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Cite as: Phys. Plasmas 29, 062507 (2022); https://doi.org/10.1063/5.0090260
Submitted: 04 March 2022 • Accepted: 01 June 2022 • Published Online: 14 June 2022
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Cite as: Phys. Plasmas 29, 062507 (2022); doi: 10.1063/5.0090260
Submitted: 4 March 2022 · Accepted: 1 June 2022 · Published Online: 14 June 2022

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ABSTRACT
Evidence that density shoulder broadening is dependent on high main-chamber neutral density is presented. Shoulder broadening does not occur when the sources for main-chamber neutrals are minimized using divertor baffles and wide gaps to the first wall (3 < L < 3). Removing the baffles or reducing the gap to the inner wall both act to increase the density shoulder amplitude in otherwise identical TCV discharges. Radial turbulent transport is correlated with shoulder amplitude.

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I. INTRODUCTION
Scrape-off layers (SOL) in tokamaks often exhibit a two-layer structure with a steep density decay length close to the separatrix and a longer one in the far-SOL. This structure called the "density shoulder" cannot be modeled using radially constant cross field diffusion coefficients, nor with combinations of constant diffusive and convective transport coefficients. Far-SOL density profiles have been observed to broaden with increasing divertor collisionality, increasing the plasma density at the first wall by up to an order of magnitude. This makes the prediction of main chamber plasma flux highly uncertain for future devices and even for current tokamaks. This uncertainty also precludes accurate predictions of main-chamber recycling (with implications for core fueling and density control), main chamber erosion, impurity sputtering, dust generation, and the first wall lifespan.

Many studies support the link between filamentary transport and density shoulder formation when the normalized collisionality A > 1. (A is described in Refs. 19 and 20, and below.) However, impurity seeding experiments have shown that high A is not sufficient by itself to guarantee shoulder formation, indicating that our understanding is incomplete.

Therefore, alternative mechanisms for shoulder formation must be considered. One hypothesis is that high main-chamber neutral pressure drives density shoulder formation by increasing upstream ionization rates. High main-chamber neutral density may also increase radial turbulent transport by dampening zonal flows, or by increasing filamentary transport via inter-filament ionization. Another possibility is that changes in the plasma sink to the target is the primary mechanism controlling shoulder formation. Changes in divertor geometry in JET affected shoulder amplitude without changing midplane neutral pressure, while a strong correlation between divertor D intensity and shoulder amplitude was observed. Modeling using the GBS turbulence code shows that increased divertor ionization can cool the divertor, reducing the parallel flux toward the targets. Particle
balance indicated that it was the reduction in the sink term rather than changes in turbulent transport which caused the density shoulder broadening.28

II. EXPERIMENTAL SETUP

Ohmic L-mode density ramps were performed with and without baffles with \( B \times \nabla B \) pointing upward (unfavorable for H-mode). Shape, \( I_p = -340 \text{ kA} \), and \( B_t = 1.4 \text{ T} \) were held constant. The main-chamber neutral density was modified using the divertor baffles, which are extended graphite tiles that separate the vessel into the main and divertor chambers3,34 as shown by the green area in Fig. 1. The main-chamber neutral density was further modified by changing the inner wall gap, which is \( R_{\text{wall}}-R_{\text{sep}} \). This provides four scenarios with the shot numbers listed in Fig. 1.

The “large gap” scenarios have 3.6 cm between the separatrix and the inner wall, which is \( R_{\text{wall}}-R_{\text{sep}} = 2.3 \text{ cm} \) when mapped to the outer midplane (OMP) or \( \sim 3 \times \lambda_{\text{de},\text{near}} \). The “small gap” scenarios have a 2.0 cm inner gap, which is \( R_{\text{wall}}-R_{\text{sep}} = 1.2 \text{ cm} \) or \( \sim 1.5 \times \lambda_{\text{de},\text{near}} \). The first flux surface to intersect the outer baffle has \( R_{\text{sep}} = 2.7 \text{ cm} \), and the first to intersect the outer wall has \( R_{\text{sep}} > 4.5 \text{ cm} \). (i.e., the gap between the separatrix and the outer wall is at least 4.5 cm).

