Cryopump and fuelling location impacts on upstream density and detachment on MAST-U

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MOTIVATION

- **Fusion Challenges**: Next-generation devices (ITER, DEMO, STEP) require robust divertor solutions to manage heat and particle fluxes for efficient power exhaust and component longevity.
- **Mega Ampere Spherical Tokamak-Upgrade (MAST-U)**: enables study of advanced divertor geometries, comparing Conventional Divertor (CD) and Super-X Divertor (SXD) configurations [1].
- **SXD Benefits and Challenges**: SXD reduces target heat fluxes through extended connection length and flux expansion, to the extent that we struggle to achieve attached regimes.
- **Cryopump**: Installed in the MAST-U lower divertor (MU04 campaign). It improves density control, assists detachment front management, enhances impurity removal, and enables access a more attached lower outer divertor.
- **Baffled Divertor**: decouples divertor neutral pressure (P_n@DIV) from upstream, allowing localised tuning of P_n @DIV via divertor fuelling and cryopump operation.

2. Scaling of $n_{e,sep}$ vs. sub-divertor P_n

- **Divertor fuelling**: weak scaling, $n_{e,sep} \propto P_n^{0.3}$ [4, 5] → consistent with other devices,
- **Main chamber fuelling**: stronger scaling (exponent >0.6).

