INTERACTION OF NARROW BEAM WITH PLASMA

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ABSTRACT

This paper deals with the interaction of the narrow beam with plasma in plasmatrons based on plasma-beam discharge. The calculations of plasma-beam instability growth rate are carried out for two cases: interaction of the narrow beam with narrow plasma and interaction of the narrow beam with infinite in cross-direction plasma.

1. INTRODUCTION.

In a series of papers presented at the previous plasma chemical conferences it was communicated about experimental evidence of high efficiency of plasmatrons based on plasma-beam discharge for carrying out the plasma-chemical reactions (1). It is of importance to know the exact value of the electron beam relaxation length in plasma with a different density and geometry for further increasing of the efficiency of these reactors. The relaxation length is the distance where the electron beam power (up to the 70%) is transferred to the Langmuir's oscillations of a plasma. According to quasilinear theory the relaxation length of the boundless in the cross direction electron beam under stationary injection is given by

$$X = \frac{\Lambda}{2\pi} \cdot \left(\frac{\Delta V}{V_b}\right)^2 \cdot \frac{n_p}{n_b} \cdot \frac{V_{gr}}{\omega_{pe}} \qquad (1)$$

where n_p, ω_{pe}, V_{gr} -are respectively the plasma density, Langmuir frequency, and group velocity of Langmuir oscillations; n_b, V_b and ΔV - are respectively the density, the velocity and the spread in the velocity space of the electron beam, and Λ -is the Coulomn logarithm. But the relaxation length experimentally obtained usually exceeds the length which was definded in (1). In some cases it is due to nonlinear processes resulting in transmission of the Langmuir oscillations from the resonance region where $\omega_{pe}=K_x V_{Tb}$ in to the nonresonance region. If the rate of transmission is greatly exceed the quasilinear relaxation rate and the wave absorbtion in a nonresonance region is strong, there is a stationary solution when the beam is stable. An intermediate case is of cause possible when nonlinear processes do not result in stabilization of plasma-beam instability but decreases to some extent it's growth rate due to decreasing of Langmuir noises level in the resonance region. According to a modern conceptions of plasma physics the direct collapse is thought to be the most rapid process (2). The condition of depressing of the plasma-beam instability due to the direct collapse may be written as follows (2):

$$t_c \gamma_B = \frac{1}{6} \cdot \frac{K_D^2}{(\Delta K)^2} \left(\frac{v_B}{\Delta v_B} \right)^2 \cdot \frac{n_B}{n_0} \ll 1 \qquad (2)$$

