TEMPERATURE GRADIENT DRIVEN INSTABILITY IN THE EDGE PLASMA OF A FIELD REVERSED CONFIGURATION

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Drift instability of plasma in a field reversed configuration is considered. Kinetic model takes into account resonant effects associated with particle drift due to magnetic field gradient and force line curvature.
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In this work we consider drift instability in the plasma of a field reversed configuration (FRC). Main feature of kinetic model under consideration is connected with magnetic drift of a particle in non-uniform magnetic field of FRC. Such an approach allows taking into account resonant effects associated with particle drift due to magnetic field gradient and force line curvature.

We have obtained solutions for such instability for relatively low-β regions of the FRC plasma. This condition corresponds to edge FRC plasma.

Instability under consideration is similar to ion temperature gradient (ITG) instability but it has essential features for the FRC plasma.

In our calculation we consider full perturbed kinetics both for ions and for electrons with no adiabatic response assumption. Perturbed part of the velocity distribution function is [1, 2]

$$f_\alpha^{\sim} = -\frac{q_\alpha \varphi^{\sim}}{k_B T_\alpha} f_{0\alpha} + \frac{\omega + \bar{\omega}_{*\alpha}}{\omega + \omega_{D\alpha} - k_\parallel \upsilon_\parallel} J_0^2(\Lambda_\alpha) \frac{q_\alpha \varphi^{\sim}}{k_B T_\alpha} f_{0\alpha}. \quad (1)$$

Here α means ions or electrons ($\alpha = i$, e), k_B is the Boltzmann constant, $f_{0\alpha}$ is equilibrium (Maxwellian) velocity distribution function, $\varphi^{\sim}$ is wave potential, q_α is the particle charge, T_α is temperature, $k_\parallel$ is wave number along magnetic field, $\upsilon_\parallel$ is velocity of the particle along magnetic field, $J_0(\Lambda_\alpha)$ is the Bessel function of the argument $\Lambda_\alpha = k_\perp \upsilon_\perp / \omega_{c\alpha}$, $k_\perp$ is perpendicular wave number, $\upsilon_\perp$ is perpendicular velocity of the particle, $\omega_{c\alpha}$ is gyrofrequency of the particle, $\omega_{D\alpha} = \mathbf{k} \cdot \mathbf{V}_{D\alpha}$, $\mathbf{V}_{D\alpha}$ is magnetic drift velocity,

$$\bar{\omega}_{*\alpha} = \omega_{*\alpha} \left[1 + \eta_\alpha \left(\frac{m_\alpha \upsilon^2}{2 k_B T_\alpha} - \frac{3}{2} \right) \right], \quad (2)$$

$\omega_{*\alpha} = \mathbf{k} \cdot \mathbf{V}_{*\alpha}$, $\mathbf{V}_{*\alpha}$ is diamagnetic drift velocity, $\eta_\alpha = L_{N\alpha} / L_{T\alpha}$, $L_{N\alpha} = -N_\alpha / \nabla_\perp N_\alpha$, $L_{T\alpha} = -T_\alpha / \nabla_\perp T_\alpha$, N_α is a density, m_α is a mass of the particle.

We consider electrostatic instability and use neutrality condition

$$\sum_{\alpha = i,e} q_\alpha \int f_\alpha^{\sim} d^3 \upsilon = 0 \quad (3)$$

as for drift waves $k r_D << 1$ (r_D is the Debay radius).

For FRC

$$\omega_{*\alpha} = k_\perp \frac{k_B T_\alpha}{q_\alpha B L_{N\alpha}}, \quad (4)$$

$$\omega_{D\alpha} = -\frac{L_{N\alpha}}{L_B} \omega_{*\alpha} \frac{m_\alpha}{k_B T_\alpha} \left(\upsilon_\perp^2 / 2 - \alpha_R \upsilon_\parallel^2 \right), \quad (5)$$

where B is magnetic field induction, $L_B = B / \nabla_\perp B$,

$$\alpha_R = L_B / R, \quad (6)$$

$1/R$ is averaged magnetic force line curvature on the particle orbit.

Note, $L_{N\alpha}$, $L_{T\alpha}$ and L_B are positive in considered FRC geometry.

For circulating particles $1/R \approx 1/a$, where a is FRC separatrix radius. For trapped particles curvature value depends on the ratio $\upsilon_\parallel^2 / \upsilon_\perp^2$ connected with the fraction of the trapped particles ε_{Tr}.

Let's consider hydrogen plasma with $\eta_i = \eta_e = \eta$. In this case

$$L_N / L_B = (1 + \eta) \beta / (1 - \beta), \quad (7)$$

where $L_N = L_{Ni} = L_{Ne}$.

As $k_\perp \rho_{Te} << 1$ (ρ_{Te} is thermal electron gyroradius) finally dispersion equation has a form

$$\Theta \int \frac{\omega + \bar{\omega}_{*i}}{\omega + \omega_{Di} - k_\parallel \upsilon_\parallel} J_0^2(\Lambda_i) f_{0i} d^3 \upsilon + \int \frac{\omega + \bar{\omega}_{*e}}{\omega + \omega_{De} - k_\parallel \upsilon_\parallel} f_{0e} d^3 \upsilon = \Theta + 1, \quad (8)$$

where $\Theta = T_e / T_i$ and $\Lambda_e << 1$.

The solution of the formulated problem $\omega(k_\perp, k_\parallel)$ depends on the following parameters: ε_{Tr}, Θ, α_R, β and η.

Numerical analysis has shown no solutions in adiabatic electron response regime for $k_\perp \rho_{Ti} \lesssim 1$ (ρ_{Ti} is thermal ion gyroradius). So, "familiar" ITG instability has not realized in considered local FRC approximation.

