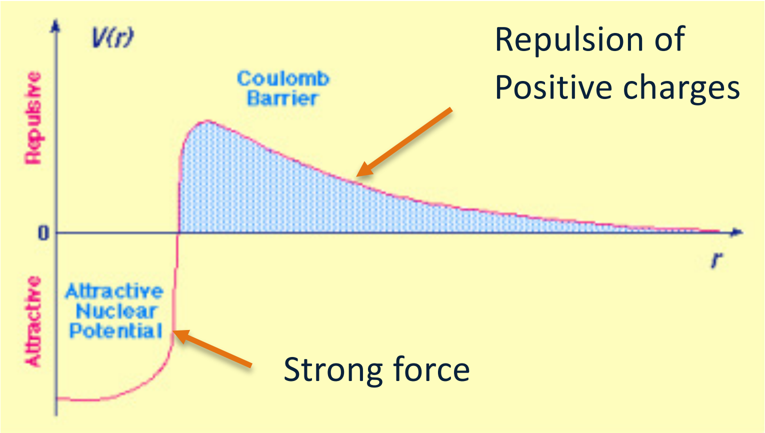
Introduction to Fusion Power

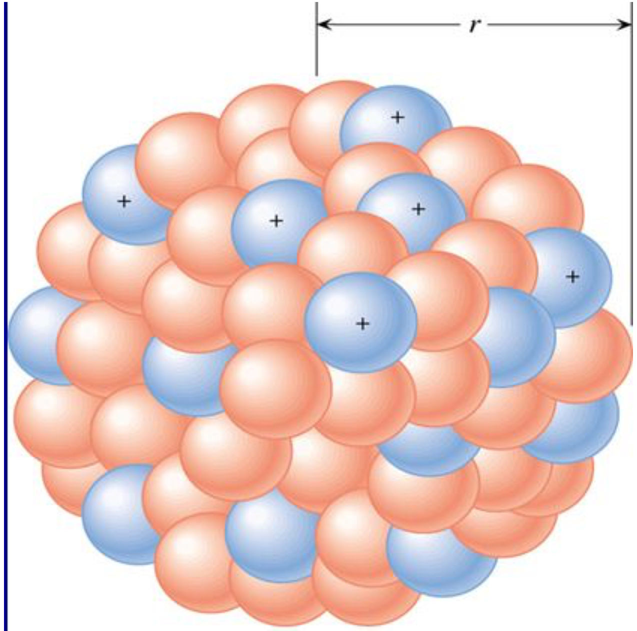
Steve Cowley, Princeton

Building a Nucleus



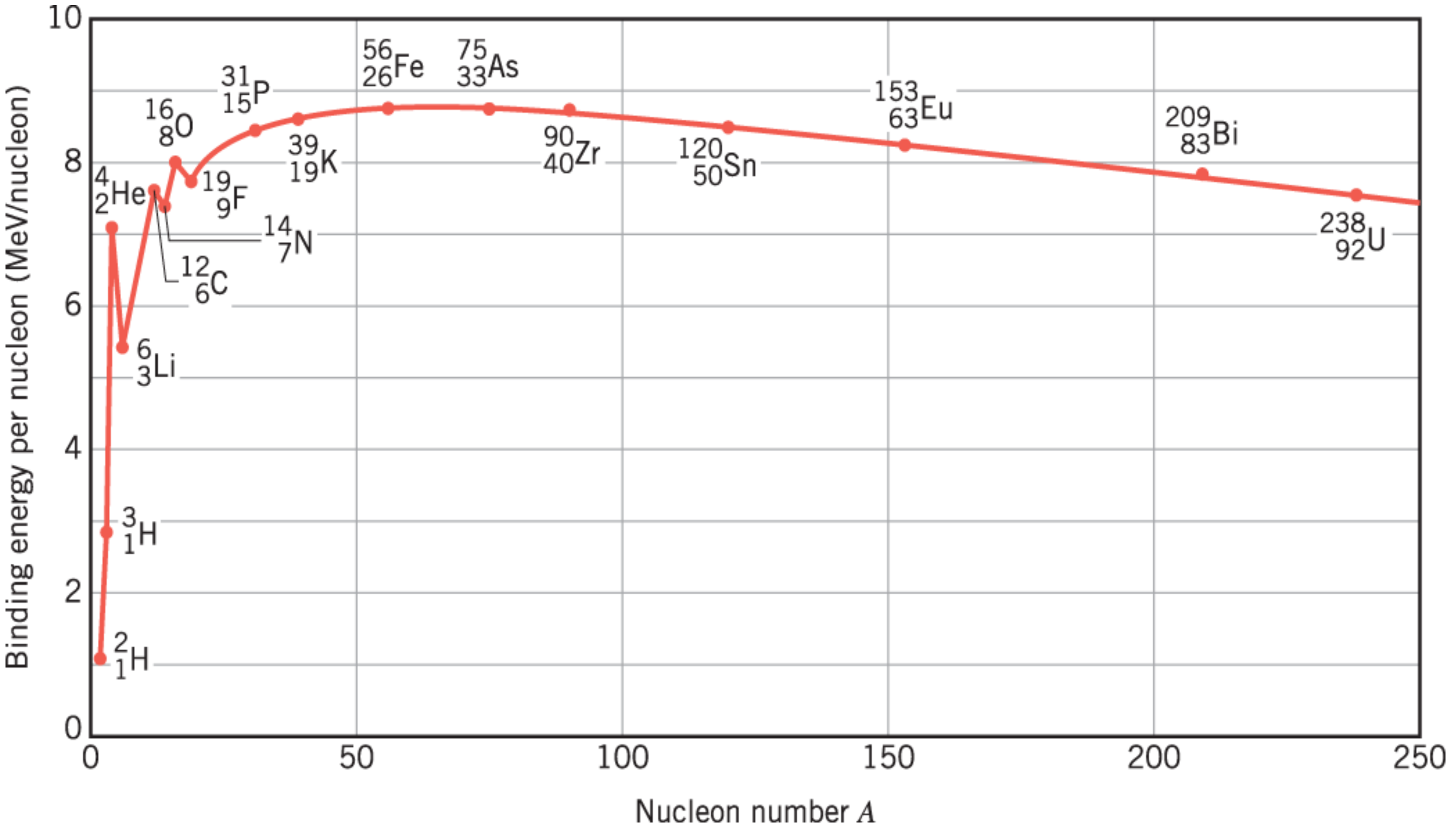
Binding energy per nucleon of a nucleus with N_p protons and N_n neutrons.

