Cross-field and parallel dynamics of SOL filaments in TCV

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Abstract
Using recently installed scrape-off layer diagnostics on the tokamak à configuration variable, we characterise the poloidal and parallel properties of turbulent filaments. We access both attached and detached divertor conditions across a wide range of core densities ($f_G \in [0.09, 0.66]$) in diverted L-mode plasma configurations. With a gas puff imaging (GPI) diagnostic at the outer midplane we observed filaments with a monotonic increase in radial velocity (from $390$ m s$^{-1}$ to $800$ m s$^{-1}$) and cross-field radii (from $8.5$ mm to $13.4$ mm) with increasing core density. Interpreting the filament behaviour in the context of the two-region model by Myra \textit{et al} (2006 \textit{Phys. Plasmas} 13 112502), we find that they populate the ideal-interchange regime ($C$) in discharges at very low densities, and the resistive $X$ ($RX$)-point regime for all other discharges. The scaling of filament velocity versus size shows good agreement with this interpretation. These results are discussed and compared with previous probe-based measurements for similar conditions, which mostly placed filaments in TCV in the resistive ballooning ($RB$) regime (Tsui \textit{et al} 2018 \textit{Phys. Plasmas} 25 072506). In addition, for the first time in TCV, the parallel filament extension is studied by magnetically aligning the GPI measurements at the outboard midplane with a reciprocating probe in the divertor. In agreement with the filaments being in the ideal-interchange and the RX-point regimes, they are found to extend beyond the X-point into the outer divertor leg.

Keywords: filamentary turbulence, SOL turbulence, cross-field transport, blobs, two-region model, turbulent transport regime, parallel dynamics

(Some figures may appear in colour only in the online journal)

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1. Introduction

The study of turbulence in the scrape-off layer (SOL) of magnetic fusion devices—the region outside the last closed flux surface (LCFS), where the magnetic field lines intercept the vessel walls—is of strong interest in nuclear fusion research. SOL dynamics and associated radial heat and particle transport determine, to a large extent, core performance and integrity of the surrounding wall structures. In particular, the interaction of plasma with the first wall can limit the lifespan of the surrounding wall structures. In particular, the interaction of plasma-facing components due to erosion and influences main chamber recycling [3], tritium retention, and impurity generation by sputtering [4, 5], which causes radiative losses in chamber recycling [3], and degradation of plasma-facing components due to erosion and influences main chamber recycling [3], tritium retention, and impurity generation by sputtering [4, 5], which causes radiative losses in chamber recycling [3], and degradation of the first wall can limit the lifespan of the surrounding wall structures. In particular, the interaction of plasma-facing components due to erosion and influences main chamber recycling [3], tritium retention, and impurity generation by sputtering [4, 5], which causes radiative losses in the core and reduced confinement performances [3, 6]. Turbulent motion in the SOL in the form of filamentary structures [7–10], also known as blobs, represents a substantial fraction of radial heat and particle transport [7, 11, 12]. These filaments are coherent plasma structures with higher density and temperature than their surroundings, elongated along the magnetic field and moving radially outwards through the SOL. They are observed in all tokamaks, e.g. TCV [2], DIII-D [13], NSTX [14], MAST [15], Alcator C-Mod [16], TESATOR [17] and confinement regimes [2, 7, 18]. More generally, filaments are also observed in magnetized plasmas [19], such as those found in TORPEX [20], RFX-mod [21], and other devices [22]. Due to the key role filaments play in transporting the tokamak SOL profiles [18, 23] and the level of plasma interaction with the first wall [6], a good understanding of the physics governing their cross-field motion is of great importance.

Figure 1. $\Theta-\Lambda$ parameter space with the different filament regimes and their respective velocity scaling. Reprinted from [1], with the permission of AIP Publishing.

While the physics governing filament motion in basic plasma devices with relatively simple magnetic geometries is well understood [20, 24], the picture in tokamaks is harder to study due to the more complex geometry and limited diagnostic access and, thus, available information. In our current vision [8, 25, 26], a filament is generated in the edge through interchange or drift wave instabilities, driven by pressure and magnetic field gradients. It develops a dipole electric polarisation, which extends along the magnetic field lines reaching, in some cases, the divertor region and the vessel structures themselves [1, 8, 25]. This results in an $E \times B$ outwards drift which leads to velocities of up to several km s$^{-1}$ [2, 27, 28]. To date, the relation between the dynamics of turbulence upstream and the divertor is not completely understood. It is not yet clear how exactly and in which conditions the geometry of the divertor can influence the filaments’ behaviour and transport upstream. This is of relevance, particularly in view of the engineering constraints on heat depositions, both at the vessel walls and the divertor plates [29, 30]. It is, therefore, important to study filament propagation regimes and the mechanism governing their motion, and how they depend on SOL/divertor parameter and magnetic geometry.

