Energy transport in RFP enhanced confinement regimes

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In Reversed Field Pinch (RFP) plasmas the dynamo effect, which sustains the magnetic configuration, is produced by the nonlinear interaction of resistive MHD modes resonant inside the toroidal field reversal surface, so that coherent fluctuations of velocity and of magnetic field are generated [1]. In standard discharges this results in a broad n spectrum of m=1 and m=0 modes, which deteriorates confinement in the plasma core. Experimental techniques have been recently investigated to alleviate the need of the dynamo field and mitigate stochasticity, thus improving confinement. Pulsed poloidal current drive (PPCD) has been the most effective and extensively studied method: poloidal currents are inductively driven by pulsing the toroidal field coils [2,3]. This paper presents new measurements from recent PPCDs performed in the RFX experiment [4]. They confirm results reported in [2]: the temporal evolution of the electron temperature (T_e) along a diameter chord, measured by the SXR double filter (DF) technique [5], shows a significant increase during PPCD. In the meantime a small decrease of the electron density (n_e), a marked reduction of the input power and a small variation of the total radiated power are measured. Furthermore, enhanced confinement (EC) regimes like PPCD have recently been found associated to a transition toward a quasi single helicity (QSH) state. A wide spectrum of modes was generally considered intrinsic to the RFP configuration, however an individual m=1 helicity is theoretically sufficient to drive the poloidal current necessary to sustain the toroidal magnetic flux [6]. Temporary and stationary transitions to such QSH states have been experimental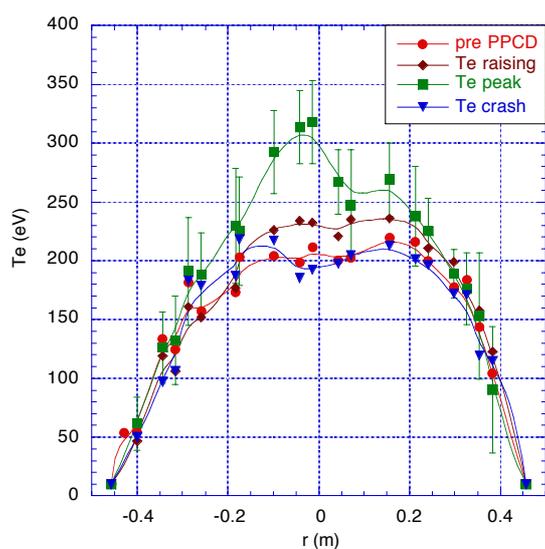ly observed in RFP machines [7]. In RFX they can be described in detail mainly by the Thomson scattering (TS) diagnostic and by the tomographic soft x-ray imaging of the plasma, which clearly shows the growth of an hot island at the resonance radius of the dominant m=1 mode [8].

Time evolution of T_e and n_e profiles. A multipoint Thomson scattering diagnostic has been used to characterize the shape of T_e and n_e profiles during various EC regimes such as PPCD and transitions to QSH states. The TS diagnostic measures the electron temperature (T_e) profile along an equatorial plane from r/a = -0.94 to r/a = 0.84, with 2.4 cm spatial resolution [9]. The diagnostic has been upgraded from 10 to 20 positions: the increased spatial resolution allows to
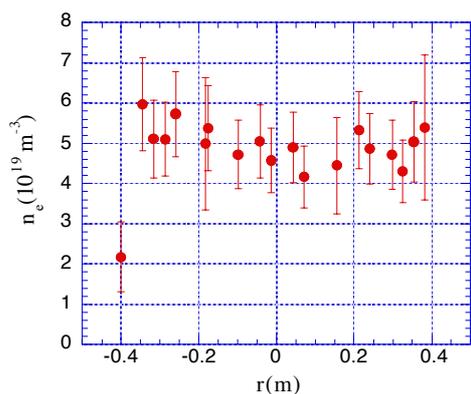

Fig.1 Time evolution of T_e profiles during PPCD

Fig.2 Example of n_e profile during PPCD

recognise with higher detail local features previously unseen. It has been also calibrated against a known light source scanning all positions so that it provides measurements of the relative electron density profiles. Their shapes are generally in agreement with the inverted density profiles from the multichord interferometer [10]. Their peculiar feature is to be local measurements simultaneous with the T_e profile. Since only one profile per shot is provided, temporal evolution is obtained by ensemble averaging measurements taken over different phases of PPCDs from similar shots (Fig.1). The T_e profile, which is fairly flat in the core (|r/a| < 0.5-0.6) during standard operation, begins to grow in this region as soon as T_e starts to rise and finally reaches a very peaked shape at the maximum value of T_e. In all phases the maximum value of T_e is in good agreement with T_e measured by the DF diagnostic. No significant change outside the error bars is observed in the external region (|r/a| > 0.6). If the profile is fitted with a simple analytical function $1 - |r/a|^\alpha$, values of α are found to change from 4 to even less than 2.

