Blobs on the High Field Side of Tokamaks

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Turbulence-induced high density filaments, *blobs*, might represent the new paradigm for radial convective transport in the Scrape-Off-Layer of magnetic fusion devices. Models for individual blob dynamics, considering their generation on the Low Field Side (LFS) of the torus have been put forward. We investigate the existence of blobs in the peripheral region of the High Field Side (HFS) of the FT-2 tokamak. Langmuir probe measurements are used to detect and characterize blobs. The results were obtained in plasmas with enhanced Lower Hybrid Heating and data was acquired with a new fast data acquisition system with 50 MHz sampling rate. While the majority of the blobs are observed to move towards the wall as expected, some are observed to move inwards towards the core. This effect is not understood in the light of existing models for the LFS where only the outward direction is expected. Further characterization of plasma blobs should therefore involve both HFS and LFS. This could be done at ASDEX Upgrade where reflectometry systems are capable of measuring simultaneously the density turbulence on both HFS and LFS. The dependence between radial velocity, size and density of the blobs is also investigated.

Keywords: fusion, plasma turbulence, plasma transport, plasma blob, Langmuir probe

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1. Introduction

It has long been known that radial transport of particles and energy in a tokamak's toroidal geometry could not be explained by neo-classical theory [1]. Anomalous transport had to be invoked and it is now recognized that turbulent plasma processes are responsible for the enhanced transport, determining to a great extent the plasma confinement in magnetic fusion devices. However, there is not yet a first principles theory describing anomalous transport properly and covering the whole experimental database [2]. Edge turbulence in both tokamaks and stellarators has shown to exhibit the same basic properties in the different devices. Endler *et al* decomposed its structure into spatial-temporal "events" in the early 90 s [3], and characterized it for both ASDEX tokamak and W7-AS stellarator [4]. These events are today described as turbulence-induced high density filaments and have also been called *blobs*. The aim of this work is to analyze the blob phenomena in the FT-2 tokamak, by multi-pin Langmuir probe diagnostics and a new data acquisition system based on a 12 bit analogue-to-digital converter with a sampling rate of 50 MHz.

2. Turbulent Transport

Experimental evidence of large amplitude turbulence with an intermittent character in the edge region of tokamaks is a well-established fact. Filamentary coherent structures, for instance, could be observed along the magnetic field lines with a high-speed video camera in the MAST spherical tokamak [5]. Such filaments (blobs) are thought to be responsible for the strong intermittency observed with probes at the Scrape-off-layer (SOL) plasma. Further studies showed that blobs are a transversal phenomena appearing in both tokamaks and stellarators, supporting the idea of the ubiquitous nature of transport phenomena in toroidal magnetic devices.

The role that blobs play in the global edge plasma transport was highlighted by experimental data from Alcator C-Mod showing that a large fraction of the plasma particle flux coming from the core into the SOL was indeed transported radially to the chamber walls and not toroidally to the divertor plates [6]. In particular, it has been demonstrated at the FT-2 tokamak in ohmic regimes that turbulence induced radial particle transport can account for up to 60-100% of the total radial particle flux [7]. To explain this behavior of plasma transport in the SOL, a convective based mechanism was first suggested by Krasheninnikov [8].

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3. Blob Models

Models for individual blob dynamics have been proposed and significantly extended [9–11], sustaining the new paradigm that considers blobs to be the fundamental entity for convective transport in the SOL. It is generally assumed that due to some turbulent process a filament with large plasma density is peeled off the bulk plasma, in some region close to the last closed flux surface (LCFS) on the Low Field Side (LFS) of the torus. Effective gravity drifts on the LFS due to curvature and a gradient of $\boldsymbol{B}$ in tokamaks, i.e. particle drifts of the type $\boldsymbol{F} \times \boldsymbol{B}$, will then result in a charge polarization. The resulting electric field causes a radial $\boldsymbol{E} \times \boldsymbol{B}$ convection of the blob directed to the chamber wall. The convection speed will depend on the magnitude of the electric field, which in turn will be determined from the subtle balance of polarization and parallel currents inside these structures. Different current closure schemes can be considered according to the specific plasma regime under study, which will correspond to different damping mechanisms and ultimately different scalings for the radial speed of the blobs. For a detailed insight on these scenarios and their mathematical treatment we refer to [11, 12]. In the case of a sheath-connected blob (this could correspond to a blob in the far SOL) the radial velocity is given by [11],

$$V = 2c_s \left(\frac{\rho_s}{S_{\text{pol}}}\right)^2 \frac{L_{\|}}{R} \tag{1}$$

where c_s is the acoustic speed, ρ_s is the ion gyro-radius, S_{pol} is the poloidal scale length of the blob, $L_{\|}$ is the blob parallel length and R is the major radius of the tokamak. This is a prediction for blob propagation in vacuum, the background plasma not being taken into account. If the current loops close locally in the midplane region, the scaling for the radial blob velocity can be given by [13],

$$V = c_s \left(\frac{2S_{\text{pol}}}{R} \frac{n}{n_{\text{sol}}}\right)^{\frac{1}{2}} \tag{2}$$

where the influence of the background plasma is now present, through a factor containing the ratio between the blob density and the background SOL density.

