Divertor Requirements and Performance in ITER

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Overview of requirement and prediction for divertor performance taking ITER case as an example

(1) Required divertor performance
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(3) Further model development needed and remaining uncertainty
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With contributions from:
A. Kukushkin, A. Loarte and ITER IT Physics Unit
1. Required divertor performance

(i) Heat removal
(ii) Fuel density control
(iii) Exhaust of helium ash and other impurities
(iv) Providing proper magnetic configuration for enhanced confinement (H-mode)

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<th>Requirements</th>
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<td>1. Peak power load on the target plates ($q_{pk}$)</td>
<td>$q_{pk} \leq 10$ $\text{MW/m}^2$</td>
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<tr>
<td>2. Helium concentration in the core plasma ($C_{He}$)</td>
<td>$C_{He} \leq 0.06$</td>
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<td>3. $Z_{eff}$ in the core plasma</td>
<td>$Z_{eff} \leq 1.6$</td>
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<td>4. Upstream plasma density ($n_s$)</td>
<td>$n_s \leq \bar{n}_e / 3$</td>
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<td>5. D-T particle throughput ($\Gamma_{DT}$)*</td>
<td>$\Gamma_{DT} \leq 200$ $\text{Pa} \cdot \text{m}^3 / \text{s}$</td>
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<tr>
<td>6. Core fuelling ($\Gamma_{DT}^{core}$)*</td>
<td>$0 \leq \Gamma_{DT}^{core} \leq 100$ $\text{Pa} \cdot \text{m}^3 / \text{s}$</td>
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- 6 requirements must be simultaneously satisfied
  * are also control actuators

Specific features for divertor control

(i) Control actuators; not so many
  - Divertor geometry
  - Gas-puffing (Throughput ; $\Gamma_{DT}$)*
  - Core fuelling ($\Gamma_{DT}^{core}$)*
  - Pumping speed
  - Impurity seeding (Ne, Ar)
(ii) Divertor and Core Performance are closely linked; SOL/Divertor ⇔ Pedestal ⇔ Core

- Development of Modelling to include Pedestal continues, but not yet complete.
- Presently CEI (5cm inside separatrix) is calculation boundary and transport barrier is not yet properly modelled.
2. Predicted divertor performance

Prediction by B2/Eirene divertor code

**Basic models**
- $D = 0.3 \text{ m}^2/\text{s}$, $\chi = 1 \text{ m}^2/\text{s}$
  - w/o parameter and spatial dependence
- ELM effect is not included (time averaged)
- Carbon sputtering (physical + chemical), but they are absorbed at every surface encountered
- Partial detachment (only near separatrix is detached)

**Optimization of divertor geometry**
Key strategy to reduce peak power load:
- Enhance neutral accumulation, in particular, near the separatrix region for outer target plate

- **Vertical Target Plate + Divertor Dome**
- **V-shape Target geometry**; effective in accumulating neutrals near separatrix (JET)

$\Rightarrow \approx 30\%$ reduction of $q_{pk}$ in ITER

(Kukushkin, EPS 2001)
• Gas flow between inner and outer divertor;
  \[\Rightarrow \text{increase neutral recirculation in the outer divertor target region (higher power flux)}\]
  \[\Rightarrow \text{reduce peak heat load (JET, JT-60U)}\]

- \(\approx 20\%\) reduction of \(q_{pk}\) by gas flow between inner and outer divertor

**Separatrix density**

Dominant effect on divertor performance and can be controlled by gas puffing (throughput; \(\Gamma_{DT}\)) to some extent

\[\Gamma_{DT} = \Gamma_{gas}^{DT} + \Gamma_{core}^{DT}\]

• Saturation corresponds to detach. of inner divertor (increased neutral density)

• Higher \(n_s\) for higher power to detach
Inductive operation

- Peak power load and helium concentration

  \[ q_{px} \text{ [MW/m}^2 \text{]} \]

  \[ n_s \text{ [10^{20} m}^3 \text{]} \]

Reference operation
\( P_{SOI}=86\text{MW}(P_f=410\text{MW}, P_{total}=123\text{MW}, Q=10, f_{rad}=0.3) \)

High fusion power with high Q
\( P_{SOI}=100\text{MW} \ (P_f=600\text{MW}, P_{total}=145\text{MW}, Q=24, f_{rad}=0.4) \)

High fusion power with low Q
\( P_{SOI}=130\text{MW} \ (P_f=600\text{MW}, P_{total}=187\text{MW}, Q=9, f_{rad}=0.3) \)

