



Physics of fusion power

Lecture 14: Anomalous transport / ITER

[Thursday]

- Guest lecturer and international celebrity Dr. D. Gericke will give an overview of inertial confinement fusion



Instabilities

- Consider a density blob on a magnetic surface
- This blob will smear out on a time scale

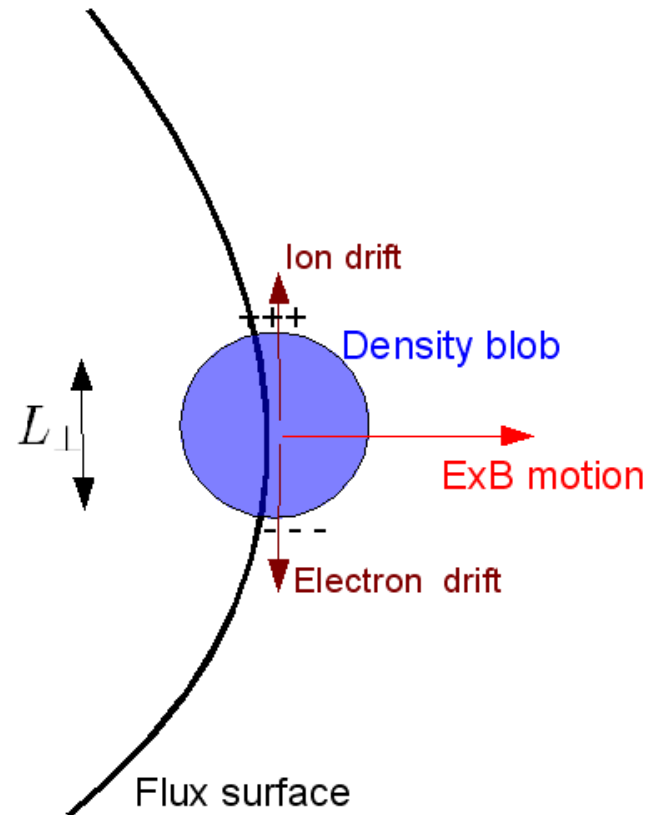
$$\tau_{\parallel} = \frac{2\pi qR}{v_{th}}$$

