STUDIES ON MAGNETIC DYNAMICS IN RFX

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Abstract

The RFP configuration is maintained by an intrinsic dynamo mechanism associated to resistive MHD tearing modes. These dynamo modes are responsible for field line stochasticity and have a strong influence on plasma confinement. RFX results relevant to the subject are discussed both in terms of the influence of the magnetic boundary and of the characteristics of the RFP enhanced confimenement regimes. The dynamo modes are often locked in phase and to the wall, which spoils the stabilising effect of the conducting shell and leads to severe plasma-wall interactions. The driven rotation of the locked dynamo modes has been studied in RFX by means of a new Toroidal Field Modulation System. A rotating toroidally localised perturbation of the toroidal magnetic field couples to the modes and induces their rotation

I. DYNAMO MODES AND CONFINEMENT REGIMES IN THE RFP

In the Reversed Field Pinch (RFP) the internal poloidal currents necessary to generate the magnetic configuration are maintained by an intrinsic dynamo mechanism, which is associated to MHD current driven tearing instabilities resonant internally to the field reversal radius [1]. The consequent magnetic fluctuations lead to magnetic field stochasticity in the plasma core, thus playing an important role in particle and energy transport. Indeed enhanced confinement regimes have been found in RFPs [2-4] in connection with the mitigation of the dynamo activity, as deduced from both the toroidal flux generated by the plasma and the spectrum of the dynamo modes [5].

In the RFX experiment ($a = 0.46$ m, $R = 2$ m) [6] the self-generated toroidal flux is larger than in other RFPs with similar size, such as MST. This is interpreted [5,7] in terms of different marginal stability limits due to the larger distance between the plasma and conducting stabilising shell ($b/a=1.18$ in RFX). A consequence of the larger plasma-shell distance in RFX could be the systematic locking in phase and to the wall of the dynamo modes (dubbed LDM for locked dynamo modes). The LDM in RFX are made of a spectrum of $m=1$ $n \geq 7$ internally resonant and $m=0$ modes resonant at the field reversal radius, as shown in fig.1(a). The LDM, beside causing magnetic stochasticity in the plasma core and interfering with the achievement of enhanced confinement regimes, result in a large stationary helical deformation of the plasma, which is responsible for severe plasma-wall interaction [8].

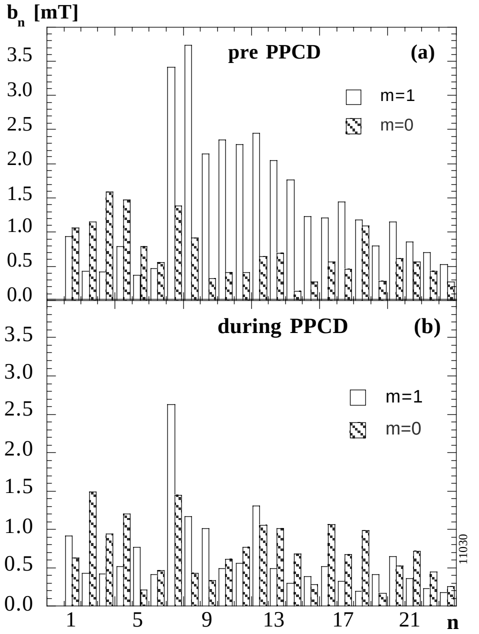

Fig. 1. Typical n-spectra of m=0,1 modes: (a) during a standard pulse and (b) during a PPCD experiment

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[1] Also at INFM unità di Padova

A spontaneous enhanced confinement mode is seen also on RFX [5,7] in correlation to reductions of the LDM amplitude. It has been dubbed α-mode because one of its signatures is a reduction of the self-generated toroidal flux, which is seen as a sudden change in the α parameter of the μ&p model [9] [1]. The α-mode may last for several energy confinement times and is associated to a change of the LDM spectrum towards a single helicity state, similarly to the enhanced confinement modes seen in other RFPs.