where t_c - is the time of the direct collapse, γ_B - is the growth rate of a plasma-beam instability, K_D -is the inverse Debye radius, ΔK - is the width of Langmuir wave packet in K-space. Physically it means, that the beam instability is stabilized if the inverse growth rate of the beam instability is greater than the direct collapse time. Stabilization occurs when an amplitude of Langmuir waves reaches the value three times as much as threshold amplitude for direct collapse (2) which is by several orders of magnitude less than an amplitude of Langmuir waves on quasilinear stage of beam relaxation. In this case the relaxation length is increased appreciably in comparison with the quasilinear length (1). Under condition $\Delta K = K_0/6$ (2) leads to the following result $3 \cdot 10^2 (v_{TB}/v_{Te})^2 (n_B/n_P) \ll 1$, here v_{Te} - is the plasma electrons thermal velocity. It is seen that this condition is valid only for a small-density beams. In the plasmatrons, based on a plasma-beam discharge the ratio $n_B/n_P \simeq 10^{-3}$ $v_B/v_{Te} \simeq 10^2$, so that (2) isn't fullfilled. Thus we come to conclusion that under experimental conditions typical for plasmatrons based on the plasma-beam discharge, nonlinear processes do not affect the relaxation length unless n_B/n_P is not too small. In our case the increasing of the relaxation length may be caused by the effects of finite geometry. Optimal conditions for chemical reactions in plasmatrons, based on plasma-beam discharge are realized when the pressure of a molecular gas in the reaction zone is of the order of some tors. For a reliable operation of an electron gun low pressures of the order of 10^{-4} - 10^{-5} tors are necessary. Consequently, there are two regions with different pressure regimes in such plasmatron: the low pressure channel connecting the electron gun with a reaction zone and reaction zone with dense plasma where the beam relaxes transferring its energy to plasma. In the reaction zone the chemical reactions are carried out. For further increase of plasmatron efficiency it is essential to assure minimum losses of an electron beam energy in the channel connecting electron gun and reaction zone and to achieve total relaxation of an electron beam in reaction zone. The purpose of present work is to investigate the effect of finite geometry on the instability of a narrow electron beam propagating in plasma. Two cases will be considered: 1) - interaction of a narrow electron beam with plasma of the same dimentions, 2) - interaction of a narrow electron beam with plasma of infinite dimensions. It has been shown in (3), that the effect of finite geometry is expected to appear when $K_x d \leq 1$, here K_x - is the wavenumber of Langmuir oscillation in the direction of an electron beam propagations, d - is the width of the beam. This means that infinite plasma and beam approximation is reasonable when the wavelength of Langmuir oscillations arising in plasma due to plasma-beam instability is small compared to the cross dimensions of the system considered. When on the contrary the wavelength is of the order or greater than the cross dimensions of the system effect of finite geometry and appropriate boundary conditions become important. Plasma density in the channel connecting electron gun and reaction zone is about 10^{10} cm^{-3}, beam energy $\sim$10KeV. In this case $K_x = \frac{\omega_{pe}}{u} = 0{,}8$ cm. The width of a ribbon-like electron beam used in plasmatrons based on plasma-beam discharge is about 0,5 cm. Mean plasma density in reaction zone is about $10^{12} \div 10^{13}$ cm^{-3}, but there is experimental evidence that plasma is partly carried out from the region of the beam at the distance equals to Larmor radius of ions. Thus plasma density in the beam region is about 10^{10}–10^{11} cm^{-3} (4), while the density averaged over the whole volume is about $5 \cdot 10^{12}$ cm^{-3}. This means that the effect of finite geometry must be taken into account in both cases-when ribbon-like electron beam propagates along the connecting channel and when it moves in reaction chamber.

2. DERIVATION OF THE DISPERSION RELATION AND CALCULATION OF THE INSTABILITY GROWTH RATE.

Let's now consider the case when the narrow electron beam is propagate along the channel the same width filled with plasma. Axis X - is the direction an electron beam propagation. Axis Z - is the direction of the ununiformity. The derivation of the dispersion relations consists in simultaneous consideration of the Maxwell equations, the equation distribution function of the electrons taking into account boundary conditions, which assume equality of tangential components of an electric field E_x and normal components of the magnetic field H_y. It should be noted that we consider the potential oscillations. Thus the dispersion relations can be written as:

$$2 \sum_{n=0}^{\infty\, ev} \frac{1}{A_n} \cdot \frac{1}{\varepsilon_{\parallel}\left(K_x^2 + \frac{n^2\pi^2}{d^2}\right)} = -\frac{1}{K_x}$$

$$2 \sum_{n=1}^{\infty\, un} \frac{1}{A_n} \cdot \frac{1}{\varepsilon_{\parallel}\left(K_x^2 + \frac{n^2\pi^2}{d^2}\right)} = -\frac{1}{K_x}$$

$$A_n = \begin{cases} d, & n=0 \\ d/2, & n \neq 0 \end{cases}$$

Depending on detailed structure of dielectric tensor Eq.(3) permits two sorts of eigen solutions, the first one - for volume Langmuir waves $\omega = \omega_{pe}$ and the second - for surface waves with $\omega = \omega_{pe}/\sqrt{2}$ propagating along the plasma boundary (5). In order to obtain the instability growth rate for surface waves we take $\varepsilon_{II} = 1-\omega_{pe}^2/\omega^2$ and expand (3) taking into account that $n_B/n_p \ll 1$. Thus we obtain in zero approximation the eigen solution $\omega_0 = \omega_{pe}/\sqrt{2}$. Then supposing that $\omega = \omega_0 + i\delta$, we get in the first approximation the following expressions for the growth rate of even and uneven modes:

$$\delta^{unev}/\delta_{max} = \frac{2{,}1\cdot\alpha^4}{th\,\alpha\pi/2}\cdot\sum_{n=1}^{\infty\, unev}\frac{exp\{-\Delta^2\alpha^2/\alpha^2+n^2\}}{(\alpha^2+n^2)^{5/2}}; \tag{4}$$

$$\delta^{ev}/\delta_{max} = 1+\frac{2{,}1\cdot\alpha^4}{cth\,\alpha\pi/2}\cdot\sum_{n=2}^{\infty\, ev}\frac{exp\{-\Delta^2\alpha^2/\alpha^2+n^2\}}{(\alpha^2+n^2)^{5/2}};\ \alpha=\frac{K_x d}{\pi};\ \Delta=\frac{\omega-K_x u}{K_x v_{TB}}$$

Here δ_{max} - is the maximum growth rate of plasma-beam instability which is obtained under approximation of infinite plasma and beam. In similar way, but supposing $\varepsilon_{II} = 1 - \omega_{pe}^2/(\omega^2-K^2 v_{Te}^2)$ the growth rate of volume Langmuir oscillations can be obtained:

$$\delta^{ev,unev}/\delta_{max} = \frac{\sqrt{2e}\,\sum_n \frac{\Delta\,\alpha_x^3}{(\alpha_x^2+n^2)^{3/2}}\,exp\left\{-\frac{\Delta^2\alpha_x^2}{\alpha_x^2+n^2}\right\}\Big/\frac{(\alpha_z^2-n^2)^2(\alpha_x^2+n^2)}{[\alpha_x^2(\beta^2-1)-n^2]^2}}{\sum_n \frac{[\alpha_x^2(\beta^2-1)-n^2]^2}{(\alpha_z^2-n^2)^2(\alpha_x^2+n^2)}} \tag{5}$$

Here $\alpha_x = K_x d/\pi$; $\alpha_z = K_z d/\pi$, $\beta = u/v_{TB}$; $\gamma = u/v_{Te}$

On Fig.1 the ratio δ/δ_{max} for the surface waves is shown as function of $\omega_{pe}d/\sqrt{2}u$. The ratio δ/δ_{max} increases linearly from zero as $\omega_{pe}d/\sqrt{2}u$ varies from 0 to 2. The increasing of δ/δ_{max} slow down when $\frac{\omega_{pe}d}{\sqrt{2}u}$ varies from 2 - 3 and then saturation occur at $\delta/\delta_{max} \sim 1$. On Fig.1 the ratio δ/δ_{max} for volume Langmuir waves is plotted against $\omega_{pe}d/\sqrt{2}u$. It is seen that the effect of finite geometry is essential up to the $\alpha \sim 1$. Then ratio δ/δ_{max} tends smoothly to 1, that is in a good agreement with the expression (5), where $\alpha \to \infty$. It is interesting to compare the results presented here with the results obtained in an infinite geometry. Under assumption that gas in channel is 10% ionized the plasma density is equal to $n_p \simeq 3\cdot 10^{10}$ cm^{-3} at the pressure about 10^{-5} tors. For instance, for the beam's energy ~10 KeV the growth rate of Langmuir waves is reduced by the factor of 10 compare to its value in an infinite geometry (for the width of beam equals 1 cm). According to the experimental conditions (6) an electron beam with the same parameters which is propagate in a plasma channel loss less than 10% of its energy at the 20 cm length. The decreasing of the width of the beam and channel results in the increasing an electron beam relaxation length. Consider now the second case. The narrow beam propagates in an infinite plasma. Due to infinite geometry an electric E and magnetic H fields can be expanded into the Fourier-integral in the plasma region and into the Fourier-series in the region with beam and plasma. After calculations similar to those used in the first case we get the growth rate of the instability, which occurs in such system. Here also the expression obtained is normalized on the maximum growth rate of the beam plasma instability; obtained in the case when electron beam as well as plasma posseses infinite cross section

