HIGHER PERFORMANCE DOUBLE-NULL PLASMAS UNDER RADIATING DIVERTOR AND MANTLE SCENARIOS ON DIII-D

T.W. PETRIE
General Atomics
San Diego, CA, USA
Email: petrie@fusion.gat.com

B. GRIERSON
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

F. TURCO
Columbia University
New York, NY, USA

T. OSBORNE, C. PETTY, J.R. FERRON, H. GUO, R. LA HAYE, A.W. LEONARD
General Atomics
San Diego, CA, USA

E. HINSON
University of Wisconsin
Madison, WI, USA

S.L. ALLEN, M.E. FENSTERMACHER, C.J. LASNIER, A.G. MCLEAN, B. VICTOR
Lawrence Livermore National Laboratory
Livermore, CA, USA

H. WANG
Oak Ridge Associated Universities
Oak Ridge, TN, USA

J.G. WATKINS
Sandia National Laboratories
Livermore, CA, USA

Abstract

The opportunities and challenges in reducing divertor heat flux in high power, high performance advanced tokamak (AT) plasmas on DIII-D by radiating divertor and mantle approaches are presented. The radial profiles for both intrinsic and injected impurities were much less peaked when the location of the electron cyclotron (EC) deposition was closer to the plasma center. Analysis indicates that EC deposition near the central plasma favored a net screening of impurities from the plasma center, while EC deposition farther out produced a strongly inwardly directed pinch acting on these impurities. DIII-D high performance plasmas were very vulnerable to confinement-draining MHD activity (e.g., 5/2 and 3/1 modes) triggered during impurity injection, and this severely limited the goal of significant divertor heat flux reduction while at the same time maintaining high energy confinement. Moreover, these results were very similar whether the injected seeds were neon or argon. Additional divertor closure enhanced impurity seed presence in the primary divertor for both double null divertor (DND) and single-null divertor (SND) configurations, thus leading to a larger drop in the divertor heat flux in the more closed case. Particle pumping from the high-field side of the DND had little effect in controlling the argon inventory in the cases examined. For the SND configuration, this picture was complicated by whether the inner divertor leg was attached or detached, with significant argon removal by the inner pump only occurring in the former. Finally, previously-reported predictions by ELITE that $T_e$ would improve with power input, $q_{95}$, and magnetic balance closer to the DND shape under prescribed deuterium gas injection scenarios was shown to be largely consistent with experiment, thus providing additional confidence that ELITE analysis can be a useful tool in understanding plasma behavior in higher power, AT plasmas. The plasmas discussed are characterized by: $H_{98} \approx 1.4-1.7$, $b_N \approx 3-4$, $q_{95} \approx 5-7$, neutral beam plus EC power input $P_{IN}$ up to 15 MW, with the distance between the separatrices connected to the upper and lower divertors $|dR_{sep}| = 3-25$ mm.

1. INTRODUCTION

Future tokamaks that have high power exhaust will be faced with the simultaneous needs to avoid damaging
power loads at their divertor targets, to maintain desirable high performance plasma metrics, e.g., elevated energy confinement time and low plasma dilution, and to sustain adequate pumping for particle control. Two approaches that may be helpful in achieving this goal are (1) the radiating “mantle” and (2) the radiating divertor, as, for example, in Refs. 1–4. In the former, seed impurities are injected into the main chamber with the goal that they accumulate in the outer region of the main plasma. This, in turn, would lead to a strong rise in local radiative emissivity and, due to the relatively large radiating volume of the outer plasma, would result in a strong rise in radiated power in the main plasma, a reduction in power flow into the scrape-off layer (SOL), and ultimately lower power deposition at the divertor targets. In the latter approach, “seed” impurities are injected directly into the divertor, where these impurities can radiate a significant fraction of the plasma-conducted power before the plasma particles reach the divertor surfaces. This study focuses on issues that may impede the effectiveness of both radiating mantle and radiating divertor methods, when applied to high power, high performance advanced tokamak (AT) plasmas.

