

ION-BEAM SOURCE, BASED ON STABILIZED IN PLASMA VOLUME ELECTRIC DOUBLE LAYER

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High-current ion beams with energies of a few ten kiloelectronvolts are of great importance for using in modern technologies. Among variety of existing or being developed gas-discharge ion sources the ion sources based on a plasma-beam discharge are of special interest [1]. One of the methods for charged particle beam formation in the beam-plasma discharge, which has been realized, for example, in a straight beam-plasma discharge, is to accelerate charged particles in a plasma volume. In such systems formation of strong double electric layers took place [2]. Practically all potential drop applied to the discharge was concentrated in the double layer. Formation and acceleration of contrary ion and electron flows occurred in the electric field of the double layer.

However, in refs. [1–2] the formation of double layers moving along the discharge gap was observed. This fact makes difficult to use the double layer as an accelerating system in ion sources based on a straight beam-plasma discharge.

In this paper we present the results of theoretical investigations of dynamics of high-current ion beam formation in the electric field of the double layer stabilised by spatial reversal of magnetic field in the volume of a pulsed straight discharge at low pressures.

We consider the processes accompanying the formation of a double electric layer and the generation of charged particle beams in a magnetized plasma placed in an external electric field. The system is axially symmetrical. The magnetic field configuration is chosen such that reversal of the magnetic field direction occurs at the middle of the system length. The magnetic barrier exhibits an anomalous resistance to the current of magnetized electrons.

From current continuity follows connection of electric fields in plasma out of reversal E_p and in plasma in reversal E_i $E_p = E_i \sigma_i / \sigma_p$. Here σ_i , σ_p are plasma conductivities. Then potential $\Delta\phi$ is distributed as follows $\Delta\phi = \Delta\phi_i [1 + (L - l_i) \sigma_i / \sigma_p l_i]$. Here $\Delta\phi_i$ is the potential, distributed in inverse region; L is the system length, l_i is the length of inverse.

Taking into account that $\sigma_i = v_{ei} \omega_{pi}^2 / 4\pi\omega_{ce}^2$, $\sigma_p = \omega_p^2 / 4\pi v_{ei}$, where v_{ei} is an electron collision frequency; ω_{ce} is electron cyclotron frequency, ω_{pi} , ω_p are electron plasma frequencies in inverse and out it. Because $v_{ei} \ll \omega_{ce}$, then $E_p \ll E_i$ and all potential is distributed in inverse region

$$\Delta\phi = \Delta\phi_i [1 + [(L - l_i) / l_i] (v_{ei} / \omega_{ce})^2 (n_i / n_o)] \approx \Delta\phi_i$$

To describe the spatial distribution of electrostatic potential in the system, we use Poisson's equation $\phi'' = 4\pi e (n_e - n_i)$, where $\phi'' = \partial^2 \phi / \partial z^2$.

Integrating it we obtain

$$(\phi')^2 = 8\pi e \int d\phi (n_e - n_i). \quad (1)$$

First, let us consider the case when in the cathode region, i.e., between the cathode and magnetic field reversal, and in the reversal region ($z \leq z_0 - \Delta z_r / 2$, where z_0 , Δz_r are the longitudinal coordinate and the width of reversal region, respectively) the plasma density is negligibly low. Hence, the spatial change of the electrostatic potential profile near the reversal in the cathode region occurs smoothly and, therefore, the electrostatic potential distribution in this region has the following approximate dependence

$$\phi \approx \frac{z\phi_{ra}}{\Delta z_c - \Delta z_r}. \text{ Here } \Delta z_c \text{ is the distance between}$$

the cathode and reversal, ϕ_{ra} is the potential at the anode end of reversal, Z is the longitudinal coordinate. Conversely, in the anode region near the reversal ($z \geq z_0 + \Delta z_r / 2$), the spatial change of the electrostatic potential occurs sharply. Therefore, from the continuity condition of electric field

$$\phi' \Big|_{z=z_0 + \frac{\Delta z_r}{2} - 0} = \phi' \Big|_{z=z_0 + \frac{\Delta z_r}{2} + 0} \text{ one can obtain}$$

$$\phi_{ra} \approx \Delta\phi.$$

We use the following expressions for spatial distributions of electron and ion densities of the anode plasma:

$$\begin{aligned} n_e &= n_a \exp[e(\phi - \Delta\phi) / T_a], \\ n_i &= n_a / \sqrt{1 + 2e(\Delta\phi - \phi) / T_a}, \end{aligned} \quad (2)$$

where n_a and T_a are the density and temperature of the anode plasma, respectively.

