Introduction to Fusion Part 1.

Steve Cowley,
PPPL

1920 The British Association

Arthur Stanley Eddington -- delivered the presidential address.

One of the many questions he addressed is:

Where does the energy radiated by the stars/sun come from?

F. W. Aston had measured the masses of elements and shown:

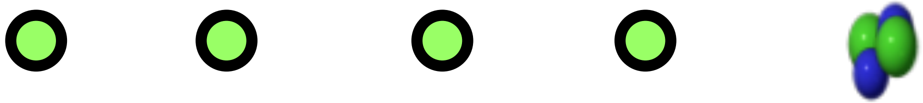
$M_{hydrogen} = 1.008$ and $M_{helium} = 4.0$

“F. W. Aston's experiments seem to leave no room for doubt that all the elements (nuclei) are constituted out of hydrogen atoms bound together with negative electrons”.

Simple Maths and $E = mc^2$

Eddington assumed that the sun puts four hydrogens together to make helium.:

H + H + H + H ➔ He



Capture 2 electrons

Mass difference is energy by Einstein's relation **$E= mc^2$**.

Hydrogen mass 1.00794 (atomic units) Mass of helium 4.0026

Thus approximately: 1.008 kilograms of hydrogen ➔ 1 kilogram of Helium

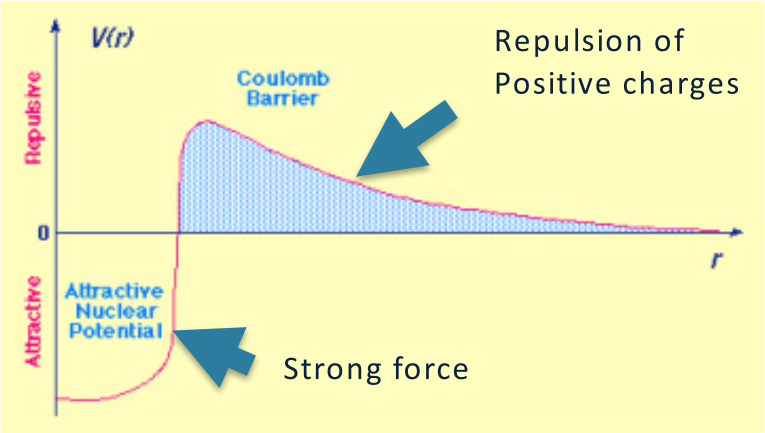
8 grams ➔ 7.5×10^{14}J of Energy.

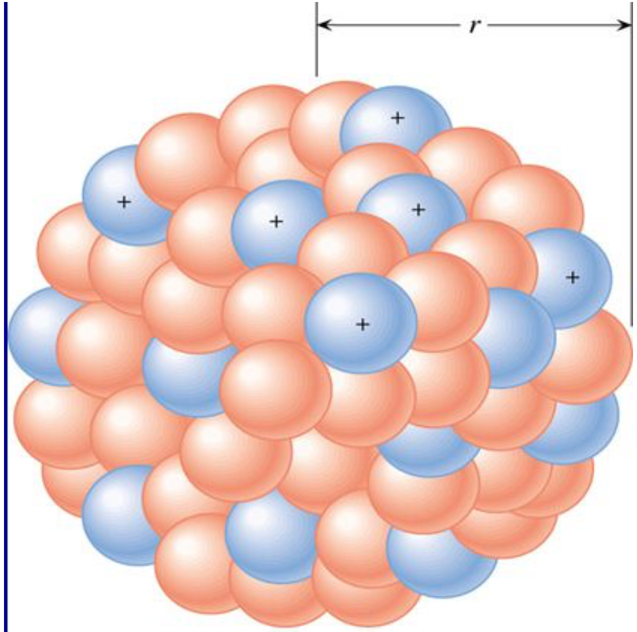
That will supply you with all your energy needs for about 10,000 years.

Binding energy of nucleus

Where does the fusion energy come from?

