Pulsed Poloidal Current Drive experiments in RFX

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1. Introduction.

Active poloidal current profile control has been proposed as a promising way of improving confinement properties of the reversed field pinch (RFP) configuration. Indeed tests of this concept, performed by a technique named Pulsed Poloidal Current Drive (PPCD) on the MST reversed field pinch, support this hypothesis showing strong reduction of magnetic fluctuations measured at plasma edge and suppression of sawteeth MHD activity [1,2]. Magnetic fluctuations in particular are believed to be responsible for a large part of the measured global energy flux in RFP's. The origin of these magnetic fluctuations is mostly from resistive kink instabilities with m=1 and toroidal mode numbers $n \approx 2R/a$. As these instabilities are driven by the current density gradient [3], its modification can stabilise them and reduce the associated particle and energy transport. Driving poloidal currents inductively is a simple way to induce transient modifications of current and magnetic fields profiles and to test the effectiveness of profile control on magnetic confinement.

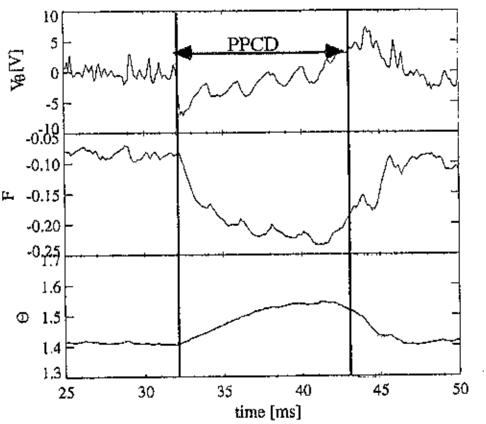

Fig.1. Time evolution during PPCD operation of: (a) poloidal loop voltage, (b) reversal parameter $F=B_\phi(a)/<B_\phi>$, (c) pinch parameter $\Theta = B_\theta(a)/<B_\phi>$ (shot #8183).

2. PPCD description.

Recently PPCD experiments were carried out in RFX [4], the largest (R=2 m, a=0.457 m) RFP in operation. Poloidal currents have been driven in the plasma outer region by applying a series of one to five poloidal voltage pulses on the toroidal magnetic system.

A parametric study has been done by varying the parameters of the single PPCD pulse (amplitude, time constant of the external circuit), the relative timing of the pulses during the discharge and the target plasma parameters (density, reversal parameter $F = B_\phi(a)/<B_\phi>$, plasma current) in order to determine the optimum performance.

An optimum range has been found operating at shallow reversal (-0.1<F<-0.05) and medium plasma densities (2.5 10^{-14}< I/N <4.5 10^{-14} Am). Effective PPCD, in terms of magnetic fluctuations reduction and soft X-ray increase, were realised at three different plasma currents: 400 kA, 600 kA and 800 kA. Some results of a 800 kA PPCD experiment are shown in Fig.2.

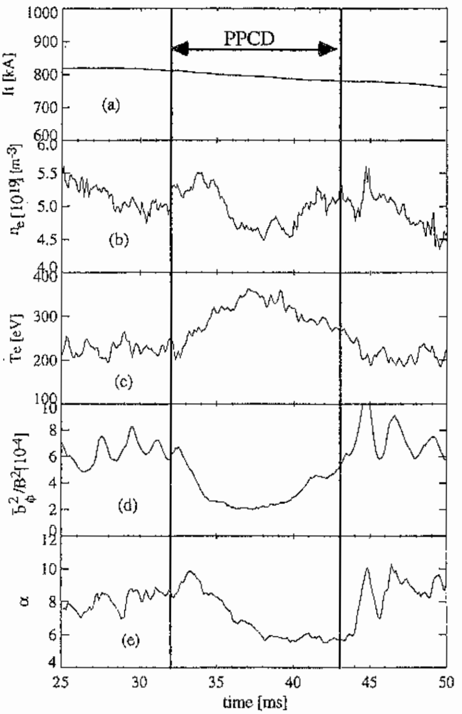

Fig. 2. Time evolution of : (a) plasma current, (b) central electron density,(c) electron temperature, (d) normalised energy of toroidal magnetic fluctuations, α parameter fro μ&p model (shot #8183).

3. Experimental results.

Optimising I/N and F, we can reproducibly obtain improvements in many plasma parameters lasting, in the best cases, for several milli-seconds, i.e. for a time greater than the energy confinement time, which is of the order of 1 ms for standard RFX discharges.

