Investigations of the impact of cross-field drifts on divertor detachment in DIII-D with UEDGE

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Partially detached divertor conditions are presently foreseen as mandatory in ITER to reduce the heat fluxes on the divertor plasma facing materials below 10 MW/m^2, while operating at high fusion performance [1]. Cross-field drifts have been observed to strongly impact plasma conditions and the degree of detachment at each divertor plate for given main plasma conditions [2, 3, and reference therein]. To investigate the impact of drifts on the divertor conditions, dedicated sets of low and high confinement (L- and H-mode) plasmas with the **B**×∇B-drift direction towards (fwd. B$_T$) and away (rev. B$_T$) from the active X-point were conducted in the DIII-D tokamak [4, 5]. H-mode plasmas were carried out in a low triangularity configuration at toroidal field strength of 1.8 T and plasma current of 0.9 MA (DIII-D shot numbers 160997 – 161008, 161136 – 161151), while the L-mode plasmas were studied in a low triangularity configuration at toroidal field strength of 2.0 T and plasma current of 1.3 MA (DIII-D shot numbers 160299 – 160302, 160323 – 160327). The total heating power in the H-mode discharges is about 3.8 MW, and in the L-mode discharges 1 MW of Ohmic power with 100 ms NBI blips for C^{6+} temperature and density measurements. The divertor strike points (SP) were swept to obtain 2D Divertor Thomson Scattering (DTS) profiles [6]. Extreme SP sweeps were conducted in the H-mode plasmas to cover both low and high field side (LFS/HFS) divertor legs with the DTS system [4]. These plasmas were simulated with the multi-fluid code UEDGE [7]. UEDGE encompasses a Braginskii fluid plasma model with a fluid neutrals model. Magnetic and electric cross-field drifts are fully included and the electrostatic potential equation includes parallel electron currents with related plate boundary conditions on sheath potential. The code boundary conditions used in this study are described in [8].

Experimentally, in H-mode plasma conditions in DIII-D, the low field side (LFS) divertor plate detaches at 20% lower LFS mid-plane separatrix density, $n_{e,SEP,LFS-MP}$, in rev. B$_T$ than in fwd. B$_T$ (Fig. 1a). The H-mode data point in fwd. B$_T$ at $n_{e,SEP,LFS-MP} \sim$ 2.1e19 m^{-3} shows well
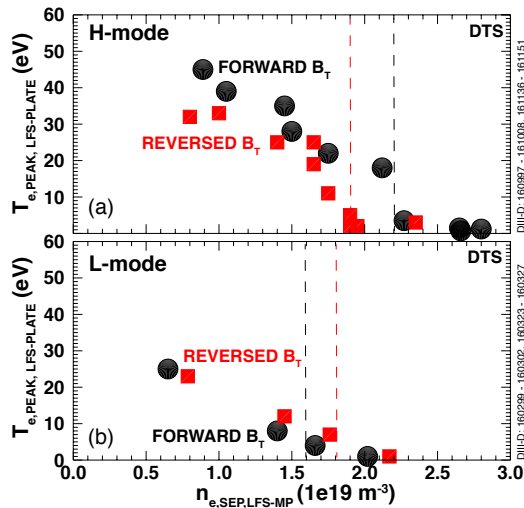
Figure 1. DTS measured LFS plate peak electron temperature as a function fo LFS mid-plane separatrix electron density: a) H-mode conditions, b) L-mode conditions. The red squares stand for rev. B_T plasma and the black circles for fwd. B_T plasmas.

attached LFS divertor conditions both in 2D DTS profiles as well as in 2D distribution of the CIII (465 nm) emission. In contrast to the H-mode observations, in L-mode conditions, the LFS divertor plate reaches electron temperatures less than 5 eV at 10% higher $n_{e,SEP,LFS-MP}$ in rev. B_T than in fwd. B_T (Fig. 1b). These trends are also qualitatively observed in UEDGE simulations including magnetic and electric drifts and SOL currents. Whereas in L-mode conditions, the LFS plate detachment threshold density in the UEDGE simulations is within 10% of the experimental levels, in H-mode conditions, UEDGE requires about 40% higher $n_{e,SEP,LFS-MP}$ than experiments for LFS plate detachment in rev. B_T. The UEDGE simulations indicate that the relatively stronger poloidal $\mathbf{E} \times \mathbf{B}$ drifts in the H-mode conditions lead to the observed difference of the impact of field reversal on the LFS detachment threshold in L- and H-mode condition. In both L- and H-mode conditions the radial $\mathbf{E} \times \mathbf{B}$ drifts dominate over the radial diffusive fluxes in the simulations [8]. On the other hand, in L-mode the poloidal particle fluxes in the divertor are dominated by recycling drive, whereas in H-mode the poloidal $\mathbf{E} \times \mathbf{B}$ drift dominates over the recycling drive [8].

