Vortex-Induced Diffusivity In Reversed Field Pinch Plasmas

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Coherent structures identified in two reversed field pinch experiments are interpreted as a dynamic balance of dipolar and monopolar vortices growing and evolving under the effect of the $E \times B$ flow shear. For the first time their contribution to the anomalous transport has been estimated in fusion related plasmas, showing that they can account for up to 50% of the total plasma diffusivity. The experimental findings indicate that the diffusion coefficient associated with 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.

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Understanding and controlling the mechanism behind anomalous transport driven by plasma turbulence is a key issue in experiments for thermonuclear fusion research. The observation of regimes of improved confinement, associated with plasma flow shear increase, has fostered the research on turbulence properties and regulation by flow shear. The outer region of plasmas confined in a reversed field pinch (RFP) configuration has shown several analogies with other magnetic configurations [1], among which are a highly sheared $E \times B$ velocity, v_{ExB}, and a particle transport mainly due to electrostatic turbulence. The radial profile of the turbulent particle flux was noticed to be related to the spontaneous $E \times B$ flow shear and transport suppression, by its modification, has been reported [2,3].

Recently, coherent structures emerging as intermittent bursts from the background turbulence have been identified in RFP experiments [4]. It has also been found that these structures have a relationship with the $E \times B$ flow shear, as they have traits of vortices with a prevalent direction of rotation determined by the local mean velocity shear [4]. These structures tend to cluster close to the reversal surface, i.e., the magnetic surface where the toroidal magnetic field changes sign, after events of magnetic reconnection cyclically occurring in RFP plasmas [5,6]. Similar structures have also been investigated [7–13] in plasmas confined by different magnetic configurations and deserve special interest as they are believed to give a significant contribution to the anomalous transport [14].

The aim of this paper is to investigate the contribution of these structures to the particle transport in the RFP devices RFX [15], and Extrap-T2R (T2R) [16]. These two experiments are characterized by different major radius R and minor radius a, namely $R/a = 2$ m/0.5 m and $R/a = 1.24$ m/0.183 m respectively, and first walls (a full armor of graphite tiles in RFX and poloidal arrays of molybdenum limiters in T2R) and have been operated at relatively low plasma current I_p, namely $I_p = 300$ kA (plasma density $n = 1.5 \times 10^{19}\text{m}^{-3}$) in RFX, and $I_p =$ 60–80 kA ($n = 1.0 \times 10^{19}\text{m}^{-3}$) in T2R. The probes have been inserted in the outer region which extends between the reversal surface and the first wall. The reversal surface is typically located at $r/a \approx 0.85$, so that the outer region has a width of about 7 cm in RFX and 3 cm in T2R. Fluctuations have been investigated by different arrays of probes: in RFX the array consists of 7 pins with a radial resolution of 8 mm, in T2R the arrays consist of six triple probes with a 3 mm radial resolution, and three triple probes with a 6 mm radial resolution.

The measured fluctuations have been decomposed in time scales by a Mexican hat wavelet, focusing on those time scales which contribute to the transport [1,6], namely, from 5 to 50 μs in RFX and from 2.5 to 20 μs in T2R. In term of spatial scales these ranges correspond to a toroidal wavelength ranging from 0.15 to 1 m in RFX and from 0.06 to 0.6 m in T2R. A subset of time scales, τ, (5, 10, and 20 μs for RFX and 2.5, 5, and 10 μs for T2R) has been further selected in order to reduce the overlapping of the spectra due to the continuous wavelet transform analysis [17]. The toroidal extent Δz of the structures corresponding to a given τ is of the order of a few tens of centimeters, as deduced by applying the frozen turbulence hypothesis $\Delta z \approx v_{E\times B}\tau$ [18].

Figure 1 shows the average radial profile of the coherent structure obtained by ensemble conditional average over intermittent events of floating potential and detected in the location indicated by the vertical line in each graph. Data refer to events with negative peaks in RFX, but similar result are found in T2R, as well as for positive peaks. The radial profile shape slightly changes at different radial positions and this effect might be due to the $E \times B$ flow shear. A radial extent Δr of floating potential structures can be estimated from the radial width at half

