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Cylindrical Model of RWM in RFP Plasmas and Application on RFX-mod

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The RWM instabilities have been demonstrated to be successfully controlled by the feedback equipment implemented in the experiments of RFX-mod[1]. The observations give an evidence that the system of the active control has a sufficient efficiency and a large flexibility, therefore can provide an excellent environment to apply and to test RWM physical modeling and various control scenarios.

Apart from some similar behaviour in both RFP and Tokamak configurations, the RWMs in RFP plasmas are current driven instabilities; while in Tokamak the RWMs are normally driven by the plasma pressure. Furthermore, in RFPs the external kink instabilities, having their rational surfaces outside the plasma, exist as so called externally non-resonant modes (ENRM),which have their rational surfaces located at q < q(a) <0 (q(a) is the safety factor at the plasma edge); and internally non-resonant modes (INRM) with rational surfaces corresponding to q > q(0) > 0. This fact leads to a more severe condition on the stabilization by plasma rotation and dissipation. In addition, the current driven RWM instability in a RFP, where the strong poloidal magnetic field leads to a "bad curvature" dominant along the entire poloidal angle, has much weaker ballooning structure than in a tokamak.

In the present work, we study RWM instabilities in cylindrical RFP plasmas by MHD theory, in which the effects of the plasma pressure, compressibility, plasma inertia, longitudinal rotation and parallel viscosity (tensor) have been taken into account. The resistive wall is modeled with a finite thickness, which allows to treat a large equilibrium flow in the plasma and $\ \ _b$>>1 (is the mode frequency and $\ _b$ is the wall penetration time scale length). In the RFP configuration the poloidal asymmetry in the equilibrium magnetic field is much weaker than in a tokamak, the existing studies in toroidal geometry of RFPs have shown a weak influence of the toroidal coupling effects on the growth rate of the RWM modes [2]. As a first step of the study, in present work we adopt a periodic cylindrical model while the effects of the toroidal geometry will be investigated in a future work.

I. RFP equilibrium and eigenmode equation. Considering a cylindrical plasma with minor radius r=a, surrounded by a resistive wall at r=b with thickness h and conductivity , and assuming the form of the perturbed displacement as $\vec{\ } = \vec{\ }_1(r)\exp[-i \ \ + i(m\Theta + kz)]$, we derived the eigenmode equation from the linearized MHD equations, which can be briefly written as[3]

$$\frac{d}{dr}(A(\ )\frac{d}{dr}\ ) - C(\ ) \quad = 0 \qquad (1)$$

where,

$A = [(\ \ /r)/(D + i\ \ )](\ ^2 - \ _a^2)[(v_s^2 + v_A^2)(\ \ - \ _h^2) - i\ \ _o E/\ \ ]$, $E = E(\ )$, $\ = (\ ,\ _o)$
$D = D(\ ) = \ ^4 - k_o(v_s^2 + v_A^2)\ ^2 + v_s^2\ \ _a^2 k_o^2$, $\ = r\ _r$, $\ = \ - \vec{k}\cdot\vec{v}_o$, $\ _a^2 = \hat{F}^2/(\ \ _o\ )$,
$\hat{F} = kB_z + (m/r)B_\Theta$, $\ _h^2 = v_s^2\ \ _a^2/(v_s^2 + v_A^2)$, $\ _o$ is the parallel viscosity coefficient, is the mass density and v_o is plasma rotation velocity. As for the RFP equilibrium, the usual " -p model"[4] is adopted, given as $\nabla\times\vec{B}_o = \ \vec{B}_o + (\ _o\vec{B}_o\times\nabla p)/B_o^2$, where $\ = 2\Theta_o[1-(r/a)\ \ ]/a$, and Θ_o=(a/R)/ q(0). In order to compare with the experimental measurements, two models for the plasma pressure profiles are applied: 1) $p' = -\ (r)(r/2\ _o)[\ B_o^2/(2B_\Theta) - B_z/r]^2$ which gives Suydam's necessary condition for stability when (r)<1; and 2) $p = p_o n(r)T(r)$, where n(r) and T(r) are given functions provided by experimental data. Finally, an appropriate boundary condition is adopted as given in Ref.[3].