Experimental measurements with the DTS, as well as UEDGE simulations, indicate that in the L-mode conditions the radial $\mathbf{E} \times \mathbf{B}$ drift in the divertor shifts particles from the far SOL towards the separatrix in the LFS divertor leg in fwd. B_T (Fig. 2). As a result, electron densities and radiation levels are increased and electron temperatures reduced close to the LFS strike point for a given upstream density. This facilitates onset of LFS detachment at lower upstream density than in rev. B_T, as is observed experimentally. In rev. B_T, the radial $\mathbf{E} \times \mathbf{B}$ drift in the LFS divertor leg is reversed, shifting particles from the strike point region towards the far SOL (Fig. 2). As a result, the strike point densities and radiation levels are reduced for a given upstream density, increasing the detachment threshold density.

In H-mode conditions, experimental measurements with the DTS in both divertor legs and UEDGE simulations indicate that strong poloidal $\mathbf{E} \times \mathbf{B}$ drift in the private flux region shifts particles from the LFS divertor to HFS divertor in the fwd. B_T (Fig. 3). As a result, the LFS

divertor densities and radiation levels are reduced for a given upstream density, therefore, increasing the detachment threshold $n_{e,SEP,LFS-MP}$ in fwd. B_T. Reversing the toroidal field reverses the direction of these $\mathbf{E \times B}$ drifts. As a result, in rev. B_T the LFS divertor densities and radiation levels are increased for a given upstream density, therefore, reducing the detachment threshold density. In UEDGE simulations, reversing the field leads also to re-attachment of the HFS divertor plate. However, this is not observed experimentally and is presumably caused by a slight overestimation of the $\mathbf{E \times B}$ drift flows and inaccuracies of the fluid neutrals model.

In H-mode conditions, UEDGE predicts radial electric fields of the order of 7kV/m in the private flux region next to the separatrix. These values are consistent with previous reciprocating probe measurements in DIII-D in H-mode conditions [10]. With the toroidal field strength of 1.8 T, this results into poloidal $\mathbf{E \times B}$ drift velocity of the order of 3.5 – 4.0 km/s from the LFS to HFS in fwd. B_T configuration, reversing with the toroidal field reversal. The recycling process in the divertor leads to near sonic parallel-$\mathbf{B}$ flows towards the nearest divertor plate. At divertor temperatures around 20 eV, the sonic flows of deuterium are of the order 50 km/s. With a B_{POL}/B_{TOT} ratio of a few per cent, this results into poloidal recycling driven flow component of the order of 0.5 – 2.5 km/s. Therefore, as is observed in the simulations, one would expect radial electric fields of the order of 7kV/m to lead to poloidal $\mathbf{E \times B}$ drifts dominating over recycling driven flows. These strong poloidal $\mathbf{E \times B}$ drifts lead to particle transport between the divertor legs, increasing detachment threshold density in fwd. B_T and reducing it in rev. B_T. In the simulated L-mode conditions, the radial electric fields in the private flux region are less than 1kV/m. As a result, the poloidal $\mathbf{E \times B}$ drift flux remains lower than the poloidal component of the recycling driven particle flux in the divertor legs, and strong in-out asymmetric transport in the private flux region does not occur. In these conditions, the radial $\mathbf{E \times B}$ drifts can reduce the LFS divertor detachment threshold density in fwd. B_T, by transporting particles radially towards the strike point.

