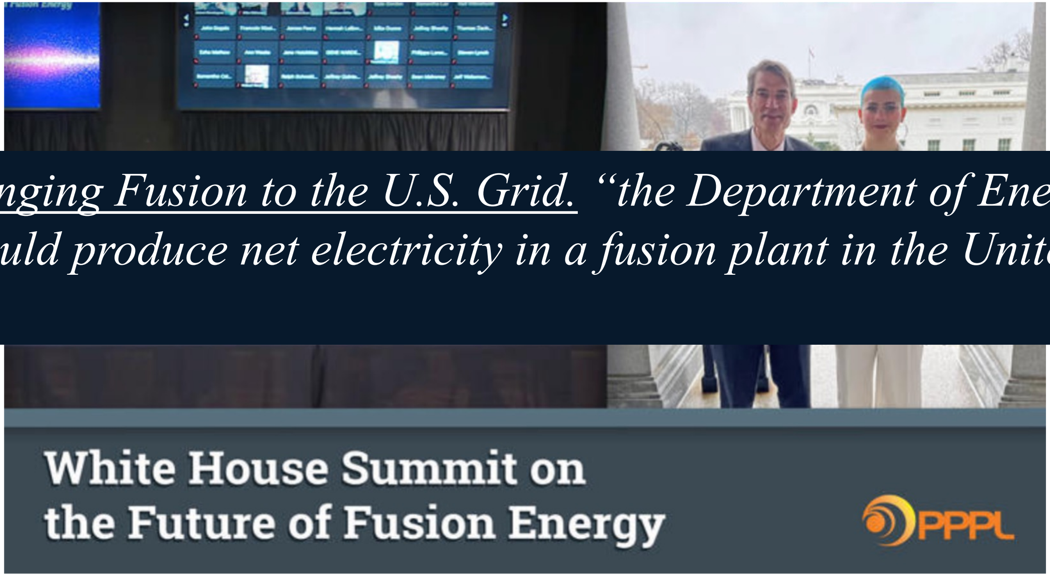
Getting to a Fusion Pilot Plant – the Challenge.

Steve Cowley – Princeton Plasma Physics Lab.

April 2024

US Decadal Strategy to Accelerate Fusion to Commercialization

- *"The DOE will launch an agency-wide initiative, coordinating across program offices, to develop a decadal strategy to accelerate the viability of commercial fusion energy in partnership with the private sector. The 2021 National Academies of Sciences, Engineering, and Medicine (NASEM) report 'Bringing Fusion to the U.S. Grid' serves as a guiding document for the new initiative."* White House March 2022



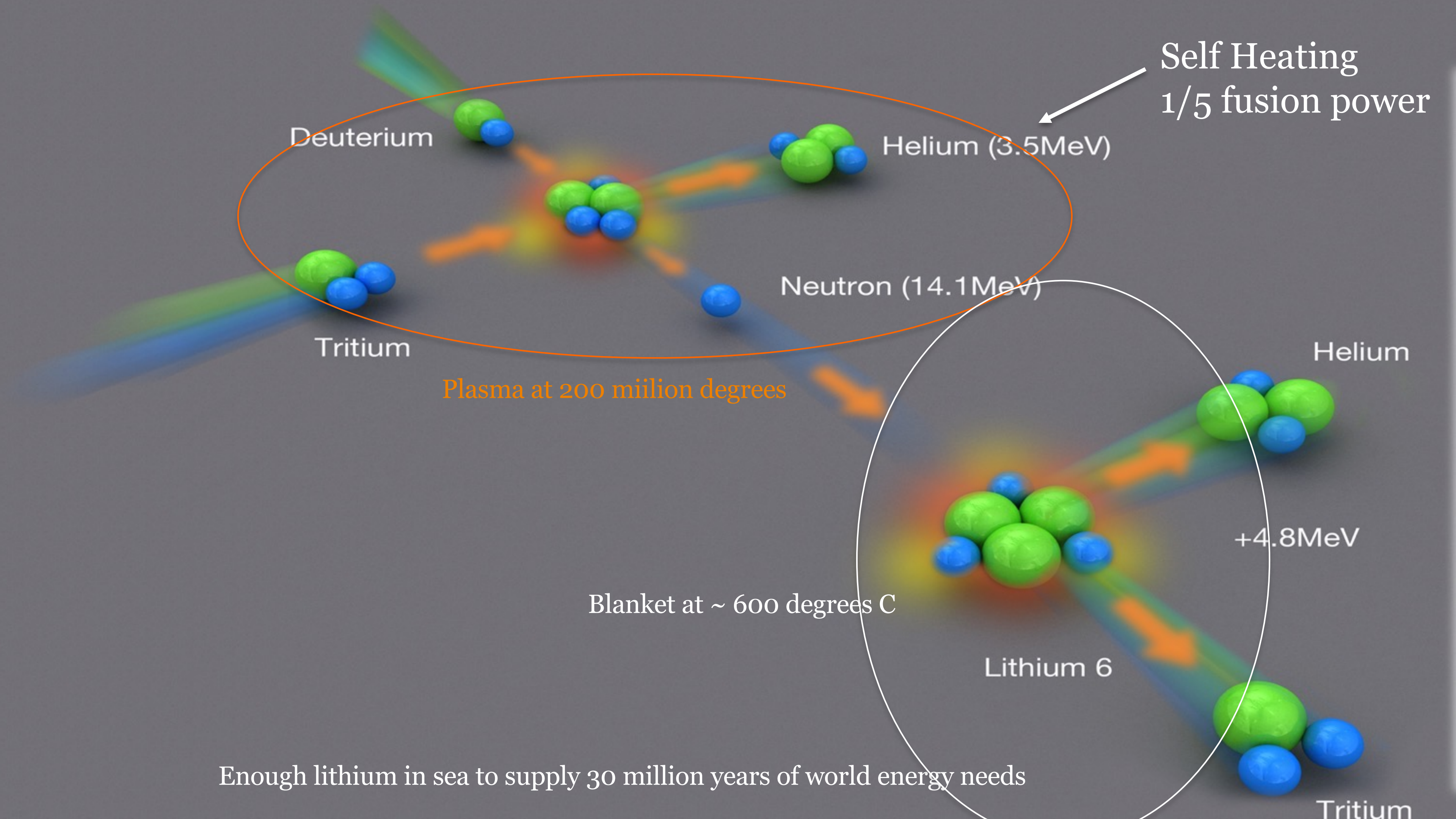
Bringing Fusion to the U.S. Grid. *"the Department of Energy and the private sector should produce net electricity in a fusion plant in the United States in the 2035-2040 timeframe."*

Is this possible? This talk.

