

## Externally Induced Rotation of the Resistive Wall Modes in RFX-mod

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### Introduction

During the last years, significant progress was made in the control of resistive wall modes (RWMs) in reversed field pinches (RFPs). It was demonstrated on several different devices that static current driven RWMs can be completely suppressed and controlled [1,2]. It is well known that also tokamak advanced scenarios suffer from RWM instabilities. The RWM in a tokamak is typically detached from the wall and rotates together with the plasma. In fact, plasma rotation is one of the most important stabilizing mechanisms present in the tokamak case, though it is expected to be strongly reduced in ITER. This RWM rotation is one of the main differences between tokamaks and RFPs. In RFP plasmas, RWMs are usually detected as non-resonant, wall locked instabilities, and the only possible stabilization strategy is the use of an active coil system.

### Results and modelling of the rotation experiments on RFX

The RFX-mod RFP device (Padova, Italy) is equipped with a very flexible active system for MHD mode control [3]. It consists of 192 active coils, fed by 192 independent amplifiers and controlled by a digital PID controller. The active coil set entirely covers the RFX-mod external surface, providing optimal control on the radial component of the perturbed magnetic field. Signals from a large number of sensors can be used as input in order to study different optimal control strategies. Using this system it is also possible to separate and work with a particular mode. This technique is widely used in RFPs to separate the mode of interest from the other MHD activities and investigate this mode separately. In the reported experiments, the target mode was the most unstable internal non-resonant resistive wall mode, i.e. the instability with toroidal mode number = -6 and poloidal mode number = 1. The other modes were suppressed by active control in order to optimize the plasma discharge. Two sets of experiments were made at low (400kA) and high (600kA) plasma currents. It was demonstrated in both cases that application of the variable complex gain in the close loop operation is able to rotate the mode as clearly seen in figure 1.

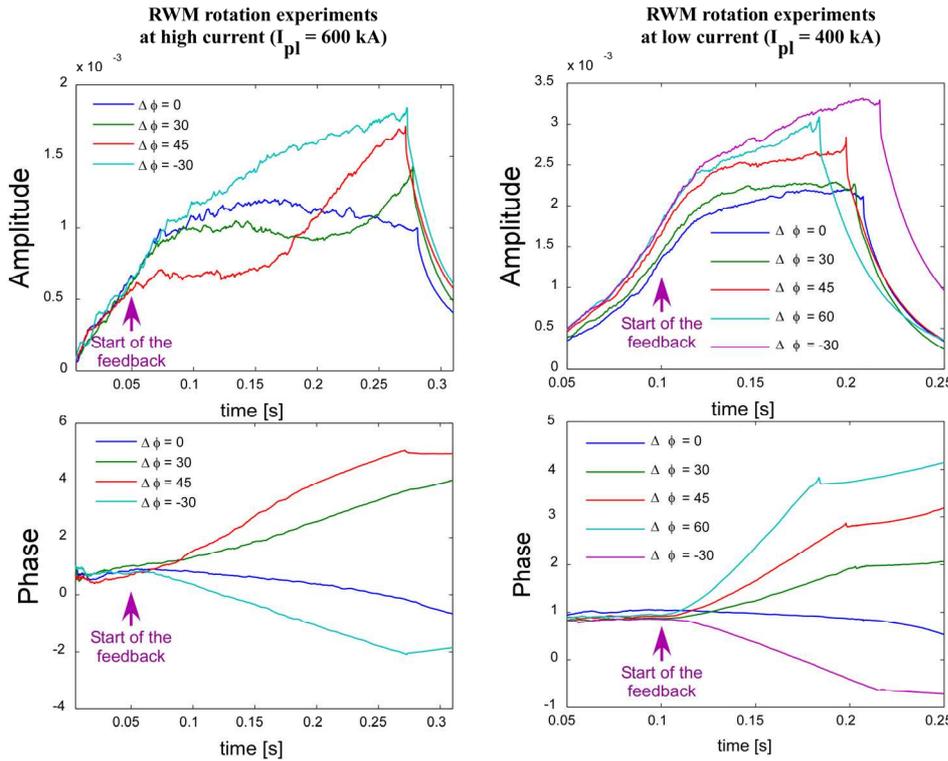


Figure 1. Results of the RWM rotation experiments with close loop feedback at two different plasma currents. The mode rotation ( $m=1, n=-6$ ) strongly depends from phase shift between the mode and externally applied perturbations.

