LETTER

Drift-Alfvén vortex structures in the edge region of a fusion relevant plasma

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Abstract

Edge turbulent structures are commonly observed in fusion devices and are generally believed to be responsible for confinement degradation. Among their origin drift-Alfvén turbulence is one of the most commonly suggested. The drift-Alfvén paradigm allows the existence of localized vortex-like structures observed also in various systems. Here we present the evidence of the presence of drift-Alfvén vortices in the edge region of RFX-mod reversed field pinch device, showing how these structures are responsible for electromagnetic turbulence at the edge and its intermittent nature.

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(Turbulence represents an outstanding critical issue in the physics of magnetically confined plasmas for thermonuclear fusion research. Indeed plasma turbulence has been recognized since the beginning as the cause of the so-called anomalous particle and energy transport [1]. In recent years it has been observed that, within incoherent fluctuations, coherent structures emerge similar to vortices observed in fluid turbulence [2]. These structures have been detected in a variety of devices, ranging from tokamaks [3–5], through stellarators [6], up to reversed field pinches [7] and linear devices [8] and represent a feature shared with astrophysical plasmas [9]. Turbulent structures, often referred to as blobs, are responsible for the generally observed high degree of intermittency. Indeed the generation of these structures, arising because of the presence of various instabilities in the non-linear regime, is responsible for the breaking of self-similarity in the energy cascade process [10].

Blobs arising in fusion relevant plasmas have been extensively studied in the plane perpendicular to the main magnetic field [4], and only recently have their 3D features been experimentally addressed [11]. This interest is enhanced by some analogies with edge localized modes (ELMs), which are indeed thought to be associated with parallel current filaments [12]. Present theories about blob formation and dynamics suggest an interchange-like origin, with effects induced by sheath-boundary conditions [13].

Plasma quasi-neutrality implies the condition $\nabla \cdot J = 0$ on the total current $J$: considering the non-vanishing $\nabla_{\perp}$ components of the diamagnetic and polarization current, a parallel current density perturbation $\tilde{j}_{\parallel}$ must arise [14]. Experimental evidence on the existence of filaments associated with blobs has been found [5, 11]. Although interchange is believed to be responsible for blobs in the scrape-off layer plasmas, it does not represent the only possible mechanism for the generation of electromagnetic coherent structures. Drift-wave instability, which is thought to dominate plasma turbulence in the edge confined region [15], is a non-linear, non-periodic motion involving disturbances on a background pressure gradient of a magnetized plasma and eddies of fluid-like motion in which the advecting velocity of all charged species is the $E \times B$ velocity [16]. On the theoretical level the electron dynamics is purely electrostatic if the parallel Alfvén transit frequency is greater than the thermal electron transit frequency (or equivalently if $\beta \ll m_{e}/M_{i}$) and larger than any drift-wave frequency. Actually these conditions are not satisfied in the edge region of fusion devices [15] and the resulting turbulence and transport level will be determined by electromagnetic effects in the framework of drift-Alfvén dynamics, which represents the paradigm for the description of the coupling of drift waves with kinetic Alfvén waves (KAWs) [17]. The key distinction between drift-Alfvén dynamics and magnetohydrodynamics (MHD) is the inclusion of...
of parallel electron motion and electron pressure effects. The disturbances in the electric field arising from the presence of fluid eddies are caused by the tendency of the electrons to establish a force balance along the magnetic field lines. Pressure disturbances have their parallel gradients balanced by a parallel electric field, whose static part is given by a parallel gradient of the electrostatic potential. Turbulence itself is driven by the background gradient and the electron pressure and electrostatic potential are coupled together through parallel currents. The corresponding magnetic fluctuations could not contribute to a direct enhancing of cross-field transport through the so-called magnetic flutter transport [15], but provide an additional coupling between parallel drift current and electrostatic drift-wave potential [8]. As shown in [15], electromagnetic effects are important for drift-wave dynamics at much smaller values of plasma β than expected by pure MHD considerations.

In the non-linear regimes, drift-Alfven turbulence may generate non-linear structures in the form of electromagnetic vortices [18–20]. As already mentioned, these structures are generated by the non-linear coupling of drift waves and KAWs. The latter exhibit a dispersion relation of the form

\[ k_i = \omega/\nu_A/[1 + (k_i^*)^2]^{1/2} \]

where \( \nu_A \) is the Alfvén velocity and \( \rho_i \), the ion sound gyroradius \( \rho_i = c_i/\Omega_i \), with \( c_i \) ion sound velocity and \( \Omega_i \) ion gyrofrequency. These structures have been observed both in astrophysical plasmas [9, 21] and in linear devices [8], but up to now they have not been experimentally observed in fusion relevant devices. In this letter we present clear experimental evidence of the existence of drift-Alfvén-kinetic (DKA) vortices in the edge region of the RFX-mod reversed field pinch experiment [22].