Building a Nucleus

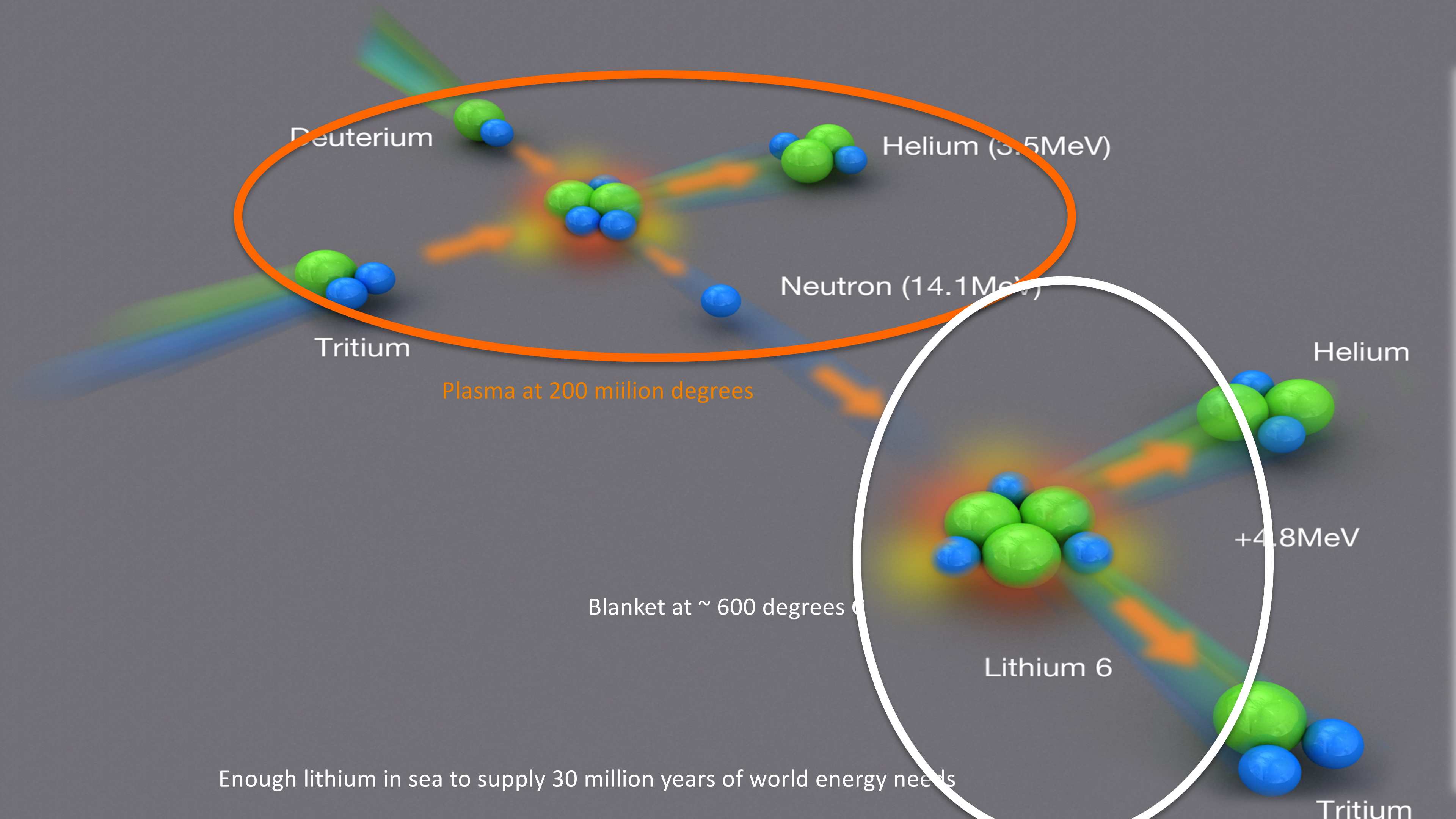




Binding energy per nucleon of a nucleus with N_p protons and N_n neutrons.

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

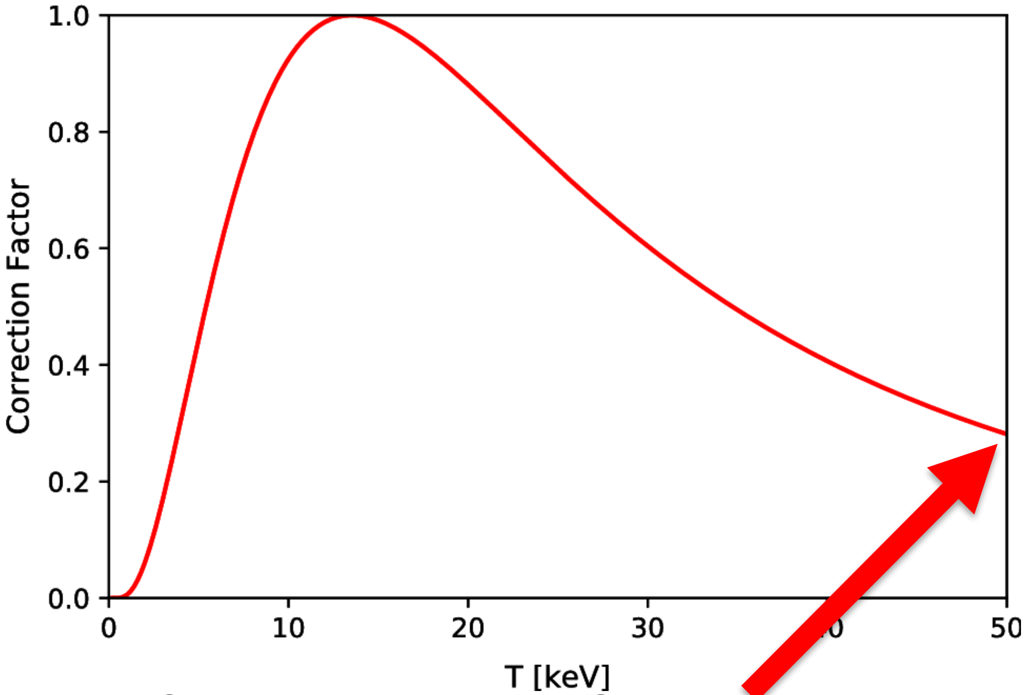
$$m_p = mass\ of\ proton$$
$$m_n = mass\ of\ neutron$$
$$M = mass\ of\ nucleus$$


Deuterium
Helium (3.5MeV)
Tritium
Neutron (14.1MeV)
Plasma at 200 miilion degrees
Helium
+4.8MeV
Blanket at ~ 600 degrees C
Lithium 6
Enough lithium in sea to supply 30 million years of world energy needs
Tritium

Reaction Rate

Simple calculation yields
The power generated in
Each cubic meter.

Approximately



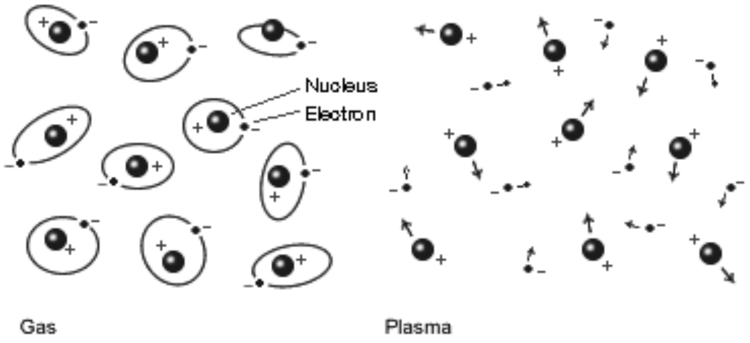
Fusion Power Density

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

Plasma pressure in atmospheres. *For a 50-50 DT mix.*

Plasma

We need temperatures of ~200,000,000° C!
at these temperatures Deuterium D and
Tritium T are ionized – a **PLASMA**



Pressure

Ideal Gas Law roughly holds for plasmas

$$PV = N_{moles}RT = N_{particles}kT$$

$$\rightarrow P = nkT$$

Boltzmann's constant

Density of particles

What is the pressure of a plasma at 200,000,000° C?

