SOL Width Studies for ITER Ramp-up/Down

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Motivation

- The present ITER scenarios foresee initial and final ramp-up/down limiter phases in Ohmic or L-mode with very low additional heating.

- Power flux e-folding length is a crucial design parameter for the limiters.

- For the diverted L-mode phase a scaling law derived from divertor power flux measurements on JT-60U, JET, and ASDEX-Upgrade is assumed (with an uncertainty of a factor of ~ 2 around this value):

\[ \lambda_p \ (m) = (1 \pm 1/3) \times 3.6 \times 10^{-4} \times R(m)^2 \times P_{\text{div}}(\text{MW})^{-0.8} \times q_{95}^{0.5} \times n_e (10^{19} \text{m}^{-3})^{0.9} \times Z_{\text{eff}}^{0.6} \]

- The same L-mode scaling has been applied to the limiter phases by:
  - replacing the power to the divertor by the power to the limiters
  - taking into account number and spatial location of the limiters (HFS vs LFS)

- ITER STAC-5 report: The local \( \lambda_p \) at the limiter PFCs is expected to be ~4 times larger if the plasma is limited at the HFS than at the LFS (mostly due to the strong ballooning component of the edge transport)

- Of this factor, ~1.6 is due to the flux expansion at HFS; if \( \lambda_p \) is measured at the LFS, HFS- and LFS-limited cases should differ by a factor of ~ 2.5
Limiter Options in DIII-D

- Inner wall and top “knee” limiter are toroidally symmetric
- LFS limiters are localized and have small poloidal extent
Diagnostic Arrangement

- 5-pin array
- Measured parameters: $I_{si}$, $T_e$, $V_f$
- Derived parameters: $n_e$, $V_p$, $E_\theta$, $\Gamma_\perp$, $Q_\perp$

Power flux e-folding length is estimated from the probe data assuming $T_i = T_e$.

$$Q_\parallel \propto n T_e^{3/2}$$

$$1/\lambda_p = 1/\lambda_n + 3/2 \lambda_T$$
Limited and Diverted Plasma Shapes Studied

HFS-limited $\equiv$ IWL

Lower Single Null $\equiv$ LSN

Top-limited $\equiv$ TL

$k = 1.43$

$k = 1.51$

24 discharges, 37 profiles

10 discharges, 10 profiles

1 discharge, 2 profiles

We did not run LFS-limited shape because LFS-limited SOL lacks toroidal symmetry
Parameter Space Covered

- **IWL**: \( n_e \) scans performed at three \( I_p \) levels and two \( P_{NBI} \) levels (0 and 1.25 MW)
- **LSN**: \( n_e \) performed at three \( I_p \) levels
- **SOL** profiles taken during stationary phases

**Parameter ranges:**

\[ q_{95} = 3.2 - 7.4 \rightarrow \text{x2.3 variation} \]

\[ n_e = 1.1 - 4.5 \times 10^{13}\text{cm}^{-3} \rightarrow \text{x4 variation} \]

\[ P_{LCFS} = P_{Ohmic} + P_{NBI} - P_{rad\_core} = 0.1 - 1.4 \text{ MW} \rightarrow \text{x14 variation} \]
**SOL $n_e$ and $T_e$ e-folding Lengths Obtained from Probe**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$I_p$ (MA)</th>
<th>$n_e$ ($10^{13}$ cm$^{-3}$)</th>
<th>$P_{LCFS}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IWL</td>
<td>0.88</td>
<td>2.37</td>
<td>0.4</td>
</tr>
<tr>
<td>LSN</td>
<td>0.88</td>
<td>1.76</td>
<td>0.23</td>
</tr>
<tr>
<td>TL</td>
<td>0.87</td>
<td>2.16</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Near-LCFS e-folding lengths are of interest for the scaling.
SOL $n_e$ and $T_e$ e-folding Lengths are Correlated

\[ \lambda_{T_e} \sim 1.2 \lambda_{n_e} \]

- SOL width in IWL is larger than in LSN and TL
- The expected difference per ITER STAC report should be $\sim x2.5$
- Our results are roughly consistent with the ITER expectations
Comparison of $\lambda_p$ with ITER Scaling

\[ \frac{1}{\lambda_p} = \frac{1}{\lambda_{ne}} + \frac{3}{2} \lambda_{Te} \]

IWL data divided by 2.5

- Most of IWL data within the assumed uncertainty of the ITER scaling
- At the highest $I_p$ (lowest $q_{95}$) the agreement is the best
- There is a tendency of the measured $\lambda_p$ to be lower than predicted by the scaling, particularly in LSN and higher elongation IWL
Radiation-dominated discharges (with $P_{\text{LCFS}} < 0.25 \text{ MW}$) are removed.

This improves agreement with the scaling (except in lower-$\kappa$ IWL).

All remaining lower-$\kappa$ IWL points are within the scaling uncertainty.

The points are scattered so $\lambda_p \text{ measured} \propto \lambda_p \text{ scaling}$.

1/ $\lambda_p = 1/ \lambda_{ne} + 3/2 \lambda_{Te}$  IWL data divided by 2.5
No Clear Dependencies of $\lambda_p$ on $n_e$, $q_{95}$, $P_{LCFS}$

All data from lower-$\kappa$ IWL

- $I_p = 1.2$ MA, $P_{NBI} = 1.2$ MW
- $I_p = 0.9$ MA, $P_{NBI} = 1.2$ MW
- $I_p = 0.6$ MA, $P_{NBI} = 1.2$ MW

- $n_e = 2.2-2.7 \times 10^{13}$ cm$^{-3}$, $P_{NBI} = 1.2$ MW
- $n_e = 1.9-2.4 \times 10^{13}$ cm$^{-3}$, $P_{NBI} = 0$
- $I_p = 1.2$ MA, $n_e = 2.1-2.7 \times 10^{13}$ cm$^{-3}$
- $I_p = 0.9$ MA, $n_e = 2.3-2.6 \times 10^{13}$ cm$^{-3}$
- $I_p = 0.6$ MA, $n_e = 1.8-2.27 \times 10^{13}$ cm$^{-3}$

Scaling: $\lambda_p \propto n_e^{0.9}$

Scaling: $\lambda_p \propto q_{95}^{0.5}$

Scaling: $\lambda_p \propto P^{-0.8}$

- Experiment shows some tendency for $\lambda_p$ to increase with $n_e$ and $q_{95}$
- No clear trend with power
- Shot-to-shot variation and interdependence of parameters make it hard to determine $\lambda_p$ dependencies on the individual parameters
Summary

- We have benchmarked ITER SOL power flux width scaling in limited and diverted configurations in DIII-D.

- In low-elongation Inner-Wall-Limited (IWL) configuration, our data agree with the scaling within the assumed uncertainties.

- In higher elongation IWL and in diverted LSN configurations, the SOL power width in DIII-D tends to be below that given by the scaling.

- Dependencies of the SOL power width on the individual discharge parameters could not be confirmed due to shot-to-shot variations and parameter interdependence.