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Recent Progress towards a Quantitative Description of Filamentary SOL Transport

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Heat and particle transport onto plasma-facing components is a key issue for next generation tokamaks, as it will determine the erosion levels and the heat loads at the main chamber first wall. In the scrape-off layer (SOL), this transport is thought to be dominated by the perpendicular convection of filaments. In this work, we present recent experiments which have led to an improved picture of filamentary transport, and its role on the onset of a density profile flattening, known in the literature as the density “shoulder” [1]. First, L-mode experiments carried out in the three tokamaks of the ITER stepladder (COMPASS, AUG and JET) showed how normalized divertor collisionality can be used to scale both filament size and the density e-folding length in the far SOL. Furthermore, a transition in the filament regime is found to be the reason for the formation of the density shoulder, as it coincided with a change in the scaling of filament size with propagation velocity from Sheath Limited regime to Inertial regime [3]. This result was later confirmed in AUG by independent experiments which showed how the polarization term in the charge conservation equation became dominant after the onset of the shoulder and how the transition was reversed as filaments propagate radially across regions of decreasing collisionality. Besides, measurements carried out in AUG with a Retarding Field Analyzer in equivalent discharges have led to the discovery of a strong reduction of $T_i$ in the far SOL after the onset of the shoulder, both in filaments and background plasmas, which can not be explained by the minor reduction of $T_i$ at the separatrix. Finally, equivalent experiments in H-mode carried out in AUG have shown how inter-ELM filaments follow the same general behaviour as L-mode filaments, and how a density profile flattening reminiscent of the density shoulder is observed when collisionality is increased over a similar threshold. Besides, Thomson Scattering data indicate the same sharp increase on the e-folding length of density and electron temperature in the near SOL above a critical collisionality.

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Recent progress towards a quantitative description of filamentary SOL transport

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Abstract. A summary of recent experiments on filamentary transport is presented: L-mode density shoulder formation is explained as the result of a transition between sheath limited and inertial filamentary regime. Divertor collisionality is found to be the parameter triggering the transition. A clear reduction of the ion temperature takes place in the far SOL after the transition. This mechanism seems to be generally applicable to inter-ELM H-mode plasmas, although some refinement is still required.

1. Introduction

Heat and particle transport onto plasma-facing components of fusion devices is determined in the Scrape-off Layer (SOL) by the balance between parallel and perpendicular transport. While parallel transport is mostly caused by conduction, perpendicular transport can have a dominant contribution due to perpendicular convection of coherent structures known as filaments. This is a key issue for next generation tokamaks, as the filaments will determine the erosion levels and the heat loads at the main chamber first wall.

Basic models for filaments [1] describe their ExB propagation as the result of a polarization caused by curvature drifts [2]. In order to keep charge conservation, conventional models had this polarization compensated by a parallel current flowing along the filament into the wall [3]. This is known as the Sheath Limited regime (SL). It was later proposed that some mechanisms, such as a large increase of SOL collisionality, might electrically disconnect the midplane from the walls, leading to the so-called inertial regime (IN). The transition from SL to IN regime could have important global implications, as it would cause filaments to propagate faster [3,4] and lead to an enhanced perpendicular transport [5], thus potentially increasing particle and heat loads on the first wall. A well known example of this would be the onset of the density profile flattening known in the literature as the density “shoulder”, reported in many tokamaks when a certain density threshold is exceeded during L-mode
operation [6-8], and which has been explained as the result of filament disconnection from the wall [9].

