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by


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EFFECT OF CHANGES IN SEPARATRIX MAGNETIC GEOMETRY ON DIVERTOR BEHAVIOR IN DIII-D

by

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Abstract. We report results and interpretation of recent experiments on DIII-D designed to evaluate divertor geometries favorable for radiative heat dispersal. Two approaches studied involved lengthening the parallel connection in the scrape-off layer, $L_{||}$, and increasing the radius of the outer divertor separatrix strike point, $R_{OSP}$, with the goal of reducing target temperature, $T_{TAR}$, and increasing target density, $n_{TAR}$. Based on 1-D two-point modeling: $n_{TAR} \propto [R_{OSP}]^2 [L_{||}]^{6/7} [n_{SEP}]^3$ and $T_{TAR} \propto [R_{OSP}]^{-2} [L_{||}]^{-4/7} [n_{SEP}]^{-2}$, where $n_{SEP}$ is the midplane separatrix density. These scalings suggest that conditions conducive to a radiative divertor solution can be achieved at low $n_{SEP}$ by increasing either $R_{OSP}$ or $L_{||}$. Our data are consistent with the above $L_{||}$ scalings. On the other hand, the observed dependence of $n_{TAR}$ and $T_{TAR}$ on $R_{OSP}$ displayed a more complex behavior, under certain conditions deviating from the above scalings. Our analysis indicates that deviations from the $R_{OSP}$ scaling were due to the presence of convected heat flux, driven by escaping neutrals, in the more open configurations of the larger $R_{OSP}$ cases.

1 Introduction

Future high-powered tokamaks will require a means of reducing heat load on the divertor targets. Prior investigations have shown that steady power load can be reduced with radiating divertor approaches [1–4] although projecting such approaches to future generation tokamaks is uncertain. Other approaches exploit divertor geometry, as, for example, with the Super-X [5] and Snowflake [6] concepts. In theory, power flow into the divertor can be dissipated and divertor temperature lowered by increasing the distance that heat from the main plasma entering the scrape-off layer (SOL) must traverse along a magnetic field line to the divertor target or by raising the radial isolation of the outer divertor target. These ideas are based on well-known physics in the SOL and can best be expressed at its simplest level using a one-dimensional Two-Point Model (TPM) [7]:

$$T_{TAR} \propto \left[ P_{IN} (1 - f_{RAD}) \right]^{10/7} \left( R_{TAR} n_{SEP} \right)^{-2} \left( \frac{f_{R}}{f_{R} - 1} \right) \left[ L_{||} \ln \left( f_{R} \right) \right]^{4/7}, \quad (1)$$

and

$$n_{TAR} \propto \left[ R_{TAR} \right]^2 \left[ n_{TAR} \right] \left[ P_{IN} (1 - f_{RAD}) \right]^{-8/7} \left[ L_{||} \ln \left( f_{R} \right) \right] \left( f_{R} - 1 \right)^{6/7}, \quad (2)$$

where $R_{TAR}$ is the radial location of the outer divertor separatrix target, $L_{||}$ is the parallel connection length in the SOL between the midplane (or X-point) and the divertor target, $n_{TAR}$ is the electron density at the outer divertor target, $T_{TAR}$ is the electron temperature at the outer divertor target, $n_{SEP}$ is the upstream electron density on the separatrix, $P_{IN}$ is the power input, $f_{RAD}$ is the fraction of radiated power, and $f_{R}$ is the ratio $R_{OSP}/R_{OMP}$, where
ROMP is the radial location of the separatrix at the outer midplane. These simple scalings suggest that conditions conducive to a radiative divertor solution can be achieved at lower $n_{\text{SEP}}$ by increasing either $R_{\text{OSP}}$ or $L_{||}$. We report results and interpretation of recent experiments on DIII-D designed to evaluate divertor geometries that might be favorable for radiative heat dispersal by testing how specific variations in $R_{\text{OSP}}$ and $L_{||}$ affect $n_{\text{TAR}}$, $T_{\text{TAR}}$, and peak heat flux at the outer divertor target $Q_{\perp,0}$.

