Recent Results from Real Time Active Control of MHD Modes in RFX-mod

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Abstract. The paper focuses on the recent results achieved using the technology developed for the RFX-mod real time control system of MHD modes, which provides features unique in the worldwide fusion experimental program. The paper highlights the successful technological aspects that have led to the outstanding scientific achievements obtained in the recent machine operation, including a dramatic increase in plasma duration and performance and a significant decrease in magnetic perturbations. RFX-mod addresses the MHD mode control by acting on the radial magnetic field configuration at the boundary. The approach is not limited to the stabilization of Resistive Wall Modes in RFX-mod, but it also aims at acquiring experimental knowledge on MHD mode control that can be relevant for high β discharges in tokamaks. To the purpose, an ad-hoc field correction coil system has been installed, consisting of 192 saddle coils covering the whole torus surface arranged in 48 poloidal arrays, each made up of 4 equispaced coils. Each coil is fed independently. By means of this actuating system, magnetic field poloidal and toroidal harmonic components (m, n) can be generated with m=0 n=0÷24 and m = 1 n=-23÷24. Two basic control strategies have been developed: the *Selective Virtual Shell* and the *Mode Control*. The former cancels all modes (*Virtual Shell* concept) except for selected preset ones (*Selectivity* concept). The Selectivity concept allows operating without interfering with the axi-symmetric equilibrium field (m=1, n=0) and studying the growth of selected unstable RW modes. The Mode Control interacts with single or multiple modes, taking into account the mode penetration into the passive structures.

1. Introduction

RFX-mod has been operating since experiment resumption in late 2004, with a scientific program having as central objective the demonstration of the feasibility of magneto-hydrodynamic (MHD) mode control. To the purpose, important modifications of the load assembly and power supplies were carried out and ad-hoc innovative active control tools and techniques were developed [1]. MHD mode control is a key issue for RFX, since the systematic phase locking of modes - to each other and to the wall – is responsible for localized deformation of the plasma column and consequent enhanced plasma-wall interaction with local power deposition up to 40 MW/m^2 on the first wall graphite tiles. The development of techniques for MHD mode control is a relevant issue also for tokamaks, since MHD resistive external kink modes, referred to as Resistive Wall Modes (RWM), arising in toroidal plasmas due to non-zero current and pressure profile gradients, limit the achievable β in advanced scenarios. RWMs, unstable in the presence of a resistive wall, are stable when an infinitely conducting wall is placed close to the plasma surface. Since a passive ideal boundary, acting as a perfect conductor during the plasma pulse of a fusion device, is not feasible, the development of successful technology for active feedback control of MHD instabilities is mandatory for the operation of ITER and future fusion reactors. Much effort is,

thus, spent in fusion community to address the problem [2,3].
Plasma instabilities are usually described in terms of two-dimensional spatial Fourier decomposition along the poloidal and toroidal directions and the relevant harmonic components are indicated with the mode numbers m and n, respectively.
RWMs have been predicted also for Reverse Field Pinch (RFP) machines and, according to theory, growth of RWMs showing poloidal and toroidal components $m=1$, $2<|n|<7$ and growth times of some tens of ms have been observed experimentally in RFX-mod during the recent campaigns [4]. The RFP is a low q magnetic profile machine - with $q(0) \approx 0.5a/R$ decreasing monotonically to $q(a) \leq 0$ - whose spectrum of unstable modes is dominated by those with m=1 and n in a large range of values. In RFX (a=0.459 m, R=2.0 m) the modes with $n \leq -7$, *internally resonant Tearing Modes* (TM), are responsible for the dynamo sustainment. The modes with $-7<n<0$ and $n>0$ are, instead, *non-resonant* (internally or externally) RWMs. As a consequence, RFX-mod shows a very rich spectrum of MHD modes and is, thus, an excellent environment where to study the mode phenomenology and the techniques for mode control. Fig. 1 shows by striped bars the amplitudes of m=1 modes measured at the plasma edge in reference RFX-mod pulses executed without mode control.
RFX-mod addresses the control of MHD modes by acting on the magnetic configuration at the plasma boundary. This corresponds to the concept of a discrete active shell as proposed for the first time in late Eighties [5]. To the purpose, two major modifications were necessary on the RFX original load assembly: the installation of a dedicated radial field coil system, to perform active control on non-axisymmetric radial magnetic field at the boundary, and the replacement of the previous conducting shell, having long time constant for radial field penetration (~450 ms for m=1 n=0), with a new one with lower time constant (~60 ms for m=1 n=0), thus allowing the diffusion into the plasma region of external magnetic field on the pulse timescale (nominally 250 ms).