- Typical time for charge separation

$$\tau_{\perp} = \frac{RL_{\perp}}{\rho v_{th}}$$

- The blob can move radially if

$$\tau_{\perp} < \tau_{\parallel}$$



Instabilities

- Condition for radial motion

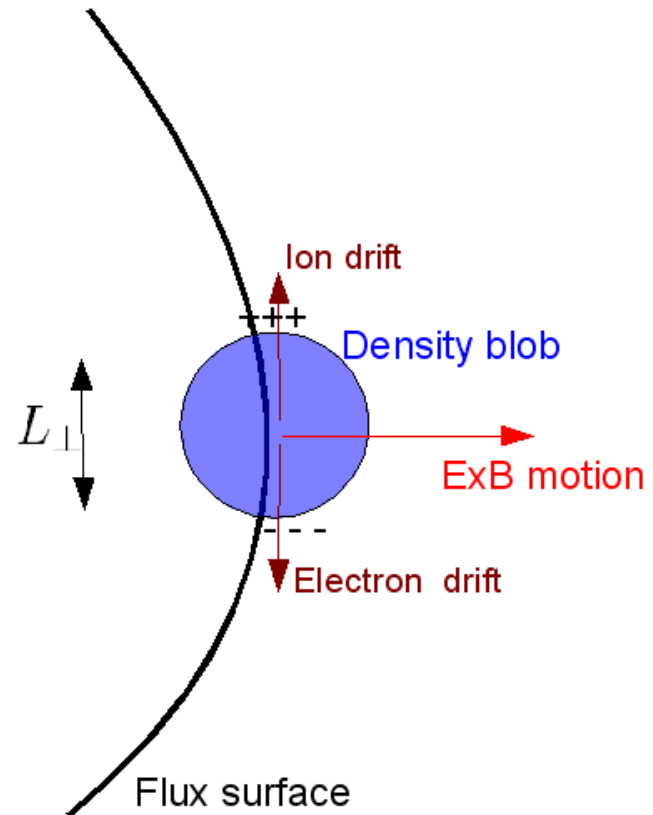
$$\tau_{\perp} < \tau_{\parallel}$$

$$\frac{RL_{\perp}}{\rho v_{th}} < \frac{2\pi qR}{v_{th}}$$

$$L_{\perp} < 2\pi q\rho$$

- For the largest structures the typical time is set by the parallel time scale

$$\tau = \frac{2\pi qR}{v_{th}}$$



Instabilities

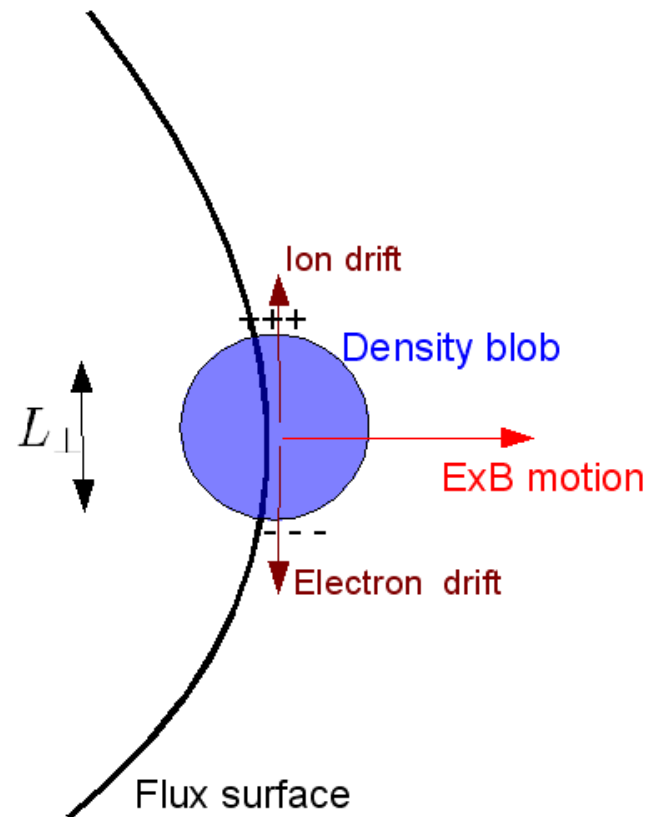
- One can again build a diffusion coefficient

$$D = \frac{L_{\perp}^2}{2\tau} = \pi q \rho^2 \frac{v_{th}}{R}$$

$$\frac{D_{\text{anomalous}}}{D_{\text{classical}}} = \frac{2\pi q v_{th}}{R\nu} \approx 3000$$

$$D_{\text{anomalous}} \approx 24 \text{ m}^2/\text{s}$$

- Much larger than the collision driven transport



**Gyrokinetic Simulations
of Plasma Microinstabilities**

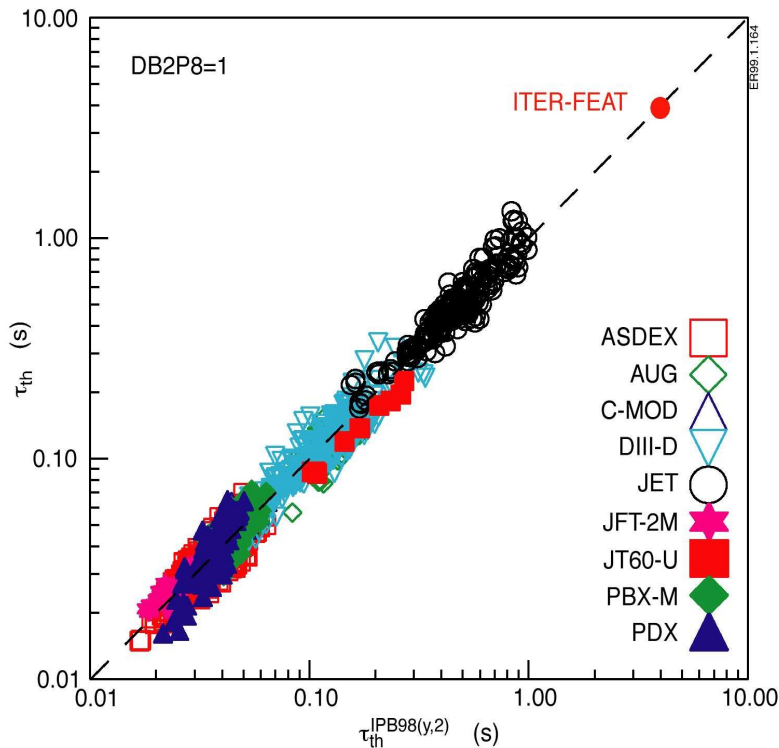
simulation by

Zhihong Lin et al.

