The effect of ion current density amplification in a diode with passive anode in magnetic self-isolation mode

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The results of a study on gigawatt power pulsed ion beam parameters are presented here. The pulsed ion beam is formed by a diode with an explosive-emission potential electrode, in magnetic self-isolation mode [A. I. Pushkarev, J. I. Isakova, M. S. Saltimakov *et al.*, Phys. Plasmas **17**, 013104 (2010)]. The ion current density is 20–40 A/cm^2, the energy of the ions is 200–250 keV, and the beam composition is of protons and carbon ions. Experiments have been performed on the TEMP-4M accelerator, set in double-pulse formation mode. To measure the beam parameters, we used a time-of-flight diagnosis. It is shown that the carbon ion current density, formed in a planar diode with graphite potential electrode, is five to seven times higher than the values calculated from the Child–Langmuir ratio. A model of ion current density amplification in a diode with magnetic self-isolation is proposed. The motion of electrons in the anode-cathode gap is simulated using the program CST PARTICLE STUDIO. © *2010 American Institute of Physics*. [doi:10.1063/1.3526736]

I. INTRODUCTION

Planar diodes, with explosive-emission cathodes, are widely used for the generation of wide-aperture pulsed ion and electron beams, with a current density of more than 20 A/cm^2. In spite of much progress in the development of powerful ion beam sources, many processes in ion diodes have not been researched enough. In particular, there is a small amount of data on the experimental values of the ion current density in ion diodes with magnetic self-insulation, as compared to values calculated from the Child–Langmuir ratio.

The results of measurements of proton current density formed by an ion diode with coaxial construction in an external magnetic field are given by Dreike *et al.*[1] in 1976. The total diode current is described by the Child–Langmuir ratio for proton current (subject to diode geometry) when changing the accelerating voltage from 120 to 200 kV, with pulse duration of 50 ns and magnetic induction in the anode-cathode gap of 1 T. When the magnetic induction drops to 0.52 T, the total current exceeds the calculated value of ion current by a factor of 2. Good agreement with experimental values of ion current density in the Child–Langmuir limit with a uniform magnetic field in the anode-cathode gap and magnetic induction of $B > 1.5B_{cr}$ was highlighted by Humphries.[2]

The theoretical analysis of ion current density as a function of a uniform transverse magnetic field in a diode with magnetic isolation was given by Werner *et al.*[3] It was shown that at low magnetic induction, the amplification coefficient K (ion current density in relation to calculated ion current density obtained from the Child–Langmuir ratio) is equal to 1.86. This can be explained by a partial compensation of space charge with oncoming electron flow (bipolar flow in the ion diode). As the magnetic induction increases, so does the ion current density and when $B \approx B_{cr}$ the amplification coefficient goes up to 2.5–3. With further increase in magnetic induction, the ion current density tends to reduce and, when $B > 1.5B_{cr}$, it is equal to the calculated ion current density found from the Child–Langmuir ratio for unipolar flow ($K=1$). The authors explain that the current growth occurs when $B \approx B_{cr}$ with an additional compensation of the space charge of ions by magnetized electrons.

The theoretical analysis of the amplification effect of ion current density in a diode with magnetic isolation at the expense of electron motion in Larmor orbits, of length greater than the anode-cathode gap, was given by Bergeron.[4] It was shown that the ion current density can exceed the Child–Langmuir limit by three to six times.

The first attempt at a systematic investigation of explosive-emission plasma dynamics and ion current density value was given by Xin *et al.*[5] They studied a focused ion diode, with accelerating voltage of 250–300 kV, pulse duration of 100 ns, and focusing current density of up to 200 A/cm^2. However, their experimental data do not allow a determination of the ion current density behind the anode mesh before focusing.

Operation of an ion diode with magnetic self-insulation set in double-pulse mode during the first (negative) pulse is analogous to the operation of an electron diode with explosive-emission cathode. Investigations of the voltage-current characteristics of a diode with an explosive-emission cathode during pulsed electron beam generation have been carried out since the 1970s. It has been shown that from when the voltage is applied until a dense surface plasma forms on the cathode, the electron current is limited by the emissive ability of the cathode. Later, after covering the cathode surface with plasma, the electron current of the diode is limited only by the space charge of electrons in the anode-cathode gap.

