Turbulent transport and plasma flow in the Reversed Field Pinch

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Abstract. The results of an extensive investigation of electrostatic and magnetic turbulence in the edge region of two European Reversed Field Pinch (RFP) experiments EXTRAP-T2R and RFX are reported. In both experiments particle transport is driven by turbulence and almost 50% of the particle losses is due to coherent structures emerging from the fluctuation background. It has been found that the collision of these structures results in a diffusion coefficient comparable to that due to the background turbulence. A spontaneous highly sheared E×B flow is observed in the edge region of both experiments. The flow shear is found to result mainly from the balance between the Reynolds Stress and the anomalous viscous losses. The results indicate that a turbulence self-regulation process is in action in the edge region.

1. Introduction

Turbulence plays a fundamental role in magnetically confined plasmas, as it enters in the particle and energy losses. Despite the differences between tokamaks and RFP's (the magnetic configuration is highly sheared at the edge and almost entirely generated by internal currents) it has been observed that several properties observed in RFP edge turbulence are similar to those observed in tokamaks and stellarators [1]. Among the most remarkable similarities are the observations that the edge particle transport is mostly driven by electrostatic turbulence and that a highly sheared plasma flow, mainly due to ExB drift velocity, takes place in that region. It is worth recalling that, as the magnetic field is mainly poloidal at the edge, the drift velocity is mainly in the toroidal direction. It has been observed that this spontaneous flow shear has a value close to that necessary for turbulence suppression [2,3]. This last feature has been experimentally confirmed by the fact that increasing the ExB velocity shear by external means, as edge biasing induced by electrodes inserted in the edge region of the plasma, reduces the turbulent transport [4]. These features underlay a dynamical link between ExB flows and turbulent transport which eventually leads to a self-regulation process for edge turbulence as proposed for tokamaks and stellarators [5]. This contribution is focused on the issue of the relationship between ExB velocity shear and turbulent transport in

RFP's, reviewing the most recent results and highlighting the elements useful for to the general understanding of this issue in magnetic configurations for Controlled Thermonuclear Fusion research in general.

2. Experimental set up

A detailed study of edge turbulence has been performed in the two European RFP experiments EXTRAP-T2R (a=0.18m,R=1.2m) and RFX (a=0.5m, R=2m). The two experiments differ in size and first wall (a full armor of graphite tiles in RFX and poloidal arrays of molybdenum limiters in T2R). To allow the insertion of probes in the edge region, both experiments have been operated at relatively low plasma current (I~ 300 kA in RFX and I~ 80kA in T2R) . Due to the different particle recycling at the wall, the experiments operate at different edge plasma density ($n \sim 10^{19}$ m^{-3} in RFX and $n \sim 3\ 10^{18}$ m^{-3} in T2R) and corresponding slightly different electron temperature (10 eV in RFX and 30 eV in EXTRAP T2R).

Magnetic and electrostatic fluctuations at the edge have been investigated by different arrays of probes. The probe array used in RFX is described elsewhere [2] while the probe array used in EXTRAP-T2R consists of a Boron Nitride case where 17 molybdenum electrostatic pins and 2 three-axial magnetic probes are housed. The molybdenum pins protrudes 1 mm from the case surface and are arranged as shown in figure 1. The five pins on the tip of the probe are used as a five-pin triple balanced probe whereas the remaining ones measure the floating potential. The two 3-axial magnetic probes, spaced 13 mm toroidally, measure the time derivative of the three component of the magnetic field. Each probe consists of three coils obtained by winding a 0.2 mm diameter wire around a small parallelepiped-shaped support ($7x7x8\ mm^3$).

The probes have been inserted in the edge region which extends from the toroidal field reversal surface to the first wall. As the reversal surface for both experiments is typically located at r/a~ 0.85, the outer region has a width of about 7 cm in RFX and 3 cm in T2R.

3. Results

3.1. Coherent structures and anomalous transport

In both experiments it has been found that particle flux Γ is anomalous and driven by electrostatic turbulence, namely $\Gamma=<\delta n\ \delta v_r>$, where the radial velocity δv_r is given by $\delta v_r = \delta E_\phi\ x B_\theta / B_\theta^2$, and the electric field is approximated as the derivative of the floating potential measured by the Langmuir probes. The time scales which contribute to the particle transport result comprised in both experiments between the MHD time scale (~100 μs and ~ 30 μs respectively in RFX and Extrap-T2R) and the inverse of the Ion Cyclotron frequency (~1μs) i.e. from 5 to 50 μs in RFX and from 2.5 to 20 μs in T2R. The corresponding spatial scales of the associated toroidal wavelengths are found to range from 0.15 m to 1 m in RFX and from 0.06 m to 0.6 m in T2R.

