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PERFORMANCE OF HIGH TRIANGULARITY PLASMAS AS THE VOLUME OF THE SECONDARY DIVERTOR IS VARIED IN DIII-D

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ABSTRACT

This paper examines the sensitivity of edge pedestal and divertor performance parameters to changes in the volume of a secondary divertor that tends to form inside the vacuum chamber in high triangularity plasma shapes. The sensitivity was examined by varying the vertical distance of the secondary X-point from the target plate, Z_x^S , while holding the primary X-point height fixed. The ion ∇B drift was in the direction of the primary divertor. Discharges with and without active primary divertor cryo-pumping were examined. The effective rate of rise of the core density at the L-H transition increased 80% as Z_x^S was reduced. At high density achieved by gas injection, the core line averaged density at the H-L back transition decreased by 30% as Z_x^S was reduced. Both of these results indicate that performance may be affected when core plasma screening of neutrals in the secondary divertor is reduced as Z_x^S decreases. The peak heat flux in the secondary divertor was nearly constant for high Z_x^S until a threshold was reached at $Z_x^S \sim 3$ cm where it increased a factor of 3. This indicated that the secondary divertor target was beginning to act as a heat flux limiter when the flux surface that was one scrape-off-layer (SOL) power width from the primary separatrix at the midplane was seen to have negligible divertor leg length in the secondary divertor.

1. INTRODUCTION

The design of any future tokamak begins with a decision on the shape of the core and divertor plasmas [1]. The desire is to achieve the performance advantages of high triangularity (high- δ) operation [2] with the core plasma volume maximized and the divertor volume minimized. However, there is very limited data from systematic experiments to guide the decision on the optimum plasma shape [3].

This paper describes experiments that have increased our understanding of the complex coupling of core plasma performance to plasma cross section and divertor plasma shape. Systematic shape variation experiments were done using Type I [4] ELMing H-mode plasmas in DIII-D (see Fig. 1). The response of core, pedestal, scrape-off-layer (SOL), and divertor plasma performance was examined versus triangularity, δ [5], up/down magnetic balance [6], and secondary divertor volume as described below.

This paper reports on a series of high- δ H-mode discharges in DIII-D in which the effect of variation in the secondary divertor volume on edge pedestal and divertor performance was examined (see inset in Fig. 2). At low δ in single-null (SN) divertor configurations, only the primary X-point is present inside the vacuum vessel. As δ is increased for fixed PF coil set the location of the secondary X-point, which maps at the midplane to a flux surface radially outboard of the primary, tends to move from outside the vacuum vessel to inside and divertor physics (recycling, target heat flux etc.) can become important in this secondary divertor. The studies were done by varying the height of the secondary (lower) X-point from the target plate, Z_x^S in Fig.2. Since the volume within the vacuum vessel that is made unavailable to the core plasma by the presence of a divertor scales with Z_x^S , the focus of the study was to determine the minimum Z_x^S consistent with good core, pedestal and divertor performance.

The data showed that the presence of a second X-point in these unbalanced double-null (DN) shapes does not degrade the plasma performance if the secondary X-point is sufficiently

