Feedback control of the m=2,n=1 mode in RFX-mod tokamak plasmas with $q_{cyl}(a)\approx 2$

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RFX-mod is the largest reversed-field pinch presently operating: thanks to its MHD control system it is exploring the 2MA plasma current regime [1]. Given the flexibility of the power supply system, RFX-mod can also be operated as a circular cross section, high aspect ratio, ohmic tokamak with plasma current up to 150kA and pulse length up to 1s. We present here the results of experiments at $q_{cyl}(a)\approx 1.8$, in which the active feedback system was able to suppress the m=2,n=1 mode for the duration of the discharge. Without active control the mode either grows exponentially on the resistive shell time scale or causes a minor disruption during the current ramp phase, when $q_{cyl}(a)$ is still above 2. It is found that the choice of the feedback variable is a key issue for successful operations: in particular, it is necessary to remove from the radial field measurements the aliasing of the sideband harmonics produced by the saddle coils [2]. Interestingly, this is not required for RWM stabilization in the RFP configuration, as foreseen theoretically[3] and confirmed experimentally [4].

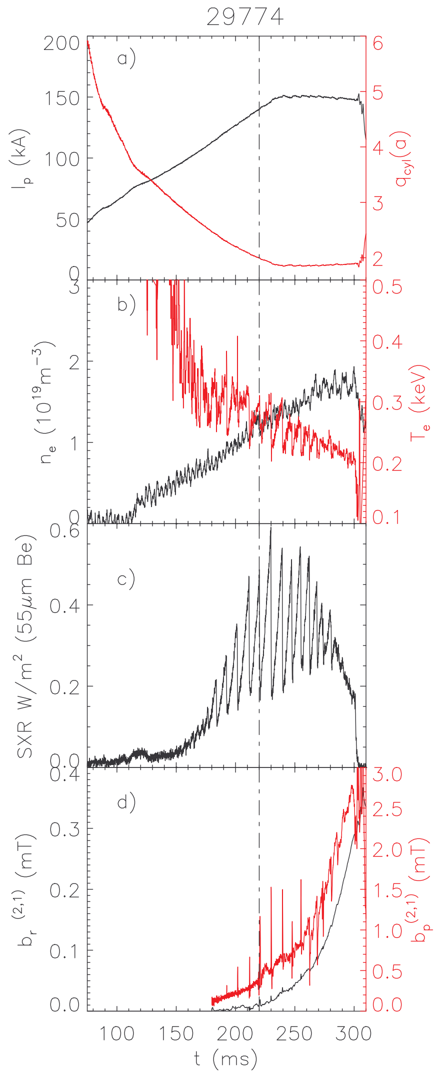

Fig.1) a) Plasma current and $q_{cyl}(a)$; b) electron density and temperature; c) SXR signals; d) radial and poloidal (2,1) harmonics

RFX-mod geometry and control system. The major radius is R=2m and the circular cross section radius is a=0.459m. RFX-mod is enclosed by a 3mm thick copper shell (penetration time of the vertical field 50ms) whose radius b is 1.12a. In order to operate on time scales longer than the shell time, RFX-mod is equipped with 48x4 independently driven saddle coils, supported by a stainless steel mechanical structure (penetration time 14ms), located at radius c=0.58m. 48x4 radial field loops are located outside the vacuum vessel (r=0.507m) with approximately the same area of the active coils. Moreover, 48x4 bi-axial pick-up probes, sensing the toroidal and poloidal field are mounted on the inner side of the copper shell (r=0.508m). Higher poloidal resolution is possible in 4 toroidal locations (non equally spaced) where 8 bi-axial pick-up probes are available. For the experiments described here real-time radial field measurements are used. Moreover 48x4 measurements of the currents flowing into the control coils are used by the real-time system to remove the aliasing of the sidebands.