Science 281, 1835 (1998)

Confinement time

Experimental basis



The figure shows observed energy confinement time (s) in various experiments versus value derived from the scaling law:

$$\tau_{E,th} = 0.0562 H_H I_p^{0.93} B_T^{0.15} P^{-0.69} n_e^{0.41} M^{0.19} R^{1.97} \epsilon^{0.58} K_a^{0.78}$$

where

I_p = plasma current (MA)

B_T = on-axis toroidal field (T)

P = internal + external heating power

(MW)

n_e = electron density ($10^{19}m^{-3}$)

M = atomic mass (AMU)

R = major radius (m)

ϵ = inverse aspect ratio (a/R)

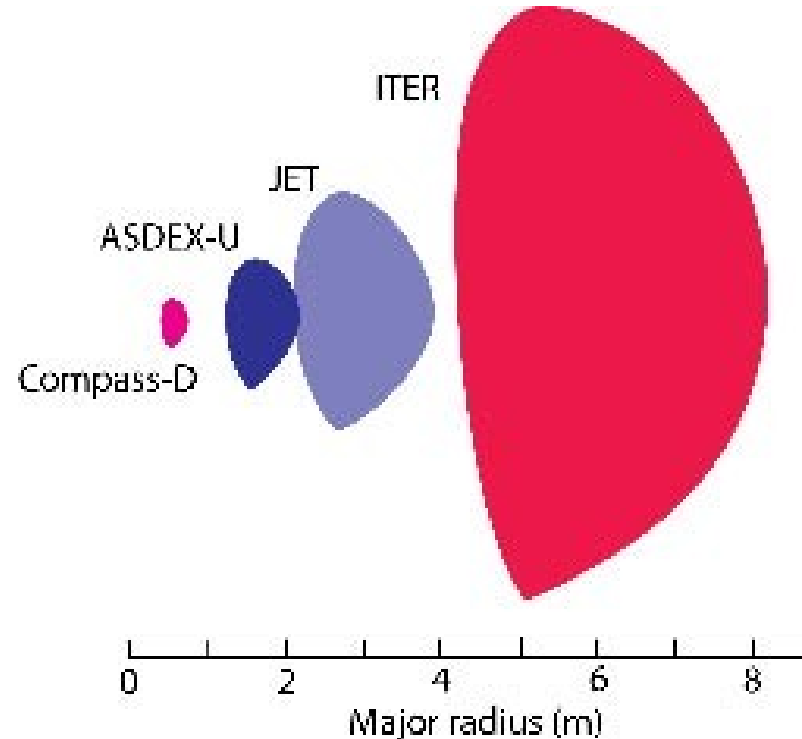
$K_a = S_o/\pi a^2$, S_o = plasma x-sectional

area.

H_H , the confinement time enhancement factor, measures the quality of confinement (= 1 for the dotted line in the figure).

What is ITER?

- ITER = (International Tokamak Experimental Reactor) is the next step in tokamak research.
- Largest tokamak in world
- Project has started in Cadarache, France
- Joint project of Europe, China, Japan, Korea, Russia (and Maybe the US).



Cross section of the plasma area in the poloidal plane for different devices

[More on ITER]

