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Comments on Electrostatic Drift Instabilities in a Field Reversed Configuration

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Abstract

The model of electrostatic drift instabilities (short wave drift-dissipative and convective drift instability in kinetic limit) is revised on the base of the new theoretical results in plasma physics. The results show that electrostatic drift waves in FRC will be unstable with the very small probability. Arguments are presented in favor of Alfven-type instability in inhomogeneous high beta FRC plasma as a source of anomalous transport.

Keywords:FRC, Instabilities, Drift Waves,Kinetic.

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I. INTRODUCTION

For the long time main attemptions in the analysis of microinstabilities in FRC have been performed in the field of potential drift microinstabilities. Drift-dissipative instability hypotesis has been used in the model of anomalous transport in FRC [1]. But later experiments show no presence of such instability in large scale FRC experiment [2], [3]. Below we present the results of our studying, in which we, even staying in the framework of local approximation, but on the base of the correct expression for plasma permittivity [4] have revised previous results on such instabilities in FRC plasma.

First of all in an inhomogeneous plasma wave amplithude varies due to two processes: an exchange of energy between particles and waves and the change of group velocity. As it was shown in [4]the correct expression for the permittivity tensor $\varepsilon_{\alpha\beta}$ describes correctly the energy exchange and guarantees equivalence for inversion of wave. Also in [4] was shown as an example that correct expression for permittivity leads to considerable corrections in the theory of drift instabilities, and drift-cyclotron instability has been considered.

Here we use this theory in the analysis of previously studied drift-dissipative instability,and also apply it to the analysis of convective type instability in FRC plasma.

Such analysis together with the experimental data shows that these instabilities could hardly be the source of anomalous transport. Also on the base of a few arguments from the nonlocal theory of drift waves we propose to consider not drift, but Alfven type instabilities as such source.

II. SHORT-WAVE DRIFT-DISSIPATIVE INSTABILITY.

Kinetic theory of drift dissipative instability in an inhomogeneous plasma was well developed [5]. Below we also use local approximation for the permittivity, not an eikonal form of dispersion relation. If we will limit ourselves by Low Frequency short wavelengths drift oscillations in collisionless inhomogeneous plasma, (just these oscillations have been studied in [1]), and suppose that velocity distribution is Maxwellian, then the local dispersion equation will be

$$\varepsilon\left(\omega,k,x\right)=1+\sum_{a}\frac{\omega_{pa}^{2}}{k^{2}v_{Ta}^{2}}\langle 1-\sum_{n}\frac{\omega}{\omega-n\Omega_{a}}1-\frac{k_{y}v_{Ta}^{2}}{\omega\Omega_{a}}\frac{\partial\ln N_{a}}{\partial x}+$$

$$+\frac{\partial T_{a}}{\partial x}\frac{\partial}{\partial T_{a}}A_{n}\left(\frac{k_{\perp}^{2}v_{Ta}^{2}}{\Omega_{a}^{2}}\right)Z_{+}\left(\frac{\omega-n\Omega_{a}}{k_{z}v_{Ta}}\right)\rangle=0 \qquad (1)$$

where $\omega_{pa},\Omega_{a},v_{Ta},T_{a},N_{a}$- plasma and gyrofrequencies,thermal velocity, temperature and density of particles of the species "a" respectively. $A_{n}\left(z\right)=I_{n}\left(z\right)\exp\left(z^{2}\right)$. Here I_{n}- Bessel function of the first kind. Z_{+}- plasma dispersion function.

Neglecting the higher cyclotron harmonics, and assuming that $k_{\perp}\rho_{i}\gg 1$, $k_{\perp}\rho_{e}\ll 1$ and that $v_{Ti}\ll\frac{\omega}{k_{z}}\ll v_{Te}$ from Eq.1 one obtains the local dispersion relation:

$$\varepsilon\left(\omega,k,x\right)=1+$$

$$+\frac{\omega_{pi}^{2}}{k^{2}v_{Ti}^{2}}\left(1+\frac{k_{y}v_{Ti}}{\sqrt{2\pi}k_{\perp}\omega}\frac{\partial}{\partial x}\ln\frac{N}{\sqrt{T_{i}}}\right)+\frac{\omega_{pe}^{2}}{k^{2}v_{Te}^{2}}\left(1+i\sqrt{\frac{\pi}{2}}\frac{k_{y}v_{s}^{2}}{|k_{z}|v_{Te}\Omega_{i}}\frac{\partial}{\partial x}\ln\frac{N}{\sqrt{T_{e}}}\right)=0 \qquad (2)$$

