Transport and fluctuation studies on RFX

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Abstract The paper highlights the progress made in the modelling and understanding of the mechanisms underlying particle and energy transport in the RFP. A transport analysis has been performed on the perturbed transport coefficients for pellets of different characteristics launched both in standard RFP plasmas and in combination with pulsed poloidal current drive, this latter scenario potentially allowing an efficient fuelling and a good energy confinement. The study has confirmed the importance of large-scale MHD modes in determining the transport properties in the RFP core. As far as confinement in the edge is concerned, the analysis has been focussed on the role played by burst events on the electrostatic particle flux and to the 'intermittent events'. The intermittent events cluster during relaxation processes and such behaviour is more evident close to the magnetic reversal surface. This result confirms an interplay between the small scale edge turbulence and the large scale relaxation events driven by core-resonant tearing modes.

1 Introduction

On the RFX reversed field pinch different transport mechanisms govern the centre and the edge of the plasma [1]. Core transport is driven by parallel transport in a stochastic magnetic field [2], giving rise to an outward directed particle convection velocity [3]. At the edge, roughly corresponding to the region outside the magnetic toroidal field reversal surface (where q = 0), electrostatic fluctuations are an important loss channel [4], but more than 50% of the power losses have been associated to localised plasma-wall interaction due to the non-axisymmetric magnetic perturbations caused by locked modes [5,6]. In the edge region the presence of a strong **E**×**B** flow velocity shear gives an important contribution to the decorrelation of the turbulence and, together with the existence of good magnetic surfaces, to the creation of a transport barrier [7]. Indeed in standard pulses such barrier accounts for most of the global confinement.

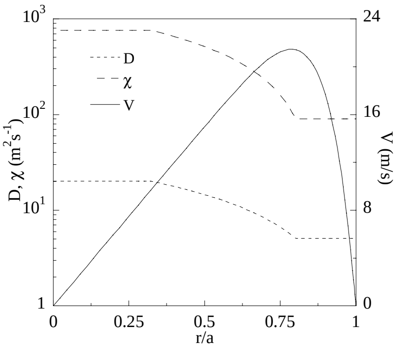

FIG. 1. Empirical transport coefficient profiles.

Typical profiles of transport coefficients that fit the experimental data are shown in fig.1. As for the region inside the reversal surface, the magnetic turbulence causing the magnetic field stochastisation is due to a wide spectrum of m=1, n = 7-15 modes resonating inside the q = 0 surface (a regime dubbed multiple helicity or MH). The transport coefficients in such region are consistent with a magnetic fluctuation amplitude of the order of 1-1.4 %. This is in agreement with the amplitude of the modes deduced from external measurements shown in fig. 2, with the caveat that the value given is a lower estimate, since it accounts only for the amplitude of each mode at the resonance surface and not

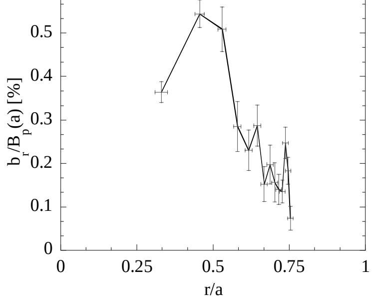

FIG. 2 b_r perturbation (from external measurements extrapolated to resonance radius of each mode).

for the global amplitude due to the full spectrum. Techniques to improve confinement have been developed. The amelioration of the quality of the magnetic configuration can be achieved by either applying a pulsed poloidal current drive [8] (a technique dubbed PPCD) or by a spontaneous transition to an MHD spectrum dominated by a single, low n, m=1 mode (a regime dubbed QSH for quasi single helicity [9]). Both the PPCD and the QSH state have beneficial effects also on edge confinement, since they entail a smaller localised perturbation of the magnetic surfaces compared to the normal MH regimes. This results in a more uniform plasma-wall interaction and in a reduction of direct parallel losses along field lines intercepting the vessel. In the following we present the most recent progress made in the modelling and understanding of the above mechanisms underlying particle and energy transport. The main subjects are perturbative transport studies by pellet injection and the analysis of intermittency processes in relation to edge particle transport.

