Coherent structure diffusivity in the edge region of Reversed Field Pinch experiments

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Abstract. Coherent structures emerging from the background turbulence have been detected by electrostatic measurements in the edge region of two Reversed Field Pinch experiments, RFX (Padua) and Extrap-T2R (Stockholm). Measurements have been performed by arrays of Langmuir probes which allowed simultaneous measurements of temperature, potential and density to be carried out. These structures have been interpreted as a dynamic balance of dipolar and monopolar vortices, whose relative population are found to depend on the local mean $E \times B$ flow shear. The contribution to the anomalous transport of these structures has been investigated and it has been found that the corresponding diffusion coefficient accounts up to 50\% of the total diffusivity. The experimental findings indicate that the diffusion coefficient associated to the coherent structures depends on the relative population of the two types of vortices and is minimum when the two populations are equal. An interpretative model is proposed to explain this feature.

1. Introduction

Coherent structures emerging from the background turbulence have been observed \cite{1, 2, 3, 4, 5, 6, 7, 8, 9} in magnetised plasmas including those confined in devices for the study of controlled thermonuclear fusion. These structures deserve a special interest as they are believed to play an important role in anomalous transport in plasmas \cite{10}. In Reversed Field Pinch (RFP) configurations these structures have been identified \cite{6} investigating the spatial structure of intermittent events \cite{11} sorted out from the turbulence background by statistical methods, based on wavelet analysis.

The edge region of RFPs is characterized by a double shear layer in the average $E \times B$ velocity \cite{12}, with a mainly poloidal magnetic field and these structures have traits of vortices rotating in a radial-toroidal plane, with velocity close to the $E \times B$ drift velocity and with a prevalent rotation direction determined by the local mean flow velocity shear \cite{6}. Both monopolar and dipolar vortices have been detected in the edge region of RFPs, with a tendency to decrease of relative population of the dipolar ones in the regions with a high $E \times B$ velocity shear \cite{13}, as...
predicted by numerical simulations [14, 15]. In the fig. 1 an example of dipolar structure obtained by a radial array of probes, measuring simultaneously floating potential (bottom panels) and density (upper panels), is shown. The structure has been obtained as conditional average on intermittent events detected on fluctuations of floating potential signals at a given radial position. A phase-shift of about $\pi/2$ has been typically observed between density and potential structures, it is worth noting that this finding is analogous to what observed in tokamak experiments [2].

The origin of these structures is still under investigation though it has been noticed a remarkable correlation with events of magnetic reconnection [16, 17] cyclically occurring in RFP plasmas.

Aim of this paper is to investigate the contribution of these structures to the particle transport and in particular to the diffusion process in the edge region of Reversed Field Pinch experiments. The second section is devoted to a short description of the experimental setup based on Langmuir probe measurements, in the third section a generalization of the Horton-Ichikawa model [10] for estimating the contribution to diffusivity by coherent structures is presented. A description of the experimental results obtained in two different RFP experiment as well as their comparison with the model prediction is described in the last section.

Figure 1. Conditional average obtained on simultaneous fluctuation measurements of density (upper panels) and floating potential (bottom panels) by a radial array of probes. The reference events are intermittent positive events with a time scale $\tau = 5\mu s$ detected on $V_f$, at the radial position $r=188$ mm (Extrap-T2R). Data are normalized to the local RMS values.

2. Experimental setup

Measurements have been performed comparing two RFP devices: RFX (aspect ratio $R/a=2m/0.5m$) [18] and Extrap-T2R (T2R) (aspect ratio $R/a=1.2m/0.183m$) [19]. The data refer to low plasma current, respectively 300 kA and 60-80 kA, to allow the insertion of Langmuir probe arrays.

The average electron density in RFX was about $n = 1.5 \cdot 10^{19} m^{-3}$, and about $n = 1.0 \cdot 10^{19} m^{-3}$ in T2R, in both experiments hydrogen was the filling gas. Different arrays of Langmuir probes have been used: in RFX a "rake probe" with 7 pins aligned along the radial direction and 8 mm far apart each other, and a "FLIP" probe with 5 pins aligned along the toroidal direction and arranged in a 5-pin balanced triple probe; in T2R two kinds of 2D-array of probes have been used with different combinations of floating potential and triple probe measurements, specifically the
"matrix probe" with 4x3 pins covering an area of 10 mm (toroidally)x 12 mm (radially) and the "3x6" pins probe covering an area of 5 mm x 15 mm. Boron nitride cases have been used for all probes, while graphite pins and molybdenum pins have been used respectively for RFX and T2R probes.

