Experimental impurity concentrations required to reach detachment on AUG 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) 086203, and J. Mallick 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)

MOTIVATION

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

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

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

MACHINE SIZE SCALING

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

\[ C_N = 5.89 \pm 2.73 \times 10^{-4} \times \rho_{\text{gas}}^{1.38} \times P_{\text{input}}^{0.02} \times B_{\text{T}}^{0.08} \]

Systematic uncertainty: reducing AUG by 1 cm gives \( C_N \approx 2 \times 10^{-4} \times \rho_{\text{gas}}^{1.38} \times P_{\text{input}}^{0.02} \times B_{\text{T}}^{0.08} \)

Consistent with Goldston scaling \( C_N \approx \rho_{\text{gas}}^{1.38} \times P_{\text{input}}^{0.02} \times B_{\text{T}}^{0.08} \)

IMPUITY SPECIES SCALING

DETACHMENT EXPERIMENTS

The Reinke scaling \( \propto C_N^{0.7} \sigma_A^{0.3} \) where \( \sigma_A \approx 7 \times 10^{-4} \) gives \( C_N \approx 0.3 \sigma_A \)

Sealing laws are average SOL prediction: need to consider enrichment

ENRICHMENT MEASUREMENTS

Direct comparison of the impurity enrichment factors, \( \eta_p = \frac{C_p}{C_N} \), are possible by comparing core concentrations from CIXRS

Neon enrichment is \( \eta_p \approx 0.8 \pm 2 \)
Nitrogen enrichment is \( \eta_p \approx 2 \pm 5 \)
Argon enrichment is \( \eta_p \approx 10 \pm 20 \)

EXPERIMENTAL DIVERTOR CONCENTRATIONS

A database now exists of divertor \( c_p \) measurements from JET-ILW and ASDEx Upgrade H-mode plasmas with partially detached outer divertors

Machine size

Least squares regression of spectroscopic \( c_p \) measurements from JET and AUG gives

\[ c_p = 5.89 \pm 2.73 \times 10^{-4} \times \rho_{\text{gas}}^{1.38} \times P_{\text{input}}^{0.02} \times B_{\text{T}}^{0.08} \]

Impurity species

New divertor measurements of \( c_p \) show similar values to \( c_p \) in partially detached plasma, 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 \( n_{\text{crit}} \) but differ significantly on absolute concentrations

CONCLUSIONS

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

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FIG. 3. The results of the least squares regression analysis of the database of \( c_p \) measurements.

FIG. 4. The total heating power and radiated power from AUG Upgrade H is shown in (a). The \( c_p \) and \( c_A \) measurements for the shots given in (b).

FIG. 5. The impurity concentrations for Ar are shown in the top panels, the core concentrations from CIXRS are shown in the middle panels, and the corresponding enrichment factors are shown in the bottom panels.