Resistive-Wall-Mode Active Rotation in the RFX-Mod Device

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The fundamental question of how the flow velocity of the background plasma can influence the motion of magnetohydrodynamics instabilities and, in the ultimate analysis, their stability is addressed. The growth of resistive-wall-mode instabilities in toroidal confinement devices well represents one example of such a problem. In this Letter, we illustrate a new strategy that allowed, for the first time in a reversed field pinch experiment, a fully controlled rotation of a nonresonant instability by means of a set of active coils and how the new findings compare with numerical modeling.

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Resistive Wall Modes (RWMs) are global MHD instabilities growing on time scales that depend on the typical penetration time of the surrounding magnetic boundary. They are common to many toroidal confinement devices such as reversed field pinches (RFPs) [1], tokamaks [2], and spherical tokamaks [3]. In the tokamak configuration, they pose one of the most severe limits to the achievement of the so-called advanced tokamak operational regime, aiming at maintaining the plasma in a high-beta, high-bootstrap current fraction regime. In the Reversed Field Pinch configuration, RWMs are found as current driven instabilities and can be always detected when the discharge duration is longer than the penetration time of the passive conducting structures containing the plasma. For these reasons, during the last years, significant efforts have been spent to develop efficient control strategies. Among them we can mention the cancellation of residual field errors and the sustainment of a fast plasma rotation by using beams of energetic particles in the tokamak configuration, and the use of active coils controlled in feedback in both tokamaks and RFPs (see [4] and references therein for the tokamak case and [5,6] for the RFP experiments). In fact, though sharing many common features, RWMs in tokamaks and RFPs reveal also some differences. While in tokamaks they grow as resonant, pressure driven instabilities, in RFPs, they resonate with the magnetic field outside the plasma and their stability mainly depends on the current profile gradients. It has been shown numerically that these differences lead to a substantial independence of RWM growth rates on plasma flow for the RFP configuration: in fact, rotations of the order of some percents of the Alfvén velocity would be required to stabilize them [7], and this is not the case in present devices where there are no sources of additional momentum input and the input power is mainly Ohmic. For this reason, modern RFP devices developed sophisticated active control systems in order to extend the pulse duration well beyond their typical wall time constant. Since in the RFP case external active coils are the only way to influence the RWM growth rates, this configuration is gaining more and more attention from the fusion community as an ideal test bed for benchmarking numerical models of plasma stability [8] and of active control strategies.

Despite these important progresses in RWM control, however, in the RFP case, the role of plasma rotation on RWM stability is still waiting experimental verifications. This is also due to the fact that in RFPs, changing plasma flow velocities is not trivial since external sources of momentum input are still in the development phase. To fill this gap, dedicated experiments were conducted in the largest RFP facility presently in operation, the RFX-mod device [9] (major radius $R = 2$ m, minor radius $a = 0.46$ m, maximum reached plasma current 1.6 MA) built in Padova, Italy. The aim of the new experiments is to show how the relative rotation of fluid plasma and MHD instability can be changed by directly acting on the mode itself. This perspective can be viewed as complementary to the one aiming at studying the RWM stabilization by plasma rotation either braking the plasma with external field errors [10] or changing its flow velocity with differently balanced tangential injection of momentum [11,12]. The new load assembly of RFX-mod is particularly suited for active MHD control studies. Its thin copper shell has a vertical field penetration time $\tau_{V,\mathrm{shell}} = 50$ ms, 1 order of magnitude shorter than the discharge duration. The resistive shell outer surface is entirely covered by a system of 192 active saddle coils divided into 48 poloidal arrays of 4 coils (top-in-bottom-out positions, at $r = 0.58$ m). The 60-turn active copper coils have an average surface of approx. 0.27 m^2 and can carry a maximum current of 400 A producing a maximum local dc B_r field of approximately 50 mT; each saddle coil is fed by its own power supply. The whole system is controlled by a programmable proportional-integral-derivative (PID) digital controller with a maximum latency time of 330 μs, where the operator can specify the particular control schemes to be applied to the plasma (feedback, feed-forward, zero, or nonzero reference value, Fourier mode control, and others

[13,14]). The digital controller performs a real-time FFT of 192 radial field signals provided by measurement saddle coils placed just outside RFX-mod vacuum vessel, at $r = 0.51$ m, together with a real-time FFT of 192 toroidal field pick-up coil signals to extrapolate the radial field to the inner surface of the vessel, and of 192 measurements of the current flowing in the active coils for sideband correction.