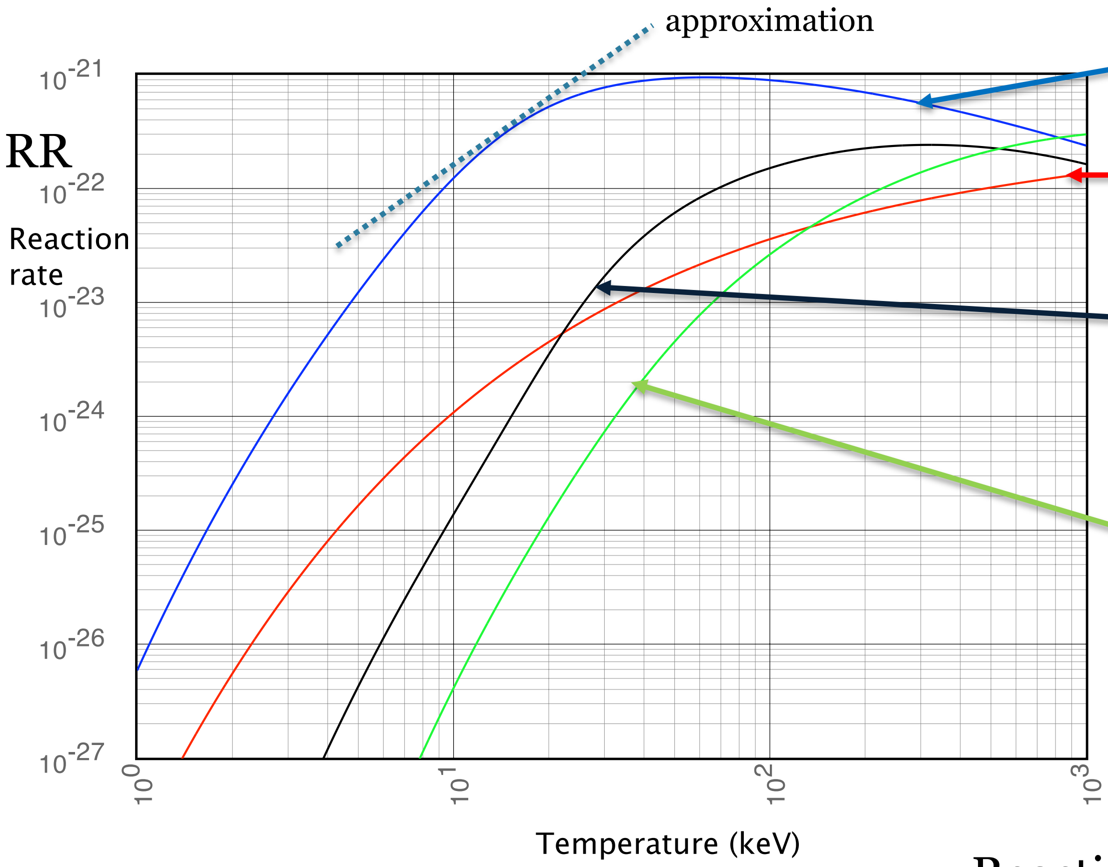
- This is a declared plan to build a *"Fusion Pilot Plant" – FPP,* with *"Net electricity"* by 2035-40.
- What is a *"Fusion Pilot Plant." "Net electricity,"* how much? Is this a prototype of a commercial plant?
- Can we build a plant with today's knowledge? With today's materials?
- I will give you a personal view of the challenge.
- This will be based on simple scaling – more accuracy is not often very possible.
- The bottom line is that I believe that we must aim for a low power density FPP system to minimize the impact of the key unknowns. Chief unknown is material performance in the neutron flux.
- Stellarators make better low power density Pilot Plants

PRINCETON PLASMA PHYSICS LABORATORY

What is it?


Self Heating
1/5 fusion power
Deuterium
Helium (3.5MeV)
Neutron (14.1MeV)
Tritium
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

Other Reactions



$D + T \longrightarrow He^4(3.5\ \text{MeV}) + n(14.1\ \text{MeV})$

$D + D \xrightarrow{50\%} T(1.01\ \text{MeV}) + p(3.02\ \text{MeV})$

$ \xrightarrow{50\%} He^3(0.82\ \text{MeV}) + n(2.45\ \text{MeV})$

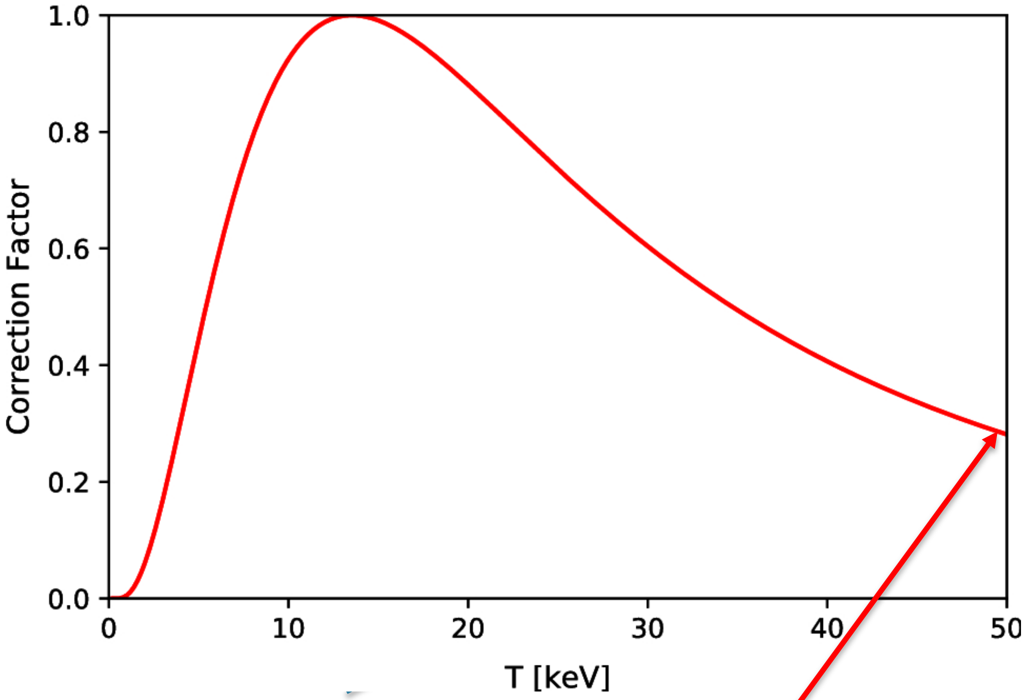
$D + He^3 \longrightarrow He^4(3.6\ \text{MeV}) + p(14.7\ \text{MeV})$

$p + B^{11} \longrightarrow 3\ He^4 + 8.7\ \text{MeV}$

$\text{Reactions}/m^3 = n_D n_T(RR)$

Reaction Rate – D-T

Simple approximation yields the power generated in each cubic meter from 3.5MeV alpha particles.



