52nd European Physical Society Conference on Plasma Physics, Edinburgh, UK 29 June – 3 July 2026

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

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We compare the **exhaust performance of N_2 seeded and divertor D_2 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.

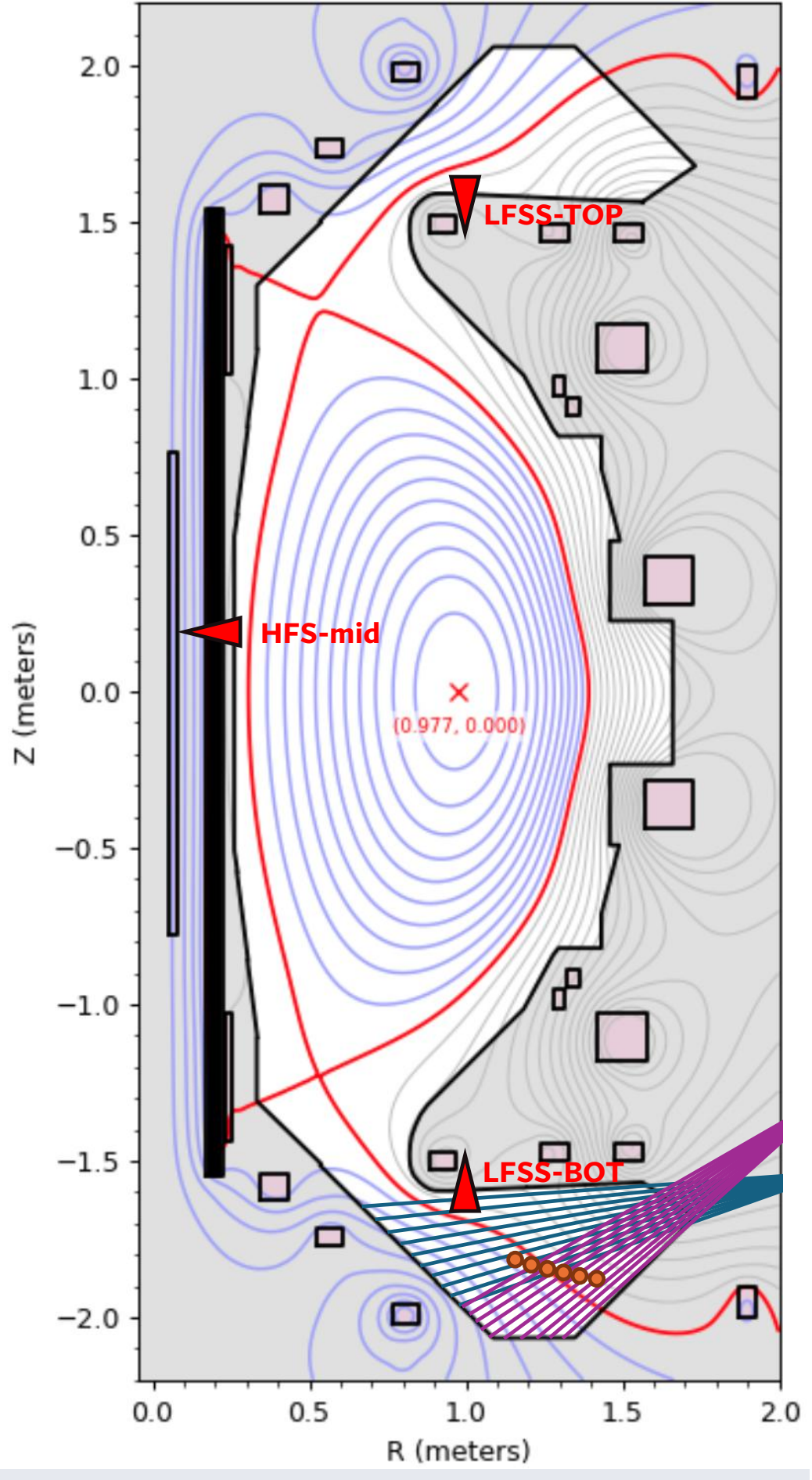
Our findings show that for similar upstream conditions and detachment front locations **D_2 puffing generates lower temperatures in the divertor than N_2 seeding, as the latter considerably undermines hydrogenic power loss processes**.