II. **Instability growth rates and comparison with experiments**. The growth rates of the RWM modes in a RFP plasma for both (m=1) ENRM and INRM are calculated as a function of toroidal wave number k where k=n (a/R) and n is the toroidal mode number: n<0 represents INRM and n >0 is for ENRM. For a given equilibrium parameters F, Θ, $_p$ (F is the reversal parameter, Θ is the pinch parameter and $_p$ the poloidal), both types of modes are found to be unstable inside certain k intervals, which correspond to several n modes. A machine with larger aspect ratio has more n modes unstable. Fig.1 is the plot of the growth rates of RWMs using RFX-mod (a/R=0.2295) parameters for various values of F, and q(0)=0.153, $_p$=0. It shows that a deeper reversal results in larger growth rates of ENRMs, among which the most unstable mode is n=3; a shallow reversal (smaller |F|) leads to larger growth rates of INRMs, and n=-6 is the most unstable mode. This result is consistent with the experimental observation and the previous study[5]. It is also found that the growth rates increase with $_p$ value, which implies that the plasma pressure enhances the instabilities. Table 1 shows the comparison of the growth rates between the theoretical calculation and the experimental measurements for different n modes (m=1) in several experimental shots. In the

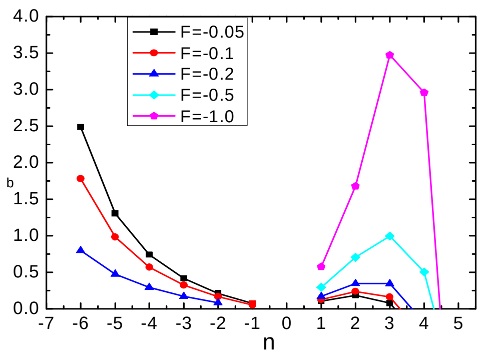

Fig.1 Growth rates of RWM by numerical calculation for various F values, for RFX-mod parameters.

theoretical computation we adjusted the equilibrium parameters in order to well fit the experimental measured values of F, Θ and $_p$. The obtained growth rates show rather good agreements with the experimental results. It is also found that based on the above equilibrium model, different pressure profiles, even corresponding to the same global values of F, Θ, and $_p$, can result in different growth rates. For the most unstable m=1, n=-6 mode the above mentioned two types of pressure profiles give around 10-15% discrepancy of the mode growth rates.

Shot No.	18544(A)		18621(B)		18556(C)		20227(D)		25467(E)		17275(F)		22259(G)	
	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory
F	-0.0464	-0.0464	-0.0169	-0.0168	-0.0731	-0.0722	-0.0513	-0.0509	-0.0474	-0.0477	-0.2304	-0.2304	-0.0808	-0.0797
βp	0.0157	0.0161	0.0153	0.0153	0.018	0.0185	0.0329	0.0332	0.0211	0.0205	0.0227	0.0231	0.0183	0.0186
Θ	1.4045	1.396	1.358	1.3563	1.441	1.4525	1.4273	1.4189	1.4065	1.4161	1.5503	1.5488	1.4348	1.4287
n	-4	-4	-4	-4	-5	-5	-5	-5	-6	-6	-6	-6	-6	-6
g.r.(s^{-1})	7.6925	6.1948	9.2574	6.5952	11.6	11.797	12.941	11.621	24.341	23.437	9.0874	9.1526	20.624	18.149

Table1. Comparison of the growth rates for different n modes between the theoretical calculation and the experiments observation for well matched values of F, Θ and $_p$