The strength of the potential dipole in a filament and its facility to extend along the magnetic field depend upon the plasma collisionality and the filament size. The leading filament model for tokamaks is the two-region model [1], where the SOL is divided into regions above and below the magnetic X-point. Here and in the following, we assume a lower single null (LSN) configuration for the location designation (upstream, downstream). $E \times B$ and curvature drifts in the upper region drive vertical charge separation within the filaments. The resulting potential difference, that sets the radial $E \times B$ velocity, depends upon the magnitude of the return currents that can take different paths. Filaments are therefore classified into different regimes, depending upon the strongest return-current path (e.g. through the divertor plate, across the field near the X-point, or in the upstream region). In this model, the filament regime is determined by a parameter space given by a normalized filament size $\Theta$ and a normalized collisionality parameter $\Lambda$ [1, 2, 31] (figure 1). Within this model, one expects filaments to follow different velocity scalings, and to extend—or not—across the X-point depending upon this $\Theta-\Lambda$ space location.

Numerical studies confirm that filament motion is sensitive to plasma collisionality [31, 32], and that their $\Theta-\Lambda$ space position influences both their poloidal and parallel dynamics. Filaments in both resistive ballooning (RB) and resistive $X$ (RX) regimes were observed in GBS simulations of L-mode diverted plasmas [31, 33], where filaments in the RB regime do typically not extend into the divertor region [31]. Increasing plasma collisionality was found to correlate with increasing filament size and fluctuation levels [31, 34]. This is symptomatic of a flattening in the density and temperature equilibrium profiles in the SOL.

Several recent experimental studies have shed light upon filament characteristics and dynamics on several devices, such as C-Mod [35], TCV [2, 28], and ASDEX-U [18]. The scalings in figure 1 [1] have been tested [2, 36], and shown to represent an upper boundary for the radial propagation velocity of filaments [2, 20]. Although filament motion in the plane perpendicular to $\vec{B}$ is extensively documented, and the general effect of
increasing plasma collisionality confirmed \([11, 18, 37]\), relatively little is known about the three-dimensional filament character. They are understood to form upstream close to the LCFS, and extend along the magnetic field lines. Their cross-field shape is squeezed by the magnetic field shear around the X-point \([38]\), and their can elongate into the divertor region, with a characteristic parallel fluctuation propagation velocity of the order of the electron thermal velocity \([39]\). A recent study \([40]\) explored the parallel extension and connection between midplane and divertor plate in NSTX in attached plasma conditions \((f_0 = 0.2–0.3)\), finding that filaments, estimated to be in the \(C_s\) regime, were electrically connected from the outer midplane to the divertor plate in the outer SOL. Towards the separatrix, consistently with a stronger magnetic shear \([41, 42]\), filaments were not found to be connected, as well as displaying a generally weaker connection when transiting into the \(RX\) regime.

In this work, we combine cross-field and, for the first time on TCV, parallel measurements to characterise the filaments and verify the two-region model for both attached and detached plasma conditions. With a recently installed gas puff imaging (GPI) diagnostic \([27]\) and a reciprocating divertor probe array (RDPA) \([43]\), we measure the cross-field motion of filaments and, simultaneously, directly probe the filament parallel extent. We examine these findings from the perspective of the two-region model and discuss the measured cross-correlation (c.c.) of SOL fluctuations between the outer midplane and the divertor. The paper is structured as follows: section 2 briefly reviews the predictions of the two-region filament motion of filaments and, simultaneously, directly probe the filament parallel extent. We examine these findings from the perspective of the two-region model and discuss the measured cross-correlation (c.c.) of SOL fluctuations between the outer midplane and the divertor. The paper is structured as follows: section 2 briefly reviews the predictions of the two-region model and section 3 presents the experimental setup and diagnostic techniques used for the poloidal and parallel analysis of filaments. Section 4 presents our findings, which are compared to previous probe-based measurements and then interpreted with the two-region model. Finally, in section 5 we conclude with a discussion on the implications of our findings and the outlook for further studies.

2. Theoretical background

In the two-region filament motion model by Myra et al \([1, 36]\), the normalized cross-field size \(\hat{a}\) and the normalized filament radial velocity \(\hat{v}\) \([36]\),

\[
\hat{a} = \frac{a_0 R^{1/5}}{L_{\parallel}^{2/5} \rho_{\parallel}^{1/5}}, \quad \hat{v} = \frac{v_R}{c_s \left( \frac{2L_{\parallel}^3 \rho_{\parallel}}{m} \right)^{1/5}}, \tag{1}
\]

follow scalings depending upon the current closure regimes, defined by a normalized cross-section size parameter \(\Theta\) and an effective collisionality parameter \(\Lambda\). These are defined \([1, 2]\) as follows:

\[
\Theta = \hat{a}^{5/2}, \quad \Lambda = 1.7 \cdot 10^{-1} n_e \frac{c_s \left( m \right) L_{\parallel} \left( m/eV \right)}{T_e \left( eV \right)^2}, \tag{2}
\]

where \(a_0\) is the filament radius, \(R\) the radial coordinate, \(L_{\parallel}\) the parallel connection length to the outer divertor target, \(\rho_{\parallel}\)

\(m_c c_s/(e B_0)\) the ion sound Larmor radius for a particle of mass \(m\) in a magnetic field \(B_0\), \(c_s\) the ion sound speed, \(v_R\) the radial velocity, and \(n_e, T_e\) the local electron density and temperature, respectively. This model assumes cold ions, i.e. \(T_i \approx 0\). The filament regimes, determined by \(\Theta\) and \(\Lambda\), in figure 1, can be summarised as follows:

(a) For negligible collisionality and large filament size, filaments are electrically connected to the outer target. Parallel current to the wall is the main mechanism damping the potential dipole of the filament upstream and, hence, its radial \(\vec{E} \times \vec{B}\) velocity. These parallel currents are limited by the target sheath resistance. This regime is, therefore, termed the connected sheath (CS) regime. An increasing filament cross-field size lowers the drive term and enhances damping by parallel currents, resulting in a velocity scaling \(\hat{v} \sim 1/\hat{a}^2\).