4. FT-2 Tokamak Experiment

The FT-2 is a small tokamak equipped with auxiliary on-axis lower hybrid heating (LHH). It has a major radius of $R = 0.55$ m and a poloidal limiter at the radius $a = 0.079$ m. The steady discharge phases have typical parameters of plasma current $I = 22$ kA, and toroidal magnetic field of $B = 2.2$ T. It has been shown that the effective ion heating caused by LHH improved the core confinement and triggered an L-H transition [14]. This transition results in significant changes of the statistical characteristics of the periphery fluctuations. The Probability Density Functions after the transition become more peaked and symmetrical [15]. The typical LHH experiment consists of a discharge with total duration time of approximately 50 ms. The LHH pulse ($f = 920$ MHz) with duration of 5 ms is switched on during the steady-state phase of the discharge, 30 ms after the switch-on of the toroidal field. The LHH input power corresponded to twice the value of the Ohmic power, P(LHH) ~ 180 kW ~ 2P(OH). The electron density found in the SOL is ≈ 3-6 × 10^{18} m^{-3} while in the plasma core ranges from 3-5 × 10^{19} m^{-3}.

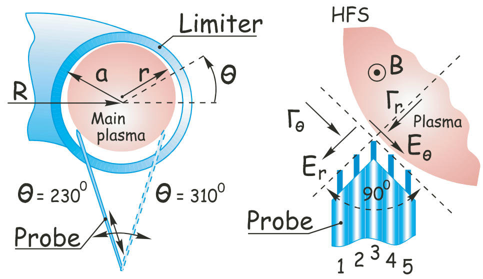

Fig. 1 Schematics showing the movable 5-electrode Langmuir probe measurements on the poloidal cross-section of FT-2.

A five electrode probe used on FT-2 and shown in Fig. 1 combines single and double probes, with molybdenum tips of 0.5 mm diameter, 1.5 mm length and 2.1 mm of separation between neighbouring tips. Hence, both ion saturation current and plasma floating potential fluctuations can be measured [16]. The locations of the probe at poloidal angles 230° and 310° at High Field Side (HFS) and LFS respectively are determined to allow direct measurements of radial and poloidal components of the electric field. At these angles the probe has 3 electrodes reasonably aligned with the poloidal direction, and 3 aligned perpendicularly, along the radial direction (see Fig. 1). Poloidal and radial components of the electric field can be found using $E \approx -\Delta\varphi/\Delta x$ where $\Delta\varphi$ is the difference between floating potentials measured at two properly chosen pins and Δx is the distance between the measuring pins (~ 0.42 cm), and assuming that the local electron temperature remains constant. The velocity of the radial $\boldsymbol{E} \times \boldsymbol{B}$ drift can then also be estimated. The fluctuation components of the ion saturation current and of the floating potential measured directly by the Langmuir probe are respectively proportional to the fluctuation components of the plasma density and plasma potential, under the same assumptions as in [16]. For the case of probe location at the HFS, the radial particle flux caused by fluctuations of the poloidal electric field and plasma density is given by: $\tilde{\Gamma}_r \propto \tilde{I}_{\text{IS}} (\tilde{\varphi}_3 - \tilde{\varphi}_5)$, where I_{IS} is the ion saturation current measured at pin 4 and φ_i is the floating potential measured at the i numbered pin.

The SOL width in these experiments should lie within the interval of $r = 74$-80 mm and a secondary SOL (white region with crescent shape at Fig. 1) created by a plasma column shift is also present resulting in a magnetic configuration similar to a diverted tokamak [17].

5. Experimental Results and Discussion

Due to technical constraints the present work regards measurements on the HFS only. The fluctuating component of the radial particle flux, obtained as previously explained, is analyzed in two distinct periods of the plasma discharges, before (25-29 ms) and after (36-40 ms) the LHH, and sub-intervals of 0.5 ms are taken to define the root mean square (RMS) as a reference level. Bursts which are above 2.5 times the RMS level are stored in a database. Moreover, if the corresponding time resolved density signal is above the average density during these intervals, we define the detected structure as being a blob. The observed fluctuation bursts can be formed not only by single peaks but also by multiple adjacent peaks, usually two or three. They can represent up to 20 % of the detected structures and could be read as the effect a blob undergoes due to growth in size over a critical stability value. Their characterization is too complex to compare with existing models and hence we exclude these structures from the database. Upon detection of the isolated blobs, we can extract the associated poloidal electric field and the radial velocity due to the $\boldsymbol{E} \times \boldsymbol{B}$ drifts. Positive values of the drift velocity correspond to a direction towards the wall. Furthermore, to have an estimate of the radial size of the blobs we take the product of the calculated radial velocity with the observation time of the blob peak.

