Diffusivity induced by vortex-like coherent structures in Reversed Field Pinch plasmas

M. Spolaore §, V. Antoni, E. Spada, R. Cavazzana, E. Martines, G. Regnoli ‡, G. Serianni, N. Vianello

Consorzio RFX, Associazione EURATOM-Enea sulla fusione, C.so Stati Uniti 4, I-35127, Padova Italy

‡ Associazione EURATOM-ENEA sulla fusione, C.R. Frascati, C.P. 65, 00044, Frascati, Italy

H. Bergsåker, J.R. Drake

Division of Fusion Plasma Physics (Association Euratom/VR), Alfvén Laboratory, Royal Institute of Technology, SE10044, Stockholm, Sweden

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.

Coherent structures emerging from the background turbulence have been observed in magnetised plasmas including those confined in devices for the study of controlled thermonuclear fusion research [1, 2, 3, 4, 5]. These structures deserve a special interest as they are believed to play an important role in anomalous transport in plasmas [6]. In Reversed Field Pinch (RFP) configurations these structures have been identified [7] investigating the spatial structure of intermittent events sorted out from the turbulence background by statistical methods, based on wavelet analysis [8]. Furthermore these events tend to cluster during the relaxation processes typical in RFPs, highlighting a strong non linear coupling between internally resonant MHD modes and electrostatic fluctuations at the edge [8, 9].

§ To whom correspondence should be addressed (monica.spolaore@igi.cnr.it)

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.

Measurements have been performed comparing two RFP devices: RFX (aspect ratio R/a=2m/0.5m) [10]and Extrap-T2R (T2R) (aspect ratio R/a=1.2m/0.183m) [11]. The data refer to low plasma current, respectively 300 kA and 60-80 kA, to allow the insertion of Langmuir probes 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 so to obtain a triple balanced Langmuir probe; in T2R two kinds of 2D-array probe 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 μs in RFX and 2.5 to 20 μs in T2R.

Theory predicts that in magnetised plasmas, as in ordinary fluids, dipolar vortices are the natural solution in absence of sheared flow, the role of shear is to select a preferred rotation versus accordingly to its sign [6], and these findings are supported by numerical simulations [12]. Both RFX [13] and T2R [9] are characterised in the outer region by a double layer sheared flow, so that we can expect the simultaneous presence of both kind of vortex structures.

Dipolar and monopolar vortices have been observed in both experiments and in the specific case of T2R, where density and potential structures have been measured simultaneously, they exhibit a typical phase shift of $\pi/2$ [14]. An example of the vortices is provided in figure 1 for RFX data, where from a radial array of floating potential time series an electric field structure has been deduced on the radial-toroidal plane, by using the frozen turbulence hypothesis [15], so that vortex like $E \times B$ pattern have been reconstructed. The rotation direction of the vortex depends on V_f sign.

In order to have an estimate of the two populations of vortices, we assume that positive and negative structures in V_f combine to maximize the dipolar vortices population, so that $N_m = |(N_{pos} - N_{neg})|$ represents the monopolar vortex population, while the dipolar one is given by $N_d = (N_{pos} + N_{neg} - N_m)/2$, where N_{pos} is the number of the positive structures and N_{neg} that of the negative ones.

In the figure 2a,b and 2d,e the result of this statistical estimate is shown as a function of the radial position and compared with the average $E \times B$ profiles measured respectively in RFX and T2R. It results that the dipolar population constitutes the larger one, especially where the shear is close to zero, but tends to decrease in the higher sheared regions. This result is then in agreement with what expected from theory. A further interesting experimental result can be deduced by using a conditional average analysis on different radial positions as shown in figure 3. In the data shown here the conditional average have been applied to time series of V_f measured by a radial array of pins in the T2R experiment, but similar results have been obtained in RFX. The six 2D graphs show the quantity $(V_f - < V_f >)$ normalised to the root mean square, σ, in a time window of 20 μs, as result of a conditional average performed on intermittent events detected respectively on six different radial positions and indicated by the vertical lines in the six bottom plots. These last plots show respectively the average radial profiles as obtained at time t=0 of the time window. It can be observed that structures, identified by potential wells, are distributed continuously in the edge region, and this result is consistent with a radial diffusion of these structures.