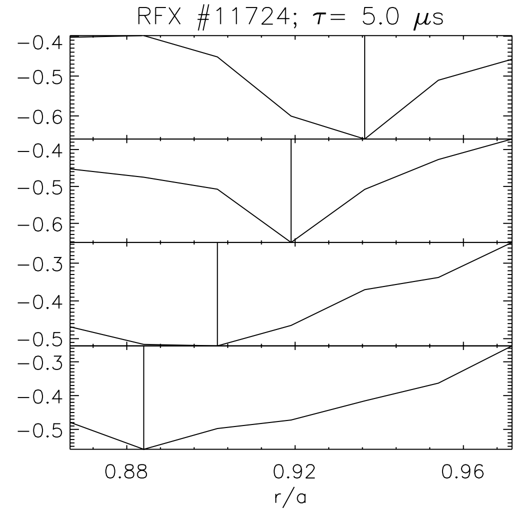

FIG. 1. Radial profile of V_f structures, normalized to the local RMS values, obtained by conditional average on intermittent events detected at the locations indicated by the vertical lines.

minimum and it results in about $0.3 \div 0.5$ times the width of the outer region. As the magnetic field is mainly poloidal in the edge region, structures identified as minima or maxima in floating potential in a radial-toroidal plane result in a vortexlike $E \times B$ velocity pattern with opposite direction of rotation [4]. In Fig. 1 it can be observed that the minima, representing the average structure center, correspond to the position of the probe where the events have been detected, so that a continuous distribution of structures in the outer region can be deduced. It can be noted that this distribution is consistent with a radial diffusion of these structures with average displacements smaller than their size.

The investigation performed in T2R by an array of triple probes has allowed the simultaneous reconstruction of the structure of the plasma potential and density. Previous conditional average analysis has shown that the mean potential structures are reminiscent of monopolar vortices [4], and that potential and density structures are well correlated with a phase shift almost $\pi/2$ [19]. New data and analysis of single events or selected conditional averages have shown also the presence of structures reminiscent of dipolar vortices with two counter rotating monopoles mainly aligned along the toroidal direction. The simultaneous presence of monopolar and dipolar vortices is consistent with theory and numerical simulations of plasma turbulence, as both predict that, in the absence of flow shear, the vortices arise as dipolar [14,20] and then evolve to monopolar ones if diffusing in sheared flow regions [20,21]. It is worth noting that the presence of both types of vortices has been reported to occur in other magnetized plasmas [10,22].

As reported above, previous studies have found that at the reversal surface intermittent events tend to cluster during relaxation processes [5]. Therefore the experimental results are consistent with a model in which the vortices rise as dipolar ones close to the reversal region and tend to evolve to monopolar ones diffusing in the highly sheared outer region. As a result both types of vortices are expected to coexist in a dynamic balance of formation and evolution ruled by the $E \times B$ flow shear. Theory and numerical simulations also predict that both types of vortices contribute to the anomalous transport through their diffusion and interaction. The former process is more relevant for dipolar structures as they can make larger excursions in the direction of the gradients perpendicular to the magnetic field [23,24]. The latter process results in particle transport even for displacements that are small compared with the vortex size [14,24], as transport occurs through reorganization of the vorticity patterns [14]. Therefore, in order to investigate their contribution to the anomalous transport, it is important to estimate their relative populations.

Despite the vortex dynamic evolution, a crude estimate of the two populations can be obtained, on a statistical basis, assuming that intermittent events with positive or negative peaks, previously interpreted as monopolar vortices, combine to maximize the population of dipolar vortices. Therefore the total number of monopolar N_m and dipolar vortices N_d results in: $N_m = |(N_{\text{pos}} - N_{\text{neg}})|$ and $N_d = (N_{\text{pos}} + N_{\text{neg}} - N_m)/2$ where N_{pos} is the number of intermittent events with a positive peak, while N_{neg} is the number of intermittent events with a negative peak.

In Fig. 2 the $E \times B$ mean velocity and the relative population of dipolar and monopolar vortices is shown for RFX at a time scale of 5 μs and for T2R at a time scale of 2.5 μs. The normalized radius r/a corresponds to the radial position where the floating potential V_f vanishes. It results that dipolar vortices constitute the larger population, with a tendency to decrease in the regions with higher $E \times B$ flow shear.