2. Tools for MHD Mode Control

The radial field coil system consists of a bi-dimensional mesh, including 192 equispaced saddle coils, mounted to cover the whole outer surface of the shell [6]. The mesh can be thought of as made up by four toroidal and 48 poloidal arrays. With reference to the toroidal reference system used in RFX, the centre of the generic saddle coil is identified with the coordinates ($r=0.581$ m, $\vartheta_i=i\pi/2$ rad, $\varphi_j=j\pi/24$ rad) where $0 \leq i \leq 3$ and $0 \leq j \leq 47$. For both measure and control, a couple of sensors is associated with each saddle coil, including one pick-up coil, detecting both toroidal and poloidal components, and one saddle probe sensing the average radial field [7]. The pick-up coils are located on the inner surface of the shell, aligned with the centre of the corresponding correction coil, whereas the saddle probes are mounted on the outer surface of the vacuum vessel on the projection of the correction coil onto the vacuum vessel itself. Fig. 2 shows the assembly of the saddle coils on the mechanical structure enclosing the shell and the vacuum vessel. Each saddle coil is fed independently through its own power amplifier, consisting of one four-quadrant, IGBT-based H-bridge [8]. Table I displays the power ratings for both coils and power units.
The system capability to generate field modes spans, in principle, in the range m=0 n=0÷23, m=1 n=-24÷23, m=2

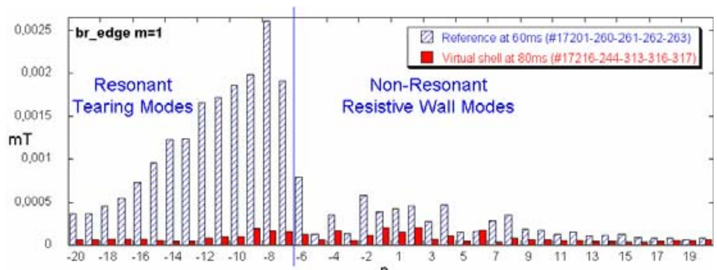

FIG. 1. m=1 toroidal Spectra of Br at sensors with (red) and without (blue striped) mode control.

n=0÷23, that allows to study the control of typical RFX TMs, without sidebands in the region of interest. The filter actions of both vacuum vessel and passive structures limit the magnetic field penetration. The vacuum vessel acts as a low-pass filter on the radial field measurements with cut-off frequency in the range of 1000 rad/s, whereas the shell along with the other passive structures has a dramatic shielding effect - with cut-off frequency of ~16 rad/s for m=1 n=0 - on the radial field at the plasma edge. The relative position of shell, correction coils and field sensors represents a compromise between the contrasting requirements of minimizing the shell proximity and maximizing the correction coil effectiveness [9]. Fig. 3 illustrates, as an example, the open loop generation of the m=1 n=-7 mode rotating at f=50 Hz. From above to below, it displays the currents and the corresponding radial field in four poloidal arrays located at the toroidal coordinate 0≤φ≤π/8 rad (16 coils) along with the m=1 current and radial field spectra. It is worth noting that the current amplitudes are uniform within one poloidal array, whereas the radial field amplitudes are not, due to the presence of an equatorial insulating gap. Differences in radial field amplitudes are also present in toroidal direction (not shown in fig.), due to the presence of a vertical insulating gap and various ports for pumping and diagnostics access.

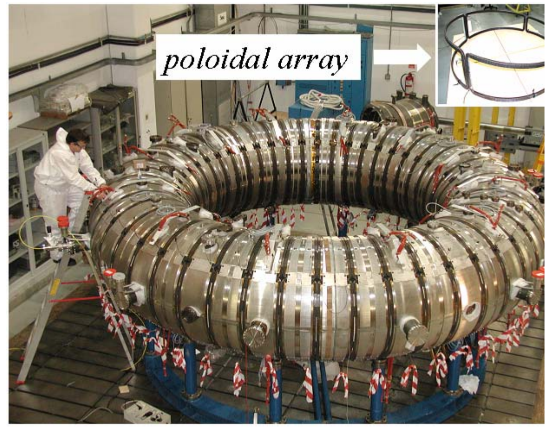

FIG. 2. Assembly of saddle coils on mechanical structure. Top right corner shows a poloidal array consisting of four saddle coils.

