MAGNETIC FIELD CONFIGURATION AND LOCKED MODES IN RFX

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1. Introduction

The Reversed Field Pinch experiment RFX (R_0=2m, a=0.46m) is presently operated at approximately 500 kA of plasma current to establish confinement properties at low levels of energy and power. The magnetic configuration is presently characterized by rather large distortions that, like in other RFP experiments [1], play an important role in determining energy losses. Active control of the poloidal field configuration has been one of the main experimental objectives so far, and plasma behaviour has been improved by centering the plasma column and by reducing the stray field at the poloidal gaps; nevertheless, unstable MHD modes grow during the pulse and lock to the first wall, producing highly localized heat fluxes on it.

First, the paper deals with horizontal plasma equilibrium, that has been controlled by means of a bias vertical field, since the long time constant of the stabilizing shell prevents fast control during the pulse. Then the field perturbations are analyzed and the characteristics of mode locking are described. Finally, the origin of mode locking and the effect of field errors on plasma confinement are discussed. More details are given in ref. [2].

2. Toroidal equilibrium

For the present pulse length ≤ 0.1 s, the toroidal equilibrium is determined by the shell and by the bias vertical field applied prior to the discharge, that is limited to $<9\div10$ mT because of gas breakdown problems. The position of the last magnetic flux surface fully contained by the first wall is computed using local magnetic field and global poloidal flux measurements. In particular it is possible to measure the plasma horizontal and vertical shift in 6 toroidal positions, evenly spaced around the torus. The horizontal position can also be estimated from the density profile using the 8 chord interferometer measurements [3]. Magnetic and interferometric shift measurements are in good agreement and show that the plasma equilibrium position is consistent with the applied bias vertical field: at 0.5 MA of plasma current, with ≈ 8 mT the shift is ≈ 1 cm,, with no vertical field it is ≈ 3.7 cm.
The toroidal loop voltage on axis, $V_t(0)$, is clearly correlated with the horizontal shift (fig.1).

3. Field errors and mode locking

3.1 Sources of errors

The main sources of deviation from axial symmetry in RFX are:
1 - the 48 toroidal field coils, giving rise to an almost steady m=0, n=48 radial field ≈1.5 mT
2 - the 72 vessel poloidal stiffening rings; they produce an m=0, n=72 radial field that, during a fast aided reversal, can reach ≈30 mT; during flat top it vanishes if flux is conserved;

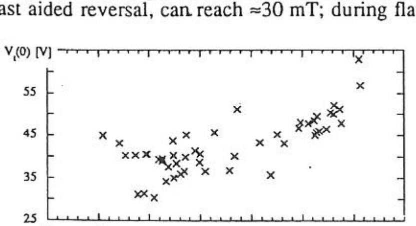

Fig. 1: toroidal resistive loop voltage $V_t(0)$ as a function of horizontal shift

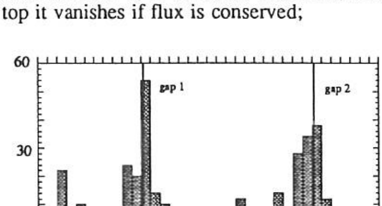

Fig.2: statistical distribution of the toroidal position of TF perturbations.

3 - the two vertical gaps in the shell; they produce an m=1 radial field at the plasma, having a wide n spectrum and going down from 20 to 2 mT when applying an optimum control.
In the presence of magnetic fluctuations from plasma instabilities, eddy currents are created on conducting structures surrounding the plasma so further errors are produced by electrical discontinuities in the shell wall, mainly the two vertical and the two equatorial gaps.

3.2 Magnetic field locked perturbations: space and time analysis

RFX is equipped with a set of 508 probes located inside the shell [4]; the toroidal magnetic Field (TF) component is measured by two toroidal arrays of 72 TF probes, located near the internal and external horizontal gaps and by eigth poloidal arrays of 8 (or 16) TF probes. Due to the presence of the metal vessel between plasma and probes, the cut off frequency is less than 5 kHz. The radial field at the two gaps is measured by four saddle coils, and by two new sets of 16 probes each, measuring the B_r component in 16 poloidally equispaced locations.
In all the pulses, the toroidal magnetic field exhibits large distortions along the torus; in most cases the distortion locks to the wall after the beginning of the RFP phase and remains at the same location and with the same shape for tens of ms. There are preferred locations for locking, as shown in fig. 2 that refers to 350 unselected pulses; locking at gaps is more frequent in poorly controlled pulses. Fig. 3 shows measurements near the inner equatorial gap for a pulse whose plasma current waveform is shown in fig.6.
Moving along the toroidal direction, the perturbation is typically seen as a double swing of the TF and is always of opposite sign at the two horizontal gaps. The distribution in poloidal direction, measured by the poloidal arrays, always displays a prevailing m=1 mode, so the TF perturbation consists of a helical pattern along the torus with total length of 30 to 50 degrees in the toroidal direction and typically two turns in the poloidal direction.

