Physics and control of multiple external kink instabilities with realistic 3D boundaries: recent understandings from experiment and modelling

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Introduction

The external kink ideal MHD instability is one of the most severe limiting instabilities in magnetically confined fusion plasmas and establishes hard operational boundaries for both the tokamak and the Reversed Field Pinch (RFP) configurations [1]. In real experiments the growth rate of this ideal instability is reduced by the presence of passive structures surrounding the plasma and the instability in this case is often referred to as Resistive Wall Mode (RWM) instability. The destabilization of a single RWM (either current or pressure driven, depending on the equilibrium characteristics) and its control have been extensively studied in existing tokamaks, but the same is not true for situations where more than one RWM are simultaneously unstable. A spectrum of multiple unstable RWMs in fact is expected in tokamak plasmas operating at β_N values much larger than the so-called no-wall limit, as is in the case of scenarios being developed in view of steady state DEMO reactors. A different situation can be found in Reversed Field Pinch (RFP) plasmas, where a spectrum of (current driven) multiple unstable RWMs is always present due to the peculiarity of its current equilibrium profile [2,3]. For this reason RFPs provides an ideal playground for the study of 3D RWM passive and active stability. Physics and control of this unstable system are made even more challenging by the intrinsic 3D nature of the problem that involves both the role of the passive structures details and of the 3D fields produced by dedicated coil systems that might act as actuators in a feedback control loop. In the following we will report on recent experiments and modelling activities on RFP plasmas that have been explicitly tailored to study the effect of a realistic (i.e. composed by a reduced number of coils) RWM active control system and to suggest some of the main issues future tokamaks operating at very high β_N values could face when feedback controlling multiple RWMs.

Experimental setup and modelling tools

Experiments have been performed in RFX-mod [4], a flexible medium size (R=2 m, a=0.459 m) fusion device able to confine RFP plasmas with currents up to 2 MA as well as low-current, low-q(a) tokamak plasmas. RFX-mod is equipped with a state-of-the-art MHD control system made by a total of 192 (4 in poloidal direction x 48 in the toroidal one) independently fed active coils that cover the whole plasma surface (Figure 1, top) and that are complemented by a set of more than 600 magnetic sensors acquired in real time. RFX-mod real time control software has been recently upgraded and is operating under the MARTe framework; all the control functions related to RWM control schemes are now fully integrated in this framework and a user friendly graphical interface has been implemented as well [5]. This gives the operator the full freedom of reproducing and expanding proof of principle studies done in the past [6] by low-level modifications of the control software. The different software blocks and the overall control architecture for virtual reconfiguration of the active coils is represented in Figure 2. An example of possible new virtual configuration made possible by the new software is shown in Figure 1 (bottom), where a coil configuration "4x24" with active coils of double toroidal extension is represented.

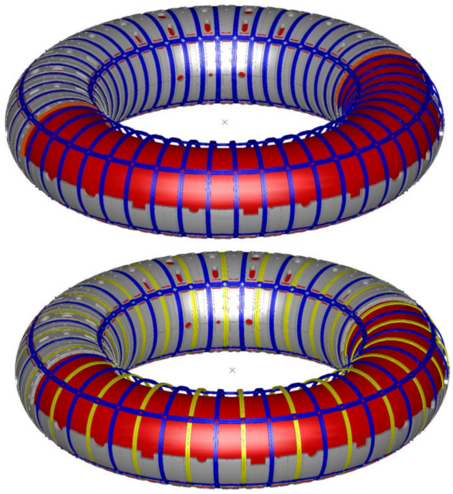

Figure1. Top: representation of the full set of 192 active coils in RFX-mod. Bottom: one of the possible virtual configurations that can be obtained by using the new control software options.

To properly model this complex physical system, the CarMa code [7], a tool already used to predict RWM stability under open and closed loop conditions in several tokamaks, including ITER, has been upgraded. The new CarMa version can now incorporate information on the stability of more toroidal harmonics at the same time while of course keeping its previous multi-modal capability also on the poloidal direction. In this way the model can account for possible toroidal couplings induced on the plasma by passive or active currents flowing outside the plasma. The upgraded multimodal CarMa version has been then integrated in the full dynamic simulator of RWM control already implemented for RFX-mod experiments and presented in [8].

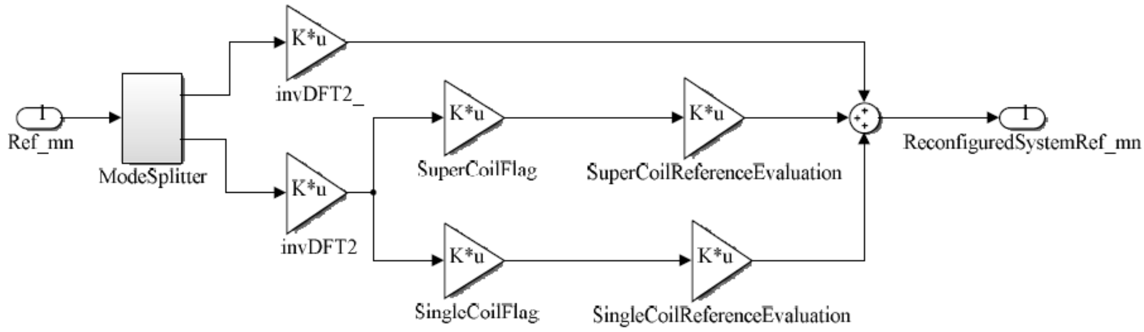

Figure2. Software architecture for active control reconfiguration tools as implemented in the new RFX-mod control system. More details can be found in [5].