The experimental arrangement and representative plasma parameters are described in section 2. Experimental results are presented in section 3. In section 3.1, the distributions of both the injected and intrinsic impurities inside the main plasma are shown to be heavily dependent on the radial location of the electron cyclotron heating (ECH) deposition. In section 3.2, candidate seed impurities commonly used in radiating mantle or divertor scenarios, such as neon and argon, are shown result in both the formation of confinement-killing MHD and in severe fuel dilution in the core during high power AT operation. In section 3.3, the degree to which seed impurity pumping is affected by divertor closure and divertor magnetic balance is discussed. In section 3.4, the role that an inner divertor pump may play in controlling argon and deuterium inventory in DND and SND configurations is demonstrated. Finally, in section 3.5, recent data that support the predictions made by the ELITE boundary stability code [5] for ways to further improve confinement and fueling in high power, high performance plasmas is presented. In section 4, we summarize our results and present our conclusions.

2. EXPERIMENTAL ARRANGEMENT

We exploit the plasma shaping capabilities of DIII-D in producing the high triangularity, DND and SND shapes generally associated with elevated energy confinement and $\beta_N$. Figure 1 shows examples of both the lower-biased (a) and upper-biased (b) DNDs used in this study. These plasmas were characterized (1) by the ion $B \times VB$ drift directed away from their primary divertor, (2) by particle pumping of deuterium and seed impurities from up to three poloidal divertor locations, and (3) by D$_2$ gas injection from the low-field side and by seed impurity injection from their respective private flux regions and from a non-divertor location.

These high performance ELMing plasmas were also characterized by high energy confinement (e.g., $H_{95} = 1.4 – 1.7$ and $\beta_N \geq 3.0$). Plasma parameters were: $I_p = 1.0–1.2$ MA, $q_{95} = 4.7–6.5$, and total power input ($P_{IN}$) $\approx 11–15$ MW, where the applied ECH provided up to 3.5 MW. Safety constraints limited line-averaged density imposed by concern over ECH cutoff/reflection to $\leq 6.4 \times 10^{19}$ m$^{-3}$ (or $\approx 70\%$ of the Greenwald density) during ECH usage. Except where noted, off-axis ECH deposition was used in these studies.

Since the interior of the DIII-D vessel is protected by graphite tiles, carbon was the main intrinsic impurity. The choice of injected “seed” species for these studies were low-Z recycling neon and medium-Z recycling argon.Heat flux in both divertors were based on infrared (IR) camera measurements. Two Penning gauges provide D$_2$ and seed impurity partial pressures inside the plenums of the two outer divertor pumps; no Penning gauge was available for the upper inner pumping plenum. Electron density and temperature at the divertor targets were based on Langmuir probe measurements, while upstream density and temperature were based on Thomson scattering.
These measurements are taken between type-I ELMs. The radial density profiles of both carbon and seed impurities were based on charge-exchange recombination (CER) measurements.

3. RESULTS

3.1 Effect of ECH deposition location

Radial profiles of both intrinsic (carbon) and seed impurities depended strongly on the radial location of the ECH deposition. Two AT hybrid plasmas with qmin \(\geq 1\) were identically-prepared, except for the deposition locations of the applied ECH. The plasma was a DND, similar to the one shown in Fig. 1(a). Neon was injected from the non-divertor location. When the deposition location was closer to the magnetic axis (i.e., \(\rho_{\infty} \approx 0.20\)), the radial profiles of both the neon and carbon were relatively flat (Fig. 2a,b). For the off-axis ECH deposition case (i.e., \(\rho_{\infty} \approx 0.45\)), however, these profiles were more peaked. As a result, the \(\rho_{\infty} = 0.45\) case had a greater deuterium fuel ion deficit in its central plasma than did the \(\rho_{\infty} = 0.20\) case: \(n_0(0)/n_0(0) = 0.58\) for \(\rho_{\infty} = 0.45\) and 0.74 for \(\rho_{\infty} = 0.20\), where \(n_0(0)\) and \(n_0(0)\) are the on-axis \(D^+\) and electron densities, respectively.

