Physics and Control of External Kink Instabilities with Realistic 3D Boundaries: a Challenge for Modern Experiments and Modeling[*]

Tommaso BOLZONELLA, Matteo BARUZZO, Yueqiang LIU[1], Giuseppe MARCHIORI,
Go MATSUNAGA[2], Leonardo PIGATTO[3], Anton SOPPELSA, Manabu TAKECHI[2]
and Fabio VILLONE[4]

Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, Padova, Italy
[1]*Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, UK*
[2]*Japan Atomic Energy Agency, Naka 311-0193, Japan*
[3]*Università di Padova, Italy*
[4]*Ass. Euratom/ENEA/CREATE, DAEIMI, Università di Cassino, Italy*

(Received 10 December 2013 / Accepted 28 February 2014)

In present day devices, the external kink ideal MHD instability establishes hard operational boundaries for both the tokamak and the Reversed Field Pinch (RFP) configurations. An interesting feature of it is that its growth rate critically depends on the device passive boundary characteristics and this can slow it down to time scales accessible to modern real time feedback control systems, normally using external active coils as actuators. 3D passive structures and external fields play a key role in determining physics and control of this instability. This is in particular true for equilibria with multimodal unstable RWM spectra where modes can couple to specific 3D features of passive and active magnetic boundary. In the paper we will present recent data and simulations from RFX-mod, a medium size ($R = 2$ m, $a = 0.459$ m) device able to confine RFP and tokamak plasmas with currents up to 2 MA and 120 kA, respectively. Successful quantitative modeling of multimodal RWM control experiments performed using different actuator configurations will be presented and commented.

Keywords: MHD stability, MHD feedback control, Resistive Wall Modes, 3D modeling, FEM modeling, tokamak, Reversed Field Pinch

DOI: 10.1585/pfr.9.3402081

1. Introduction

The external kink ideal MHD instability has been one of the first and most severe limiting instabilities encountered in magnetic confinement of fusion plasmas and is at present one of the most challenging issues in MHD stability and control [1]. During the growth phase its interaction with resistive structures surrounding the plasma decreases its growth rate and opens the possibility of controlling its amplitude by feedback control. The external kink instability evolving in presence of a resistive wall is often referred to as Resistive Wall Mode (RWM) instability. In this paper we will concentrate on the role of 3D features of passive structures and external fields. In fact, moving from the qualitative cylindrical assumptions to a fully quantitative investigation under realistic 3D boundary conditions is a very hard challenge for both modern experiments and modeling tools, especially when the closed loop analysis including feedback control is tackled. On the numerical side, the need for inclusion of detailed and realistic description of the device structure to be then coupled to multi-modal plasma stability analyses leads to the implementation of advanced simulation techniques. On the other hand, designing experiments able to give clear and robust data for detailed benchmarking of numerical codes to be then used in view of the design of future devices is a non-trivial experimental task.

To discuss all these aspects we present recent data and simulations from RFX-mod [2] ($R = 2$ m, $a = 0.459$ m). RFX-mod is a circular cross section, flexible device that can be run as Reversed Field Pinch (RFP) with currents up to 2 MA and also as low current, limited tokamak with plasma current I_p up to 120 kA. The RFP configuration is always characterized by the simultaneous instability of multiple tearing mode (sustaining the so-called dynamo mechanism) and RWM spectra. This might be recognized also in the peculiar profile of the RFP safety factor compared to a typical tokamak one in Fig. 1: in the RFP case, several $m = 1$ resonant modes (corresponding to the tearing mode spectrum) can be identified; RWMs appear instead as non-resonant, current driven instabilities. To control the negative effects of these instabilities, RFX-mod has been equipped with a very powerful and flexible system made up 192 (4 poloidal × 48 toroidal) active coils independently fed and covering the whole outer surface of the RFX-mod resistive shell [2]. Of course this situation ap-

---

author's e-mail: tommaso.bolzonella@igi.cnr.it

[*] This article is based on the presentation at the 23rd International Toki Conference (ITC23).

