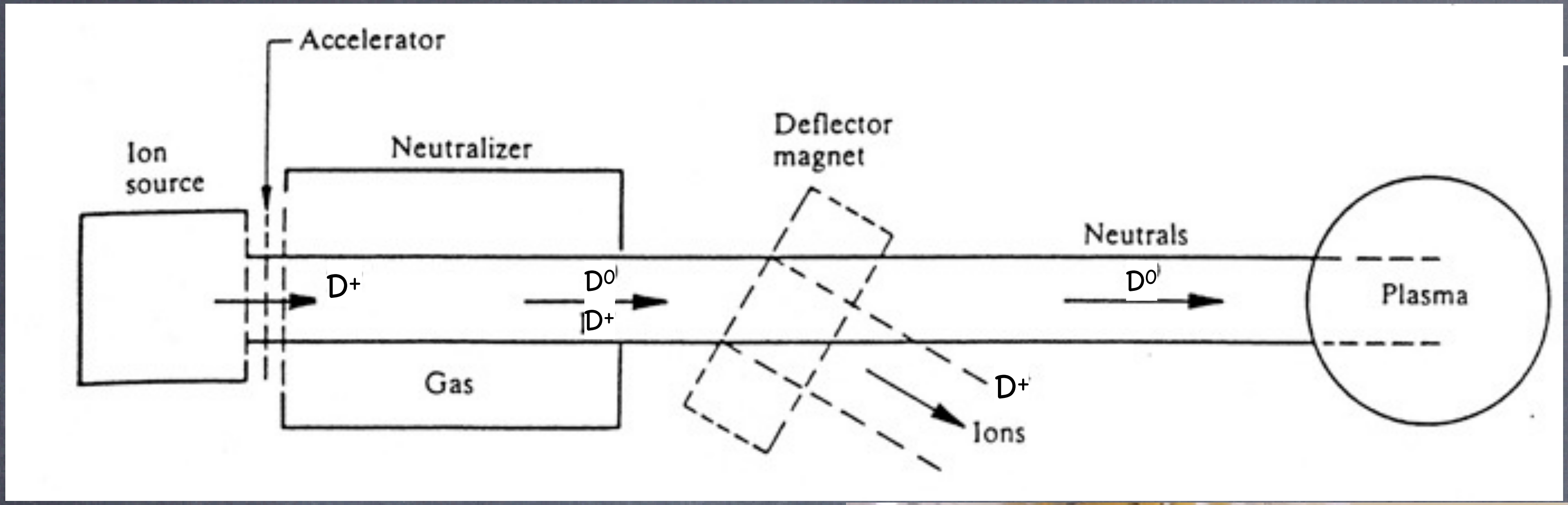
Next Up: ITER

Concept for a Tokamak Fusion Pilot Plant



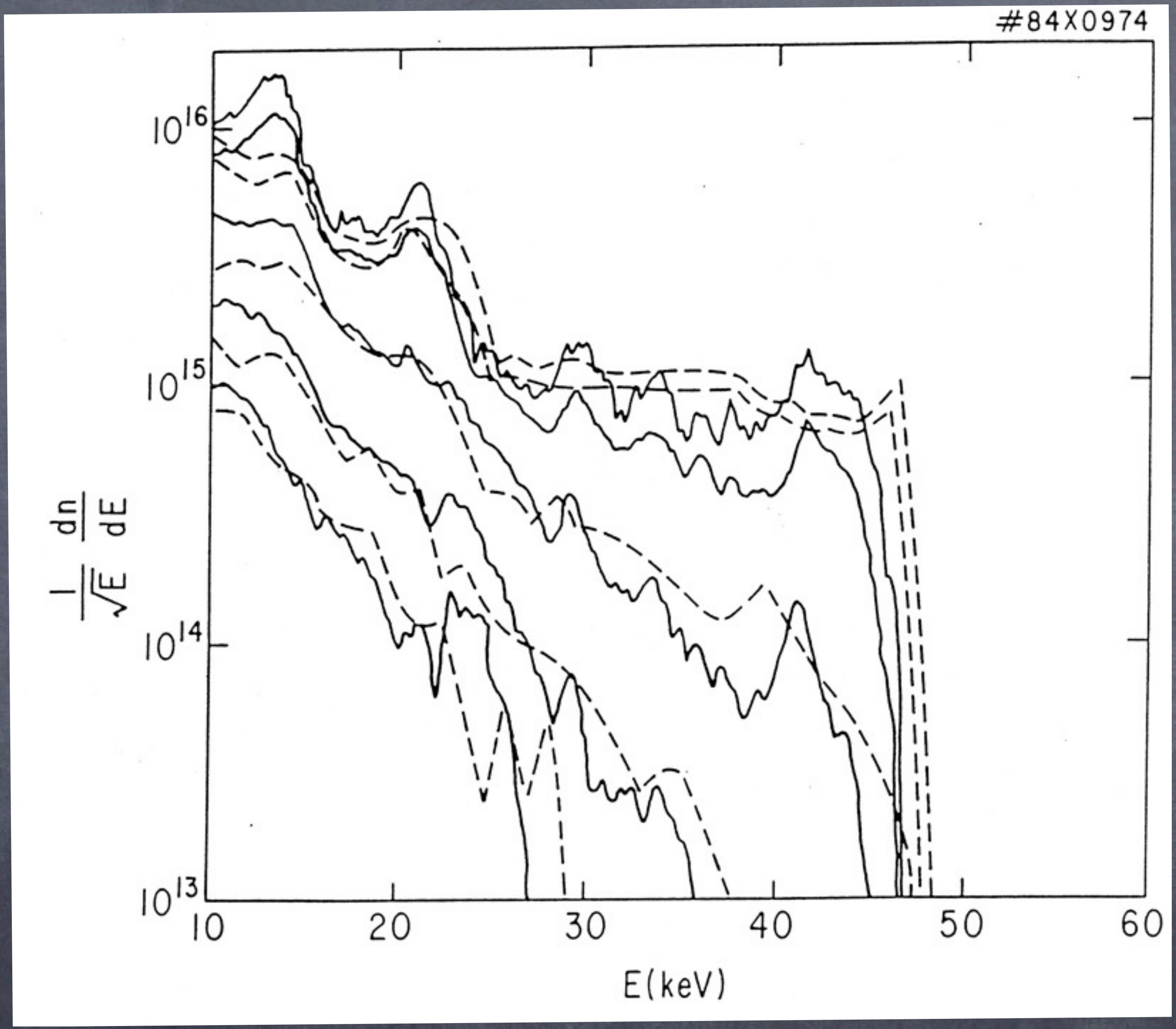
Gets magnetic twist with plasma current

Positive-ion Based Neutral Atom Beams is a Well Developed Technology



Up to 40 MW was delivered to TFTR at PPPL

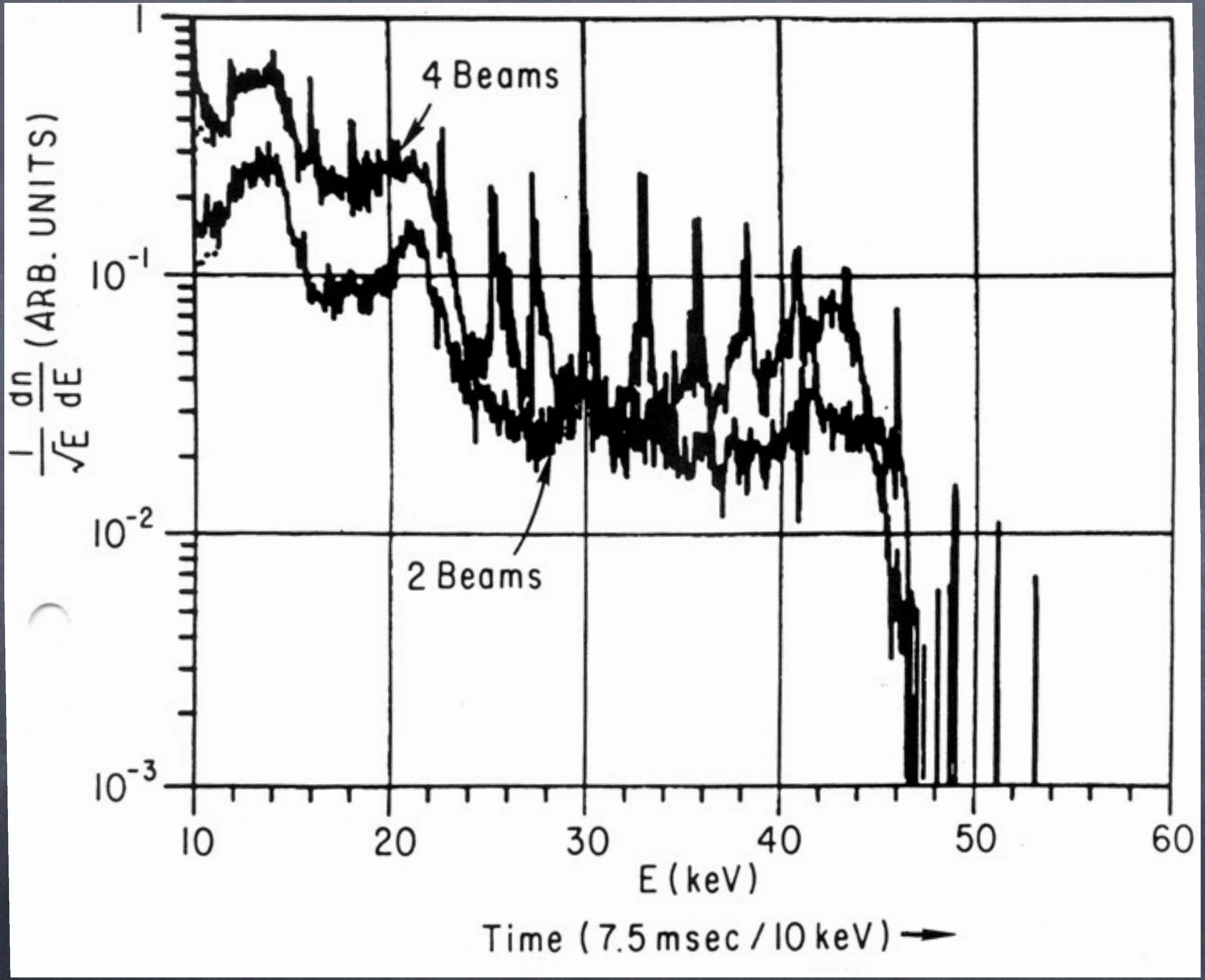
When Fast Ion Pressure is Modest Ions Slow Down by Binary Collisions with Plasma