2 Experiment

The poloidal cross-sections of three of the plasma shapes used in this study are shown in Fig. 1. The maximum variation in radial placement of the outer divertor separatrix $R_{\text{OSP}}$ for these lower single-null (SN) plasmas covers 1.20 m (black) to 1.71 m (green), as shown in Fig. 1. In this experiment, we distinguish between two regions of the divertor: floor and shelf, as shown. The floor region is much less open than the shelf region, which sits atop of the lower divertor baffle structure. The minimum and maximum poloidal extensions from the X-point to the outer divertor target for the plasmas in this experiment were 0.25 m (red) to 0.75 m (black), respectively, in Fig. 1. These poloidal distances correspond to parallel connection lengths $L_{||-\text{XPT}}$ of 17 m and 25 m, respectively. In all cases, the parallel path lengths in the SOL are referenced to the flux surface 0.15 cm radially outside the outer midplane separatrix.

Upstream electron density and temperature were determined by Thomson scattering, while electron density and temperature downstream at the outer divertor target were based on Langmuir probe measurements. Heat flux across the lower divertor was deduced from infrared camera measurements. The ion $B \times \nabla B$ drift was directed toward the X-point in all cases. There was no active particle pumping.

3 Results

3.1 Initial assessment of the dependence of $n_{\text{TAR}}$, $T_{\text{TAR}}$, and $Q_{\perp,0}$ on $R_{\text{OSP}}$

Two matched ELMing H-mode plasmas provided the data for comparison to Eqns (1) and (2), since their respective $R_{\text{OSP}}$ represent the widest range possible in this experiment, i.e., 1.20 m (black) and 1.67 m (green) in Fig. 1. For either case, $n_{e}/n_{G} = 0.4$, $H_{89P} = 1.6$, and $f_{\text{RAD}} = 0.4$. Edge and divertor properties are summarized in Table 1. The dependence of $n_{\text{TAR}}$ and $T_{\text{TAR}}$ did not follow TPM predictions of Eqns (1) and (2), i.e., $n_{\text{TAR}}$ should increase by ≈20% and $T_{\text{TAR}}$ should decrease by ≈26% between the $R_{\text{OSP}} = 1.20$ m and 1.67 m. From experiment, however, $n_{\text{TAR}}$ decreased by ≈51% and increased by ≈33% (Table 1). In addition, the peak heat flux at the outer divertor target $Q_{\perp,0}$ was ≈25% higher for the $R_{\text{OSP}} = 1.67$ m case.
### 3.2. \( R_{OSP} \) scans in L-mode and H-mode

Results from a radial sweep of the outer strike point (OSP) across both floor and shelf, shown in Fig. 2, demonstrates the \( n_{TAR} \) and \( T_{TAR} \) behaviors between these \( R_{OSP} \) endpoints. The endpoints of this sweep in L-mode were \( R_{OSP} = 1.20 \) m and 1.60 m. Figure 2 indicates that the \( n_{TAR} \) and \( T_{TAR} \) behaviors qualitatively track the predictions of the Two-Point Model across the floor and the shelf, individually. Both \( n_{TAR} \) and \( T_{TAR} \) have much stronger dependences on \( R_{OSP} \) along the floor than the “expected” quadratic dependence from the TPM. However, \( n_{TAR} \) and \( T_{TAR} \) on the shelf have a weaker dependence on \( R_{OSP} \) compared with the floor result and are more in-line with TPM. Figure 2 suggests that there may a discontinuity in both \( n_{TAR} \) and \( T_{TAR} \) across the floor-shelf boundary. Note that when one only considers the \( n_{TAR} \) and \( T_{TAR} \) values at the endpoints, the results in Sec. 3.1 and Table 1 are qualitatively recovered.

In order to examine H-mode behavior, a modest radial sweep of the OSP across the floor was used to assess changes to the divertor plasma due to the proximity of the baffle facing at \( R = 1.37 \) m. Because any shape changes in the main plasma were minimized by the limited range of the radial sweep (i.e., \( R_{OSP} = 1.21–1.30 \) m), ELMing H-mode core properties remained fairly constant over the sweep, e.g., \( H_{89P} = 1.9–2.0 \) and \( n_{SEP} = 0.85 \times 10^{19} \) m\(^{-3} \).