$$\Delta E = \frac{[N_p m_p + N_n m_n - M]c^2}{N_p + N_n}$$



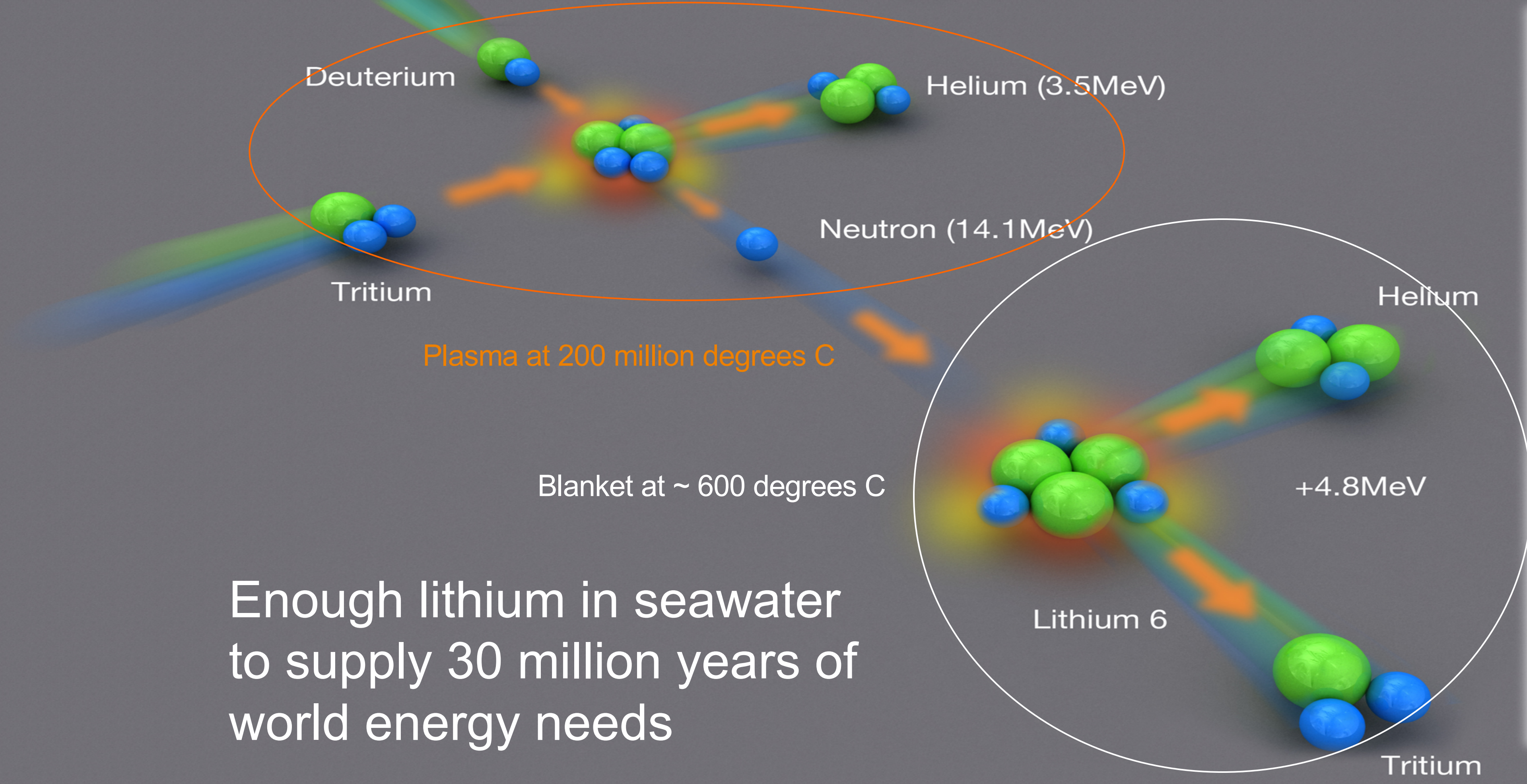
$$m_p = mass\ of\ proton$$
$$m_n = mass\ of\ neutron$$
$$M = mass\ of\ nucleus$$

Nuclear binding Energy



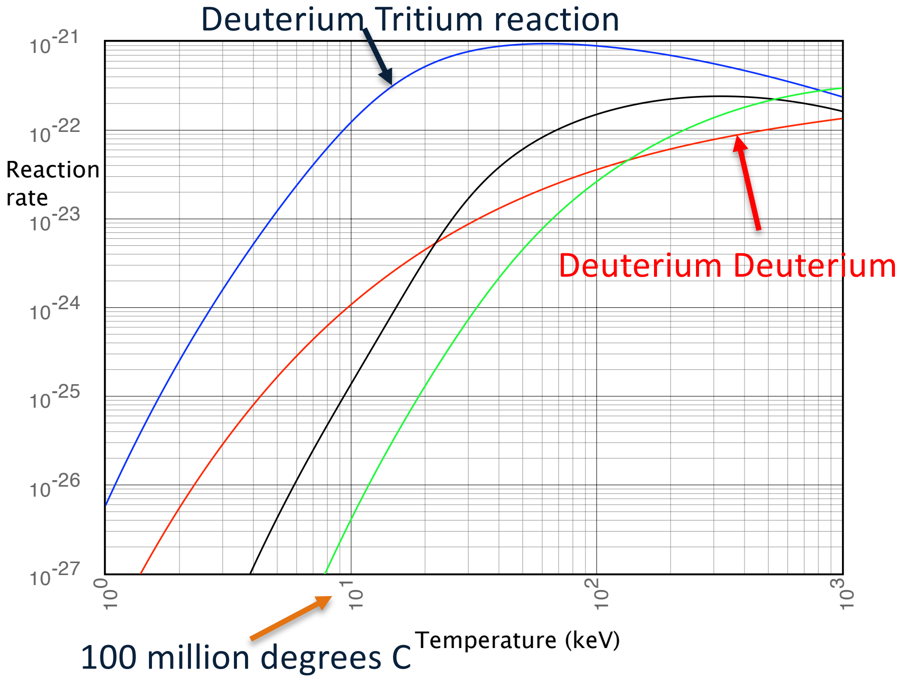
Number of protons plus neutrons

Power density = $0.1(\text{Pressure in atmospheres})^2$ (MWm^{-3})



Enough lithium in seawater to supply 30 million years of world energy needs

Reaction Rate



Simple calculation yields

The power generated in

Each cubic meter.

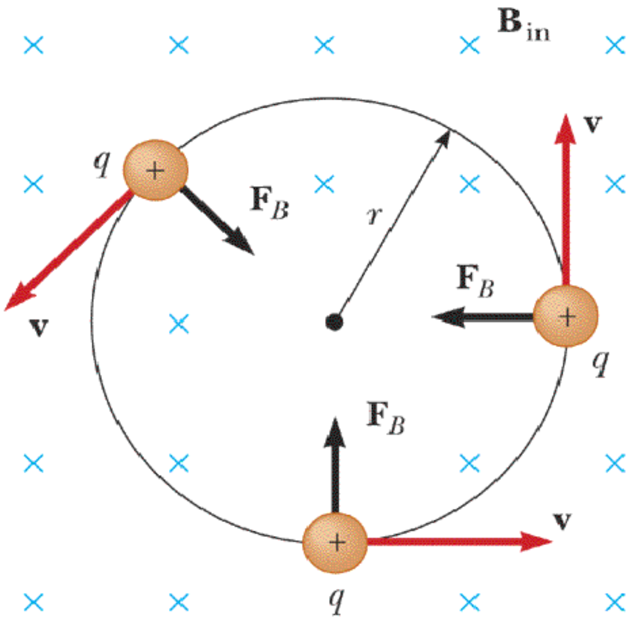
Approximately

$$\mathcal{P}_{Fusion} = 0.08P^2 \; (MWm^{-3})$$

Plasma pressure in atmospheres

Magnetic Confinement?

Motion of Particle in a Magnetic Field



Force on Particle in a Magnetic Field

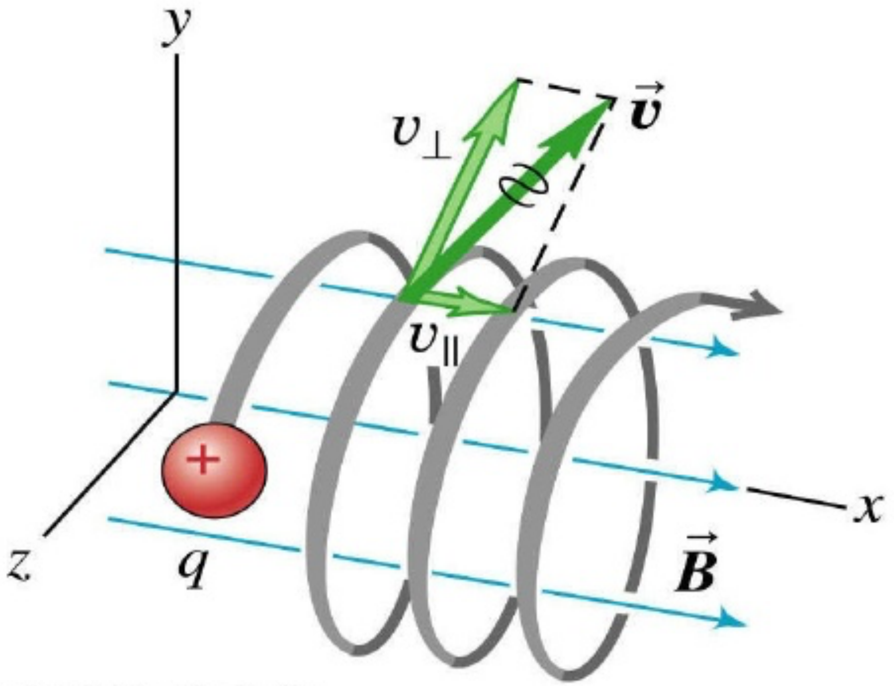
$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

Makes a circle around field line.
Motion along field unimpeded.

