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ENHANCED SCRAPE-OFF LAYER PLASMA IN DIII-D DOUBLE-NULL DISCHARGES

by

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This is a preprint of a paper to be presented at the
Eleventh International Conference on Plasma
Surface Interactions in Fusion Devices, May 23-27,
1994, Ibaraki-ken, Japan, and to be printed in the
Proceedings.

Work supported by
U.S. Department of Energy
Contract Nos. DE-AC04-94AL85000, W-7405-ENG-48,
✓ DE-AC03-89ER51114 , and Grant No. DE-FG03-89ER51121

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GENERAL ATOMICS PROJECT 3466
JULY 1994

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ABSTRACT

In this paper, we examine a denser and broader scrape-off layer (SOL) plasma, first seen in VH mode, in the DIII-D tokamak. The enhanced SOL appears in many types of double-null (DN) discharges and is not a property of VH-mode only. The DN enhanced SOL density and temperature profiles exhibit a 5–6 cm broad profile outside the separatrix. For DN and single-null (SN) boundary geometry with similar core plasma conditions, the enhanced SOL is only observed in high triangularity discharges. The origin of the enhanced SOL is, however, not yet understood.

1. INTRODUCTION

In this paper we examine the nature of broad scrape-off layer (SOL) plasmas which are sometimes observed in DIII-D discharges. Previously, Lippmann [1] reported that the high confinement VH-mode phase of some double-null (DN) divertor discharges exhibited a broadened SOL plasma compared to the H-mode phase which followed it. Since then, such enhanced scrape-off layers have been observed, not only in VH-mode, but in a wider range of double-null discharges, including low to medium power L- and H-modes as well as high power, high β_p H-modes (Jong [2], Carlstrom [3]). This paper describes the enhanced SOL in low to medium power L- and H-mode. We have also studied the scaling of the enhanced SOL in VH-mode as a function of current and triangularity. We also consider possible origins for this broad scrape-off layer, including up-down magnetic asymmetries, field errors, and enhanced fast-ion loss from the edge plasma.

A broader, denser scrape-off layer plasma is desirable for several reasons. First, improved shielding against impurities sputtered from the plasma facing components should be obtained, which lowers the radiative losses and increases energy confinement in the main plasma. Second, a thicker SOL plasma should mean a lower peak divertor heat flux and electron temperature, since the power is spread out over a larger area on the divertor targets. Finally, a broader SOL may help entrain gas and build up the plasma density in the divertor, which should lower the target plate sputtering and make density control easier.

2. OBSERVATIONS

The enhanced SOL has been observed in L-, H- and VH-mode discharges. Previously, only VH-mode was observed to exhibit this type of enhanced SOL. In Figs. 1(a) and 1(b), we compare enhanced SOL density and temperature profiles of L-, H-, and VH-mode. The VH-mode enhanced SOL profiles are steeper than L- and H-mode SOL profiles. All of these profiles are from neutral beam heated, high triangularity, DN discharges.

Fig. 1. SOL plasma (a) density and (b) temperature profiles provided by Thomson scattering are shown for L-, H-, and VH-mode discharges.

In Fig. 2, enhanced DN SOL profiles are compared with normal single-null (SN) SOL density and electron temperature profiles for two neutral beam heated L-mode discharges. The single-null shot exhibits the more usual exponential n_e and T_e profiles with exponential decay lengths of 1.5 and 3.0 cm, respectively. Density and temperature profiles for the double-null discharge shown demonstrate the broader SOL produced with high triangularity DN discharges. Features of the broadened profile include (1) a nearly linear decrease in density from about $1 \times 10^{19} \text{ m}^{-3}$ just outside (0.005 m) the separatrix to nearly zero density 0.08 m (near the wall) beyond the separatrix, and (2) a broad, flat temperature profile in the range of 10–20 eV, as compared to the steeper SN discharge temperature profile.

Fig. 2. SOL plasma density and temperature profiles provided by Thomson scattering and scanning Langmuir probe diagnostics are shown for two representative DN and SN discharges. Broadened SOL plasma profiles are observed for the DN discharges.