In these experiments, there was no external action on the (1,-6) unstable RWM for the first 50ms (600 kA case) or 100 ms (400kA case).

After that time, a small real gain was given to the feedback action in order to keep the mode to a finite amplitude, without complete stabilization ( $\Delta\phi=0$  traces in figure 1). On this reference case, experiments with complex gain (i.e.  $\Delta\phi\neq 0$ ) were executed.

The experimental traces presented in fig.1 are summarized in figure 2. The feedback system

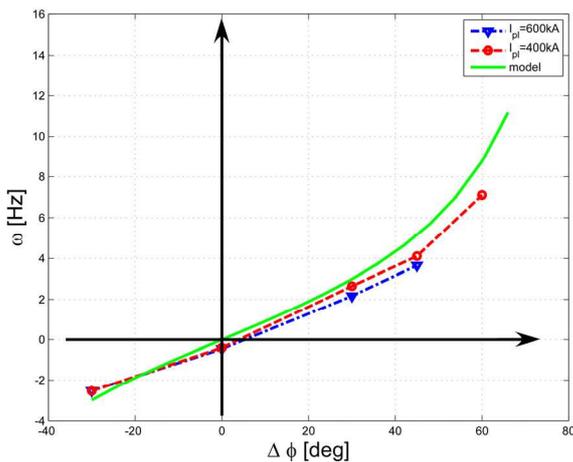


Figure 2. Dependence of the mode rotation from the phase shift (between the mode and external perturbations). Experimental results show that the rotation frequency of the mode strongly depends on the phase shift and does not depend from plasma current. Plasma rotation is also not important which is demonstrated by applying the rotated perturbations in two opposite directions ( $\Delta\phi = \pm 30$ ). The model is discussed in the text.

in closed loop operations keeps the phase shift between the mode and externally applied perturbations at a constant value. Experimental results show that the rotation frequency of the mode strongly depends on the phase shift and has almost no dependency on plasma current. Plasma rotation is also not important which is demonstrated by applying the rotated perturbations in two opposite directions ( $\Delta\phi = \pm 30$ ).

We propose the following periodic cylindrical model for the analysis of the mode acceleration. The

model assumes a plasma surrounded by a resistive wall at  $r_b$  and the feedback coil at  $r = r_f$ . The indexes  $b$  and  $f$  correspond to the resistive wall and the feedback coils respectively. In the vacuum region outside the plasma, the most general solution of Laplace equation  $\Delta\chi = 0$ , with  $\vec{b} = \nabla\chi$  ( $\vec{b}$  is the magnetic fluctuation field) and the solution for the perturbed magnetic flux  $\psi = r b_r$  can be obtained as  $\hat{\psi}_{m,n}(r) = A_j k r I'_m(kr) + B_j k r K'_m(kr)$ , where  $I_m(kr)$  and  $K_m(kr)$  are the modified Bessel functions,  $k = n/R$ ,  $j$  is index for the vacuum region. We consider only one external kink mode with poloidal mode number  $m$  and toroidal mode number  $n$ . The perturbed magnetic flux is written as

$$\hat{\psi}_{m,n}(r, \theta, \phi, t) = \hat{\psi}_{m,n}(r) \cdot \exp(i \cdot (m\theta - n\phi - \omega t))$$

Using the similar approach as Ref. [4], we express the total magnetic flux as the linear combination of two parts.

