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# Impact of drifts on divertor power exhaust in DIII-D

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# ABSTRACT

Radiative divertor experiments and 2D fluid simulations show strong impact of cross-field drifts on the low field side (LFS) divertor target heat flux and volumetric radiation profiles when evolving to detached conditions in DIII-D high confinement mode (H-mode) plasmas with forward and reversed toroidal field configurations. In both field configurations, the peak heat flux is reduced by about a factor of 2 in detachment by  $D_2$ -injection and by factor of 3 - 4 in detachment by  $N_2$ -injection. Operating with the  $\mathbf{B} \times \nabla \mathbf{B}$ -drift towards the X-point (fwd.  $B_T$ ), the LFS divertor radiation front is observed to shift step-like from the target to near to the X-point at the onset of detachment. In contrast, operating with the  $\mathbf{B} \times \nabla \mathbf{B}$ -drift away from the X-point (rev.  $B_T$ ), the radiation front is observed to be radially shifted towards the far SOL. These phenomena occur with detachment induced both with  $N_2$ - and  $D_2$ -injection. The step-like detachment onset is consistent with recently published theory of the role of poloidal  $\mathbf{E} \times \mathbf{B}$ -drift in the private flux region in driving highly non-linear detachment onset in fwd.  $B_T$  [22].

## 1. Introduction

To avoid overheating of the plasma facing materials, a controlled state of partially to fully detached divertor conditions with power exhaust dominated by radiation is foreseen to be mandatory in reactor scale fusion devices [1,2]. These conditions are routinely obtained in existing fusion devices by injecting deuterium and impurities in the plasma to increase radiative power fraction and divertor plasma densities, reducing divertor electron temperatures,  $T_e$ , down to below a few eV. At these temperatures, atomic physics processes can become efficient in mitigating plasma pressure in front of the divertor target plate and particle flux to the divertor plate. The impact of magnetic and electric cross-field drifts on the asymmetries of densities, temperatures, and radiated power between the low and high field side divertors (LFS, HFS) has been widely studied within the fusion community, including experimental, numerical, and theoretical approaches [3, [4-10], 11, and references therein]. Conventionally, operating with the  $B\times \nabla B$ drift towards the X-point, the HFS divertor is observed to exhibit higher densities, lower temperatures, and higher radiative powers than the LFS

divertor. Reversing the toroidal field, which reverses the direction of all cross-field drifts, has been observed to lead to more balanced divertor conditions between the LFS and HFS divertor legs. Due to increased non-linearity of the scrape-off layer (SOL) physics by the electric  $(\mathbf{E} \times \mathbf{B})$  and magnetic drifts, it is often numerically very challenging to include these terms in the 2D SOL fluid codes, such as UEDGE, EDGE2D-EIRENE and SOLPS [5,12–14]. These codes are the primary tools for interpretation of divertor power exhaust physics in existing devices as well as in design activities of new divertors for existing and next step devices [15,16]. Due to the difficulty in including the drift effects, these terms are often omitted in the simulations. It is sometimes argued in these studies that the penalty of neglecting drifts is acceptable as long as the focus is only on a single divertor leg and in-out asymmetries are not considered, see for example [17]. In this work, we will show experimental observations and numerical studies for DIII-D high confinement mode (H-mode) plasmas indicating that this argument would be overly simplifying and not justified at least for these plasmas. The focus is on the impact of cross-field drifts on divertor profiles of density, temperature, and radiation in the LFS divertor leg. The radial

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**Fig. 1.** Magnetic equilibria used in the experiments. The black solid line represents the base configuration and the dashed lines the extent of the strike point sweep. Thomson scattering [18] measurements locations are illustrated with red points. Lower target Langmuir probes [19] are illustrated with purple circles. The deuterium and nitrogen gas injection locations are illustrated with the black arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and poloidal drifts are observed to have a substantial impact on the characteristics of the LFS divertor plasmas, including transition to detached conditions as well as poloidal and radial structure of density, temperature and radiation profiles. These impacts are large enough that they cannot be considered as corrections to a divertor solution primarily driven by sources and sinks not related to drift transport. Section 2 briefly describes the setup of the experiments and simulations in this study. Section 3 describes the findings in detached plasmas with strong  $D_2$ -injection. Section 4 describes the findings in detached plasmas with strong  $N_2$ -injection. Finally, the results are further discussed in Section 5.