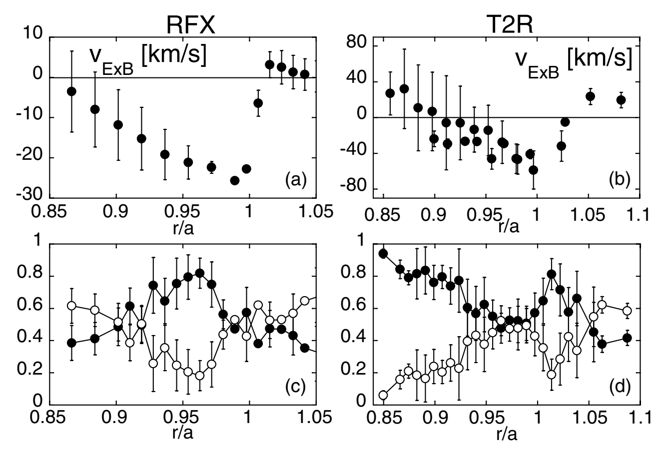

FIG. 2. Radial profiles of the average $E \times B$ velocity measured in RFX (a) and T2R (b) and of the relative fraction of dipolar (•) and monopolar (○) vortices in RFX (c) and T2R (d).

According to the Horton-Ichikawa theory [14], in the presence of coherent structures, independently from their origin, the diffusion coefficient D can be separated in a part, D_v, due to the plasma trapped in the vortices and in a part $D_{\rm uncor}$ due to the background uncorrelated turbulence, where $D_{\rm uncor}$ is set equal to the Bohm diffusion, $D_{\rm Bohm} \simeq \frac{1}{16}\frac{T}{B}$. The experimental data reported in this Letter allow these terms to be compared for the first time. An experimental estimate of the diffusion coefficient D is usually derived by applying Fick's law, namely, $D = -\Gamma/\nabla n$, to the experimental turbulent particle fluxes Γ and density gradients ∇n. It is worth noting that in RFPs D is in general close to or higher than $D_{\rm Bohm}$ [2,6], calculated with the experimental values of temperature and magnetic field in the outer region. On the other hand, the coherent structure diffusivity D_v can be written, in terms of measurable quantities [14], as $D_v = r_0 v_d f_v^2$, where v_d is the relative speed of the vortices, r_0 their average radius, estimated as $r_0 \approx \sqrt{\Delta r \Delta z}/2$, and f_v is the packing fraction which represents the fraction of area occupied by the vortices in a plane perpendicular to the magnetic field.

The packing fraction has been estimated as $f_v(r) = \sum_\tau [S_v(r,\tau)/S_T(r,\tau)]$, where the total area occupied by vortices with time scale τ is $S_v(r,\tau) = N_v(r,\tau)\Delta r(r,\tau)\Delta z(r,\tau)$ and $S_T(r,\tau) = 2\pi(R+r)\Delta r(r,\tau)$ is the corresponding perpendicular plasma section. N_v is the total number of vortices laying in the section S_T, Δr is their radial width and Δz is estimated as $\Delta z(r,\tau) \approx v_{E\times B}\tau$. In terms of measurable quantities the packing fraction results in $f_v \approx \sum_\tau \tau dN_v(r,\tau)/dt$,where the number of structures observed per unit of time dN_v/dt corresponds to the rate of intermittent events, which can be obtained by statistical techniques [5]. To avoid double counting of the vortex areas when summing, all smaller scale vortices, nested into larger scale ones, have been discarded. In Fig. 3 the radial dependence of the total packing fraction for RFX and T2R is shown. The packing fraction has values between 15% and 30% in RFX, between 20% and 40% in T2R and is slightly dependent on the radial position. As the f_v results relatively high, the contribution of the Bohm diffusion to the total diffusion must be weighted over the region free from vortices. Therefore the total diffusivity D of the plasma must be rewritten as

$$D = D_{\rm Bohm}(1 - f_v) + D_v \tag{1}$$

so that an experimental estimate of D_v can be obtained by subtracting the weighted Bohm contribution. In Figs. 4(a) and 4(c) the experimental diffusion coefficient D, the Bohm estimate $D_{\rm Bohm}$, and the resulting D_v are shown for the two experiments. Within experimental errors, negative values of D_v shown in Fig. 4 are probably due to the estimate of $D_{\rm Bohm}$. In both experiments the maximum value of D_v has values comparable with the local Bohm estimate, thus showing that coherent structures can contribute up to 50% of the total diffusivity. It is worth noting that this result is consistent with previous measurements which have shown that the particle flux is almost equally carried out by background turbulence and bursts [25]. Despite the different radial behavior (the maxima occur in different radial locations), in both experiments D_v is at a maximum where the population of the dipolar vortices exceed that of the monopolar ones and tends to a minimum where the two populations are equal (see Fig. 2).