(b) For low collisionalities, and sufficiently small filament size, where cross-field ion polarisation currents dominate the return current path, filaments are in the connected ideal-interchange (CI) regime. Current closure in the divertor region is enhanced by an elliptical distortion of the filaments resulting from magnetic shearing. Here, the strength of ion polarisation current closure decreases with filament size, resulting in a velocity scaling \(\hat{v} \sim \hat{v}_s \sqrt{\hat{a}}\). Here, the factor \(\hat{v}_s\) accounts for the distortion of the cross-field geometry of the filament due to flux expansion and magnetic shear in the SOL. In diverted plasmas, it can be approximated \([2, 44]\) as \(\hat{v}_s \approx 1/f_x\), which, for the discharges analysed in this work, results in \(\hat{v}_s \approx 0.3\).

(c) In the RX-point regime, collisionality along the path up to the X-point dominates the current closure in the divertor region, which, as in the CI regime, occurs through ion polarisation currents. The higher the upstream collisionality, the less efficiently current can flow towards the X-point to achieve closure. Conversely, a larger filament size favours parallel transport to the X-point, thereby reducing the filament drive which results in a scaling \(\hat{v} \sim \Lambda/\hat{a}^2\).

(d) For sufficiently high collisionality, upstream filaments are electrically disconnected from the X-point and divertor region, as parallel conductivity is strongly suppressed. Here, in the RB regime, cross-field ion polarisation currents in the upstream region remain the sole charge return path. Filaments do not extend past the X-point into the divertor region \([31]\), and magnetic shear effects can, therefore, be neglected. The larger the filament, the easier it is to sustain the filament dipole, resulting in a scaling \(\hat{v} \sim \sqrt{\hat{a}}\).

It is to be noted that the two-region model is an asymptotic model. It does not mean that current closure and filament velocities undergo a sharp phase transition from one regime to another, but rather present a behaviour resulting from a combination of these current closures in the transition regions (see, e.g., \([20]\)).
3. Experimental approach and diagnostic techniques

In this section, we present experiments and the diagnostic techniques employed to characterise cross-field and parallel filament properties in TCV.

3.1. Plasma scenarios and key diagnostics

Experiments were performed on TCV in LSN L-mode plasma discharges with step-wise density scans at constant $B_\Phi$ (1.42 T) and $I_P$ ($\sim$231 kA). In order to avoid H-mode, experiments were performed with the ion $\nabla B$ drift direction unfavourable to H-mode access. The geometry, unchanged across the whole data set, is shown in figure 2(a), together with the line-averaged density traces, figure 2(b). The analysed time intervals are highlighted with the appropriate colours and annotated by symbols used consistently throughout this paper. The density ranges over Greenwald fractions [0.09–0.66], accessing both attached and detached conditions. The detachment onset can be noted by a roll-over of the total outer target ion flux (figure 2(c)), determined from Langmuir probes (LPs) embedded in the vessel floor [45]. Detachment is also recognisable in the C-III emission front movement towards the X-point [46, 47].

Figure 3 shows the electron density and temperature profiles in the SOL, evaluated with a spline interpolation in the magnetic flux coordinate of the data from TS and LPs at the outer wall. Panels (a) and (b) show an example of a single profile reconstruction. An overview of the SOL profiles across the range of core densities is shown in panels (c) and (d). Temperatures measured by the TS above and just below the main plasma agree well, and are consistent with those measured by the OMP LPs in all discharges. From these measurements, we deduce that temperature and density are approximately constant along the field lines in the upstream region. We will use these temperature and density measurements rather than those at the target LPs. This is justified a posteriori by our classification of the propagation regimes of the filaments (see section 4.1) and the measurement of their parallel extension, indicating filaments that do not connect to the target nor extend deeply beyond the X-point (section 3.2.2). The temperatures and densities measured upstream, therefore, are good approximations for the average value along most of the filament volume in $C_i$ and $R_X$ [31].

SOL filaments are measured with a recently installed GPI diagnostic, described in Han et al [27]. D$_2$ gas is injected at the outer midplane and the resulting D$_\alpha$ emission ($\lambda = 656$ nm) captured tangentially to the local magnetic field. This yields a 2D poloidal section of the local dynamics with a field of view (FoV) of 5 x 4 cm, shown in figure 2(a), covered by a grid of 12 x 10 avalanche photodiode views acquiring at 2 MHz. This resolution is sufficient to image typical-sized (10–15 mm) filaments at the TCV outboard midplane, moving at velocities up to a $\approx$10 km s$^{-1}$ [48].