Reductions of the dynamo modes amplitude comparable to that of the α-mode are induced in RFX during pulsed poloidal current drive (PPCD) experiments, where the dynamo is controlled by applying a transient poloidal voltage. As soon as the voltage pulse is applied, the plasma reacts with a prompt reduction of the dynamo, as shown e.g. in fig.1(b). At the same time, an increase of the energy confinement time is seen, which is due to a reduction of the core thermal conductivity [10]. This is consistent with the picture of a core plasma confinement which, being governed by parallel transport along stochastic field lines, greatly improves by reducing the amplitude of the modes. Moreover, perturbation studies with on-axis and off-axis pellet injection give evidence that the hotter plasma core achieved during enhanced confinement modes may play a role in their self-sustainment by reducing the growth rate of the modes [7].

II. THE TOROIDAL FIELD MODULATION SYSTEM

The wall-locking of the dynamo modes, due to field diffusion into the conducting shell, spoils its stabilising effect on the modes themselves. This on the one hand may worsen the core confinement and, on the other hand, causes a larger plasma wall interaction because of the increasing radial magnetic field at the edge [11]. Hence, in parallel with the experiments on the reduction of LDM (such as PPCD), it is very important to develop new techniques to actively control the LDM position. To this end, first a test has been done by unbalancing the current in the twelve sectors of the toroidal field winding, which proved effective in coupling to the LDM and determining its toroidal location with high reliability [12].

This encouraged us to develop the Toroidal Field Modulation (TFM) system [13] for the driven rotation of the locked dynamo modes. The TFM system generates an independent current modulation in the twelve sectors of the toroidal field winding, using high voltage and current Gate Turn-off Thyristor as switching devices. In this way it is possible to apply a rotating toroidally localised perturbation of the toroidal magnetic field (dubbed RTFM for rotating toroidal field modulation) which couples to the LDM and induces their rotation. The non-homogeneous current distribution produces local radial and toroidal magnetic field inside the shell because of the high flux which can pass through the large equatorial gaps of RFX. As an example, in a vacuum shot, an increase of 1 kA of the current in 6 adjacent toroidal field winding sectors modulated to generate a rotating error field, produces a B_{ϕ_even} with a fundamental component (m=0, n=1) and with an amplitude (as measured by the probes) between 8 and 12 mT.

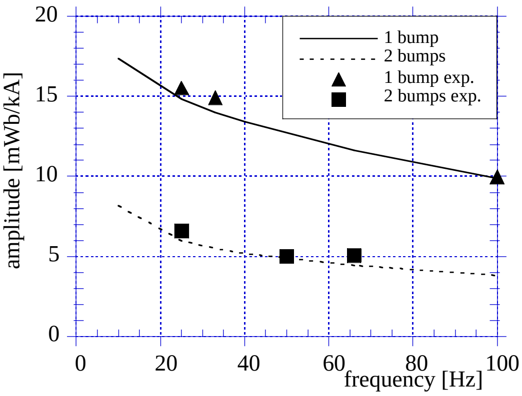

Fig.2. Modulation of the toroidal flux produced by a 1 kA current unbalance. Computed and experimental data.

Finite element electromagnetic analyses have been carried out to compute the modulation along the toroidal direction of the toroidal flux linked with the vessel. The flux modulation, produced with 1 kA of current unbalance modulated with different frequency, is shown in fig 2. Two cases are shown, related to the experimental conditions in which one

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[1] The μ&p model magnetic field profile assumes the normalized parallel current density $\mu \equiv \mu_0 J_{//}/B$ to be $\propto 1-(r/a)^{\alpha}$

