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Experimental impurity concentrations required to reach detachment in AUG and JET

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Substantial seeding of impurities into the divertor has been used for a long time in tokamaks to reduce the power and particle fluxes impacting on the divertor targets and is one of the main techniques to be utilised on ITER to facilitate stationary divertor operation [1]. There have been attempts to predict how the impurity concentration required for detachment should scale with different plasma parameters, such as the power crossing the separatrix, P_{sep}, and the upstream separatrix density, $n_{e,sep}$ $[2-4]$. In [3] the machine size scaling enters through the minor radius, a_{min}, due to the dependence on the poloidal magnetic field. Including the LH threshold scaling provides a dependence on $B_T^{0.88}R^{1.33}$[4]. Since there are no experimental results to test these scaling laws, this work uses spectroscopy to measure the divertor nitrogen concentration, c_N, in the outer divertor to examine the parameter dependencies both within and across the ASDEX Upgrade (AUG) and JET tokamaks.

From a database of N-seeded H-mode AUG discharges, spanning P_{sep}=3.5–12 MW and $n_{e,sep}$=1.8–4x10^{19} m^{-3}, with line averaged core densities from 7–10x10^{19} m^{-3}, and plasma currents from I_p=0.8–1.2 MA, the c_N measurements at the onset of detachment will be presented. A similar database of JET pulses have been collected, with P_{sep}=12–16 MW, $n_{e,sep}$=1.6–2.7x10^{19} m^{-3}, and I_p=2–2.5 MA. In these JET pulses, the outer target magnetic geometry is in a vertical configuration for a fairer comparison with both AUG and ITER. On both machines, the elongation is κ~1.7 while a_{min}~0.5 and a_{min}~0.9 on AUG and JET, respectively. The power to the outer divertor is calculated as ~P_{sep}/2.5 to account for power to the inner divertor and to the main chamber wall. Although the JET results still require validation, a first regression of the parameter dependencies on both devices gives c_N=15.9$P_{sep}^{1.32}$[MW] $I_p^{1.17}$[MA] $n_{e,sep}^{-3.44}$ [10^{19} m^{-3}] $(1+\kappa^2)^{-1}a_{min}^{-2.85}$ [%] (see figure 1); a result in good agreement with [3] but with a stronger dependence on $n_{e,sep}$ ($c_{N,2Pmodel}$~$P_{sep}I_p n_{e,sep}^{-2}(1+\kappa^2)^{-1}a_{min}^{-3}$). The stronger $n_{e,sep}$ dependence is also found from SOLPS-ITER simulations which show that $c_{Ne} \propto n_{e,sep}^{\alpha}$ where α varies between -2 and -4 depending on the power radiated below the X-point [1].

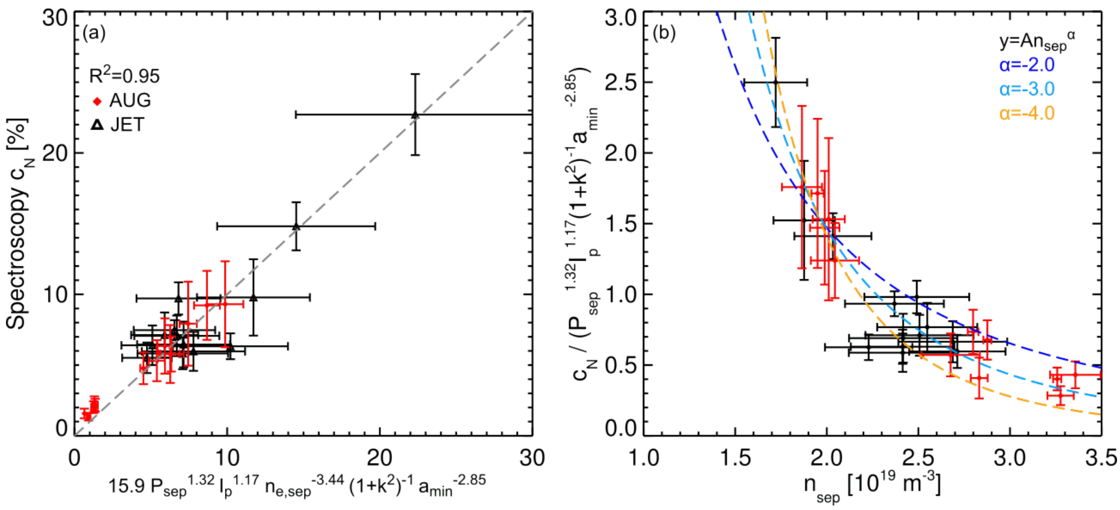

Figure 1: Measurements of c_N in the outer divertor in partially detached conditions on AUG (red) and JET (black) are plotted against the derived scaling law in (a). In (b) the normalised c_N measurement is plotted against n_{sep} with three best fit lines fitted to the function An_{sep}^{α} for α=[-2,-3,-4].

Measurements of the N concentration in the outer divertor are taken when the divertor plasma reaches partial detachment. For AUG, the divertor target shunt measurements are used to provide a real-time estimate of the divertor temperature. Typically, the divertor is in a partially detached state when this real-time temperature is T_{div}~5 eV. Such a real-time estimate is not available on JET, and therefore spectroscopy is used to determine the detachment state. The ratio of the line-integrated N II intensity between sightlines viewing close to the divertor target and close to the X-point, which should vary according to the electron density front movement, typically follow the trends of J_{sat} from the probe measurements and therefore provides a robust estimate of the detachment state. Using the ratio of sightline intensities is also possible on AUG, however T_{div} is typically more reliable.

