X-Divertors for Facilitating Detachment without Degrading the DIII-D H-Mode

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Highly flared, highly flux-expanded X-Divertors (XD) on DIII-D detached at a lower Greenwald fraction and higher pedestal pressure than standard divertors (SD), strongly reducing problematic plasma exhaust at the target, allowing for improved control of the detachment front, and maintaining a higher-confinement H-mode necessary for a future fusion reactor. XDs exhibit lower parallel ion fluxes to the target than the SD, as evidenced by probe ion saturation currents. Because the fluxes calculated are field-parallel fluxes, their reduction in the XD cannot be explained by projection due to flux expansion alone. C-III emission images illustrate the differences in detachment evolution between XDs and SDs, where the XD temperature front is seen moving away from the target for lower pedestal densities and higher pedestal pressures. SOLPS models support the notion of an XD-stabilized detachment front. Poloidal profiles of model electron temperatures show that XDs achieve very low temperatures at the target, while still maintaining high temperatures near the X-point, “insulating” the core from the target. This temperature gradient indicates resistance to upstream migration of the detachment front, preventing core confinement loss and X-point MARFEs. Achieving stable detachment for less gas puffing, lower Greenwald fraction, and higher H-mode pedestal pressure will be critical to satisfy simultaneously the needs for good core performance and effective divertor heat load mitigation, in ITER and a future reactor. X-Divertors lower the puffing threshold for stable detachment magnetically, by increasing the electron/ion path length through the neutral-dense region at the target, and increasing plasma-neutral dissipative reaction rates. In this way, X-Divertors may offer a simple, magnetic solution to the problem of robust, detached divertor operation.
X-Divertors for Deeper Detachment Without Degrading the DIII-D H-Mode

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Abstract. The X-Divertor geometry on DIII-D has demonstrated reduced particle and heat fluxes to the target, facilitating detachment onset, at ~20% lower upstream density and higher H-mode pedestal pressure than a standard divertor. SOLPS modeling of the X-Divertor corroborates and lends interpretation of the results of the experiment. The model suggests that the XD’s detachment facilitation at lower density cannot be explained by an increase in total connection length alone, but rather by the addition of connection length specifically in the neutral-dense volume near the target, via poloidal flux expansion and flaring. Sustainable divertor detachment at lower density has beneficial consequences for energy confinement and current drive efficiency in the core for advanced tokamak (AT) operation, while simultaneously satisfying the exhaust requirements of the plasma-facing components.

1. Introduction

Improved confinement and higher core plasma temperatures on the path to fusion ignition exacerbate the problem of exhaust heat fluxes on the tokamak walls, such that the plasma-surface interaction can quickly dictate the efficiency of the entire tokamak. Future tokamaks’ heat fluxes may soon push past the mitigation capabilities that radiative and neutral cooling can offer in the standard divertor (SD) geometry – that is, when excessively high densities to bring the divertor deeper into detachment cause divertor temperature collapse, degrade the H-mode pedestal, compromise core energy confinement, and reduce current drive efficiency. If deeper detachment at higher density is prohibited for the sake of the pedestal, then it becomes advantageous to modify the divertor magnetic geometry, with greater connection length, flux expansion, and target wetted area, to reduce target heat loads. Wetted area can be increased by poloidal flux expansion, as in the cases of the X-Divertor (XD) [1] and Snowflake Divertor (SF) [2], or by combined toroidal and poloidal flux expansion, as in the case of the Super X-Divertor (SXD) [3]. For the purposes of this paper, ‘flux expansion’ will refer specifically to poloidal flux expansion, unless otherwise stated.

Due to the relative weakness of \( B_p \) compared to \( B_t \), poloidal flux expansion alone does not geometrically reduce the field-parallel heat flux in the SOL, \( Q_{||} \), but rather its perpendicular projection on the target, \( Q_{\text{perp}} \). Reducing \( Q_{\text{perp}} \) via poloidal flux expansion is functionally equivalent to making the target plate more parallel to the total incident field (i.e., reducing \( \sin\theta = (B_p/B)\sin\theta_p \), where \( \theta_p \) is the angle between \( B_p \) and the target). Since there are practical limits to the lower bound of \( \theta \), the geometric reduction of heat flux by poloidal flux expansion at the target is fundamentally limited for an attached plasma.

