Current profile modifications with active feedback stabilization of resistive wall modes in a reversed field pinch

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Introduction

Successful active feedback stabilization (AFS) of multiple resistive wall modes (RWMs) has been experimentally demonstrated in the EXTRAP T2R reversed-field pinch [1]. In addition to the simultaneous suppression of several non-resonant RWMs and in a significant prolongation of the plasma discharge duration up to 10 wall penetration times, AFS also affects the dynamics of the tearing modes (TMs) resonant in the plasma centre which are characterised by a sustained rotation. Typical phenomena associated with the TMs such as the dynamo activity and the "slinky-mode" formation and rotation are similar to those observed in standard discharges. In addition, global plasma parameters, such as the plasma current I_p, the pinch parameter Θ, the resistive loop voltage V_{res} and the plasma density and temperature are maintained by AFS at values comparable to those obtained in thick shell devices, indicating that the confinement with AFS is similar to that in thick shell RFP operation. In this work, we present the first preliminary results of the simultaneous use of AFS and current profile control with the pulsed poloidal current drive (PPCD) [2] technique.

Experimental set-up

The experiments presented here have been obtained at shallow reversal (F = -0.22 , Θ = 1.6) at a plasma current of approximately 75 kA with AFS in the intelligent shell configuration [3]. Magnetic sensors measuring the radial and toroidal components of the perturbed magnetic fields are used to measure the amplitude and helical angular phase velocity Ω of both the internally resonant TMs and of the non-resonant internal and external RWMs (with poloidal and toroidal mode numbers $m = 1$, $-15 \leq n \leq 16$ respectively). The toroidal rotation of the impurity ions in the plasma is determined through measurements of the Doppler shift of the OV spectral line at 278.1 nm. Three monochromators are used to monitor the influx of high Z materials from the first wall (Fe and Cr) and from the limiters (Mo) by looking at the spectral lines from Mo I, Cr I and Fe I. A SXR detector is used as an indicator of PPCD performances. Single PPCDs of different amplitudes (inductively applied poloidal electric field at the edge $E_\theta(a)$ in the range 1.5 - 3 Vm^{-1}) are fired during the current flat top.

Experimental observations

The comparison of a standard discharge (with AFS) and one where PPCD was applied at t = 20 ms, corresponding to $E_\theta(a)$ = 1.5 Vm^{-1}, is shown in figure 1. The plasma response to the PPCD is quite typical: the equilibrium is temporary changed to Θ = 1.77 and F = -0.89, the plasma current increases slightly while the SXR signal increases significantly. The resistive loop voltage decreases indicating a reduction of the plasma resistivity and therefore a higher electron temperature. It is interesting to note that, after PPCD, all the global plasma parameters returned to their reference values, thus indicating that the plasma condition after the application of PPCD is as good as before it. Figure 2 shows the line emission of high Z impurities together with the SXR and the H_α signals averaged over different PPCD discharges: the emission activity is quieter being characterised by fewer and smaller peaks.

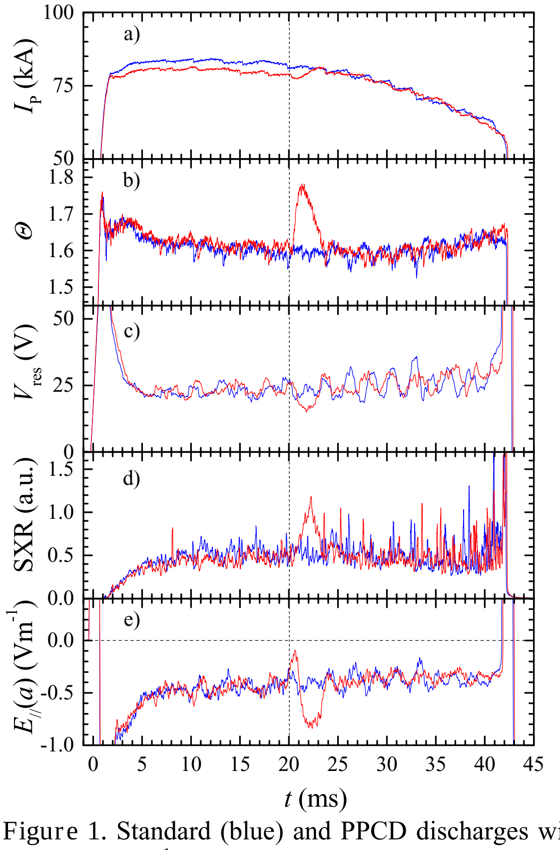

Figure 1. Standard (blue) and PPCD discharges with E_θ of 1.5 Vm^{-1} (red). (a) Plasma current; (b) Θ; (c) resistive loop voltage; (d) SXR signal; (e) parallel electric field.