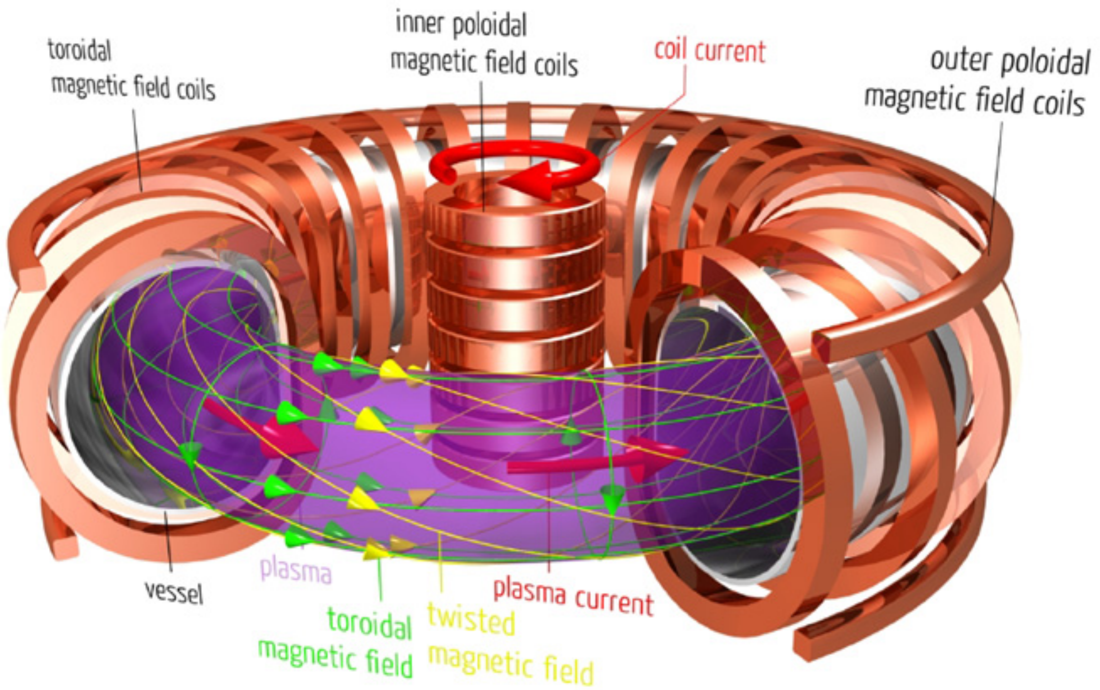
$$Orbital\ period = \frac{2\pi m}{qB}$$

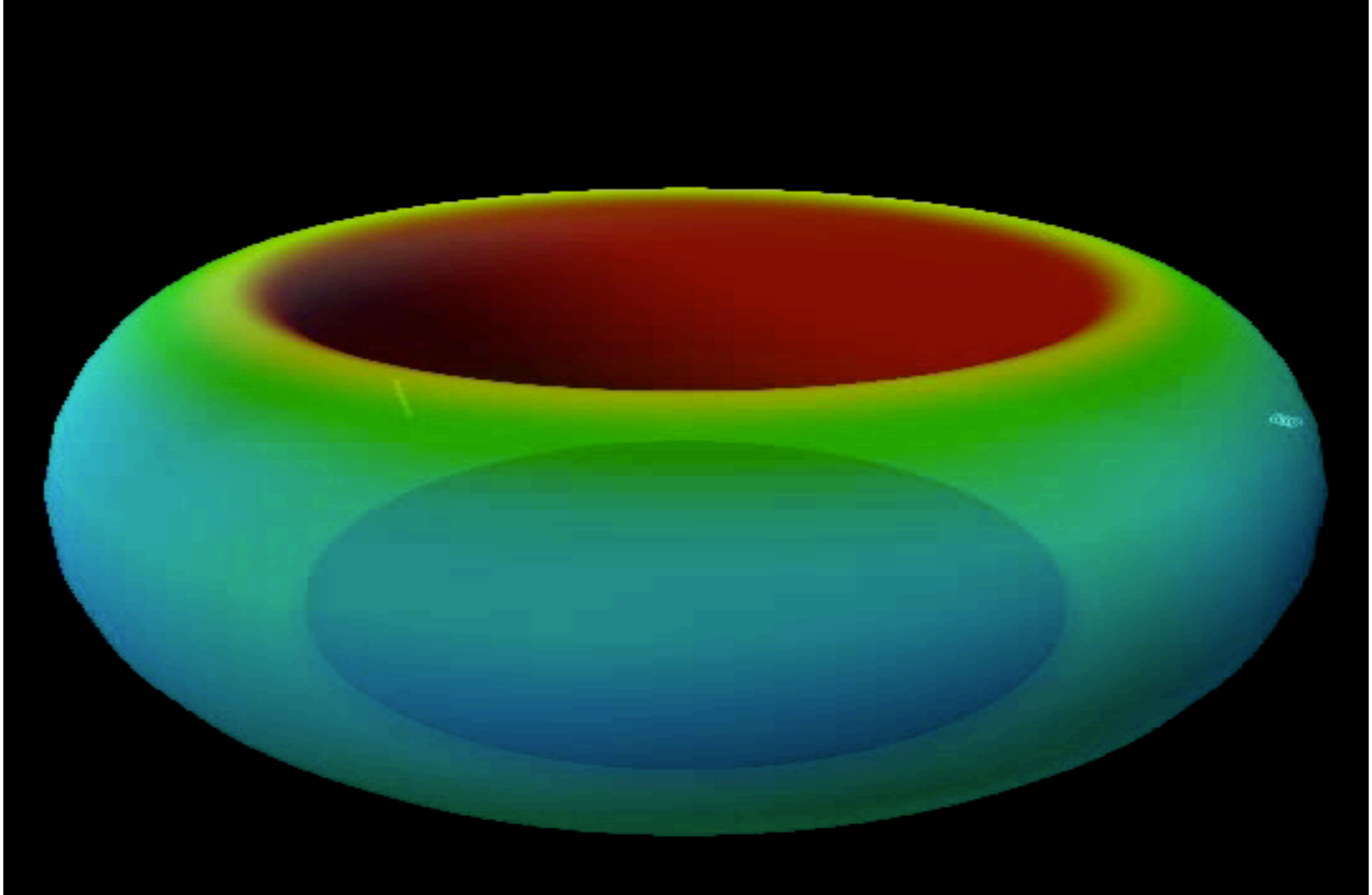
$$radius\ = \rho = r = \frac{vm}{qB}$$

Motion of charged particles in a magnetic field

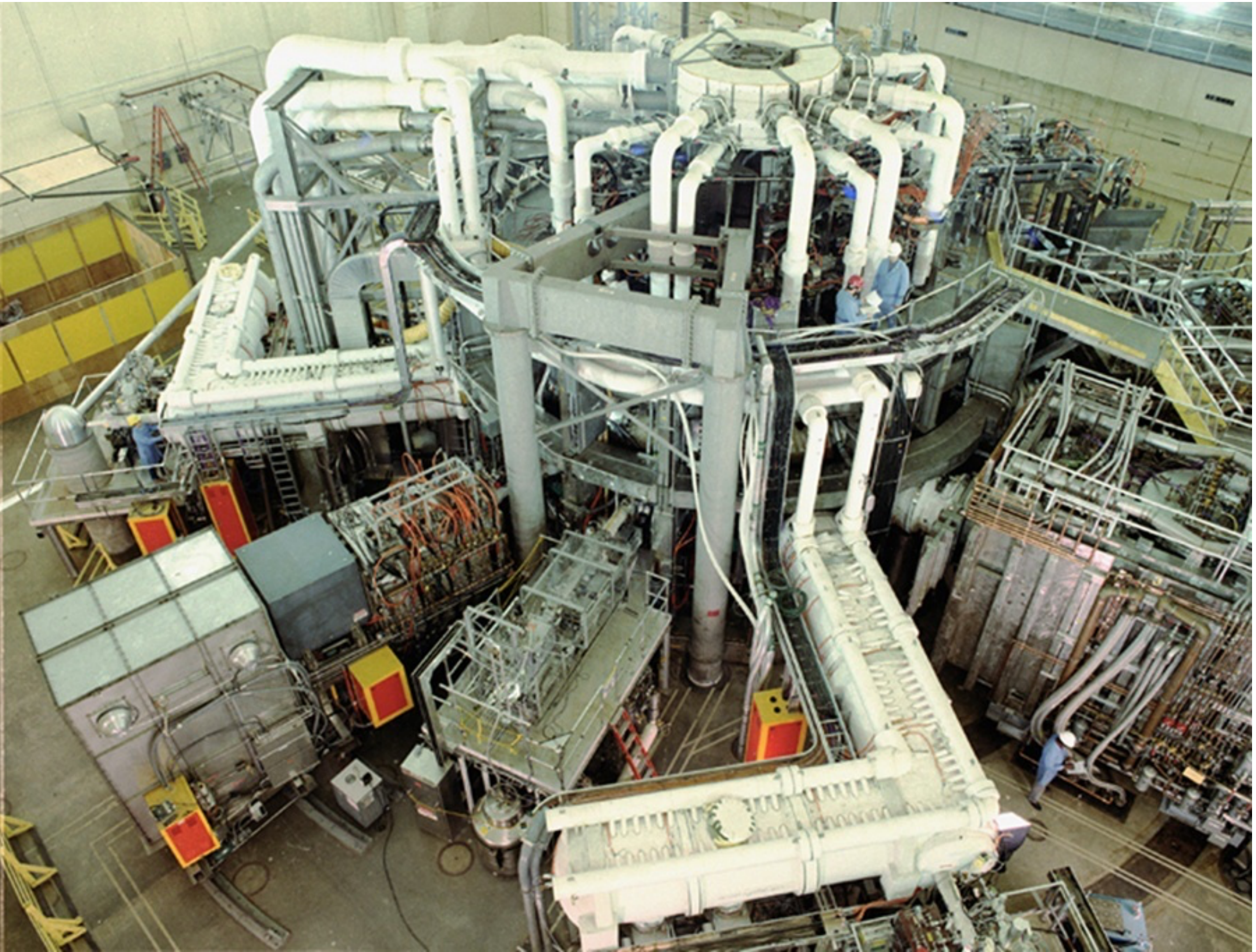


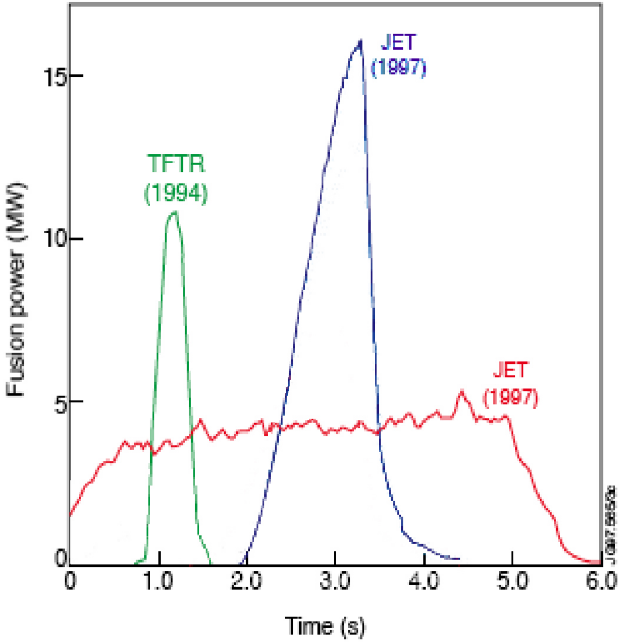
Magnetic fusion – making a bottle





Princeton First -- TFTR





ITER

First sustained burning plasma

Starts in 2025

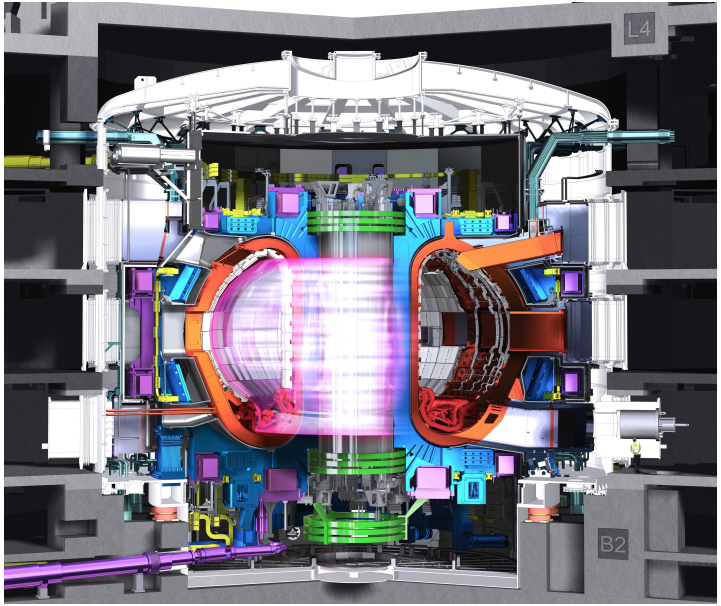