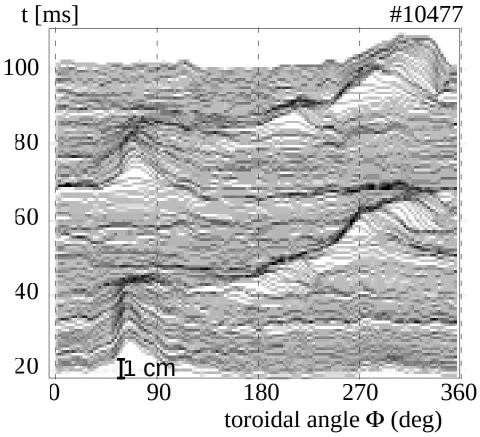

Fig.3 Induced LDM rotation in RFX: radial amplitude of the helical perturbation versus Φ for several times during the pulse. The curves (0.5 ms averages) are vertically shifted to show the evolution.

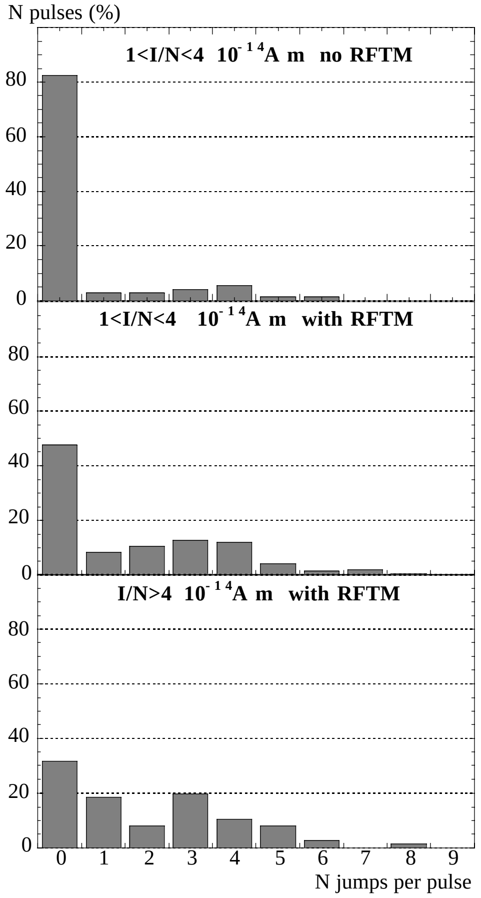

Fig.4 Mode rotation per pulse statistics. From top: no RTFM, with RTFM low I/N, with RTFM high I/N

and two rotating local toroidal field enhancements (bump) were generated along the torus, so that n=1 and n=2 are respectively the fundamental harmonics produced by the external current unbalance. The figure shows that the diffusion of the magnetic field in the equatorial gap increases the local flux generation at lower frequency rotation; the double bump case also produces a lower flux inside the vessel.

The RTFM can apply modulations with adjustable duty cycle and a period ≥ 2 ms, so that the maximum toroidal rotation frequency for an n=1 mode is 500 Hz, corresponding to a toroidal velocity of 6.2 km/s. The maximum current unbalance which can be produced in the toroidal sectors is about 2 kA.

III. FIRST RESULTS OF RTFM EXPERIMENTS

The RTFM shows to be most effective when applying perturbations with relatively slow rotation, i.e. one toroidal turn in 30-40 ms. In this way continuos rotations or multiple toroidal jumps of the LDM are often induced [12].

A typical result is shown in Fig. 3. The locking position is stationary at ≈70° during the first 40 ms. Then the rotating perturbation couples to the mode and causes a complete rotation around the torus. The same pattern is repeated between 65 and 100 ms. It is worth noting that not all the n modes contributing to the LDM rotate: the main mode (typically n=8) remains stationary, hence the region of maximum perturbation is seen to move approximately around an helical path. The result is that the localised perturbation does not move in a travelling-wave fashion: the position of the nodes of the wave remains unchanged, while the peak-to-peak amplitude is reduced in one toroidal region and increased in another region.

