Quasistationary Magnetic Fluctuation Control in the Reversed Field Pinch: A Proof of Principle Experiment

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We present the results of the first successful experiments aimed to control in a quasistationary way the magnetic fluctuation dynamics in a reversed field pinch (RFP) device. This is done by the application of an oscillating poloidal electric field to the plasma edge. Although the additional power input is negligible, a stationary positive effect on the electron temperature is obtained. Temperature increases up to 50% over the standard values. This experiment demonstrates that in principle a stationary current profile and magnetic fluctuation control technique is feasible in the RFP.

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Stationary reversed field pinch (RFP) plasmas are sustained for times much longer than those allowed by resistive diffusion by simply applying a constant toroidal electric field. This entails a dynamo mechanism that drives internal poloidal electric currents [1–3]. The RFP dynamo has a magnetohydrodynamic (MHD) nature [1,4]: the required poloidal electric field is produced by fluctuations related to current driven tearing instabilities resonant in the plasma core which lead to magnetic field stochastization and transport degradation. This accounts for a large part of the measured global energy flux. As these instabilities are driven by the current density gradient, active poloidal current profile control by rf waves [5] or dc injection [6] has been proposed as a technique to improve the RFP confinement. A test of the concept on a transient basis has been done by a technique known as pulsed poloidal current drive (PPCD), used in the MST (Madison Symmetric Torus) [7] and RFX (Reversed Field eXperiment) [8] devices. With PPCD a poloidal electric field is driven inductively at the plasma edge by pulsing the current in the toroidal field coils. This results in a strong reduction of magnetic turbulence and in a simultaneous significant energy confinement improvement [9–11]. While extremely interesting conceptually, one practical limit of the PPCD is its intrinsically transient nature. In fact, in order to inductively drive a poloidal electric field in the plasma one has to ramp the external toroidal field toward more negative values. After a few ms the toroidal field reversal is so deep that the magnetic configuration becomes prone to spontaneous large relaxation events and the PPCD has to be stopped anyway. Nonetheless, a comparison with stationary discharges [8] shows that the improvement is linked to the presence of the induced poloidal electric field.

In this Letter, we present the results on the first successful attempt of a quasistationary current profile control experiment in the RFP. This experiment has been performed in RFX [12] by exploiting the oscillating poloidal current drive (OPCD) technique. OPCD consists of the application of an oscillating poloidal electric field to the plasma edge. The results obtained in these experiments show that the transient nature of the PPCD can be overcome and demonstrate that in principle a stationary current profile and magnetic fluctuation control technique is feasible in the RFP.

RFX is a large RFP with minor radius $a = 0.46$ m, major radius $R = 2$ m. The oscillating poloidal electric field $E_\theta(a)$ is produced by modulating the current in the toroidal field coils. The period of the applied oscillation can be varied with a lower limit of 2 ms. The resulting poloidal voltage modulation is of the order of a few volts, comparable to that produced during PPCD experiments [11]. During one half period of the oscillation the applied poloidal electric field drives current in a way similar to PPCD operation, i.e., in the same direction as that driven by the spontaneous turbulent dynamo. We call this "codynamo" action, since it helps the natural dynamo and decreases the need of it. In the second half period the applied poloidal electric field drives current in the opposite direction; we call this "counterdynamo" action. In the following the sign assumption for the poloidal electric field and the associated voltage is such that negative values correspond to the codynamo action.

OPCD experiments at plasma currents ranging between 0.8–1.1 MA have been performed. Wave forms of significant global plasma parameters during a typical 1 MA OPCD experiment are shown in Fig. 1. Plasma current [Fig. 1(a)] and electron density [Fig. 1(f)] have been maintained nearly constant during the experiment. The poloidal electric field oscillations are evident in the $E_\theta(a)$ wave form [Fig. 1(b)]. The power input from the toroidal circuit, $V_\theta I_\theta$, oscillates between ±2 MW. This is $<7\%$ of the total power input, and its average value is <0.2 MW, a negligible fraction ($<0.5\%$) of the global input. Because of the coupling of the toroidal and poloidal systems via the plasma, oscillations of similar amplitude are present also in the $V_\phi I_\phi$ term. On the average the plasma parameters range to get optimum OPCD performance are the same as those favorable to PPCD [8], namely plasma density n and

