Plasma Tamed -- Fusion Power and the Theoretical Challenge

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CCFE
CULHAM CENTRE FOR FUSION ENERGY

Talk

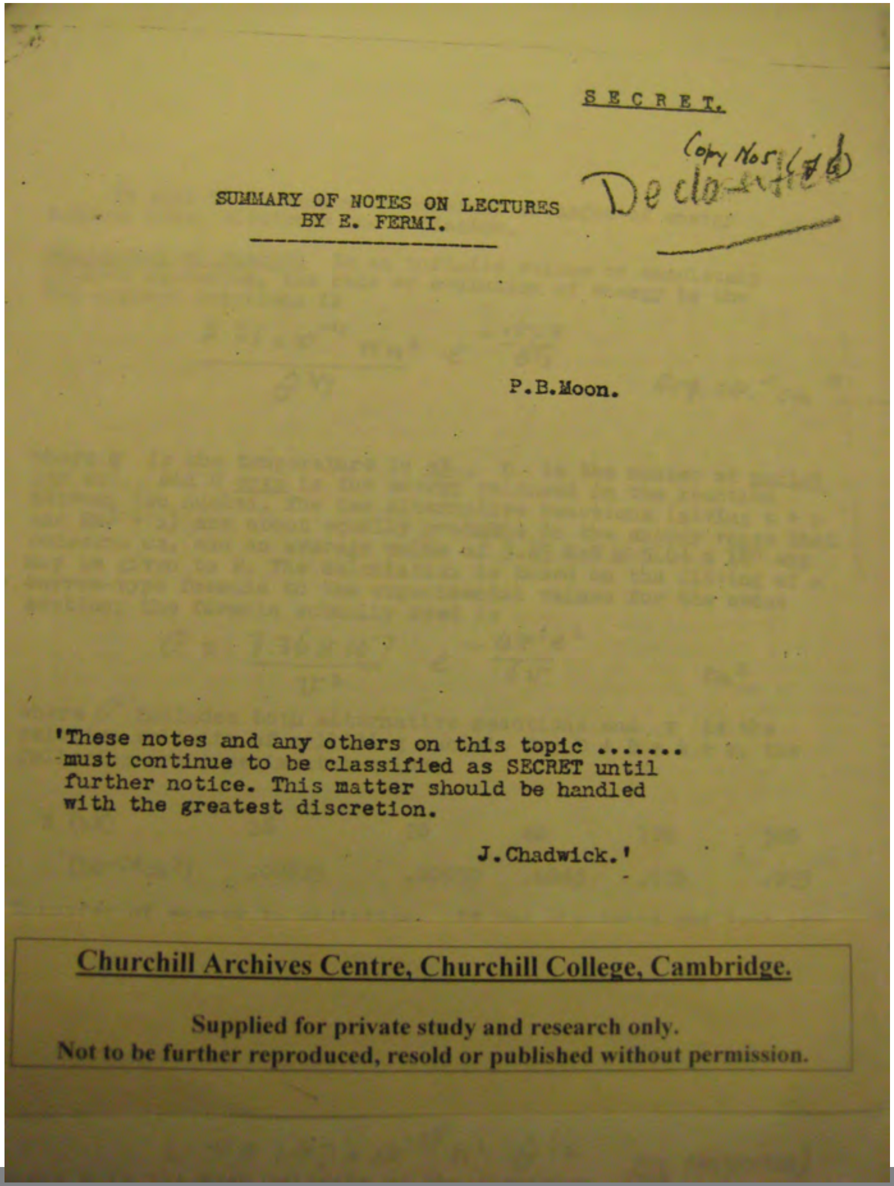
Delivering fusion at a cost and scale that will ensure commercial success.

1. Electricity when?
2. ITER, what will it do?
3. Threats to ITER – disruption, power handling, erosion.

2. Challenge of going further.

CCFE CULHAM CENTRE FOR FUSION ENERGY

The Start



SECRET.

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SUMMARY OF NOTES ON LECTURES
BY E. FERMI.

P.B.Moon.

'These notes and any others on this topic ....
must continue to be classified as SECRET until
further notice. This matter should be handled
with the greatest discretion.

J.Chadwick.'

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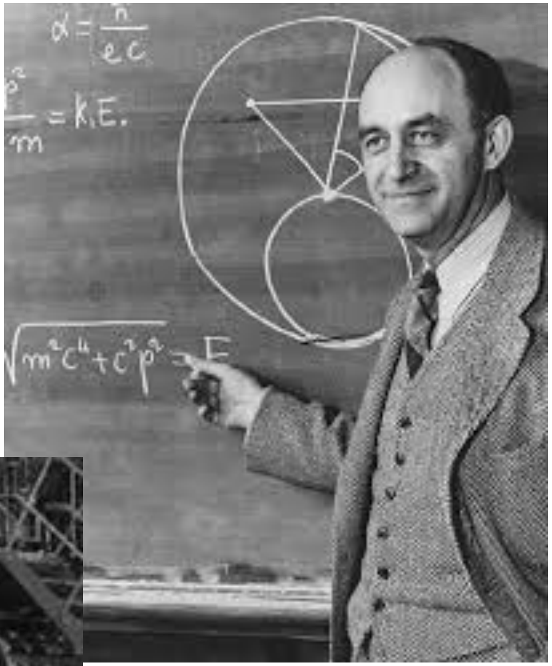
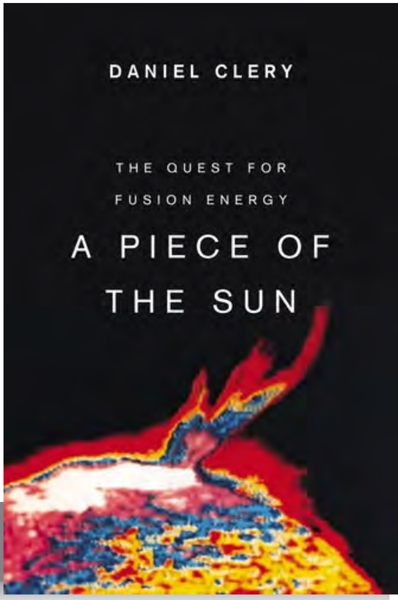
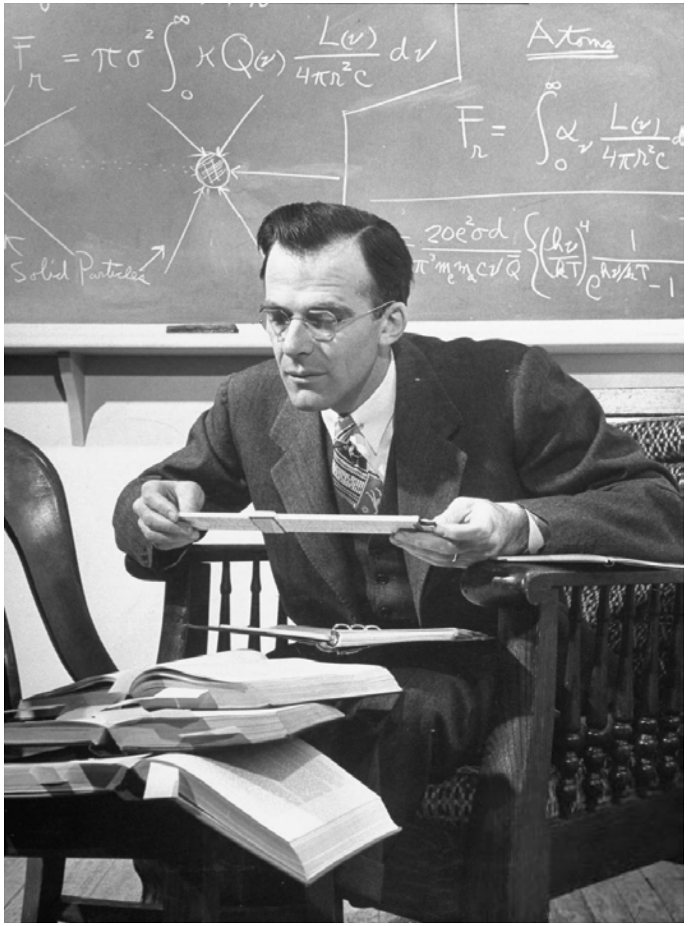
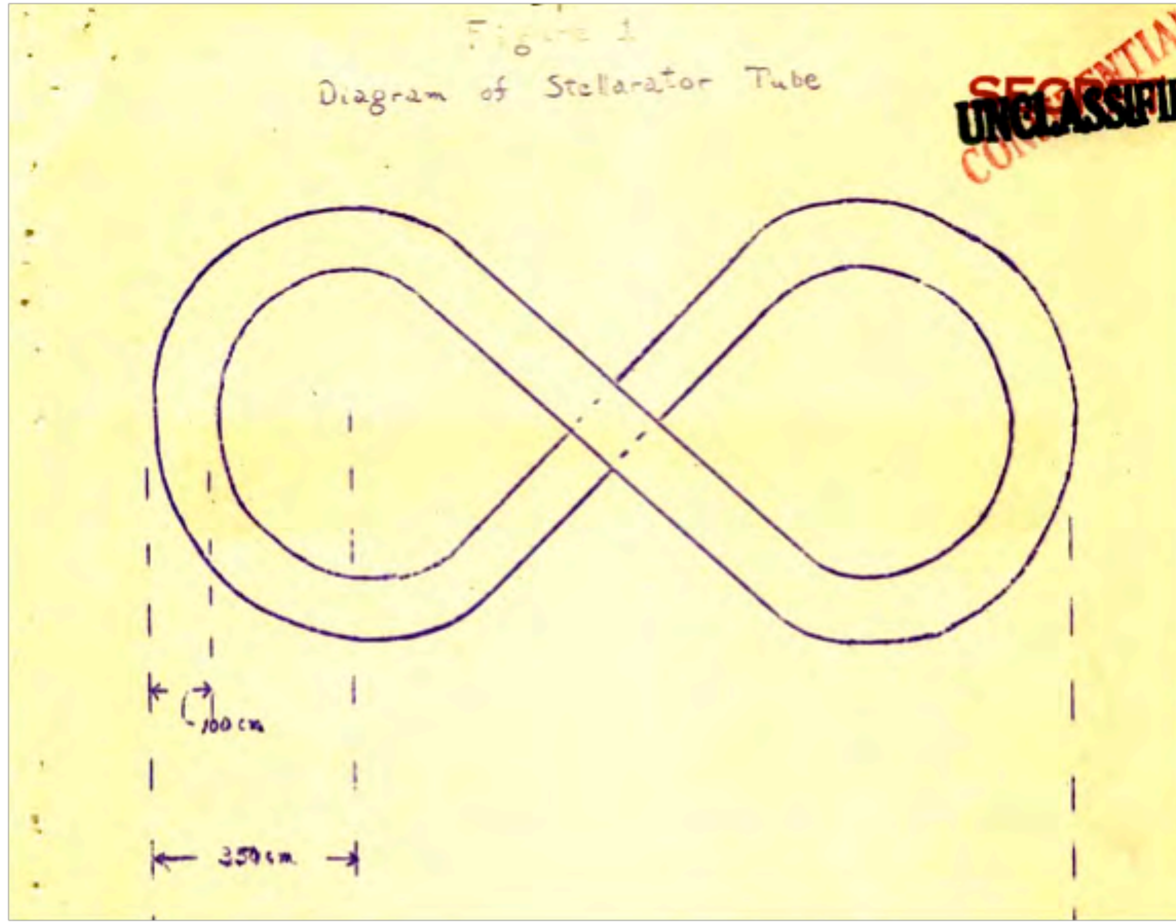