Measurements of electrostatic quantities, floating potential, $V_f$, plasma density, $n$, and electron temperature, $T_e$, have been performed with 1 MHz sampling rate in RFX and 3 or 2 MHz in T2R. The maximum bandwidth was 400 kHz in both experiments due to electronic conditioning of signals. It has been observed that the $T_e$ fluctuations do not affect the main features of structures so that, in this contest, we have assumed that fluctuations of $V_f$ and ion saturation current, $I_s$, are representative respectively of plasma potential and density fluctuations.

The statistical analysis, based on wavelet, was performed taking into account the most significant time scales for the electrostatic particle flux, which is in the range from 5 to 50 $\mu$s in RFX and 2.5 to 20 $\mu$s in T2R.

3. Vortex diffusivity interpretative model

The contribution of coherent structures emerging from background turbulence to the diffusion has been treated by Horton and Ichikawa [10]. In their model the total plasma diffusivity $D$ is given by the sum of two contributions: the first one due to coherent structures and the second one due to the background turbulence, which is given by the Bohm estimate, $D_{Bohm}$, so that

$D = D_v + D_{Bohm}$, where $D_{Bohm} = \frac{1}{16}T_B$.

In particular the contribute due to the coherent structures is given by

$$D_v = r_0 v_d f_v^2$$ (1)

where $r_0 = \sqrt{\Delta r \Delta z}/2$ is the average vortex radius (with $\Delta r$ the radial and $\Delta z$ the toroidal width), $v_d$ their relative velocity and $f_v$ the packing fraction, i.e. the fraction of area occupied by vortices. The model predicts that a diffusion due to coherent structures is provided mainly by vortices interaction, which causes a rearrangement of their vorticity pattern and consequently a faster spreading and escape of the advected particles [10].

In the edge region of the two RFP experiments both monopolar and dipolar vortices has been detected [13], so that the Horton's formula has been generalised in order to account for three different types of possible interactions between vortices, namely dipolar-dipolar (d-d), monopolar-monopolar (m-m) and dipolar-monopolar (d-m).

Therefore the formula has been rewritten as

$$D_v = r_0 v_d f_v^2 (\alpha f_d^2 + \beta f_d f_m + \gamma f_m^2)$$ (2)

where $f_m$ is the packing fraction of monopolar vortices and $f_d$ is the packing fraction of dipolar vortices. It has been assumed that the region occupied by a dipolar vortex is twice that for a monopolar one.

Normalizing the relative packing fraction to the total one $f_v = f_d + f_m$ the eq.(2) becomes

$$D_v = r_0 v_d f_v^2 (\alpha x_d^2 + \beta x_d x_m + \gamma x_m^2)$$ (3)

where $x_d = \frac{f_d}{f_v}$ and $x_m = \frac{f_m}{f_v}$ and $x_m + x_d = 1$.

4. Experimental results and discussion

In order to test the Horton-Ichikawa model for diffusivity of vortices, detected in the edge region of RFX and T2R, the quantity $D_v$ has been estimated for the two experiments. In terms of the measurable quantities involved in eq.(1), it can be observed that the average radial dimension
of structures, $\Delta r$, is easily obtained by radial arrays of probes, whether the toroidal dimension, $\Delta z$, can be estimated by applying the frozen turbulence hypothesis [20], accounting for the time scale of structures $\tau$ and the local $E \times B$ flow, $v_{E \times B}$, so that $\Delta z \approx \tau v_{E \times B}$. The packing fraction, $f_v$, has been estimated at each radial position [21] as the relative area occupied by vortices in the edge region. In the figure 2e-f the radial behaviour of the packing fraction for dipolar, $f_d$, and monopolar, $f_m$, vortices is shown for both experiments. The total packing fraction $f_v = f_d + f_m$ slightly depends on radial position and results about 20 - 30% for the two experiments, so that the contribution to the total diffusivity of the background turbulence should be weighted according to the plasma region free from coherent structures, and it results:

$$D_v = D - (1 - f_v)D_{Bohm}$$  (4)

From eq.(4) an estimate of $D_v$ can be obtained in the edge region for the two experiments, accounting for a total diffusivity $D = -\Gamma/\nabla n$, where $\Gamma$ is the electrostatic particle flux and $\nabla n$ the radial gradient of density. The radial profiles of the total diffusivity, of the Bohm estimate and of the $D_v$ estimate are shown in the fig 2a-d. A first noticeable result is given by the observation that $D_v$ profile exhibits values comparable with the Bohm estimate in both experiments, so that it can be argued that diffusivity due to coherent structures can account for up 50% of the total diffusivity.

It is worth noting that this result is consistent with the finding that [22] bursts in electrostatic particle flux, that in all RFP experiments represents most of the particle transport [12], can account for up 50% of the particle flux as observed in other magnetic configurations [23].

