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Linear control model for m=0 modes in the RFX-mod Reversed Field Pinch

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Introduction. The RFX-mod experiment ($a = 0.459m$, $R_0 = 2m$, $I \le 2MA$) is a RFP equipped with a sophisticated active control system composed by 192 active saddle coils, arranged in 4 toroidal arrays of 48 poloidal coils each located on the external surface of the shell (average radius $r_c = 0.5125m$, shell time constant for the penetration of the vertical field (1,0) $\tau_w = 50ms$) and indipendently powered. The corresponding magnetic sensors, able to measure the radial and toroidal components of the magnetic field, are positioned in the inner side of the shell at $r_w = 0.508m$. The system can interact with the typical broad perturbation spectrum of the RFP plasma, mainly modes with poloidal numbers m=0,1. The system of sensors and active coils can be used to realize different feedback schemes: e.g. the so called Virtual Shell (VS) is able to make the radial magnetic field to vanish at r_w, with a stabilizing influence on the unstable modes, a reduction effect on error fields and in general a strong beneficial effect on the plasma [1,2]. In this work we concentrate our attention on the 48 toroidal coils, normally used to generate the axisymmetric (n=0) toroidal magnetic field, that can also generate m=0 modes with different toroidal *n* harmonics. The coils are assembled in 12 clusters of 4, so we have 12 indipendent currents. Purpose of our study is to present a model, in cylindrical geometry, which enables to evaluate the plasma response to the induced m=0 non axisymmetric perturbations. We use a formulation similar to that in [3], where the model is specialized for the arrays of 48 feedback toroidal coils (and 12 indipendent currents). As regard the measurements, we use the complete 192 toroidal field sensors. Owing to the limited number of coils, the feedback is affected by the coupling of different Fourier components (sidebands effect) [3], but also in the present case we will study how the sidebands generated by the toroidicity of the system should be taken into account.

Description of the m=0 model.

In [3] a theoretical cylindrical model for plasma response was derived, considering a finite number of active coils and sensors (with the same dimensions). Using the similar approach we obtained a model for the specific case of the toroidal field coils; the final relation, $b_{0,n} = a_{0,n} M_{0,n} b^{fc}_{0,n}$, links each harmonic $b_{0,n}$ of the toroidal field at the sensor with the field

$b^{fc}_{0,n}$ generated by the coils. Introducing: the coil shape factor $F_{0,n}$ relative to (0,n)-mode (related to the geometry and disposition of coils), the indexes for the sidebands calculation $n' = n + \nu N_c$ ($N_c = 12$ is the number of coils current, $\nu = -\bar{n},\ldots,+\bar{n}$ and we fixed $\bar{n} = 6$) and defining $(\varepsilon_c, \varepsilon_w) = (r_c, r_w)/R_0$, the fields $b^{fc}_{0,n}$ is

$$b^{fc}_{0,n} = -\frac{\mu_0}{\pi a} \cdot \left[-\pi n^2 \varepsilon_c \varepsilon_w K_0'(|n|\varepsilon_w) I_0'(|n|\varepsilon_w) \right] \cdot F_{0,n} \sum_{\nu=-\bar{n}}^{+\bar{n}} I^{coils}_{0,n'} \qquad (1)$$

Note that, for circular coils as in our situation, only toroidal sidebands are produced (and then we have not summation in *m*). The mutual-inductances matrix, i.e. the radial transfer function (ratio of the radial field at r_w to the free-space field generated at r_w), and the coefficients $a_{0,n}$ (the ratio of the toroidal field inside r_w to the radial field generated at r_w) are:

$$M_{0,n} = \frac{1}{2\tau_w \Gamma^w_{0,n}} \cdot \frac{1}{K_0'(|n|\varepsilon_w) I_0'(|n|\varepsilon_c)},$$

$$a_{0,n} = \frac{\mathrm{sgn}(n)}{|n|\varepsilon_w} \cdot \left[\frac{2\tau_w \Gamma^w_{0,n}}{|n|\varepsilon_w} - \frac{K_0(|n|\varepsilon_w)}{K_0'(|n|\varepsilon_w)} \right].$$

$\Gamma^w_{0,n}$ is a quantity related to the penetration rate of the mode through the wall in absence of feedback. Our model is therefore able to predict the "vacuum" field generated by the system of 48 toroidal coils taking into account the effect of the conductive shell and of the sidebands.

