Core Transport Improvement during Poloidal Current Drive in the RFX Reversed Field Pinch

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We describe plasma profiles evolution during pulsed poloidal current drive experiments performed with the RFX reversed field pinch device. With external drive of edge poloidal current, magnetic fluctuations are reduced suggesting a concomitant reduction of the spontaneous dynamo action. The electron temperature profile is seen to peak in the plasma core, consistently with a reduction of the heat conductivity due to a substantial decrease of MHD dynamo fluctuations. Our results also indicate that the magnetic turbulence due to these fluctuations, which dominates heat transport in the core of the reverse field pinch configuration, does not drive an appreciable heat flux at the edge. [S0031-9007(98)08371-9]

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A growing body of experimental and theoretical work is indicating that in the reverse field pinch (RFP) configuration [1] for magnetic confinement of a thermonuclear plasma a large fraction of the energy losses is due to transport mechanisms linked to MHD turbulence. In fact, magnetic fluctuations are intrinsic to the RFP, since the configuration is usually maintained by a strong dynamo mechanism, which converts part of the energy externally supplied by the toroidal transformer to the poloidal magnetic field component B_θ into energy associated with the toroidal component B_ϕ. This process regenerates toroidal magnetic flux lost by resistive diffusion.

Many of the mechanisms (see [2], and references therein, and [3,4]) proposed to explain the dynamo are based on the nonlinear interaction of global, low-m resistive MHD modes resonant inside the toroidal field reversal surface. According to the most developed theory, the MHD dynamo (see [2] for a review), they produce coherent magnetic field $\tilde{b}$ and velocity $\tilde{v}$ fluctuations which combine to generate an electromotive electric field, $\vec{E}_d = \langle \tilde{v} \times \tilde{b} \rangle$. This dynamo electric field is found in three-dimensional numerical simulations [5–7] and has been directly measured [8]. Magnetic fluctuations in the RFP are then intimately connected to the dynamo, and in standard conditions they are somewhat unavoidable. This leads to the stochasticization of the magnetic field lines over a large part of the core plasma and, as a consequence, thermal isolation is only provided by a thin layer located at the plasma edge. The mechanism controlling the edge energy transport in a RFP is still a matter of debate, as there are not yet definite conclusions on whether electrostatic or magnetic turbulence is mostly responsible for it. Recent measurements [9–11] have shown the existence of a strongly sheared plasma flow in the edge region of a RFP discharge, suggesting a quenching of turbulent transport with a mechanism similar to the one identified in tokamaks [12].

Reducing the impact of magnetic turbulence on transport has become one of the major challenges of RFP research. In particular, external poloidal current drive has been proposed as a tool for improving confinement properties of the RFP configuration by alleviating the need of the dynamo field. Driving poloidal currents inductively by pulsing the toroidal field coils, a technique dubbed pulsed poloidal current drive (PPCD), is a simple way to test this concept inducing transient modifications of current and magnetic fields profiles. Pioneering experiments with this technique, performed on the Madison Symmetric Torus (MST) RFP [13,14], have shown a strong reduction of magnetic fluctuations and a noticeable plasma performance improvement.

In this Letter we describe the first measurements of plasma profile evolution during PPCD experiments in a RFP. These data have been exploited to perform a local transport analysis which provides direct evidence of transport improvement in the plasma core. The experiments have been performed in the reverse field pinch device RFX [15], the largest RFP presently in operation (minor radius $a = 0.46$ m, major radius $R = 2$ m, maximum plasma current 2 MA). The principal new result obtained consists in the peaking of the electron temperature profile in the plasma core when the external drive of poloidal current is applied. The steepening of the core T_e gradients indicates that the thermal diffusivity in the plasma core becomes comparable to the edge and reaches record low values for RFX.

The quantitative transport investigations presented in this paper are made possible by the availability in RFX of an extended diagnostics setup capable of providing profile measurements for electron temperature and density and for radiation losses [16–19].

The poloidal electric field E_θ which drives poloidal current in the plasma is induced by using a series of capacitor banks, whose timing and charging voltage can be

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independently adjusted, in order to fire up to 5 fast current pulses in the toroidal field coils. Effective PPCD shots were obtained at three different plasma currents: 0.4, 0.6, and 0.8 MA. Here we will describe in detail the results obtained at the highest current level where the operational density is higher and the diagnostic system produces the cleanest measurements.

The waveforms of plasma current I_ϕ, toroidal magnetic flux Φ, toroidal field at the surface $B_\phi(a)$, toroidal and poloidal components of edge electric field, E_ϕ and E_θ, and reversal and pinch parameters F and Θ (defined, respectively, as $F = \pi a^2 \frac{B_\phi(a)}{\Phi}$ and $\Theta = \pi a^2 \frac{B_\theta(a)}{\Phi}$) are shown in Fig. 1. As a result of the application of PPCD, the toroidal magnetic field at the wall becomes more reversed and the toroidal flux decreases.

