Effects of Shell Gap Modifications on RFX Plasma Behaviour

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1. Introduction

All pulses of RFX evidence wall locking of MHD modes [1]. Rotation of phase locked modes has been obtained in MST by reducing the field errors at the shell vertical gap [2]; significant confinement benefits derived from these actions. In RFX, the influence of field errors at the shell vertical gap on confinement is clear since they can be varied by acting on the equilibrium control, whereas no information is available on effects of equatorial gap and port errors, since they depend only on plasma behaviour and cannot be varied on purpose. Since the vertical ports on the shell give a little contribution to field errors [3], it has been decided to act on both the vertical and the equatorial gap errors. The feedback control of currents in the field shaping coils has been improved [4] and one of the two vertical gaps and the outer equatorial gap of the shell have been short-circuited.

Since the error reductions did not succeed in unlocking modes (with some exceptions that will be discussed in the last section), the paper presents the effects of gap modifications mainly in terms of loop voltage variations. In the first section, the relationships between loop voltage and magnetic perturbations are given; then the field quality improvements after closing the gaps are shown and their effects on loop voltage are discussed. Finally, some evidences of temporary, low-speed mode rotations are shown, whose enhanced rate can be also related to shell modifications.

2. Sensitivity of loop voltage to magnetic perturbations

Owing to several improvements on the gap field error compensation system (introduction of feedback control, shorter response time of the amplifiers), the correction of field errors at the vertical gaps is now very effective. In the present range of field errors (B_r at the shell surface is always less than 6-8% of the poloidal field B_θ and on the plasma surface it is typically less than 2-3%) no clear correlation with the loop voltage is found. The significant dependence presented before [5] is overcome, since errors are kept within the range where their influence on loop voltage is negligible.

The sensitivity of the loop voltage to the amplitude of the stationary field perturbation (mode locking to the wall) has also been analysed. Two parameters have been chosen to quantitatively characterise the perturbation: the peak-to-peak amplitude of the toroidal field undulation along the toroidal coordinate ΔB_ϕ and the energy of the modes m=1, n=7 to 15. Both parameters show a very weak correlation to the loop voltage; the loop voltage is slightly lower (1.5 V on average) in the case of locking located far from the gaps. It is worth noticing that ΔB_ϕ ranges between 20 and 45 mT in all the pulses and thus no data are available for the case of small perturbations.

These results suggest that the locked magnetic perturbation is "saturated"; its amplitude mainly depends on machine parameters like the distance between plasma column and stabilising shell.

3. Reduction of magnetic perturbations

Field error correction at the equatorial gap. The outer equatorial gap of the shell has been short-circuited by means of 96 copper bars, bolted to the shell halves as near as possible to the insulating gap. The radial field through the equatorial gap is measured by means of probe coils, located around the 12 pumping ports, which also link the flux due to eddy currents in the stabilising shell, in the vacuum vessel and in the pumping port itself. A numerical model of all these conductors has been developed to calculate the radial field at the plasma boundary as a function of the flux measured by the probes; the short-circuiting bar effect can be also taken into account. The experimental results show that the short-circuit produced a clear reduction of the fast (>500 Hz) radial field fluctuations: the peak-to-peak amplitude, calculated at the plasma edge and averaged on a number of comparable pulses, has been reduced from 6.3 mT to 2.3 mT during the start-up phase. A similar reduction applies to the fast fluctuations during flat-top, but in this phase the radial field is mainly composed by low frequency (<50 Hz) harmonics, and marked differences between signals from adjacent probes are always measured close to the toroidal position of the locking [3]. Since the electromagnetic time constant of the short-circuiting system is around 5 ms for the horizontal field, frequency components below 200 Hz are not attenuated; in fact, no variation of the low frequency radial field components during flat-top has been observed after modifying the equatorial gap.

Field error correction at the vertical gaps. To reduce the stray field through the vertical gaps, in particular during the setting-up phase when the feedback efficiency is lower due to the limited bandwidth of the control amplifiers, one of the two vertical gaps has been short-circuited by means of metallic plates [6] and the currents through them are routinely measured. Their distribution in the poloidal direction gives a useful information on the actual distribution of the currents induced in the stabilising shell. Both gaps are equipped with two saddle coils which give a measurement of the vertical field component on the inner surface of the shell. The open vertical gap is also equipped with 16 radial field probes located at the outer surface of the shell.