Measurements at radial positions of 77, 78 and 79 mm were performed moving the probe on a shot to shot basis. The majority of blobs detected had radial velocities in the outward direction but a few (1-10 %) were seen to move inwards. A typical time trace of the sampled signals is shown in Fig. 2 where blobs of density with opposite direction of movement can be seen.

The detection of blobs travelling towards to the wall at the HFS had already been observed at the T-10 tokamak [18]. And this can be expected by reasoning that if we extend our blob along the magnetic field line to the inner part of the torus we will find that we have an inverse polarization inside the blob because of the helical magnetic structure. This electric field would then again produce a drift to the wall. The "negative" blobs (moving inwards) though, are not predicted by the proposed models. The ones in our database were indeed verified to have poloidal electric field peaks in the inverse direction of the "positive" ones, and though of rare occurrence their presence increased after the LHH. An example of the results obtained in experimental series #071224, at one radial position for both periods of time considered can be seen in Fig. 3.

The measurements on different radial positions were made with many identical shots assuming the same plasma conditions were established. The mean values for velocities and sizes on each position fall on the uncertainty intervals of the other positions mean values. So, one could assume that both sizes and velocities remain constant along the radial movement. The mean values for radial velocity and radial scale length found for "positive" blobs are roughly of V = 3.5 km/s and S = 2.7 mm before the heating, and V = 1.1 km/s and S = 0.8 mm after the LHH. Regarding the "negative" blobs we find V = 5.1 km/s and S = 1.8 mm before LHH, and V = 0.8 km/s and S = 0.4 mm in the later period. These would correspond (with electron temperature estimates from the Langmuir probes) to a drop from 6 % to 3.5 % of the acoustic speed in the "positive" blob velocities, and from 9 % to 2.5 % in the "negative" ones. One should mention that the radial sizes presented here are not of the blob itself but regard the observation time between the blob limits as defined to construct the database. The density ratio between the average blob density and the background plasma density was also somewhat constant in the range of 2-2.6 on average for each time period and radial position.

The general trend observed, as seen in Fig. 3, is that radial velocity increases with the radial scale length of the blobs, contrary with the prediction for a sheath-connected blob, given by equation (1), where this dependence is inversely proportional. The damping mechanism through local diamagnetic currents seems more reasonable, as equa-

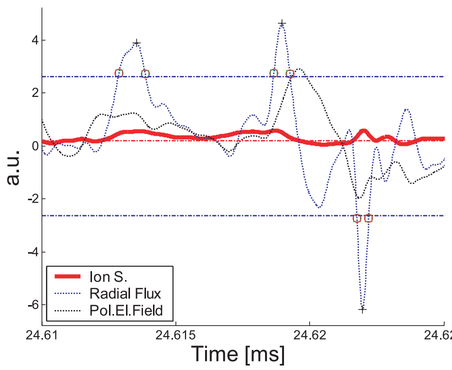

Fig. 2 Time series of sampled signals with mean ion saturation current and 2.5 RMS thresholds of radial flux in horizontal lines.

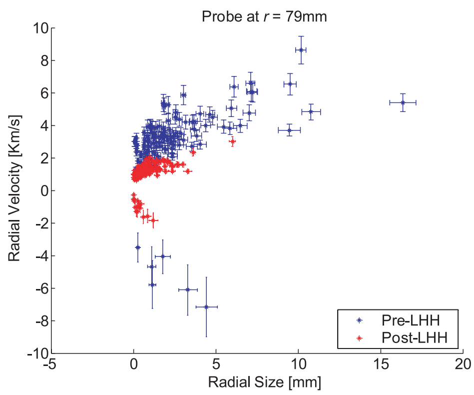

Fig. 3 Radial velocity and radial size estimates for blobs detected in periods before and after LHH, at the HFS and r = 79 mm.

