Advanced Control of MHD Instabilities in RFX-mod

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Abstract. The RFX-mod device is particularly suited to explore innovative concepts in MHD control by means of active coils thanks to the power and the flexibility of its system. Important advances on MHD active control have been accomplished during the last two years in different areas of active MHD control, fostering in addition interest and collaborations from many external laboratories. First of all, different degrees of couplings between actuators and sensors have been taken into account and used to successfully improve control of error fields and MHD instabilities. As to tearing mode control an optimization of the feedback laws aiming at keeping to the lowest possible level their edge amplitude has been performed both empirically and with the help of a new numerical code, which includes the tearing mode non-linear dynamics. Resistive Wall Mode control studies in the last two years focused on indentifying problems common to RFP and tokamak configurations and contributing to their solution. The issue of mode non-rigidity has been tackled, in particular testing the influence of different coil geometry and number by means of an innovative control software technique. Significant advances were produced also in the modeling of RWM control: a new dynamical integrated simulator for closed loop control experiments was developed and successfully benchmarked against experimental data. Last but not least, preliminary ohmic tokamak experiments at q(a) below 2 have been performed on RFX-mod avoiding disruptions in feedback controlled conditions and so opening the possibility of using the same device as test bench for advanced control strategies in both tokamak and RFP configurations.

1. Introduction

Optimized active control of plasma magnetic boundary and of MHD instabilities is a critical issue in fusion research shared by different toroidal configurations. The RFX-mod device is particularly suited to explore innovative concepts in MHD control by means of active coils thanks to the power and the flexibility of its system [1]. In particular, important advances on MHD active control have been accomplished during the last two years fostering the interest and the collaboration of many external laboratories. Given the different underlying physics that reflects in specific aspects of active control strategies, in the following, after presenting some recent advancement in the general feedback techniques, we will distinguish between Tearing Mode (TM) and Resistive Wall Mode (RWM) active control achievements.

2. General active control developments

The RFX-mod system for active MHD control is made of 192, independently fed, saddle coils playing the role of actuators in a feedback loop with approximately 600 magnetic signals as

real time inputs and a total cycle frequency of approximately 3-5 kHz, depending on the control law selected for the single experiment. It is clear that in such complex system taking into account in real time operations the coupling between active coils and sensors, that in principle takes the form of a 192x192 time dependent matrix, is a very challenging task.
For that reason feedback optimizations done in the past, such as the clean mode control [2], did not take into account any coupling effect; this is equivalent to state that the decoupling matrix used for most of the past experiments was a time independent, diagonal matrix with only one's as non-zero element values (see Fig. 1a). In the last years a staged approach has being pursued in order to include in the active MHD control system loop the couplings induced by coil-sensor proximity, toroidal geometry and deviations from uniformity of the passive structures (gaps, portholes, …). A first approach is based on the elaboration of a non-diagonal, stationary decoupling matrix that basically takes into account the first two aforementioned effects. The dynamical pseudo-decoupler [3] is a more elaborate approach which takes into account also the frequency dependence of the couplings between actuators and sensors. Another approach to dynamical decoupling based on coupling between actuator currents and radial field harmonics ("modal" decoupler) is at present under development with the aim of reducing the effect of sideband aliasing [4]. Note that despite some of these approaches are still too heavy from the numerical point of view for a full real-time implementation on the RFX-mod control system, off-line versions have been developed and have allowed important advances for example on the subject of dynamic error field correction.

