Study of filament motion and their active control

C. Theiler, I. Furno, P. Ricci, A. Fasoli, B. Labit

Ecole Polytechnique Fédérale de Lausanne (EPFL)
Centre de Recherches en Physique des Plasmas (CRPP)
Association Euratom Confédération Suisse
Station 13, CH-1015 Lausanne, Switzerland

Introduction

Radially propagating filaments of enhanced plasma pressure, also called blobs, are an important element of cross-field particle and heat transport in the scrape-off layer (SOL) of fusion devices. They influence the density and temperature profiles of the SOL, its impurity screening characteristics, recycling in the main chamber and, especially for filaments associated with ELMs in tokamaks, the lifetime of main-chamber components and impurity generation rates [1].

Radial filament motion is generally ascribed to charge dependent drifts, such as those generated by magnetic field gradients and curvature, that lead to a polarization of the filament [2]. The resulting electric field inside the filament gives rise to an $\mathbf{E}\times\mathbf{B}$ convection. A good understanding of the properties of filaments, such as their radial velocity, could allow to actively influence them and thus also the properties of edge/SOL turbulence.

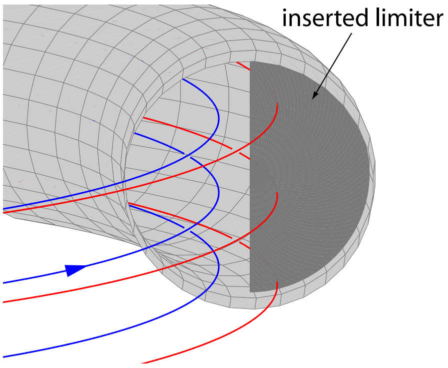

Figure 1: Sketch of the TORPEX vacuum vessel with the inserted limiter and examples of field lines.

In this paper, we investigate filament motion in TORPEX [3], a toroidal device dedicated to the study of plasma turbulence and transport. TORPEX features open magnetic field lines, obtained by superimposing a relatively weak vertical field component on a toroidal field of ≈ 80 mT (see sketch in Fig. 1). Plasmas are produced and sustained by microwaves in the electron cyclotron frequency range with typical electron densities $n_e \lesssim 10^{17}\ \mathrm{m}^{-3}$, electron temperatures $T_e \lesssim 15$ eV and ion temperatures $T_i \ll T_e$. Recently, the mechanism of filament/blob generation from interchange waves was experimentally identified in TORPEX. Filaments form from radially extending positive crests of a wave that are sheared apart by the $\mathbf{E}\times\mathbf{B}$ flow. The radial elongation of the wave is attributed to a decrease in the radial pressure scale length [4, 5, 6].

In Sec. I, we present measurements of blob vertical size and radial velocity in a simple geometry and interpret the data on the basis of 2D thermalized blob models. In Sec. II, we present an experimental setup for TORPEX that aims to actively influence the blob velocity. The idea is based on a prediction in [7] which suggests that parallel currents may be altered by varying the angle between magnetic field lines and wall. This effect is also predicted to be relevant for divertor localized blobs in tokamaks [8].

I. Filaments in a simple geometry

We study filament motion in a relatively simple setup with constant curvature along the magnetic field lines, nearly constant connection length $L \approx 2\pi R$ ($R = 1$ m is the major radius), and near-perpendicular incidence of the magnetic field on the wall. This is achieved by inserting a steel limiter as sketched in Fig. 1. Filament propagation is investigated with a 2D Langmuir probe array, that covers the whole cross-section of TORPEX and that is toroidally displaced by 97° from the limiter. A snapshot of the instantaneous ion saturation current (I_{sat}) profile is shown in Fig. 2 (a). The time averaged profile, indicated by white contour lines, peaks on the high-field side. In the limiter shadow region, a filament (black contour) as well as its location 36 μs later (white dashed contour) is visible.