Pressure of plasma
In atmospheres

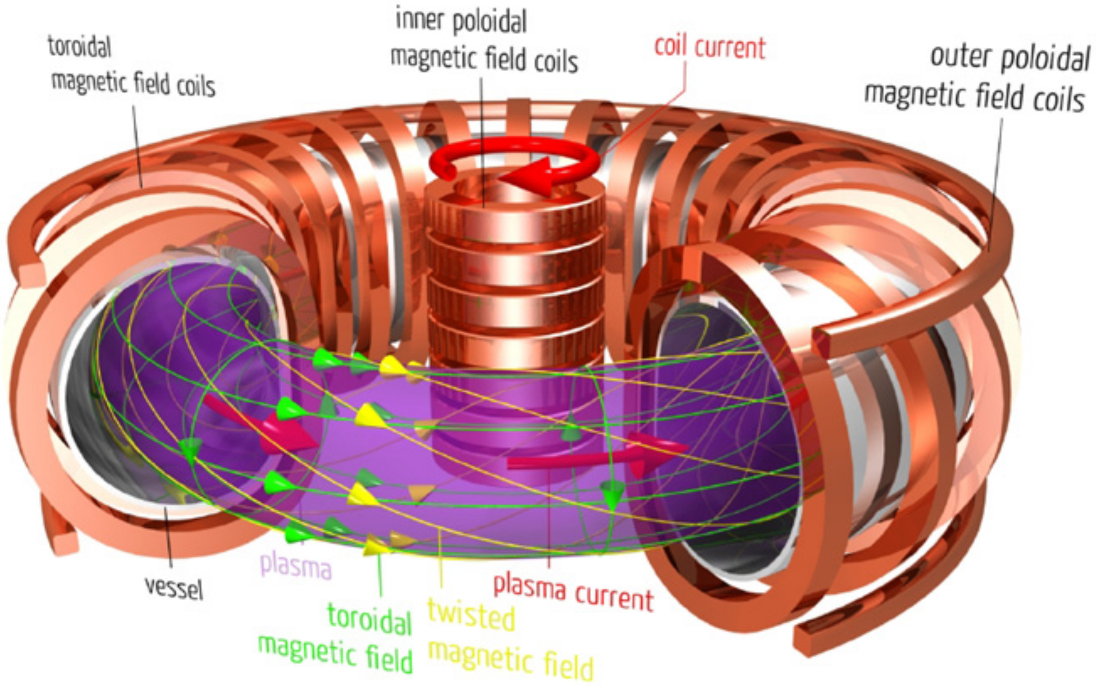
$$\frac{P_{plasma}}{P_{air}} = \frac{n_{plasma}}{n_{air}} \frac{T_{plasma}}{T_{air}}$$

$$= \frac{n_{plasma}}{n_{air}} 10^6$$

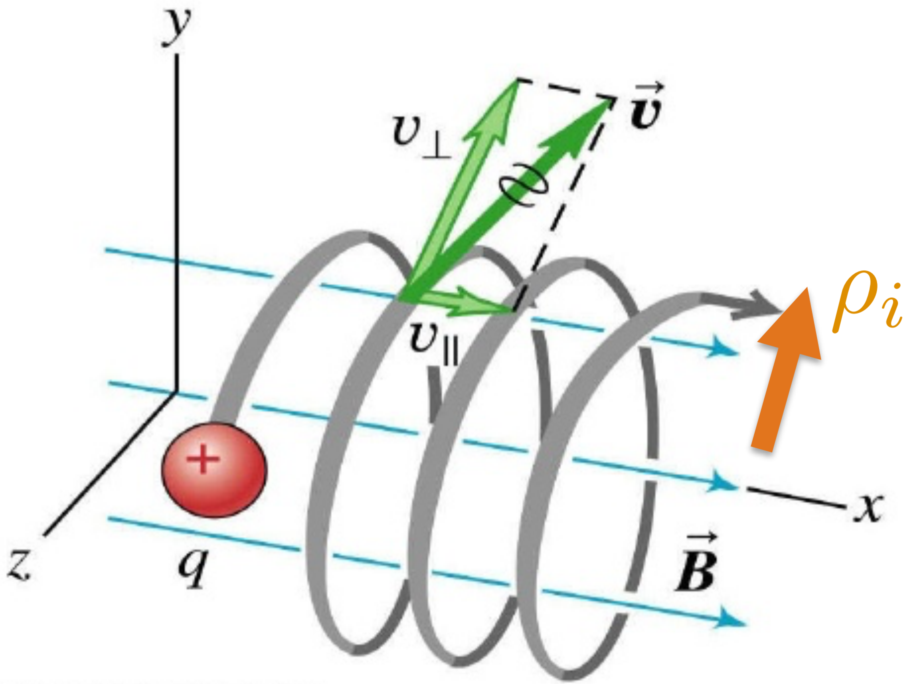
Vessels can only hold a few tens or hundreds of Atmospheres.

Therefore we can either do fusion in a very low density plasma or in an exploding plasma.

