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POSSIBILITY OF HEATING IONS IN A PLASMA BY EXCITING DRIFT-BEAM INSTABILITY WITH A FEEDBACK SYSTEM

V.V. Arsenin
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The buildup of drift-beam (collisionless current-convective) instability [1 - 3] in a magnetized plasma broached by an electron beam is accompanied by heating of the plasma ions to a temperature on the order of the electron energy in the beam) [4]. This phenomenon is used to prepare a hot plasma in an open trap [5]. The concentration of the plasma that can be heated in this manner is limited. If n_1 and n_2 are the concentrations of the electrons in the beam and in the plasma at rest, a is the beam radius, and R is the transverse dimension of the plasma, then the instability develops (in full accord with the linear theory) only when the ratio n_2a^2/n_1R^2 is not too large [6] (see condition (2) below).

We shall show that by using special electronic circuity (a feedback system) that measures the oscillations of the electric field and controls the beam current it is possible to excite drift-beam instability in a plasma that is much denser than in the absence of feedback. Since the spatial structure of the oscillation is in this case the same, and the increment is of the same order, as in the "natural" instability (without the feedback), and since it is immaterial from the point of view of particle acceleration what causes the accelerating field, it follows that heating can be expected at sufficiently large oscillation amplitudes[1])

Let us determine the buildup conditions.

We direct the z axis of a cylindrical coordinate system along the axis of a compensated electron beam with concentration $n_1(r) = n_1(1 - r^2/a^2)$, passing through a plasma of concentration $n_2(r) = n_2(1 - r^2/R^2)$ along a magnetic field $\vec{H}$. Let us consider the instability of the beam against perturbations of the electric potential $\psi = \phi(r) \exp(i\ell\theta + ik_z z - i\omega t)$, where θ is the azimuthal angle, under the assumption that $\omega_{Hi} \ll |\omega| \ll \omega_{He}$ and $|\omega| \ll k_z u$, where ω_{Hi} and ω_{He} are the ion and electron cyclotron frequencies and u the electron velocity in the beam. In order not to write down the differential equations, we confine ourselves to quasiclassical perturbations $\phi(r) \simeq \exp(ik_r r)$, $k_r a \gg 1$. For the large-scale oscillations of real interest, we should put $k_r \sim a^{-1}$.

We assume that electron sources with intensity $S = s\psi = -ic\ell n_1 H^{-1}a^{-2}\Delta(\omega)\psi$ are distributed through the volume of the beam. The experimentally observed wave number of the unstable perturbation is $\bar{k}_z \simeq \pi L^{-1}$, where L is the length of

1)Since there is no linear theory (nor is there one for the "natural" instability), the oscillation level required for the heating can be established only experimentally. It can be assumed that amplitudes sufficient for this purpose are of the order of amplitude observed under conditions when heating occurs without feedback.

the plasma. A source having such a structure is realized simply by modulating the current density in the beam, at constant U, in accordance with the law

$$\frac{\partial j}{\partial t} = A\psi|_{z=z_0} = A\phi \exp(i\ell\theta + ik_z z_0 - i\omega t),$$

where z_0 is the coordinate of the potential (electric field) pickups. Indeed,

$$\int_0^L A\psi|_{z=z_0} \exp(-i\ell\theta - i\bar{k}_z z + i\omega t)dz \equiv \sigma \neq 0,$$

so that the change of the beam concentration $(eu)^{-1}(\partial j/\partial t)$ contains the required Fourier harmonic[2] $\exp(ik_z z)$. Here $s = (eu)^{-1}\sigma$.

Under the foregoing assumptions, the dispersion equation, with allowance for the sources, is

$$1 = \frac{\omega_1^2}{k^2 u^2} + \frac{2\omega_1^2 \ell(1+\Delta)}{k^2 k_z u \omega_{He} a^2} - \frac{2\omega_2^2 \ell}{k^2 \omega \omega_{He} R^2} + \frac{k_z^2 \omega_2^2}{k^2 \omega^2} + \frac{m}{M}\frac{\omega_1^2 + \omega_2^2}{\omega^2}, \quad (1)$$

where ω_1 and ω_2 are the Langmuir frequencies corresponding to the beam and plasma concentrations, m/M is the ratio of the electron and ion masses, $k^2 = k_r^2 + \ell^2/r^2 + k_z^2$, and the quantity $\Delta(\omega)$ characterizes the electronic circuitry.

