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Applying the Radiating Divertor Approach to Innovative Tokamak Divertor Concepts

EX-D

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The effectiveness of three innovative tokamak divertor concepts in reducing divertor heat flux while maintaining acceptable plasma confinement under radiating divertor (RD) conditions has been assessed in DIII-D. These concepts include: (1) high performance standard double-null divertor (DND) plasmas, (2) high performance double-null "snowflake" (SF-DN) plasmas, and (3) single-null H-mode plasmas with different isolation from their divertor targets (Fig. 1). In general, all three concepts are attractive, achieving reduced divertor heat flux and good H-mode confinement. Significant reductions in both divertor heat flux and electron temperature were observed in both standard DND and SF-DN plasmas under neon/deuterium-based RD conditions, while still maintaining high performance metrics, e.g., $\beta_N \cong 3.0$ and $H_{98(Y,2)} \cong 1.4$. It is demonstrated that not only is the peak heat flux ($q_{\perp,P}$) reduced by extending the parallel connection length ($L_{//-XPT}$) in the scrape-off layer (SOL) between the X-point and divertor targets, but also partial detachment at the outer divertor target under RD conditions occurred at lower density in the longer $L_{//,XPT}$ cases.

For the DND plasmas [Fig. 1(a)], $q_{\perp,P}$ was reduced after the RD was applied by more than 50% and 85% at the outer and inner targets, respectively, while $\beta_N \cong 3.0$ and $H_{98(Y,2)} \cong 1.35$ were maintained. Due to strong edge radiated power during RD, however, the task of maintaining the profile in the current density was exacerbated, e.g., the *minimum* of the safety factor profile, initially at $q_{min} \cong 1.5$, approached 1.0 near the end of the RD discharge. Typically under these RD conditions, less than 20% of the power input P_{IN} (=10-13 MW) was radiated inside the separatrix, while more than 40% was radiated outside the separatrix. The fuel dilution fraction in the core was typically 15%-30%, although fuel dilution levels could be much higher for impurities injected from poloidal locations

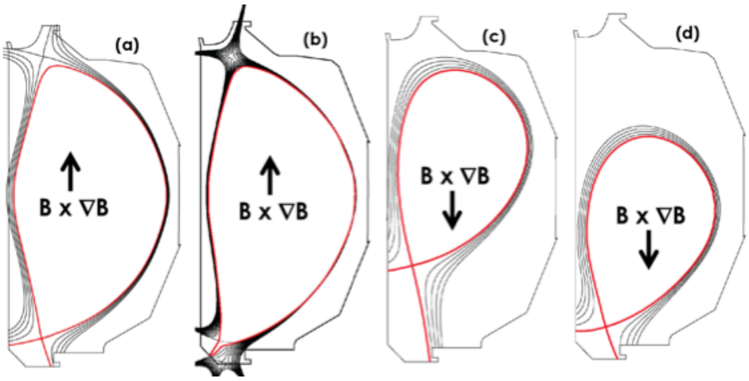

Fig. 1. Plasma performance under RD evaluated for: (a) DND that is magnetically biased toward the lower (primary) divertor (dRsep = -0.5 cm), (b) double-null with "Snowflake" lower divertor and upper (secondary) divertor similar to the DND to (a), (c) longer outer divertor leg ($L_{//-XPT}$ = 25 m) and (d) the corresponding shorter outer divertor leg ($L_{//-XPT}$ = 17 m). The impurities (neon) were injected into the PFR of the primary (lower) divertor and deuterium from a main chamber location.

other than from the private flux region (PFR) of the primary divertor; UEDGE indicates that this is due largely to the effects of particle drifts in the SOL/divertor. We deployed β_N feedback during RD operation, and this resulted in $q_{\perp,P}$ at the *secondary* (upper) outer divertor target *increasing*. The peak density $\bar{n}_{e,P}$ at each of the three targets increased with line-averaged density n_e, as expected [Fig. 2(a)]. However, while the peak temperatures $T_{e,P}$ at both inner and outer divertor targets in the (lower) primary divertor decreased with increasing n_e, $T_{e,P}$ at the upper outer (secondary) divertor target showed no decrease [Fig. 2(b)]. The peak heat fluxes ($q_{\perp,P}$) at the lower divertor targets fell sharply with increasing $\bar{n}_e$, but $q_{\perp,P}$ in the upper divertor increased by about 70% [Fig. 2(c)]. This was largely due to the higher power input (P_{IN}) required to compensate for the drop in τ_E while maintaining constant β_N.