A contribution to the diffusion due to vortex structures emerging from turbulence background has been proposed in the Horton-Ichikawa model [6]. The model proposes two contributes to the total effective diffusion D: 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 $D_{Bohm} = \frac{1}{16}\frac{T}{B}$.

In particular the contribute due to the coherent structures is given by $D_v = r_0 v_d f_v^2$, where $r_0 = \sqrt{\Delta r \Delta z}$ is the average vortex dimension (with Δr the radial and Δz 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 [6].

In order to account for different kind of vortex interactions, due to the presence of both dipolar and monopolar vortices, a generalization of the Horton's formula has been proposed [16], that in its simplified form, taking into account that experimentally, where N_m matches N_d, D_v is minimum, is given by $D_v = r_0 v_d (f_d - 2f_m)^2$, where f_d and f_m represent the packing fraction for dipolar and monopolar structures respectively.

The estimate of packing fraction has been performed on different radial positions 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, where N_v is the total number of vortices laying in the section S_T and Δz is estimated as $\Delta z(r,\tau) \approx v_{E\times B}\tau$. So that in terms of measurable quantities the packing fraction results $f_v \approx \sum_\tau \tau dN_v(r,\tau)/dt$. As 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 [8], the estimate of f_v follows.

The quantities f_d and f_m have been calculated taking into account of a toroidal extent of dipolar structures twice that of the monopolar ones, so that $f_d \approx \sum_\tau 2\tau dN_{dip}(r,\tau)/dt$ and $f_m \approx \sum_\tau \tau dN_{mono}(r,\tau)/dt$, with $f_v = f_d + f_m$. To avoid double counting of the vortex areas when summing, all smaller scale vortices, nested into larger scale ones, have been discarded.

In figure 2c,f the the estimate of f_v for RFX and T2R is shown. The packing fraction is slightly dependent on the radial position and is in the range from 15 to 40%. Therefore the D_v estimate becomes: $D_v = D - (1 - f_v)D_{Bohm}$. In figure 4 the measured radial behaviour of the total diffusivity $D = -\Gamma_{es}/\nabla n$, where Γ_{es} is the measured radial electrostatic particle flux and ∇n the experimental density gradient, D_v and D_{Bohm} are shown for the two experiments. It can be observed (figures 4b,e) that D_v accounts for up to 50% of the total diffusivity. It is worth noting that this result is consistent with the finding that bursts in the electrostatic particle flux can account for up to 50% of the total particle losses[17].

Furthermore it can be observed that, where the two populations are balanced, D_v is minimum.

In the figure 4 c,f the radial behaviour of the term $(f_d - 2f_m)^2$ is also shown and it results similar to the D_v radial profile in both experiments.

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 10 km/s is found for v_d and this value is consistent with the local average $E \times B$ flow velocity.

It can be concluded that the diffusion coefficient exceeding the Bohm diffusion can be explained by interaction of monopolar and dipolar vortices traveling in the edge region with the electric drift velocity. Present results also show that the diffusion ascribed to vortices is reduced where the two vortex populations are equal and can account for up to 50% of the total diffusivity.

References

[1] O. Grulke, T. Klinger, M. Endler, A. Piel and W7-AS Team, Phys. Plasmas **8**, 5171 (2001)

[2] J. A. Boedo et al., Phys. Plasmas, 8 (2001) 4826

[3] R. Jha, P. K. Kaw, S. K. Mattoo, C. V. S. Rao, Y. C. Saxena, Phys. Rev. Lett. **69**, 1375 (1992)

[4] O. Grulke, T. Klinger, A. Piel, Phys. Plasmas 6, 788 (1999)

[5] Å. Fredriksen, C. Riccardi. L. Cartegni, H. Pécseli, Plasma Phys. Control. Fusion **45** (2003) 721

[6] W. Horton and Y.-H. Ichikawa, Chaos and Structures in Nonlinear Plasmas, World Scientific Publishing, Singapore (1996)