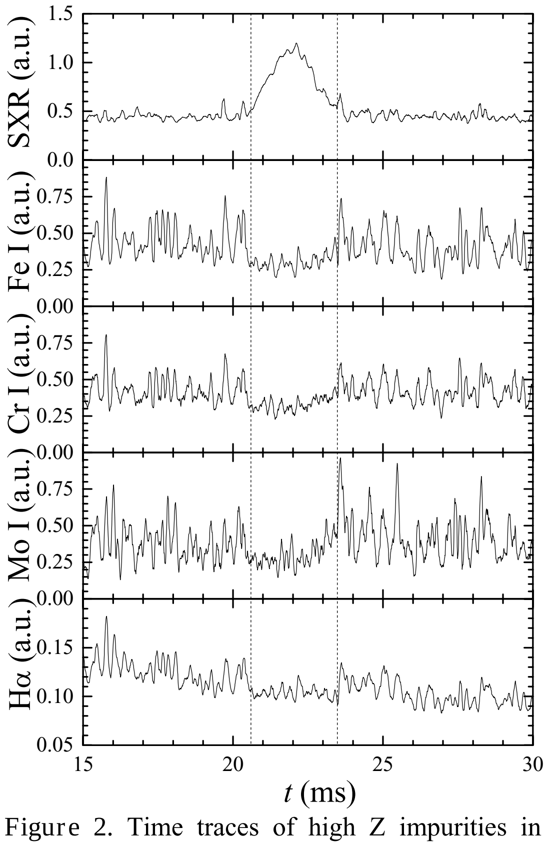

Figure 2. Time traces of high Z impurities in the plasma together with the SXR and H_α signals for a discharge with PPCD (1.5 Vm^{-1} poloidal electric field).

Without PPCD, the influx of wall impurities, as measured by the line emission of Fe, Cr and Mo, is highly fluctuating, occurring in intermittent bursts: similar events have been observed in edge turbulence measurements [4], and explained by coherent electrostatic vortex structures, occurring after magnetic reconnection events. These structures give a significant contribution to anomalous particle transport in the edge plasma. Since the impurity influx from the wall is caused by plasma wall interaction it is plausible that the quiet phase indicates also reduced intermittent turbulence bursts in the edge plasma region, and thus improved particle confinement. This conjecture implies improved confinement of high energy electrons which is consistent with the increase in the SXR intensity observed. Possible effects explaining the quiet period are: (i) PPCD may directly suppress the magnetic reconnection through current profile changes and (ii) the increased magnetic shear due to the deeper reversal may act to suppress the electrostatic turbulence. A key parameter for PPCDs is the parallel electric field at the edge $E_{//}(a)$, the condition $E_{//}(a) > 0$ Vm^{-1} being required for the best performances [5]. The applied $E_\theta(a)$ was increased to 2 Vm^{-1} resulting in $E_{//}(a) > 0$ Vm^{-1} and in a significantly higher SXR intensity as shown in figure 3 (together with data from figure 1 for comparison).

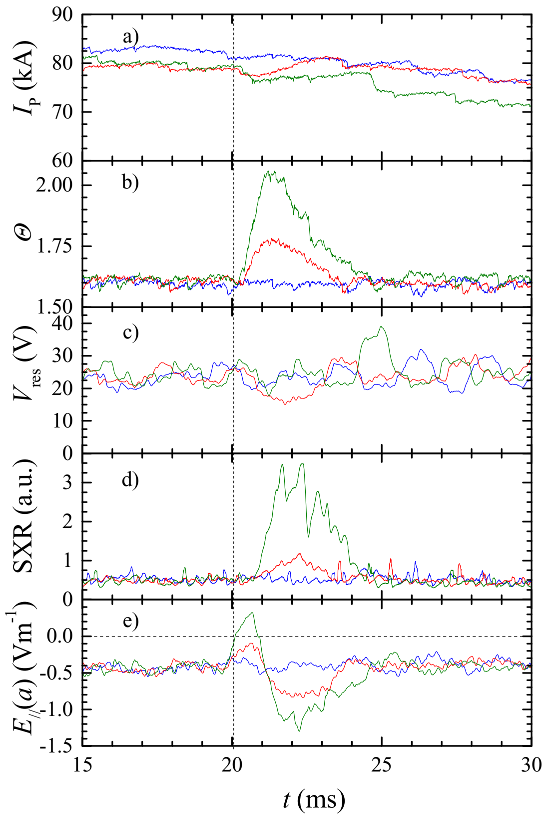

Figure 3. Standard (blue) and PPCD discharges with E_θ of 1.5 Vm^{-1} (red) and 2 Vm^{-1} (green). (a) Plasma current; (b) Θ; (c) resistive loop voltage; (d) SXR signal; (e) parallel electric field.