$$\Psi_{m,n}(r, t) = \Psi_b \hat{\psi}_b(r) + \Psi_f \hat{\psi}_f(r)$$

By applying Ampere's law at  $r_b$  and  $r_f$ , and asymptotic matching the above solutions in vacuum region, we obtain the following relations at the resistive wall and at the coils, written as

$$\left[ r \frac{d\Psi_{m,n}}{dr} \right]_{r_b^-}^{r_b^+} = E_{b,b} \Psi_b + E_{b,f} \Psi_f = -i \cdot \omega \cdot \tau_b \Psi_b$$

and 
$$\left[ r \frac{d\Psi_{m,n}}{dr} \right]_{r_f^-}^{r_f^+} = E_{f,b} \Psi_b + E_{f,f} \Psi_f = -\mu_0 S(m, n) I_f (m^2 + n^2 \varepsilon_f^2)$$

where  $E_{i,j} = \left[ r \frac{d\hat{\psi}_j(r)}{dr} \right]_{r_i^-}^{r_i^+}$ ,  $i, j = b, f$ ; and  $\tau_b = (\mu_0 \sigma \delta r_b)^{-1}$ ,  $\omega = \omega_r + i\gamma$

$S(m,n)$  is the coefficient related to the structure of the feedback coils. As for the feedback circuit, the simple model equation is adopted as:

$$-L_f \frac{dI_f}{dt} + (\Psi_b G) = R_f I_f,$$

where we assume that the sensors is close to the shell at  $r_b$ .  $I_f$  is the current flowing in the feedback coils,  $L_f$  is inductance and  $R_f$  is resistance. The final dispersion relation has the following form:

$$\hat{E}_{b,b} + i \cdot \omega \cdot \tau_b + \frac{E_{b,f}}{E_{f,f}} \frac{\hat{G}}{1 - i \cdot \omega \cdot \tau_f} = 0$$

$$\text{where } \hat{E}_{b,b} = E_{b,b} - \frac{E_{f,b}E_{b,f}}{E_{f,f}}, \quad \hat{G} = \frac{\mu_0 S G}{R_f} (m^2 + n^2 \varepsilon_f^2)$$

Here, the gain ( $G$ ) is a complex quantity. The feedback system keeps the phase shift constant ( $\Delta\phi = \arctg(\text{Im}(G)/\text{Re}(G)) = \text{const.}$ ). A linear stability code is used to solve the Newcomb's equation for the non-resonant internal kink mode and to calculate the instability index  $\hat{E}_{b,b}$  for RWM, with the equilibrium parameters  $F = -0.05$ ,  $\Theta = 1.47$ ,  $\alpha = 3.0$ ,  $\varepsilon_0 = 0.23$ . The other indexes  $E_{ij}$  have been calculated by asymptotically matching the vacuum solutions of the modified Bessel functions. The feedback coil L/R time constant is taken as  $\tau_f \approx 2ms$ , and the time constant of the shell is  $\tau_b \approx 100ms$ . In the computation, we simulate the experimental procedure as follow: the first is finding out the value  $\text{Re}(\hat{G})$ , which can keep the (1,-6) mode having almost zero growth rate with  $\Delta\phi = 0$  (without rotation); then by keeping the same  $\text{Re}(\hat{G})$  as a constant and varying  $\Delta\phi$  the corresponding complex  $\omega$  is obtained from the dispersion relation, which indicates the mode rotation frequency. It is shown that the dispersion relation can well predict the dependence of mode rotation on the phase shift. The result is in very good agreement with experimental measurements as shown in figure 2. This fact suggests that our simple model takes into account all main features of the experimental system.

## Conclusions

It was demonstrated for the first time in RFPs that the internal non-resonant resistive wall mode can be detached from the resistive wall using an external perturbation. The observed constant rotation of the mode seems to be slower than the inverse resistive wall time and depends on the phase shift between external perturbations and the mode. It was found that plasma rotation, plasma current and coupling to other modes have no impact on the rotation frequency of the mode. The proposed simple analytical model gives good description of the experimental results.

## References

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