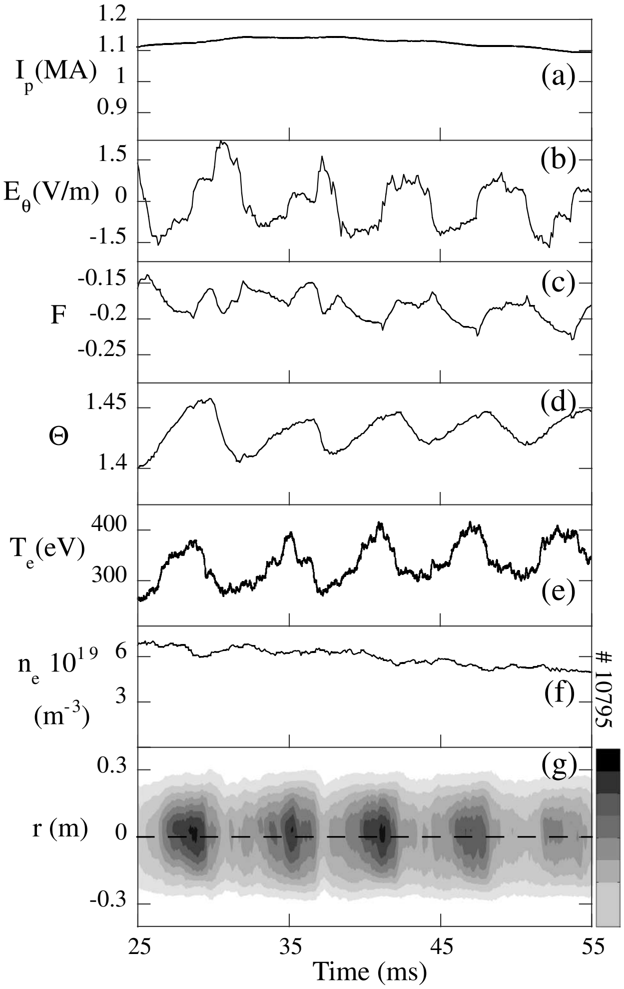

FIG. 1. Time evolution of global plasma parameters during an OPCD experiment in RFX (#10795). (a) Plasma current; (b) applied poloidal electric field; (c) reversal parameter; (d) pinch parameter; (e) on axis electron temperature; (f) electron density; (g) SXR brightness (the color legend covers a uniform range from 0 to 120 W/m^2).

field reversal parameter $F = B_\phi(a)/\langle B_\phi \rangle$ in an intermediate range ($I/N \equiv I/\pi a^2 \langle n \rangle \approx 3\text{–}4 \times 10^{-14}$ A m, $F \approx -0.25\text{–} -0.1$). It has been found that for the OPCD to achieve a positive effect the oscillation period must be in the range 6–8 ms. In this way the time scale of the codynamo phase is similar to that of PPCD in RFX [11]. Shorter time scales do not produce improvements in the plasma, possibly because they are too short to allow for current density profile modifications through MHD mechanisms. As a result of the application of $E_\theta(a)$, the magnetic configuration is cyclically modified, as shown by the F and $\Theta = B_\theta(a)/\langle B_\phi \rangle$ wave forms [Figs. 1(c) and 1(d)]. During the codynamo phase, the F and Θ values are compatible with an on-axis peaking of the current density profile [1]. The beneficial effects of $E_\theta(a)$ on the plasma are indicated by regular oscillations of the core electron temperature $T_e(0)$ trace [Fig. 1(e)]. $T_e(0)$ corresponds to an average temperature over a core region extending radially in the range $|r/a| \leq 0.25$ [13]. $T_e(0)$ maxima and minima occur, respectively, during the codynamo and counterdynamo phases. The temperature and energy confinement time increase up to 50% during the codynamo phase. The periodic heating is confirmed in Fig. 1(g) by the time evolution of the soft x-ray (SXR) brightness radial profile. The figure shows that the radial extent of the hot region spreads over a large fraction of the plasma core. The detailed timing between $E_\theta(a)$ and $T_e(0)$ will be discussed later.