An analysis by the STRAHL impurity transport code [6] backed out the transport properties of the neon by determining the transport coefficients that reproduced the measured neon profiles as the profiles evolved. This analysis indicated a strong inwardly-directed pinch in the deep core for neon in the \(\rho_{\infty} = 0.45\) case. On the other hand, STRAHL indicated a degree of screening of the neon from the central plasma in the \(\rho_{\infty} \approx 0.20\) case.

Hence, the radial location of ECH had a substantial effect on the neon transport coefficients, which was clearly reflected in the final neon density profiles. Other tokamaks have reported similar impurity ion behaviors between ECH applied on-axis and off-axis, e.g., tungsten in ASDEX-U H-mode plasmas [7] and argon in KSTAR L-mode plasmas [8]. A stationary radial profile that exhibits a positive local gradient, as seen in Fig. 2 (black curves), can be produced with a non-diffusive positive outward particle transport mechanism. An assessment of the neoclassical and turbulent particle transport responsible for this result is ongoing, but these results resemble studies of high-Z impurity transport in hybrid plasmas in JET [9].

3.2 Effect of impurity selections on deterioration in fuel dilution and triggering MHD

While issues related to unacceptable fuel dilution and inimical MHD activity can be found in tokamak plasmas under a variety of operating conditions, these issues can be particularly troublesome in plasmas at high power input and \(\beta_0\). In this section, we show how reducing divertor heat flux with the buildup of highly radiating seed impurities inside the main plasma, either by design (i.e., by radiating mantle) or inadvertently (e.g., by leaky divertor), can easily compromise high power, high \(\beta\) operation.

We first compare an argon-based radiating mantle with a neon-based radiating mantle. Both had the same 40% reduction in peak divertor heat flux, i.e., from 4.5 MW/m² to 2.6 MW/m², as well as the same initial \(\beta\) (\(\approx 3.5\)), \(H_{98} (\approx 1.5)\), power input (\(\approx 14.5\) MW), and lower-biased DND (dRsep = -7mm). Central electron and ion temperatures for both cases were 4 keV and 6 keV, respectively. Profiles of the radiative emissivity for the neon and argon cases are shown in Fig. 3(a). For comparison, a control case, i.e., no impurity injection, is included. Strong radiative peaking in the edge region of the main plasma (i.e., the "mantle") in both neon and argon cases was largely responsible for nearly doubling the total radiated power in the core relative to the control case. Since
argon was not completely ionized on-axis and the neon was, emissivity for the argon case was much higher on axis.

The density profiles for Ne\textsuperscript{10+} and Ar\textsuperscript{16+}, as determined from CER analysis, are shown in Figs. 3(b,c). The high power input used to heat these plasmas required a significant impurity seed buildup inside the plasma in order to provide the radiated power needed to assure a tolerable heat flow into the SOL. As a result, the cost to fuel dilution of using either argon or neon-based radiating mantles was severe. STRAHL analysis to date has indicated that Ar\textsuperscript{16+} is the dominant charge state of argon for \( \rho = 0.80-0.85 \). The estimated fuel dilution \((n_D/n_e)\) at \( \rho = 0.8 \) is \( \approx 0.65 \), although when all the argon charge states are accounted for in the final analysis, this estimate may prove optimistic. For the neon mantle at \( \rho = 0.8 \), dilution was worse, i.e., \( n_D/n_e \approx 0.28 \). For comparison, fuel dilution in the control case was also problematical, i.e., \( n_D/n_e \approx 0.74 \), and was due to significant carbon buildup in the core during high PIN operation. The source of the carbon was largely from the SOL plasma interacting with the divertor graphite tiles.

