Tokamak Divertor System Concept and the Design for ITER

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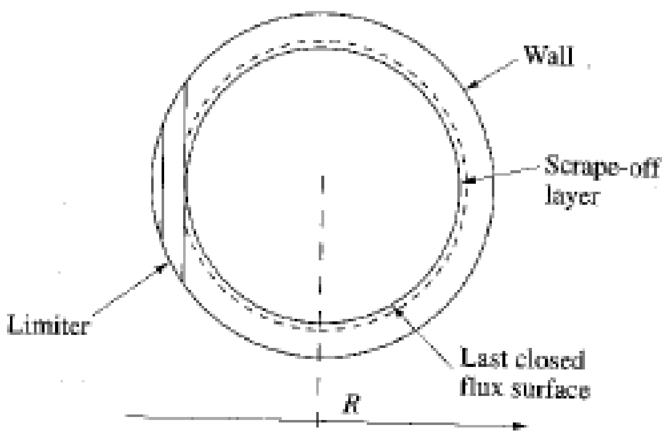
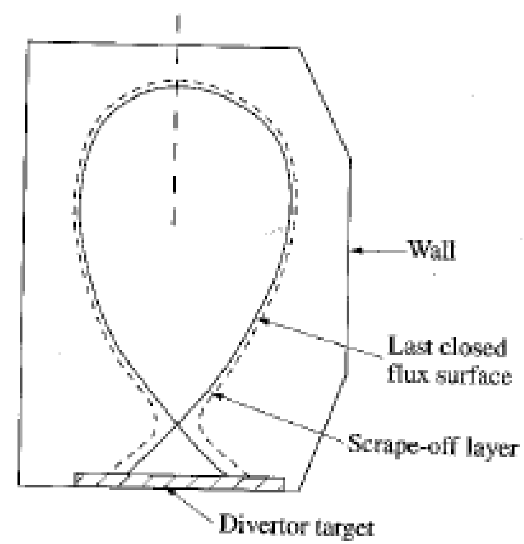
Presentation Overview

- Divertor concept and purpose
- Divertor physics
- General design considerations
- Overview of ITER divertor design
- Review each major ITER divertor component

Divertor Concept

- A divertor sets the confined plasma boundary, called the Last Closed Flux Surface (LCFS), using magnetic fields.
  - As opposed to a limiter, which uses a solid surface.
  - A scrap-off layer (SOL) is generated at the boundary where ionized impurities flow along field lines into the divertor.
- Allows for the D-shaping of the plasma, which makes H-mode plasmas easier to obtain.
  - Part of HBT-EP proposal for the upgrade involves the implementation of a divertor, mostly for plasma shaping capabilities.





Wesson, 1997

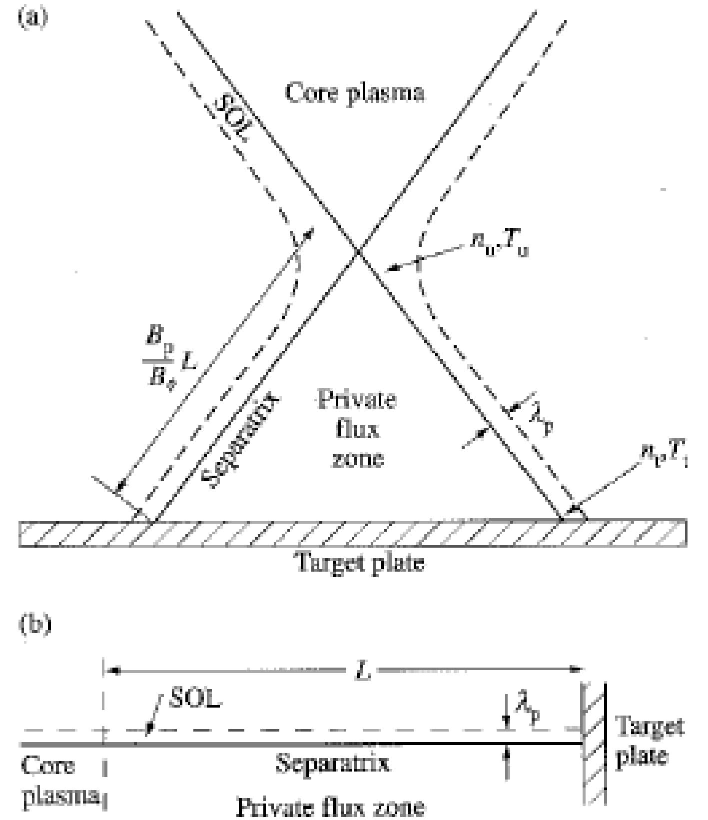
Divertor Purpose

- **Reduce impurity content:** plasma-surface interactions remote from confined plasma and particle flow prohibits impurities from entering the confined plasma.
- **Remove alpha-particle power:** transfer heat to a fluid, which can be used to generate electrical power.
- **Remove helium ash:** pump out helium to avoid dilution of fusion fuel.

Wesson, 1997

Particle Flow Model

- For simple analysis of the particle and heat flow in the scrape-off layer a one-dimensional model is used.
  - Fluid model
    - Momentum conservation
    - Electron heat conduction
    - Boundary conditions of plasma flows at target
  - Radiation is neglected
    - Plays an important role in divertor physics
  - Only looks at region between X-point and target
  - Uses sheath analysis for plasma-surface interaction



Wesson, 1997

Particle Flow Model - Sheath

Poisson's Equation: $$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} = \frac{e}{\epsilon_0}(n_e - n_i)$$

Electron Boltzmann distribution: $$n_e = n_0 e^{e\phi/T_e}$$

Ion energy conservation: $$\tfrac{1}{2}m_i v_i^2 = \tfrac{1}{2}m_i v_0^2 - e\phi$$

For a small potential variation outside the sheath region, these equations become:

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2} = \left(1 - \frac{T_e/m_i}{v_0^2}\right)\frac{\phi}{\lambda_D^2}$$

Thus, ignoring the ion temperature, this equation requires the ion sound speed to be:

$$c_s = v_0 \cong \sqrt{T_e/m_i}$$

Wesson, 1997

Particle Flow Model - SOL

Momentum conservation: $nT(1+\gamma M^2) = \text{Constant}$

M is the Mach number, set to 0 at LCFS, making it 1 at sheath edge

γ is the ratio of specific heats, assumed to be 1

Therefore $n_u T_u = 2 n_t T_t$

Subscript u indicates LCFS and t indicates target

Heat transport along SOL $\kappa \frac{\mathrm{d}\, T_e}{\mathrm{d}\, z} = -q_{\|}$

z is along field line

$q_{\|} = \gamma_s n_t T_t c_{st}$ is the parallel heat transport

$c_{st} = \sqrt{2T_t/m_i}$

The heat conduction coefficient $\kappa = \alpha T_e^{5/2}$

Where $\alpha \sim 2000\,\mathrm{W\,m^{-1}\,s^{-1}\,eV^{-5/2}}$

Wesson, 1997

Particle Flow Model - SOL

Introducing the perpendicular heat flow a requiring the heat flux to be zero at the scrape-off layer:

$$\nabla \cdot q = \nabla \cdot q_{\perp} + \nabla \cdot q_{\|} = 0$$

Yields parallel heat flow and SOL thickness:

$$q_{\|t} = 2.0 \times 10^{15} \frac{L^{5/9} q_{\perp s}^{14/9}}{(\chi_{\perp} n_s)^{7/9}} \, \mathrm{W/m^2}$$

$$\lambda_p = 5.0 \times 10^{-16} \frac{L^{4/9} (\chi_{\perp} n_s)^{7/9}}{q_{\perp s}^{5/9}} \, \mathrm{m}$$

Where $\chi_{\perp}$ is the thermal diffusivity

Wesson, 1997

Particle Flow Model - SOL

- Typical reactor parameters yield a poloidal heat flux density of hundreds of MW/m², which is not tolerable for any solid surface in steady state.
- The power flux density to a solid surface should not exceed 5-10 MW/m².

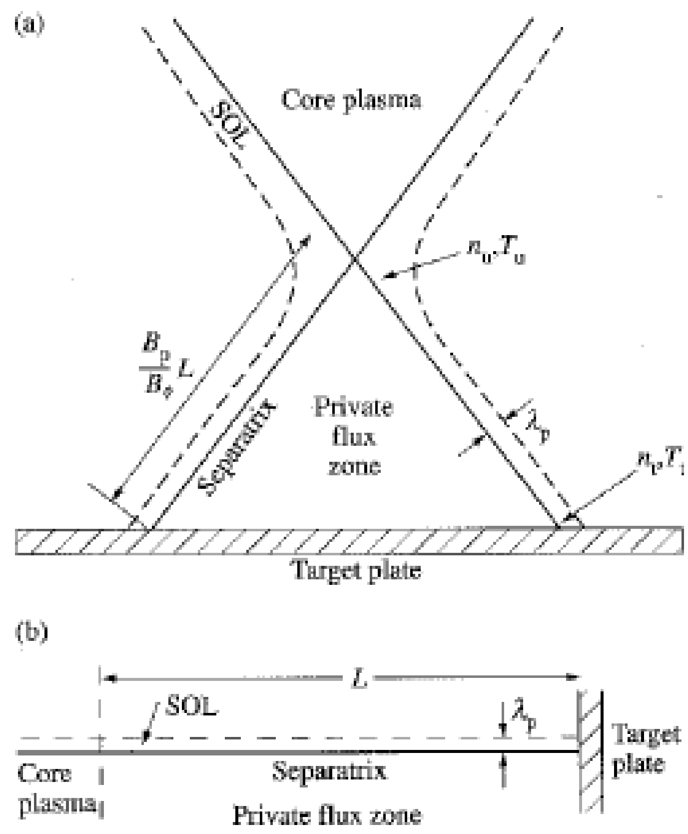
$$q_{\perp s} = 0.5\,\mathrm{MW/m^2}$$

$$L = 150\,\mathrm{m}$$

$$\chi_\perp = 1\,\mathrm{m^2/s}$$

$$n_u = 1 \times 10^{20}\mathrm{m^{-3}}$$

$$\lambda_p = 0.01\,m$$



Wesson, 1997

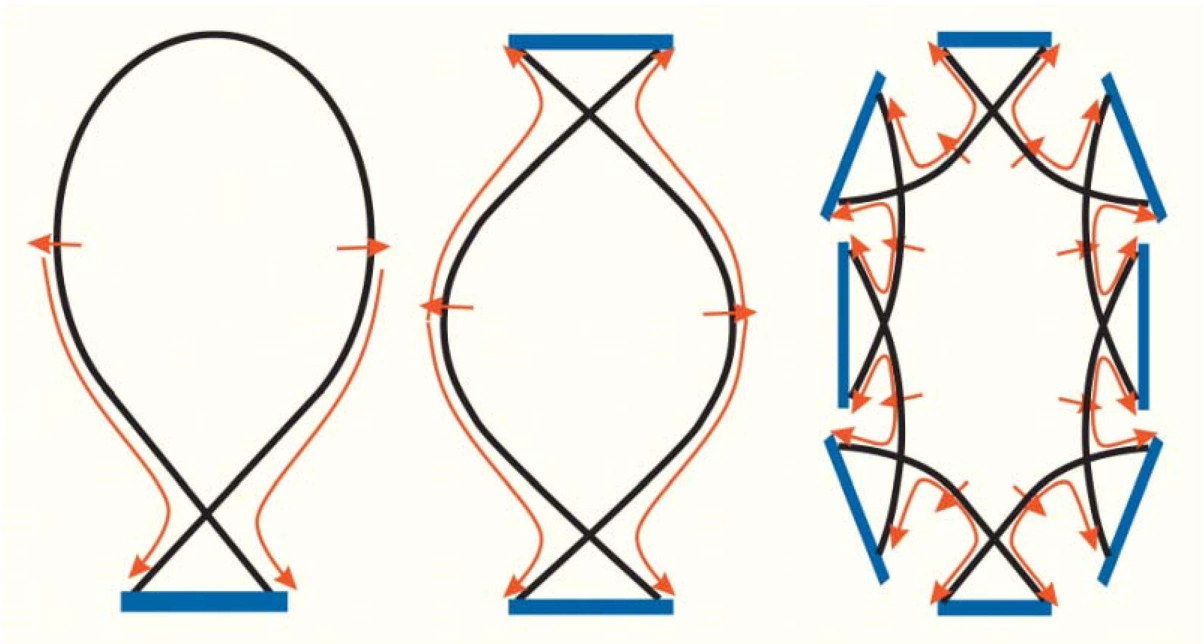
Heat Flux Considerations

- A reactor sized Tokamak producing 3 GW of thermal power would produce 600 MW of alpha particle power and a heat flux density of 600 MW/m^2 in the SOL.
- No solid material can handle this power in steady state (maximum 5-10 MW/m^2), so the power density needs to be reduced:
  - Place tiles at oblique angle to field lines.
  - Flux expand the field lines at they approach the divertor target.
  - Magnetic sweeping of the strike point.
  - Radiate power from particles in the divertor region.
  - Transfer energy to neutral particles in the divertor region.

Wesson, 1997

Design Considerations
Single Vs. Double Null

- Double null configuration doubles the wall interaction area, but halves connection length to target.
- Double null allows for greater triangularity to achieve higher β.
- Double null requires a more complex poloidal field.



Wesson, 1997

http://fusionwiki.ciemat.es/fusionwiki/index.php/File:Divertors.png

Design Considerations
Target

- Flat plates are simple, rigid, and have easy diagnostic access.
- Enclosure
  - Reduces flow of neutrals back to plasma
  - Allows for an increased neutral density
- Tiles
  - Non-uniform thermal expansion suggests the use of small tiles (20 – 30 mm)
  - Tilt for increasing effective area
    - Finite distance between tiles make some field lines normal to adjacent tile.
  - Alignment is important
    - Issues include thermal expansion, magnetic and vacuum forces, and large areas to align.

Wesson, 1997

Design Considerations
Materials

- High temperatures and heat fluxes in the divertor require materials that can handle the conditions.
- Erosion, mostly due to sputtering, causes issues in changing the thickness and impurity introduction.
- Most viable materials include beryllium, tungsten, and carbon fiber-reinforced carbon composite (CFC).

Wesson, 1997

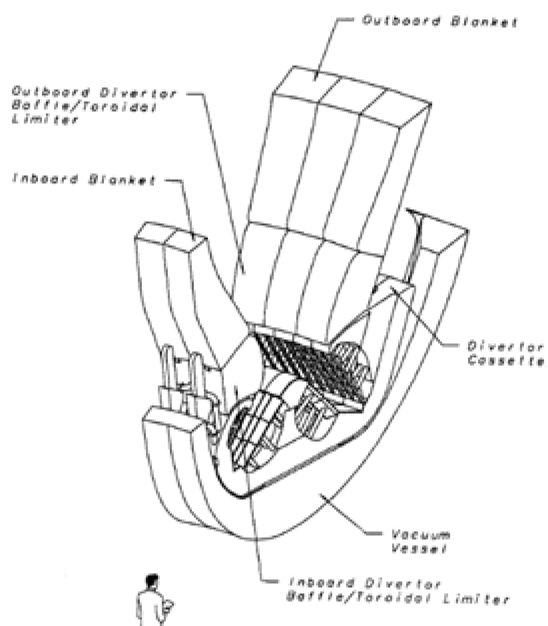
Overview of ITER Divertor

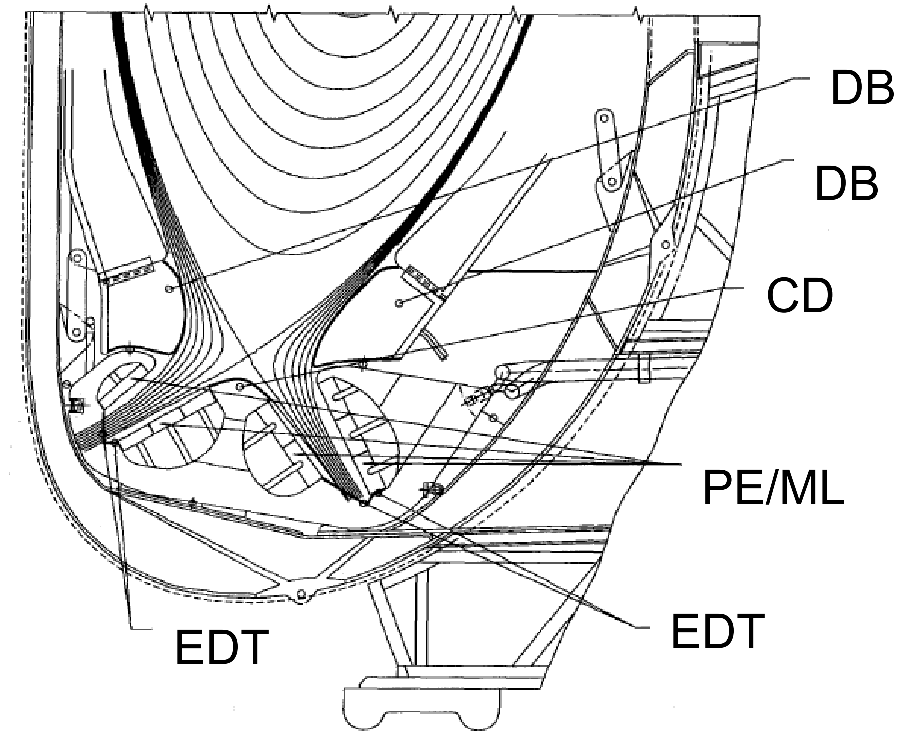
- ITER-FEAT will have fusion power of ~500 MW.
  - Based on ratios from (Wesson, 1997) and (Janeschitz, 1995), the heat flux of alpha particles in the SOL of ITER-FEAT will be ~100 MW/m^2.
  - Heat flux onto the target will be reduced through the divertor design.
- The divertor is split into 54 removable sections for easy replacement and repair.

http://www.iter.org/mach/divertor

ITER Divertor Components

- The main components of the ITER divertor include:
  - Central dome (CD)
  - Divertor baffles (DB)
  - Power exhaust and momentum loss region (PE/ML)
  - Energy dump target (EDT)