Early Reactor Concepts





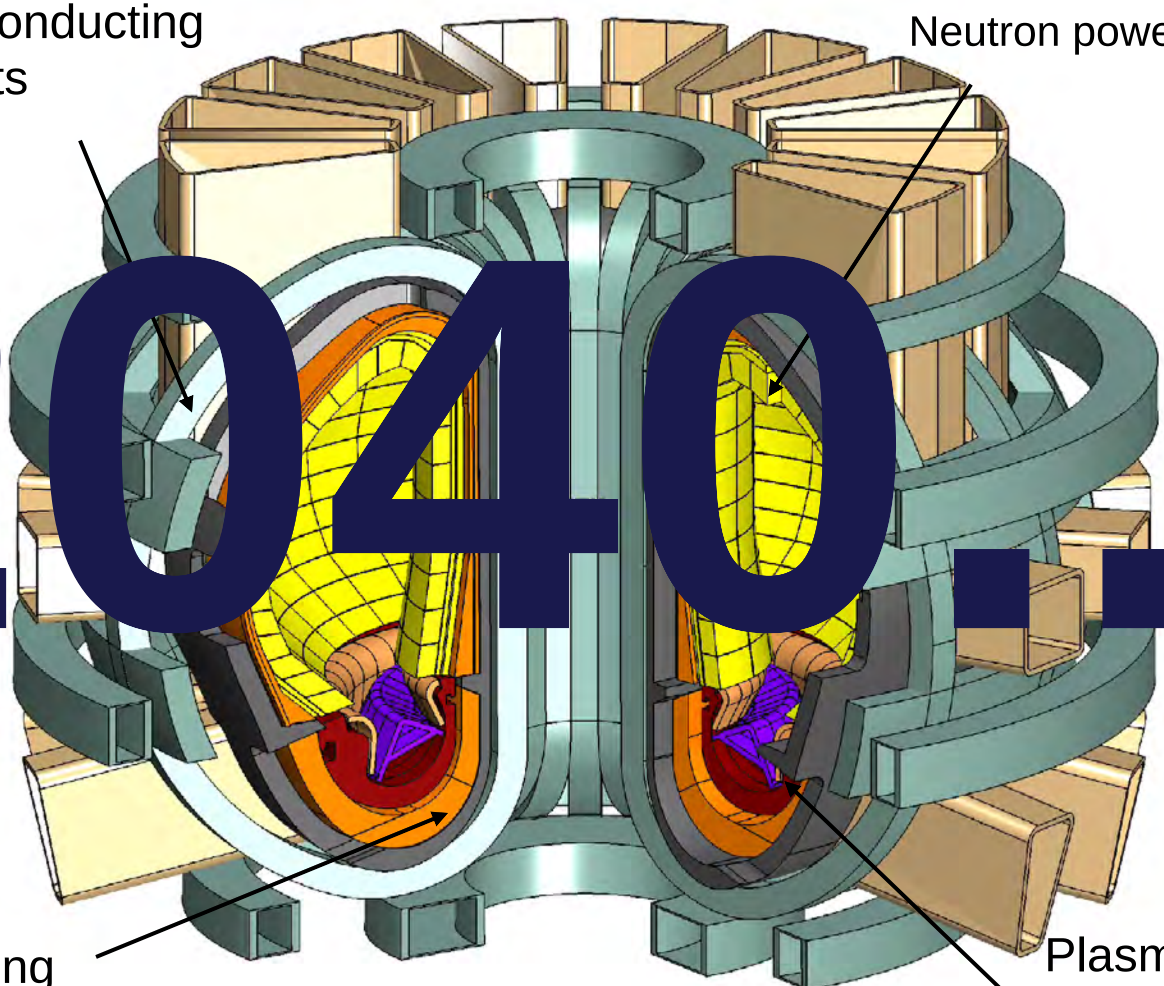
Spitzer's figure 8 Stellarator from July 23rd 1951 proposal to AEC

First Electricity When?

EU Demonstration Reactor.

Superconducting magnets

Blanket for tritium breeding and heat exchange. ~ 2MWm^{-2} Neutron power crossing boundary



2040..?

Shielding

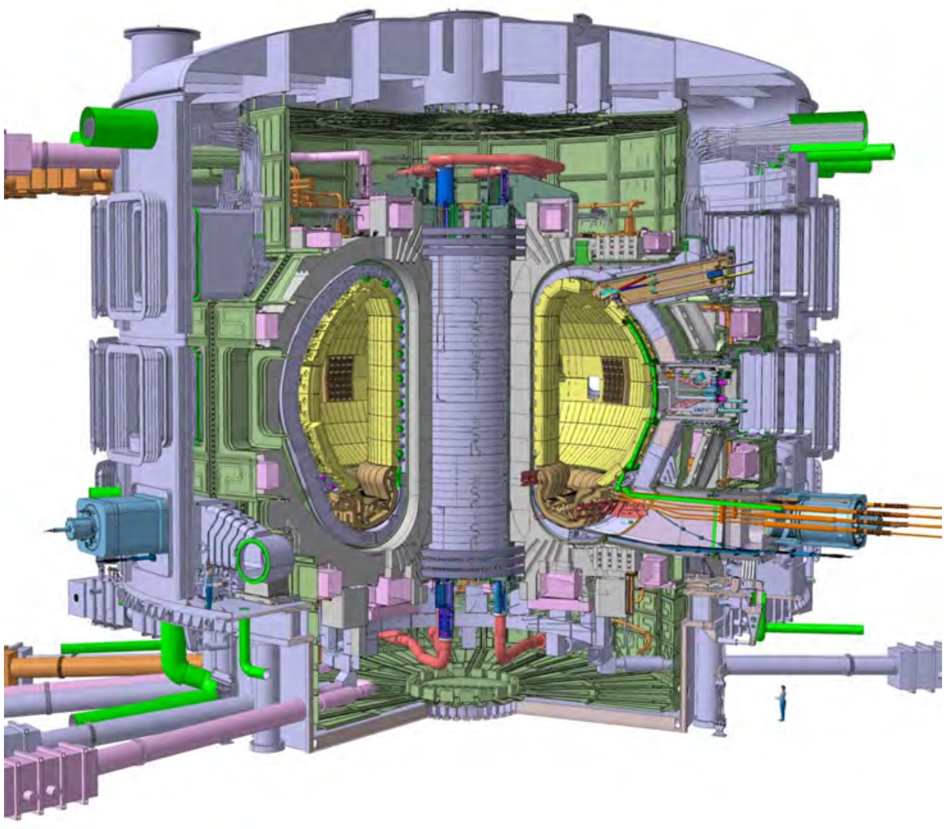
Plasma exhaust, power loading >10MWm^{-2}

First self sustained fusion burn?

ITER

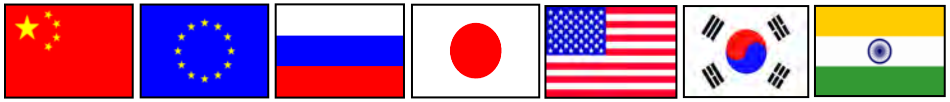
First sustained burning plasma.

Starts in 2020.