------ Theory
—— Exp't

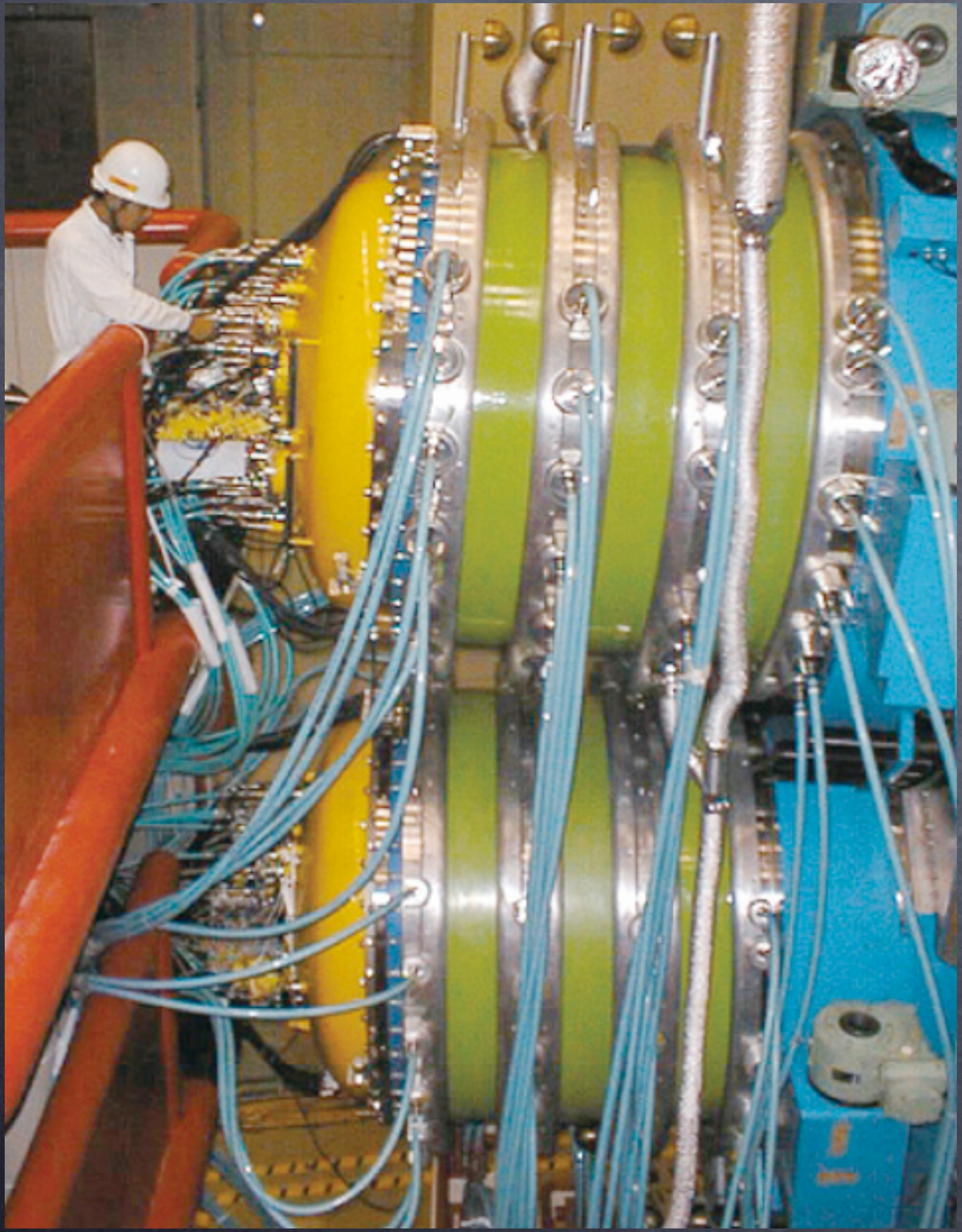
Both the energy and angular dependence of the measured spectra agree with theory

Things Get More Interesting at High Fast Ion Pressure



ITER will study fast ion effects with 3.5 MeV α's

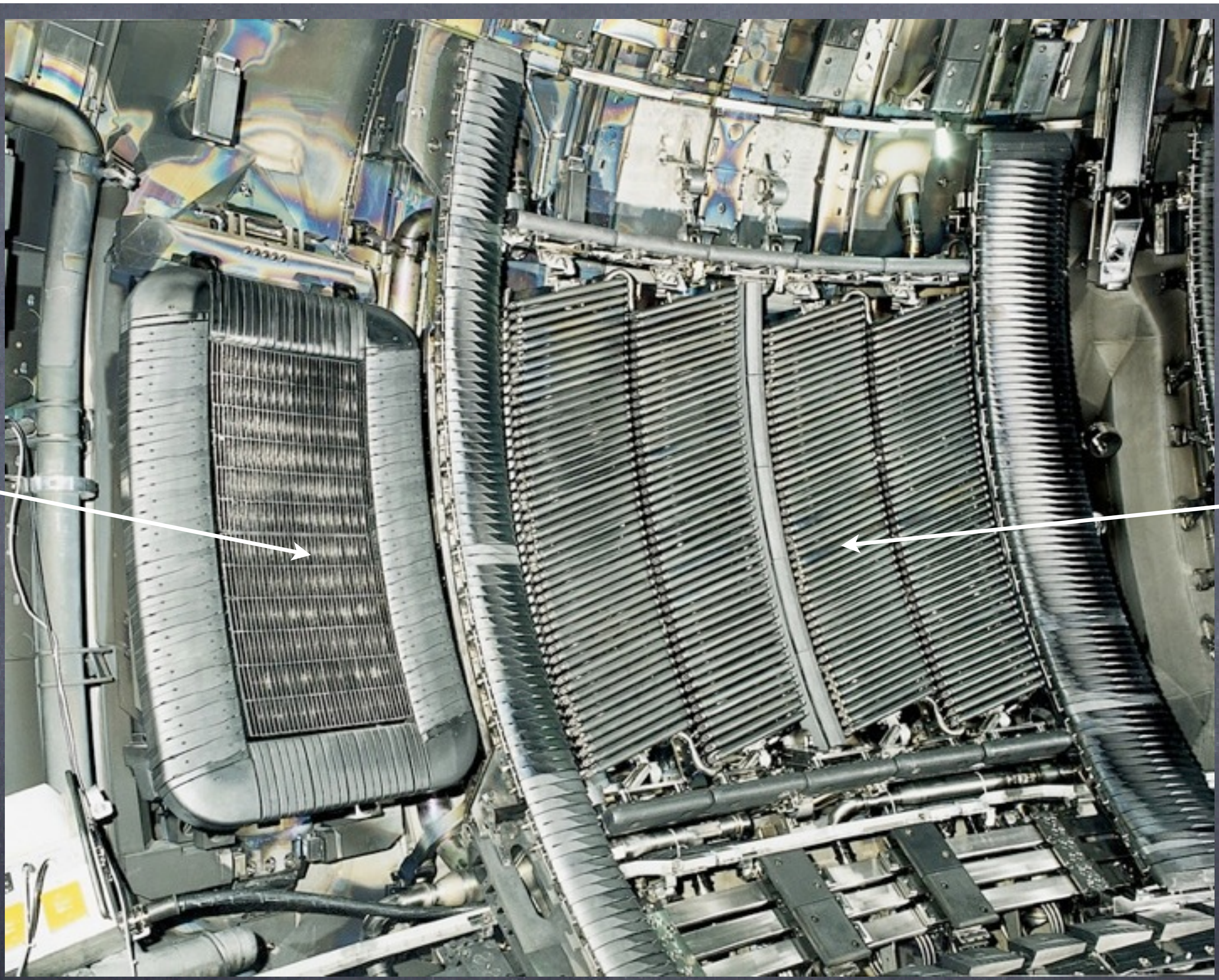
Negative-Ion Based Neutral Beams are a Challenging Technology