#### 2. Setup of the experiments and simulations

Detachment experiments in a lower single null (LSN) configuration with the LFS strike point on the shelf of DIII-D were conducted (Fig. 1). Magnetic field strength and plasma current were 1.8 T and 0.9 MA. Both forward (fwd. B<sub>T</sub>) and reversed (rev. B<sub>T</sub>) toroidal field configurations were studied, where in the fwd.  $B_{\rm T}$  configuration the  $\nabla B$ -drift is pointing towards the X-point. The total heating power was about 4.2 - 4.5 MW, sufficient for high confinement mode in both toroidal field directions. Deuterium and nitrogen injection were applied with the gas injection valve located around the crown of the plasma (Fig. 1). This gas injection valve was chosen to avoid the injection location moving from common SOL to private flux region during the X-point sweep. The Xpoint was swept from the nominal configuration with the strike point on the radial location of the divertor Thomson scattering system (DTS [18]) of DIII-D both inwards and outwards to characterize the 2D distributions in both divertor legs (Fig. 1). The extent of the sweep is illustrated with the dashed line configurations in Fig. 1. The sweep is rather long, changing divertor geometry and lower triangularity quite substantially. As a result, the plasma conditions cannot be assumed to stay strictly speaking constant throughout the sweep. However, the analysis in this presentation is based on the LFS divertor profiles, which are obtained during the early parts of the sweep, propagating through a more limited extent. The full sweep is done to obtain the data for the HFS divertor leg as well, but caution should be used in detailed



**Fig. 2.** Time traces of unfuelled, unseeded, attached base case (black), and detached (red) plasma induced with  $D_2$ -injection in fwd. (a) and rev. (b)  $B_T$  configurations. First row: Heating power and total radiated power. Approximate radiated power fractions are also given in the figure. Second row:  $T_e$  in front of the LFS divertor plate, measured with the first DTS channel from the floor. Third row: LFS divertor peak heat flux, measured with DIII-D infra red camera system (IRTV) [23]. Fourth row: deuterium injection rate. The time traces are plotted before the start of the X-point sweep at 2500 ms. The step-like detachment onset is highlighted with the grey bar in Figure a. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interpretation of the HFS leg data. The pump located under the lower divertor shelf was turned off in these experiments to avoid change of the pumping conditions over the wide sweep.

This paper is primarily focused on reporting and documenting the experimental observations. However, 2D fluid simulations with the simulation code UEDGE [5] including full cross-field drifts were conducted to analyze the role of cross-field drifts in the divertor characteristics in these plasmas. To limit the extent of this report, these simulations will be further analyzed in forthcoming publications. The simulation setup is similar to simulations documented in [6]. Carbon impurities are included in the simulations as individual fluids with carbon sputtering calculated according to published sputtering yields [20,21]. Deuterium molecules are included in the model as diffusive fluid species with a constant temperature of 0.1 eV. This number is obtained by assuming the thermally released molecules from the wall to have about  $\sim 0.3 - 0.5$  eV of energy, based on peak wall temperature



**Fig. 3.** Measured LFS target  $T_e$  as a function of measured edge line average density (DIII-D signal DENSV3 [29]). The data is obtained for the same time interval as is shown in Fig. 2.



**Fig. 4.** Measured heat flux profiles at the LFS target plate in attached (black) and detached (red) conditions in fwd.  $B_T$  (a) and rev.  $B_T$  (b) operation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of about 500 K, and assuming some molecule heating through collisions with plasma ions. Further analysis of experimental and numerical studies of the step-like detachment onset, which will be discussed in the following sections, was recently published in [22].