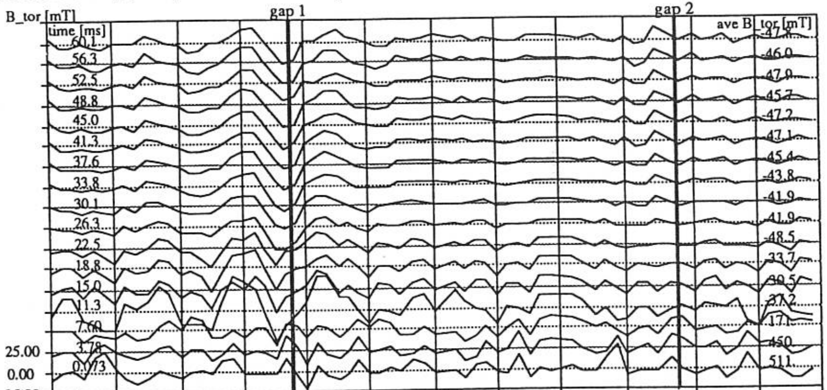

Fig.3: toroidal field deviation from average field at different times: perturbation locked on gap 1; pulse nr 3507

The perturbation amplitude can be as large as 15% of the poloidal field and 100% of the TF at the wall; sometimes, in the perturbed zone, the TF does not reverse at all. The local equilibrium position of the plasma is severely affected by these phenomena: a preliminary estimate gives, for a 20 mT TF perturbation, a plasma shift of ≈2 cm (confirmed by local electron density measurements) and a radial field of ≈4 mT.
As far as the two vertical gaps are concerned, fig 4 shows the radial field component from the 16 probes; when a perturbation locks far from the gaps (left), the radial field is almost equal at the two gaps, unlike when modes lock at gap 1 (right). In any case, modes with m>1 are present at the gaps, whose origin is attributed to the controlling action of FS amplifiers, that are driven to compensate for the m=1 field error. The radial field at plasma edge is typically 1/3 of that measured at the gap.

3.3 Applied field corrections

Active control of the currents in the sixteen FS coils allows the magnetic configuration to get as

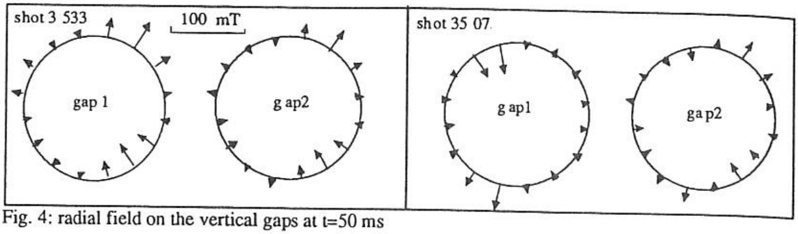

Fig. 4: radial field on the vertical gaps at t=50 ms

close as possible to axisymmetry, with a typical delay of 20 ms. It is apparent that loop voltage depends on stray field at the gap B_V [5]: the loop voltage increase is typically 10V for B_V=20 mT. On the other hand, if the horizontal shift is larger than 2 cm, the local stray field does not significantly affect the loop voltage.

To reduce B_V during the first 20 ms, we superimposed to the natural FSW currents a current distribution which produces in the poloidal gap regions a field opposite in sign to the field error, by inserting in series to each FS coil an inductor or resistor of proper value. Two equivalent groups of shots, before and after the insertion of passive elements, have been compared over the first 10 ms of plasma current: the correction reduced the maximum field error Bv, measured by the saddle coils on the two gaps, from 30 ± 8 mT to 8 ± 2 mT and reduced the plasma wall interaction on the gap region, as observed by CCD cameras.

3.4 Magnetic mode analysis

The deformation of the toroidal field configuration has been analysed in terms of Fourier modes. From Fourier analysis of the sums and differences of the two toroidal arrays of probes, the deformation results to be made up of modes with odd m and with n=7 to 15, with prevalence of the mode n=8. A typical spectrum is shown in fig.5; the main features of it are common to all pulses. Mode n=24 is associated to the combined effect of TF windings and vessel rings. Signals from the poloidal arrays of probes show that the poloidal mode number is m=1, and that the modes are resonant inside the reversal surface: the sharp variation of amplitude between n=6 and n=7 suggests an on-axis q value between 1/7 and 1/6.

