Profile Modifications in PPCD Experiments on RFX

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Abstract. In this paper we analyze the effect of Pulsed Poloidal Current Drive (PPCD) on the profiles of magnetic field, electron and impurity densities and electron temperature in RFX. 3D MHD non-linear simulations and 1D time dependent transport codes show that the external inductive drive pinches and peaks the current profile driving the configuration through a transient phase, where the spontaneous dynamo action is quenched and consequently the magnetic fluctuations and the transport are reduced.

1. Introduction

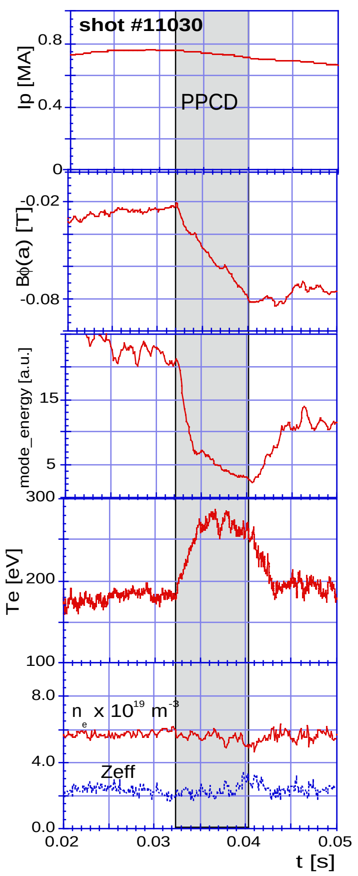

Fig.1: Main plasma parameters during PPCD. From top to bottom: plasma current,toroidal field at the wall, normalized total mode energy,T_e,n_e,Zeff

The Reversed Field Pinch (RFP) is a magnetic configuration whose symmetry is broken by unstable m=1 resistive MHD modes. This symmetry breaking generates electric fields producing a drift velocity field and consequently a **v** x **B** dynamo field. In the multiple helicity (MH) regime a broad spectrum of MHD modes resonating inside the toroidal field reversal surface produces magnetic chaos. A way to reduce the magnetic fluctuations and the associated transport is the application of a pulsed poloidal electric field at the plasma edge (the so-called Pulsed Poloidal Current Drive), which brings the system away from the steady state, driving it into a transient regime where the request for the dynamo action is reduced.

PPCD experiments have been performed in various RFP devices [1, 2], resulting in an increase of the core electron temperature and a reduction of transport through the reduction of the magnetic fluctuations. The aim of this paper is to analyze the modifications induced by PPCD on the magnetic, temperature and density profiles in RFX, and the related decrease of the transport.

2. Summary of experimental observations

To recall the main features of a PPCD experiment in RFX, the time evolution of typical plasma parameters is shown in fig.1. It is clearly seen the reduction of the total mode energy and the increase of the on-axis electron temperature in the initial phase of PPCD, when the edge toroidal magnetic field is becoming more negative.

According to a standard axisymmetric equilibrium reconstruction, the deepening of the edge toroidal field produced by PPCD results in an inward displacement of the reversal surface and a peaking of the current profile in the central region. These profile changes are consistent with the edge measurements (performed at low plasma current, ~300 kA), that show a reduction of the electrostatic transport at the edge, interpreted as a combination of a displacement and a shrinking of the plasma column [3]. A similar picture is suggested by the edge toroidal rotation measurements from the Doppler shift of C III emission lines. In RFX in stationary conditions C III emits from the last 3-5 cm of the plasma radius, outside the field reversal surface. When PPCD is applied, a significant decrease of the C III velocity, proportional to the radial electric field E_r, is observed, indicating that the finite Larmor radius losses at the edge are reduced. Also, to simulate the impurity behavior during PPCD by a diffusion model the edge region of low diffusion found in stationary conditions has to be broadened (its range goes from 0.9≤r/a≤1 to 0.8≤r/a≤1) [4].