- Larger denser plasmas need higher energy beams for adequate penetration
- Higher energy D^+ beams don't charge-exchange well b/c velocity too high
- Make D^- beams, and strip them of their extra electron
- Very tricky new technology

Lower Hybrid and Ion Cyclotron Frequency Antennas in JET

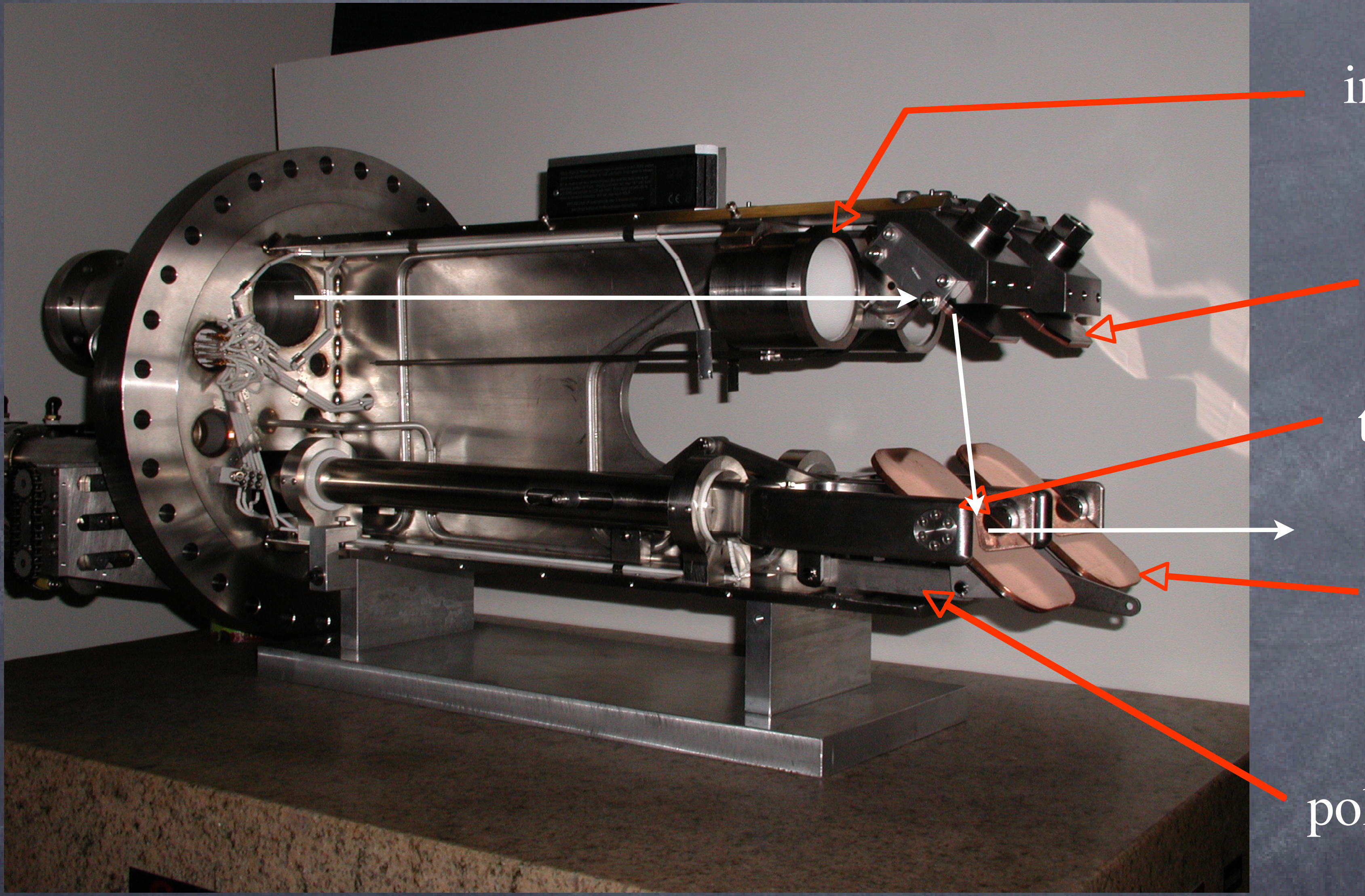
Lower Hybrid
3.5 GHz
(Drives current, hard to couple)



Ion Cyclotron
30MHz
(Cheapest, hard to couple)

- Neither wave propagates in vacuum with impressed k
- Antenna near field must be in contact with plasma

Electron Cyclotron Antenna Manufactured by PPPL



input waveguide holder

fixed mirror

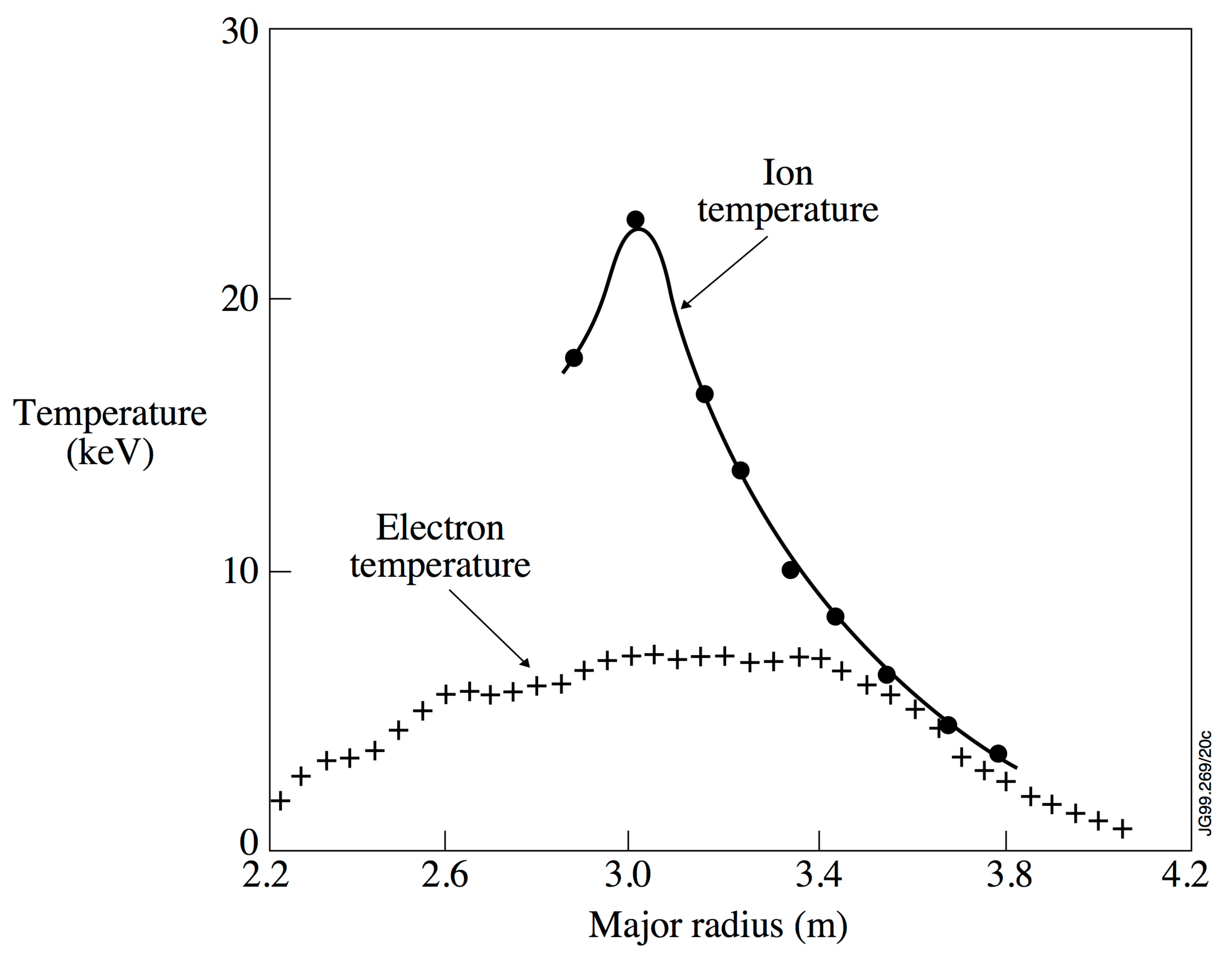
toroidal steering fork

steerable mirror

poloidal push mechanism

- Steerable waves propagate in vacuum to plasma
- Very high frequency sources are coming along well.