Vacuum shots results.

To verify and validate the model, we first apply it to a set of vacuum shots, i.e. shots without plasma, where however a non axi-symmetric current distribution over the 48 toroidal field coils generates a non axi-symmetric toroidal field. For these experiments we compare the model calculated toroidal field with that measured by the 192 sensors, both in cases of applied rotating or non-rotating perturbations. As first step, we have determined the "effective" penetration time of the wall by looking the minimum reconstruction error (see below). As shown in Fig.1 this actually gives a value of about 75 ms to vacuum shots with an applied (0,4) slowly (10 Hz) rotating perturbation. For static perturbation this con-

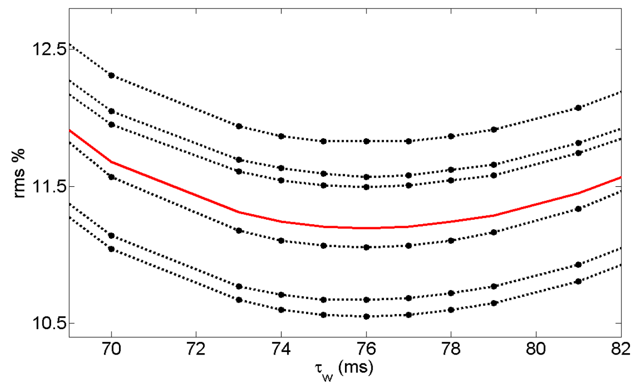

Fig.1: rms vs *$_w$ for different vacuum rotating shots; the red continuous thick curve is the average.*

stant is about 64 ms. These are our best estimates for the penetration of the (1,0) mode. The reconstruction error is defined as

$$(N-1)\cdot rms^2 = \sum_k \left(b^{(0,n)}_{meas,k} - b^{(0,n)}_{calc,k}\right)^2$$

and it is similar for non-rotating and rotating perturbations (about 10%). By comparing the cylindrical model with the data we are also able to extract informations about the toroidicity induced effects. The (0,4) mode generates (by coupling with the dominant (1,0) toroidal field correction) (1,4)+(1,–4) modes that once interact among them, give rise to the mode (0,8) with amplitude $(a/R_0)^2$ with respect to the original (0,4). We found that this contribute is small enough to be neglected in first approximation. In Fig.2 we show instead the sideband generation due to the limited number of indipendent coils currents, as deduced from Eq.1.

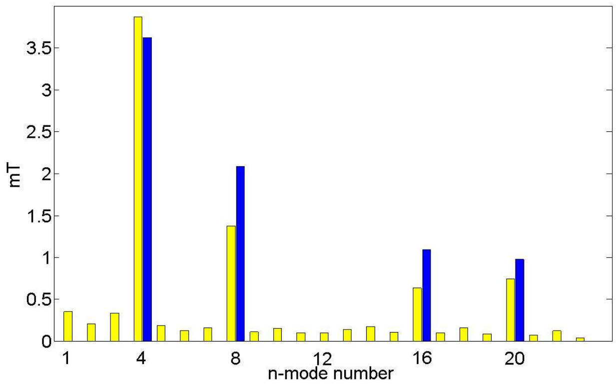

Fig.2: #20079 m=0 mode spectrum. Averaged ampli-tudes of harmonics in the time window of application of (0,4) mode: measured (light bars) and calculated (dark bars).

Plasma shots results.

