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Magnetic and electrostatic structures measured in the edge region of the RFX-mod experiment

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ABSTRACT

Coherent structures emerging from turbulence background have been detected in the edge region of the RFX-mod Reversed Field Pinch fusion device by using a new and original probe system measuring simultaneously and on the same location magnetic and electrostatic fluctuations. In agreement with theory it has been experimentally found that pressure structures detected in the cross-field plane, often referred in literature as 'blobs', correspond to $E \times B$ vorticity structures and are associated to current density filaments, oriented along the main magnetic field. The results are compared with those provided by the measured relationship between magnetic fluctuations and coherent structures on HeI emission observed by the Gas Puffing Imaging system, confirming the presence of such structures also at high current regimes.

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1. Introduction

Understanding and controlling the mechanism behind anomalous transport is a key issue for thermonuclear fusion oriented experiments. The observation of improved confinement regimes [1] and associated reduction of plasma fluctuations has fostered the research on plasma turbulence with strong emphasis on the underlying mechanisms. Experimental observations performed in tokamaks [2–4], stellarators [5], Reversed Field Pinches [6] and linear devices [7] has revealed the intermittent nature common to plasma turbulence in all the different devices, and the fact that intermittency is generally associated to the presence of blobs or structures. These structures are the results of strong non-linearities and are generally described as 3D structures elongated in the parallel direction.

A growing interest is devoted to the study of these structures because it is believed that they play a major role in driving the transport in the edge region [8,9]. A recent complete review can be found in [10].

Scope of this paper is to investigate as much detail as possible the electrostatic features of such structures observed in the boundary region of the RFX-mod experiment. The investigation will be performed in terms of local fluctuations of pressure, velocity patterns and vorticity, simultaneously related to the local features of magnetic fluctuations.

2. Experimental setup

Measurements reported herein have been obtained in the edge region of the RFX-mod [11] Reversed Field Pinch experiment (RFP), a toroidal device with major radius $R = 2$ m and minor radius $a = 0.459$ m, characterized by a first wall completely covered by graphite tiles. It is reminded here that in Reversed Field Pinches the main magnetic field at the plasma edge lies in the poloidal direction.

For the present measurements a probe head has been used, dubbed 'U-probe'. The probe consists of two fingers, 88 mm apart each other along the toroidal direction, each equipped with a 2D array of electrostatic pins with a radial and toroidal resolution of 6 mm. Inside each one of the fingers a radial array of 3-axial magnetic probes has been placed with the same radial resolution; a picture of the probe is shown in Fig. 1. The electrostatic pins have been arranged in such a way to obtain information simultaneously and in the same location on plasma density, electron temperature and floating potential as well as on their respective radial gradient. Both electrostatic and magnetic probes are digitally sampled at 5 MSample/s with a minimum bandwidth of 700 kHz.

The Gas Puff Imaging (GPI) [12] is an optical diagnostics that measures the light emission fluctuations of neutral gas puffed into the plasma edge. It observes the cross-field plane covering a region of 80 mm × 40 mm (toroidal × radial). The system is also equipped with three 3-axial magnetic coils of the same type described above, located at $r = 0.47$ m. All the signals are sampled at 10 MSamples/s.

The typical plasma discharge considered is a H discharge with low plasma current, $I_p = 350$ kA, and plasma density of about 1.5–$2 \cdot 10^{19}$ m^{-3}, in order to allow insertion of the U-probe up to

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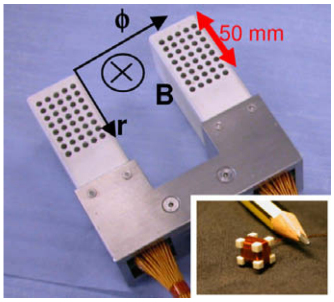

Fig. 1. Picture of the ‘U-probe’ and of a magnetic sensor. The probe orientation with respect to the toroidal (φ) and radial (r) reference machine system and to B_θ are indicated.

50 mm inside the first plasma wall. Larger plasma current regimes, up to 1.5 MA, have been explored by the GPI.

3. Results and discussion

Measurements of different electrostatic quantities have been analyzed using the statistical techniques described in [13,14], with the aim of identifying coherent structures associated to strong bursts in the fluctuation time series. The average features of these events have then been extracted by applying the conditional average method on time window widths adequate to their time scale. A frequency range of few hundreds of kHz has been used for the present analysis, close to the typical time scale which characterizes the particle transport flux measured in the edge region [15].

