PARTICLE AND ENERGY TRANSPORT IN THE RFX EXPERIMENT

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Abstract

The particle and energy transport mechanisms have been investigated in RFX. In the core the particle diffusivity and thermal conductivity are consistent with a stochastic magnetic field model. At the edge particle transport is mainly driven by electrostatic fluctuations, whereas radiation, electrostatic and magnetic turbulence account only for 50% of the total energy losses.

1. INTRODUCTION

Transport in a reversed field pinch (RFP) configuration is anomalous and fluctuation driven as confirmed by measurements in different RFP experiments [1]. In order to investigate the mechanisms underlying the particle and energy transport in the RFX experiment new measurements of electron density and temperature profiles and of their time evolution have been performed in various plasma conditions with a set of dedicated diagnostics, including a 13-chord mid-infrared CO_2 interferometer, a 20-points Thomson scattering system, edge probes, a bolometric tomographic system and a multifoil soft x-ray spectrometer which allows highly time resolved electron temperature measurements. Electrostatic fluctuations have been measured at the edge by triple Langmuir probes and the corresponding energy and particle flux have been derived. The energy flux driven by magnetic fluctuations has been measured at the edge by a pyrobolometer combined with magnetic coils. In this paper particle and energy balance in two regions, the core and the edge, separated by the toroidal field reversal surface at r/a~0.85-0.9, will be addressed.

2. TRANSPORT IN THE CORE PLASMA

Density profiles are found to be flat or hollow in the core with whole the gradient appearing at the edge in a 2÷4 cm thick layer [2]. The shape of the profile depends only on the *I/N* parameter (defined as the ratio of plasma current over line density), varying from flat or slightly peaked at high *I/N* to clearly hollow at low *I/N*, as shown in Fig. 1. The systematic existence of stationary hollow density profiles implies the presence of an outward directed fluid velocity in the core. A one dimensional particle transport code has been used [2] to simulate the density profiles and the neutral source from the wall and to derive the radial profiles of the diffusion coefficient D and of the convective velocity. The analysis indicates that the particle diffusivity *D* in the core is of the order of 10 m^2s^{-1}, consistent with the value expected from a stochastic diffusion model based on the quasi linear estimate of the magnetic field line diffusivity D_m [3]. Indeed a wide stochastic region is expected in the core of RFX due to the overlapping of the magnetic islands produced by a wide spectrum of MHD instabilities with high amplitude (b/B>1%) and with poloidal periodicity m=1 and toroidal periodicity n in the range 7-20. These instabilities correspond to internally resonant resistive MHD modes, related to dynamo process [4] and are locked to the wall giving rise to a stationary magnetic disturbance localized in a toroidally restricted area. The picture for core particle transport is consistent with what is found for energy transport. A typical electron temperature profile at I≈0.65 MA standard conditions is shown in Fig. 2. As for the density, the largest gradient appears at the edge, outside the reversal surface, thus indicating that most of the energy confinement in RFX takes place there. Moving from this pedestal region inward, the temperature profile in the core is characterized by a region where a second gradient, $\nabla T_{e,core}$ is present, as also shown in Fig. 2. The magnitude of this gradient and the radial extension over which it is present have been found to depend on electron density and on plasma current, with a trend for the profile to peak at low n_e and high I [5]. This behaviour has been summarized in a trend with the magnetic Lundquist number S: in particular as S increases, more peaked profiles are observed, with the region spanned by the core gradient extending further inward [5].