While avoiding fuel dilution can be challenging in itself under these conditions, confinement-robbing MHD activity triggered during impurity injection also presents severe problems. Figure 4(a1) is the MHD spectrogram for a control shot, i.e., no seed impurity injection. A steady \( m=4/n=2 \) mode was present over the times of interest, i.e., between 2.5 s (well-established target plasma shape) and 4.8 s (near the start of ramp-down in power input). The spectrograms for plasmas with neon injection (Fig. 4(b1)) and argon injection (Fig. 4(c1)) also had a 4/2 mode present initially. The amplitudes of this 4/2 mode were comparable in these three cases, i.e., 2.1 G to 2.5 G. A low amplitude bursty 1/1 mode, possibly fishbones and common to all three plasmas, was also observed. In addition to the 4/2 mode, other modes appeared during seed-injection. In both neon and argon injection cases, 5/2 and 3/1 modes were triggered \( \approx 1 \) second and \( \approx 2 \) seconds, respectively, after impurity injection began. These modes clearly impacted energy confinement. The effect that each of these MHD modes had on plasma energy confinement can be estimated using the “belt model”, which estimates the loss to plasma pressure based on the radial location and width of the MHD mode \([10]\). From this, the cost in energy confinement from the presence of the 4/2 mode was found to be a modest 4-6\% at \( t = 2.5 \) s in the three cases discussed above, as shown in Fig. 4(a2, b2, c2). The triggering of additional MHD modes during both neon and argon injection further degraded energy confinement. For argon, we estimate that by 4.0 s the 5/2 mode had degraded \( \tau_e \) by an additional \( \approx 8\% \) relative to \( \tau_e \) at \( t = 2.5 \) s (Fig. 4(c2)), and by \( t = 4.8 \) s, we estimate the presence of both 5/2 and 3/1 modes (but without the 4/2 mode) had reduced \( \tau_e \) by \( \approx 20\% \) relative to

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**Fig. 3.** (a) Radial profile of the radiative emissivity for the control plasma case (black), for the neon-seeded plasma case (red), and for the argon-seeded plasma case (green). (b) Radial profile for Ne\textsuperscript{10+} from the neon case. (c) Radial profile for Ar\textsuperscript{16+} from the argon case.

**Fig. 4.** (a1) Spectrographs are shown for a control shot, (b1) for the neon-seeded shot, and (c1) for the argon-seeded shot. The theoretical loss in energy confinement is plotted in (a2), (b2), and (c2). The vertical lines denote the times when impurity puffing was initiated.
$\tau_e$ at $t = 2.5$ s. These predicted losses in energy confinement are consistent with the data. The experimentally measured decrease in $\tau_e$ by $t = 4.8$ s was $\approx 22\%$ relative to its 2.5 s value. A similar analysis was carried out for the neon case and again we find consistency between the predicted reduction in energy confinement time between 2.5 s and 4.8 s ($\approx 19\%$) and the measured reduction in $\tau_e$ ($\approx 17\%$). The contribution of each MHD mode to plasma energy reduction was treated as additive. Attempts to avoid triggering the harmful 5/2 and 3/1 modes by reducing the argon or neon injection rates in order to provide a more controlled plasma evolution were unsuccessful. The above cases use off-axis ECH.

### 3.3 Effect of divertor closure and magnetic balance on particle exhaust

A more closed divertor had a measurable effect on where seed impurities in SNDs and DNDs were pumped. In particular, divertor closure contributed to localizing where the argon was pumped. Before proceeding, however, it is important to show that good particle accountability, e.g., the number of seed impurities that are removed by pumping is consistent with the number of seeds that are injected into the system. Argon was the seed impurity used here and, in all cases, argon was injected into the private flux region (PFR) of the primary divertor. Argon was removed by the two cryopumps that were adjacent to the outer divertor legs. The upper inner pump was de-activated to ensure that argon was pumped only from locations covered by Penning gauges. Both double-null and single-null configurations were considered. Figure 5 indicates that good particle accountability for argon was achieved. The argon that was injected into the PFR of the primary divertor was pumped at a 10-20% higher rate in the closed (upper) divertor than in the more open (lower) divertor. This was true for both the DND ($|dR_{sep}| = 3$ mm) and the SND ($|dR_{sep}| = 21$ mm), as shown in Fig. 6(a) and Fig. 6(b), respectively. For the same argon injection rate, the argon removal rate for both the upper-biased DND and SND (red circles in Fig. 6(a,b)) was $\approx 10-20\%$ higher in this closed configuration than if the DNDs and SNDs were biased toward the more open lower divertor (black squares in Fig. 6(a,b)). Hence, the improved closure led to stronger localized argon removal in the primary divertor of both DND and SND cases. Since the pumping speeds of the upper and lower outer pumping systems are nearly equal (i.e., 36000 liters/s), higher pumping rates imply a higher argon presence in the closed divertor. And a higher argon presence in the closed upper divertor would be favorable to lower divertor heat fluxes. In fact, for the cases examined, a $\approx 20\%$ lower divertor peak heat flux was observed in the more closed divertor cases.

