Direct Measurement of Current Filament Structures in a Magnetic-Confinement Fusion Device

M. Spolaore, N. Vianello, M. Agostini, R. Cavazzana, E. Martines, P. Scarin, G. Serianni, E. Spada, M. Zuin, and V. Antoni
Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, Corso Stati Uniti 4, 35127 Padova, Italy

(Received 10 November 2008; published 20 April 2009)

Turbulent structures detected in the edge plasma of fusion devices, often described as *blobs*, are generally believed to be responsible for confinement degradation. Recent experimental evidence and theories have suggested their filamentary electromagnetic nature. In this Letter the first direct experimental measurements of the parallel current density associated with turbulent structures in a fusion experiment are reported. The electromagnetic nature of structures is clearly shown by identifying the current filaments with a vortexlike velocity pattern and the associated pressure perturbation.

DOI: 10.1103/PhysRevLett.102.165001 PACS numbers: 52.55.Hc, 52.35.Ra, 52.35.We, 52.70.Ds

Understanding and controlling the mechanism behind anomalous transport are key issues for the experiments devoted to the magnetic confinement of fusion-relevant plasmas. The observation of improved confinement regimes [1] and of the associated reduction of plasma fluctuations has fostered the research on plasma turbulence, with strong emphasis on the understanding of the underlying mechanism. In recent years, observations performed in tokamaks [2–4], stellarators [5], reversed field pinches (RFPs) [6], and linear machines [7,8] have revealed the intermittent nature common to plasma turbulence in all the different devices. Intermittency is generally associated with the presence of *blobs* or *structures*. These structures are the result of strong nonlinearities and have been generally experimentally investigated in the plane perpendicular to the local magnetic field, although strong interest is arising nowadays around their three-dimensional (3D) characteristics, with strong emphasis on the parallel motion and features. This interest is enhanced by some analogies with edge localized modes [9], which are indeed believed to be associated with current filaments parallel to the guiding magnetic field. Present theories about blob formation [10] and dynamics in tokamaks suggest that blobs develop as a result of an effective gravity force (due, for example, to magnetic curvature effects), which causes plasma polarization and a corresponding $\mathbf{E}\times\mathbf{B}$ convection. To ensure plasma quasineutrality, $\nabla\cdot\mathbf{J}=0$, a parallel current density perturbation $\tilde{J}_{\parallel}$ arises as a response to the charge separation induced by curvature and grad-B effects in the perpendicular plane. From the experimental point of view hints of the electromagnetic features of the blob structure have been found in linear devices [11], and indications of not purely electrostatic filaments have been found in MAST experiments [9,12]; however, no direct experimental evidence of a parallel current density associated with structures has been obtained up to now in fusion devices in order to support this theory.

In the case of RFPs, resistive interchange modes [13,14] are found to be unstable because of unfavorable magnetic curvature both in the outer and inner part of the torus. This mechanism does not represent the only possibility for the formation of electromagnetic current-carrying structures, as shown, for example, in [15,16], and thus direct experimental measurements are mandatory in order to correctly describe formation and dynamics of turbulent eddies. In the present Letter the first direct experimental measurements of parallel current density perturbations associated with intermittent structures are reported: this represents an outstanding result proving the electromagnetic nature of intermittent blobs.

The outer region of RFPs, the magnetic configuration to which the data presented hereafter refer to, is found to share many characteristics with other magnetic configurations, such as tokamaks and stellarators. It has been reported that edge parameters, such as electron density, plasma potential, or electrostatic radial particle flux, exhibit a strong intermittent character [6,17–19]. Intermittency manifests itself as a clear departure from self-similarity, which can be detected through a multiscale analysis of the probability distribution function of signal fluctuations.

In ordinary fluid and plasma turbulence theories, intermittency is the result of the presence of organized structures, which make the process of energy cascade inhomogeneous. These *intermittent structures*, detected in the edge of fusion plasmas [17–20], have been found to exhibit a vortexlike shape on the plane perpendicular to the magnetic field. In RFPs the appearance of these structures has also been linked to global MHD activity which governs the configuration [20,21], although it was not clear in which way the two things are related. A further evidence of a link between electrostatic and magnetic fluctuations can be deduced from the observation of a strong coherence between pressure and magnetic fluctuations in a frequency range between 50 and 300 kHz [22]. This is not surprising, taking into account the typical edge parameters investigated, with a density n_e in the range of 1×10^{19} m^{-3}, temperature T_e around 20–40 eV, and a magnetic field B, in the set of discharges to which the data refer, of the order of 0.15 T. These conditions make the electrostatic limit

$\beta \ll m_e/M_i$, where $\beta = n_e T_e/(B^2/2\mu_0)$, not so easily satisfied. This implies that electromagnetic effects might be important, in particular, the parallel dynamics, where magnetic induction, resistivity, or electron inertia may play a role in the linear response of the parallel current density to the parallel gradients [23].