The ideal approach to heat flux mitigation is divertor detachment, the condition in which neutrals dominate over ions and electrons at the target. Full detachment is characterized by a sequence of events at the target as a result of increased gas puffing: very low plasma temperatures (less than 1-2 eV), a strong reduction in the parallel heat flux, a strong reduction...
in plasma pressure, and a rollover of the plasma density and ion current. For the purposes of this paper, ‘detachment onset’ will refer to the first of these events: the reduction of the peak target electron temperature, with some consideration of heat and ion fluxes as well. The region in the SOL over which the transition from plasma-dominated physics to neutral-dominated physics occurs is known as the detachment front, or ionization front. Detachment not only results in a dramatic reduction of heat flux and temperatures at the target, but it also ensures that the persisting power load is more isotropically spread over the target, via photons’ and neutrals’ indifference of the local magnetic field direction.

2. Divertor Flaring and Detachment

Full detachment has been historically elusive, as the detachment front tends to migrate upstream to the core, resulting in degradation of the H-mode pedestal pressure, loss of energy confinement in the core, and x-point MARFE-ing. And while flux expansion is limited in mitigating the heat flux of attached plasmas, it may facilitate the detachment of the plasma altogether. As it is, the standard divertor exhibits a decrease in flux expansion as it approaches the target, resulting in an ever-sharper angle of the total field B with respect to the target downstream. By contrast, a strong X-Divertor causes flux expansion to sharply increase downstream, by introducing a second x-point near the strike point, resulting in an ever-shallower angle between B and the target. This positive gradient in flux expansion toward the target is called poloidal flaring, named for the divergent character of the field lines. X-Divertors, with their flux expansion preferentially maximal at the target, are defined by their poloidal flaring [4].

Near detachment, the XD’s poloidal flaring may be critical to the neutral interaction with the plasma. Because recycled neutrals at the target are not confined by the local magnetic field, they are free to exchange energy and momentum with the incoming plasma upstream and away from the target. Thus, a divertor with high flux expansion and shallow total field angle near the target, where collisionality is highest, encourages ion and electron energy/momentum losses in the neutral-dense volume (Fig. 1). These losses indirectly reduce the divertor temperature, pressure, and $Q_{\parallel}$, encouraging detachment for lower neutral pressures, less gas puffing, and lower upstream densities. Moreover, if the divertor is also highly flared, as is the case for the XD, flux expansion upstream is weaker, and the total field angle is sharper through the neutral buffer. The energy/momentum loss mechanisms are weakened, and $Q_{\parallel}$ is higher (Fig. 1). Thus, in a strong XD, with both flux expansion and poloidal flaring, a negative gradient in $Q_{\parallel}$ can be induced from divertor throat to target, encouraging detachment at the target, yet resisting upstream migration of the detachment front to the core.

![Diagram](image.png)

**FIG. 1.** Target flux expansion increases the path length of ions and electrons through the neutral-dense region, increasing dissipative reactions and indirectly reducing $Q_{\parallel}$. A gradient in flux expansion, known as flaring, creates a subsequent gradient in $Q_{\parallel}$, resisting the upstream migration of the detachment front.
Flux expansion, coupled with sufficiently large poloidal flaring, may (a) bring about detachment for a lower core Greenwald fraction, and (b) resist the migration of the detachment front upstream to the core, preserving the H-mode pedestal in deeper divertor detachment. To explore the effect of flaring on detachment, XDs with large, positive gradients in $B_p$ are required.