3. Control System for Plasma Control

To allow flexible control of plasma and MHD modes, an integrated, distributed, digital control system has been implemented, including, so far, seven computing nodes exchanging data during operation via a real time network. Fig. 4 illustrates the architecture of the system that is implemented as a general real time framework for feedback control (both hardware and software) integrating a high-performance computing system with a comprehensive analogue input/output section [10]. MHD mode control is directly

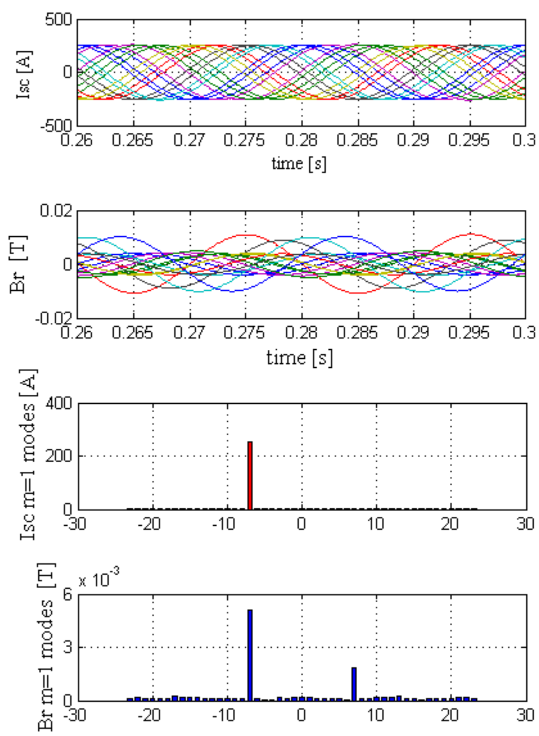

FIG. 3. Open loop generation of m=1 n=-7 mode. From above to below: currents and radial field in the poloidal arrays located at the toroidal coordinate 0≤φ≤π/8 rad; m=1 spectra for current and radial field.

Table I
Rating of saddle coils and power amplifiers

Saddle Coils and Power Amplifiers	
Voltage [V]	*650*
Peak Current [A]	*400*
Magneto motive force [kAt]	*24*
PWM frequency [kHz]	*10*
Response time [ms]	*<1*
Br at plasma edge at DC [mT]	*50*
Br at plasma edge at 100 Hz [mT]	*3.5*

addressed by four nodes, the *Radial* and *Toroidal Field Processors* and the *MHD A* and *B Controllers*. The processors acquire and elaborate the homonymous components of the magnetic field, whereas the controllers compute the control algorithms generating the references to drive the power amplifiers. Two controllers are used, instead of a single one, so as to keep the size of nodes manageable. Each controller acquires, in fact, 96 analogue signals (currents in the power amplifiers) and produces 96 driving references. The *Axisymmetric Processor* and *Controller* execute control on axisymmetric parameters, such as the plasma equilibrium and position, the magnetizing current, the flat-top sustainment of plasma current and the bias toroidal field. Interaction exists between equilibrium and MHD mode control because of the penetration of the vertical component on the m=1 n=0 magnetic field (equilibrium field). Eventually, the *Toroidal Controller* controls the reversed toroidal field and contributes to the generation of m=0 toroidal and radial field components, being the toroidal winding split into 12 sectors independently fed during the reversal phase. Though the whole system acquires more than 750 analogue channels and produces more than 250 analogue references, the cycle latency - i.e. the delay from acquisition of an input sample to generation of corresponding output references - is kept between 200÷400 μs depending on control algorithms, which is a suitable value for control of modes with growth times of the order of tens of ms. The framework implements a variety of alternative control algorithms [11]. In the following we will discuss on the implementation of two specific algorithms: the so called *Selective Virtual Shell* (SVS), that has been extensively tested producing very successful results, and the *Mode Control* (MC) currently being experimented.