Despite the peculiar magnetic topology, the edge region of RFP plasmas shares many features with other magnetic devices, among which the strong intermittent character of electrostatic fluctuations [7], and the highly sheared \( E \times B \) flow detected at the edge [23]. Intermittency manifests itself as a clear departure from self-similarity and can be imputed to the presence of organized structures, intermittent structures, which make the process of energy cascade inhomogeneous. They have been extensively studied from the experimental point of view, observing their vortex-like shape on the perpendicular plane with an associated pressure perturbation [7, 11]. They contribute to the cross-field transport for up to 50% of the particle losses [7]. Recently their electromagnetic features have been experimentally described, revealing the existence of a parallel current density fluctuation \( j_\parallel \) associated with the pressure perturbation, which can represent up to a few percent of the total parallel current [11]. Considering the pressure gradient and the \( \beta \) condition encountered, the drift-Alfven paradigm may be considered a possible framework for the interpretation of these structures. Moreover recent results [24] reveal that resistive interchange instabilities with an \( m = 1 \) poloidal periodicity, which are expected to be unstable in RFPs [25], have been observed only in discharges with a different poloidal periodicity, which are expected to be unstable in RFPs. The corresponding \( \beta \) are in the range 1–2% thus ensuring the condition \( \beta \gg m_e/\mu_i \), whereas the typical scale length \( \rho_i \approx c_i/\Omega_i \) is equal to 3–4 mm. It is worth remembering that in the edge region of RFP plasmas the magnetic field is essentially poloidal, so that the perpendicular plane corresponds to the radial–toroidal plane. All the data presented have been obtained with probe inserted in the plasma at normalized radius \( r/a = 0.92 \), thus completely embedded in the confined region. This makes us confident that shear-boundary effects typical of scrape-off layer turbulence may be ruled out.

A new insertable probe, dubbed U-probe, developed in order to study electromagnetic turbulence and described elsewhere [26], has been used to explore the last 5 cm of the plasma column. The system consists of two boron nitride cases, each of them housing 5 × 8 electrostatic pins radially spaced by 6 mm. The pins are used as five pins balanced triple probe, allowing the simultaneous measurement of plasma density, electron temperature, electron pressure, plasma potential and their radial profiles at the same toroidal location as well as the radial and toroidal components of the \( E \times B \) plasma velocity. The particular arrangement of electrostatic measurements allows a direct estimate of the local fluctuation of vorticity \( \omega = \nabla \times \mathbf{v} \), where \( \mathbf{v} \) is the electric drift velocity, from the floating potential ones \( V_i \), as \( \omega_{ij} = (1/B)V_i \partial_{r_i} V_{j} \), where plasma potential has been approximated by floating potential as usually done [27]. 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. Thus a direct estimate of the parallel current density can be done from Ampere’s law, which in cylindrical coordinates (r, θ, φ) turns out as \( j_i \propto j_0 = 1/\mu_0(\partial \mathbf{b}_r - \partial \mathbf{b}_\theta) \), virtually in the same toroidal position of the vorticity measurements. Data were digitally sampled at 5 MHz with a minimum bandwidth of 700 kHz. The probe is inserted on the equatorial plane at poloidal angle \( \theta = 0 \). The data collected with the insertable probe have been completed with measurements obtained from a toroidal and poloidal distributed arrays of magnetic pick-up coils located inside the vacuum vessel, pertaining to the ISIS system [28]. The data analysis technique used to disentangle coherent structures from the turbulent background is based on wavelet analysis and has been extensively described elsewhere [29]. It allows to locate within the signal the presence of structures at a given temporal scale. This method has been used together with the traditional conditional averaging technique to better disclose the common features of the observed structures.

In figure 1 the results of a conditional average procedure are shown. All the time windows used for the average have been chosen using the appearance of an intermittent structure at characteristic time scale \( \tau = 4 \mu s \) (well above the 1/Ω time scale) on the pressure signal. It can be easily recognized in panel (a) the pressure peak, typical of plasma blobs, determined mainly by electron density (b). The resulting temperature structure displays a doubly peaked pattern, whose impact on the plasma pressure is less important, but contributes in determining the plasma potential pattern, shown in panel (d) It can also be easily recognized that electron density and
plasma potential are nearly in phase, with a phase difference around 1 μs, suggesting the drift origin of the observed non-linear structure. Interestingly the same potential pattern is also observed for drift vortices observed in the magnetosphere [21]. The expected pattern of parallel current density associated with these measurements is shown in panel (e) of the same figure. The existence of a current peak associated with the electron pressure blob can be easily recognized. The slight phase shift observed may be imputed to the small deviation of the nominal pressure 

$$\delta p_e [\text{Pa}]$$

$$\delta n_e [10^{20}\text{m}^{-3}]$$

$$\delta T_e [\text{eV}]$$

$$\delta V_p [\text{V}]$$

$$\delta J_e [\text{kA/m}^2]$$

Figure 1. Average coherent structure detected at scale \(\tau = 4\mu\text{s}\) using the electron pressure as reference signal. All waveforms represent variations with respect to average values: (a) electron pressure, (b) electron density, (c) electron temperature, (d) plasma potential, (e) parallel current density.