The N concentration is calculated using $c_N = 4\pi I_{NII}/(f_N + PEC_{exc} + f_{N2} + PEC_{rec})/\Delta L/n^2_{e,NII}$ [5] where ΔL is the length of the N II emission region, I_{NII} is the measured intensity, and $PEC_{exc/rec}$ and f_{NZ} are photon emissivity coefficients and fractional abundances. The electron temperature and density, $T_{e,NII}$ and $n_{e,NII}$, are derived from spectroscopic N II line ratios. ΔL is estimated based on inverted camera images on JET and SOLPS modelling on AUG. In partially detached conditions, this length is approximately 7cm on both devices and is localised in the private flux region. This is also consistent with the N II line ratios, which show electron temperatures mostly between 3-4 eV, close to the zero-transport prediction of maximum fractional ion abundance. This work will also examine the robustness of the measurement and provide comparisons to a simple approximation of c_N derived from the ratio of the impurity and fuel gas valve fluxes. In stationary scenarios with high measured intrinsic N intensities, indicative of fully saturated vessel surfaces, the two measurements agree on AUG and JET as shown in figure 2; however, when the intrinsic N intensity is low, the two measurements can differ by an order of magnitude. While the gas valve ratios can provide a good proxy for the impurity concentration in the divertor neutral domain with fully saturated walls, spectroscopy provides a direct, instantaneous, line-integrated measurement in the outer divertor plasma.

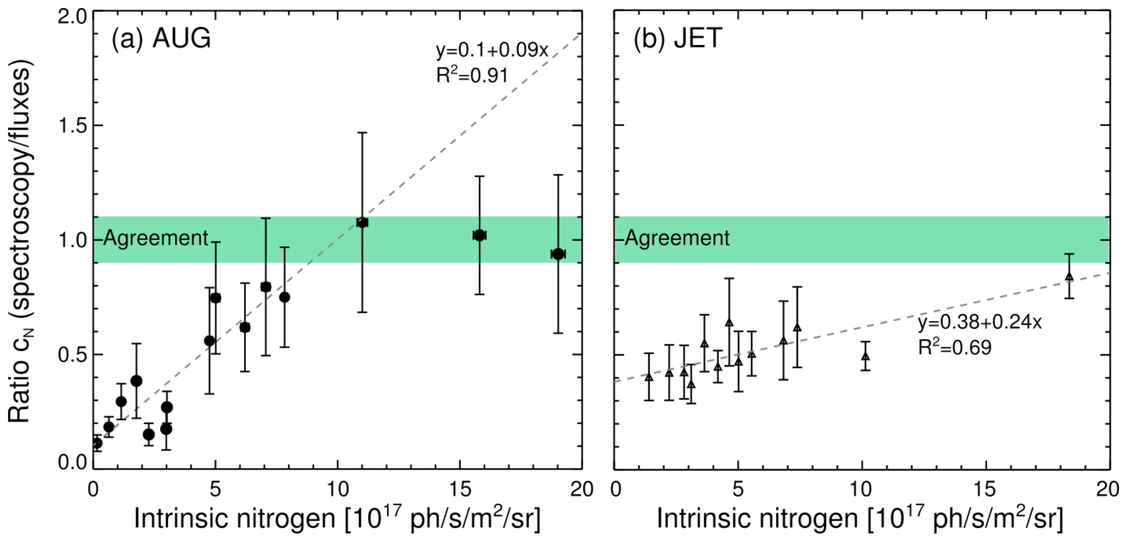

Figure 2: Comparison of c_N measurements from spectroscopy and gas valve ratios for (a) AUG and (b) JET. The intrinsic nitrogen is measured in one sightline up to 0.5s before seeding. Agreement is most likely achieved when the wall surfaces are saturated with N.

Finally, this work will compare a database of JET discharges with horizontal outer target magnetic geometries to assess any differences due to divertor geometry. It is also clear that the scaling of the impurity concentration is dependent on the seeding gas species. This work has focused on N, due to the abundance of scenarios with N_2 seeding in current devices; still, it is important to assess results for Ne and Ar. The Ne II emission also radiates in the visible spectral range and scenarios on JET with Ne seeding will therefore be used to present a first assessment of the species scaling. It is not yet possible to measure the Ar concentration spectroscopically; however, a database of AUG discharges with different input powers and fractions of Ar and N_2 seeding will be presented to evaluate whether an optimum mixture of impurities exists with regards to the radiation distribution and plasma confinement.

[1] R. Pitts et al. 2019 NME 20 100696; [2] A. Kallenbach et al. 2016 PPCF 58 045013; [3] R. Goldston et al. 2017 PPCF 59 055015; [4] M. Reinke 2017 Nucl. Fusion 57 034004; [5] S. Henderson et al. 2018 Nucl. Fusion 58 016047 and †See the author lists of B. Labit et al 2019 Nucl. Fusion 59 086020, †† H. Meyer et al 2019 Nucl. Fusion 59 112014and †††E. Joffrin et al. 2019 Nucl. Fusion 59 112021

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