Experimental impurity concentrations required to reach detachment in ASDEX Upgrade and JET

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* See the Appendix of H. Meyer et al., Nucl. Fusion 59 (2019) 112014, B. Labit et al., Nucl. Fusion 59 (2019) 086020, and J. Mailloux et al., to be published in Nuclear Fusion Special issue: Overview and summary papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

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Impurity seeding is generally regarded as a viable technique for dissipating the target power load, with divertor detachment of central importance for reactor designs.

The goal is to measure the difficulty of achieving divertor detachment in terms of: input power, machine size, density, plasma current, impurity species.

The simple analytical Lengyel model provides the basis for relating the divertor conditions to the power dissipated. Other derivations have since followed:

- **Goldston derivation**
  \[ c_I \propto P_{sep} n_{e,sep} I_p \alpha_{min} \]

- **Reinke derivation**
  \[ c_I \propto B_T^{0.88} f_{LH}^{1.14} n_{e,sep} R_{maj}^{1.33} M_{L,I}^{-1} \]

- **Kallenbach derivation**
  \[ c_I \propto P_{sep} R_{maj}^{-1} P_0^{-1} \]

Experimental measurements needed to challenge theoretical scaling laws.
Impurity seeding for tokamak exhaust

Impurity seeding is generally regarded as a viable technique for dissipating the target power load, with divertor detachment of central importance for reactor designs.

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Passive spectroscopic measurements of singly charged ion emission provide a transient, non-perturbative, and local estimation of the divertor concentration.

$$c_I = \frac{4\pi \int \varepsilon_{i,Z} \, dl}{TEC_{i,Z} \Delta L_n e}$$

- Ion emission
- Atomic coefficient
- Length of emission
Poloidal emission distribution

To perform a least squares regression of JET and AUG data, first the poloidal distribution of N II emission must be established to quantify $\Delta L$

Absolute values are set (to account for reflections on JET) as:

**AUG:** $\Delta L=0.052I_p^{-0.62}$ \( (e.g. \ I_p=0.6 \ MA \ \Delta L \sim 7 \ cm) \)

**JET:** $\Delta L=0.124I_p^{-0.62}$ \( (e.g. \ I_p=2.5 \ MA \ \Delta L \sim 7 \ cm) \)

*These are likely upper limits, especially on AUG*
A database now exists of divertor $c_N$ measurements from JET-ILW and ASDEX Upgrade H-mode plasmas with partially detached outer divertors in vertical geometry.

<table>
<thead>
<tr>
<th></th>
<th># points</th>
<th>$P_{\text{sep}}$ [MW]</th>
<th>$n_{e,\text{sep}}$ [$10^{19}$ m$^{-3}$]</th>
<th>$I_p$ [MA]</th>
<th>$a_{\text{min}}$</th>
<th>$B_T$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUG</td>
<td>13</td>
<td>3.5 – 12</td>
<td>2 – 4</td>
<td>0.8-1.2</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>JET</td>
<td>10</td>
<td>14 – 15.5</td>
<td>2.2 – 3.5</td>
<td>2.5</td>
<td>0.9</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Experiments to challenge scaling predictions

A previous study performed a least squares analysis of the data from JET and AUG separately to study the scaling of $P_{sep}$ and $n_{e,sep}$:

\[
\text{AUG: } c_N \propto P_{sep}^{1.19 \pm 0.32} n_{e,sep}^{-2.77 \pm 0.36} \\
\text{JET: } c_N \propto n_{e,sep}^{-2.43 \pm 0.27}
\]

Consistent with theoretical scaling of $P_{sep}$, but suggests stronger dependency on $n_{e,sep}$ and lower absolute values

[Henderson et al., PSI 2020]
Machine size scaling

Performing least-squares regression of data from both JET and AUG gives

\[ c_N = 5.89 \pm 2.73 \ p_{\text{div,outer}}^{1.16\pm0.23} \ n_{e,\text{sep}}^{-2.72\pm0.22} \ I_P^{1.05\pm0.6} \ a_{\text{min}}^{-2.36\pm0.88} \]

Systematic uncertainty: reducing AUG \( \Delta L \) by 1 cm gives \( c_N \propto a_{\text{min}}^{-2.64\pm0.89} \)

Consistent with Goldston scaling \( c_N \propto I_P a_{\text{min}}^{-3} \)
Divertor geometry assessment