BASIC PARAMETERS:

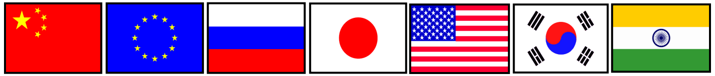
Fusion Power 500MW

Burn Flat Top > 400 seconds

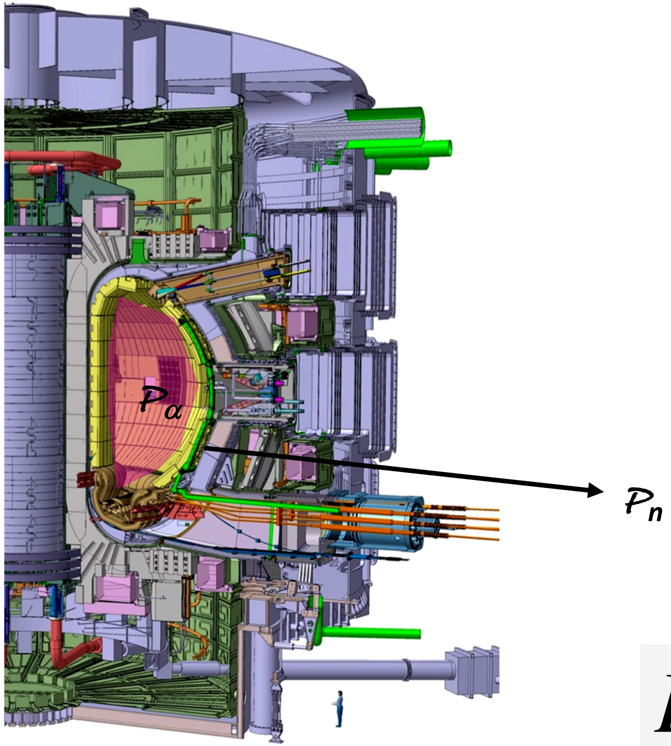
Power Amplification Q>10

Cost is > 12 Billion Euro





Fusion energy balance in ITER



'Baseline Performance'

Power in alphas captured by Plasma $\mathcal{P}_\alpha$ ~ 100MW.

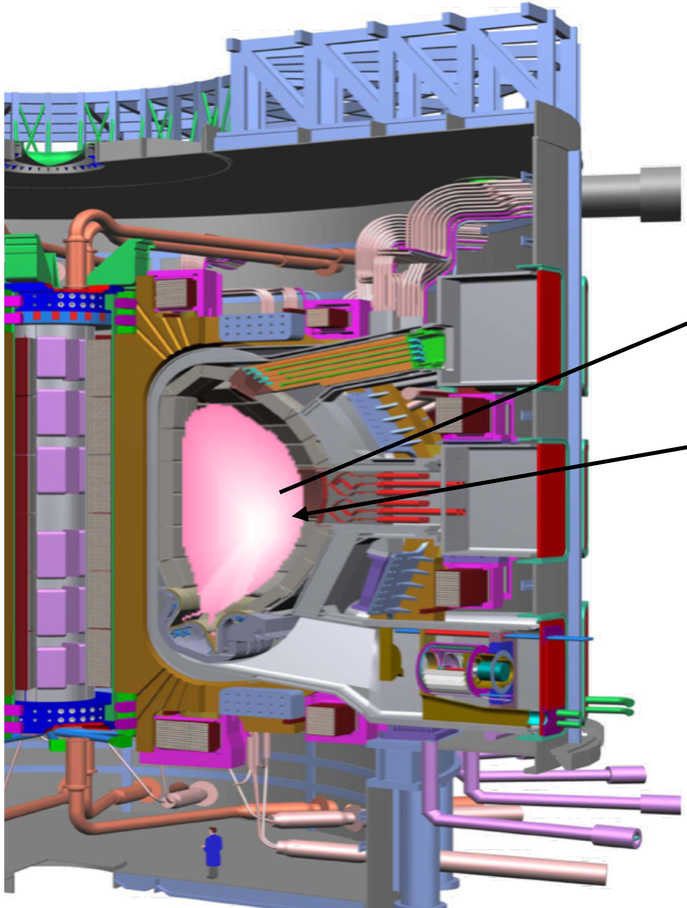
Power in neutrons escaping Plasma $\mathcal{P}_n$ ~ 400MW.