2 Particle and energy transport analysis of pellet fuelled discharges

A perturbed transport study [10] has been performed launching hydrogen pellets both in standard plasmas and in combination with PPCD. The pellets ablate completely in the plasma: faster pellets (v_p=400÷500 m/s) reach the centre producing a transient peaking of the density profile, whereas the slower ones (v_p=100÷200 m/s) suffer large deflections and deposit most of their material at r/a>0.5. In both cases, for each pellet the volume average density is roughly doubled, whereas the central temperature is reduced by 30÷40%. In standard discharges fast pellets reaching the plasma centre trigger a dynamo relaxation event (DRE) that enhances the global transport and prevents the temperature recovery after injection. An example is given in fig.3 (pulse 8066), where the particle diffusion coefficient in the simulation code has to be quickly increased by a large factor in order to reproduce the experimental data. However, in a few cases when the plasma is spontaneously evolving towards a QSH state, the DRE does not occur. Also, no degradation of confinement is seen for pellets injected at low velocity. This is shown in fig.3 (shot 8092) where a low speed pellet misses the centre and completely ablates at r/a > 0.7. Despite a large density increase, no DRE is excited and the confinement remains constant for several ms. Actually a transient decrease in the edge χ is seen.

The detailed behaviour observed with PPCD in RFX is described in [11]. Here we concentrate on the effect of a pellet during PPCD, where we find that two cases are possible. If the pellet is injected in the early phase of the PPCD when its mode stabilising effect is strong enough, a synergy between pellet injection and PPCD is seen: the plasma enhanced confinement is maintained leading to an increase of the global β. This is shown in fig. 4 (pulse 8059). In this case PPCD starts at 32 ms, at the same time as the pellet enters the plasma. Both D and χ decrease, as in a successful PPCD experiments unperturbed by pellets. On the other hand, for pellet injected at later times, the PPCD is less effective and the transport reduction is lost (fig. 4 pulse 8040, PPCD starts at 32 ms, pellet enters the plasma at 36 ms). Hence the

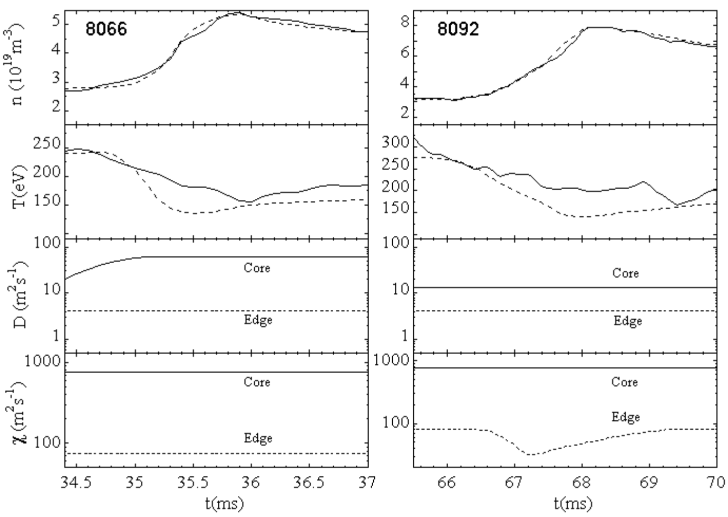

FIG.3: Experimental (solid) and simulated (dashed) central density and temperature, simulated central and edge D and χ for shot 8066 and 8092.

main trends of the transport modification are well established: a pellet penetrating up to the centre degrades both the energy and particle confinement; this does not occur when the pellet is ablated at the plasma periphery or when the plasma is in an improved confinement regime. These results show that the presence of a relatively hot core is crucial for the achievement of a good confinement in the RFP via the mitigation of the MHD activity. Moreover, the robustness of improved confinement regimes is confirmed by their resiliency to large density and temperature perturbations. For the transport coefficients obtained from the simulations, the χ/D ratio is 10÷20. Hence, although the absolute values are consistent with transport due to magnetic field lines stochasticity, the χ/D ratio is less than predicted by the collisionless Rechester and Rosenbluth model [2], which would simply predict $\chi/D = (m_e/m_i)^{1/2} \approx 40$. Another partial inconsistency with the model is seen in the value of the outward convective velocity, which in some of the discharges perturbed by pellets is lower by a factor of ≈2 than the value found for standard discharges. On the other hand, a transport study of the main impurities validated against measurements of their emission, also results in a radial profile of the particle convective velocity different from that of the main gas. In particular in the region r/a ~0.8÷1 the impurities are subject to an inward pinch, which suggests that other mechanisms could be at work and further investigations are called for in order to reach a fully consistent explanation of the transport phenomena.