Previous work carried out on ASDEX Upgrade (AUG) [10] already established the relation between shoulder formation and a clear transition in the properties of filaments. The threshold coincided with the point where collisions disconnected the midplane from the wall. Such a disconnection was defined using the effective collisionality criterion proposed by Myra et al. [11], \( \Lambda > 1 \), where \( \Lambda = \frac{L/c_s \Omega_i}{1/n_e \Omega_{ei}} \), and \( c_s \) the sound speed, \( v_{ei} \) the electron–ion collision frequency and \( \Omega_{ei} \) the gyrofrequency of species \( \alpha \). Later work confirmed these results in a multimachine study including the tokamaks JET, AUG and COMPASS[13], which due to their similar magnetic configuration and difference in size form a “Stepladder” to ITER [12]: In the first two, the density was high enough to achieve \( \Lambda > 1 \), and both the filament transition and the shoulder formation were observed. In COMPASS, where \( \Lambda > 1 \) was not achieved, filaments and density profiles remained constant for the whole range of observed densities. Still, it could not be decided if the process was triggered by the density – as suggested by previous literature -, the collisionality in the midplane, \( \Lambda_{\text{mid}} \) (defined using far SOL \( T_e \) and \( n_e \) values and the connection length as \( L \)), or the local collisionality at the divertor, \( \Lambda_{\text{div}} \) (defined using \( T_e \) and \( n_e \) at the divertor target and a fraction of the connection length as \( L \)).

In this work, we present the experimental effort that has been carried out in recent years in the subject of understanding the basic mechanism determining filamentary transport in order to improve current estimations of first wall loads for ITER and DEMO. Most of this work has been done in L-mode plasmas, which allow for greater diagnostic coverage. However, the conclusions achieved in such simplified L-mode experiments are later expanded into the more relevant H-mode. In section 2, the parameter triggering the transition is determined. In section 3, a study on the scaling of filaments is presented. In section 4, the impact on SOL temperatures is discussed. Finally, previous results are extended to H-mode in section 5 and conclusions are outlined in section 6.

2. The role of divertor collisionality

In order to disentangle the relative contributions of midplane and divertor collisionalities in the shoulder formation, a series of L-mode density ramps were carried out on AUG [14]. Different heating powers (including pure ohmic, 300 and 600 kW of ECH power) were used. Also, some 300 kW discharges using nitrogen seeding were included in the analysis (although no filament data is available in these). Density profiles were measured using a lithium beam [15], and filaments in the far SOL (\( \rho_p \sim 1.02 \)) were characterized using a multipin Langmuir probe mounted on a midplane manipulator (MPM) [10]. Also, divertor density and temperature were measured by flushed mounted Langmuir pins at the target plates. As can be seen in Fig. 1a, the \( T_e \) drop at the divertor associated to the high recycling regime of the LFS divertor takes place at different densities (indicated here as the line integrated density at the edge, \( n_{\text{edge}} \), measured by interferometry) depending on power and seeding. This results, as seen in Fig. 1b, in \( \Lambda_{\text{div}} > 1 \) being achieved at different \( n_{\text{edge}} \) values. Instead, as will be seen in Section 4, \( T_e \) in the far SOL does not depend on the heating power, and \( \Lambda_{\text{mid}} \) remains constant practically for the whole range of \( n_{\text{edge}} \). In Figs. 1c and 1d, it is clear that the transition does not take place for a given density value, as filament size, \( \delta_b \), and the density e-folding length in the far SOL, \( \lambda_n \), increase at different \( n_{\text{edge}} \) values. \( \Lambda_{\text{mid}} \) is neither the driving parameter, as it
remains constant through the transition in all cases. Instead, as shown in Fig. 1e and 1f, all points converge into a single curve when $\delta_b$ and $\lambda_n$ are represented as a function of $\Lambda_{\text{div}}$ regardless of heating power or seeding. In this case, two clear regimes can be seen, with global particle transport becoming strongly enhanced for $\Lambda_{\text{div}} > 1$. Interestingly, seeded discharges (represented in Fig. 1 as hollow/solid violet circles indicating the times in the discharge before/after the seeing) converge with the others, indicating that the result is independent from how the high collisionality is achieved. In Fig. 1f data points from JET and COMPASS have also been included, in good agreement with previous results [12]: In JET, where $\Lambda_{\text{div}} > 1$ values are achieved, a transition remarkably similar to the one at AUG is observed. In COMPASS, where $\Lambda_{\text{div}} < 1$ for the whole data set due to a more limited range of achievable densities, all data points are in the low collisionality branch of the figure.