OPCD does not induce a net current drive nor does it apply a significant power input to the plasma over a complete oscillation period. Hence one could expect that any effect associated to each codynamo [negative $E_\theta(a)$] pulse should be canceled by the subsequent counterdynamo one. On the contrary, despite the $T_e(0)$ decrease that follows the negative $E_\theta(a)$ phases, we observe on the average a global improvement of the plasma confinement properties. This is seen in Fig. 2, where we report the core electron temperature vs I/N for standard and OPCD plasmas. Two sets of experiments at different plasma current (0.8 and 1 MA) are considered. In this figure crosses refer to $T_e(0)$ in standard plasmas; squares and diamonds correspond, respectively, to the maximum and minimum values of $T_e(0)$ measured during an OPCD oscillation. $T_e(0)$ oscillates between two extremes, the lower one being comparable and not worse than $T_e(0)$ of standard pulses. This is consistent with the fact that the level of magnetic turbulence present in the plasma core during the counterdynamo phases has little impact on the global confinement. This can be explained considering that the standard RFP global confinement is largely determined by a transport barrier present in the outer part

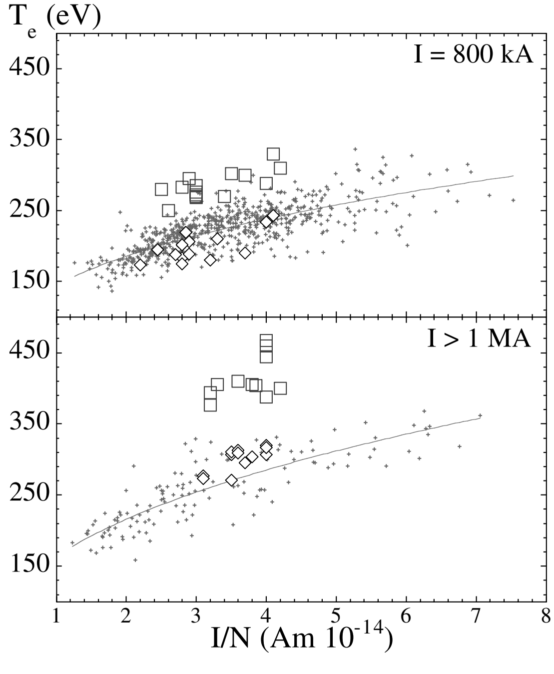

FIG. 2. Maximum (squares) and minimum (diamonds) values of $T_e(0)$ during oscillations induced by OPCD compared to a standard pulse database (crosses) vs I/N.

of the plasma, i.e., around or even outside the magnetic field reversal surface. Hence, on the average, OPCD allows one to produce a hotter plasma. In addition, the comparison of the two data sets at 0.8 and 1 MA shows that the difference between the maxima of $T_e(0)$ during OPCD and $T_e(0)$ in standard discharges is larger for the higher current data set. The ratio $\langle T_e^{\mathrm{OPCD,max}} \rangle / \langle T_e^{\mathrm{std}} \rangle$ is 1.22 at 0.8 MA and 1.49 at 1 MA, where $\langle\ \rangle$ is an average for data points with I/N ranging from 3×10^{-14} to 4×10^{-14} Am. This can be interpreted as a favorable scaling of the OPCD performance: the higher the current, i.e., the higher the magnetic Lundquist number S, the larger is the observed transport reduction. A synergy with the natural positive S scaling of the magnetic fluctuation amplitude [14] is perhaps exploited in this case. The reduction of magnetic turbulence results in a nonlinear change of plasma transport properties that allows OPCD plasma to reach S number regimes not obtained during standard plasmas at the same plasma current.

Previous analyses showed that the origin of the confinement improvement during PPCD is related to the magnetic fluctuation change driven by the current density profile modification [7,8]. The periodic nature of the OPCD becomes then a useful tool to study the relative timing between current drive, MHD mode dynamics, and the related temperature and confinement increase. It is important to notice that OPCD is effective in both the main configurations of $m = 1$ mode spectra found in RFP experiments: the so-called quasi single helicity (QSH) configuration [15], characterized by the presence of one dominant ($m = 1, n = n_0$) mode with amplitude much larger than that of the others, and the usual multiple helicity configuration (MH), where many $m = 1$ modes with different toroidal mode number n have comparable amplitude. OPCD technique appears to rely on a robust mechanism, unaffected by internal magnetic mode energy distribution. This is described in Fig. 3, where we analyze the time behavior of electric poloidal field, electron temperature, energy of the core resonant $m = 1$ modes, and energy of the $(0, 1)$ mode resonant at the field reversal surface, for two different shots at 1 MA. The one on the left (pulse #10795) is characterized by a QSH regime that starts at $\approx$23 ms during a codynamo phase. The amplitude of the dominant ($m = 1, n_0 = 7$) mode is 6 times larger than that of the other modes for the whole current flat-top period. The one on the right (pulse #10688) shows a standard MH mode spectrum.