2.1. Static decoupling matrix

Due to the high number of sensors and actuators involved, the elaboration and implementation in the real time loop of a static decoupling matrix proved to be a non-trivial step. The definition of the coefficients took advantage of the integrated identification of RFX-mod active control system from experimental data and finite element model presented in [5] and [6]. Starting from those couplings identification techniques, real time implementations of decoupling matrixes have been implemented and compared. In figure 1 three different choices are visually compared; note that different colors correspond to different coupling coefficients

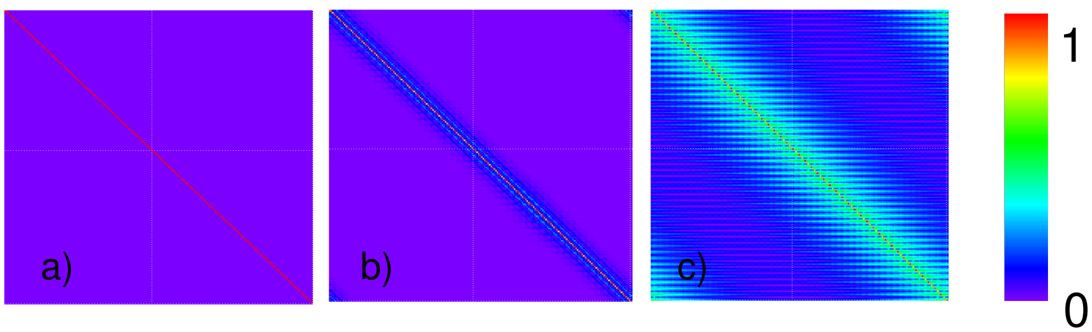

Fig.1: Visualization of three 192x192 different decoupling matrixes implemented in real time experiments.

where zero means perfect decoupling and one means complete coupling. Figure 1 presents in panel a) the simple identity decoupling matrix, in panel b) a decoupling matrix obtained via an experimental estimate of the couplings made during vacuum shots (and assuming certain symmetry properties of the machine description), and finally in panel c) the decoupling matrix obtained from a finite element model of the machine. It has to be noted how the third choice in particular presents a high number of non-zero elements out of the diagonal. The direct use of these matrices both in vacuum and plasma experiments allowed to prove the effectiveness of the new schemes in reducing the harmonic distortion of the control signals, not only for static waveforms, but also, partially, in the case of slowly rotating external perturbations.

2.2. Dynamic decoupling matrix and error field correction

In RFX-mod large error fields (EFs) are produced mainly during the setting-up of the discharge when, in few tens of milliseconds, the plasma current achieves its flat-top value that can reach up to 2 MA (see Fig.2a). In this phase the vertical magnetic field necessary to maintain the plasma in the correct position has to vary very quickly in time, but, due to the peculiar geometry of RFX-mod passive structures [1], penetrates faster around two toroidally localized positions where the boundary non-uniformity is more evident. As a consequence, an EF of few mT is observed, as shown in Fig. 2b. For a chosen operational scenario, the error fields and their time evolution are fairly reproducible so that characterization measurements could be acquired in dedicated dry-shots. As in the startup phase the configuration evolves on time scales faster than what the feed-back system can cope with, the goal was to add a feed-forward scheme for error correction based on this reproducibility. The magnetic field measurements provided by the 192 saddle sensors underlying the active coils were analyzed in dedicated shots for an off-line evaluation of the additional current references to be used in the shots with plasma. The magnetic field measured by each sensor is the result of the dynamical contribution of many coils and this must be taken into account to optimize the system response. To do that, an off line dynamic decoupler of the active coil system based on the estimated transfer function matrix between the active coils and the sensors was used. By

