Study of electromagnetic drift instabilities in high β plasmas

Zhe Gao, J. Q. Dong, C. T. Ying, and G. J. Liu
Department of Engineering Physics, Tsinghua University, Beijing 100084, P. R. China
Email address: gaozhe97@mails.tsinghua.edu.cn

I. Introduction

In advanced devices, such as a spherical torus, β can reach a very high value, e.g. in the START [1], β_T~40% and β_0>100%. However, previous electromagnetic drift mode studies [2-5] only considered the coupling between the ion/electron temperature gradient modes (ITG/ETG modes) and shear Alfvén waves (SAWs), which is a good approximation only in low β plasmas. Effects of β have to be reconsidered when the ∇B effect and the coupling to compressive Alfvén waves (CAWs) are included. Moreover, a large current and a weak-shear regime usually exist in a spherical torus. Such factors as the sheared flow, the current and the magnetic shear should be studied in high β plasmas with the ITG and ETG together.

A series of integral equations for the study of the slab electromagnetic drift instabilities in any β (plasma pressure/magnetic pressure) plasmas are developed in the present work and a systematic study is currently in progress. The local studies and part of the nonlocal studies have been performed.

II. Integral equations

We consider a sheared magnetic field with a magnetic gradient $\vec{B} = B_0\left[\hat{z}(1 + x/L_B) + \hat{y}(x/L_s)\right]$, where L_s and L_B are the length scale of the magnetic shear and the magnetic gradient, respectively. The magnetic gradient is included to maintain the pressure equilibrium for high β plasmas even in a slab, so the L_B is not an independent with the pressure profiles: $L_n/L_B = \sum(\beta_j/2)(1+\eta_j)$.

Introducing three fluctuating values: $\tilde{\phi}$, $\tilde{A}_{//}(=\tilde{\vec{A}}\bullet\hat{b})$, and $\tilde{A}_2(=(\tilde{\vec{A}}\times\hat{e}_\perp)\bullet\hat{b})$, where $\hat{e}_\perp = \vec{k}_\perp/|k_\perp|$ and $\vec{k}_\perp = k_y\hat{e}_y - i\partial/\partial x\,\hat{x}$, and using $\tilde{f}(x) = (1/\sqrt{2\pi})\int f(k)\exp(ikx)dk$, we describe the dynamics of the electromagnetic fluctuation with $\omega << |\Omega_j|$ and $k\lambda_d << 1$ by the quasi-neutrality condition and the Ampere's law

$$\sum\left(q_j^2 n_0/T_j\right)\Big\{\hat{\phi}_j(k) + (1/2\pi)\int dk'\int dx\exp[i(k'-k)x]\Big[L_j(0,0,0,0)\hat{\phi}_j(k')$$
$$+\left(v_{tj}/v_{te}\right)L_j(0,1,1/2,0)\hat{A}_2(k') + \left(v_{tj}/v_{te}\right)L_j(0,0,0,1)\hat{A}_{//}(k')\Big]\Big\} = 0, \tag{1}$$

$$\hat{A}_2(k) - \sum\left(\beta_j/2\pi b_j\right)\Big\{\int dk'\int dx\exp[i(k'-k)x]\Big[\left(v_{te}/v_{tj}\right)L_j(1,0,1/2,0)\hat{\phi}_j(k')$$
$$+ L_j(1,1,1,0)\hat{A}_2(k') + L_j(1,0,1/2,1)\hat{A}_{//}(k')\Big]\Big\} = 0, \tag{2}$$

$$\hat{A}_{//}(k) - \sum\left(\beta_j/2\pi b_j\right)\Big\langle\int dk'\int dx\exp[i(k'-k)x]\Big\{\left(v_{te}/v_{tj}\right)\left[L_j(0,0,0,1) + \left(V_{0j}/v_{tj}\right)\left(1 + L_j(0,0,0,0)\right)\right]\hat{\phi}_j(k')$$
$$+\left[L_j(0,1,1/2,1) + \left(V_{0j}/v_{tj}\right)L_j(0,1,1/2,0)\right]\hat{A}_2(k') + \left[L_j(0,0,0,2) + \left(V_{0j}/v_{tj}\right)L_j(0,0,0,1)\right]\hat{A}_{//}(k')\Big\}\Big\rangle = 0. \tag{3}$$