Its spectrum will be

$$\omega=-\frac{T_{e}}{\left(T_{e}+T_{i}\left(1+k^{2}r_{De}^{2}\right)\right)}\frac{k_{y}v_{Ti}}{\sqrt{2\pi}k_{\perp}}\frac{\partial}{\partial x}\ln\frac{N}{\sqrt{T_{i}}} \qquad (3)$$

and the increment (decrement) of such waves:

$$\gamma = \frac{T_e^2}{\left(T_e + T_i\left(1 + k^2 r_{De}^2\right)\right)^2} \frac{1}{2} \frac{k_y^2 v_{Ti}^3}{k_\perp |k_z|} \frac{1}{v_{Te}\Omega_i} \left(\frac{\partial}{\partial x} \ln \frac{N}{\sqrt{T_i}}\right) \left(\frac{\partial}{\partial x} \ln \frac{N}{\sqrt{T_e}}\right) \qquad (4)$$

The corrections to the permittivity tensor $\varepsilon_{\alpha\beta}$ which have been found in [4] are as follows:

$$\varepsilon_{\alpha\beta}^{eff} = \varepsilon_{\alpha\beta} + \sum_{n=1}^{\infty} \frac{1}{n!} \left(\frac{i}{2}\right)^n \frac{\partial^{2n} \varepsilon_{\alpha\beta}}{\partial k_i^n \partial r_i^n} \qquad (5)$$

If we as usually will assume that the scale length of inhomogeneity L is much larger than wavelengths k^{-1}, then we can proceed with only one term from infinite expansion Eq.5. Moreover this new technique allows to study not so trivial cases - it is only necessary to keep more terms in Eq.5. This causes the appearance of additional term in the expression for permittivity Eq.2, namely in its anti-Hermitian part:

$$\delta\varepsilon^{AH} = -\frac{k_y k_x}{k^2 k_\perp^3 \sqrt{2\pi}\omega} \frac{4\pi e^2}{\sqrt{m_i}} \frac{\partial^2}{\partial x^2} \left(\frac{N}{\sqrt{T_i}}\right) \qquad (6)$$

and its sign is opposite to the original one. Hermitian part of the permittivity does not change, so the spectrum remains the same. But the expression for growth/damping rate Eq.4 changes $\gamma = \gamma^0 + \delta\gamma$ where

$$\delta\gamma = -\frac{k_y k_x}{k_\perp^3} r_{Di}^2 \sqrt{8\pi} \frac{e^2 v_s \sqrt{T_e}}{\left(T_e + T_i\left(1 + k^2 r_{De}^2\right)\right)} \frac{\partial^2}{\partial x^2} \left(\frac{N}{\sqrt{T_i}}\right) \qquad (7)$$

And this additional term describes the damping process. So the whole growth/damping rate is the result of certain balance between γ^0 and $\delta\gamma$.

If we take as a model profiles of density and temperature $\sim \exp\left(-\left(\frac{x}{a}\right)^2\right)$ [2], which well describes the experimental situation, then the ratio of these two parts is:

$$\left|\frac{\delta\gamma}{\gamma}\right| \sim \sqrt{\frac{m_i}{m_e}} \Omega_i \qquad (8)$$

So providing strong damping of drift oscillations in the low frequency range. Previously practically in all studying on drift instabilities permittivity $\varepsilon_{\alpha\beta}$ has been used, but not the $\varepsilon_{\alpha\beta}^{eff}$. This way provides correct transformation to the limit of homogeneous plasma and gives correct zero-order term in the Hermitian part of $\varepsilon_{\alpha\beta}$ [4].Anti-Hermitian part is strongly modified, so if inhomogeneity is important, then the usage of simple local $\varepsilon_{\alpha\beta}$ may lead to incorrect expressions for the growth/damping rates, to the nonconservation of energy and vice versa to the appearance of false instabilities [4]. The fact that the additional term in 6 is not explained as follows. The anti-Hermitian part in permittivity2 is the consequence of Cherenkov dissipation on electrons, which change its sign in the range of drift frequencies. This is a sort of resonant interaction. As was shown in [4] in the case of resonant interaction the correction to $\varepsilon_{\alpha\beta}^{AH}$ can be of the same order and even more, due to the exponential feature of the phase synchronism.

III. CONVECTIVE INSTABILITY IN FRC

It is well known, that if in the equilibrium state charged particles in plasma have a directional motion, then instabilities may appear of beam or current nature. Usually these last are called the convective instabilities. In the steady FRC equilibria [6] the total azimuthal current j_θ is the sum of the following two parts:

$$j_\theta = j_{beam} + j_{\theta p} \tag{9}$$

where j_{beam} - some beam current required for the MHD stability, and $j_{\theta p}$- inherent current produced by the particle's drift in the nonuniform magnetic field:

$$v_{D\theta} \sim \overrightarrow{B} \times \nabla B \tag{10}$$

Let's consider the inhomogeneous plasma with such a current in the longitudinal magnetic field which profile describes FRC middle cross-section. Such case corresponds to the highly elongated FRC,e.g. separatrix radius $a \ll b$ - the separatrix length. If again as in Sec.2. we will limit ourselves by low frequency case, then the local permittivity will be [7]:

$$\varepsilon(\omega,k,x) = k_x^2\left(\frac{\omega_{pi}^2}{k^2\Omega_i^2}+\frac{\omega_{pe}^2}{k^2\Omega_e^2}\right)+1-$$

$$-\frac{\omega_{pi}^2}{k^2}\left(\frac{k_z^2}{(\omega-k_y u_i)^2}-\frac{k_y^2}{\Omega_i^2}-\frac{k_y}{\Omega_i(\omega-k_y u_i)}\frac{\partial}{\partial x}\ln N_i\right)- \tag{11}$$

$$-\frac{\omega_{pe}^2}{k^2}\left(\frac{k_z^2}{(\omega-k_y u_e)^2}-\frac{k_y^2}{\Omega_e^2}-\frac{k_y}{\Omega_e(\omega-k_y u_e)}\frac{\partial}{\partial x}\ln N_e\right)$$

In the MHD limit (large wavelengths) dispersion equation Eq.11 describes well-known current-convective MHD instability. Below we will consider the opposite limit of short wavelengths and take into account corrections Eq.5.

This, generally according to the theory [4] modifies the permittivity. If at first permittivity was Hermitian, the correct expression leads to the appearance of the anti-Hermitian part, so we will limit ourselves with one term in expansion in Eq.5, thus obtaining:

$$\delta\varepsilon \equiv Im\varepsilon = \frac{k_x}{k^2}\left(\frac{\omega_{pi}^2}{\Omega_i^2}\frac{\partial}{\partial x}\ln N_i+\frac{\omega_{pe}^2}{\Omega_e^2}\frac{\partial}{\partial x}\ln N_e\right) \tag{12}$$

In this model we take into account the inhomogeneity of the density directly, and the inhomogeneity of the magnetic field is taken into account by the $u_{i,e}$ in the denominators in Eq.11 - the drift velocities.

Under the conditions of kinetic limit $k_y r_{De} \gg 1, k_z$ - small,but finite value, then, due to the physical limitations on drift velocity $k_y u_{i,e} > \omega$ and terms in the second power can be neglected. After some algebra, from usual relation $Re\varepsilon = 0$ (with neglecting of the terms of the second order of smallness) we obtain the spectrum of such oscillations:

$$\omega = k_y u_e - \frac{k_y\Omega_e}{k_x^2(\rho_{mi}/\rho_{me}+1)+k_y^2}\frac{\partial}{\partial x}\ln N_e \tag{13}$$

where $\rho_{mi,me}$- mass density for ions and electrons respectively.

Then growth/damping rate is evaluated directly from $\gamma = -Im\varepsilon/\left(\partial Re\varepsilon/\partial\omega\right)$:

$$\gamma = -\frac{k_x k_y}{k^2}\left(\frac{\omega_{pi}^2}{\Omega_i^2}\frac{\partial \ln N_i}{\partial \ln N_e} + \frac{\omega_{pe}^2}{\Omega_e^2}\right)\frac{\Omega_e^2}{\left[k_x^2\left(\rho_{mi}/\rho_{me}+1\right)+k_y^2\right]^2} \tag{14}$$

As we suppose the FRC plasma to be ambipolar then the ration of relative gradients in first brackets in Eq.14 is equal to unit and in such kinetic limit these oscillations are strongly damped.

