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Analysis of Drifting Electron Concentration in a Self-Magnetically Insulated Ion Diode

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Abstract—The drifting electron concentration in a self-magnetically insulated ion diode is analyzed using a TEMP-4M accelerator operating in a double bipolar pulse regime with the first pulse (300–600 ns and 150–200 kV) being negative and the second (120 ns and 250–300 kV) being positive. The electron concentration in the drift region is shown to be 10^{13}–10^{14} cm^{-3}. It is established that the Lorentz force acting on electrons in crossed electric and magnetic fields is 150–200 times greater than the Coulomb repulsion force, which ensures a higher electron concentration in the drift region as compared with the space charge region.

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High-efficiency generation of high-power ion beams (HPIBs) in magnetically insulated diodes is ensured mainly by suppression of the electron component of the bipolar flow in the anode–cathode (A–C) gap. In a self-magnetically insulated ion diode, the cathode is connected to a chamber casing only at one end (cantilever). During HPIB generation, electrons are emitted from the cathode surface and, when moving from the fixing point to the emission point, form a self-insulation magnetic field with the magnetic induction vector in the A–C gap perpendicular to the electric field strength vector. Under the action of the Lorentz force in these crossed electric and magnetic fields, electrons change the direction of their motion from transverse (from the cathode to the anode) to longitudinal (along the cathode to the diode free end).

The electron concentration in the drift region of the magnetically insulated ion diode, which determines its operation regime, remains understudied. At the high electron concentration in the drift region, electrons can form a virtual cathode and ions are accelerated in the effective A–C gap betwen the plasma layer and virtual cathode [1]. At a small drift region thickness, drifting electrons form a self-insulation magnetic field in the effective A–C gap and, thus, enhance the magnetic field uniformity along the diode [2]. In the ion diode with external magnetic insulation with two coaxial cylindrical cathodes (barrel diode), the mean drifting electron concentration is estimated as 6×10^{11} cm^{-3} [3]. The ion current density (70% H^+) was 100 A/cm^2 at an accelerated proton energy of 350 keV. However, in this case, the proton concentration is $\approx 10^{12}$ cm^{-3}, which is higher than the electron concentration in the virtual extracting cathode. Similar electron transport conditions are implemented upon electron beam pinching. At an accelerating voltage of 1 MV and an initial electron beam density of ~100 kA, the beam is compressed to a density of over 1 MA/cm^2 [4]. In the rod-pinch diode at an accelerating voltage of 1–2 MV, a total current of 30–70 kA, and a pulse length of 70 ns (Gamble II accelerator), the electron current density near the conic anode exceeds 10^6 A/cm^2. At an electron energy of more than 1 MeV, the electron velocity is close to the speed of light. Then, the electron concentration in the pinching region is 2×10^{14} cm^{-3}. The authors of study [6] reported an electron beam density of 2.5×10^6 A/cm^2 at an accelerating voltage of 1.8 MV, a total current in the pinch diode of 35 kA, and a pulse length of 80 ns at the rod anode top, which corresponds to an electron concentration of 5.2×10^{14} cm^{-3}.

This article presents data on the electron concentration in the drift region of the self-magnetically insulated ion diode. The investigations were carried out on a TEMP-4M accelerator [7] operating in a double bipolar pulse regime. The first, plasma-forming, pulse was negative (300–600 ns, 150–200 kV) and the second, generating, pulse (120 ns, 250–300 kV) was positive. The total current in the diode was 50–60 kA. The diagnostic equipment of the TEMP-4M accelerator and the calibration data have been described in detail in our previous studies [8, 9].

If the total diode current is equal to the drifting electron current (the ion current is small and electrons do not leave the drift region), the drifting electron concentration can be calculated as

$$n_{dr}(t) = \frac{I(t)}{S_{dr} e v_{dr}(t)} = \frac{I(t)}{eh\Delta(t) v_{dr}(t)},$$

where S_{dr} is the drift region cross section ($S_{dr} = h\Delta$), h is the diode width, and Δ is the drift region thickness.

