Modelling and experimental study of tearing mode control with the new RFX-mod feedback control system

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The non-axisymmetric edge magnetic radial field of the RFX-mod experiment is actively controlled by a network of 48x4 independently driven active coils[1] connected to a centralized digital feedback system. The active control of the radial field due to Resistive Wall Modes (RWM) ($m=1$, $-6\leq n\leq 6$ depending on the equilibrium) and to Tearing Modes (TM) ($m=1, n\leq -7$) led to a significant increase of the pulse duration and allowed, after several control optimizations[2], including in particular a sidebands cleaning algorithm[3], to explore the 2MA regime.

While RWMs[4] are not observed in feedback controlled discharges with optimized gain, the same does not apply to TMs, which are nonlinearly saturated resonant resistive modes[5] locked to the wall in RFX-mod in the plasma current regimes explored so far. These modes are present even with an ideal magnetic boundary, i.e. a perfectly conducting wall located at the plasma edge; moreover their radial profile is global. TMs are responsible for plasma–wall interaction: the shape of the last closed magnetic surface (LCMS) is, in fact, deformed in a non-axisymmetric way by their edge radial magnetic field. The active control system can reduce such deformation when optimized feedback laws are used. Standard control theory tools cannot be applied to TMs control, due the non-linear character of the electromagnetic torque, which rules the interaction between TMs and the external conductive structures such as shell, vacuum vessel and active coils. For example, TMs are wall locked for gains lower than a certain threshold, whereas above it they start rotating. The feedback induced frequencies are much smaller than the natural ones (in the kHz range), but in any case large enough to determine a radial field screening by the resistive shell, and therefore a quasi-ideal shell boundary condition. The non-linear dynamics of the TMs under feedback controlled conditions has been investigated with the RFXlocking code[6] that simulates the behaviour of closed loop feedback evolution by driving currents in the coils subject to a feedback law that aims at cancelling the feedback variable. This is the radial field at the plasma edge, obtained as a linear combination of the radial and toroidal magnetic field harmonics at the sensors radius, with relative weights computed with the vacuum cylindrical model[2] (hence the name "*extrapolated radial field*"). The phase dynamics of the tearing mode is governed by a torque equation that takes into account the viscous torque due to the plasma fluid motion and the electro-magnetic torque both due to the external conductive structures and the non-linear TMs self-interaction. The RFXlocking code uses a cylindrical geometry and three passive structures (conducting shell, vacuum vessel and mechanical structure) which characterize the RFX-mod magnetic boundary. TMs radial profiles are described by Newcomb's equation, solved with self-consistent simulated boundary conditions. The input of the code is the time evolution of the tearing mode amplitude at the resonant radius, estimated by another Newcomb's equation solver based on experimental edge measurements.

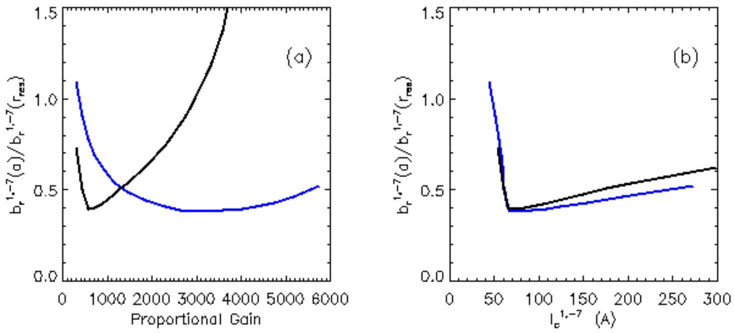

Figure 1) RFXlocking single mode simulations with different proportional gains. Radial magnetic field amplitude normalized as a function of (a) the gain and (b) the current harmonic; (c) rotation frequency vs current harmonic .Black: standard extrapolated feedback variable, blue: feedback at sensor radius.