We are interested in the case when the larger of the two beam terms in (1) is convective, and therefore the first term in the right-hand side can be omitted. We put for concreteness $k_z^2 n_2/k^2 > m(n_1 + n_2)/M$ and $\omega_2 \ell > k k_z r^2 \omega_{He}$. Then, in the absence of feedback ($\Delta = 0$), buildup of the mode $\exp(i\ell\theta + ik_z z)$ ($\mathrm{Im}\,\omega > 0$) takes place when

$$\frac{n_1 R^2}{n_2 a^2} > \frac{\ell u}{2k_z R^2 \omega_{He}}. \quad (2)$$

Let now Δ be a positive constant. The effect of the feedback is in this case equivalent to an increase of $|dn_1/dr|$ by a factor $1 + \Delta$. We obtain instead of (2) the buildup condition

$$\frac{n_1(1+\Delta)R^2}{n_2 a^2} > \frac{\ell u}{2k_z R^2 \omega_{He}}. \quad (3)$$

The introduction of feedback makes it therefore possible, at the given beam parameters, to excite drift-beam instability of the same mode in a plasma that is denser by a factor $1 + \Delta$.

The excitation occurs also when Δ is a complex constant, since we get in this case $\mathrm{Im}\,\omega > 0$ for one of the roots of the quadratic equation (1).

In order that introduction of feedback cause buildup of the oscillations, it is obviously necessary that the sensitivity of the pickups of the potential ψ be not lower than the level of ψ at the instant when the feedback is turned

[2]Unlike the case of stabilization problems (cf., e.g., [7]), there is no need to worry about the stability of the remaining harmonics in the excitation problem.

on. If the noise level due to the buildup of oscillations of other types [8] is insufficient, it is necessary to produce the initial perturbation purposefully, for example, by an initial perturbation of the concentration (current) of the beam, $\delta n_1 = A \exp(i\ell\theta)$.

It is also easy to obtain the buildup conditions for cases when the system responds to a perturbation not of the potential (field) but of some other quantity. For example, if $S = \Omega(\omega)\delta n_1$, the dispersion equation is obtained from the equation for the "free" beam by replacing $\omega - k_z u$ in the beam terms by $\omega - k_z u - i\Omega(\omega)$.

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PHOTON EMISSION BY FAST CHARGED PARTICLES IN A SINGLE CRYSTAL

V.G. Kudryavtsev and M.I. Ryazanov
Moscow Engineering-physics Institute
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1. It is known that a charged particle can emit a photon only by interacting with a third body (an atom of matter). For electrons, the most important process is the one in which the quantum is emitted directly by a fast particle (bremsstrahlung). For heavy particles, an important role is played by a mechanism in which a quantum is emitted by an electron of matter as a result of its scattering the particle's own field [1]. For example, for hard quanta, the cause of the radiation can be Compton scattering by the bound electrons. As shown in [2], in an amorphous medium this mechanism becomes predominant, even for electrons, at energies $E \geq 10^5$ eV and frequencies $\omega \leq 10^7$, owing to the suppression of the bremsstrahlung by the polarization of the medium [3].

We consider below a mechanism analogous to that of [2] for radiation in a single crystal. An essential feature of a single crystal is the strong enhancement of Compton scattering in the region of small angles, for which the wavelength transmitted in the longitudinal direction (a quantity inverse to the longitudinal momentum transfer) exceeds the lattice constant a. Indeed, the Hamiltonians of the interaction between the quantum and the atoms is the sum of the Hamiltonians of the interaction with each atom. Then, neglecting the interaction of the atoms with one another, we can write the matrix element for the scattering of a quantum by the entire crystal in the form of the sum of the matrix elements for the scattering by each atom: