CRYOPUMP AND FUELLING LOCATION IMPACTS ON UPSTREAM DENSITY AND DETACHMENT ON MAST-U

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A cryopump has recently been installed in the lower divertor on MAST-U at the beginning of its 4th scientific campaign (MU04), to serve the purpose of improving density control and detachment front control, expanding the operational space to lower densities, as well as removing unwanted impurities. We have conducted both numerical and experimental studies to ensure that the designed purpose can be achieved in the ongoing MU04 campaign and the future.

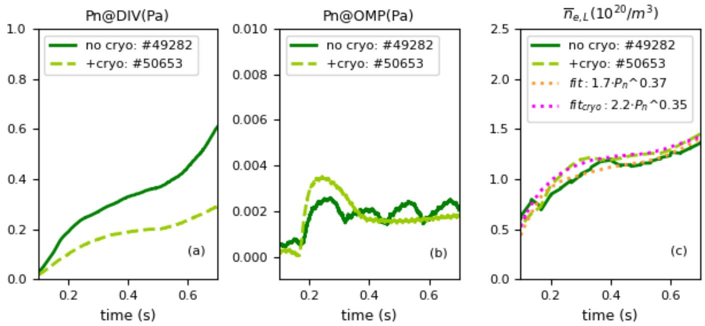

Figure 1: The changes of (a) the neutral pressure in the lower divertor, (b) the neutral pressure on the midplane, and (c) the line averaged densities in two comparison shots (Both shots were in SXD with divertor fuelling). The dotted lines in (c) show the power law fittings between (c) the line averaged density and (a) the neutral pressure in the divertor ($\overline{n}_{e,L} = A \cdot P^{x}_{n,div}$).

The tightly baffled divertor chamber on MAST-U implies that the neutral environment in the divertor chamber is quasi-isolated from the main chamber volume on MAST-U [1]. We could thus use divertor fuelling (compared to high field side (HFS) and low field side (LFS) fuelling in the main chamber) and the cryopump to tune the neutral pressure locally in the divertor, without significantly changing the upstream neutral pressure in the main chamber. This result is evidenced by early MU04 experiments in L-mode, as shown in Fig. (1): We could maintain the line averaged density ($\overline{n}_{e,L}$) and the neutral pressure (P_n) measured on the midplane when the cryopump was activated, despite the fact that the P_n measured at the entrance of the sub-divertor could drop by 50% in the Super-X divertor (SXD) configuration. The dotted lines in Fig.(1c) show that the line averaged density scales weakly with the divertor neutral pressure, and the scaling factor remained the same when the cryopump was activated. This is similar to the evaluated correlations between the separatrix density ($n_{e,sep}$) and the divertor neutral pressure in SOLPS simulations with divertor fuelling (green markers in Fig. 2).

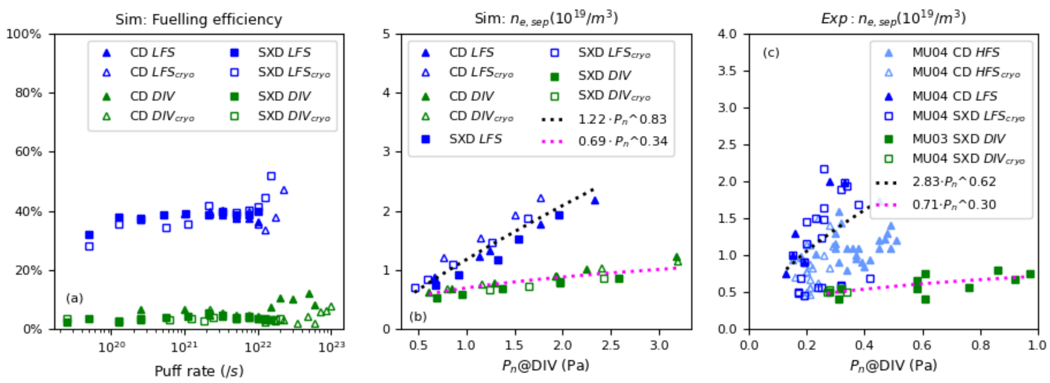

Figure 2: (a) the fraction of input fuel atoms being ionised in the core from simulations in conventional (CD) and SXD configurations with different fuelling locations. The upstream electron density ($n_{e,sep}$ evaluated at the separatrix on the outboard midplane) versus the neutral pressure in the divertor (P_n): (b) data come from SOLPS simulations on MU03, (c) experimental data in multiple shots (including early shots in MU04). The dashed lines show the power law fittings on the data with LFS fuelling and divertor fuelling separately.