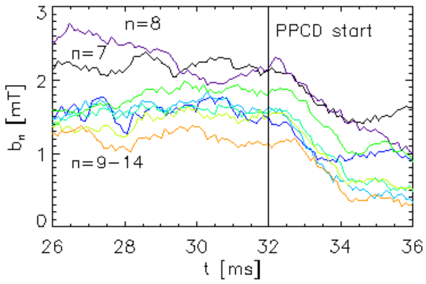

Fig.2 : Time evolution of the m=1 n=7-14 magnetic modes during PPCD

In addition, in the region where magnetic modes are locked, the reconstruction of the last closed magnetic surface shows that PPCD reduces its radial outward displacement from ~2-4 cm to ~1 cm. As a result of this less severe plasma-wall interaction, both hydrogen and impurity influxes decrease drastically at the locking position. Since this local contribution to the total influxes has been evaluated to be about 50% (both for hydrogen and impurities) [5], a strong reduction in the locking region leads to a decrease of the total H and impurity source up to a factor of 2.

As previously reported [2] in RFX, during PPCD, a strong decrease of the magnetic fluctuations is observed. Moreover, the timescale of the magnetic mode amplitude reduction is of the order of 1 ms and from recent analysis it has been observed that the most internal m=1 modes (n=7-8) decrease simultaneously or just before the more external ones (fig.2). This confirms that in the plasma core the effect of PPCD is faster than the resistive diffusion.

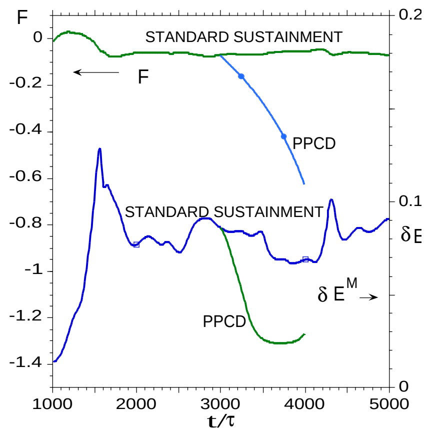

Fig.3: Reversal parameter F=Bϕ(a)/<Bϕ> and magnetic perturbation energy obtained from the 3D code. The simulation of a standard sustainment is shown for comparison.

When the temperature increase during PPCD is above 40%, in most of the cases a helical thermal structure is observed by the Soft X-ray (SXR) tomography and by Thomson scattering (TS). This structure is often associated to a situation where one magnetic mode dominates over the others [6, 7]. By the simultaneous analysis of TS profiles and data from a double filter SXR system it is possible to discriminate the temperature inside and outside the localized structure, concluding that in any case the temperature on axis increases (fig.1) and the profile peaks during the transient phase of PPCD.

The behavior of the electron density is quite different. The central chord value decreases slightly during PPCD (see fig.1), while the profile is usually hollow before the start of PPCD experiments and does not change significantly.

Despite the reduction of the influxes, the plasma effective charge Z_{eff} increases slightly or remains about constant during PPCD, mainly because of the decrease of the electron density and of a higher ionization degree, associated with the higher temperature.

3. 3D MHD simulations

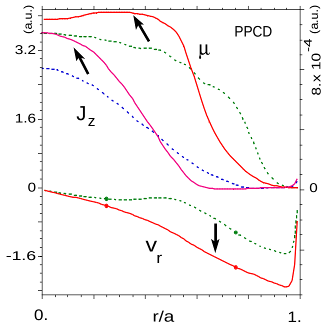

Fig.4: Comparison of the profiles of the toroidal current density , of μ =J·B/B^2 and of the radial velocity obtained from the 3D simulation before and at the end of PPCD