3.1. Selective Virtual Shell

The active cancellation of the radial magnetic field at the sensor radius is referred to as *Virtual Shell (VS)*, in analogy with the passive cancellation by an ideal superconducting shell. The active action could be implemented as the operation of 4x48 independent flux control

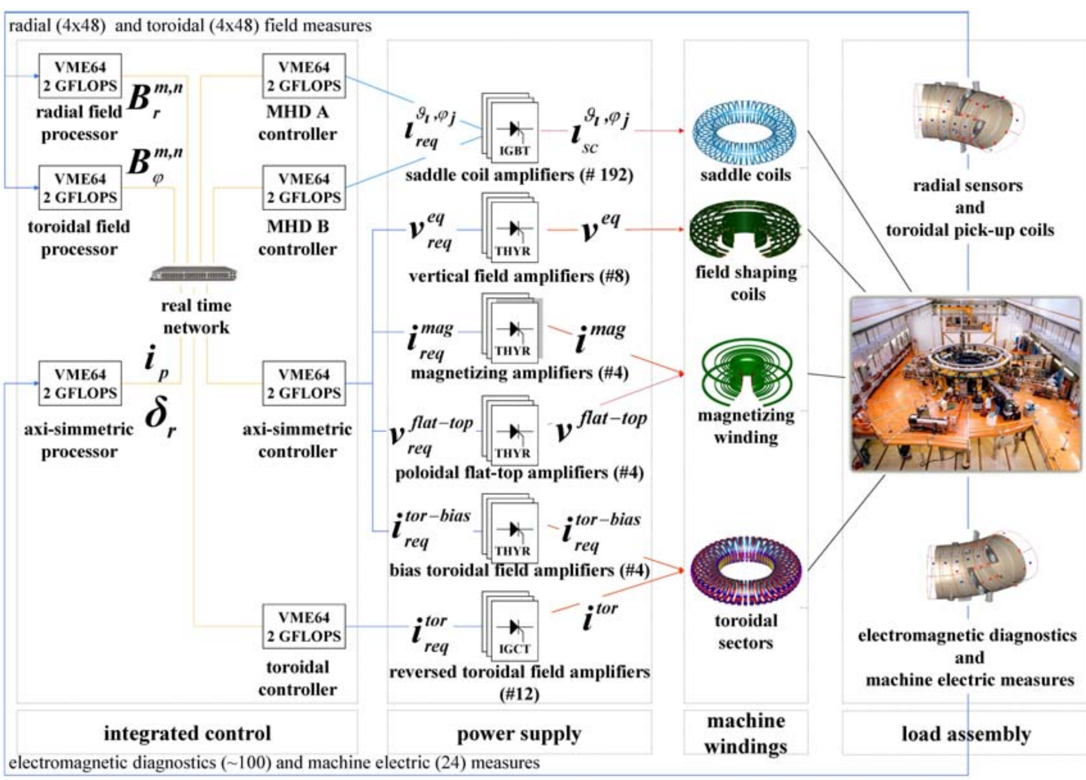

FIG. 4. Layout of the RFX-mod plasma control system.