Fusion Temperatures have Been Achieved



Joint European Torus

Fusion Power Density Depends on $\langle\sigma v\rangle/T^2$, β and B

Fusion power density, $p_{fus} = n_D n_T \langle\sigma v\rangle_{DT} E_{fus}$ (Watts/m^3)

Magnetically confined plasmas are generally limited in

$\beta \equiv$ plasma pressure / magnetic pressure

$\beta \equiv (n_i + n_e)T/(B^2/2\mu_0) \Rightarrow$ for $n_i \propto n_e$, & $n_D \approx n_T \approx n_i/2$

$$p_{fus} \propto n_D n_T \langle\sigma v\rangle_{DT} \propto \beta^2 B^4 (\langle\sigma v\rangle_{DT}/T^2)$$

p_{fus} is a key bang-for-the-buck parameter.

Implications:

- There is a lot to be said for high β
- There is a drive for high-field magnets
- Operate at the T that maximizes $\langle\sigma v\rangle_{DT}/T^2$
- You also have to worry about fusion energy gain.

Plasma Energy Gain is Set By Balance Between Heating and Losses

- Local power 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

- α heating is in the core and only core radiation short-circuits magnetic confinement of heat.
- Here we assume 100% efficiency of α particle heating. ITER will test this!
- When we come to plant efficiency, we will need to include the efficiency of producing p_{aux}.

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

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

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

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

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

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

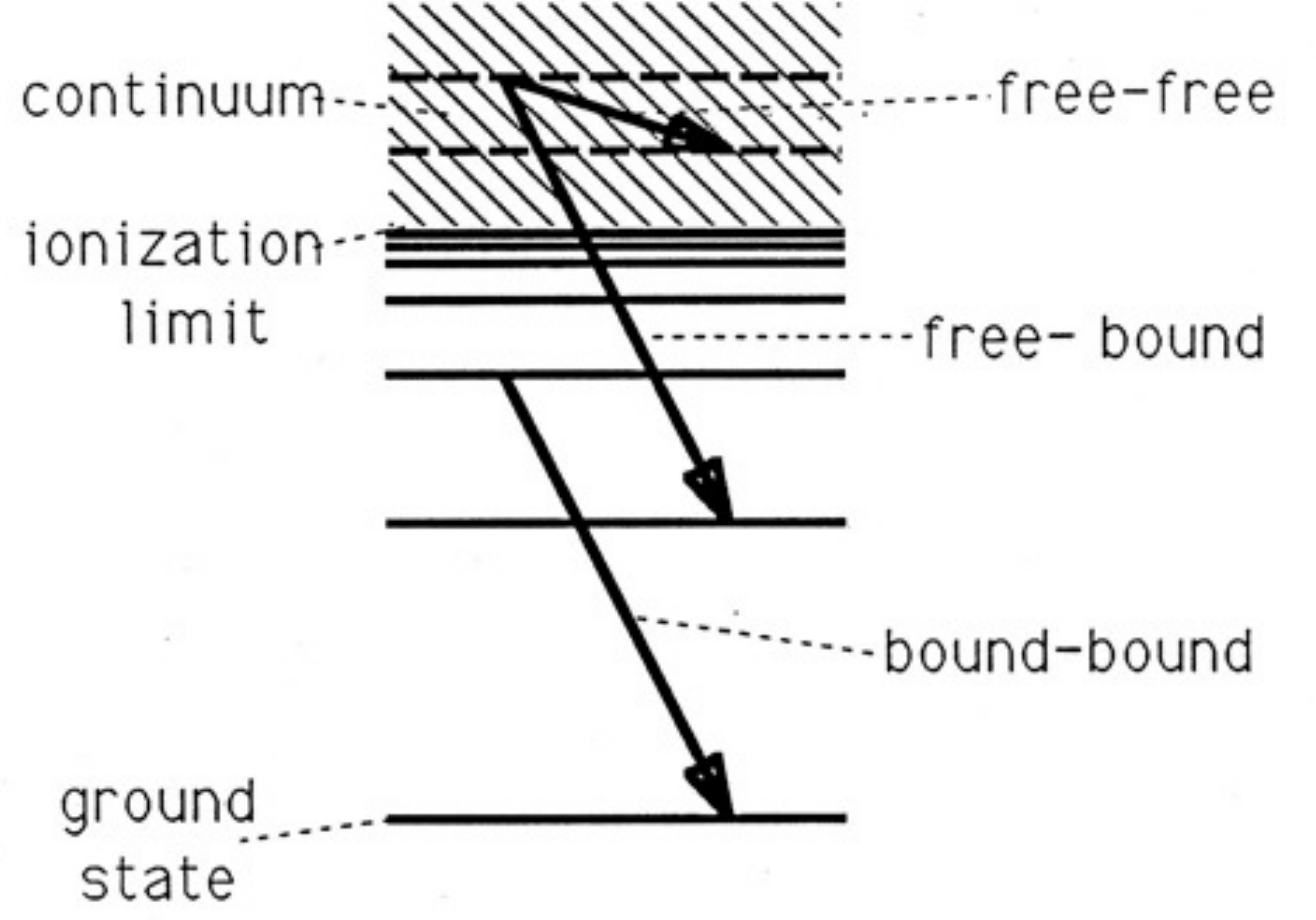
Fusion "triple product"

Looking at the whole plasma:

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

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

P_{rad} Comes in Many Forms
Core P_{rad} Short-Circuits Magnetic Confinement



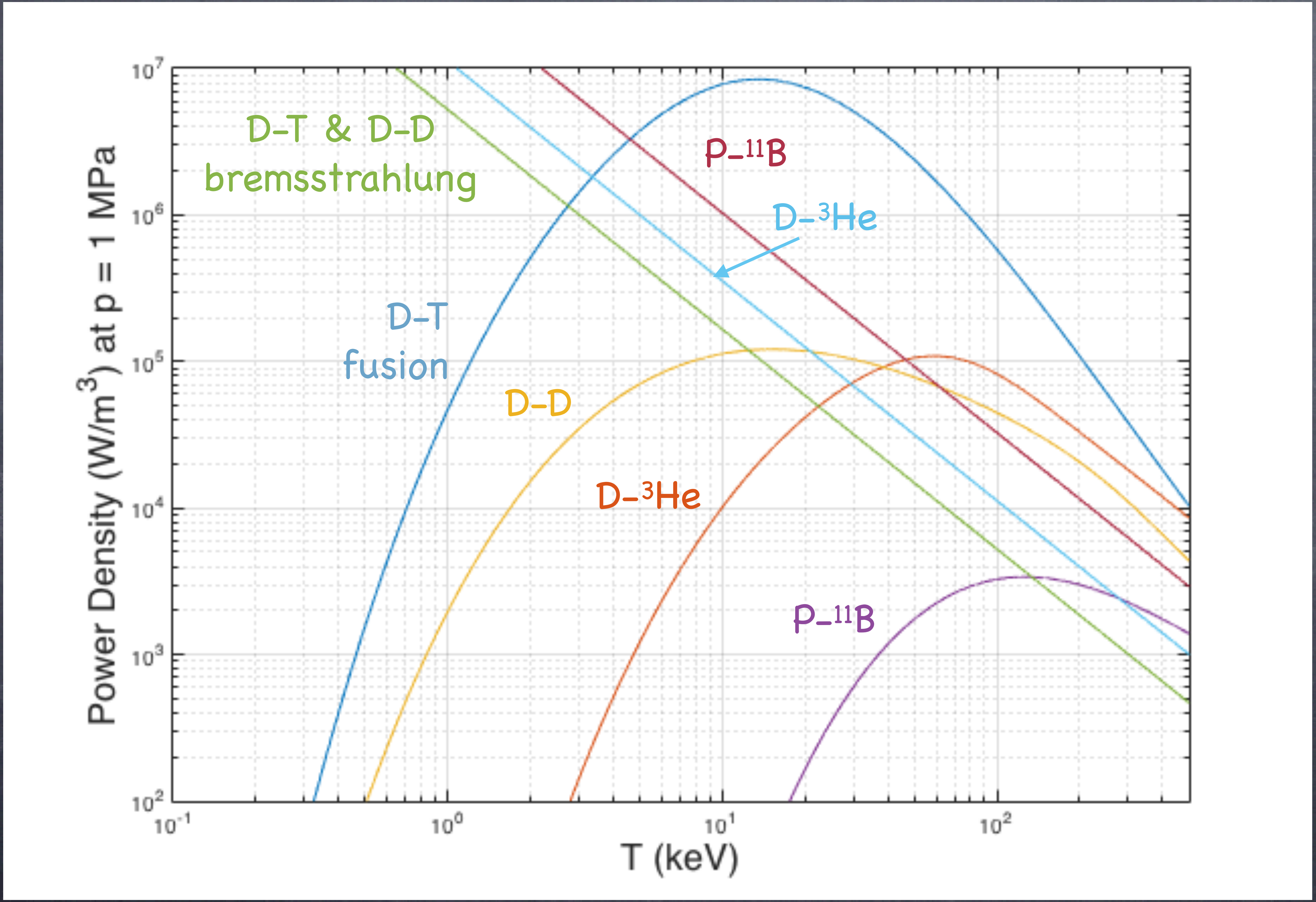
Continuum Bremsstrahlung

Continuum Recombination

Line radiation

At fusion temperatures bremsstrahlung dominates.

Bremsstrahlung can be a Significant Factor



All power densities scale as p^2: $n^2 \propto p^2$ for given T.

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

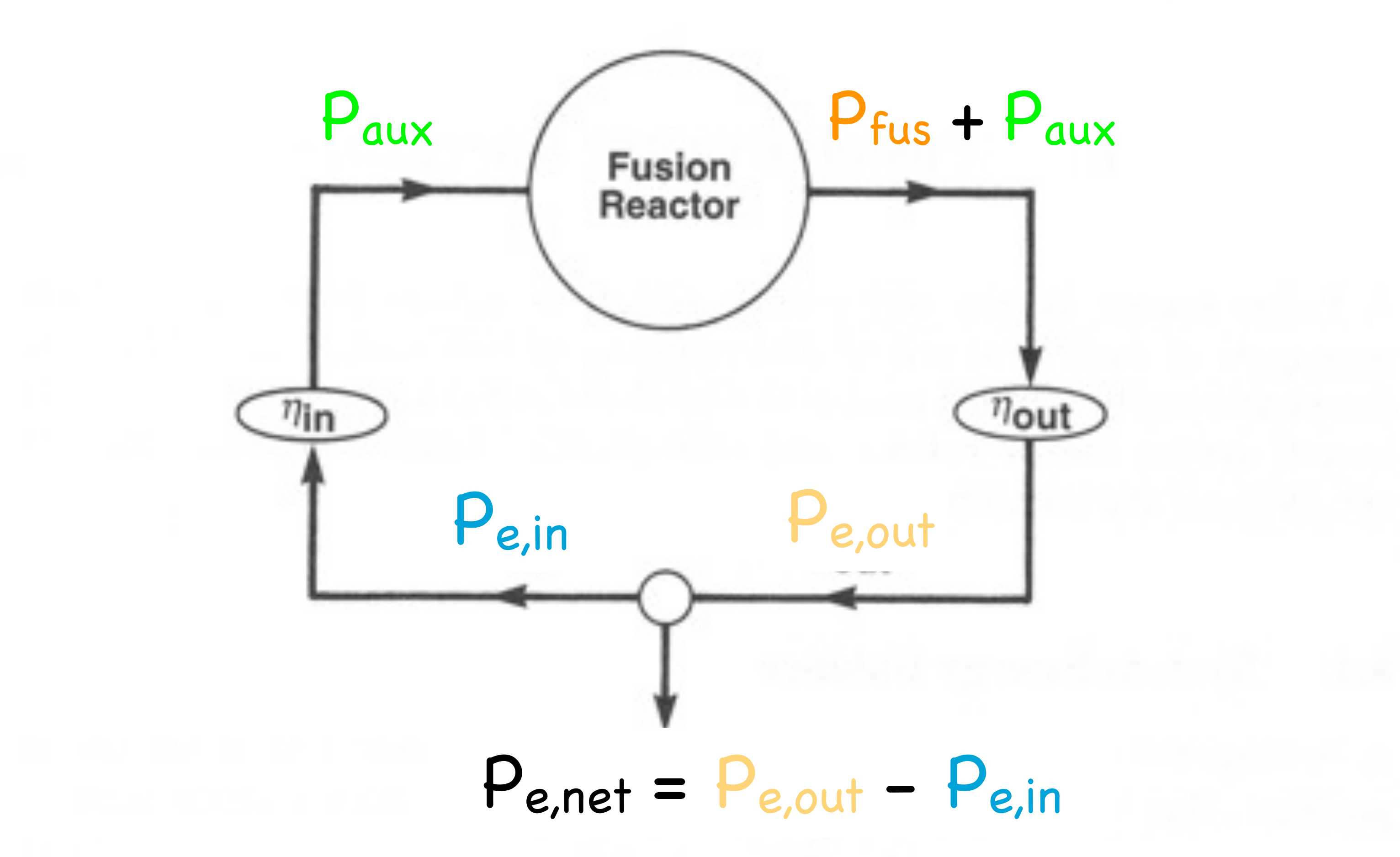


Fig. 8.1: Depiction of energy components associated with a general fusion power plant.

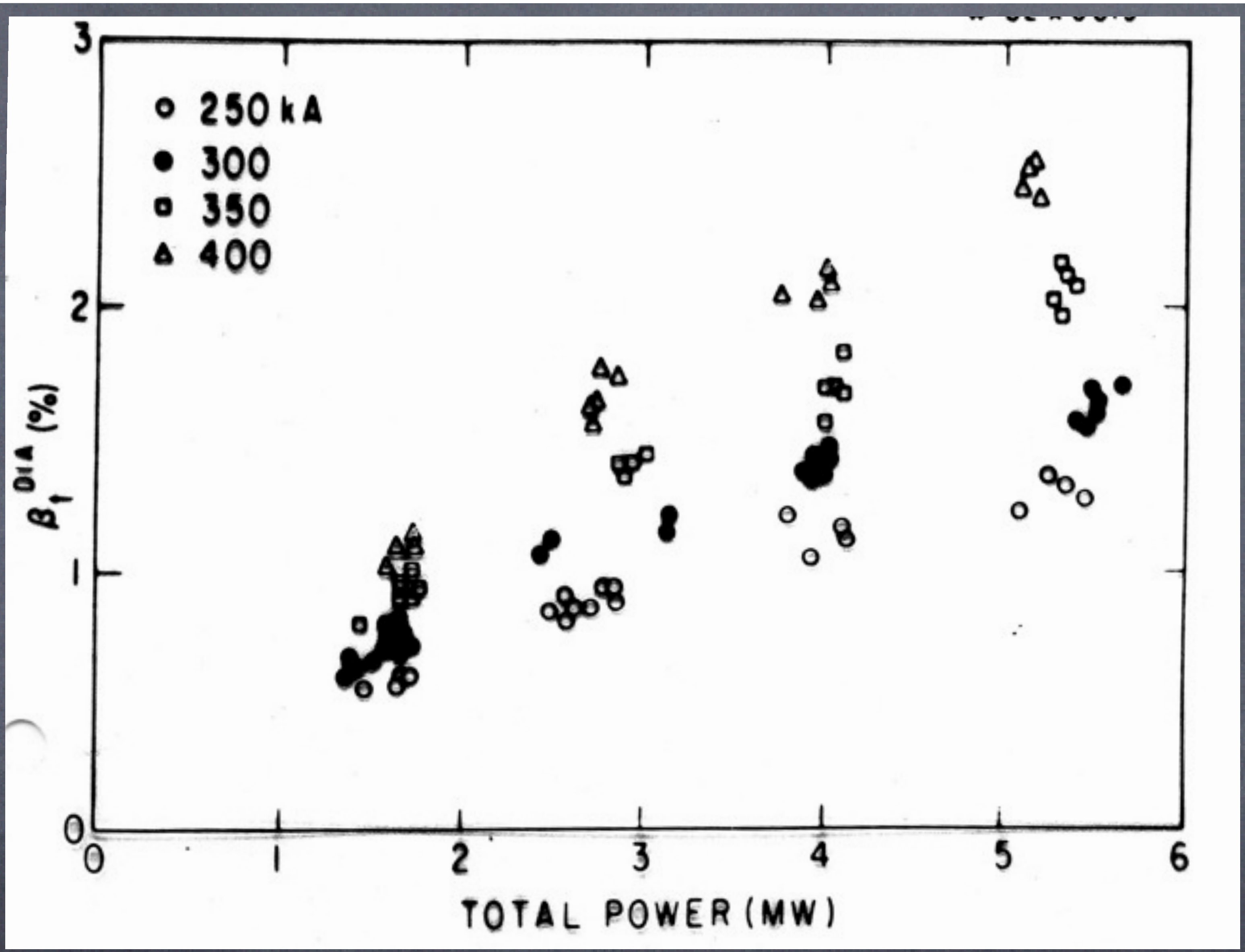
(These are Powers in Watts, not power densities in Watts/m³.)