Like the L-mode case above, the response of \( n_{TAR} \) and \( T_{TAR} \) to changes in \( R_{OSP} \) was considerably stronger than expected from the TPM (Fig. 3). Density and temperature data from two H-mode shots having comparable core plasma characteristics but with their OSP on the shelf are also shown. As in the L-mode case with OSP on the shelf, \( n_{TAR} \) increased with \( R_{OSP} \) and \( T_{TAR} \) decreased with \( R_{OSP} \), although still with a somewhat higher dependence on \( R_{OSP} \) than predicted by TPM. As in the L-mode case, there

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**Table 1. Large \( R_{OSP} \) vs. low \( R_{OSP} \)**

<table>
<thead>
<tr>
<th>Shot</th>
<th>Low ( R_{OSP} )</th>
<th>High ( R_{OSP} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{OSP} ) (m)</td>
<td>1.20</td>
<td>1.67</td>
</tr>
<tr>
<td>( L_{X-Y} ) (m)</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>X-point height (m)</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>( n_{SEP} ) ( \times 10^{19} ) m(^{-3} )</td>
<td>0.91</td>
<td>0.92</td>
</tr>
<tr>
<td>( T_{SEP} ) (eV)</td>
<td>91</td>
<td>71</td>
</tr>
<tr>
<td>( n_{TAR} ) ( \times 10^{19} ) m(^{-3} )</td>
<td>3.4</td>
<td>1.7</td>
</tr>
<tr>
<td>( T_{TAR} ) (eV)</td>
<td>18.0</td>
<td>24.0</td>
</tr>
<tr>
<td>( Q_{L,0} ) (MW/m(^2))</td>
<td>1.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

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![Fig. 2. \( n_{TAR} \) (closed) and \( T_{TAR} \) (open) are shown as a function of \( R_{TAR} \) = 1.47740 L-mode](image)

![Fig. 3. \( n_{TAR} \) (closed) and \( T_{TAR} \) (open) are shown as a function of \( R_{TAR} \) = 1.47739, 1.49609, 1.49613 H-Mode](image)
is no apparent monotonic trend for either $n_{\text{TAR}}$ or $T_{\text{TAR}}$ across both floor and shelf. These results may be explained by the degree by which neutrals are trapped by the baffle structure, as we discuss later in this paper.

As $R_{\text{OSP}}$ on the floor approached the baffle structure, $Q_{\perp,0}$ decreased. However, $Q_{\perp,0}$ was considerably greater when $R_{\text{OSP}}$ was located on the shelf (Fig. 4) and its dependence on $R_{\text{OSP}}$ was not monotonic [Fig. 5(a)]. This result can be partially explained by noting that the poloidal flux expansion ($f_{\text{EXP}}$) and the angle between the poloidal separatrix flux surface and the divertor target ($\Theta_T$) both increase with $R_{\text{OSP}}$. From geometry alone one expects that $Q_{\perp,0} \propto \sin \Theta_T / [R_{\text{OSP}} \times f_{\text{EXP}}]$. Based on the $\Theta_T$ and $f_{\text{EXP}}$ values (listed in the caption to Fig. 5), one expects that $Q_{\perp,0}$ to behave with $R_{\text{OSP}}$ as represented by the “open” symbols shown in Fig. 5(a); note that $Q_{\perp,0}$ has been normalized to the $Q_{\perp,0}$ value at $R_{\text{OSP}} = 1.40$ m case. The difference in the $Q_{\perp,0}$ based on geometrical considerations and the measured $Q_{\perp,0}$ increases with $R_{\text{OSP}}$. Interestingly, the full-width at half maximum (FWHM) of the measured heat flux profiles on the shelf is approximately constant ($\approx 2$ cm) with changes in $R_{\text{OSP}}$. This result would not be expected if geometry were the only consideration, since the range in $f_{\text{EXP}}$ on the shelf is 1.3–3.2. These measured heat flux profiles on the shelf can be mapped back to the outer midplane along SOL field lines. The resulting parallel heat flux profile referenced to the outer midplane ($q_{||}$) is useful for factoring out geometric effects of heat flowing to the divertor target. The peak in parallel heat flux at the midplane ($q_{||,0}$) is found to fall off rapidly with increasing $R_{\text{OSP}}$ [Fig. 5(b)], while the FWHM of the $q_{||}$ profile strongly increased with $R_{\text{OSP}}$ (Fig. 5(c)). Our explanation for this behavior will be discussed in Sec. 4.

