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RESISTIVE WALL MODE SPECTRA AND COUPLINGS IN RFX-mod

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Introduction One of the most critical issues in present and future fusion experiments is the control of MHD performance limiting instabilities. In the case of Reversed Field Pinch (RFP) configuration, Resistive Wall Modes (RWM) instabilities [1] are probably the most critical ones since, if not controlled, they lead to an abrupt discharge termination on time scales of the order of the wall time of the device. It should be noted that in RFPs RWMs grow as current driven, non-resonant instabilities and that the stabilization mechanism due to plasma flow plays a minor role if compared with the tokamak case [2]. Under the control point of view, the RFP situation can be then compared to the tokamak case in the presence of a very small plasma flow, as expected for example for the next generation of very large tokamaks facilities as ITER. In this case, the most effective stabilization mechanism is the action of an active coil set controlled in feedback loop. In order to implement an effective active control system, precise mode identification is a fundamental issue. In the RFP case, given a current density profile, many RWMs can be simultaneously unstable, with different growth rates. Linear numerical calculations in cylindrical geometry show that the mode structure can be well represented by Fourier harmonics with poloidal number m=1 and toroidal numbers n that in general depend on the machine aspect ratio [see e.g. 3], each of them characterised by a different growth rate. In this approximation the unstable modes can be identified by a network of equally spaced sensor and independently controlled. Further works suggest that non-linear effects should play a minor role in determining the growth rate of an unstable RWM [4]. However, more refined numerical models recently predicted that the inclusion of realistic 3D geometry of the boundary can indeed lead to a distortion of the unstable mode geometry and to a modification of its growth rate [5]. The main aim of this paper is to investigate experimentally the issue of RWM identification and couplings in RFPs.

Experimental setup Given its thin resistive shell (with a vertical field penetration time of $_{V,shell} \approx 50$ ms much shorter than the 500 ms discharge duration) and its powerful MHD active control system, one of the main scientific objectives of the RFX-mod Reversed Field Pinch is the study of Resistive Wall Modes (RWMs) and of their control. The RFX-mod MHD control system consists of 192 active coils fully covering the outer plasma boundary, independently fed and controlled by 192 independent digital PID controllers [6]. Taking advantage of its control system, RFX-mod can benefit from a great flexibility in terms of experimental control scenarios and correspondingly physical issues to be addressed. By designing different control schemes it has been possible in RFX-mod not only to carefully measure RWM growth rates under many stability conditions, but also to study the relevance of different sources of deviation from the RWM spectra foreseen by cylindrical calculations. This has been made possible by the selective control of different poloidal or toroidal harmonics in experiments characterized by the same macroscopic plasma parameters. In the paper possible harmonic distortions to the RWM spectrum due to toroidal geometry, to (toroidal) mode couplings and to inhomogeneities present in the passive boundary are taken into account and discussed together with their implication on optimal RWM control. The mode structure is identified by 192 saddle sensors, covering the same solid angles of the active coils, but placed closer to the plasma, just outside the RFX-mod vacuum vessel. This sensor system is also the main system used as input by the real time feedback control.

RWM experimental coupling identification The first aspect we investigate is the poloidal structure of an unstable RWM in RFX-mod (again, remember that according to cylindrical theory, only m=1 modes should be unstable). To do this, we analyze a set of discharges where not only the most unstable RWM, but also its poloidal harmonics are in turn included or excluded from the control loop. In all the discharges the main plasma parameters (plasma current, electron density, toroidal field at the edge) are carefully kept constant. In absence of internal field measurements, the current profiles are monitored by keeping constant the F parameter, defined as the ratio between the toroidal field at the edge (that is controlled by the operator) and the toroidal field averaged on a poloidal section. Note that this parameter can be easily related to the q at the edge parameter more commonly used in the tokamak community. In Figure 1 the results of such an experiment is presented: all the three cases displayed are relative to discharges in which the most unstable RWM is identified, according to cylindrical linear stability modelling, by the m=1, n=-6 Fourier coefficients, but with different control schemes on other harmonics. The black lines are relative to a discharge where only the (1,-6) harmonics is not controlled, while the red ones describe the case of free growth of all the poloidal harmonics of the n=-6. It is evident that, when not controlled by the active feedback control system, also the (0,6) and the (1,+6) harmonics growth exponentially as the main unstable RWM with comparable growth rates (around 27 s^{-1} in this case). The (2,6) harmonics, not shown in figure, follows the same behaviour reaching similar amplitudes. In Figure 1 the logarithm of the (1,-6) harmonic amplitude is also shown to highlight the very clear exponential behaviour (linear in log scale) of the instability growth. The growth rate calculation is performed in a time interval automatically selected in order to have the best linear interpolation of the log(Amp) signal. To better understand the origin of these harmonics (that should be stable according to 2D numerical calculations) in the spectrum of the unstable RWM, a second set of experiments have been performed. Following a procedure already developed to study other aspects of RWM physics [7], on the same target plasma, the most unstable RWM is controlled with subcritical gains (i.e. the growth rate is reduced by the action of the control system, but it is still positive), while its poloidal harmonics are not controlled at all. In figure 2 the time traces of relevant mode amplitudes as measured by the saddle sensor system are presented. We see that the (0,6), (1,+6) and (2,6) amplitudes follow the time behaviour of the main unstable mode, suggesting a close relation between the (1,-6) growth and the growth of its poloidal harmonics.