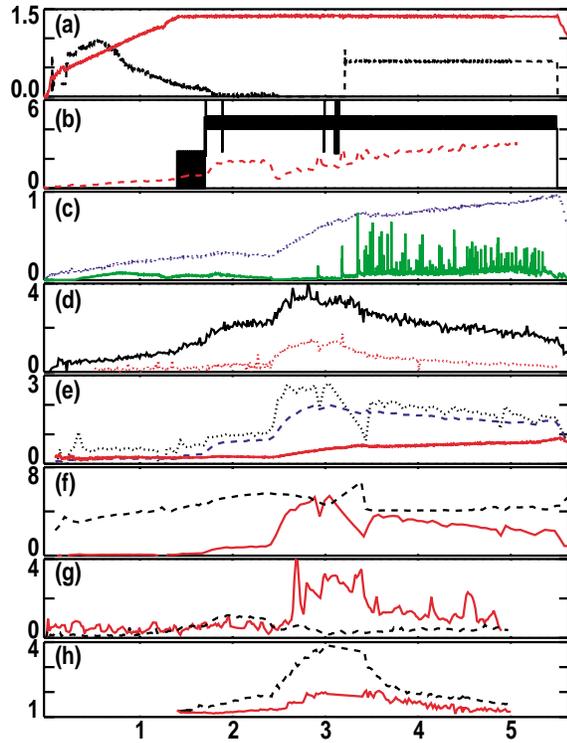


Fig. 1. Typical evolution of discharge parameters: (a) plasma current I_p (solid) and gas injection (dashed), (b) injected beam power (solid) and radiated power – total (dashed), upper divertor (dash-dot), lower divertor (dotted), (c) $D\alpha$ signal (solid), line averaged (dotted), (d) electron temperature – central (solid), pedestal (dotted), (e) fraction of Greenwald density (solid), β_N (dashed), enhancement, H_{89P} , over ITER89P confinement [5] (dotted), (f) $\beta_N H_{89P}$ (solid) and $4 \ell_i$ (dashed), (g) peak heat flux – upper (solid) and lower (dashed) divertor, (h) Z_{eff} – central (solid) and edge (dashed).

far inside the vacuum vessel. These results, combined with those of Refs. 5 and 6, indicate that for high δ operation an unbalanced DN shape has some advantages over a single-null shape for future high power tokamak operation.

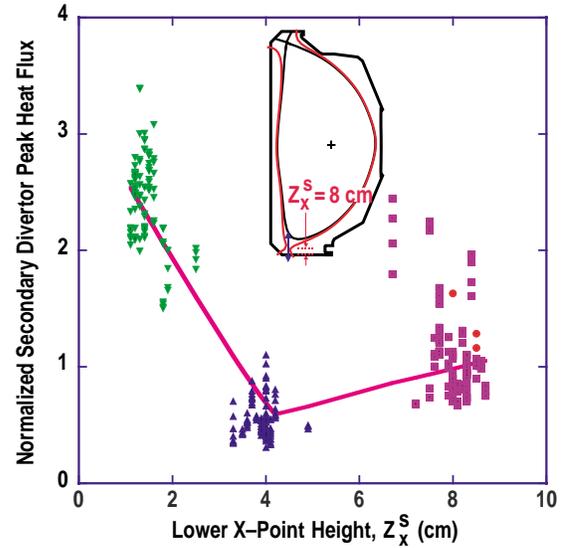


Fig. 2. Normalized peak heat flux in secondary divertor versus secondary X-point height, Z_x^S . Peak heat flux was normalized to expected value for $Z_x^S = 16$ cm and constant up/down magnetic balance. Peak heat flux decreases initially as Z_x^S decreases due to flux expansion, then increases as secondary divertor becomes an effective limiter.

2. DESCRIPTION OF EXPERIMENTS

The plasmas used in these experiments were operating in standard Type I ELMing H-mode [4] with neutral beam injection. No special profile control techniques were used and the radial profiles of the core plasma parameters (density, temperature, current, impurities) were typical of an ELMing H-mode well above the power threshold. Time histories of typical discharge parameters are shown in Fig. 1. Discharge parameters held constant throughout the scans of Z_x^S were: plasma current, $I_p = 1.4$ MA, toroidal field, $B_T = 2.0$ T, major radius, $R_0 = 1.75$ m, minor radius, $a = 0.6$ m, and injected neutral beam power, $P_{inj} = 4.6$ MW. Given the sensitivity of the divertor performance to variations in up/down magnetic balance shown in Ref. 6, an attempt was made to hold the magnetic balance constant as the secondary divertor volume varied. However, some up/down balance variation occurred and the results of Ref. 6 have been used in the analysis below to try to distinguish the effect of divertor volume variation from the effect of up/down balance variation. Finally, the unpumped plasmas had an average triangularity, $\delta = 0.75$ and the pumped plasmas had $\delta = 0.6$. Elongation varied in the range $\kappa = 1.88$ – 2.15 and this produced a variation in safety factor at the 95% flux surface, $q_{95} = 4.6$ – 5.4 . The goal of the discharges in this study was to examine the performance variations as a function of density within each shot and as a function of secondary divertor volume from one shot to the next.

