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Effect of plasma shape on particle flux and particle removal in DIII-D

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Abstract

Measurements from balanced or slightly unbalanced, double-null, ELMing H-mode plasmas show that the upper, more closed, divertor strike point particle fluxes are larger than the lower, more open, divertor strike point particle fluxes for comparable conditions. Comparison of the upper and lower outer strike point peak particle fluxes measured with Langmuir probes during scans of the magnetic balance shows an asymmetry around the magnetic balance point which is consistent with both the enhanced upper recycling and the expected direction of private region $E \times B$ drifts. Comparison of the inner and outer peak particle fluxes in the upper divertor shows a dependence on magnetic field direction that is also consistent with the private region $E \times B$ drift direction.

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1. Introduction

Tokamak plasma shape has been found to play an important role in core plasma performance. The diverted tokamak is a particularly successful shape which introduced a poloidal field null (X-point) that separates the open field lines, which interact with the vacuum vessel walls, from the closed field lines which confine the core plasma. The highest performance diverted plasmas are found at high triangularity which generically have two X-points and tend to be classified as double-null (DN) or, in the case where the two X-points in a DN plasma are not on the same flux surface, an unbalanced DN. These triangular shapes utilize more of the high magnetic field region at smaller major radius of the toroidal geometry. and can be discussed quantitatively in terms of the magnetic balance.

Magnetic balance describes the proximity of the secondary X-point flux surface (which is further away from the core plasma) to the primary X-point flux surface (which bounds the core plasma) and can be described by the parameter, drsep. Drsep is defined as the radial separation at the outer magnetic midplane of the two flux surfaces that intersect the two X-points. Positive values of drsep correspond to plasmas magnetically balanced upward such that the upper divertor functions as the primary divertor. The secondary X-point flux

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surface would then be drsep centimeters further out into the scrape-off layer of the primary separatrix at the outer magnetic midplane.

Magnetic balance is an important parameter which can control the symmetry in the divertor interactions with the target plates and, under some conditions, can strongly influence core plasma behavior. For instance, the magnetic balance significantly changes the H-mode power threshold [1,2], which leads to changes in the core plasma energy confinement as well as current and pressure profile evolution. The magnetic balance has been used as a tool for core plasma profile control for experiments exploring negative central shear and advanced tokamak reactor scenarios [3–6]. Plasma/wall interactions such as the divertor plate heat and particle flux distributions also change significantly with the magnetic balance. It is the study of these divertor plate conditions and how they respond to changes in the magnetic balance that will be the subject of this paper.

2. Magnetic balance experiments

The plasmas used in this study were initially configured in an almost balanced DN shape with standard ELMing H-mode conditions [7] and then balanced up or down to a different drsep value. The magnetic axis was held fixed. No pumping was used in this experiment and no gas puffing was used after the H-mode transition in order to let the plasma reach steady state conditions. Experiments were performed using both directions of the toroidal magnetic field in order to change the directions of the $B \times \nabla B$ and $E \times B$ particle drifts as shown in Fig. 1. Target plate conditions were monitored with an array of fixed Langmuir probes [8,9] mounted in the upper and lower divertor tiles also shown in Fig. 1. Since there are presently no centerpost Langmuir probes in the lower divertor, measurements are only available at three of the four strike points for these high triangularity shapes: both inner and outer strike points in the upper divertor and the outer strike point in the lower divertor. By changing the direction of the toroidal field, the upper centerpost Langmuir probes could be used to monitor the inside strike point for both drift configurations but these cases may not be directly comparable due to differences in the divertor target configurations.

The upper and lower divertors in DIII-D have different configurations for the plasma facing surfaces. The baffle structures in the upper divertor [10,11] protects two in-vessel cryopumps used for density control and conform more closely to the higher triangular plasma shapes to form a more closed divertor geometry. The lower divertor is more open with no structures conforming to flux surfaces but does have another baffle and cryopump at larger major radius for use with lower triangularity plasmas.

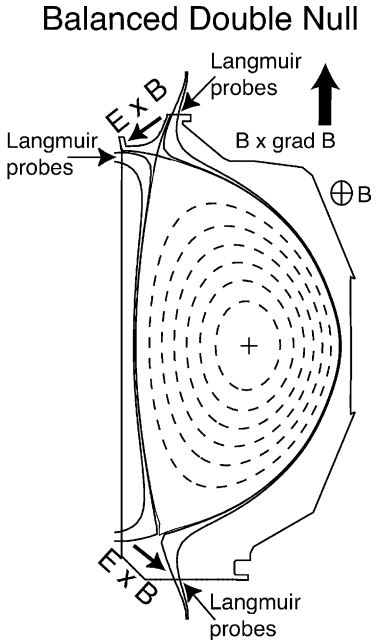

Fig. 1. This $E \times B$ diagram represents the direction and location of the predicted $E \times B$ flux for one of the cases considered in the magnetic balance experiment. When reversing the magnetic field, the $E \times B$ drift direction would also reverse. The figure also shows the locations of the target plate Langmuir probes used in this study.