To probe the filament extent along the magnetic field, c.c. analysis is performed between diagnostics that are field-aligned at different poloidal (and toroidal) locations in the SOL. With a characteristic time trace showing a steep front
Figure 3. SOL profiles are determined by a spline interpolation of TS data and LPs embedded in the outer wall. In (a) and (b), an example of such reconstructions, in which TS (black circles) and LP (green dots) data are used to generate the blue profile. The GPI view locations used to perform the conditional averaging of filaments (see section 3.2.1) are marked by blue asterisks. An overview of the temperature and density profiles from all the discharges is shown in (c) and (d), with the respective locations of the filament measurement locations marked by the respective symbols.

Figure 4. Snapshot of a conditionally averaged filament, normalized to its maximum, $\bar{S}(\vec{r}, \tau)/\bar{S}_{\text{max}}$. The location used to trigger the averaging ($\vec{r}_{\text{tr}}$) is marked by the magenta cross. The HM contour is shown in magenta, with the HM contours 3 $\mu$s before and 3 $\mu$s after the triggering time shown in red and black, respectively. The continuous magenta line shows the largest poloidal extension of the HM contour, which we take as the filament’s diameter ($=2a_b$, in equation (1)).

and trailing tail, a turbulent filament simultaneously passing through the two field-aligned locations results in a strong positive correlation between the signals [39, 48]. To perform this measurement, we employed mainly the GPI $D_e$ emission at the outer midplane and the signal from the RDPA, as well as wall-embedded LPs and the X-point GPI [49]. During the vertical reciprocation (see figure 2(a)), the RDPA intercepts the magnetic field lines passing through the FoV of the GPI, and the two diagnostics are thus, temporarily, measuring at locations which are magnetically field-aligned. The RDPA carries a horizontal array of 12 Langmuir Mach probes operated in ion saturation current mode and acquiring at 2 MHz, synchronous with the GPI. The plunges extend vertically over 370 mm and last for a total of 350 ms. The probe thus moves at a velocity of $\approx 2$ mm ms$^{-1}$ and takes several milliseconds to cover the typical poloidal size of filaments ($\approx 10 - 20$ mm), and it can, therefore, be regarded as static compared to the filament dynamics.

3.2. Analysis techniques

3.2.1. Conditional average sampling. Filament velocities and sizes are determined from the GPI signal $S(\vec{r}, t)$, obtained from the raw brightness $I(\vec{r}, t)$ using

$$ S(\vec{r}, t) = \frac{I(\vec{r}, t) - \langle I(\vec{r}, t) \rangle_{1\text{ms}}}{\langle I(\vec{r}, t) \rangle_{1\text{ms}}}, $$

where $\langle I(\vec{r}, t) \rangle_{1\text{ms}}$ indicates a moving average of $I(\vec{r}, t)$ over 1 ms, performed to average out the influence of the background neutral gas density and other possible low-frequency trends [27, 50]. The signal is processed using conditional average sampling (CAS) [50]. Here, the GPI window is averaged over all the times at which the signal of a chosen trigger location $\vec{r}_{\text{tr}}$ exceeds a threshold and reaches a local maximum in brightness:

$$ \bar{S}(\vec{r}, \tau) = \frac{1}{N} \sum_{j=1}^{N} S(\vec{r}, t_j + \tau). $$

Here, $t_j$ are the times where the triggering condition is met at $\vec{r}_{\text{tr}}$. The locations $\vec{r}_{\text{tr}}$ are chosen in such a way that most of the SOL is covered, excluding the borders of the domain, where filaments properties could not be unambiguously analysed. We use a threshold of 2.5 standard deviations of the signal $S(\vec{r}_{\text{tr}}, t)$ calculated across the whole GPI puffing time. Averages are built over a sample size $N$ of 100–300 triggering events, for
Figure 5. Examples of highly correlated signals obtained when magnetically connecting different diagnostics in different locations in the SOL above, around, and below the X-point. In the left-hand panels, the plasma geometries with the locations of the detected correlation. In the right-hand panels, a comparison of the signals of the respective diagnostics, normalized to their standard deviation. (a) Midplane GPI and wall-embedded LPs (above the X-point, $\rho \Psi \approx 1.069$). (b) Midplane and X-point GPI ($\rho \Psi \approx 1.056$). (c) Midplane GPI and RDPA (unbaffled discharge, $\rho \Psi \approx 1.061$). In (d)–(f), the signals with the highest c.c. found in the geometries shown in (a)–(c), respectively.

Figure 6. (a) Evolution of the c.c. for $f_{\alpha} = 0.23$ (Δ) between a GPI view and an RDPA probe tip at $\rho \Psi \approx 1.08$. The value reaches its maximum as the RDPA sweeps through the field lines that are mapping the location of the GPI FoV downstream. (b) The signals of the GPI and the RDPA at the time of highest c.c., normalized to their respective standard deviation.