1. 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**.

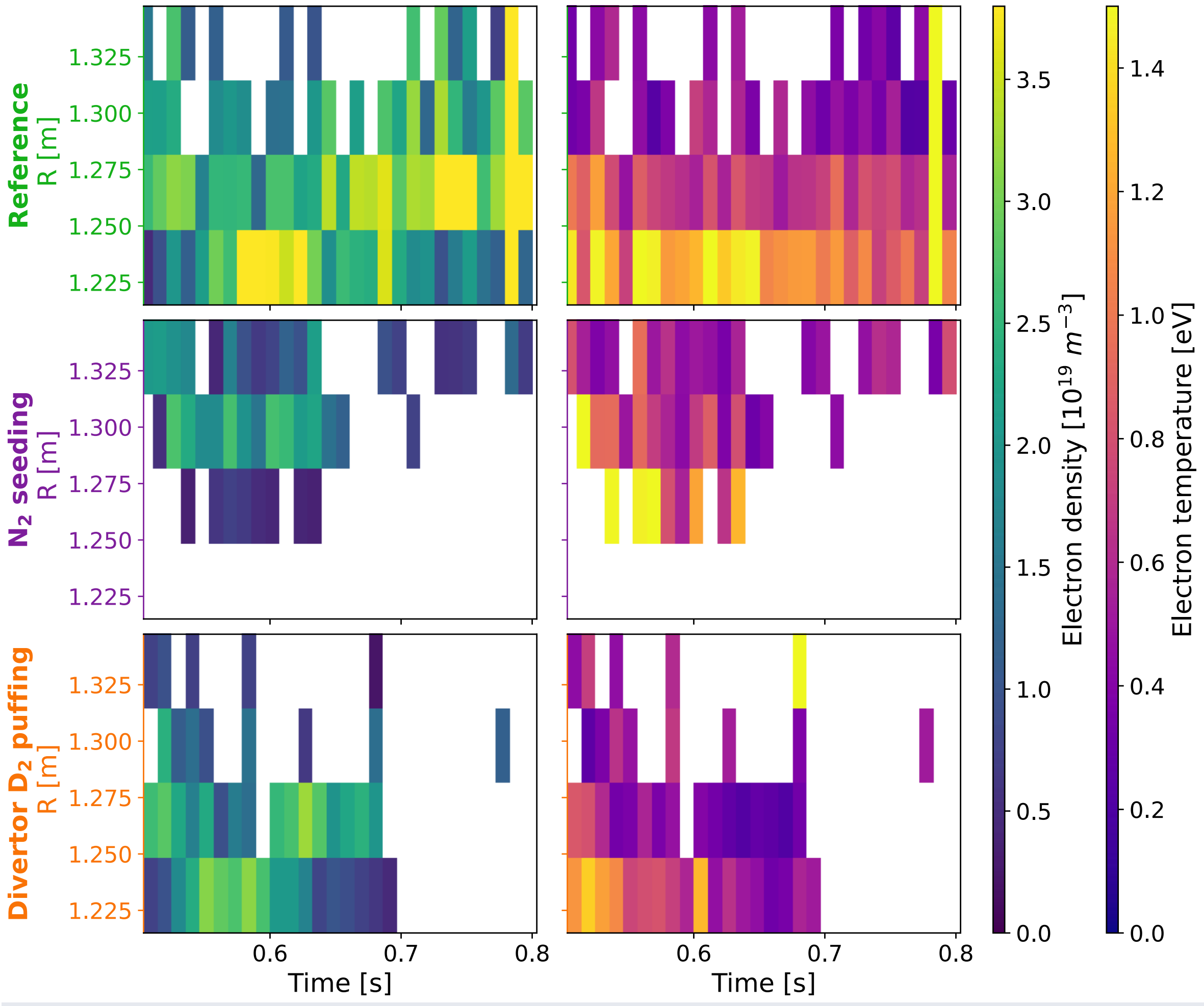
MAST Upgrade demonstrates **improved access to detachment in SXD over its conventional divertor** (CD) configuration in both experiments and modelling [7-9]. Spectroscopic studies have shown that its **tight baffles intensify plasma-neutral interaction in SXD**, achieving deep detachment [5]. In the following, we investigate the plasma response to divertor N_2 and D_2 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.