3. RESULTS

Variation of secondary divertor volume produces changes in a wide variety of plasma parameters. This section will examine only three of the variations as functions of Z_X^S : 1) the effect on the up/down balance of peak heat flux to the divertors, 2) the effective fueling rate of the core plasma and 3) the highest density achieved just before the H-L back transition. Finally, a point comparison was done between an unbalanced DN plasma and a SN shape for which the sum of the X-point heights in the DN (i.e. the total length of the divertor legs) was equal to the X-point height (divertor leg length) in the SN.

3.1. HEAT FLUX BALANCE

Reduction of Z_X^S did not produce a significant change in up/down balance of peak divertor heat flux until Z_X^S dropped below a threshold value. This indicates that the distribution of power in the SOL is unaffected by X-point height variation until one of the divertors begins to act more like a limiter at small X-point height. The normalized peak heat flux in the secondary divertor as a function of Z_X^S is shown in Fig. 2 for the pre-gas ELMing H-mode phase of unpumped plasmas. There is non-negligible variation in the up/down magnetic balance of the plasmas in this dataset. To compare the data fairly, each point in Fig. 2 represents the value expected for the same up/down magnetic balance of the equilibrium. The results of Ref. 6 were used to factor out the variation in peak heat flux due to changes in up/down magnetic balance. A value of 1.0 in Fig. 2 indicates the peak heat flux in the secondary divertor is the expected value [6] for $Z_X^S = 16$ cm, a value less than (greater than) 1.0 means the secondary divertor is getting less than (greater than) the expected heat flux. For high Z_X^S the heat flux is the expected value consistent with the studies in Ref. 6. As Z_X^S was reduced, the normalized peak heat flux in the secondary divertor decreased. However, for low Z_X^S the peak heat flux jumped to three times the expected value.

These variations can be understood by considering the mapping of a flux tube which is one radial scale length of the power outboard of the primary separatrix at the midplane. As Z_x^S is reduced the mapping of this flux tube to the secondary divertor shows greater flux expansion at the target plate and the peak heat flux decreases due to broadening of the profile on the target. However, when Z_x^S is reduced enough that this flux tube maps to the secondary divertor target with negligible divertor leg length, then the secondary divertor begins to act more like a limiter than a divertor and the peak heat flux increases sharply. For the plasmas in this study, the midplane SOL scale length of the parallel heat flux is about 0.6 cm. At $Z_x^S = 2-3$ cm the leg length of this flux tube in the secondary divertor becomes negligible.

3.2. EFFECTIVE FUELING

The effective rate of rise of the core line averaged density at the L-H transition increases as the volume of the secondary divertor decreases. This indicates that the fueling rate of the core plasma is increased for lower secondary X-point height. Data from shots with and without divertor cryopumping are shown in Fig. 3. The effective fueling source, S_{eff} , was obtained from an exponential fit to the increase in the total core particle content during the ELM-free period (approximately 400 ms) after the L-H transition. The contribution to the core fueling by the neutral beams, S_{nb} , was subtracted out to obtain the fueling contribution from around the separatrix. Finally, the values were normalized to midplane neutral pressure and core pedestal density to eliminate shot-to-shot variation in neutral and electron densities in the fueling region near the edge of the core plasma. Fig. 3 shows a clear trend to higher core fueling as Z_x^S was reduced.

The trend in Fig. 3 suggests that ionization of neutrals from the secondary divertor region plays a significant role in fueling the core plasma for unbalanced DN configurations. In contrast to SN equilibria which have the secondary X-point well outside the vacuum chamber and particle recycling only in the primary divertor region, nearly up/down balanced DN