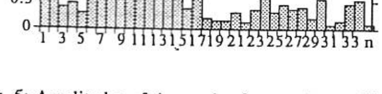

Fig. 5: Amplitudes of the modes from n=1 to n=35 (odd m), averaged over the flat-top phase; pulse nr 3507.

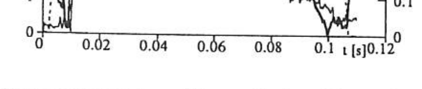

Fig. 6: Time behaviour of the amplitudes of the modes n=8 and n=11 (odd m), superposed to the plasma current waveform; pulse nr 3507.

The spectrum and the time history shown in fig. 5 and 6 can in general be described in the following way:

a) before the reversal, the passage of q through the rational values causes the excitation and subsequent rapid decay of the corresponding resonant modes with (m=1,n=1/q), and sometimes also (m=2,n=2/q) and (m=3,n=3/q). As F approaches 0, many resonant surfaces develop in the plasma, so that many modes are excited simultaneously, and then decay when the RFP configuration is established. When the reversal happens at high levels of plasma current, this event is correlated with a transient drop in plasma current.

b) once the configuration is established, the localised deformation grows, and so do the modes composing it. This growth is usually strong before the plasma current reaches its maximum;

subsequently the time history depends on various parameters, such as pulse programming and field error correction. In general, phase b is not directly affected by the events in phase a. The mode phases are almost constant (locked at the wall) from the onset of the RFP onwards.

4. Discussion

4.1 Mode locking

The presence of large wall-locked magnetic disturbances is an indication of quite a strong interaction of plasma dynamics with the imposed boundary conditions.
The fact that this localized disturbance appears preferentially located at one of the poloidal gaps, together with the observation of large amplitude radial magnetic field at these positions, suggests that its origin is due to poloidal gap field errors as already observed in the MST experiment [1]. Theoretical considerations support this explanation because poloidal gap field errors are characterized by the same kind of spectrum as the fluctuations typical of RFP dynamics [6]. Thus tearing modes can be directly fed by this kind of magnetic field error.
Moreover, the effects of the 8 cm wide vacuum region which separates plasma from the shell might play a role in explaining the fact that such disturbances never appear to rotate in the laboratory frame, as is most typical in other experiments [7][8][9][10][11]. In fact, this kind of boundary condition could be responsible both for slowing down of rotating tearing modes and for destabilizing on-axis internal ideal modes locked in the laboratory frame [12].

4.2 Effects on loop voltage

The plasma horizontal shift reduces plasma cross-section: for instance, a 30 mm shift in RFX produces a 15% increase in Joule losses, i.e. a 3 MW increase in input power and a 6V increase in loop voltage, that is less than measured (fig. 1). The further loss may be attributed to shift enhanced pertubations.
As far as magnetic perturbations are concerned, when locking is at gap, by means of an electromagnetic model of the shell [13] it is possible to calculate the total flux Φ_g through a gap as a function of the measured m=1 radial field at the gap Bv. For a wide frequency range (5 to 50 Hz), they are proportional and the "effective plasma-wall interaction area" is

$$A_g = 2\,\Phi_g\,n_g\,/\,B_\theta(a) = 0.35\,B_v\,/\,B_\theta(a)$$

For instance, a 10% stray field corresponds to $A_g = .035\ \mathrm{m}^2$ and by taking the measured parallel fluxes at the plasma edge (approx. 300 MW/m^2 and 100 MW/m^2 respectively on the electron and on the ion drift side [14]), a power loss of 7 MW is calculated, corresponding to a loop voltage increase of 14 V, to be compared to ≈10V from experimental data [5].

5. Conclusions

Magnetic measurements in RFX, supported by many other diagnostics, evidence that MHD unstable modes lock to the wall in every pulse. The preferred locking position is at the two vertical gaps, where relatively large radial fields are present and are enhanced by the locking itself. A tendency for better behaviour is observed when the modes lock away from the gaps (now only ≈ 30% of pulses); to avoid locking at gaps, feedback control of the poloidal magnetic field and gap shielding are planned to allow further optimization studies and to spread the distribution of the heat flux onto the wall, so that higher currents can be reached on a regular basis.

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