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

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

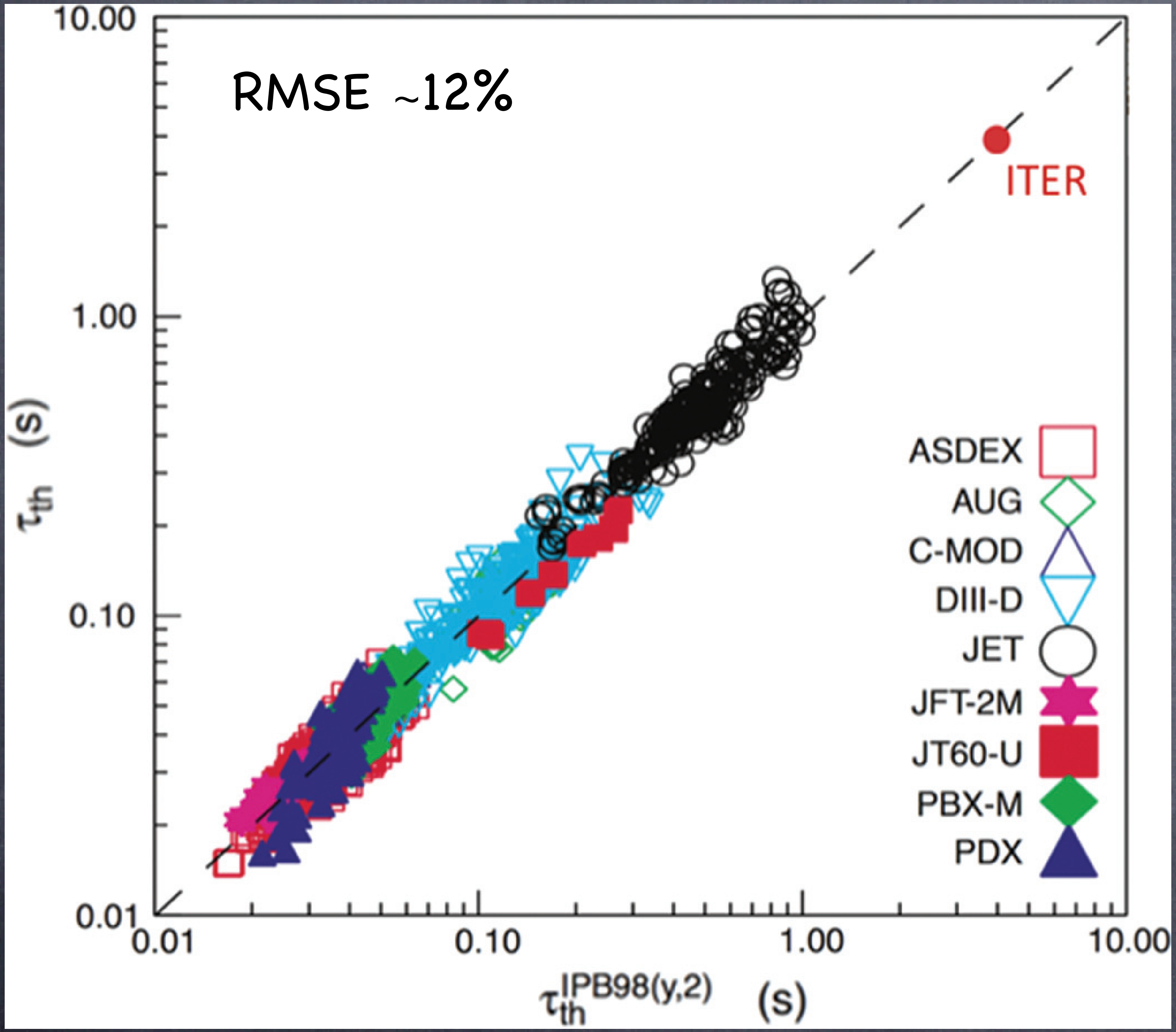
$\tau_E \equiv W_{plasma} / P_{heat}$ has Been Studied Extensively - I

$\beta_t \propto W_{plasma}$ = Stored Energy



Power, current, magnetic field, plasma density are varied systematically to find scalings (e.g., Goldston, 1982). Only include conditions with low $P_{rad,core}$ to get $\tau_E^{transport}$.

$\tau_E^{\text{transport}}$ has Been Studied Extensively - II



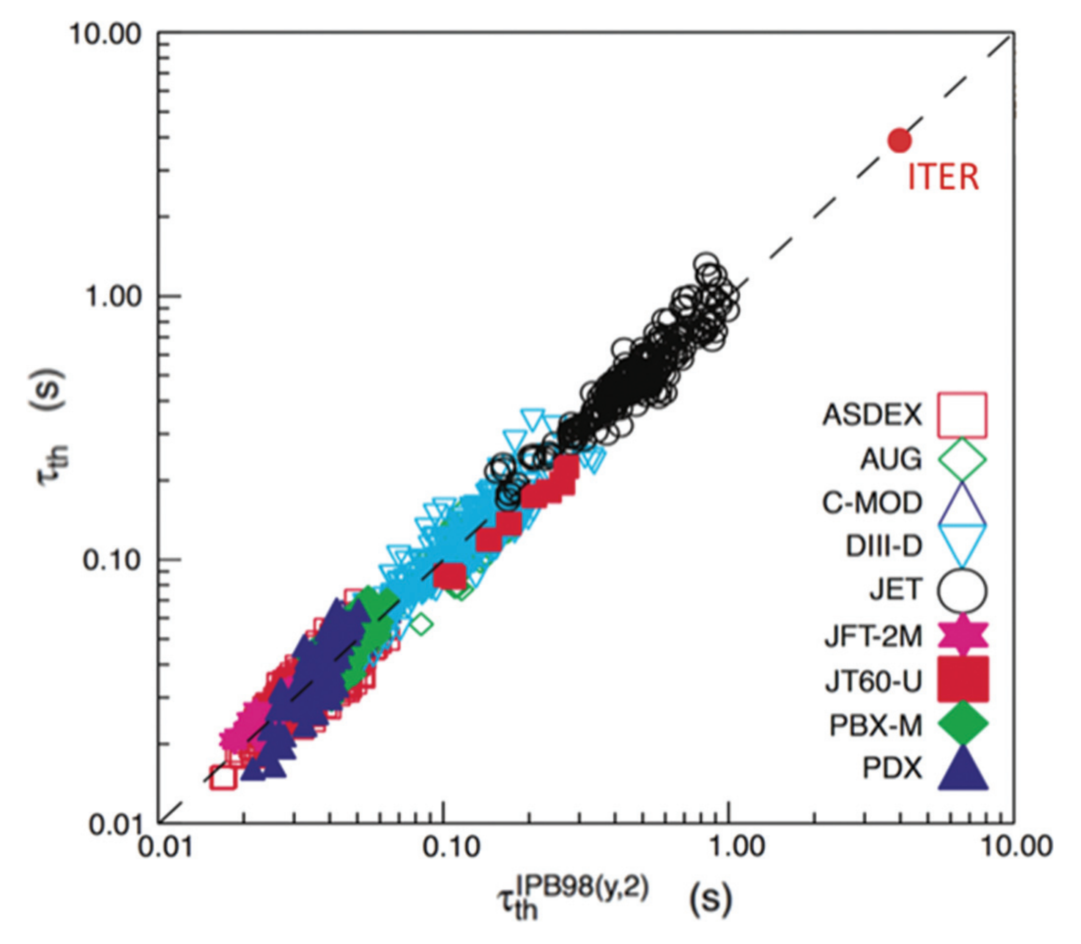
RMSE ~12%

Scaling with size is determined by bringing together results from many different experiments