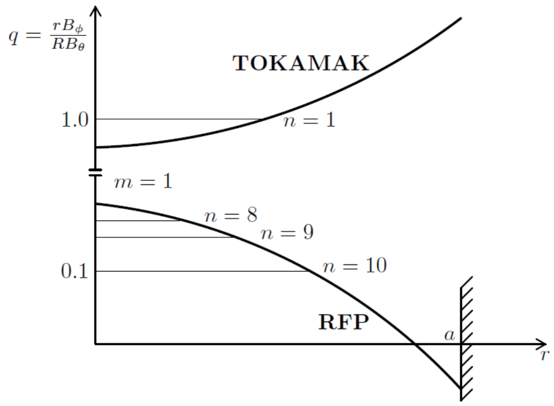

Fig. 1 Comparison of typical tokamak and RFP safety factor profiles. The location of some resonant surfaces is also shown.

pears to be very different from the situation of tokamaks equipped with active coils, where only a fraction of the outer surface can be covered by active coils which total number is usually of the order of 10 - 20. To improve the relevance of RFX-mod experiments in RWM control, recently its feedback software has been extended in order to allow the study of RWM stability under different actuator configurations simply by modifying few control parameters and not the whole hardware system [3, 4]: in this way it is also possible to use a reduced set of actuators for the control of only selected RWM modes, while maintaining the full set for the control of other modes and error fields. 3D effects induced by different actuator configurations on RWM stability can be experimentally characterized in great detail and decoupled from the optimal control of the background plasma. The modeling of these experiments for a direct, quantitative comparison between numerical tools and experimental data involves dynamic representation of toroidal plasma equilibrium and stability, 3D passive boundary, 3D active external field distribution and feedback control software algorithms. This task has been recently successfully accomplished by appropriate upgrading and tuning the CarMa code [5, 6], that was first adapted to RFX-mod to reproduce the measured RWM passive growth rates [7] and then coupled to a realistic representation of the RFX-mod control system. In this way a full dynamic model of RWM control experiments (a "flight simulator") has been implemented [8]. The model has been extensively validated against experimental data including the plasma response of the most unstable mode, which in the RFX-mod case, for a standard RFP equilibrium, is the internally non resonant $m = 1$, $n = -6$ in RFX-mod, where m and n stand for poloidal and toroidal mode number of a 2D Fourier analysis, respectively; see ref [9] for more details on RWM physics in the RFP configuration. Recently an enriched version of the dynamic model has been developed featuring the plasma response of RWMs with abs(n) = 1, 2, 3, 4, 5, 6. This is a key feature to analyze the effect of reduced actuator configurations since it allows the simultaneous study of modes which could be amplified by the low n order sidebands produced by the coils (Resonant Field Amplification).

2. The Multimodal Plasma Response Model

The dynamic model for RWM physics and control studies presented in [8] describes the plasma stability following many poloidal harmonics, but only one toroidal harmonics. This is the most appropriate choice for the tokamak case, where in the large majority of cases the most unstable mode has one clear dominant harmonics in the toroidal direction while many poloidal harmonics are needed to properly describe the unstable mode in the poloidal direction. In the new multimodal model, the plasma response is built in such a way that information on the stability of more toroidal harmonics is present at the same time. Therefore, the model can for example foresee how the control field needed to stabilize the most unstable mode can affect the stability of a mode with different toroidal mode number (via its unavoidable sidebands). The introduction of the new model is essential to fully explain the complex phenomenology of RWM control in the RFP configuration, but, as commented in the last section, will also help the simulation of RWM control tools for future tokamak devices operating at very high values of beta normalized. The new multimodal plasma response model was developed for the same reference equilibrium assumed in the previous analyses. This allowed an immediate consistency check between the results provided by the previous single mode (abs(n) = 6) plasma response model and the new extended version. To fully exploit the new multimodal capabilities of the model, open loop growth rates were evaluated and compared with experimental ones, when no feedback control is applied. From a control point of view, the open loop model is a dynamic system whose inputs are the saddle coil currents and whose outputs are the radial component of the magnetic field as measured by the saddle probes mounted on the RFX vacuum vessel outer surface. To identify the most unstable modes present in the model, the same approach exposed in previous papers [3, 8] was followed: we evaluated the Fourier transform of the outputs associated to the main eigenvectors (i.e. the eigenvectors associated to the largest unstable eigenvalues) and then looked for the one which exhibits the higher relative content in the selected (m, n) harmonic. Under this assumption it is possible to correlate harmonic components and eigenvalues and to perform a direct comparison with the results of 2D Fourier analyses on the experimental saddle sensors measuring the radial component of the magnetic field. In Fig. 2 the full spectrum of internally ($n < 0$) and externally ($n > 0$) non resonant RWMs is presented as extracted by the multimodal plasma response model. The model predicts an unstable behavior for the internally non resonant harmonic components, while a stable response is expected