To interpret this result, Horton's formula has been generalized in order to account for the three different types of interactions between vortices, namely, dipolar-dipolar, monopolar-monopolar, and dipolar-monopolar. Therefore D_v can be rewritten as $D_v = r_0 v_d(\alpha f_d^2 + \beta f_d f_m + \gamma f_m^2)$, where f_m is the packing fraction for monopolar vortices and f_d is the packing fraction for dipolar vortices, estimated by assuming that the surface occupied by a dipolar vortex is twice that for a monopolar one. Normalizing the relative packing fraction to the total one $f_v = f_d + f_m$, D_v can be rewritten as $D_v = r_0 v_d f_v^2(\alpha x_d^2 + \beta x_d x_m + \gamma x_m^2)$ where $x_d = f_d/f_v$, $x_m = f_m/f_v$ and $x_m = 1 - x_d$. In the hypothesis that v_d is slightly dependent on x_d, the radial behavior of f_v,

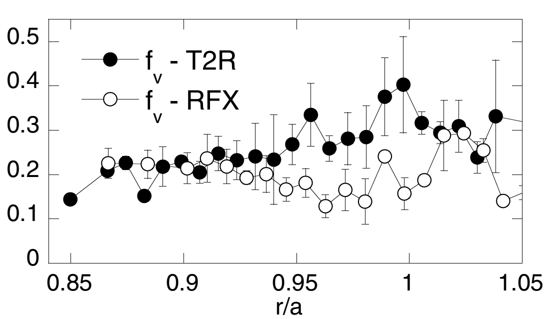

FIG. 3. Total packing fraction f_v in T2R and RFX.

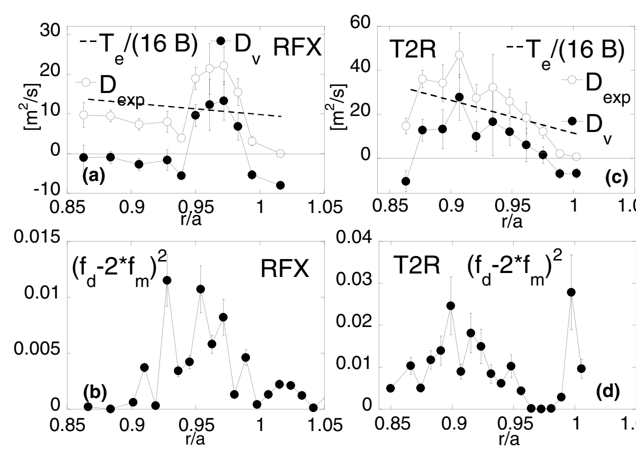

FIG. 4. Radial profiles of the experimental estimate of $D_{\rm Bohm}$, total diffusivity $D_{\rm exp}$, and D_v in RFX (a) and T2R (c), and of the $(f_d - 2f_m)^2$ term calculated in RFX (b) and T2R (d).

shown in Fig. 3, implies that for a minimum in D_v the necessary condition is a minimum in the polynomial $y = \alpha x_d^2 + \beta x_d x_m + \gamma x_m^2$. As the experimental data show that the minimum in D_v occurs when the dipolar and monopolar populations are equal, this implies that D_v has a minimum for $x_d = 2x_m$, i.e., for $x_m = 1/3$, if $\gamma \geq \alpha$ and $\beta = 4\alpha - 2\gamma$. Thus y becomes $y = \alpha[(x_d - 2x_m)^2 + kx_m(2x_d - x_m)]$, where $k = 4 - \gamma/\alpha$. Therefore the diffusion due to the vortices can be rewritten as the contribution of two terms $(f_d - 2f_m)^2$ and $f_m(2f_d - f_m)$.

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

It is worth noting that for $f_m = 0$, the formula corresponds exactly to that given in Ref. [14] assuming $\alpha = 1$. The parameter k is constrained between zero and three as it must be larger or equal to zero for a positive definite diffusion and less than three to allow a minimum in y. The experimental fitting of the radial profile of D_v gives $k \approx 0.1$, so that the second term in Eq. (2) is negligible, then weakening the initial hypothesis on a slight dependence of v_d on x_d. A negligible k value corresponds to the case $\beta < 0$, i.e., suppression of diffusion due to the interaction between monopolar and dipolar vortices, and Eq. (2) can be approximated as $D_v \approx r_0 v_d(f_d - 2f_m)^2$.

In Figs. 4(b) and 4(d) the parameter $(f_d - 2f_m)^2$ computed for RFX and T2R is shown. In both experiments it is found that it tracks fairly well the spatial behavior of D_v, therefore supporting the hypothesis beyond the generalization of the Horton-Ichikawa model.