The typical gas puff duration of 50–100 ms. By also considering the time evolution shortly before ($\tau < 0$) and shortly after ($\tau > 0$) the triggering events, we obtain the average spatio-temporal evolution of the detected structures. Figure 4 shows a conditionally averaged filament and the time evolution of the half-maximum (HM) contour of the signal $S(\vec{r}, \tau)$. Taking the GPI signal as a proxy for the filament density, we calculate the diameter of the filament as the largest poloidal FWHM at the triggering time (FWHM = $2\Delta \theta$, in equation (1)). The filament cross-field velocity is then measured by tracking the center of an ellipse fit of the HM contour. The inclination of the filament with respect to the local poloidal magnetic field is then defined as the angle between the major semi-axis of the ellipse and the local poloidal field. Choosing different $\vec{r}_m$, one can, thus, evaluate these filament properties at different radii.

3.2.2. Parallel c.c. analysis. The passage of a filament through a Lp or across a GPI view typically shows a characteristic steep front and trailing tail signature in the time traces. Measurements of filaments at different locations in the SOL, provided the latter are field-aligned, unambiguously present similar traces and result in strong c.c. ($>0.5$) [39, 48]. If a filament is sufficiently extended along the magnetic field, it can thus be detected simultaneously at different locations in the SOL. To use this method to probe the parallel extent of filaments, an accurate field-alignment of the SOL diagnostics is important. We tested the accuracy of the magnetic reconstruction and field line tracing routines by first studying the interception of the shadow that the RDPA casts along the magnetic field lines with the floor, as measured by the Lps (see figure 3(e), in De Oliveira et al [45]. Comparing the vertical position of the RDPA during the shadowing with the location given by the magnetic reconstruction yields a precision of the reconstructed magnetic field lines floor mapping of $\approx 1$ cm, for a single full toroidal transit, at an incidence angle $1^\circ \leq \alpha \leq 5^\circ$.

Using the field line tracing, we then configured a plasma discharge to field-align different diagnostics in the SOL. Short distances in baffled discharges were first examined: LPs embedded in the top sides of the baffles (see figure 5(a)) were aligned and correlated to the outer midplane GPI, separated by a parallel distance of $\approx 1.5$ m. We then extended the measurements to the X-point GPI [49], with a parallel separation of
4. Results and discussion

In the following, we apply the techniques presented above to determine the filament properties across and along the magnetic field for a range of plasma densities.

4.1. Cross-field characteristics and propagation regimes

Using CAS, we obtained the average sizes and velocities of filaments across the density scan discussed in section 3 at different locations in the FoV of the GPI. For the same locations, we obtain local densities \(n_d^{\text{SOL}}\) and temperatures \(T_e^{\text{SOL}}\) from the profiles presented in figure 3. Figure 7 shows how the poloidal velocities, filament size and inclination to the local poloidal field vary with the local density. For every discharge, we average the filament properties over all the CAS measurement locations for a clearer view of the trend. The data scatter is shown by the error bars. The values for the average radial velocity, size, density, temperature, and additional quantities are reported in table 1.

As already observed in published numerical [31, 32, 51] and experimental studies [28], we record a nearly monotonic increase in filament size with density (\(\approx 57\%\)), from a poloidal cross-field radius of 8.5 mm to 13.4 mm and an increase of \(2 \times\) in radial velocity (from 390 m s\(^{-1}\) to 800 m s\(^{-1}\)). This trend tends to enhance cross-field transport and is qualitatively consistent with the appearance of shoulders at higher density [11, 23, 28].

The decrease in poloidal velocity (figure 7(b)) with increasing density is consistent with the poloidal \(\vec{E} \times \vec{B}\) drift, if a radial electric field of \(\vec{E} = -\nabla \Phi\), with a potential \(\Phi \sim 3 T_e\) is assumed. In fact, the measured poloidal velocities are in fair agreement (within factor 2 or better) with an estimated vertical drift of \(v_b = (\vec{E} \times \vec{B})_y \approx E_r/B_b \approx -3 (\Delta T/\Delta R)/B_b\). The aspect ratio of the filaments and their shape (see figure 4) is roughly constant throughout the SOL and the density scan. In particular, there is no indication for a significant shearing of the filaments. Therefore, the poloidal \(\vec{E} \times \vec{B}\) flow and its shear is not expected to influence the filament radial velocity.

We use the quantities reported in table 1 to populate the \(\Theta-\Lambda\) parameter space using equation (2). We obtain values for \(\Lambda\) spanning from \(\approx 0.1\) to \(\approx 10\) and for \(\Theta\) from \(\approx 1\) to \(\approx 10\), as shown in figure 8. The discharge at very low density shows filaments located deeply in the \(C_i\) regime. With increasing density, filaments quickly move towards the border between the \(C_i\) and the \(RX\) regime. Shortly before detachment onset \((\varphi_0 \gtrsim 0.23)\), filaments already appear in the \(RX\) regime, where most filaments are located.

We next assess to what extent the filament propagation regimes identified in figure 8 are consistent with the observed filament velocity vs size dependencies. In figure 9, we show the normalized velocity as a function of normalized filament size (see equation (1)), together with other quantities that facilitate a comparison with the scalings from the model presented.