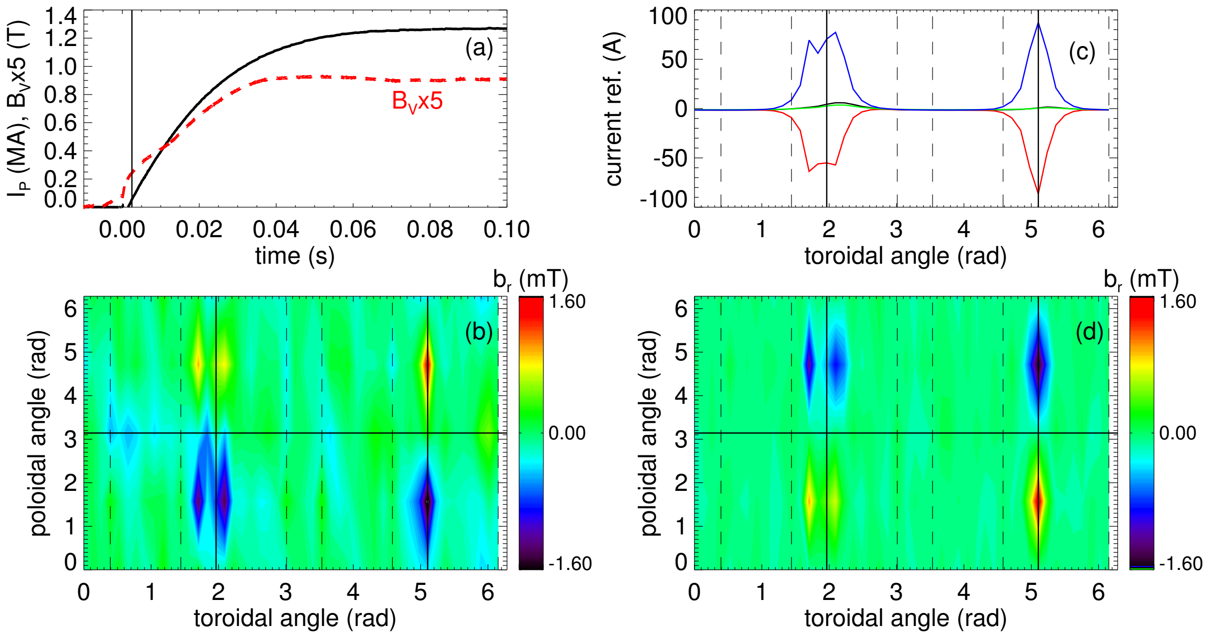

Fig.2: (a): plasma current; (b) contour plot of radial field without control at 5 ms; (c): pre-programmed currents at 5 ms; (d): contour plot of the radial field produced by the pre-programmed currents of panel (c) in a vacuum shot.

feeding the dynamic decoupler with the opposite of the magnetic field waveforms measured by the sensors, the optimal set of current reference waveforms could be evaluated off-line (panel 2c). They are then applied during the pulse as feed-forward reference signals to the coil current controllers and summed to the (slower) current references produced by the MHD mode feedback control system. Panel 2d shows the field produced by the feed forward part alone in a dedicated vacuum shot: the similarity to panel 2b, with opposite signs, is evident. This technique was successfully used, in connection with optimized feedback control gains, especially in high plasma current experiments (Ip>1.5 MA) where the deleterious effects of EFs are particularly evident.

3. Tearing Mode control studies

The dynamics of TMs under feedback controlled conditions is highly nonlinear and therefore standard control theory tools cannot be directly applied. In the last two years, an optimization of the feedback laws have been performed in order to find the best compromise between the lowest possible level of TMs edge amplitude and the maintenance of their differential rotation: an empirical approach and a single-mode model based approach have been performed and compared. Additionally, investigations on the effect of different non-zero resonant and non-resonant edge radial fields were performed. In addition to that, important physics issues were touched by studying the effect of non-zero references as feedback boundary conditions.

3.1. Gain optimization

The optimization of the gains to apply in the Clean Mode Control of RFX-mod boundary has been addressed by means of a model based investigation and then applied to experimental plasmas [7]. The original model considers the non-linear dynamics of interacting tearing modes, including their feedback control, and balancing the viscous and electromagnetic