The probability of inducing rotations of the LDM is an increasing function of the I/N parameter (plasma current / line density $N \equiv \pi a^2 n$) and depends on the amplitude of the applied RTFM. This is shown in fig. 4 and 5. The number of mode jumps and rotations in a shot has been evaluated as the number of locking movements, during the quasi-stationary phase, larger than 30 degrees. In fig. 4 the statistics of locking movements are reported comparing shots without and with the RTFM; the shots with RTFM have been also divided in high and low I/N. The shots with RTFM show a statistically significant increase of the locking movement and this effect is more evident at low density. The correlation between the average number of locking movements during RTFM and the flux modulation amplitude, normalised to the plasma current, is shown in fig. 5 for high and low I/N: the number of movements increases with the normalised flux modulation amplitude and, as already shown, is larger at high I/N.

Although only a limited number of experiments has been performed to date, some beneficial effects on the plasma performance have been seen. The possibility of avoiding the occurrence of carbon blooms when operating at currents of ≈ 1 MA is reported in a companion paper at this conference [14]. In some cases the rotations or the jumps of the LDM have been found to be accompanied by large reductions of the modes amplitude, the α parameter and the loop voltage and increases of the electron temperature and the energy confinement time (see fig. 6). The phenomenology is very similar to that of an α-mode. Conversely the reduction in mode amplitude is comparable to that observed with PPCD and, indeed, the confinement improvement is of the order of 50%, which opens encouraging prospects of inducing enhanced confinement regimes with the RTFM.

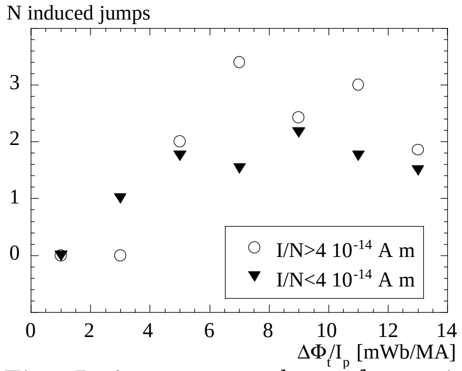

Fig. 5 Average number of rotations during RTFM experiments Vs. normalised flux modulation.

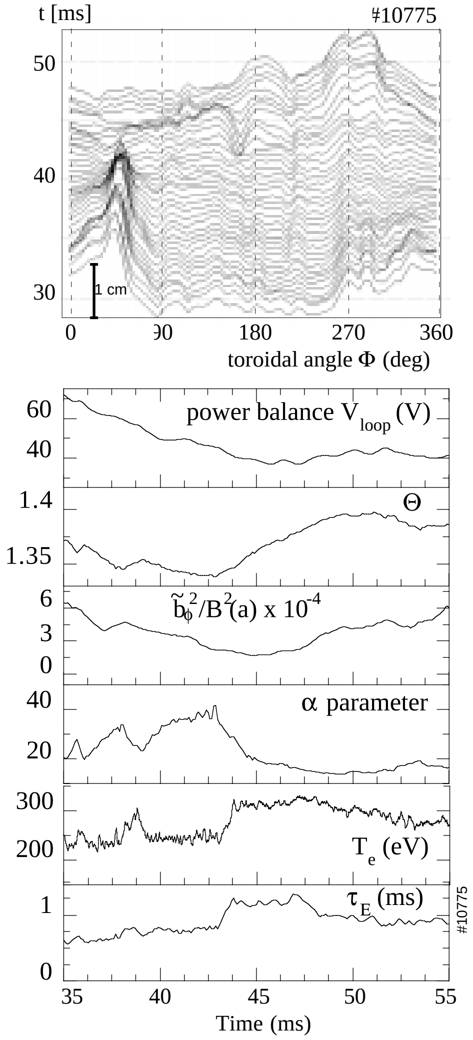

Fig.6 Waveforms of some plasma parameters during RTFM. The LDM decrease in amplitude and change position after ≈40 ms, as shown by the multiple perturbation profile in the top frame

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