3.3. Variation of heat flux under higher density, radiating divertor conditions

The data presented in Sec. 3.2 suggests that locating the OSP on the floor adjacent to the baffle structure produces a significantly different divertor heat flux than placing the OSP a few centimeters outboard of that location on the shelf. In this section we examine this idea more closely by comparing two $R_{\text{OSP}}$ cases, i.e., 1.30 m (floor) and 1.40 m (shelf). We will refer to the former as the “closed” divertor configuration and the latter as the “open” divertor.
configuration. Figure 6(a) shows that the time-averaged peak heat flux (which include ELMs) \( \langle Q_{\perp,0} \rangle \) in the closed configuration was \(~20\%\) lower than in the open configuration at the lowest density; this \(20\%\) difference was also observed when comparing respective \( q_{\parallel,0} \) values, where the FWHM of the 1.30 m case was \(\sim20\%\) higher. This difference increased as core density was raised. The OSP in the closed configuration detached between ELMs well before evidence of detachment occurred in the open configuration [Fig. 6(a)]. This difference in \( \langle Q_{\perp,0} \rangle \) between open and closed divertor cases primarily occurred between ELM events [Fig. 6(b)] and not during ELMs [Fig. 6(c)]. Note that whether the divertor was open or closed at any given density considered here produced little difference on \( Q_{\perp,0} \) during ELMing events. Even though the peak heat flux was significantly lower in the closed configuration at any given density, whether the divertor was “open” or “closed” made no difference in the normalized energy confinement, pedestal density, and pedestal temperature when compared at a common density. Isolating the divertor target from the core plasma \( (L_{||-XPT} = 25 \text{ m}) \) may have been helpful in this regard. The closed configuration extended the operating range to lower core density while still maintaining a lower value of heat flux. For example, if the allowable upper limit for \( Q_{\perp,0} \) were set to \( 2\,\text{MW/m}^2 \), then Fig. 6(a) shows that it is possible to operate at a lower line-averaged density in the closed divertor case than with the open divertor case, i.e., \( \approx 3.4 \times 10^{19} \text{ m}^{-3} \) vs \( \approx 4.0 \times 10^{19} \text{ m}^{-3} \).

3.4. Variation of \( n_{\text{TAR}} \), \( T_{\text{TAR}} \), and \( Q_{\perp,0} \) with \( L_{||-XPT} \)

Equations (1) and (2) predict that lengthening the outer divertor leg increases \( n_{\text{TAR}} \) and decreases \( T_{\text{TAR}} \). To test this, we compared two H-mode plasmas having significantly different \( L_{||-XPT} \) but virtually the same \( R_{\text{OSP}} \). Their shapes are shown as the black (high X-point) and red (low X-point) curves in Fig. 1. Langmuir probe measurements indicate that the case with larger \( L_{||-XPT} \) (=25 m) resulted in higher \( n_{\text{TAR}} \) and lower \( T_{\text{TAR}} \) (Table 2). This is in qualitative agreement with TPM predictions. Equations (1) and (2) can be combined with data from the lower \( L_{||-XPT} \) (=17 m) case (Table 2) to predict \( n_{\text{TAR}} \) and \( T_{\text{TAR}} \) for the \( L_{||-XPT} \) (= 25 m) case. The two-point model predicts for the longer parallel connection length case: \( n_{\text{TAR}} = 4.6 \times 10^{19} \text{ m}^{-3} \) and \( T_{\text{TAR}} = 17 \text{ eV} \). These are in quantitative agreement with the actual measurements for the higher X-point case (Table 2).
Although $f_{\text{EXP}}$ was lower for the $L_{\parallel\text{-XPT}} = 25$ m case, i.e., $\approx 3.2$ versus $\approx 5.6$ for the $L_{\parallel\text{-XPT}} = 17$ m case, the peak heat flux $Q_{\perp,0}$ was greater in the latter, as shown in Fig. 7. The FWHM of the deposited heat flux profiles in both cases was comparable, i.e., $\approx 3.5$ cm; not surprisingly, $q_{\parallel,0}$ for the $L_{\parallel\text{-XPT}} = 25$ m case was roughly half that of the 17 m case and its FWHM of $d_{\parallel}$ was roughly double. This result is consistent with the idea of competing parallel and perpendicular transport on field lines in the SOL, which we discuss in the following section.