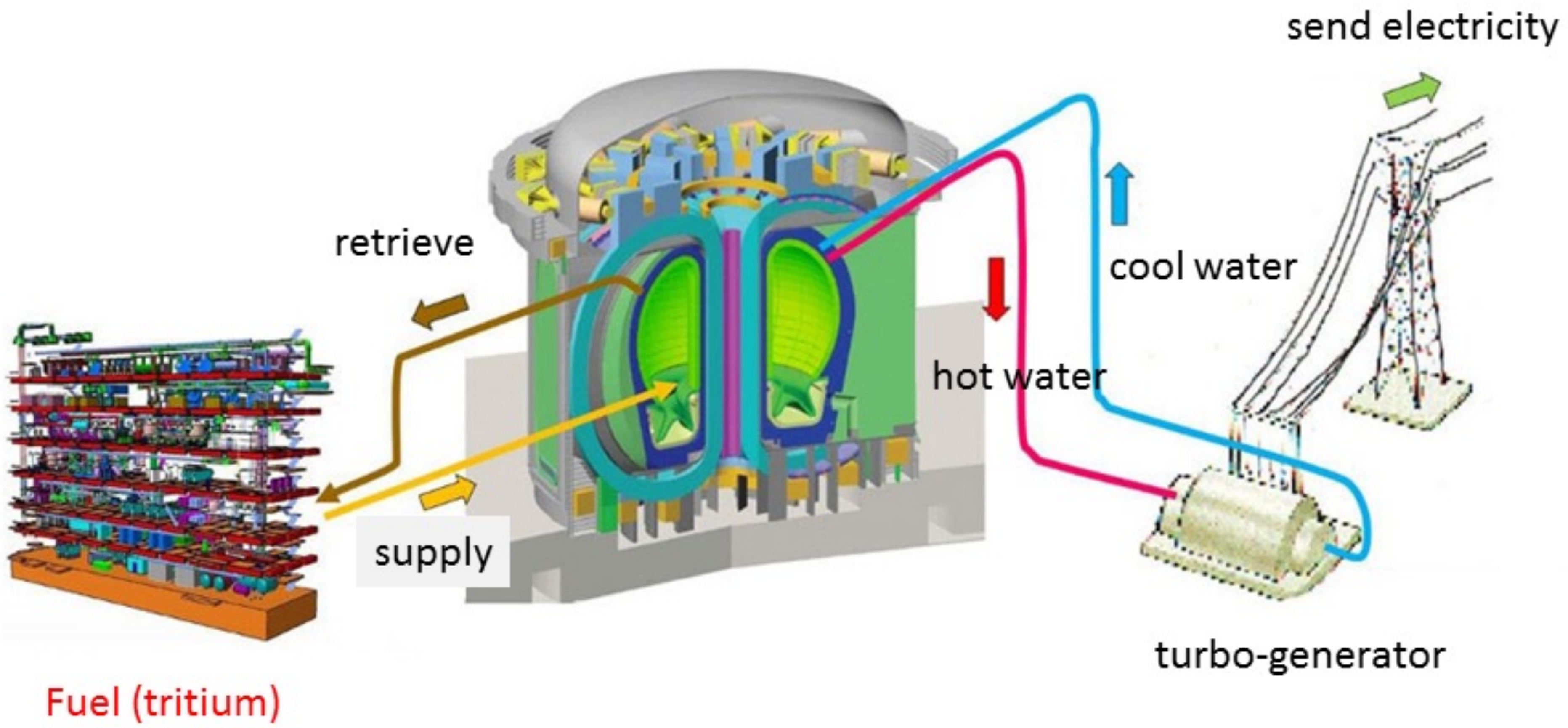
Fusion Power Density

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

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

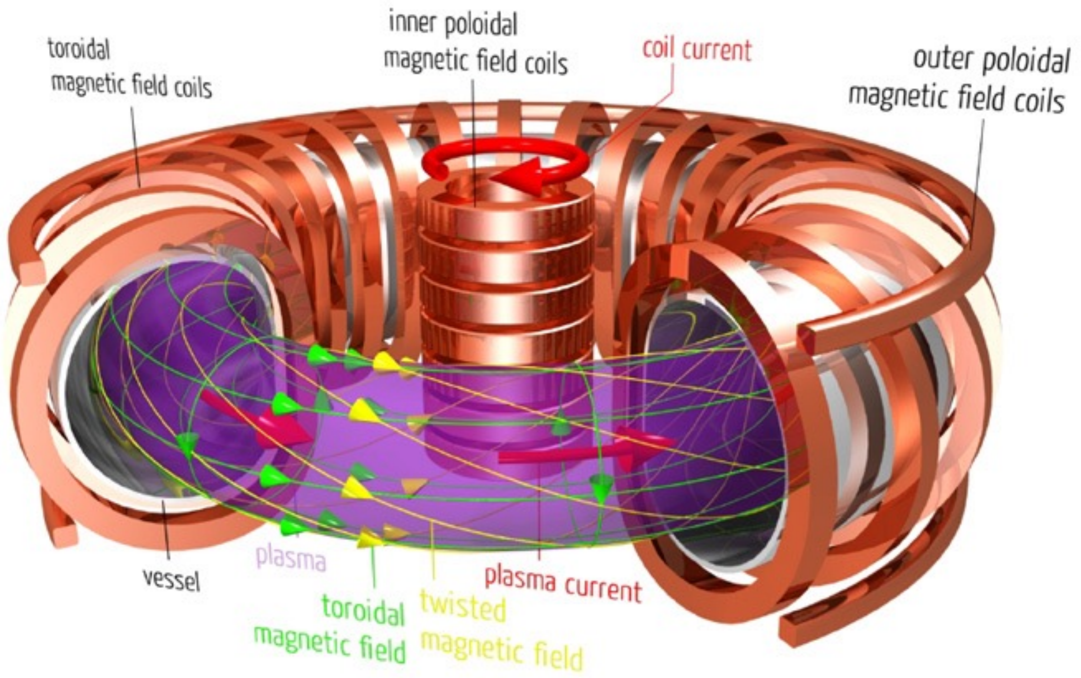
Making Electricity?

Neutrons to Electricity – Balance of Plant



Confining the plasma?

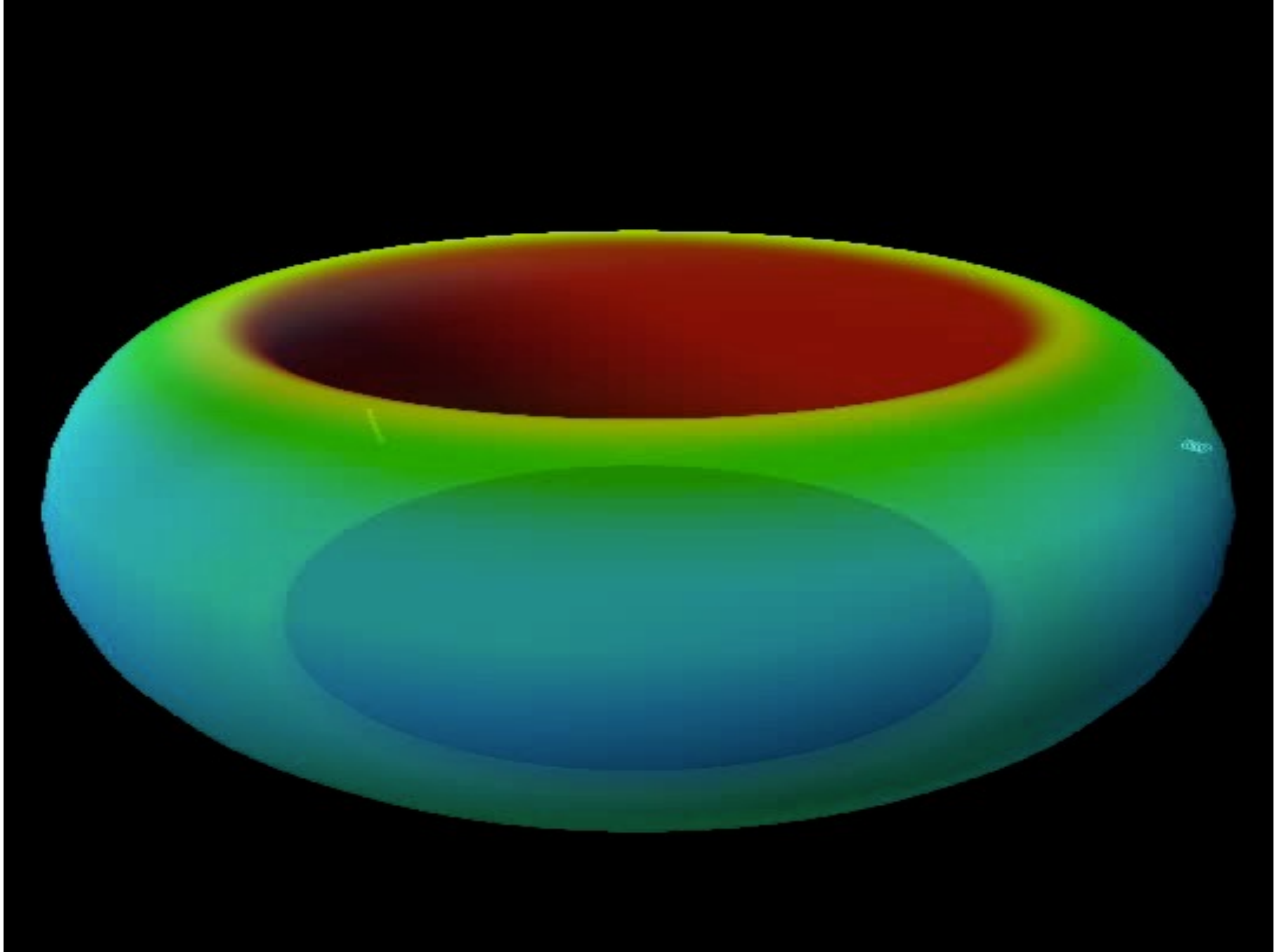
Magnetic fusion – making a bottle



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

Magnetic Field in Tesla

Figure of merit $\beta = P/P_{magnetic}$ a few percent



How does the heat get out?

