Towards a general scaling of the Scrape-off Layer density width

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The width of the Scrape-off Layer –defined here as the typical radial distance travelled by particles ejected at the separatrix before hitting some PFC- is a key feature for next generation tokamaks, as it will determine erosion levels and heat loads at many critical plasma facing components, and most critically at the main chamber first wall. Recent L-mode experiments carried out on the ITER stepladder (including COMPASS, ASDEX Upgrade and JET tokamaks) [1] have proven the link between an increase in filament size at the outer midplane and the onset of the density profile flattening known as "shoulder" [2-4]. This study indicates that the increased effective collisionality, Λ_{div}, [5,6] in the divertor region at the onset of detachment leads to a change in the regime of filamentary propagation, greatly enhancing radial particle and heat transport. This has been explained as the effect of filament disconnection from the wall: when collisionality along the field line increases over a certain value, the parallel term of the charge conservation equation becomes negligible and the filament goes from Sheath Limited (SL) regime [7] to Inertial (IN) regime [8]. In order to refine the findings in [1] and confirm the validity of this model, a series of dedicated experiments have been carried out in AUG.

First, the dependence of shoulder formation on Λ_{div} has been investigated. For this, several L-mode density ramps were carried out at different heating powers (ohmic heating plus 0, 300 and 600 kW of ECH power) in conditions equivalent to those described in [4]. By these means, the density threshold of the onset of divertor detachment is changed without

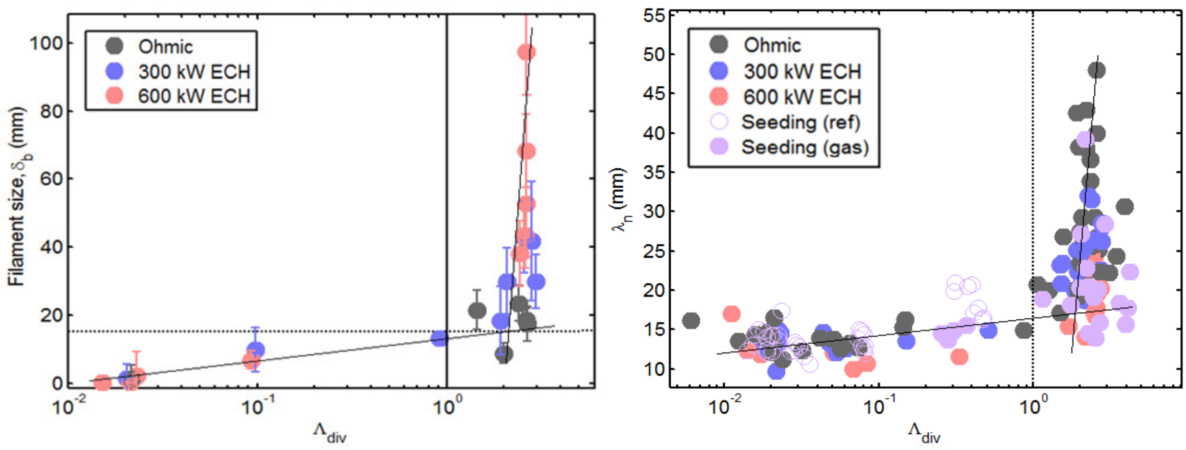

Figure 1: Filament size (left) and density e-folding length (right) as a function of divertor collisionality, Λ_{div}. Two different regimes can be seen on both sides of $\Lambda_{div} \sim 1$.

