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by

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A comparison of radiating divertor behavior in single- and double-null plasmas in DIII-D

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Abstract. "Puff and pump" radiating divertor scenarios, applied to both upper single-null (SN) and double-null (DN) H-mode plasmas, result in a 30-60% increase in radiated power with little or no decrease in τ_E. Argon was injected into the private flux region of the upper divertor, and plasma flow into the upper divertor was enhanced by a combination of deuterium gas puffing

upstream of the divertor targets and particle pumping at the targets. For the same constant deuterium injection rate, argon penetrated the main plasma of *SN*s more rapidly and reached a higher steady-state concentration when the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction was *toward* the divertor $\left(V_{\nabla B\uparrow}\right)$ rather than *away from* the divertor $\left(V_{\nabla B\downarrow}\right)$. We also found that the initial rate at which argon accumulated inside *DN* plasmas was more than twice that of comparable *SN* plasmas having the same $\boldsymbol{B}x\nabla\boldsymbol{B}$ -ion drift direction. In *DN*s, the radiated power was not shared equally between divertors during argon injection. Only in the divertor *opposite* $\boldsymbol{B}x\nabla\boldsymbol{B}$ ion drift direction were both significant increases in divertor radiated power and an accumulation of argon, based on spectroscopic measurements of ArII, observed. Our data suggests that a *DN* shape that is biased in the direction *away* from the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction may provide the best prospect of successfully coupling a radiating divertor approach with a higher performance H-mode plasma.

1. INTRODUCTION

Excessive thermal power loading on the divertor structures can be a major problem for future, highly powered tokamaks. One way to decrease divertor power loading in steady state is to "seed" the divertor plasma with impurities that radiatively reduce the conducted power before it can reach the divertor targets. For this approach to be practical, however, the confinement and the stability of the plasma must not be compromised by leakage of the seeded impurity into the main plasma. Previous studies have shown that the concentration of impurities in the divertor can be increased by raising the flow of deuterium ions $\left(D^{+}\right)$ into the divertor by a combination of upstream deuterium $\left(D_2\right)$ gas puffing and active particle exhaust at the divertor targets, i.e., *puff–and–pump* [1-3]. An enhanced deuterium particle flow toward the divertor targets exerts a frictional drag on impurities, inhibiting their escape from the divertor. This approach is most effective in a closed divertor, where baffling inhibits the vacuum paths of neutral impurity atoms back into the main chamber. A puff-and-pump scenario using argon as the impurity was successfully applied in recent DIII-D experiments to single-null plasmas. Good confinement $\left(H_{ITER89P} = 2.0\right)$, a low core radiated power fraction $\left(P_{RAD,MAIN}/P_{IN} < 0.25\right)$, and a 2-3 times reduction in the peak divertor heat flux were achieved and maintained [4].

Previous studies on DIII-D and other tokamaks, however, have indicated that both the direction of the toroidal magnetic field $\boldsymbol{B}_T$ and the degree of magnetic balance between divertors [i.e., the degree to which the plasma shape is considered single-null $\left(SN\right)$ or double-null (DN)] are important in determining recycling behavior [5] and effectiveness of active particle pumping [6]. In light of these results, it becomes uncertain as to whether the favorable results of the puff-and-pump experiment reported in Ref. [4] can be extended to cases having different magnetic balance and/or $\boldsymbol{B}_T$ direction.

We first present data showing that reversing the direction of $\boldsymbol{B}_T$ had a significant impact on the effectiveness of the puff-and-pump approach as applied to ELMing H-mode plasmas. Reversing the direction of $\boldsymbol{B}_T$ is equivalent to reversing the direction of the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion particle drift (and other $\boldsymbol{B}$-field dependent particle drifts) found in the scrape-off layer (SOL) and divertor plasmas [7]. In this paper we will find it convenient to classify the direction of $\boldsymbol{B}_T$ in terms of the more common parlance of the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion particle drift direction.

We next compare how well a puff-and-pump scenario can be maintained in ELMing H-mode plasmas that have different magnetic balance, such as SN and magnetically-balanced DN. The balanced DN has a higher average "triangularity" than a corresponding SN shape and can theoretically reach higher levels of energy confinement and plasma beta than the comparable SN shapes with lower average triangularity [8]. For this reason, the DN shape may be an attractive design option for future tokamaks. If the DN were further shown to be compatible with heat flux reduction methods, such as puff-and-pump, then the DN configuration may provide a viable platform for future tokamak operation. With the recent modifications of the lower DIII-D divertor (described below), it is now possible to make a preliminary assessment of how a DN H-mode plasmas behaves in a $puff\text{–}and\text{–}pump$ environment.

The experimental arrangement and methodology are described in Section 2. In Section 3 we present results from our study of SN and DN $puff\text{–}and\text{–}pump$ studies for both $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction. We discuss the results in Section 4.