An example of the result for the floating potential is shown in Fig. 2. In this case the detection of a burst on pressure signal has been used as a reference for conditional averaging.

Due to the presence of a radial electric field, and to a magnetic field essentially poloidal, $B \sim B_\theta$, the edge region is characterized by an average toroidal E $\times$ B flow velocity, that has been found to be of the order of 10^4 m/s [16].

From the average time behaviour of the V_f structure a toroidal information on the structure itself can be deduced by assuming the structure to be frozen while passing the probe location, so that $dz \sim v_{E\times B}dt$. The hypothesis that these structures travel in the edge region with the main plasma flow is confirmed by the observation of emission blob by GPI system on the toroidal array of 16 adjacent chords having a resolution of 5 mm.

Within this framework the V_f average structure of Fig. 2 (bottom panel) exhibits a dipolar structure and this is confirmed also by applying the conditional average procedure to a complete radial

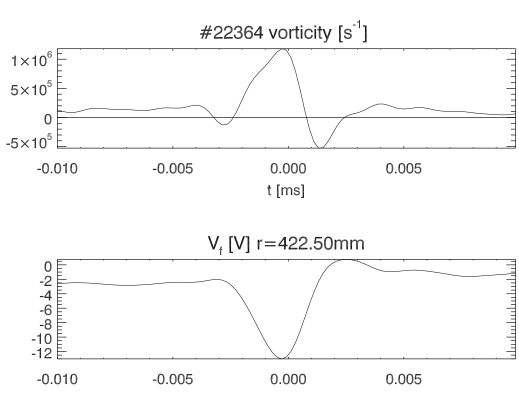

Fig. 2. Conditional average on vorticity (top) and V_f (bottom) signals, pressure bursts at 300 kHz time scale have been used as reference events.

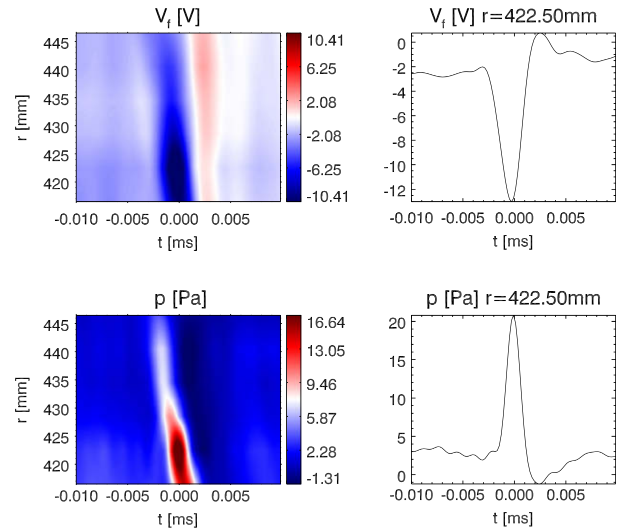

Fig. 3. Conditional average triggered on pressure events at $r = 422.5$ mm. Top panels: V_f (r,t) (left); V_f (t) at $r = 422.5$ mm (right); bottom panels: analogous quantities for pressure.

array of V_f measurements which revealed a finite spatial structure in the cross-field plane (Fig. 3).

The U-probe arrangement however provides also information on a 2D array of V_f measurements and specifically they allow an experimental estimate of the local vorticity given by $\omega = \nabla \times v$, where v is the measured local flow. The field aligned component of vorticity ω_θ can be estimated by $\omega_\theta = \partial_\varphi v_r - \partial_r v_\varphi \approx \frac{1}{B_\theta}\nabla^2_\perp V_f$, as proposed in [17] and the result is shown in Fig. 2 (top panel). It can be observed that peaks of vorticity are consistent with the features of a V_f structure as deduced by a single point measurement, confirming that peaks and valleys in the V_f correspond to $E \times B$ vortices rotating in the cross-field plane.

Given that vorticity peaks and V_f time behaviour are strictly correlated, it can be concluded that structures can be considered frozen while passing the measurement location and the Taylor's hypothesis applies [18].

Simultaneous measurements of radial arrays of plasma density, n_e, and temperature, T_e, provide a 2D picture in the cross-field plane also of these quantities. In Fig. 3 the average structure of pressure, $p = n_eT_e$, is shown. It is clearly related to the V_f average structure and covers a radial range of few centimetres.