loops, each controlling one saddle coil through the feedback measure from the corresponding radial field sensor. This realization, though simple and robust, is not suitable for toroidal devices, since it prevents from controlling the plasma equilibrium by external vertical field, as routinely done in most experiments, either tokamaks or RFP machines. Moreover, it does not allow operating selectively on MHD modes and can not integrate control schemes relying on feedback signals originating from complex elaboration of magnetic field measurements. To override these limitations, the VS has been implemented in RFX-mod in a more flexible way. At any control cycle, the radial and toroidal field processors compute in real time the two-dimensional spatial harmonic analyses on a complete sample of the corresponding magnetic field components, and distribute the results to the two MHD controllers that process control algorithms and generate the control references. The real time implementation of harmonic analysis allows controlling the MHD modes selectively. By this scheme it is possible to permit the penetration of the external axi-symmetric field for plasma equilibrium, shape and position control and, in addition, to study the effect of the control on single or multiple modes, for example the control of the sole RWMs, letting TMs evolve freely, or vice versa. This scheme is referred to as *Selective Virtual Shell* and its block diagram is shown in Fig. 5. The radial field $b_r^{\vartheta i,\varphi j}$ is measured by the 192 sensors and the real time 2D spatial Fast Fourier Transform (FFT) is computed to produce the Fourier components $B_r^{m,n}$. Feedback control is applied on a subset of selected modes $B_{feed}^{m,n}$. The inverse FFT is applied on the selected modes to obtain the feedback control signals $b_{feed}^{\vartheta i,\varphi j}$. The reference control signals $B_{ref}^{m,n}$ are set directly in the Fourier transform domain and reported to space domain references $b_{ref}^{\vartheta i,\varphi j}$ through an inverse FFT. When a mode reference is set to zero, the control system operates to cancel the corresponding mode, whereas when it is preset to a complex number, the control system acts to produce the corresponding mode. A set of 192 independent PI regulators computes the field request $b_{req}^{\vartheta i,\varphi j}$ on each radial sensor (ϑ_i, φ_j) using as feedback the error signal $b_{err}^{\vartheta i,\varphi j}$. The matrix $M^{-1}S$, taking into account the static magnetic mutual coupling of the saddle coils and sensors (M) and the radial sensor surfaces (S), transforms the field requests into the current requests $i_{req}^{\vartheta i,\varphi j}$ that are used as current references for the saddle coil power amplifiers implementing their own local current control loops. The entire pulse can be subdivided into multiple segments, associated to different time spans during the pulse that can be pre-programmed independently. In this way, it is possible, for example, to program a first segment including control on a certain mode at plasma rise, to let the mode free to evolve in a second segment and, finally, to re-apply control in a third segment.

The *SVS* is applied on a toroidal surface at the radius of the radial field sensors. Alternative more complex schemes, computing the field distribution in the region external to the plasma, allow applying the *SVS* beyond sensors' radius [12]. This technique, referred to as *Closer Virtual Shell* and currently being experimented, can force the magnetic boundary at any radius in the vacuum region between the last closed flux surface and the correction coils.

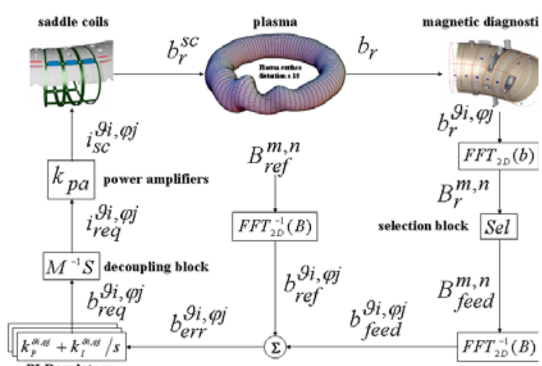

FIG.5. Block diagrams of Selective Virtual.

3.2. Mode Control

Direct mode control has been also implemented introducing a derivative control to compensate for the radial field penetration delay due to the passive structure. As the delay depends on the mode order, it was not possible to model the compensation in the SVS. Fig. 6 displays the block diagram of MC. The main difference with *SVS* is that the regulators act directly on the harmonic components. To smooth the derivative action, a filter (1-pole Butterworth) is applied to the mode components. Due to the success of SVS, MC has not obtained yet the experimental time needed for a real use on the machine.

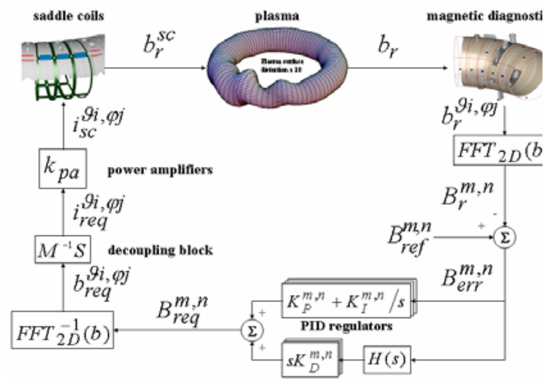

FIG.6. Block diagrams of Mode Control.

4. System Capability

Extended tests have been performed by generating single modes to evaluate the system's capacity to produce pure spectra not affected by spurious modes.