In 2008–2009, we performed studies on the voltage-current characteristics of a planar diode in pulse electron

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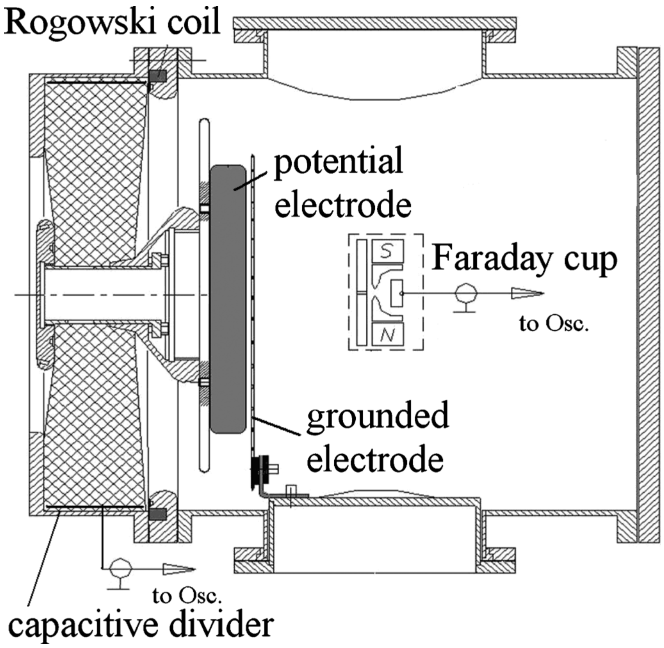

FIG. 1. Diode connection of the TEMP-4M accelerator.

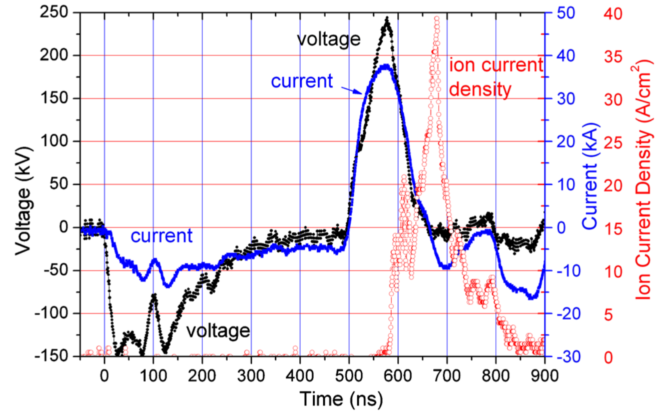

FIG. 2. (Color online) Oscilloscope traces of accelerating voltage, total current, and ion current density of a flat diode with self-isolation.

beam generation with current density of 0.2–0.4 kA/cm^2, electron energy of 350–450 keV, and pulse power of 1–3 GW in agreement with the diode impedance and output resistance of the nanosecond generator.[6] The results of experimental investigations of a diode with explosive-emission cathode made of graphite, carbon fabric, and copper (solid and multiple-point), with multipoint tungsten cathode were analyzed together. It was found that the electron current of the diode is satisfactorily described by the Child–Langmuir ratio, provided the reduction of anode-cathode gap and increase of emission surface area by the expanding plasma are taken into account.

We have carried out research on the operation of an ion diode with potential electrode made of graphite measuring 4×25 cm^2 (plane and focusing geometry) in the magnetic self-insulation mode.[7] The experiments show that the total current of the diode in the first (negative) pulse is well described by the Child–Langmuir ratio for electron current (taking into account the geometry of the diode) at a constant expansion velocity of graphite explosive-emission plasma equal to 1.3 cm/μs. The purpose of the work is to investigate and analyze the ion current density in a planar diode with magnetic self-isolation.

II. EXPERIMENTAL INSTALLATION

Investigations were conducted at the TEMP-4M accelerator[8,9] set in double-pulse mode: the first pulse is negative ($\approx$100 ns, 150–200 kV) and the second is positive (80 ns, 200–250 kV).[10] Beam composition is of ions of carbon (C^+ or C^{2+}+C^{3+}) and protons, ion current density is 20–40 A/cm^2, pulse frequency is 5–10 pulses per minute. Figure 1 shows a block diagram of the diode connection in the TEMP-4M accelerator and the voltage and current measurements.

Figure 2 shows typical waveforms of the potential electrode voltage, total diode current, and ion current density. The anode-cathode gap is 8 mm; the distance to Faraday cup is 17 cm. The experimental setup and diagnostic equipment are described in more detail in our previous paper.[7]

III. BEAM COMPOSITION AND ION CURRENT DENSITY INVESTIGATIONS

To analyze the composition of the ion beam formed by the diode, a time-of-flight diagnostic, based on a single high-speed sensor (Faraday cup with magnetic cutoff) was used.[11] This method allows the beam composition (ion type and degree of ionization), the absolute values of ion current density and the energy spectrum for each type of ion to be determined, with an accuracy of more than $\pm10\%$. It was assumed that different types of ions are formed simultaneously during the accelerating voltage pulse and their drift velocity does not change. The ion beam density, formed by the TEMP-4M accelerator, does not exceed 10^{13} cm^{-2}, so the probability of collision (and velocity change) in the drift space is low.