DIII-D Shot 121717

GYRO Simulation

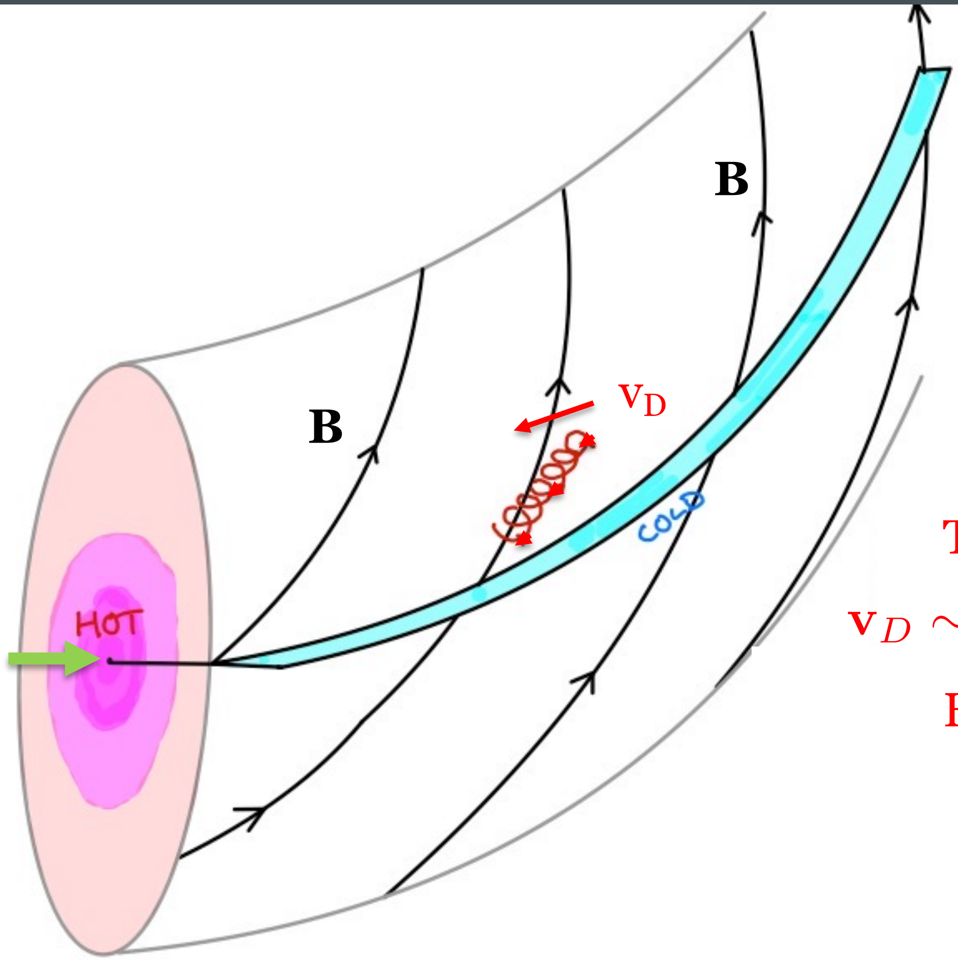
Cray X1E, 256 MSPs

Thanks to Ron Waltz, Geoff Can

Cartoon Physics of Instability

Temperature gradient.

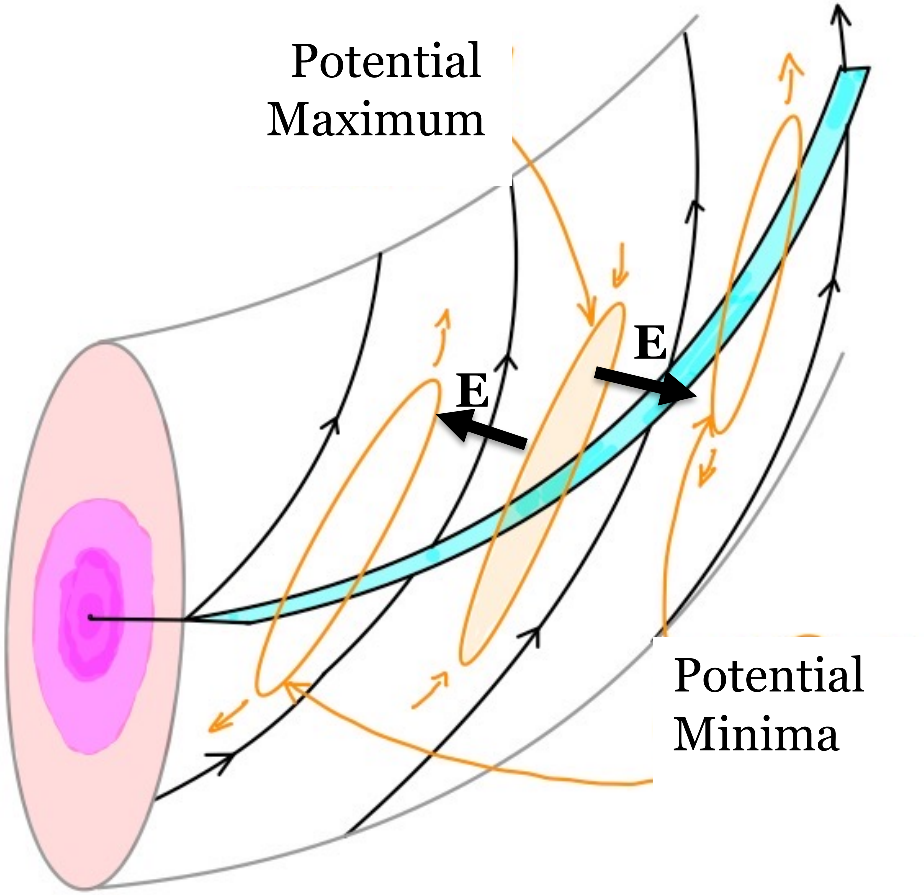
∇T_i



Toroidal ion drift

$$\mathbf{v}_D \sim \frac{v_\perp^2}{\Omega_i}\mathbf{b} \times \nabla \ln B \sim \frac{\rho_i}{R} v_{thi}$$

Hotter ions drift faster



The plasma must be almost neutral
Thus, ion density perturbation = electron density perturbation.

$$\delta n_i = \delta n_e$$

Electrons move so fast they set up thermal equilibrium along the Magnetic field lines

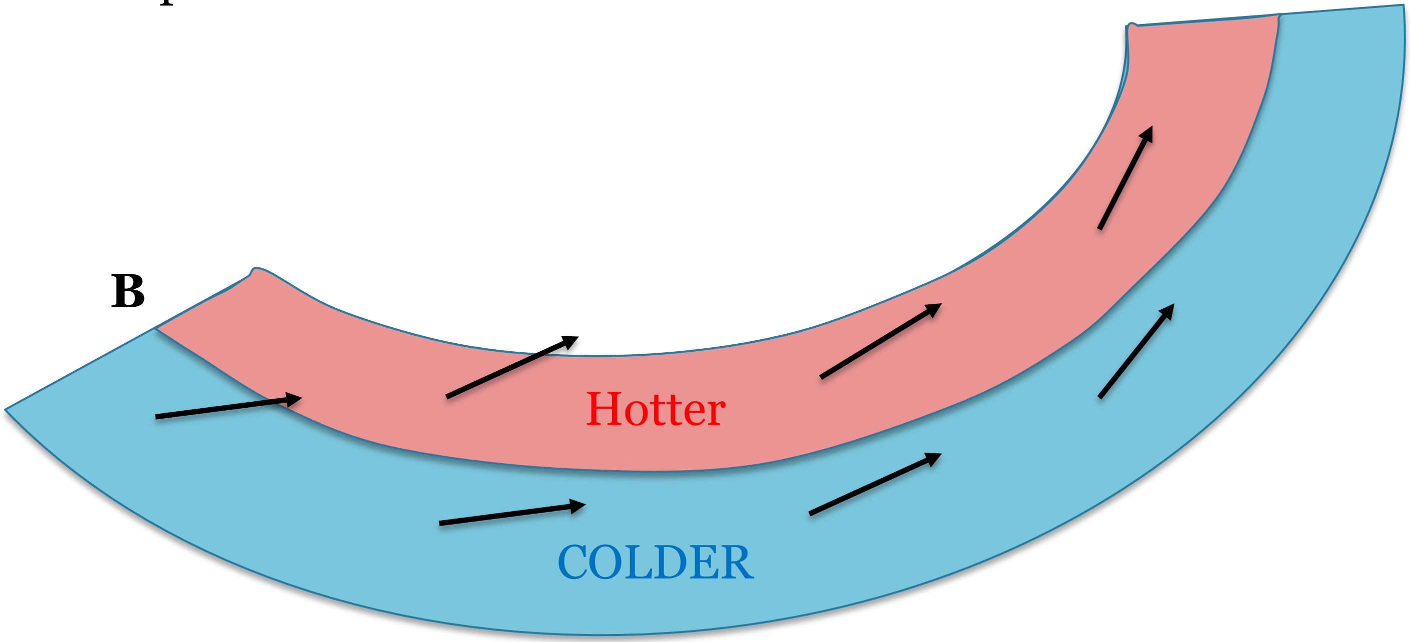
$$n_e = n_0 e^{\frac{e\phi}{T_e}} \rightarrow \delta n_e = n_0 \frac{e\phi}{T_e}$$