$\mathcal{P}_n + \mathcal{P}_\alpha = \mathcal{P}_{Fusion}$

$$D + T \rightarrow He^4 + n$$

3.5MeV 14MeV

Fusion Energy Balance in ITER



Turbulent Plasma Energy Loss

$$\mathcal{P}_{loss} = \frac{0.15P}{\tau_E}(MWm^{-3})$$

Confinement Time

External Plasma heating

$\mathcal{P}_{Heat}$~50MW

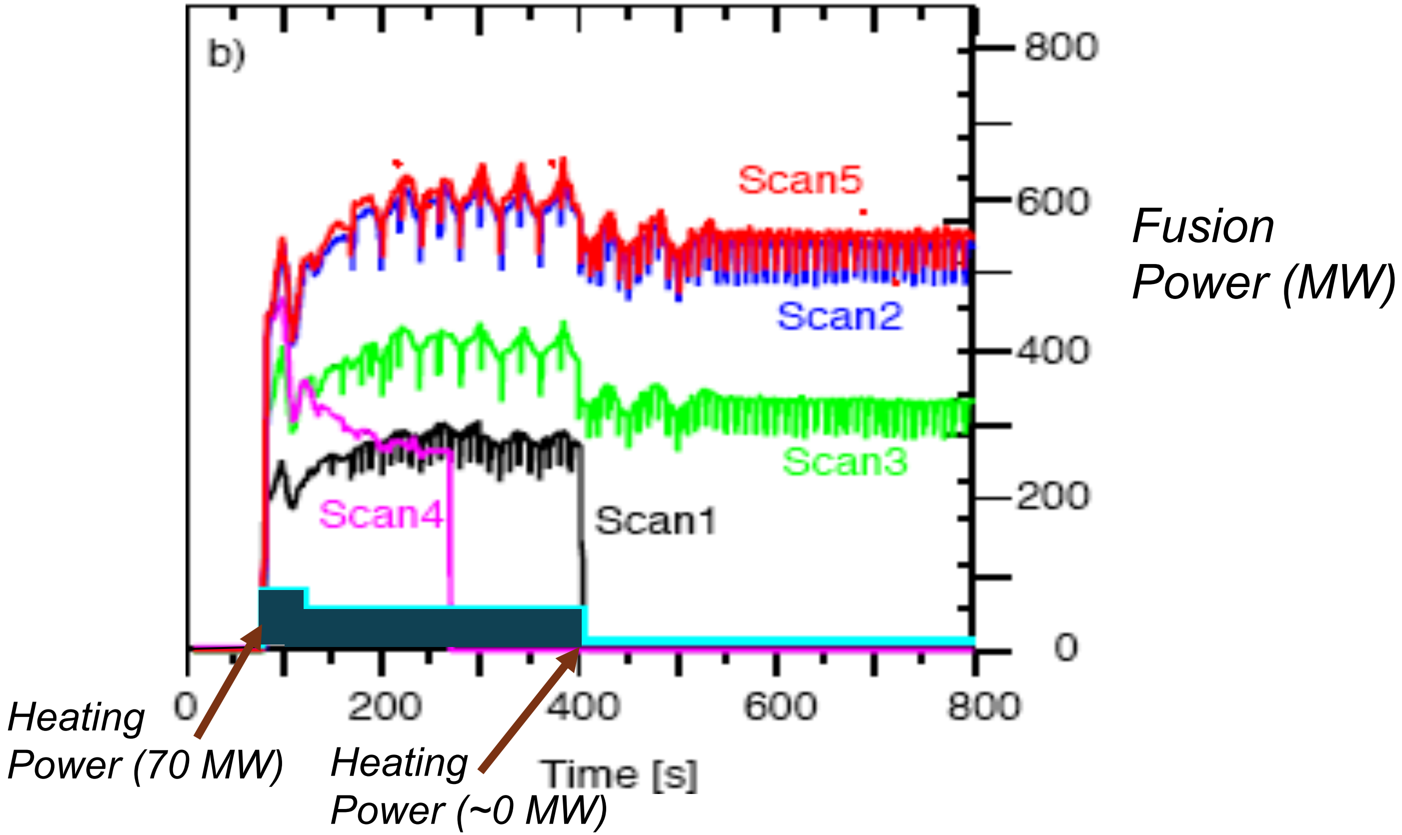
Energy Balance

$$\frac{\mathcal{P}_{Fusion}}{5} + \mathcal{P}_{Heat} = \mathcal{P}_{loss} \sim 0.15\frac{P}{\tau_E}$$

Energy Gain = Q > 10

ITER computer modelling

Simulation by Bob Budny:



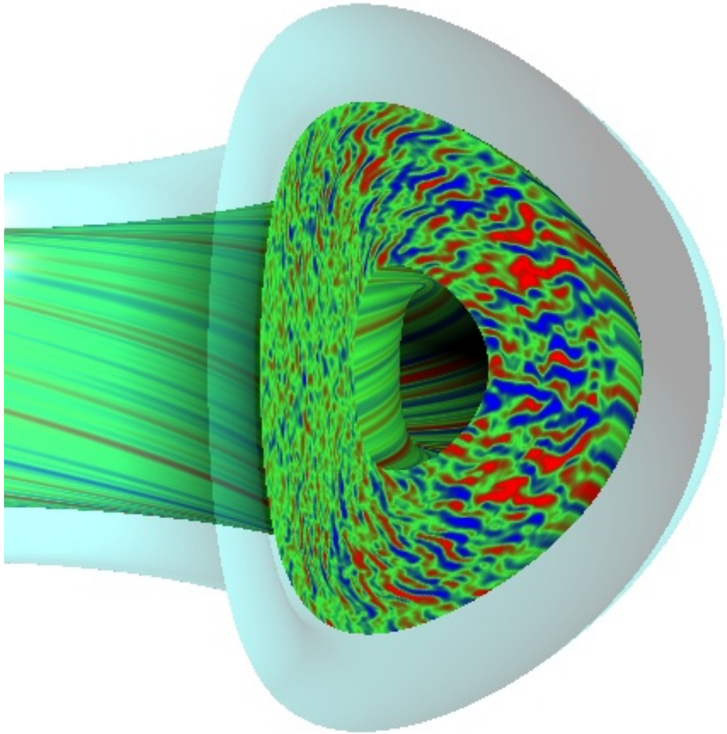
Will ITER Burn?

DIII-D Shot 121717

GYRO Simulation

Cray X1E, 256 MSPs

Energy Confinement -- Random walk of heat/particles.



L = typical machine size

Δ= radial eddy size ∝ Ion larmor radius ρ_i = random step.