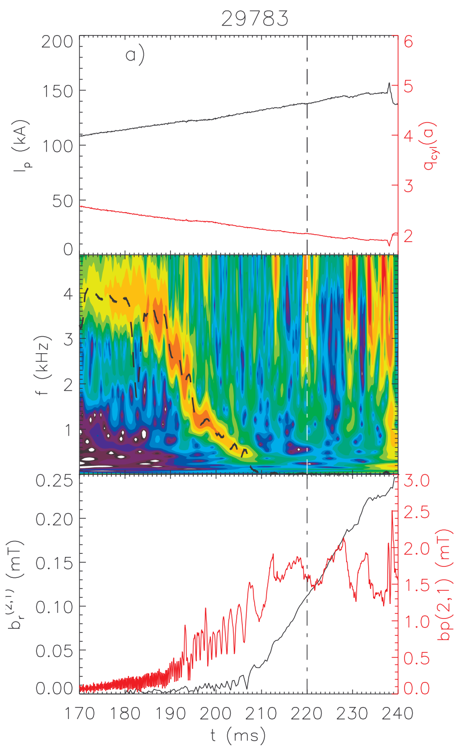

Fig. 2a) Plasma current and $q_{cyl}(a)$; b) wavelet spectrum of internal bp; c) radial and poloidal (2,1) harmonics

RFX-mod tokamak discharges w/o feedback. The on-axis toroidal field for these experiments is 0.55T, close to the design limit for the 48 RFX-mod TF coils. The loop voltage required to sustain a given plasma current waveform is feedback controlled. The plasma column fills the vacuum chamber (i.e. there are no limiters) and the horizontal equilibrium is feedback controlled by means of 8 couples of field shaping coils. Density is sustained through pre-programmed hydrogen puffing that needs to be adjusted shot by shot in order to compensate for graphite retention. Helium glow discharge cleaning is used to reduce wall loading and recover lower density operations. An example of a non feedback controlled discharge is shown in Fig. 1: sawtooth activity is observed in SXR signal and a non-rotating, exponentially growing (2,1) mode appear as long as $q_{cyl}(a)<2$. The amplitude of the (2,1) harmonic is obtained by a DFT analysis based on signals whose baseline is evaluated during the discharge, between 150 and 180ms, in order to remove pickups from the measurements. In some discharges, an initially rotating (2,1) mode may grow when $q_{cyl}(a)>2$ and eventually lock to the wall. Fig 2b) shows a wavelet spectrum of an internal non integrated poloidal field pick-up probe, whose maximum correspond to the rotation frequency inferred from the phase velocity of (2,1) harmonic of the 48x4 b_p array, located outside the 3ms time constant vacuum vessel. Once the mode locks to the wall, the radial field penetrates the shell and a disruption occurs.

RFX-mod tokamak discharges with feedback. Closed loop operations allowed avoiding disruptions, in the experiments performed so far. Radial loop sensor signal baselines are evaluated in real time in a short time window during the discharge, 20 ms before the start of the control phase. Simultaneously, the feedback system samples the currents flowing into the control coils and computes the aliasing of the sidebands [2] (15 sidebands are computed in real-time for each harmonic). An FFT of sensor signals (raw harmonics) is performed and the contribution of the sideband aliasing is removed giving the "clean" harmonic, to be used as the feedback variable in the Clean Mode Control (CMC) algorithm [2]. The references (a.k.a. commands) for the 48x4 power supplies of the saddle coils are obtained by inverse FFT of the "clean" feedback variable multiplied by the gain. A proportional and integral controller is used, with gains similar to the ones used for RWM control in the RFP [5]. An example of a feedback stabilized discharge is shown in Fig. 3. As long as $q_{cyl}(a)$ remains below 2 the (2,1) poloidal harmonic remains at a constant level of 0.5mT. The blue trace in panel c) describes the (2,1) harmonic of the radial field produced by the control coils at the sensors radius, taking into account the presence of the shell. The red trace in the same panel is the "clean" (2,1) radial field harmonic, which is the feedback variable in this experiment, while the black trace is the "raw" harmonic, i.e. the (2,1) harmonic polluted by the aliasing of the sidebands produced by the control coils