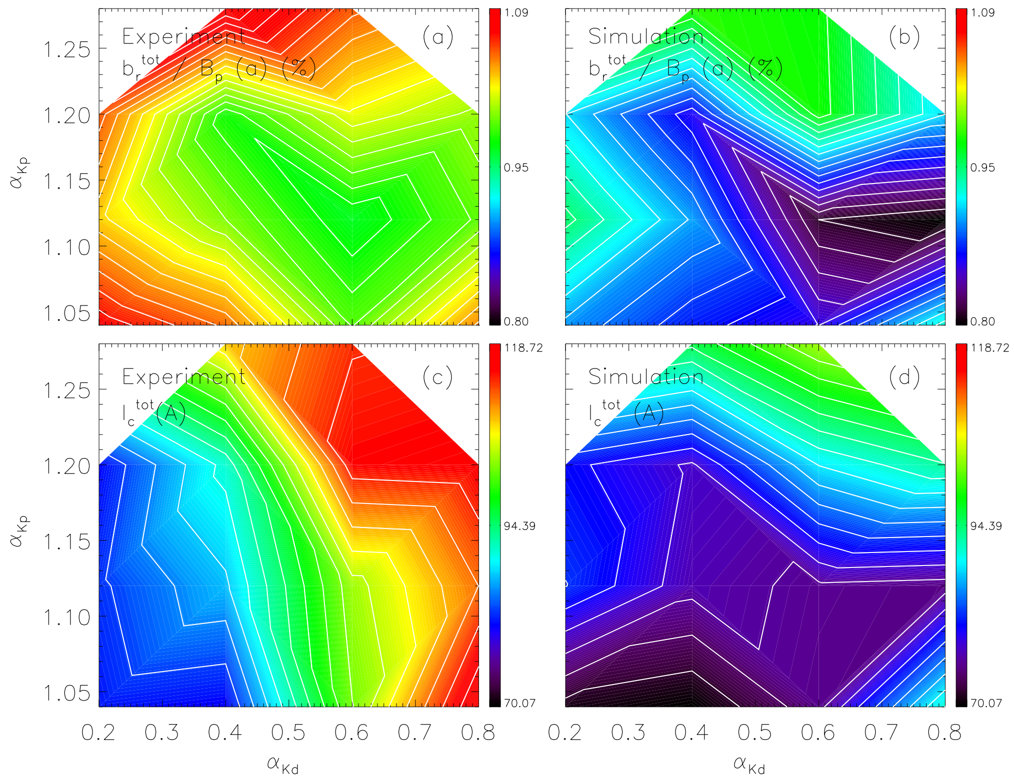

Fig. 3: Contour plot of the total normalized radial field and of the total current flowing in the active coils respectively for (a-c) the experiment and (b-d) the simulation as a function of Kp and Kd.

torques [8], and for the present study has been adapted to the multiple-shell structure of RFX-mod. The resulting code has been dubbed RFXlocking. As the system allows the definition of the PID gains for each mode, the model was used to simulate the dynamics of each TM independently by changing the proportional (Kp) and derivative (Kd) gains aiming at a configuration with the minimum value of the radial field. This was done considering also two more elements as representative of an improvement in control effectiveness: the rotation of the modes (or at least of their phase locked structure) and the reduction of the required current in the coils. Both aspects proved to be crucial for a successful control of TM in high plasma current regimes. Given the high number of variables involved in the optimization, a simpler 2D scan has been applied on each single mode at a time, neglecting the non linear interaction in the electromagnetic torque. The gains determined with the model have been tested in an experimental campaign of reproducible discharges in the range of plasma current Ip = (0.8, 1.1) MA at fixed magnetic equilibrium, see Fig. 3. An experimental gain scan has been performed by multiplying all proportional gains and all derivative gains by some factors, varied independently. Such a scan confirmed that the minimum of radial field is obtained for the proportional gain predicted by the model, while a slightly lower derivative gain is required.

3.2. Non zero reference studies

The effect of an external perturbation on resonant modes has also been tested in preliminary experiments based on the work presented in [9]: an external perturbation with a well defined helicity should be able to sustain a helical state. The paper, based on the VMEC equilibrium solver, suggests that an external perturbation with a helicity opposite to the dominant mode of the Single Helical Axis (SHAx) spectrum should be able, if large enough, to prevent its interruption. First experiments gave no clear indications on the effectiveness of the technique, probably due to the enhanced plasma-wall interaction induced by the high amplitude of the external fields used. More refined tests are planned in future campaigns.