Here $L_j(m,n,s,l) = \left(-q_j/|q_j|\right)^{m+n}\int_0^{+\infty} dt\,t^s\exp(-t)J_m(\sqrt{2b_j t})J_n(\sqrt{2b_j' t})\left[\omega_{*j}/(\omega - \omega_{Dj}t)\right]K_{lj}$

$K_{1j} = (\omega/\omega_{*j} - 1)[\xi_j Z(\xi_j)] - \eta[\xi_j^2 + (\xi_j^2 - 1/2)\xi_j Z(\xi_j)] - \eta(t-1)[\xi_j Z(\xi_j)] + 2\hat{V}_{0j}'(k_{//}/|k_{//}|)\xi_j[1 + \xi_j Z(\xi_j)]$

$K_{2j} = (k_{//}/|k_{//}|)\xi_j[K_{1j} + (\omega_0/\omega_* - 1) - \eta(t-1)]$, $K_{3j} = (k_{//}/|k_{//}|)\xi_j K_{2j}$, $b_j = (k_\perp^2 T_j)/(m_j\Omega_j^2)$,

$\omega_{*j} = (k_\perp T_j)/(\Omega_j m_j L_n)$, $\omega_{Dj} = -\omega_{*j} L_n/L_B$, $\xi = (\omega - \omega_d t)/|k_{//}|v_t$, $k_{//} = (x/L_s)k_y$,

$\hat{\phi}_j = \phi - V_{0j}A_{//}/c$, $\hat{A}_{//} = -v_{te}A_{//}/c$, $\hat{A}_2 = iv_{te}A_2/c$, and $Z(\xi)$ is the plasma dispersion function.

III. Local studies

As $k = k' = 0$, Eqs.(1)-(3) reduce to a simple algebraic equation which gives the local results. Our earlier paper [6] studied the stabilizing mechanism of finite β on the local mode in nonisothermal plasmas. Fig. 1 shows that ∇B affects the high β drift mode strongly. Fig.2 shows that β_i stabilize the modes mainly by decreasing T_e/T_i while β_e does directly. β_e is the dominant-stabilizing factor for a fixed T_e/T_i, while an increase of T_e/T_i is to up the stable critical β value. The effects of parallel velocity shear (PVS) of ions and plasma current on the high β mode are also studied locally in another paper [7]. It is shown in Fig.3 that a finite β not only weakens the driving mechanism of PVS directly but also reverses the effect of the current on the modes from weakly destabilizing to stabilizing. However, in the local theory the eigenvalue depends on the sign of the velocity shear.

IV. Nonlocal studies

From Eqs.(1)-(3), we can obtain the nonlocal results. Fig.4 shows that the mode studied in previous works [2,3] cannot be stabilized by finite β with the ∇B effect included. Advanced studies indicate that the mode stabilization is subtle. Generally, the more low frequency mode is more difficult to stabilize since finite β cannot effectively change the frequency in the low frequency regime.

A large bootstrap current causes a wide weak-shear regime in the interior of the torus. In a weak-shear geometry, high order (l=1,2…) drift modes are more stable than the fundamental mode (l=0), which is shown in Fig.5. However, finite β stabilizes these modes more easily since they have higher frequencies.

V. Conclusions

A series of integral equations for the study of the slab electromagnetic drift instabilities in any β (plasma pressure/magnetic pressure) plasmas are developed. The modes in high β cases are very different from those in the low β assumption mainly because of the ∇B effect. The local results show that β_e is dominant in the mode stabilization while the corresponding increase of T_e/T_i is up to the stable critical β value. However, the nonlocal results indicate that the finite-β stabilization is very subtle. The local results also show the effects of PVS and current on the high β mode, and the nonlocal studies are currently in progress.