The isolation of the divertor chamber on MAST-U means that, when fuelling D_2 from the divertor, only 5% of puffed neutrals reach the separatrix to be ionised on closed field lines (green markers in Fig. 2a, which we define as "fuelling efficiency"). Comparing the scaling between the simulations and MU04 experiments, we found a consistent correlation $n_{e,sep} \propto P_n^{0.30-0.34}$, which aligns with measurements on other devices [2,3,4], as demonstrated in Fig. (2b, 2c). This weak dependence on P_n suggests that the upstream density is not highly sensitive to the neutral pressure in the baffled divertor on MAST-U when fuelling from the divertor. While the scaling factor is influenced by fuelling locations, it remains similar between CD and SXD configurations. In contrast to divertor fuelling, gas puffing from the main chamber is much more efficient at increasing upstream density on MAST-U; Approximately 40% of the neutrals puffed from the LFS in the main chamber can directly fuel the plasma (blue markers in Fig. 2a). This results in a stronger scaling between $n_{e,sep}$ (also $\overline{n}_{e,L}$) and P_n (Fig. 2b, 2c), with the scaling exponent for main chamber fuelling exceeding 0.6 in both simulations and preliminary experiments - a result that has not yet been reported on other devices.

Because of the weak impact of the cryopump on the upstream plasma, we could achieve lower P_n in the divertor with the same upstream electron density. The reduction of P_n in the divertor can help the SXD plasma to attach/re-attach. Thus, the use of the cryopump can assist in controlling the detachment front, potentially pushing it closer to the target (Fig. 3a). One challenge in the previous MAST-U campaigns was to obtain a more attached divertor (to observe the particle flux rollover clearly) in SXD configurations [5]. Because of the extended connection length and flux expansion, the particle and energy flux load on outer targets were small and the ~5eV front was typically detached from the target. Our modelling suggests the cryopump could increase the upstream density required for rollover onset by 40%-60% in SXD when it is running at the full pumping speed, as shown in Fig. (3b). This allows us to study a wider operational space, with a full scan from the attached regime to radiative collapse.

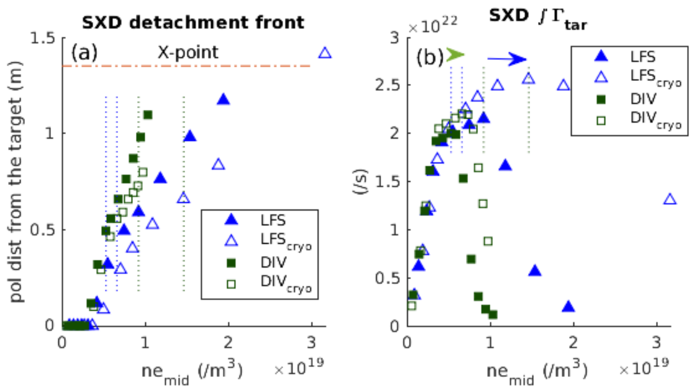

Figure 3: (a) the 5eV detachment front position in the poloidal direction as functions of the upstream separatrix electron density in the SXD configuration with the lower cryopump switched on/off. (b) the corresponding total particle fluxes to the outer lower target, in which the arrows show the increase in the rollover thresholds for different fuelling locations. The vertical dotted lines indicate the rollover onsets.

Further research will be conducted to expand the database (e.g., HFS fuelling modelling, higher input power, H-mode scenario w/wo impurities [6]), and calibrate the detachment front movement in experiments. We will also consider other impacts of the lower cryopump, including the asymmetry induced between the upper and lower divertor.

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