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:
\[ \frac{d^2 \phi}{dx^2} = \frac{e}{\varepsilon_0} (n_e - n_i) \]

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

Ion energy conservation:
\[ \frac{1}{2} m_i v_i^2 = \frac{1}{2} m_i v_0^2 - e\phi \]

For a small potential variation outside the sheath region, these equations become:
\[ \frac{d^2 \phi}{dx^2} = \left( 1 - \frac{T_e/m_i}{v_0^2} \right) \frac{\phi}{\lambda_D^2} \]

Thus, ignoring the ion temperature, this equation requires the ion sound speed to be:
\[ c_s = v_0 \approx \sqrt{T_e/m_i} \]

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.

\( \gamma \) 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:
\[ \kappa \frac{d T_e}{d z} = -q_{||} \]

\( z \) is along field line.

\[ q_{||} = \gamma_s n_t T_t c_{st} \]

is the parallel heat transport.

\[ c_{st} = \sqrt{2 T_t/m_i} \]

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

Where
\[ \alpha \sim 2000 \text{ W m}^{-1} \text{ s}^{-1} \text{ eV}^{-5/2} \]

Wesson, 1997
Particle Flow Model - SOL

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

\[ \nabla \cdot q = \nabla \cdot q_\perp + \nabla \cdot q_\parallel = 0 \]

Yields parallel heat flow and SOL thickness:

\[ q_\parallel = 2.0 \times 10^{15} \frac{L^{5/9} q_\perp^{14/9}}{(\chi_\perp n_s)^{7/9}} \text{ W/m}^2 \]

\[ \lambda_p = 5.0 \times 10^{-16} \frac{L^{4/9} (\chi_\perp n_s)^{7/9}}{q_\perp^{5/9} q_\perp} \text{ m} \]

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.

\[
q_{\perp s} = 0.5 \text{ MW/m}^2 \\
L = 150 \text{ m} \\
\chi_{\perp} = 1 \text{ m}^2/\text{s} \\
n_n = 1 \times 10^{20} \text{ m}^{-3} \\
\lambda_p = 0.01 \text{ m}
\]

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/m² in the SOL.
- No solid material can handle this power in steady state (maximum 5-10 MW/m²), so the power density needs to be reduced:
  - Place tiles at oblique angle to field lines.
  - Flux expand the field lines as 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 $\beta$.
- Double null requires a more complex poloidal field.

Wesson, 1997
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/m².
  – 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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