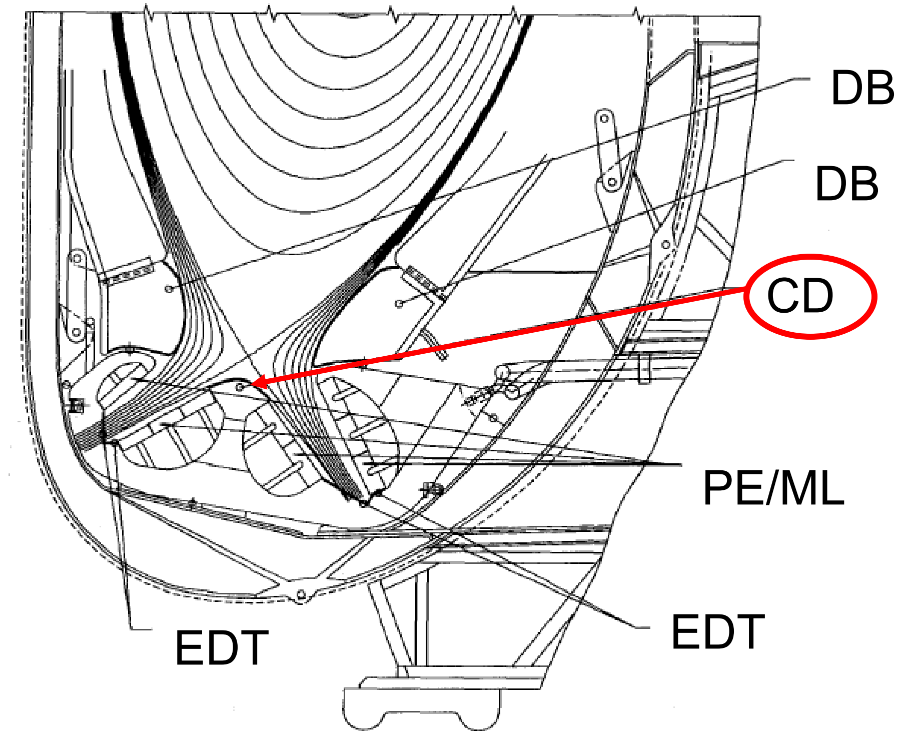




Dietz et al, 1995

ITER Divertor Components
Central Dome

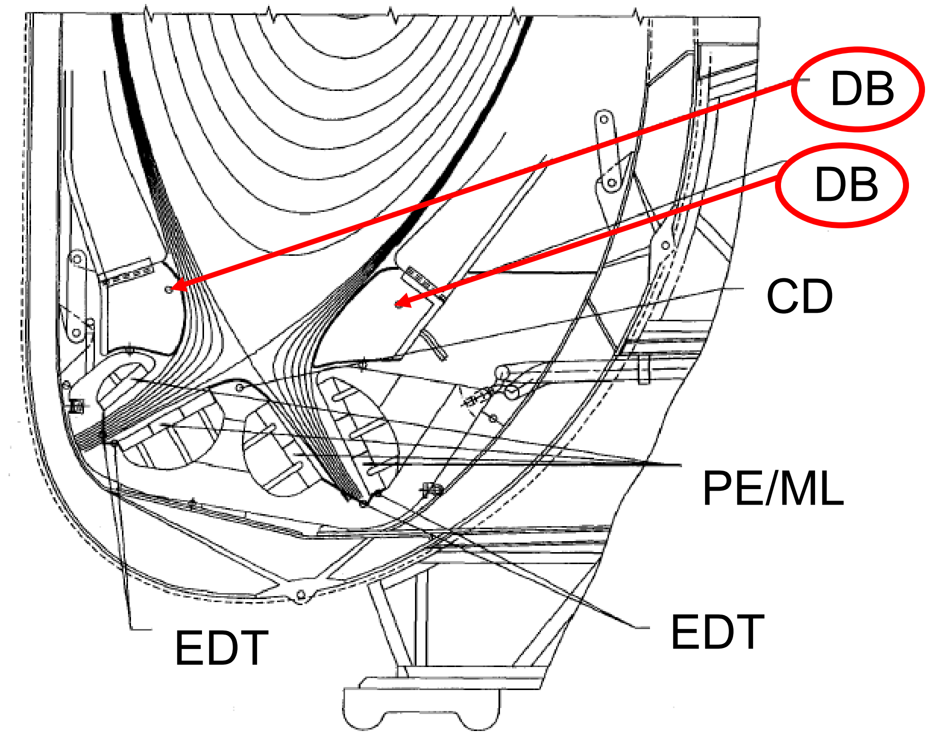
- Protects other components during plasma formation and abnormal plasma movement (ELMs, vertical displacements, etc.).
- Provides baffling of the neutrals in the divertor.
- Shaped to follow magnetic field line under null point.