From (1) and (2) we get the expression for the spatial electric field distribution:

$$\begin{aligned} (\phi')^2 / 8\pi n_a T_a &= \{ \exp[e(\phi - \Delta\phi) / T_a] + \\ &+ [1 + 2e(\Delta\phi - \phi) / T_a]^{1/2} - 2 \}. \end{aligned} \quad (3)$$

From the continuity of electric field at the anode end of reversal, i.e., with $z = z_0 + \Delta z_r/2$ or with $\varphi = \varphi_{ra}$, we obtain

$$\varphi_{ra} \approx \Delta\varphi \left[1 - \left(3T_a/2e\Delta\varphi \right)^{1/3} \left(r_{da}/(\Delta z_c + \Delta z_r) \right)^{2/3} \right]. \quad (4)$$

From (4) one can obtain $\varphi_{ra} \approx \Delta\varphi$.

The motion of anode plasma ions toward the cathode essentially changes the spatial potential distribution in the cathode region. Because the reversal ensures a large resistance to electric current, the potential drop partially occurs in the reversal region, and the absence of any considerable secondary electron emission provides the formation of the precathode layer of potential drop. At the stage of existence of the precathode potential jump the plasma density near the cathode increases.

We find the potential distribution using the following expressions for electron and ion densities in the precathode region

$$\begin{aligned} n_e &= n_c \exp \left[e(\varphi - \varphi_c)/T_c \right] + \\ &+ (j_e/e)(m_e/(T_c + 2e\varphi))^{1/2}, \quad (5) \\ n_i &= (j_e/e)[m_i/(T_c + 2e(\varphi_c - \varphi))]^{1/2}, \end{aligned}$$

where T_c , φ_c , n_c are the temperature, potential and density of plasma in the cathode region, respectively, j_e is the electron current density from the cathode, j_i is the ion current density from the plasma toward the cathode. Introducing (5) in (1) if $j_e \ll j_i \sqrt{m_i/m_e}$ and $e\varphi_c \gg T_c$, one can find that the field intensity in the precathode layer $|\varphi'_c|$ is determined, in the main, by ions and equals approximately $(\varphi'_c)^2 \approx 8\pi j_i (2m_i\varphi_c/e)^{1/2}$. When the emission current density satisfies the condition $j_i \geq j_e \sqrt{m_e/m_i}$, the field intensity in the precathode layer can be written as

$$\begin{aligned} (\varphi'_c)^2 &\approx \\ &\approx 8\pi j_i (2m_i\varphi_c/e)^{1/2} \left[1 - (j_e/j_i)(m_e/m_i)^{1/2} \right]. \quad (6) \end{aligned}$$

To describe the electrostatic potential distribution in the vicinity of magnetic field reversal, we use (2) and the following expression for electron density in the cathode region $n_e = n_c \exp[e(\varphi - \varphi_c)/T_c]$. The ion density in the cathode region, which includes the plasma ions of the cathode region of maximum density n_{ci} and the ion beam accelerated from the anode plasma and neutralized by the plasma electrons of the cathode region, can be written as

$$\begin{aligned} n_i &= n_{ci} \exp \left[e(\varphi_c - \varphi)/T_c \right] + \\ &+ n_a / \left\{ 1 + \left[2e(\Delta\varphi - \varphi)/T_a \right] \right\}^{1/2}. \quad (7) \end{aligned}$$

Using (1), (2), (7), from field continuity condition in the reversal vicinity, i.e., in $z = z_0 \pm \Delta z_r/2$, and from approximate constancy of electric field $E_{reversal} = (\varphi_{ra} - \varphi_{rc})/\Delta z_r$ in the reversal region we get that, with $n_a \gg n_c$ and $(e\Delta\varphi/T_a)(r_{da}/\Delta z_r) \leq 1$, the potential change in the plasma of the anode region $\Delta\varphi - \varphi_{ra}$ is in the order of T_a and $\Delta\varphi - \varphi_{ra} \ll \Delta\varphi$, where r_{da} is the Debye radius of plasma electrons in the anode region. The potential change in the plasma of the cathode region is $\varphi_{rc} - \varphi_c \ll \Delta\varphi$. In other words, the potential $\Delta\varphi - \varphi_c$ is distributed over the interval of magnetic field reversal. Here, φ_{ra} and φ_{rc} are the potentials at the anode and cathode ends of the reversal, respectively.

It is necessary to note that, at a low plasma density in the cathode region, the conditions for ion beam formation in the reversal region are non-optimum since a value of potential jump in the anode region in the reversal region ($z_0 < z < z_0 + \Delta z_r/2$) is small and since the density of electrons in the cathode part, that neutralize the space charge of the ion beam, is low.

As the plasma density increases up to $n_c \gg n_a$, the potential distribution in the system changes. Namely, the ion space charge layer near the cathode disappears and, since the magnetic field reversal produces a large resistance to electron current, practically all the potential difference applied to the electrodes is concentrated in the vicinity of the reversal as a double electric layer.