2. EXPERIMENTAL SETUP

2.1. Pumping Geometry

To study ELMing H-mode plasmas under *puff–and–pump* conditions, we take advantage of DIII-D's capabilities to make *SN* and *DN* shapes with high-triangularity and then to pump those shapes. Prior to 2006, DIII-D radiating divertor studies focused on the *DN* cross-sectional shape that was *biased upward* $\left(dRsep = +1.0 \text{ cm}\right)$, as shown in figure 1(a). For purposes of discussion, we will refer to this shape as "single-null". In-vessel pumping of deuterium and argon (the seeded impurity) was done by cryo-pumps located inside the *upper outer* and *upper inner* divertor pumping plenums, indicated "plus" and "minus" in the respective plenums. To increase the ion D^+ flow toward these two pumps, deuterium gas $\left(D_2\right)$ was introduced near the bottom of the vessel. Argon (Ar) was injected directly into the private flux region (PFR) of the upper divertor near the outer divertor target. The inner and outer divertor strike points were situated adjacent to the entrances of the dome and baffle plenums.

For the 2006 campaign, the lower divertor of DIII-D was modified to enable pumping of the lower outer leg of high-triangularity *DN* shapes. The hatched region in figure 1(b) represents the extended shelf installed to channel neutrals from the recycling region near the entrance to the lower outer divertor pumping plenum to the cryopump inside the plenum. With this modification to the lower divertor, simultaneous particle pumping is possible at both (outer) divertors. As with the 2005 *puff–and–pump* experiments, argon was again injected directly into the upper PFR in the 2006 *puff–and–pump* experiments. However, the experimental setup of 2006 differs from that of 2005 in that deuterium gas was injected from the low-field side of the plasma in 2006 rather than from the bottom of the vessel due to the reconfigured pumping geometry.

2.2. Plasma operating parameters

Representative operating parameters for this experiment were: plasma current $I_\mathrm{p} = 1.2$ MA, toroidal field $\boldsymbol{B}_T = 1.75$ T (with the capability to run with either toroidal field direction), $q_{95} \approx 4.3$, power input $P_{IN} \approx 6$ MW, line-averaged density $\bar{n}_\mathrm{e} \approx (0.60 - 0.75) \times 10^{20}$ m^{-3} (or $\bar{n}_\mathrm{e}/n_\mathrm{G} \approx 0.55 - 0.70$, where n_G is the Greenwald density [9]), and $H_{ITER89P} = 1.7 - 2.0$ [10]. All discharges had Type-1 ELMs. Two configurations are examined in this paper: *SN* plasmas biased toward the top of the vessel with a *dRsep* value of +1.0 cm (e.g., figure 1a) and *DN* plasmas with $dRsep = 0$ (e.g., figure 1b). While the argon injection rate (Γ_{Ar}) was varied from trace to perturbing levels in this experiment, the deuterium gas puffing rate (Γ_{D2}) was maintained at 108 torr l/s for the cases discussed in this paper. Deuterium fueling contributed by the neutral beams was typically 13 torr l/s.

Argon was selected as the seeded impurity, because it radiates effectively at the temperatures prevailing in the divertor and pedestal regions of DIII-D ELMing H-mode plasmas and has a relatively short ionization mean free path. Carbon is the dominant intrinsic impurity in DIII-D discharges.

3. RESULTS

For the purpose of discussion, we refer to cases where the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift is directed toward the top of the DIII-D vessel as "$V_{\nabla B\uparrow}$" and to cases where the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift is directed toward the bottom of the vessel as "$V_{\nabla B\downarrow}$".

3.1. Deuterium exhaust behavior without argon injection

Deuterium pumping using the 2005 configuration (figure 1a) was shown to depend on both the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction and $dRsep$ for both SN and DN shapes in DIII-D [6]. The large differences in particle removal rates that were observed between the inner and outer pumps in the upper divertor were believed to result from the existence of particle drifts in the SOL and divertor(s). With the addition of the lower outer divertor pump in the 2006 campaign (figure 1b) the total particle exhaust rate (Γ_{TOTAL}) increased but the particle removal rate of each of the three pumps individually (i.e., upper inner Γ_{UP-IN}, upper outer Γ_{UP-OUT}, and lower outer $\Gamma_{LOW-OUT}$) still maintained clear dependence on both the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction and $dRsep$. This is shown in Table 1, where the relative importance of each of these pumps to Γ_{TOTAL} are measured for SN and DN shapes under both $V_{\nabla B\downarrow}$ and $V_{\nabla B\uparrow}$ conditions.