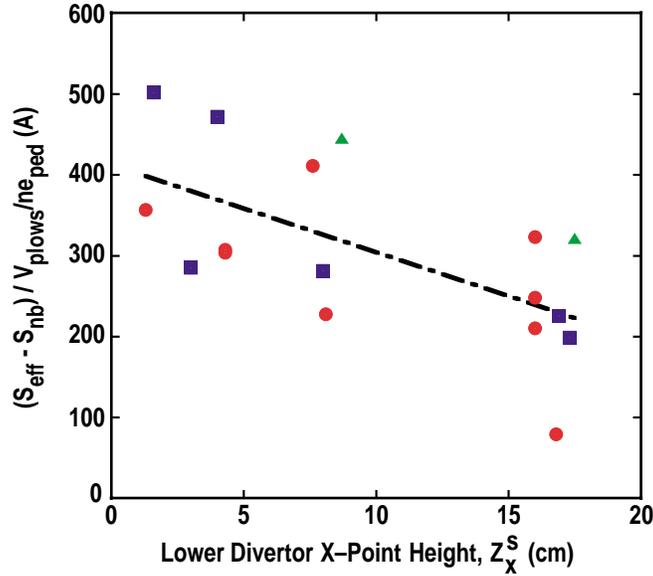


Fig. 3. Normalized core fueling source versus secondary X-point height for unpumped (circles), partially pumped (triangles) and well-pumped (squares) discharges. A substantial increase in fueling is seen as Z_x^S decreases for all discharges taken together (dot-dashed) and for each dataset with constant pump conditions. Vertical scatter at fixed Z_x^S and constant pump conditions shows evidence of changing wall conditions – effective fueling source increases with each successive repeat shot.

configurations produce appreciable recycling flux in the secondary divertor. The plasmas in this study had the up/down magnetic balance shifted slightly toward the primary divertor and therefore the majority of the power flux went to the primary divertor. This means the secondary divertor plasma is colder than the primary, and recycled neutrals in the secondary have a high probability of reaching the edge of the core plasma. The trend in Fig. 3 is consistent with this picture and the expectation that the penetration probability of a neutral from the secondary divertor target into the core would increase with decreasing Z_x^S .

3.3. DENSITY AT H-L BACK TRANSITION

The maximum density that was obtained during ELMing H-mode in these discharges, before a back transition to L-mode, decreased as Z_x^S was reduced. The line averaged and pedestal densities [7] at the transition time are plotted as functions of Z_x^S in Fig. 4 for both unpumped and pumped discharges. Both of these quantities decreased as Z_x^S was reduced. The absolute

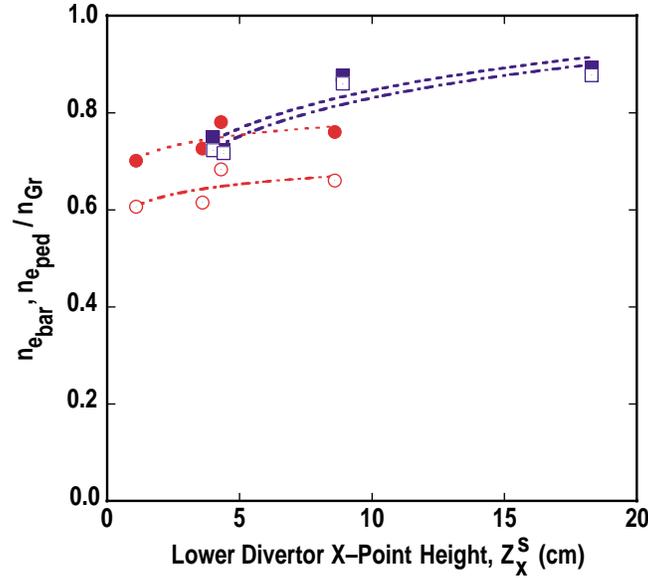


Fig. 4. Line-averaged (closed) and pedestal (open) densities at the H-L back transition normalized to Greenwald density versus Z_x^S for unpumped (circles) and pumped (squares) discharges. All of these densities decrease as secondary divertor volume decreases. Pumping produced higher absolute density at the H-L transition than the unpumped cases.

density in the unpumped discharges was lower than with pumping at high Z_x^S . However, the density limit dropped more rapidly with Z_x^S reduction in the pumped cases yielding similar results at low Z_x^S . The density profile width was larger in the unpumped plasmas indicating a greater penetration of neutrals without pumping.

The dominant physics that explains the trend in Fig. 4 is again the increase in neutral escape probability from the secondary divertor as Z_x^S was reduced. In this case the effect of increased neutral ionization in the edge of the core is to lower the pedestal temperature for fixed core density as Z_x^S was reduced thereby inducing the H-L back transition at lower core density. This also explains the higher density limit with pumping at moderate to high Z_x^S .