Role of the feedback variable. Experiments were performed with either the "clean" (Clean Mode Control) or with the "raw" (2,1) radial field harmonic as the feedback variable. In particular, if the "raw" $b_r^{(2,1)}$ harmonic is used for feedback, the mode growth is only reduced, as shown in Fig. 4). The black traces correspond to the magnetic field harmonics for an uncontrolled discharge, while the red ones are for a "raw" control case and the blue ones for a "clean" control case. In the "raw" control case, the measured radial field harmonic reaches very rapidly a low level, and the feedback system does not provide the required current in the control coils for cancelling the plasma mode. When conditions for the (2,1) braking and wall locking are met, Clean Mode Control allows avoiding the disruption due to the rapid growth of the mode: as the $q_{cyl}(a)$ goes below 2, the mode (as observed in the poloidal field component) decreases. In all of the 6 CMC discharges performed so far the penetrated radial field produced by the control coils is approximately of the same amplitude and phase, suggesting that the feedback system is also correcting the resonant component of an intrinsic error field.

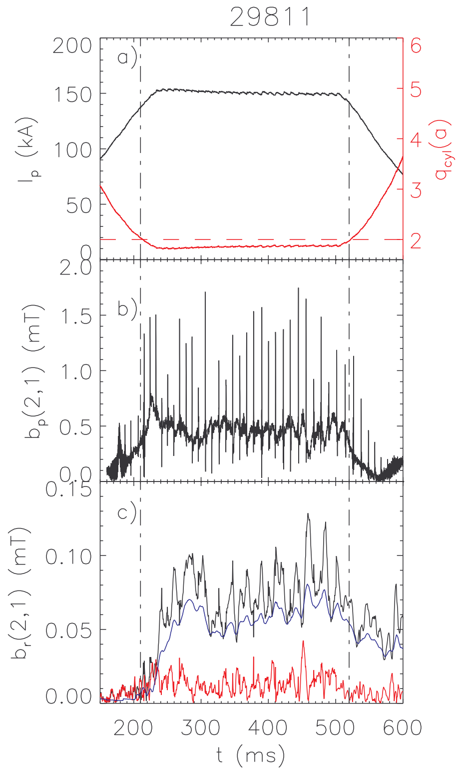

Fig. 3) a) Plasma current and $q_{cyl}(a)$; b) (2,1) Poloidal field; c)(2,1)radial field. Black: "raw", red: "clean", blue: (2,1) field produced by coils.

Equilibrium reconstruction. The edge value of the safety factor is determined in cylindrical approximation $q_{cyl}(a)=r\ B_t(a)\ /\ R_0\ B_p(a)$, where $B_p(a)$ derives from plasma current measurement and $B_t(a)$ from currents flowing in the TF coils. On axis q oscillates around 1, as the discharges are characterized by a sawtoothing activity (see Fig. 1). A rough estimate of the q profile is obtained by using a parametric representation of the current density $j=j_0(1-(r/a)^2)^{\alpha}$ with $\alpha\approx1.0$ and with a parabolic pressure profile. More detailed reconstructions are shown elsewhere [6]. Zero β MARS-F computations show that for the estimated q profile, the (2,1) external kink is ideally stable with an ideal wall located at b=1.12a, indicating that the observed mode is a shell mode. In toroidal geometry, the code predicts the presence of higher m harmonics which are also observed experimentally. Growth rates are very sensitive to the equilibrium details that cannot at present be resolved.