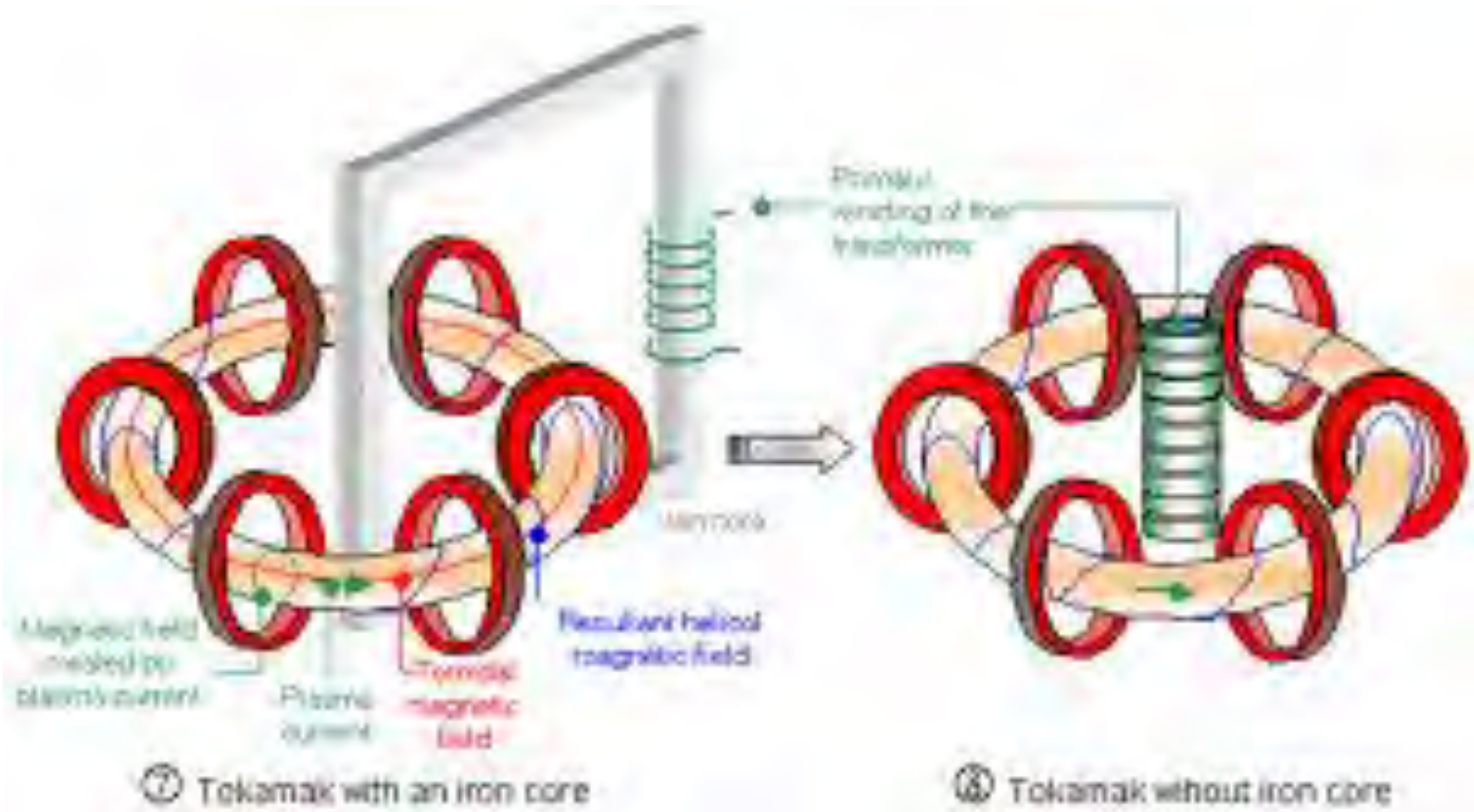


BASIC PARAMETERS:

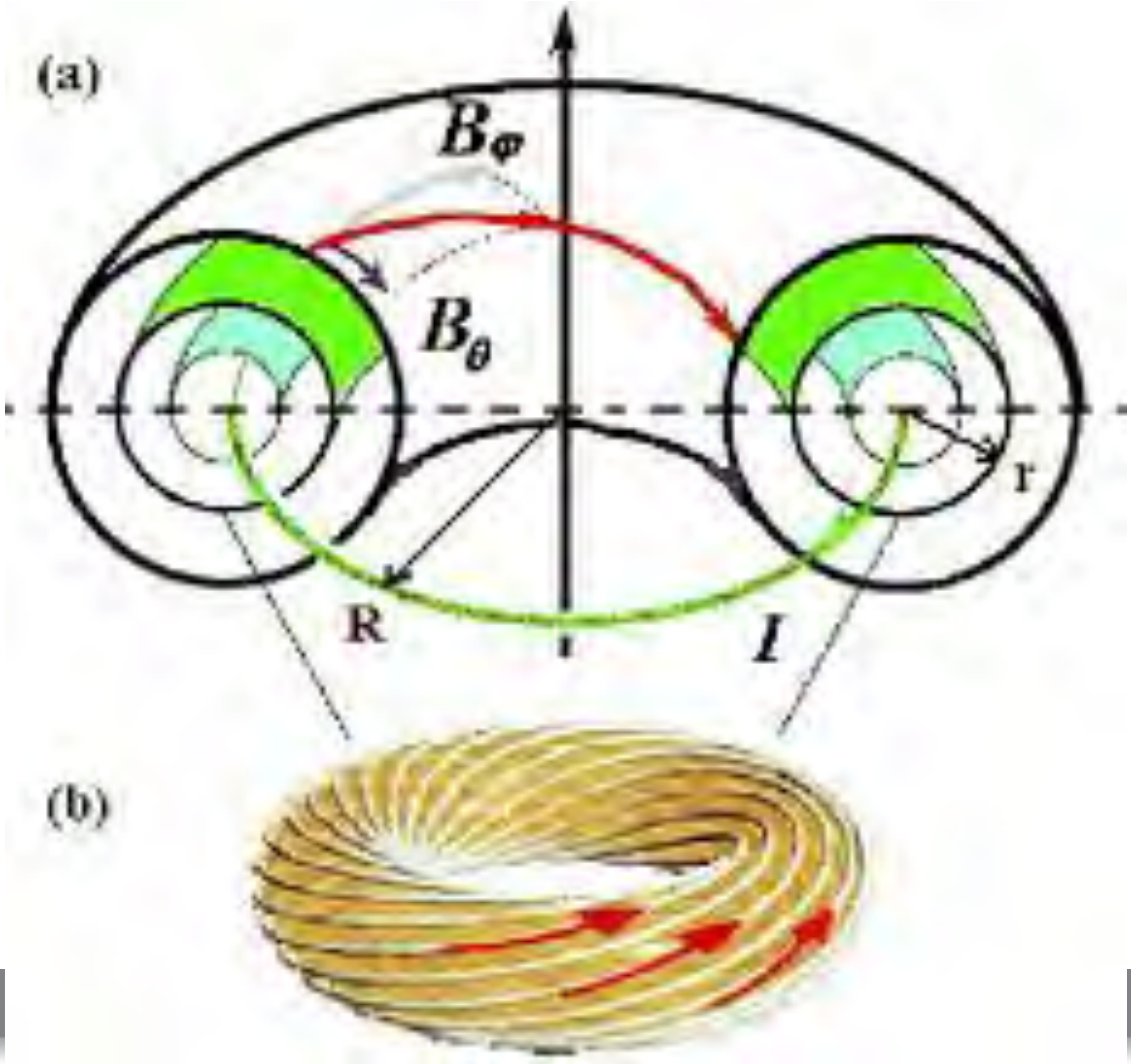
- Plasma Major Radius 6.2m
- Plasma Minor Radius 2.0m
- Plasma Current 15.0MA
- Toroidal Field on Axis 5.3T
- Fusion Power 500MW
- Burn Flat Top >400s
- Power Amplification Q>10
- Cost is > 10 Billion Euro.