With $V_{\nabla B\downarrow}$, the dominant pump for either SN or DN plasmas was the upper outer divertor pump. Even for the balanced DN, the pumping rate for the upper outer pump was more than twice that of the lower outer divertor pump. When the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction was reversed, Γ_{UP-OUT} was still greater than $\Gamma_{LOW-OUT}$, although the difference between the pumping rates was significantly reduced. We think that Γ_{UP-OUT} and $\Gamma_{LOW-OUT}$ did not exchange values when the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction was reversed because the upper divertor structure is much more closed than the lower divertor structure, leading to better particle trapping (and pumping) in the upper divertor. For DN shapes with either $V_{\nabla B\downarrow}$ or $V_{\nabla B\uparrow}$, Γ_{UP-IN} played only a minor role in particle removal, since Γ_{UP-IN} was only $\approx 10\%$ of Γ_{TOTAL}. For the $SN\,(dRsep = +1.0\text{ cm})$ with $V_{\nabla B\uparrow}$, $\Gamma_{UP-IN} > \Gamma_{UP-OUT}$, but for $V_{\nabla B\downarrow}$, we find that $\Gamma_{UP-IN} < \Gamma_{UP-OUT}$.

3.2. Radiating plasma behavior of single-null plasmas as a function of $\boldsymbol{B}x\nabla\boldsymbol{B}$ *drift direction*

For upper SN plasmas, argon accumulated in the main plasma at a faster rate and reached a higher steady state concentration for $V_{\nabla B\uparrow}$. This is shown in figure 2, which compares a SN H-mode plasma with $V_{\nabla B\uparrow}$ to a SN H-mode plasma with $V_{\nabla B\downarrow}$. Deuterium gas puffing was initiated at $\text{t} = 2.0\text{ s}$ and reached its flattop by $\text{t} = 3.0\text{ s}$; a constant argon gas injection rate $(\Gamma_{Ar} = 1.0\text{ torr l/s})$ was initiated at $\text{t} \approx 2.7\text{ s}$ (figure 2a). With identical Γ_{D2}, the line-averaged density $\bar{n}_\text{e}$ in the $V_{\nabla B\uparrow}$ case reached a level that was $\approx 20\%$ higher than $\bar{n}_\text{e}$ in the $V_{\nabla B\downarrow}$ case (figure 2b). Argon initially accumulated in the main plasma at a higher rate for $V_{\nabla B\uparrow}$ than for $V_{\nabla B\downarrow}$, and reached a steady argon level that was $\approx 3\text{–}4$ times greater than that of $V_{\nabla B\downarrow}$ (figure 2c); here, we consider the relative argon density n_{Ar}, which is taken as proportional to the I_{ArXV}/n_e signal, where I_{ArXV} is the intensity of an ArXV line (22.15 nm) with its chordal view through the main plasma. A partial detachment of the inner leg for the $V_{\nabla B\uparrow}$ case occurred at $\text{t} = 3.3\text{ s}$, as evidenced by a pronounced drop in neutral pressure (P_{RDP}) inside the upper inner baffle plenum (figure 2d) and a strong increase in the signal along the bolometer chord looking directly through the X-point (*bolo–Xpt* in figure 2e). The total radiated power (P_{RAD}) also increased somewhat more in the $V_{\nabla B\uparrow}$ case (figure 2f). More argon was removed by the upper outer cryopump for $V_{\nabla B\downarrow}$ than for $V_{\nabla B\uparrow}$, as implied by the higher argon pressure in the $V_{\nabla B\downarrow}$

case, as measured by the Penning gauge inside the upper outer divertor pumping plenum (P_{Ar} in figure 2g).

Given that both the argon pumping and the deuterium pumping changed so dramatically when the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction was reversed, it is not surprising that the radiated power in the divertor would be distributed differently for the $V_{\nabla B\downarrow}$ and $V_{\nabla B\uparrow}$ cases discussed in figure 2. The radiated power along the inner divertor leg in the $V_{\nabla B\uparrow}$ was spread out before detachment but was concentrated near the X-point afterwards, as shown by the tomographic inversion of the bolometer data (figure 3a,b). This strongly contrasts with the $V_{\nabla B\downarrow}$ case, where the radiative emissivity was more distributed around the divertor both before and after argon injection was initiated (figure 3c,d). Unlike the $V_{\nabla B\uparrow}$ case, the inner leg of the $V_{\nabla B\downarrow}$ case remained attached throughout the discharge. The latter behavior is consistent with that previously reported in Ref. [4] under similar operating conditions.