In order to automatically identify a large number of filaments, we apply a pattern recognition method [9]. For each filament, we compute radial velocity v_{blob}, vertical size a (HWHM) and background density. Details of this procedure are presented in [10]. In Fig. 2 (b), we show the joint probability of blob velocity versus size in adimensional units $\left(\tilde{a} = \frac{a}{\rho_s}\left(\frac{\rho_s R}{4L^2}\right)^{1/5},\ \tilde{v}_{blob} = \frac{v_{blob}}{c_s}\left(\frac{R^3}{2L\rho_s^2}\right)^{1/5},\ c_s \text{ and } \rho_s \text{ are ion sound speed and radius, respectively}\right)$. The relatively strong variations in the adimensional blob size $\tilde{a}$ ($0.15 \lesssim \tilde{a} \lesssim 1.75$) are achieved by performing discharges in different working gases (H_2, He, Ne, Ar). In the same figure, a scaling law for blob velocity proposed in [10] is superimposed on the experimental data (white solid). It retrieves the scaling laws $\tilde{v}_{blob} \propto \frac{1}{\tilde{a}^2}$ [2] and $\tilde{v}_{blob} \propto \sqrt{\tilde{a}}$ [11] for large and small values of $\tilde{a}$ and agrees well with the data. In agreement with theoretical and numerical work on 2D thermalized blobs in Refs. [12], this scaling law shows that for $\tilde{a} \lesssim 1$, blob velocity is limited mainly by cross-field ion polarization currents, while par-

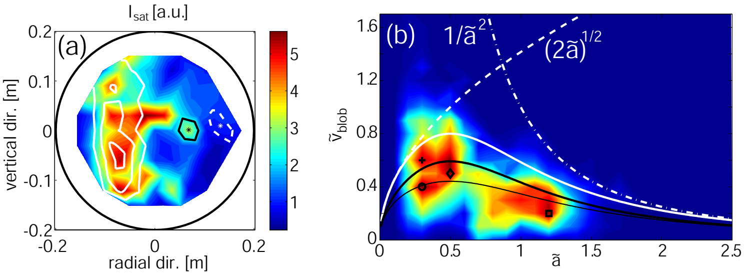

Figure 2: (a) Snapshot of I_{sat} in a He discharge. (b) Joint probability of blob velocity versus size. Symbols indicate the peak of the distribution $\tilde{v}_{blob}$ vs. $\tilde{a}$ obtained in (□) H_2-, (◇) He-, (+) Ne- and (○) Ar-plasmas.

allel sheath currents become the dominant damping term for $\tilde{a} \gtrsim 1$. This scaling law does further not change drastically, if we include the effect of a finite background density (thick black) and additionally a drag due to ion-neutral collisions (thin black).

II. A setup aimed to influence filament motion

We now describe a setup where the angle α between the magnetic field and the limiter can be reduced to values $\alpha \ll 1$ instead of $\alpha \approx \pi/2$ as in the experiment discussed in Sec. I. In this case, the parallel electron current is predicted to depend on α [7] and varying α could therefore allow influencing the velocity of filaments.

The reason for the α-dependence is illustrated in Fig. 3 (a). For small values of α, a magnetic pre-sheath (MPS) forms in addition to the usual Debye sheath [13], with a thickness of the order of ρ_s (green layer in Fig. 3 (a)). In the MPS, an electric field component E_y exists. While all ions entering the MPS get ideally absorbed by the wall, a large fraction of electrons is reflected in the MPS due to the potential barrier. These reflected electrons undergo trajectories as qualitatively illustrated by the red dashed curve in Fig. 3 (a): They enter the MPS along a magnetic field line, then $\mathbf{E} \times \mathbf{B}$ drift in the $-x$-direction due to the electric field component E_y, and are finally reflected along a different field line. Provided that the electron pressure varies along x, this results in a change of the parallel electron current. Ref. [7] finds a contribution of these reflected electrons to the outwards directed parallel current of

$$j_{\|e}^{refl} = -en_{se}\frac{V_{E,y}}{\alpha} + sign(B_z)\frac{1}{\alpha B}\frac{\partial p_e^{se}}{\partial x}. \tag{1}$$

n_{se} and p_e^{se} are the electron density and pressure at the plasma side of the MPS. Corrections in case of an $\mathbf{E} \times \mathbf{B}$ drift $V_{E,y}$ along the y axis are also taken into account. Adding the contribution of the small fraction of electrons that overcome the potential barrier and get absorbed by the wall $j_{\|e}^{abs} = -en_{se}c_s \exp^{-\frac{(\phi-\phi_f)e}{T_e}}$ as well as a parallel ion current of the form $j_{\|i} = en_{se}(c_s + \frac{V_{E,y}}{\alpha})$ [14], we find for the parallel current at the entrance to the MPS

