Influence of Divertor Geometry and Baffles on Nitrogen seeded H-mode detachment in TCV

Harshita Raj[1], C. Theiler[1], A. Thornton[2], F. Bagnato[1], P. Blanchard[1], C. Colandrea[1], H. de Oliveira[1], B. Duval[1], O. Février[1], S. Gorno[1], A. Perek[3], H. Reimerdes[1], U. Sheikh[1], M. Vallar[1], B. Vincent[1], the TCV Team[4], the Eurofusion MST1 Team[5]

[1] EPFL, SPC, Lausanne, Switzerland, [2] CCFE, OX14 3DB, UK, [3] DIFFER, Eindhoven, NL,
[4] See author list of S. Coda et al. 2019 Nucl. Fusion 59 112023,
[5] See author list of B. Labitet al 2019 Nucl. Fusion 59 086020

Introduction: Detached divertor operation will be essential for the safety of plasma facing materials (PFC) in future fusion reactors such as ITER and DEMO where the unmitigated flux to the wall can well exceed the material limits [1, 2]. Advanced divertor geometries like X-divertor (XD) and X-point target (XPT) offer promising solutions with lower heat fluxes and lower detachment thresholds [3,4]. The XD geometry has a large poloidal flux expansion at the outer strike point (OSP) and the X-point target (XPT) exhibits a secondary X-point which splits the outer leg and increases the connection length, $L_{\parallel}$ (figure (1)). Increased divertor neutral pressure by introduction of baffles is also known to result in a cooler divertor plasma and facilitates access to detachment in TCV [5,6]. In this work, nitrogen (N_2) seeded detachment has been achieved in XD $(f_x{\sim}10)$ and XPT H-mode plasmas with and without baffles and is compared to similar Single-Null plasmas (SN) with small flux expansion $(f_x{\sim}3)$. The experiments have been carried out in an ELMy H-mode scenario with $I_p = 170\ kA$, $B_t = 1.4\ T$ and at neutral beam heating power, $P_{NBI} = 0.75\ MW$ & $1.3\ MW$, with ion ∇B directed towards the primary X-point, favourable for H-mode access. Langmuir probes (LP), Multispectral Advanced Narrowband Tokamak Imaging System (MANTIS), Thomson Scattering, bolometry and other standard diagnostics have been used to investigate the divertor and core plasma properties.

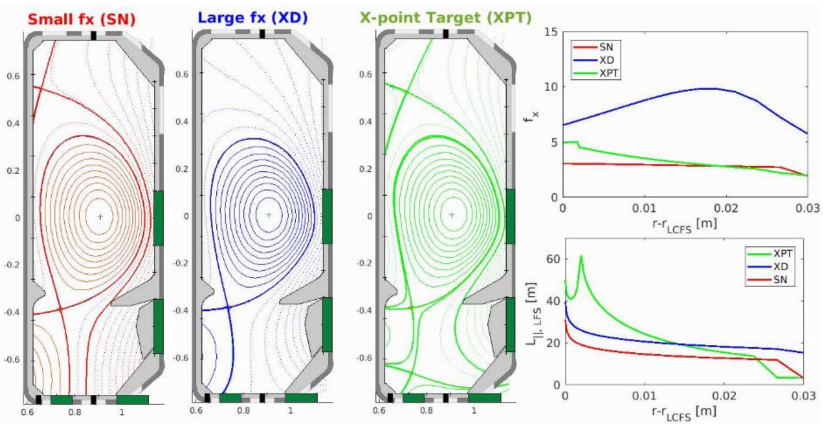

Figure 1: (Left) Equilibria of SN (red), XD (blue) and XPT (green). (Right) radial profiles of f_x and $L_{\parallel}$ for each geometry.