Magnetic fusion – making a bottle

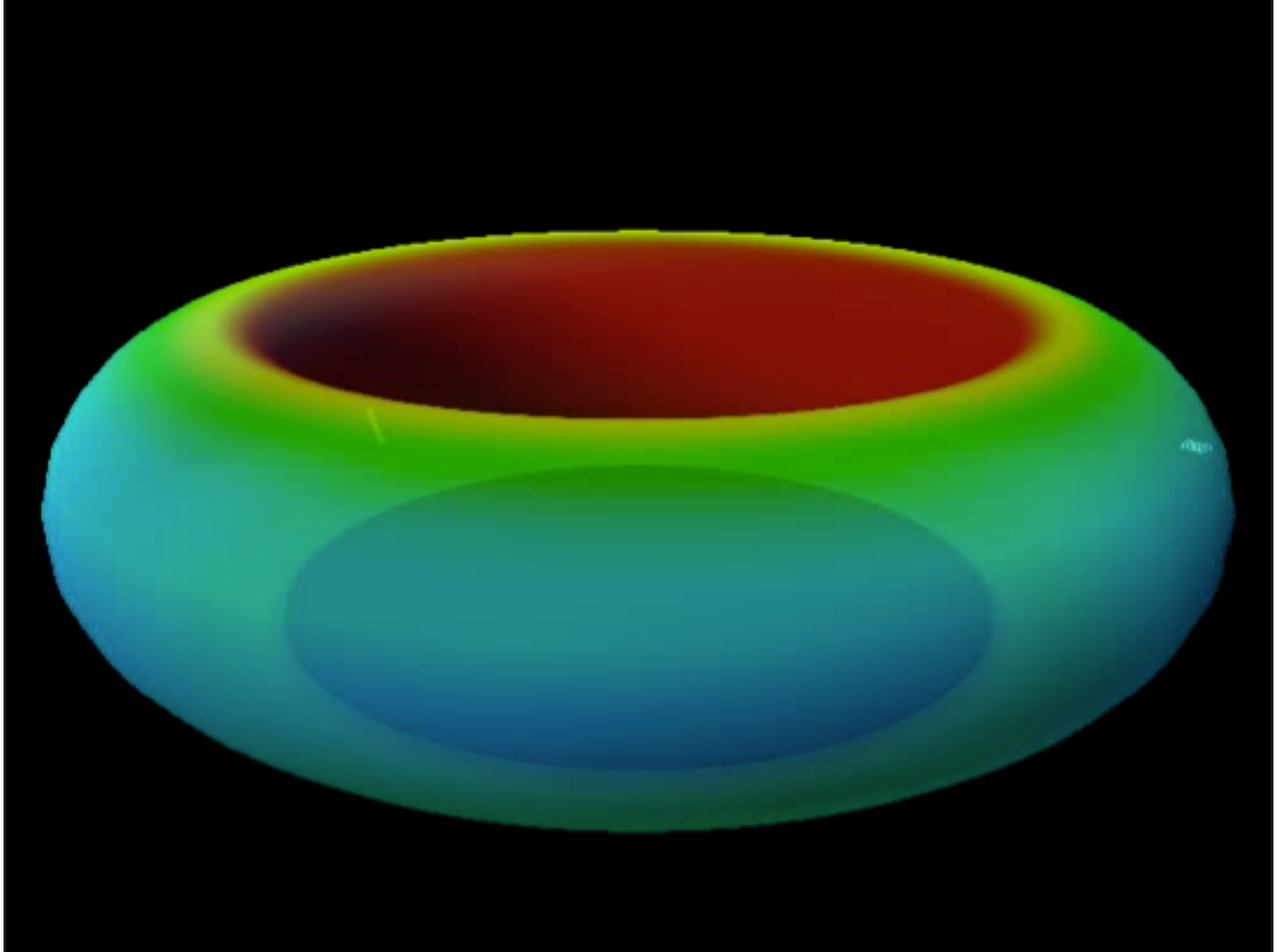


Motion of charged particles in a magnetic field



ρ_i Larmor Radius

See Will Fox’s lecture tomorrow at 13:30



Magnetic Pressure

Magnetic Field has to push on the particles $\mathbf{F}_{total} = \sum q_i \mathbf{v} \times \mathbf{B}$

$$\sim 2\pi R \mathbf{I} \times \mathbf{B}$$

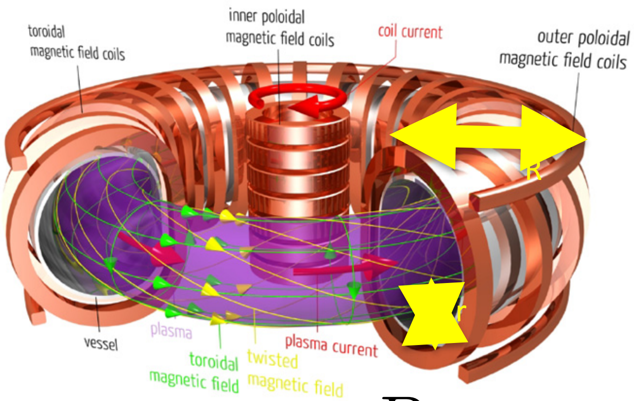
Ampere's law for a current carrying wire

