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Advances in MHD mode control in RFX-mod

G. Marchiori, L.Marrelli, L.Novello, R.Paccagnella, P.Piovesan, L.Piron, A.Soppelsa, P.Zanca

Consorzio RFX – Associazione Euratom-ENEA – Padova, Italy

RFX-mod is a Reversed Field Pinch experiment equipped with an extended set of 48x4 saddle coils that actively control the magnetic boundary. Each coil is fed by an individual power supply unit, controlled by an internal current regulator. Reference signals for the power supply regulators are generated by a complex external control system, which is now operated in the so called "Mode Control" scenario, suppressing Resistive Wall Modes and producing partial phase and wall unlocking of m=1 resistive kink tearing modes (TMs). Since the discovery and correction of the systematic error due to the aliasing of sidebands produced by the active coils [1,2], the system has been further improved. Several gain optimizations, aiming at reducing the effect of TMs have been attempted: it has been found that by adding a complex gain on high n TMs (n<-12), a further reduction of phase locking is obtained, allowing more reproducible 1.5MA operations [3]. Attempts to reduce m=0 modes are still in progress, but the geometry of the saddle coils set stringent limits on the possibility of reducing the edge value of these modes.

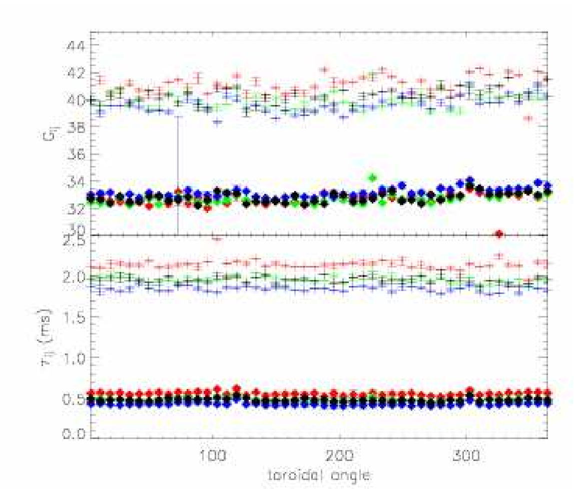

Fig 1) a) Gain and b) time constant as a function of toroidal position. (+) PI regulator, (◊)P regulator. Color describes coils poloidal position. red: HFS, blue LFS, black, upper and green lower

Improvements of the control system. The real-time computation of the sideband correction required an additional node in the control system architecture devoted to real time acquisition of coil currents. This allowed increasing the cycle frequency from 1.7 to 2.5 kHz.

Moreover, the internal controller of the inverters supplying the saddle coils has been optimized, in order to improve their dynamic response. In fact a time constant of ≈2 ms between the reference signal and the current supplied by the inverters was found using the previous proportional-integral regulator (K_P=1, K_I=2). Changing it with a purely proportional regulator (K_P=3) the time constant has been reduced to ≈0.5ms. In fact this modification permitted to increase the closed loop bandwidth of the current control system, at the expense of introducing a steady state error. Neglecting the coupling between neighbor

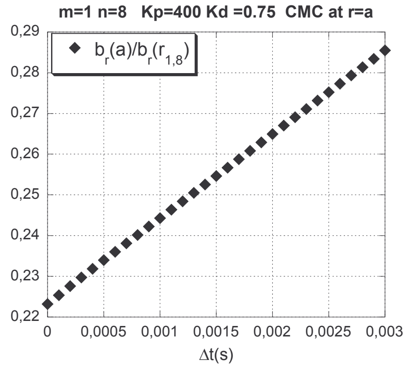

Fig. 2) edge value normalized to the value at the resonance vs. the one pole time constant τ

saddle coils, the transfer function between references and generated currents has been determined by a system identification approach: i.e an estimation of the 1 pole transfer function F(s) = G / (1 + τ s) parameters has been performed from the experimentally measured references and generated currents. Fig. 1) shows the gains G_{ij} and the time constants τ_{ij} as a function of the toroidal position of the saddle coils, estimated from a series of plasma shots with the old (PI) and the new (P only) regulator of the power supplies. Different colors represent parameters related to coils in different poloidal positions: the slight difference between internal (High Field Side) and external (Low Field Side) coils is related to the toroidal geometry. The optimization of the power supply gains further reduces such a difference.