Effect of geometry on core confinement and detachment: Core and divertor plasma properties for baffled plasmas in SN, XD and XPT geometry at $P_{NBI} = 1.3\ MW$ are shown in figure 2. The experiments indicate little effect (<10%) of divertor plasma geometry on the stored energy (W_{MHD}) and H-factor (H_{98}) in attached as well as detached phase. In the attached phase, inter-ELM peak parallel particle fluxes at the OSP $\Gamma_{\parallel,OSP}^{peak}$ in XD as well as at the active OSPs (SP2 and SP4) of XPT are ~3-4 times lower than in SN. N_2 injection at ~1.25s leads to detachment at the OSP, during which the total radiated power increases and H_{98} decreases by <10% for each geometry. In the detached phase, $\Gamma_{\parallel,OSP}^{peak}$ decrease by ~70% in each geometry, except at the SP4 in XPT where N_2 seeding effect is weaker. Total radiated power in the XD is 10% higher than in the SN. XD and SP2-XPT perform equally well with ~75% lower $\Gamma_{\parallel,OSP}^{peak}$ as compared to the SN. In addition, $\Gamma_{\parallel,ISP}^{peak}$ and peak parallel heat flux at the inner strike point in the XD and the XPT were also found to be lower than in the SN.

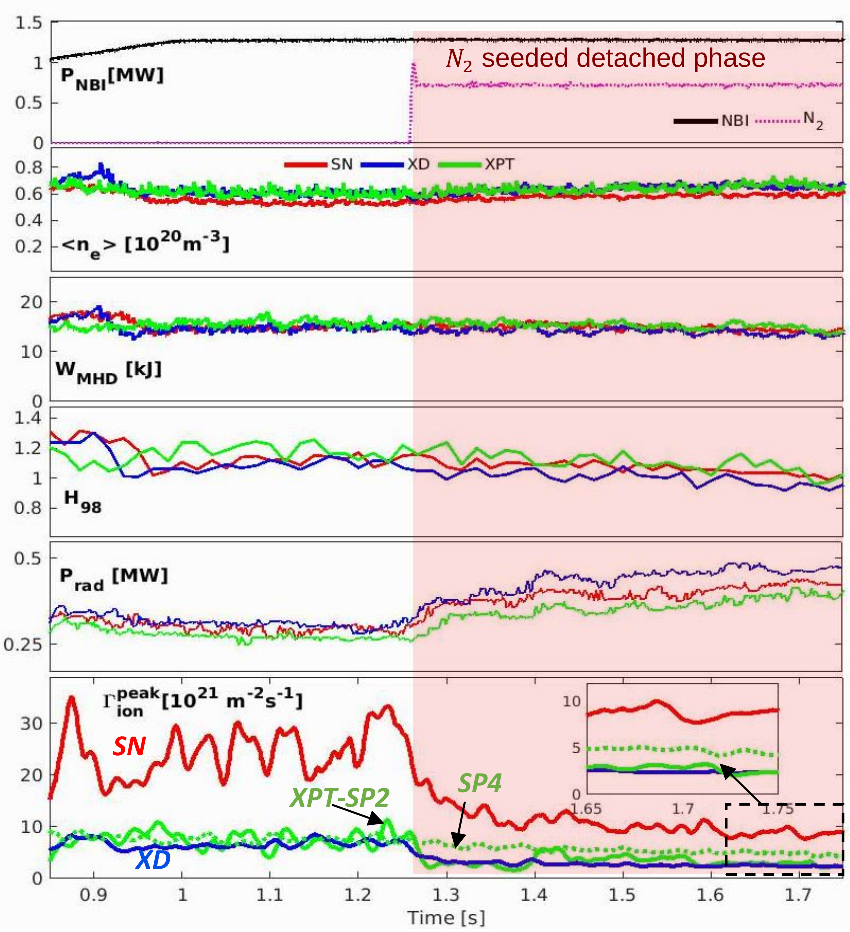

Figure 2: Time evolution of P_{NBI} and N_2 seeding pulse, line average density, W_{MHD}, H_{98}, total radiated power, and $\Gamma_{\parallel,OSP}^{peak}$ (top to bottom) for baffled SN (red), XD (blue) and XPT (green).