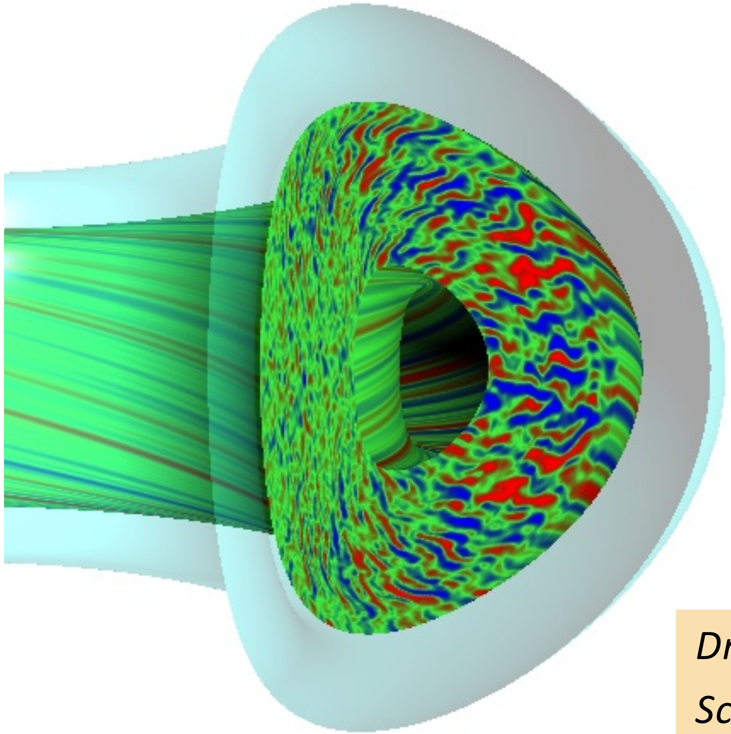
N = number of steps to random walk out of plasma

$$L \sim \sqrt{N} \rho_i$$

$$N = (\frac{L}{\rho_i})^2 \equiv (\frac{1}{\rho_i^*})^2$$

For ITER N ~ 10^6.

Energy Confinement -- Random walk of heat/particles.



Eddy turnover time =

$$\tau_{eddy} = \left(\frac{L}{v_{thi}}\right)$$

$$\tau_E \sim N\tau_{eddy} \sim \frac{L^3}{\rho_i^2 v_{thi}}$$

$$\propto L^3 B^2 T^{-3/2}$$

Dramatic scaling with size!

Scaling approximately agrees with data BUT geometry dependant.

Simple considerations – things we all know

For plasma at 10-20Kev temperatures (100-200M°C) D-T fusion power density is approximated by:

$$\mathcal{P}_{Fusion} = 0.08P^2 \; (MWm^{-3})$$

Plasma pressure in atmospheres

Magnetic pressure = $P_{Magnetic}$ ~ 4 B^2 (atmospheres)

Magnetic Field in Tesla

Figure of merit β = $P/P_{Magnetic}$

$$\mathcal{P}_{Fusion} = 1.28\beta^2 B^4$$

Simple considerations

The energy confinement time τ_E is defined by:

$$Power\ lost\ by\ transport\ from\ plasma = \frac{stored\ energy}{\tau_E}$$

Equating the heating from fusion alphas to the transport/turbulent power lost
LAWSON CRITERION.

$$P\tau_E \geq 20$$

P= Central Plasma pressure (atmospheres)
τ_E in seconds

or

$$\beta B^2 \tau_E \geq 5$$

Magnetic Field in Tesla

HOW DO WE FIND AND EXPRESSION FOR τ_E

Supercomputing and experiments predict GYRO-BOHM LIKE SCALING

$$\tau_E \sim H^{3.2} B^2 R^3$$

Or in engineering parameters ignition requires

PHYSICS

ENGINEERING

$$H^{3.2} B^4 R^3 \geq 14000 \quad \Rightarrow \quad B \propto R^{-3/4}$$

For ITER like tokamaks. R is major radius in metres
B is central magnetic field in tesla

SELF SIMILAR SCALING

Smaller Faster Cheaper?

Physics and Engineering Innovation

Sheffield, Freidberg, Meade etc. Empirical fit to the machines/experiments that have been built

$$\$ \propto R^2(1 + c_1 B + c_2 B^2)$$

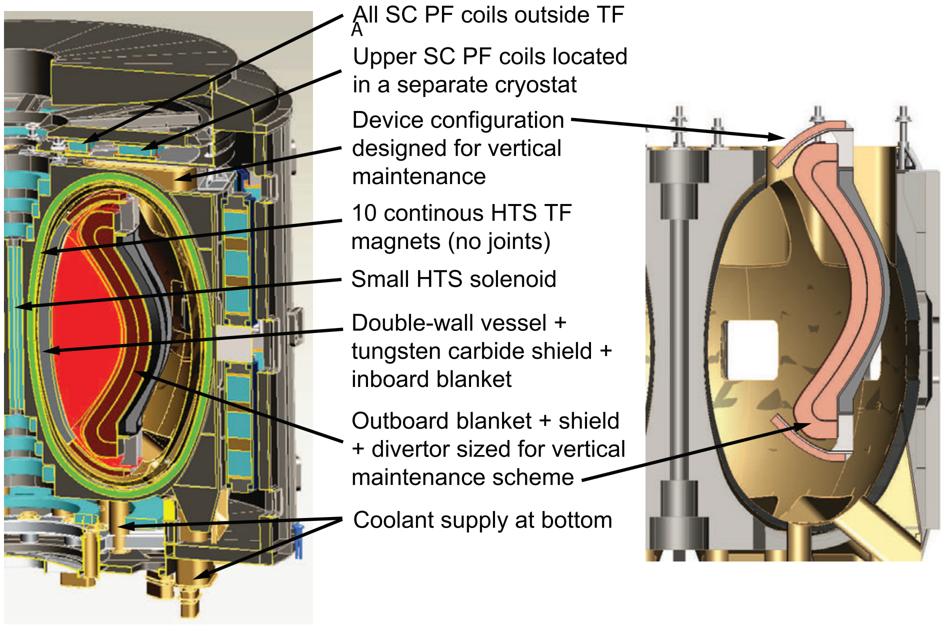
constants

This formula results from the cost of engineering not the cost of stuff (steel, tungsten, niobium etc.).

SIMPLICITY MATTERS

Getting to Commercial Fusion – innovation

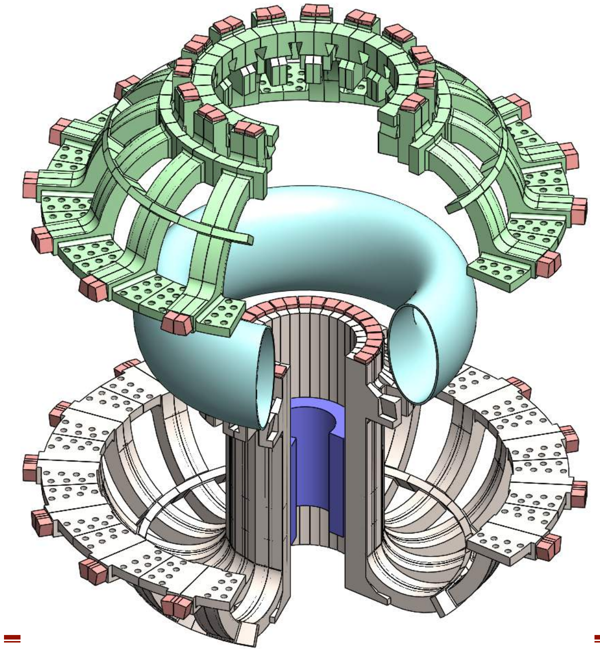
Nucl. Fusion **56** (2016) 106023 J.E. Menard *et al*



Spherical Tokamak Pilot Plant – less than 1% of the volume of the EU demonstration reactor