The data presented hereafter have been obtained in the RFX-mod reversed field pinch device ($R/a = 2m/0.459m$) [24], operating at relatively low plasma current ($I_p \leq 400$ kA) with average normalized density values in the range $n/n_g \approx 0.4$–0.5 (n_g is the Greenwald density [25]). A new insertable probe, dubbed U probe, specifically designed to investigate the electromagnetic features of the edge turbulence, has been installed in RFX-mod. The system consists of two boron nitride cases, 8.8 cm toroidally spaced. Each case contains 40 electrostatic pins, combined in eight 5-pins rows acting as balanced triple probes, 6 mm radially spaced. A radial array of 7 three-axial magnetic coils is located in each case, in order to measure the fluctuations of the three components of the magnetic field. In this way, the probe can measure simultaneously and in the same location the electron pressure, the radial and toroidal components of the fluctuating $\mathbf{E} \times \mathbf{B}$ velocity, and the resulting vorticity, plus the poloidal component of current fluctuations, which in the RFP edge corresponds to the parallel component. Data were digitally sampled at 5 MHz with a minimum bandwidth of 700 kHz. According to our knowledge this is the first time that all these measurements are available simultaneously in the same location with a high temporal and spatial resolution. The diagnostics setup is completed by a gas puffing imaging system (GPI). The GPI is a spectroscopic nonintrusive diagnostic that measures the light emission of the neutral gas puffed in the plasma edge [26]. The equipment is completed with three triaxial magnetic coils (of the same type of those installed in the U probe) measuring the local components of the magnetic field. The data analysis technique used to disentangle coherent structures from the measurements described above is based on a wavelet analysis and has been described elsewhere [20,27]. It allows locating within the signal individual events related to the presence of structures at a given scale. Time windows surrounding these events are then averaged together, obtaining a conditional average of the considered structure. The possibility offered by the probe head system of measuring different plasma parameters locally with their respective radial gradients allows obtaining information on the structure associated with the strongest bursts in the plane perpendicular to the average magnetic field (radial-toroidal for the edge of a RFP).

A first experimental observation is given in Fig. 1, where the conditional average of different plasma parameters is shown as a function of minor radius for structures with a time scale $\tau = 5$ μs. The conditional averaging procedure has been applied on radial arrays of sensors measuring, respectively, the floating potential V_f, the electron temperature T_e, and the plasma density n_e, so that also the pressure $p = n_e T_e$ can be estimated. Events detected on pressure fluctuations measured at $r = 421$ mm were used as a trigger for the conditional average. The obtained 2D images can be considered as pictures of the average spatial features associated with intermittent bursts in the cross-field plane, due to the fact that they move toroidally according to the average $\mathbf{E} \times \mathbf{B}$ flow, as proved by toroidally distributed measurements [22]. In Fig. 1 a well defined structure on pressure is clearly visible, and its radial extension seems to be larger than the range of 3 cm covered by the radial array of probes and corresponding to about 5 times the ion sound gyroradius $\rho_s = C_s/\Omega_i$ (given by the ratio of ion sound velocity to ion cyclotron frequency). The structure appears to be also slightly stretched in the toroidal direction, likely due to the presence of a radially sheared toroidal flow that characterizes the edge region. The pressure structure is the result of more complex features characterizing the corresponding ones of T_e and n_e, although a fairly clear blob emerges also from the plasma density picture.