**Fig. 5.** Comparison of measured IRTV heat fluxes (blue) and inferred Langmuir probe heat fluxes (grey) at the LFS divertor plate in attached conditions in fwd. B<sub>T</sub> (a) and rev. B<sub>T</sub> (b) operation. The profiles are plotted only within the high heat flux region  $\Psi_n \sim 0.99 - 1.02$ . The IRTV profiles have been shifted by  $\Delta \Psi_n = +0.005$  to align the peak heat flux in IRTV and Langmuir probe measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 3. Detachment with D<sub>2</sub>-injection

Detached divertor conditions were obtained with deuterium gas injection in both fwd.  $B_T$  and rev.  $B_T$  configurations (Fig. 2). In both field configurations, the radiated power fraction increases from about 50% to 80% as LFS divertor detachment is induced with strong  $D_2$  injection. The definition of detachment in this paper is that the measured target  $T_e$  drops to or below 2 eV. In the rev.  $B_T$  plasmas this is important, since according to more restricted detachment definitions, such as roll-over of target Langmuir probe saturation current, the rev.  $B_T$  series does not reach detachment.

Consistent with previous experimental findings [24,25], it is observed that in fwd. B<sub>T</sub>, the LFS divertor undergoes a step-like detachment onset (Fig. 2a). At around 1800 ms, the target  $T_e$  collapses from about 20 eV down to less than 1 eV. Between 1800 ms and 2250 ms the target  $T_e$  is seen to dither between about 10 eV and below 1 eV until the plasma settles into robust detachment at 2250 ms. In contrast, in rev. B<sub>T</sub>, target  $T_e$  is reduced more smoothly with increasing plasma density, and several measured target  $T_e$  values between a few and 10 eV exist between 1500 ms and 2000 ms before the plasmas settles into detached conditions (Fig. 2b). Fig. 3 further illustrates how this data maps the operational space in edge line average density and target  $T_e$ . It can be clearly seen in Fig. 3 that there is a gap of only a few isolated data points in fwd. B<sub>T</sub> between about 2 and 12 eV, while in rev. B<sub>T</sub> several data points are accumulated in this temperature range. A highly non-



Fig. 6. Measured electron temperature (a), density (b), saturation current (c), and electron pressure (d) profiles at the LFS target plate in attached conditions in fwd.  $B_T$  (black) and rev.  $B_T$  (red) operation. Small points represent Langmuir probe measurements and large solid symbols DTS measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 7.** (a,d): 2D reconstructions of radiated power, measured with the DIII-D bolometer system [32] in attached conditions in fwd.  $B_T$  (a) and rev.  $B_T$  (d). (b,c,e,f): 2D reconstructions of divertor  $n_e$  and  $T_e$  from divertor Thomson scattering measurements in attached conditions in fwd.  $B_T$  (b,c) and rev.  $B_T$  (e,f).

linear, nearly step-like detachment onset is not an unusual occurrence in tokamak experiments [26, 27, 28, and references therein]. The key strength of DIII-D in investigating this type of divertor detachment behavior is the DTS system, which enables direct measurement of  $T_e$ and  $n_e$  in the divertor volume. The experimental findings of step-like onset of strong detachment in fwd.  $B_T$  and smoother onset of shallow detachment in rev.  $B_T$  are consistent with the theory of bifurcated detachment onset driven by the interdependence of the **E** × **B** drifts on the divertor  $T_e$  and potential in fwd.  $B_T$  configuration [22]. According to this theory, corroborated by



**Fig. 8.** (a,d): 2D reconstructions of radiated power, measured with the DIII-D bolometer system [32] in detached conditions in fwd.  $B_T$  (a) and rev.  $B_T$  (d). (b,c,e,f): 2D reconstructions of divertor  $n_e$  and  $T_e$  from divertor Thomson scattering measurements in attached conditions in fwd.  $B_T$  (b,c) and rev.  $B_T$  (e,f).