#### 3.4 Contribution of the inner pump to argon inventory

Recent experiments have addressed questions related to active particle pumping on the inboard side of upper-biased DND and SND high power AT plasmas. The results are summarized in

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**Fig. 5.** The argon injection rate ($\Gamma_{\text{AR-INJ}}$) is approximately equal to the argon exhaust rate ($\Gamma_{\text{AR-EXH}}$), as measured by the two Penning gauges described in section 2.

**Fig. 6.** Argon removal rate for the upper and lower outer divertor pumps is shown as a function of the argon injection rate for both double-null (a) and single-null (b) configurations. Upper-biased plasmas are in red and lower-biased plasmas are in black. Circles represent pumping from the upper divertor and squares connote pumping from the lower divertor.
Tables 1 and 2. Argo was injected at low, medium, and high levels. For each injection level, we examined argon removal in two similarly-prepared AT plasmas, one in which the inner pump was activated and the other in which the inner pump was not activated.

For the DND case, the upper inner pump had virtually no role in argon removal at any of the argon injection levels (Table 1). The exhaust rate of the inner pump ($\Gamma_{\text{AR-ID}}$) was determined by inference, i.e., $\Gamma_{\text{AR-ID}} = \Gamma_{\text{AR-INJ}} - \Gamma_{\text{AR-UOD}} - \Gamma_{\text{AR-LOD}}$, and is denoted with an asterisk. At each $\Gamma_{\text{AR-INJ}}$ level, the upper outer divertor pumping rate for argon ($\Gamma_{\text{AR-UOD}}$) and lower outer divertor pumping rate for argon ($\Gamma_{\text{AR-LOD}}$) changed very little whether the inner pump was activated or not. This would be consistent with previous studies where argon injected into the private flux region of the upper divertor and ionized in the upper divertor would be preferentially swept away from the inner divertor target toward the outer target by $E \times B$-based particle flow [11,12]. Here, $E_r$ is the radial electric field pointing into the PFR and $B$ is the total magnetic field. Finally, in all cases the inner pump removed only $\approx 10$ - $15\%$ of the deuterium injected into the main chamber.

Repeating these comparisons for the SND cases led to more complicated results (Table 2). For low $\Gamma_{\text{AR-INJ}}$, activating the inner pump made no difference in the argon pumped, similar to the DND result. For moderate $\Gamma_{\text{AR-INJ}}$ and higher deuterium gas puffing, the plasma is cooled but still attached, so that $E_r \times B$-driven flow is weakened sufficiently to allow some ionized argon in the PFR to diffuse over the upper inner target, and (3) At high $\Gamma_{\text{AR-INJ}}$, the inner divertor leg is no longer in contact with the inner divertor target, so that argon presence near the inner divertor pump entrance is greatly reduced and inner divertor pumping becomes negligible. Whether or not these SND plasmas are attached, deuterium exhaust by the inner pump still accounted for $\approx 30\%$ - $40\%$ of the deuterium removed.

### 3.5 Improved energy confinement scheme tested

Previous experiments dealing with highly powered DND plasmas have found that the energy confinement time could be improved by at least 10% during a density ramp via deuterium gas injection. As detailed in [13], this improved performance was shown to be tied to higher pedestal pressure which, according to peeling-ballooning mode stability analysis with ELITE, increased with density along the kink/peeling stability threshold. On the other hand, the pedestal pressure gradient at lower power would be limited by the ballooning threshold. ELITE analysis identified plasma conditions that could facilitate access to this improved performance, specifically (a) very high $P_{\text{IN}}$, (b) proximity to magnetic balance, and (c) higher $q_{95}$. In this section, we summarize recent experiments that have directly tested these predictions.