$$B \sim \frac{\mu_0 I}{2\pi r}$$

$$A = 2\pi r 2\pi R = area\ toroidal\ surface$$

$$\rightarrow F_{total} \sim \frac{AB^2}{\mu_0}$$

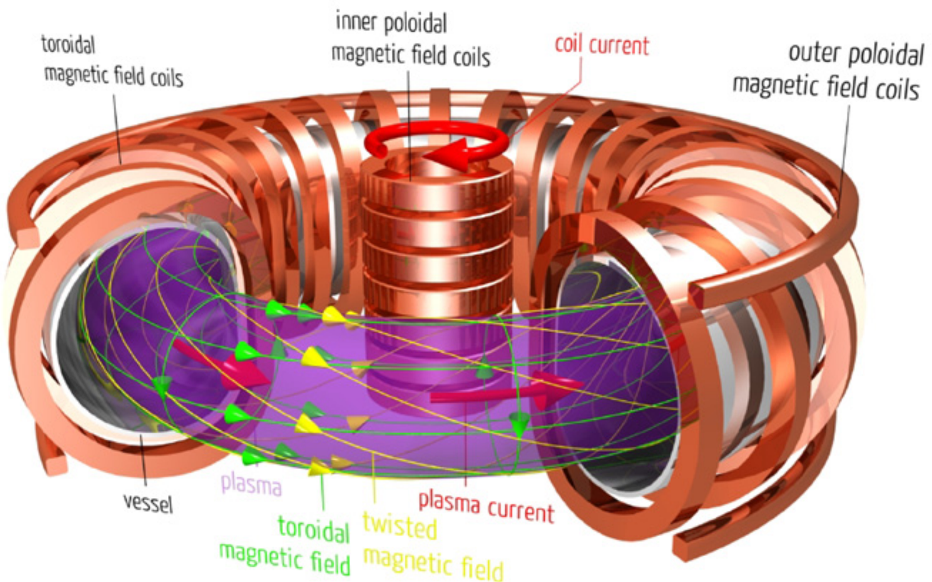
Magnetic pressure



$$P = \frac{B^2}{\mu_0}$$

$$P_{magnetic}(atmospheres) \sim 4B^2(Tesla)$$

Equilibrium



$$\nabla P = \mathbf{J} \times \mathbf{B}$$

Plasma Pressure force

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

Ampere's law

$$\rightarrow \nabla P = -\nabla \frac{B^2}{2\mu_0} + \mathbf{B} \cdot \nabla \mathbf{B}$$

Magnetic pressure force

Magnetic Curvature force

Simple considerations – things we all know

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

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

Plasma pressure in atmospheres

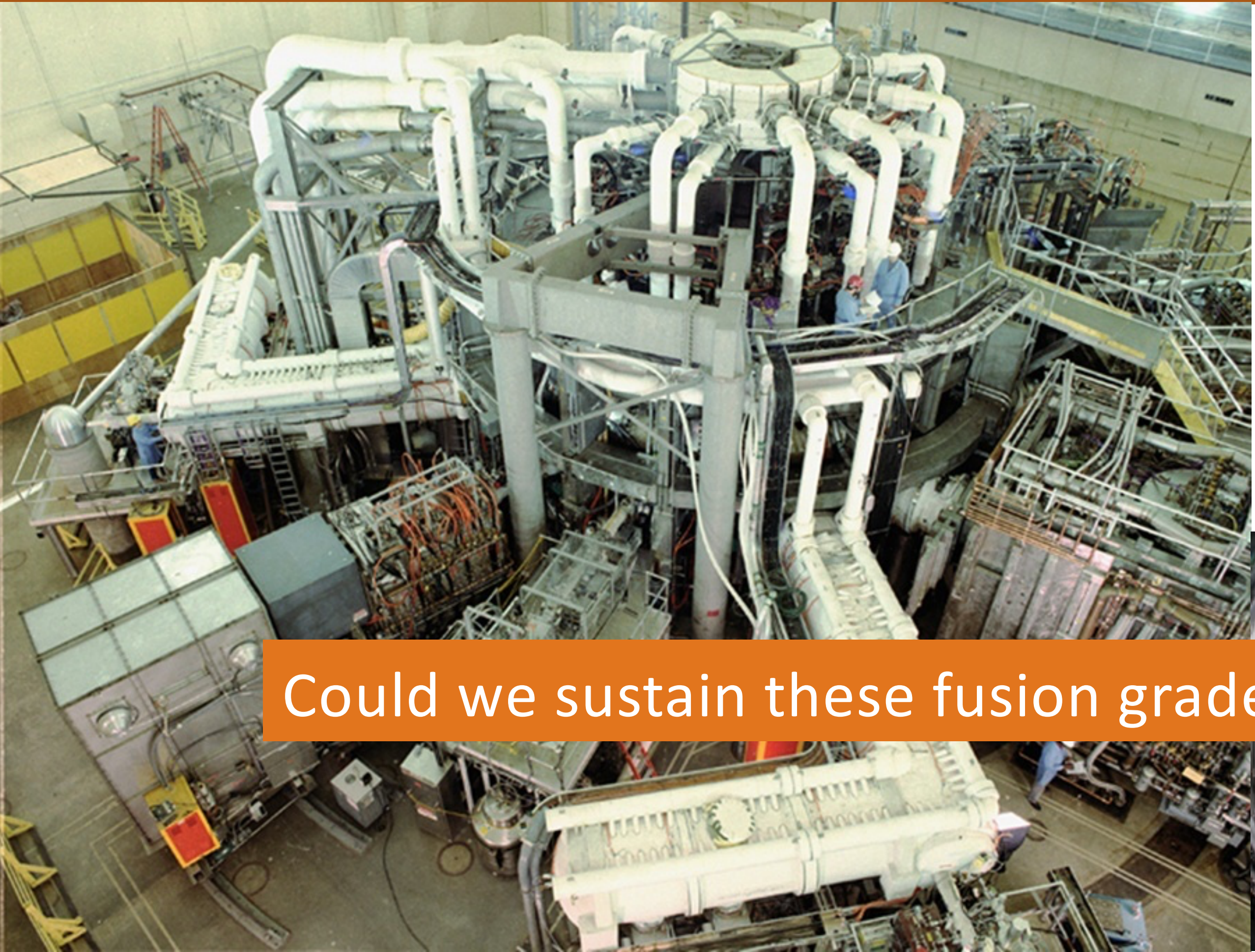
Magnetic pressure:

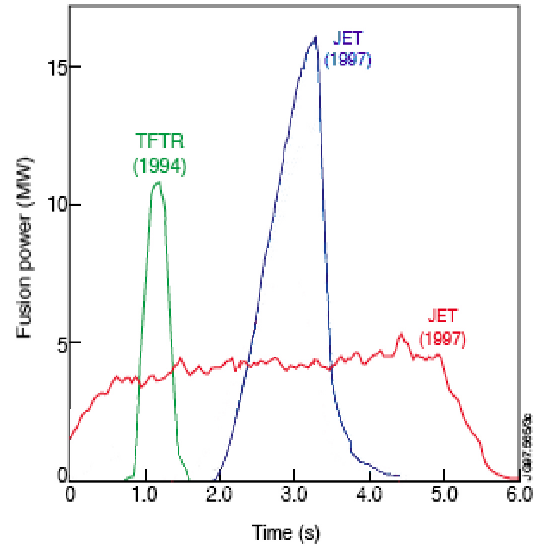
Figure of merit

Limited by stability: $\beta = \dfrac{P}{P_{magnetic}}$

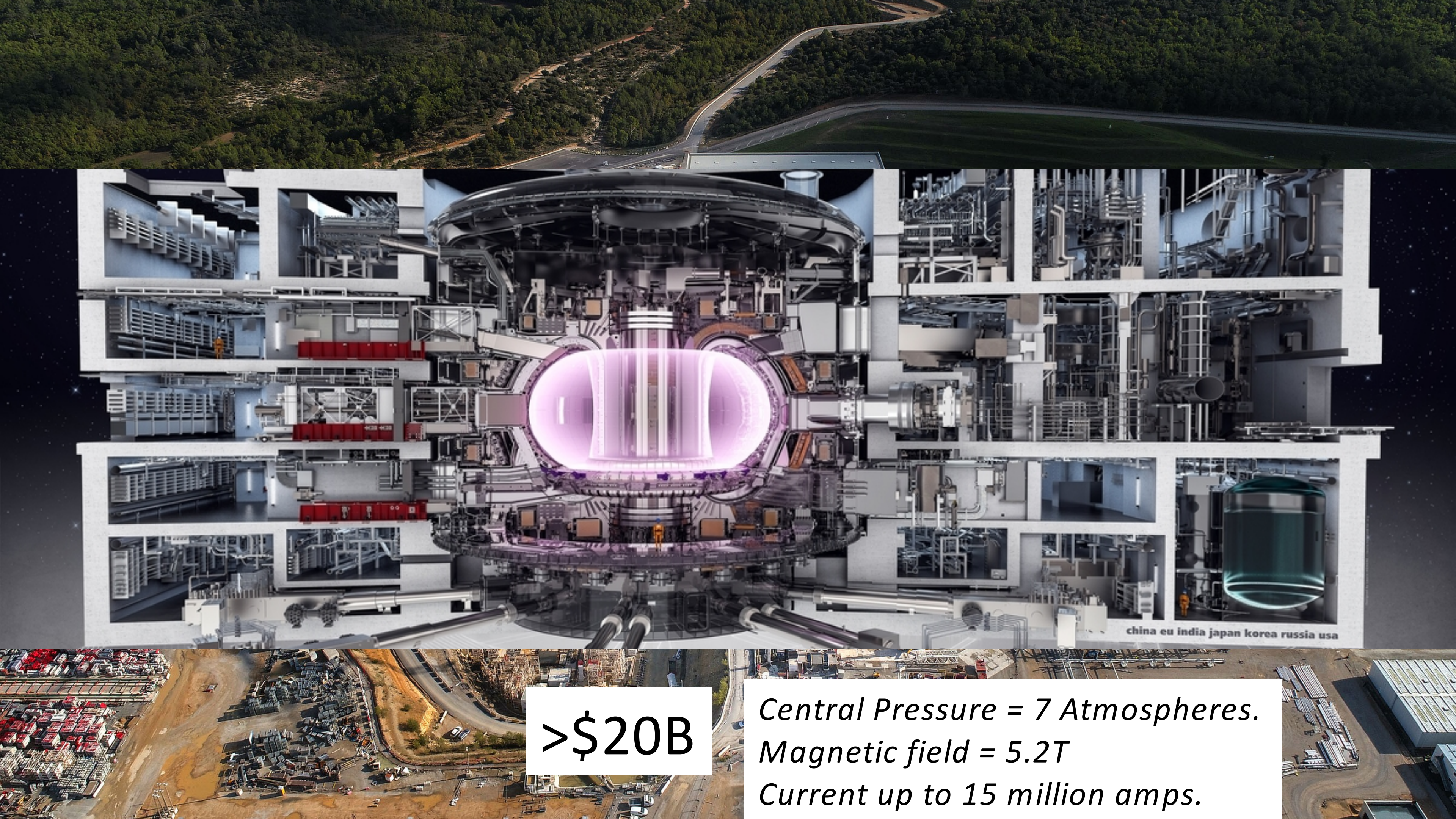
$$\mathcal{P}_{Fusion} = 1.28\beta^2 B^4$$

Princeton – TFTR 1994, JET 1997





Could we sustain these fusion grade plasmas?

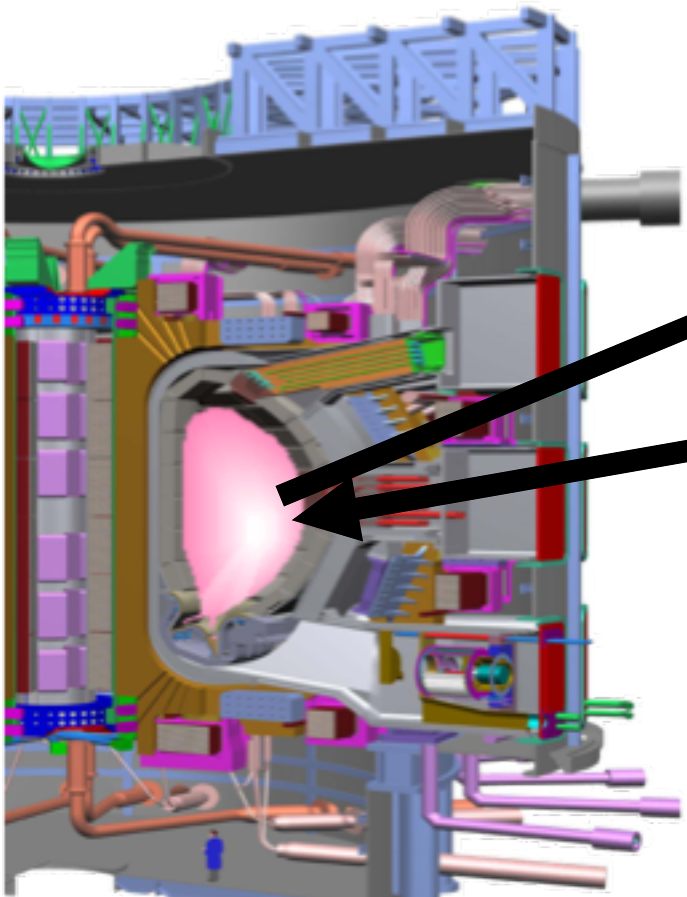


>$20B

Central Pressure = 7 Atmospheres.
Magnetic field = 5.2T
Current up to 15 million amps.