3.4. COMPARISON OF OPTIMIZED DN VERSUS SN

A direct comparison of several “optimized” unbalanced DN discharges with a comparable SN discharge shows that the DN shape has advantages for future tokamak operation.

Performance parameters from three unbalanced DN discharges and a SN discharge are shown in Table 1. The X–point height of the SN discharge was 16 cm. The DN shapes were “optimized,” in the sense of maximizing core volume while minimizing secondary peak heat flux (Fig. 2), by sharing the total X–point height between the primary and secondary divertors as $Z_X^P = 9$ cm and $Z_X^S = 7$ cm respectively. The table shows that the advantages of the DN configuration over the SN shape are: 1) lower core fueling rate which should allow greater density control, 2) higher normalized performance, β_{NH89P} [8], in the ELM-free phase which might be exploited in advanced tokamak scenarios, 3) reduced outer leg peak heat flux which should make divertor design easier, and 4) higher achievable H–mode density for maximizing fusion power.

This comparison also pointed out the importance of wall conditions in these discharges. The performance of the three DN discharges was somewhat different even though they were as nearly identical as possible in terms of shape, injected power, and current. The first DN plasma came after a set of discharges with no supplemental gas injection so the walls were probably depleted and pumping. The next plasma in sequence had substantial gas injection in the latter phase to bring the density to the H-L back transition. This probably saturated the walls so that in the final discharge the walls were acting as a source. The effective fueling rates and maximum β_{NH} in these three shots clearly shows the effect of the wall source.

Table 1
Comparison of Performance Parameters from SN and “Optimized” DN Discharges with Comparable Total Divertor X-point Height

Parameter	SN Reference Shot 98397	Optimized DN Shot 98392	Optimized DN Shot 98393	Optimized DN Shot 98394
S_{eff} at L-H Transition (normalized)	289	25 - 80	40	126
Maximum $\beta_N H_{89P}$	3.77	9.14	7.16	4.83
Maximum Outer Leg Heat Flux/Injected Power	332	178	N/A	125
Line averaged density at L-H back transition	8.83	N/A	9.0	11.0
Wall conditions	Saturated; acts as source	Depleted, pumping	Neutral, gas injection later	Saturated, acts as source

4. DISCUSSION AND FUTURE WORK

Results obtained in this study and those in Ref. 5 and 6 show that for high δ operation an unbalanced DN plasma shape has some advantages over a SN shape for future high power tokamak operation. However, maximizing the core plasma volume by minimizing the secondary divertor volume, in an attempt to achieve the performance advantages of a high- δ unbalanced DN configuration, produces both positive and negative effects on performance.

The advantage of having the secondary divertor share some of the SOL heat flux was not strongly degraded by reduction in the secondary divertor volume provided the secondary X-point was well inside the vessel. As Z_x^S was reduced the peak heat flux in the secondary divertor actually decreased somewhat due to flux expansion. Secondary peak heat flux increased only when the flux surface that was one SOL power scale width from the primary separatrix at the midplane was seen to have negligible divertor leg length in the secondary divertor.

The advantages for core performance of greater volume, elongation and safety factor at constant current as Z_x^S is reduced are partially offset by degradation of other core performance measures. The effective rate of rise of the core n_e at the L-H transition increased and the line averaged n_e at the H-L back transition decreased as secondary X-point height decreased. This was due to reduced screening of neutrals from the core as Z_x^S decreased. These trends in combination effectively reduce the core plasma density operating window monotonically with Z_x^S reduction. For steady state scenarios the reduction in fueling control may outweigh advantages of greater volume and current capability. For high neutron flux scenarios the change in fusion rate scales linearly with volume and as the square of the density so that even though the reduction in density limit is small this may more than offset the advantage of larger volume.

The direct comparison of a SN discharge with several comparable “optimized” unbalanced DN discharges showed that a carefully selected DN shape may still perform better than a SN shape with the same divertor height. However, more work must be done in this area to achieve an

unambiguous comparison because uncontrolled factors such as wall conditions were playing a role in the comparison discharges in this study.

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