The time response of confinement-related plasma quantities to the poloidal current drive pulse is shown in Fig. 2. First of all, a strong reduction of magnetic fluctuations measured at the plasma edge is observed, consistent with the observation reported from MST [14]. This is shown in Fig. 2a which displays the time evolution of the mean square value over the toroidal angle of the $m = 1$ toroidal component of the fluctuating magnetic field, normalized to the total edge magnetic field, $\frac{\tilde{b}_\phi^2}{B^2}$. The measured spectrum of these fluctuations in RFX has mostly a poloidal mode number $m = 1$ and toroidal mode numbers in the range 7–24 with a peak around $n \approx 7$–10, as expected for internally resonant dynamo tearing modes. The $m = 0$ modes resonating at the reversal radius are also detected but they have usually a smaller amplitude. The spectral composition of magnetic fluctuations remain unchanged during the PPCD pulse in the shot being analyzed while a narrowing of the spectrum around one or two dominant n modes has been observed in other shots.

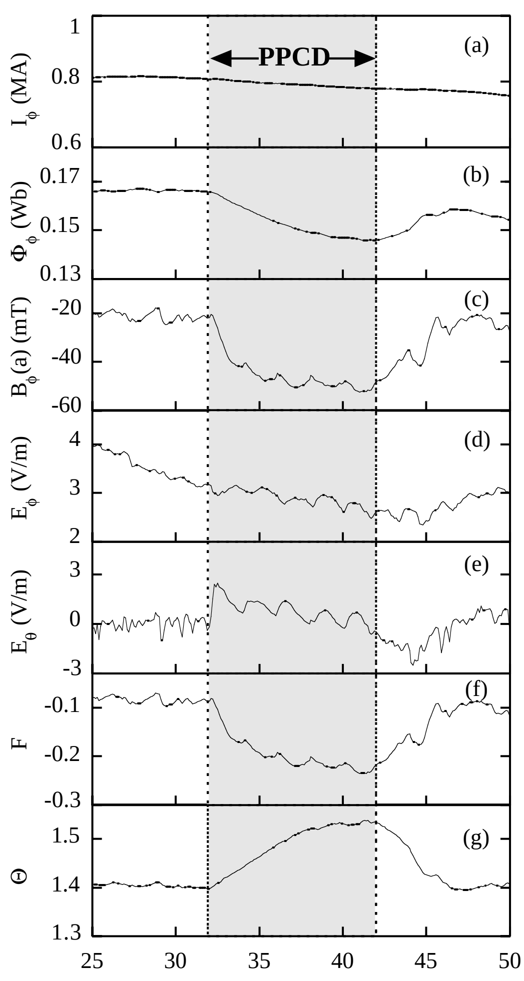

FIG. 1. Waveforms of (a) plasma current I_ϕ; (b) toroidal magnetic flux Φ; (c) toroidal field at the surface $B_\phi(a)$; (d) toroidal and (e) poloidal components of edge electric field, E_ϕ and E_θ; (f) F and (g) Θ during RFX shot 8183. The region between the two lines indicates the PPCD-on period.

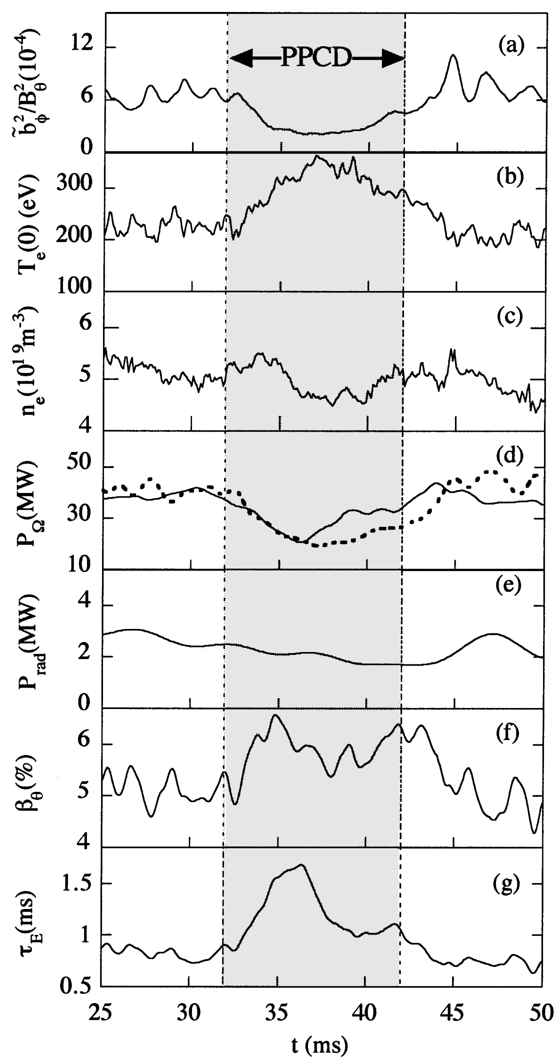

FIG. 2. Waveforms of (a) normalized mean square value of the toroidal component of the fluctuating magnetic field; (b) on-axis electron temperature; (c) central electron density; (d) input power (solid line) and Ohmic dissipation (dashed line); (e) total radiated power; (f) poloidal beta; and (g) energy confinement time for RFX shot 8183.