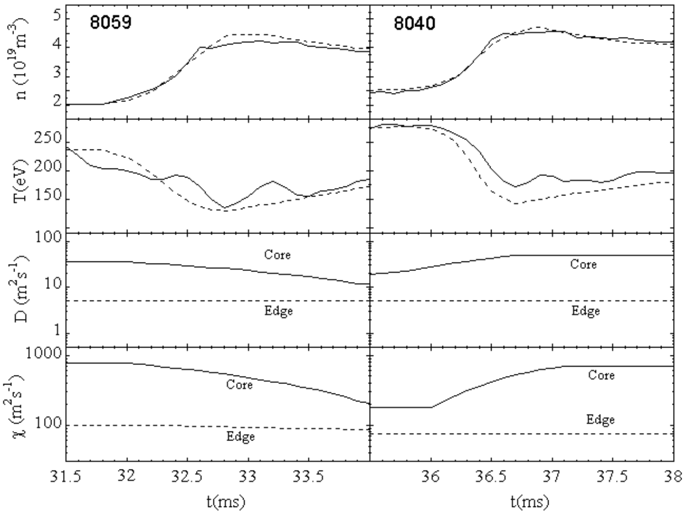

FIG.4: Same as Figure 3 for shot 8059 and 8040.

3 Edge Physics and Transport Processes investigation

An issue that has received a great deal of attention in recent years is the appropriateness of diffusive models for the description of transport processes in fusion plasmas. Indeed, it is now well known that transport is not continuous, but takes place in bursts [12]. In RFX advanced analysis techniques have been developed and applied to edge probe measurements, which have the necessary time resolution, in order to elucidate this issue. As already found in other magnetic confinement devices, it has been observed that the edge particle flux, which is driven by the electrostatic turbulence, exhibits intense bursts, which account for more than 50% of the losses [13]. The study of the probability distribution function (PDF) of electrostatic and magnetic turbulence measured in the edge region by means of insertable probes has shown the presence of intermittency [14,15], defined as the violation of self-similarity when going from large to small time scales [16]. The fluctuations at a given scale are obtained using the wavelet transform as a scale-selection tool [14]. The general behaviour found is that, while the PDFs for large scale fluctuations exhibit gaussian features, at small scales they develop strong tails. These tails are due to strong events which occur more frequently than in the gaussian case. Such events have been ascribed to turbulent structures that are convected toroidally by the **E**×**B** plasma rotation. An algorithm originally developed for the detection of structures in fluid turbulence [17,18] has been applied to floating potential and ion saturation current measurements, in order to gain information about the features of the structures giving rise to intermittency. The algorithm, based on a quantity called Local Intermittency Measure (LIM) [17], signals the time instant at which a turbulent structure

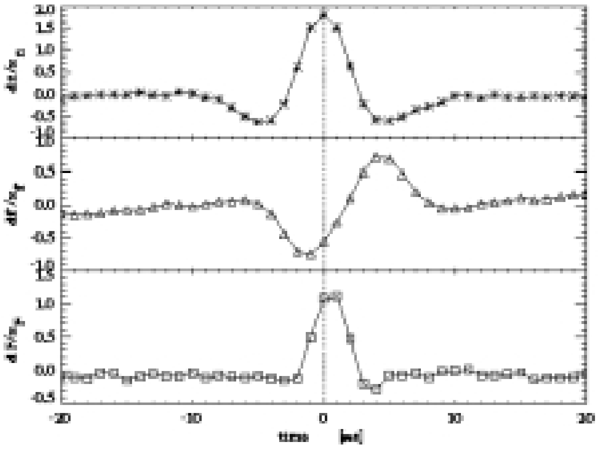

FIG.5: Density intermittent structure (top), corresponding plasma potential (middle) and resulting outward particle flux event (bottom).

passes by the probe. By taking a time window around this instant, a realisation of the "typical" structure is obtained. By averaging these realisations (a procedure usually called conditional averaging) the typical structure is reconstructed. This is the procedure that has been applied on the RFX probe data, with the further provision of separating positive (hills) and negative (wells) structures prior to averaging, so as to avoid a cancellation effect. An example of the resulting average structures, both for electron density and plasma potential, are shown in fig.5. The data used for the analysis have been obtained using a triple probe. The potential and density structures are found to have a well defined phase relationship, so that they give rise to flux events preferentially outward directed. A relevant fraction of the total particle flux driven by the electrostatic turbulence can be ascribed to the intermittent structures.

Structures that can be visualised as potential wells or hills are associated to a local vortex-like **E**×**B** motion taking place in the radial-toroidal plane. Although structures with both directions of the vortical motion are detected, a preference for one direction or the other is found, according to the radial position. The preferred rotation direction of the eddies is found to be related to the local radial profile of the average **E**×**B** plasma motion [19]. This is shown in fig.6. In the top frame, the average **E**×**B** velocity profile measured in the RFX edge is shown, with the typical double velocity shear layer [20]. The bottom frame shows the fraction of positive and negative potential structures. The correlation between the sign of the structures and the sign of the velocity shear is clearly seen. In fact, the so-called prograde structures are the prevalent ones, i.e. those which are favoured by the average velocity profile [21]. Such behaviour is indeed predicted by simulations of Scrape Off Layer turbulence [22].