The less argon that is removed by the upper outer divertor pump, the more argon that will be found elsewhere. Spectroscopic data indicates that argon presence for $V_{\nabla B\uparrow}$ is much more poloidally spread out than for the $V_{\nabla B\downarrow}$ case (figure 4b). Both the upper and the lower divertors are monitored by several spectrometer channels at 461.0 nm, representing one of the ARII lines (figure 4a). The U5, U2, and the L4 channels monitored the argon photon flux from the upper outer divertor target, the upper inner divertor target, and the lower outer target of the secondary divertor, respectively. This data indicates an argon presence near the *lower* divertor outer target to be considerably higher for the $V_{\nabla B\uparrow}$ case. Using the density and temperatures obtained from Langmuir probe data and following the methodology discussed in Ref [11,12], we estimate that the argon flux at the lower outer target was roughly ten times higher for the $V_{\nabla B\uparrow}$.

While the deuterium and argon injection rates in the above two cases were comparable, the total radiated power was ≈ 0.8 MW higher for $V_{\nabla B\uparrow}$ than for $V_{\nabla B\downarrow}$ after steady state was reached. Table 2 summarizes the above $\Gamma_{Ar} = 1.0$ torr 1/s case, including the radiated power in the main plasma $\left(P_{RAD,MAIN}\right)$, the radiated power in the (upper) divertor $\left(P_{RAD,DIV}\right)$, and the radiated power in the scrape-off layer $\left(P_{RAD,SOL}\right)$. Comparisons with similar discharges having trace argon are also included. In order to match the total radiated power of $V_{\nabla B\downarrow}$ with that of the $V_{\nabla B\uparrow}$, the argon injection rate of the $V_{\nabla B\downarrow}$ was raised by about a factor of two. While the rates at which argon accumulated were initially comparable, the steady state argon concentration in the $V_{\nabla B\downarrow}$ case was still below that of the $V_{\nabla B\uparrow}$ case. Even at comparable *total* radiated power output, the radiated power *distribution* in the divertor still maintained the same spatial distribution as shown in figure 3d, and the inner leg was still attached.

3.3 Radiating plasma behavior of double-null plasmas as a function of $\boldsymbol{B}x\nabla\boldsymbol{B}$ *drift direction*

Measurable increases in radiated power in *DN* plasmas were observed first in the divertor *opposite* the direction of the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift, even though the argon was, as the *SN* cases, injected into the private flux region near the upper outer divertor. This is shown in figure 5 $\left(V_{\nabla B\downarrow}\right)$ and figure 6 $\left(V_{\nabla B\uparrow}\right)$. As with the single-null comparisons in section 3b, $\Gamma_{D2} = 108$ torr 1/s and $\Gamma_{Ar} = 1.0$ torr 1/s. Shots with trace argon are included in each figure (dashed curves) for comparison. For $V_{\nabla B\downarrow}$, the radiated power in the upper divertor showed a clear response to the injected argon (figure 5b), but virtually *no* radiative response in the lower divertor (figure 5c). For $V_{\nabla B\uparrow}$, on the other hand, the radiated power in the upper divertor showed virtually *no* radiative response to argon injection into the private flux region of the upper divertor (figure 6b), but a clear increase in the lower divertor (figure 6c).

For the $V_{\nabla B\downarrow}$ case, argon injection did not appreciably change how the radiated power was distributed in the divertors. Figures 7a,b, which compare the radiated power distribution of the trace *Ar* timeslice with the perturbing *Ar* timeslice of figure 5, show an increase in the radiated power coming from the upper divertor with argon injection, but little change in the radiated power coming from the lower divertor. The locations of the three main radiating regions in the upper divertor for this *DN* case were similar to those observed in the *SN* case for $V_{\nabla B\downarrow}$. When argon was injected, these regions increased in intensity but did not appreciably change location. For $V_{\nabla B\uparrow}$, figure 8a,b shows a strong increase in the radiated power coming from the *lower* divertor but little change in the radiated power coming from the *upper* divertor. The injected argon increased the radiated power in the lower divertor, but the locations of the peaked radiated power did not change appreciably. Table 3 summarizes these results, including the radiated power from the upper divertor $\left(P_{RAD,UPDIV}\right)$ and the radiated power from the lower divertor $\left(P_{RAD,LOWDIV}\right)$.

As with the up/down distribution of the divertor radiated power, the up/down distribution of argon in the two divertors of *DN*s depended on the direction of $\boldsymbol{B}x\nabla\boldsymbol{B}$. Figure 4c suggests that the argon presence for the $V_{\nabla B\downarrow}$ case in the upper outer divertor (U5) was much higher than that in the lower divertor (L4). This behavior was reversed in the $V_{\nabla B\uparrow}$ case, where argon presence in the lower divertor was much more pronounced. With the density and temperature data from the divertor Langmuir probes and the methodology of Refs. [11,12], the ratio of argon flux at the upper outer divertor target to that of the lower outer divertor target $\left(\Gamma_{\mathrm{Ar,U5}}/\Gamma_{\mathrm{Ar,L4}}\right)$ is estimated to be ≈ 0.4 for $V_{\nabla B\uparrow}$ and ≈ 2.0 for $V_{\nabla B\downarrow}$ (Table 3). For the $V_{\nabla B\downarrow}$ case, the ratio of argon flux at the upper inner divertor target to that of the upper outer divertor target $\left(\Gamma_{\mathrm{Ar,U2}}/\Gamma_{\mathrm{Ar,U5}}\right)$ was only about 0.2, indicating that argon accumulation at the upper inner target would be insignificant compared with that of the upper outer target.