Multimodal control experiments and simulations

An extensive set of experiments have been performed in RFX-mod taking advantage of the new software capabilities. Several combinations of active coils in terms of number, position and geometries have been applied to different sets of unstable and marginally stable modes to study the couplings between the plasma, the active control fields and the passive boundary, with the ultimate aim of optimizing the control characteristics of a feedback system in the presence of a spectrum of multiple unstable RWMs. Experimental data obtained in this way have also been used to benchmark and validate the extended CarMa model. In figure 3 the high degree of agreement between experiment and model is shown for one of the possible virtual reconfiguration applied to the control of the most unstable RWM, that for the plasma equilibrium selected is found to be represented by the (1,-6) Fourier harmonics.

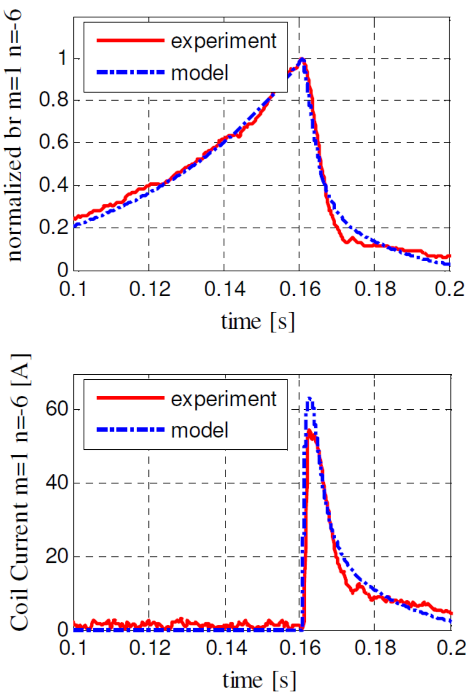

Figure3. Control reconfiguration example (1x16 outer "large" coils): model results (blue) are compared to experimental data (shot 33977, red). Amplitude of (1,-6) RWM (top) and coil currents for the same harmonics (bottom) are shown. Feedback control starts at 0.16s.

The multimodal capabilities of the model are exemplified in Figure 4: the open loop RWM spectrum is compared to two different control schemes using the 1x8 control configuration. It is clear that while this control system is able to control the two most unstable modes, the same is not true when also (1,-4) and (1,-3) harmonics are included in closed loop. Not only in the latter case one of the modes, the (1,-4), is not controlled because of the periodicity of the active coil system, but also the control of the (1,-5) is lost due to the coupling of the mode to other control fields. It has to be finally noted that also the (1,-3) is destabilized by the closed loop action of the control system in the last case.

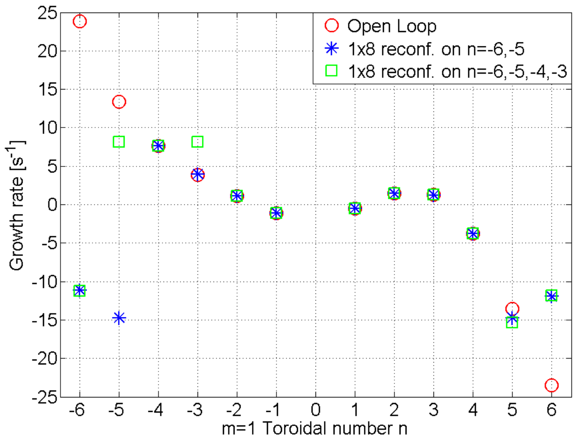

Figure4. Open loop (red) growth rates are compared to two different control schemes using 1x8 reconfigured coil system.

Conclusions

Recent extensions of both experimental capabilities of RFX-mod and of modelling tools provide the fusion community of a unique facility to study characteristics and issues of multimodal RWM control by means of active coil systems. Important limitations introduced by the coupling of external fields and plasma modes have been found and discussed.

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References

[1] M.S. Chu and M. Okabayashi, Plasma Phys. Control. Fusion **52** (2010) 123001.

[2] P. Brunsell et al, Phys.Plasmas, **10** (2003) 3823.

[3] R. Paccagnella et al, Phys. Rev. Lett. **97** (2006) 075001.

[4] P. Sonato et al, Fusion Eng. Des. **66–68** (2003) 161.

[5] T. Bolzonella et al., "Software tools for actuator flexible configurations in real time MHD control: from design to application in magnetically confined plasmas", submitted to Fusion Engineering and Design.

[6] M. Baruzzo et al, Nucl. Fusion **52** (2012) 103001.

[7] R. Albanese et al., IEEE Trans. Magn. **44** (2008) 1654.

[8] G. Marchiori et al,. Nucl. Fusion **52** (2012) 023020.