Clearer results have been obtained on the direct sustainment of a given tearing mode at desired edge amplitude, both in static and rotating conditions. This is particularly important for the key effort done by the RFP community to optimize the helical state and to make it a reproducible and robust operational scenario. Experiments have been realized targeting the (m=1,n= -7) helicity, which is that of the dominant resistive kink mode in single helicity states in RFX-mod. The mode amplitude, frequency, and control gains have been varied in preparatory numerical scans searching for the best conditions that allow inducing such helical states with the lowest possible edge radial magnetic field, to avoid excessive plasma-wall interaction, and using the lowest possible coil current. One example is summarized in Figure 4 where the m=1, n=-7 mode amplitude and phase, along with the coil current on the same harmonic, are shown in black for a 1.5MA RFX-mod discharge. The helical boundary conditions are applied from

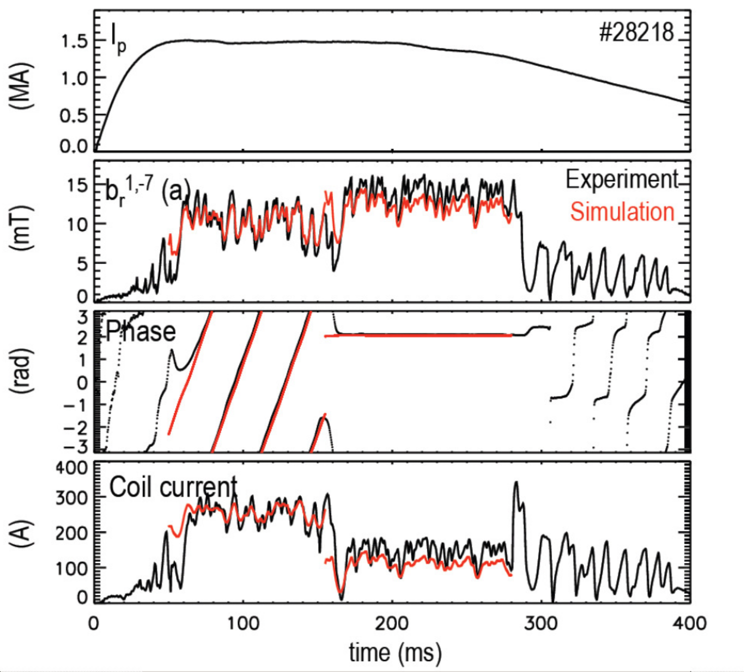

Fig.4: Non-zero tearing mode reference experiments in RFX-mod. From top to bottom: plasma current, m=1, n =-7 mode amplitude and phase, coil current amplitude for the same harmonic.

0.05 s to 0.28 s. An almost stationary helical equilibrium can be produced, either rotating or static in the laboratory frame. It is also noticeable the agreement shown with a simulation of the same discharge performed by the RFXlocking code (red line in figure).

4. Resistive Wall Mode control studies

Recent RWM studies in RFX-mod focused on solving problems shared with other magnetic confinement configurations and holding a strong relevance to general active MHD control issues. Examples of these studies are the complete characterization of poloidal and toroidal harmonic composition of a single unstable RWM, the mode behavior under subcritical control conditions (in support to a new simulation tool of the whole control loop), and the control of RWM instabilities with a set of active coils reduced by using a new real time software. It is important to remember also that in parallel also theoretical studies on the physics of RWM continued with a tight collaboration between experiment and numerical modeling: in particular a new stability code has been developed at Consorzio RFX [10] and applied to specific subjects such as the role of pressure profile in affecting the RWM stability properties.