What will ITER do?

Fusion Energy Balance in ITER



Turbulent Plasma Energy Loss

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

Confinement Time in seconds

External Plasma heating

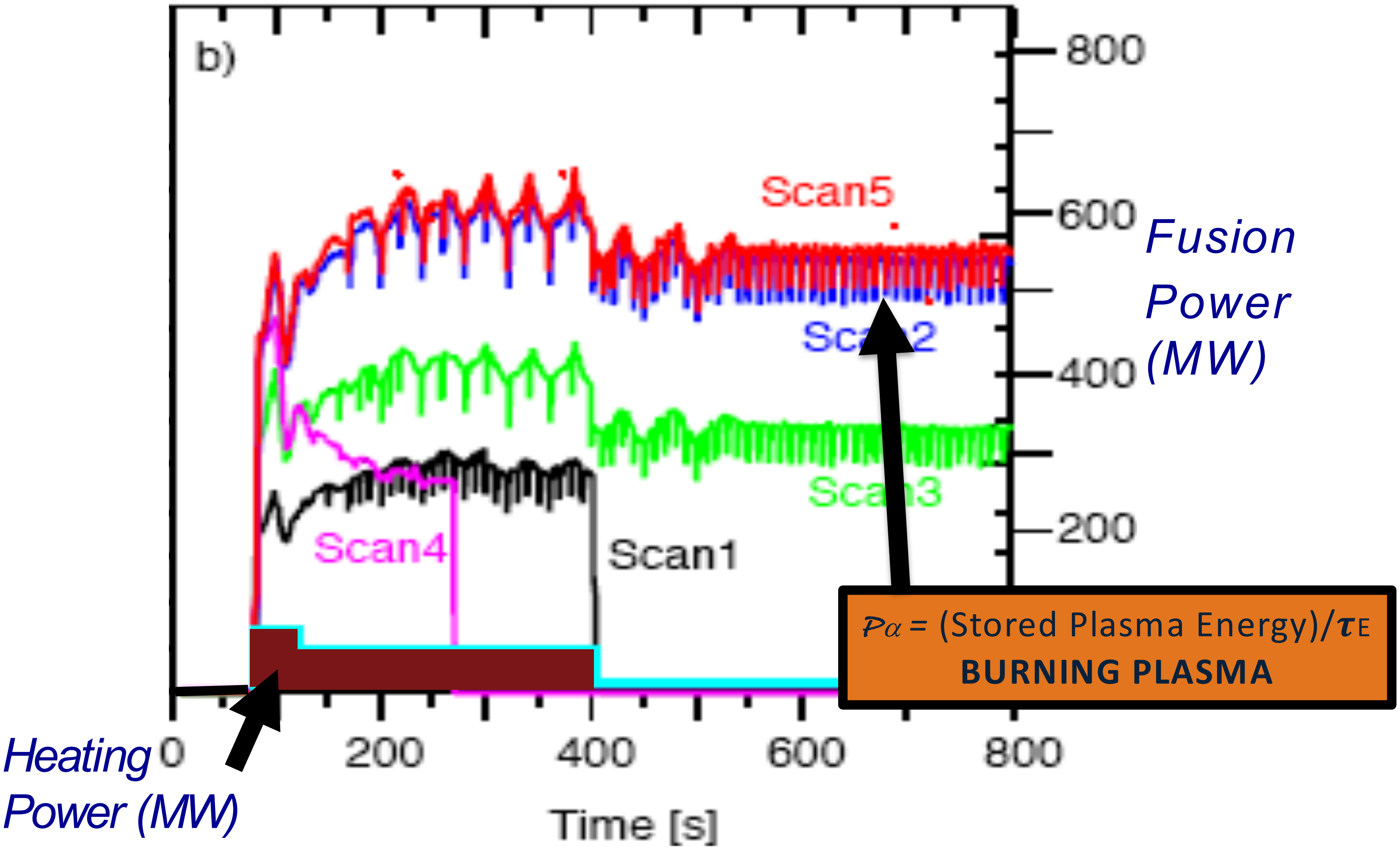
$\mathcal{P}_{Heat}$ ~50MW

Energy Balance

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

Energy Gain = Q > 10

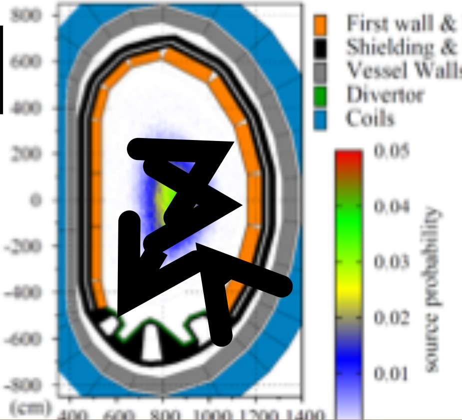
Simulation by Bob Budny: Based on JET results from 2008-2013