IV. ANOMALOUS TRANSPORT AND MICROINSTABILITIES.

We propose to consider FRC as a pure kinetic system. Under the term kinetic we mean that all its transport properties are defined by kinetic, not MHD effects. Many MHD instabilities have been predicted for the FRC plasma and have not been detected, in the few cases when they exist, they saturate at a low level [8].

Also confinement times in FRC experiments are less than classical, and this fact, together with the detection of magnetic field fluctuations, which exceed thermal level [2] may be considered as an argument in favor of microinstabilities as a source of anomalous losses.

Then, let's have a look on the two main sets of microinstabilities:electrostatic and electromagnetic. First of all FRC plasma has high beta. Near the null magnetic field local $\beta \to \infty$. Generally speaking, in such situation it seems less probable for the electrostatic instabilities to occur, than for the electromagnetic. But there exist other arguments.

To obtain the correct (in quantitative sense) results for the wave spectra in the inhomogeneous plasma with spatial dispersion it is necessary to use nonlocal analysis on the base of WKB approximation together with quasiclassical quantization rules [9]. So that wave spectra are defined from phase integral:

$$\int_a^b Re k_x(\omega, k_y, k_z)dx = \pi n, n \gg 1 \tag{15}$$

The integration limits a, b are defined from the condition $Re k_x^2(\omega, k_y, k_z) = 0$. In general case it is hard to solve Eq.15, but the qualitative results are well known.

If density profile belongs to the class of functions similar to $\exp(-r^2/L^2)$ then potential (electrostatic) oscillations are closed inside plasma and their reflection (or accumulation in the case $Rek_x^2 \to \infty$) points in which $\omega_{pi} = \omega$, and ω_{pi}-ion plasma frequency. So even in the presence of such an instability, it will occur in the inner plasma region. And will not occur outside reflection points. Then, the anomalous transport, caused by such an instability will lead to the transfer of particles from this inner region to the external regions. But these last are also placed inside plasma. So there will be no significant increasing of radial particle losses out of plasma.

Now let's consider electromagnetic waves. Strictly speaking in an inhomogeneous plasma it is impossible to perform pure selection of Alfven and magnetosonic waves. Instead of this we use the definitions fast-type and Alfven-type waves, meaning that in the limit of homogeneous plasma the corresponding dispersion relations describe Alfven and fast magnetosonic spectra respectively. Under the same assumptions for the density profile fast-type waves are closed in plasma and have discrete spectra. As above, this means, that fast waves could not be the source of radial losses. Alfven-type waves have two regions of propagation: to the left and to the right from two reflection points, determined from $\omega_{pi}(x) = k_z v_A$ and have continuous spectra. In a laboratory plasma we always have conductive walls that border plasma and close the propagation region for Alfven-type waves, so spectra will be discrete.

Now, in the case of the instability of Alfven-type waves the region of anomalous transport (we do not discuss here it's particular mechanism, some models could be find in [10]) contacts with separatrix region in FRC, thus "opening the gates" for the particles to move outside, providing the enhanced radial losses of particles and, vise verca, anomalous properties and confinement time.

Except Alfven, only longitudinal electron plasma waves with $\omega \geq kv_{Te}$ propagate in the peripheral regions. But usually, such high frequency instabilities have small saturation time, and do not cause enhanced radial losses.

V. CONCLUSIONS

In conclusion, we have revised the drift dissipative low frequency and convective instability on the base of new theoretical approach developed in [4]. The results show that potential microinstabilities of these two types could hardly exist in a Field Reversed Configuration plasma. The general analysis shows that moreover electrostatic waves are usually closed inside plasma, so the transport induced by them will only transfer particles to the external plasma region, where such waves do not exist and plasma is stable. So anomalous radial fluxes in FRC cannot be described by the models based on the electrostatic instabilities. Such FRC feature as high beta value causes the interest to electromagnetic instabilities. Among them only Alfven-type waves will exist in the peripheral plasma region and could provide essential fluctuation level for the particle radial transport to be the anomalous one.

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