Therefore, density perturbation makes electric field

$$\mathbf{E} = -\nabla \phi$$

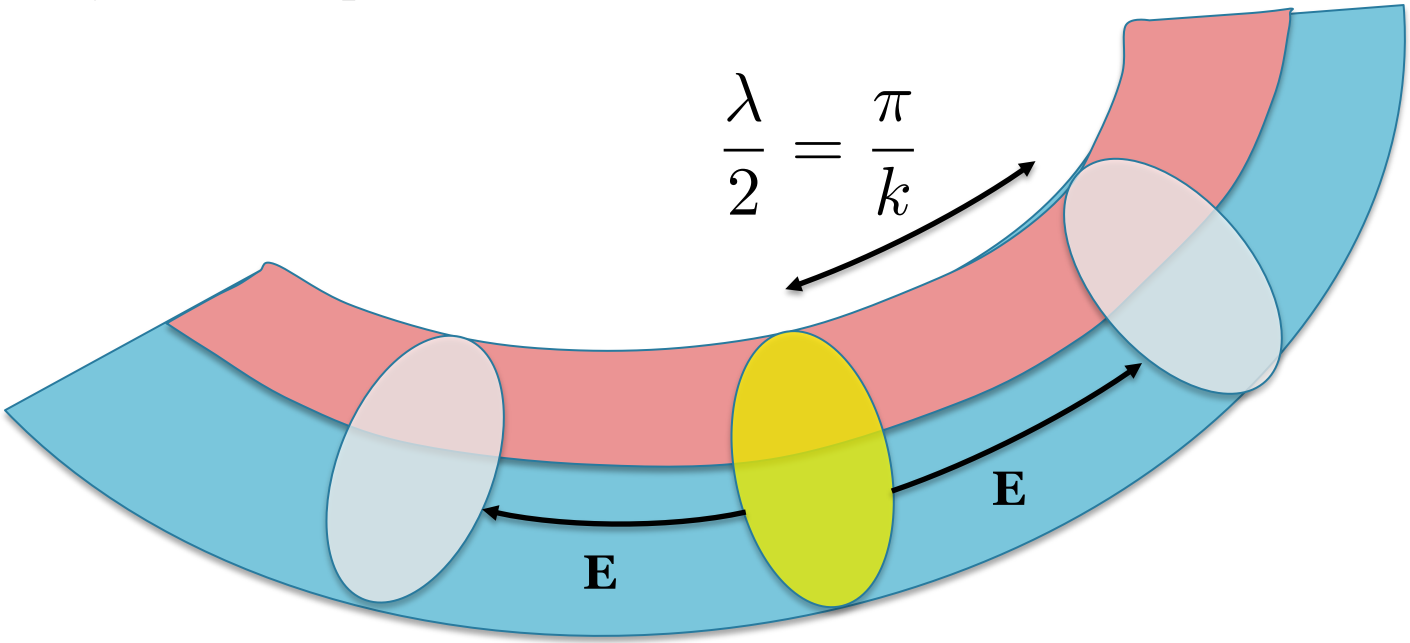
ExB motion

Outer midplane



ExB motion

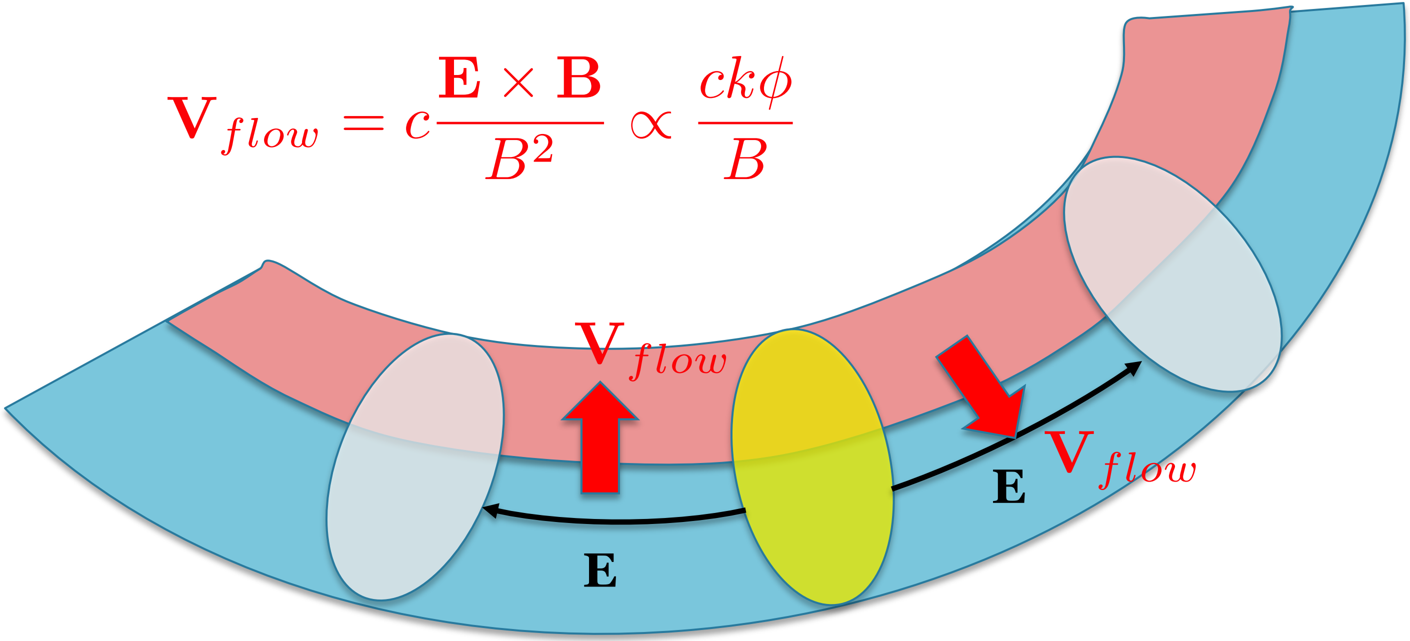
Density/Potential perturbations.



ExB motion

Potential causes flow.

$$\mathbf{V}_{flow} = c\frac{\mathbf{E}\times\mathbf{B}}{B^2} \propto \frac{ck\phi}{B}$$



Toroidal Drift perturbed

$$\frac{\partial \delta n_i}{\partial t} = -n_0 \nabla \cdot \mathbf{v_D}$$

$$\gamma \delta n_i \sim n_0 k \delta v_D \sim n_0 k v_D \frac{\delta T_i}{T_0}$$

$$\gamma \delta n_i \sim \gamma n_0 \frac{e\phi}{T_0} \sim n_0 k v_D \frac{c k \phi}{\gamma B L_T}$$

$$\boxed{\gamma \sim k\sqrt{v_D v^*}} \quad where \;\; v^* = \frac{\rho_i}{L_T} v_{thi}$$

Energy Confinement -- Random walk of heat/particles.

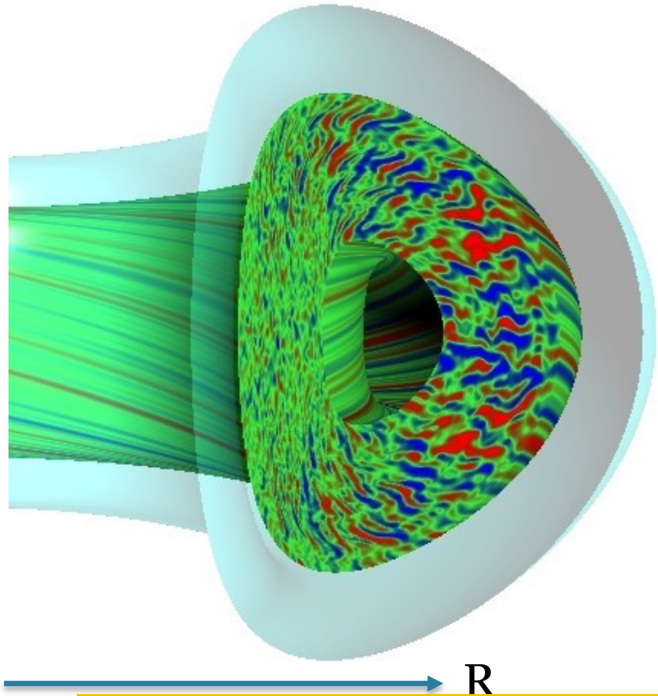
N random turbulent steps to leave machine, Eddy size ρ_i – Larmor radius

V_{thi} = ion thermal velocity

$$R \sim \sqrt{N}\rho_i \rightarrow N \sim (\frac{R}{\rho_i})^2$$

For ITER N ~ 10^6.