- Peak power load and helium concentration for reference operation mode is well within the requirement.
- Fusion power (helium source) and throughput dominate helium concentration, while pumping speed is less important
- Reasonably wide operation window is available for the reference inductive operation mode, while density window is not so wide \( (\Delta n_s \text{ between } q_{max} \text{ and complete detachment}) \)
Steady state operation

Steady state
\( P_{SOL} = 100 \text{MW} \)
\( P_f = 340 \text{MW}, \ Q = 5.7, \)
\( P_{\text{total}} = 128 \text{MW}, \ f_{\text{rad}} = 0.2 \)
Longer connection length
with \( q_{95} = 4.5 \)
\( \Rightarrow \) same \( q_{pk} \) with
lower \( n_s \)

cf.

Inductive operation
\( P_{SOL} = 100 \text{MW} \)
\( q_{95} = 3.0 \)

- \( n_s (at \ q_{pk} = 10 \text{MW/m}^2) = 0.26 \)
  \( \Rightarrow \) somewhat higher than \( n_s \approx \bar{n}_e / 3 \approx 0.23 \)
  \( \Rightarrow \) Impurity seeding will be needed

- Initial calculations with neon seeding (0.4%);
  \( \Rightarrow \approx 30\% \) reduction of \( q_{pk} \) (radiation region is getting
  far from target plate compared with carbon)
  \( q_{pk} = 10 \text{MW/m}^2 \) at \( n_s = 0.23 - 0.24 \)
  \( \Delta Z_{\text{eff}} \approx 0.4 \) (total \( Z_{\text{eff}} \approx 1.6 \))
3. Further model development needed and remaining uncertainty

(1) Transport in SOL region
(2) Separatrix density under good H-mode confinement

(3) Consistent pedestal model is not yet developed;
   - $D = 0.3 \text{ m}^2/\text{s}$, $\chi = 1 \text{ m}^2/\text{s}$ are too large in the pedestal (transport barrier) region
     => low pedestal density ($n_{ped} \approx (3.5 - 4.5) \times 10^{19} \text{ m}^{-3}$)
     => e.g., neoclassical level $D = 0.06 \text{ m}^2/\text{s}$ and proper width model for pedestal must be implemented
     => Consistent boundary condition for core plasma transport (to be developed)

=> By proper pedestal model, core fuelling requirements can be properly specified, which is consistent with the expected density pedestal in ITER

Core fuelling is needed because;

- Gas-puffing is very inefficient due to thick SOL in ITER

- Only small fraction of gas-puffed neutrals can penetrate across separatrix
Specification of required core fuelling for expected density pedestal in ITER

Particle balance across separatrix and pedestal

- **Core fuelling** $\Gamma^C_{\text{core}}$;
  Fuelling inside pedestal

- **Pedestal fuelling** $\Gamma^P_{\text{core}}$;
  Fuelling between separatrix-pedestal

- With proper transport model in the pedestal and core or pedestal fuelling can achieve the expected pedestal density

- Fuelling in the pedestal region is also possible but factor of two larger fuelling is needed

- High field side pellet is prepared for ITER
  ⇒ required core fuelling is possible
  $50-100 \text{ Pa} \cdot \text{m}^3/s$
  $500 \text{ m/s}$ (deposition depth $\approx 0.15a$ ; inside pedestal)
4. ELM effects and mitigation

High pedestal pressure required for good confinement can result in large divertor erosion due to Type-I ELMs

- Limit for divertor erosion due to ELMs
  \[ \Delta W_{\text{ELM}} / \left( S_{\text{ELM}} \sqrt{\tau_{\text{ELM}}} \right) \] ; surface temperature rise

(Federici; SOFE, 2002)

- Specification for \( \tau_{\text{ELM}} \approx 200 \) \( \mu s \)
- \( \tau_{\text{ELM}} \) in JET for various density and triangularity
  \( \tau_{\text{ELM}} \approx 200 \mu s \)
• Specification for \( S_{ELM} \approx 2 \times S_{ss} \)

\( \lambda_q \); Power deposition width mapped on midplane has large uncertainty

• Experimental data for \( S_{ss} \) are mostly taken from attached condition

\[ \Rightarrow \lambda_q \approx 5\text{mm} \]

\[ \Rightarrow S_{ELM} \approx 6 \text{ m}^2 \]

• From power load profile in ITER; \( \lambda_q = (10-13) \text{ mm} \) due to detachment

\[ \Rightarrow S_{ELM} \approx 15 \text{ m}^2 \]