Simplified model for the (2,1) mode control. The lack of stabilization of the (2,1) mode with raw control can be qualitatively described by a simple ideal MHD model in cylindrical geometry. A single and continuous thin shell with b/a=1.12 is used. By assuming the current density profile previously estimated but neglecting the pressure, the Newcomb equation is used to compute the boundary conditions at the shell which depend both on the plasma stability and on the coil currents. According to the thin-shell relation [7] the diffusion of the (2,1) perturbation across the shell is governed by the equation:

$$\frac{d\Psi_w^{2,1}}{dt} = \gamma^{2,1}\ \Psi_w^{2,1} + \lambda^{2,1}\ \hat{I}_c^{2,1}$$

being $\Psi_w^{2,1}$ =-irb$_r^{(2,1)}$. In CMC the feedback variable is proportional to $\Psi_w^{2,1}$ and it can be shown that a simple proportional $I_c^{2,1}=-K_p\,\Psi_w^{2,1}$ control law stabilizes the mode. In the "raw" control the feedback variable is given by the sum of $\Psi_w^{2,1}$ and all the sidebands: in particular, given the RFX-mod geometry of sensors and coils, the lack of stabilization of the (2,1) mode can be qualitatively reproduced by considering only the lowest order (-2,1) sideband and using the Newcomb equation to compute the coefficients $\gamma^{(-2,1)}$ and $\lambda^{(-2,1)}$. The feedback law is, therefore,

$$I_c^{2,1}=-K_p\,(\Psi_w^{2,1}+\Psi_w^{-2,1})$$

The (-2,1) harmonic has opposite helicity compared to the (2,1). The stability of the system can be studied by inspecting the locus of the poles and zeros of the open loop transfer function: in raw control, a zero of the open loop transfer function is positive, and therefore it is impossible to stabilize the system with a proportional gain. More detailed control simulations, taking into account the 3D structure of RFX-mod wall, are presented in [6].

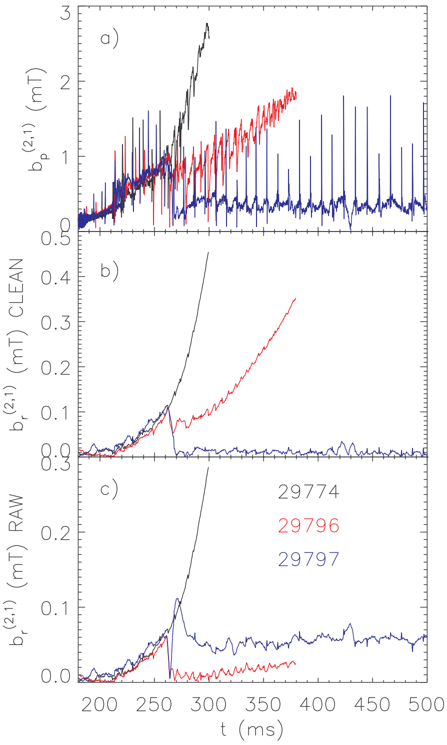

Fig 4) (2,1) mode evolution w/o control (black), with raw control (red) and with CMC (blue). a) poloidal field; b) "clean" radial field; c) raw radial field

Discussion. RFX-mod tokamak experiments confirm that the choice of the feedback variable is important for a successful stabilization of unstable modes. The unavoidable sidebands due to the finite size of the control coils place constraints both on the actuators and on the sensors geometries. On the one hand, in fact, the coupling with unstable plasma modes needs to be avoided; on the other hand, the aliasing of sideband harmonics in the control ones depends on the number of sensors in poloidal and toroidal direction and on the specific helicity of the mode to be controlled. Resistive Wall Modes in the RFP configuration (typically m=1,n=-5,..,+6) can be controlled with the "raw" control variable, which is not affected by the aliasing of the sidebands. The same does not apply to the RFX-mod tokamak (2,1) RWM as the aliasing of m=-2,n=1 sideband is crucial. These results may be consistent with the published literature on the superior performance of poloidal with respect to radial field sensors as summarized in [8], pag S146-S147, and suggest that, in tokamaks, a proper removal of sidebands aliasing might lead to significant improvement of the performance of radial field sensors as feedback variables. Moreover, more studies are planned to investigate the role of error fields on mode locking and on RWM evolution.

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