In addition to the four nearly identical examples, reciprocating probe plunges were collected from similar discharges to make an expanded database. Variations in \( I_p \) of up to 10% and small changes in probe plunges were collected from similar discharges to make an expanded database. Variations in \( I_p \) of up to 10% and small changes in shape were permitted. Only discharges which fit into the baffled large gap (green) and unbaffled small gap (red) categories were included. The additional unbaffled small gap cases have \( R_{\text{wall}}-R_{\text{sep}} \leq 1.2 \text{ cm} \), and the additional baffled large gap cases have \( R_{\text{wall}}-R_{\text{sep}} > 2.0 \text{ cm} \).

The locations of the reciprocating probe measurements and the fueling valve are shown in Fig. 1, left. Capacitance monometers were used to measure the neutral pressure in a midplane port (upper magenta rectangle) and in the lower duct ahead of a turbo molecular pump (lower magenta rectangle). The turbopump reduced the pressure measurements by a constant \( \sim 30\% \) compared to when the pump duct was closed in tests with no plasma.

Reciprocating probe electrodes are labeled based on their function in Fig. 1, right. The electron temperature \( T_e \) was measured using the “double probe” electrodes, electron density \( n_e \), and its fluctuating component \( \langle n_e \rangle \) were calculated using the saturation current from the “\( I_{\text{sat}} \) electrode.” The electrode collection area was calculated as a function of \( I_{\text{sat}} \) and \( T_e \) accounting for Debye sheath expansion and finite Larmor radius.3 The floating potential \( V_f \) and the fluctuating component of the poloidal electric field \( E_p \) were estimated from the two \( V_f \) electrodes.” The radial turbulent flux to be determined using32

\[
\Gamma_{\text{turb}} = \frac{\langle n_e \rangle \bar{E}_p}{\bar{B}_t},
\]

where the angled brackets indicate a time average over 2 ms intervals. Fluctuating quantities were sampled at 10 MHz.

III. DIVERTOR CLOSURE EFFECTS

The effects of divertor closure on divertor conditions have been investigated at length, and are only summarized here. Figure 2 shows the evolution of the divertor conditions as a function of the line-averaged density \( \langle n_e \rangle \) for the four scenarios. The outer target \( I_{\text{sat}} \) rollover [Fig. 2(a)] occurs earlier [at lower \( \langle n_e \rangle \)] and more deeply for the baffled discharges confirming that the baffles provide improved access to detached conditions.33-34 This is consistent with Fig. 2(b) which shows that the baffled divertor plasmas are colder and denser with higher normalized divertor collisionality \( \Lambda_{\text{div}} \). This estimate was formulated in Ref. 20 and refined in Ref. 8 to use plasma conditions measured at the target since the changes in collisionality near the onset of detachment are stonger in the divertor:

\[
\Lambda \sim \Lambda_{\text{div}} = 1.7 \times 10^{-14} \frac{n_e L_{\text{div}}}{T_e^2},
\]

where \( L_{\text{div}} \) (cm) is the connection length from the target to the X-point region, \( n_e \) (cm\(^{-3}\)) is the electron density, and \( T_e \) (eV) is the electron temperature obtained from the outer-target Langmuir Probes.39,40 Since \( \Lambda_{\text{div}} \) varies with \( R_{\text{sep}} \), the median is taken to provide a representative value for the outer target.

\( \Lambda_{\text{div}} \) [Fig. 2(b)] is between 3 and 25 for all scenarios, i.e., in the range of the “Resistive X-point regime,” where filamentary transport is expected to increase with collisionality39,40, and where strong density shoulders have previously been observed in unseeded TCV discharges.34,17,23 \( \Lambda_{\text{div}} \) increases with \( \langle n_e \rangle \) and is consistently higher for the baffled scenarios than the unbaffled ones. Detailed target profile of \( n_e \) and \( T_e \) as a function of \( \langle n_e \rangle \) for similar plasma conditions are available in Ref. 33.

The divertor neutral pressure [Fig. 2(c)] is \( \sim 2-3 \times \) higher for the baffled scenarios consistent with previous measurements33,34 and...
The main-chamber neutral pressure gauge is below the noise floor [Fig. 2(d)] and cannot be used to directly verify the changes to the main-chamber neutral pressure.\cite{34} [Note that each point represents an individual reading from the pressure gauge, where the vertical scatter is a result of the “noise floor” of the gauge and its electronics. Some values are negative because the pressure is equal to zero within the gauge’s uncertainty. The discrete spacing in the pressure values show the quantization noise of the digitizer (i.e., rounding to the nearest bit).]