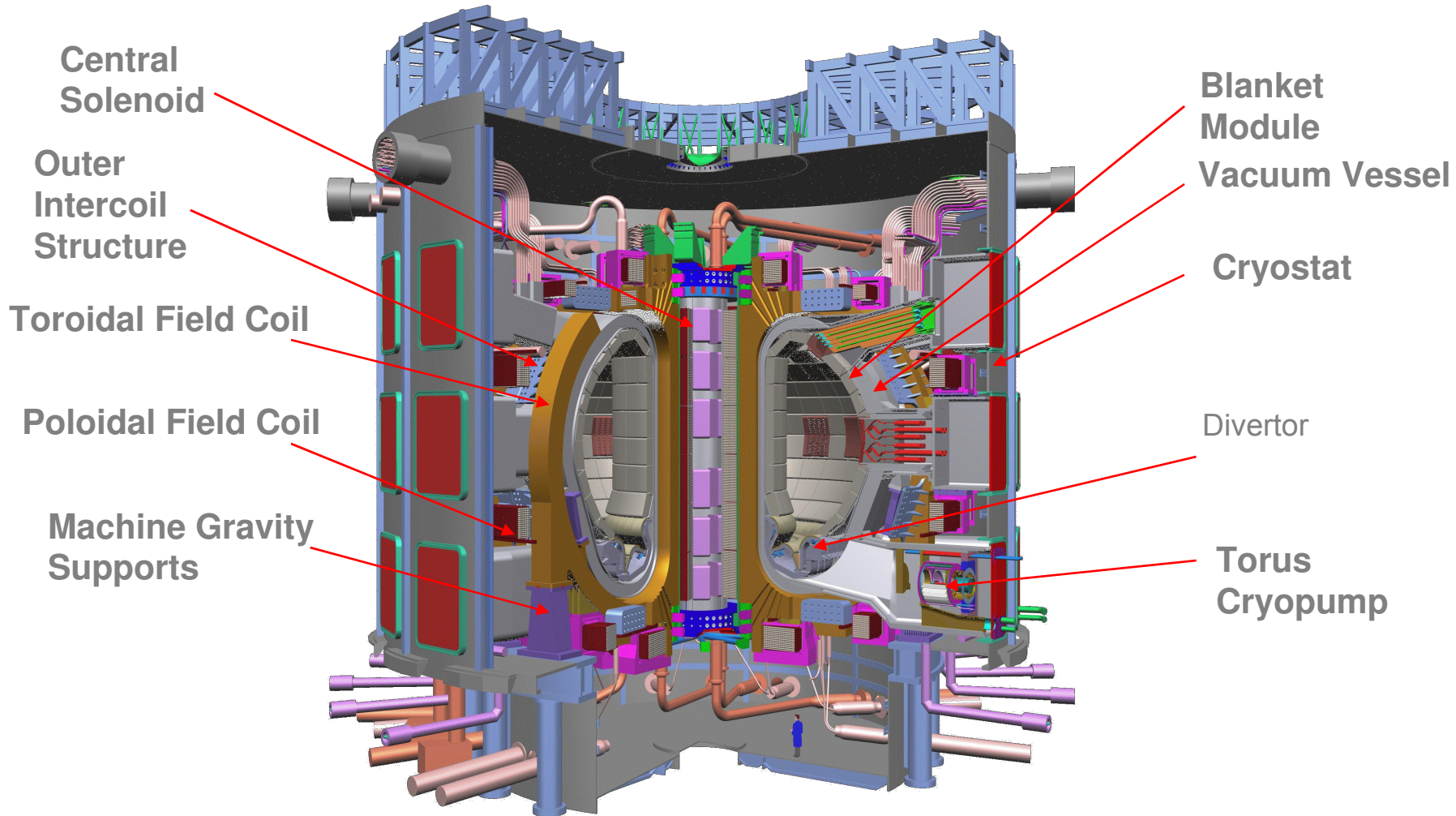
Main objective

- Demonstrate the feasibility of a fusion reactor. This includes generating a plasma that is dominantly heated by fusion reactions, but also demonstrating that an integrated design can meet the technological constraints

Project

- Cost 5 billion euro construction + 5 billion euro for operation (most expensive experiment on earth)
- Construction of building starting in 2008 /Assembly starting on 2012
- Assembly estimated to last 7 years
- 20 years of operation planned

Design - Main Features



ITER parameters

■ Total fusion power	500 MW
■ $Q = \text{fusion power/auxiliary heating power}$ (inductive)	≥ 10
■ Average neutron wall loading	0.57 MW/m ²
■ Plasma inductive burn time	≥ 300 s
■ Plasma major radius	6.2 m
■ Plasma minor radius	2.0 m
■ Plasma current	15 MA
■ Vertical elongation @95% flux surface/separatrix	1.70/1.85
■ Triangularity @95% flux surface/separatrix	0.33/0.49
■ Safety factor @95% flux surface	3.0
■ Toroidal field @ 6.2 m radius	5.3 T
■ Plasma volume	837 m ³
■ Plasma surface	678 m ²
■ Installed auxiliary heating/current drive power	73 MW (100 MW)

