THE NEUTRALIZATION BY IONS AND A TYPE OF OSCILLATIONS OF THE ELECTRON BEAM

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The neutralization factor is deduced for a partly compensated electron beam in a longitudinal magnetic field. The neutralization factor depends on macroscopic quantities and can be computed for a given configuration. This is used in the dispersion relation and the frequency of self-excited oscillations of the two-stream instability of rotating nonneutral electron-ion beam is found. This frequency modulates the electron beam current. The existence of such oscillations is proved experimentally and the used experimental technique is described.

1. INTRODUCTION

Instabilities and creation of oscillations in electron beams are related to phenomena much studied in plasmas. Most of the instabilities exist for ideal plasmas with a certain correction for nonneutral plasmas. There exists one instability in longitudinal magnetic field of rotating streams, which is built up only when the neutralization factor is between zero and one. This situation can easily happen in electron beams in high vacua but, to our knowledge, has not yet been studied. In the following we give a simplified theory and confront it with our experimental results.

2. THEORETICAL

Ions in the beam

An electron beam without ions is an unreal object. Even at very low pressures (~10 nPa) ions are formed by impact of electrons on neutral particles of residual gases. (Ionization gauge is used even with ultrahigh vacua.) An interesting question is to what degree the space charge of the electron beam can be partly neutralized as the ions and secondary electrons behave differently. It is easy to prove that in an electron beam of circular cross-section focused by a longitudinal magnetic field, where the primary electrons have a higher concentration \( n_e \) than the originating ions \( n_i \), no ions can escape from the beam in the radial direction, while the secondary electrons (most of them having lower velocities than the beam electrons) envelop the beam, their maximum distance from the original cross-section being

\[
r_{\text{max}} \approx \frac{v_r}{\Omega},
\]

where \( v_r \) is the radial velocity, \( \Omega \) the cyclotron frequency.
Now supposing that the electron space-charge density in the beam is higher than the ion space-charge density, the neutralization factor can be found. Because of the magnetic field the ions can move essentially only in the longitudinal direction, so that the ion current density \( i \) has only one component \( i_z \) (\( z \) being the direction of the axis of the beam and of the magnetic field \( B = B_z \)). For \( i_z \) we get

\[
\frac{di_z}{dz} = eP,
\]

where \( P \) is the number of ions originating by impact in a unit volume per second. As the ions which pass the plane \( z = \) const originated in various distances from this plane and so they have various velocities, the integral positive space-charge density is composed of various parts of infinitesimal currents, so that

\[
\varrho_i = \int_0^z \frac{eP \, d\xi}{V(\xi)} = eP \int_0^z \frac{d\xi}{\sqrt{2 \frac{e}{M} \{V(\xi) - V(z)\}}},
\]

where \( V(\xi) \) is the potential at \( \xi \). \( V(\xi) \) can be easily calculated when the homogeneous beam of radius \( R_b \) is surrounded by a cylindrical electrode of radius \( R_a \) at a potential \( V_a \). Making use of the Gauss theorem we get at the beam axis (\( r = 0 \))

\[
V_0 - V_a = \frac{R_b^2}{4\varepsilon_0} \left( 2 \ln \frac{R_a}{R_b} + 1 \right) (\varrho_i - \varrho_e)
\]

and for our purpose

\[
V_0(\xi) - V_0(z) = \frac{R_b^2}{4\varepsilon_0} \left( 2 \ln \frac{R_a}{R_b} + 1 \right) [\varrho_i(\xi) - \varrho_i(z)].
\]

It seems to be more correct, however, to take the average value of the homogeneous beam potential at \( r = R_b/2 \) which gives

\[
V(\xi) - V(z) = \frac{R_b^2}{4\varepsilon_0} \left( 2 \ln \frac{R_a}{R_b} + 1 \right) \left[ \varrho_i(\xi) - \varrho_i(z) \right] = c(\varrho_i(\xi) - \varrho_i(z))
\]

and the charge density is then expressed by the following integral equation

\[
\varrho_i(z) = \frac{eP}{\sqrt{2 \frac{e}{M} C}} \int_0^z \frac{d\xi}{\varrho_i(\xi) - \varrho_i(z)}.
\]

This equation was used in [1] and its solution leads to

\[
\frac{3meP_z}{2[\varrho_i(0)]^{3/2} [2(e/M) C]^{1/2}} = \left( 1 + \frac{2\varrho_i(z)}{\varrho_i(0)} \right) \left( 1 - \frac{\varrho_i(z)}{\varrho_i(0)} \right)^{1/2}.
\]