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Advanced divertor research on the TCV tokamak

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Introduction

Continuous operation of a power plant-scale fusion reactor (i.e. DEMO) will require the safe exhaust of 10^8 W of power via a 10^{-3} m thin scrape-off layer (SOL) surrounding the confined plasma. Although expanded in the divertor, the SOL thickness (set by plasma transport physics) limits the volume available for radiative and collisional energy losses, as well as the surface area of the reactor-wall usable for exhaust. Several concepts have been proposed to improve upon the conventional magnetic geometry of the single-null divertor (SND). These aim to enlarge the SOL volume (V_{SOL}) and plasma-wetted wall area (A_{wet}), and thereby lower the heat fluxes to the walls. Since the flux expansion at the target in any divertor configuration is limited by the minimum acceptable total fieldline angle, the alternative concepts aim to increase A_{wet} by enhancing the cross-field transport. TCV contributes to a DEMO exhaust solution by investigating the exhaust physics of a wide range of alternative divertor concepts. In previous work, cross-field transport was shown to be significantly enhanced in the Snowflake divertor (SFD) [1], possibly in part due to instabilities at high β_{pol} (normalized plasma pressure) [2]. This paper highlights recent TCV results on how diffusion and drifts affect the target profiles in the SFD, and compares the spatial distribution of radiation in the X-divertor (XD), and X-point Target Divertor (XTD) with that of the better known SND.

Scrape-off layer plasma transport in the Snowflake divertor

SFD configurations generally feature a second x-point, X_2, (and associated separatrix) in the vessel and in the proximity of the primary one. The lower poloidal field (B_p) in the null region locally increases V_{SOL} and the connection length ($L_{//}$) compared to the SND, which also facilitates access to a detached divertor state. V_{SOL} and $L_{//}$ only increase in the near-SOL in TCV, whereas the full SOL benefits in larger tokamaks [3]. The manifestation of any potential benefits and the spatial target profiles depend strongly on the location of X_2 relative to the primary

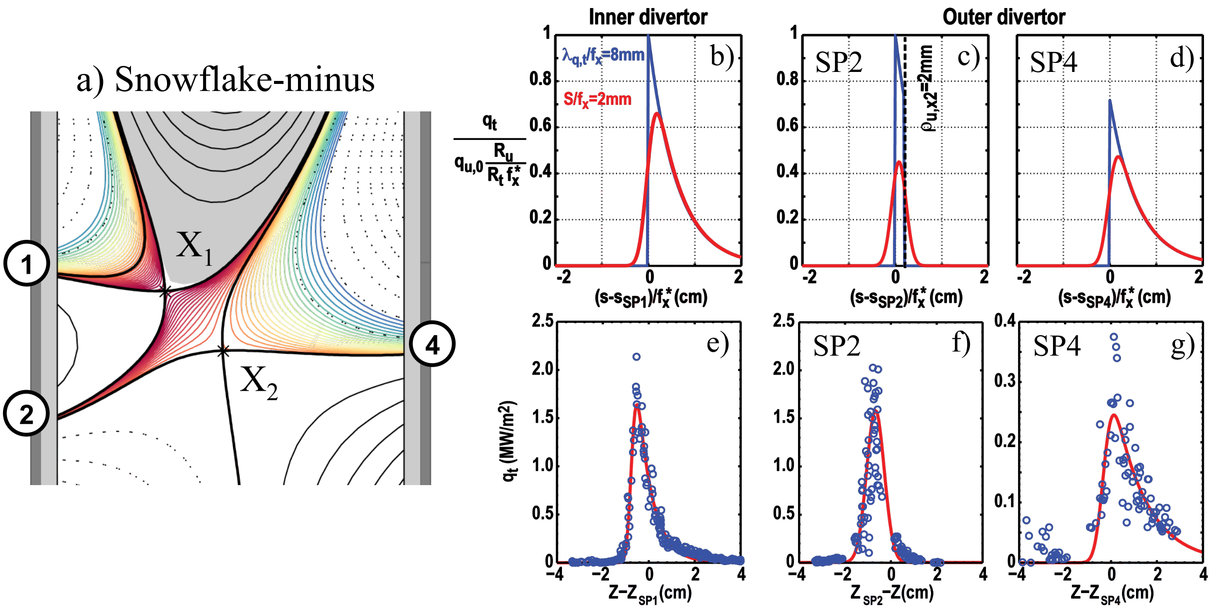

Figure 1: *a) SOL geometry of the Snowflake-minus configuration. The secondary separatrix forks the SOL and diverts parts of the plasma to two strike points. Colors indicate the expected heat flux density. b-d) Calculated target profiles at SP1,2,4 (mapped upstream and normalized to the upstream heat flux) without (blue) and with (red) cross-field diffusion modeled by convoluting an exponential SOL power density profile with a Gaussian distribution, following [5]. e-g) Target profiles measured by Langmuir probes near the same SPs of the SF- configuration, fitted with an Eich-profile.*

x-point [4], c.f. the experimental results below.