Connected with the reduction of magnetic fluctuations we observe a simultaneous warming up of the plasma core, as indicated in Fig. 2b by the behavior of on-axis electron temperature, $T_e(0)$. The increase of $T_e(0)$ can reach up to 75% of the pre-PPCD values. In the meantime a small decrease in the electron density without appreciable profile modifications (Fig. 2c), a marked reduction of the input power (Fig. 2d), and a small variation of the total radiated power, P_{rad} (Fig. 2e) are measured. The ion temperature is measured in the outer half of the plasma cross section, and it remains always close to the electron temperature. Given the high collisionality, we assume $T_e = T_i$ over the whole plasma radius. Taking into account the profile evolution, as described below, the poloidal beta is calculated to increase from 5% to more than 6% (Fig. 2f). The energy confinement time on the average doubles during PPCD (Fig. 2g), with improvements up to a factor of 3 in the best cases.

Similar to MST, a large fraction of the estimated confinement improvement derives from the decrease of the Ohmic input power during PPCD (Fig. 2d), as deduced from a magnetic energy balance. This includes a significant contribution from changes in the internal magnetic energy calculated from the μ and p model magnetic-field profile [2]. With this approach the normalized parallel current density profile $\frac{J_{\parallel}}{B}$ is reconstructed assuming a dependence as $1 - r^{\alpha}$, where α is chosen to match the F and Θ measurements. However, if the additional constraint of matching the measured variation of the plasma internal inductance is imposed [14], we find that the changes in the internal magnetic energy are weakly dependent on the class of profile chosen for $\frac{J_{\parallel}}{B}$. Moreover, the estimated change in power input is also in good agreement with the changes in power dissipation, as described below, which further strengthen our confidence in the confinement estimates.

The strongest signature of the transition towards an enhanced confinement regime is given by the behavior of electron temperature profile. As illustrated in Fig. 3, which shows the $T_e(r)$ profile as obtained from an ensemble average of many reproducible shots, the main change is recorded in the core ($r/a \leq 0.5$–0.6), with the onset of a radial gradient in a region where in normal operation the profile was quite flat. The core T_e gradient $\nabla T_{e,\mathrm{core}}$, defined as the average slope of the profile in the region extending from the toroidal field reversal up to $r/a \approx 0.2$, increases from about 470 eV/m to about 800 eV/m. No significant change in the very edge T_e gradient is observed, although the limited amount of information in this region suggests to consider this result with some care. In the same figure the density profiles before and during PPCD show no major modification except for a slight decrease in the average value.

The beneficial effects of PPCD on the core plasma are demonstrated by a local transport analysis. In stationary conditions we obtain the heat flux $q(r)$ from the 1D power balance equation,

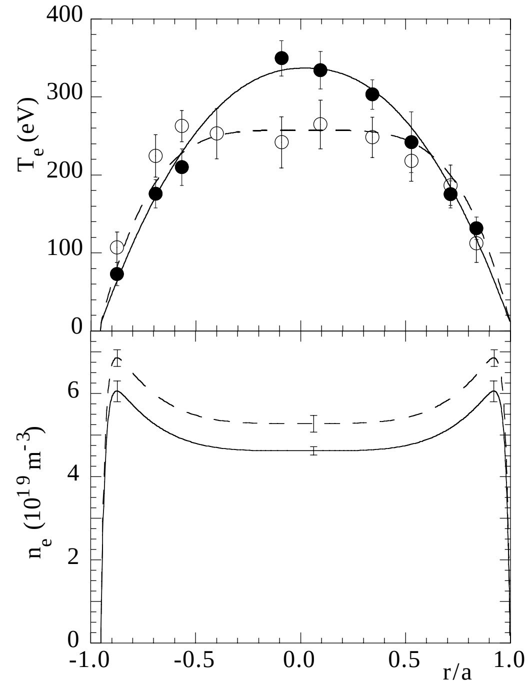

FIG. 3. (upper panel) Electron temperature profiles during standard operation (open dots) and during PPCD (full dots). (lower panel) Electron density profiles before (dashed line) and during PPCD (solid line). The standard temperature profile is taken in discharges with values of Θ similar to the one obtained during PPCD.

