CONTROL OF THE LOCKED MODE POSITION IN RFX

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1.   Introduction

In RFX wall locked modes are always present [1]. The locked modes are responsible for an enhanced plasma-wall interaction with a clear consequent degradation of the experiment performance especially at high plasma current [2,3].

Since wall locked modes have been identified on RFX, some active and passive improvements have been implemented in the control of the magnetic configuration in order to prevent or mitigate the locked modes appearance. All the modifications done so far have not succeeded in eliminating the locked modes, but they have, mainly, produced a modification in the toroidal localization of the locked modes.

Fig.1 briefly reports the history of the locked mode toroidal position in consequence of these modifications. At the beginning of the RFX operation the locked modes were mainly located at the two poloidal insulated gaps of the shell positioned at a toroidal coordinate of 112°30' and 292°30' as it is shown in fig.1a). Approximately 50% of the shots had the locked modes positioned under the poloidal gaps whereas the occurrence of the other 50% was distributed around the torus. After the installation of the analog feedback control in the axis-symmetric poloidal magnetic configuration [4] a significant reduction in the locked modes events at the poloidal gaps has been recorded (fig.1b)). But a further concentration of the locked mode events at the two poloidal gaps has been recorded after a partial short-circuiting of the external equatorial insulated gap of the shell [5]. Finally, after the short-circuiting of the poloidal gap at 112°30', a reduction of the locked modes at this gap has been also recorded (fig.1d)).

Fig.1 - *History of the locked mode position: a) Initial distribution; b) With feedback control; c) Short-circuit at one equatorial gap; d) Short-circuit at one poloidal gap*

This analysis shows that, to prevent the formation of the locked modes at the poloidal gaps, it is important the control of their field errors and it is also important to control the field errors penetrating through the equatorial gaps. Nevertheless there is no evidence of locked mode free configurations with reduced field errors in RFX.
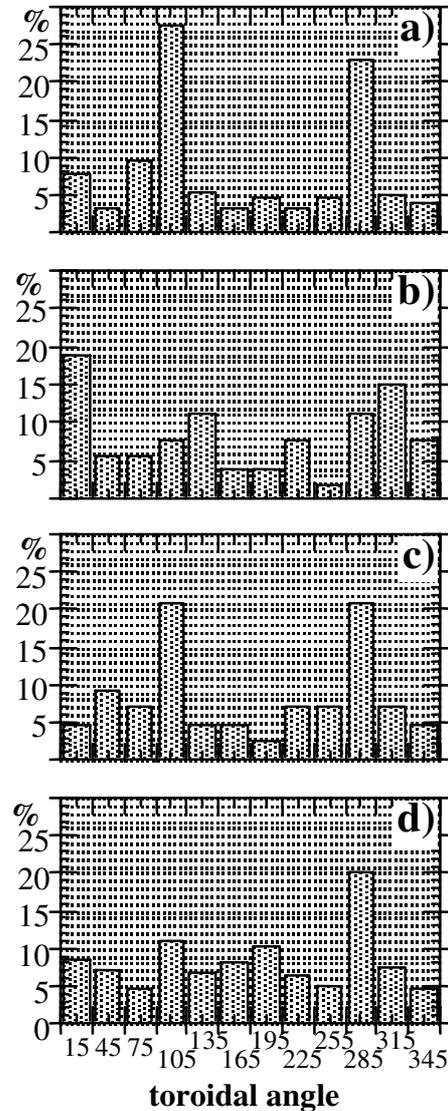
2. Effect on the locked mode position of a non-axis-symmetric toroidal field

The toroidal winding of RFX includes 48 coils that are grouped in 12 sectors [6]. In each sector are included 4 adjacent coils connected in series. The 12 sectors can be differently connected to the capacitor bank and to the power supply. During the RFX operation the 12 toroidal sectors have been preferentially connected in parallel. A modification of the current in the sectors adjacent to the locked modes, induced by a magnetic coupling of the plasma with the current in the sectors, has been observed. Following this observation, an artificial modification of the current has been produced in one or more toroidal sectors to verify its influence on the locked mode position.

It has been found that an enhancement of the mean toroidal field in one sector induces an attraction of the locked modes and, vice-versa, a reduction of the mean toroidal field induces a repulsion of the locked modes. In fig.2 the percentage of locked mode events, in the region where the mean toroidal field has been increased, is shown. It is evident that in all the pulses the locked modes are attracted in the region where the toroidal field is increased. Vice-versa, in fig.3 is shown an example of a set of pulses where the mean toroidal field has been reduced with a consequent occurrence of the locked modes outside the region where the field has been reduced.