For each instant of time that the voltage is applied to the diode (time step interval of 0.4 ns), we calculated the current density of certain ion types and the arrival delay of these ions to the Faraday cup. The calculated curves were compared with experimental data. In the space charge limitation mode, in a nonrelativistic approximation, taking into account the plasma emissive surface expansion, the ion current density flowing in the diode is defined by the Child–Langmuir ratio,

$$J_{\text{ion}} = \frac{4K\varepsilon_0\sqrt{2z}}{9\sqrt{m}} \cdot \frac{U^{3/2}}{[d_0 - v(t-t_0)]^2}, \quad (1)$$

where d_0 is the initial anode-cathode gap, ε_0 is the absolute permittivity, v is the plasma expansion rate, m is the ion mass, z is the ion charge, t_0 is the time when the polarity on the potential electrode reverses, and K is an amplification coefficient.

Figure 3 shows a typical oscilloscope trace of the accelerating voltage (second pulse) and ion current density in the planar diode. The anode-cathode gap is 8.5 mm.

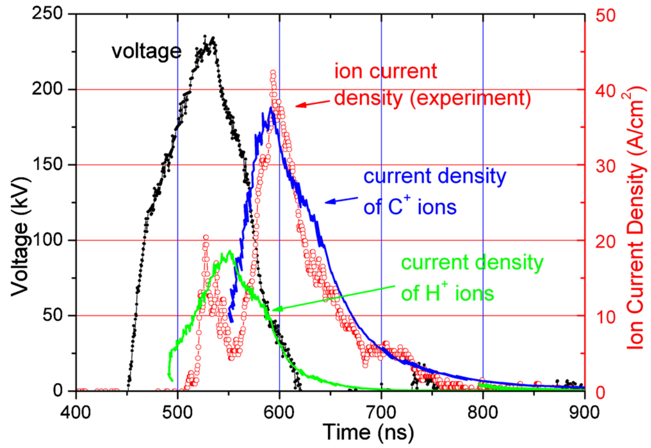

FIG. 3. (Color online) Oscilloscope traces of voltage and ion current density (dots) in the planar diode. The estimated current density of C+ ions, when $K=7$, and the estimated current density of protons, when $K=2$. The distance to the Faraday cup is 11 cm.

As the distance from the diode to the Faraday cup increases, the ion current delay relative to the accelerating voltage increases as well. Figure 4 shows a typical waveform of the accelerating voltage (second pulse) and experimental and calculated curves of ion current density in the planar diode when the distance to the Faraday cup is 17 cm.

In this case, experimental and calculated values of ion current density coincided. The beam composition formed by the planar diode does not change. It confirms that the developed technique works correctly.

IV. CALCULATIONS OF ANODE-CATHODE GAP

A significant increase in the ion current density in the diode with an explosive-emission potential electrode might be associated with a reduction of the anode-cathode gap as the plasma expands. In the space charge limitation mode, the current density of the singly ionized carbon ion C^+ is 0.7% of the electron current density. Optimization of the design of ion diode with magnetic self-isolation and its operating

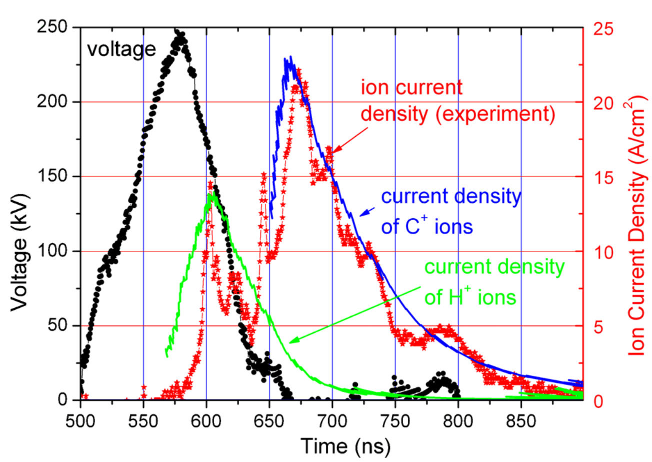

FIG. 4. (Color online) Oscilloscope traces of voltage and ion current density (dots) in the planar diode. The estimated current density of C+ ions, when $K=6$, and the estimated current density of protons, when $K=1.5$. The distance to the Faraday cup is 17 cm.

