

# Impurity Seeding and Divertor Fuelling in MAST Upgrade's Super-X Divertor

Noé Bundschuh<sup>1,2\*</sup>, Lingyan Xiang<sup>2</sup>, David Moulton<sup>2</sup>, Kevin Verhaegh<sup>3</sup>, Nicola Linigro<sup>2</sup>,  
Nick Osborne<sup>2</sup>, Sheena Menmuir<sup>2</sup>, Zhouji Huang<sup>2</sup>, Jack Lovell<sup>4</sup>, Peter Ryan<sup>2</sup>, Kirsty  
McKay<sup>1</sup>, the MAST Upgrade Team [1] and the EUROfusion WPTETeam [2]

<sup>1</sup>Department of Electrical Engineering and Electronics, University of Liverpool, Brownlow Hill, Liverpool, L69 3GJ, UK

<sup>2</sup>United Kingdom Atomic Energy Authority, Culham Campus, Abingdon, Oxfordshire, OX14 3DB, UK

<sup>3</sup>Department of Applied Physics, Eindhoven University of Technology, Eindhoven 5600 MB, The Netherlands

<sup>4</sup>Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

## Summary

We compare the exhaust performance of N<sub>2</sub> seeded and divertor D<sub>2</sub> fuelled H-mode plasma discharges with maximal NBI heating power (3.2 MW) in double-null Super-X Divertor (SXD) configuration from MAST Upgrade's latest experimental campaign.

Our findings show that for similar upstream conditions and detachment front locations D<sub>2</sub> puffing generates lower temperatures in the divertor than N<sub>2</sub> seeding, as the latter considerably undermines hydrogenic power loss processes.

## Divertor Detachment and Exhaust Control

Detachment occurs below a divertor electron temperature of ~5 eV, as enhanced atomic and molecular interactions induce substantial power and pressure loss. [3-5] These processes can be controlled via the targeted injection of neutrals. [6] Extrinsic impurities are commonly used to amplify collisional and radiative losses.

MAST Upgrade demonstrates improved access to detachment in SXD over its conventional divertor (CD) configuration in both experiments and modelling [7-9]. Spectroscopic studies have shown that its tight baffles intensify plasma-neutral interaction in SXD, achieving deep detachment [5]. In the following, we investigate the plasma response to divertor N<sub>2</sub> and D<sub>2</sub> puffing.

## The Benefits of Divertor Neutral Injection

The following WPTETeam experiments with identical start-up configurations and similar bulk plasma conditions between divertor N<sub>2</sub> and D<sub>2</sub> puffing have been selected: **#53107** with HFS midplane fuelling only, used as reference; **#54336** with HFS midplane fuelling and LFSS N<sub>2</sub> seeding; and **#53898** with HFS midplane fuelling and LFSS D<sub>2</sub> puffing.

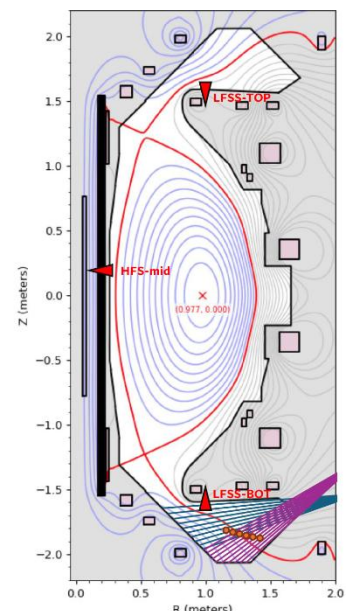


Figure 1: SXD equilibrium with valve locations, DMS LoS, and DTS measurement points indicated.

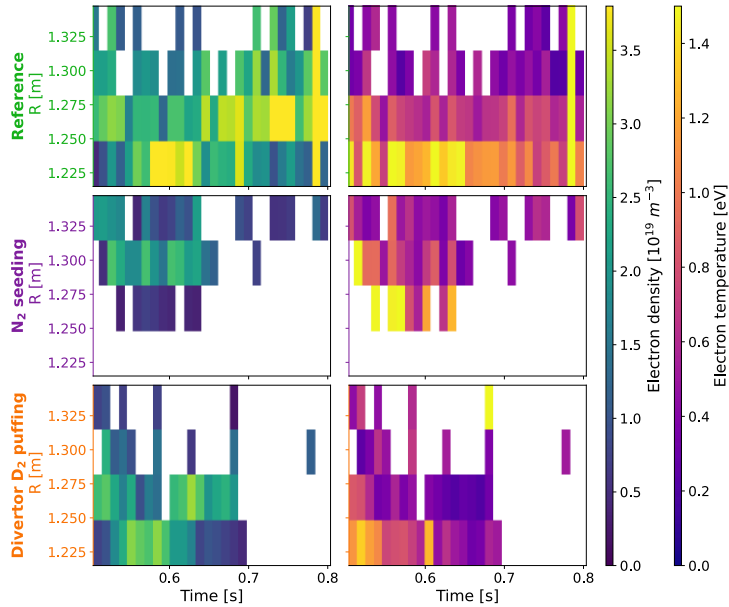


Figure 2: DTS data on electron density and temperature from the start of divertor injection ramps (0.5 s) onwards. Missing points below measurement thresholds.

the ionisation fronts receding farther; and Divertor Thomson Scattering (DTS) indicates reduced electron density and temperature.