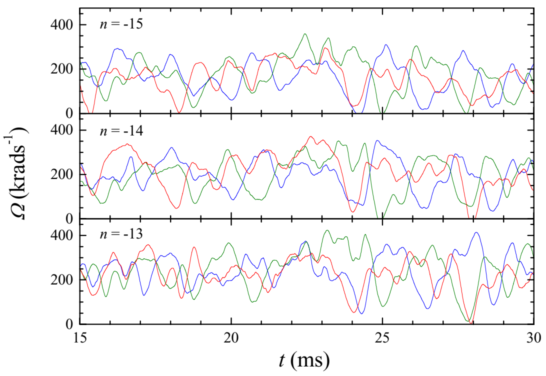

Figure 4. Helical angular phase velocity of three TMs for standard (blue) and PPCD discharges with $E_\theta(a)$ of 1.5 Vm^{-1} (red) and 2 Vm^{-1} (green).

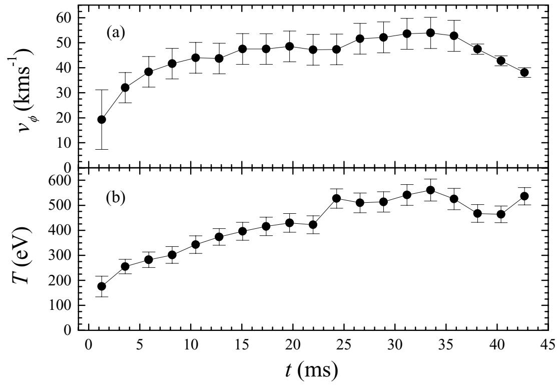

Figure 5. OV toroidal velocity (a) and temperature (b) for discharges with PPCD ($E_\theta(a) \approx 1.7$ Vm^{-1}).

No increase in the plasma current is observed and after the PPCD the plasma global parameters are slightly different than those before the PPCD (for example V_{res} increases from 20 to 37 V). A further increase of the applied $E_\theta(a)$ (3 Vm^{-1}) worsened the performances immediately causing a drop in I_p from 81 to 73 kA and was followed by spikes in V_{res} and in the metal impurity influx, and by a premature discharge termination (34 ms instead of 42 ms long). The SXR showed large crashes in 100 % of the discharges compared to 60 % for $E_\theta(a)$ = 2 Vm^{-1} and no crashes for $E_\theta(a)$ = 1.5 Vm^{-1}. The effect of the combined action of AFS and PPCD on the dynamic of the TMs is shown in figure 4. While large fluctuations in Ω are observed for all the discharges, there is no clear indication of acceleration in Ω as a result of PPCD. The plasma rotation velocity estimated from the OV emission (see figure 5) showed no increase of the toroidal rotation velocity either. The OV temperature increased at the end of PPCD. Ion heating is thought to be driven by MHD turbulence and typically the end of PPCD is accompanied by a burst in MHD activity. The fact that OV ions are heated after the PPCD is an indication that PPCD is applied successfully. In previous PPCD experiments in EXTRAP T2R it was observed that in unsuccessful PPCD ion heating occurred earlier in time than in successful ones (and no SXR increase was observed) [6].

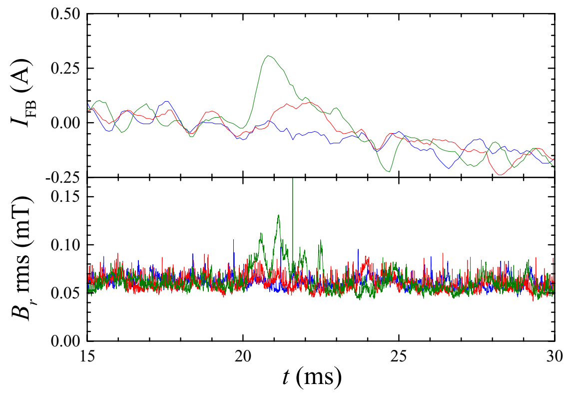

Figure 6. Discharge with FB (blue) and with PPCD: E_θ of 1.5 (red) and 2 (green) Vm^{-1}. Top: current in the FB active coil. Bottom: Rms value of the m = 1 perturbed magnetic field.

Figure 6 shows the effect of PPCD on the AFS system: when PPCD with $E_\theta(a)$ = 2 Vm^{-1} is applied, the current in the coils of the AFS system increases. The increased current is capable of counteracting the larger amplitude of the m = 1 radial component of the perturbed magnetic field associated with the change in the equilibrium: the most internally resonant TMs becomes non resonant and start therefore to grow.

Conclusions

The results presented here indicate that it is possible to operate an RFP in a regime of suppressed RWMs amplitude in improved confinement scenarios. Future activity will focus on the development and optimization of PPCD scenarios with AFS at shallow reversal and at deep reversal (initial Θ of approximately 2) which have provided the best confinement improvements in EXTRAP T2R already with $E_\theta(a)$ of 1.5 Vm^{-1} [6].

References

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