Transport Mechanisms and Enhanced Confinement Studies in RFX

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Abstract: The results of an extensive study on transport mechanisms and on improved confinement scenarios in RFX are reported. The scaling of the thermal conductivity in the core with the Lundquist number indicates that the magnetic field in this region is not fully stochastic, as proved by the existence of thermal barriers observed in Single Helicity configurations. The electrostatic transport at the edge has been proved to depend on the highly sheared ExB flow which has been interpreted by fluid and Monte Carlo models. Regimes of improved confinement have been obtained in the core by Poloidal Current Drive techniques and the electrostatic transport has been reduced at the edge by biasing experiments. A radiation mantle by impurity seeding has been found to successfully reduce the local plasma wall interaction without significantly deteriorating the plasma performance.

Introduction

The improved knowledge of the MHD dynamics and the active means developed to influence the behaviour of the modes, namely the Rotating Toroidal Field Modulation (RTFM) technique [1] have allowed to access high current regimes in the Reversed Field Pinch (RFP) experiment RFX (R=2m, a=0.46 m). In particular the capability of distributing over the torus the severe power outfluxes associated with the surface deformations caused by the mode phase locking, has led to the suppression of carbon blooming phenomena, to an efficient plasma density control and therefore to reproducible discharges up to plasma currents of the order of 1MA. It has therefore become possible to extend to high plasma current regimes the scaling studies on transport and radiation losses as well as to verify the applicability of the enhanced confinement scenarios found at lower currents. At the same time, significant improvements of the diagnostic potential have allowed much deeper insight into the RFP physics. Soft X-ray tomographic reconstruction has revealed a much more structured core than previously believed while the upgrading of the Thomson scattering system to 20 spatial points has yielded a reliable core heat diffusivity evaluation. New active techniques aimed at improving energy and particle confinement have been applied. In particular oscillating poloidal current drive (OPCD) and edge biasing have been used to improve the core and edge confinement respectively, while radiation mantle and locked mode rotation have been used to minimize the effects of plasma wall interaction.

Magnetic fluctuations, transport and enhanced core confinement by OPCD

The core region has been investigated in regimes of Multi-Helicity (MH) and Quasi Single-Helicity (QSH) configuration [1] and in a wide range of experimental parameters (plasma current from 0.2 to 1.1 MA, electron density from 1 to 10×10^{19} m^{-3}) corresponding to different regimes of Lundquist number S, which ranged from 2×10^{5} to 4×10^{6}. The electron heat diffusivity in the core χ_e has been found to decrease with S as $S^{-0.77\pm0.14}$ as shown in fig.1, while its radial profile decreases towards the reversal surface. This result indicates that the scaling of χ_e with S in the plasma core is more favourable than the scaling of the magnetic fluctuations. Indeed the normalized magnetic fluctuations show a weak dependence with the Lundquist number as $b/B \sim S^{-0.16\pm0.02}$ in standard discharges [2] as shown in fig.2. The S number was estimated by using a Spitzer's expression for the plasma resistivity with the experimental values of electron temperature and Z_{eff} from Bremsstrahlung emission. It is worth noting that the experimental scaling is consistent with a 3-D numerical simulation of visco-resistive MHD instabilities [3]. The stronger dependence of the thermal conductivity on S suggests that, in the core, plasma regions with fully stochastic magnetic field could alternate with regions with better energy confinement. An indication in favour of that is the fact that operating in QSH configuration, i.e. with a reduced number of MHD modes, steeper temperature gradients have been measured and regions of better confinement associated to internal thermal barriers have been identified [4].

The OPCD technique consists in driving a continuous oscillation of the poloidal electric field in the outer region of the plasma; it is basically an extension of the Pulsed Poloidal Current Drive (PPCD) which has proved to be a successful technique to improve the energy confinement [5]. The oscillating poloidal voltage for OPCD operation in RFX is obtained by modulating the current in the toroidal field coils by the same high power switch system used also for the RTFM experiments. The period of the applied oscillation can be varied with a lower limit of 2 ms and an amplitude of a few volts. A series of OPCD experiments has been performed at plasma currents of 0.8÷1 MA. It has been found that, in optimised operating conditions, effects similar to those of PPCD are observed during each of the OPCD phases where the driven poloidal current sums up the current driven by the RFP dynamo. As shown in Fig.3, where the energy of the dynamo modes with n in the interval 10-14 is shown, a reduction of the magnetic fluctuation energy b_φ^2/B^2 of the high n modes (n higher than 9) is observed, accompanied by an increase of the temperature near the axis up to 75%. The energy confinement time and the poloidal beta increase also by ≈50% [6]. During the phases where the direction of the driven current is opposite to that of the dynamo, the high n magnetic fluctuations increase and the central temperature decreases. On a statistical basis, the central temperature during the antidynamo phase of the OPCD is similar to that of standard pulses. Analysing ensemble-averaged data of single-pulse Thomson scattering measurements, it is found that the temperature profile is more peaked during the positive current drive phases of the OPCD, whereas it is flatter and quite similar to that of standard pulses during the antidynamo ones. The change in the T_e profile entails a τ_E enhancement due to a significant decrease of the heat conductivity in the plasma core ($r/a \leq 0.8$). The reduction of heat conductivity is consistent with the reduction of parallel losses along stochastic field lines, as a result of the mitigation of the dynamo modes in a wide region inside the field reversal surface. Successful OPCD experiments have been performed both in MH and QSH pulses, where in the latter cases the amplitude of the innermost resonating mode is actually seen to increase during the positive current drive phases.