Eddy turnover time = $\tau_{eddy} \sim \frac{R}{v_{thi}}$



Time for energy/heat to leave plasma τ_E

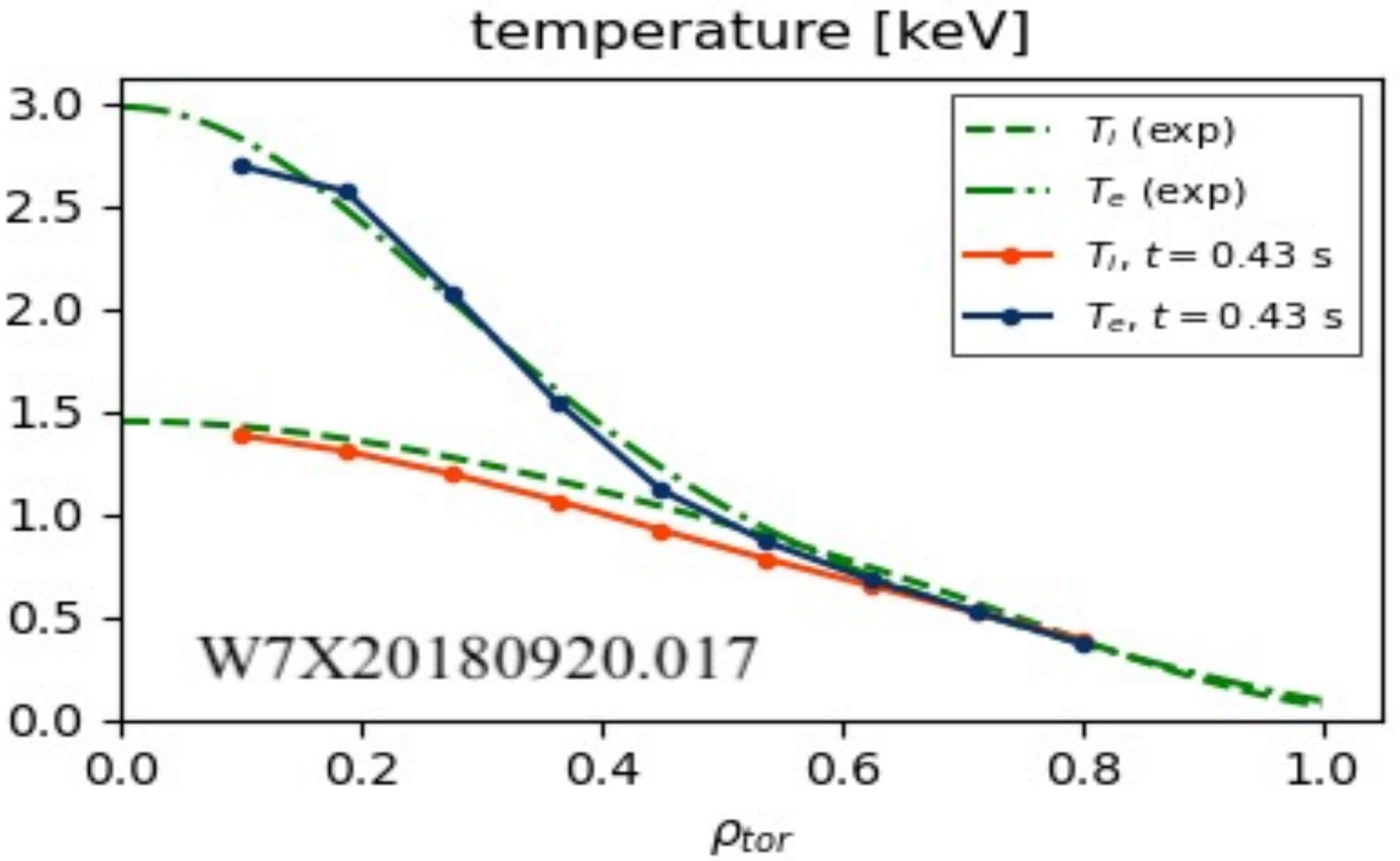
$$\tau_E = N\tau_{eddy} \propto B^2R^3T^{-3/2}$$

Work at constant temperature the community defines an enhancement factor H such that

Empirical Scaling (ITER 1998).

$$\tau_E \propto H^{3.23}B^{1.7}R^{2.7}$$

Validation: direct comparison with W7X20180920.17



›erimental ECRH

18.5 hrs

24 nodes (96 GPUs)

Noah Mandel
Bill Dorland
Patrick Kim

Burning – self heated plasma (heated by alpha particles)

$$\mathcal{P}_\alpha = \frac{energy\ \ density}{\tau_E} = \frac{3P}{2\tau_E} \qquad self\ \ heated$$