Numerical simulations. The RFXlocking code has been modified to investigate numerically the behaviour of a new feedback variable. In detail, as suggested in [7], a harmonic feedback variable with different weights of the radial and the toroidal component has been tested. Single mode simulations show that the dependence of the TM edge radial field (normalized to the amplitude at the resonance) on the proportional gain is qualitatively similar to the extrapolated case, even though the gain threshold strongly depends on the relative weight between the radial and the toroidal component in the feedback variable. Continuous traces in Fig. 1a show the edge radial field $b_r^{17}(a)$ normalized to its value at the resonant radius $b_r^{17}(r_{res})$, for a series of simulations with different gains in two extreme cases: the blue curve corresponds to simulations where the radial field at the sensors was used as feedback variable, while the back one to the standard extrapolated feedback variable. Cases with different relative weights are in between these extremes, while further increasing the weight of the toroidal component does not lead to significant changes. Despite the significant variation of the magnitude of the gain, if the dependence on the control current harmonic ($I_c^{1,-7}$) is considered, the normalized edge radial field (Fig. 1b) and the phase velocity (Fig 1c) are found to collapse to curves close to each other.

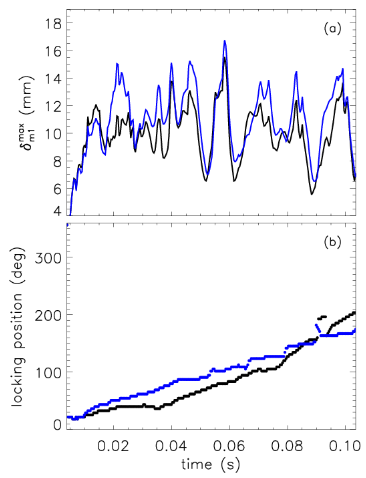

Figure 2) Time evolution of (a) the maximum m=1 displacement and (b) the locking position for different locations of the feedback sensors. black:r=0.507 (sensor radius), blue r=0.459 (plasma radius).

Given the results of single mode simulations, a model-based optimization similar to the one adopted in [3] has been used to find the best feedback PID control parameters for multimode simulations. In particular, the PID gains have been selected to have a coil current request similar to the standard case, and to obtain a displacement of the localized bulging due to TMs phase locking. Comparison of a standard feedback variable simulations and a non-extrapolated one with numerically optimized PID gains are shown in Fig. 2: the simulations have been carried out using the same input values, i.e. keeping the same time evolution of the radial magnetic field at the resonant radius for each tearing mode. The first panel compares the time behaviour of the m=1 displacement of LCFS, while the bottom one shows the toroidal position at which the tearing modes are phase-locked. The numerical simulations indicate that, after a proper gain optimization, a comparable non-axisymmetric displacement δ^1_{max} and a similar movement of the locking position can be obtained. The weak dependence on the feedback variable just discussed reflects the quasi-ideal shell boundary condition produced by the feedback induced rotations[6]. Papers such [7] claiming the possibility for the feedback of stabilizing TMs better than the ideal shell condition neglect electromagnetic torque and the ensuing feedback rotations.

Experimental results. Several experimental campaigns have been performed in order to test the effect of the non-extrapolated feedback variable on the control of TMs: Helium is used as filling gas for better discharge reproducibility. The plasma current is in the 1.1-1.4 MA range, the reversal parameter $F=B_p(a)/\langle B_\phi \rangle$ is around -.02 and density ranges between 1 and 6 10^{19} m^{-3}.

At first, a gain scan on the dominant tearing mode m=1.n=-7 has been performed. The experimental data shown in Fig 3 represent, from the top to the bottom of the figure, the normalized radial magnetic field, the mode frequency and the coil current request on the m=1, n=-7 mode. Points represent the median of the time series during a current flat-top phase, while error bars correspond to the 25th and the 75th percentile. The dispersion of the data is due to the fact that the dominant mode amplitude fluctuates in time (while in single mode simulations constant amplitude at the resonance is assumed).