Fig. 7 shows, as an example, by yellow bars the measured normalized amplitudes of magnetic field modes when the system is used to generate in closed loop only the m=1 n=-7 mode. In the mode generation no decoupling is used among coils. In this case, due to toroidal geometry, the magnetic field spectrum achieved shows the presence of two spurious modes, the m=0 n=7 and m=2 n=7 ones, with noticeable amplitudes. To enhance the spectrum quality, a dynamic electromagnetic model has been developed and validated, and through this model the static matrix M has been obtained accounting for the mutual coupling among saddle coils and among saddle coils and sensors. In solid bars the spectrum is displayed when the generation is performed using the decoupling block. As shown in figure, the spurious mode suppression achieved is very effective. A m=0 n=7 component arises in the current spectrum when using the decoupling block to cancel the m=0 n=7 radial field mode. Analyses are currently under way to extend the model to the dynamic case to account for the field penetration into the load assembly with the aim of improving the system time response.

The capability of the system to control single modes has been checked by canceling the pre-programmed m=1 n=0 and m=0 n=4 perturbations, produced with the field shaping and toroidal windings, respectively. Fig. 8 shows the feedback actions canceling both modes in few tens of ms. The response time is acceptable in both cases, even though improvements are expected including in the model the passive structures.

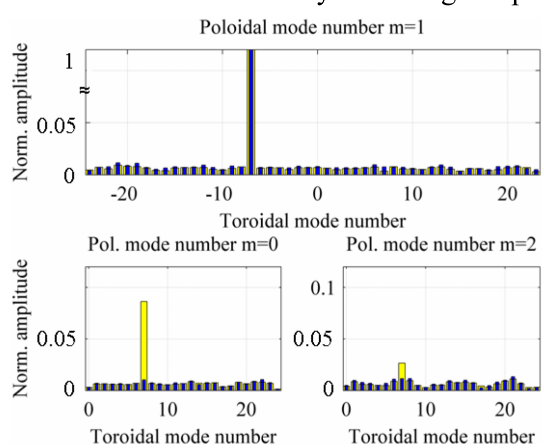

FIG. 7. Generation of m=1 n=-7 mode. Magnetic field spectra obtained without (yellow) and with decoupling (solid).

5. Results

Since the commissioning of the MHD mode control system, SVS has been used routinely in the machine experimental sessions, to control both RWMs and TMs, contributing significantly to the successful results obtained [14,15,16].

5.1. RWM and TM Control

To characterize the RWM growth and their control, extensive experimental campaigns have been carried out in 2006 at 600 kA [4], in which the SVS has allowed studying in the same pulse both evolution and control of RWMs. Fig. 9 highlights the case, comparing three pulses programmed with the same parameters (the m=1 n=-6 being the most unstable RWM), but differing in how RWMs are controlled. Pulse #17301 (blue) is executed excluding m=1 n=-6 to -3 RWMs from control. The m=1 n=-6 unstable mode grows and when its amplitude reaches a few mT the pulse is early terminated. Pulse #17287 (red) is executed with full VS control (except, as usually, for the m=1 n=0 equilibrium field). The amplitude of the m=1 n=-6 mode is kept at negligible values and the plasma current is well sustained up to 250 ms. Pulse #17304 (green) is executed letting the m=1 n=-3 to -6 free to grow until t=150ms and at this point control is applied on the modes reducing promptly the mode amplitude - in ~10ms - to very low values.

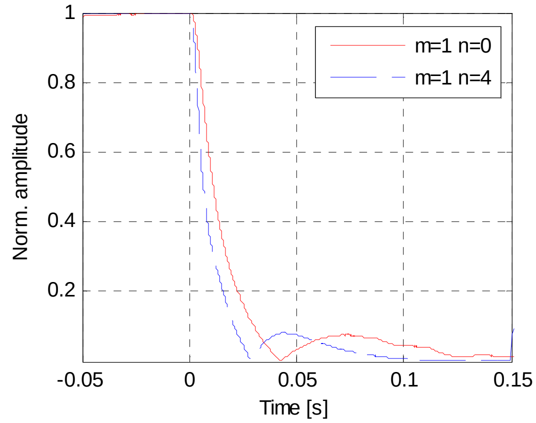

FIG. 8. Cancellation of disturbance m=1 n=0 and m=0 n=4 modes produced by field shaping and toroidal windings, respectively

Fig. 1 compares the spectra of Br measured at the sensor radius without (striped blue) and with (red) mode control, illustrating the system effectiveness in reducing the amplitudes of both RWMs and TMs at sensor radius. TM activity is also reduced in the plasma core, as confirmed by Thomson scattering and SXR double filter diagnostics [15]. TM mode rotation has been achieved routinely applying the SVS, contributing significantly to the alleviation of the plasma wall interaction and allowing, so far, scaling of plasma current up to 1MA [16]. Experimental campaigns are in progress up to full design performances. The control of the radial field boundary allowed the execution of well controlled plasma pulse up to 360 ms, corresponding to six shell times, far beyond the original design value of 250 ms.