Dietz et al, 1995

ITER Divertor Components
Divertor Baffles

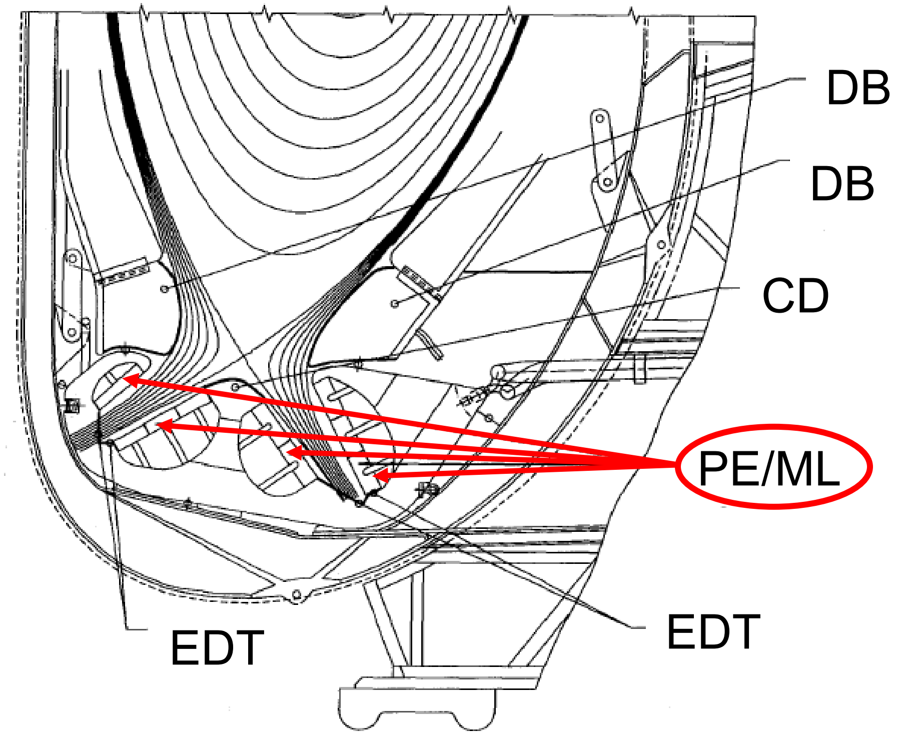
- Protects other components during plasma formation and abnormal plasma movement (ELMs, vertical displacements, etc.).
- Acts as toroidal limiter during start-up and ramp-down.
- Provides baffling of the neutrals in the divertor.
- Alignment is critical.



Dietz et al, 1995

ITER Divertor Components
Power Exhaust and Momentum Loss Region

- Provide means for power reduction through radiation.
- Exhaust radiative power.
- Contain high energy neutrals in the divertor and reduce their energy.