$$q(r) = \frac{1}{r} \int_0^r [\vec{E}(r') \cdot \vec{J}(r') - \epsilon_{\mathrm{rad}}(r')] r' \, dr', \qquad (1)$$

where $\epsilon_{\mathrm{rad}}(r)$ is the total emissivity profile. The electric field includes the dynamo contribution and is modeled via a local Ohm's law with Spitzer resistivity with a factor k to account for possible anomalous dissipation due to the dynamo mechanism. The current density profile is reconstructed with the μ and p model, and Z_{eff} is assumed uniform with a value corresponding to the line integral obtained with measurements of the visible continuous plasma emission [20]. We find that the global power dissipation evaluated in this way is in good agreement, with $k \approx 1$ within the experimental uncertainty, with the Ohmic power input to the plasma as deduced from magnetic analysis both in stationary and time varying conditions. A suprathermal electron's contribution to the plasma current is not observed at the electron density of the discharge considered. Hence we adopt $k \approx 1$ throughout the plasma cross section.

Adopting a single fluid approach, the plasma heat diffusivity $\chi(r)$ is then obtained as

$$\chi(r) = -\frac{q(r)}{n_e(r) \nabla T_e(r)} \,. \qquad (2)$$

We have neglected convective losses, which amount to less than 10% of the Ohmic input and are mainly concentrated in the edge region [21]. In the standard phase

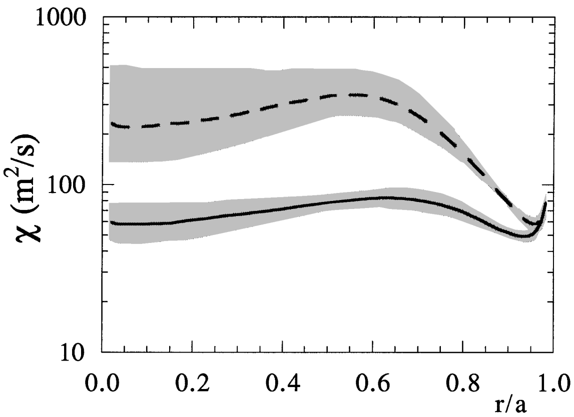

FIG. 4. χ profiles during standard operation (dashed line) and during PPCD (solid line). The shaded region around each profile corresponds to 25%–75% confidence interval, estimated with a Monte Carlo code.

of the discharge pressure profiles are relatively flat with strong edge gradient, and the resulting χ profile has its minimum value $\chi_{\min}$ very close to the edge (typically at $r/a \approx 0.90$–0.94) sharply increasing moving inward (Fig. 4). Since we are interested in deducing a lower limit to the value of the heat conductivity χ in the plasma core, a Monte Carlo analysis of the T_e profiles has been performed adopting a class of parametric profiles monotonically decreasing toward the plasma edge. The main information one obtains from this analysis is that there is at least a factor of 3 between the minimum χ value and its average value in the core. This is consistent with a plasma core poorly confined in a standard situation, where a large region of stochastic magnetic field, produced by dynamo fluctuations, is likely present. In these conditions the global confinement is therefore determined by the diffusivity of the edge which still is 2 orders of magnitude larger than the classical value. These findings are consistent with the results obtained with probes in MST [22] which show that the heat flux driven by magnetic fluctuations is strongly reduced in the edge region. More recently it has been reported that in RFX [21] particle transport too is dominated by magnetic stochasticity except in a narrow region located at the plasma edge where electrostatic turbulence becomes dominant, in agreement with probe results obtained both on MST and RFX [23,24]. It is also worth noting that the minimum value of χ is located approximately in the region of the strong radial electric field gradient recently identified in RFX [9].

The situation changes quite drastically when PPCD is applied, as also shown in Fig. 4. The pressure profile is now more peaked and the input power is reduced by a factor of about 2. Global confinement correspondingly increases. The transport analysis shows that the improved energy confinement is caused by a reduction of the heat transport in the plasma core. The core χ is reduced by a factor of 3 and becomes comparable to $\chi_{\min}$. This is consistent with the change in the heat diffusivity one can get from a Rechester-Rosenbluth expression [25], considering the decrease of the magnetic fluctuation amplitude; see Fig. 2a.

The confinement enhancement takes place mostly inside the radius of toroidal field reversal: The steepening of the T_e profile is evident in the core, whereas no significant modifications are detected in the edge value of χ. This confirms that magnetic transport due to dynamo modes does not drive any appreciable heat flux at the plasma edge where a different mechanism should be responsible for heat transport.

In conclusion, RFX results confirm that poloidal current drive is an effective technique to suppress heat transport driven by magnetic fluctuations in a RFP by reducing the amplitudes of dynamo modes. Moreover, we observed for the first time that by reducing the dynamo an effective thermal isolation is recovered in the plasma core of the RFP configuration.

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