This enhanced scrape-off layer is observed only in high triangularity discharges. Typically DN discharges in DIII-D are highly triangular ($\delta > 0.7$) with the two X-points near the inside wall. The enhanced SOL has been observed for discharges with triangularity above 0.7. High triangularity SN discharges, which are approaching a DN shape, have exhibited the enhanced SOL as well. No enhanced SOL was observed for low triangularity discharges ($\delta \approx 0.3$ –0.4) in either DN or SN. A comparison of SOL density profiles for different triangularity discharges is shown in Fig. 3(a) for DN discharges and Fig. 3(b) for SN discharges.

Fig. 3. (a) SOL plasma density profiles are shown to compare low and high triangularity VH-mode discharges. A normal (nonenhanced, low δ) L-mode profile is shown for reference. The enhanced H-mode profile has a higher SOL density than the reference L-mode profile. (b) High triangularity single- and double-null SOL density profiles look very similar and both have an enhanced SOL.

Figure 4 shows the flux contours for SN, DN and unbalanced DN discharges. The unbalanced DN configuration is obtained by shifting the plasma current axis up or down. This action causes one of the X-points to dominate over the other. The extent of the shift is characterized by the parameter DR_{sep} , which is defined as the radial location at the outer midplane of the flux surface passing through the lower X-point minus the radial location at the outer midplane of the flux surface which passes through the upper X-point. For this definition of DR_{sep} , a shift down which makes the lower X-point dominant corresponds to a positive value of DR_{sep} . When shifted, one of the DN X-points is in the SOL, a unique feature of the unbalanced DN configuration.

Fig. 4. Magnetic flux surface configurations for (a) a SN discharge with triangularity of 0.3, (b) a DN discharge with triangularity of 0.85, and (c) a DN discharge with triangularity of 0.85 ($DR_{sep} = -0.5$).

Shifting the DN plasma up or down (unbalanced DN) increases the enhanced SOL density. Figure 5(a) shows the density at the separatrix and 6 cm deep in the SOL for five different DN discharges with $-0.5 \leq DR_{sep} \leq 0.6$. Note that significant plasma densities ($3-8 \times 10^{18} \text{ m}^{-3}$) are observed for each discharge as far as 0.06 m outside the separatrix. In Figure 5(b), the plasma densities 0.06 m beyond the separatrix are normalized to

separatrix densities for each shot and plotted versus DR_{sep} . This figure shows that the degree of enhancement of the SOL density depends upon the magnitude, but not the direction, of the up/down shift. The balanced DN configuration, $DR_{sep} = 0$, is found to have the smallest but still significant enhancement. The symmetry of Fig. 3(b) about $DR_{sep} = 0$ shows that the direction of the grad-B drift is not the cause of the enhancement in the SOL. It is interesting to note that as the DN plasma was shifted up, the grad-B drift was away from the dominant upper X-point and the H-mode threshold increased by a factor of four (Carlstrom [4]).

Fig. 5. The effect of up/down plasma shift on SOL density profiles. DR_{sep} describes the separation between the two X-point flux surfaces at the outer midplane. The minimum SOL width shown is for a balanced double-null discharge ($DR_{sep} = 0.0$).

The SOL density enhancement in VH-mode decreases at higher plasma current. This behavior, shown in Fig. 6, is consistent with reduced connection length and reduced radial transport (τ_E and τ_p are higher) at higher current. The figure plots the density at 0.03 m outside the separatrix normalized to the separatrix density because no data is available from the Thomson scattering system at 0.06 m outside since the profiles are steeper in VH-mode especially at higher current.

Fig. 6. (a) SOL densities measured with Thomson scattering at and 0.03 m radially beyond the separatrix for 10 MW NBI heated, DN, high triangularity ($\delta = 0.8$) discharges with various plasma currents. (b) SOL densities at 0.03 m beyond the separatrix normalized to the density value at the separatrix.

3. DISCUSSION

We have examined several possible mechanisms which may be responsible for producing these enhanced SOL plasmas, including differences in connection length between SN and DN configurations, the effect of field errors in the magnetic geometry, and the influence of triangularity on fast ion loss.