• Criteria of \( \Delta W_{ELM} / W_{ped} \) for surface temperature rise up to critical one

\[ \tau_{ELM} = 200 \text{ } \mu s \]

\[ S_{ELM} \approx 6 - 15 \text{ m}^2 \]

<table>
<thead>
<tr>
<th>Allowable ( \Delta W_{ELM} / W_{ped} ) (%) for ( 10^6 ) ELM events with deposition area</th>
<th>CFC</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_{ELM} \approx 2 \times S_{ss} \approx 6 - 15 \text{ m}^2 ) ( W_{ped} \approx 100 \text{ MJ} )</td>
<td>3.4- 8.3</td>
<td>4.4- 11</td>
</tr>
</tbody>
</table>

* This is also necessary to maintain plasma purity \((\approx 10^{22} \text{ carbon/ELM event is produced})\)
Proposed models for experimental data summary

Collisionality ($V^*$) (Loarte, IAEA 2000)

$$\frac{\Delta W_{ELM}}{W_{ped}} \propto (V^*)^P$$

$P \approx -0.33$

(15-20) % for ITER

Parallel transport ($\tau_{//}$) (Janeschitz, PSI 2000)

$$\frac{\Delta W_{ELM}}{W_{ped}} = \frac{(\Delta W_{ELM})_0}{1 + \tau_{//}/\tau_{ELM}}$$

$$\tau_{//} = \frac{2L}{C_s} (1 + \sqrt{3/2} V^*)$$

$$\tau_{ELM} \approx 200 \ \mu s$$

(12-15) % for ITER

Sheath model (Shimada, 2001)

$$\Delta W_{ELM} = \gamma k T_{ped}$$

$$\times (B_p / B_T)_{om} 4\pi R_{om} \Delta_{om} \Delta t$$

Upper limit

($\approx 5$) % for ITER

All models still need much more work for ITER extrapolation
ITER Prediction

- Very severe predictions based on $V^*$ and $\tau_{//}$ models.
- Range of uncertainty and difference between models are significantly large.
Possible mitigation methods

(1) Further inclination of divertor plate

- Poloidal projected angle $22.8^\circ$ (2.1° real) $\Rightarrow$ 11.4°

- Possible disadvantage can be acceptable
  - Particle recycling on the upper part of divertor plate;
    $\Rightarrow$ not significantly increased (B2/Eirene)

- Separatrix line position control;
  $\Rightarrow$ may be acceptable once operation mode is fixed for engineering testing (life time becomes a more important issue for this phase).
  $\Rightarrow$ use of W divertor plate may also be possible during this phase due to low disruption probability.
(2) Discharge regime of high pedestal pressure with small ELMs (Type II)

- Most of the present machines show that
  - high \( q_{95} \) (≥ 3.5-4)
  - high \( \delta_X \) (≥ 0.4-0.5)

are needed to obtain this alternative ELM regime.

- \( \delta_X \) for ITER (=0.5) satisfies the required condition.

- Q=10 and \( P_{\text{fusion}} \approx 250\text{MW} \) operation with \( q_{95}=3.5 \) (Ip=13MA) is possible, though window is narrow.

![1.5D simulation (PRETOR)](image)

- Further increase of HH-factor
  - with lower density (many machines)
  - with higher \( q_{95} \) (HH=1.3 with \( q_{95}=3.6 \), \( \bar{n}/n_G \approx 1 \) and very small ELMs in AUG)

window becomes much wider.

- This small ELM regime will be accessible for Hybrid and steady-state scenario (\( q_{95}>3.5 \)).

- Further R&D is needed to extend this small ELM regime to the reference high Q inductive operation mode.
  - Type II ELMs in-between Type I (\( q_{95}=3, \ \delta_X=0.5; \ JET \)) could be a clue for R&D
5. Summary

- Divertor requirements for ITER are summarised.

- B2/Eirene code calculations show that these requirements will be satisfied for inductive operation mode.

- For non-inductive operation mode, impurity seeding will reduce the peak heat load to meet the requirement.

- Further model development is necessary for B2/Eirene to include proper pedestal model. It is indicated that gas-puffing cannot fuel across the separatrix to form proper density pedestal. High field side pellet fuelling is prepared in ITER to fuel inside the pedestal.

- Effect of Type-I ELMs on divertor plate could be severe for high pedestal pressure required for good confinement, while present prediction by proposed models are still primitive, and thus further development/improvement of the models as well as the database are necessary.

- Possible mitigation methods for Type-I ELM effect are summarised; inclination of target plate and Type-II ELMs. Hybrid and steady-state scenarios can be operated with Type-II ELM regime. Further exploration to extend this regime to high Q inductive operation mode should be promoted.