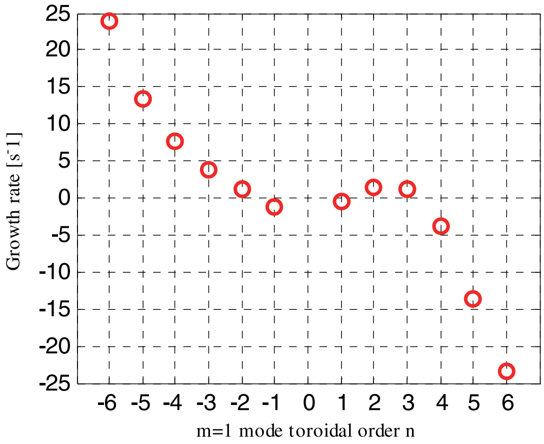

Fig. 2 Open loop largest eigenvalues of multimodal plasma response model.

for most of externally non resonant harmonics. Please note that here internal and external indicate the position relative to the surface where the toroidal magnetic field changes sign.

The agreement with the experimental growth rates reported in [3] is satisfactory, even if a wider dispersion of experimental estimates is observed for $n = 4$ and 5, probably due to their slower growth rate and to the limited length of plasma discharges. We also note here that for the same reason the dynamic characteristics of marginally stable/unstable modes ($|n| \leq 2$) is not easily observable and thus in the following we will focus our attention on the $|n| \geq 3$.

3. Control of RWMs with Reduced Set of Active Coils

Different configurations of active coils have been tested to investigate the minimum set of coils capable of stabilizing the whole group of RWMs, in particular trying to improve our knowledge on the rigidity of the plasma response. We use this term to define the possibility of controlling a single mode even by a reduced set of coils without triggering the growth of other modes originally stable. On the contrary, the mode rigidity can be defined as the possibility of controlling that single global mode by applying a local control action.

To better understand the results of plasma experiments, the field produced by each active coil configuration was first investigated in vacuum experiments and then compared with the results of the numerical model. In Fig. 3 two configurations used to investigate the role of toroidal extension of actuators are presented as example. In the first case (1 × 12 with single extension, top plot in Fig. 3), only 12 equally spaced active coils are used. In the second case (1 × 12 with triple extension, bottom plot in Fig. 3), a coil configuration similar to the previous one is used, but now the 12 coils have "virtually" a larger toroidal extension, obtained by averaging in real time the references of three neighboring coils.

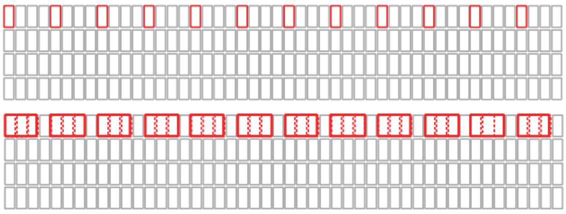

Fig. 3 Cylindrical representation of two possible configurations of actuators obtained by software control: 1 × 12 single extension (top) and 1 × 12 triple extension (bottom). Toroidal angle goes from left to right, poloidal one from bottom to top.