Comparing with horizontal geometry provides assessment of neutral compression

**Parameters for JET #89421**

\[ P_{\text{div,outer}} = 1.24 \text{ MW}, \ n_{e,\text{sep}} = 2.9 \times 10^{19} \text{ m}^{-3}, \ I_p = 2 \text{ MA}, \text{ and } a_{\text{min}} = 0.94 \]

\[ c_N \sim 1\% \]

Measured \( c_N \) higher than scaling law predictions, suggests achieving detachment harder in horizontal configuration
Impurity species scaling

Reactor scale tokamaks will likely require Ne or Ar to radiate tokamak exhaust

A new set of spectroscopic lines and atomic data are used to analyse $c_{Ne}$ and $c_{Ar}$

Total emission coefficients of N II, Ne II and Ar II all exist over a narrow $T_e$ range
Comparing N and Ar concentrations

AUG experiment with partially detached scenario using $N_2$ and Ar seeding

Measurements show $c_{Ar} \sim c_N$ in the window of N-only and Ar-only

The Reinke scaling $c_I \propto P_{sep}^{1.14} M_{L,I}^{-1}$ where $M_{L,Ar} \sim 7 - 8M_{L,N}$ gives $c_{Ar} \sim 0.3c_N$

Scaling law is average SOL prediction: need to consider enrichment
Comparing N and Ar radiated power

Database of AUG plasmas are combined to assess changes to radiated power

Comparing Ar-only to N-only

» **Divertor radiation** decreases by factor 2x
  • Using $n_e^2 c_{Ar} L_{Ar} = 0.5 n_e^2 c_{N} L_{N}$ then $c_{Ar} \sim c_{N}$

» **Main chamber radiation** increases by factor 2x
  • Using $n_e^2 c_{Ar} L_{Ar} = 2 n_e^2 c_{N} L_{N}$ then $c_{Ar} \sim 0.2 c_{N}$
Direct comparison of the impurity enrichment factors, $\eta_I = \frac{c_{I,\text{div}}}{c_{I,\text{core}}}$, are possible by comparing core concentrations from CXRS.

**Neon** enrichment is $\eta_{Ne} \sim 0.8 - 2$

**Nitrogen** enrichment is $\eta_{N} \sim 2 - 5$

**Argon** enrichment is $\eta_{Ar} \sim 10 - 20$
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- Measurements show divertor $c_{Ar} \sim c_N$
- Measurements show core $c_{Ar} \sim 0.1c_N$
- Scaling law prediction $c_{Ar} \sim 0.3c_N$

This is approximately within the bounds of the scaling law prediction
Conclusions and next steps

Spectroscopic divertor measurements of N II, Ne II, and Ar II are used to challenge theoretical scaling laws of impurity concentration thresholds for divertor detachment

**Machine size**

- Least squares regression of spectroscopic $c_N$ measurements from JET and AUG

$$c_N = 5.89 \pm 2.73 \, P^{1.16\pm0.23}_{\text{div,outer}} \, n_{e,sep}^{-2.72\pm0.22} \, I_P^{1.05\pm0.6} \, a_{\text{min}}^{-2.36\pm0.88}$$

**Impurity species**

- New divertor measurements of $c_{Ar}$ show similar values to $c_N$ in partially detached plasmas, but Ar shows a stronger enrichment factor in comparison to N

**Theoretical scaling laws**

- Generally consistent with experimental parameter dependencies with a moderate discrepancy on $n_{e,sep}$ but differ significantly on absolute concentrations

**Where next**

- Expand database to include scan of $B_T$
To perform a least squares regression of JET and AUG data combined, first need to quantify uncertainty of ΔL – absolute magnitude and how it varies with I_p

New analysis of inverted camera data on JET suggest a scaling of ΔL~I_p^{−0.62}

Due to the dependence of ΔL on T_e and n_e, and therefore on spreading factor S
Appendix: divertor geometry assessment

Comparing with horizontal geometry provides assessment of neutral compression

Same model applied to scenario with horizontal outer divertor geometry but with a larger $\Delta L$

Vertical: $\Delta L=0.124I_p^{-0.62}$ (e.g. $I_p=2.5$ MA $\Delta L \sim 7$ cm)

Horizontal: $\Delta L=0.154I_p^{-0.62}$ (e.g. $I_p=2.0$ MA $\Delta L \sim 10$ cm)