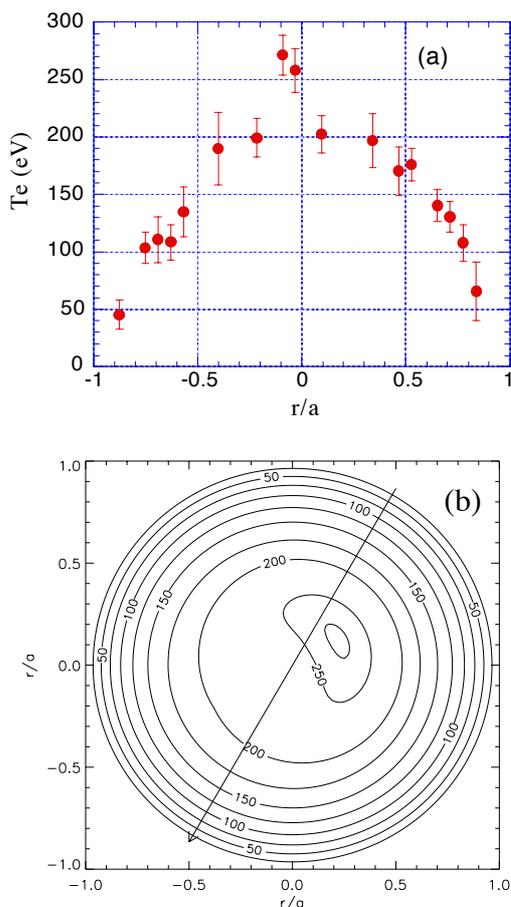*Fig. 3 Hot island corresponding to QSH state during PPCD seen by TS (a) and by the T_e reconstruction from SXR tomographic measurements (b)*

In the decay phase, which in some cases can be quite fast, the profile returns to the original flatness. Another clear characteristic of the T_e profile at the maximum of the peaking phase, is that sometimes an asymmetry grows and a narrower peak appears slightly towards the inside, as can be observed in fig.1, where the error bars represent the dispersion of data about the average. There is not evidence of such structures during the T_e rise phase. They have been recently associated with the formation of an island which demonstrates the transition to a QSH state. Electron density profiles from TS show that during PPCD no significant change is observed in the profile shape, which remains fairly flat or slightly hollow (fig. 2). The absolute value of n_e from TS is found to be on average slightly lower during PPCD, as measured also by the interferometer.

Characterization of T_e structure. In order to study in greater detail such structures, single shots have been analyzed. As an example we consider here shot 11193, where the TS profile (fig.3a) is simultaneous with the maximum value of T_e from DF. At the same time the Fourier
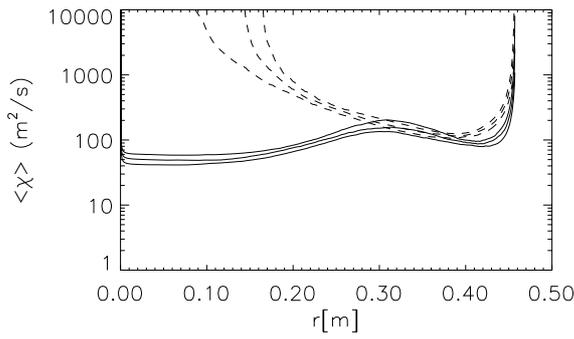
Fig.4 Surface averaged electronic heat conductivity profile during a PPCD with QSH state (solid line) and for a similar standard discharge(dashed line)

decomposition of the toroidal magnetic field spectrum from pick up coils, shows that a single m=1, n=7 mode is dominant. Simultaneously the SXR emissivity filtered by a 75 μm thick Be film, obtained from the tomographic diagnostic, shows an intense m=1 structure, which is in good agreement with the magnetic measurement. Due to the filter thickness and the typical RFX T_e value and impurity level, it is reasonable to assume that the SXR emissivity is mainly due to bremsstrahlung (with a radially constant enhancement factor). So the enhanced SXR emissivity can be ascribed to a T_e increment, since the density profile do not show any clear asymmetry or structure and since there is no evidence of impurity accumulation in the centre, or of strong plasma rotation. By assuming then that 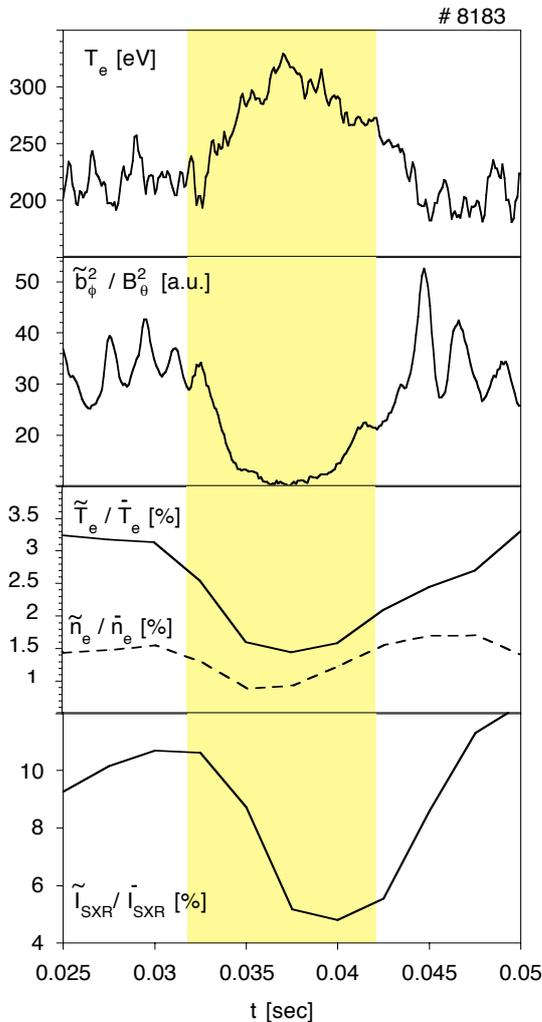T_e has a radial dependence of the kind $1-r^\alpha$, plus an m=1 structure, a rough 2D reconstruction of T_e can be obtained (fig.3b). The region of enhanced T_e shown in fig.3 can thus be ascribed to an m=1, n=7 island, with a constant T_e along its axis. In fact, taking into account the helical symmetry of the single mode perturbation $(m\theta + n\phi)$, the poloidal positions of the island seen by the two diagnostics are in good agreement: the equatorial diameter observed by the TS corresponds to the arrow across the SXR reconstruction if turned around an n=7 helix.