affecting greatly the midplane conditions, thus varying Λ_{div} over several orders of magnitude ($\Lambda_{div} \in [10^{-2}$-5]), while keeping the midplane collisionality, Λ_{mid}, fixed ($\Lambda_{mid} \sim 0.6$). Λ_{div} and Λ_{mid} are calculated as in [1]. Meanwhile, filament size at the far SOL (around 20 mm outside the separatrix) was measured with a multipin probe in the midplane manipulator, and edge density profile was measured using the Li Beam [4]. As a result, it has been observed that both filament size and density e-folding length, λ_n, scale with Λ_{div} (Fig. 1). No dependence on heating power was found, indicating that neither Greenwald density fraction, f_{GW}, nor Λ_{mid} are directly responsible for the transition. The same scaling is obtained when the detachment is induced by Nitrogen seeding in equivalent discharges, implying that the mechanism causing the high divertor collisionality is not important. Finally, the same results were obtained when an equivalent analysis was carried out in JET, studying the formation of the shoulder in L-mode [1]. In agreement with predictions in the literature [6], two different regimes are observed, roughly separated by the $\Lambda_{div} \sim 1$ threshold. For $\Lambda_{div} < 1$, the filament is still connected to the wall and remains in SL regime. For $\Lambda_{div} > 1$, collisionality dominates and filaments are in the IN regime. This has been confirmed by observing the dependence of perpendicular velocity, $v_\perp$, with filament size, δ_b (Fig. 2). In agreement with the models, scaling of filament velocity transits from a second power law (SL, $v_\perp \propto \delta_b^{-2}$) to a square root one (IN, $v_\perp \propto \delta_b^{1/2}$). Interestingly, filaments in the IN regime are closer to the theoretical prediction for cold ions (in the SL the difference is not so pronounced). Second, a Reversed Field Analyser (RFA) installed in the midplane manipulator [9] was used to characterize the ion energies of filaments and background before and after the shoulder formation. This study was carried out in a series of L-mode

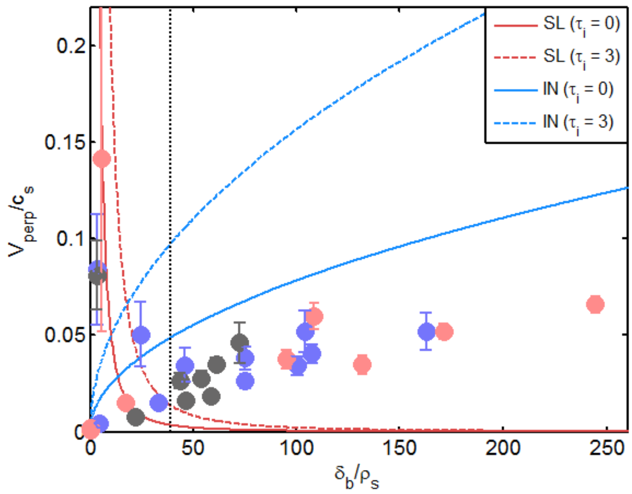

Figure 2: Filament perpendicular velocity as a function of size (normalized with sound speed and Larmor radius, respect.). SL and IN scaling are displayed for hot/cold ions ($\tau_i = T_i/T_e = 3/\ \tau_i = 0$).

discharges equivalent to those already described [4]. In this case, low/high constant density values were kept to stay below/over the shoulder formation threshold, while the plasma was displaced horizontally with respect to the midplane manipulator (in order to observe the dependence on radial distance to the separatrix). The results are displayed in Fig. 3, with temperatures normalized to values measured in the separatrix by CXRS, to account for the fact that, since heating is kept constant at 400 kW of ECH, higher density plasmas have lower temperatures. Below the shoulder formation, filaments retain a large fraction of the ion energy at the separatrix, and also remain substantially hotter than the background. Besides, T_i drops clearly with the radial distance to the separatrix. This is all in good agreement with previous measurements carried out in equivalent conditions [9]. However, after the onset of the shoulder, filaments cool down to a small fraction of the $T_{i,sep}$, losing the radial dependence and coming close to the background values. These results are consistent with the cold ion scaling observed for the IN regime in Fig 2. However, it remains to be explained which mechanism cools down the plasma in the $\rho \in$ [1.00-1.02] region. A plausible explanation for this would be an increase of recycling in the main wall as a result of the shoulder formation [10].