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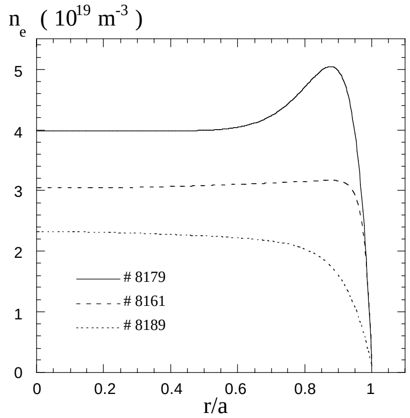

FIG. 1. Density profile for three 800

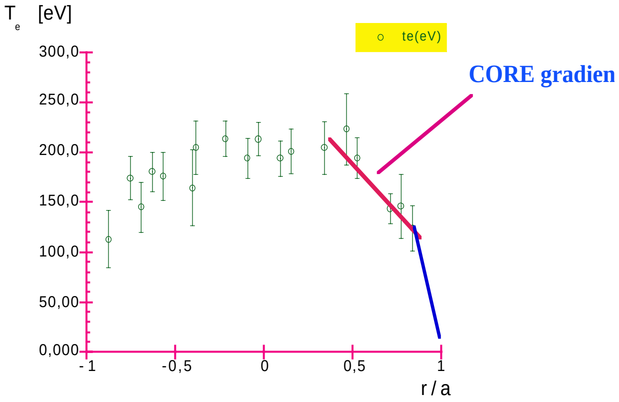

FIG. 2 Temperature profile with I≈0.65 MA.

Starting from these measurements an effective thermal conductivity χ_{eff} has been estimated as $\chi_{eff}(r) = -\frac{q_\perp(r)}{n_e(r)\nabla T_e(r)}$ where the energy flux has been derived from the local power balance as $\nabla \cdot q_\perp(r) = \Omega(r) - \varepsilon(r)$, where ε(r) is the experimental total radiation emissivity and *Ω(r)* the ohmic power deposition profile given by *E(r) j(r)*; the electric field is modelled via a local Ohm's law with Spitzer's resistivity and the current density profile is reconstructed with external magnetic measurements. It must be noticed that in standard discharges radiation losses account for less than 20% of the total losses and most of the radiation is lost in the outer region [6]. The resulting effective core conductivity is of the order of 400 ± 200 m^2s^{-1}, a value consistent with that expected in the quasi-linear estimate [3] corrected for collisional effects [7]. In Fig. 3 the particle diffusivity and the thermal conductivity for plasma current ~800kA are shown. It is interesting to note that the ratio χ_{eff}/D is of the order of 40 i.e approximately the square root of the ion and electron mass ratio, in agreement with a stochastic model applied to a hydrogen plasma with T_e=T_i.

The role played by magnetic fluctuations in driving core energy transport finds a striking confirmation when the behaviour of the core χ_{eff} is studied As a function of S [5]. As a consequence of the previously discussed trend of $\nabla T_{e,core}$ a function of *S*, also the average value of χ_{eff} in the core is found to decrease with *S*. Since magnetic fluctuations decrease with *S*, as predicted by numerical simulations [8] and measured in various RFPs [9-10-11], the observed trend of χ_{eff} with *S* offers a direct experimental confirmation of the theory [3], indicating that an improved confinement, with the onset of core transport barrier, is measured when magnetic fluctuations decrease. The crucial role played by dynamo related magnetic fluctuations in the core transport has been confirmed also by a substantial modification of the core thermal diffusivity observed in regimes where magnetic fluctuations are reduced. An example comes from Pulsed Poloidal Current Drive (PPCD) experiments, where a poloidal current is externally driven thus alleviating the resort to spontaneous dynamo [12-13]. One of the most clear effects of this technique is a substantial reduction of magnetic fluctuations, which is associated with a strong peaking of the T_e profile and a decrease of χ_{eff} in the core, where χ_{eff} becomes comparable to its absolute minimum value reached at the edge. A noticeable improvement of confinement is obtained in these conditions. As a final point it is worth mentioning that a recent interpretation [14] opens new perspectives for the understanding of core transport in the RFP. It has been in fact observed that in RFX, as in other RFPs, the plasma, under certain spontaneous or driven (like PPCD) conditions, moves from a state characterized by a broad toroidal spectrum to a quasi single helicity state, characterized by a toroidal mode spectrum where one m=1, n=n_0 ~7-8 mode is dominating over the others. This single helicity situation corresponds to one branch of a bifurcated state where confinement is improved; this fits theoretical expectation [15] since a turbulent dynamo is replaced by a laminar process, thus recovering a situation where good flux surfaces are present and a much narrower stochastic region is expected.