5.2. Power Consumption

To quantify the power needed in RFX-mod for mode control, fig. 11 shows the power supplied by the power amplifiers to control the MHD modes by means of SVS in pulse #19648 at 1 MA. In the pulse the references for the m=1 n=-7, -8, -10, -11, -12 TM are not preset to cancel the modes, but to produce rotating modes. The figure shows, from above to below, the plasma current, the power supplied by the amplifiers for MHD mode control, the ohmic power associated with the plasma, and the m=1 spectrum at flat-top, respectively. During the flat-top the power needed to control the MHD mode is ~1% of the plasma ohmic power.

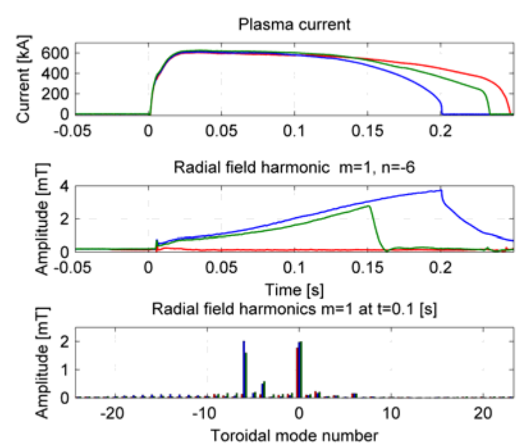

FIG. 9. Feedback control on RWMs. Comparison among pulses programmed with same parameters, but differing in RWM control.

6. Conclusions

RFX-mod represents a unique environment for advanced studies on MHD mode control and the flexibility and robustness of its control system have permitted a significant step ahead in the demonstration of the feasibility of active control of MHD modes. The MHD mode control by imposing the magnetic boundary through active correction coils has proven very effective in RFX-mod to achieve significant stationary confinement improvements and full feedback stabilization in conditions where multiple unstable modes are present. The application of MHD control has produced remarkable and reproducible effects on the plasma [16]. The robustness of the MHD feedback control qualifies the system as an important step for possible studies and applications on RWMs, TMs and sidebands in tokamaks and fusion reactors

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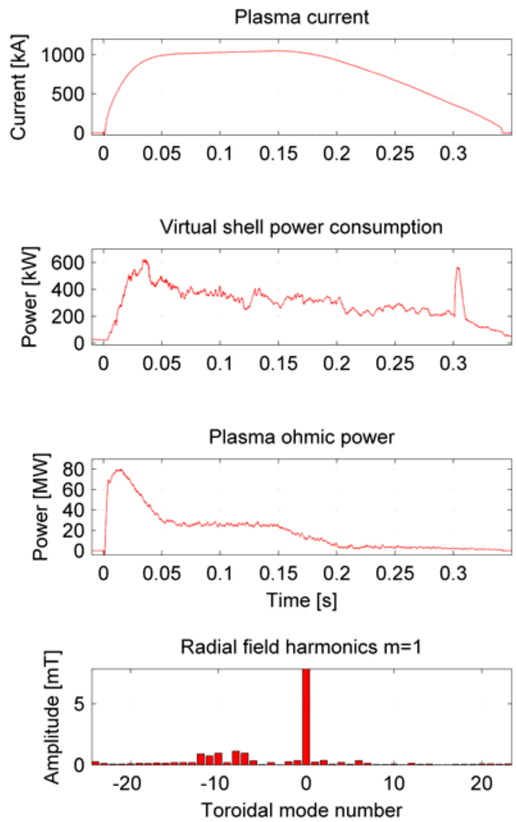

FIG. 10. Power consumption associated to MHD mode control

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