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Towards understanding the relative role of divertor geometry and magnetic topology on detachment

A. Fil*[,1], D. Moulton[2], B. Dudson[1], B. Lipschultz[1], K. Verhaegh[1,3], O. Février[3], O. Myatra[1], C. Theiler[3], M. Wensing[3], EUROfusion MST1 teams[4] and the TCV team[5]

[1]*York Plasma Institute, University of York, Heslington, York, YO10 5DQ, UK*

[2]*Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, OX14 3DB, UK*

[3]*École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland*

[4]*See the author list in "H. Meyer et al 2017 Nucl. Fusion 57 102014"*

[5]*See the author list of "S. Coda et al 2017 Nucl. Fusion 57 102011"*

*Alexandre Fil: alexandre.fil@york.ac.uk, alexandre.fil@ukaea.uk

1) Introduction

The ITER divertor plasma is required to be in a detached regime to reduce the divertor power loading over at least the first λ_q in the SOL. For a DEMO of similar size to ITER the power crossing the separatrix, P_{SOL}, will likely be 3-5x higher, making detachment much more difficult to achieve. Through simple analytic models (e.g. [1,2]) one can show that achieving detachment at higher P_{SOL} at fixed upstream density, n_{eu}, is equivalent to achieving detachment at lower neu for fixed P_{SOL}. In this study we investigate the roles and effects of magnetic topology and divertor geometry on the TCV detachment threshold in n_{eu} (here defined as the upstream density at which the total ion flux to the target rolls-over). We vary the divertor magnetic topology by moving the outer strike point(s) from a major radius, R_t ~ below the X-point ('conventional' or low-R_t divertor) to a lower magnetic field (B) region (i.e. larger R_t) relative to the X-point, so-called "Super-X". This change in "total flux expansion", denoted f_R (= $B_u/B_t \approx R_u/R_t$, where "u" stands for "upstream", or X-point, and "t" for "target") has already been investigated in simple analytic modelling (e.g. [1-3]), which showed that the target electron density and temperature scales approximately with f_R^2 and $1/f_R^2$, respectively, while the target ion flux scales as $1/f_R$. Increasing f_R (decreasing B_T, increasing R_t) increases total flux expansion [2,3] & decreases the n_{eu} detachment threshold [2]. Our modifications of the divertor geometry are aimed at examining the effect of varying the trapping of neutrals in the divertor, by adding baffle structures or changing the angle between the divertor leg and the divertor target (i.e. going from a 'vertical' to a 'horizontal' target).

Our studies utilise the 2D transport code SOLPS-ITER [4] to both explain TCV experimental results on total flux expansion (section 2) and to study the relative effect of changes in magnetic topology and divertor geometry on the n_{eu} detachment threshold (section 3).

2) Lack of effect of total flux expansion on TCV detachment

Experiments on the TCV tokamak [5] have been conducted to investigate the effect of total flux expansion on detachment, especially its effect on the detachment density threshold. The midplane density was ramped up for 4 different configurations, with R_t ranging from 0.62 m to 1.06 m, an increase in total flux expansion (f_R) of ~ 1.7. Special care was taken to obtain similar upstream plasma conditions (including density, parallel connection length, input power and power crossing the separatrix).

The 2 best diagnosed configurations, which we focus on for the rest of the paper, are shown on the two left plots of Figure 1.

Both are ohmic L-mode plasmas with I_p = 320 kA, B_T = 1.42 T in which the density was ramped up from 0.35 n_G to 0.75 n_G (where n_G is the Greenwald density). They correspond to R_t ~0.68 m (TCV pulse 52066, referred to as the "low-R_t" divertor configuration) and ~ 0.92 m (52064, referred to as the "high-R_t" configuration). The corresponding total flux expansion change is thus 0.92/0.68 ~ 1.35. If total flux expansion was the only change between those configurations, it would mean that the detachment threshold of the high-R_t case would be 1.35 lower than the detachment threshold of the low-R_t case.

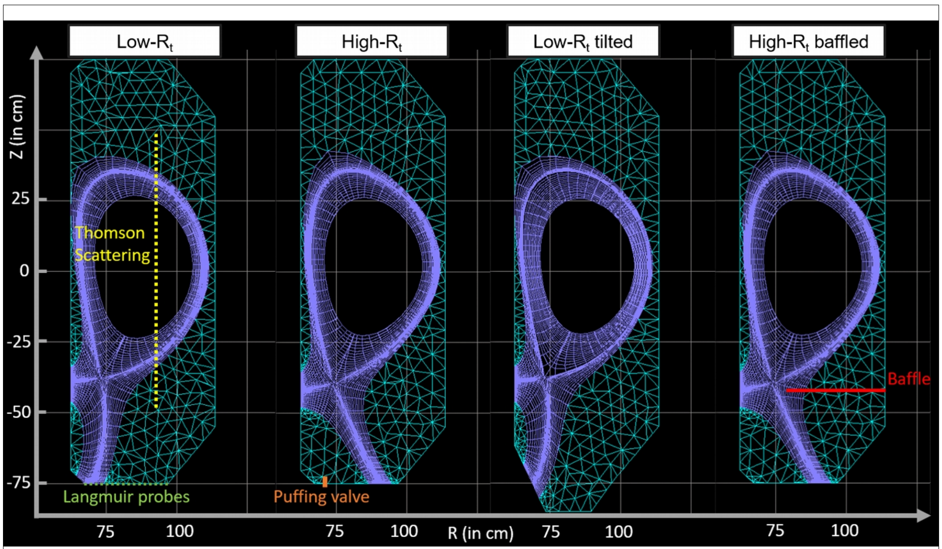

Figure 1: B2.5 plasma grids ("low-Rt", "high-Rt", "low-Rt tilted", "high-Rt baffled"). Also shown is the position of the Thomson Scattering measurement, the Langmuir probes which cover the outer target and the position of the gas valve from which we puff particles in the simulation.