UEDGE simulations with cross-field drifts, the attached LFS condition in fwd. B<sub>T</sub> is characterized by a strong electric potential gradient between the common SOL and private flux region. This potential gradient drives strong poloidal  $\mathbf{E} \times \mathbf{B}$ -flux from the LFS divertor to the HFS divertor in the private flux region (PFR). This  $\mathbf{E} \times \mathbf{B}$ -flux provides a particle sink in the LFS, reinforcing low density, high temperature attached conditions in the LFS divertor. As the LFS divertor detaches, the radial potential gradients are diminished, reducing significantly this poloidal  $\mathbf{E} \times \mathbf{B}$ drift in the PFR, such that the LFS divertor can evolve non-linearly to strongly detached conditions with a small change in upstream plasma parameters. Reversing toroidal field reverses the direction of all crossfield drifts, such that the poloidal  $\mathbf{E} \times \mathbf{B}$ -drift in the PFR provides a particle source in the LFS. Reduction of this  $\mathbf{E} \times \mathbf{B}$ -flux with reducing divertor potential gradients would, therefore, limit the rate of density increase in the LFS and be stabilizing for the detachment onset. Therefore, in rev. B<sub>T</sub>, this drift mechanism is not expected to lead to highly non-linear detachment onset.

In both field configurations, the reduction of the peak LFS target heat flux is about a factor of 2 (Figs. 2, 4), measured with the DIII-D infra-red camera system (IRTV) [23]. The peak heat fluxes in detached conditions are about 0.6 and 0.7 MW/m<sup>2</sup> in fwd. and rev. B<sub>T</sub>, respectively (Fig. 4). In the detached cases, the estimated peak radiative heat flux on the plate is around 0.15 – 0.2 MW/m<sup>2</sup> in both field directions, indicating that about 0.4 – 0.5 MW/m<sup>2</sup> remains to be carried by the plasma and neutrals to the plate in detached conditions (Fig. 4).

Estimating the plasma and recombination heat fluxes to the plate using Langmuir probe measurements show peak heat fluxes consistent with the lower end of the fluctuation of IRTV measurements in attached conditions (Fig. 5). Sheath heat transmission coefficient,  $\gamma$ , of 7 and recombination heat potential,  $E_{pot}$ , of 15 eV for each ion was assumed, including 13.6 eV of atomic recombination and small contribution (~ 1.4 eV) of molecular recombination. The heat flux was then calculated according to the equation  $Q_{\text{target}} \approx (\gamma T_e + E_{\text{pot}})\Gamma_{\text{target}}$ , where  $\Gamma_{\text{target}}$  is the particle flux to the plate measured with the Langmuir probes. However, while the heat flux profile is in good agreement between IRTV and LP in fwd. B<sub>T</sub>, in rev. B<sub>T</sub> the heat flux profile calculated with Langmuir probes is a factor of 3 narrower than measured by IRTV (Fig. 5). UEDGE simulations with cross-field drifts also show that the target heat flux profile is about a factor of 3 narrower in rev. B<sub>T</sub> in attached conditions than in fwd. B<sub>T</sub>, therefore being closer to the Langmuir probe estimations than IRTV in the rev. B<sub>T</sub> case. The discrepancy between IRTV and Langmuir probes for the rev. B<sub>T</sub> can probably be partially explained by radiative heating of the target plate away from the separatrix, as the

radiation front in the divertor leg is moved towards far SOL in rev.  $B_T$  (Fig. 7d). However, the overall magnitude of the radiative heating is not sufficient to fully explain this discrepancy. Charge exchange heating from neutrals, as discussed in [30] on JET IR data analysis, may also impact this discrepancy.

In detached conditions, using temperature measurements from DTS and Langmuir probe measurements for particle fluxes, the estimated plasma and recombination heat fluxes to the plate are reduced down to about 0.2 MW/m<sup>2</sup> in both field configurations, which is a factor of 2 lower than estimated based on IRTV measurements with radiative heat load subtracted. The remaining discrepancy could potentially be explained by heat transported by neutrals to the divertor plate.

In attached, low density, unfuelled conditions, the measured electron pressure profiles at the LFS target plate are very similar to each other in fwd. and rev.  $B_T$  configuration (Fig. 6d). This indicates that the SOL electron pressure profiles are predominantly determined by transport physics that are not sensitive to the direction of cross-field drifts. The measured heat flux and electron pressure profiles are roughly about 3 mm at the LFS mid-plane, being consistent with the ITPA scaling [31] for LFS mid-plane separatrix poloidal magnetic field of 0.3 T.