3. A change of filament scaling

As explained in the Introduction, a transition between SL and IN filamentary regimes has been proposed as the explanation for the shoulder formation [9]. This would be consistent with the strong change of scaling of filament size shown in Fig. 1e, which clearly mirrors that of $\lambda_n$. Nevertheless, this transition has been observed in basic plasmas [16] but was yet to be confirmed in fusion-relevant machines like AUG. Therefore, in order to verify this hypothesis, the scaling of filament size as a function of perpendicular velocity was studied in the experiments described in the previous section [14]. Sheath limited filaments scale as $\delta_b \propto (v_{\text{perp}})^{-2}$ [3], while filaments in the inertial regime scale as $\delta_b \propto (v_{\text{perp}})^{1/2}$ [3]. By using a multipin probe head to calculate correlations between radially and poloidally spaced pins, the sizes and perpendicular velocities of conditionally averaged filaments during the density ramps were obtained [10]. As can be seen in Fig. 2, a clear transition in the scaling is observed around $\Lambda_{\text{div}} = 1$, with filaments in the $\Lambda_{\text{div}} < 1$ branch scaling according to the SL
model, and filaments in the $\Lambda_{\text{div}} > 1$ branch according to the IN. The transition is indicated in the figure by a vertical solid line which corresponds to the size for which the collisionality threshold is achieved in Fig. 1e, where it is marked as a horizontal solid line. In order to illustrate this, theoretical predictions [17] for both regimes have been also represented in the figure considering both cold and warm ions, with $\tau_i = T_i / T_e$. Interestingly, IN regime filaments are clearly better modelled by the cold ion approximation. This novel result confirms that, coinciding with the onset of the density shoulder, the disconnection of filaments caused by a critical collisionality value leads to a transition of the propagation mechanism of filaments, which become larger and denser.

4. Effect of the shoulder formation on SOL temperatures

The evolution of $T_e$ and $T_i$ through the onset of the density shoulder has been investigated, as it determines the amount of energy transported by filaments and background. First, $T_e$ was measured by means of a swept Langmuir pin installed on the MPM. By plunging the probe close to the separatrix at high and low $\Lambda_{\text{div}}$ conditions, a typical radial profile can be obtained for each case. As can be seen in Fig. 3, both profiles are quite similar in the far SOL were $T_e$ remains roughly constant at $T_e \sim 10-15$ eV. This is consistent with previous measurements in AUG [18]. Instead, a drop in $T_e$ is observed in the near SOL at high collisionality. This can be explained as the result of the general cooling of the plasma when the density is increased to achieve high $\Lambda_{\text{div}}$ while the heating power is kept constant. $T_e$ was also measured at $\rho_p \sim 1.02$ during the density ramps discussed in previous sections. As can be seen in the insert of Fig. 3a, with the only exception of very low densities (corresponding to collisionality values of $\Lambda_{\text{div}} \sim 0.01$), a constant $T_e \sim 15$ eV is observed regardless of heating power or $n_{\text{edge}}$.

Second, $T_i$ has been measured in the far SOL by means of a Retarding Field Analyzer (RFA) installed on the MPM [19]. In this case, discharges with different constant density levels were carried out on AUG featuring low and high collisionalities ($\Lambda_{\text{div}} \sim 0.01$ and $\Lambda_{\text{div}} \sim 10$). In each case, the MPM was plunged to different distances to the separatrix to form a radial profile in the far SOL. Unfortunately, in this case no measurements are available close to the near SOL. By conditional averaging, $T_i$ values of filaments and background are calculated separately. As can be seen in Fig. 3b, a strong reduction of $T_i$ takes place after the transition: for $\Lambda_{\text{div}} \sim 0.01$, a radial exponential decay can be seen both for filaments and background, while for $\Lambda_{\text{div}} \sim 10$ the profile seems to remain radially constant at $T_i \sim 20$ eV for both. This result is in good agreement with the fact that disconnected filaments fit better with the cold IN regime, as discussed in Fig. 2. In this case, a drop in separatrix $T_i$ can not be accounted for this change,
as it goes from $T_{i,\text{sep}} \sim 175$ eV to $T_{i,\text{sep}} \sim 150$ eV over the transition, as measured by CXRS. Also, as can be seen in the insert of Fig. 3b, before the transition, filaments are clearly warmer than the background at the innermost positions, while similar values are measured for high $\Lambda_{\text{div}}$. Interestingly, filament $T_i$ value, which seems to increase exponentially as the separatrix is approached, is already similar to $T_{i,\text{sep}}$ at $\rho_p \sim 1.02$, suggesting that these structures must be generated inside the confined plasma, where $T_i$ is equal or greater than the one measured in the filament at the far SOL.