\(\approx 4\) m (see figure 5(b)). Both attempts obtained a positive correlation, as shown in figures 5(d) and (e). However, to account for uncertainties in the magnetic reconstruction, slow scans of the plasma current across the discharges were necessary to obtain this alignment. As this was not a very efficient use of TCV operation, and to be able to keep a constant magnetic field, current and geometry throughout the data set, we employed the RDPA that sweeps vertically through the divertor region. It is, therefore, at certain moments (at a parallel distance of \(\approx 9\) m) field-aligned to the GPI FoV upstream, as shown in figure 5, panels (c) and (f). This method has also the advantage of delivering data during the alignment with GPI views at different radii in a single discharge, and it is therefore the approach used in the following.

The transitory field-alignment of the RDPA (measuring the ion saturation current from its LPs, proportional to \(en_v c_i\) [45]) and the GPI (measuring the \(D_n\) brightness from the local puff [50]), with a consequent high correlation in their signals, is shown in figure 6. Here, in panel (a), we show an example of the c.c. between a GPI view and an RDPA LP during the RDPA sweep. In panel (b) we show both signals around the time of highest correlation, normalized to their respective standard deviations for a better comparison. It should be noted that a clear correlation between GPI and floor LPs, as well as between the RDPA and the floor LPs, was not found. Further experiments are, however, required to categorically rule out such a connection to the outer divertor target, as the longer \(\approx 15\) m), limited accuracy over several torus, and the shadowing of the probe itself make the measurement more difficult.

In the following, the correlations shown are all measured for the unbaffled discharges shown in figures 2(a) and 5(c) and between the midplane GPI and the RDPA in the divertor region. For each density, we subdivide the time traces of the respective signal into windows of 1 ms, the time over which the RDPA moves by \(\approx 2\) mm. Then, for each time window, we cross-correlate the signal \(S(\hat{t}, t)\) from each GPI view with \(\rho_q > 1\) to all RDPA probe signals, which underwent the same normalization as \(S(\hat{t}, t)\). In addition, both signals are also smoothed with a Gaussian-weighted moving average window of 5 \(\mu\)s. Here, \(\rho_q\) is the normalized flux coordinate defined by \(\rho_q = \sqrt{(\Psi - \Psi_0)/(\Psi_{\text{LCFS}} - \Psi_0)}\), where \(\Psi_0\) is the poloidal magnetic flux, and \(\Psi_{\text{LCFS}}\) the magnetic flux at the LCFS. For each GPI view, we thus obtain a c.c. time trace with every RDPA LP probe. As the RDPA sweeps across the divertor, every GPI view will, at some time, be magnetically connected to one of the probes on the RDPA.

The peaks in the c.c. traces typically last for approximately 5–10 ms (see figure 6), which can be explained as follows: in order to see a correlation between the RDPA and the GPI signals due to filaments, the two diagnostics need to be aligned magnetically within a precision of approximately the cross-field size of the filaments (10–20 mm, in accordance with the midplane measurements of filament sizes). Considering the vertical RDPA velocity of \(\approx 2\) mm ms\(^{-1}\), this is the case for \(\approx 5\) – 10 ms. For each GPI view, we select the highest correlating GPI–RDPA pair, and only consider the significant ones, i.e., those which present a peak in their correlation trace which is above three standard deviations, such as the one shown in figure 6. This yields c.c. profiles as a function of \(\rho_q\).
in Myra et al [1]. The scaling that best represents the data, in panel (a), is that of the RX regime ($\tilde{v} \sim \Lambda/\tilde{a}^2$). For clarity, this is presented as a plot of $\tilde{v}/\Lambda$ vs $\tilde{a}$. Note that $\bigtriangleup (f_g = 0.09)$ is the only datum that is deeply in the $C_i$ regime, while $\nabla (f_g = 0.16)$ and $\Delta (f_g = 0.23)$ are on the border between the $C_i$ and RX regimes. In contrast, panel (b), where we plot $\tilde{v}$ vs $\tilde{a}$, shows a clear inconsistency with the $C_i$ regime ($\tilde{v} \sim 1/\tilde{a}^2$). Also, the dependence of $\tilde{v}/\sqrt{\tilde{a}}$ on $\Lambda$, shown in panel (c), excludes the RB ($\tilde{v} \sim \sqrt{\tilde{a}}$) and $C_i$ ($\tilde{v} \sim \tilde{a} \sqrt{\tilde{a}}$) regimes. The measured velocities, therefore, confirm that filaments in the presented discharges are predominantly in the RX regime.

4.2. Parallel extension of filaments

We now proceed with the parallel correlation analysis from section 3.2.2, to determine whether the filaments extend into the divertor region. This imposes a further constraint on our assessment of the filament regime. In particular for RB, such extension is not expected [31]. A 3D representation of the magnetic geometry is shown in figure 10. The highest correlations between GPI and RDPA signals were detected when the probe was approximately at the location predicted by field line tracing.