Even though the electron pressure profiles are not impacted significantly, the individual profiles of electron density, temperature, and radiated power are strongly impacted by the direction of the cross-field drifts (Figs. 6a, b and 7). The rev. B<sub>T</sub> configuration is observed to lead to significantly narrower  $T_e$  profile at the target than is observed in fwd. B<sub>T</sub> configuration (Figs. 6a and 7). Fig. 6a also shows that, while at strike points in  $T_e \sim 30$  eV the DTS and LP measurements are in good agreement, in common SOL away from the strike point DTS measures a factor of 2 – 3 lower  $T_e$  than inferred from LP measurements. Consistently, the inferred  $n_e$  from LPs is a factor of 2 – 3 lower than measured directly by DTS. Also the target particle flux profile in rev.  $B_T$  is observed to have a second peak, shifted radially away from the separatrix, while in the fwd. B<sub>T</sub> configuration the saturation current profile peaks near the strike point and decays exponentially towards the far SOL (Fig. 6c). Divertor Thomson scattering and bolometer measurements also show that in the fwd. B<sub>T</sub> configuration, the LFS divertor density and radiated power peak close to the separatrix (Figs. 7a and b), while in the rev.  $B_T$  configuration,  $n_e$  and radiated power are observed to peak radially outward from the separatrix in the LFS divertor (Figs. 7d and e). These radial shifts of  $n_e$  and radiated power profiles and changes in the  $T_e$ -profiles are consistent the radial  $\mathbf{E} \times \mathbf{B}$ -drift directions in the LFS divertor leg (Figs. 6c, 7 a and d).



**Fig. 9.** Measured parallel-**B** profiles of  $T_e$  and  $n_e$  near the LFS separatrix ( $\Psi_n \sim 1.000 - 1.004$ ) as a function of distance from the LFS target. The location of the X-point is illustrated by a grey bar. Black circles represent detached conditions in the fwd.  $B_T$  and red squares detached conditions in the rev.  $B_T$ . The profiles are constructed by plotting the radial profiles for each DTS channel as a function of  $\Psi_n$  and picking a representative value within  $\Psi_n \sim 1.000 - 1.004$ . The radial profiles are constructed from the X-point sweeps. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In fwd. B<sub>T</sub>, the LFS divertor leg collapses into a deeply detached state at the onset of detachment (Figs. 8–10). The peak of the LFS divertor radiation front is observed to shift from the target towards the X-point, as is typically observed in tokamak detachment experiments in fwd. B<sub>T</sub> (Fig. 8). As this happens, the LFS divertor leg collapses to  $T_e$  below a few eV and the region of high  $n_e$  above  $10^{20}$  m<sup>-3</sup> extends up to and beyond the X-point (Figs. 8 and 9).

In contrast to step-like evolution to strong detachment in fwd.  $B_T$ , in rev.  $B_T$ , the LFS divertor settles into shallow detachment at the at the onset of detachment (Figs. 8–10). The peak of the LFS divertor radiation front remains in the far SOL and the radiation front expands towards the separatrix (Fig. 8). It is also observed that the region of high  $n_e$  above  $10^{20}$  m<sup>-3</sup> remains localized right in front of the LFS target, and the region of low  $T_e$  below 5 eV extends only about 1 m away from the LFS target plate along the field line (Figs. 8 and 9). Furthermore, the target  $T_e$  is reduced only to about 2 eV, whereas in fwd.  $B_T$  configuration, the target  $T_e$  drops down to below 1 eV (Fig. 9). In the 2D DTS profile, it can be seen that the plasma flame front of  $T_e$  above 10 eV is significantly narrower in rev. than in fwd.  $B_T$ , and extends deeper in the LFS divertor leg (Fig. 8).



Fig. 10. Measured Langmuir probe saturation current profiles along the LFS target in detached conditions with  $D_2$ -injection in fwd. (black), and rev.  $B_T$  conditions.