The parallel gradient in pressure and $Q_\perp$ as a result of poloidal flaring in the X-Divertor is an indirect effect, with momentum/energy loss from the plasma-neutral interaction acting as the intermediary. It would be ideal to induce the gradients directly instead, by geometric expansion of the SOL flux tube. This is synonymous with a reduction in $B_t$, which is only achieved by moving the divertor strike point out to a larger major radius – i.e., the prescription of the SXD. The SXD has previously been touted as a means to increase target plasma-wetted. However, for the reasons explained in the context of the XD, we can expect that an SXD would have even greater benefits to detachment facilitation, with its combined toroidal and poloidal flaring. But because optimal SXDs tend to require more complicated PF current distributions, XDs may offer a simpler, sufficient approach to detachment facilitation and control. Equilibrium modeling in CORSICA has shown that XDs with large flaring are feasible on several present-day tokamaks [5].

3. DIII-D X-Divertor Detachment Modeling with CORSICA and SOLPS

Equilibrium and transport modeling of X-Divertors with CORSICA and SOLPS largely motivated XD experiments on DIII-D. CORSICA free-boundary equilibria of DIII-D XDs acted as the target equilibria for the development of plasma control schemes. SOLPS modeling was used to compare heat and particle transport of the XD and SD geometries.

A third geometry was also created artificially: the same SD poloidal field geometry, but with more of the total field $B$ allocated to the $B_t$ component (hereafter referred to as the SDL geometry), to decrease field pitch and match the larger outer midplane connection length of the XD. In this way, the importance of XD target flux expansion and flaring could be isolated, by controlling for the added connection length that the flux expansion bestows.

The geometries were modeled in SOLPS using constant radial heat and density-driven particle diffusion coefficients, $X=0.5$ and $D=.15$, to simulate a narrow, H-mode-like power SOL width – about 2 mm. Total input power across the core boundary was 5 MW, equally shared between ions and electrons, to simulate 5.5 MW of NB heating, with 0.5 MW of core radiation. A constant-particle-flux condition was enforced at the core boundary, with an external, constant $D_2$ gas puff fueling the core density from far upstream. This condition ensures stable, steady-state conditions at the boundary, while also allowing the core density to evolve in response to the neutral fueling, which may or may not be an explicit relationship. A very weak pumping surface was used to achieve global particle balance without strongly affecting the local neutral density.

First, we inspect the upstream density threshold for full detachment onset, defined here as the point where the peak target temperature is about 1-2 eV. Fig. 2 summarizes the conditions of the 3 divertor geometries’ target profiles at similar upstream separatrix density ($n_{\text{sep}}$), where the XD is at detachment onset. All target profiles are plotted against normalized poloidal flux, to act as a standard radial coordinate along the target surface, despite the much larger heat footprint that the XD’s flux expansion creates in real space. Fig. 2 clearly shows the advanced state of detachment at the XD target, compared to the SD or SDL targets. Comparing the SD
and SDL geometries, it is clear that extra connection length has a beneficial effect for detachment onset, but cannot fully account for XD detachment facilitation. Rather, the greater flux expansion and lower field angle at the target may be responsible (Fig. 2f).

**FIG. 2.** SOLPS target profiles for the SD, SDL, and XD geometries at a similar upstream density. The XD exhibits a stronger degree of detachment with lower temperatures ($T_e$), lower plasma pressure ($P_e$), lower parallel heat flux ($Q_\parallel$), higher parallel ion current ($J_\parallel$, prior to rollover), and higher neutral density ($n_{\text{neut}}$). The advanced state of detachment of the XD can be understood by the very shallow B-field angle ($\theta$) maintained at the neutral-dense target with flux expansion.