In the reported experiments, the plasma current is kept at moderate values (two sets of data at $I = 0.4$ MA and $I = 0.6$ MA, respectively) in order to minimize the plasma wall interaction due to the growth of RWM instabilities. Plasma density is about 1.5×10^{19} m^{-3} for the 0.4 MA discharges and 2.3×10^{19} m^{-3} for the 0.6 MA discharges in order to keep the same normalized density for all the data ($I/N \approx 4 \times 10^{-14}$ A/m^{-2}, where N is the line averaged density). Plasma equilibrium is characterized by $F = -0.05$ and $\Theta = 1.47$, where F and Θ are defined as $F = B_\varphi(a)/\langle B_\varphi \rangle$ and $\Theta = B_\theta(a)/\langle B_\varphi \rangle$, $B_\theta(a)$ and $B_\varphi(a)$ being, respectively, the poloidal and the toroidal field measured at the plasma edge. Even though direct measurements of plasma flow were not available during the experiments described in the present Letter, from [15], it is possible to infer, for the experimental conditions of interest, a toroidal plasma rotation of the order of 1–2 Km/s at mid radius, decreasing towards the plasma edge, changing sign around the position where the toroidal field reverses (reversal surface), and finally increasing and becoming small and positive again at the very plasma edge.

The target mode for these experiments is the most unstable (for that equilibrium) RWM, i.e., the internal nonresonant instability with $(m, n) = (1, -6)$. In order to obtain clear results, the key decision for the experimental setup was to work on a mode of finite, approximately constant, amplitude. The first step was then to study how to keep it at finite amplitude, while suppressing the other unstable modes. It was decided to operate in the so-called "mode control" scheme in which the gains of the feedback controller are relative not to the single coils (error field control in real space), but to single modes (error field control in Fourier space). The control was split into two time windows. In the first one, the mode was not controlled, and the typical exponential growth was found with high reproducibility; in the second one, the mode was initially feedback controlled with a pure real proportional gain. However, instead of using an optimized gain to fully control the mode, a scan was performed and a value relative to a marginal stability of the system (growth rate close to zero) was selected. The results of the scan with decreasing real proportional gain are shown in Fig. 1 and can be interpreted also as the possible results of feedback control systems with not enough power to cope with the growth of the selected instability. Of course, in these experiments, the external field is always opposing the plasma error field with the same helicity, and no net force is present to induce a controlled rotation.

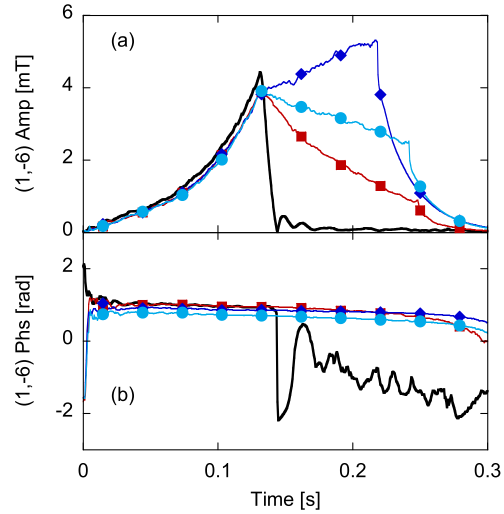

FIG. 1 (color online). Effect of a real proportional gain scan: (a) mode amplitudes, (b) mode phases. Black full traces $Gp = 800$ (full control), squares $Gp = 200$, circles $Gp = 150$, diamonds $Gp = 100$. Note that an extremely good reproducibility of the RWM growth rate can be obtained under controlled experimental conditions.

The second part of the experiment was then to compare the behavior of the partially controlled RWM, with the behavior of similar discharges where a small imaginary part was added to the proportional gain. In this way, the external, feedback action has a phase difference with respect to the plasma mode and reacts to keep constant that phase difference. The real part was kept constant, leading to different modules of the proportional gain thought of as complex number. Two sets of experiments were made at low (0.4 MA) and medium (0.6 MA) plasma currents. In both cases, it was demonstrated that application of an imaginary component to the proportional gain in the close loop operation is able to rotate the finite amplitude mode as seen in Fig. 2 for two 0.4 MA cases.