3.4. Comparison of single-null with double-null plasmas

From the above discussion it is clear that changing the direction of the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift had a direct bearing on how argon was distributed both inside and outside the main plasma for SN and DN configurations. We next do a direct comparison of the argon-induced puff-and-pump approach, as applied to SN and DN shapes having the *same* $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction. Figure 9a shows the *initial* rate at which the argon accumulated in the main plasma $\left[d(n_{Ar})/dt\right]$ as a function of the argon injection rate Γ_{Ar}. Given the same Γ_{Ar}, the argon built up in the DN at roughly twice the rate that it did in the SN for the $V_{\nabla B\downarrow}$ case. Reversing the direction of $\boldsymbol{B}x\nabla\boldsymbol{B}$ did not appreciably change the ratio of $d(n_{Ar})/dt$ between the DNs and SNs, i.e., still roughly a factor of two in the $V_{\nabla B\uparrow}$ case. The rates for $V_{\nabla B\uparrow}$, however, were higher than those corresponding to the $V_{\nabla B\downarrow}$.

Figure 9b shows core n_{Ar} in "steady state" (solid symbols) and immediately before the H-to-L transition (open symbols) once again plotted against Γ_{Ar}. Argon accumulation in the main plasma was smallest in SNs with a $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift *away from* the X-point (i.e., $V_{\nabla B\downarrow}$). For example, n_{Ar} at $\Gamma_{Ar} \approx 0.5$ torr l/s was 4-5 times higher for the DN with $V_{\nabla B\downarrow}$ than for SNs with $V_{\nabla B\downarrow}$. Alternatively, approximately four times the argon injection rate for SNs would be needed to reach a similar argon concentration that was found for DNs in the $V_{\nabla B\downarrow}$ cases. While our data set for $V_{\nabla B\uparrow}$ is more sparse, it is still clear that the accumulation of argon in the main plasma for SNs with $V_{\nabla B\uparrow}$ was considerably higher than that for SNs with $V_{\nabla B\downarrow}$ (e.g., $\approx 2\text{–}3$

times higher at $\Gamma_{Ar} \approx 0.5$ torr 1/s). The open symbols (i.e., H-L transition) are useful in setting a hard limit on how high Γ_{Ar} can be for these shots.

4. DISCUSSION

ELMing H-mode *SN* plasmas under puff-and-pump conditions demonstrated significantly different behaviors for $V_{\nabla B\downarrow}$ and $V_{\nabla B\uparrow}$. We noted earlier that the outer divertor pump is not as effective in pumping deuterium when the $\boldsymbol{B}x\nabla\boldsymbol{B}$–ion drift was directed toward the X-point. This was also the case for argon. The argon neutral pressure in the outer (upper) divertor pumping plenum was lower in the $V_{\nabla B\uparrow}$ case, implying that the rate at which argon was removed by the upper outer divertor pump was also lower for $V_{\nabla B\uparrow}$. Thus, more argon in the $V_{\nabla B\uparrow}$ case would build up in the divertor and would be "available" to leak out of the upper divertor. Unlike $V_{\nabla B\downarrow}$, the inner leg of the $V_{\nabla B\uparrow}$ plasma detached during argon injection, and this would further enhance the argon leakage from the divertor. Hence, with more argon present in the main chamber, argon would accumulate in the plasma at a higher rate and achieve a higher steady state density for $V_{\nabla B\uparrow}$.

Argon accumulated faster in the main plasma of *DN*s with $V_{\nabla B\uparrow}$ than with $V_{\nabla B\downarrow}$ for reasons similar to those of *SN*s discussed above. For *DN*s, deuterium is not as effectively removed by either of the *outer* divertor pumps when the $\boldsymbol{B}x\nabla\boldsymbol{B}$ drift direction points into the divertor where that pump is located (Table 1). Likewise, we found this true for argon, as evidenced by the lower argon pressure in the upper outer plenum for $V_{\nabla B\uparrow}$. As with the *SN* cases, the argon leakage rate out of upper divertor (where the argon was injected) would be greater for $V_{\nabla B\uparrow}$ than for $V_{\nabla B\downarrow}$, and so more of the injected argon would be available to "fuel" the main plasma.