(a) **Power dependence:** We successfully reproduced the plasma discharge, first observed in 2014 [13], and showed that $\tau_e$ improved as density was raised via deuterium gas puffing at high power input ($\approx 15$ MW).
Differences in ECH deposition locations (i.e., $\rho_{ECH} = 0.2$ in 2014 versus $\rho_{ECH} = 0.45$ in the 2017 experiment) did not have a discernable impact on the observed improvement in energy confinement. In the 2017 experiment, three DND plasmas were heated at power levels of 11-, 13- , and 15 MW under a steady deuterium gas injection rate of 60 Torr l/s. Baseline $H_{98}$ and $\beta$, were 1.5 and 3.5, respectively. There was a 15% improvement in $H_{98}$ and $\beta$, with the highest power case, virtually no change for $H_{98}$ and $\beta$, in the intermediate $P_{IN}$ case, and a 15-20% deteriorations in $H_{98}$ and $\beta$, at the lowest power case. These results are consistent with ELITE projections that a minimum power input of 12-13 MW would be necessary to trigger this improved energy confinement regime [13].

(b) $q_{95}$ dependence: According to ELITE, $\tau_s$ would improve during deuterium gas injection at higher safety factor $q_{95}$. For the parameters used in this study (Fig. 7(a)), ELITE predicted that for a $q_{95} = 6.1$ case, $H_{98}$ and $\beta$, would improve with deuterium gas injection but deteriorate at lower $q_{95} (= 4.9)$. For the same level of deuterium gas puffing used in the $P_{IN}$ scan discussed above, Fig. 7(b) shows that the line-averaged plasma density for the $q_{95} = 6.1$ case increased almost 50% between 2.5 s and 3.8 s, while density for the 4.9 case increased by only 10%. For the $q_{95} = 6.1$ case, $H_{98}$ increased from 1.50 to 1.70 between 2.5 s and 3.8 s and $\beta$, increased from 3.55 to 4.01 (Fig. 7(c,d)). For the $q_{95} = 4.9$ case, $H_{98}$ decreased from 1.58 to 1.48 between 2.5 s and 3.8 s and $\beta$, decreased from 3.55 to 3.45.

(c) Magnetic balance dependence: Finally, ELITE predicted that improvement of energy confinement would become increasingly difficult as the magnetic balance moves farther from the double-null plasma shape. We considered three values of magnetic balance, i.e., $drse = -0.75$ cm (near-DND), -1.50 cm, and -2.25 cm (quasi-SND). From the experiment, the near-DND case showed $H_{98}$ up 15% and $\beta$, up 12%. With the intermediate $drse$, positive changes in both $H_{98}$ and $\beta$, were < 5%. For the $drse = -2.25$ cm case, both $H_{98}$ and $\beta$, decreased 5-10%. ELITE analysis for these discharges predicted that any improvement in $H_{98}$ and $\beta$, would vanish closer to $drse = -1.0$ cm.