Even if the result of Fig. 2 is very clear, in order to give a correct interpretation to the experimental data, we must take into account that amplitudes and phases shown there are relative to the sum of all $(1, -6)$ fields measured by the saddle coil sensors, i.e., to both the plasma and the active coil modes. To overcome this problem, a model was used to decouple the two effects. This model is currently used to study the performances of the control system, and it allows the calculation of the field produced by the coils at the sensor radius starting from the measurements of the currents flowing on the single active coils [16]. The effect of passive elements is taken into account by the model and independent tests on both vacuum, and plasma discharges confirmed the reliability of its calculations. The analysis results of RWM rotation experiments are shown in Fig. 3, where the decomposition of measured amplitude and phase for mode $(1, -6)$ into plasma and external contribution is shown. It can be noted that, at $t = 100$ ms, immediately

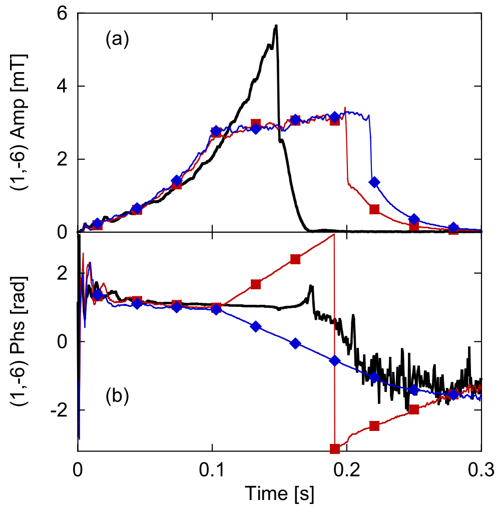

FIG. 2 (color online). Effect of a complex proportional gain scan: (a) mode amplitudes, (b) mode phases. Black full traces represent a reference shot where $(1, -6)$ RWM is free to grow up to 0.13 s and then is fully controlled. Squares and diamonds traces show the effect of the application of a complex proportional gain: the rotation of a selected RWM can be induced in both opposite directions (feedback in action from 0.1 s).

after the application of the feedback control, the RWM growth rate decreases and finally reaches a value close to zero. Both the plasma mode and the external field keep a constant value and a constant phase difference, while rotating in the laboratory frame of reference for a long time. By changing the imaginary part of the proportional gain, the same situation is recovered, but different rotation speeds can be detected. Note that, being a feedback and not an open loop operation, this procedure is different from the active MHD spectroscopy used, for example, in DIII-D to probe the stability of RWM close to their pressure limit [17].

The results of a first phase scan experiment are summarized in Fig. 4 for the two current values. Experimental results show that the rotation frequency of the mode strongly depends on the phase shift and have almost no dependency on plasma current. These results are also suggestive that plasma fluid rotation is not playing a major role, which is demonstrated by applying the rotating perturbations in two opposite directions ($\Delta\varphi = \pm 30$) and obtaining almost the same rotation frequency.

As final point of the Letter, we compare the experimental results with the predictions of a simple electro-magnetic model describing the interaction between the plasma and the external fields. For the study of mode dynamics in RFP plasmas, since the resistive wall modes are nonresonant instabilities (i.e., the resonant magnetic surfaces are outside the plasma), the usual approach of torque balance can not be directly applied. We propose an alternative approach, in which the effect of the feedback system is involved in the calculation of the mode dispersion relation. The model assumes a cylindrical plasma surrounded by a resistive wall at r_b and the feedback coil at $r = r_f$. In the vacuum region outside the plasma, the solution for the perturbed magnetic flux $\psi = rb_r$ is obtained as $\hat{\psi}(r) = A_j krI'_m(kr) + B_j krK'_m(kr)$, where $I_m(kr)$ and $K_m(kr)$ are the modified Bessel functions. The perturbed magnetic flux for one given external kink mode with poloidal mode number m and toroidal mode number n is written as

$$\Psi_{mn}(r, t) = |\hat{\Psi}_{mn}(r)| \exp[i(m\theta - n\varphi - \omega t)].$$

Using the similar approach as [18], we express the total magnetic flux as the linear combination of two parts:

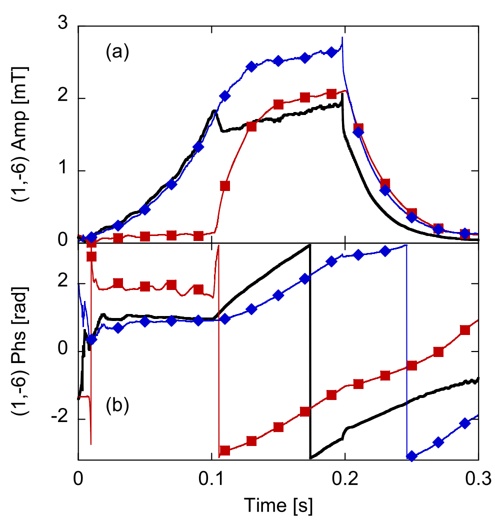

FIG. 3 (color online). Decomposition of the measured mode amplitude and phase into plasma and external field components: full black line: total $Br\,(1, -6)$ as measured by the sensor arrays, diamonds: reconstructed plasma Br, squares: reconstructed external Br applied by the active control system.