Transport properties. Steep gradients of T_e in the core correspond to an improved confinement, as demonstrated by an increase of the global energy confinement time, which on average doubles. The enhanced T_e in the magnetic island is indicative of a reduction of transport. A rough estimate of such a reduction can be obtained by applying the 1D steady state power balance equation [11] to poloidally averaged quantities. In order to give correct results, this approach requires a poloidally averaged T_e profile: $<T_e>$. By considering that $T_e(r,\theta)$ is only composed of m=0 and m=1 components, then, when the O-point of the magnetic island is at either $\theta=0°$ or $\theta=180°$, $<T_e>$ can be approximated by:

$$<T_e> \approx [T_e(r,\theta=0°) + T_e(r,\theta=180°)]/2.$$

Fig. 5 Time evolution of Te(0) and of the relative fluctuations of the toroidal magnetic field (m=1, n=7-20), of $T_e(0)$ and n_e and of the SXR intensity during a PPCD
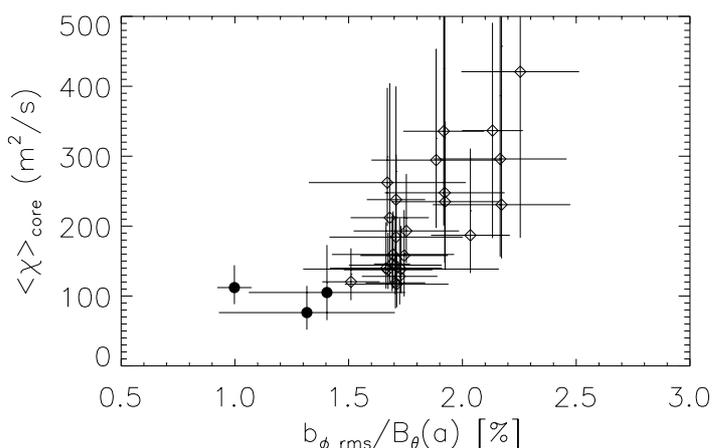
Fig. 6 χ vs toroidal magnetic field fluctuations (m=1,n=7-20) for standard (empty diamonds) and PPCD (full circles) discharges

Fig.4 shows the surface averaged electronic heat conductivity (χ) profile during a PPCD with QSH state compared to the χ profile obtained for a similar standard discharge. The beneficial effect of the island formation is clear in the plasma centre, where a value of χ even lower than that at the edge is found.

Fluctuations. The reduction of transport during EC regimes (particularly affecting the island region) has been correlated with a reduction of the fluctuation level of relevant plasma parameters. In particular during PPCD experiments, a reduction of the fluctuation amplitude is always observed linked to improved confinement, not only in quantities already analysed like SXR intensity and magnetic field, but even in the electron temperature and density (Fig. 5). Estimating the relative temperature fluctuations from the DF signals has been particularly challenging, due to the significant level of measurement noise. The estimate of T_e fluctuations has been obtained by using an "adaptive" statistical method, known as Singular Spectrum Analysis (SSA) [12], which is based on the Principal Component Analysis and has been used for years in digital signal processing.

The tight link between reduced transport and magnetic fluctuation level has been studied statistically, and the results are shown in fig. 6, where the averaged value of χ between r = 0.15m and r = 0.35m is plotted versus the rms amplitude of the MHD modes m=1, n=7 to 20, for standard and PPCD discharges. Each point is an ensemble average over many discharges. A clear separation of the two regimes is visible.

Conclusion. The observed thermal behaviour during EC regimes can be interpreted as an increased confinement in the plasma core. This is consistent with the observation that there are no particle sources and that density profiles are rather flat in the core region. The ohmic power is a sufficient source to increase the energy content of the magnetic island.

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