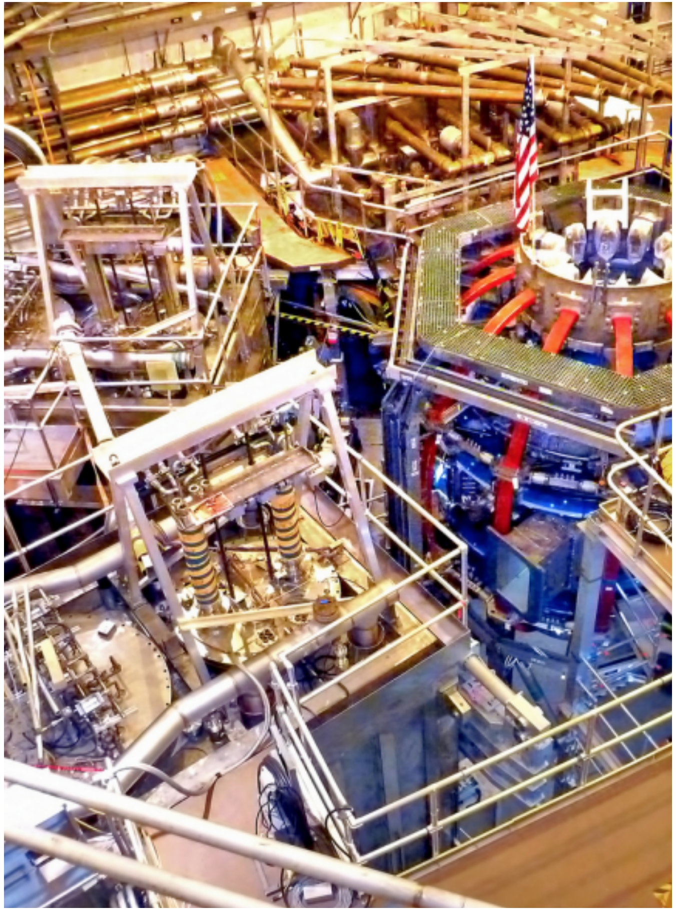
MIT group

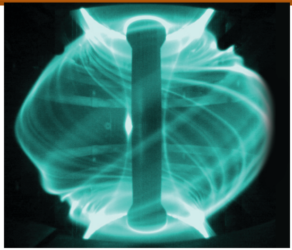
Sorbom et. al.



Commonwealth Fusion Systems

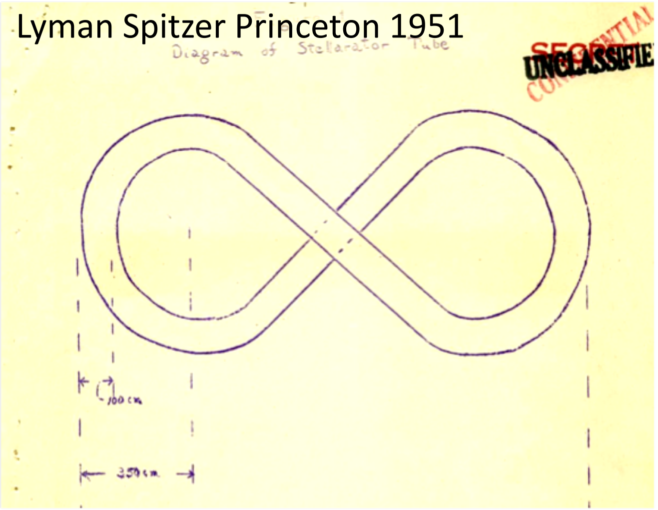
NSTX-U is Crucial



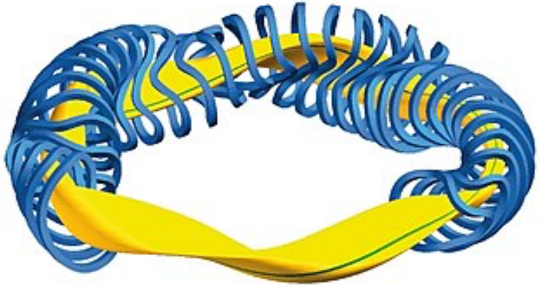


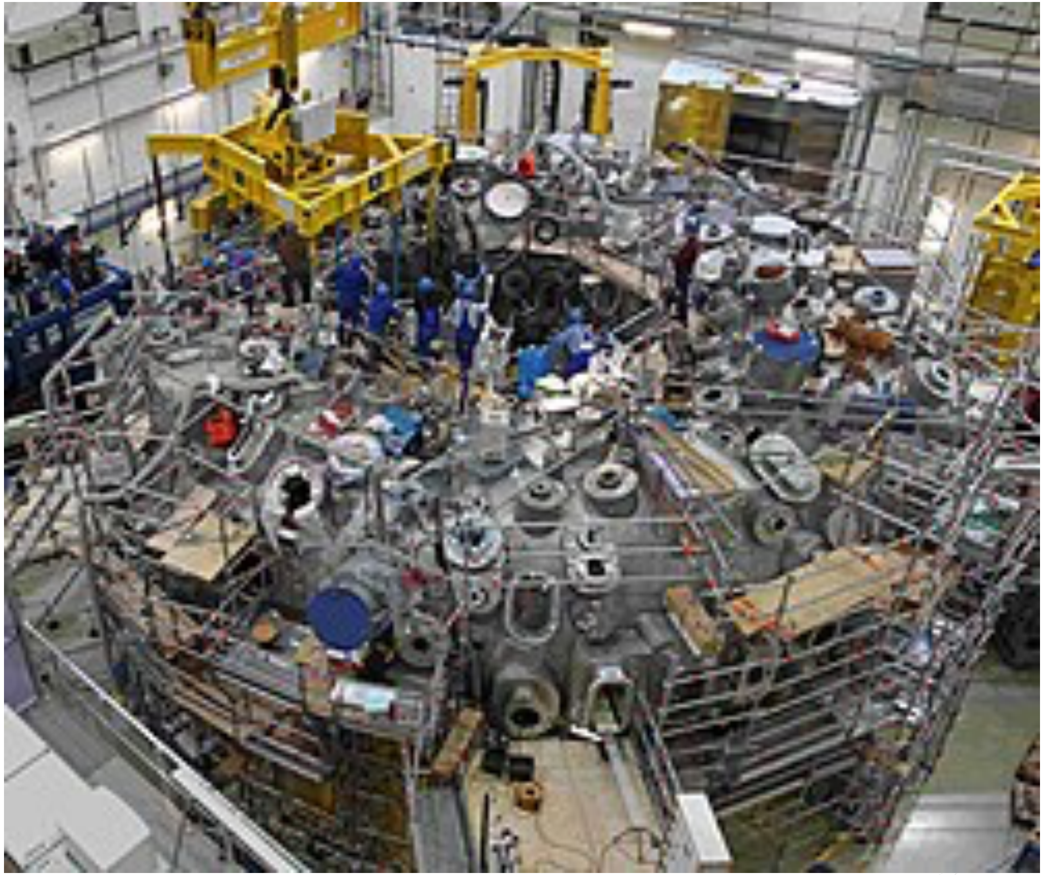
- NSTX-U is a platform for discovery
  - 'Spherical Tokamak': Does it confine the plasma better?
  - Can we control it at high pressure (β)?
  - Can we exhaust he heat from this high power density plasma?
- Impact:
  - Long-lever validation of theoretical models
  - Evaluate Spherical Tokamak as a compact, less-expensive fusion system

