Investigation of Kinetic Effects on Resistive Wall Mode in Reversed Field Pinch

D. Yadykin[1], Y. Q. Liu[2], R. Paccagnella[3]

[1] *Euratom/VR Fusion Association, Chalmers University of Technology, Gothenburg, Sweden*

[2] *Euratom/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14-3DB, UK*

[3] *Consorzio RFX, and C.N.R, Padua, Italy*

Introduction

Resistive wall mode (RWM) stabilization is an important task for the several fusion devices. In tokamaks the RWM is the pressure limiting instability for the steady state scenario[1,2], whilst in Reversed Field Pinch (RFP) the RWM is one of the discharge duration limiting factors[3]. Two mechanisms are considered to be effective for the RWM stabilization. Active feedback mechanism relies on the direct suppression of the mode using the externally produced magnetic field. Theoretical predictions [4,5] showing the possibility of such suppression are confirmed experimentally in tokamak[6,7] and RFP [8,9]devices. Several active feedback schemes are possible relying on the different active coil configurations[10,11] or sensor types[12].

Another method of RWM control is so-called rotational stabilization, where the plasma rotation is used together with the certain damping mechanism. Several damping mechanisms are proposed to be the cause of the RWM stabilization. They rely basically on the resonance of the mode with certain plasma wave or particle motion. Different mechanisms can be distinguished according to the plasma rotation frequency range where certain mechanism is efficient. Continuum damping [13-15] is present for the relatively large rotation frequencies (in the range of the several percent of the Alfvén frequency). Another mechanism relies on the so-called kinetic effect i.e. the mode resonance with the plasma particle motion [16,17]. It is effective for much smaller rotation frequencies and therefore considered to be the realistic damping mechanics for the present fusion devices and future reactor experiment ITER.

Present work is concentrated on the numerical investigation of the kinetic effects on the RWM stability in the RFP geometry. In particular the configuration and parameters similar to the RFX device [9] are chosen. From the experimental observation it is known [18] that the toroidal plasma rotation frequency in RFX is quit low (in order of fraction of one percent of the Alfvén frequency). Therefore damping mechanism that could possibly affect the RWM stability in RFX is due to the resonance of the mode with the particle motions. The full MHD stability code MARS-K is used for the present studies. Recently, the code was modified [19] in order to include contribution from the kinetic effects.

Model

For the numerical studies of the kinetic effects a model is used in which the resonances with the particle motion are included self consistently in the MHD equations. In this section the model is briefly described. The equilibrium is modeled using equilibrium solver CHEASE [20]. The Grad-Shafranov equation is solved in the toroidal coordinate system. The current density (FF') given by the Θ_0-α model [21] and the pressure given by the polynomial similar to the one used in [22] are used. The toroidal plasma rotation is modeled with a parabolic profile. RWM growth rate is obtained by solving eigenvalue problem using MARS-K code. Additional dissipative term [13] is added to the fluid equations in order to remove unphysical resonance behavior near the sound frequency. The kinetic effects are included in the MHD equations model by introducing a pressure tensor: $\mathbf{p}=p\mathbf{I}+p_{||}\mathbf{bb}+p_{\perp}(\mathbf{I}-\mathbf{bb})$ where p is the scalar fluid pressure perturbation, $p_{||}$ and $p_{\perp}$ are parallel and perpendicular components of the kinetic pressure perturbations, $\mathbf{b}=\mathbf{B}/B$, $B=|\mathbf{B}|$, $\mathbf{B}$ – equilibrium magnetic field, $\mathbf{I}$ – unit tensor. The pressure tensor is included self consistently in the MHD equations. Contribution from $p_{||}$ and $p_{\perp}$ introduces the resonances of RWM with the particle motions. These resonances are visible in the resonance operator[19]:

$$\lambda_{m,l} = \frac{\left[n(\omega_{*N} + (\varepsilon_k - 3/2)\omega_{*T} + \omega_E\right] - \omega}{n\omega_d + \left[\alpha(m+nq)+l\right]\omega_b - i\nu_{eff} - \omega}$$

here ω is the complex mode eigenvalue, ω_b - bounce frequency of the particles, ω_E - ExB drift frequency that is equal to the plasma rotation frequency Ω, ω_d - precession drift frequency, ω_{*T}, ω_{*N} - diamagnetic drift frequencies due to the temperature and density gradients, ν_{eff} - collision frequency, ε_k - normalized particle kinetic energy, m, n - poloidal and toroidal mode numbers, l - bounce Fourier harmonic number, with α=1 for passing particles and α=0 for trapped particles. The mode resonance only with the *trapped* particles is considered in this work.