2. The Benefits of Divertor Neutral Injection

The following **WPTE experiments with** identical start-up configurations and similar bulk plasma conditions between **divertor N_2 and D_2 puffing** have been selected:

#53107	HFS midplane fuelling only, used as **reference**
#54336	HFS midplane fuelling with LFSS **N_2 seeding**
#53898	HFS midplane fuelling and LFSS **D_2 puffing**

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.

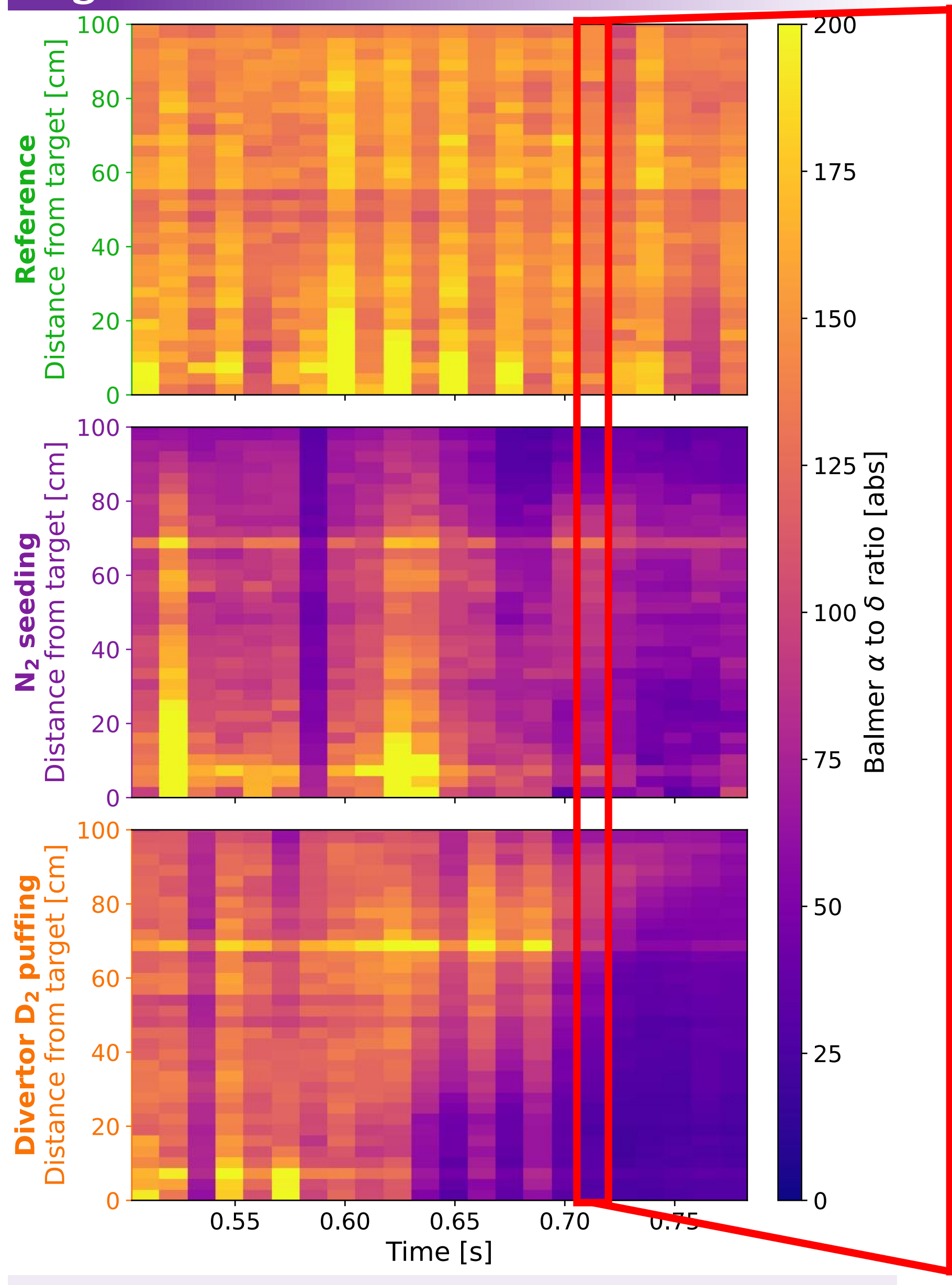
Both **N_2 seeding and divertor D_2 puffing** improve exhaust characteristics:

- Langmuir Probes measure **lower target ion fluxes compared to reference case**;
- Multi Wavelength Imaging (MWI) shows the **ionisation fronts receding farther**;
- Divertor Thomson Scattering (DTS) indicates **reduced density and temperature**.

Despite the similar detachment front locations, **D_2 puffing generates higher electron density but lower temperature in the divertor than N_2 seeding** – see **Figure 2**. DTS measurement thresholds are reached ~0.7s, but spectroscopy enables further analysis.

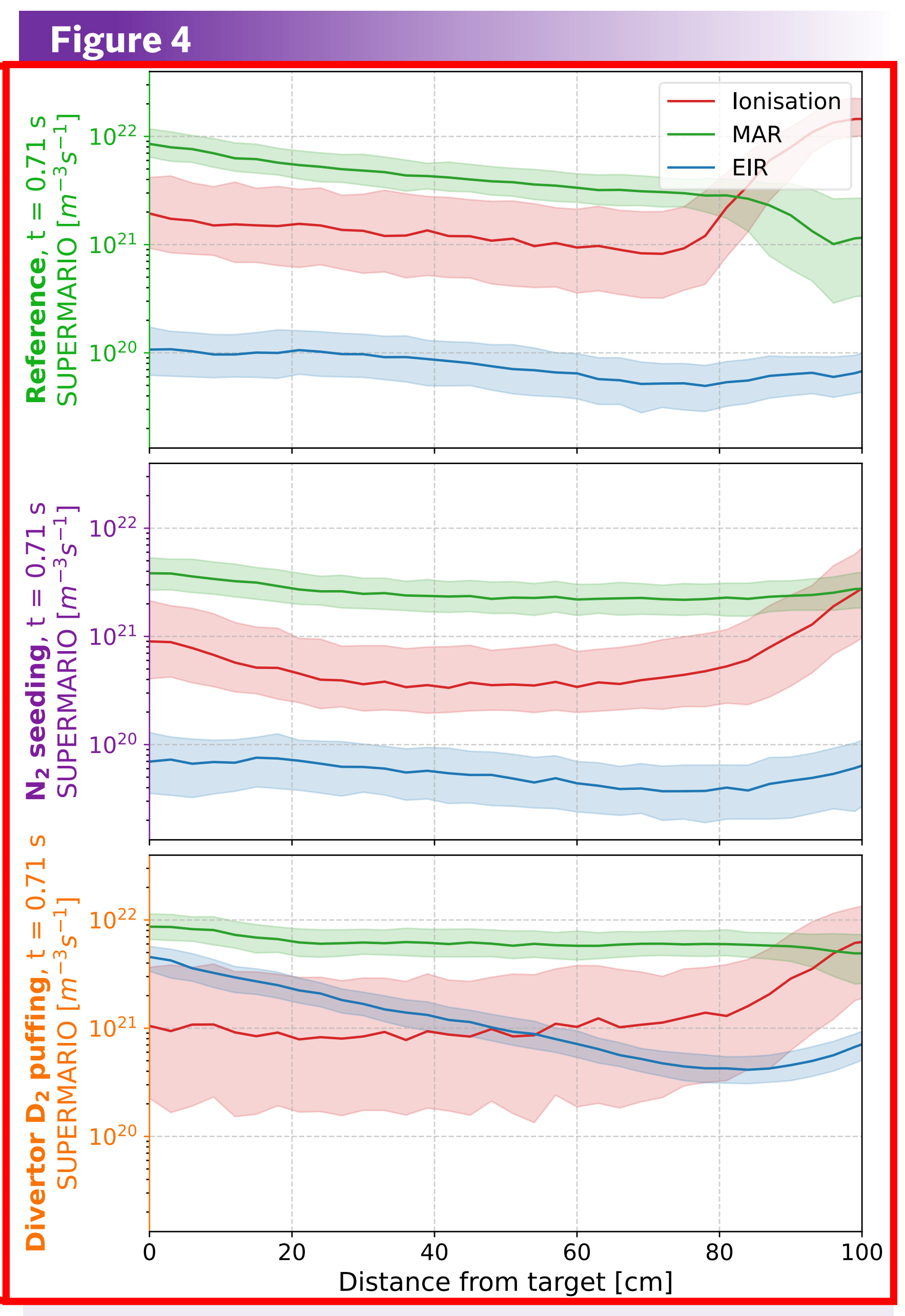
The denser plasma from **D_2 puffing** appears to plug the divertor, **increasing the neutral pressure** throughout the injection ramp; whereas **in N_2 seeding** impurities move upstream as the ionisation front recedes, and the **divertor pressure stagnates**.