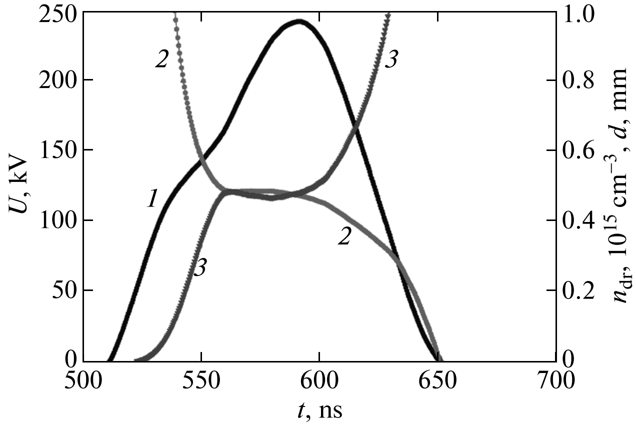

Fig. 1. (*1*) Accelerating voltage oscillogram (second pulse), (*2*) variation in the electron drift motion trochoid height, and (*3*) electron concentration in the drift region.

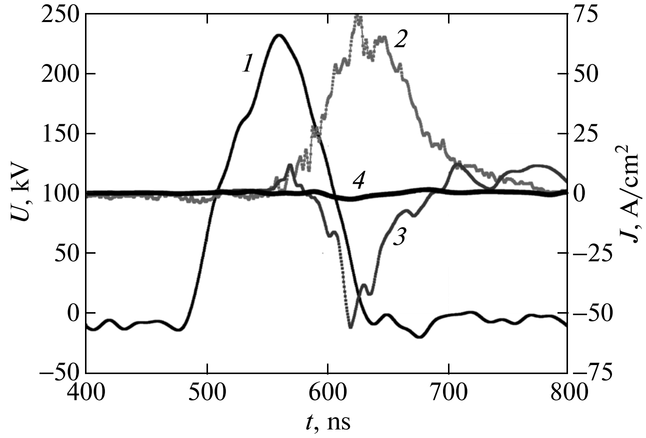

Fig. 2. (*1*) Accelerating voltage oscillogram (second pulse) and variation in the density of (*2*) ion and (*3*) compensated HPIB current. (*4*) Density of the current measured by the Faraday cylinder without cutoff of electrons covered by a 10-μm-thick Al foil.

In calculation of the electron drift velocity in the diode with the explosive emission cathode during ion beam generation in the double pulse mode, it is necessary to take into account the reduction of the A–C gap due to plasma extension and the effect of plasma compression at the accelerating voltage polarity reversal [10]. The electron drift velocity in the crossed electric and magnetic fields is [11]

$$v_{dr}(t) = \frac{E}{B} = \frac{U(t)}{d(t)B(t)} = \frac{U(t)}{[d_0 - v(t-t_0)]B(t)},$$

where E is the electric field strength, d_0 is the A–C gap, B is the magnetic induction, t_0 is the first pulse length ($t_0 = 520$ ns in Fig. 1), and v is the plasma extension velocity.

The electron drift layer thickness corresponds to the electron drift motion trochoid height and amounts to two Larmor electron radii [11],

$$\Delta(t) = \frac{2m_eE}{eB^2} = \frac{2m_eU(t)}{e[d_0 - v(t-t_0)]B(t)^2}.$$

Figure 1 shows the variation in the electron drift motion trochoid height and in the mean electron concentration in the drift region during electron beam generation. The magnetic induction distribution in the A–C gap was calculated using an ELCUT program [12] with regard to the magnetic field damping by the anode material.

In addition, the drifting electron layer thickness can be determined with the use of the formula [4]

$$\Delta = d\left(\frac{B_{cr}}{B}\right)^2.$$

In the self-magnetically insulated ion diode, the magnetic induction in the A–C gap exceeds critical magnetic induction B_{cr} by a factor of 3.5–4 for over 90% of the ion beam generation time [10]. Thus, at an A–C gap of 8 mm, the electron drift layer thickness is 0.5 mm. In the ion diode with external self-magnetic insulation (300 kV, 40 kA, and 80 ns), the electron drift region thickness is 0.5–0.7 mm at an A–C gap of 8 mm [3]. At a trochoid height of less than 0.5 mm and an A–C gap of 8 mm, the kinetic energy of electrons is no more than 16 keV.

The electron drift motion trochoid height was calculated under the assumption of field constancy, i.e., with disregard of the variation in the accelerating voltage and total diode current for the trochoid period. At a magnetic induction of 1 T, the trochoid period is 3.6×10^{-11} s. In our experiments, the ratios between the variation rate and value of the accelerating voltage and between the variation rate and value of the total diode current are no more than 3×10^7 s^{-1}. This ensures variation in the electric field strength and magnetic induction for the trochoid period by no more than 0.1%. Therefore, the electric and magnetic field variations in the calculation of the trochoid height create no significant error.