**Fig. 11.** Simulated 2D  $n_e$  (a,c,e) and  $T_e$  (b,d,f) profiles in attached conditions in fwd. B<sub>T</sub> (a,b), and detached conditions with D<sub>2</sub> in fwd. B<sub>T</sub> (c,d) and rev. B<sub>T</sub> (e,f) configurations. The direction of the radial **E** × **B**-drift in the LFS divertor leg is illustrated with the arrows in the density Figures a, c, and e. The colormap is the same as is used with DTS profiles in Figs. 7 and 8.

Consistent with the shallow detachment in rev.  $B_T$ , the LFS target peak saturation current is observed to only saturate around 30 A/cm<sup>2</sup>, while in fwd.  $B_T$ , reduction of the peak saturation current from 30 A/cm<sup>2</sup> down to less than 20 A/cm<sup>2</sup> is measured at the onset of detachment (Fig. 10). Actually, if a more restricted definition of detachment, such as



**Fig. 12.** Time traces of unfuelled, unseeded, attached base case (black), and detached plasma induced with N<sub>2</sub> injection (red) in fwd. (a) and rev. (b) B<sub>T</sub> configuration. First row: Heating power and total radiated power. Approximate radiated power fractions are also given in the figure. Second row:  $T_e$  in front of the LFS divertor plate, measured with the first DTS channel from the floor. Third row: LFS divertor peak heat flux, measured with DIII-D infra red camera system (IRTV) [23]. Fourth row: deuterium injection rate. The time traces are plotted before the start of the strike point sweep at 2500 ms. The grey shaded area shows the region that is illustrated in more detail in Fig. 13 for the shot 174287. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

roll-over of saturation current, would be used here, then these rev.  $B_T$  plasmas would be considered high-recycling, not detached. Tokamaks without DTS system would probably consider this type of plasma attached.

The leading hypothesis to explain the observation shallow detachment in rev.  $B_T$  is that the radial  $\mathbf{E} \times \mathbf{B}$ -drift shifts particles away from the strike line, depleting deuterium and carbon densities along the separatrix. As this process takes place, the volumetric extent of low temperature, highly radiating plasma in front of the target remains limited and the plasma cannot reach strongly detached conditions. This is clearly observed in UEDGE simulations (Fig. 11). In attached conditions in fwd.  $B_T$ , the LFS  $n_e$  2D profile peaks along the separatrix, consistent with experimental observations (Figs. 7b and 11 a). At the onset of detachment, the divertor solution bifurcates to a strongly detached state also consistent with experimental observations (Figs. 8, 11 c and d), as is further discussed in [22]. In contrast, in the rev.  $B_T$  configuration, the high  $n_e$  region is shifted radially away from the separatrix and the divertor leg settles into shallow detachment (Figs. 8 and 11 e, f).

Further analysis of the simulations indicate that the radial  $\mathbf{E} \times \mathbf{B}$ drifts reorganize the particle recycling fluxes in the divertor probably contributing significantly in the observed differences in the detachment front structure in fwd.  $B_T$  and rev.  $B_T$ . In fwd.  $B_T$ , the radial  $\mathbf{E} \times \mathbf{B}$ -drift shifts plasma is towards the PFR (Fig. 11a). In attached conditions, this radial flux is fully compensated by the poloidal  $\mathbf{E} \times \mathbf{B}$ -drift towards the HFS in the PFR, such that particle recycling in the PFR is not increased by the radial  $\mathbf{E} \times \mathbf{B}$ -drift, as was discussed in [22]. At the onset of detachment, the  $\mathbf{E} \times \mathbf{B}$ -drift in the PFR is diminished leading to a factor of 6 increase of recycling neutral production in the PFR in the LFS divertor leg, increasing ionization,  $n_e$  and radiation near the separatrix pushing the plasma into strong detachment [22]. In detached conditions in fwd. B<sub>T</sub>, 35% of the LFS recycling neutral production occurs in the PFR. In contrast, in detached conditions in rev.  $B_T$ , the radial  $\mathbf{E} \times \mathbf{B}$ -drift shifts plasma towards the far SOL, such that only 7.6% of the recycling neutral production occurs in the PFR. The absolute neutral production rate in the PFR is a factor of 3.65 lower than in fwd. B<sub>T</sub>, while the total neutral production rate in the LFS divertor leg is 24% higher in the rev.  $B_T$  than in the fwd.  $B_T$  simulation. To further investigate this, a simulations was run based on the rev.  $B_T$  case by freezing the  $T_e$ -distribution and changing the field direction to fwd. B<sub>T</sub>. This simulation converges to a solution where the total deuterium ionization rate in the LFS divertor leg within  $\Psi_n \sim 1.000 - 1.004$  increases by a factor of 3 relative to the rev.  $B_T$  base case and the neutral production rate in the PFR increases by a factor of 5.5. If the electron temperature is allowed to evolve in this simulation, the simulation converges to the detached branch in fwd. B<sub>T</sub> shown in Fig. 11.

