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The Effect of Magnetic Balance and Particle Drifts on Radiating Divertor Behavior in DIII-D Ex-D

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Recent DIII-D experiments indicate that both magnetic balance and particle drifts play an important role in minimizing the rate of core argon accumulation during “puff and pump” radiative divertor operation in high performance H-mode tokamak plasmas [1]. The ion $\boldsymbol{B}x\boldsymbol{\nabla}\boldsymbol{B}$ drift direction is observed to have a large effect on core argon accumulation (~ factor of 4) while operation in a near double-null configuration reduces the argon accumulation rate by a factor of 2 relative to double-null operation (Fig. 1). Utilizing these two effects together, successful radiative divertor operation in a high performance H-mode plasma has been demonstrated with $\tau_E/\tau_{89P} = 1.8\text{-}2.1$, $\beta_N = 2$, $n_e/n_{eG} = 0.6\text{-}0.7$, $P_{RAD}/P_{INJ} \approx 0.6\text{-}0.7$, and $Z_{eff} \approx 2$. These observed sensitivities to magnetic balance and particle drifts are much greater than that observed when comparing the relative effects of divertor closure (i.e., open vs closed). These results have important implications for the design of future fusion devices that will require high radiative fraction while maintaining a clean, high performance core plasma.

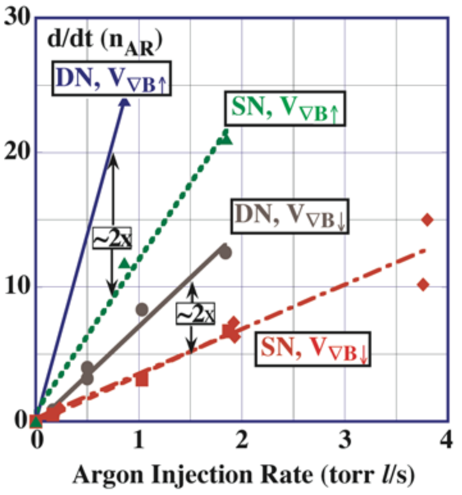

Fig. 1. The initial rate at which argon accumulated in a DN is roughly twice that of a SN, given the same $\boldsymbol{B}x\boldsymbol{\nabla}\boldsymbol{B}$ direction.

In these studies, two fundamental plasma cross-sections were used: (1) the magnetically *balanced* double-null plasma, which we denote as “DN” and (2) the magnetically *unbalanced* double-null with $|dRsep| \simeq 1.2$ cm, which we denote as “SN.” Argon (Ar) was injected into either of two private flux regions (PFRs). Plasma flows to the divertor were enhanced by a combination of exhaust near the divertor targets and deuterium (D_2) gas puffing upstream of the divertor.

ELMing H-mode SN plasmas with identical shape and puff-and-pump waveforms behaved very differently, depending on whether the direction of the ion $\boldsymbol{B}x\boldsymbol{\nabla}\boldsymbol{B}$ drift was *toward* (V∇B↑) or *away from* (V∇B↓) the X-point of the dominant divertor into which the argon was injected. Roughly 90% of the injected argon was removed by the outer divertor pump for the V∇B↓ case, while only ≈35% of the argon was similarly pumped for the V∇B↑ case. This resulted in greater argon leakage into the main chamber for the V∇B↑ case, and ultimately faster argon accumulation in the main plasma (dn_{AR}/dt in Fig. 1), as well as a higher steady-state argon density in the main plasma.

For DNs, argon accumulated significantly faster inside the main plasma when $\boldsymbol{B}x\boldsymbol{\nabla}\boldsymbol{B}$ was directed *toward* the divertor with the argon source (V∇B↑) than when it was directed *away from* that divertor (V∇B↓). In addition, the fraction of Ar pumped in the divertor with the argon source was also higher (i.e., ≈75% for V∇B↓ and ≈20% for V∇B↑). Hence, the leakage of Ar particles from the divertor for the V∇B↑ case was greater than it was for the corresponding V∇B↓ case, and, as with the SN, more of the injected argon was available to contaminate the main plasma.

Important characteristics for these DNs were strong up/down asymmetries in Ar accumulation and radiated power observed in the two divertors. The Ar accumulated in the divertor opposite the direction of the ion ***Bx∇B*** drift, regardless of which divertor served as the argon source, and led to a corresponding asymmetry in the divertor radiated power, as shown in Fig. 2(a,b). This suggests that particle flows in the scrape-off layer (SOL) and divertor(s) that depend on the direction of the toroidal field may play a role. Previous analysis [2] of pumping data from DIII-D indicated that the poloidal distribution of neutrals between inner and outer divertors was strongly influenced by ***Bx∇B*** and ***ExB***-induced particle flows in the divertor and SOL. (The electric field driving the ***ExB*** flow is largely generated by the radial gradient of the electron temperature with respect to the flux surfaces in the SOL and divertor.) The role of these particle flows will be discussed in detail in the context of UEDGE [3] analysis.

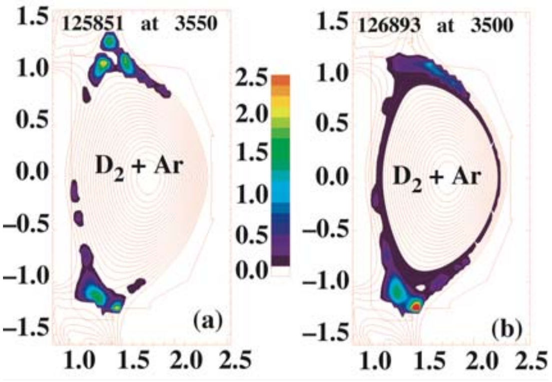

Fig. 2. Bolometrically-inverted radiation distributions for H-mode plasmas under puff-and-pump conditions always show higher radiated power in the divertor opposite the ion ***Bx∇B*** drift direction. (a) ion ***Bx∇B*** directed toward lower divertor and (b) ion ***Bx∇B*** directed toward upper divertor.

Argon accumulated in the main plasma of DNs at about twice the initial rate as in the corresponding SNs with the same ion ***Bx∇B*** direction. This is because DNs differ in three important ways from SNs. First, the characteristic electron temperature for the SOL plasma on the high-field side (HFS) of the DN is less than that of a comparable SN, and the SOL density profile is also much narrower [4]. Since both inner divertor targets of DNs are typically only tenuously attached to begin with, full detachment of the inner divertor legs occurs relatively easily during puff-and-pump operation, resulting in a less obstructed route for Ar to leak into the SOL on the HFS and a more direct access of the Ar to the main plasma than for SNs. Second, the leakage of Ar out of the divertor and the subsequent buildup of argon inside a SN plasma can be reduced by increasing the D_2 flow into the divertor, e.g., by increasing the gas puff rate Γ_{D2} upstream of the divertor targets [1]. However, gas puffing from the low-field side of the DN does little to increase the D_2 flow into the divertors on the HFS, because the HFS SOL is magnetically isolated from the LFS SOL. Third, since the exhaust rates of argon (and D_2) by both outer divertor pumps depend strongly on the direction of the ion ***Bx∇B*** drift, it is problematical that a given value of Γ_{D2} that is effective in trapping impurities in one divertor would be as effective in trapping impurities in the other divertor.

The behavior of H-mode plasmas in a puff-and-pump, radiating divertor environment to different ion ***Bx∇B*** drift directions, divertor magnetic balance, and divertor closure should be particularly relevant for ITER radiating divertor scenarios.

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