Figure 3



Balmer α to δ 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.

3. 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 α intensity over Balmer δ with D_2 puffing in Figure 3**, **supporting the DTS temperature readings** (or lack there of) **in Figure 2**.

Combining DMS measurements with databases of atomic and molecular processes, **SUPERMARIO†** employs Bayesian analysis to **reconstruct the sources and sinks of hydrogenic ions** corresponding to observed Balmer emissions – see **Figure 4**:

- **Hydrogenic processes diminish with N_2 seeding over the reference case** in deep detachment due to the low neutral pressure and reduced plasma density;
- Even as the ionisation peak moves upstream with **divertor D_2 puffing**, the increasing neutral pressure **amplifies all atomic and molecular processes**.

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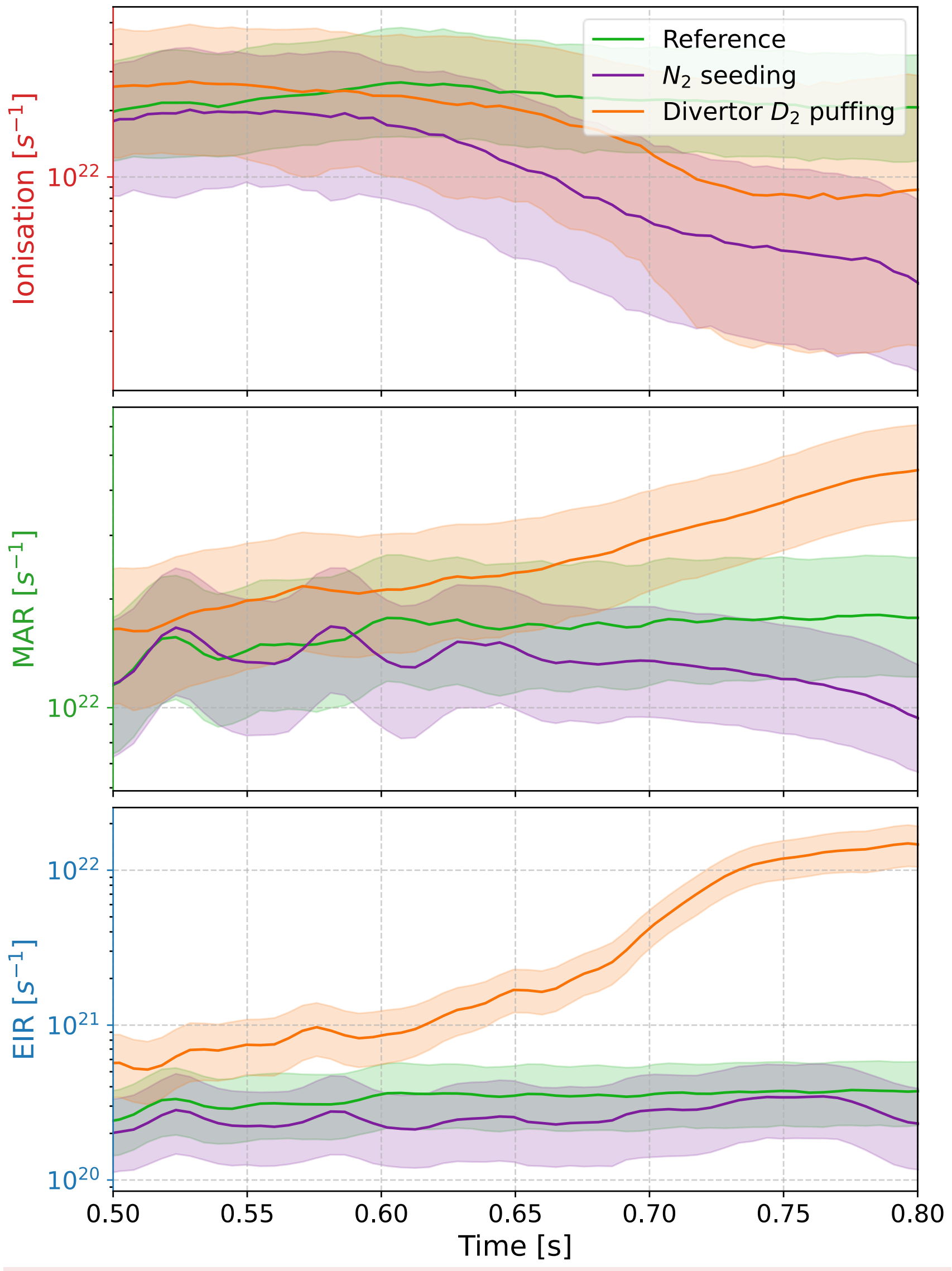
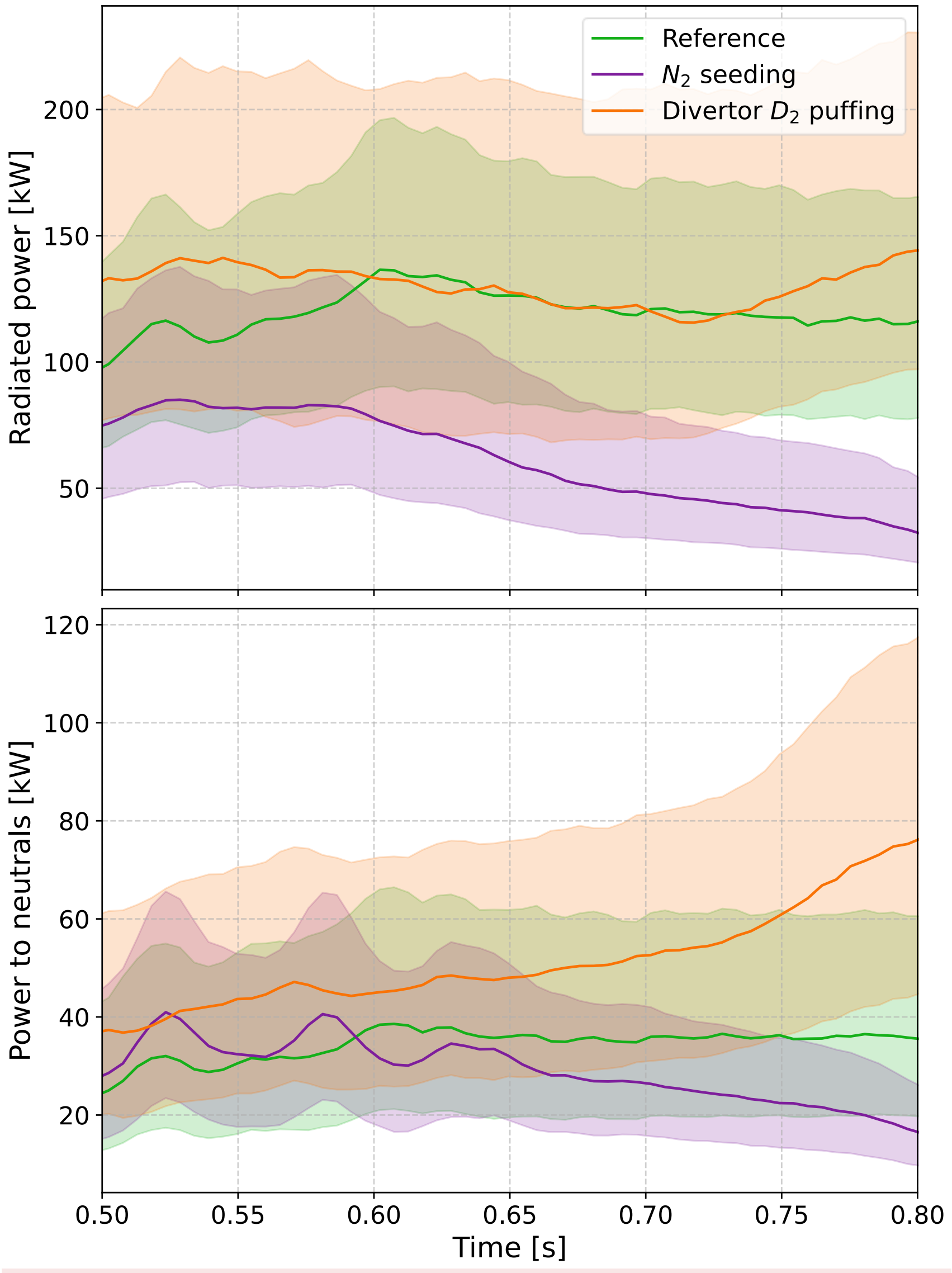
†hydrogen **S**pectroscopy with **U**ncertainty **P**ropagation for **E**xcitation **R**adiation of **M**olecular **A**ctivated **R**ecombination and **I**onisation **O**utputs