Next, we examine detachment “stability” of the divertor geometries, where the accompanying upstream conditions are compared when all three divertor geometries are at detachment onset. Ideally, the divertor should achieve low temperatures and heat at the target while maintaining high values upstream, for better core performance. Fig. 3 is a collection of poloidal profiles of the three divertors at their respective detachment onset thresholds. Note the different $n_{\text{sep}}$ for which these occur: 2.7e19 m$^{-3}$ for the XD, 3.5e19 m$^{-3}$ for the SD, and 3.1e19 m$^{-3}$ for the SDL. The radial locations for these 1D profiles were chosen based on the location of the peak values at the divertor entrance. While the ionization fronts for all three geometries are similarly located (Fig. 3c), the positive gradient in flux expansion (flaring) of the XD (Fig. 3a), and its greater distribution of connection length near the target (Fig. 3b) dissipate nearly all the power very near the target (Fig. 3d), resulting in much steeper gradients in temperature and $Q_\parallel$ (Figs. 3e and 3f), as expected. Thus, the XD model not only detaches at lower density (Fig. 2), but it also more effectively resists the migration of the volumetric power losses to the core, insulating the core from the target.

Additionally, we examine carbon impurity concentrations and subsequent radiation patterns at detachment onset, as one would see from a bolometer. The XD more effectively restricts carbon impurities near the target, while the SD and SDL geometries allow carbon ions near the core x-point (Fig. 4). Radiation in the model correlates strongly with carbon concentration, as has been previously observed experimentally.
FIG. 3. SOLPS poloidal profiles for the SD, SDL, and XD geometries in a similar state of detachment. \( L_{\text{pol}} \) is the distance along the poloidal field line to the target. The vertical, dashed line indicates the location of the ionization front. Greater flux expansion (\( f_{\text{exp}} \)) at the XD target distributes a greater portion of the total connection length (\( L_{||} \)) at the target, so while the ionization front (\( D^+ \) source) of all three geometries is similarly located (albeit for significantly different densities), the XD dissipates its power much closer to the target, resulting in very steep poloidal gradients in \( T_e \) and \( Q_{||} \), and better insulation between the target and the core upstream.

FIG. 4. SOLPS 2D color plots of temperature, carbon impurity concentration, and radiated power in the SD, SDL, and XD geometries in similar states of detachment. The XD reduces its temperature in a volume much closer to the target. Carbon impurities in the XD are also confined to the target region, while carbon in the SD and SDL geometries is free to radiate at the core x-point, possibly compromising energy confinement.

In summary, the XD model much more effectively reduced heat and particle fluxes to the target at lower density than either the SD or SDL models (Fig. 5). The SDL model, whose midplane connection length matched the XD, shows that the XD’s better performance is not simply explained by added connection length due to flux expansion, but rather the distribution of flux expansion and connection length preferentially at the target, encouraging dissipation downstream, and discouraging it upstream.
4. Experimental X-Divertor Detachment Results on DIII-D

To test the benefits of divertor flaring to detachment suggested in the models of Section 3, XD geometries were created alongside SDs, for the same lower single-null H-mode plasma, in an experiment on DIII-D. An XD/SD pair was created at high plasma triangularity, such that the outer strike points resided on the lower floor. Indeed, these geometries were intended to match the model geometries analyzed in Figs. 2-5. Because the floor is close to the PF coils, the XD’s secondary x-point could be brought very close to the strike point, strongly increasing the flux expansion at the target. Both divertor geometries – over several, successive shots – were puffed deep into detachment, until ultimately the H-mode pedestal was significantly degraded. In this sense, the gas puffing scan was a failure test to determine (a) the pedestal density at which the divertor detached, and (b) how deeply the divertor could be detached before the pedestal pressure degraded.

On the DIII-D lower floor, detachment diagnostics consisted of target Langmuir probes for ion current and an IR camera for heat flux, with a tangential camera and bolometer available for 2D reconstructions of radiation. While probes can also be used to infer plasma density and temperature as well, the interpretation of these values becomes more ambiguous at the low temperatures characteristic of detachment onset. Carbon emissions were therefore relied upon to give quantitative measure of $T_e$ in the divertor leg. Note that while the models compared detachment for a given $n_{e,sep}$, the experiment compares detachment at a given pedestal density, $n_{e,ped}$. Experimental values for $n_{e,sep}$ are inferred from the midplane profiles, to compare the implications of the model to the experiment directly.

