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Resistive Wall Mode growth and control in RFX-mod

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Introduction Resistive Wall Mode (RWM) instabilities are a critical issue for different toroidal magnetic configurations. In particular, RWMs limit tokamak high β_N operations where a large fraction of non-inductive current is generated (advanced, quasi-steady state scenarios). Despite their importance for the tokamak configuration, RWMs were first experimentally found on HBTX1C [1], a Reversed Field Pinch (RFP) device. The main difference between the two configurations is that while in tokamaks RWMs grow as pressure driven instabilities, in RFPs their stability depend on radial current profiles, generally parameterised by the quantity $F=B_\phi(a)/\langle B_\phi \rangle$.

In RFPs these instabilities can be passively stabilised by a thick conductive wall placed close to the vacuum vessel (as was done in the previous RFX experiment), or controlled by a system of active coils (as is now currently done in RFX-mod [2]). Another interesting difference between the two configurations is that RWM stabilisation in RFPs is not affected by plasma rotation as strongly as in tokamaks, and then, when successful, can give a clear test of the feasibility of control schemes based only on active coil operations.

Experimental setup The new load assembly of RFX-mod (R=2.0 m, a=0.459 m) is particularly suited for active MHD control studies. Its thin resistive shell has a vertical field penetration time $\tau_{V,shell}$ ≈50 ms much shorter than the >300 ms discharge duration. The resistive shell outer surface is entirely covered by a system of 192 active saddle coils divided into 48 poloidal arrays of 4 coils (top-in-bottom-out positions, at r=0.58 m). The active copper coils are 60-turn, have an average surface of approx. 0.27 m^2 and can carry a maximum current or 400 A for 300 ms producing a maximum local dc B_r field of ≈50 mT. Each saddle coil is fed by its own power supply, which can perform an independent control of the current in the coil. The whole system is controlled by a programmable digital controller with a maximum latency time of 330 μs, where the operator can specify the particular control schemes to be applied to the plasma (feedback, feed-forward, zero or non-zero reference value, Fourier mode control, and others). The digital controller performs a real-time FFT of 192 radial field signals provided by measurement saddle coils placed just outside RFX-mod vacuum vessel, at r=0.51 m. A test version of this digital controller was installed in Stockholm on the T2R device and allowed the first proof of principle of active control of multiple RWM in the RFP configuration [3]. Active coils and digital controller are the main components of the RFX-mod MHD active control system that can act on different instabilities such as tearing dynamo modes [4] or RWMs, as will be presented in the following of this paper.

The experimental setup is completed by approximately 900 electro-magnetic signals that give a complete description of magnetic mean and fluctuating quantities with high spatial and temporal resolution, and by many other diagnostics providing information on spectroscopic and kinetic properties of the plasma.

Experimental results Experimental results can be divided in two main areas, RWM physics and RWM control.

In order to characterize RWMs in RFX-mod, one control scheme dubbed "selective virtual shell" proved to be very effective. It consists in controlling by the active system all the modes but a subset of which we are interested in studying the free evolution. In this way RWM spectra and growth rates for different mean current profiles have been measured. As predicted by the theory, internal, non-resonant RWMs are the most unstable ones for shallow (≈ -0.1) values of the F parameter, whereas at deep (≈ -0.4) F external, non-resonant RWMs are dominant in the spectrum. In Fig. 1 the time traces of an internal (n=-6) and an external (n=+4) RWM for 3 different F values are shown.

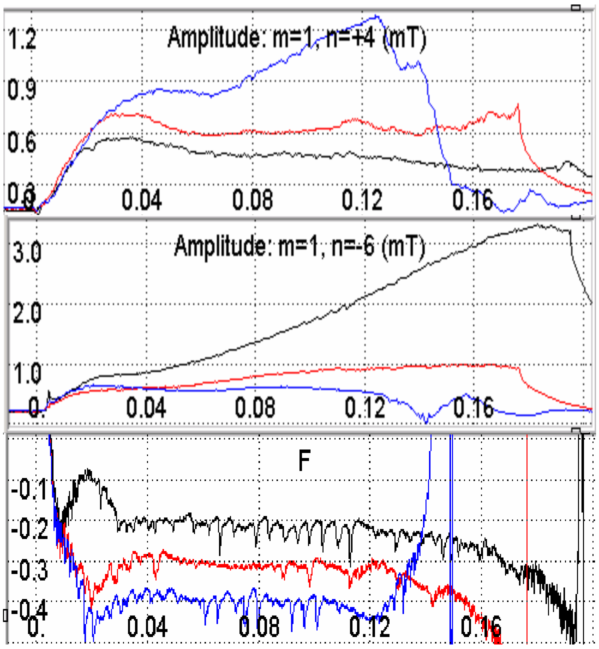

Figure 1: RWM spectrum characterisation at different F values; time is in seconds.

Similarly to other RFP experiments [5], RWMs appear as wall locked m=1 low n (|n|<7 for the RFX-mod aspect ratio) instabilities, where m and n represent poloidal and toroidal mode numbers, respectively. In the case of free growth (selective virtual shell experiments) the characteristic exponential growth rate is very clear, allowing precise experimental estimates of RWM growth rates. In the same way it is also possible to compare the effect on the plasma of single or multiple RWMs at a give time.

To test the effectiveness of the control system, the selective character of the virtual shell can be changed during the discharge. In Fig.2 a comparison between 3 discharges with different programming of the control is shown. The fast response of the control system, less than 10 ms to fully control a RWM with amplitude of around 2 mT, should be noted. In order to test the sensitivity of the control system to small (less than 0.5 mT) instabilities, experiments like the one shown in Fig.3 have been successfully performed.

