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Dissipative Instability of Overlimiting Electron Beam

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Influence of dissipation on development of overlimiting electron beam instability caused by aperiodical modulation of beam density in medium with negative dielectric constant is investigated. It is shown that growth rates of dissipative instability of overlimiting electron beam depend on parameter characterizing dissipation more critically as compared with sublimiting e-beams. The influence of dissipation on mode structure, space distribution and development dynamics of overlimiting e-beam instability and its gradual transition to that of dissipative type with increase in level of dissipation is investigated in detail.

Recently most of beam-plasma interaction experiments are gradually changed over to more and more high-current electron beams. It is known that beam current that can pass through given vacuum electrodynamic system is limited by the beam space charge. Plasma filled systems can operate with beams current that are several times higher that limiting vacuum current. Overlimiting electron beam instability has distinction in kind of physical nature [1-4]. As the beam current increases the fields of beam space charge play more and more significant role and change physical character of beam-plasma interaction as compared with sublimiting electron beams. Traditional statement about physical nature of electron beam instability related to induced radiation of the system proper waves by beam electrons might not be applied to overlimiting beams. Physical character of their instability is due either to aperiodical modulation of the beam density in medium with negative dielectric constant [1,3] or to excitation of beam pace charge wave with negative energy.

Along with the increasing of the beam current one more trend is dominant in contemporary microwave electronics: change over to higher frequencies. This trend leads to increasing of energy active losses in the walls of resonators due to decreasing of the skin depth. The Q-quality of resonators falls dawn and dissipation increases. Apart from increasing of beam current dissipation of high level also changes the physical nature of beam instability. Dissipation can play an important role in the dynamics of beam-plasma instability development. It can become not only deciding factors in the limiting spatial and temporal growth and determining the magnitude of the fields. The dissipation can also significantly influence on the mode structure of instability and reduce the growth rate [5-7]]. But dissipation never suppresses beam instability completely. Dissipation of high level transforms conventional beam instability to that of another type - dissipative beam instability. This type of instabilities comes to be developing in systems with electron beams where the beam space charge wave with negative energy exists. Actually dissipation is nothing else as a channel of energy withdrawal for excitation of the beam wave with negative energy. Growing of slow space-charge wave causes instability of charged particle beam under its interaction with dissipative or inductive walls. This type of dissipative instability is an important issue in particle accelerators and applications to microwave devices. Recently this phenomenon has received new attention especially in connection with its role in high current induction linacs as drivers for heavy ion inertial fusion. Dissipative beam instabilities have an array of characteristic peculiarities [5-7]. In particular dissipative instabilities differ from conventional beam instability by low growth rates as well as by relatively low energy of excited oscillations. Some aspects of gradual transition of monoenergetic e-beam instability to that of dissipative type with increase on level of dissipation are investigated in [8]. Dissipative and resistive wall instabilities of electron beam underly on the operation of so-called amplifier on dissipation. The idea of such a type of amplifier was proposed comparatively long ego and was developed further [9]. It has some characteristic peculiarities as compared with traditional TWT – wide bandwidth, absence (or very weak) of inner feedback, and its amplification does not depend on operation regime (beam current etc). It seems, change over to overlimiting electron beams keeps these properties unchanged.

Dissipative instability of overlimiting electron beam has not been considered yet. Present investigation considers the influence of dissipation on development of overlimiting electron beam instability caused by aperiodic modulation of beam density in media with negative dielectric constant. Fully magnetized beam-plasma waveguide is considered. It is shown that the well-known dispersion relation [1-4] in the case of overlimiting beam currents has solutions for growth rates that are proportional (in absence of dissipation) to the beam Lengmuire frequency and inverse proportional to the parameter characterizing dissipation (in systems with high level of dissipation). But for sublimiting al) e-beams the respective growth rates have another dependence on these parameters. The change in the physical nature of the instability relates to the effect of beam space charge fields, which leads to distortion of the polarization of the waveguide fields. As we think, the dependences become more critical because of with

increasing of the beam current its proper oscillations of reveal themselves more efficiently, the mode related to beam wave with negative energy is excited and serve as a channel for energy withdrawal.