$$\delta^{ev,unev}/\delta_{max} = \frac{\sqrt{2}\,\alpha_x^3 \cdot 2 \sum_n \frac{\alpha_z^4 \alpha_x \left[\Delta^2 \alpha_x^2 (\zeta-1)^2 g^2 - \alpha_x^2 - n^2\right]}{(\alpha_x^2+n^2)(\alpha_z^2-n^2)^2} \exp\left\{\frac{\Delta^2 n^2}{\alpha_x^2+n^2}\right\}}{(\zeta-1)\, g \left(\Delta^2 \alpha_x^2 (\zeta-1)^2 g^2 - \alpha_z^2\right)^{3/2} \left[2 \sum_n \frac{\alpha_x^2 \alpha_z^4}{(\alpha_x^2+n^2)(\alpha_z^2-n^2)^2} + \frac{\pi \alpha_x \alpha_z^4}{2(\alpha_x^2+\alpha_z^2)^2}\right]}$$

where $g = v_{TB}/v_{Te}$; $\zeta = u/v_{TB}$

On Fig.2 $\delta/\delta\ max$ is plotted against $\frac{\omega_{ped}}{u}$ for the case of an infinite plasma and narrow beam. In the range ω_{ped}/u from 0 up to 3-4 the growth rate is equal almost 0.2 part of the growth rate obtained in an infinite geometry. Hence, varying the beam width one can get essential decreasing of the beam relaxation length in such case interesting from the experimental point of view. Function $\delta/\delta max$ smoothly increases to the 1, i.e. the system turns into an infinite regime. So one can say about fullfilled limited case $d \to \infty$ and fullfilled standartization. The results obtained can be useful for the plasmachemical reactors based in the plasma-beam discharge and in devices, when interaction of the narrow beam with plasma occurs.

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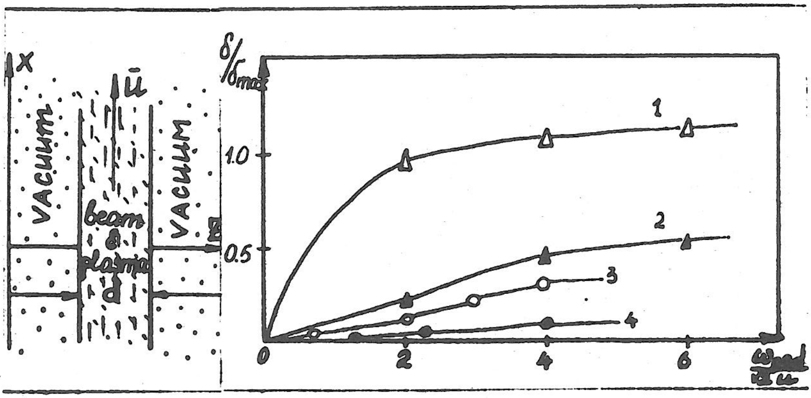

Fig.1. 1,2surface waves ,even and uneven modes accordingly.3,4,-volume waves,even and uneven modes accordingly.An electron beam and plasma have the same cross dimentions.

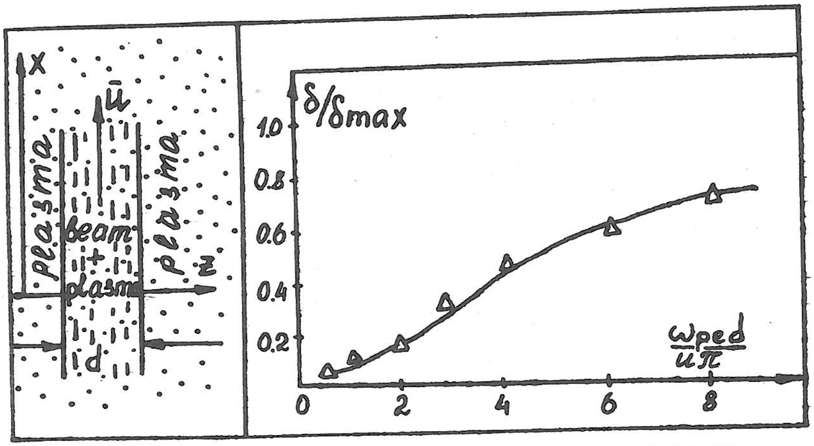

Fig.2.The narrow beam propogates in plasma infinite in cross dimension.Even modes.