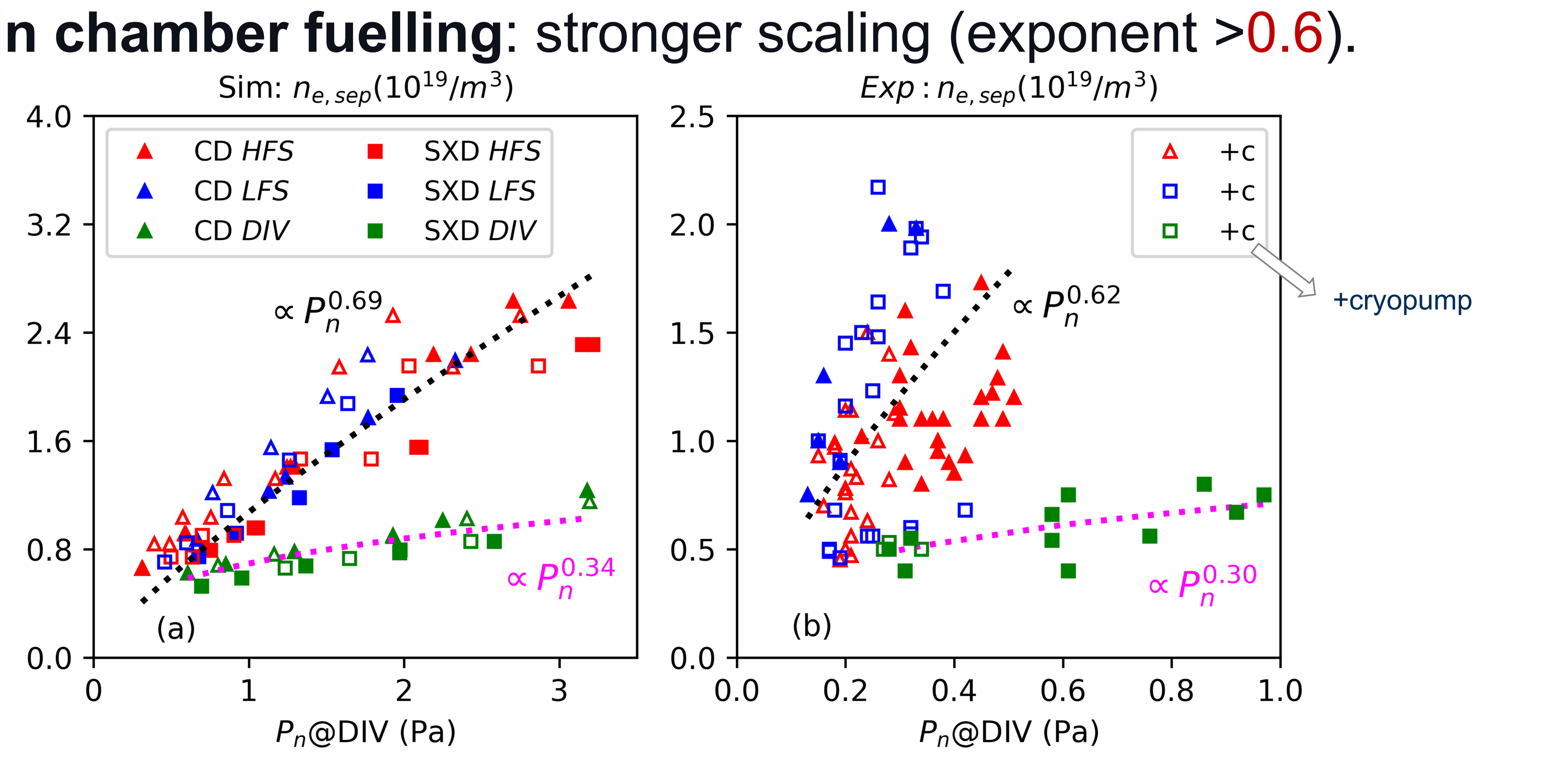

Fig. 2: $n_{e,sep}$ at the OMP vs. sub-divertor P_n^* : (a) SOLPS simulations, (b) experimental discharges in MU03 and MU04. Dashed lines = the power-law fits for LFS and divertor fueling separately.

"P_n from simulations (Fig. 1) are higher than measured by FIGs in experiments. See EX-D/3044"

4. Detachment Front Control

- Divertor fuelling: raises P_n@DIV by up to 50% → deeper detachment level *for the same upstream conditions* [6],

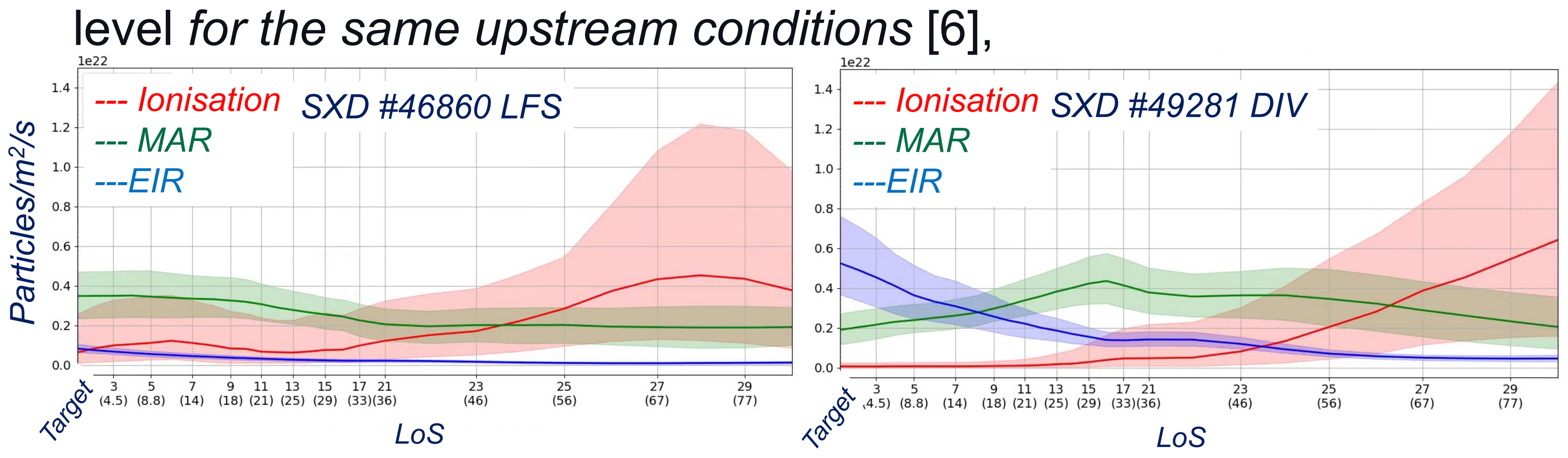

Fig. 4: Ion sources/sinks in the lower outer divertor for discharges with different fuelling locations; upstream $n_{e,sep}$ matched ($f_{GW} = 0.32$). LoS ≈ $distance\ from\ target/cm$.