Edge transport and radiation.

It is generally observed in RFX and other RFP experiments that most of the particle flux is driven by electrostatic turbulence [7], while a small fraction of the energy flux is driven by this mechanism. In RFX this last contribution has been estimated to be less than 30% and the energy flux has been found to be mainly convective [8]. A highly sheared ExB flow velocity has been observed at the edge and this flow has been related to the local fluxes driven by the electrostatic turbulence. It is worth noting that, since in RFP experiments the main magnetic field at the edge is in the poloidal direction, the ExB drift is along the toroidal one. The impurity flow has been obtained from the Doppler shift of impurity lines of C III (2296 Å, 5th order), B IV (2822 Å, 4th order) and C V (2271 Å, 5th order) by means of a spectrometer (0.68 m focal length) coupled by an optical combiner to a fast optical multichannel analyzer. The ion spatial distribution and therefore the diamagnetic contribution to the velocity was estimated by a 1-D impurity diffusion model. The resulting ExB flow were in agreement with with the findings of an array of Langmuir probes measuring directly the radial electric field and indicating that the ExB flow was larger than the diamagnetic one at the edge. Typical values of plasma rotation at the edge are around 10-20 km/s while the velocity shear is of the order of 10^5 - 10^6 s^{-1} in the spontaneous layer, a few cm thick, usually observed in standard discharges. This shear was already observed to be marginal regarding turbulence stabilization in RFX. The spontaneous radial electric field E_r observed at the edge has been simulated by a Monte Carlo model [9], which includes losses due to finite ion Larmor radius of hydrogen and impurities. A fluid model has been applied to describe the flow shear deeper inside. In this model the flow velocity, and thus E_r, is determined from the balance between the toroidal momentum lost by the plasma ions, including friction with neutrals and anomalous plasma viscosity, and the torque exerted by the electron return current balancing the ion losses due to Finite Larmor Radius (FLR). The same model was applied to simulate the flow modification induced by edge biasing experiments .

Negative edge biasing experiments have been performed inserting two electrodes into the plasma up to $r/a \approx 0.8$ [10]. Fig. 4 shows an example of plasma waveforms during negative edge biasing with one electrode inserted. The picture illustrates the plasma current, the electrode current and the line-average electron density, which increases by 40%. The density profile was found to become more hollow, showing a peak at $r/a \sim 0.8$ with steeper edge gradients. During edge biasing the core temperature decreased by 30% in the core and that was attributed to the cooling effect of higher density. The impurity contamination has been estimated to come mainly from boron and nitrogen. In fact, while the emissions from C and O roughly follow the density time behaviour, the emissions of B and N increase more rapidly than density. A 0-D model, based on two reservoirs, the plasma and the wall, has been applied to interpret the temporal behaviour of the density and of the H_α signals which remained constant or slightly decreased during negative edge biasing. The best agreement was reached when τ_P changes linearly from 1.2 ms to a value ~35% higher, during the electrode current rise. The radial density profiles have also been interpreted by means of a 1-D particle transport model, which confirmed that the diffusion coefficient at the edge decreases as the electrostatic particle flux. In the frame of this model the experimental results are consistent with a reduction of the transport at the edge without affecting the core transport. The discrepancy between the local decrease of the electrostatic particle flux and the smaller increase in τ_p suggests that another transport mechanism enters the particle balance and this term has been identified with the parallel losses due to the locked modes.

A radiation mantle in the edge generated by neon seeding has been proven to be compatible with the RFX performance and to be effective in reducing the convective power load in high-density discharges, with radiated power fraction of 60 to 70 % and with minor deterioration of global confinement. The radiation mantle is effective in creating an evenly distributed power dissipation region at the edge mitigating the plasma-wall interactions, which in standard discharges are strongly non-axisymmetric, with power densities that locally may exceed 100 MWm^{-2}. Indeed it has been shown that neon injection into high density plasmas ($n_e \geq 7$-8 $10x19m^{-3}$) can decrease the fraction of power lost to the wall by convection, with plasma transport degradation contained within 10- 20 % [11]

Conclusions

The favourable scaling of the thermal conductivity with the Lundquist number and the presence of thermal barriers when the number of MHD modes is reduced, open a new scenario for core confinement in RFP, where regions with good magnetic surfaces could alternate regions were the magnetic field is completely stochastic. Magnetic turbulence has been reduced and improved confinement regimes have been obtained by oscillating poloidal current drive technique and electrostatic transport reduction has been achieved by edge biasing. The setting up of a radiative mantle by impurity seeding, has been proved to have beneficial effects on plasma wall interactions. The combination of this operation with the RTFM technique appears to be promising for further exploration of higher current regimes.