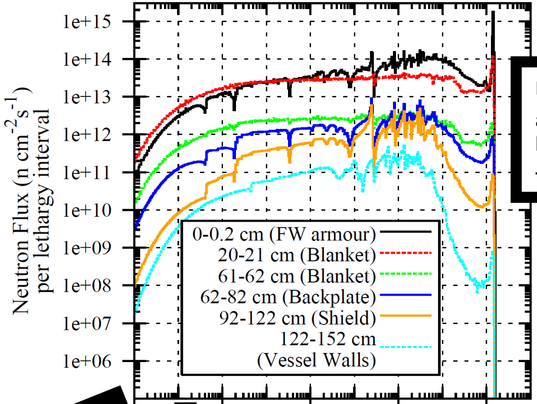


Assessment of materials lifetime: an integrated approach

See Lauren Garrison's talk Tuesday next week

Plasma as a 3D neutron source

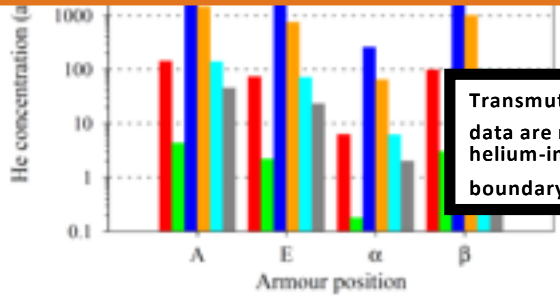




Neutron spectra at various locations in a tokamak

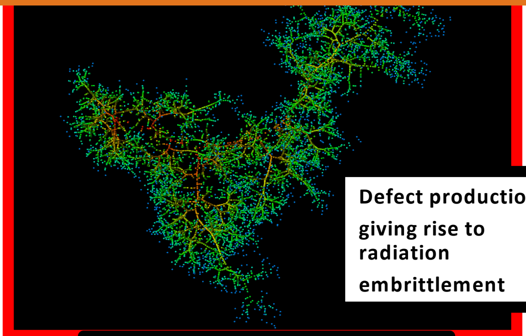
Rule of thumb.

1MW per square meter of wall moves each atom in he wall ten times in a "full power year".



Transmutation cross-section data are required to predict helium-induced grain boundary embrittlement

M.R. Gilbert *et al.*, Nucl. Fusion **52** (2012) 083019; J. Nucl. Mater. **442** (2013) S755



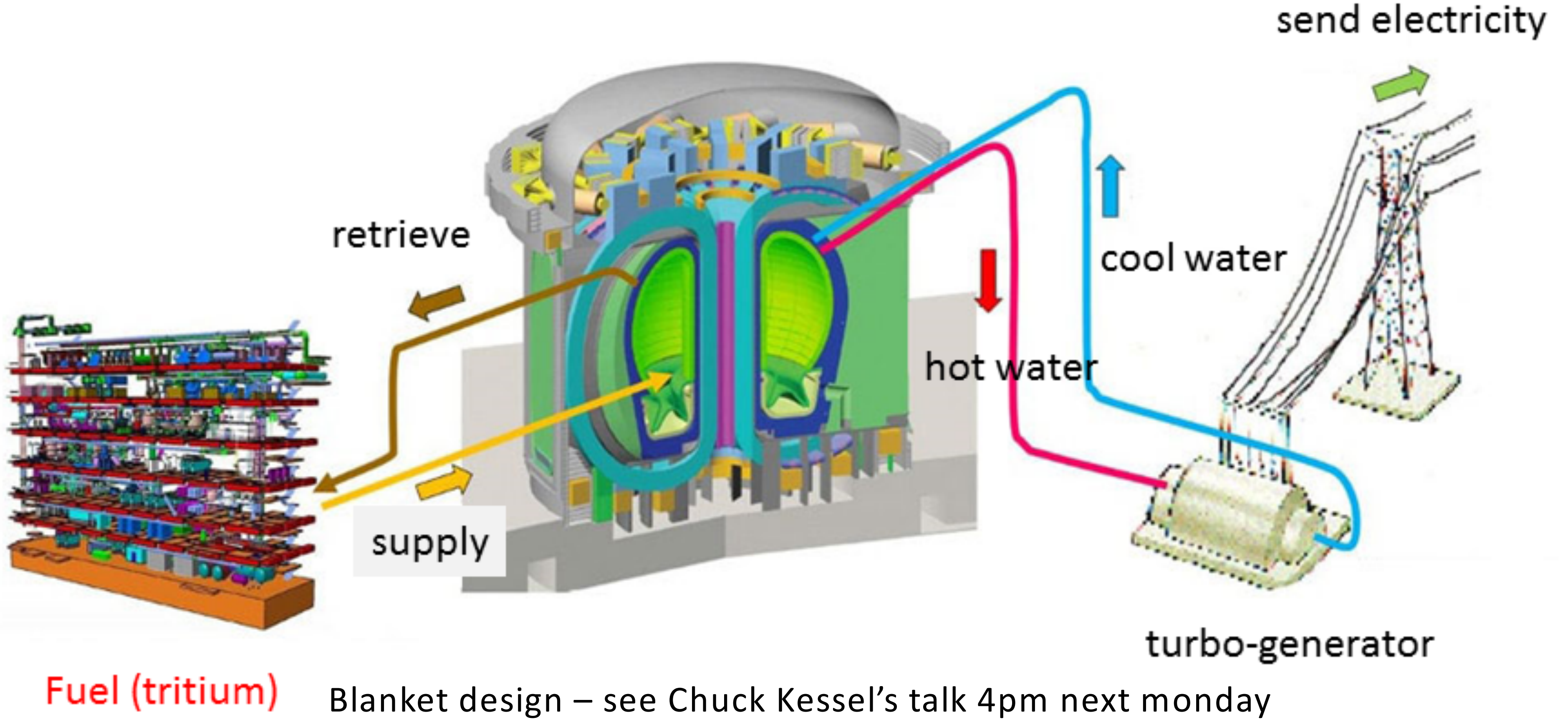
Defect production, giving rise to radiation embrittlement

A. Sand *et al.* EPL **103** (2013) 46003

So you thought you had Tungsten on the Wall

Thanks to M.R. Gilbert

Neutrons to Electricity – Balance of Plant



Blanket design – see Chuck Kessel's talk 4pm next monday

End of Part 1.