5. H-mode shoulder formation

Since next generation machines will be with all likelihood operated in H-mode, any attempt to predict their behavior must be valid in this regime of confinement. Therefore, an additional line of work was dedicated to determine the validity of the L-mode studies in H-mode [20]. With this aim, a series of discharges have been carried out in AUG in which the L-mode scenario with 300 kW of heating power used in previous work was achieved as a reference, and then brought into H-mode by increasing the heating power up to 1-4 MW. Then, the collisionality in the divertor was increased by increased fueling or nitrogen seeding, in order to reach the $\Lambda_{\text{div}} > 1$ condition. In order to disentangle the effects of nitrogen and deuterium fueling on the $\Lambda_{\text{div}}$ values, different fueling rates for both gases ($N_{\text{rate}}$ and $D_{\text{rate}}$) were used, roughly dividing the data set in four scenarios, as detailed in Table 1: A) low power discharges with low $N_{\text{rate}}$ and $D_{\text{rate}}$ values; B) discharges including both NBI and ECH heating, strong nitrogen seeding and a low $D_{\text{rate}}$; C) A discharge in which $\Lambda_{\text{div}} > 1$ is achieved only by means of a strong density fueling with no nitrogen; D) discharges with full power, and both high $N_{\text{rate}}$ and $D_{\text{rate}}$ values. As before, density e-folding length, $\lambda_n$, and filament size, $\delta_b$, were measured with the LiB and MPM diagnostics, respectively. Thermoelectric currents to the divertor [21], $I_{\text{div}}$, are used to detect ELMs in order to separate conditionally averaged inter-ELM values of all measurements [20].

Results are presented in Fig. 4 following the same arrangement employed in Fig. 1 for L-mode results: First, in Fig. 4a and c, $\delta_b$ is presented as a function of $n_{\text{edge}}$ and $\Lambda_{\text{div}}$, respectively. As can be seen, a filament transition takes place for L-mode filaments at $n_{\text{edge}} \sim 2 \cdot 10^{19} \text{ m}^{-3}$, which coincides with the value for the 300 kW discharges in Fig 1. Then, when additional power is injected to access H-mode, the collisionality is reduced again and $\delta_b$ drops. Finally, when density is increased over a second threshold, $n_{\text{edge}} \sim 3.5 \cdot 10^{19} \text{ m}^{-3}$, a similar transition takes place for H-mode inter-ELM filaments. As in Fig. 1e, both transitions
converge and take place around $\Lambda_{\text{div}} \sim 1$ when represented as a function of collisionality. Regarding the onset of the shoulder, represented in Fig. 4b and d, the same general trend as in L-mode is observed when considering the point cluster as a whole: Shoulder formation coincides again with both the $n_{\text{edge}} \sim 3.5 \times 10^{19} \text{ m}^{-3}$ threshold for H-mode filament transition and with the general $\Lambda_{\text{div}} \sim 1$ transition condition, with points taking similar values as the ones in Fig. 1f (indicated in Fig. 4d as a shaded area). However, when the four scenarios are considered individually, a clearer trend is found: discharges from scenario A display low levels of $\Lambda_{\text{div}}$ and do not access the higher transport regime. The same is valid essentially for scenario C, albeit slightly higher $\Lambda_{\text{div}}$ (and thus $\lambda_n$) values are achieved. Instead, all discharges from scenario D develop a clear shoulder, achieving a significant increase in $\lambda_n$ at higher values of $\Lambda_{\text{div}}$. Interestingly, discharges in scenario B, displaying similar $\Lambda_{\text{div}}$ and $n_{\text{edge}}$ values as those in scenario D, fail to achieve high $\lambda_n$ values. This reveals a more complex picture than in L-mode, as $\Lambda_{\text{div}} > 1$ seems to be necessary but not sufficient for the shoulder formation, with the level of $D_{\text{rate}}$ playing also some role in it. Since scenarios B and D feature similar $n_{\text{edge}}$ values, such a role is not likely to be related to the fueling of the main plasma, but instead to some mechanism taking place in the SOL. The result is consistent with L-mode observations carried out in TCV, where also a minimum level of fueling has been found to play a role in shoulder formation [22]. One possible explanation for this would be that the shoulder formation requires a high recycling rate at the main wall on top of the increased convective transport [23]. This would be consistent with the ion cooling described in the previous section. Nevertheless, the precise determination of this second threshold and the identification of the underlying physical mechanism will be the subject of forthcoming work.