### 4 Discussion

Modeling of the edge and divertor plasmas was done using the SOLPS suite of codes [8], which provide a 2-D model to couple plasma and neutral transport. The plasma transport was calculated using the fluid code B2 [9] and the neutral transport was calculated using the Monte-Carlo code EIRENE [10]. Classical drifts were not included. SOLPS was used in an interpretive sense, with the primary constraint being the measured midplane density and temperature profiles, which were matched in the simulation by adjusting the specified radially varying, poloidally constant transport coefficients [11]. No anomalous convection was included, so these represent “effective” cross-field diffusivities. The measured divertor heat flux effectively constrained the position of the midplane profiles relative to the separatrix. With the midplane data matched to the measured profiles, the simulated divertor density and temperature profiles were then compared to the measured values. SOLPS calculations for the two $R_{\text{OSP}}$ cases discussed in Sec. 3.1 show that with $Q_{\perp,0}$ constrained by measurement $n_{\text{TAR}}$ and $T_{\text{TAR}}$ are in qualitative agreement with experiment. SOLPS modeling indicates that $n_{\text{TAR}}$ is higher and both $T_{\text{TAR}}$ and $Q_{\perp,0}$ are lower for the low $R_{\text{OSP}} = 1.20$ m case. Both $T_{\text{TAR}}$ and $Q_{\perp,0}$ are in reasonable quantitative agreement ($\approx 25\%$) with the data. The experimental $n_{\text{TAR}}$ is well within a factor of two in either $R_{\text{OSP}}$ case, and is qualitatively in agreement. SOLPS/EIRENE modeling indicate more neutrals escape the outer divertor target in the more open configuration $R_{\text{OSP}} = 1.67$ m case. A fraction of these neutrals return to the SOL plasma upstream of the target, are ionized, and flow back to the target, thereby increasing the convective component of the parallel power flow to the divertor target more than would occur in the more closed configuration ($R_{\text{OSP}} = 1.20$ m case). Increasing the convective component of the power flow can be expected to increase $T_{\text{TAR}}$ and reduce $n_{\text{TAR}}$ [12]. For a location slightly upstream of the divertor target, SOLPS modeling indicates that, for the $R_{\text{OSP}} = 1.67$ m case, convection carries virtually the entire heat flux outside the radial location of the FWHM of the $Q_{\perp}$ profile, while for the $R_{\text{OSP}} = 1.20$ m case...
1.20 m case at FWHM of the $Q_{\perp}$ profile, conduction still plays a substantial role (~30%). It is worth noting that the role of neutral trapping has been confirmed by performing SOLPS simulations with the baffle structure removed so that neutral trapping in both cases are similar; the result was to reverse the trends of $n_{\text{TAR}}$ and $T_{\text{TAR}}$ with $R_{\text{OSP}}$ discussed above.