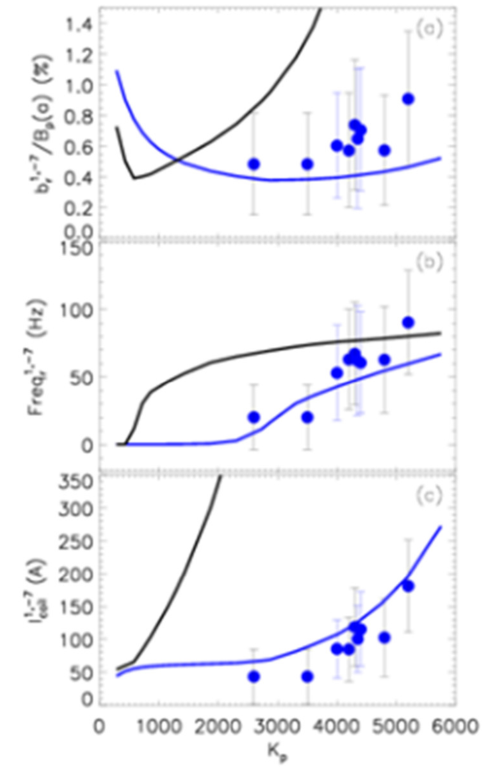

Figure 3) a) radial magnetic field amplitude normalized to the equilibrium field of the m=1, n=-7 mode, b) mode frequency and c) coil current request on the same mode as a function of proportional gain. Continuous lines: RFX-locking simulations. Blue: feedback at sensor's radius; black: standard feedback at plasma radius.

Interestingly, the dominant mode rotation frequency is significantly higher for feedback at sensor radius, compared to feedback at plasma radius at comparable harmonic coil current. Such a difference is bigger than what obtained in the simulations for comparable harmonic current (as shown in Fig 1): a possible explanation is that the radial profile of the dominant mode magnetic is modified by the feedback law. Further investigations are left for future work. Moreover, the time variation of the dominant mode phase is more irregular compared to standard feedback, as it often changes direction during the discharge.

Upon the dominant mode gain scan, the proportional gain selected as optimal corresponds to k_p=4350. As long as secondary tearing modes are concerned, i.e. modes with m=1,n=-8,..,-20, a scan has been performed by multiplying the numerically determined optimal gains by a two constants α_{kp} and α_{kd}, multiplying the proportional and derivative gains, respectively. The contour plot of Fig 4 shows

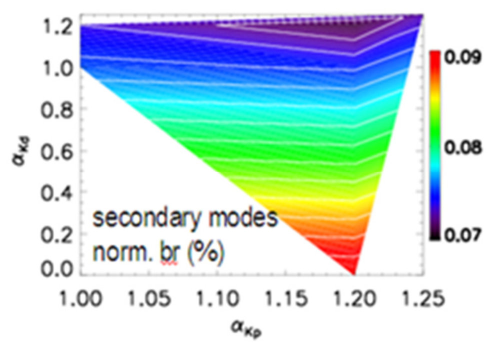

Figure 4) Contour plot of the normalized radial magnetic field amplitude of secondary modes in the proportional-derivative space.

the results of the gain scan: a weak minimum of the normalized value of the average of the secondary modes occur for derivative and proportional gains 20% higher than the ones obtained in simulations.

An ensemble of reproducible discharges has been performed, comparing the standard feedback variable with the non-extrapolated ones. For given plasma current, the normalized average amplitude of the secondary modes $b_r^{sec}/B_p(a)$ (Fig 5a) and δ^1_{max} (Fig 5b) with non-extrapolated feedback (blue dots) is comparable to standard extrapolated feedback (black dots). Rotation frequency of the dominant mode $\omega^{1,7}$ is much higher (Fig. 5c) and the requested harmonic coil current is slightly higher. In order to reduce $\omega^{1,7}$, a feedback law with a 30 Hz non-zero reference[2,8] value for the dominant (m=1,n=-7) mode has been set: with this modified feedback law, a more regular rotation is obtained, again with $b_r^{sec}/B_p(a)$ and δ^1_{max} (red dots).