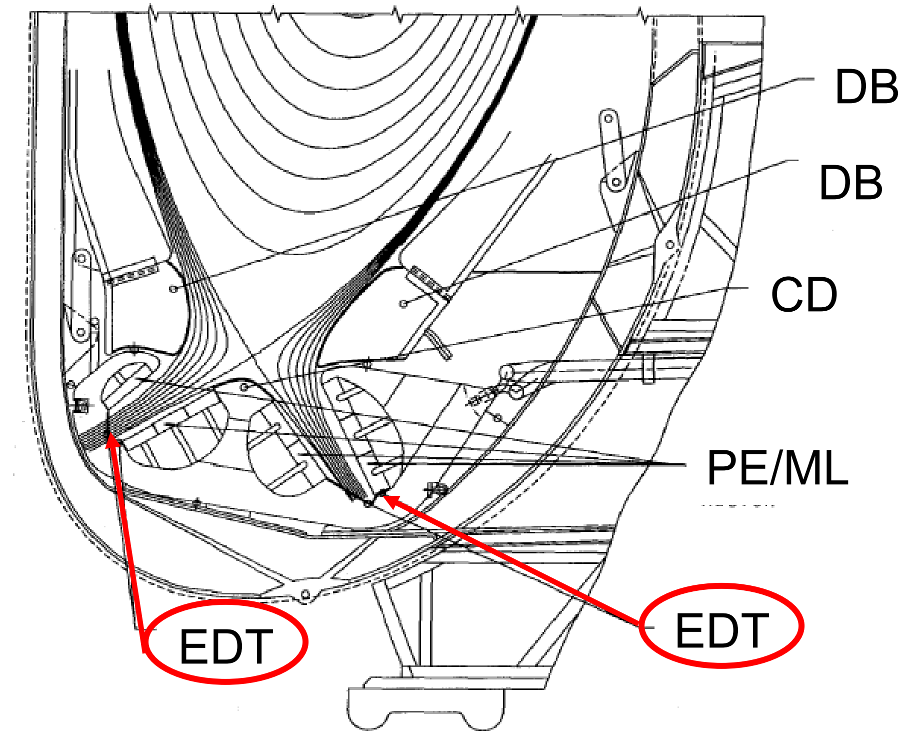


Dietz et al, 1995

ITER Divertor Components

Energy Dump Target

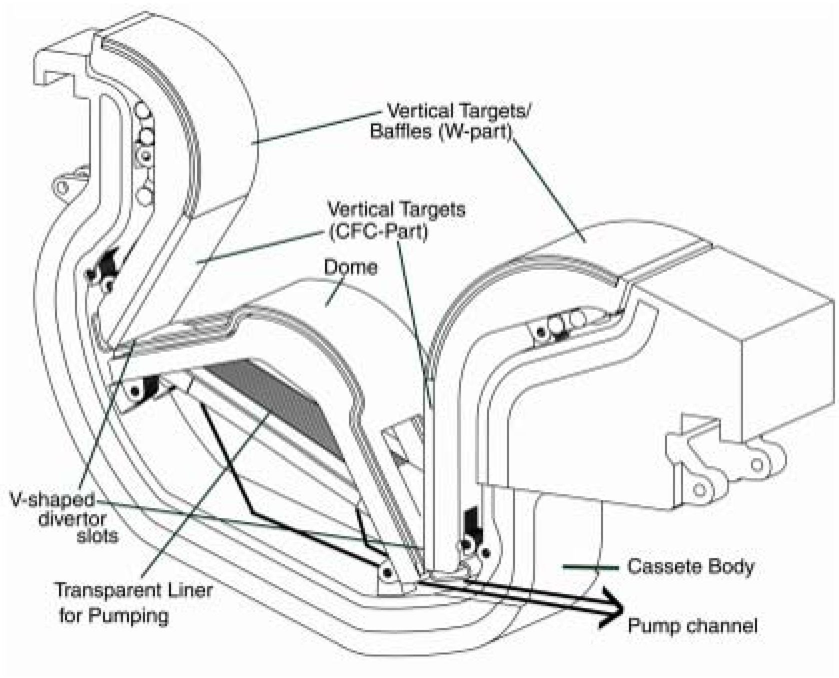
- Exhaust a fraction of the energy from the SOL through heat transfer to cooling system.
- V-shape tilt relative to field lines to increase effective area.
- Specific geometry to avoid hot spots.
- Faces high energy particle bombardment.



Dietz et al, 1995 and Kukushkin et al, 2002

ITER Divertor Material

- Carbon based material CFC will be used in the initial phase of ITER because of larger thermal conductivity.
- Due to tritium retention in CFC, once deuterium is used in ITER, the CFC will be replaced by tungsten.



Janeschitz et. al.

ITER Divertor Power Reduction Methods

- The ITER divertor design employs many techniques to reduce the power flux density on the structure.
  - Target is tilted to increase the effective area.
  - Field lines are flux expanded into divertor.
  - Power is radiated from particles through ionizing collisions and electron relaxation.
    - Some radiation from impurities from sputtering, which may be self-regulating because an increase in temperature introduces more impurities and thus more cooling.
  - Energy is transferred to neutral particles in the divertor through charge exchange and collisions.

Janeschitz et. al.

References

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