This behaviour seems consistent with a coupling mechanism between plasma locking and m=0, n≠0 components of the toroidal field produced by the sectors of the toroidal field winding. This coupling is possible because the plasma mode locking itself produces a m=0, n≠0 toroidal magnetic dipole.

Fig. 2 *Effect of an attractive bump; locking frequency (upper) and sector current distribution (lower)*
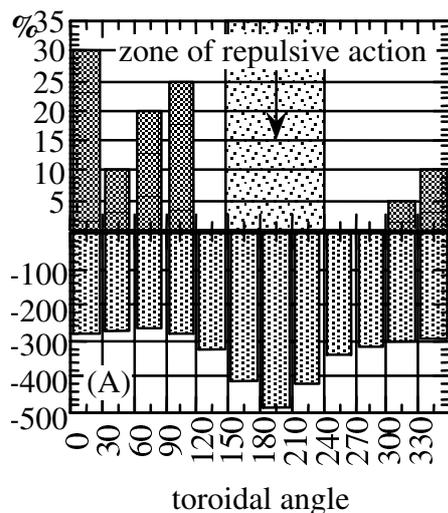
Fig.3 *Effect of a repulsive bump; locking frequency (upper) and sector current distribution (lower)*

3. The locking movement

After the encouraging results obtained in localizing the locked modes, a new power supply for the generation of a rotating perturbation was realized; it includes switching devices (Gate Turn-off Thyristor) to modulate the current in the toroidal winding sectors during the reverse current phase [7]. The system is able to produce, unbalancing the current in the sectors, rotating perturbations along the torus with variable amplitude and frequency.

3.1 The mode locking movement

Under some conditions, movements and rotations of mode locking along the toroidal direction has been induced with this system.
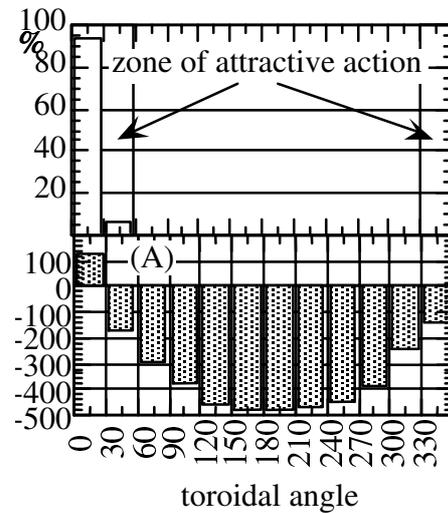
To detect the magnetic plasma edge configuration and the locking position, the distribution of the toroidal magnetic field is measured at the inner surface of the shell by means of two toroidal arrays of pick-up coils located at $\theta=20.5$ and $\theta=200.5$ respectively (near the internal and the external equatorial gaps). The harmonic components of the field perturbation with odd (B_{ϕ_odd}) and even (B_{ϕ_even}) poloidal order are obtained, respectively, as the difference and the sum of the signals from the external and internal arrays. Twelve flux measurements located at the pumping ports on the external equatorial gap, also give a signal which is mainly related to the radial field at the plasma edge. By means of these measurements, the evaluation of the radial field produced by plasma locking and by the external field perturbation is possible.

Fig. 4 - B_{ϕ_odd} *vs. the toroidal coordinate, at various times for shot #10459 (time step=2 ms; each time step corresponds to 20 mT)*

A typical locking movement obtained with a rotating perturbation is shown in Fig. 4, where B_{ϕ_odd} is plotted vs. the toroidal angle for shot #10459 (peak plasma current 685 kA, reversed toroidal field 37 mT, I/N 4.5 10^{-14} Am); different lines are time-shifted. The locking position changes during the pulse: in the first 60 ms the locking has three different localization and it changes suddenly its position; between 60 and 100 ms a continuous movement of locking position can be recognized. It is worth noting that, when the displacement takes place, the localized perturbation does not move in a traveling-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.

First results seem to point out that the displacement is more likely to take place when the n=1 error field is applied (single-bump experiments), when the rotation velocity is small, i.e. of the order of 200-500 m/s and during low density shots (I/N>3 10^{-14} Am).

The Fourier analysis of B_{ϕ_odd} shows that transient reduction of the amplitude of the main RFX modes (n=7,8,9) which compose the locking takes place during the perturbation displacement, as shown in Fig. 5 for shot #10459.

