*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.092 (2006)*

Experiments of active control of internal resistive MHD modes in RFX-mod

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The modified RFX (RFX-mod) [1] reversed field pinch (RFP) device is a unique facility to study the physics of RFP plasmas with a thin shell and the effect of active control of the magnetic boundary. RFX-mod is in fact equipped with 48×4 saddle coils devoted to active control of MHD activity, capable of generating modes up to $m = 2$ and up to $|n| = 24$ [2]. Reference discharges are performed in the Virtual Shell scenario, i.e. a feedback law is set up in order to minimize the radial component of the field at the sensors for every helicity (excluding the equilibrium field $m = 1, n = 0$). The flexibility of the system allows to specify different feedback laws for the various helicities (Selective Virtual Shell, SVS). Experiments targeting non resonant modes (Resistive Wall Modes $|n| < 6$) are shown in [3]. We report here about experiments aimed at studying the effect of different boundary conditions on the dominant resonant modes ($m = 1$, $n = -7, -8, -9, -10$) and in particular at investigating the possibility to stimulate the onset of Quasi Single Helicity spectra: an experimental characterization of spontaneously occurring QSH spectra in SVS experiments is presented elsewhere [4]. Experiments have been performed on standard 600 kA matched and, recently, on ramping 800 kA discharge. In Selective Virtual Shell the radial field of every harmonics resolved by the sensor coils can be independently controlled. In fact, each control saddle coil current is determined by a proportional and integral (PI) controller that compares the $b_r(\theta_i, \phi_j)$ signal measured below the saddle coil with a reference value $b_r^*(\theta_i, \phi_j)$.

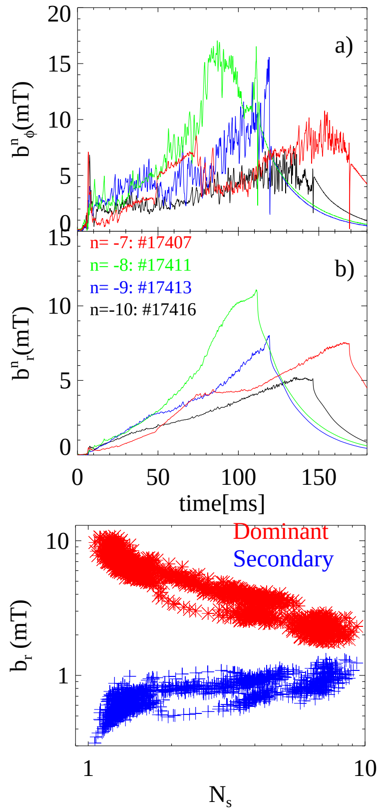

Figure 1: *Time evolution of (a) b_ϕ^n and (b) b_r^n of the uncontrolled mode. c) Amplitude of the dominant and average of the secondary modes as a function of N_s.*

$$I = k_P(b_r - b_r^*) + k_I \int_{t_{start}} (b_r - b_r^*)dt \qquad (1)$$

In the Virtual Shell scenario, the reference values $b^*(\theta_i, \phi_j)$ are all zero. In the Selective

Virtual Shell scenario, the $b_r(\theta_i, \phi_j)$ measurements are spatially filtered before the PI stage. At each time step, the control system performs a real time FFT of input measurements, sets to 0 the selected Fourier coefficients and computes the spatially filtered radial field $\tilde{b}_r(\theta_i, \phi_j)$ by inverse FFT. In all discharges, including reference ones, the $m = 1, n = 0$ component of the field is always filtered out, in order not to interfere with the plasma horizontal displacement control.

Natural evolution. In these experiments, the control of a selected resonant mode is inhibited. For helicities $m = 1, n = -7, \ldots n = -10$, corresponding to the most unstable tearing modes, both the toroidal and the radial component of the field grow (Fig. 1-a and b). In particular the radial component time evolution is due to the penetration of the shell and it is related to the toroidal component by the following relation (obtained in cylindrical geometry)

$$\frac{\tau_w}{r_w}\frac{db_r^{m,n}}{dt} - M_{m,n} b_r^{m,n} = -A_{m,n} b_\phi^{m,n} \qquad (2)$$

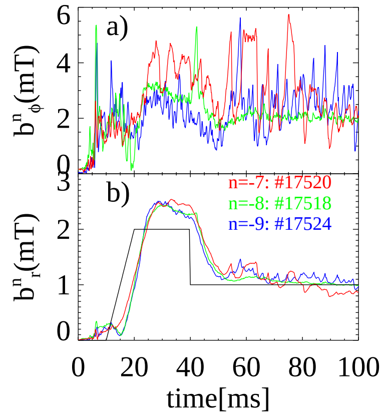

Figure 2: *Time evolutions of a) b^n_ϕ and b) b^n_r field for non zero reference value shots.*

where $M_{m,n}$ and $A_{m,n}$ are constants depending on the mode number (obtained by matching the vacuum solutions outside and inside the shell) and τ_w is the penetration time of the shell. This relation is formally identical to the bolometer equation [5], where the sensor temperature corresponds to the radial field and the absorbed power to the toroidal component. Similarly to what happens in spontaneous transition to QSH, the increase of the dominant mode occurs simultaneously with a decrease of secondary modes, as shown, for the shot #17407, in Fig. 1-c: both quantities are plotted as a function of the spectral spread parameter N_s that quantify the width of the magnetic spectrum: $N_s = 1$ indicates a pure Single Helicity. Transient formations of SXR structures, correlated with the position of the island O-point, are observed. Discharge duration is systematically shorter than the reference discharges, as the the increase of the radial component implies a considerable non axisymmetric shift of the last plasma surface [6].