Figure 11, shows the c.c. profiles between the GPI and the RDPA in the SOL. The significant levels of c.c. are consistent with the filaments populating the RX and $C_i$ regimes.
rather than $RB$ in which a connection between the midplane and the divertor region is not expected. From the profiles in figure 11, it appears that in the far SOL ($\rho_0 > 1.05$) filaments always extend from the midplane into the outer divertor leg region. In contrast, in the near SOL, $C_i$ filaments lose coherence near the separatrix, whereas $RX$ filaments are always connected.

A possible explanation for the loss of correlation for $C_i$ filaments in the near SOL is the overall smaller size of the filaments, combined with the higher temperatures (and higher value of the gyroradius $\rho_s$) in the low density discharges. In fact, magnetic shear in the vicinity of the X-point is thought to squeeze filaments to poloidal sizes comparable to $\rho_s$, thereby enhancing local current closure [41, 42, 52–54]. The relevant quantity to consider is, therefore, the local filament radius normalized by the local gyroradius. When this becomes comparable to the flux expansion, the magnetic shear is able to short-circuit, and therefore disconnect, the filaments. In figure 12, we show $(a_b/\rho_s)/f^*_z$ for the trigger locations of the CAS. Here, $f^*_z$ is the local flux expansion calculated for the trigger locations at the X-point. The critical size $(a_b/\rho_s \approx f^*_z)$ is reached at lower density discharges as the LCFS is approached. The combined effect of decreasing size and increasing temperature seems therefore enough to explain the loss in parallel coherence to the midplane that we observed in the near SOL of lower density discharges, while $RX$ filaments better survive the magnetic shear passage near the separatrix.

The drop in signal correlation in the near SOL for $C_i$ filaments is more likely caused by a loss in filament connection past the X-point, rather than by changes in the GPI signal response. Self-consistent GPI simulations with the GBS turbulence code, including a kinetic neutral model with both deuterium atoms and molecules [55], showed that far from the gas puff, at/beyond the peak in the $D_\alpha$ emission profile, plasma density and GPI measurements are not necessarily positively correlated. In the present experiments, however, all our analysis is performed on GPI measurements well to the right of the peak in the emission profiles (which all peak inside the LCFS). Thus, we can still expect a strong positive correlation between the GPI measurements and plasma density fluctuations. A few examples of the correlating signals at different densities and $\rho_0$ coordinates are shown in figure 13, with discharges before ($\Delta$), around ($\Delta$) and after ($\square$) detachment. From these time traces we can also exclude an absence of fluctuations as the reason for lower correlation.

It is to be noted that the parallel propagation velocity of potential fluctuation along the filaments was estimated to be
Figure 10. 3D representation of magnetic field lines passing through the GPI FoV and the region accessed by the RDPA. In the inset, the RDPA is shown at the highest position it reached during the scans. The markers indicate the respective location of maximal correlation met by RDPA. As a comparison, we also show the expected locations of maximal correlation of the six GPI views corresponding to the magnetic field lines shown in red, according to the field line reconstruction (cyan hexagrams).

Figure 11. c.c. profiles found for different core densities, as a function of the normalized flux coordinate. For low density, corresponding to filaments in the \( C_i \) regime and at the transition between \( C_i \) and \( RX \), in the near SOL the correlation vanishes, to then increase with \( \rho \Psi \) to the values of \( RX \) filaments in the far SOL (\( \rho \Psi \gtrsim 1.05 \)).

of the order of the electron thermal speed [39], and, therefore, any delay over the parallel distance over which the correlation is measured lies within our temporal and spatial resolution and is therefore not discerned and is unlikely the cause of the loss in correlation. Further dedicated experiments and/or simulations to directly study the reconnection of filaments to the divertor region once they clear the region of high magnetic shear are yet to be performed, and will likely employ the recently installed X-point GPI system at TCV [49].

It is worth mentioning that the measured radial coordinate of the RDPA at maximal c.c. with GPI is displaced by roughly 0.02 in \( \rho \Psi \), compared to the one measured upstream (see figure 14). A possible explanation for this, is the radial \( \vec{E} \times \vec{B} \) drift at/below the X-point, which would be consistent, in direction, with the direction of the shift (see, e.g., figure 11 in [56]). This hypothesis could potentially be tested by performing similar experiments in favourable ion \( \nabla \vec{B} \) drift direction. Another possible explanation is a combined effect of systematic errors in the magnetic reconstruction and uncertainties in the spatial calibration of GPI. Upstream, a \( \Delta \rho \Psi \) of 0.01 corresponds to a \( \Delta R \) of roughly 4 mm in real space. Downstream, in the region where RDPA records the highest correlation, it corresponds to \( \approx 10 \) mm. A displacement of 0.02 in \( \rho \Psi \) would thus represent an error of \( \approx 20 \) mm in real space. This is within the accuracy of the magnetic reconstruction (\( \approx +/−1 \) cm for 1.5 toroidal transits) combined with the spatial calibration of the GPI upstream (\( \approx +/−5 \) mm).