Strong up/down asymmetries were observed in the divertor radiated power and the divertor argon presence for *DN*s. Even though argon was injected from one poloidal location, argon accumulated in the divertor opposite the $\boldsymbol{B}x\nabla\boldsymbol{B}$ direction and this accumulation led to a greater increase in the radiated power from that divertor over the other divertor. Of particular interest was the $V_{\nabla B\uparrow}$ case, where even though the argon was injected into the upper divertor, the only measurable change in radiated power was observed in the lower divertor, implying that argon was not well confined to the upper divertor. The differences between the two $\boldsymbol{B}x\nabla\boldsymbol{B}$ cases strongly suggests that particle flows that depend on the direction of the toroidal field may be at work. For example, previous work in analyzing particle pumping data from DIII-D [6] indicated that the poloidal distribution of neutrals between inner and outer divertors (and ultimately the exhaust rates of each divertor cryopump) was strongly influenced by $\boldsymbol{B}x\nabla\boldsymbol{B}$ and $E \times B$-induced particle flows in the divertor and SOL. (The electric field driving the $E \times B$ flow is largely generated by the radial gradient of the electron temperature with respect to the flux surfaces in the SOL and divertor.) Efforts to model these cases with the UEDGE edge transport code [13] that include particle drift physics with DN and near-DN geometry are in progress and will be reported elsewhere.

Argon buildup in DNs was higher than in comparable SNs with the same $\boldsymbol{B}x\nabla\boldsymbol{B}$ direction. DNs differ in two important ways from SNs. First, a previous study of DIII-D SN and DN plasmas has shown that the characteristic electron temperature for the inboard SOL plasma of the DN is less than that of a comparable SN, while the SOL density profile is also narrower for the DN [14]. Since both inner divertor targets are only tenuously attached (and even detached), it is relatively easy for neutral deuterium (and argon) to leak into the SOL on the high-field side, and once there, the argon can access the main plasma of the DN more readily than they can for the SN. Second, the SOL of the DN is largely quiescent on the inboard side, because the ELMs, produced almost exclusively on the low-field side, are cut-off from the high field SOL plasma [15]. This quiescence would also facilitate argon "fuelling" of the DN from the high field side.

The leakage of argon out of the divertor and its subsequent buildup inside a *SN* plasma can be reduced by increasing the deuterium flow into the divertor, i.e., by raising Γ_{D2} [1]. Based on the higher deuterium fueling and argon accumulation rates for *DN*s observed in these experiments, such a solution for the *DN* would be problematical, however. First, gas puffing from the low-field side of the *DN* would enhance the deuterium flow into the two divertors on the low-field side of the SOL. However, this would do little to enhance the deuterium flow into the divertors on the high-field side, because the high-field SOL is cut off magnetically from the low-field SOL, leaving no direct route from the low-field side to the high-field side. It may also be problematical whether enhancing deuterium flow into the two inner divertors by puffing deuterium from the midplane *on the high-field side* would induce the deuterium flow necessary to impede the leakage of argon from inner divertor locations. In either case, increasing Γ_{D2} would increase the density of the main plasma if the pumping capability is not increased commensurately. Second, because the particle removal rates of argon (and deuterium) by both outer divertor pumps depend strongly on the direction of $\boldsymbol{B}x\nabla\boldsymbol{B}$, it is again problematical that a chosen value of Γ_{D2} that might be effective in trapping impurities in one of the divertors would be as effective in trapping impurities in the other divertor, e.g., the second pump may not be able to handle the enhanced deuterium flow as efficiently. The poloidal redistribution of the argon impurities suggest that they are subject to significant particle flows in each divertor that at present are not well understood. The issue of applying the standard puff-and-pump technique to *DN* H-mode plasmas will be examined in a future study.

5. CONCLUSION

The success in applying the puff-and-pump approach to ELMing H-mode plasmas is found to depend on the magnetic balance of the plasma configuration and the direction of the toroidal field (or $\boldsymbol{B}x\nabla\boldsymbol{B}$ ion drift). Under conditions representative of DIII-D plasma operation, injected argon impurities penetrate single-null plasmas *with the* $\boldsymbol{B}x\nabla\boldsymbol{B}$*-ion drift directed toward the X-point* (as well as double-null plasmas with $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drifts in either direction) much more readily than single-null plasmas with the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift directed away the from its X-point. Based on this result, the *SN* shape in which the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift is directed *away* from the divertor evidently provides the best chance of successfully coupling a radiating divertor approach with a higher performance H-mode plasma.

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References

[1] M.J. Schaffer, *et al*., J. Nucl. Mater. **241-243** (1997) 585.

[2] M.R. Wade, *et al*., J. Nucl. Mater. **266-269** (1999) 44.

[3] J.A. Goetz, *et al.*, J. Nucl. Mater. **266-269** (1999) 359.