Effect of baffles and f_x on peak heat flux: Inter-ELM peak parallel heat flux at OSP ($q_{\parallel,OSP}^{peak}$) obtained from LPs also reveals clear benefits of baffling and increasing f_x, as shown in figure 3 (for attached plasma with P_{NBI}~0.75 MW). Addition of baffles results in ~40% decrease in $q_{\parallel,OSP}^{peak}$ in SN, which is consistent with earlier observations in L-mode plasmas [6]. Whereas a

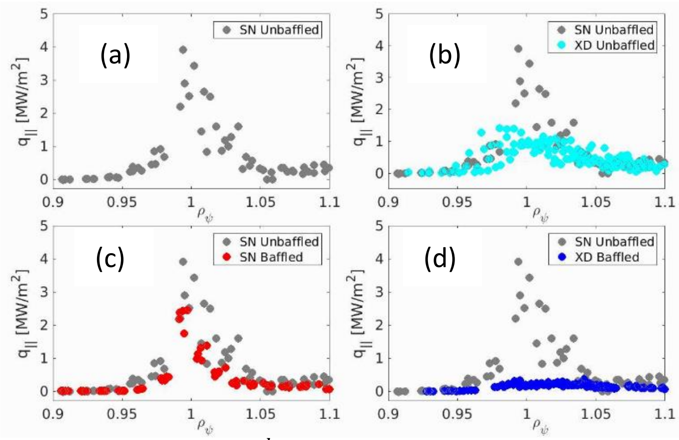

Figure 3: Radial $q_{\parallel,OSP}^{peak}$ profile from LPs in (a) unbaffled SN (b) unbaffled XD (c) baffled SN and (d) baffled XD in attached plasma phase with 0.75 MW NBI power.

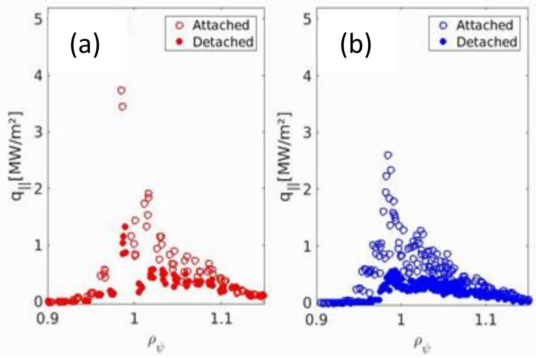

Figure 4: Radial $q_{\parallel,OSP}^{peak}$ profile from LPs in baffled (a) SN and (b) XD, attached (open circle) and detached (filled circles) with 1.3 MW NBI power.

~3 folds increase in f_x (in XD) leads to ~60% decrease in $q_{\parallel,OSP}^{peak}$. A synergistic effect of baffling and increasing f_x is demonstrated in baffled XD plasmas where $q_{\parallel,OSP}^{peak}$ is reduced by >75% in comparison to unbaffled SN in attached condition. In these low power (P_{NBI}~0.75 MW) divertor plasma, further impact of f_x on $q_{\parallel,OSP}^{peak}$ in the detached phase was difficult to discern because of low $q_{\parallel,OSP}^{peak}$ ($< 1\ MWm^{-2}$) in both the SN and the XD plasma. Therefore, these experiments were repeated at a higher power with P_{NBI}~1.3 MW in SN, XD and XPT geometry with baffles. In these high power baffled divertor plasmas, a clear reduction in $q_{\parallel,OSP}^{peak}$ in attached (~50%) as well as detached phase (~65%) was observed due to the increase in f_x, as shown in figure 4. $q_{\parallel,OSP}^{peak}$ at SP2 of XPT was also >65% lower as compared to the SN divertor plasma. However, a weaker effect of N2 seeding on $q_{\parallel,OSP}^{peak}$ was observed at SP4 in the XPT. Likely this poloidal asymmetry in detachment is due to localised N_2 seeding closer to the SP2 in XPT. These results from LPs were also verified with MANTIS which views the lower divertor of TCV to monitor the spatial distribution of spectral emission lines in the visible spectrum [8]. The intensity profile of the CIII emission line along the divertor leg estimated with the MANTIS is used to estimate poloidal distance of the CIII emission front from the X-point (CIII front), which is a recognized marker to characterise the divertor plasma and assess detachment. The CIII front data is median filtered (25 ms) to eliminate the ELM contamination and plotted in figure 5 and 6. Normally, in an attached unbaffled SN, the CIII front stays close to the OSP. It gradually moves upward and migrates close to the X-point with N_2 seeding as the OSP detaches (figure 5). During the attached phase, we find that the CIII front is closer to the X-point in XD and XPT as compared to the SN, which is indicative of colder divertor plasma. As the N_2 seeding starts, the CIII front in the XD reaches the X-point, a little earlier