Acknowledgement

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References

[1] Sykes, A. *et al.*, Nuclear Fusion, Vol. **39**, 1271 (1999)
[2] Dong, J. Q. *et al.*, Physics of Fluids Vol. **30**, 2694 (1987)
[3] Reynders, J. V. W., Physics of Plasmas Vol. **1,** 1953 (1994)
[4] Kim, J.-Y. *et al.*, Physics of Fluids B, Vol. **3**, 1167(1993)
[5] Dong, J. Q. *et al.*, Nuclear Fusion, Vol. **39**, 1041 (1999)
[6] Gao Zhe *et al.*, Physics of Plasmas, Vol. **8**, 2816 (2001)
[7] Gao Zhe *et al.*, Physics of Plasmas, Vol. **8**, to be published in Sep. 2001

Figures

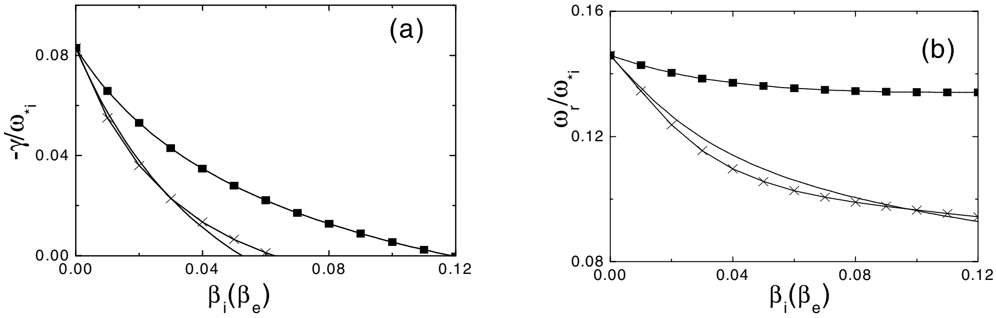

Fig.1: Mode growth rate and frequency vs. β_e for k_zL_n=0.1, η_i=η_e=2, m_i/m_e=1836, β_i =β_e, and b_i=0.5. The lines with squares, crosses, and no symbols denote the results only with the coupling to SAW, with the coupling to SAW and the ∇B effect, and with the coupling to SAW and CAW and the ∇B effect, respectively.

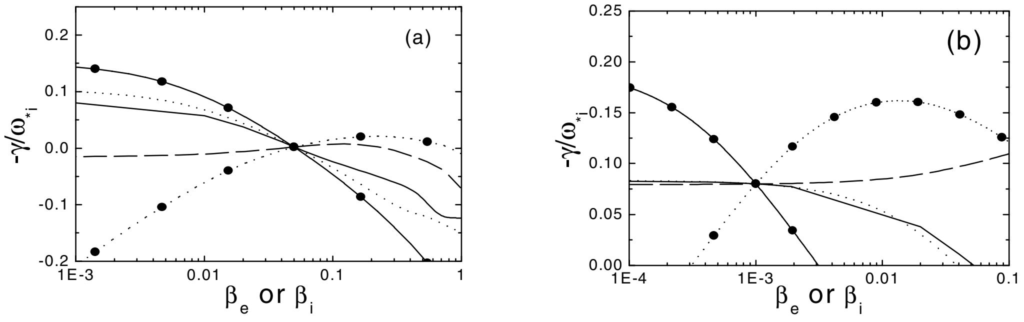

Fig.2: Mode growth rate vs. β_i (or β_e). The solid lines are for β_i=β_e, the dashed lines without symbols are for fixed β_e(=0.05) and T_e/T_i(=1), the dotted lines without symbols are for fixed β_i(=0.05) and T_e/T_i(=1), the dashed lines with circles are for fixed β_e(=0.05) and variable T_e/T_i (with β_i), and the dotted lines with circles are for fixed β_i(=0.05) and variable T_e/T_i (with β_e). The other parameters are the same as Fig. 1. Fig. b is the same as Fig. (a) except that the fixed β_i (or β_e) equals 0.001.