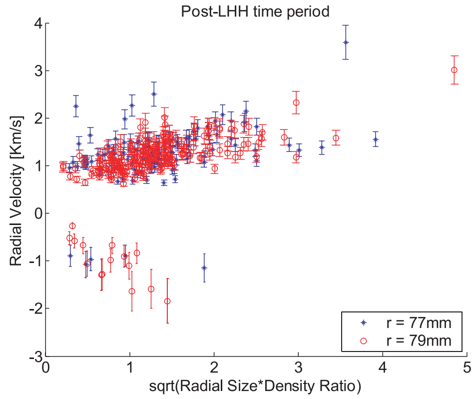

Fig. 4 Radial velocity versus the square root of the product of radial size with density ratio, for blobs found after heating, at 2 radial positions.

tion (2) can more likely be reproduced by the experimental results, as in Fig. 4 where the linear dependence of the radial velocity on the square root of the radial scale length and density of the blobs seems to emerge. But we would have to assume that a linear relation between the measured radial sizes and the poloidal blob size (relevant quantity in the predictions) exists, for a possible fitting to the equation (2).

Similar results, regarding the relation between velocity, size and density of outwards moving blobs, have been presented by Schmid *et al* for measurements carried out only at the LFS of the ASDEX Upgrade tokamak, and regarding filaments induced by Edge Localized Modes [19]. This might be surprising due to the very probably different plasma regimes in the two cases. Nevertheless, both ELM filaments and other blob structures can be considered in the proposed models.

6. Conclusions

Regarding the HFS of fusion devices the results on blob characterization are scarce and the theory predicts generation and movement of these structures on the LFS only. The study of blobs on the HFS of the FT-2 tokamak has been addressed with data sampled with improved accuracy from Langmuir probe measurements. Blob velocities and sizes were obtained by analysing time-resolved signals of radial flux and density. It was observed that the predominant direction of movement of the blobs is towards the wall. However, inward movement of blobs is also deduced, remaining the question if this is due to a complex internal structure of blobs, a possible effect of the interface geometry of the impinging blob on the probe, or a need for better theoretical understanding. The prediction of blob velocity regardless the direction of movement seems to be in agreement with the prediction that it scales with the square root of size and density. For future work it is advisable to perform a similar study as presented here for the LFS of the FT-2 tokamak as well as to extend studies performed on other machines to the HFS of those devices. Further understanding and characterization of blobs could be achieved by localised measurements of edge density turbulence as provided by reflectometry diagnostics. This could be performed for instance at ASDEX Upgrade where reflectometry systems are installed and allow simultaneous probing on both high and low field sides of the tokamak.

Acknowledgments

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[1] G. D. Conway, Plasma Phys. Control. Fusion **50**, 124026 (2008).
[2] R. B. White, *The Theory of Toroidally Confined Plasmas* (Imperial College Press, London, 2006) p.313.
[3] M. Endler *et al*, 20th EPS Conference on Contr. Fusion and Plasma Phys. Lisbon **17C**, part II, 583 (1993).
[4] M. Endler *et al*, Physica Scripta **51**, 610 (1995).
[5] A. Kirk *et al*, Phys. Rev. Lett. **96**, 185001 (2006).
[6] M. V. Umansky, S. I. Krasheninnikov, B. LaBombard and J. L. Terry, Phys. Plasmas **5**, 3373 (1998).
[7] L. A. Esipov *et al*, Zh. Tekh. Fiz. **67**, N4, 48 (1997).
[8] S. I. Krasheninnikov, Czechoslovak J. of Phys. **48**, Suppl. S2 (1998).
[9] S. I. Krasheninnikov, Phys. Lett. A **283**, 368 (2001).
[10] D. A. D'Ippolito, J. R. Myra and S. I. Krasheninnikov, Phys. Plasmas **9**, 222 (2002).
[11] S. I. Krasheninnikov, D. A. D'Ippolito and J. R. Myra, J. Plasma Phys. **74**, 679 (2008).
[12] J. R. Myra and D. A. D'Ippolito, Phys. Plasmas **12**, 092511 (2005).
[13] O. E. Garcia, Plasma Fusion Res. **4**, 019 (2009).
[14] S. I. Lashkul *et al*, 30th EPS Conference on Contr. Fusion and Plasma Phys. St. Petersburg **V1**, 422 (2003).
[15] S. I. Lashkul *et al.*, 33rd EPS Conference on Plasma Phys. Rome **30I**, P4-099 (2006).
[16] A. N. Levitskii, I. E. Sakharov and S. V. Shatalin, Prib. Tekh. Éksp. **5**, 153 (1992).
[17] S. V. Shatalin *et al*, Plasma Phys. Reports **33**, N3, 169 (2007).
[18] G. S. Kirnev, V. P. Budaev *et al*, Nucl. Fusion **45**, 459 (2005).
[19] A. Schmid, A. Herrmann, H. W. Müller and the ASDEX Upgrade Team, Plasma Phys. Control. Fusion **50**, 045007 (2008).