The neutrals trapping effect is particularly evident in the radial sweep in $R_{\text{OSP}}$ (Sec. 3.2). SOLPS modeling showed that the baffle structure had an important role in determining divertor properties. For the endpoints of this sweep, i.e., $R_{\text{OSP}} = 1.21$ m and 1.30 m with $Q_{\perp,0}$ constrained by measurement, SOLPS indicates that $T_{\text{TAR}}$ was reduced as $R_{\text{OSP}}$ was moved from 1.21 m to 1.30 m. This result was in reasonable agreement with experiment, both qualitatively and quantitatively (Fig. 8). In addition, $n_{\text{TAR}}$ increased with $R_{\text{OSP}}$, again in agreement with experiment. Modeling shows that with greater proximity of the OSP to the baffle structure enhanced neutral trapping. Increased neutral trapping raised recycling, resulting in increased $n_{\text{TAR}}$ and lowered $T_{\text{TAR}}$. This is consistent with observation. As $R_{\text{TAR}}$ was moved toward the baffle structure, neutral pressure measured in the lower divertor pumping plenum increased by a factor of 3–4, and $D_{\alpha}$-emissivity increased by a factor of $\approx 2$. These observations indicate the increased presence of neutrals near the outer divertor target. Furthermore, the higher $n_{\text{TAR}}$ and lower $T_{\text{TAR}}$ conditions in the $R_{\text{OSP}} = 1.30$ m case resulted in an increase in radiated power along the outer divertor leg ($\approx 30\%$) and was clearly helpful in reducing $Q_{\perp,0}$. To a lesser degree, this behavior was observed on the more open shelf top, where the barrier on the high-R side of the shelf can still trap neutrals in the SOL of the $R_{\text{OSP}} = 1.71$ m case more effectively than in the $R_{\text{OSP}} = 1.51$ m case.

The above discussion covering the large vs. small $R_{\text{OSP}}$ experiment and the $R_{\text{OSP}}$ sweep experiment both illustrate the role of neutrals trapping and its contribution to upstream convection along the outer divertor leg. This applies to the results from the “closed” (with effective neutrals trapping) vs “open” (with considerably less effective neutrals trapping) divertor experiment (Sec. 3.3). The result is that the peak heat in the “closed” case is lower than that of the “open” case at upstream similar density and detachment is possible in the former at lower density.

Changing the parallel connection length $L_{||-\text{XPT}}$ in the SOL resulted in behaviors in $n_{\text{TAR}}$ and $T_{\text{TAR}}$ largely in agreement with the TPM. More generally, cross-field diffusion can also affect these results, if $L_{||-\text{XPT}}$ differs significantly, as in Sec. 3.4. One formulation, which has attempted to factor in cross-field transport [12], concludes a slightly stronger contribution from $L_{||-\text{XPT}}$ to $n_{\text{TAR}}$ and $T_{\text{TAR}}$ than predicted by Eqns (1) and (2), although for the cases

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**Fig. 8. SOLPS modeling for two H-mode cases in Sec. 3.2, where $R_{\text{OSP}} = 1.21$ m (black) and $R_{\text{OSP}} = 1.30$ m (red). (a) $n_{\text{TAR}}$, (b) $T_{\text{TAR}}$, and (c) $Q_{\perp}$ are shown vs divertor separatrix location $R_{\text{SEP}}$. The experimental peak values are quoted in parenthesis next to the SOLPS predictions.**
discussed in this paper this effect produced little difference between these 1D and 2D predictions. However, \( Q_{\perp,0} \) was lower for the case with lower \( f_{\text{EXP}} \), i.e., the high X-point case; this would be unexpected, based on geometrical considerations only. In addition, the FWHM of \( Q_\perp \) in both cases was almost the same. Increasing the connection length affected \( Q_{\perp,0} \) and its profile width as much as the purely geometric effect of increasing \( f_{\text{EXP}} \). SOLPS results indicate that increased cross-field transport effects were clearly involved, so that, as \( L_{\parallel} \) increased, the width of the heat flux at the target also increased. The presence of such cross-field energy transport should be particularly evident in cases when \( f_{\text{EXP}} \) is small and connection length is relatively long. This is the case of \( R_{\text{OSP}} = 1.71 \) m, \( f_{\text{EXP}} = 1.3 \), and \( L_{\parallel \cdot \text{XPT}} = 21 \) m in the \( R_{\text{OSP}} \) scan in Fig. 5. In the cases where \( R_{\text{OSP}} = 1.51 \) m and \( 1.40 \) m, \( f_{\text{EXP}} \) is much higher, so that energy transport across field lines, which depend on spatial gradient, would be more masked.

In summary, we find that experiment and 2-D modeling show overall improved divertor conditions with larger SOL connection length and \( R_{\text{OSP}} \).

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References