However, in both experiments and modelling that is not the case. Both configurations detach at similar upstream densities within the experimental uncertainties, and even at lower upstream density for the low-R_t than for the high-R_t cases in the modelling, as can be seen on Figure 2.

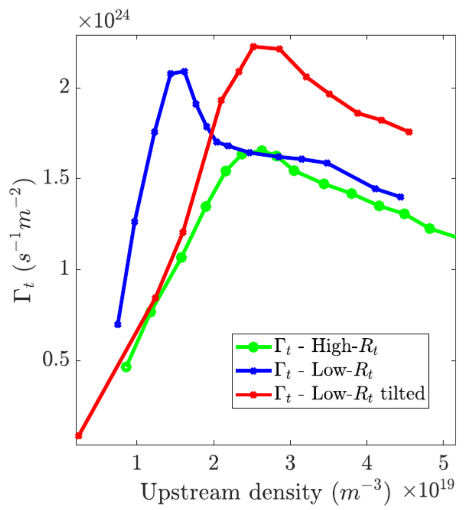

Figure 2: Evolution of the ion flux to the outer target of the flux tube where the peak ion flux is in attached conditions, for the low-Rt, high-Rt and low-Rt tilted configurations.

3) Examining the trade-off between magnetic topology and divertor geometry in modifying the detachment threshold

With additional extensive modelling, we have demonstrated that two neutral effects vary between the two TCV configurations and counteract the effect of total flux expansion. The first neutral effect is caused by the strike point to target angle which changes significantly between the low-R_t configuration ('vertical' target) and the high-R_t configuration ('horizontal' target; see both outer target strike points on Figure 1). By changing the low-R_t configuration to match that of the large R_t case by tilting the TCV wall (see Figure 1) the low-R_t n_{eu} detachment threshold increases by a factor ~ 2, as shown on Figure 2 (the low-R_t tilted configuration, Figure 1) partially recovering the total flux expansion effect. However, it is not clear yet if this is mainly due to the strike point angle change or to the additional divertor volume that this configuration created (or both). We quantify the effect of the strike point angle on divertor trapping of neutrals in the divertor by defining the neutral trapping, η_{RI}, as the fraction of total ion target flux that is ionized in a flux tube just outside the separatrix $\eta_{RI}[\%] = 100 \times \int \frac{S_{ion} dV_{ft}}{\Gamma_t}$.

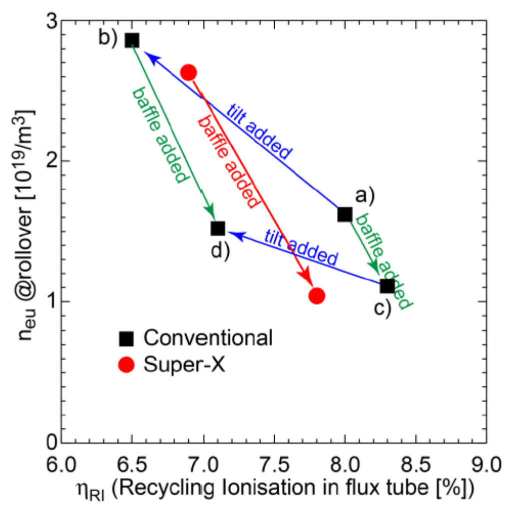

Figure 3: Relationship between the upstream density detachment threshold and the percentage of the target ion current ionizing in the flux tube studied. a) low-Rt configuration; b) low-Rt tilted configuration; c) low-Rt baffled configuration; d) low-Rt tilted and baffled.

Figure 3 shows that as the divertor target strike point angle changes ('a' to 'b') that the increase in detachment neu corresponds to a ~20% drop in η_{RI}; there is some correlation between n_{eu} and η_{RI}.

The second neutral effect is that of “closing” the divertor by adding a baffle from the wall to near the X-point (Figure 1; the baffle acts on neutrals only). The baffle reduces η_{RI} for all configurations (Figure 3). Figure 3 displays the effect on n_{eu} and η_{RI} of all the magnetic topology and divertor geometry changes studied. The amount of drop in n_{eu} with added baffling is stronger the more open and less neutral trapping the divertor geometry and has more effect for the the high-R_t case than for the low-R_t case in TCV. In general, changing the strike point angle has a bigger effect on neutral trapping than adding a baffle, but baffling leads to a larger change in n_{eu}. The TCV low-Rt configuration (case a) already has higher neutral baffling, we think due to the good strike point angle AND the closeness of the inner wall where recycling neutrals are aimed. This is the opposite of the case for DIII-D [1] where the large R_t case appears to have better neutral trapping and has a larger drop in n_{eu} than predicted by just total flux expansion.

3) Conclusions

SOLPS-ITER simulations of TCV experiments studying the effect of total flux expansion on detachment have been performed and reproduce the lack of total flux expansion effect observed experimentally. The f_R scaling is only recovered when the divertor geometry is changed in order to equalize the neutral trapping between both configurations (High-R_t baffled vs low-R_t baffled and tilted in Figure 3; compare ‘d’ and lower red dot). This study thus shows that the divertor geometry and its neutral trapping properties is as important as the magnetic topology in determining the density detachment threshold and should be carefully chosen [1].

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