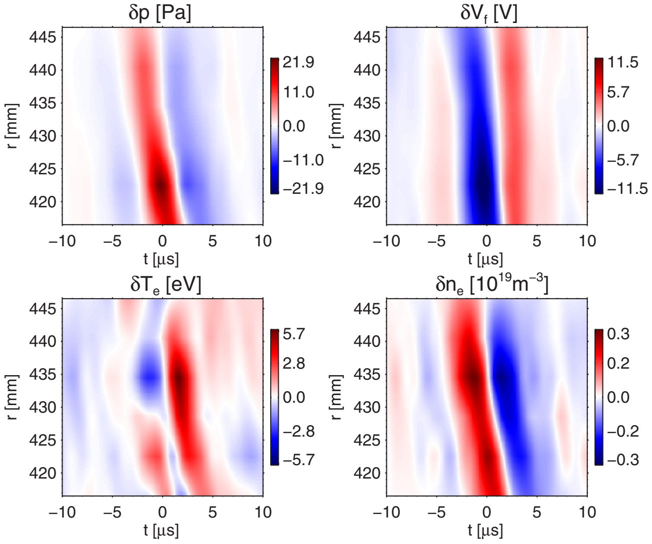

FIG. 1 (color online). Two-dimensional imaging on electrostatic parameters obtained as conditional average, taking as reference events bursts on a pressure signal measured at $r = 421$ mm.

The distribution of V_f sensors on the probe head includes arrays extending in both radial and toroidal directions, with an arrangement that specifically allows a direct estimate of the local fluctuation of vorticity, $\omega = \nabla \times \mathbf{v}$, where $\mathbf{v}$ is the local flow. Accounting for the mainly poloidal local magnetic field, the parallel component of vorticity can be estimated as $\omega_\parallel = \frac{1}{B_\theta} \nabla_\perp^2 V_f$ [28].

The average parallel vorticity structure corresponding to the pressure event is shown in Fig. 2(a). The vorticity pattern provides two main opposite peaks, with a further small peak around $t = -4$ μs. The resulting structure is rather complicated resembling an asymmetric dipolar vortex partially modified with a small positive peak. The

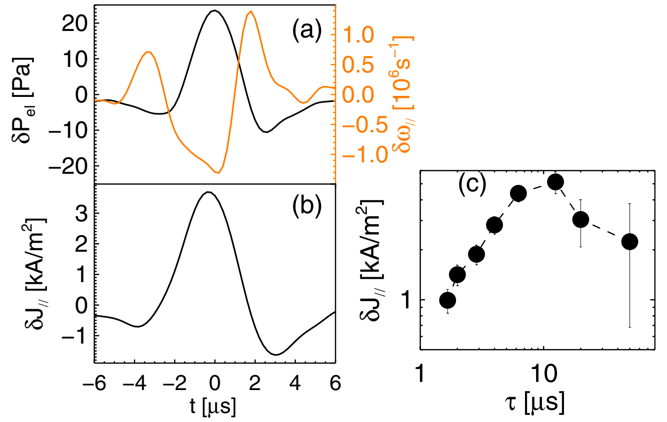

FIG. 2 (color online). (a) Pressure and vorticity structures, (b) parallel current density associated with pressure structures. Data obtained from conditional average over intermittent bursts on pressure signal at scale $\tau = 5$ μs. (c) Scaling of $J_{\parallel}$ peak associated with pressure perturbation as a function of scale τ.

asymmetric dipolar structure may be reasonably imputed to the surrounding sheared ambient flow. Dipolar structures hardly survive in a strongly sheared plasma flow, as in the present case, where one of the poles of a dipolar vortexlike structure is prograde and the other is adverse so that one could expect a not-symmetric structure [6,29]. Furthermore the averaging procedure could affect the detailed structure; however, the vorticity pattern confirms what can be guessed from conditional average imaging of floating potential shown in Fig. 1, where two main peaks of opposite sign are clearly visible. Given that the estimate of vorticity is obtained by simultaneous information coming from a 2D probe array and that it was found that such a structure travels in the edge region according to the local average flow, the consistency with the local measurement of V_f allows the conclusion that Taylor's hypothesis of frozen turbulence applies [30].

As already mentioned, an analysis of the coherence between the local measurements of pressure and magnetic fluctuations has been performed, providing not-negligible values of this parameter within the range from 50 to 300 kHz, suggesting a not purely electrostatic nature of the above described structures [22]. However more precise information can be provided by a direct estimate of the current density associated with the electrostatic structures. The set of magnetic sensors installed into the probe head allows an estimate of $\mathbf{\nabla} \times \mathbf{B}$, so that a measurement of the current density can be obtained by applying the Ampère's law. In particular, the field aligned component of current density, approximately corresponding to the poloidal component in the external region of RFPs, can be estimated as $J_{\theta} = \frac{1}{\mu_0}(\partial_{\phi} b_r - \partial_r b_{\phi})$.

The result of a conditional average on the measured parallel current density fluctuations is shown in Fig. 2(b), where again bursts on pressure fluctuations have been used as trigger events. The figure shows a clear relation between the pressure structures and a peak of parallel current density, confirming the relationship between pressure, current, and vorticity postulated by [16,31]. The observed current results in the order of a few kA/m^2 and represents a fraction of a few percent with respect to the total parallel current.