A first indication of a not purely electrostatic feature of the above described structures can be provided by the analysis of the coherence between pressure and magnetic fluctuations measured by the ‘U-probe’. An example of this kind of analysis is shown in Fig. 4, where the coherence between p and b_φ is shown: the coherence between these two quantities depends on frequency range and in particular a broad peak of coherence is found in the range from 50 to 300 kHz.

The arrangement of the 3-axial magnetic sensors in the U-probe head allows a direct measurement of the magnetic field curl and then of the local current density by applying the Ampère's law. In order to investigate if any current density is associated to the above described electrostatic structures the conditional average triggered on the occurrence of pressure structures has been applied to the current density signal.

In particular the parallel component of the local average current density has been evaluated as $J_\theta = \frac{1}{\mu_0}(\partial_\varphi b_r - \partial_r b_\varphi)$ and the result is shown in Fig. 5. A peak in the parallel current density is clearly associated to the peak of pressure. It is worth mentioning that the relationship between the electric structure the parallel current and pressure structure is known from theory [19–21]. In the same

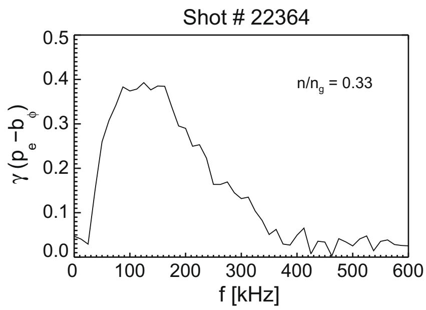

Fig. 4. Spectral coherence between b_φ and pressure fluctuations measured by U-probe in a typical shot.

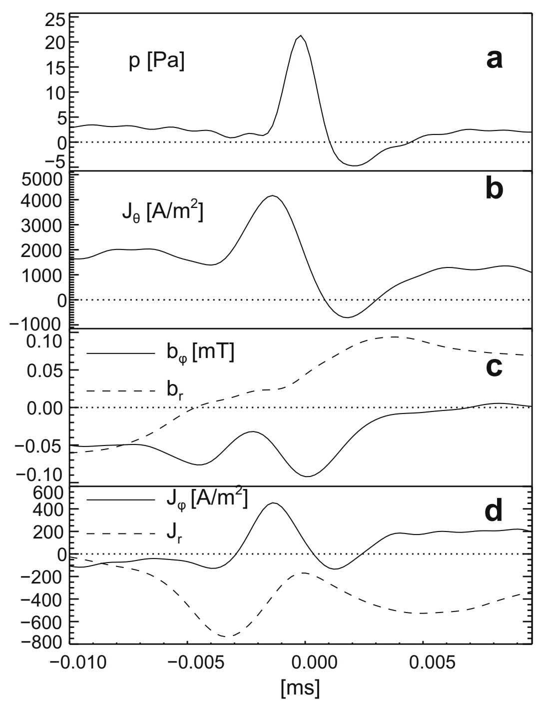

Fig. 5. Conditional average triggered on pressure events on a group of shots with $I_p \sim 350$ kA: (a) average structure of pressure, (b) of poloidal current density, (c) of b_r and b_φ and (d) of J_r and J_φ measured by U-probe.

Fig. 5 the corresponding average features of the b_r and b_φ fluctuations are also shown.

Within the approximation of small derivative of magnetic fluctuations along the direction of B_θ (parallel direction), the arrangement of the U-probe allows the estimate also of the radial and toroidal components of the current density, J_r and J_φ, respectively. The result is also shown in Fig. 5: both J_r and J_φ exhibit average values about one order of magnitude lower with respect to J_θ. From this result it can be deduced that the peaks of J_θ, represent current density filaments essentially aligned along the magnetic field.