A PPCD experiment has been simulated by means of a 3D MHD non linear code (SpeCyl). The PPCD external drive is applied as a boundary condition with a prescribed decrease in time of toroidal magnetic field at r=a, instead of the standard condition of constant toroidal magnetic flux [8]. Constant poloidal magnetic field and initial conditions of MH at Θ=1.6 have been used. The Lundquist number is S=3x10^4 (~ 10^6 in the experiment). Like in the experiment, the typical evolution of PPCD corresponds to characteristic times of the external action several orders of magnitude larger than the Alfven time scale (τ_{PPCD} ~ 10^3 τ_A in RFX, ~ 10^2 τ_A in simulation) and much lower than the resistive time (10^{-3} τ_R both in experiment and simulations). Two values for the Prandtl number (P=1,20) have been considered. Likewise the experiments, this set of cases shows a significant reduction of magnetic perturbation energy (both as volume content and edge values), which is accompanied by a concentration and shrinking of the magnetic profiles. Fig. 3 shows the temporal behavior of the reversal parameter and of the magnetic perturbation energy for a standard sustainment and an example of PPCD simulation. In the simulation a sort of saturation in the decrease of the perturbation energy δE^M is found, despite the persistence of the external action. In Fig.4 the simulated profiles of toroidal current density $J_z(r)$, μ (r) =J·B/B^2 and radial velocity $v_r(r)$ before PPCD action (dotted curves) and at the end (plain line) show a profile concentration in all of the quantities, with an increase of the radial pinch velocity v_r.

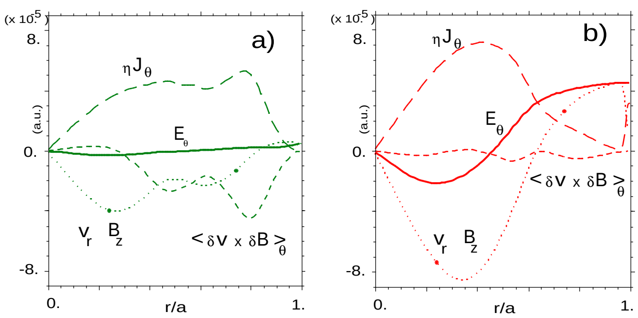

Fig 5: Profile of E_Θ and of its three terms before (a) and at the end (b) of PPCD

A simulation has also been done prescribing a temporal variation of resistivity resembling the typical experimental behavior in RFX. The resulting magnetic profiles are negligibly affected, although in this case v_r displays a milder variation.

Concerning the evolution of the dynamo terms, figs. 5a,b show at the beginning and at the end of PPCD the components of the poloidal electric field along the radius. This quantity accounts for the toroidal flux variation inside the surface of radius r: E_Θ (r) = [η J_Θ+ v_r B_z - < δ v x δ B >$_\Theta$] = - 1/2πr (dϕ (r)/dt). In particular we display the total E_Θ (r) and its three terms related respectively to the diffusion, pinch velocity (laminar dynamo) and fluctuating fields (turbulent dynamo). At the beginning of PPCD the plasma is almost in a steady state and the turbulent dynamo balances the resistive diffusion term in the outer part of the domain, whereas the pinch velocity term is more important in the inner part. At the end of the transient PPCD phase, when the fluctuations are highly depressed, the increase of the toroidal flux in the core is related to a negative poloidal electric field and to a large pinch velocity term. This picture differs from the original one of a resistive diffusion of the current from the plasma edge during PPCD.

4. Transport simulations

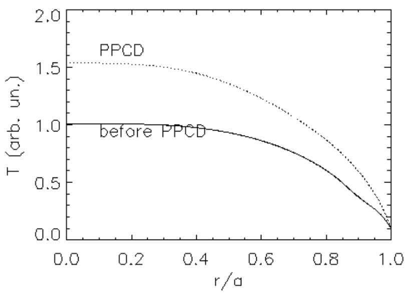

Fig.6: Electron temperature profiles as obtained by the 1D transport model RFXPORT before and during PPCD

A 1D time dependent transport code (RFXPORT, [9]) has been applied, that solves the equations for the evolution of the magnetic profiles together with the temperature profile. The simulation of PPCD has been done by reducing the dynamo field ($E_d=\alpha B$ in the code), consistently with the experimental decrease of the magnetic fluctuations. The peaking of the current profile is a common feature between this model and the 3D simulation, though transport is not present in the 3D code. Again, the profile redistribution is essentially due to the reduction of the turbulent dynamo field during PPCD. The code also reproduces the experimental variation of the temperature with a thermal diffusivity χ decreasing during PPCD from ~500m^2/s to ~100m^2/s in the plasma core (figs.6, 7). This decrease is about proportional to $(\delta B/B)^2$, as predicted by the stochastic model [10,11].