- Cryopump operation:
  - Reduces divertor P_n,
  - Raises rollover threshold $n_{e,sep}$ by $40 - 60\%$, consistent with simulations
  - Enables attached SXD operation (normally always detached).

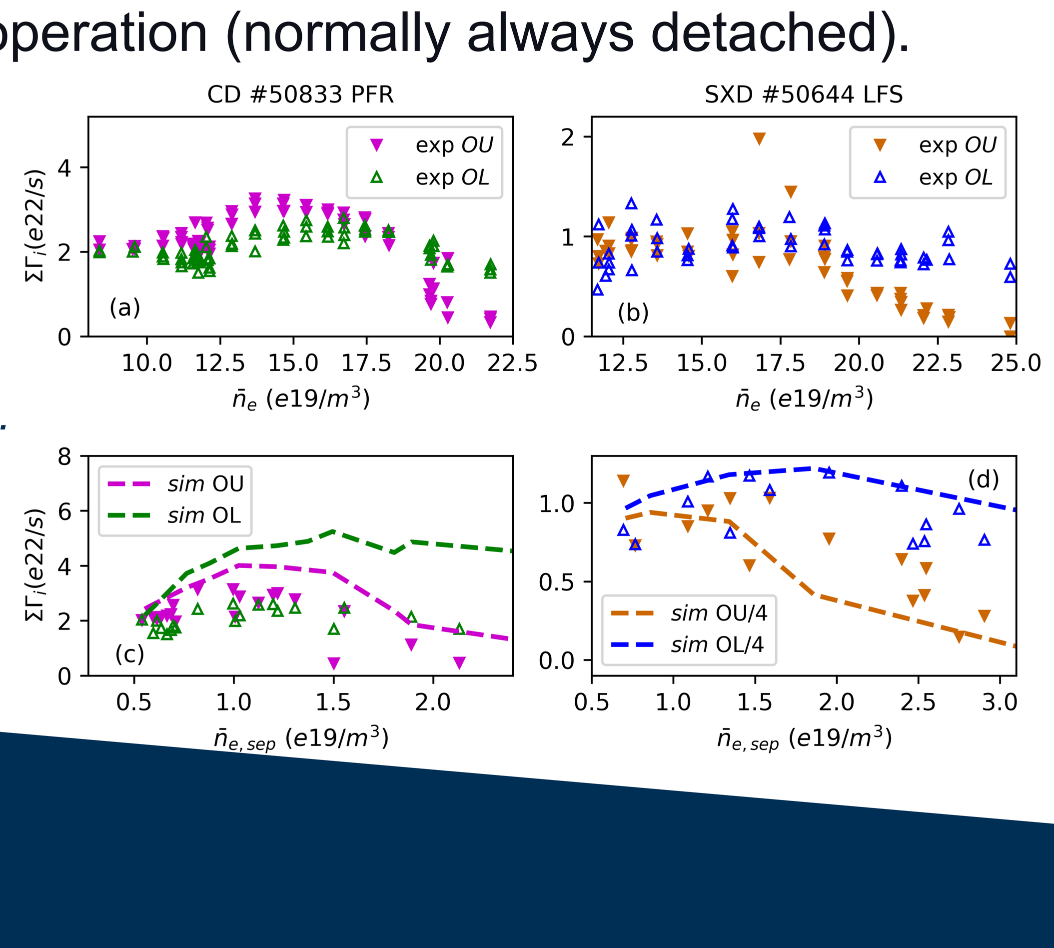

Fig. 5: (Top) Line-averaged $\bar{n}_e$ vs. total outer target ion fluxes ($\Sigma\Gamma_i$) in CD (left) and SXD (right) discharges. (Bottom) $n_{e,sep}$ vs. $\Sigma\Gamma_i$. Simulation results are shown as dashed lines.