Given the evidence of a current density parallel to the main magnetic field, as said before, the balance imposed by a charge conservation equation requires a transverse current $J_{\perp}$. In the equivalent circuit of a blob the theoretical picture foresees an elongated current structure [10,32,33] due to the low parallel resistivity and to the low ratio between parallel and transverse perturbation wave vectors. With the experimental setup described, the radial and toroidal components of the current density associated with a single blob can be estimated by neglecting the parallel derivative ($\partial_{\theta} \approx 0$). These components correspond to the transversal current within the experimental uncertainty of an exact probe orientation. The experimental estimates of J_r and J_{φ} result in at least 1 order of magnitude lower than the measured parallel one, supporting the picture of current structure filaments essentially aligned along the main magnetic field.

The average value of the parallel current density associated with a pressure perturbation has been found to depend on the τ scale as shown in Fig. 2(c). The scaling has been calculated still considering the pressure structure as a trigger event. The current density intensity is found to scale as a power law up to $\tau \lesssim 6$–7 μs and exhibits a peak around 10 μs. It can be observed that the larger values correspond to the range of scales typical of the electrostatic particle flux [34].

In order to extend the investigation of the presence of such structures to higher plasma current regimes, a GPI diagnostic is used. Since the GPI does not have any mechanical part directly facing the plasma, these measurements can be performed up to the highest plasma current reached by RFX-mod, namely, about 1.5 MA. The emission fluctuations measured by this diagnostics depend on those of electron density and temperature, but if their phase difference is small [35–37], the spatiotemporal dynamics of turbulent density fluctuations can be assumed to be similar to that of the emission fluctuations.

The left panel of Fig. 3 shows the average emission structure measured by the GPI and the corresponding structures in the radial and toroidal component of the magnetic field for a low current plasma discharge ($I_p = 0.3$ MA). The bursts on emitted radiation are selected with the same statistical method cited above at the same time scale used in Fig. 2(a). The relation between the coherent fluctuations detected by the GPI and the cross-field components of the magnetic field fluctuations confirms the result obtained by the probes: the density blobs are associated with a magnetic structure, and the circular polarization in the perpendicular plane shown in the hodogram of Fig. 3 strengthens the conclusion that the blobs are current-

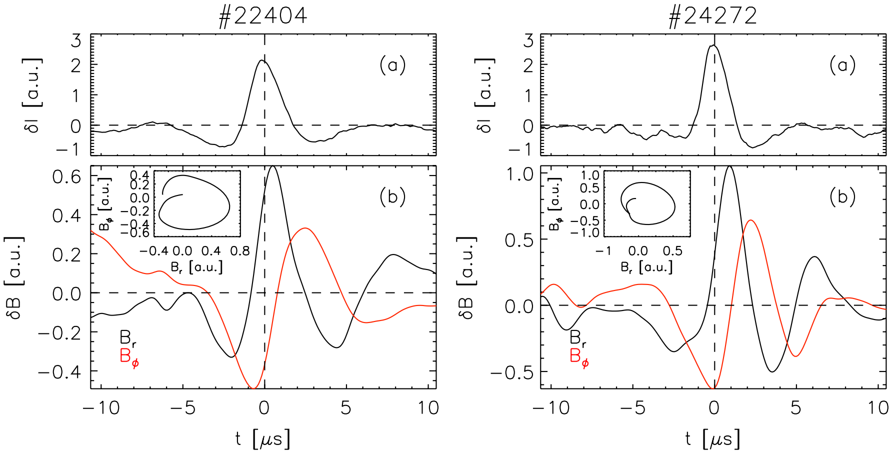

FIG. 3 (color online). (a) Average emissivity structure measured by the GPI; (b) corresponding structures of radial (black solid line) and toroidal [gray (red) solid line] local magnetic field and respective hodogram. Left and right panels refer to a low ($I_p = 0.3$ MA) and high ($I_p = 1.5$ MA) current discharge, respectively.

carrying filaments elongated in the parallel direction. An analogous result obtained at higher plasma current (1.5 MA) can be seen in the right panel of Fig. 3. Therefore, the electromagnetic feature of the edge structures has been assessed within a wide range of plasma current operating regimes, from 0.3 to 1.5 MA, by means of electrostatic, magnetic, and optical diagnostics.