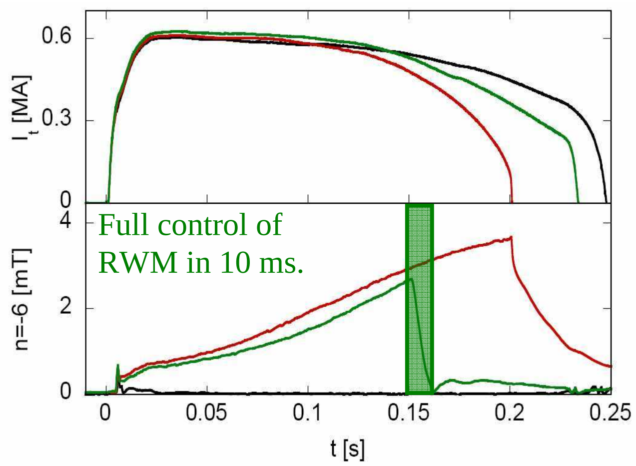

Figure 2: RWM active stabilization. Black curves (#17287) correspond to a full virtual shell scenario (very low amplitude of the m=1, n=-6); red curves (#17301) refer to a shot where the m=1, n=-3÷-6 are excluded from the control (selective virtual shell scenario); green curves (#17304) refer to a shot similar to #17301 until t=150 ms when the control on the m=1, n=-6 mode is switched on.

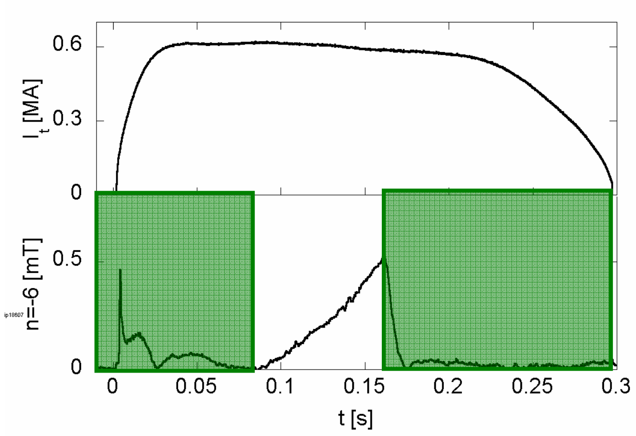

Figure 3: Control of small amplitude RWM (n=-6) in the middle of a plasma discharge. In green the time intervals where the mode is controlled.

The same control system has also been tested in open loop to investigate the so called Resonant Field Amplification (RFA) involving marginally stable modes and resonant static or rotating error fields. In this way it is for example possible to assess the importance for RWM growth of static error fields present during the setting up phase of the discharge.

It is important to underline that he full RWM (and tearing mode) control in RFX-mod operations, allowed extending the pulse length from 130 ms to more than 330 ms at plasma currents up to 1 MA [6]. Even in the longest discharges RWM amplitudes are kept at the measurement threshold (less than 0.1 mT), with a significant improvement of plasma performances.

Numerical results Experimental results can be used to benchmark numerical models and numerical stabilisation schemes. In Fig.4 RWM growth rates calculated for

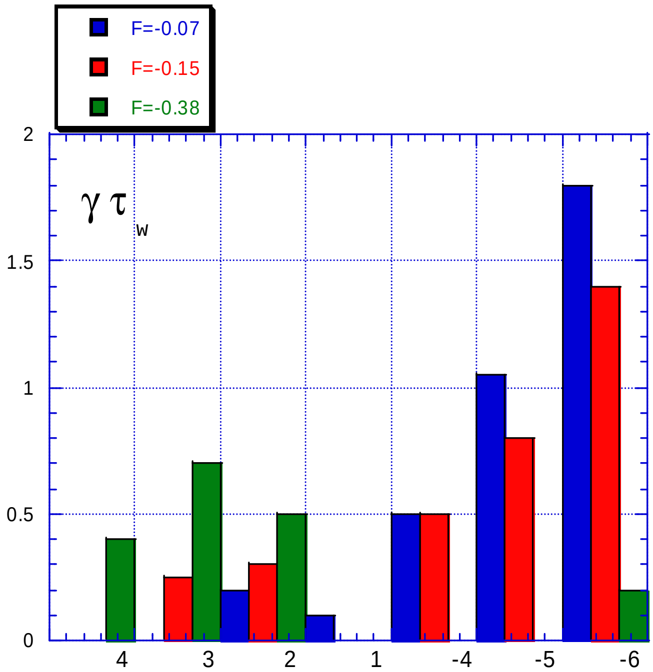

Figure 4: Numerical normalised RWM growth rates for different values of the F parameter.

equilibrium parameters close to the experimental ones are shown. The model used is linear, cylindrical, and assumes ideal, zero-pressure plasma (more information on the model assumptions can be found in [7]). Discrepancies between experimental and numerical estimates can be attributed to shot to shot plasma variations that cannot be modelled in the code.

Conclusions RFX-mod operations with selective virtual shell offer to the fusion community a convenient way to study RWM physics and control in a well-diagnosed device and at relevant values of plasma parameters. First experiments using the new control system have been fully successful extending the plasma duration well beyond the diffusion time of the wall. Future experiments will explore new control schemes, in order to give useful information also to the tokamak community: control with incomplete set of coils, control with different geometry of the active coil system, use of complex gains, use of different set of sensors as input for the control.

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