An analysis of the times of occurrence of the intermittent structures on the floating potential signal has shown that they tend to appear during DREs. This is shown in fig.7, where the top frame shows the reversal parameter $F \equiv B_\phi(a)/\langle B_\phi \rangle$ and the bottom frame displays a floating potential signal measured at the edge, with vertical lines marking the occurrence of intermittent structures at the scale $\tau = 5$ μs. It is clear that the structures tend to cluster at the time of occurrence of the DREs (identified by the crashes of F). This suggests the presence of a link between large scale MHD modes, responsible for core transport and associated to the DREs, and small scale electrostatic fluctuations responsible for edge particle transport [23].

The possibility that the intermittent structures are manifestations of the avalanches predicted by the Self Organised Criticality (SOC) paradigm has been tested by studying the probability distribution of the times between subsequent bursts (waiting times), and comparing the results with numerical simulations of different SOC models. This analysis

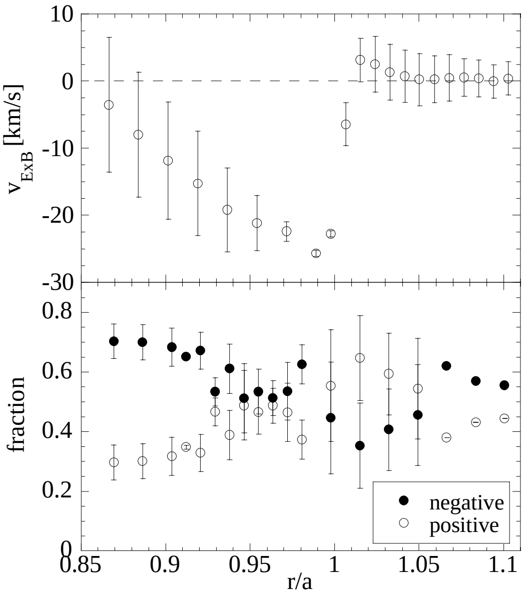

*FIG.6: Radial profile of the **E**×**B** velocity in the outer region (top) and fraction of positive and negative potential structures (bottom).*

revealed that laminar times between bursts of density fluctuations, independently measured by microwave reflectometry and electrostatic probes, show a power law distribution, typical of a system with a strong internal interaction [24]. On the contrary, standard SOC models show an exponential decay in the waiting time distribution, which is characteristic of a random system without memory. This result, together with the self-similarity violation already mentioned, is in contrast with the predictions of the SOC paradigm. So it is concluded that there is no experimental evidence of avalanche-like processes in RFP plasmas [13].

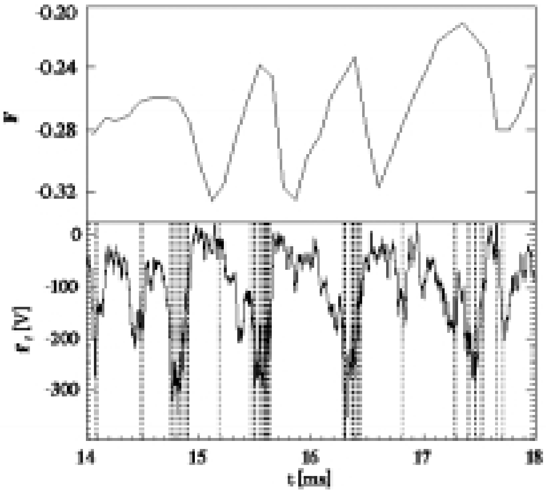

FIG. 7: F waveform (top), edge floating potential (bottom) and times of intermittent structures (vertical lines).

4 Summary

The perturbative transport analysis of pulses with pellet injection has shown the importance of controlling large-scale MHD modes in order to maintain good transport properties in the RFP core. The existence and robustness of improved confinement modes has also been proven. On the other hand, the role played by intermittent structures in the edge transport driven by electrostatic turbulence has also been shown to be important. Furthermore, a link between large-scale MHD modes, responsible for the dynamo and for the transport in the core, and small-scale electrostatic fluctuations responsible for particle transport in the region outside the reversal surface has been established, while the applicability of the SOC paradigm has been ruled out. These observations suggest that large scale resistive MHD modes might have an influence on transport in all regions of the device. A natural consequence of such results is the need to develop new techniques for the active control of MHD modes in order to fully explore the physics of the confinement in the RFP.

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