Effect on Tearing Modes. The 1-pole model for the transfer function of the power supplies is used in a stationary torque balance model for tearing modes [1]. By assuming that the TM radial field at the resonance is not changed, it is found that a reduction of the time constant of the power supplies is related to a slight decrease of the minimum value of the radial field at the edge (Fig 2). In order to compensate for the reduced steady state gain G_{ij} of the current control system, an optimization campaign, with criteria similar to the ones illustrated in [1,2] was performed: as a result the gains on some tearing modes (m=1,n=-7 and m=1, -12≤n≤-10) were increased. An example is shown in Fig 3), where the averaged amplitude of the edge radial field of the m=1, n<-7 mode is shown, as a function of the plasma current.

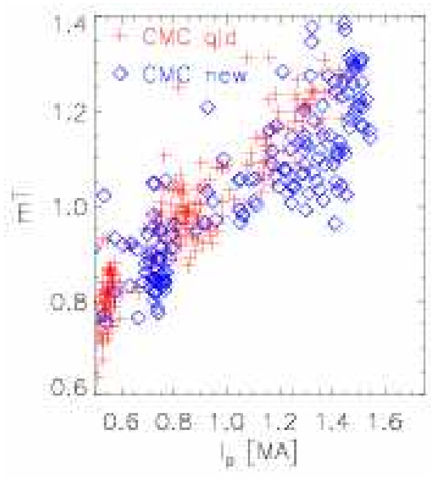

Fig 3) Edge value of the radial field for secondary modes (n<-7) old (red) and new (blue) power supplies control algorithm.

Complex gains on Tearing Modes.

In order to further reduce the phase locking among modes, and therefore to further decrease the maximum value of the non axisymmetric distortion of the plasma column, experiments were performed in order to control the direction of rotation of the dominant tearing modes. In

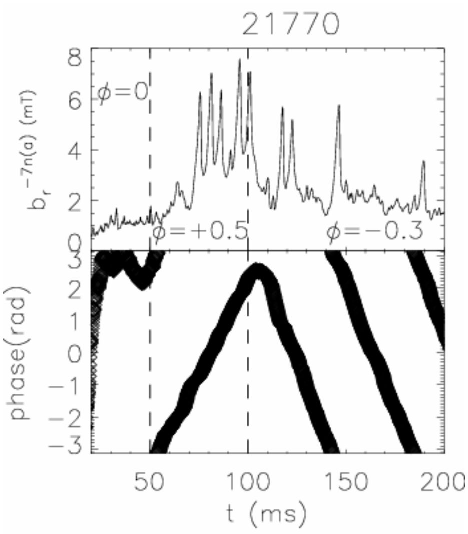

Fig. 4) Evolution of amplitude and phase of the edge value of m=1,n=-7

the Clean Mode Control algorithm the reference value for the applied field for each mode is given by the following feedback law

$$b^{coil}_{m,n}(t) = -K_{P,m,n}\exp(i\varphi_{m,n})b_{r,m,n}(t)$$

The error signal $b_{r,m,n}(t)$ is the clean Fourier harmonic complex coefficient (which represents both the amplitude and the phase of the mode) while $K_{P,m,n}$, and $\phi_{m,n}$ are the amplitude and the phase of the complex proportional gain. The phase $\phi_{m,n}$ therefore represents the phase difference between the *measured* field harmonic and the *applied* field harmonic. A first set of experiments was performed on the dominant m=1,n=-7 mode, with different values of the phase. It was found that the direction of the mode rotation is reproducibly determined by the sign of the phase $\phi_{m,n}$, as shown in Fig. 4), where a different sign is set in different time windows.

The value of the phase does not seem to influence the rotation frequency, at least for the chosen value of $K_{P,1,-7}$. It is also possible to determine simultaneously the sign of the rotation for several modes: complex gains of opposite sign have been set on the dominant modes. As the m=1, n=-7 is the helicity of the Quasi Single Helicity state, that does not contribute significantly to the maximum displacement, as shown in [2], the alternate pattern was applied on "secondary" modes, i.e. for $n \leq -8$. While the direction of the phase rotation actually follows the alternate pattern, no significant reduction of the maximum displacement due to the m=1 modes is observed. This may be explained by the fact that when the phase is non zero, the effective gain is reduced and therefore, a slight increase of the radial field at the edge occurs. Moreover, the deformation of the last closed magnetic surface tends to show a secondary local maximum of similar amplitude, as shown in Fig. 5). In time the maximum of the deformation jumps between these two locations. Consequently, complex