To simulate the behavior of the density profiles, a 1D cylindrically symmetric transport code has been used in a predictive scheme [12]. The particle flux is expressed as: $\Gamma = \Gamma_{an}+\Gamma_0 =- (D_{an}+ D_{el})\nabla n + v_{an}\cdot n + v_{ExB}\cdot n$, where D_{el} is a term added to the diffusion coefficient to account for the electrostatic transport at the edge. D_{an} and v_{an} are related by $v_{an}= -D_{an}\nabla T_e/2T_e$ according to the stochastic ambipolar diffusion model [13]. The stationary density profile has been reproduced with a diffusion coefficient of the order of 40 m^2/s in the center decreasing to 1m^2/s at the edge (fig.7). During PPCD, the source term in the particle continuity equation, i. e. the neutral density, has been decreased by a factor 2, consistently with the experimental decrease of the hydrogen total influx. The density profile has been well simulated with a lower D (figs7 and 8), indicating that, though the density profile does not change, the particle diffusion could be lower in this phase.

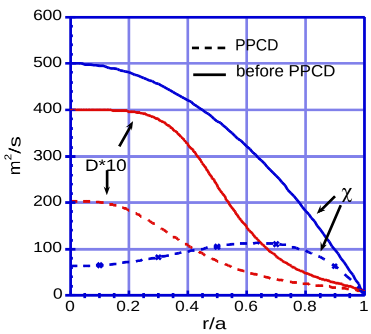

Fig.7: Thermal diffusivity used to simulate the temperature (RFXPORT) and particle diffusion coefficients (used in the particle diffusion model) in stationary conditions and during PPCD

5. Summary and conclusions

The effect of the application of PPCD on magnetic, n_e and T_e profiles has been studied in RFX. The simulation with a non linear 3D MHD code confirms the concentration and peaking of the magnetic profiles predicted by a simple equilibrium reconstruction model and experimentally found on other devices [14]. This effect appears to be essentially due

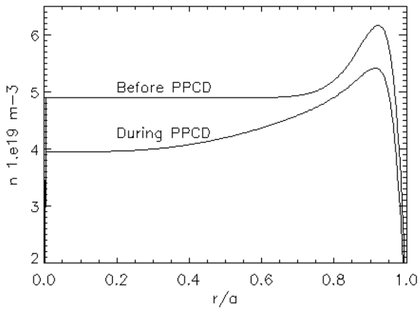

Fig.8: Simulation of the density profiles obtained from a 1D diffusion code before and during PPCD

to the decrease of the turbulent dynamo term and to an increase of the pinch velocity due to the toroidal flux modifications associated to the external drive.

1D time dependent transport codes show that the thermal diffusivity decreases during PPCD by a factor proportional to $(\delta B/B)^2$ and the particle diffusion coefficient decreases as well.

The general picture of a PPCD experiment in RFX emerging from this analysis is the following. The external drive produces a drop of the magnetic fluctuations and a concentration of the toroidal flux in the core. Indeed the non-stationarity of the system makes unnecessary the symmetry breaking of a stationary ohmic device (Cowling theorem). The almost ideal character of the plasma induces its shrinking as a shielding to the external toroidal field change. Consequently the magnetic and temperature profiles peak, transport is reduced and T_e increases.

In conclusion, since the MHD dynamo is related to the sustainment of profiles which would otherwise decay, the reduction of the fluctuations and the associated electron temperature increase and transport improvement are strictly linked to the transient nature of the external drive. In fact in RFX both the decrease of the magnetic fluctuation amplitude and the temperature increase are correlated with the increasing applied poloidal electric field [6].

In this context, a promising technique to extend the reduced dynamo phase is the application of an oscillating poloidal electric field at the plasma edge. Experiments performed in RFX demonstrated that, despite intrinsically transient, the inductive current drive leads to an improved regime if conceived in a repetitive scheme [15]. Another possibility to obtain a steady state without magnetic turbulence is that of an Ohmic Single Helicity state [16], though yet to be experimentally achieved. Alternatively, non-magnetic techniques such as RF current drive could be experimented in RFPs to demonstrate the accessibility of a stationary low turbulence regime.

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