Since a long time electrostatic turbulence in RFP's has been shown to exhibit an intermittent character [6] and a bursty behaviour in primary (plasma density and potential) and derived (particle flux) quantities: bursts belonging to the non Gaussian tail of the probability distribution function of the particle flux [7] account for almost 50% of the particle losses at the edge, whereas bursts of plasma potential correspond to coherent structures. These structures emerge in clusters from turbulence background during magnetic relaxation and this process has been found particularly pronounced in the region close to the reversal surface [8, 9]. These coherent structures in plasma potential have been found to correspond to monopolar or dipolar vortices in ExB velocity, with a prevalent direction of rotation determined by the local mean flow velocity shear [10]. By ensemble conditional average techniques, the radial and toroidal extent of these vortices has been deduced [11]. In fig. 2 examples of monopolar and dipolar vortices, as obtained in RFX, are shown. Their radial extent results in both experiment to be a substantial fraction of the extent of the edge region, being typically almost half of the width of the outer region or lower, while the toroidal extent, is in the range 10-50 cm in both experiments.

It has also been observed that the vortex relative population is determined by the local ExB shear [10]. In fig. 3 the relative population of dipolar and monopolar vortices are compared with the ExB velocity profile in RFX for two cases: a standard discharge in Hydrogen where the ExB flow is highly sheared and a high density discharge in Helium where the velocity shear tends to vanish in the inner region. It appears that, where the flow shear is low, almost the entire population is made by dipolar vortices, while the population of monopolar ones has a tendency to increase in the regions with the higher flow shear.

In T2R the plasma density structure associated to these vortices has been obtained. It has been found that both monopolar and dipolar vortices give structures in density reminiscent of density blobs observed in the egde region of tokamaks [12]. Theory and numerical simulations [13,14] predict that both type of vortices contribute to the anomalous transport through their diffusion and interaction. In particular the latter process results in particle transport even for displacements small compared with the vortex size [13,14] as transport occurs through reorganization of the vorticity patterns.

In order to estimate the contribution of the vortices to the transport, a model [14] has been applied, according to which the diffusion coefficient D can be separated in a part, D_v due to the mutual collision of these vortices and in a part D_{un} due to the background uncorrelated turbulence, where the latter one is set equal to the Bohm diffusion coefficient. According to ref. [14], D_v can be written in terms of measurable quantities, namely $D_v = r_0 v_d f_p^2$, where v_d is the relative velocity of the vortices, r_0 their average radius, and f_p is the so called packing fraction which represents the fraction of space occupied by the vortices in a plane perpendicular to the magnetic field. From the number and size of vortices per toroidal unit length, the packing fraction in the edge region has been estimated and it has been found to have values between 15 and 30% in RFX and 20-40 % in T2R, almost constant in the whole edge region, as shown in fig.4. Substituting the experimental packing fraction, the average radius r_0, obtained from the reconstruction of the vortices for each time scale, and finally assuming the relative velocity close to the mean ExB toroidal velocity at the edge, D_v can be estimated. The estimate of D_v results lower or comparable to the Bohm diffusion coefficient with a maximum in the region of the second velocity shear layer, where the population of dipolar vortices is dominant. It has been found that in the edge region the sum of D_{un} and D_v equates the experimental estimate of the global plasma diffusion coefficient [11] obtained dividing the experimental turbulent particle flux by the density gradient. It should be noticed that a more detailed analysis has shown that D_v depends also on the relative population of the two types of vortices showing that the diffusivity is at minimum when the two populations are equal [11].

3.2. Turbulence and ExB flow shear

A highly sheared ExB toroidal flow is found in the edge region of both experiments, as shown in figure 3. The velocity profiles exhibit a minimum which separates the region in two velocity shear layers. The layer closer to the wall has a width comparable in both experiments to a Larmor radius so that it has been suggested that ion Larmor losses are responsible for the radial electric field which originates the corresponding ExB velocity [15]. On the other hand the second shear layer, extending deeper inside the plasma, takes place in a region where the turbulent particle flux has a maximum. It has been demonstrated in both experiments that this spontaneous velocity shear has a value which is close to that required for turbulence suppression [2]. This result has fostered the investigation on the origin of the velocity shear in this region. For this purpose, the momentum balance for the toroidal component of equations of motion for compressible plasma has been written in stationary equilibrium condition. Under reasonable assumptions, as toroidal and poloidal symmetry for mean and fluctuating quantities and negligible curvature effects, the equation has been simplified and all terms depending on fluctuations experimentally measured [16]. It results that the momentum equation can be simplified as:

