AMPLITUDE OF OSCILLATIONS OF THE POTENTIAL OF A QUASINEUTRAL ION BEAM

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The amplitude of the oscillations of the potential of a quasineutral ion beam is calculated approximately as a function of the dc and ac components of the ion-current density, the residual gas pressure, and the accelerating voltage. It is shown that at a limited potential amplitude the total ion-beam current does not depend on its height.

The dynamic decompensation of the space charge of quasineutral ion beams was described in a number of earlier papers [1 - 4]. These papers do not contain, however, an analysis of the relation between the beam potential oscillation amplitude and the depth of modulation of the ion-current density. The present article is devoted to this question.

Let the density j of the ion current in a quasineutral ion beam have an ac component $\Delta j \sin \omega t$. The time of compensation of the additional charge $2\Delta j/v = \xi j/v$ is equal to $\tau_\xi = \xi\tau$, where τ is the total compensation time. At a modulation frequency $\omega > 2\pi/\tau\xi$, the neutralization process is retarded. Therefore the beam introduces into the plasma periodically an excess positive charge, and the plasma potential varies synchronously from the stationary value $\phi_0 \sim T_e \ln\sqrt{M_2/m}$ (T_e is the electron temperature, M_2 and m are the ion and electron masses) to a certain maximum ϕ which is to be calculated.

When the excess positive charge appears, the resultant electric field compresses the electron gas, leaving the plasma quasineutral, and the excess charge is instantaneously "spilled over" into the layers next to the wall.

If the beam moves transversely to a strong magnetic field $\vec{H}$, then the electron gas compresses in practice only in the direction of $\vec{H}$.

Under this assumption, the plasma potential is given by the following approximate algebraic equation:

$$\Delta \rho A \approx 2(d - d_0) j_2/v_2, \tag{1}$$

where A is the height of the ion beam, j_2/v_2 is the space charge of the secondary ions outside the beam near the walls of the vacuum chamber ($en_2 = -j_2/v_2$), $d(\phi) = [(2e/M_3)^{1/2}\phi^{3/2}/9\pi j_2]^{1/2}$ is the thickness of the layer of positive charge near the wall, $j_2 = jn_0(\sigma_i + \sigma_{ce})A/2$ is the density of the secondary-ion current to the wall, σ_i and σ_{ce} are the ionization and charge-exchange cross sections, and n_0 is the concentration of the residual-gas atoms in the vacuum chamber.

Since the velocity of the fast ion increases with increasing plasma potential, we have

$$\Delta\rho = (\xi + \phi/2u - \phi_0/2u) j/v, \tag{2}$$

where u is the potential of the ion source relative to the walls of the vacuum chamber.

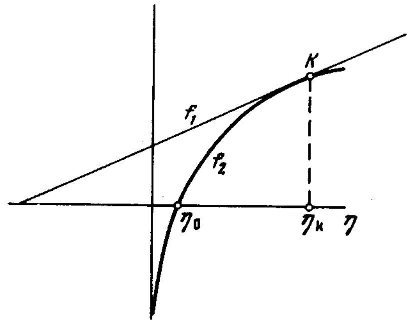
It is convenient to represent (1) in dimensionless form:

$$a(2\xi + \eta - \eta_0) = \eta^{3/4} - \eta_0^{3/4} \ldots, \tag{3}$$

where $\eta = \phi/u$, $\eta_0 = \phi_0/u$ ($\eta_0 \leq \eta \ll 1$),

$$\alpha = \frac{1}{4} \sqrt{i/i_\lambda} \;\cdots, \tag{4}$$

$$i_\lambda = \frac{M_2}{M} \sqrt{2e/M_2}\, u^{5/2} (9\pi A \lambda T_e)^{-1} \cdots \tag{5}$$



M is the mass of the beam ions, and

$$\lambda = [n_0(\sigma_i + \sigma_{ce})]^{-1}. \tag{6}$$

The left-hand side of Eq. (3) represents the perturbation of the positive space charge, and the right-hand side represents the negative charge forced out of the plasma region ($d - d_0$) near the wall.

The plasma potential η is then determined by the point of intersection of the functions $f_1(\eta)$ and $f_2(\eta)$ representing the left- and right-hand sides of Eq. (3), respectively.