[4] T.W. Petrie, *et al*., "Compatibility of the Radiating Divertor With High Performance Plasmas in DIII-D," (to be published in J. Nucl. Mater., 2007).

[5] T.W. Petrie, *et al*., J. Nucl. Mater. **313-316** (2003) 834.

[6] T.W. Petrie, *et al.,* Nucl. Fusion **46** (2006) 57.

[7] A.V. Chankin, J. Nucl. Mater. **241-243** 199 (1997).

[8] T. Taylor, Plasma Physics and Controlled Fusion **39** (1997) 47.

[9] M. Greenwald, *et al*., Nucl. Fusion **28** (1988) 2199.

[10] P.N. Yushmanov, *et al.*, Nucl. Fusion **30** (1990) 1999.

[11] R. C. Isler, Nucl. Fusion **24** (1984) 1599.

[12] H. P. Summers, "Atomic Data and Analysis Structure," JET Joint Undertaking report JET-IR(94)06, 1994.

[13] T. D. Rognlien, *et al*., Phys. Plasma **34** (1994) 362.

[14] T.W. Petrie, *et al*., J. Nucl. Mater. **313-316** (2003) 834.

[15] T.W. Petrie, *et al*., Nucl. Fusion **43** (2003) 910.

Table 1. The deuterium exhaust percentage of each pump is affected by both $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction and plasma shape: DN $(dRsep = 0\text{ cm})$ versus upper SN $(dRsep = +1\text{ cm})$.

		$V_{\nabla B\downarrow}$		$V_{\nabla B\uparrow}$	
		DN	SN	DN	SN
$\Gamma_{UP-IN} / \Gamma_{TOTAL}$	(x 100%)	11.8	26.5	9.0	50.5
$\Gamma_{UP-OUT} / \Gamma_{TOTAL}$	(x 100%)	63.4	66.7	54.5	36.8
$\Gamma_{LOW-OUT} / \Gamma_{TOTAL}$	(x 100%)	24.8	6.8	36.5	12.7

Table 2. Effect of the $\boldsymbol{B} x \nabla \boldsymbol{B}$-ion drift direction on radiated power for SN H-mode discharges $(dRsep = +1\ \text{cm})$.

	$V_{\nabla B\uparrow}$		$V_{\nabla B\downarrow}$		
	trace Ar	perturbing Ar	trace Ar	perturbing Ar	perturbing Ar
Γ_{D2} (torr liter/s)	108	108	108	108	108
Γ_{Ar} (torr liter/s)	0	1.0	0.20	1.0	1.9
n_e (10^{20} m^{-3})	0.67	0.74	0.61	0.61	0.62
n_{Ar} (a.u.)	0	10	0.6	2.7	5.2
H_{ITER89}	1.9	1.8	1.7	1.7	1.9
P_{IN} (MW)	5.3	5.8	6.0	6.0	6.7
P_{RAD} (MW)	2.3	3.6	2.4	2.8	3.6
$P_{RAD,MAIN}$ (MW)	1.0	1.4	0.8	1.0	1.4
$P_{RAD,DIV}$ (MW)	0.6	1.3	0.9	1.1	1.3
$P_{RAD,SOL}$ (MW)	0.7	0.9	0.7	0.7	0.9

Table 3. Effect of the $\boldsymbol{B}x\nabla\boldsymbol{B}$-ion drift direction on radiated power for DN H-mode discharges $(dRsep = 0 \text{ cm})$.

	$V_{\nabla B\uparrow}$		$V_{\nabla B\downarrow}$	
	trace Ar	perturbing Ar	trace Ar	perturbing Ar
Γ_{D2} (torr liter/s)	108	108	108	108
Γ_{Ar} (torr liter/s)	0	1.0	0	1.0
n_e (10^{20} m^{-3})	0.70	0.71	0.72	0.74
n_{Ar}	0	12	0.6	11
H_{ITER89}	1.7	1.6	1.9	1.8
P_{IN} (MW)	6.4	6.8	6.2	5.8
P_{RAD} (MW)	2.8	3.8	2.7	3.5
$P_{RAD,MAIN}$ (MW)	1.1	1.5	1.1	1.4
$P_{RAD,UPDIV}$ (MW)	0.5	0.5	0.7	0.9
$P_{RAD,LOWDIV}$ (MW)	0.9	1.1	0.7	0.7
$P_{RAD,SOL}$ (MW)	0.3	0.6	0.2	0.5
$(\Gamma_{Ar,U5}/\Gamma_{Ar,L4})$	-	0.4	-	2.0
$(\Gamma_{Ar,U2}/\Gamma_{Ar,U5})$	-	-	-	0.2

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Figure 1. The poloidal locations of particle pumping- and gas injection during the (a) 2005 campaign and (b) 2006 campaign are superimposed on the single-null $(dRsep = +1\text{ cm})$ and double-null $(dRsep = 0)$ plasma cross-sections used in this study. The divertors are the shaded regions. By definition, $dRsep \equiv (R_L = R_U)$, where R_L is the radius at the outer midplane of the lower divertor separatrix flux surface and R_U is the radius at the outer midplane of the upper separatrix flux surface.