However, three independently run simulations using SOLPS-ITER\cite{35,36} and SOLEDGE2D-Eirene\cite{37} show that the baffles reduce neutral pressure in the main chamber by a factor of $2-5 \times$ over a wide range of $\langle n_e \rangle$ and input power. Even in simulations where the baffles were intentionally too short (poor divertor closure) or too long (increasing the recycling on top of the baffle), the main-chamber neutral pressure was still reduced by at least $2 \times$ compared to the un baffled simulations.\cite{37}

Baffled plasmas also feature higher CIII fronts, more divertor radiation, and inner target $I_{sat}$ rollover,\cite{33,34} while simulations show a $3-10 \times$ increase in divertor Balmer-alpha emission.\cite{36}

Reciprocating probe plunges were taken at low $\langle n_e \rangle = 5.1 \pm 0.7 \times 10^{19}$ m$^{-3}$ and high $\langle n_e \rangle = 11.1 \pm 0.4 \times 10^{19}$ m$^{-3}$ in each scenario as represented by the vertical dashed lines in Fig. 2.

At first glance, the divertor conditions suggest that the baffled scenarios should have higher density shoulder amplitudes since they have higher $\Lambda_{div}$ (associated with increased filamentary transport) and lower outer target flux (which is related to the density sink via parallel drainage). In Sec. IV, we will show that the opposite is true.

**IV. DENSITY SHOULDER DEPENDENCE ON MAIN-CHAMBER NEUTRALS**

The SOL density profiles at the midplane are compared between the four scenarios in Fig. 3. The location of the separatrix (dashed vertical line) has uncertainties of $\pm 3$ mm, shown by the shaded region. The low $\langle n_e \rangle$ density profiles (lines) match within measurement uncertainty for all four scenarios. A small but non-negligible shoulder is observed in the low $\langle n_e \rangle$ density profiles, i.e., the density decay length in the far-SOL ($\lambda_{far} = 2.7 \pm 1.2$ cm) is longer than in the simulations.\cite{35-37}

![Figure 2](image2.png)

**FIG. 2.** The evolution of (a) the integrated particle flux to the outer target, (b) the normalized divertor collisionality $\Lambda_{div}$, and (c) the neutral pressure measured in the divertor and (d) the main-chamber, as functions of line averaged density $\langle n_e \rangle$. Vertical dashed lines show the $\langle n_e \rangle$ of the reciprocating probe plunges.

![Figure 3](image3.png)

**FIG. 3.** Density profiles measured low $\langle n_e \rangle = 5.1 \pm 0.7 \times 10^{19}$ m$^{-3}$ (lines—un baffled, dashed lines—baffled) and high $\langle n_e \rangle = 11.1 \pm 0.4 \times 10^{19}$ m$^{-3}$ (markers) for each scenario (see legend). The shaded region indicates the $\pm 3$ mm uncertainty in the location of the separatrix.
near-SOL ($\lambda_{ne,near} = 0.9 \pm 0.2$ cm). At $R-R_{sep} > 2.7$ cm, the flux surfaces of the baffled scenarios (dashed lines) intersect with the outer baffle, but this does not cause a change in the profiles which continue to agree with the unbaffled profiles (solid lines).

We define a simple density shoulder amplitude

$$A_{4,4} = \frac{n_e (R-R_{sep} = 4 \text{cm})}{n_e (R-R_{sep} = 0)},$$

(3)

where the low ($n_i$) profiles have $A_{4,4} \sim 0.05$. The choice to consider $n_e$ at $R-R_{sep} = 4$ cm is arbitrary. We found that this definition reduced the scatter compared to other definitions of shoulder amplitude, especially at intermediate values of ($n_e$).

Comparing the baffled large gap scenario at low and high ($n_e$) (Fig. 3, green dashed line vs green triangles) shows no density shoulder broadening, with a small reduction in $A_{4,4}$ from 0.05 to 0.04. Relative to this case (green triangles) the density shoulder amplitude is increased by either removing the baffles (black circles, $A_{4,4} = 0.07$) or reducing the inner wall gap (magenta diamonds, $A_{4,4} = 0.10$). The effects appear to be cumulative as the scenario without baffles and with small gaps (red squares) has the strongest density shoulder with $A_{4,4} = 0.16$.

$A_{4,4}$ is plotted as a function of ($n_e$) for the expanded dataset in Fig. 4. The large symbols show $A_{4,4}$ for the profiles in Fig. 3, including the two black and magenta datapoints. $A_{4,4}$ remains constant across the range of ($n_e$) for the baffled large gap dataset (green triangles), i.e., density shoulder broadening does not occur even at the density limit in detached conditions. In contrast, the unbaffled small gap dataset (red squares) shows typical density shoulder evolution where $A_{4,4}$ increases with ($n_e$).