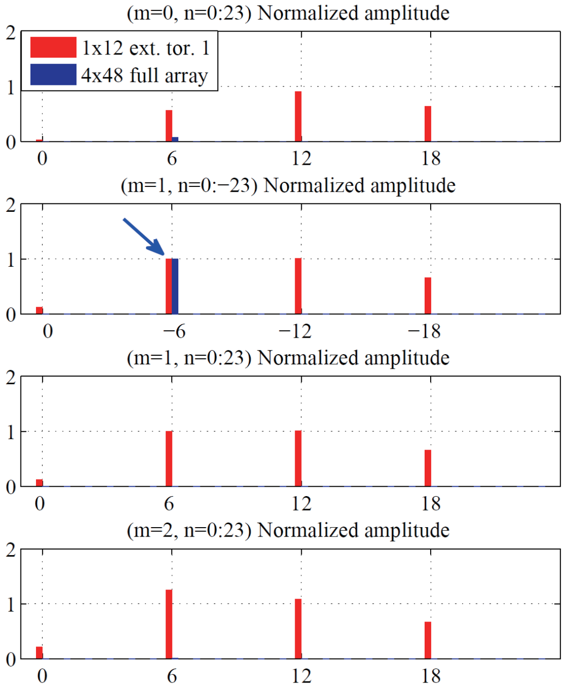

Fig. 4 Br spectrum for a (1, −6) target harmonics by the full system of 4 × 48 active coils (blue) and by the 1 × 12 single extension configuration (red).

One can understand the difference of multimodal RWM control experiments (and modeling) with a reduced set of coils already by comparing the vacuum spectrum generated by the full system of 192 coils and the first reduced configuration of Fig. 3 when trying to produce one single harmonic. This is done in Fig. 4, where the target harmonic for both systems is the (1, −6) and all other amplitudes are normalized to the amplitude of the (1, −6) one: while the field generated by the full system is basically monochromatic, the reduced array produces many other unwanted sidebands, both in poloidal and toroidal directions. To further quantify this effect and easily compare different configurations, we introduce here the concept of (squared) Total Harmonic Distortion (THD) defined as:

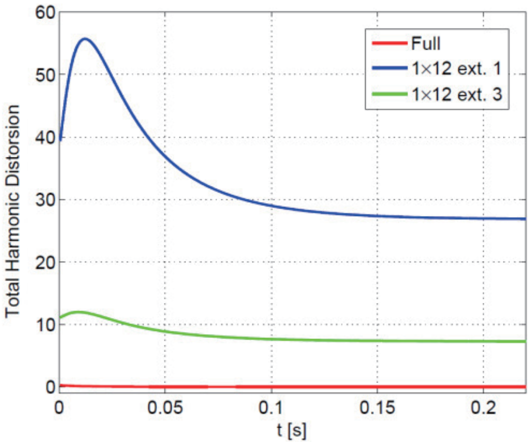

Fig. 5 Total Harmonic Distortion for three different active coil configurations: 4 × 48 (red), 1 × 12 triple (green) and 1 × 12 single (blue).

$$THD = \frac{\sum_i B_i^2 - B_{\text{target}}^2}{B_{\text{target}}^2},$$

where B_{target} is the amplitude of the target harmonics and B_i scans the amplitude of all the other harmonics (sidebands) produced by the specific coil configuration. In the case presented in Fig. 5, the THD parameter is used to compare in time the effectiveness of the full 4×48 array with the spectrum produced by the two reduced configurations of Fig. 3. The dynamical characteristics of the model allow the estimation also of THD during transients, that for the RFX-mod typical timescales can be of the order of 50 - 100 ms. The analysis in time highlight the importance of coil shape, showing that the case with coils larger in the toroidal direction (1×12 triple) produces much less sidebands during the transient phase than the case with the same number of coils, but narrower (1×12 single).