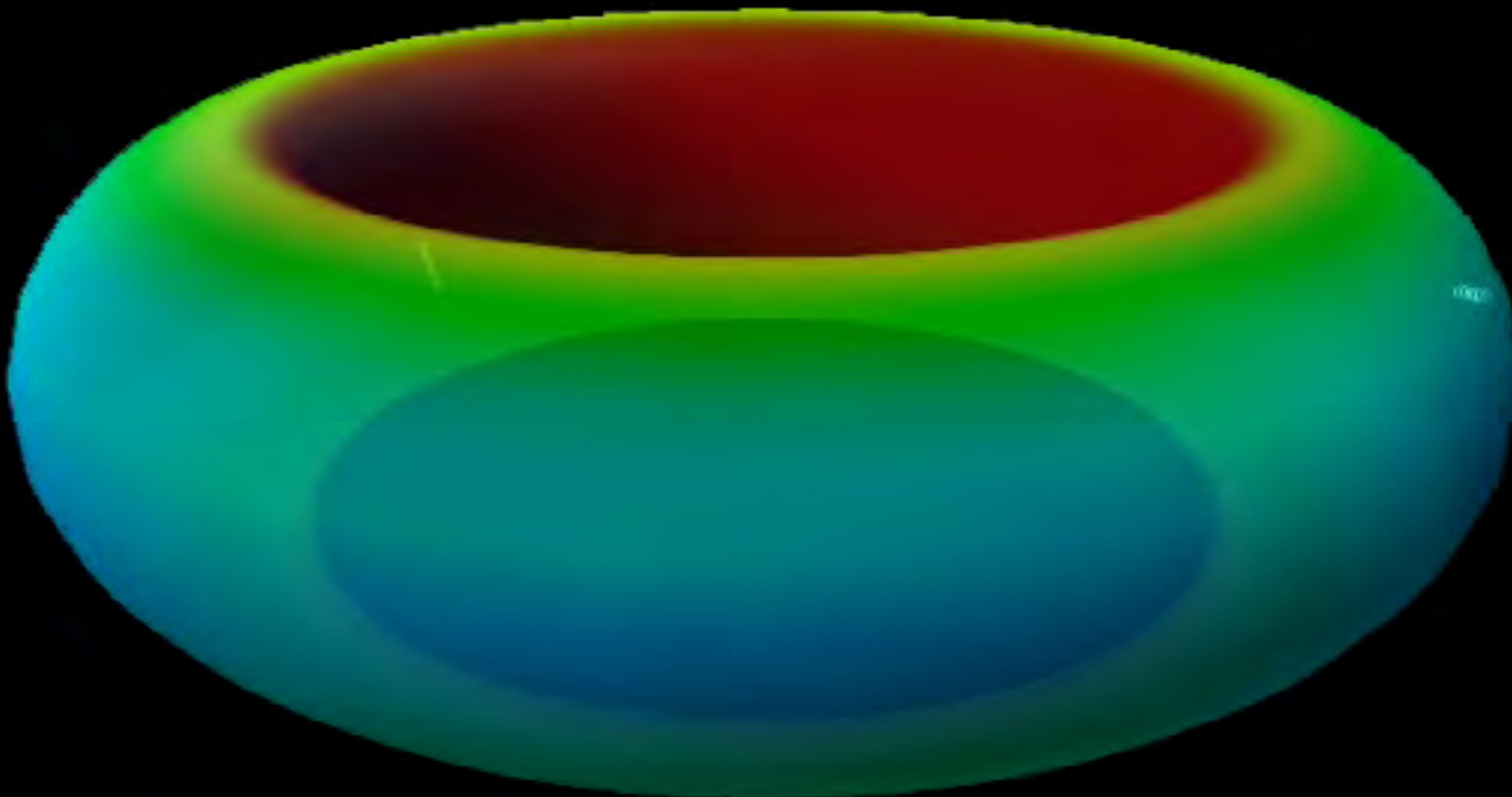


Equilibrium

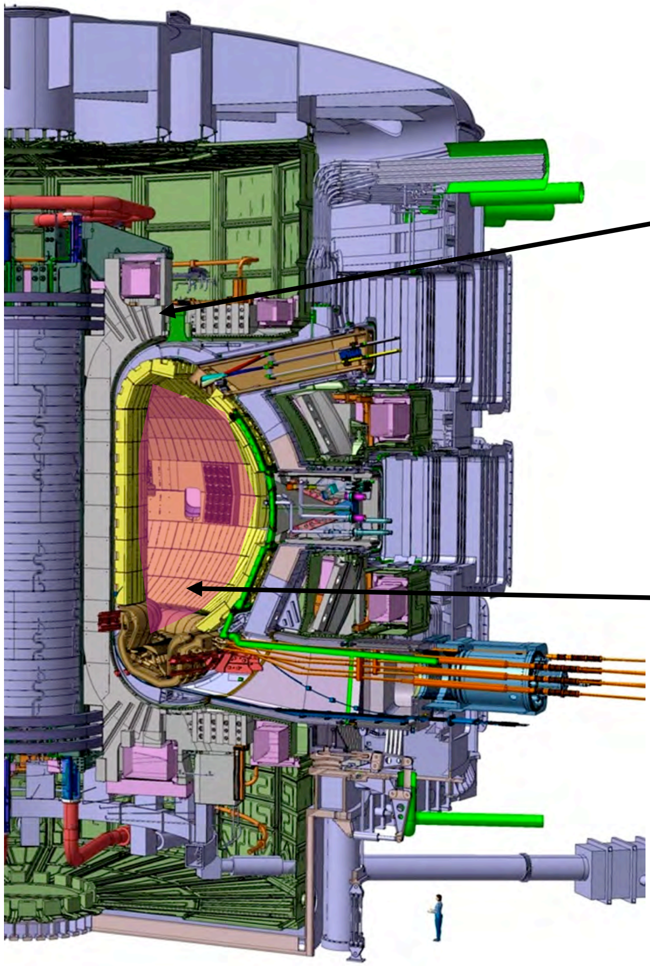


Equilibrium





Fusion force balance in ITER



Superconducting Coils

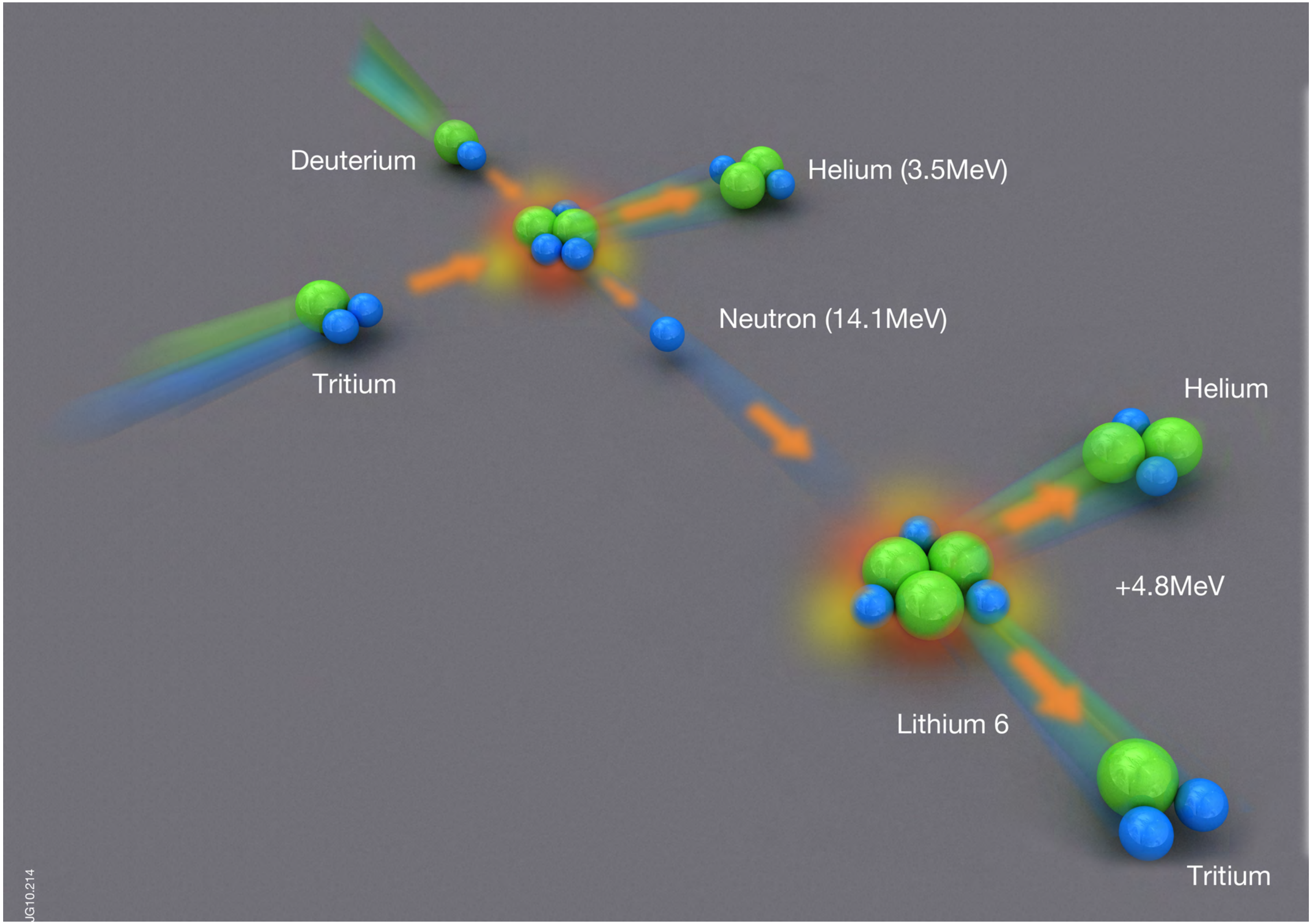
central B field 5.2 Tesla

$P_{magnetic}$ ~ 100 atmospheres

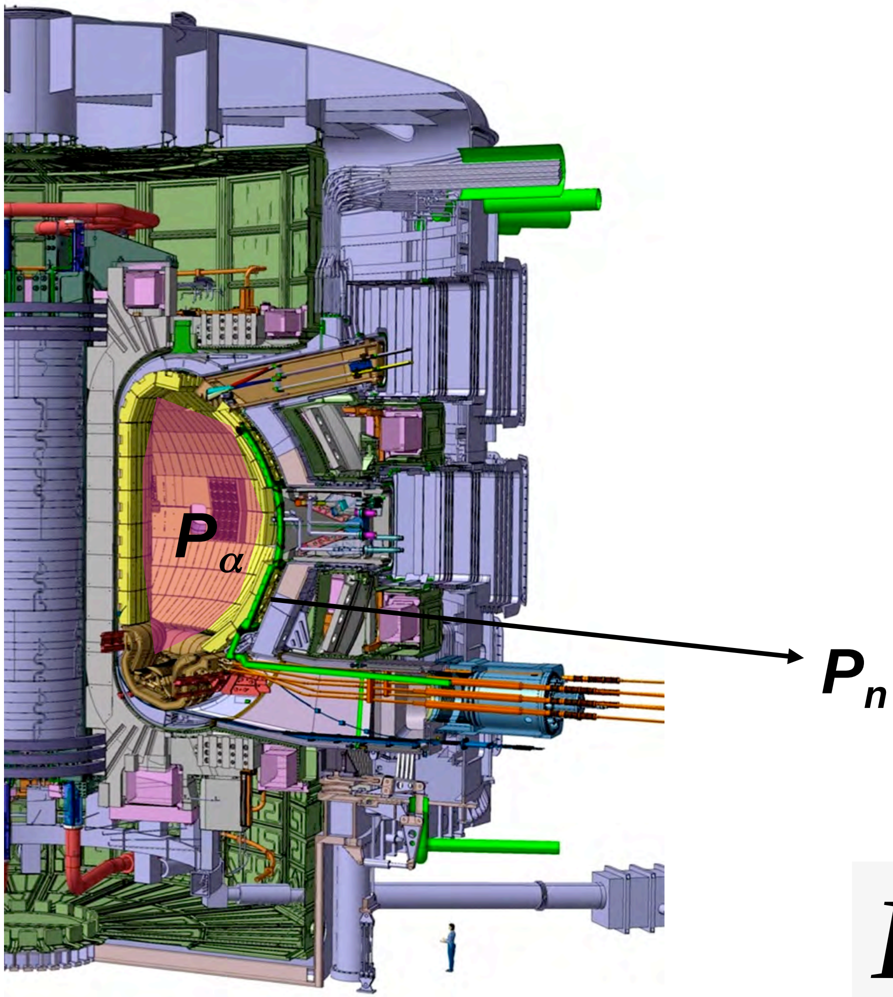
Central Temperature >20keV

P =Plasma Pressure ~7 atmospheres

Which fusion?



Fusion energy balance in ITER



'Baseline Performance'

Power in alphas captured by Plasma P_α ~ 100MW.

Power in neutrons escaping Plasma P_n ~ 400MW.