Under typical conditions of FRC experiments [3–9] confinement times for plasma energy, magnetic flux and particles have the same order, i.e. $\tau_E \approx \tau_\phi \approx \tau_N$. Plasma parameters the experiments [3–9] are as follows: separatrix radius a ~ 0.1 m, magnetic field of external coils B_0 ~ 0.1 T, total temperature $T_t = T_i + T_e$ ~ 100 eV, ion temperature $T_i \approx 0.7 T_t$, particle confinement time

$\tau_N \sim 10^{-4}$ s. For analysis we assume that $\eta \sim 2$. Note, for the mentioned above conditions classical diffusion time is $\tau_{\rm cl} \approx a^2 / D_{\perp \rm cl} \gtrsim 10^{-3}$ s, where $D_{\perp \rm cl}$ is classical diffusivity.

Here we report results of the calculations. They have indicated very weak influence of $\varepsilon_{\rm Tr}$ on the instability. The increment has a maximum at $k_\perp \rho_{Ti} \approx 0.25$. Modes are unstable for $|\omega / k_\parallel| > \upsilon_{Te}$, where υ_{Te} thermal electron velocity.

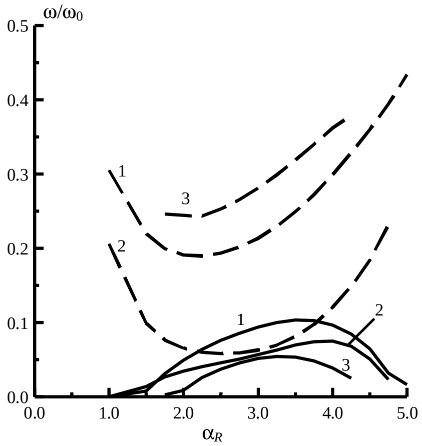

Fig. 1. Real frequency (dashed lines) and increment (solid lines) versus α_R. $k_\parallel=0$, $\varepsilon_{Tr}=0$, $\tau=0.5$, $\eta=\eta_i=\eta_e=2$, $\beta=0.07$. 1 – $k_\perp\rho_{Ti}=0.2$, 2 – $k_\perp\rho_{Ti}=0.05$, 3 – $k_\perp\rho_{Ti}=0.35$

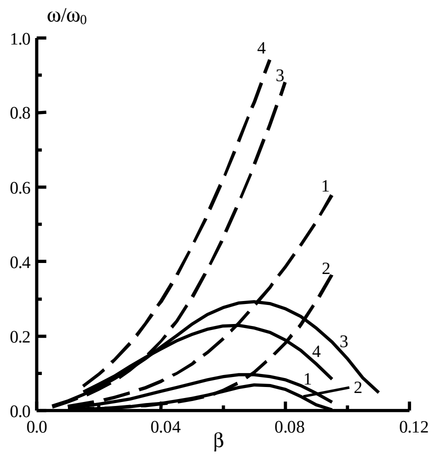

Fig. 2. Real frequency (dashed lines) and increment (solid lines) versus β. $k_\parallel=0$, $\varepsilon_{Tr}=0$, $\tau=0.5$, $\alpha_R=3$. 1 – $\eta=2$, $k_\perp\rho_{Ti}=0.2$; 2 – $\eta=2$, $k_\perp\rho_{Ti}=0.05$; 3 – $\eta=5$, $k_\perp\rho_{Ti}=0.2$; 4 – $\eta=5$, $k_\perp\rho_{Ti}=0.35$

Some results of the calculation of real frequency $\omega_R = \mathrm{Re}(\omega)$ and increment $\gamma = \mathrm{Im}(\omega)$ are presented in Figs. 1 and 2. Frequency scale is $\omega_0 = k_B T_i /(eBL_N \rho_{Ti})$. In unstable regime $\alpha_R = L_B / R \sim 3$ and $\beta \sim 0.1$.

As $1/R \approx 1/a$ and $L_B = L_N (1-\beta)\beta^{-1}(1+\eta)^{-1}$, consequently, $\alpha_R \approx L_B / a = (L_N / a)(1-\beta)\beta^{-1}(1+\eta)^{-1}$, and at $\alpha_R \sim 3$, $\beta \sim 0.1$ one can find density gradient scale length for unstable regime $L_N \sim a$. In limiting cases $L_N >> a$ и $L_N << a$ increment decreases.

The main conclusion based on the calculation results is that considered drift instability in the FRC plasma is sufficiently differ from well known “universal” or ITG drift instabilities. The necessary conditions for considered instability are magnetic drift resonance and non-adiabatic responses of ions and electrons.

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НЕУСТОЙЧИВОСТЬ, ВЫЗЫВАЕМАЯ ТЕМПЕРАТУРНЫМ ГРАДИЕНТОМ В КРАЕВОЙ ПЛАЗМЕ ОБРАЩЕННОЙ МАГНИТНОЙ КОНФИГУРАЦИИ

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Рассматривается дрейфовая неустойчивость плазмы в обращенной магнитной конфигурации. Кинетическая модель учитывает резонансные эффекты, связанные с дрейфом частицы из-за градиента магнитного поля и кривизны силовых линий.

НЕСТІЙКІСТЬ, ВИКЛИКАНА ТЕМПЕРАТУРНИМ ГРАДІЄНТОМ У КРАЙОВІЙ ПЛАЗМІ ЗВЕРНЕНОЇ МАГНІТНОЇ КОНФІГУРАЦІЇ

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Розглядається дрейфова нестійкість плазми в зверненій магнітній конфігурації. Кінетична модель враховує резонансні ефекти, зв'язані з дрейфом частки через градієнт магнітного поля і кривизни силових ліній.