As for multimodal plasma experiments, we show in this paper the effect of sidebands when a configuration 4×3 (3 full poloidal arrays of 4 coils evenly spaced along the toroidal direction) is applied to the $m = 1$, $n = -6$, -5, -4 unstable harmonics. This configuration proved to be capable of stabilizing all the targeted unstable modes, at the price of increasing of about one order of magnitude the proportional gains with respect to the standard control case. Experimentally this was verified in shot # 31982 and reproduced by the dynamical model as shown in Fig. 6. It is worth noting that the increased gains used in the experiment did not cause any unstable behavior of the control loop. In Fig. 6 we compare the open loop RWM growth rates (red circles, this is the same data already plotted in Fig. 2) with the growth rates obtained by the model when using the same set of gains used in the experiment (blue diamonds). It is evident also by this eigenvalue analysis of the model results that the reduced system of actuators is able to stabilize $m = 1$, $n = -6$, -5, -4 modes. We also notice that $m = 1$, $|n| = 2$ modes change their growth rate as consequence of the coupling with harmonics produced to control the $m = 1$, $n = |4|$ modes. It is also important to notice that the system in this case is not attempting to stabilize the $m = 1$, $n = |3|$ modes, that in fact have the same growth rate in both cases. What was found in another set of experiments (not shown here), is that when the control system is closed also on the $m = 1$, $n = |3|$ modes, the coupling with the $m = 1$, $n = |6|$ ones makes the system unstable and the discharge is lost. This is due to the particular unstable spectrum of this equilibrium, where the marginally stable $|n| = 3$ naturally couples with the most unstable RWM characterized by $|n| = 6$.

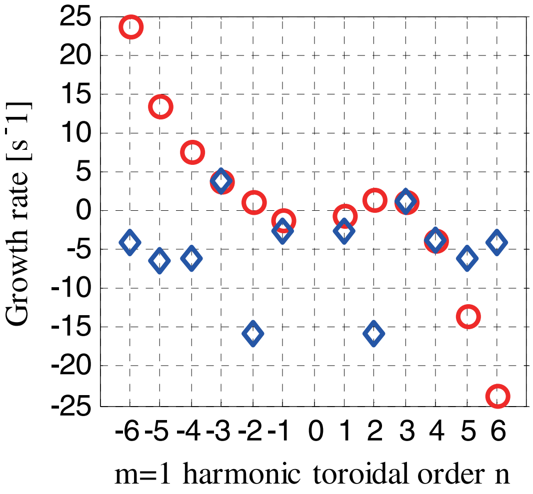

Fig. 6 Model largest eigenvalues for two cases. Open loop growth rates: red open circles, closed loop growth rates for reconfiguration of active coils “4×3”: blue diamonds.

4. Discussion and Conclusions

The multimodal version of the dynamic model for the study of RWM stability in RFX-mod is now available and validation tests performed up to now are encouraging about the possibility of its use as a predictive tool to assist the experimental investigations on the control of RWMs by means of a limited number of active coils. This case can be representative of some control issues typical of multimodal control in the presence of reduced number/size of actuators. In particular, we stress the fact that unwanted sidebands generated especially during fast transients by reduced actuator configurations can couple the control external field with other, non-controlled, harmonics. This coupling can be a virtuous one, as in the case of Fig. 6, but can also lead to the destabilization of otherwise (marginally) stable modes by the Resonant Field Amplification mechanism. We suggest that this might also be the case of future tokamak devices operating at high values of normalized beta, where more than one pressure driven RWM might approach the stability threshold.

Acknowledgements

This work was partially supported by the European Community under the Contract of Association between EURATOM and ENEA/Consorzio RFX, and by the Italian MIUR under PRIN grant 2010SPS9B3. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1] M.S. Chu and M. Okabayashi, Plasma Phys. Control. Fusion **52**, 123001 (2010).
[2] P. Sonato *et al.*, Fusion Eng. Des. **66/68**, 161 (2003).
[3] M. Baruzzo *et al.*, Nucl. Fusion **52**, 103001 (2012).
[4] T. Bolzonella *et al.*, “Software tools for actuator flexible configurations in real time MHD control: from design to application in magnetically confined plasmas”, submitted for publication to Fusion Engineering and Design.
[5] R. Albanese *et al.*, IEEE Trans. Magn. **44**, 1654 (2008).
[6] Y. Liu *et al.*, Phys. Plasmas **15**, 112503 (2008).
[7] F. Villone *et al.*, Phys. Rev. Lett. **100**, 255005 (2008).
[8] G. Marchiori *et al.*, Nucl. Fusion **52**, 023020 (2012).
[9] Z.R. Wang *et al.*, Phys. Plasmas **17**, 052501 (2010).