Despite the similar detachment front locations, D<sub>2</sub> puffing generates higher electron density but lower temperature in the divertor than N<sub>2</sub> seeding – see Figure 2. DTS measurement thresholds are reached ~0.7s, but divertor spectroscopy enables further analysis.

The denser plasma from D<sub>2</sub> puffing appears to plug the divertor, increasing the neutral pressure throughout the injection ramp; whereas in N<sub>2</sub> seeding impurities move upstream as the ionisation front recedes, and the divertor pressure stagnates.

## Reconstructing Hydrogenic Processes

For the relatively low densities in SXD, ionisation processes associated with lower band Balmer emissions peak between 3-5 eV. Ion losses are dominated by Molecular Activated Recombination (MAR) between 0.5-3 eV, and by Electron Ion Recombination (EIR) directly capturing electrons in higher orbits below 0.5 eV. [4, 5]

Starting around 0.65 s Divertor Monitoring Spectroscopy (DMS) reveals a significant decline in Balmer  $\alpha$  intensity over Balmer  $\delta$  with D<sub>2</sub> puffing in Figure 3. This suggests an increase in recombination compared to ionisation, supporting the DTS temperature readings (or lack thereof) in Figure 2.

A detached SXD – see Figure 1, is established in all three discharges before the LFSS valves engage. Divertor injection is ramped linearly starting at 0.5 s, with H-mode maintained until ~0.8 s. Figures depict data from this time interval.

Both N<sub>2</sub> seeding and divertor D<sub>2</sub> puffing improve exhaust characteristics: Langmuir Probes measure lower target ion fluxes compared to reference case; Multi Wavelength Imaging (MWI) shows

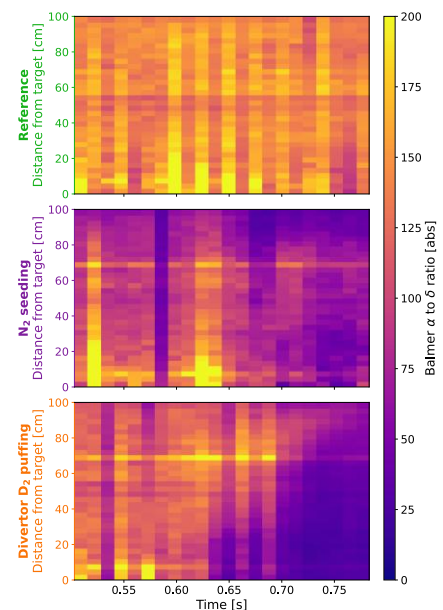


Figure 3: Balmer  $\alpha$  to  $\delta$  ratios in the SXD chamber over time. Lower values indicate lower electron temperatures.

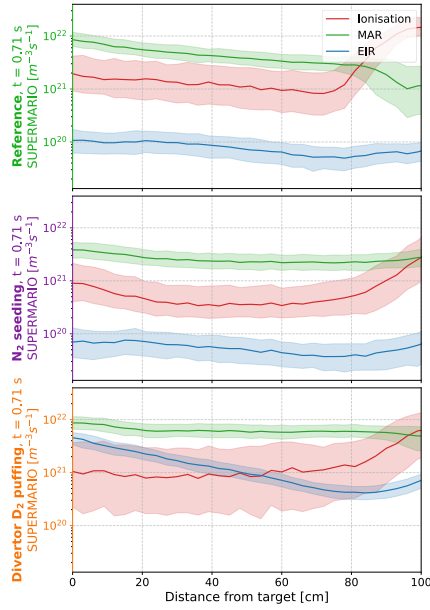


Figure 4: SUPERMARIO results on the spatial distribution of hydrogenic ion sinks and sources at 0.71 s.

Combining DMS measurements with databases of atomic and molecular processes, the “hydrogen Spectroscopy with Uncertainty Propagation for Excitation Radiation of Molecular Activated Recombination and Ionisation Outputs” (SUPERMARIO) code employs Bayesian analysis to reconstruct the sources and sinks of hydrogenic ions corresponding to observed Balmer emissions – see Figure 4. We find that hydrogenic processes diminish with  $N_2$  seeding in deep detachment over the reference case due to the low neutral pressure and reduced plasma density. With divertor  $D_2$  puffing however, even as the ionisation peak moves upstream, the increasing neutral pressure amplifies all atomic and molecular processes.