$$\frac{\partial}{\partial r}\left(\left\langle \tilde{v}_r \tilde{v}_\phi \right\rangle - \frac{\left\langle \tilde{b}_r \tilde{b}_\phi \right\rangle}{\bar{\rho}\mu_0} \right) \approx \mu \frac{\partial^2 \overline{V}_\phi}{\partial r^2}$$

where $\left\langle \tilde{v}_r \tilde{v}_\phi \right\rangle - \frac{\left\langle \tilde{b}_r \tilde{b}_\phi \right\rangle}{\bar{\rho}\mu_0}$ is the complete Reynolds stress tensor, including the magnetic component usually neglected in tokamaks, and μ is the plasma viscosity. Therefore it results that the viscous force is mainly balanced by the Reynolds Stress. The latter quantity has been measured and in fig. 5 is shown its radial profile separating the electrostatic and magnetic components. The two components result comparable in magnitude though with different radial behavior: the velocity component increases inside the plasma, while the magnetic one has a less pronounced radial dependence. Therefore the radial gradient of the Reynolds Stress, which enter in the momentum balance, results mainly determined by electrostatic turbulence, in analogy to what observed in stellarators and tokamaks [17,18,19].

Finally the perpendicular viscosity has been estimated [16] as the ratio between the Reynolds stress and the velocity second derivative. In fig. 6 is shown the comparison between the average diffusivity obtained dividing the viscosity by the average mass density at the edge and the effective diffusivity obtained dividing the turbulent particle flux Γ by the density gradient. Within the error bars, the two different estimates result comparable, then suggesting that in RFP's viscosity is anomalous and closely related to electrostatic turbulence.

4. Discussion and conclusion

The simultaneous presence of monopolar and dipolar vortices is observed in the edge region of RFP’s. This observation is consistent with theory and numerical simulations of plasma turbulence, as both predict that, in absence of flow shear, vortices arise as dipolar ones [20] and then evolve to monopolar ones if diffusing in sheared flow regions [20,21]. Therefore the experimental results suggest that dipolar vortices appear in the region close to the reversal surface during magnetic relaxation phase and tend to evolve to monopolar ones diffusing in the region of highly sheared flow which separates the reversal surface from the wall. As a result, both type of vortices coexist in a dynamic balance of formation and evolution ruled by the ExB flow shear. The results shows that in RFP edge region density structures, reminiscent of blobs observed in tokamaks, are associated to vortices of both types. As these vortices correspond to bursts in plasma signals and the bursts have an intermittent nature, therefore a clear correspondence between blobs, vortices and intermittency can be established in RFP’s. This result is consistent with recent numerical simulations of intermittent transport in SOL of magnetized plasmas [22] which describe the spatio-temporal behaviour of coherent structures emerging in the edge region of tokamaks. As it has been demonstrated that the interaction of coherent structure contributes to almost 50% of the total particle losses, therefore the E×B velocity shear is confirmed to play a leading role in controlling particle losses at the edge. Indeed it rules the relative populations and interaction of vortices and at the same time has a value marginal for suppression of background turbulence. This observation, joined to the role of plasma turbulence in the setting up of the ExB flow at the edge discussed above, indicates the existence of a dynamic interplay between turbulence properties, anomalous transport and mean flow profiles in RFP’s. Finally present results allow the similarities with tokamaks and other magnetic configurations to be extended. In particular RFP's shares with tokamaks [23,24,25] the occurrence of bursty transport and coherent structures and the observation that the electrostatic component of the Reynolds stress drives the ExB flow at the edge . This last result indicates some universality of the role played by the electrostatic turbulence at the edge, despite the amplitude of the magnetic fluctuations and the different magnetic shear. On the other hand in RFP's the origin of the coherent structures seems related to the MHD activity in the plasma core, a result which could be peculiar of this configuration.

In conclusion, the studies of edge turbulence carried out in the RFP prove that the results can contribute to a better understanding of the properties of turbulent transport in magnetized plasmas and in particular can contribute to better understand the role of magnetic fluctuations, as they refer to a plasma characterized by a rich MHD activity in the core and a high magnetic turbulence at the edge.

