Drift flows impact island divertor operation in Wendelstein 7-X

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The stellarator Wendelstein 7-X (W7-X) is set to demonstrate not just stellarator optimization but also the suitability of the island divertor for stellarator fusion reactors. Steady-state operation at relevant heating powers (defined at W7-X as 10MW ECRH for 30 minutes) crucially requires detailed understanding and control of heat loads to the divertor.

In this work we demonstrate the significant impact of ExB drift flows on island divertor operation in stellarators. Experiments in attached plasmas in W7-X show the ubiquitous existence of stationary ExB drift flows in the Scrape-Off Layer (SOL). The flows are oriented predominantly in the poloidal/bi-normal direction, have velocities of some km/s, and can feature a fine spatial structure with multiple shear layers across the width of SOL islands. They can be a key towards understanding the non-monotonic radial profiles of T_e and n_e that are typically observed in the island divertor SOL; they also contribute to differences in predicted versus experimentally observed heat loads to divertor targets. This has implications not just for W7-X steady state operation but also for future stellarators on the path to reactors, whose divertor models rely on the same tools that are employed at W7-X so far.

In comparison to poloidal divertors in tokamaks, the island divertor features much longer connection lengths from the upstream position to divertor targets of typically some 100 to 1000 m. As a consequence, transport from drift flows on island flux surfaces is much more efficient, as it effectively short-circuits the parallel transport, see the sketch in Fig. 1a). There, the cyan arrow shows the poloidal pathway to the divertor being a factor 1000 shorter than the parallel pathway by following a field line (blue arrows), which can be expressed via the field line pitch $\Theta = B_r/B_{tor} \sim 10^{-3}$ (compare to $\Theta = B_{pol}/B_{tor} \sim 0.1$ in tokamaks). The effect of poloidal drift flows is therefore amplified by Θ^{-1} against parallel (conductive + convective) transport.

Notably, such drift flows are not included in current 3D transport codes for modeling the island divertor (e.g. EMC3-EIRENE), which treat perpendicular transport via prescribed diffusion only [1]. The radial transport across flux surfaces (red arrow), in contrast, has an even shorter distance to the target but is weakened due to the small level of turbulent cross-field in W7-X [2]. The poloidal flows are so far the most promising explanation for the characteristic non-monotonic T_e and n_e profiles that are observed in the W7-X island divertor SOL by reciprocating probes [2], line-ratio spectroscopy on a thermal Helium beam in the divertor (see Fig. 1b), and Alkali beam emission spectroscopy in the outboard mid-plane, as they can transport heat across the islands and into the "shadowed" regions of short connection lengths (which exist as a consequence of the toroidally segmented divertor targets).

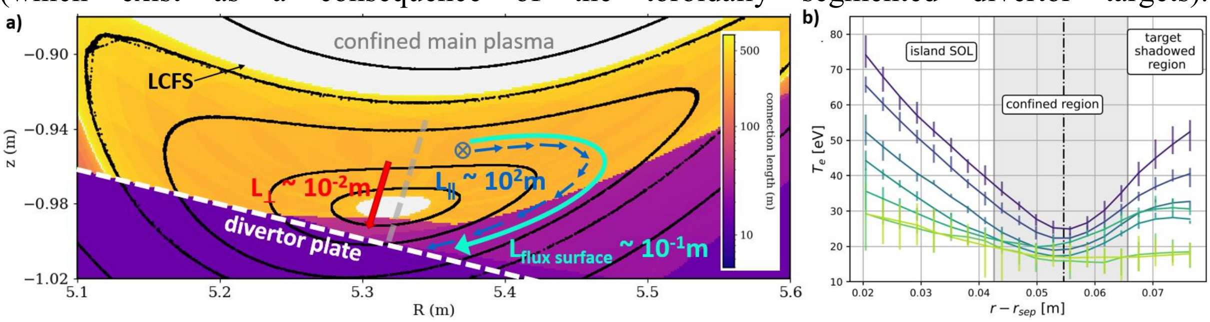

Figure 1 a) connection length (color coded) and Poincare plot (black) in a magnetic island at a lower divertor in W7-X. The arrows schematically indicate paths for parallel, poloidal, and radial transport. b) Radial T_e profiles from thermal He beam spectroscopy for plasmas with low density (blue) to high density (yellow) along the line of sight indicated by a grey dashed line in a) [3].