Main differences

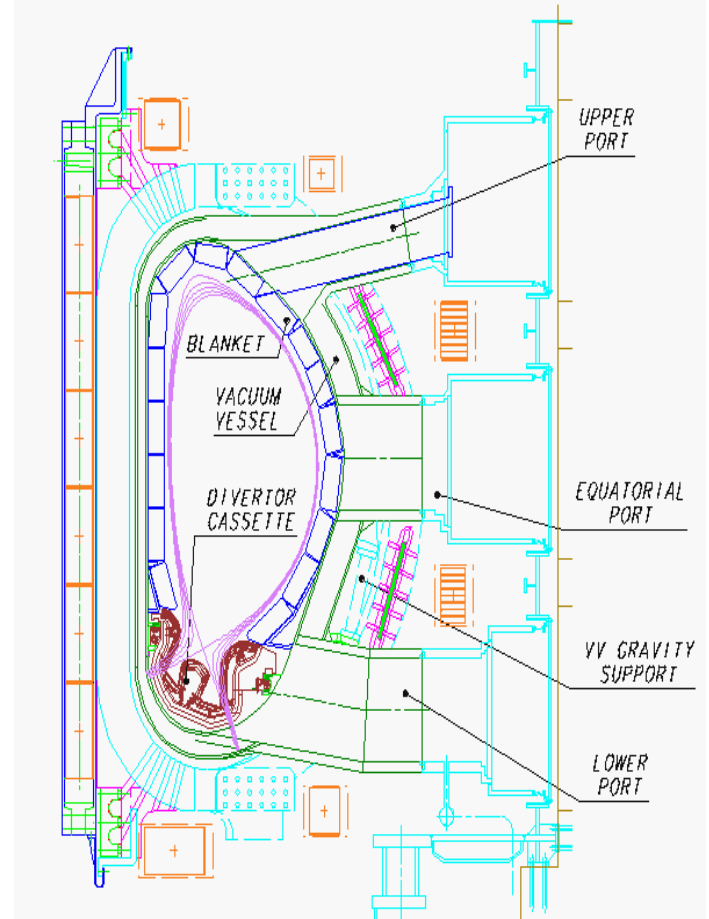
- All components must be actively cooled
- Superconducting coils. For 5 T and a major radius of 6 m one can work out the total current in the toroidal field coils

$$I = \frac{2\pi}{\mu_0} B_t R \rightarrow 150 \text{ MA}$$

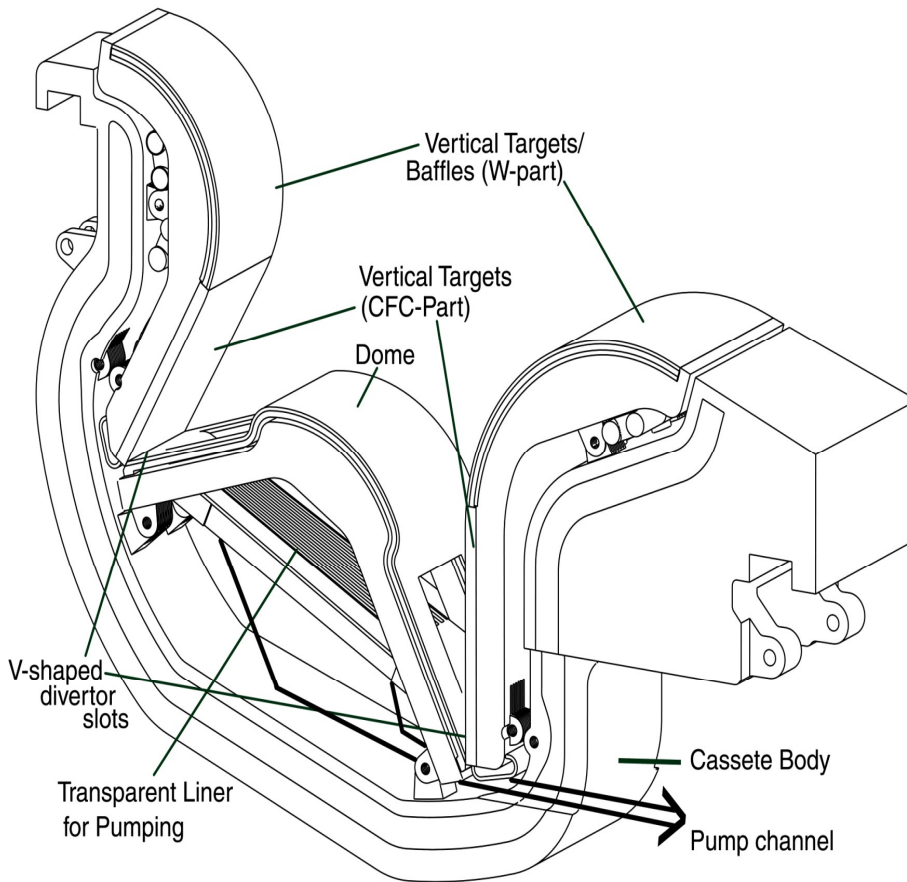
- If the electric field is 1 V/m this will lead to a dissipation (EJ Volume) of 4.5 GW. Much more than the fusion power.
- The best superconductor has a critical magnetic field of around 11 T. This limits the field in the plasma to 5 T !!!!
- Neutron shielding. Superconducting coils must be shielded from the neutrons, which could damage the material or lead to the quenching of the superconductor