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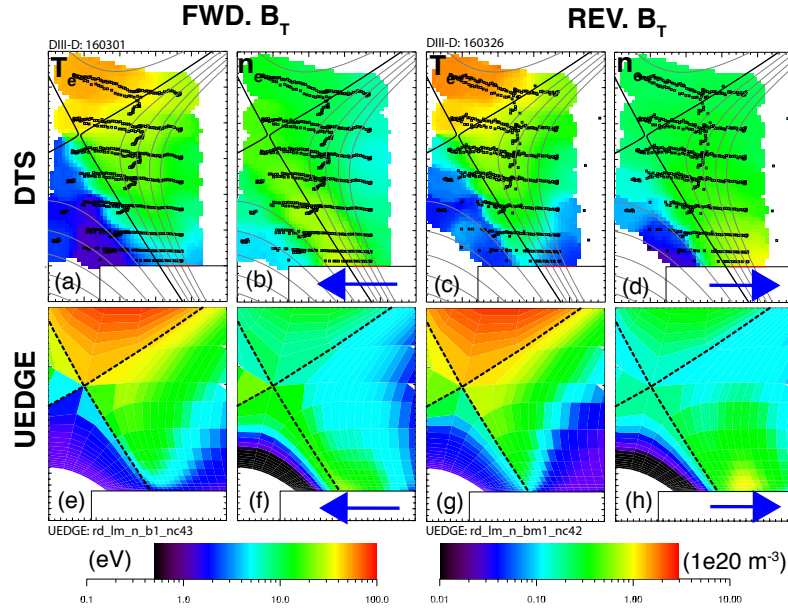[10] J.A. Boedo, *et al. Phys. Plasmas* **7** (2000) 1075

Figure 2. L-mode 2D profiles of electron temperature, T_e, and density, n_e, in the LFS divertor leg as measured by the DIII-D DTS system in fwd. B_T (a, b) (160301) and rev. B_T (c, d) (160326) configurations at $n_{e,SEP,LFS-MP}$ of about 1.65 – 1.75e19 m^{-3}. UEDGE predictions of 2D T_e and n_e distributions in the LFS divertor leg in fwd. B_T and rev. B_T configurations are $n_{e,SEP,LFS-MP}$ of 1.8e19 m^{-3}. The blue arrows represent the direction of the radial **E×B** drift in the LFS divertor leg.
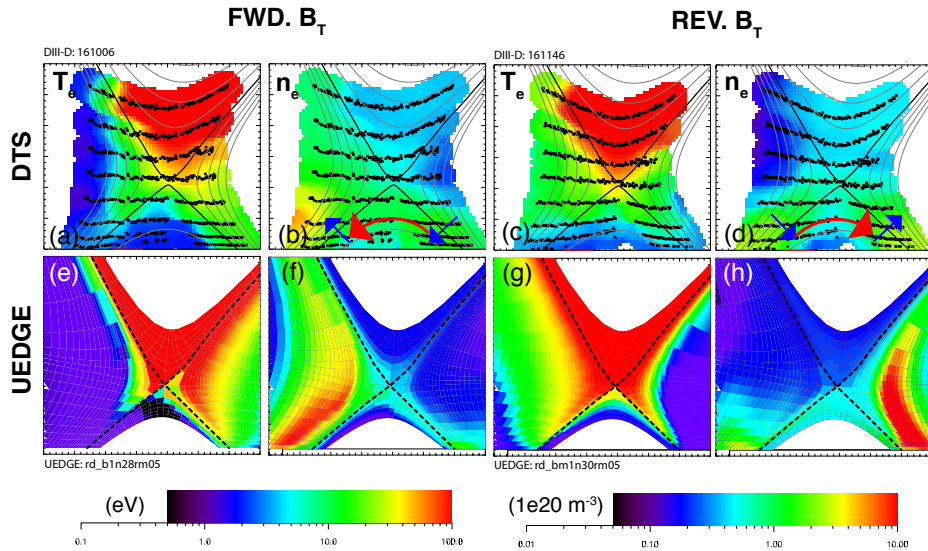

Figure 3: H-mode 2D profiles of electron temperature, T_e, and density, n_e, in the HFS and LFS divertor legs as measured by the DIII-D DTS system in fwd. B_T (a, b) (161006) and rev. B_T (c, d) (161146) configurations at $n_{e,SEP,LFS-MP}$ of about 2.1e19 m^{-3} and 1.9e19 m^{-3}, respectively. UEDGE predictions of 2D T_e and n_e distributions in the HFS and LFS divertor legs in fwd. B_T and rev. B_T configurations are $n_{e,SEP,LFS-MP}$ of 2.7e19 m^{-3}. The blue arrows represent the direction of the radial **E×B** drift in the HFS and LFS divertor legs, and the red arrow represents the direction of the poloidal **E×B** drift in the private flux region.