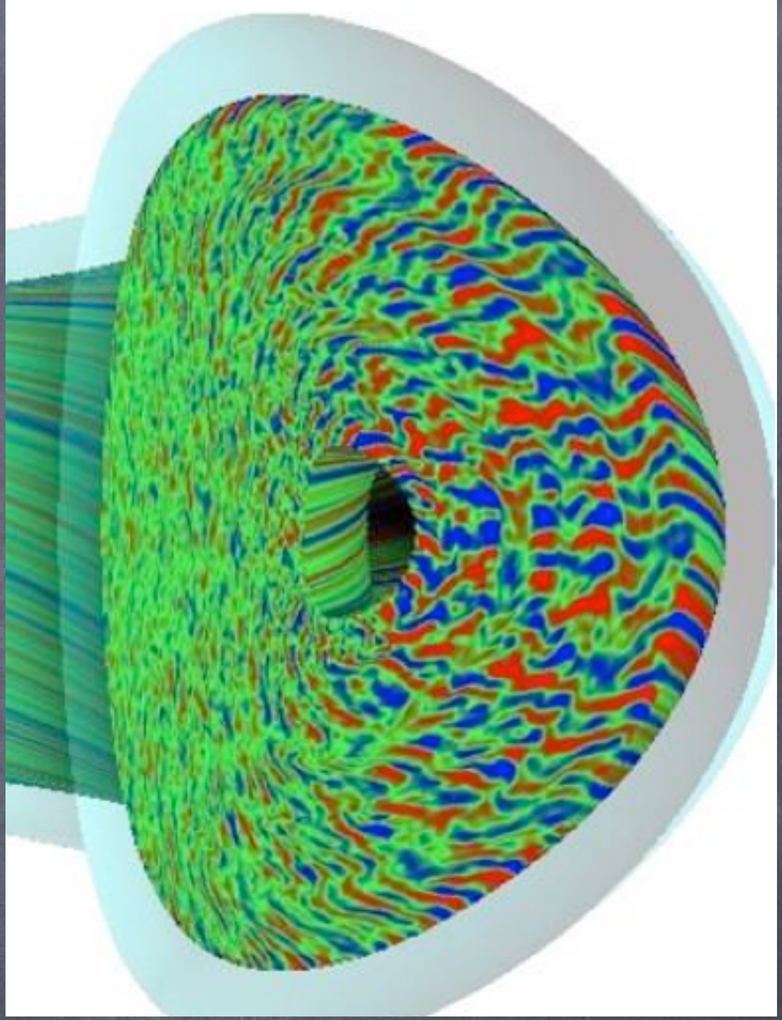
$$\tau_E(s) = 0.0562 M^{0.19} \kappa_a^{0.78} I_p^{0.93}(MA) B_T^{0.15}(T) n_e^{0.41}(10^{19} m^{-3}) P_L^{-0.69}(MW) a^{0.58}(m) R^{1.39}(m)$$