3. TRANSPORT IN THE EDGE PLASMA

Electrostatic and magnetic fluctuations have been measured at the edge by insertable probes in low current discharges (I~300kA) giving normalized values for density δn/n~0.5-1, electron

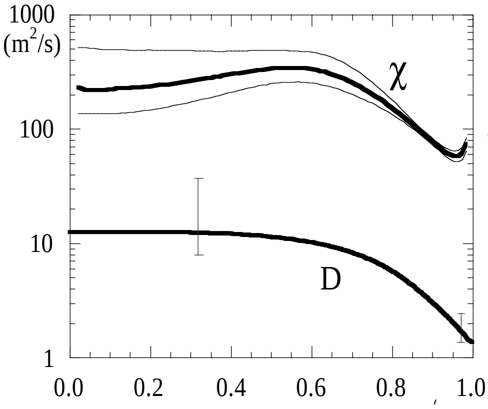

FIG. 3 Thermal conductivity and particle diffusivity profile with I≈800kA.

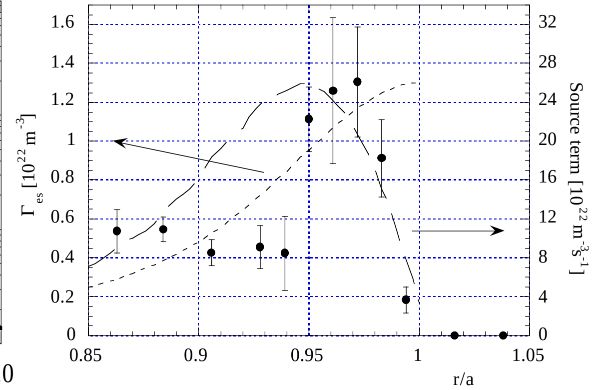

FIG. 4 Electrostatic Particle flux and neutral source. Lines results of a 1-D code.

temperature $\delta T_e/T_e$~ 0.4-0.5, plasma potential $e\delta V_p/T_e$ ~1-2 and radial component of the magnetic field b_r/B~0.5%. The electrostatic turbulence has broad band features with average wavevector <k> and frequency <f> comparable to the respective spectral widths.