$0.018P^2$

CONDITION TO BE SELF HEATED

$$P\tau_E > 10(atmopsphere,\ s) \quad \text{“}Lawson\ Triple\ Product\text{”}$$

$\tau_E \propto H^3 B^2 R^3$

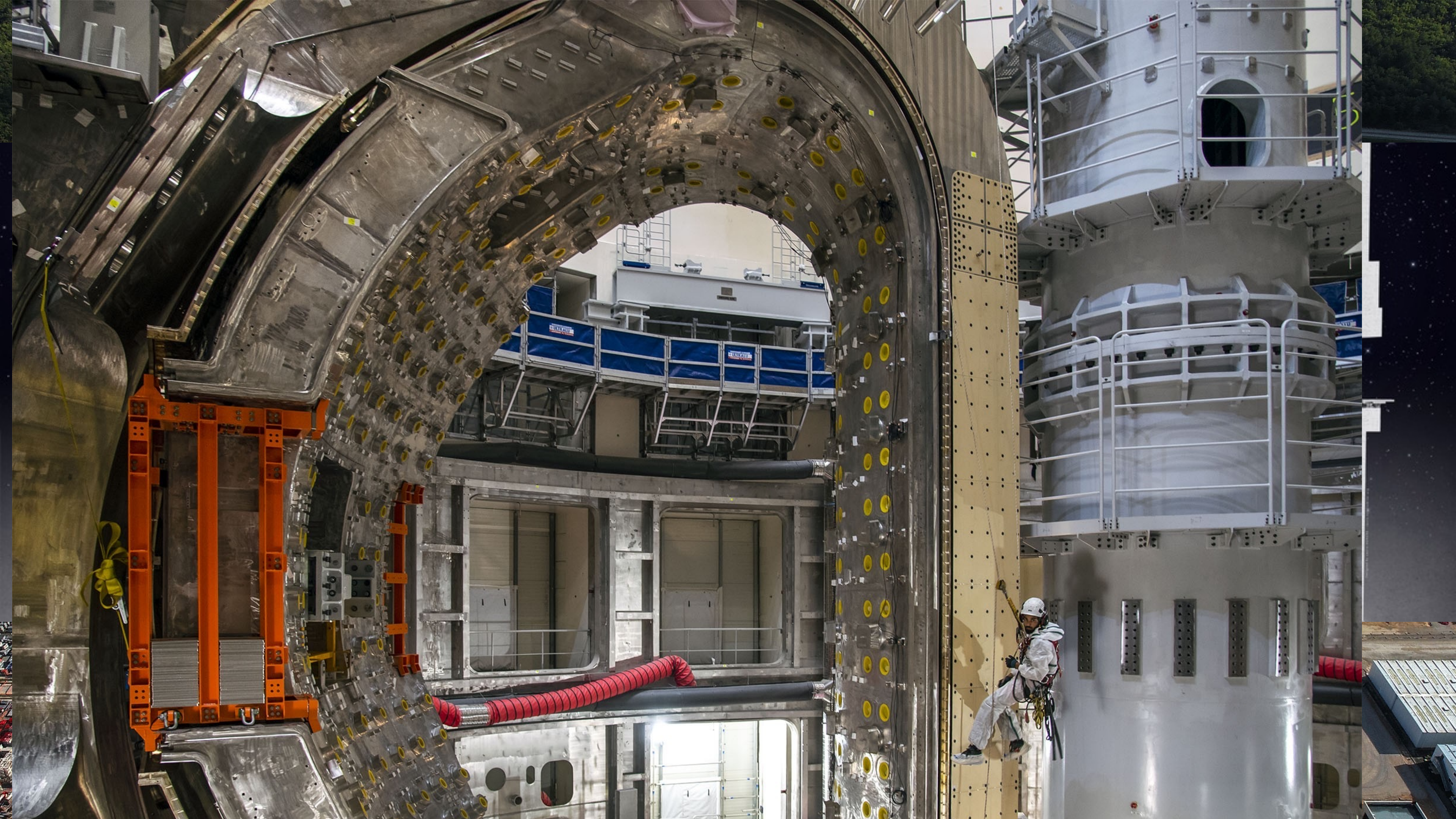
$P = 4\beta B^2$

$$\beta H^3 B^4 R^3 \geq constant$$

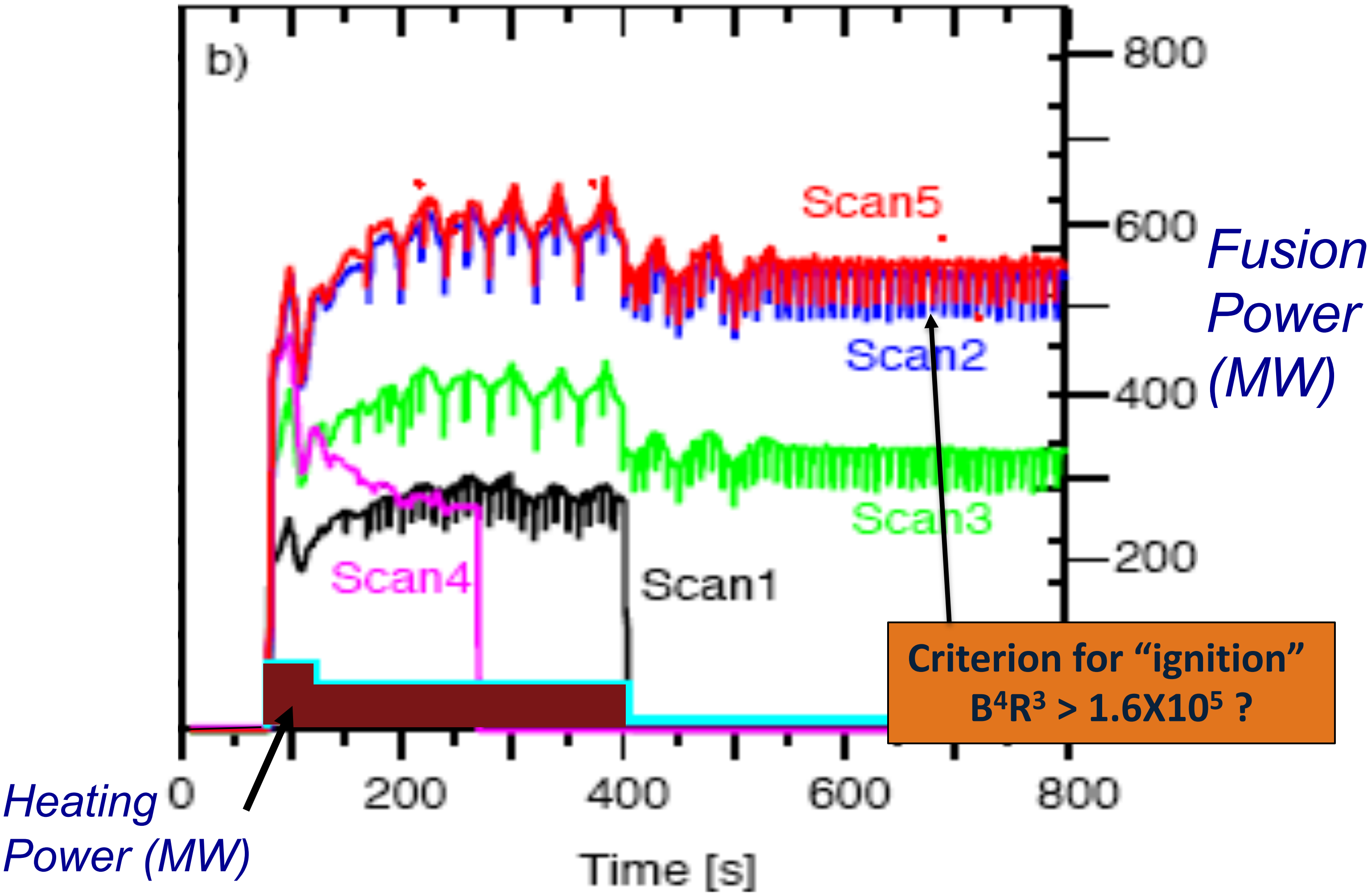
H and beta depends on shape profiles etc. Physics!

SCALING FOR SELF SIMILAR TOKAMAKS

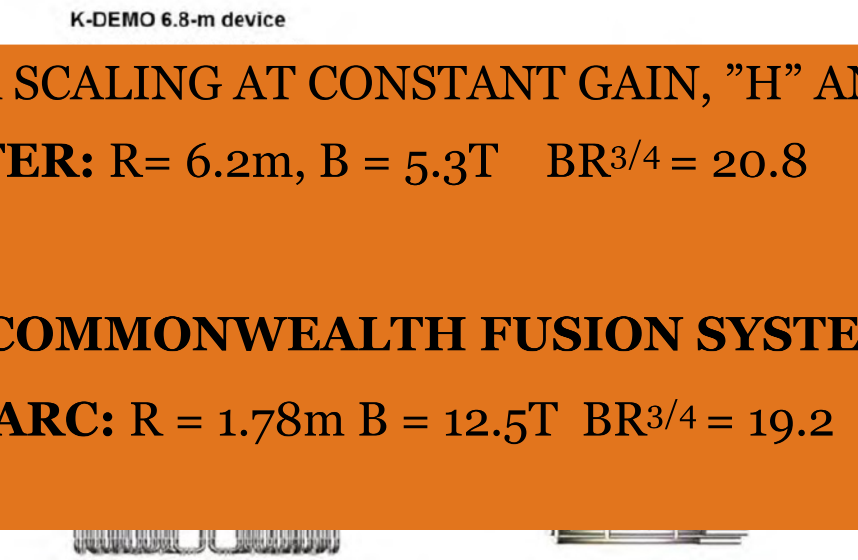
$$(\beta^{1/4} H^{3/4})\ B R^{3/4} \geq constant$$



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



National Academy of Sciences calls for Pilot Plant by 2040



SELF SIMILAR SCALING AT CONSTANT GAIN, "H" AND SHAPE

ITER: R= 6.2m, B = 5.3T BR$^{3/4}$ = 20.8

MIT + COMMONWEALTH FUSION SYSTEMS

SPARC: R = 1.78m B = 12.5T BR$^{3/4}$ = 19.2

FIGURE 4.2 Illustration of the DEMO approach and the pilot plant approach to next-step fusion energy development devices. On the left is a design of the K-DEMO capable of producing as much as 600 MW of electricity. On the right is a diagram of a smaller and less-costly pilot plant. While not producing as much electricity, a compact pilot plant would allow low-cost testing and development of the science and technology for commercial fusion power. SOURCE: T. Brown, "U.S. Next Step Strategy for Magnetic Fusion," submitted to the U.S. Workshop on Strategy for Magnetic Fusion, Madison, WI, July 2017.

High field compact

'ARC

on

S

Superconductors

~25T on coil

Tom Brown, Jon Menard PPPL

Self Similar Power and Stored Energy

$$\beta H^3 B^4 R^3 = constant$$ IGNITED DEVICE

FUSION POWER FROM DEVICE =

Use scaling

$$\mathcal{P}_{Fusion} \times Volume \propto \beta^2 B^4 R^3 \propto \frac{\beta}{H^3}$$

Total power essentially independent of size/field
Small high field devices have large heat fluxes

ENERGY STORED IN PLASMA PER UNIT WALL AREA: Use scaling

$$\frac{\mathcal{E}_{plasma}}{Area} \sim \frac{3P \ Volume}{2 \ Area} \propto \beta B^2 R \propto \frac{\beta^{2/3}}{H} B^{2/3}$$