At definite critical values of the parameters, $\alpha = \alpha_c$ and $\xi = \xi_c$, the equality $f_1 = f_2$ occurs at the tangency point K, at $\eta = \eta_c$. This case is shown schematically in the figure.

It is easy to show that

$$\alpha_K = 3/4\eta_c^{1/4} \;\cdots, \tag{7}$$

$$6\xi_c/\eta_0 = 3 + \eta_c/\eta_0 - 4(\eta_c/\eta_0)^{1/4}. \tag{8}$$

The critical regime (α_c, ξ_c, η_c) is unstable, since an infinitesimal perturbation of α, ξ, or η produces in the beam a "virtual anode." This instability is analogous to the Pierce electrostatic instability in a quasineutral electron beam. The maximum value $\alpha_c = \alpha_{max}$ occurs at $\eta_c = \eta_0$, while $\xi_c = 0$ and determines the criterion for the intrinsic electrostatic instability, i.e., in the absence of external perturbations

$$\alpha \geq \alpha_{max} = 3/4\eta_0^{1/4}\,.. \tag{9}$$

or

$$i \geq i_0 = 9i_\lambda/\sqrt{\eta_0}\,. \tag{10}$$

A result similar to (10) was obtained earlier by Popov [5]. In most practical problems the beam potential is limited so that $\eta < \eta_c < 20\eta_0$. At the same time, the depth of modulation of real ion beams is quite high, so that $\xi_c \ll \xi \lesssim 10^2\eta_0$. Real values of the parameter α are therefore low, $\alpha \ll \alpha_c$.

Taking the foregoing into account, we can approximate $f_2(\eta)$ with satisfactory accuracy by the expression

$$f_2(\eta) \approx \eta_g^{-1/4}(\eta - \eta_0) \;\cdots, \tag{11}$$

where η_g is the maximum permissible value of the potential ($\leq 20\eta_0$). In this approximation we obtain in place of (3)

$$a \approx \eta_g^{-1/4}(\eta/\eta_o - 1)(2\xi/\eta_o + \eta/\eta_o - 1)^{-1} \ldots \quad (12)$$

In the case when $\eta/\eta_0 >> 1$ and $\xi/\eta_g >> 1$ we have

$$a \approx \eta_g^{-1/4}\eta(2\xi)^{-1} \ldots\ldots \quad (13)$$

or, using (4) and (10), we obtain

$$j/j_o \approx 4\sqrt{\eta_o/\eta_g}\,\eta^2(3\xi)^{-2}. \quad (14)$$

Equation (14) yields the sought approximate dependence of the beam potential η on the modulation depth ξ and on the ion current density j(ξ, η).

For example, for $\eta = \eta_g = 10\eta_0$, $\eta_0 = 3 \times 10^{-4}$, $\xi = 6 \times 10^{-2}$, $u = 3 \times 10^4$ V, $T_e = 2$ V, A = 20 cm, $\lambda = 10^3$ cm, $M_2 = 28$, and M = 56 we obtain $j_0 = 10$ A/cm^2, j = 3.5 mA/cm^2, and the total ion current per centimeter of width is I = jA = 70 mA/cm. These figures are in satisfactory agreement with the characteristics of ion beams in electromagnetic isotope separators [2 - 4].

It is useful to note that under the natural limitation $\eta \leq \eta_g$ = const we obtain from (14) the condition

$$jA\lambda\xi^2 u^{-5/2} = \text{const}. \quad (15)$$

Consequently, at a given potential η_g, the total current does not depend on the height of the beam, and the permissible current density increases with decreasing height. This may be the reason why it was impossible to increase the productivity of electromagnetic separation installation by increasing the beam height.

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EFFECT OF SCREENING ON THE CRITICAL CHARGE OF A NUCLEUS

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The critical charge Z_c was calculated for a "bare" nucleus, i.e., without allowance for the screening of the Coulomb field $V(r) = -Z\alpha/r$ by the electron shell. The screening weakens the attraction of the electron to the nucleus:

$$V(r) = -\frac{Z\alpha}{r}\chi(r), \quad 0 < \chi(r) < 1, \quad (1)$$

and Z_c increases correspondingly. Here χ(0) = 1 and (for a neutral atom)