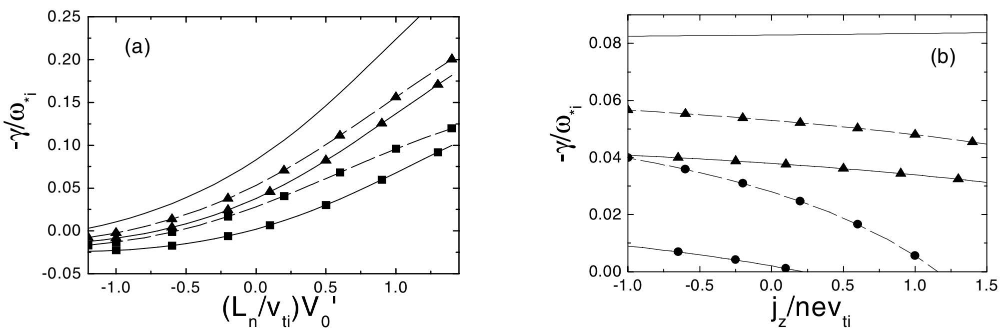

Fig.3. Mode growth rate vs. V_0' (a) and j_z (b). The lines with no symbols, triangles and circles denote the results with β=0, 0.04 and 0.1**,** respectively. The dashed lines denote the results without ∇B drift effect and the coupling to CAW. The other parameters are the same as Fig. 1.

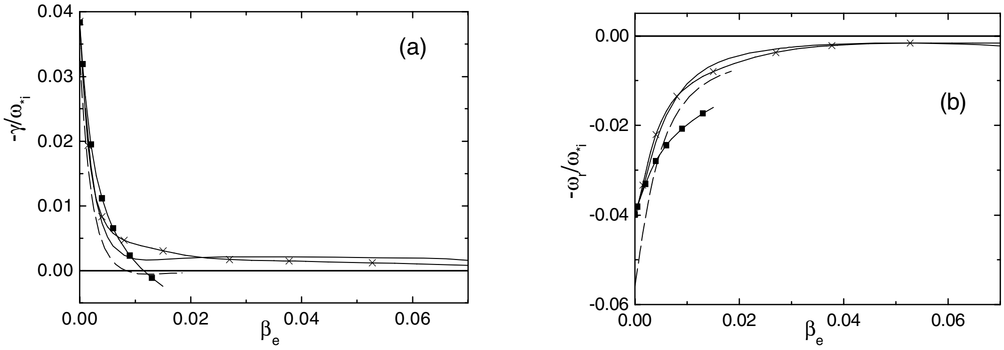

Fig.4: Mode growth rate and frequency vs. β_e for $\eta_i=\eta_e=2$, $m_i/m_e=1836$, $\beta_i=\beta_e$ and $b_i=0.5$. The notation is the same as Fig. 1 and the dashed lines denote the results for $\eta_e=1$.

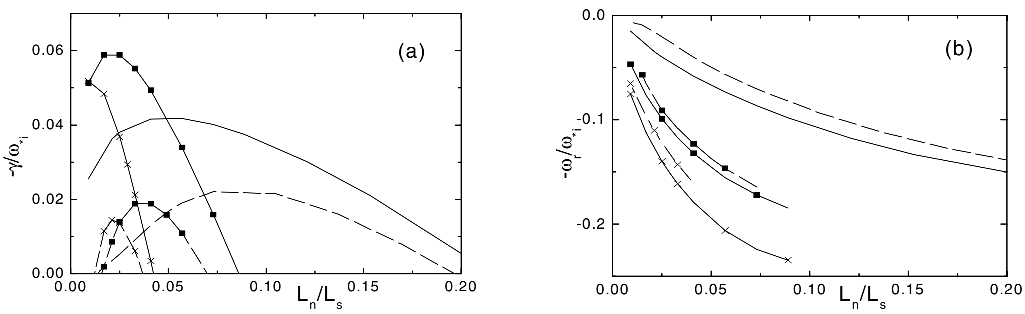

Fig.5: Mode growth rate and frequency vs. L_n/L_s for $\eta_i=\eta_e=2$, $m_i/m_e=1836$ and $b_i=0.5$. The solid lines denote the results from the electrostatic model, the dashed lines denote those for $\beta_e=\beta_i=0.005$, and the lines without symbols, squares and crosses denote those for l=0, 1 and 2 mode, respectively.