Figs. 6-9 summarize the observations of X-Divertor detachment facilitation in DIII-D. Fig. 6 illustrates how the temperature front evolves in the XD and SD. While the collapse of the SD temperature front is almost instantaneous, the XD temperature front collapse is more gradual, suggesting a passive resistance due to flaring. Fig. 7 illustrates how the XD radiating volume persists at the target, where there is more ion/electron path length. Fig. 8 shows conditions directly at the target via probe $J_{sat}$ measurements, where the XD leads $J_{sat}$ rollover. Finally, Fig. 9 summarizes the measured target quantities as a function of $n_{e,sep}$ and $P_{ped}$, where the XD curve is closer to the ideal operating space: low density, high pressure, and low target fluxes.

Quantitatively, the XD model (Sect. 3) predicts a reduction of 23% in $n_{e,sep}$ for detachment onset (i.e., peak target $T_e < 2$ eV, Fig. 5) over the SD model, from 3.5e19 to 2.7e19 m$^{-3}$. Experimentally (Sect. 4), when the separatrix densities are inferred from the midplane profiles.
FIG. 6. Very low target $T_e$ is the first predictor of detachment onset. $C^3+$ emissions can be used to track the location of the temperature front for the XD (a-c) and the SD (d-f) at incremental pedestal densities. At the lowest density, the XD detachment front begins to peel away from the target (a), while the SD remains firmly attached (d). At higher density, the XD is completely detached (b), with the SD still showing strong emissions at the target (e). At the highest density, both divertors (c and f) are finally fully detached and MARFE-ing.

FIG. 7. During detachment, bolometer reconstructions show the regions in the outer divertor where radiation is strongest (green, yellow, red). The XD’s radiating volume stays near the target (b), while the SD begins to radiate throughout the divertor volume (e). This is consistent with the idea that the XD’s poloidal flaring can discourage upstream volumetric losses, preventing the migration of the detachment front, until at very high density both geometries exhibit MARFE-ing activity (c and f).

FIG. 8. Comparison of three pairs of XD/SD shots’ target profiles of parallel ion current at progressively higher pedestal densities. Following the strong erosion of the target electron temperature profile at detachment, the ion current to the target rolls over and decreases. At lower densities (left and middle plots), the XD exhibits ion current reduction ahead of the SD. At very high densities (right plot), the two profiles finally exhibit similar ion current reduction. The values plotted ($J_i$ vs. $\psi_n$) normalize for any geometric projection of the flux tube on the target, so the XD’s lower ion current is a result of advanced detachment, and not merely an increase in plasma-wetted area.

and power accounting [6] for the shots in Fig. 6, the reduction in $n_{e,sep}$ is about 20%, but from 1.9e19 to 1.5e19 m$^{-3}$. SOLPS’ more pessimistic prediction of a higher detachment threshold $n_{e,sep}$ is likely more evidence of the documented dissipation shortfall in several fluid SOL codes [7], coupled with the narrower transport profile ($X=0.5$, $D=0.15$) employed in the model. Nevertheless, the model and the experiment agree remarkably well that poloidal flaring at the divertor target can reduce the detachment density threshold.
5. Conclusions

X-Divertors on DIII-D have strongly suggested that target flux expansion and flaring can lower the detachment density threshold (here, ~20%), which is important for AT operation in compliance with proper exhaust power and particle handling. Equally importantly, the experiment has shown XD detachment at higher pedestal pressure, which allows the core to maintain higher energy confinement. SOLPS models have corroborated and given interpretation of these observations, by showing how XDs and SDs differently dissipate energy and momentum in the divertor volume due to their geometries. It is clear, from this experiment and the argument illustrated in Fig. 1, that poloidal flux expansion and flaring must work in tandem with efficient neutral trapping to see a lower density threshold for detachment. Therefore, future experiments can build on the benefits of magnetic flaring to detachment by (a) enhancing neutral compression at the target, (b) improving strike point and flux expansion precision with secondary x-point control, and (c) considering target toroidal and poloidal flux expansion with Super X-Divertors.

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