High performance SF-DN plasmas mirrored the results of high performance DNDs under comparable RD conditions, in maintaining both high performance metrics and reduced heat flux in the primary divertor. Due to nearly identical inner divertor geometry, their respective heat flux profiles under their *inner* divertor legs were similar to each other, both prior to and during gas injection [Fig. 3(a,c)]. However, the peak heat flux profile of the SF-DN at the outer divertor target was about a factor of two lower than the DND case, both before and during RD operation [Fig. 3(b,d)]. Neon impurity build up in the main plasma, however, was 15%-20% higher in the SF-DN under similar RD operating conditions, leading to a higher dilution fraction. This may result in part from the difficulty in pumping the SF-DN at the outer divertor target due to the broad density profile under the outer divertor leg.

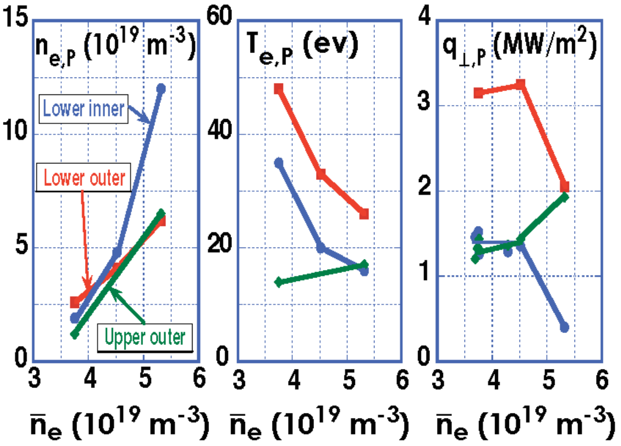

Fig. 2. Divertor plasma behavior at three of the four divertor targets (color-coded) of the DND [Fig. 1(a)] as a function of line-averaged density: (a) peak density, (b) peak temperature, and (c) peak heat flux. Parameters: q_{95} = 4.7, $H_{98(y,2)}$ = 1.1-1.4, P_{IN} = 9-12 MW and n_e/n_G = 0.45-0.63.

The plasma configuration with longer $L_{//\text{-}XPT}$ [Fig. 1(c)] had lower peak heat flux than that with the shorter $L_{//\text{-}XPT}$ [Fig. 1(d)] at lower density, e.g., $\bar{n}_e/n_G$=0.3. SOLPS modeling has indicated that cross-field transport between the X-point and the divertor target is an important process here, resulting in a broadened heat flux profile and reduced $q_{\perp,P}$. Under comparable RD conditions at higher density, e.g., $\bar{n}_e/n_G$=0.5-0.6, the longer $L_{//,XPT}$ cases maintain a clear advantage in heat flux reduction over the shorter $L_{//,XPT}$ cases by at least 50%. Moreover, partial detachment at the outer divertor target under RD conditions occurred at lower density in the longer $L_{//,XPT}$ cases.

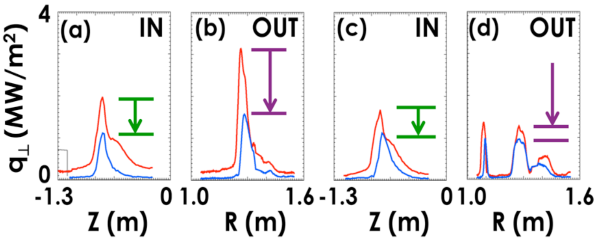

Fig. 3. Heat flux profile of DND [Fig. 1(a)] and corresponding SF-DN [Fig. 1(b)] plasmas during both non-puff (red) and full radiating divertor (blue) cases; Inner and outer divertor target of the DND (a,b); and SF-DN (c,d). Parameters: q_{95} = 5.2, $H_{98(y,2)}$ = 1.2-1.4, P_{IN} = 10 MW, and n_e/n_G = 0.45-0.6

These studies represent a first systematic step in examining potential solutions to the excessive power loading expected in future generation high-powered tokamaks. We re-iterate that all three concepts are attractive, with good heat flux control and energy confinement.

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