1. METHODS

- **Simulation tool:** SOLPS-ITER (B2.5 plasma + EIRENE neutrals) [2].
- **Cases:** CD (shot #45469) and SXD (shot #46860). **Input power:** 1.6 MW (Ohmic + NBI).
- **Fuelling:**
  - high-field side (HFS),
  - low-field side (LFS), or
  - divertor (DIV) ducts.
- **Diagnostics:** P_n monitored at divertor + midplane gauges (FIGs).
- **Pumping:**
  - Wall + Turbo = 10.7 m³/s (calibrated to match [3]),
  - Lower sub-divertor cryopump: on/off, pumping speed = 50 m³/s.

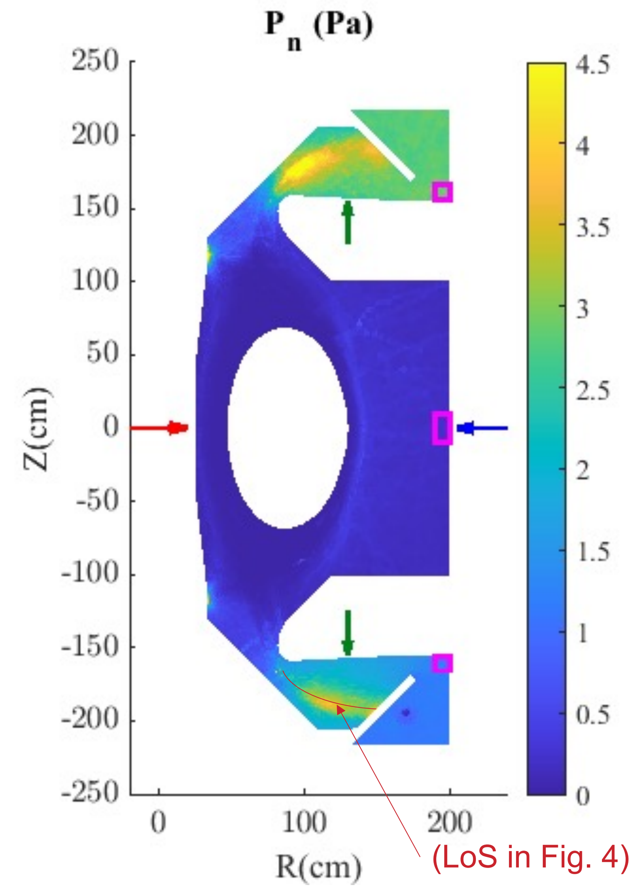

Fig. 1: Fuelling locations

3. Fuelling Efficiency

- HFS fuelling → 20% - 50%,
- LFS fuelling → 10% - 20%,
- DIV fuelling → <5%.

Core ionisation (Sp_{core}) mainly from:

- Main chamber fuelling: puffing,
- DIV fuelling: reflection,

$$\frac{puffed\ neutrals\ ionised\ inside\ LCFS}{total\ fuelling\ rate}$$

$$\frac{puffed\ neutrals\ ionised\ inside\ LCFS}{total\ ionisation\ inside\ LCFS}$$