[7] Spolaore M. et al., Phys. of Plasmas **9**, (2002) 4110

[8] V. Antoni, V. Carbone, E. Martines *et al.*, Europhys. Lett. **54**, 51 (2001)

[9] N. Vianello, M. Spolaore, G. Serianni *et al.*, Plasma Phys. Control. Fusion **44**, 2513 (2002)

[10] G. Rostagni, Fus. Eng. Design, 25 (1995) 301
[11] P. R. Brunsell et al., Plasma Phys. Control. Fusion, 43 (2001) 1457
[12] B. Krane, I. Christopher, M. Shoucri, G. Knorr, Phys. Rev. Lett. **80**, 4422 (1998)
[13] V. Antoni, R. Cavazzana, D. Desideri *et al.*, Phys. Rev. Lett. **79**,4814 (1997)
[14] M. Spolaore, V. Antoni, H. Bergsåker *et al.*, in Proceedings of 30^{th} EPS Conference on Plasma Physics and Controlled Fusion, St Petersburg, 2003, Vol 27A, P-2.158
[15] U. Frish, *Turbulence the legacy of A. N. Kolmogorov* (Cambridge University Press, Cambridge, 1995) p. 58
[16] M. Spolaore,V. Antoni, E. Spada, H. Bergsåker, R. Cavazzana, J.R. Drake, E. Martines, G. Regnoli, G. Serianni, N. Vianello *Vortex induced diffusivity in Reversed Field Pinch plasmas* to be published on Phys. Rev. Lett
[17] V. Antoni, V. Carbone, R. Cavazzana, *et al.*,Phys. Rev. Lett. **87**,045001 (2001)