Last, L-mode density and electron temperature profiles in the near SOL ($\rho \in$ [1.00-1.01]) have also been observed by Thomson scattering. Results are similar to those obtained in the far SOL: both density and temperature e-folding lengths (λ_n and λ_T) increase substantially after a certain density threshold. Again, they scale with divertor collisionality, displaying a threshold for a value around $\Lambda_{div} \sim 1$. Similar observations have been carried out during H-mode (see Fig. 3). In this case, the density threshold after which λ_n and λ_T show a steep increase is substantially higher (in the range of $f_{GW} \sim 0.8$). However, the scaling with Λ_{div} remains the same as in L-mode. These results are consistent with further work carried out in ASDEX Upgrade (AUG) [11], in which the formation of an inter-ELM density shoulder in ITER-relevant H-modes has also been reported. This shoulder occurred as well at higher

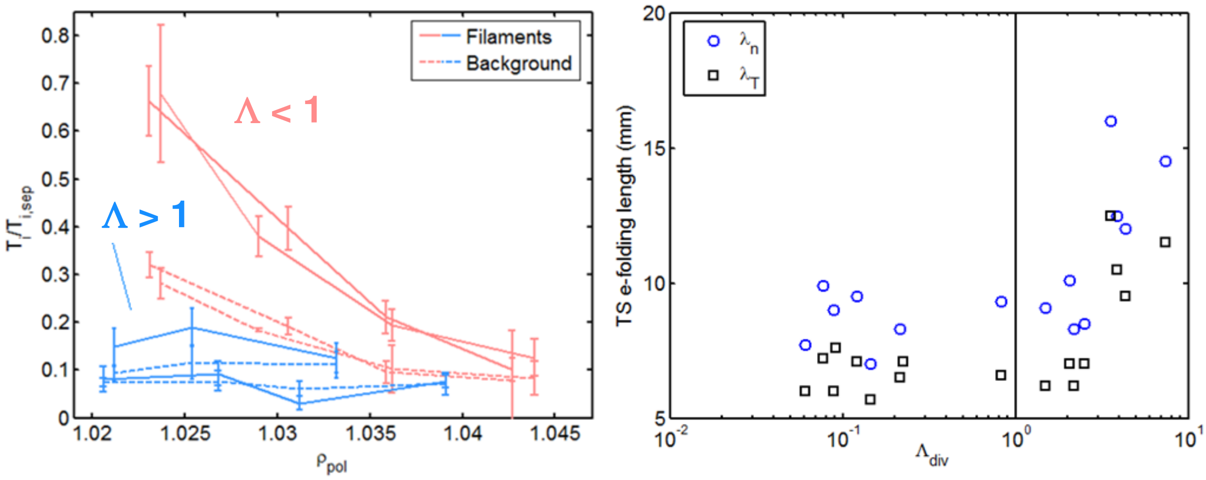

Figure 3: Left, T_i measurements carried out by RFA on filaments and background (solid/dashed lines) normalized with the separatrix T_i. Red/blue curves are measured before/after the formation of the shoulder. Right, Thomson scattering H-mode measurements of λ_n and λ_T in the near SOL ($\rho \in [1\text{-}1.01]$) as a function of Λ_{div}.

f_{GW} than in L-mode, and was not preceded by the onset of divertor detachment, but $\Lambda_{div} \sim 1$ was measured at the transition (the higher densities of H-mode yield collisional conditions even still in the high recycling phase). These results provide a valid framework to understand the physics of the shoulder in L-mode, including a measurable parameter, Λ_{div}, which determines the threshold for its formation. Besides, the basic mechanism behind filament transition is equally valid in H-mode, and several experimental observations seem to indicate that a similar dependence on Λ_{div}, holds in this regime. This paves the way for a general scaling of the SOL width, capable of improving current predictions for ITER & DEMO first wall particle and heat loads.

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