$\lambda_{ne,near} \sim 0.8 \pm 0.3$ cm and $\lambda_{ne,far} \sim 3.5 \pm 1.0$ cm remain roughly constant across the dataset, while the transition point between the steep $\lambda_{ne,near}$ and shallow $\lambda_{ne,far}$ regions move inward with increasing $A_{4,4}$. It is coincidental that some of the $\lambda_{ne}$ transition points in Fig. 3 correspond with flux surfaces that intercept parts of the main chamber.

In summary, density shoulder broadening does not occur in discharges, where the main-chamber neutral pressure is minimized using baffles and a wide inner wall gap. Removing the baffles or decreasing the inner gap both act to increase $A_{4,4}$, which varies by $4 \times$ across otherwise identical discharges.

V. CORRELATION BETWEEN TURBULENCE AND DENSITY SHOULDER AMPLITUDE

The turbulent transport characteristics are compared between the four scenarios at high ($n_e$), i.e., for identical discharges except for the different density shoulder amplitudes and differences in main-chamber neutral sources. These data are plotted up until the first electrode arc and thus are not available at or inside the separatrix.

$\Gamma_{turb}$ [Fig. 5(a)] is $\sim 2 \times$ higher for the unbaffled small gap scenario (red squares) where the density shoulder is strongest than the other three scenarios. The elevated $\Gamma_{turb}$ mainly results from an increase in density fluctuations [see Fig. 5(b) where the Isat RMS magnitude ($\langle I_{sat}^2 \rangle^{1/2}$) is taken as a proxy for ($\langle n_e \rangle_1/2$) as it requires fewer assumptions and has less scatter]. $\Gamma_{turb}$ and ($\langle I_{sat}^2 \rangle^{1/2}$) agree for the other three scenarios within their scatter.

$\Gamma_{r}$ is plotted for the expanded dataset in Fig. 6 as a function of the shoulder amplitude. The averaging interval for $\Gamma_{turb}$ [see Eq. (1)] is taken over $2 \text{ cm} < R-R_{sep} < 3 \text{ cm}$ to provide a comparable outer-

![Figure 4](image_url)

**FIG. 4.** Shoulder amplitude as a function of ($n_e$) for each scenario (see legend). The larger symbols represent the density profiles from Fig. 3.

![Figure 5](image_url)

**FIG. 5.** The radial turbulent flux (a) and the RMS level of the ion saturation current (b) for the four scenarios at high line average density.
Density shoulder broadening does not occur in baffled discharges with large inner gaps, i.e., when the sources of main-chamber neutrals are minimized. Removing the baffles reduces divertor closure and increases the density shoulder amplitude. Reducing the inner wall gap increases the source of recycling neutrals in the main-chamber and also increases the shoulder amplitude. These two effects are cumulative, and the shoulder amplitude is further increased when the small gap and lack of baffles are used together. Modifying the sources of main-chamber neutrals causes a \(4\times\) difference in shoulder amplitude in otherwise identical discharges. These results are consistent with the hypothesis that high main-chamber neutral density is required for density shoulder broadening. Radial turbulent flux correlates with shoulder amplitude, which is mainly a result of an increased \(I_{\text{sat}}\) RMS level.

These results indicate that density shoulder growth may be preventable in future tokamaks by designing for good divertor closure and by minimizing main-chamber neutral sources. Since the baseline ITER scenarios feature pellet fueling, good divertor closure, and wide gaps to the walls with a minimum \(R-R_{\text{sep}}\) of 4 cm,\(^{45}\) main-chamber neutral pressures should be low, and the conditions necessary for shoulder broadening may not be present; however, further study is required to verify if these findings extend to ITER relevant H-mode conditions.

**ACKNOWLEDGMENTS**

This work was supported by the U.S. Department of Energy under Grant No. DE-SC0010529 and by the Swiss National Science Foundation. This work has been carried out within the framework of the EURofusion Consortium and has received funding from the Euratom Research and Training Programme 2014–2018 and 2019–2020 under Grant Agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The technical contributions of L. Chousal and C. Jones are gratefully acknowledged.

**AUTHOR DECLARATIONS**

Conflict of Interest

The authors have no conflicts to disclose.

**DATA AVAILABILITY**

The data that support the findings of this study are available within the article.

**REFERENCES**