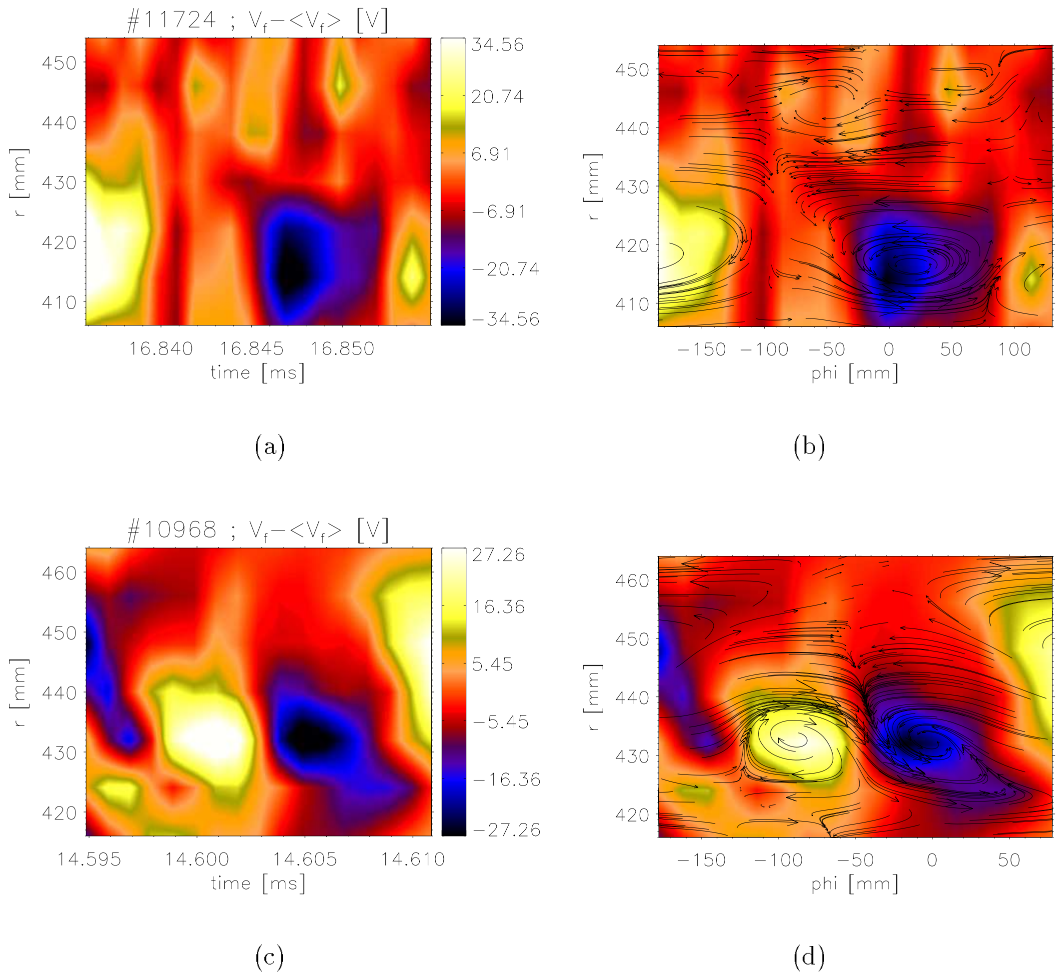

Figure 1. Example of monopolar (a,b) and dipolar (c,d) V_f structures obtained by time series of a radial array (a,c) and their $E \times B$ pattern reconstruction (b,d), data from RFX.

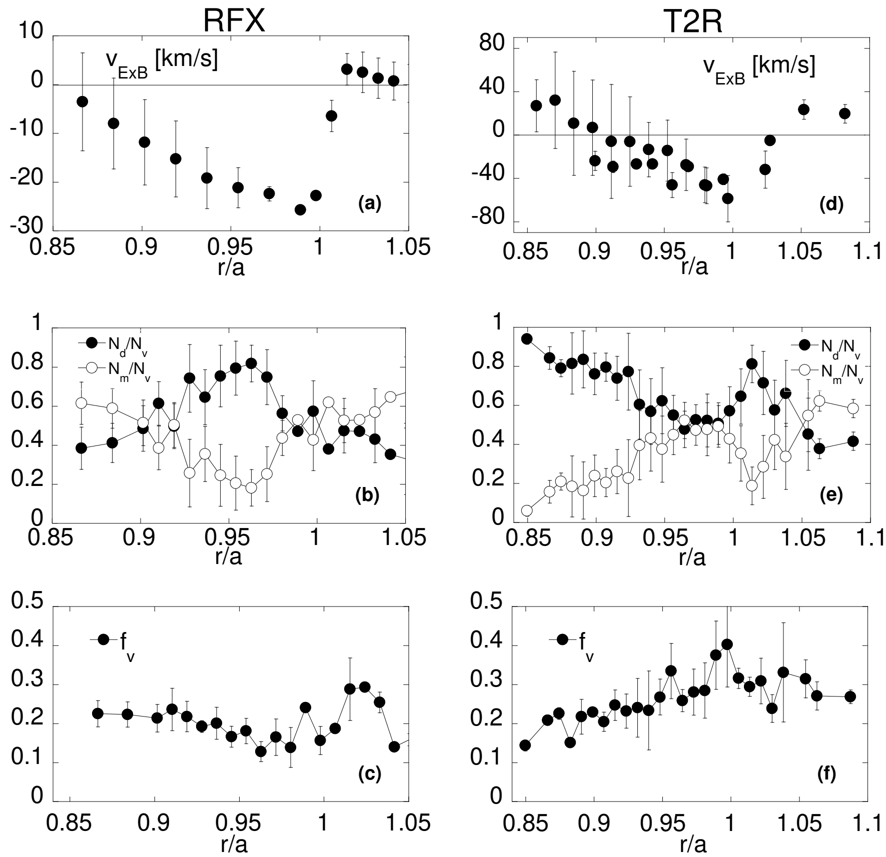

Figure 2. Radial profiles of average $v_{E\times B}$ (a,d), relative population of monopolar and dipolar vortices (b,e) and packing fraction (c,f). Data from RFX (left panels) and T2R (right panels).