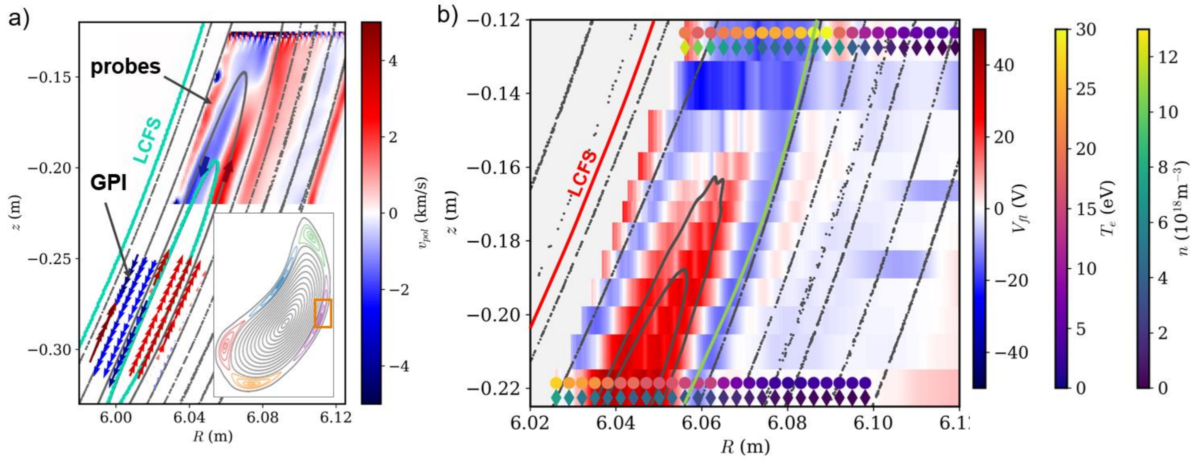

Figure 2 a) poloidal flow velocity from reciprocating probes (top) and GPI (bottom) at the outboard SOL of W7-X (see inset). b) 2D map of floating potential (color-coded) and two radial profiles of T_e, n_e (colored markers at z=-0.125m and z=-0.22m), overlaid with Poincaré plot (black) and LCFS (red).

Poloidal drift flows with velocities of some km/s are directly observed in qualitative agreement by gas puff imaging (GPI) and 2D-resolved reciprocating Langmuir probe measurements, see Fig. 2a). The stationary poloidal flow channels observed by GPI can be radially as narrow as 1cm, with multiple shear layers across the magnetic island SOL. Complementary, a reciprocating Langmuir probe array provides 2D (radially and poloidally) resolved maps of floating potential (V_f) distribution. As shown in Fig. 2b), the V_f distribution (color-coded) clearly follows the structure of the magnetic island (overlaid Poincare plot). The electric fields resulting from the potential distribution and the implied ExB flows are in qualitative agreement with GPI, see Fig. 1a). The detailed structure of flow patterns across the island and velocity magnitudes sensitively depend on small details of the magnetic island size and position.

The drift nature of these flows is confirmed in field reversal experiments, where the poloidal flow flips direction, while the electric fields remain unaffected. Field reversal experiments further showed that initially unexpected up-down asymmetries in divertor heat loads flip, suggesting that these are due to drift effects [3]. Furthermore, such experiments also show that severe distortions of counter-streaming parallel flow patterns (an intrinsic consequence of the intersection geometry between islands and divertor plates) can be attributed to poloidal drift flows via a shift of the parallel flow stagnation point [4].

Summarizing the experimental observations, we directly observe strong poloidal drift flows in the island divertor SOL and see their impact on non-monotonic T_e, n_e profiles, deformation of parallel flow structures, and divertor heat loads. Such drift flows are not included in models that were used to design the divertor and are used to predict the heat loads. Surprisingly, these simples models can predict the overall divertor heat loads and the heat load control actuators with reasonable accuracy even though they are not accounting for drift flows [5]. However, the deviations of experimental observations from simple model predictions still limit the operational space of W7-X: parts of the divertor that are not designed for high heat fluxes receive excessive heat loads from the shadowed regions of the SOL, which, in turn, can receive enhanced heat transport via drifts.

Parallel heat fluxes for typical SOL parameters in W7X are $q_{\parallel} = q_{cond} + q_{conv} \sim 10\mathrm{MW/m^2}$. In contrast, the energy transport from the observed ExB drift flows is $q_{ExB} = \frac{5}{2} T_e n_e v_{ExB} = \sim 500\ \mathrm{kW/m^2}$. However, accounting for the Θ^{-1} amplification of q_{ExB}, we obtain q_{ExB} of several $100\mathrm{MW/m^2}$, i.e. much larger than $q_{\parallel}$. While this is just a rough estimation, it emphasizes the significant role of ExB drift fluxes in the island divertor of W7-X and further motivates the implementation of drift flows into 3D edge transport models towards the development of stellarator reactor divertors.

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