#### 4. Detachment with N<sub>2</sub>-injection

Detached LFS divertor conditions were obtained with N<sub>2</sub>-injection in both fwd. and rev. B<sub>T</sub> configurations (Fig. 12). In fwd. B<sub>T</sub>, similar to detachment induced with D<sub>2</sub>-injection, the LFS divertor temperature collapses from 10 – 20 eV down to around 1 eV as detachment is induced with N<sub>2</sub>-injection (Fig. 12a). Between about 1650 ms and 2000 ms, the divertor conditions are observed to dither between these two conditions. As the ELM frequency remains comparatively low at about 50 Hz in these detached plasmas with N<sub>2</sub>-injection, it can be clearly seen that both the high temperature ( $T_e \sim 15 - 20$  eV) and low temperature ( $T_e < 3$  eV) divertor solutions exist between ELMs (Fig 13).



Fig. 13. More detailed figure of the detachment dithering part of the shot 174287 in Fig. 12: (a) LFS target  $T_e$ , (b) heat flux.



**Fig. 14.** Measured heat flux profiles along the LFS target in detached conditions induced with  $N_2$ -injection in fwd. (black), and rev.  $B_T$  (red) configuration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This indicates that the observed dithering behavior cannot be explained solely as ELMs burning through the detachment front and leading to a high temperature measurement. Rather both the high and low temperature divertor conditions are quasi stable between ELMs during this dithering phase. After about 2000 ms, the plasma is measured to settle into robustly detached conditions. In rev. B<sub>T</sub> configurations, smoother reduction of divertor  $T_e$  is observed with N<sub>2</sub>-injection, similar to the observations with D<sub>2</sub>-induced detachment (Fig. 12b). The ELM frequency in the rev. B<sub>T</sub> case in detachment with N<sub>2</sub>-injection is about a factor of 1.5 lower (~ 300 Hz) than in detachment with D<sub>2</sub>-injection (~ 500 Hz).

In detached conditions induced with N<sub>2</sub>-injection, the LFS target heat flux is reduced by about a factor of 4 in fwd. B<sub>T</sub> and by about a factor of 3 in rev. B<sub>T</sub> configuration (Figs. 4 and 14). Similar to detachment with D<sub>2</sub>-injection, with detachment induced by N<sub>2</sub>-injection in fwd. B<sub>T</sub>, the LFS divertor leg evolves into strongly detached conditions with the radiation front shifted from the target to next to the Xpoint (Fig. 15a). As this happens,  $T_e$  in the divertor leg below X-point is reduced below 5 eV (Fig. 15c and 16). Similar to observations with D<sub>2</sub>-induced detachment, in rev. B<sub>T</sub>, the LFS divertor leg evolves into shallow detachment at the onset of detachment with N<sub>2</sub>-injection (Fig. 15e and 16). The target  $T_e$  remains at 2 eV level in rev. B<sub>T</sub>, while in fwd. B<sub>T</sub> the target  $T_e$  drops to 1 eV. Also in rev. B<sub>T</sub>, the plasma flame front of 10 eV is shifted only halfway up the divertor leg (Fig. 16). The peak radiation in the LFS divertor leg in rev. B<sub>T</sub> remains in far SOL and the radiation front expands towards the separatrix at the onset of detachment with N<sub>2</sub>-injection, similar to detachment with D<sub>2</sub>-injection. In detachment induced by N<sub>2</sub>-injection in fwd. B<sub>T</sub>, the divertor  $n_e$  is about a factor of 3 – 4 lower than in detachment induced by D<sub>2</sub>-injection (Figs. 9 and 16). Detachment with nitrogen is primarily induced by increasing radiation and power depletion of the divertor, rather than density increase.