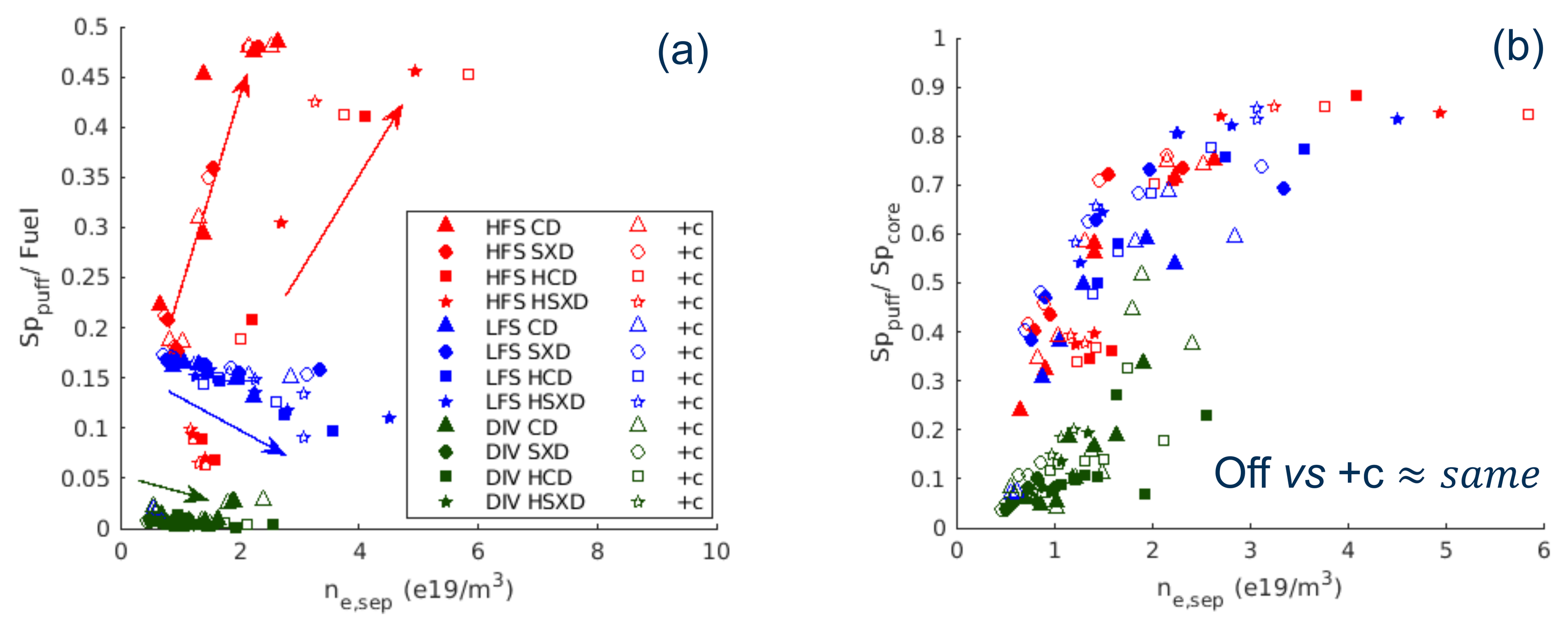

Fig. 3: Fuelling efficiency scans for CD and SXD in both L-mode and H-mode (HCD or HSXD), with lower cryopump switched Off or On (+c): Fraction of puffed neutrals ionised on closed field lines, relative to (a) the total fuelling rate, (b) the total neutrals ionised in the core region.

CONCLUSION

- The lower cryopump in MAST-U:
  - Regulates divertor neutral pressure and the detachment front,
  - Enables broader operational scans, from attached → detached → radiative collapse.
- Fuelling with baffled divertor:
  - Fuelling location matters: main chamber vs divertor fuelling shows different coupling of sub-divertor P_n to upstream density $n_{e,sep}$,
  - Cryopump + baffled divertor allows detachment front control without strongly affecting upstream density.
- Validation & implications:
  - SOLPS-ITER simulations successfully predicted the plasma-neutral interactions on MAST-U, supported by MU03/MU04 experimental results.
  - Guides fuelling and detachment strategies for ITER/DEMO/STEP.

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