Non zero reference value experiments. In these experiments, the amplitude of the radial component of a selected mode has been feedback controlled. This means that at every control cycle the system computes the required 192 reference values $b_r^*(\theta_i, \phi_j)$ corresponding to a mode of a prescribed amplitude and phase. Then the PI controllers compare this value with the spatially filtered measurements and compute the required action according to eq. (1).

An example of these experiments is shown in Fig.2. Time traces of the radial field for three different helicities in three different shots are shown. The continuous black line is the reference amplitude of a given helicity. In the cases shown, the reference phase is kept at a constant value. In this scenario the discharge duration is comparable to reference SVS discharges. The measured amplitudes of the harmonics reproducibly follow the reference value with a time delay of the order of $5-10ms$: the feedback system compensates, in fact, the different wall penetration time of the various harmonics. When the plasma is present, the harmonics of the applied field (obtained from the measured currents flowing into the control coils by a dynamic model that takes into account the mutual inductances between saddle and sensor coils [7]) are out of phase compared to the measured radial field harmonics: as long as the reference value of the field is below the value it would reach without control, the externally applied field is opposed to the one produced by the plasma. An example is shown in fig. 3, where the non zero reference value for mode $n = -7$ was started before discharge breakdown. In the first phase, when no plasma is present ($t < 0$), the model reconstructed applied field coincide with the measurement (both in amplitude and phase): i.e. the field is produced by the saddle coils only. When the plasma is present ($t > 0$), the phase of the control harmonic switches to π in order to apply a field opposed to the plasma generated one.

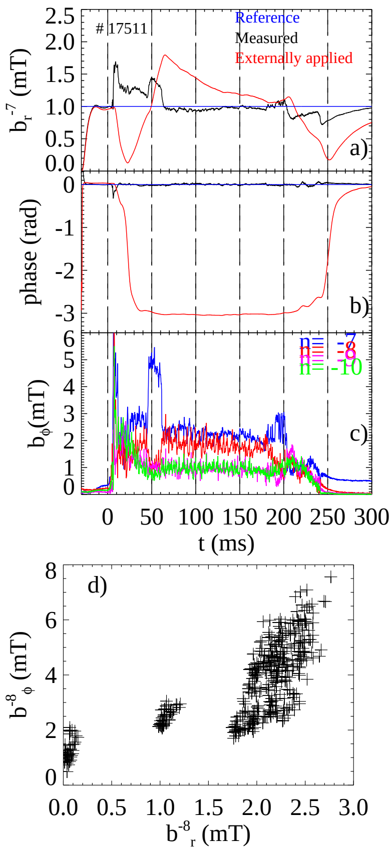

Figure 3: *Time evolution of the* $1,-7$ *mode. a) amplitude,b) phase for reference, measured and external field. c) Toroidal harmonics for the asme shot. d)* b_ϕ^{-8} *on* b_r^{-8} *dependence.*

The feedback system reacts slowly to the transition to the QSH state that occurs at 50ms and doesn't match the reference value very well, possibly suggesting that a further optimization of gains is required. While the radial component amplitude and phase can be controlled rather well, within the delay of the control system, the time behavior of the amplitude of the toroidal component is less reproducible. Fig. 3-d shows the statistical dependence of the toroidal harmonic amplitude for the mode $n = -8$ on the b_r^{-8} reference value. The b_ϕ^{-8} amplitude is higher, compared to reference shots but does not scale with the reference amplitude. On the other hand, the *phase* of the plasma mode (both radial and toroidal components) follows the reference phase, and SXR islands locations are aligned with the magnetic islands O-points. Given the evidence that the phase of the plasma mode can be controlled, in a subsequent set of experiments, the reference phase of a selected mode was varied linearly in time.

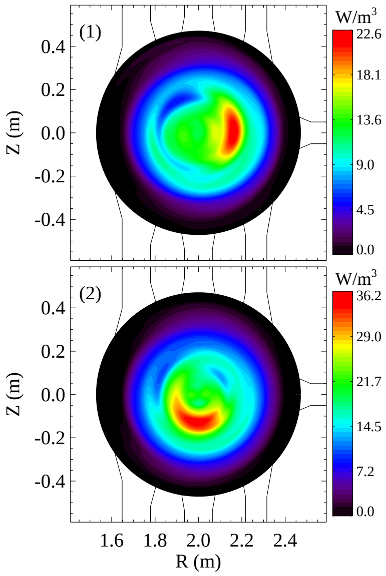

Figure 4: *SXR emissivity for shot 19030 at different times during a* $m = 1, n = -7$ *mode rotation experiment.*

It is found that rotations of the $m = 1, n = -7$ phase up to 20Hz can be obtained. Both the radial and the toroidal component phases rotates and intermittent SXR structures (indicating the presence of a core helical structure) are observed, when the magnetic spectrum display a transition to a QSH state. In particular, for the first time in RFX, the thermal structures are observed at different poloidal locations in the same discharge (Fig. 4).

In summary, this initial set of experiments showed that it is possible to interact with resonant tearing modes by suitably controlling the boundary condition for a single harmonic. Both the radial component at the edge and the phase of the modes can be controlled. Future campaigns will be devoted to verify if these results hold under different experimental conditions and if the active control of radial field at the edge can increase the probability to obtain QSH states.

Acknowledgement *This work was supported by the European Communities under the contract of Association between EURATOM/ENEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.*

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