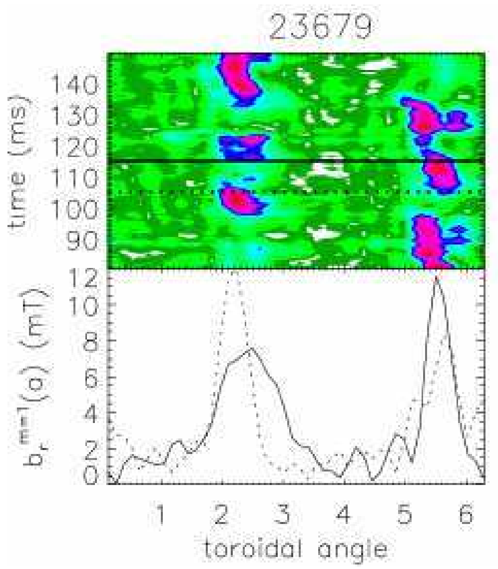

Fig. 5) time evolution of the m=1 deformation of the radial field at the plasma edge

gains were set only on low amplitude high n (n<-12) tearing modes, while different proportional and proportional-derivative gains were set for dominant modes, in order to vary the modes' phase locking.

Dynamics of m=1,n=-7 TM in QSH The optimized set of gains allowed a thorough exploration of the high current regime [3,4,5], where the onset of Quasi Single Helicity [6] is more frequent, even though sudden crashes into the Muliple Helicity state are observed. The phase dynamics of the QSH shows a reproducible behavior. The phase velocity is significantly reduced during the growth of the mode amplitude and it accelerates again when the mode crashes. Moreover, in the subsequent growth cycle, the phase is approximately at 180 degrees compared to the previous one. Such a behavior is determined by the control system: in fact, the saddle coils are located outside the mechanical structure and the shell. Therefore, once the TM amplitude drastically reduces, the applied field can only decrease on the shell penetration time scale, which, for an m=1,n=-7 is of the order of 20ms.This field is computed by means of a cylindrical model with a continuous shell. The applied m=1,n=-7 field, which was opposed to the plasma mode in order to keep the edge value as low as possible, acts as a seed for the subsequent QSH growth phase. This behavior is qualitatively reproduced by the torque balance model, described in [1], provided that the experimentally measured amplitude of the mode, instead of a constant value, is used. Therefore, while the phase dynamics of the TMs is now relatively well understood in term of a torque model [1], systematic investigations on the effect of the control system on the TM amplitude are still in progress in order to seek conditions for avoiding the crash of Quasi Single Helicity.

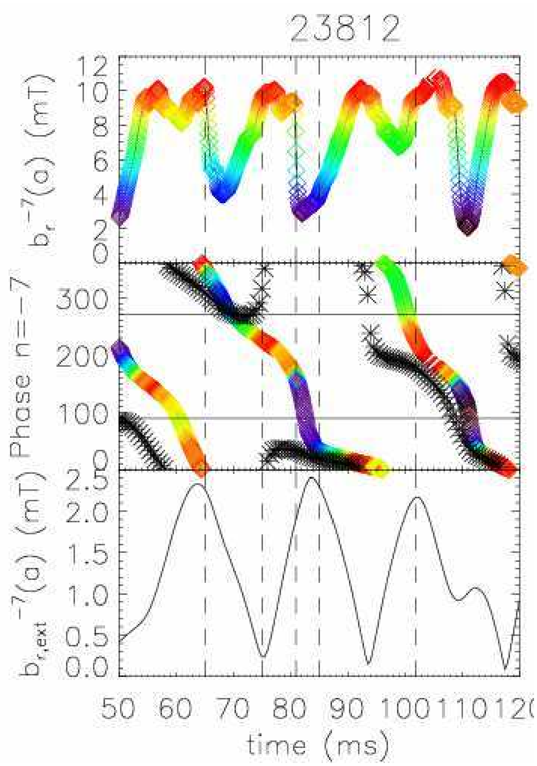

Fig. 6) QSH dynamics. a) mode amplitude, b) mode phase (color), externally applied field phase (*); c) m=1,n=-7 component of the field produced by the saddle coil, penetrated inside the shell

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