As already briefly mentioned above, no correlation could be detected between the GPI and the floor LPs, as well as between the RDPA and the floor LPs. Although this might be an indication that filaments do not reach the divertor plates, further dedicated measurements are needed to exclude this with certainty. Current measurements were limited by several factors: the floor probes were operated on a lower acquisition frequency (200 kHz), limited ion saturation current data is available as they were operated in swept voltage mode for the density and temperature profiles acquisition, the accuracy of field-line tracing is not high enough to establish alignment between the relatively small upstream GPI FoV and the floor LPs, situated at a long parallel distance to the upstream GPI window (\( >15 \) m). Furthermore, the shadow cast by RDPA along the magnetic field onto the floor LPs happens to be in concomitance with the moment of alignment. Future measurements could include the use of the X-point GPI, which uses a fast-camera with a much wider FoV, situated at a smaller parallel distance to the floor. A top-view camera might be able to resolve parallel dynamics along the magnetic field.

4.3. Comparison to previous measurements

Previous horizontal fast reciprocating probe (HFRP) measurements [2, 18] in discharges similar to those presented in this study estimated filaments to be mostly in the \( RB \) regime. To investigate this discrepancy, in dedicated discharges, #69837,
Figure 13. Examples of the signals yielding the correlation profiles in figure 11 in the near (left column) and far (right column) SOL, and for different densities. The raw signals of the GPI and the RDPA are normalized to their standard deviation and smoothed with a Gaussian-weighted moving average window of 5 μs. The depicted RDPA signals are those that displayed the highest correlation with the given GPI view.

Figure 14. Comparison of the $\rho_\Psi$ coordinate of the GPI and the RDPA at the time of maximal correlation. The shift with respect to the $\rho_{\text{GPI}} = \rho_{\text{RDPA}}$ line is either due to a radial $\vec{E} \times \vec{B}$ shift or systematic measurement error (see text).

$I_p = 250$ kA, $f_g = 0.48$ and #69847, $I_p = 250$ kA, $f_g = 0.24$, not shown here), we compared the GPI and HFRP measurements. We traced back the discrepancy to two main causes: (1) the filament size estimates as performed in [2] are systematically smaller (by a factor 2), and uncertainties in the radial velocity are larger. (2) The temperature and density used to estimate $\Theta$ and $\Lambda$ in [2] were measured at the outer target which, particularly for detached plasmas, differ substantially from those measured upstream.

Underestimating the filament size leads to an underestimation of $\Theta$, while the lower temperatures measured at the target overestimate $\Lambda$. As it can be seen in figure 8, this leads to the $RB$ regime. The direct comparison performed in the dedicated discharges confirms this shift in the $\Theta$–$\Lambda$ space. We argue here that the direct measurement of filament size by GPI is more accurate than that estimated by the probe, which is based on single point measurements and some simplifying assumptions, such as a perfectly circular filament cross-section. This conclusion is supported by the consistency of our measurements with $RX$ filaments, in particular the cross-field velocities and the parallel extension of the filaments into the divertor region, that are incompatible with the $RB$ regime.

5. Conclusions and future studies

Using an outer midplane GPI system and a RDPA in the divertor region, we have measured the size, radial velocity and parallel extension of SOL filaments in TCV. Discharges were performed both in attached and detached conditions, in LSN L-mode. A significant increase in filament size ($\sim 60\%$) and radial velocity ($\sim 100\%$) was observed with increasing core density. With no significant change in filament detection frequency, this is at least consistent with an increase in radial filamentary transport and the formation of a density shoulder as core density increases [18, 23]. The measurements were also compared to the two-region model and scalings proposed in Myra et al [1]. The location of the filaments in the $\Theta$–$\Lambda$ parameter space and the scaling of their normalized velocity and size were found to agree well with filaments transitioning from the $C_i$ regime into the $RX$ regime with increasing core density. By means of c.c. between the GPI and the RDPA, for the first time in TCV, we obtained information on the parallel extension of filaments.
The observed parallel extent of the filaments is consistent with the $C_i$ and the RX regimes. In the far SOL, both in attached and detached conditions, we measured high c.c. between the midplane GPI (upstream) and the RDPA (downstream). In the near SOL, filaments of discharges with lower core densities ($C_i$) do not extend into the divertor region, while filaments in higher densities (RX) are always connected to the divertor region. We hypothesise that the magnetic shear near the X-point is strong enough to shorten the current closure of $C_i$ filaments. In no regime did we detect a connection of upstream filaments to the floor Lps at the outer target. Although this could indicate that filaments are disconnected from the floor, further dedicated studies are needed to strengthen such a conclusion.

From the physical picture emerging, it appears that at sufficiently high density, in which filaments in TCV are in the RX regime, the upstream region is everywhere connected to the divertor region, at least for some distance beyond the X-point. This clearly differs from what would be expected for RB blobs. A possible consequence of this finding is that turbulence upstream can, potentially, be influenced by the divertor geometry, even at high densities and for detached plasma conditions. As the foreseen operational regime of future reactors will be with, at least partially, detached plasmas, this poses the question whether, and in which form, this influence of the divertor geometry on upstream turbulence exists and can be made use of. This has wider implications in the study of advanced divertor configurations and will be addressed in future research. Also, further investigation into whether filaments in the $C_S$ and RB regimes can be accessed in TCV is needed, and, if so, whether filaments in these regimes can reach into the divertor or not.

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