$$P_n + P_\alpha = P_{Fusion}$$

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

3.5MeV 14MeV

Fusion Heating?

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

One fifth of this(the alpha particles) heats plasma

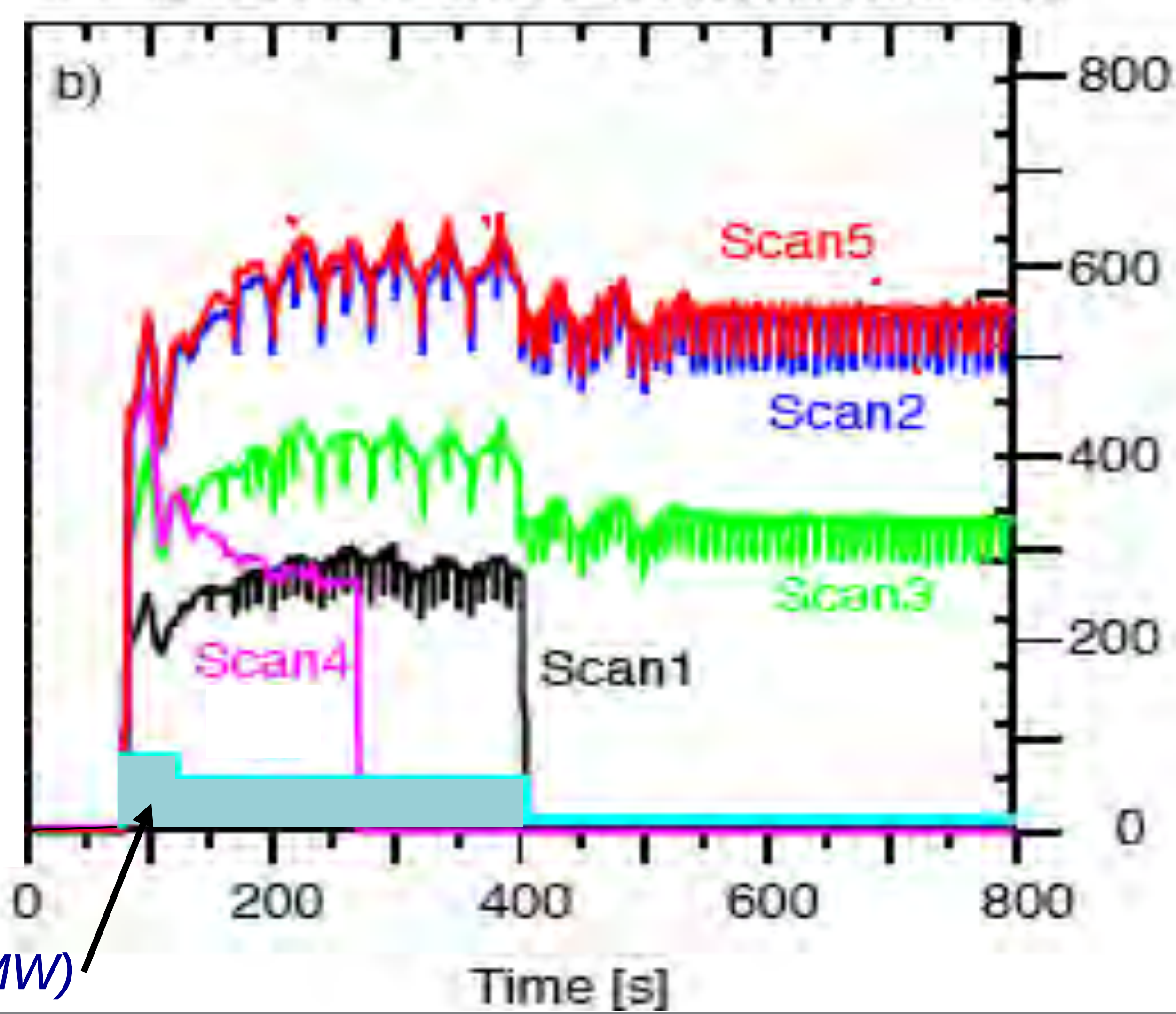
This must balance turbulent losses.

$$\frac{\mathcal{P}_{fusion}}{5} \sim \frac{P^2}{50} \sim 0.1\frac{P}{\tau_E}$$

Turbulent loss time (seconds)

ITER Detailed Modeling e.g.

Budny 2009

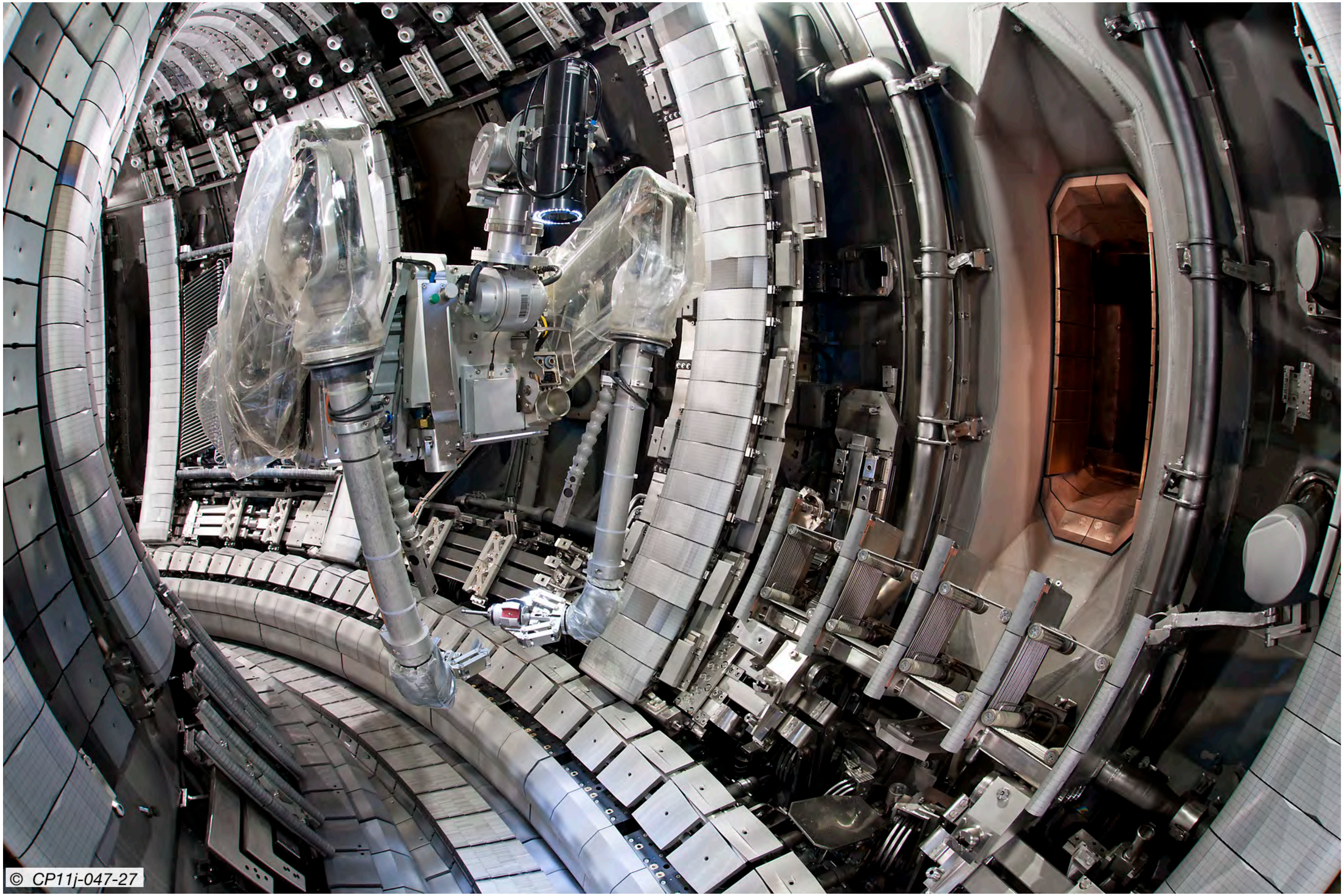


Fusion Power (MW)