We always find a strong increase of soft X ray flux measured by a 78 chords tomography, that detects also a peaking of the profile confirming that PPCD is able to drive changes in the whole plasma configuration and not only at the edge. Tomographic measurements in the double filter configuration and Si(Li) detector PHA system could follow the time evolution of on-axis T_e and confirmed an increase up to 75% with respect to the pre-PPCD value in the best cases. Electron temperature radial profiles have been measured near the maximum of the SXR flux by a single pulse 10-point Thomson scattering diagnostic. Profiles are measured along a diameter in the plasma equatorial plane, with a spatial resolution of 2.4 cm and up to r/a = 0.84. Two sets of discharges with and without PPCD, selected with the same macroscopic behaviour (plasma current, electron density, magnetic shift and Θ parameter), have been compared (Fig.3). Clear evidence is shown that T_e on axis is higher during PPCD, where an average increase $\Delta T_e/T_e \approx 30\%$ is found. Experimental T_e profiles appear to be more peaked during PPCD than without it. T_i, measured by NPA

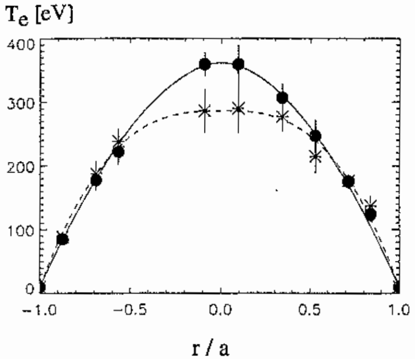

Fig.3. T_e profiles measured by Thomson scattering during PPCD (continuos line, average over 10 shots) and during conventional discharges (broken line, average over 15 shots) for the same I/N and Θ intervals.

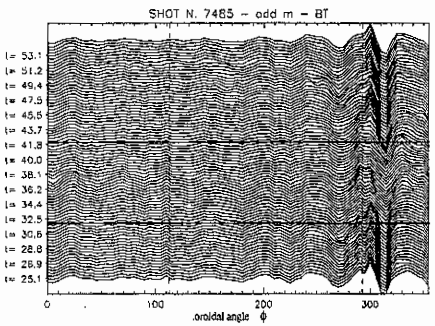

Fig.4. B_ϕ perturbation measured by two 72 coils arrays during PPCD. PPCD operation is between 32 and 42 ms (shown by horizontal lines).

diagnostic, presents little modifications due to PPCD application. In RFX we estimate T_i also from Doppler broadening of some impurity lines. These measurements show strong influence of PPCD on CIII temperature, implying an increase of edge (r/a≈0.9) ionic temperature.

Total (bolometric) radiation decreases, particularly in the outer equatorial edge region, where the main interaction with the wall is concentrated because of the Shafranov shift of the plasma. Electron density shows a little decrease and no profile modification. Z_{eff} does not show a reproducible behaviour. In some cases it decreases from 3 to 2 in agreement with a reduction found in the amplitude of influxes, particularly in the region where the MHD modes are locked to the wall.

As in MST, PPCD operations cause in RFX a strong reduction in magnetic fluctuations (Fig.4). Differently from MST, RFX discharges are affected by MHD modes which remain locked both in phase and to the wall. In none of the shots showing the greater reduction of magnetic fluctuations (≈50% in terms of global energy of magnetic modes) we found evidence of rotation of the most important modes (m=1, n=8,9). This could mean that, if there is a threshold on the magnetic fluctuation level to induce the rotation, we did not reach it during PPCD operations. Also spectroscopic measurements of plasma rotation do not show an evident and reproducible phenomenology during PPCD application.

It should be noted that during PPCD in RFX, except in the very early phase, the parallel current profile does not flatten, but actually becomes more peaked (see Fig 2e).

4. Discussion and conclusions.

A careful comparison with the performance of stationary discharges with high Θ values, comparable to the post-PPCD ones, shows that the positive effects on the central T_e and on magnetic fluctuations, which are present in both cases, are clearly more pronounced in the PPCD case. Also the peaking of the T_e profiles is greater during PPCD. These features can therefore be interpreted as due to the reduction of dynamo action induced by PPCD and not simply as an effect of a transition to higher values of Θ.

Taking into account the new values of the profile and on-axis value of temperature and electronic density, we can estimate an increase of the poloidal beta, $\beta_\theta=2\mu_0\langle nk_BT\rangle/B_\theta(a)^2$, up to 30-40% (assuming $T_e=T_i$).

For the calculation of the energy confinement time, τ_E, the ohmic input power has been estimated using the equilibrium μ&p model [5] to compute the contribution fro the variation of the plasma internal magnetic energy: τ_E can double during the period of poloidal voltage application, reaching a value of 2.5 ms which can be maintained for more than 5 ms in the best cases. As an alternative approach we have estimated the ohmic input power by mean of the ohmic dissipation taking into account the Spitzer resistivity, the measured electron temperature and Z_{eff} and modelling the magnetic profiles with the μ&p model :

$$P_\Omega \propto T^{-3/2}\langle \eta J^2 \rangle$$

obtaining results in good agreement with the previous calculation.

To investigate the influence of PPCD on the dynamo mechanism, the F-Θ behaviour in RFX has been simulated using the resistive 1-D diffusion code RFXPORT. A good matching with experimental data was obtained (without temperature and density evolution) only by applying a 30% reduction of the dynamo action during PPCD, followed by a similar increase during the subsequent discrete relaxation phase.

The analysis of the first PPCD experiments on RFX confirm that this technique can lead to improvements in terms of magnetic fluctuations reduction, on-axis electron temperature increase and general confinement properties. The stabilisation of the profile by current drive appear to be necessary only as a seed for the dynamo suppression, which then causes a peaking of the temperature profiles and triggers an improved confinement regime as can be seen during other transient regimes in RFX [6].

References:

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