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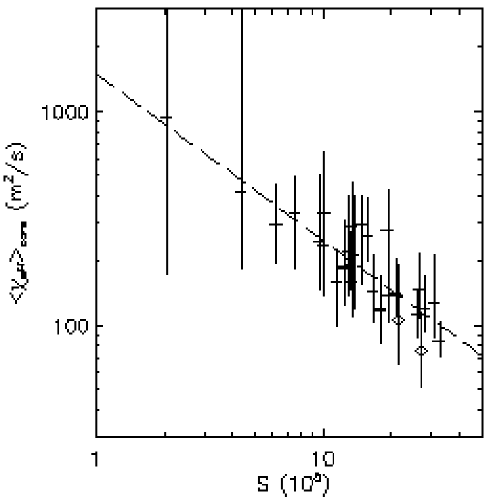

Fig.1 Thermal conductivity scaling with S

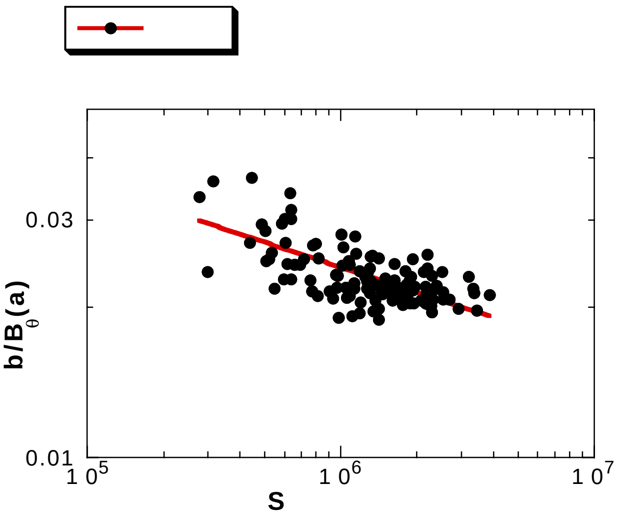

Fig.2 Magnetic fluctuation scaling with S

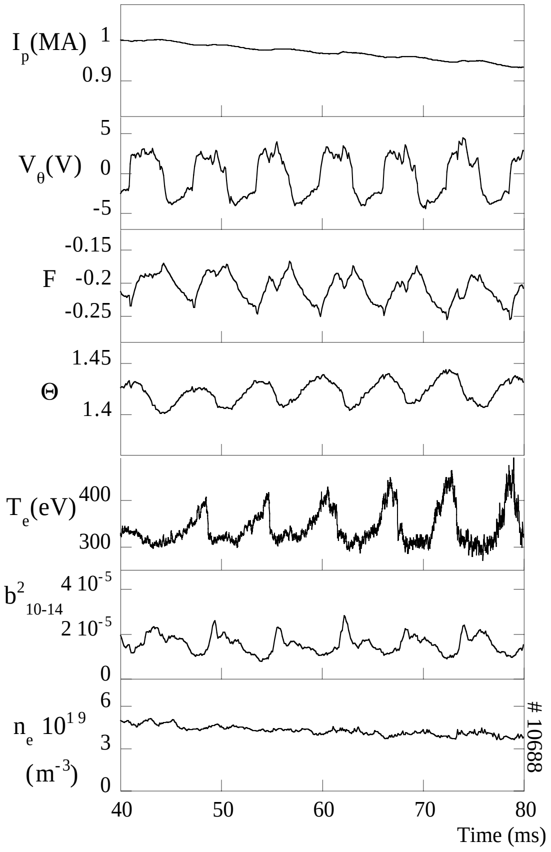

Fig. 3 OPCD waveforms

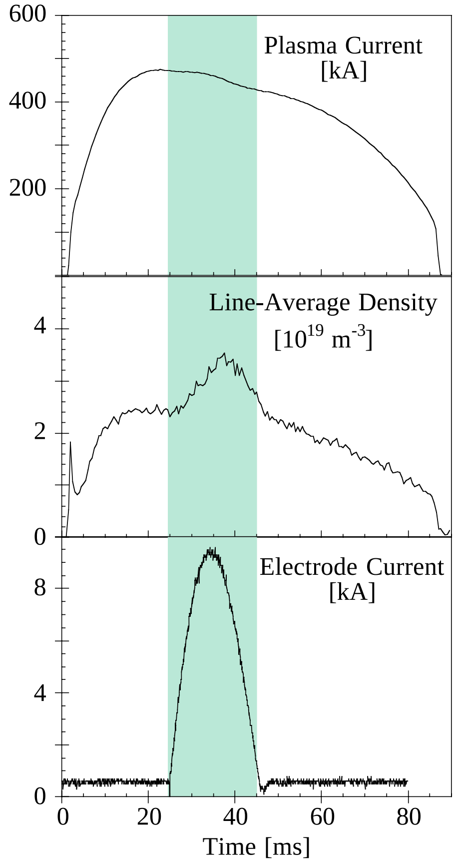

Fig.4 Edge biasing waveforms