If X_2 is placed in the common flux region, i.e. in the SF- configuration, the upstream heat flux profile on one side of the SOL splits into two strike points (SPs), SP2 and SP4 for the configuration in Fig. 2. The target profiles depend on the fraction of the SOL width inside the secondary separatrix. A simple analytical model for the target profiles in the SND was presented in [5], consisting of an exponential upstream profile (where the core provides an influx into the SOL) convoluted with a Gaussian and assuming that cross-field transport is diffusive in the divertor legs beyond the x-point. In a similar way, we truncated the exponential profiles of the SF- and convoluted them with a Gausssian. Fig. 1c shows that, with realistic values for the SOL width and the S-parameter (Gaussian spreading), the creation of two additional steep perpendicular gradients in the SOL enables a significant reduction of the peak heat flux by cross-field diffusion. Figs. 1e-g show the experimental target heat flux profiles (measured with Langmuir probes) accurately fitted with the model function. This conclusion is supported by a more detailed numerical study of cross-field diffusion in the SF- using the transport code EMC3-Eirene [6], which yielded a reduction of the *parallel* heat flux up to a factor 2.

When X_2 resides in the private flux region (a SF+ configuration), particle and heat fluxes to the extra strike points only occur through cross-field transport from the SOL. These fluxes are significantly greater than that explained by modelled cross-field diffusion alone, both in L-mode and (particularly) during ELMs [7, 1]. One of the foci of our research is to identify any non-diffusive transport mechanisms. If we assume that parallel density and temperature profiles remain unchanged, the poloidal gradients of these quantities, and the resulting ExB drifts, are enhanced in the SFD (compared to a SND). The parallel and perpendicular components of this convective flow are illustrated in Fig. 2a. Fig. 2b shows that the target profile measured at the inner primary strike point is significantly altered in the SF+, i.e. without changing the SOL topology, even leading to a second peak. This double peak disappears when any ExB drifts are reversed by reversing the toroidal field (Fig. 2c), demonstrating qualitative consistency between the experiments and a drift model developed in [8]. This and other cross-field transport mechanisms will be further explored with experiments and modelling.

Radiation peaking in the XD and XTD

DEMO operation will likely require detachment of direct plasma fluxes from the material surfaces. This requires significant volumetric energy losses upstream of the targets, notably in the form of impurity radiation. Ideally, a detachment front should be stabilized away from the core to reduce the risk of impurities affecting the performance. To this end, it is investigated how poloidal flux expansion (f_x), flux surface flaring, and total flux expansion (due to the target radius) affect detachment front stability. In [9], detachment was studied at up to $f_x = 9$, with D_α emissions suggesting that recombination occurs closer to the target and further from the separatrix at larger f_x. Recent experiments produced X-divertor [10] (x-point outside wall) and X-point Target Divertor [11] (x-point inside vessel) configurations in TCV, which give yet larger f_x ($\sim$10–40) and flux surface flaring (c.f. Fig. 3). At a density below the detachment threshold ($n_e^{avg} \approx 3e19\ m^{-3}$), we observe in the tomographically inverted bolometer data that the total emissivity peaks near the target at increased f_x, and further towards the high-field side than in [9]. The difference