### 5. Discussion and summary

The impact of cross-field drifts on the LFS divertor conditions and power exhaust were studied experimentally and numerically in DIII-D H-mode plasmas. Detached conditions in the LFS divertor leg were obtained in both fwd.  $B_T$  and rev.  $B_T$  configuration with both  $D_{2^-}$  and  $N_2$ -injection. These plasmas were numerically simulated with the 2D fluid code UEDGE.

In both field configurations, the peak heat flux is reduced by about a factor of 2 with detachment by D2-injection and by factor of 3 - 4 with detachment by N<sub>2</sub>-injection. In fwd. B<sub>T</sub> configuration, LFS divertor n<sub>e</sub> and radiated power are observed to peak close to the LFS divertor separatrix. At the onset of detachment in fwd. B<sub>T</sub>, the radiation front is observed to move from the target towards the X-point and the divertor leg collapses into low T<sub>e</sub> below 5 eV. In contrast, in rev. B<sub>T</sub>, LFS divertor n<sub>e</sub> and radiated power are observed to be shifted outwards from the separatrix, consistent with the radial  $\mathbf{E} \times \mathbf{B}$ -drift direction. As a result, the  $T_e$ -profile in the LFS divertor leg is narrower by about a factor of 2 in rev.  $B_T$  than in fwd.  $B_T$ . At the onset of detachment, the rev.  $B_T$ configuration is observed to settle into shallow detachment, characterized by the region of  $n_e$  larger than  $10^{20}$  m<sup>-3</sup> and  $T_e$  lower than 5 eV being localized within 1 m along the field line from the plate. In the fwd. B<sub>T</sub>, this region propagates more than halfway up the divertor leg. Similar differences in the detachment onset and radiation front structure between fwd. B<sub>T</sub> and rev. B<sub>T</sub> plasmas were also observed with  $N_2\mbox{-injection}$  to detachment. However, the divertor densities in these plasmas were a factor of 3 - 4 lower than in detachment induced by  $D_2$ injection, as detachment was induced mainly by increased radiation



Fig. 15. (a,d): 2D reconstructions of radiated power, measured with the DIII-D bolometer system [32] in detached conditions in fwd.  $B_T$  (a) and rev.  $B_T$  (d) with strong N<sub>2</sub>-injection. (b,c,e,f): 2D reconstructions of divertor  $n_e$  and  $T_e$  from divertor Thomson scattering measurements in attached conditions in fwd.  $B_T$  (b,c) and rev.  $B_T$  (e,f).



Fig. 16. Measured parallel-B profiles of  $T_e$  and  $n_e$  near the LFS separatrix  $(\Psi_n \sim 1.000 - 1.004)$  as a function of distance from the LFS target in detached conditions with N2-injection. The location of the X-point is illustrated with a grey bar. Black circles represent detached conditions in the fwd. B<sub>T</sub> and red squares detached conditions in the rev. B<sub>T</sub>. The hollow symbols show the detached plasmas with D<sub>2</sub>-injection for comparison, shown in Fig. 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## rather than increasing $n_e$ .

UEDGE simulations with cross-field drifts and currents show qualitative agreement with these experimental observations. The step-like detachment onset observed in fwd. B<sub>T</sub> is qualitatively reproduced by UEDGE simulations including cross-field drifts. The simulations indicate that the interdependence of divertor  $T_{e}$ , potential, and  $\mathbf{E} \times \mathbf{B}$ fluxes can drive a bifurcation of the LFS divertor solution to attached and detached branches [22]. In the rev. B<sub>T</sub> configuration, on the other hand, the radial  $\mathbf{E} \times \mathbf{B}$ -drift in the LFS divertor is observed to move plasma and impurity densities radially outwards from the separatrix, leading to shallow detachment in the simulations, similar to experimental observations.

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## Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.nme.2019.02.023.

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