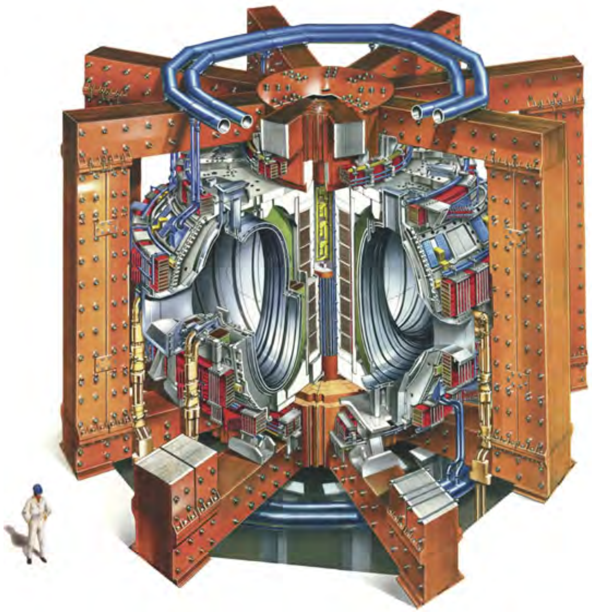
Heating Power (MW)

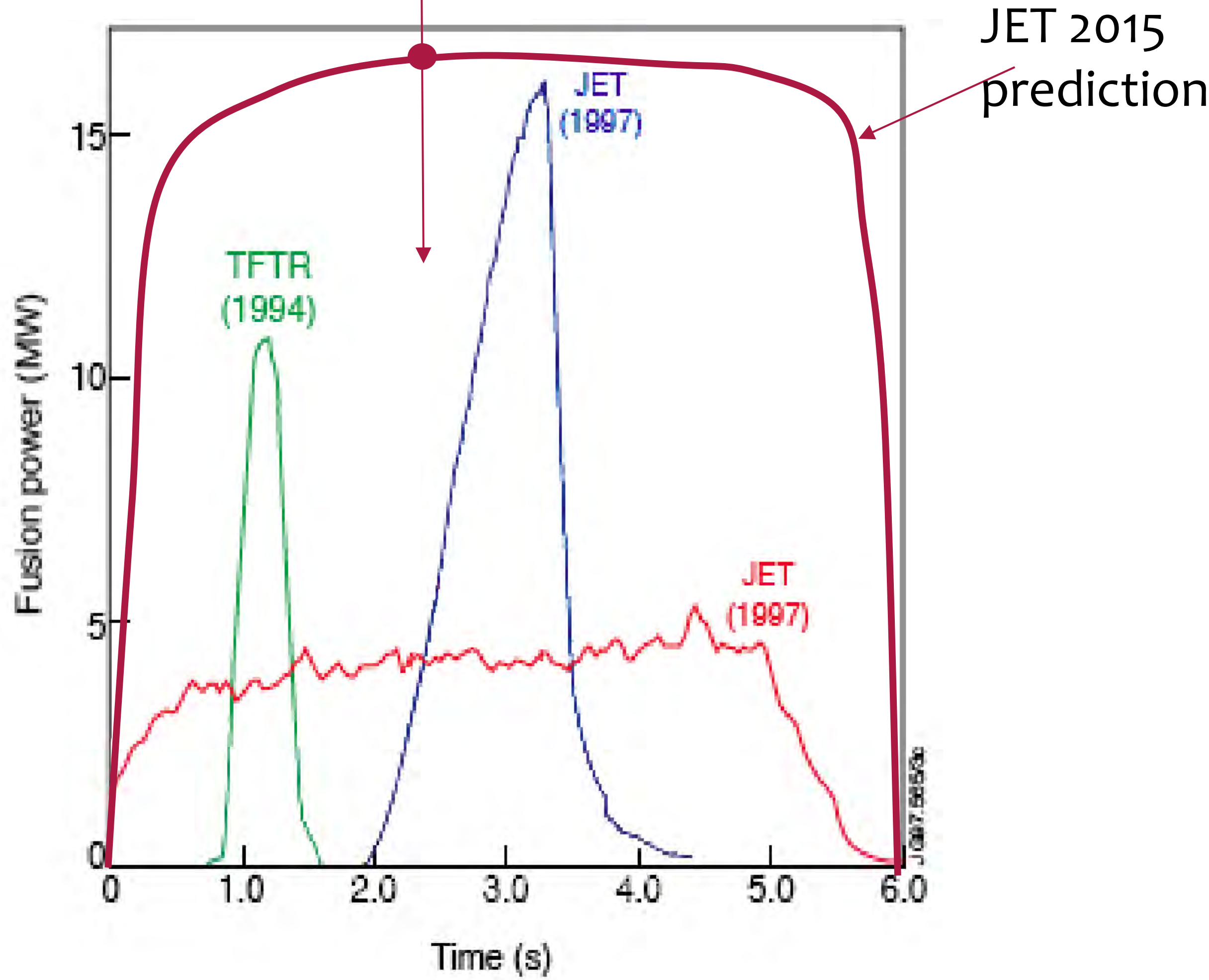
How do we know this will happen?

ITER Like Wall Installation



SUCCESS!!





JET Currently the only machine capable of fusion

Can we make it smaller/cheaper?

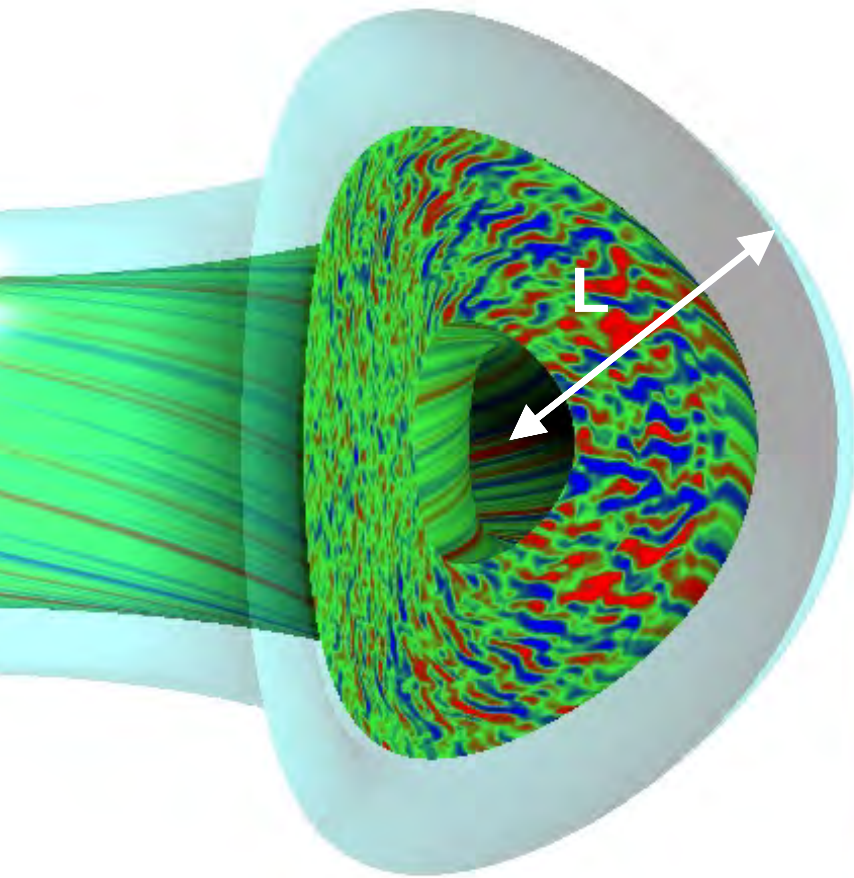
The problem is turbulence

This is where Oxford comes in.

Optimisation from theory – zero turbulence tokamaks?