4.1. Three-dimensional properties of RWM's in RFP configuration

By using the large number of available magnetic sensors, the detailed structure of an unstable RWM was investigated in RFX-mod. It was found that many poloidal harmonics contribute to describe the unstable mode even in the case of the RFX-mod circular, low-beta plasmas. Toroidal considerations seem not to be sufficient to explain the relative amplitude of these poloidal harmonics. This pointed at a clear experimental confirmation of the importance of 3D effects such as gaps and port holes not only on the overall growth rate determination (as already demonstrated by past comparison between RFX-mod experimental estimates and the 3D CarMa code simulations [11]), but also on the mode description in terms of Fourier harmonics. The results of these observations have obvious implications also for general considerations about optimal active coils design in present and future devices where the number of unwanted harmonics generated by the external control system has to be minimized.

4.2. RWM behavior under variable control configuration

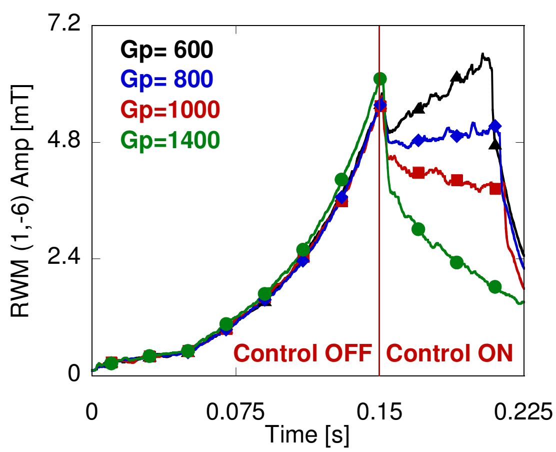

Fig.5: Proportional scan on the (1,-6) unstable RWM with only 25% of active coils coverage (inner toroidal array only).

The complementary problem of RWM rigidity under different control conditions was addressed by a software reconfiguration of the RFX-mod active control system. By acting on the digital controller programming it was possible to separate the control of one given unstable RWM and the control of all of the other unstable modes. In this way the optimal control of the plasma was preserved adding on top of that the possibility of changing the control properties (in terms of coil number or geometrical dimensions) of few selected modes. These experiments were performed in collaboration with JAEA-Naka, where the design and construction of the new superconducting tokamak JT-60SA is ongoing. Preliminary tests showed that in RFX-mod the control of the most unstable RWM can be still obtained by reducing up to 1/24 the number of active coils (surface covered by active coils goes from 100% up to 4.2%) after proper tuning of the controller gains. As a test configuration we show in Fig. 5 a proportional gain scan on the (1,-6) unstable RWM where 25% of the active coils are used. Note that in the new configuration the mode is stabilized for Gp>800, while the critical gain with full coverage is Gp≈400. An important result of these tests is that the most unstable RWM can still be controlled with a reduced set of coils and that the critical proportional gain can be experimentally evaluated, leading to an easy comparison with numerical models.

4.3. Flight simulator for realistic RWM active control operations

Another important contribution of RFX-mod activities in the field of RWM control is the development of a new integrated simulator for closed loop experiments (in collaboration with Create consortium and CCFE) and its benchmark against experimental data. The tool couples in a self consistent way a full 3D finite element description of the machine boundaries (Cariddi code), a 2D, toroidal model of RFP plasma stability (MARS code) and a true representation of the RFX-mod control system producing an overall dynamic model cast in the state variable state. In this way a full "flight simulator" of RWM control experiments has been implemented where experimental PID gains and plasma equilibrium parameters can be inserted into the model.