In both cases the amplitude of the modes $(1, 8-14)$ starts to decrease when the codynamo phase begins, and its minimum occurs $\approx$2 ms after the maximum negative electric field. The modes then increase again as the action of $E_\theta(a)$ diminishes and then changes sign. According to simple current diffusion simulations, the observed delay is comparable to the time needed by the maximum of the inductively driven current to reach the plasma region close to the field reversal surface. This indicates that $m = 0$ modes play an important role in the main $m = 1$ magnetic fluctuation dynamics seen in OPCD. A difference between the QSH and MH pulses is indicated by the relative phasing of the innermost resonant mode $(1, 7)$ and the other $m = 1$ modes [Fig. 3(c)]. In the MH pulse the increase of the $(1, 7)$ mode anticipates by $\approx$1 ms the sequence of higher n modes. This is similar to the mode cascade dynamics already observed in RFX during discrete relaxation events [16], provided that now the time evolution is set by the external OPCD cycle. In the QSH case, the amplitude of the dominant $(1, 7)$ mode is in antiphase with the other modes. The mitigation of the $(1, 8-14)$ and of the $(0, 1)$ modes by the OPCD could result in a reduction of the transfer of energy from the $(1, 7)$ mode to other modes via the 3-wave coupling. The behavior of the $(1, 8-14)$ and of the $(0, 1)$ modes shown in Figs. 3(c) and 3(d) supports such a picture, their minima being in phase with the maxima of the $(1, 7)$ mode. This suggests that OPCD might play a role in the MHD behavior by interfering with the nonlinear coupling of the modes underlying the RFP dynamo. Indeed it is well known that the coupling of $m = 1$ relatively low n modes results in the nonlinear generation of $m = 0$ modes, which in turn excite higher n's $m = 1$ modes by the back-coupling mechanism [17,18].

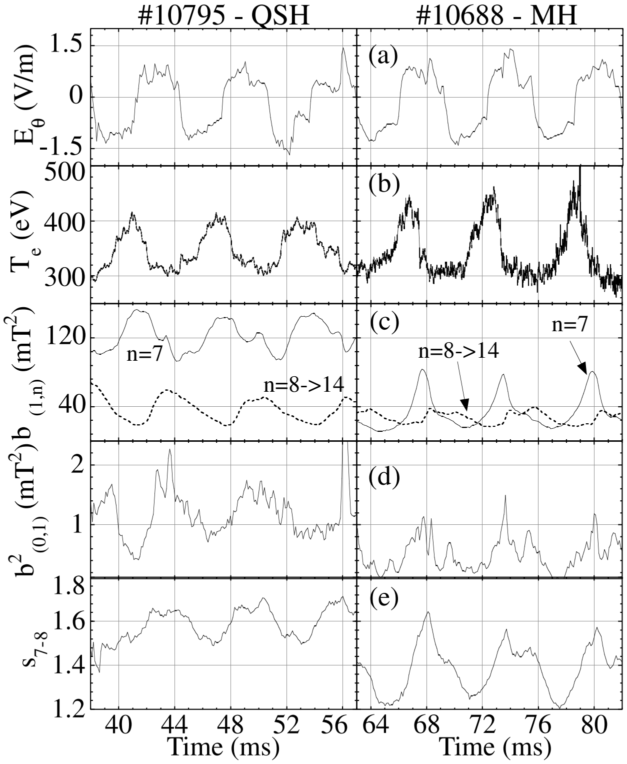

FIG. 3. Time evolution of plasma parameters during two OPCD experiments in RFX (#10795, #10688): on the left side the plasma was in the QSH state, on the right side in the MH. (a) Poloidal electric field; (b) electron temperature, (c) energy associated with $m = 1$ modes with $n = 7$ and $n = 8-14$; (d) energy associated with $m = 0, n = 1$ mode; (e) qualitative estimate of the level of stochasticity associated with the ($m = 1, n = 7$) and ($m = 1, n = 8$) modes.