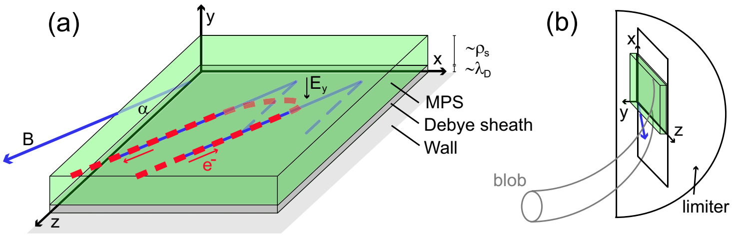

Figure 3: (a) Sketch of an electron trajectory (gyro-averaged) in the magnetic pre-sheath. (b) Sketch of a metal plate attached to the limiter in order to achieve grazing incidence of the magnetic field on the plate.

$$j_{\|} = en_{se}c_s(1 - \exp^{-\frac{(\phi-\phi_f)e}{T_e}}) + sign(B_z)\frac{1}{\alpha B}\frac{\partial p_e^{se}}{\partial x}. \tag{2}$$

Small values of α can be achieved by installing a metal plate on the limiter as sketched in Fig. 3 (b). In this case, the derivative in the α-dependant part of $j_{\|}$ in (2) is along the vertical direction and competes with the drive term of blob motion. If we assume p_e^{se} to be half of the pressure in the bulk plasma [14], the drive term in the vorticity equation of 2D blobs is changed by a factor $\left(1-\frac{R}{2L\alpha}\right)$.

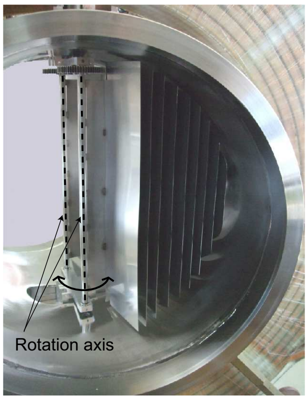

Figure 4: Limiter with metal plates attached perpendicularly to it. α can be varied by pivoting the limiter around the vertical axis. Two such limiters are installed, for both ends of the blob.

Based on the above considerations, a special limiter has been designed for TORPEX, which is shown in Fig. 4. Several plates are mounted perpendicularly to the original limiter. Different values of α (also negative ones) are achieved in a region extending over several blob radii in the radial direction by pivoting the limiter around a vertical axis. The attached plates have a length in the toroidal direction of 10 cm and are radially separated by 1.7 cm ($\approx 6 \cdot \rho_s$ in H_2). This allows obtaining values of $|\alpha| \approx 1.7/10 = 0.17$ before field lines do no longer intercept the plates but the limiter they are attached to. An experimental campaign has been started to explore the α dependence of the blob velocity. Since we can vary the factor $\left(1-\frac{R}{2L\alpha}\right)$ from ≈ 0.5 to ≈ 1.5, we expect to have measurable effects.

This work is partly supported by the *Fonds National Suisse de la Recherche Scientifique*.

References

[1] A. Loarte et al., *Nucl. Fusion* **47**, S203-S263 (2007)

[2] S. I. Krasheninnikov, *Phys. Lett.* A **283**, 368 (2001)

[3] A. Fasoli et al., *Phys. Plasmas* **13**, 055902 (2006)

[4] I. Furno et al., *Phys. Rev. Lett.* **100**, 055004 (2008)

[5] S. H. Müller et al., *Phys. Plasmas* **14**, 110704 (2007)

[6] C. Theiler et al., *Phys. Plasmas* **15**, 042303 (2008)

[7] R. H. Cohen and D. D. Ryutov, *Phys. Plasmas* **2**, 2011 (1995)

[8] R. H. Cohen and D. D. Ryutov, *Contrib. Plasma Phys.* **46**, 678 (2006)

[9] S. H. Müller et al., *Phys. Plasmas* **13**, 100701 (2006)

[10] C. Theiler et al., submitted to *Phys. Rev. Lett.*

[11] O. E. Garcia et al., *Phys. Plasmas* **12**, 090701 (2005); J. R. Myra and D. A. D'Ippolito, *Phys. Plasmas* **12**, 092511 (2005)

[12] G. Q. Yu and S. I. Krasheninnikov, *Phys. Plasmas* **10**, 4413 (2003); A. Y. Aydemir, *Phys. Plasmas* **12**, 062503 (2005); O. E. Garcia et al., *Phys. Plasmas* **13**, 082309 (2006); S. Sugita et al., *Plasma Fusion Res.* **3**, 040 (2008);

[13] R. Chodura, *Phys. Fluids*, **25**, 1628 (1982);

[14] P. C. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices*, (Institute of Physics, Berkshire, 2000);