III. Stabilization by plasma rotation and dissipation. In comparison with Tokamak, the non resonant RWM in RFPs requires much higher plasma rotating frequency for the stabilization (with dissipation). The present model only takes into account the viscosity damping and the ion sound continuous spectrum damping. The kinetic resonances effects [6] will be added in the next study. For the case having only viscosity effect (=0), it is found that when the velocity of the plasma rotation increases, due to the momentum input from the plasma via the dissipation, the mode slip frequency w. r. to the wall increases, then the stability window appears in an interval of the resistive wall position (b/a). This window starts to open in the vicinity of the critical wall distance for the ideal external kink mode ($r=b_c$). When the rotation velocity further increases, the window size extends toward the plasma boundary. For a given wall position, there is a critical value of the rotation velocity V_{oc}, above which the stability can be reached if the viscosity is sufficient. The value of V_{oc} varies with the mode number and equilibrium parameters. As the wall falls closer to the plasma, the larger V_{oc} value is needed. In the case of a resistive wall located near the plasma edge, the critical velocity required for the stabilization satisfies the condition [7] of $kV_{oc} \approx (k_{||}V_A)_a$ or $kV_{oc} \approx (k_{||}V_A)_{r=0,}$ where $k_{||}$ is the parallel RWM wave number. Both INRM and ENRM, being the non-resonant modes, have their rational surfaces far from the plasma edge, so $k_{||}(a)$ and/or $k_{||}(0)$ are larger ($k_{||}a$~0.2-1 for RFX-mod) than that of the RWM in Tokamaks (which has $k_{||}(a) \approx 0$). Therefore, the stabilization of RWMs in RFPs by plasma rotation requires higher V_{oc} than in tokamak; in particular, V_{oc} is much larger than the rotation velocity of current operated RFP plasmas where no external momentum source (e.g. NBI) is present. In Fig. 2(a) the values of kV_{oc} for both INRM and ENRM are plotted and compared with the values of

$(k_{||}V_A)_a$ and $(k_{||}V_A)_{r=0}$ for wall positions b/a=1.12 (RFX-mod) and r=1.01. The corresponding values of V_{oc} for different modes are plotted in Fig.2(b).

In the case of ≠ 0, the ion sound continuum damping has been observed in an interval of rotation velocity where V_o satisfies $\,^2_h = {}^{-2} \approx (kv_o)^2$. For the current operated RFP plasmas, $_p$~ 2-3% , the stability window for the wall position can appear even without the viscosity, but rather close to b_c. However, more complete calculation of the ion sound continuum damping needs to take into account the effect of kinetic Landau damping.

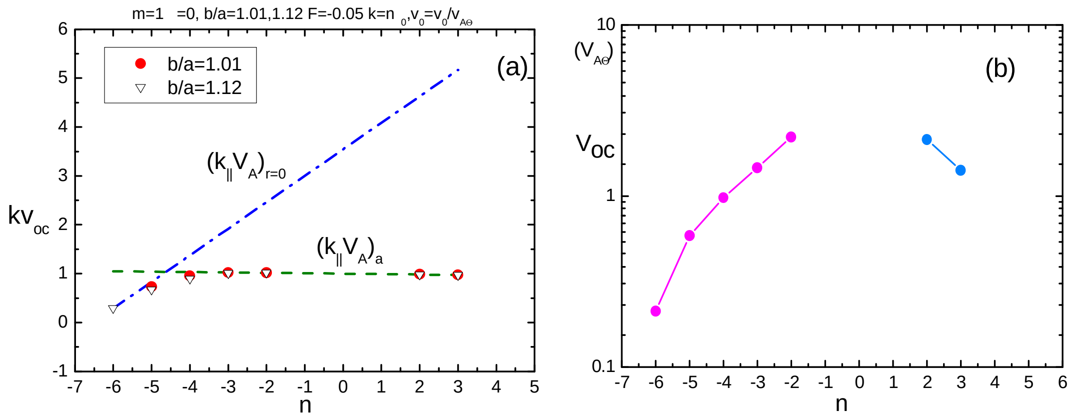

Fig.2 (a) Plot of the values of $(k_{||}v_A)_a$,$(k_{||}v_A)_{r=0}$ and kv_{oc} vs. mode number, for resistive wall position b/a=1.01 and 1.12. It shows that the critical velocities required for RWM stabilization satisfy the condition $kV_{oc} \approx \min\{(k_{||}V_A)_a, (k_{||}V_A)_{r=0}\}$ (b) Plot of the corresponding critical velocities v_{oc} for the stabilization of different (m=1) n modes.

IV. **Feedback model**. Although the RWMs in RFPs can hardly be stabilized by plasma natural rotation, the active feedback stabilization is well feasible. In fact, successful experiments have been achieved in RFX-mod[1] and T2R[8]. In order to understand better the plasma behaviours, a simple model of feed back control with complex proportional gain for a single mode has been added in the model, preliminary result shows a good agreement with the experimental data[9]. The further investigation for both close loop and open loop control is under progress.

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