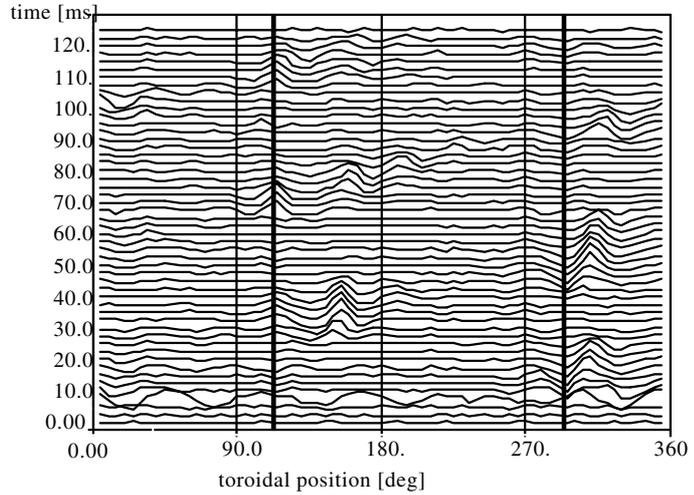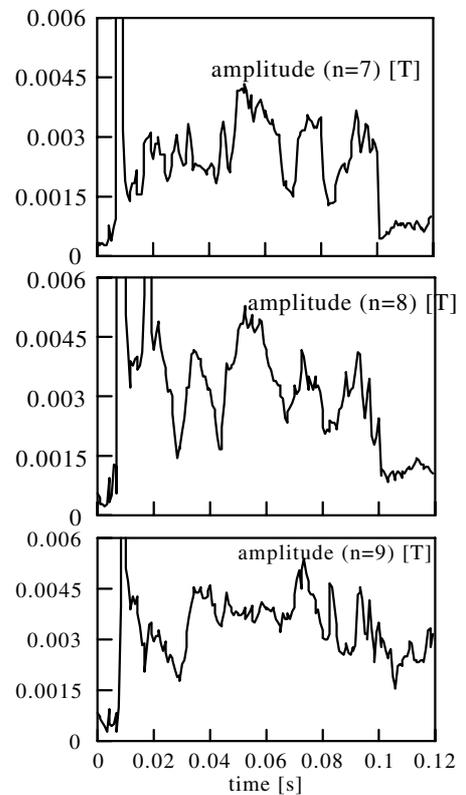### 3.2 Rotating field error during no-plasma shots

Fig. 5: B_{ϕ_odd} *harmonic components of order n=7,8,9 vs. time (#10459)*

In order to identify the magnetic field perturbation produced in the plasma region by current unbalance in the toroidal field sectors, the case without plasma has been analyzed. During the plasma pulses, the current difference among toroidal winding sectors during the modulation was between 0.5 and 1.2 kA (the mean value during reversal lies between 0.8 and 1.4 kA that corresponds to a reversal parameter $F=B_\phi(a)/<B_\phi>$ between -0.1 and -0.2); the highest current flows in six adjacent sectors - covering half torus - while the lowest in the other six.

With no plasma and a current difference of 1 kA, this condition gives a total ampere-turn difference, along the toroidal direction, of 192 kA-turns. With this difference, the major component of the rotating error field B_{ϕ_even} measured by the probes is (m=0, n=1) and has an amplitude between 8 and 12 mT; components of order (m=0, n=2) are at least 50% smaller and probably produced by the poloidal gaps. The radial field measured at the pumping ports allows to estimate the n=1 harmonic of the radial field at the first wall between 2 and 6 mT.

This analysis shows that the main component of the rotating field produced by the external coils is m=0, n≠0 and also that the m=1 component is relatively smaller. It seems reasonable to relate the torque necessary for the locking movement to the interaction of the externally generated m=0 component (which can be considered as a magnetic dipole oriented along the ϕ direction) with the magnetic dipole associated with the locking. However, being practically impossible to apply a pure m=0 rotating field, an effect of the m=1 component cannot be "a priori" excluded.

An alternative interpretation is related to the observation that the localized perturbation in most of the cases does not move in a rigid-body fashion, but actually jumps from a high magnetic shear region, relatively more stable, to a lower shear region. This is consistent with the observation that the phase of some n>9 harmonic components of the plasma perturbation typically rotates in opposite direction to the n<7, while the main component is almost stationary.

4.　　　Conclusions

The position of wall locking can be pre-set successfully in RFX with a proper m=0, n≠0 magnetic field generated with a toroidal winding sector current unbalance.

The locking position can be also varied during the pulse, thus mitigating the plasma-wall interaction and power deposition with a reduction of carbon blooms at high plasma current. Experiments are now in progress in order to optimize this new locked mode control technique.

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