Connection length variations in the DN configuration, while significant, can not fully explain the enhanced SOL plasma. A balanced double-null discharge has a shorter target to target connection length in the SOL than a single-null discharge by about a factor of 2. From this we would expect that the DN SOL plasma should be about 40% narrower than for a SN plasma while the data shows the opposite trend; high triangularity DN SOLs are much broader than SN. In the unbalanced DN configuration, connection lengths are long in the near SOL due to the presence of the second X-point null within the SOL (Fig. 7). Field lines outside of these have a more typical, shorter, DN connection length. The increased connection lengths for unbalanced DN configurations as compared to balanced DN configurations may explain the DR_{sep} dependence of the SOL enhancement shown in Fig. 5. However, one would expect this broadening to be predominantly evident in the first 0.01 m of the SOL. Figure 5 shows that the enhancement is pronounced even at 0.06 m into the SOL. As mentioned above, arguments based on connection lengths for SN versus DN configurations are inconsistent with the observed SOL broadening for high triangularity DN discharges.

Field errors may play an important role in the enhanced SOL but initial estimates show the effect is too small to explain the extent of the enhancement. Field perturbations from coil misalignments have a strong influence near the X-points because the poloidal field is zero there. Additionally, the X-point position itself could be moved by error fields or by the $n=1$ coil perturbation field. Analytic modeling shows that SOL field lines may be perturbed

by 0.4 cm vertically by the $n=1$ coil which is too small to explain the enhanced SOL effect. Numerical tracing of errant field lines confirms this analytic result (La Haye [5]) and evaluates the magnitude of the field line deflection error to be about 2 mm on the midplane, but resonant effects have not been included in these calculations.

Fig. 7. Comparison of target to target connection lengths for representative SN, balanced DN and unbalanced DN discharges. Unbalanced DN SOL field lines can be longer than SN SOL field lines near the separatrix. Field errors can expand the spatial extent of this region.

The current dependence of the enhanced SOL shown in Fig. 6 is consistent with the connection length dependence of normal scrape-off layers or the improvement of confinement with current.

The ion temperature profile in the boundary is generally observed to be broader and higher than the electron temperature profile. Since higher triangularity enhances the trapping of warm ions in the SOL, this effect may be important in supporting the enhanced SOL plasma. We are currently investigating the ion temperature profile dependence on triangularity to clarify this point.

This process, however, should be common to both SN and DN plasmas with the same triangularity. The observation of enhanced SOLs in SN discharges supports this conclusion.

In one class of discharges exhibiting the enhanced SOL which are not considered in this paper, high b_p discharges, existence of the enhanced SOL was correlated with enhanced fast ion loss (Politzer [6], Stallard [7], James [8]). The triangularity dependence of the enhanced SOL reported here suggest that fast ion loss may be important for these discharges as well. This point is under further investigation.

4. CONCLUSIONS

The enhanced SOL is observed for L-, H- and VH-mode in DN discharges and for high triangularity SN VH-mode discharges. Unbalanced DN discharges show further enhancement in the SOL density. The current dependence of the enhanced SOL is consistent with the connection length dependence we observe in normal (unenhanced) SOLs and improved confinement at higher current.

We find that there can exist a region of longer field lines outside the separatrix for unbalanced DN magnetic geometry. However, the radial extent of this region (0.01 m) cannot explain the extent of the enhanced SOL (0.05–0.08 m). Field errors could additionally spread the longer connection length region out to 0.01 m or so, but apparently not enough to explain the SOL plasma at the wall, 0.05 m outside the separatrix.

Fast ions from neutral beam injection or thermal ions with $T_i > T_e$ normally found in the plasma boundary may be important for sustaining the enhanced SOL. The collisional cross sections for the thermal ions are higher than for the prompt loss fast ions and their density is also higher and therefore they are more likely to contribute to the SOL plasma.

Further experimental studies are planned to identify the mechanisms responsible for SOL enhancement and the discharge regimes over which SOL enhancement can be produced.

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ACKNOWLEDGEMENT

Work supported by the U.S. Department of Energy under Contract Nos. DE-AC04-94AL85000, W-7405-ENG-48, DE-AC03-89ER51114, and Grant No. DE-FG03-89ER51121.

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