![Figure 2. Average radial profiles measured in RFX and T2R of the total diffusivity and Bohm estimate (a) and (b); of the diffusivity due to coherent structures (c) and (d); of the relative packing fraction for dipolar, $f_d$, and monopolar, $f_m$, vortices (e) and (f).](image-url)
Moreover comparing the radial behaviour of $D_v$ with those of the $f_d$ and $f_m$, shown in the figures 2e and 2f, it can be observed that where $f_d = 2f_m$ in the radial profile, i.e. when the dipolar and monopolar populations are equal, $D_v$ is minimum.

This experimental observation allows to simplify the general equation eq.(2) as follows.

In the hypothesis that $v_d$ does not strongly depends on $x_m$, a necessary condition for a minimum in $D_v$ is that the polynomial $y = \alpha x_d^2 + \beta x_d x_m + \gamma x_m^2 = (\alpha - \beta + \gamma) x_d^2 + (\beta - 2\alpha) x_m + \alpha$ has a minimum and it can be seen that imposing $y'(x_m) = 0$ and $y''(x_m) \geq 0$ for $x_m = 1/3$, requires $\beta = 4\alpha - 2\gamma$ and $\gamma \geq \alpha$. In order to have a positive definite diffusion, so that $y(x_m = 1/3) = k' \geq 0$, it results $4\alpha - \gamma \geq 0$, then $\alpha \geq 0$ and the polynomial becomes $y = \alpha [(x_d - 2)x_m] + 3k'/\alpha x_m (2x_d - x_m)$.

Therefore the diffusion due to the vortices can be rewritten as

$$D_v = \alpha r_0 v_d [f_d^2 + 2(k - 2)f_d f_m + (4 - k)f_m^2].$$

where $k = 3k'/\alpha$. It is worth noting that for $f_m = 0$, i.e accounting for one kind of vortices, the formula corresponds exactly to that given in ref [10] where $\alpha = 1$ has been used. Moreover $k$ is constrained between 0 and 3 as it must be larger or equal to zero for a positive definite diffusion and less than 3 to provide a minimum in $y$, different values correspond to different physics scenarios of the diffusion process. In particular: (a) if $k = 3$ it results $D_v = \alpha r_0 v_d (f_d + f_m)^2$ and implies that all vortices give the same contribution for a given packing fraction as in the original Horton formula; (b) if $2 < k < 3$ implies: $4 - k > 1$ so that the interaction among monopolar vortices give a larger contribution than that among dipolar vortices for a given packing fraction, and $k - 2 > 0$ implies positive contribution to diffusivity by dipolar-monopolar interactions, (c) $k=2$ implies no contribution for d-m interactions; (d) finally if $0 < k < 2$ implies d-m collisions mitigate the diffusivity.

An estimate of the $k$ parameter has been obtained by fitting the experimental $D_v$ radial profile with the polynomial in eq.(5) and it results negligible, typically of the order of 0.1. This corresponds to the case (b), i.e. suppression of diffusion due to interaction between monopolar and dipolar vortices. Therefore $D_v$ can be approximated as

$$D_v \approx r_0 v_d (f_d - 2f_m)^2$$

and the constraint on $v_d$ is not more necessary. In the figure 3a and b the radial behaviour of the term $(f_d - 2f_m)^2$ is shown for the two experiments and it results similar to the $D_v$ radial profile in both cases [21].

**Figure 3.** Average radial profile of the term $(f_d - 2f_m)^2$, estimated for RFX (a) and T2R(b).

An estimate of the velocity $v_d$ can be obtained, where $D_v$ is at maximum, from the ratio $D_v/(f_d - 2f_m)^2$ and taking into account of the average structure dimensions $r_0$. A value of the order of 20 - 30 km/s is found for $v_d$ and this value is consistent with the local average $E \times B$ velocity measured in the two experiments.
5. Conclusion
A detailed statistical analysis has been performed on intermittent fluctuations of electrostatic quantities comparing measurements in the edge region of two reversed Field Pinch experiments, RFX an Extrap-T2R. These strong events are associated to vortex-like coherent structures, emerging from turbulence background: in particular monopolar and dipolar structures and their relative population is consistent with a selection performed by the average $E \times B$ velocity shear. A model has been presented in order to estimate their contribution to the diffusivity. The excess of the total diffusivity with respect to the Bohm diffusion can be interpreted as interaction between vortices evolving under local average velocity shear. It has been found that the diffusion ascribed to vortices can account for up 50% of the total diffusivity and that a mitigation of $D_v$ has been observed where the dipolar and monopolar population are equal. This result can provide a new scenario in transport suppression by fine tuning of marginal velocity shear in addition to the well known turbulence suppression by high velocity shear.

6. References
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