Schekochihin, Parra, Barnes Highcock

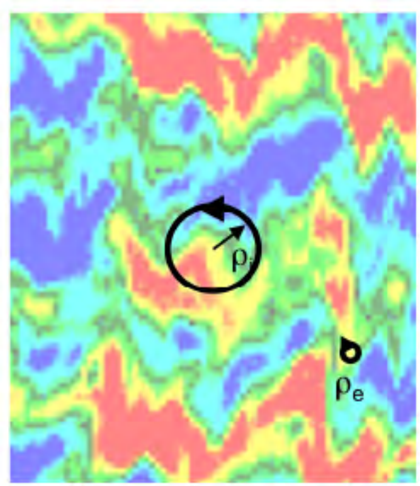
Spatial scales



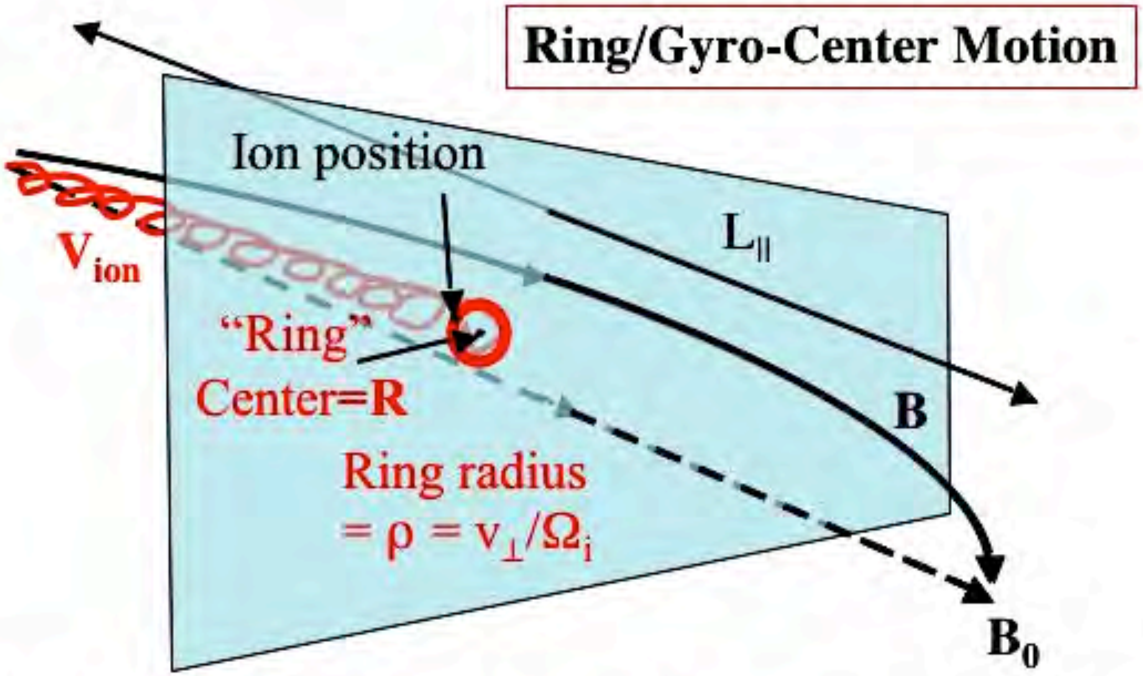
L = Equilibrium scale and parallel scale of turbulence

ρ = Ion larmor radius and perpendicular scale of turbulence

$\rho^* = \rho/L \sim 10^{-3}$ in ITER



Gyrokinetics – 5D theory.



$$< \frac{d\mathbf{R}}{dt} >= v_{\|}\mathbf{b}_0 \; - \; \frac{\partial < \chi >_{\mathbf{R}}}{\partial \mathbf{R}} \times (\frac{\mathbf{b}_0}{B_0}) + v_{\|}^2 (\frac{\mathbf{b}_0}{\Omega_0}) \times \mathbf{b}_0 \cdot \nabla \mathbf{b}_0 + \frac{v_\perp^2}{2B_0}(\frac{\mathbf{b}_0}{\Omega_0}) \times \nabla B_0.$$

Parallel Motion along Equilibrium Field

Drifts in Perturbed Field

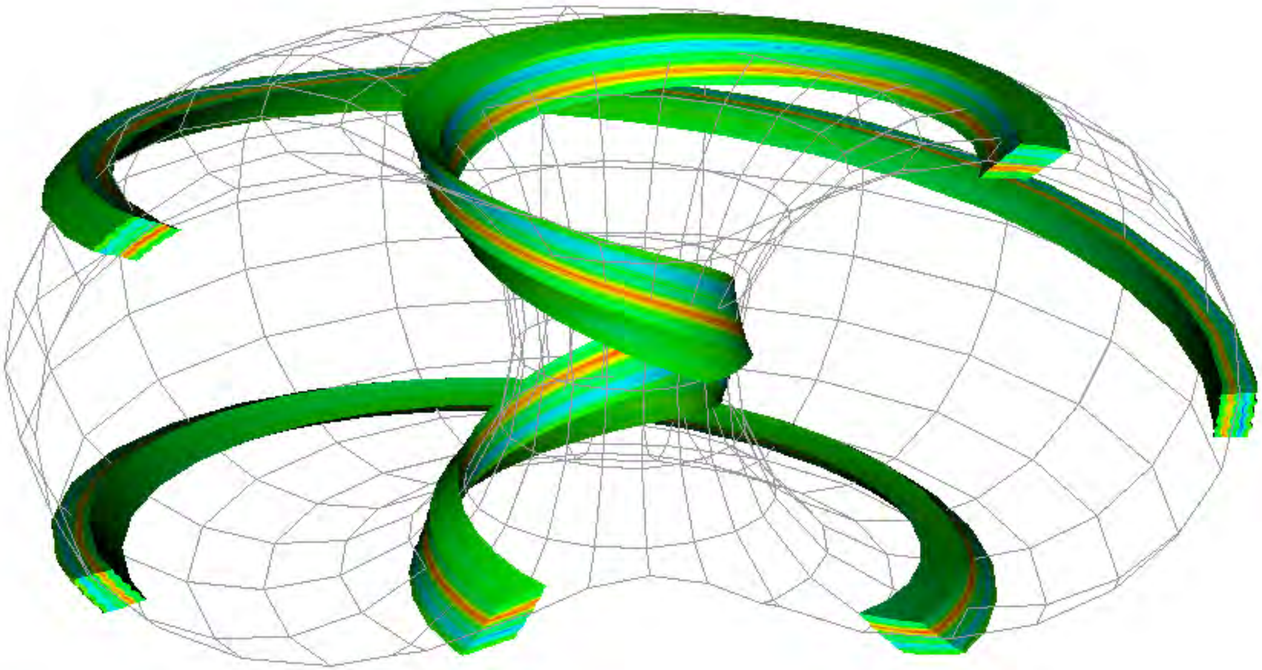
Curvature Drift in Equilibrium Field

∇B Drift in Equilibrium Field

$$\chi = \phi - \mathbf{v} \cdot \mathbf{A}$$

Distribution of rings in 5D space x, y, z, $\mathbf{v}_\perp$, $\mathbf{v}_{||}$

Minimum simulation volume -- flux tubes



Beer 1993.

Is the turbulence in the flux tube determined by the conditions in the tube?
Does turbulence propagate -- correlated or not?
We should look at turbulent Greens function -- response to stirring.

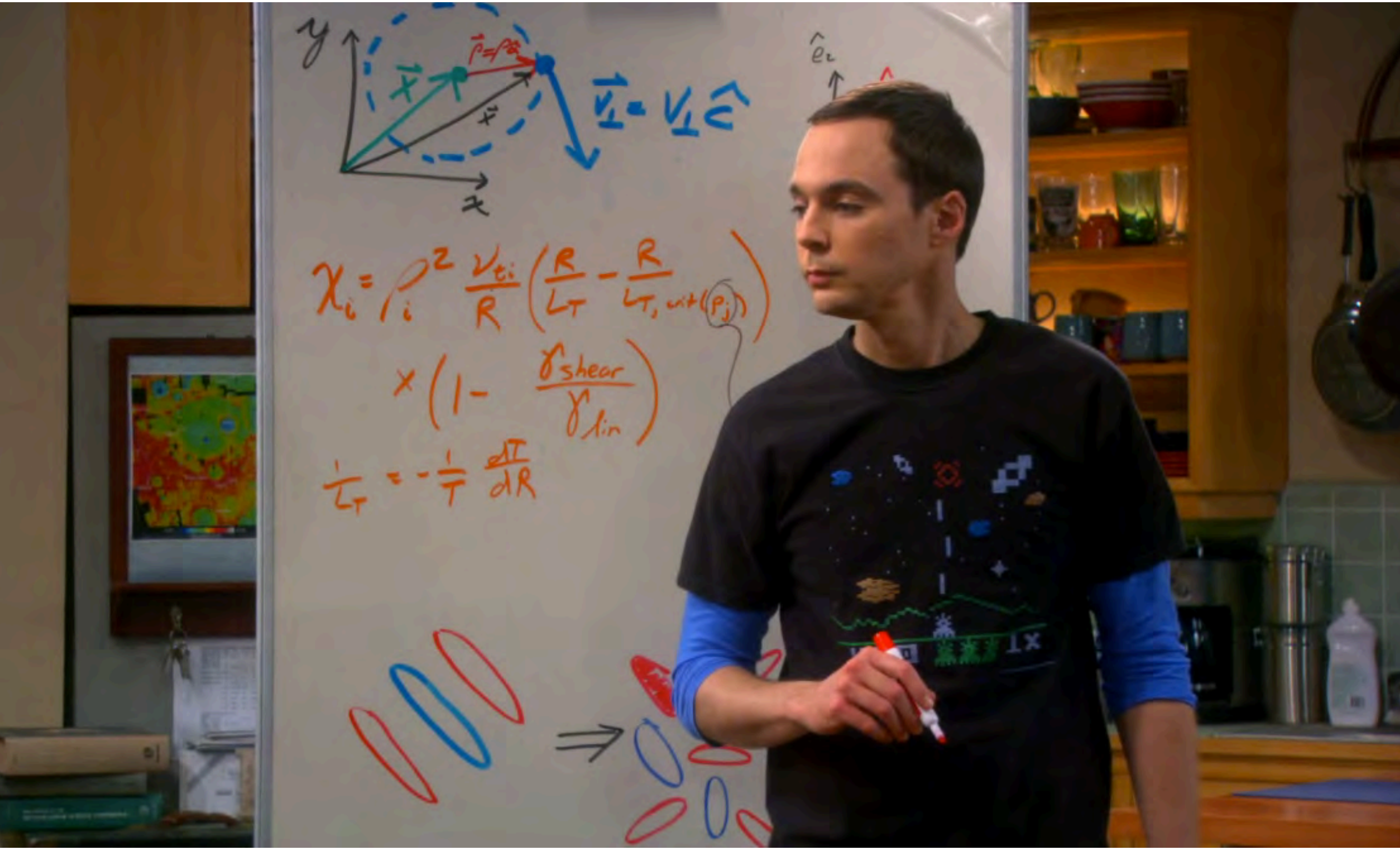
Gyro-kinetic simulation.