Stellarator – a modern approach

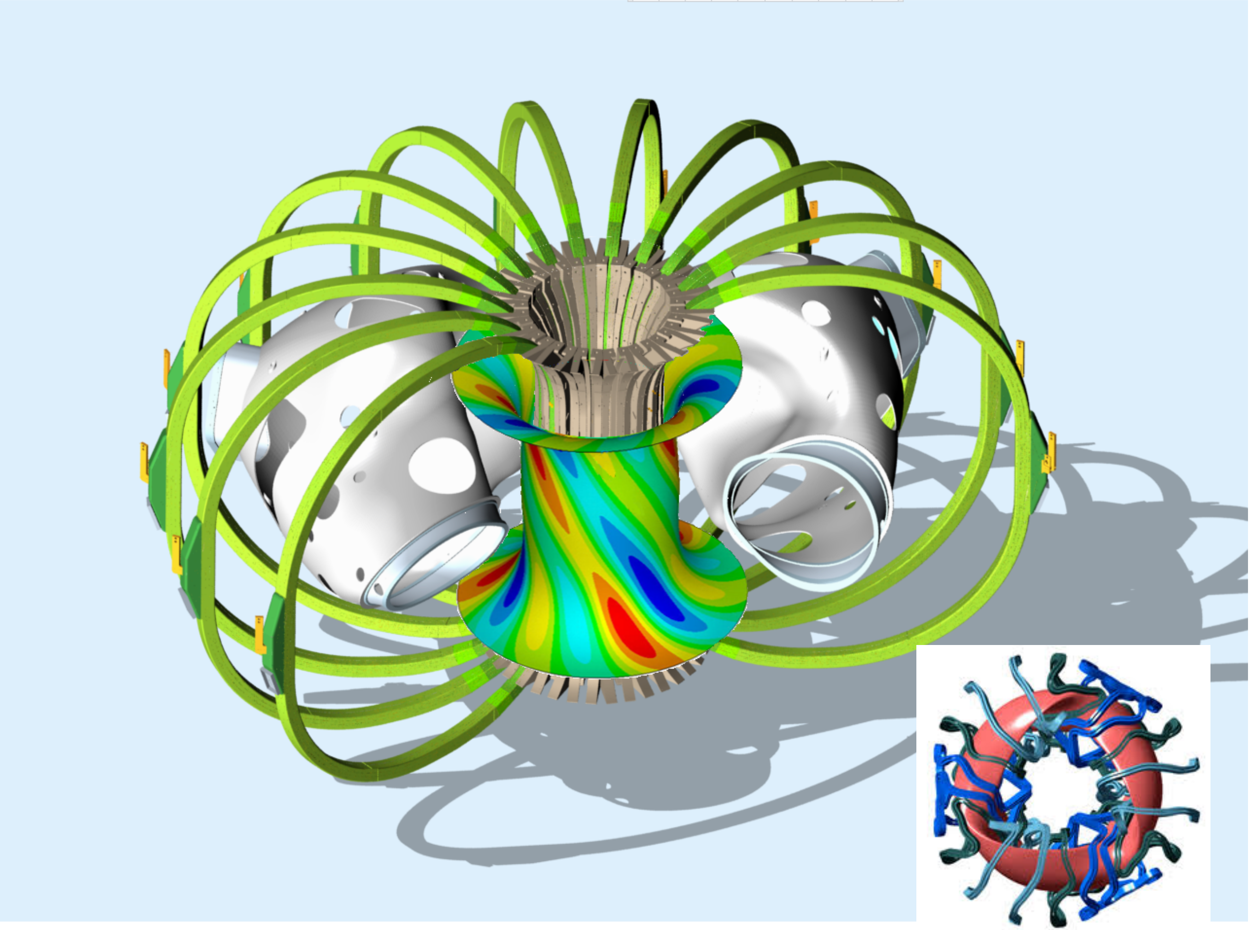


Lyman Spitzer Princeton 1951





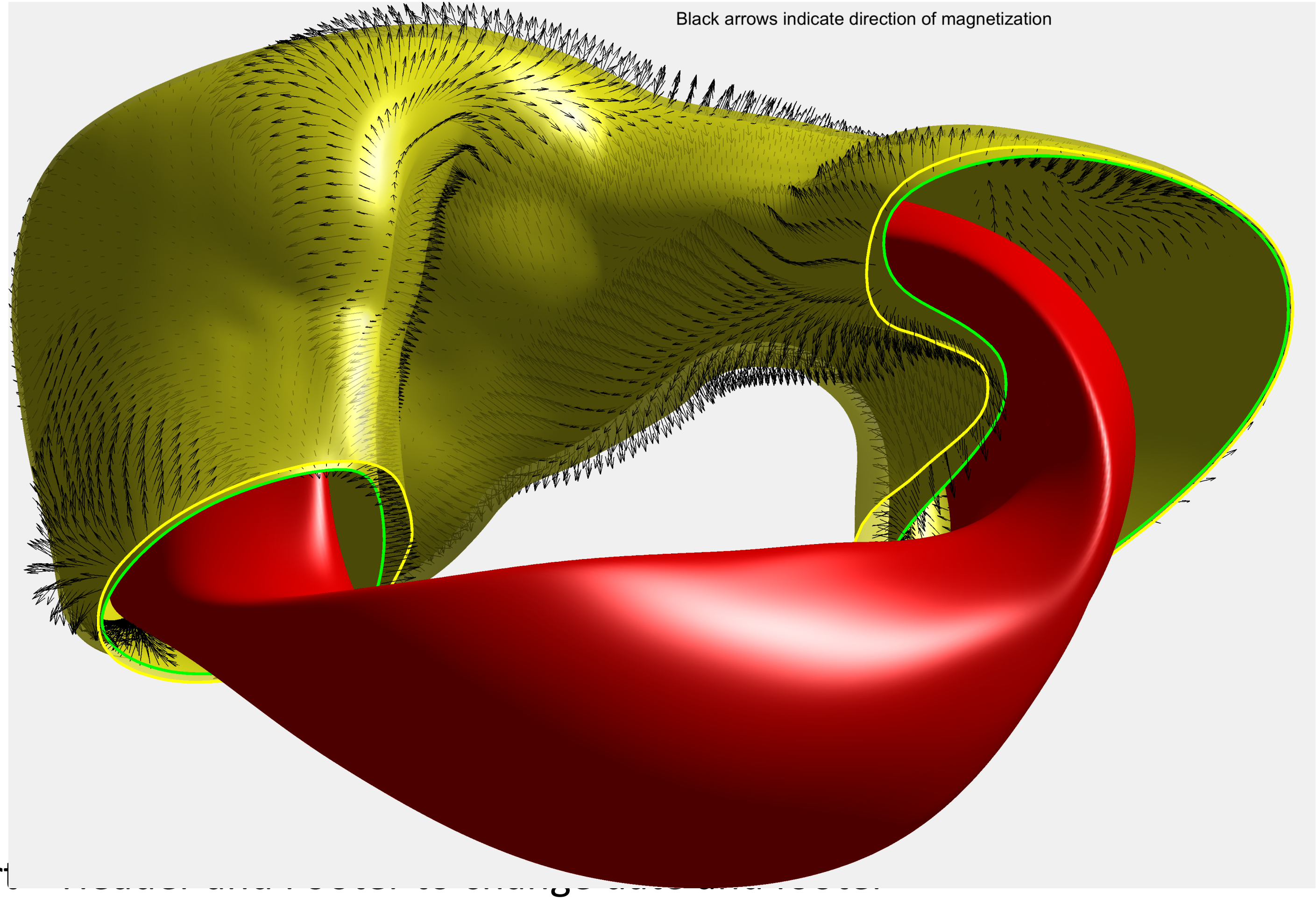
Stellarator – Simplicity – Permanent Magnets



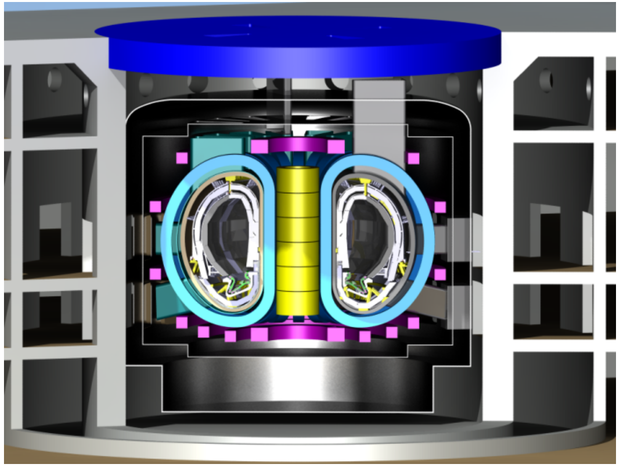
Mike Zarnstorff, David Gates, SC
Simon's Foundation: *Hidden Symmetries Collaboration*

- Neodymium Magnets to make the shaping.
- Flexible configuration precise Fields.
- Low B
- Use NCSX pieces?
- Low cost
- Demountable

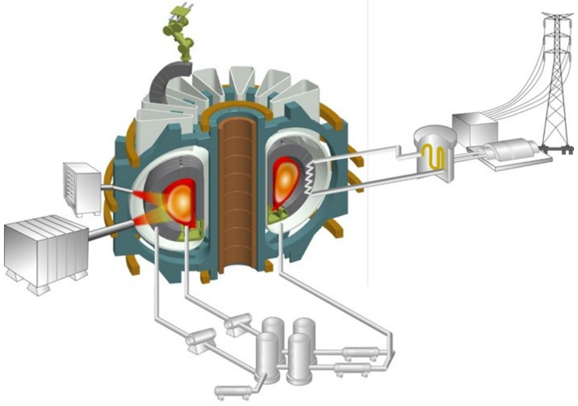
Innovation – permanent magnet stellarator



First Electricity Mid-Century



CFETR Chinese Demonstration reactor design



Korean Demonstration Reactor

Perfect Energy?

Safe, no waste legacy, abundant, minimal land use. But……

Development is not optional

We must push down the cost and scale if we are to get to market.