Figure 2. Two upper SN $(dRsep = +1\text{ cm})$ H-mode discharges with opposite ∇BxB-ion drift directions, $V_{\nabla B\uparrow}$ (solid) and $V_{\nabla B\downarrow}$ (dashed), are compared:. (a) Deuterium (Γ_{D2}) and argon (Γ_{Ar}) puff rates, (b) line-averaged electron density $(\bar{n}_\mathrm{e})$, (c) relative argon density (n_{Ar}), (d) neutral deuterium pressure in the upper inner pumping plenum (P_{RDP}), (e) signal of bolometer chord passing through the X-point $(Bolo\text{–}Xpt)$, (f) total radiated power (P_{RAD}) and (g) uncalibrated argon pressure inside the upper outer pumping plenum (P_{Ar}); neutrons produced in the experiment were responsible for the spikes on the P_{Ar} traces. “Steady-state” timeslices are denoted by the vertical lines.

Figure 3. Tomographic inversions of bolometric arrays are shown for SNs with $V_{\nabla B\uparrow}$ (a) with deuterium injection only and (b) deuterium and argon injection together. Also shown are inversions for SNs with $V_{\nabla B\downarrow}$ (c) deuterium injection only and (d) deuterium and argon injection together. Only the upper divertor region is shown. Carbon is still the dominant radiator in all cases.

Figure 4. (a) The chords of the divertor spectrometer that view the upper and lower divertors are superimposed on the upper SN plasma shape discussed in the text. The ArII signals are shown as a function of view chord designation (b) for the SN cases and (c) for the DN cases discussed in section 3b of the text. The operational parameters were: $I_P = 1.2$ MA, $\boldsymbol{B}_T = 1.75$ T, $P_{INJ} = 5.8 - 6.4$ MW, and $\Gamma_{Ar} = 0.85 - 1.0$ torr 1/s.

Figure 5. The comparison of DN, $V_{\nabla B\downarrow}$ cases with perturbing (solid) and trace (dashed) argon injection for (a) Line-averaged density, (b) the radiated power from the upper divertor $P_{R,UPDIV}$ and (c) the radiated power from the lower divertor $P_{R,LODIV}$ are shown. The operational parameters were: $I_P = 1.2$ MA, $\boldsymbol{B}_T = 1.75$ T, $P_{INJ} = 6.4$ MW, and $\Gamma_{Ar} = 1.0$ torr 1/s.

Figure 6. The comparison of DN, $V_{\nabla B\uparrow}$ cases with perturbing (solid) and without (dashed) argon injection for (a) Line-averaged density, (b) the radiated power from the upper divertor $P_{R,UPDIV}$ and (c) the radiated power from the lower divertor $P_{R,LODIV}$ are shown. The operational parameters were: $I_P = 1.2$ MA, $\boldsymbol{B}_T = 1.75$ T, $P_{INJ} = 6.0$ MW, and $\Gamma_{Ar} = 0.85$ torr 1/s.

Figure 7. Tomographic inversion of bolometric data for a $V_{\nabla B\downarrow}$ DN case (a) with deuterium injection only and (b) with deuterium and argon injection. The inversions were made at the time designated by the vertical line in Fig. 5. The operational parameters were: $I_P = 1.2$ MA, $\boldsymbol{B}_T = 1.75$ T, $P_{INJ} = 6.4$ MW, and $\Gamma_{Ar} = 1.0$ torr 1/s.

Figure 8. Tomographic inversion of bolometric data for a $V_{\nabla B\uparrow}$ DN case (a) with deuterium injection only and (b) with deuterium and argon injection. The inversions were made at the time designated by the vertical line in Fig. 6. The operational parameters were: $I_P = 1.2$ MA,

$\boldsymbol{B}_T = 1.75$ T, $P_{INJ} = 6.0$ MW, and $\Gamma_{Ar} = 0.85$ torr 1/s.

Figure 9. (a) The initial rates of argon accumulation in SN and DN plasmas is plotted versus Γ_{Ar} for both $V_{\nabla B\downarrow}$ and $V_{\nabla B\uparrow}$ cases. (b) "Steady state" argon accumulation in the main plasma (solid symbols) is plotted versus Γ_{Ar}; hollow symbols represent argon accumulation at the point of the H-L back-transition. The operational parameters were: $I_P = 1.2$ MA, $\boldsymbol{B}_T = 1.75$ T, and $P_{INJ} = 5.8 - 6.4$ MW.