The presence of an elongated parallel current structure $J_{||}$, at the basis of edge turbulence models see Refs. [22,23], following recent theories of blob formation [10,24] is suggested to arise as a response of plasma polarization induced by an effective gravity force, usually given by magnetic curvature effects; see also [25] for simulation of turbulence in linear devices. In order to ensure the plasma quasi-neutrality the parallel current is expected to be balanced by a transverse current $J_\perp$, through the relationship $\nabla \cdot J = 0$. A rough estimate of the ratio $J_\perp/J_{||}$ can be obtained by the ratio of the respective characteristic lengths $L_\perp/L_{||}$. By assuming $L_{||} \sim 2\pi a$ and $L_\perp$ of the order of the radial extent of the structure (about 5 cm, see Fig. 3) it results $J_{||}/J_\perp \sim 60$. This means that the experimental estimate of J_r and J_φ is about six times larger than expected value. From the experimental point of view it can be noticed however that this discrepancy can be reduced accounting for a possible misalignment between the U-probe and the cross-field plane (a difference of about 100 A/m^2 can be accounted for a 2° misalignment) work is in progress in order to better asses this point.

In order to investigate the link between 'blobs' and magnetic fluctuations also at higher plasma currents, where the U-probe cannot be used, the relationship between emission data from GPI diagnostics and local magnetic measurement has been studied.

By using an approach analogous to the one used for the U-probe, in Fig. 6 the average coherence between GPI and local magnetic fluctuation signals is reported for plasma current up to 1 MA and for two different values of the normalised electron density n/n_G, where n_G is the Greenwald density. The coherence is high for both ensembles, suggesting the presence of current carrying filament also at high current. It can be also observed that the frequency of the maximum of the coherence decreases with the normalised density, indicating that the typical spatial scale of the turbulent structures can change with this plasma parameter [26].

To investigate the relationship between the bursts detected in the GPI signal and the related magnetic structure, the conditional average has been applied also in this case, using as prescribed condition the presence in the optical signal of a burst with a frequency scale of 300 kHz. In Fig. 7(a) the conditional average structure of the GPI emission and the corresponding average structures of the locally measured db_r/dt and db_φ/dt, normalised to the respective rms, are shown (Fig. 7(b) continuous line). The measured local structure of magnetic fluctuations result consistent with the one expected (Fig. 7(b) dashed line) for a poloidally elongated 1D

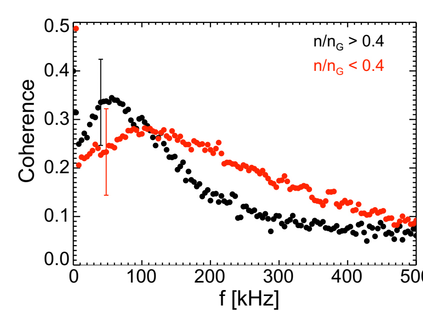

Fig. 6. Spectral average coherence between GPI and time derivative of the radial component of the local magnetic field for two different electron density regimes.

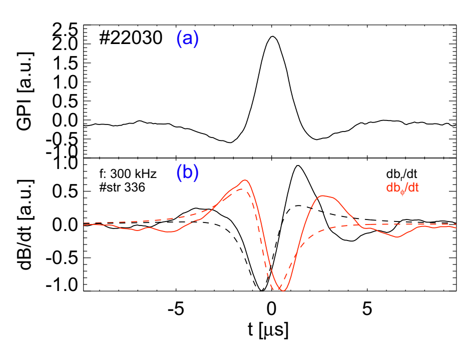

Fig. 7. (a) Average structures of GPI on a 1 MA shot; (b) correspondent structures of db_r/dt and db_φ/dt; continuous lines: experimental measurements; dashed lines: simulation of a current filament.

current filament structure moving with the local plasma $E \times B$ flow while passing the GPI location.

This experimental result then supports also for plasma current regimes up to 1 MA the link between the edge blobs and the current filaments.

4. Conclusions

A complete set of diagnostics allowed investigating in detail the presence and features of edge magnetic and electrostatic fluctuations in the edge region of RFX-mod experiment.

Coherent structures have been detected within the turbulence background and exhibit $E \times B$ local vorticity patterns and magnetic features under the form of current density. They are characterized by pressure peaks associated to current density filaments essentially aligned with the local magnetic field and traveling according to the $E \times B$ average flow. The optical and magnetic fluctuations provide a good indication that such filaments are present also in high current regimes. It is worth noting that analogous filaments have been observed also in the boundary region of tokamak experiments as described by Kirk et al. [27].

It is interesting to note that these current filaments present analogous features to what observed during MHD dynamo relaxation events at larger time scale ($\sim$100s), resulting in the formation of a poloidal current density filament [28]. Work is in progress in order to investigate to which generation mechanism these structures can be ascribed and the results of this investigation will be the subject of a following paper.

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