3. Experimental observations

The core plasma density responded to the drsep shifts as shown in Fig. 2. For both toroidal field directions shown in Fig. 2, the plasma discharges with higher density were being balanced towards the $B \times \nabla B$ drift

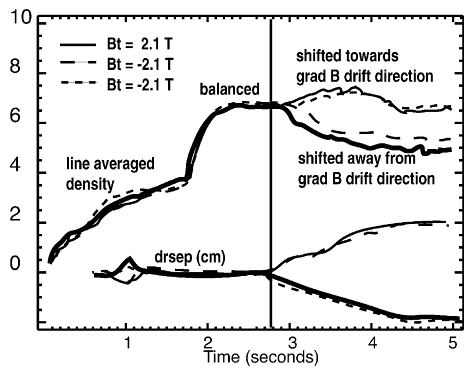

Fig. 2. This figure shows the time history of the core density ($\times 10^{19}$ m^{-3}) and drsep (cm) for several shots in the drsep scan. The higher density cases are all for the ∇B drift direction towards the dominant divertor. These shots include cases for both magnetic field directions.

direction. The other plasmas were balanced in the opposite direction and showed a density decrease. The changes in density observed during the drsep scans is one of the factors affecting the peak particle flux measured at the strike points. The pedestal temperature, the value at the top of the steep edge gradient region, remains fairly constant for all these plasmas even though the pedestal density is changing [7].

Changes in the drsep parameter affects the peak particle fluxes at the three strike points as is shown in Fig. 3. Fig. 3(a) and (b) show the results for the two magnetic field directions. The data from four plasma discharges is used to cover the range in drsep of −2 cm to +2 cm for both field directions. The increase in the outer upper particle flux as drsep is increased is seen in both Fig. 3(a) and (b) and is larger than the comparable increase in the lower outer strike point flux as drsep is decreased. Both outer fluxes seem to reach their maximum value with less than 1 cm shift in the magnetic balance which is consistent with the outer midplane flux scale-length of 1 cm. The lower outer flux shows a more symmetric dependence on drsep for the two field directions while the upper outer flux shows a sudden drop just above drsep $= 0$ in Fig. 3(a). At the inner strike point, the peak particle flux is seen to increase as drsep is increased in both Fig. 3(a) and (b) as the balance shifts to the upper divertor. There is also a sudden drop in inner strike point flux at drsep $= 1$ cm in Fig. 3(a) after the rapid increase of flux near drsep $= 0.7$. In Fig. 3(a) with $B \times \nabla B$ up, the inner strike point peak particle flux, at drsep $= 2$ cm, reaches the same value as the upper outer flux. In Fig. 3(b), with $B \times \nabla B$ down, the inner flux at drsep $= 2$ cm is about the same as in Fig. 3(a) but the upper outer flux is about twice the upper outer flux value in Fig. 3(a). The right region of Fig. 3(a), where the rise and fall variations occur in the upper fluxes, and the left region of Fig. 3(b) is where the core density increases and then decreases in Fig. 2 for shifts toward the grad B drift direction.

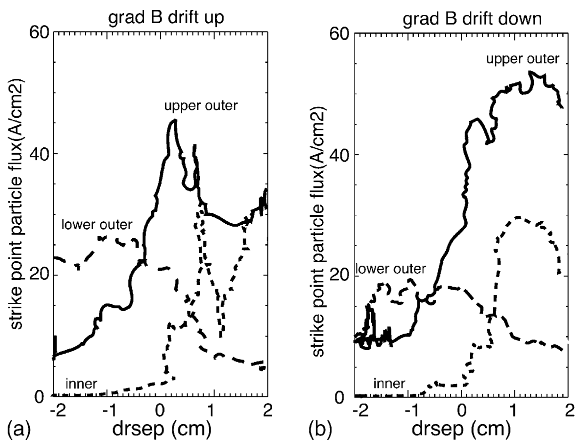

Fig. 3. The figure show the three peak particle fluxes at three strike points versus the magnetic balance parameter, drsep. The ∇B drift is up on the left (a) and down on the right (b).

To more clearly demonstrate the outer flux balance between the upper and lower divertors during the drsep scan, the ratio of the difference of the outer up and down fluxes divided by the total, $(\mathrm{jsat}_{\mathrm{up}} - \mathrm{jsat}_{\mathrm{down}})/(\mathrm{jsat}_{\mathrm{up}} + \mathrm{jsat}_{\mathrm{down}})$, is plotted in Fig. 4 for both of the magnetic field directions. This ratio would equal 1 if all the outer flux was in the upper divertor and −1 if all the outer flux was in the lower divertor. For this range of drsep $(-2, 2)$, the outer flux does not completely disappear in either divertor so the ratio never reaches 1. The two curves exhibit similar features when compared relative to the $B \times \nabla B$ direction and with the upper and lower strike point probes changing their 'up' and 'down' designations. This will be discussed further in Section 4.