### Effects on Atomic and Molecular Losses

Spatially integrated ionisation and recombination rates in Figure 5 reveal EIR much below MAR in the reference case as midplane fuelling creates a hot, low density divertor. MAR is inhibited by  $N_2$  seeding as ionisation processes recede and density drops. We see a surge in MAR and EIR with divertor  $D_2$  puffing as the neutral pressure increases.

The effects of divertor injection on power loss channels are highlighted in Figure 6:  $N_2$  seeding abates all hydrogenic losses as impurities escape the divertor, while divertor  $D_2$  puffing amplifies non-radiative losses through increased MAR and EIR.

In summary, with  $N_2$  seeding power is dissipated near the ionisation front due to the build-up of impurities. As detachment deepens, downstream electron density drops. Neutrals thus escape the divertor and recombination induced losses diminish.

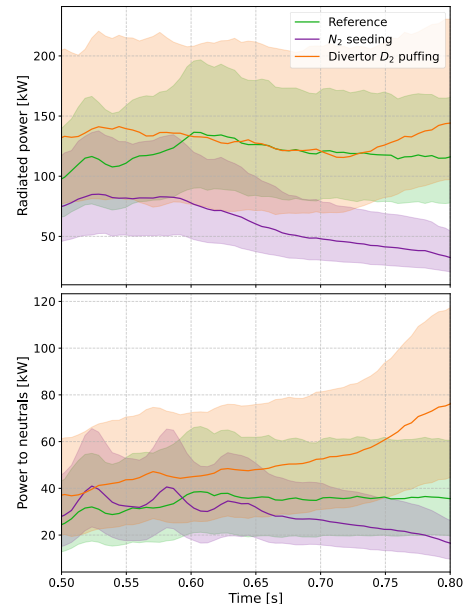


Figure 5: Hydrogenic ion sinks and sources integrated across the SXD volume over time.

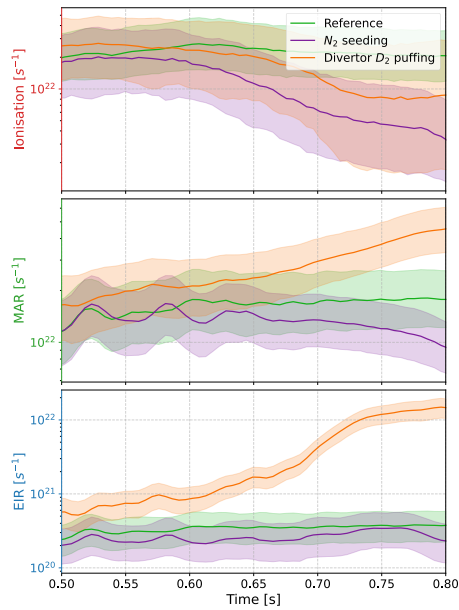


Figure 6: Integrated radiative and non-radiative hydrogenic power losses over time.

On the other hand, the higher ionisation rate across the divertor from D<sub>2</sub> puffing creates a higher density plasma, plugging the divertor. The increasing neutral pressure then enhances atomic and molecular losses, greatly reducing the temperature.

### SOLPS-ITER for Further Analysis

Interpretative SOLPS-ITER simulations of the above SXD discharges and their CD counterparts have been set up to characterise detachment conditions, and quantify differences in power, pressure and momentum losses between divertor N<sub>2</sub> and D<sub>2</sub> puffing.

Power loss channels are reconstructed by finetuning fuelling, puffing and pumping rates to reproduce

experimental emission profiles from MWI and Charge Exchange Recombination Spectroscopy. Detailed analysis of the simulations results is in progress.

### References

- [1] See author list of J. Harrison et al 2019 Nucl. Fusion 59 112011
- [2] See author list of E. Joffrin et al 2024 Nucl. Fusion 64 112019
- [3] A. A. Pshenov et al 2017 Nucl. Materials and Energy 12 948-952
- [4] K. Verhaegh et al 2021 Nucl. Fusion 61 106014
- [5] K. Verhaegh et al 2023 Nucl. Fusion 63 016014
- [6] A. S. Kukushkin et al 2016 Nucl. Fusion 56 126012
- [7] J. R. Harrison et al 2024 P. Phys. Cont. F. 66 065019
- [8] D. Moulton et al 2024 Nucl. Fusion 64 076049
- [9] O. Myatra et al 2023 Nucl. Fusion 63 096018