Summarizing, a detailed characterization of the edge region of RFX-mod has been performed. The electromagnetic nature of coherent structures detected within the turbulence background has been established without ambiguity: they are vortices in the perpendicular plane, with a pressure peak associated with current density filament aligned along the local magnetic field and traveling according to the mean **E** × **B** flow. These experimental observations support the theory reported, for example, in [10,31]; however, other mechanisms also can be invoked [38] for the presence of electromagnetic structures. This result suggests the necessity to complete the blobs' electrostatic experimental investigation with magnetic measurements also, as well as to extend the study to other magnetic configurations with different β value.

This work was supported by the Euratom Communities under the contract of association between EURATOM/ENEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The authors would like to thank V. Cervaro for the realization of the U probe.

[1] F. Wagner *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).
[2] J. Boedo *et al.*, Phys. Plasmas **8**, 4826 (2001).
[3] S. Zweben, Phys. Fluids **28**, 974 (1985).
[4] J. Terry *et al.*, Nucl. Fusion **45**, 1321 (2005).
[5] O. Grulke *et al.*, Phys. Plasmas **8**, 5171 (2001).
[6] M. Spolaore *et al.*, Phys. Rev. Lett. **93**, 215003 (2004).
[7] T. Windish *et al.*, Phys. Plasmas **13**, 122 303 (2006).
[8] G. Serianni *et al.*, Plasma Phys. Controlled Fusion **49**, B267 (2007).
[9] A. Kirk *et al.*, Phys. Rev. Lett. **96**, 185001 (2006).
[10] S. Krasheninnikov *et al.*, J. Plasma Phys. **74**, 679 (2008).
[11] O. Grulke *et al.*, Plasma Phys. Controlled Fusion **49**, B247 (2007).
[12] A. Kirk *et al.*, Plasma Phys. Controlled Fusion **48**, B433 (2006).
[13] O. Pogutse *et al.*, Plasma Phys. Controlled Fusion **36**, 1963 (1994).
[14] A. Bhattacharjee and E. Hameiri, Phys. Fluids **31**, 1153 (1988).
[15] B. N. Kuvshinov *et al.*, Phys. Plasmas **8**, 3232 (2001).
[16] J. Bergmans and T. J. Schep, Phys. Rev. Lett. **87**, 195002 (2001).
[17] V. Carbone *et al.*, Phys. Plasmas **7**, 445 (2000).
[18] M. Spolaore *et al.*, J. Phys. Conf. Ser. **7**, 253 (2005).
[19] V. Antoni *et al.*, Phys. Scr. **T122**, 1 (2006).
[20] V. Antoni *et al.*, Europhys. Lett. **54**, 51 (2001).
[21] N. Vianello *et al.*, Plasma Phys. Controlled Fusion **44**, 2513 (2002).
[22] M. Spolaore *et al.*, J. Nucl. Mater. (to be published).
[23] B. D. Scott, Plasma Phys. Controlled Fusion **39**, 1635 (1997).
[24] P. Sonato *et al.*, Fusion Eng. Des. **66**, 161 (2003).
[25] M. Greenwald, Plasma Phys. Controlled Fusion **44**, R27 (2002).
[26] M. Agostini *et al.*, Rev. Sci. Instrum. **77**, 10E513 (2006).
[27] M. Farge, Annu. Rev. Fluid Mech. **24**, 395 (1992).
[28] W. Horton *et al.*, Phys. Plasmas **12**, 022 303 (2005).
[29] B. Krane *et al.*, Phys. Rev. Lett. **80**, 4422 (1998).
[30] U. Frisch, *Turbulence: The Legacy of A. N. Kolmogorov* (Cambridge University Press, Cambridge, England, 1995).
[31] J. R. Myra *et al.*, Phys. Plasmas **14**, 102 314 (2007).
[32] A. V. Nedospasov, Sov. J. Plasma Phys. **15**, 659 (1989).
[33] X. Garbet *et al.*, Nucl. Fusion **31**, 967 (1991).
[34] V. Antoni *et al.*, J. Nucl. Mater. **313–316**, 972 (2003).
[35] M. A. Meier *et al.*, Phys. Rev. Lett. **87**, 085003 (2001).
[36] S. J. Zweben *et al.*, Nucl. Fusion **44**, 134 (2004).
[37] O. Grulke *et al.*, Phys. Plasmas **13**, 012 306 (2006).
[38] P. K. Shukla *et al.*, Phys. Rev. A **34**, 3478 (1986).