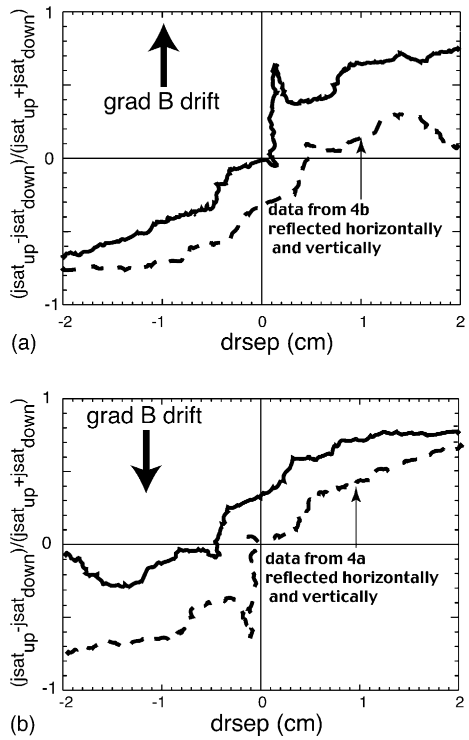

Fig. 4. The up/down particle balance is shown in this plot of the ratio $(\mathrm{jsat}_{\mathrm{up}} - \mathrm{jsat}_{\mathrm{down}})/(\mathrm{jsat}_{\mathrm{up}} + \mathrm{jsat}_{\mathrm{down}})$ for $B \times \nabla B$ up (a) and $B \times \nabla B$ down (b). The shift up in both curves is due to enhanced recycling in the upper divertor while $E \times B$ effects have opposite effects on the curves depending on the direction of the toroidal magnetic field. The dashed lines indicate the corresponding curve from the opposite toroidal field direction after exchanging the 'up' and 'down' roles of the Langmuir probes used and multiplying drsep by −1 to compare shifts relative to the grad B drift direction.

4. Discussion

Higher recycling in the more closed upper divertor is indicated by the generally higher particle fluxes in the upper divertor shown on the right sides of Fig. 3(a) and (b) and by the more rapid increase of the upper outer divertor peak particle flux at the balance point on the drsep plot. Enhanced recycling in the upper divertor would cause the upper fluxes to be larger at drsep $= 0$ and therefore both curves in Fig. 4 should be shifted upward on this diagram.

The $E \times B$ drifts, however, have opposite effects on these curves for the two opposite magnetic field directions. The $E \times B$ drift should cause the outer flux to be larger in the upper divertor and the outer flux to be smaller in the lower divertor in the $B \times \nabla B$ down case shown in Fig. 4(b). We would therefore expect the $E \times B$ drift to both shift the flux balance up at the magnetic balance point and put the actual particle flux balance point at negative values of drsep. In the $B \times \nabla B$ up case shown in Fig. 4(a), the $E \times B$ drifts would cause the outer flux to be smaller in the upper divertor and the outer flux to be larger in the lower divertor. This should bias the flux balance curve at drsep $= 0$ to be negative which would tend to cancel out some or all of the shift up due to enhanced recycling. In Fig. 4, it can be seen that both curves appear consistent with this prediction. The $E \times B$ drift may also play a role in the density behavior as both cases showing density increases in Fig. 2 have the private region $E \times B$ drift directed from the outer to the inner strike point when they are shifted towards the grad$B$ drift direction.

The two curves in Fig. 4 show similar features. To compare these two curves with each other, one must multiply drsep by -1 for one of the curves so that shifts toward the $B \times \nabla B$ represent the same direction in drsep. Additionally, one must exchange the roles of the 'up' and 'down' probes in one of the curves so that shifts toward the $B \times \nabla B$ direction are toward the 'up' probe for both of the curves. This type of comparison shown as the dashed curves in Fig. 4 reveals the common features in the two curves even though they are not perfectly congruent. The strong feature in Fig. 4(a) near drsep $= 0$ is where the upper and lower fluxes are equal and crossing over each other as one increases and the other decreases with drsep and therefore have the greatest rate of change with drsep. There is also a feature on either side of the strong crossover feature that occurs at drsep $= \pm 1$ away from the crossover point. This weaker feature is related to changes in flux at the outer strike points due to increases in flux at the inner strike point as the 1 cm flux surface wraps around to the inner divertor. The radial decay length in flux at the outer midplane is approximately 1 cm [7].

Finally, when changing the direction of the toroidal field, the changes in the inner and outer particle fluxes shown in Fig. 3 are consistent with the direction of the private region $E \times B$ drift as described in Fig. 1.

5. Conclusions

Changes in core density were observed that are related to changes in the magnetic balance. The outer peak particle flux up/down balance is consistent with both enhanced recycling in the upper divertor and $E \times B$ drifts in the private flux region. The particle balance diagram shown in Fig. 4 also exhibits features consistent with this interpretation. The inside and outside peak particle fluxes show changes with the magnetic field direction that are consistent with the $E \times B$ drift direction in the private flux region.

Acknowledgements

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