Design - Vessel

- The double-walled vacuum vessel is lined by modular removable components, including divertor cassettes, and diagnostics sensors, as well as port plugs for limiters, heating antennae, and diagnostics.
- The total vessel/in-vessel mass is ~10,000 t.
- These components absorb most of the radiated heat and protect the magnet coils from excessive nuclear radiation. The shielding is steel and water, the latter removing heat from absorbed neutrons.

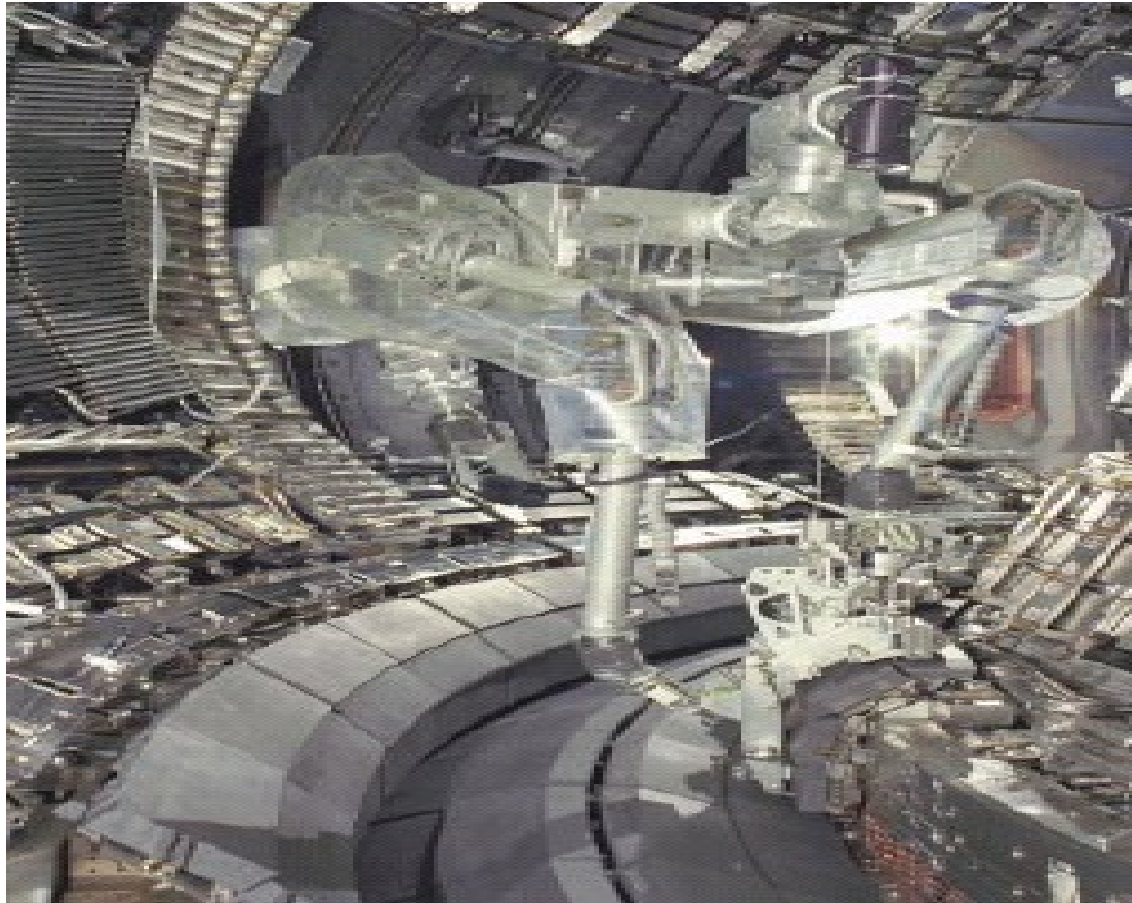


Design - Divertor

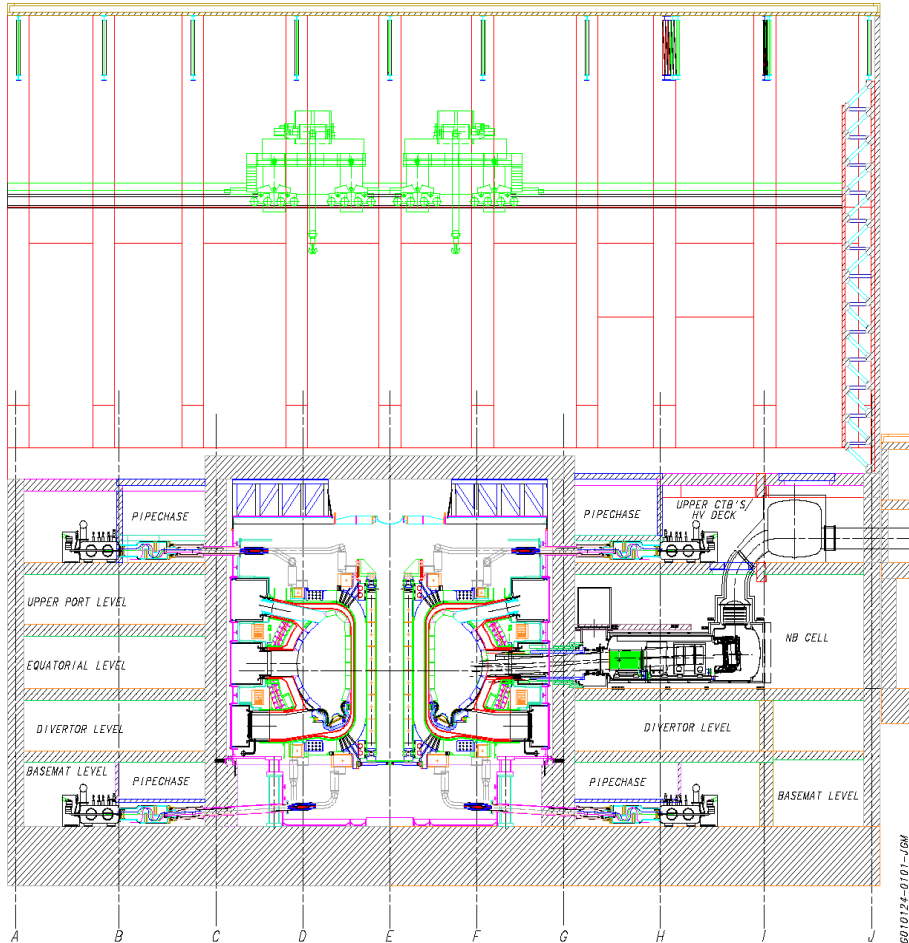


- The divertor is made up of 54 cassettes. The target and divertor floor form a V which traps neutral particles protecting the target plates, without adversely affecting helium removal. The large opening between the inner and outer divertor balances heat loads in the inboard and outboard channels.
- The design uses C at the vertical target strike points. W is the backup, and both materials have their advantages and disadvantages. C is best able to withstand large power density pulses (ELMs, disruptions), but gives rise to dust and T co-deposited with C which has to be periodically removed. The best judgement of the relative merits can be made at the time of the experiments.

Remote handling to replace to cassettes



Design – Tokamak building



- Provides a biological shield around cryostat to minimise activation and permit human access.
- Additional confinement barrier.
- Allows contamination spread to be controlled.
- Provides shielding during remote handling cask transport.
- Can be seismically isolated.

Schedule