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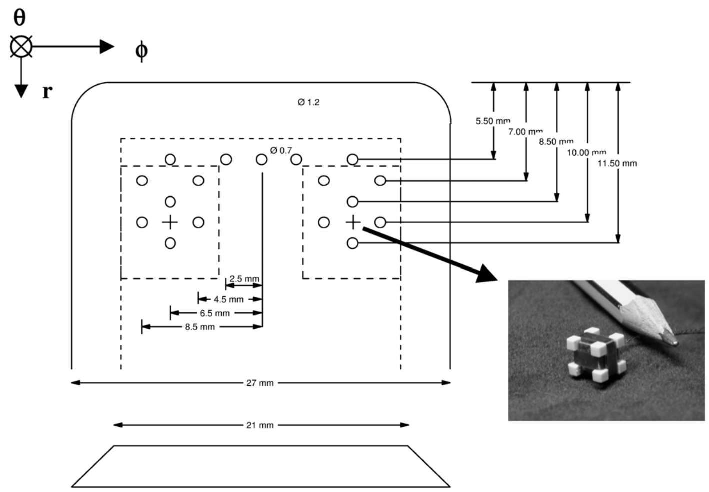

Fig. 1: Sketch of the 'Alfvén Probe Array'. With circles the position of the electrostatic pins is shown while the cross indicate the nominal position of the 3-axial magnetic coils. A picture of one of the magnetic probes is also shown

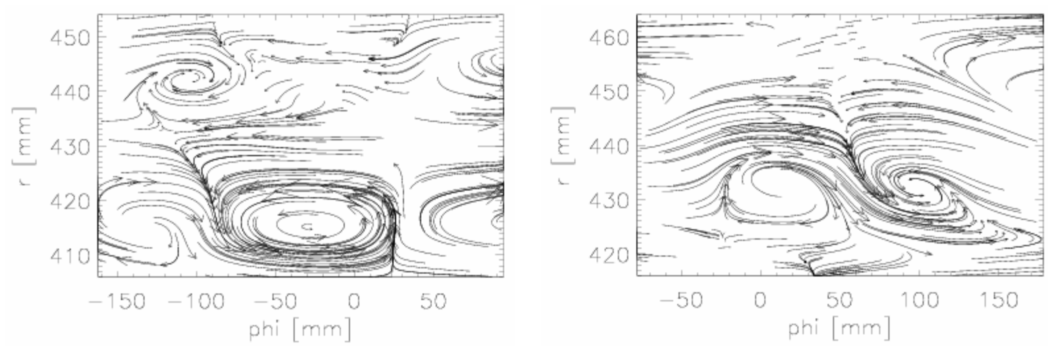

Fig. 2 Examples of monopolar and dipolar vortex

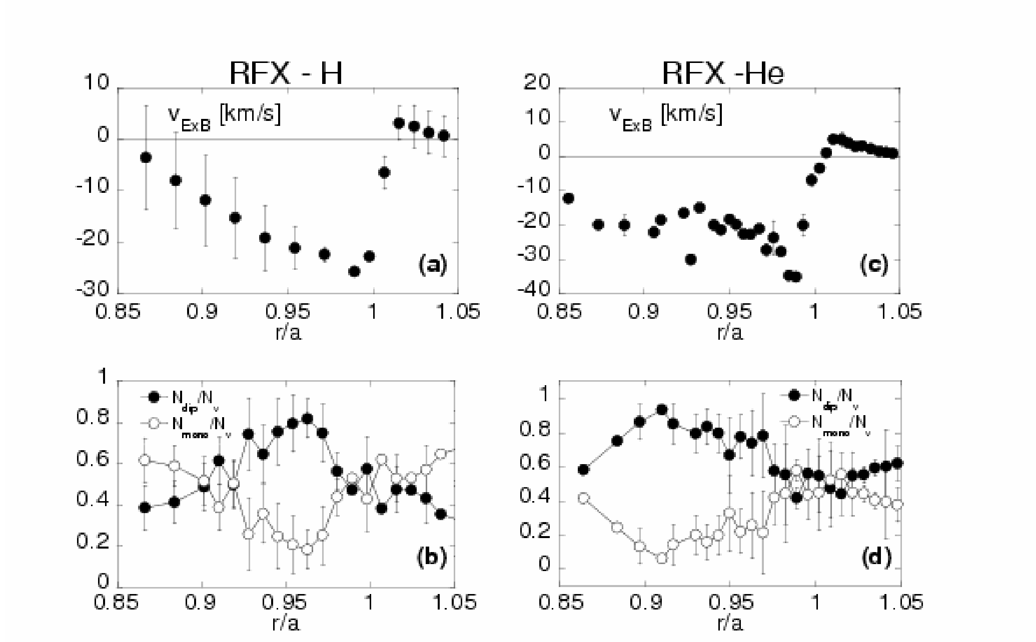

Fig. 3 Relative population of dipolar and monopolar vortices in RFX with low and high ExB velocity shear