### 6. Conclusions

Experiments carried out in AUG show how divertor collisionality, $\Lambda_{\text{div}}$, is the parameter triggering the shoulder formation in L-mode plasmas. Also, a change in filamentary regime has been measured for the first time in a fusion-relevant machine, linking the transition associated to filament disconnection from the wall to the formation of the density shoulder. These results lead to a scaling of $\lambda_n$ which is common for the three tokamaks of the “ITER Stepladder”: COMPASS, AUG and JET. Further experiments carried out in AUG show that the formation of the L-mode shoulder is also characterized by a strong cooling of the far SOL, which brings $T_i$ of both filaments and background to levels similar to those of $T_e$, $T_e \approx T_i \approx 15-20$ eV. An attempt has been carried out to extend these results into H-mode: First, the

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| Shot   | Scenario          | $P_{\text{ECH}}$ (MW) | $P_{\text{SNB}}$ (MW) | $D_{\text{rate}}$ (10^3 s^-1) | $N_{\text{rate}}$ (10^3 s^-1) | $D_{\text{rate}}$ max (10^3 s^-1) | $N_{\text{rate}}$ max (10^3 s^-1) | $T_{\text{adiv}}$ min (eV) |
|--------|-------------------|------------------------|------------------------|-----------------------------|-----------------------------|---------------------------------|---------------------------------|--------------------------|
| 31974  | A) Low N, Low D   | 1.3                    | -                      | 1.3                         | 2.8                         | 1.3                             | 3.4                             | 1                         |
| 31977  | C) High N, Low D  | 1.3                    | 1.7                    | 6.4                         | 18.8                        | 6.4                             | 8.4                             | 1.5                       |
| 33055  | B) High N, Low D  | 1.3                    | 1.7                    | 8.1                         | 1.8                         | 8.1                             | 8.1                             | 3                         |
| 33056  | C) High D, no N   | 1.3                    | 1.7                    | 6.2                         | -                           | 24.5                            | -                              | 10                        |
| 33058  | C) High D, no N   | 1.3                    | 1.7                    | 6.3                         | 2                           | 15.4                            | 8.4                             | 5                         |
| 33059  | C) High D, no N   | 1.3                    | 1.7                    | 6.3                         | 4                           | 24.5                            | 4.4                             | 5                         |
| 33475  | C) High D, High N | 1.4                    | 1.7                    | 6.2                         | 5                           | 24.4                            | 4.5                             | 7.5                       |
| 33478  | C) High D, High N | 1.4                    | 2.4                    | 7                           | 9.2                         | 24.4                            | 9.2                             | 1.5                       |

*Table 1. Main parameters of the H-mode experiments [20]. The four scenarios A-D are grouped in four colors (respectively, blue/green/black/red), based on their $D_{\text{rate}}, N_{\text{rate}}$ values.*
formation of a shoulder has been confirmed in inter-ELM H-mode plasmas. Second, the link between shoulder formation and filament transition has also been found to remain generally valid: Collisionality remains the necessary condition for the shoulder formation, but deuterium fueling seems to play an additional role. These results allow the extension of the general shoulder formation mechanism validated in L-mode to H-mode plasmas with the introduction of a few new elements which will be developed in forthcoming work.

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