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.

4. Effects on Atomic and Molecular Losses

Spatially integrated ionisation and recombination rates in **Figure 5** reveal:

- **EIR much below MAR** as **midplane fuelling** creates a hot, low density divertor;
- **MAR inhibited by N_2 seeding** as ionisation processes recede and density drops;
- **MAR and EIR surge with divertor D_2 puffing** as neutral pressure increases.

The effects of neutral injection on power loss channels are highlighted in **Figure 6**:

- **N_2 seeding abates all hydrogenic losses** as impurities escape the divertor;
- **divertor D_2 puffing amplifies non-radiative losses** through 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**.

On the other hand, the higher ionisation rate across the **divertor** from **D_2 puffing** creates a higher density plasma, plugging the divertor. The increasing neutral pressure then **enhances atomic and molecular losses**, greatly reducing the temperature.

5. SOLPS-ITER for Further Analysis

Interpretative SOLPS-ITER simulations of the above SXD discharges and their CD counterparts have been set up **to estimate impurity compression and characterise detachment conditions** – detailed analysis in progress.

Power loss channels will be reconstructed **by reproducing experimental emission profiles** from MWI and Charge Exchange Recombination Spectroscopy.

Engineering and Physical Sciences Research Council [grant number 2928960]

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

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion) and from the EPSRC Fusion Grant [grant number EP/W006839/1]. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.