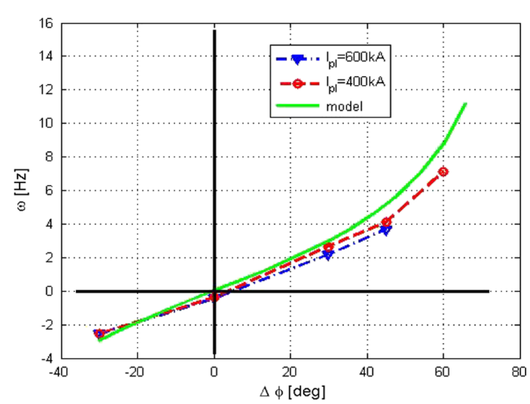

FIG. 4 (color online). Dependence of mode rotation on phase shift between the mode and the external perturbations. Full line represents the result of the model discussed in the text; circles and triangles represent the experimental rotation speeds obtained for two levels of plasma current.

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

Finally, by applying Ampere's law at r_b and r_f and asymptotically matching the above solutions in the vacuum region, we obtain two relations at the resistive wall and at the 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 are 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:

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

$$\text{where } E_{i,j} = \left[r \frac{d\hat{\psi}_j(r)}{dr} \right]_{r_i^-}^{r_i^+} i,j = b,f;$$

$$\tau_b = (\mu_o \sigma \delta r_b)^{-1}, \qquad \omega = \omega_r + i\gamma,$$

$$\tau_f = L_f/R_f \quad \text{and} \quad \hat{E}_{b,b} = E_{b,b} - \frac{E_{f,b}E_{b,f}}{E_{f,f}},$$

$$\hat{G} = \frac{\mu_0 SG}{R_f}(m^2 + n^2 \varepsilon_f^2).$$

Here, the gain (G) is a complex quantity, and $S(m, n)$ is a coefficient related to the structure of the feedback coils. The feedback system keeps the phase shift constant $\{\Delta\phi = \text{arctg}[\text{Im}(G)/\text{Re}(G)] = \text{const}\}$. A linear stability code is used to solve the Newcomb's equation and to calculate the instability index $\hat{E}_{b,b}$ for $(1, -6)$ RWM. Without feedback, the growth rate can be obtained from $\gamma\tau_b = \hat{E}_{bb}$. The equilibrium parameters $F = -0.05$ $\Theta = 1.47$, $\alpha = 3.6$, $\varepsilon_0 = 0.23$ are adopted in solving the equation. As for solving the dispersion relation, we simulate the experimental procedure: the first is finding out the value $\text{Re}(\hat{G})$, which can keep the $(1, -6)$ mode having almost zero growth rate with $\Delta\varphi = 0$ (without rotation); then by keeping the same $\text{Re}(\hat{G})$ as a constant and varying $\Delta\varphi$ the corresponding complex ω obtained from the dispersion relation, which indicates the mode rotation frequency. It is found 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 Fig. 4. This fact suggests that our simple electro-magnetic model takes into account all main features of the experimental system.

In conclusion, it was demonstrated for the first time in RFPs how the internal nonresonant resistive-wall-mode can be detached from the resistive wall in a controlled way using an external perturbation. In this way, a new possibility for changing the relative velocity of fluid plasma and MHD instability is available to the scientific community. The observed constant rotation of the mode depends on the phase shift between external perturbations and the mode. It was experimentally confirmed that plasma rotation, plasma current, and coupling to other modes have no impact on the rotation frequency of the RWM in the range explored. The proposed simple analytical model, that does not take into account any dissipation mechanism, gives good description of the experimental results. The results presented confirm that RWM growth in the RFP configuration is a relatively simple phenomena and that its description can be very useful to the scientific community as first benchmark of numerical codes devoted to the more complex tokamak case. The technique illustrated paves the way for further experiments aimed at expanding the rotation database and, in particular, at exploring the effect of faster rotations. Faster rotations in fact could highlight the presence of discrepancies between the experimental and modeled velocities, pointing out in that way the existence of possible deviation from the ideal behavior of the mode described by our simple model. The extensions of similar experiments to other toroidal devices would also help understanding the role of passive and active boundary conditions in the determination of the equilibrium angular velocity for a given phase shift between plasma mode and active control.

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