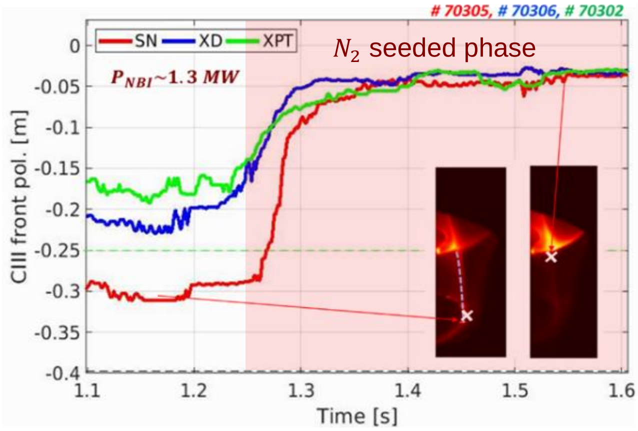

Figure 5: Time evolution of the poloidal distance of CIII emission front location from X-point along the outer leg in baffled SN (red), XD (blue) and XPT (green) at 1.3 MW NBI power.

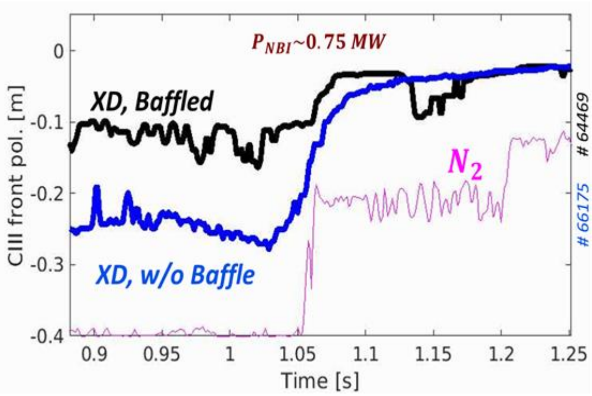

Figure 6: Time evolution of the poloidal distance of CIII emission front location from X-point along the outer leg in baffled XD (black) and unbaffled XD (blue) at 0.75 MW NBI power.

than in the XPT and the SN, which is indicative of lower detachment threshold in terms of impurity injection. However, during much of the detached phase the CIII front remains close to the X-point in all three geometries. Results from MANTIS also show that during the attached H-mode phase, the CIII front remains much closer to the X-point in baffled XD in comparison to the unbaffled XD (figure 6), indicating a colder divertor with the baffles. Furthermore, when the N_2 seeding starts, the CIII front reaches the X-point relatively earlier in the baffled XD indicating a lower detachment threshold with the baffles. These results from MANTIS overall confirm the findings from the LPs.

Conclusion: H-mode with detached divertor has been achieved in SN, XD and XPT plasmas with and without baffles in TCV. Experiments show clear benefits of baffling and advanced geometries in mitigating the peak divertor heat fluxes while maintaining similar core-confinement in attached as well as detached phases. Up to 95% $q_{\parallel,OSP}^{peak}$ mitigation was achieved as a cumulative effect of baffling, increasing f_x and N_2 seeded detachment. XD geometry offers faster detachment as well as lowest $q_{\parallel,OSP}^{peak}$during the attached and detached-mode phase. In future, these experiments will be repeated at higher power (with ECRH heating) and density to explore more reactor relevant divertor conditions.

References:

1. Pitts R A *et al* 2017 *Nucl. Mater. Energy* 1260–74

2. Wenninger R P*et al* 2014 *Nucl. Fusion* 54114003

3. Theiler C. *et al* 2017 *Nucl. Fusion* 57072008

4. Fasoli A. *et al* 2020 *Nucl. Fusion* 60 016019

5. Reimerdes H. *et al* 2021 *Nucl. Fusion* 61024002

6. Février O. *et al* 2021 *Nucl. Mater. Energy* 2710097

7. Harrison J. R *et al* 2019 *Plasma Phys. Control. Fusion* 61 065024