APPLYING THE RADIATING DIVERTOR APPROACH TO INNOVATIVE TOKAMAK DIVERTOR CONCEPTS

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APRIL 2014
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This is a preprint of the synopsis for a paper to be presented at the Twenty-Fifth IAEA Fusion Energy Conf., October 13-18, 2014 in Saint Petersburg, Russia.

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Work supported by the U.S. Department of Energy under DE-FC02-04ER54698, DE-AC52-07NA27344, DE-AC02-09CH11466, DE-FG02-07ER54917, DE-FG02-04ER54761, and DE-AC04-94AL85000

GENERAL ATOMICS PROJECT 30200 APRIL 2014
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Tokamak Divertor Concepts

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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., $\beta_N \approx 3.0$ and $H_{88(Y,2)} \approx 1.4$. It is demonstrated that not only is the peak heat flux
($q_\perp$) 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)], $q_\perp$ was reduced after the RD was applied by more than
50% and 85% at the outer and inner targets, respectively, while $\beta_N \approx 3.0$ and $H_{88(Y,2)} \approx 1.35$
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 $q_{\text{min}} = 1.5$, 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
d($dR_{\text{sep}} = -0.5$ 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 $\beta_n$ feedback during RD operation, and this resulted in $q_{\perp}$ at the secondary (upper) 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 $n_e$, 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 $\tau_e$ while maintaining constant $\beta_n$.

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.

The plasma configuration with longer $L_{\perp,XPT}$ [Fig. 1(c)] had lower peak heat flux than that with the shorter $L_{\perp,XPT}$ [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 $L_{\perp,XPT}$ cases maintain a clear advantage in heat flux reduction over the shorter $L_{\perp,XPT}$ cases by at least 50%. Moreover, partial detachment at the outer divertor target under RD conditions occurred at lower density in the longer $L_{\perp,XPT}$ cases.

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.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698, DE-AC05-00OR22725, DE-AC04-94AL85000, DE-AC52-07NA27344, and DE-FG02-07ER54917.