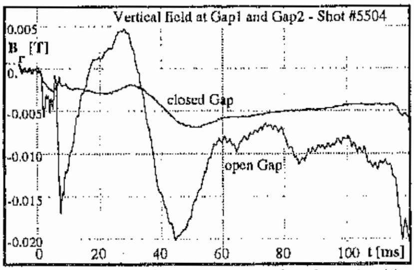

Fig.1 Field Error at the vertical Gaps after short-circuiting Gap1. Locking is far from both the Gaps

Fig. 1 shows the effect of the short-circuit in a pulse where the locking is far from both gaps. Before gap closure, the two signals were approximately the same; presently the maximum amplitude of the radial field on the closed gap is reduced by a factor of three and a very effective filtering action is evidenced on fast fluctuations. With locking far from both gaps, the cosθ (horizontal) component of the radial field at the open gap is negligible and the sinθ (vertical) component is the predominant one. Its temporal evolution is very similar to the cosθ component of the current distribution in the short-circuit.

Locking still occurs sometimes near the closed gap, in spite of the field error reduction, but now the region near the open gap exhibits a higher number of locking events. When the locking is near to the open gap, the cosθ component of the radial field at this gap becomes significant and can be even larger than the sinθ component, reaching 10% of the poloidal field. Since the RFX feedback system is not able to produce horizontal field, such component is due to the locking and not to a lack of equilibrium control.

"Matched Reversal" mode. The "matched reversal" mode is a particular setting up of the RFP configuration, in which the poloidal voltage around the plasma boundary is kept near to zero during the whole phase of toroidal current rise. Compared to the "aided reversal" mode, where the toroidal field at the edge is quickly reversed when the plasma current has already reached a level close to the final one, the "matched reversal" gives the advantages of lowering the eddy currents (and consequent field ripple) induced on passive elements and of reducing the plasma-wall interaction during the reversal phase, where losses are relatively large due to the poor confinement. On the other hand, the "matched reversal" mode precludes operation with

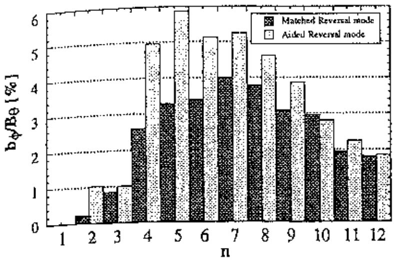

Fig.2 Amplitude of toroidal field modes with aided and matched reversal.

large vertical bias field, so reducing the possibility of centring the plasma column with respect to the first wall.

During the startup phase, before reversal, modes with increasing n become resonant in sequence, and show a growth followed by a decay [3]. The matched programming has produced a beneficial effect on the maximum amplitude reached by these modes, both in absolute and relative terms. Fig.2 shows the toroidal field modes amplitude, normalised to the poloidal field, with aided and matched reversal. A reduction of 30% in matched discharges is clearly observed for the strongest modes (n=4-9). Furthermore, the same modes are excited at a much lower level of plasma current than in aided discharges, so that in absolute terms a reduction of more than 50% is achieved. Nevertheless, after reversal no reduction is observed on the amplitude of the locked pertubation.

4. Effects on confinement

An improvement has been observed in the average dependence of loop voltage on the I/N parameter (ratio between toroidal plasma current I and average line density N) after the machine modifications: the most recent data show an average decrease of 3-5 V on the loop voltage (fig.3). Fig.4 shows the dependence of loop voltage on the magnetic shift; after the short circuit of the two gaps it is possible to operate with a larger horizontal displacement of the plasma column without significantly increasing the loop voltage. Since in RFX the plasma horizontal position is only controlled by a bias vertical field, a lower bias could be used, allowing gas breakdown at a lower toroidal field. This improvement opened the possibility of operating with the above mentioned "matched reversal mode". As discussed in Sect. 3, the short-circuit of the outer equatorial gap significantly decreased the high frequency magnetic fluctuations in the outer equatorial region; this can partially justify the reduction in loop voltage and can explain why the minimum in loop voltage is now obtained for a larger horizontal displacement, i.e. when plasma is shifted towards the short-circuited gap.