The pressure peak exhibits a radial extent of 2–3 \(\rho_s\), which is indeed the typical extent of the DKA vortex predicted for at least 30 \(\mu\text{s}\). The toroidal extension cannot be established well fulfilled in RFX-mod [26]. Using the time amplitude of the pressure perturbation (4 \(\mu\text{s}\)) shown in figure 1 and the aforementioned estimated velocity (23 km s\(^{-1}\)) it results \(\lambda_\perp = 4 \times 10^{-6} \times 23 \times 10^3 = 0.092\) m and thus \(k_\perp \approx 60\) m\(^{-1}\). The 

$$\phi$$

$$\beta$$

$$\lambda$$

$$\kappa$$

$$\Lambda$$

Figure 2. Toroidal component of the \(E \times B\) plasma velocity and of the corresponding component of Alfvén velocity. (b) The same of panel (a) but for the radial component. (c) Hodogram of the \(E \times B\) and Alfvén velocity in the perpendicular plane, showing the closed path for both the velocities.

\(v_{\perp} [\text{km/s}]\)

\(v_{\|} [\text{km/s}]\)

\(v_A [\text{km/s}]\)

\(v_e [\text{km/s}]\)

\(v_B [\text{km/s}]\)

\(v_{\phi} [\text{km/s}]\)

\(v_{\rho} [\text{km/s}]\)

\(v_{\theta} [\text{km/s}]\)

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corresponding drift-frequency $\omega_d$ with a typical diamagnetic drift velocity of 10 km s$^{-1}$ is around 600 krad s$^{-1}$. To ensure the drift origin of the observed structure a finite parallel wave vector $k_\parallel$ should be determined. The experimental evaluation of the parallel wave number is rather a complex task as it requires multiple measurements aligned along the same field line [30]: this is rather complicated to be performed on a reversed field pinch high temperature plasmas. The best approximation we can obtain is shown in figure 3(c) where the magnetic footprint associated with these structures is examined using the poloidal distributed array of pick-up coils mounted on the first wall. Clearly the magnetic perturbation is poloidally localized and its poloidal extension is shown for two different time instants in figure 3(d). The structure does not present any $m=1$ or $m=0$ periodicity, ruling out the tearing instabilities which are known to exist in RFPs as a possible triggering for these filaments: on the contrary it extends up to 300$^\circ$ corresponding to a $k_\parallel \approx 2.6$ m$^{-1}$. This is larger than what would be predicted from the KAW dispersion relation which would yield a $k_\parallel \approx 0.6$–0.8, but we emphasize that although the machine was operating at relative shallow $F$, the poloidal angle does not represent exactly the parallel one. Moreover we are considering the non-linear structure formed in the non-linear saturated regime and not a wave-like structure as done for example in [30]. On the other hand the finiteness of $k_\parallel$ cannot be imputed to a projection of $k_\perp$ on the poloidal direction as the corresponding $k_\perp$ should be greater than 100 m$^{-1}$ thus greater than what is experimentally verified. The non-zero parallel wave vector together with the observed relation between density and potential makes us confident of the drift origin of the observed structure.

As a final confirmation of the nature of the observed structures we perform a direct comparison between vorticity and parallel current density. In the drift-Alfvén framework parallel current and parallel vorticity are intrinsically related and almost proportional one to the other [20, 31, 32]. As aforementioned, the potential measurement arrangement in the U-probe allows the direct estimate of the vorticity as $\omega_\parallel = (1/B)\nabla^2\perp V_f$ and this can be compared with the parallel component of the current density $\tilde{j}_\parallel = \nabla^2\perp A_\parallel$. This comparison is shown in figure 4: the patterns of $\tilde{j}_\parallel$ and $\omega_\parallel$ result from the conditional averaging procedure with the same condition used for the previous figure. The two quantities are found to be very well correlated each other. These last observations together with the drift origin and the Alfvénicity of the fluctuating velocity clearly identify the drift-kinetic nature of the intermittent structures observed at the edge of reversed field pinches at shallow $F$. These measurements suggest the necessity of a full electromagnetic characterization of turbulence at the edge and support the theory of drift-Alfvén dynamics as a paradigm for the description of the edge.

**Figure 3.** (a) Electron pressure as a function of time and radial position normalized to ion sound gyroradius $\rho_s$. (b) Toroidal magnetic field as a function of time and toroidal coordinate normalized to $\rho_s$. (c) Toroidal magnetic field as a function of time and poloidal angle. (d) Poloidal distribution of the toroidal magnetic field perturbation in the two time instants marked in panel (c).

**Figure 4.** Comparison between parallel current density (solid curve) and parallel vorticity (dashed curve) for average coherent structure detected at scale $\tau = 4$ $\mu$s.
confined region of thermonuclear plasmas claiming the need of comparison with other magnetic configuration.

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