Turbulence Calculations Complement Experiments

Energy Confinement Time



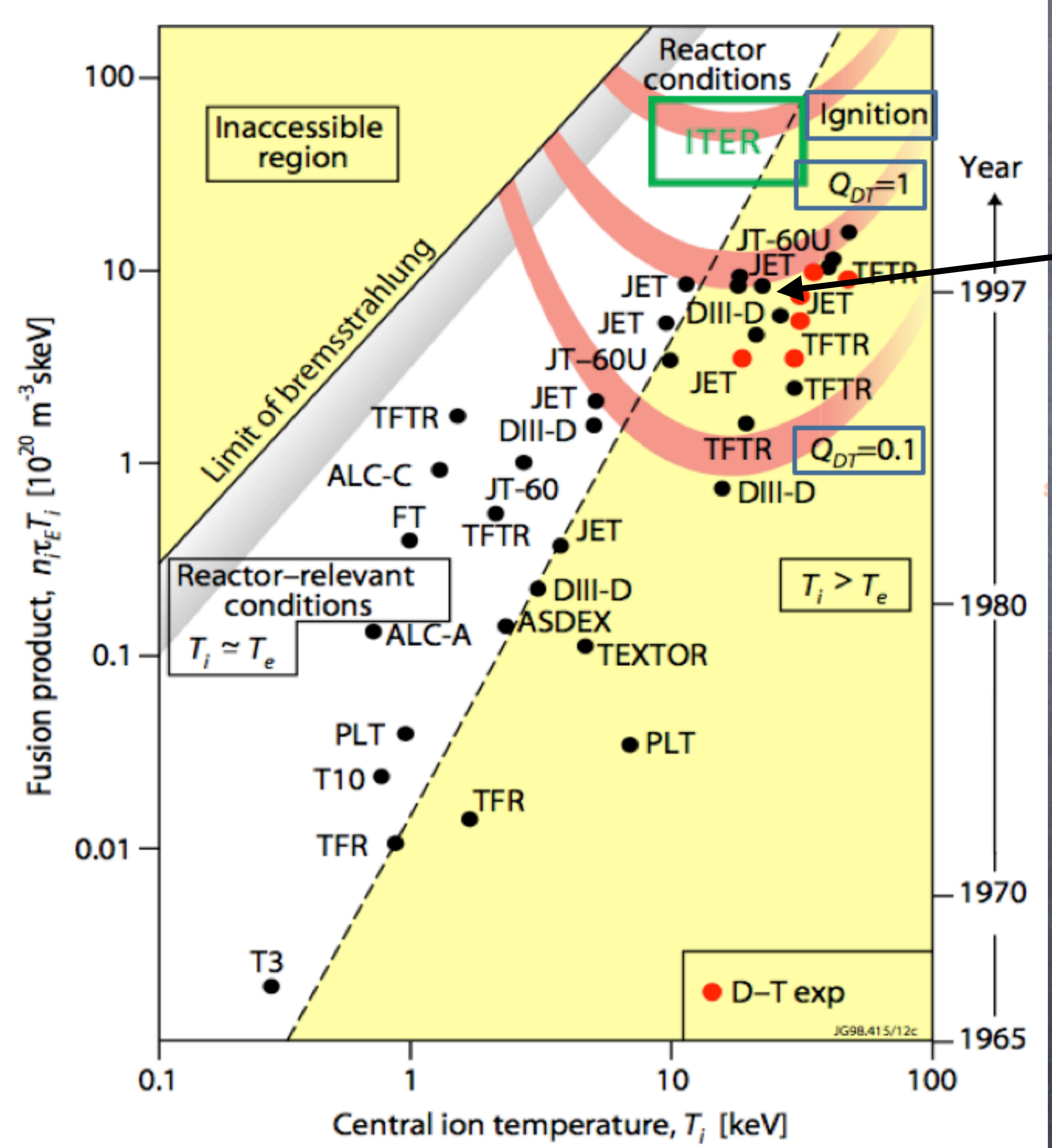
Regression Fit

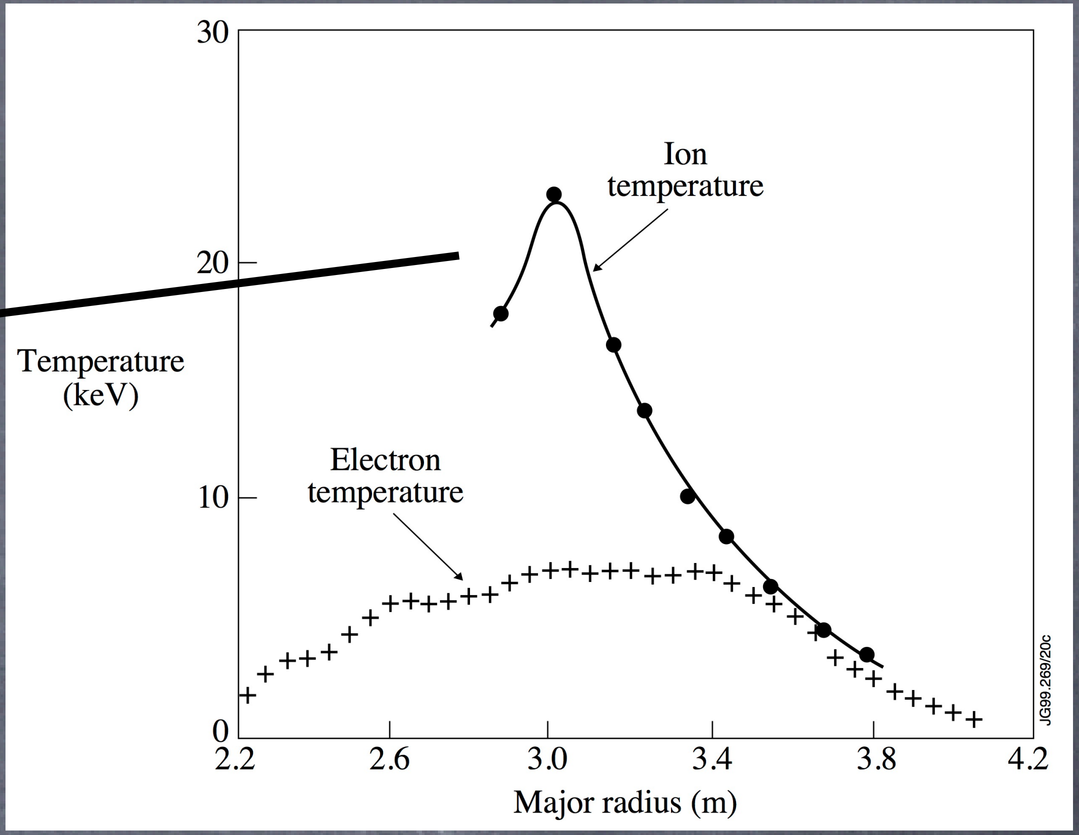


Turbulence
Simulation

… Agreement is good,
but there can always be surprises…

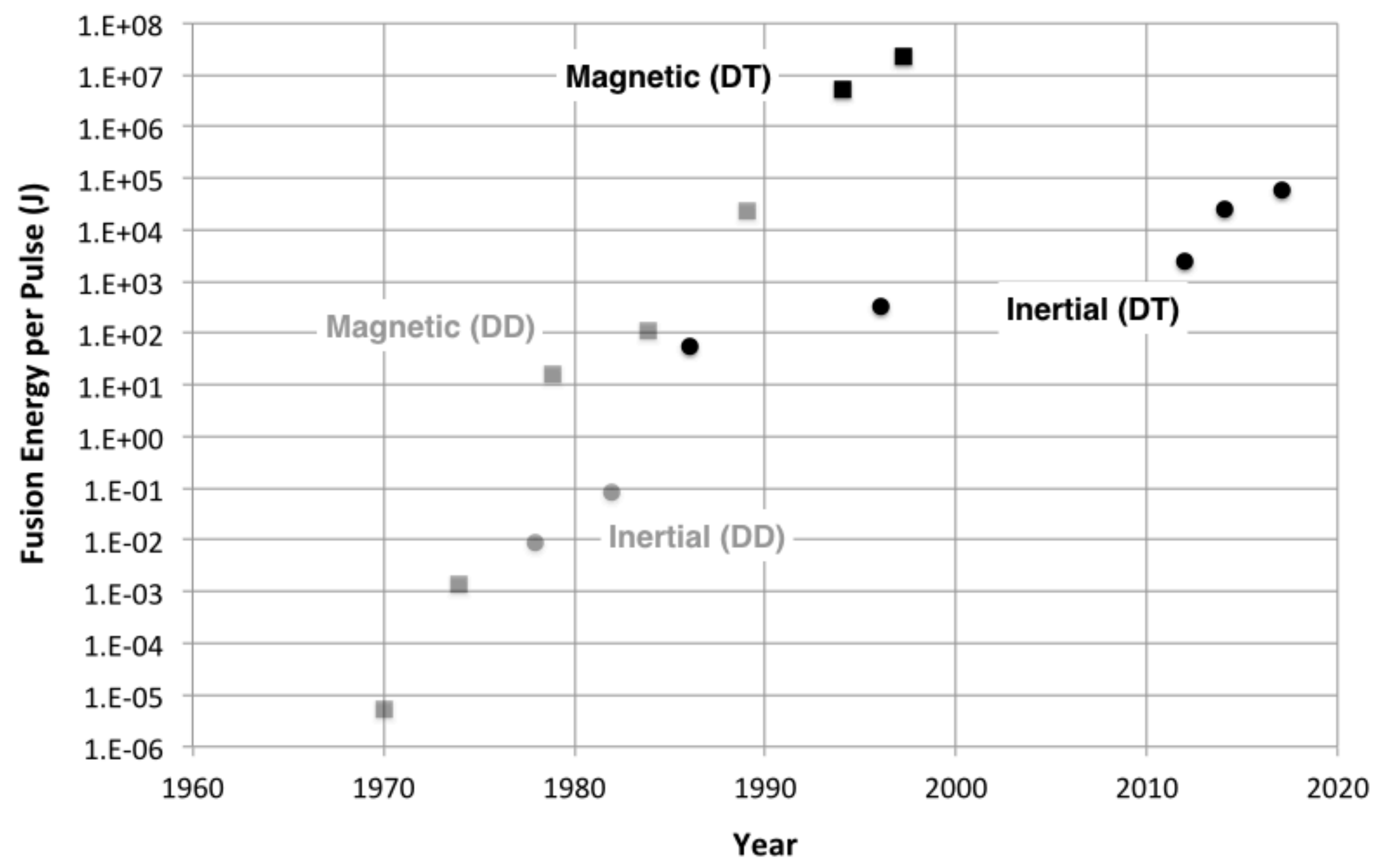
We are Getting There - I





Will we be able to achieve self-sustained plasmas?

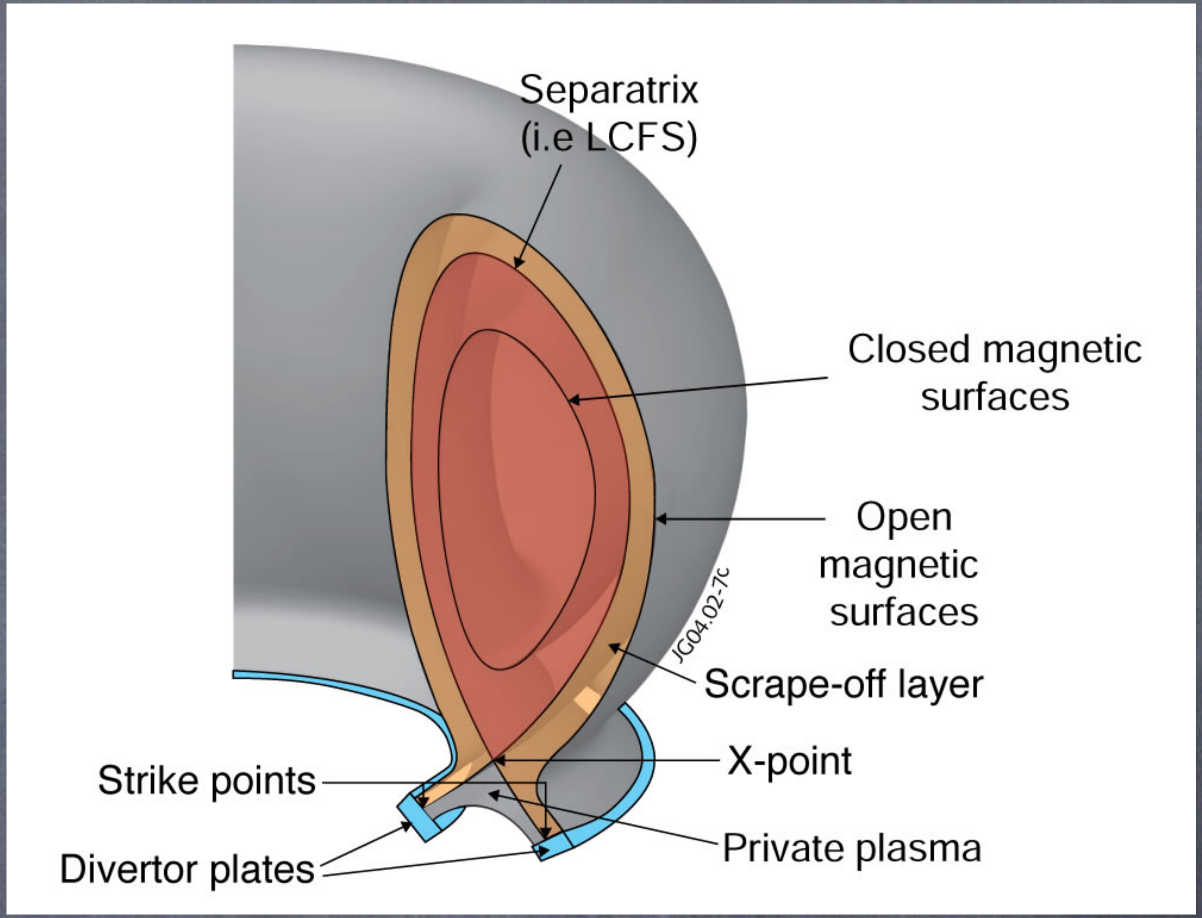
We're Getting There - II



ITER: 10^{12} J/pulse

Science & Technology Challenges Remain

- In pretty good shape (but important issues remain):
  - Plasma heating and current drive
  - Macroscopic stability
  - Turbulent transport



- An area of opportunity:
  - High temperature superconducting magnets
- The big unknowns:
  - Power efflux
  - Materials and blanket