DIII-D Shot 121717

GYRO Simulation

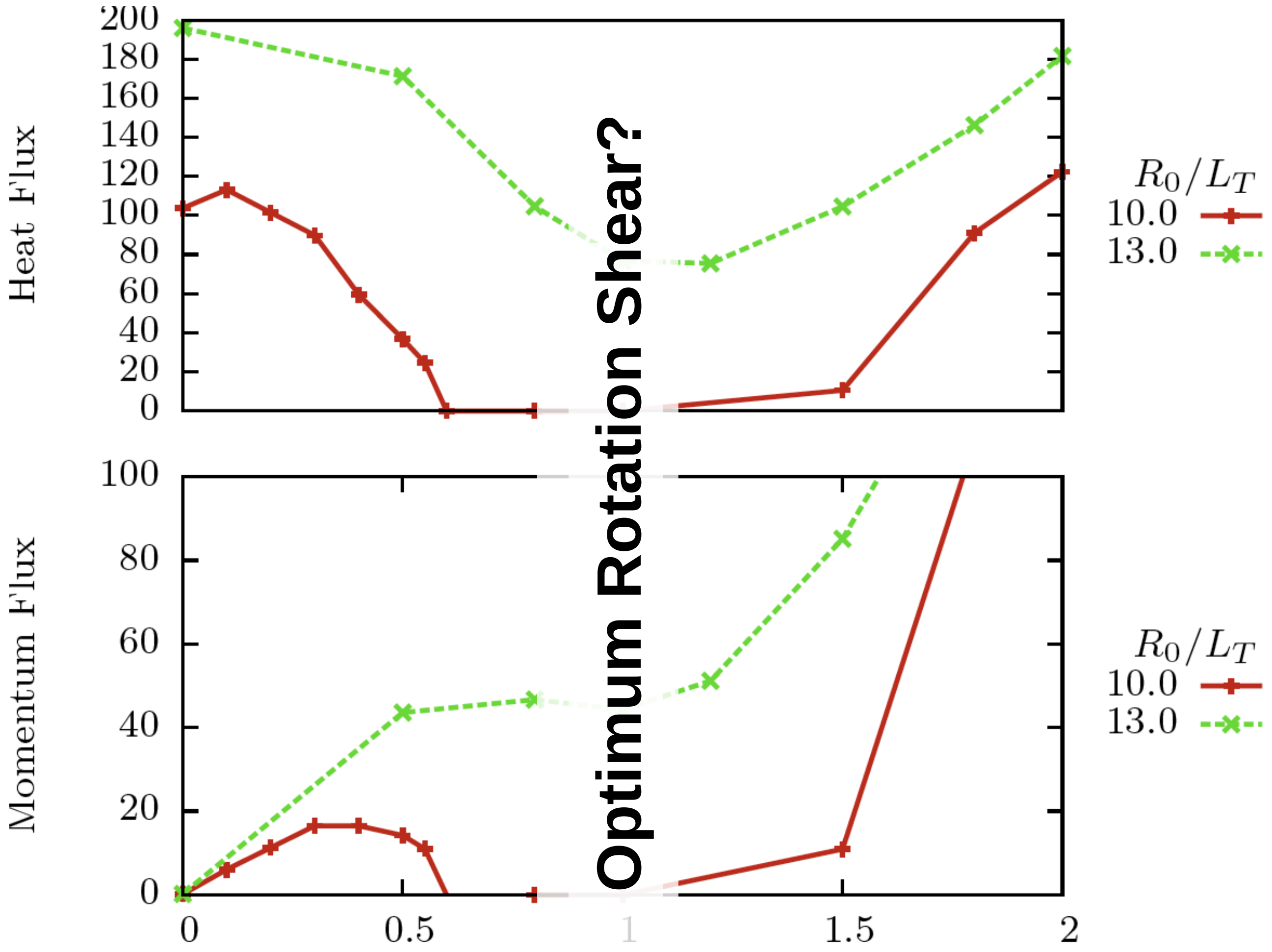
Cray X1E, 256 MSPs

Sheared Rotation



Can we shear away the turbulence?

Optimum Flow? Simulations



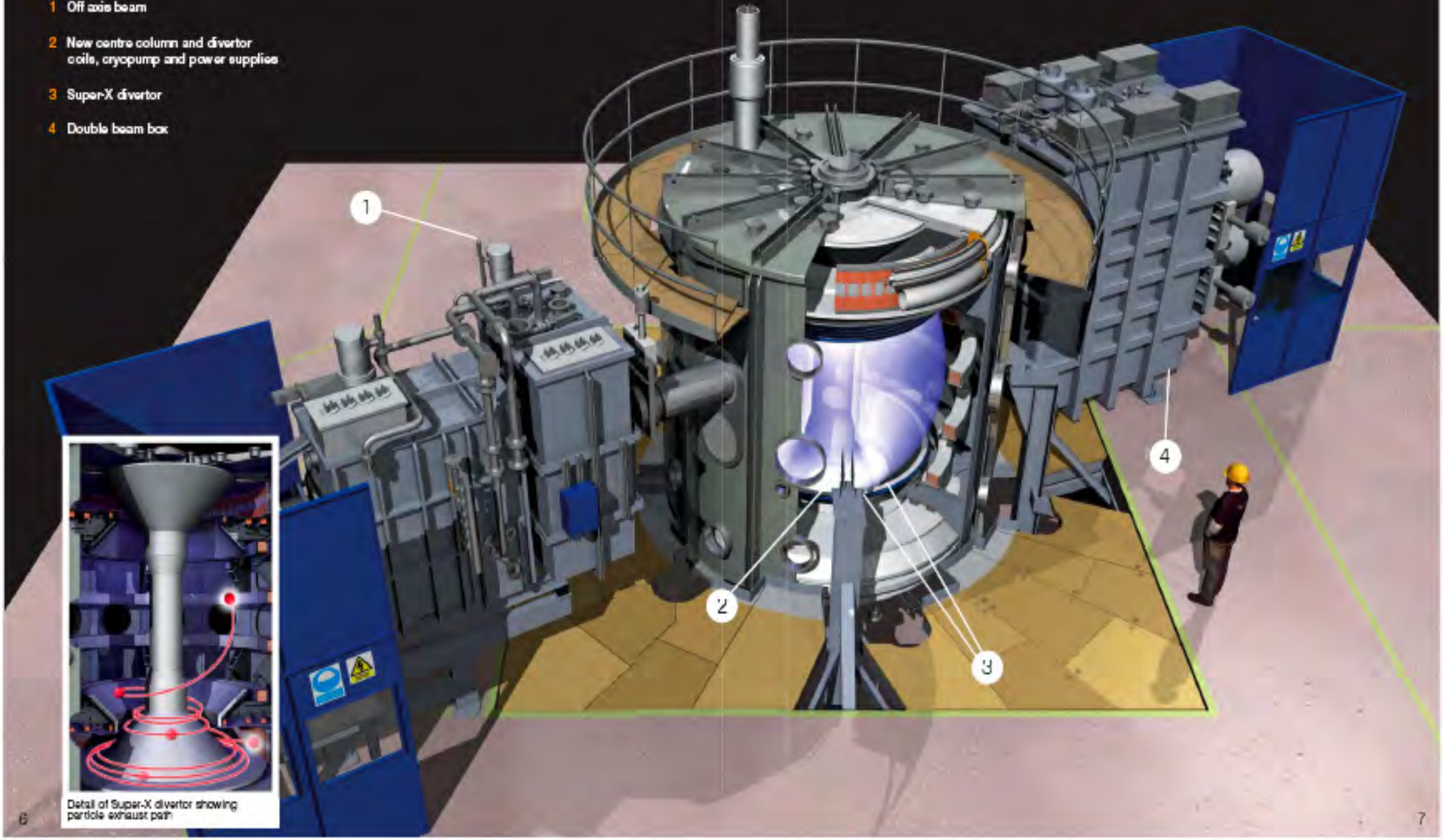
Rotation Shear

Can we make it rotate?

The new MAST

Key features of MAST Upgrade

1. Off axis beam
2. New centre column and divertor coils, cryopump and power supplies
3. Super-X divertor
4. Double beam box



Detail of Super-X divertor showing particle exhaust path

Maybe it rotates by itself?

Felix Parra has explained how the plasma can spontaneously rotate – **without momentum input**.

Theory matches observations.

How do we encourage spontaneous rotation?