As a consequence, in the region $0.95 < r/a < 0.98$ for RFX and $0.90 < r/a < 0.95$ for T2R, where D_v is maximum, the $r_0 v_d$ parameter can now be estimated. In RFX $r_0 v_d$ is about 1300 m^2/s, which gives, with an experimental estimate of $r_0 \approx 0.05$ m, a value for v_d of about 26 km/s. For T2R $r_0 v_d$ is about 1500 m^2/s and gives velocities of the order of 30 km/s for structures with $r_0 \approx 0.05$ m. It is worth noting that the estimated v_d corresponds to a value which is consistent with $E \times B$ velocity in both experiments in the region where D_v is maximum.

In conclusion, the simultaneous presence of dipolar and monopolar vortices has been deduced from the investigation of coherent structures emerging from the background turbulence. Motion and interaction of these vortices accounts for up to 50% of the total diffusivity. Comparing this diffusivity to the relative populations, it has been observed that the diffusion coefficient exceeding the Bohm estimate can be explained by the interaction of monopolar and dipolar vortices, traveling with electric drift velocity. The diffusivity is larger where the population of dipolar vortices is larger and has a minimum where the two populations are equal. This result could open a new scenario in transport control in addition to the well known one based on the suppression of the structures by strong flow shear. Indeed, the present results indicate that some transport mitigation can be achieved also in low flow shear regimes acting on the relative populations of monopolar and dipolar vortices by fine tuning of the shear.

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[1] V. Antoni, *Recent Research Developments in Plasmas* (Transworld Research Network, Kerala, India, 2002) Vol. 2, p.19.
[2] V. Antoni *et al.*, Phys. Rev. Lett. **80**, 4185 (1998).
[3] V. Antoni *et al.*, Plasma Phys. Controlled Fusion **42**, 83 (2000).
[4] M. Spolaore *et al.*, Phys. Plasmas **9**, 4110 (2002).
[5] V. Antoni *et al.*, Europhys. Lett. **54**, 51 (2001).
[6] N. Vianello *et al.*, Plasma Phys. Controlled Fusion **44**, 2513 (2002).
[7] J. A. Boedo *et al.*, Phys. Plasmas **8**, 4826 (2001).
[8] R. Jha *et al.*, Phys. Rev. Lett. **69**, 1375 (1992).
[9] O. Grulke, T. Klinger, and A. Piel, Phys. Plasmas **6**, 788 (1999).
[10] Å. Fredriksen, C. Riccardi., L. Cartegni, and H. Pécseli, Plasma Phys. Controlled Fusion **45**, 721 (2003).
[11] J. Bleuel *et al.*, New J. Phys. **4**, 38.1 (2002).
[12] S. J. Zweben *et al.*, Phys. Plasmas **9**, 1981 (2002).
[13] A.V. Filippas *et al.* Phys. Plasmas **2**, 839 (1995).
[14] W. Horton and Y.-H. Ichikawa, *Chaos and Structures in Nonlinear Plasmas* (World Scientific, Singapore, 1996).
[15] G. Rostagni, Fusion Eng. Des. **25**, 301 (1995).
[16] P. R. Brunsell *et al.*, Plasma Phys. Controlled Fusion **43**, 1457 (2001).
[17] C. Torrence and G. P. Compo, Bull. Amer. Meteor. Soc. **79**, 61 (1998).
[18] U. Frish, *Turbulence: The Legacy of A. N. Kolmogorov* (Cambridge University Press, Cambridge, England 1995), p. 58.
[19] M. Spolaore *et al.* in Proceedings of the 30th EPS Conference on Plasma Physics and Controlled Fusion, St Petersburg, July 7-11, 2003, edited by R. Koch and S. Lebedev available on CD (P- 2.158), (European Physical Society, St. Petersburg, Russia, 2003) Vol 27A.
[20] P. S. Marcus, T. Kundu, and C. Lee, Phys. Plasmas **7**, 1630 (2000).
[21] B. Krane, I. Christopher, M. Shoucri, and G. Knorr, Phys. Rev. Lett. **80**, 4422 (1998).
[22] B. K. Joseph *et al.*, Phys. Plasmas **4**, 4292 (1997).
[23] J. Nycander and M. B. Isichenko, Phys. Fluids B **2**, 2042 (1990).
[24] B. N. Kuvshinov, J. Rem, T. J. Schep, and E. Westerhof, Phys. Plasmas **8**, 3232 (2001).
[25] V. Antoni *et al.*, Phys. Rev. Lett. **87**, 045001 (2001).