After validation, the model is applied to plasma cases in order to extract information about the plasma generated m=0 component in response to the applied perturbations. Calculating with our model the contribution of the coils and the sidebands effect, we can obtain the plasma response subtracting the model calculated to the sensor measured field. As an example, Fig.3 shows the full m=0 mode spectrum (averaged in a time interval which includes the current flat-top phase) for a shot with an applied (0,1) rotating mode, before (top frame) and after (bottom frame) the application of our procedure, i.e. the plasma response to the applied field. In Fig.4, for the same shot, the dotted line represents the time-evolution of coils signal and the continuous line the plasma calculated temporal response (measured field minus model calculated field). In the bottom panel, the plasma response is compared with the signal obtained from the difference between the m=1 dominant mode, the m=1 n=–7,–8. It is seen that a good correlation in time between these two signals exists. Note that for most of the shots, also the m=1 n=–9÷–12 modes have smaller but comparable amplitude; this means that a full reconstruction of the (0,1) response should consider all the m=1 modes. Besides, in many shots, peaks in the trace obtained from the difference of the two m=1 modes, due to the sawthooth activity mainly of the n=–7 mode, are presents. Our interpretation is summarized in the following sketch: the dominant m=1 modes couple nonlinearly with n=1 and generate a (0,1) mode which is, as shown, the main plasma response component. Moreover, the coupling of the two m=1 modes with the dominant toroidal correction (1,0), generates two m=0, n=7,8 modes with amplitudes of the order a/R_0 of their progenitors (see Fig.3). Finally, the interaction with the applied (0,1) of the toroidicity generated modes, can also explain the generation of the (0,6) harmonic (see Fig.3 again).

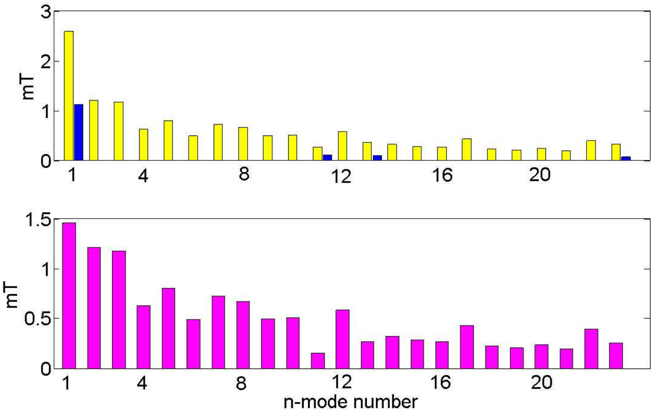

Fig.3: #19305 m=0 mode spectrum.
Top: *time averaged amplitudes of harmonics, measured (light bars) and calculated (dark bars).*
Bottom: *plasma reconstructed spectrum (see text).*

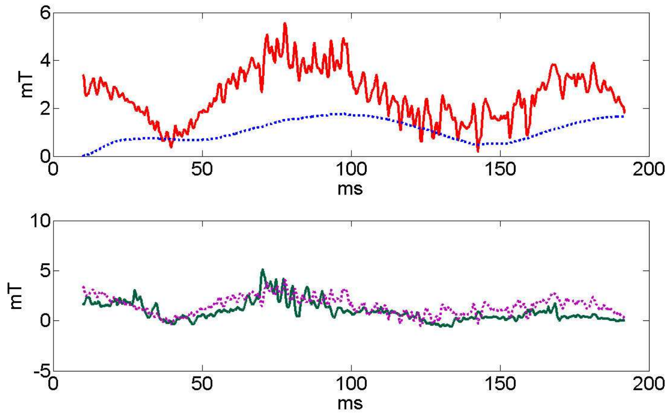

Fig.4: #19305, time-evolution of signals.
Top: *(0,1) harmonic calculated (thin dotted curve) and measured (thick curve) at the sensor.*
Bottom: *(1,–8)–(1,–7) (dark thick curve) with the same signal and plasma (0,1) reconstructed mode (light dotted curve).*

Conclusions.

We described a model for calculating the plasma response to an applied m=0 perturbation in the RFX-mod device. We initially validated the model on vacuum shots with applied static and rotating perturbations. Next, we applied it to shots with plasma, deriving the plasma response to the m=0 non axi-symmetric imposed field. In this case, we found that nonlinear coupling of the m=1 plasma modes should be considered to fully understand and interpret the measured m=0 mode spectrum. This seems to confirm that it doesn't exist an intrinsic m=0 unstable response, at least for the cases that we have considered.

References.

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