Results

Present studies are performed for the equilibrium similar to the real experimental equilibrium of the RFX RFP device. The equilibrium parameters F=-0.06 and Θ=1.4 are used that are close to the ones measured experimentally. The value of the on-axis safety factor is $q_0\approx0.159$

meaning that the mode with m=1,n=-7 is resonant on axis. The studies are performed for the internal RWM with m=1,n=-6 that is the most unstable RWM for the chosen parameters. The plasma current is I_p≈1.5 MA, on-axis magnetic field B_0=1.5 T, plasma density $n=2*10^{19}$ m^{-3}, on-axis electron temperature T_e^0=1 KeV, on-axis ion temperature T_i^0=500 eV. In order to estimate what resonance will be important for chosen parameters the frequencies present in the resonance operator are computed. They are shown on fig. 1. The dominant component is the bounce frequency (note that the value of ω_b is scaled by 0.1 to have other frequencies on the same scale). The realistic on-axis toroidal plasma rotation frequency value is taken here that is $\Omega \approx 0.006\omega_a$. In order to estimate the effect from the kinetic effects on the RWM eigenvalue, the dependence of the eigenvalue on the plasma rotation frequency is studied.

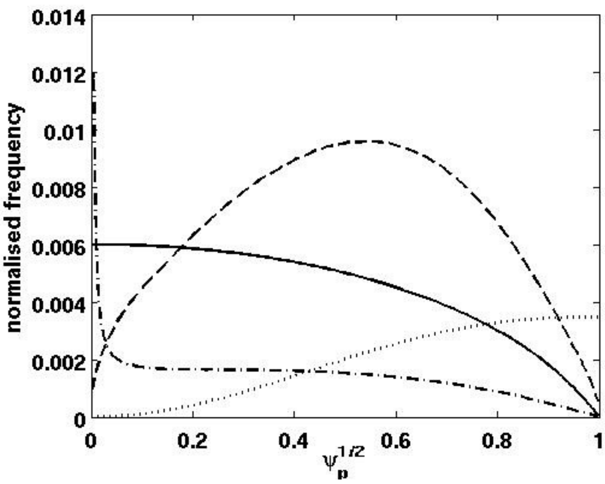

*Fig 1. Frequencies profiles. Solid line - ω_E, dashed line - ω_b*0.1, dashed-dotted line - ω_d, dotted line - ω_*. Frequencies are normalized to the ω_a^0*

The effect of the mode resonance with the different particle motions (different frequencies present in the resonance operator) is compared during these studies. The dependence of the kinetic effect on the ion-electron temperature ratio $C_p=T_i/(T_i+T_e)$ is also studied. The results are shown on fig. 2. It is seen that the kinetic resonances decrease the RWM growth rate (γ) even in the absence of the plasma rotation (Ω=0.0). Some further stabilizing effect is caused by the mode resonance with the precession drift motion of the trapped particles (dashed line) for the plasma rotation frequency range comparable to the precession

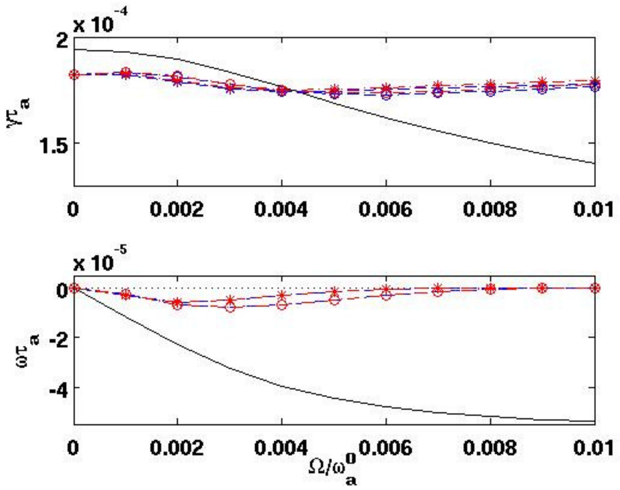

*Fig. 2. The dependence of real (γ) and imaginary (ω) parts of the RWM complex eigenvalue normalized to the Alfvén time on the plasma rotation frequency. Solid line – no kinetic effects, dashed line – mode resonance with the precession drift motion. Dashed-dotted line – mode resonance with the both precession drift and bounce motion. *- C_p=0.5, o- C_p=0.333*

drift frequency values (see fig.1). There is no significant change in the behavior of the RWM eigenvalue when the mode resonance with the bounce motion (dashed-dotted line) is included in the model (dashed and dashed-dotted lines are overlapped). There is some minor difference (γ is increasing slightly for the case when the resonance with the bounce motion is included) for the higher plasma frequencies ($\Omega \approx 0.01$). Such behavior can be explained by the fact that the ω_d and ω_b are well separated and there is almost no 'overlapping' of the effects from the different resonances. The effect of the different C_p is not obvious for both studied cases.

Conclusions

The effect on the Resistive Wall Mode stability from the resonance with the trapped particle motions was studied in the RFP geometry. The slight stabilizing effect is seen that is caused by the mode resonance with the precession drift motion ($\Omega \approx 0.002\omega_a$). The effect from the resonance with bounce motion is not observed probably due to the separation of the drift frequency values. In general it could be noted that the model with the drift kinetic dissipation included better describes the RWM stability in RFP with the plasma flow than the fluid model (no substantial RWM stabilization with rotation is seen similarly to the experimental observations).

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