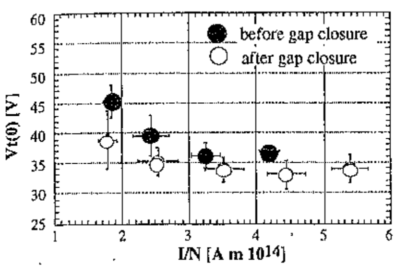

Fig.3 Loop voltage Vs. I/N for well centred discharges in the range (500 kA>I>600 kA).

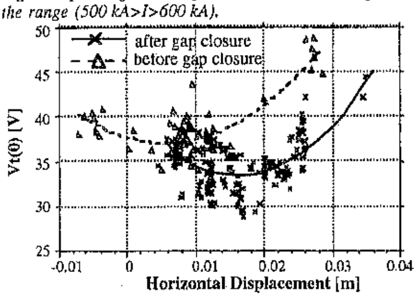

Fig.4 Loop voltage Vs. Horizontal displacement for discharges in the range (500 kA>I>600 kA) and I/N=3 10^{-14} A m. A parabolic fit of data is also shown.

5. Mode locking and rotation

Despite the presence in every discharge of RFX of modes locked both in phase and to the wall, some mode rotation events have been observed by high-pass filtering the magnetic field signals with a 100 Hz numerical filter. Measurements of the toroidal component are made by two toroidal arrays of 72 probes each, which allow to

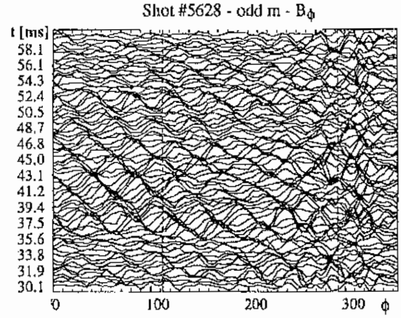

Fig.5 Example of mode rotation. Toroidal magnetic field for odd m modes is plotted as a function of the toroidal angle ϕ and of time.

obtain the odd m perturbation. The frequency range of the signals is DC-5 kHz. An example of rotation is shown in fig.5, where the toroidal magnetic field for odd m modes is plotted as a function of the toroidal angle ϕ and of time, after high-pass filtering. In this discharge the locked perturbation was at ϕ=310 degrees, and in fact a region of enhanced fluctuation is observed around this location. It is also possible to observe a rotation which appears at t=36 ms and lasts for 15 ms. Fourier analysis shows that in this case the rotating mode is n=9. In general, rotation events are observed to last from a few ms up to 10-15 ms. Often only one mode is seen to rotate, with a toroidal mode number n in the range 8-16, n=9 being the most frequently observed one. In some other cases more than one mode rotates.

By assuming rigid plasma rotation, it has been possible to compute the rotation frequencies in the toroidal and poloidal directions, f_ϕ and f_θ, through the formula $f = f_\theta + n\, f_\phi$, where m has been taken equal to 1 and f represents the rotation frequency of the mode with the specified n. In typical 600 kA discharges, f_ϕ is in the range 50-200 Hz while f_θ is in the range 0.5-2.5 kHz.

It is important to observe that, although the dominant mode of the locked perturbation (n=8) is sometimes seen to rotate in the 0.1-5 kHz range, a stationary n=8 is also present as a part of the perturbation. This is also true for higher n modes, although in some cases these are seen to rotate also in the DC-5 kHz range.

The magnetic measurements referred to above are taken outside the vacuum vessel, which behaves like a low-pass filter. Its transfer function relative to the toroidal component of the magnetic field has been computed. By approximating the vessel with a first order system, it exhibits the cut-off frequency at approximately 420 Hz. For several pulses, the signals of the toroidal arrays have been numerically reconstructed, applying the transfer function, but no clear change in the mode structure and no mode rotation at higher frequency (>200 Hz) have been observed.

Rotation events are more frequently observed after the closure of the gaps, but no visible effect on the main plasma parameters, such as loop voltage or confinement time, is observed as a consequence of them.

6. Conclusions

The short-circuit of the shell equatorial and vertical gap allowed to reduce loop voltage by more than 10 %, probably owing to the relevant reduction of magnetic fluctuations. Mode locking to the wall is still present, but temporary rotations of single modes are evidenced in selected pulses. Work is in progress to relate these events to operational conditions.

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