The coexistence of similarities and differences in the MH and QSH OPCDs is present also in the $T_e(0)$ time evolution. Figure 3 shows that in the QSH case the points where $T_e(0)$ starts to increase and decrease coincide approximately with the times when the poloidal electric field becomes negative and positive, respectively. In the MH case the turning points of the temperature oscillations show an additional delay of ≈ 1 ms. In both cases $T_e(0)$ drops are induced when dynamo mitigation obtained via the current drive is over, and $m = 1$ modes have grown enough to connect the hotter plasma core with the stochastic external region. This allows for fast energy diffusion along magnetic field lines and confinement degradation. In the MH case such a behavior is well accounted for by the parameter s_{7-8}, defined as the overlapping of the two islands width normalized to the distance between their resonant surfaces. This quantity, provided that the mode amplitudes are small, is a qualitative estimate of the level of stochasticity due to the amplitude of the mode $(1, 7)$ (associated to the hot core) and $(1, 8)$ (representing the inner edge of the stochastic region). The same quantity provides similar indications also for the QSH case even if, given the very large amplitude of the $(1, 7)$ mode with respect to the $(1, 8)$, the link between the value of s_{7-8} and the level of stochasticity induced by magnetic islands overlapping is in principle not valid [19]. The different timing of the electron temperature in the MH and QSH plasmas might be related to the different nature of the dynamo in a QSH state. The QSH dynamo is in fact a consequence of the pinch effect and of the breaking of axisymmetry due to the resistive kink mode [3]. The OPCD action might include some ideal MHD effects, working on time scales shorter than resistive time scales. These effects could interact directly with the single dominant mode and induce a faster time response to the OPCD action. Further experiments will help in clarifying the underlying physics which might include a nonlocal coupling between the applied $E_\theta(a)$ and the plasma core.

It is interesting to comment about the robustness of the OPCD action. In both cases a significant improvement of the heat core confinement is observed. In the QSH case, in addition to the decrease of the heat conductivity related to the decrease of the stochasticity caused by the secondary modes, the well-confined hotter $m = 1$ helical structure, typical of QSH states, is observed in the core. This is evident in Fig. 4, which shows the asymmetric pressure profile, measured by a 20-point Thomson scattering close to the peak of one of the OPCD oscillations for the previously discussed shot #10795. In the same figure is shown the profile measured during a standard pulse, which is also representative of the pressure profile during the counterdynamo phase. The fact that the T_e increase induced by the OPCD affects only the core region ($r/a \leq 0.8$) confirms that the improved global energy confinement obtained with OPCD is due to a strong decrease of the heat conductivity in the plasma core.

These OPCD experiments in RFX provide evidence that the poloidal current drive principle can be successfully extended from a pulsed to a continuous technique. The effectiveness of the technique and the various effects observed leave wide space for further optimization of it. Such results offer additional support to the possibility of achieving a nontransient enhanced confinement regime in RFPs by applying continuous poloidal current drive.

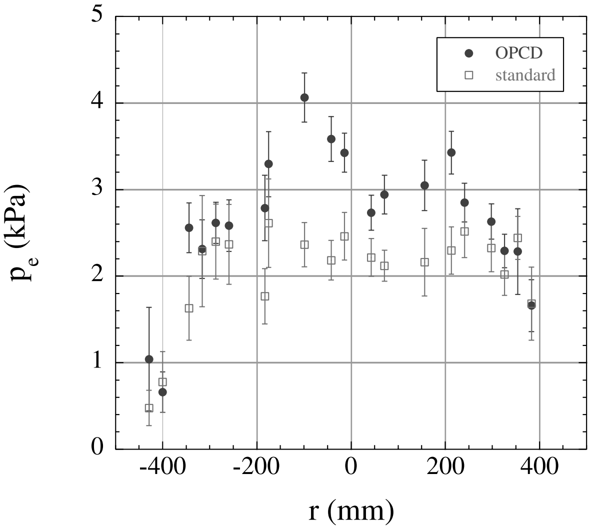

FIG. 4. Pressure profile from the Thomson scattering diagnostic. Full circles refer to OPCD (#10795) data points taken at time $t = 40$ ms. Empty squares refer to an average over standard discharges.

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