The obtained electron concentrations in the drift region are the upper limit, since they do not take into account the loss of electrons during the drift along the diode and the ion contribution to the total diode current. In the self-magnetically insulated ion diode, electrons are accelerated between the explosive emission plasma layer at the anode surface and the drifting electron layer at the cathode surface. At an ion current density of 40–80 A/cm^2 and an accelerating voltage of 250 kV, the concentration of singly ionized carbon ions is (1.3–2.5) $\times 10^{12}$ cm^{-3}. These ions pass through the dense layer of low-energy drifting electrons, which effectively neutralizes the HPIBs. We measured the HPIB charge neutralization with the use of the Faraday cylinder without cutoff of electrons. The cylinder was made from an SR50-812FV connector; the collec-

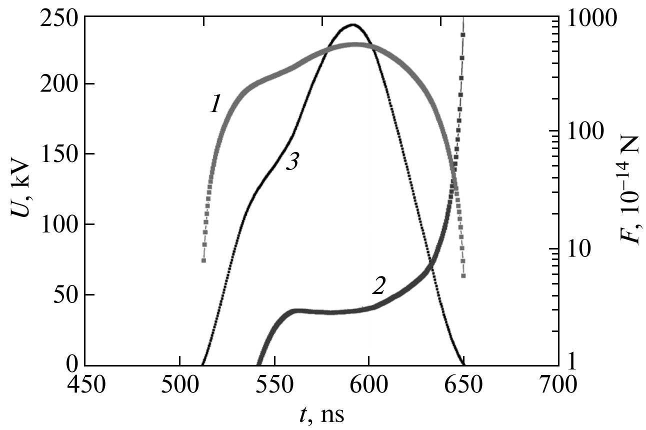

Fig. 3. Variation in the (*1*) Lorenz, Ampére, and (*2*) Coulomb forces acting on electrons in the drift region during ion beam generation. (*3*) Accelerating voltage (second pulse).

tor diameter was 8 mm and the diameter of a collimating hole in a cover was 4 mm. The ion current density was measured using the collimated Faraday cylinder with magnetic cutoff of electrons ($B = 0.4$ T). Oscillograms of the signals from the Faraday cylinders are shown in Fig. 2.

Our investigations showed that, in the self-magnetically insulated stripe diode, the electron concentration exceeds the ion concentration by a factor of 2–2.5 (at equal concentrations, the resulting current detected by the Faraday cylinder without cutoff of electrons is zero). The concentration of low-energy electrons that neutralize the positive charge of beam ions is then $(2.5–6) \times 10^{12}$ cm^{-3}. Since these electrons left the drift region but the magnetic self-insulation of electrons remained along the entire diode length, the drifting electron concentration should exceed 10^{13} cm^{-3}.

The high concentration of electrons in the drift region is caused by the fact that the Coulomb repulsion force is much weaker than the Lorenz force, which ensures the electron motion along the trochoid. The Coulomb force at repulsion of two electrons is

$$F_K = \frac{9 \times 10^9 e^2}{r^2} = \frac{9 \times 10^9 e^2}{n_{dr}^{2/3}},$$

where e is the elementary charge and r is the distance between electrons ($r \approx (n_{dr})^{1/3}$).

The Lorenz force is

$$F_m = e v_{dr} B.$$

The electron in the electric field is affected by the Ampére force,

$$F_A = eE = \frac{eU}{d} = e v_{dr} B = F_m.$$

Figure 3 shows the change in the forces that act on drifting electrons during ion beam generation. The mean Coulomb force was calculated within the pair interaction model and is related to the electrons located at the outer boundary of the drift region. In the bulk of the drift region, the electron concentration is high and the Coulomb interaction with the bulk charge of all the other electrons significantly reduces the repulsion force due to the mutual compensation. Instantaneous values of the Ampére and Lorenz forces averaged over the trochoid period are shown in Fig. 3.

Our analysis showed that, in the self-magnetically insulated diode, the force acting on electrons in the crossed electric and magnetic fields is 150–200 times greater the Coulomb repulsion force, which ensures a high (over 10^{13} cm^{-3}) electron concentration in the drift region.

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