Electron temperature and density profiles measured by insertable Langmuir probes confirm that most of the plasma pressure gradient is concentrated at the edge. Particle and energy fluxes driven by electrostatic turbulence have been measured by triple probes. The particle flux Γ has a maximum around r/a=0.97, as shown in Fig. 4, and the radial behaviour has been related to the neutral source at the edge. By comparing in stationary conditions the maximum of the particle flux with the hydrogen influx measured on a chord viewing the edge plasma in the outer equatorial region, it has been found that most of the particle transport is accounted for by electrostatic turbulence [16]. The particle diffusion coefficient D derived assuming a Fick's diffusion law, i.e. $\Gamma = -D\nabla n$, is of the order of 10 m^2s^{-1}, consistent with Bohm like diffusion. This value of D is consistent with the density profile analysis equating the source and the sink rates from collisional ionisation and total (radiative plus three-bodies) recombination to the diffusion rate. As shown in Fig. 5, the resulting D at the edge shows a favourable dependence with increasing density. A double spontaneous **E**x**B** velocity shear takes place at the edge [17]. Change in plasma rotation with radius has been confirmed by impurity rotation measured by Doppler shift of line emission [18] and by plasma flow measured by an array of Langmuir probes [19]. This velocity shear is of the order of $10^6 s^{-1}$ and results close [18] to that required to decorrelate electrostatic turbulence in RFX. Indeed the shearing frequency ω_s, which can be estimated as $\omega_s = \langle k\rangle\Delta\, dv_{ExB}/dr$, where dv_{ExB}/dr is the radial derivative of the **E**×**B** velocity, in the region of high velocity shear (r/a = 0.94), results $\omega_s = (1.6\pm0.9)\times10^5$ rad/s, i.e. close to the ambient turbulence spectral width $\Delta\omega_t = (3.3\pm0.3)\times10^5$ rad/s. The ω_s value has been derived from the experimental data of the quantities entering in the definition: $dv_{ExB}/dr=(1.1\pm0.4)\times10^6\ s^{-1}$, $\langle k\rangle=12\pm2\ m^{-1}$ and the radial correlation $\Delta= 12\pm5$ mm has been measured by reflectometer. Indeed a reduction of the particle diffusion coefficient is observed in the region where the shear is maximum and the analysis of the electrostatic fluctuations indicates that this shear influences their amplitude and coherence [20]. The energy transport at the edge has been also analysed. Radiation which is maximum at the edge has been taken into account and the radial energy fluxes due to electrostatic and magnetic fluctuations have been measured. It has been found that the electron energy flux driven by electrostatic fluctuations Q_e shown in Fig. 6, is mostly convective and < 15% of the total power losses at low current. By assuming an equal contribution for ions the electrostatic contribution is less than 30% of the total transport losses at the edge [21]. The magnetic contribution has been derived by correlating the energy flux parallel to the magnetic field with the radial component of the magnetic field $q_r=\langle\tilde{q}_{//}\,\tilde{b}_r\rangle$. It has been found that at low plasma current this contribution is negligible at the edge due to a low coherence between magnetic fluctuations and energy flux fluctuations as observed in MST [22].

The small contribution due to magnetic activity at the edge is confirmed by the negligible effect on the thermal conductivity observed during PPCD. Even taking into account the radiation

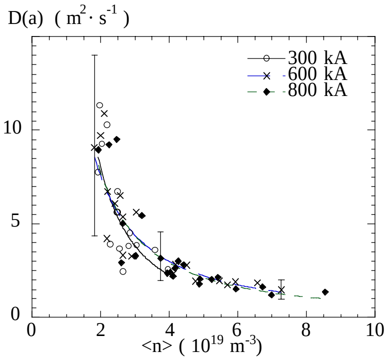

FIG. 5 Particle diffusivity at the edge vs plasma density.

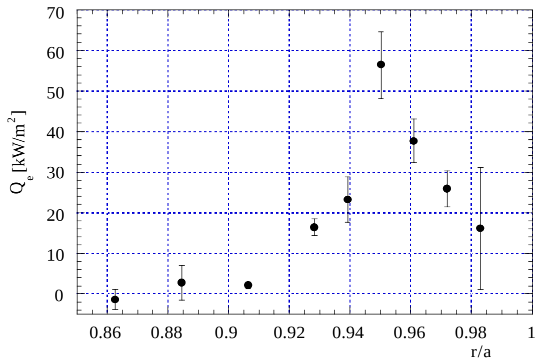

FIG.6Electrostatic energy flux.

losses, which are typically of the order of 10-20% of the total losses, almost 50% of the power balance is missing at the edge. Candidates to explain this discrepancy are the ion losses, the electrostatic contribution of non-thermal tail in the electron distribution and the effect of the locked mode.

4. CONCLUSIONS

Two distinct confinement regions have been identified in RFX: a core region and an edge region. The core region is controlled by dynamo related MHD instabilities which originate a wide stochastic region. Particle and energy transport coefficients are in agreement with a stochastic model. In the edge region particle transport is mainly driven by electrostatic fluctuations whereas the energy transport is still under investigation since only 50% can be accounted for by electrostatic fluctuations, magnetic turbulence and radiation. Energy confinement in the core has been improved at higher plasma currents or in regimes of reduced magnetic fluctuations obtained by PPCD or through transition to single helicity state. At the edge it has been found that electrostatic fluctuations are sensitive to the shear of the radial electric field, opening the possibility to achieve regimes of improved particle confinement by enhancing the plasma rotation.

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