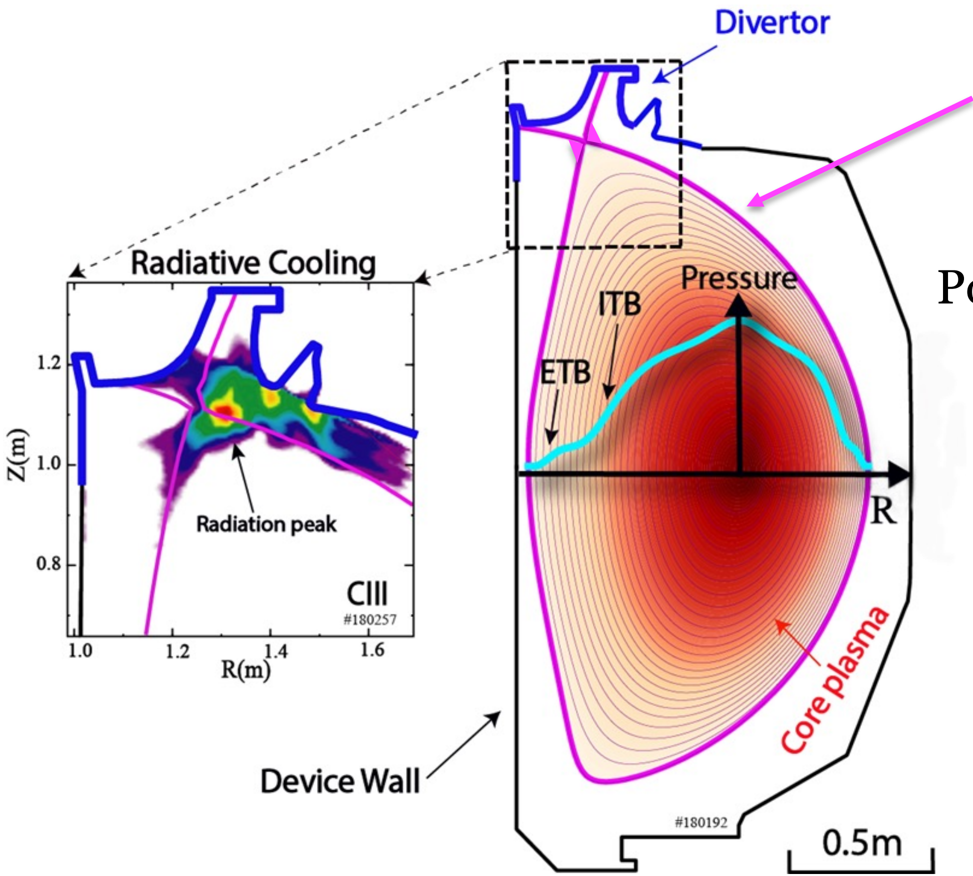
PLASMA DENSITY:

$$n \propto f_{GW} H B^{7/3}$$

Greenwald fraction

f_{GW} <1 for tokamaks can be 5 in stellarators

Plasma Exhaust



At plasma edge plasma flows along Scrape-off layer to divertor

$$\text{Width of scrape-off layer} \propto \frac{1}{B}$$

Power per unit area of divertor = heat load

$$Heat\ Load \propto \frac{\beta^2}{H^2} B^{7/2}$$

Radiation is proportional to plasma Density squared.

$$\frac{Radiative\ power}{alpha\ power} \propto \frac{H^2}{\beta^2} B^{2/3} f_{GW}^2$$

STELLARATOR?

Neutron Wall Loading

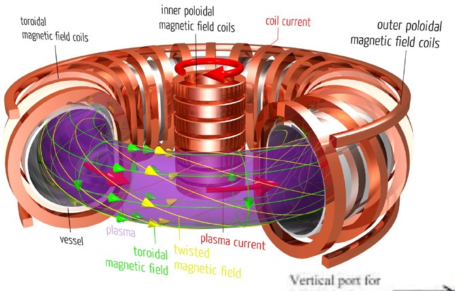
Peak Neutron Flux (from scaling EU DEMO)

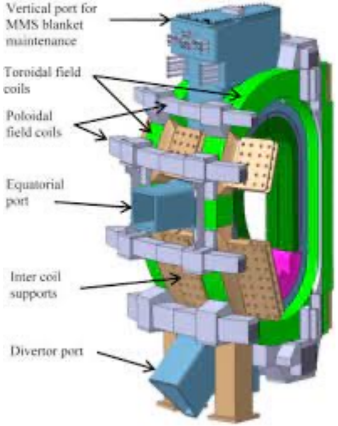
Field in tesla

$$Peak\ Flux = 2\frac{(\beta/\beta_{Demo})}{H^3}\left(\frac{R^2_{Demo}}{R^2}\right)(MW/m^2) = 2\frac{(\beta/\beta_{DEMO})^{4/3}}{H}\left(\frac{B}{6}\right)^{8/3}$$

Rule of thumb 1MW/m² for a full power year => 10DPA
How much DPA before material must be replaced?
20DPA makes material scientists nervous. We need DONES to know.
EU Demo wall lifetime (to 20 DPA) could be ~ 1 full power year
High Field devices will be a few months

Maintenance. How easy is it to replace the wall and blanket?





We may have to replace the wall and blanket components after they have been damaged by radiation and plasma. We may have to consider these components **consumables.**

Unfortunately, it is hard to get inside the coils and cryostat. One measure of the space and accessibility for replacement is the average current density through the hole in the middle. Small current density is good – lots of space!

$$AVERAGE\ \ CURRENT\ \ DENSITY \propto \frac{(R)^{1/4}}{(\frac{2}{3}R-1)^2 H}$$

The case for low power density

Tokamak	KEY PARAMETERS	DIVERTOR HEAT LOAD	RADIATIVE FRACTION	WALL LIFETIME	AVERAGE CURRENT DENSITY
EU DEMO	B=5.9T R= 9m $BR^{3/4}$=30 H=1	P_D >100MW/m²	1	1-2 FULL POWER YEARS TO 20DPA	3.37MA/m²
HIGH FIELD	B=12.5T R=3.2m $BR^{3/4}$=30 H=1	~5.7 P_D	$2(f_{GW})^2$	1.5-3 FULL POWER **MONTHS** TO 20DPA	53MA/m²
LOW FIELD	B=3T R=21m $BR^{3/4}$=30 H=1	~0.2 P_D	$0.5(f_{GW})^2$ STELLARATOR?	6-12 FULL POWER YEARS TO 20DPA	0.6MA/m²

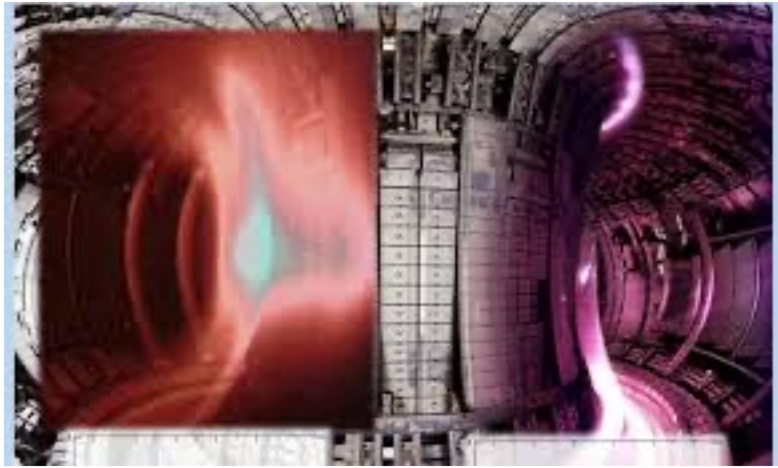
Perfect Energy?

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

We won't get to fusion by blasting the engineering.

Disruption

Sometimes the plasma becomes unstable and deposits its energy on the wall (often as relativistic electrons) this is called a disruption



Disruption energy per unit area of wall

$$\propto \frac{\beta^{1/2}}{H^{3/2} R^{1/2}}$$

Worse in smaller high field machines

Machine learning being used to predict the Disruption and avoid it.

Most disruptions driven by the plasma current.

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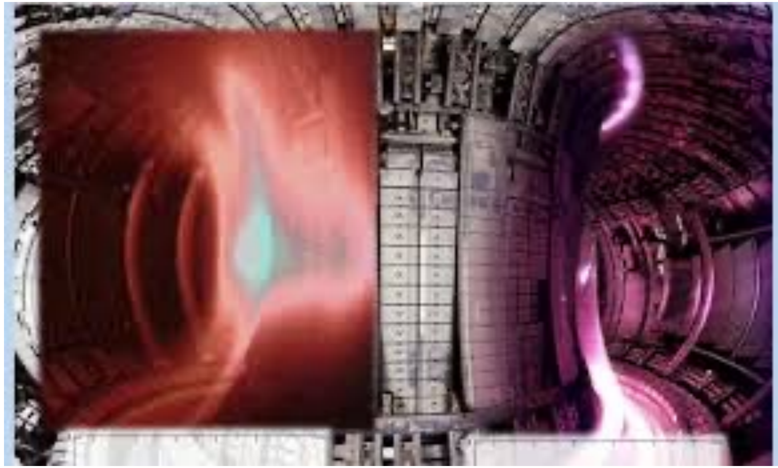

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