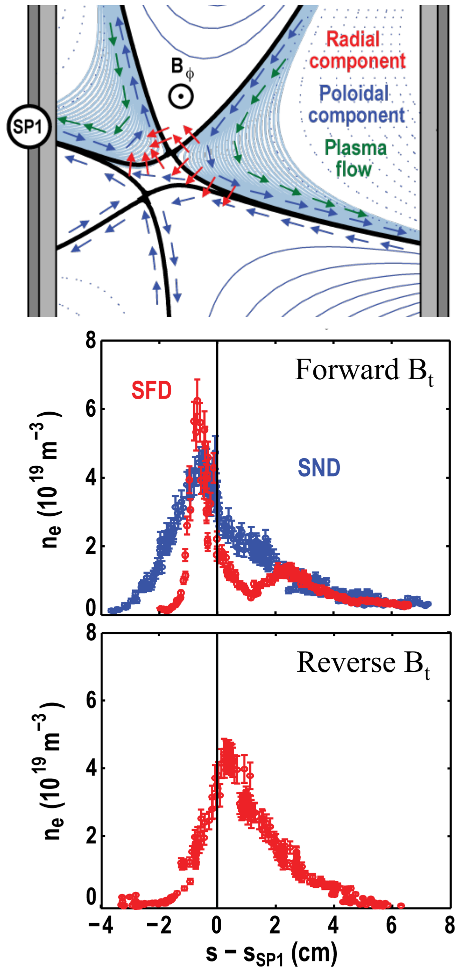

Figure 2: *a) Cartoon of the parallel and perpendicular ExB drifts expected in the SF+ divertor configuration. b) Target density profiles at the inner strike point in forward toroidal field in the SND (blue) and SFD (red) configurations. c) Target density profile at SP1 at the SFD in reversed B_t.*

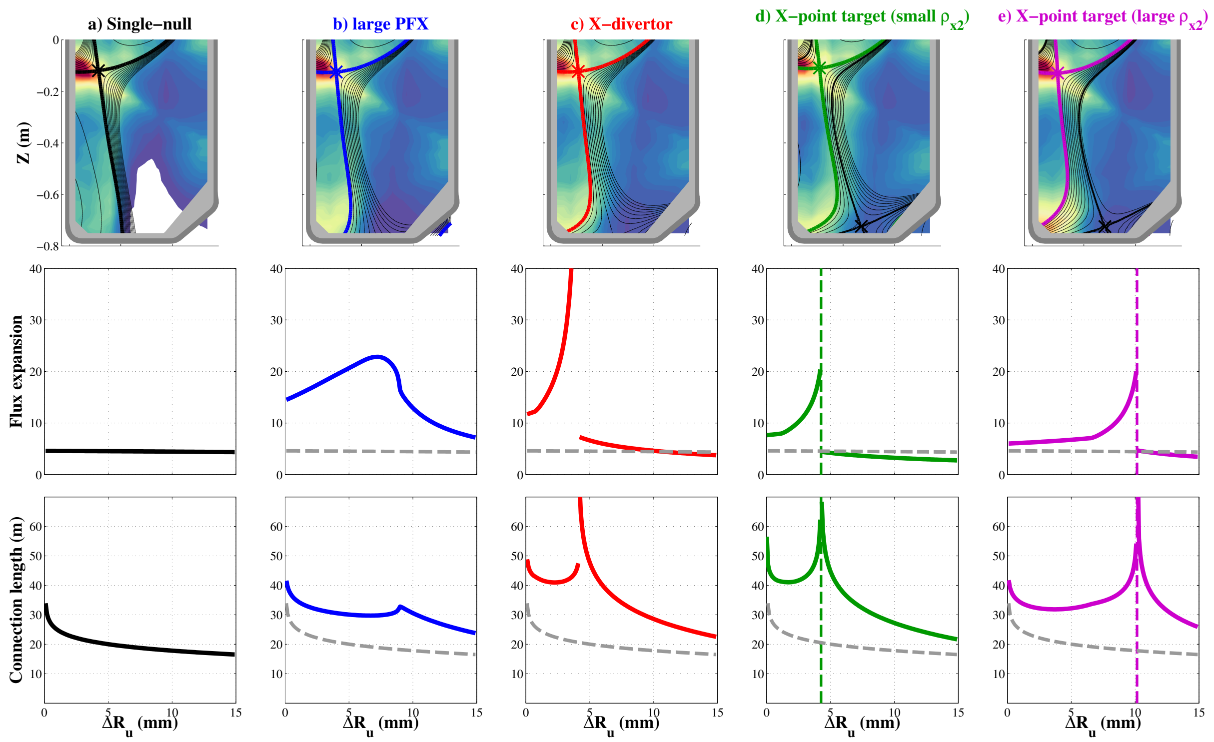

Figure 3: *The emissivity distribution (top), target flux expansion (middle) and connection length (bottom) for five configurations with large flux surface flaring in the divertor.*

between the XD and XTD is insignificant in this particular experiment. We speculate that the locally enhanced connection length (factor 1.5–2, see Fig. 3), which increases the residence time of charged particles near the target, and favorable poloidal angle of the magnetic flux surfaces with respect to the neutral recycling flux are responsible for the enhanced volumetric losses near the target. Establishing a neutral recycling flux opposite to the main poloidal plasma flow, while operating at the minimum magnetic field angle, could provide an important advantage over SND configurations with an inclined target (e.g. vertical target divertor).

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