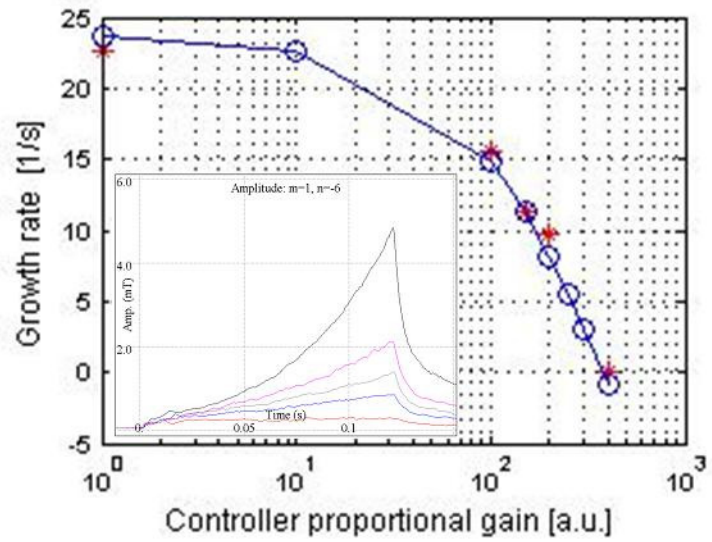

Fig.6:. Experimental data (red asterisks, see inlet for the full time behavior) and simulations (in blue) are compared.

As application of the new integrated tool, closed-loop RWM stability analyses have been benchmarked against experimental data [12]. In this way it was possible to experimentally prove that the control simulator correctly reproduces closed-loop RWM growth rates under subcritical control conditions, i.e. when a proportional gain lower than the critical one is applied to the control loop (see Fig. 6).

4.4. Tokamak MHD control on RFX-mod

Thanks to its flexibility RFX-mod can be also operated as a 150 kA, 1 s pulse tokamak. This possibility in connection with the high number of active coils available opens a wide range of possible MHD control strategies. Preliminary tests have been executed by destabilizing the (2,1) external kink mode in q(a)≈2 ohmic discharges with ramping current. The presence of the RFX-mod resistive shell slows down the (2,1) growth rate from its ideal value to values compatible with the action of the active MHD control system. In this way stable, feedback controlled operations at q(a)≈ 2 have been obtained, as shown in figure 7.

5. Conclusions and open issues

Continuous advances in active MHD control have been one of the key elements of the recent important achievements of RFX-mod device [13] and confirmed the high level of integration within the international scientific program of the Consorzio RFX group.

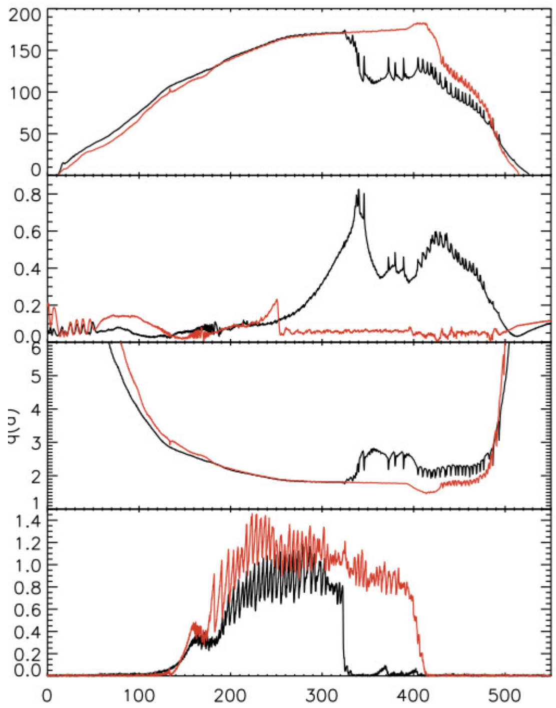

Fig.7: Tokamak plasmas obtained in RFX-mod without (black) and with (red) feedback control on the (2,1) MHD instability.

The new results obtained already suggest what could be some important lines of future, further improvements: more refined coupling models should be included in the real time loop, having as final target the dynamical pseudo decoupler described in [3]. To this aim it is clear that an upgrade of the digital control system itself will be necessary as well. New software and hardware solutions are under consideration, including the possibility of testing and benchmarking in RFX-mod ITER relevant solutions such as the MARTe real time framework. On the hardware side, the experience gained in the experiments and the successful benchmarking of the RFXlocking code, allowed a general study on the effectiveness of a different positioning of the active coils with respect to the mail conductive structures [14].

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