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Anomalous particle transport and flow shear in the edge region of RFP's

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Abstract

The effect of the $E \times B$ velocity shear on the particle flux carried by electrostatic fluctuations at the edge is discussed comparing the results of the experiments T2R ($R = 1.2$ m, $a = 0.18$ m) and RFX ($R = 2$ m, $a = 0.5$ m). In both experiments electrostatic turbulence accounts for most of the particle flux. The shear of the $E \times B$ velocity is close or larger than the value required for turbulence suppression or reduction. Particle fluxes exhibit bursts which carry a large fraction of the total particle flux, and which tend to cluster during magnetic relaxation phase. On the average a Bohm estimate of the experimental plasma diffusivity accounts for the experimental data. Finally a discussion on the methods for turbulence control is given.

Keywords: Transport; Turbulence; RFP; ExB; Velocity; Velocity shear

1. Introduction

The study of anomalous transport in reversed field pinch (RFP) configurations has been carried out in several devices [1–6] aimed to identify properties and origin of the plasma turbulence. Early investigation has soon lead to the conclusion that in most experiments most of the particle transport was driven by electrostatic turbulence [1,2,4,6]. In recent years further progress has been achieved in present RFP devices in this area and methods to mitigate the effect of the turbulence have been successfully tested. Among these methods biasing of the edge region by plasma guns [7] or electrodes [8] and current drive by pulsed poloidal current drive [9] have been proved to be effective in reducing the energy and particle transport via suppression or reduction of the electrostatic and magnetic turbulence in analogy to enhanced confinement regimes in tokamaks and stellarators.

The study of turbulent transport in RFP's has shown significant similarities with other magnetic configurations [10] as tokamaks and stellarators, and has lead to interesting analogies with fluid dynamics [11]. Studies in RFP's in general can contribute to the general understanding of turbulence in magnetic fusion experiments, offering a plasma environment highly turbulent where MHD modes of substantial amplitude and with a wide range of toroidal periodicity develop, compete and interact via non-linearly coupling processes. Typical amplitude of the magnetic fluctuations in RFP's is, in normalized units, $b/B \sim 1\%$. These MHD modes withstand with an even larger wave-number spectrum of high intensity electrostatic fluctuations. For instance the typical amplitude of normalized density fluctuations is $\delta n/n \sim 50\%$.

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The simultaneous presence of magnetic and electrostatic turbulence allows the study of their mutual coupling to be addressed. Early investigation of this subject in EXTRAP-T2 has found indications of non-linear coupling among low frequency MHD modes and high frequency electrostatic turbulence [12]. In recent works the effect of the magnetic reconnection phase in the electrostatic turbulence has been addressed in RFX and T2R [13] as discussed in the following.

Aim of this paper is to contribute to the general understanding of the turbulent transport in RFP's, with special emphasis on the role played by the $E \times B$ velocity shear, comparing the results in two experiments: RFX and EXTRAP T2R. This comparison has been carried out spanning a wide range of plasma parameters, in different geometry and with different magnetic and first wall boundary.

2. Experimental set up

In RFX the minor radius a is 0.5 m and the major radius R is 2 m, while in T2R $a = 0.18$ m and $R = 1.2$ m. The first wall in RFX consists of a complete armour of graphite tiles, while in T2R the previous graphite protection has been replaced by arrays of limiters in Molybdenum [14]. Another important difference between the two experiments is the magnetic boundary. In RFX MHD tearing modes were observed to lock in phase to the wall giving rise to localized distortion of the plasma column and then pronounced toroidal asymmetry while in T2R the same modes are normally rotating so that the magnetic boundary can be considered toroidally symmetric. It is worth recalling that the enhanced localized plasma wall interaction resulting by the locked mode, was claimed in RFX to be responsible for the somehow difficult density control and probably responsible for a substantial fraction of the power and particle balance of the experiment [15].

The two experiments have been operated at different densities: the average plasma density was $n \sim 1$–2×10^{19} m^{-3} in RFX and $n \sim 0.1$–1×10^{19} m^{-3} in T2R. As a consequence, also the edge density in T2R was lower that in RFX and higher electron temperatures have been reported in the edge of T2R [16]. The different density behaviour has been related to the different hydrogen retention and recycling of metallic first wall as proved by the fact that the previous T2 experiment with a graphite first wall was used to operate at higher density and that RFX could attain lower densities only after prolonged sessions of wall cleaning and conditioning.