Discussion. Feedback control of RFX-mod Tearing Modes is possible without using toroidal field sensors, even though it is not completely equivalent to the standard extrapolated case. This type of control has the practical advantage of requiring less real-time digitizers and less computing time, leading to a shorter latency. This is potentially an advantage, as RFXlocking simulations have shown that latencies reduction leads to reduction of edge field of tearing modes[9]. A latency reduction has been obtained thanks to the new feedback system based on the MARTe framework, with a 5 kHz cycle time[10], but significant improvements in TM control have not been observed, possibly due to latency in power supply units.

Nevertheless, the new control system is characterized by a considerably increased computing power with respect to the old one and therefore it allows the real-time implementation of new feedback algorithms. At present a more sophisticated sidebands cleaning algorithm taking into account in a more realistic way the RFX-mod passive conductors is under test. A further reduction in the number of channel could be obtained by computing the sideband cleaning using the references generated by the control system with an experimentally identified transfer function, instead of measuring the 192 currents flowing into the control coils.

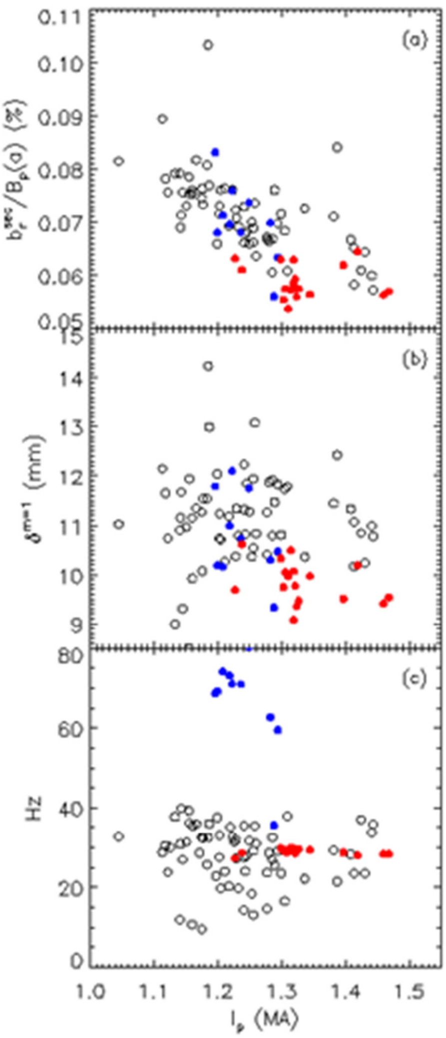

Figure 5) a) Normalized average of secondary modes, b) maximum non axi-simmetric displacement, c) rotation frequency, as a function of plasma current. Blue: feedback at sensors' radius; black: standard feedback at plasma radius; red: non zero reference values.

1 P. Sonato et al., Fus. Eng. Des., 66 (2003) 161
2 P. Zanca et al., Nucl. Fus., 47 (2007) 1425
3 L. Piron et al., Nucl. Fus., 50 (2010) 115011
4 R. Paccagnella, et al., Nucl. Fusion 42 (2002) 1102
5 S. Cappello et al., Phys. Plasmas13 (2006) 056102
6 P. Zanca, Plasma Phys. Control. Fusion 51 (2009) 015006
7 S.A. Richardson et al Phys. Plasmas 17 (2010) 112511
8 L. Marrelli et al, Plas. Phys. Contr. Fus. 52 (2007)
9 P. Zanca, Plas. Fus. Res., 5 (2010) 017
10 G. Manduchi et al., Fus. Eng. Des., (2012) http://dx.doi.org/10.1016/j.fusengdes.2012.05.014