In order to investigate the influence of dissipation on mode structure, space distribution and development dynamics of overlimiting electron beam instability we proceeded from the initial set of equations (Maxwell's, continuity and motion eqs for the beam and plasma electrons) and considered the evolution of an initial perturbation in the system. Using wide spread representation of growing fields as wave train with slowly varying amplitude we obtained equation for the envelope of waveform. This equation was solved and analytical expression for space-time distribution of the fields upon overlimiting e-beam instability development is actually derived. Characteristic properties of the wave train are following. It can be thought of as consisting of many unstable modes. In absence of dissipation the envelope is symmetric (see curve 1 in Fig1). The front of induced waveform moves at beam velocity u, back edge – at group velocity of resonant wave in considered system $v_0 < u$. This shows the convective character of overlimiting electron beam instability in laboratory frame and the frames moving at velocities $v < v_0$, and $v > u$. Unlike to the case of sublimiting beam, in the absence of dissipation, the waveform induced by overlimiting beam is symmetric i.e. its peak places on its middle at all instants.
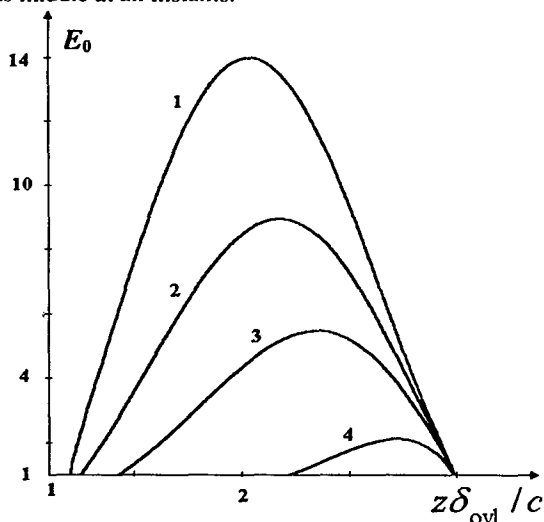

Fig1. Shapes of waveform vs on longitudinal coordinate z at fixed instant $t = 3/\delta_{ovl}$ (δ_{ovl} is the max growth rate overlimiting e-beam instability) of for various values of parameter $k = v/\delta_{ovl}$; $k_1 = 0$; $k_2 = 0.4$; $k_3 = 1.3$; $k_4 = 2.5$; ($v_0/u = 0.4$)

The growth rate of most unstable mode is equal to maximal growth rate of overlimiting e-beam instability. In other words the maximal growth rate of instability usually describing instability in given system in fact is nothing else that the growth rate in the peak of wave packet. For conventional beam instability the peak placed on 1/3 of its length from front [14]. As the beam current increases the peak of induced waveform shifts

backward to the middle of wave packet and the growth rate essentially changes its value and dependence on beam density $\omega_b^{2/3} \to \omega_b$ (ω_b is the Lengmuire frequency of the beam).
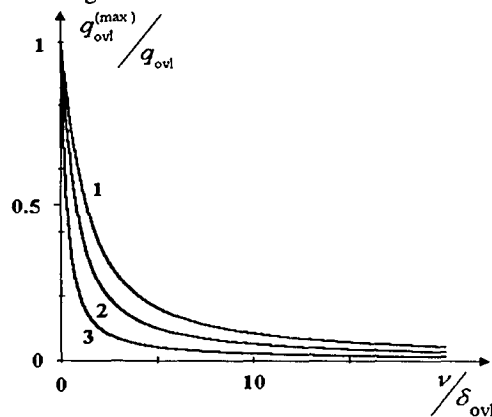
Dissipation significantly effects on growth rates and suppresses low-velocity modes. The length of induced waveform depends on dissipation level and tends to zero when the level of dissipation increases. In the limit of high-level dissipation, unstable perturbations move at velocity u and their growth rate is equal to growth rate of overlimiitng e-beam dissipative instability. If one considers injection and further propagation of an overlimiting electron beam into plasma-filled waveguide the dissipative instability can develop mainly near beam front.

The dependence of maximal spatial growth rate on dissipation level is given by simple expression

$$q_{ovl}^{(max)}(v) = q_{ovl}\left(\sqrt{1+\lambda} - \sqrt{\lambda}\right)$$

where q_{ovl} is the spatial growth rate in the absence of dissipation, $v = \text{Im} D_0 / (\partial D_0 / \partial \omega)$ characterizes dissipation in considered system, $\lambda = (v/\delta_{ovl})(u/v_0)$, δ_{ovl} is the maximal growth rate of overlimiting e-beam instability in plasma-filled waveguide. The dependence of the maximal growth rate on dissipation level is shown in Fig 2.

The maximal spatial growth rate of overlimiting e-beam instability vs on dissipation level and parameter $p = u/v_0$. $p_1 = 1.5$, $p_2 = 4$, $p_3 = 25$.

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