The data shown here are obtained at plasma density current around 4.5–6.3 $\times 10^5$ A/m^2 in RFX and 7.6 $\times 10^5$ A/m^2 in T2R in order to minimize the plasma perturbation and the probe damage. In both cases probes were inserted up to $r/a = 0.86$ into the plasma, i.e. in a location close to that where the toroidal field changes sign.

The data considered for the present comparison refer to electrostatic turbulence measured in both experiments by arrays of Langmuir probes. The sampling frequency was 1 MHz in RFX and 3 MHz in T2R, though the signal bandwidth was limited to ~400 kHz in both experiments by the same electronic equipment for signal conditioning.

3. Results

The analysis of the $E \times B$ velocity and turbulence in the edge region of the two experiments has revealed many similarities.

In Fig. 1(a) and (b) the two $E \times B$ velocity profiles are shown. It is worth reminding that in a RFP the magnetic field in the outer region is mainly poloidal so that the drift velocity is in the toroidal direction. The poloidal magnetic field was respectively 0.08 T in T2R and 0.12 T in RFX. Since the corresponding radial electric field is

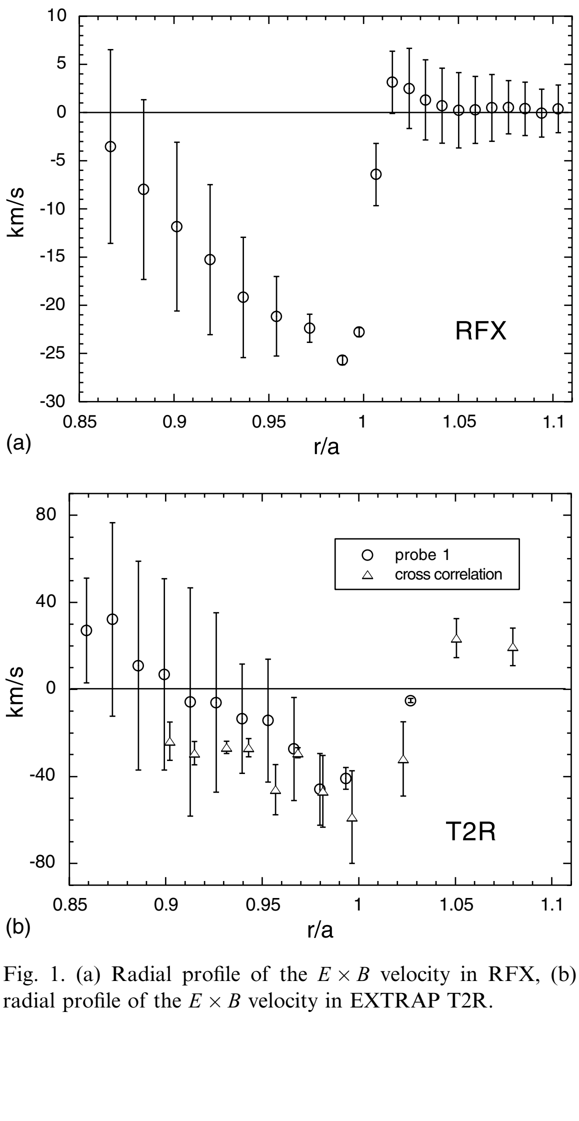


Fig. 1. (a) Radial profile of the $E \times B$ velocity in RFX, (b) radial profile of the $E \times B$ velocity in EXTRAP T2R.

directed inward the maximum velocity is always directed opposite to that of the toroidal current.

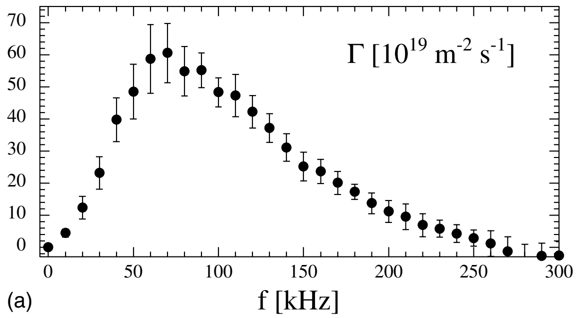
In the graph, the radius has been normalized to the radius of the LCFS, which has been assumed as the location where the floating potential, measured by Langmuir probes and referred to the vessel, vanishes.

A momentum balance equation applied to both experiments has allowed the main features of the velocity profile and value to be simulated. Within the model approximation, the higher velocity in T2R results mainly related to the lower neutral friction due to the lower edge density [16], while the slower velocity in RFX has been related to enhanced momentum losses due to locked mode perturbation [15].

In both experiments electrostatic turbulence accounts for most of the particle transport, as derived by comparing the maximum value to the H_α emission.

In Fig. 2(a) and (b) are shown the particle flux resolved in frequency (f) for both experiments. It results in that the range of time scale contributing to the transport are respectively 5–50 μs in RFX and 2.5–20 μs in T2R, while the corresponding toroidal wave length ranges from 0.15 to 1 m in RFX and from 0.06 to 0.6 m in T2R.

It is worth noticing that, despite the different aspect ratio ($a/R = 1/7$ in T2R and $a/R = 1/4$ in RFX), the



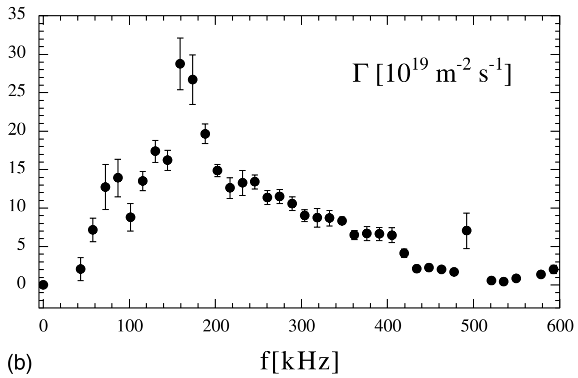


Fig. 2. (a) Frequency decomposition of the electrostatic particle flux in RFX, (b) frequency decomposition of the electrostatic particle flux in T2R.

range of toroidal number n (where $k = n/R$) is the same in both experiments, i.e. $10 < n < 100$. This is a remarkable difference with the MHD spectrum which is different in the two experiments due to the different values of safety factor q on the axis.

According to the turbulence suppression criterion [17], the shearing frequency ω_s (defined as $\omega_s = k_\perp \Delta r_t \mathrm{d}v_{E\times B}/\mathrm{d}r$ where $\mathrm{d}v_{E\times B}/\mathrm{d}r$ is the radial derivative of the $E \times B$ velocity and Δr_t is the ambient turbulence radial correlation length) must be larger than the ambient turbulence spectrum width $\Delta\omega_t$. Since the velocity shear ranges from 10^6 s^{-1} in RFX to 6×10^6 s^{-1} in T2R and typical values in RFX ($k_\perp \sim 10$ m^{-1}, $\Delta r_t \sim 0.01$ m, $\Delta\omega_t \sim 10^5$ rad/s) and T2R ($k_\perp \sim 20$ m^{-1}, $\Delta r_t \sim 0.005$ m, $\Delta\omega_t \sim 3 \times 10^5$ rad/s), it has shown that at the location of the maximum flux, both velocity shear have values close to those required for turbulence suppression or reduction [6,16].

A proof of this marginal criticality has been offered by the effect of the edge biasing experiment in RFX, where it has been observed that a doubling of the velocity shear has lowered the particle flux down to 30% of the value in standard conditions [8].

An important feature observed in both experiments and common to other fusion devices, is that time resolved analysis of particle fluxes as well as of density and potential fluctuations reveal the occurrence of bursts. These bursts, that account for less than 20% of the fluctuating power, carry up to 50% of the total particle transport in RFX [18] and have similar features in T2R. The relevant contribution of these events has motivated a statistical analysis of the fluctuations at the different spatial scales. It has been proved that in the range of frequencies relevant for the particle transport the probability distribution function (PDF) tends to develop non-gaussian tails at the shorter time scales.

Departure from self-similarity of the PDF is called intermittency. Intermittent events, defined as those events in the non-gaussian tails, have been identified at all scales by a wavelet analysis [19]. It has been noticed that intermittency tends to become more pronounced moving towards the wall [11,13]. This effect, which has a remarkable analogy with ordinary fluids [11], proves that the boundary condition provided by the material wall in fusion devices plays an important role in plasma turbulence features and then in transport mechanisms at the edge. These events tend to cluster during relaxation processes, i.e. during highly non-linear coupling phase for internal tearing modes [13,19].

Focusing the analysis on the scales relevant for transport, the spatial structure of the event has been reconstructed by a frozen turbulence hypothesis from their time behavior [20]. In Fig. 3 an example of a $E \times B$ velocity structure derived from potential measurements in RFX is shown. From the 2-D reconstruction, the structures result to have radial and toroidal extension of

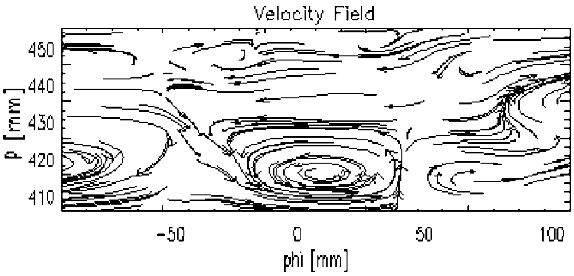


Fig. 3. Reconstruction of the electrostatic structure corresponding to an intermittent event.

the order of 5 and 50 cm approximately. A similar analysis on T2R based on the radial correlation length, has proved that typical extension of the structures is of the order of 20 cm toroidally and 1–2 cm radially.

In order to describe the average transport properties and their dependence on mean plasma parameters, an experimental diffusion coefficient D can be defined as the ratio between the experimental anomalous flux and the local density gradient. It has been observed that this value is close to that predicted by a Bohm estimate D_B ($D_B = T/16B$). The lower edge density operation in T2R has allowed the D coefficient to be compared with the Bohm value in a wider range of plasma parameters. In Fig. 4 the experimental anomalous value is shown as a function of the Bohm value. The graph contains values from T2 [13], T2R [5], and RFX in H [6], He [21], and during edge biasing [8]. The data show that the agreement is fairly good at the higher values and within a 50% error bar also at the lower values.

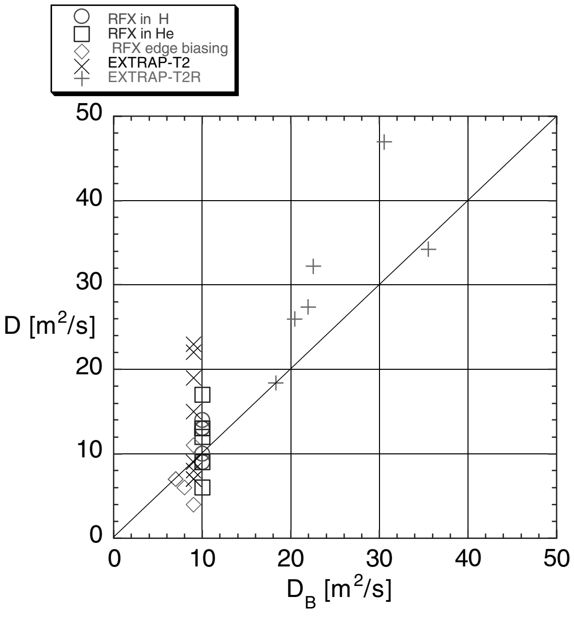


Fig. 4. D experimental versus D Bohm.

4. Conclusion

An extensive analysis of anomalous particle transport driven by electrostatic turbulence in T2R and RFX has shown remarkable similarities and has allowed to carry out this study in a wide range of edge plasma parameters including $E \times B$ velocity and velocity shear. This study has also led to a new scenario for anomalous transport in RFP's, showing that velocity shear has values close to that required for turbulence suppression and that a substantial fraction of the flux is carried by intermittent events. These events cluster during non-linear coupling of tearing modes resonating in the plasma core and increase in number towards the first wall. The MHD activity reduction during PPCD is expected to reduce the occurrence of these processes so that this technique can be usefully combined with the control of plasma velocity value and shear at the edge by edge biasing. The two methods (PPCD and edge biasing) have demonstrated the proof of principle of transport reduction, but they cannot be proposed as viable techniques for the intrinsic limitations, transient effect and/ or perturbation by intrusive objects, as efficient methods for devices operating at larger currents and longer pulses, so that future reserch will be addressed to the quest of new non-intrusive techniques [22].

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