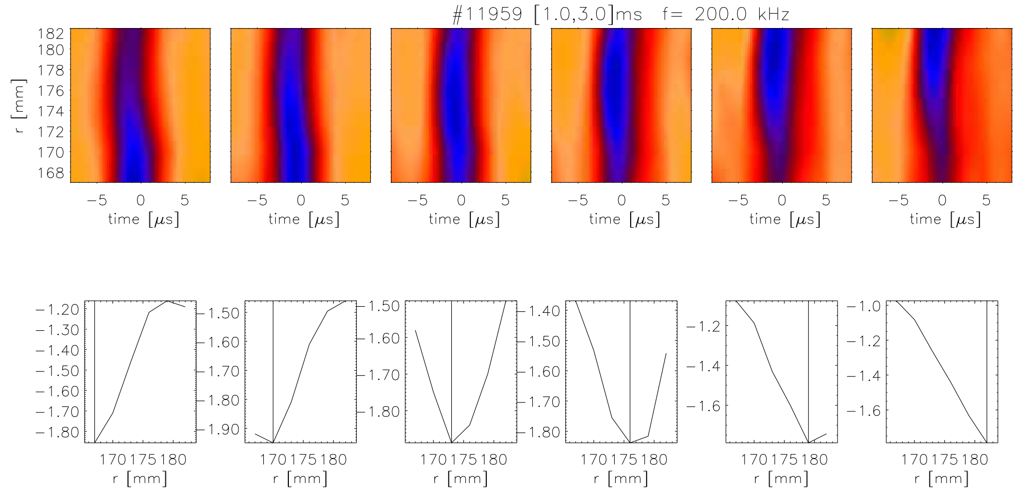

Figure 3. Conditional average on V_f intermittent events detected on different radial positions indicated by vertical lines, data from T2R.

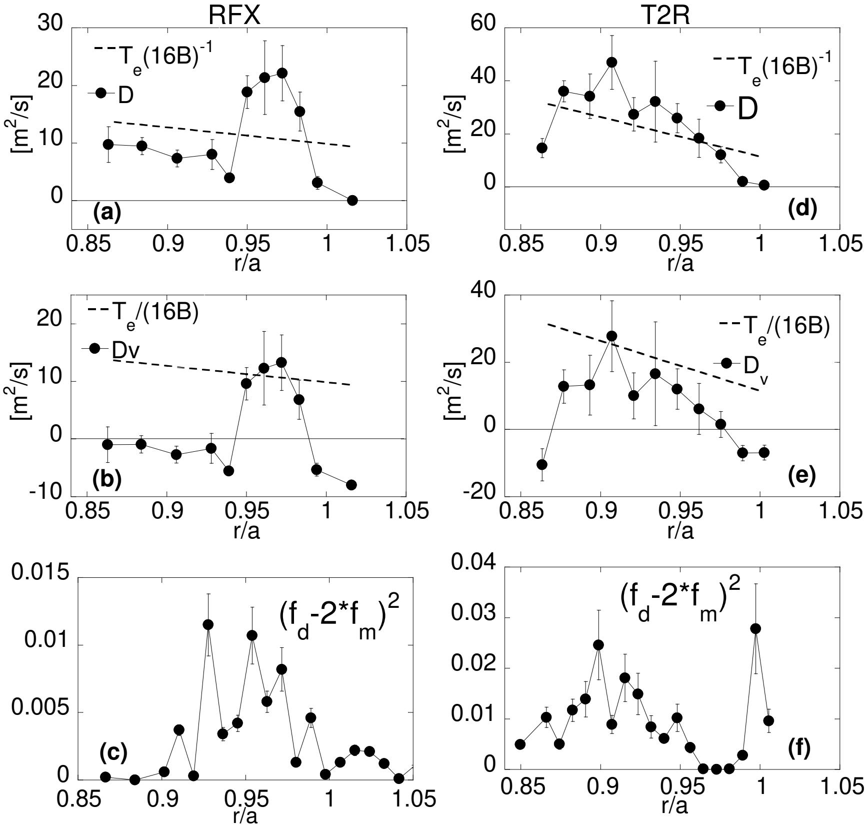

Figure 4. Radial profiles of total diffusion coefficient (a,d), diffusion due to vortices (b,e) and term $(f_d - 2f_m)^2$ (c,f). Data from RFX (left panels) and T2R (right panels)