4. Summary and Conclusions

These studies are part of a continuing effort to identify issues that may arise when the radiating mantle or radiating divertor approaches for reducing divertor heat flux are applied to highly powered, high performance DND and SND plasmas on DIII-D. Although analysis on several of the topics discussed in the paper is ongoing, there are several important observations to be made. ECH deposition well away from the plasma center produced more strongly peaked impurity concentrations than cases with ECH deposition closer to the plasma center. Plasmas that require off-axis ECH, necessary for creating broader current profiles, do not limit the inward particle pinch, as noted in section 3.1, and are susceptible to low-Z (neon) accumulation on-axis, and, as reported by tokamaks with tungsten walls, to high-Z accumulation (tungsten) on axis. At present, DIII-D surfaces inside the vessel are graphite, and so high-Z metal influx from the walls or divertor is not a concern. The inward particle pinch, however, does complicate a successful application of the radiating mantle or radiating divertor approaches to promising high power AT operating modes, such as “high q_{MIN}”, which requires significant off-axis ECH deposition. On the other hand, on-axis ECH, which is often used in hybrid-based scenarios, does suppress low-Z (neon) impurity accumulation on-axis, so that on-axis ECH deposition would be compatible with radiating mantle and divertor operation. At present, the key issue in applying radiating scenarios to high power hybrid plasmas is a diagnostic-related safety concern that limit plasma density to relatively low values (e.g., $\leq 6 \times 10^{19}$ m$^{-3}$). If this “density limit” can be raised (e.g., by modifying the ECH launch configuration), then these radiative scenarios for hybrid would become much more effective (see below). In previous studies at lower $P_{IN}$ ($P_{IN} = 7$–10 MW), peak divertor heat flux for hybrid plasmas was reduced by a factor of 2-3 by using an argon-based radiating divertor, while still maintaining reasonable fuel dilution ($n_{Ar}/n_e \geq 0.8$), $H_{98}$ ($\approx 1.2$–3.3), and $\beta_{IN}$ ($\approx 2.4$) [14]. In reducing divertor heat flux in the high power ($P_{IN} \approx 14$ MW), high
performance $H_{99} \approx 1.5$ and $\beta_N \approx 3.5$) DND plasmas examined in the paper, impurity buildup in the main plasma resulted in significant dilution of the fuel specie (D). Because of the limits on density set by ECH, raising background density sufficiently in order to enhance radiated power and still maintaining relatively low impurity levels is not an option. Instead, reducing divertor heat flux at higher levels of $P_{99}$ demands an ever-higher seed impurity density to reach the required radiated power. Ultimately, this leads to an unacceptable fuel dilution, as discussed in section 3.2, and the “pure” radiating mantle not effective, at least for DIII-D high performance plasmas that use ECH. Of more general consequence, “seeding” a radiating mantle consistently triggered confinement-killing MHD. Avoiding or at least mitigating deleterious MHD activity during impurity injection is essential to successful mantle operation. Methods requiring a radiating divertor for these high $\beta$ plasmas are also susceptible, if there is unacceptably high seed leakage out of the divertor. In sum, if the radiating mantle/divertor-based scenarios are to be compatible with the high power, high performance plasmas planned for DIII-D, high levels of fuel dilution and deleterious MHD are high priority issues requiring immediate attention.

Improving divertor closure resulted in more localized impurity seed pumping and importantly a higher argon presence in the closed upper divertor was favorable to lowering divertor heat fluxes in the primary divertor. For example, a ~20% lower divertor peak heat flux was observed when the more closed divertor was compared with the more open divertor. This would support efforts to modify divertor configuration ongoing at DIII-D (and other tokamaks) in order to optimize the positive effect(s) of divertor closure.

The results presented in section 3.4 have implications for future tokamak design. In particular, the need for an inner divertor pump to remove argon and deuterium in DNDs is shown to be minimal when the ion $B \times \nabla B$ drift is directed away from their primary divertor. Pending further investigation, of course, such a result would suggest that a futuristic tokamak that uses the high triangularity DND configuration in achieving high $\beta_N$ and $H_{99}$ may not need inner divertor pumping to control impurity and deuterium inventory. This would considerably simplify design. However, for futuristic tokamaks based on SND configuration, the results presented in the paper point to the need of an inner divertor pump.

Experimental support for the projections made by the ELITE boundary stability code to improve energy confinement and achieve high $\beta_N$ in high power AT DND plasmas has provided additional confidence in predicting one route for successfully accessing high performance regimes on DIII-D (e.g., $\beta_N = 4 - 5$). Moreover, the relatively rapid rise in plasma density that accompanies this improved particle and energy confinement during D2 gas injection is another very positive development. The ease in fueling observed during high power high performance experiments on DIII-D would provide a very useful tool in fueling futuristic high-powered plasmas with large cross-sections, such as those in DEMO-class cases.

ACKNOWLEDGEMENTS

Work supported by the U.S. Department of Energy under DE-FC02-04ER54698, DE-AC52-07NA27344, DE-FG02-04ER54761, and DE-AC04-94AL85000. DISCLAIMER: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof: DIII-D data shown in this paper can be obtained in digital format by following the links at https://fusion.gat.com/global/D3D_DMP.

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