As, now, the electric field intensity $|E_{reversal}| \approx \Delta\varphi/\Delta z_r$ and the potential drop in the vicinity of the reversal are maximum and the plasma density in the cathode region is high, we shall take into consideration the possibility for a portion of high-energy electrons to pass through the reversal. We take into account that there is an electron beam in the anode region and that all the applied potential difference is distributed in the vicinity of magnetic field reversal. By analogy with (6) we find that, with $n_c \gg n_a$ and $\delta n_0 \leq n_a \sqrt{T_a/T_c}$,

$$\begin{aligned} \varphi_{ra} &\approx \Delta\varphi \left[1 - (e\Delta\varphi/2T_a)^3 (r_{da}/\Delta z_r)^4 \right], \\ \varphi_{rc} &\approx \Delta\varphi (2n_a T_c/n_c T_a)^{1/2} (r_{da}/\Delta z_r). \quad (8) \end{aligned}$$

where δn_0 is the density of plasma electrons of the cathode region that penetrate through the reversal.

Hence, at this stage, i.e., with $n_c \gg n_a$, the following optimum conditions are formed to generate the ion beam in the vicinity of magnetic field reversal:

- i. large electric field in the vicinity of reversal;
- ii. high plasma density in the cathode region, this provides space charge neutralization of the ion beam.

We note that the pause τ in ion beam generation is no less than the time of ion beam transit between the magnetic field reversal and the cathode, i.e.: $\tau \geq \Delta z_c (m_i / 2e\Delta\phi)^{1/2}$. This is due to the fact that with disappearance of the pre-cathode potential jump the ion beam begins to be formed by the double layer located in the vicinity of magnetic field reversal.

The electron beam being formed in the field of the double layer tends to increase the plasma density in the anode region.

In this part we show that, if the plasma density of the cathode region exceeds the critical value, this leads to destruction of the double layer.

The electric field of the double layer accelerates plasma electrons of the cathode region toward the magnetic barrier. The magnetic barrier slows them down. Because of the chosen magnetic field configuration the quasi-stationary radial electric field of polarization, which balances the longitudinal field of the double layer, appears in the vicinity of the reversal. With this distribution of the crossed fields, there arises an angular electron drift with the velocity $v_\theta = c \cdot (E_z H_r - E_r H_z) / H^2$ and current $j_\theta = env_\theta$.

As soon as the magnetic field nonuniformity is suppressed so $\delta H \approx (2\pi/c) \int dz dr 2r j_\theta / (z^2 + r^2)^{3/2}$ that $\delta H \approx H_0$, the electrons of the cathode region plasma penetrate into the barrier along the cylindrical periphery region at a distance $R_{ce} = c^2 (m_e / e) (E_z / H_r^2)$ from the centre of the magnetic barrier. In this case the electrons get on the magnetic field line taking them away to the anode region. This occurs when $n_{ce} \geq H_0^2 / 4\pi e \Delta\phi$.

It is necessary to note that this consideration is holds true if the R_{ce} is less than the width of the reversal region Δz_r , namely, $\Delta z_r \geq c / \omega_{pc}$, where ω_{pc} is the Langmuir frequency of plasma electrons in the cathode region.

The electron propagation through the barrier can be provided also by instability of electron azimuth flow with V_θ relative to ions. Due to this instability the field E_θ is generated. In this case the force F appears $F = -v_{eff} V_\theta m_e$. Here v_{eff} is effective frequency of electron collisions. Due to it the electrons propagate through barrier with $V_{zo} \approx v_{eff} |V_\theta| m_e c / e H_r$ or $V_{zo} \approx c |E_\theta / H_r|$. The passage of an intense electron flow through the magnetic field reversal short-circuits the external power source and causes the destruction of the double electric layer.

So a conclusion can be made that the high-voltage discharge with the electric field distanced from electrodes is a simple and effective ion beam source. The present results indicate that the magnetic barrier effectively provides spatial and temporal stabilization of the double layer and allows one to control the place of appearance of the double layer and its lifetime. A strong double layer is formed in the vicinity of magnetic field reversal.

The optimum conditions for ion beam generation are created when the plasma of high density has been formed in the cathode region. The ion beam energy is determined by the potential jump in the double layer. The ion beam current density corresponds to Bohm's current density of the plasma in the anode part.

The pause in ion beam generation is due to the transition of the potential jump from the pre-cathode region to plasma volume, namely, to the vicinity of magnetic field reversal, with an increasing plasma density in the system.

The electron current through the magnetic barrier is effected by self-consistent penetration of electrons deep into the inhomogeneous magnetic field along the cylindrical surface. In this case, under the action of external electric and inhomogeneous magnetic fields, the electrons create the configuration of crossed fields, that provides a self-consistent suppression of the magnetic barrier owing to induction of azimuth current. At large times, when the plasma with the density higher than the critical one is formed in the system, the magnetic barrier is suppressed and the double layer is destroyed.

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