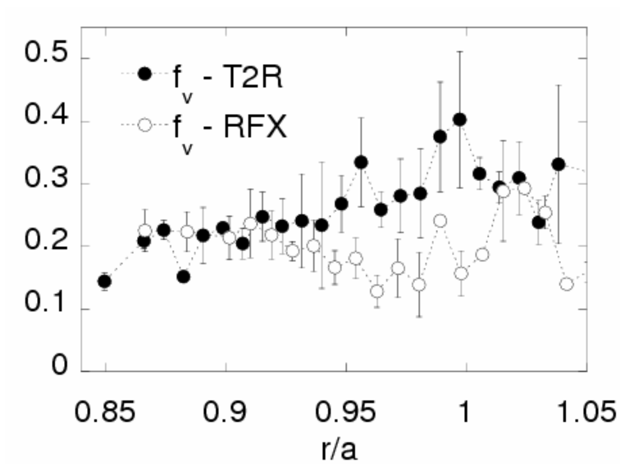

Fig. 4 Packing fraction vs normalized radius in T2R and RFX

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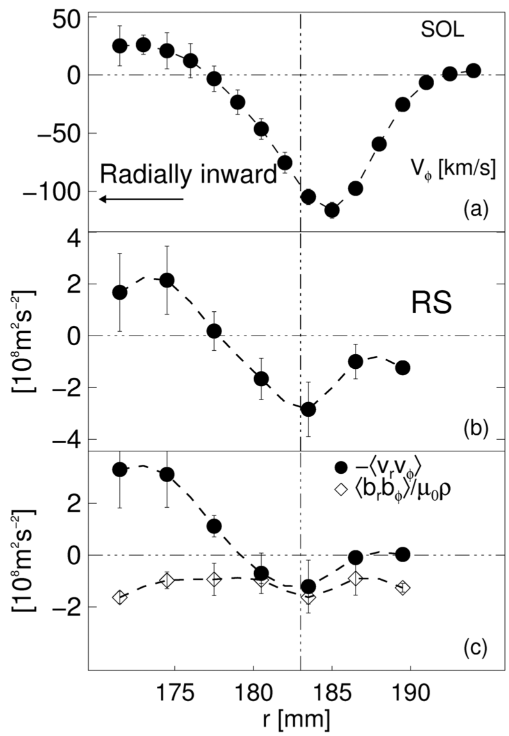

Fig 5 Reynolds Stress and velocity in the edge region

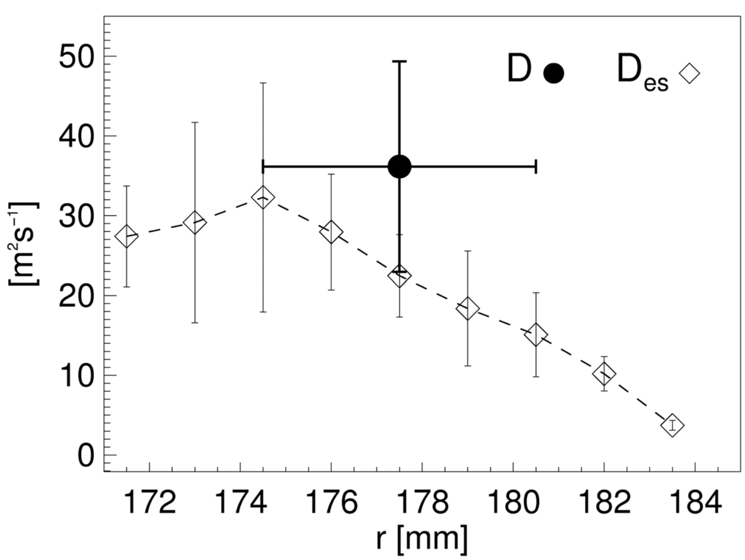

Fig 6 Radial profile of effective diffusivity and average diffusivity from viscosity