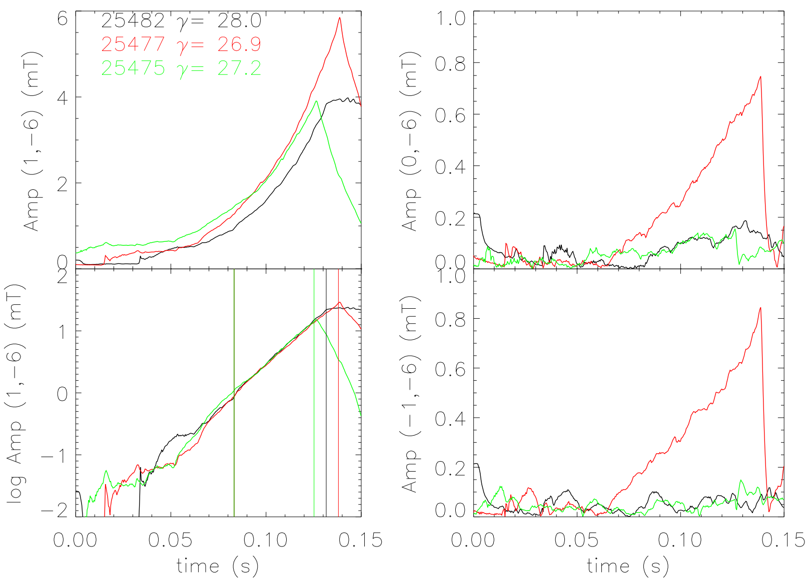

Figure 1: Comparison between three experiments with different control of the harmonics of the most unstable RWM, (1,-6). In the black only the (1,-6) harmonic is not controlled; in the red case all the poloidal harmonics of the n=6 mode are free to grow; in the green case the m=1, |n|=3, 4, 5 are free to grow. Note that all the time traces are time shifted to have the same starting point for the interpolation (reference is the time base of the black case).

Preliminary experiments on toroidal harmonics generation suggest instead that the coupling due to poloidal gaps is less important in the RFX-mod case. This is visible again in Figure 1 (green lines), where the growth rate of the main unstable mode is not modified by the different control on the closest toroidal harmonics. The problem of the direct coupling of

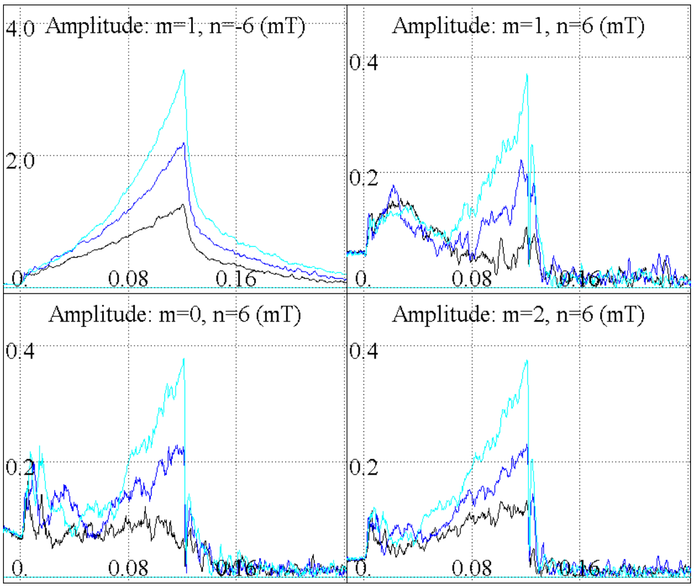

Figure 2: Mode amplitudes for three different subcritical proportional gain on the most unstable RWM, (1,-6) in the window 0-0.12s; the poloidal harmonics are instead not controlled during the same time interval.

RWM to tearing modes has also been considered, confirming that, being RWM non-resonant modes, their growth is little influenced by the dynamics of the tearing part of the spectrum.

Discussion and conclusions Experiments performed on RFX-mod clearly demonstrate the growth of harmonics that, according to cylindrical modelling, should be robustly stable. When looking carefully at relative amplitudes and phases of the different harmonics, the easiest explanation, that would only invoke a geometrical toroidal coupling, does not seem to be sufficient to explain all the results. In fact, taking into account the fact that the aspect ratio of the RFX-mod device is R/a = 2/0.459 ≈ 4, one would not expect the same amplitude for the (0,6), (2,6) and the (1,6) harmonics. Our interpretation is that these results are the first experimental demonstration of the coupling effect between the main unstable RWM and its poloidal harmonics due to the toroidal gaps of the passive machine boundary, as already suggested by 3D computations [5].

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