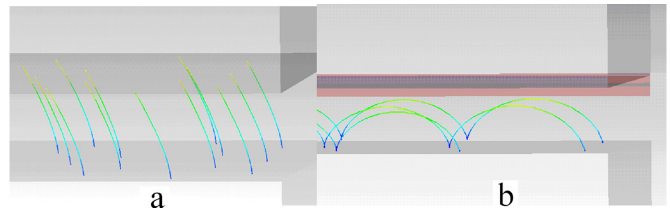

FIG. 5. (Color online) Trajectory of electrons in anode-cathode gap at $U=250$ kV, $I=10$ kA (a) and $I=20$ kA (b).

modes resulted in increased efficiency of ion current generation by a factor of 10–12 times.[7] At the same time, the ionic component of current does not exceed 10% of the total diode current. Therefore, within the measurement accuracy of the voltage-current characteristics, the dynamics of the explosive-emission plasma in the anode-cathode gap can be controlled by the Child–Langmuir ratio for the electron current component.

Analysis of the voltage-current characteristics of the diode with magnetic self-insulation in double-pulse mode shows that after the applied voltage changes polarity (second pulse) the explosive-emission plasma is released in the anode-cathode gap.[7] The size of the anode-cathode gap is restored to its original geometrical value and begins to reduce once more due to the expansion of the plasma layer on the grounded electrode. This effect in the anode-cathode gap at the beginning of the second pulse is taken into account when calculating the change of ion current density in Eq. (1).

In Fig. 5 a model of the motion of electrons in the anode-cathode gap of the ion diode with magnetic self-isolation is illustrated using the program: charged particle simulation, CST PARTICLE STUDIO. As can be observed from Fig. 5, when the current flowing to the grounded electrode reaches 20 kA, it induces a magnetic field which bends the trajectory of the electrons to an angle of more than 90° [see Fig. 5(b)].

As an additional confirmation that the plasma expansion does not affect the ion current amplification can be a weak dependence of amplification coefficient on delay in formation of the second pulse (Fig. 6). Experimental values of the amplification coefficient were obtained using the ratio

$$K = q_{\rm exp}/q_{\rm calc},$$

where $q_{\rm exp}$ is experimental ion charge density, equal to an integral of ion current density (see Fig. 2), and $q_{\rm calc}$ is calculated density of ions, equal to a time integral of Eq. (1), provided $K=1$.

In Fig. 6 the calculated values of the amplification coefficient of ion current density connected only with a reduction of anode-cathode gap are shown. The calculation was performed using the following ratio:

$$K_{\rm calc} = J/J_0, \quad \text{where} \quad J = \frac{4\varepsilon_0\sqrt{2z}}{9\sqrt{m}} \cdot \frac{U^{3/2}}{(d_0 - vt)^2},$$

$$J_0 = \frac{4\varepsilon_0\sqrt{2z}}{9\sqrt{m}} \cdot \frac{U^{3/2}}{(d_0)^2}.$$

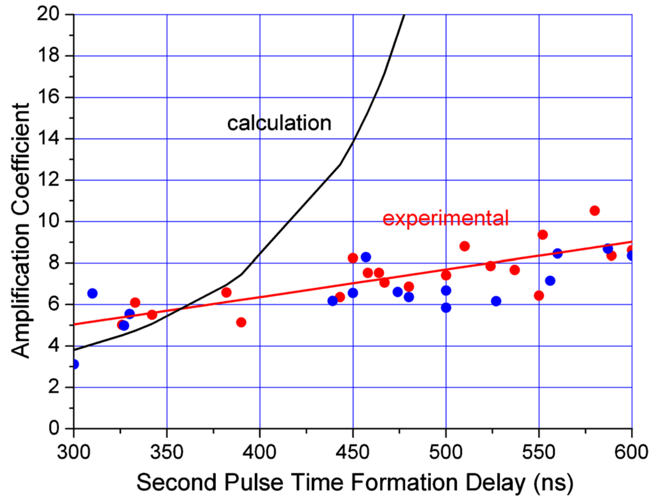

FIG. 6. (Color online) Dependence of amplification coefficient on delay in second pulse formation. The anode-cathode gap is 8 mm.

If the duration of explosive-emission plasma expansion is changed from 300 ns to 500 ns, the anode-cathode gap in the diode will be reduced from 4 to 1.5 mm (if the plasma expansion speed is 1.3 cm/μs, d_0=8 mm). In the space charge limitation mode, the ion current density should increase. It is not observed experimentally.

V. ANALYSIS OF ION CURRENT DENSITY AMPLIFICATION MECHANISM

To generate the magnetic cutoff of electrons in a diode with magnetic self-isolation, the grounded electrode is connected to the diode chamber on one side only (see Fig. 1). Electrons, moving to the electrode (or along the anode-cathode gap), induce a magnetic field. Figure 7 shows the change of magnetic induction in the anode-cathode during generation of the ion beam (calculated from the Biot–Savart law).

The calculation is performed in the middle of the diode at a point located at a distance of 1 mm from the surface of the grounded electrode (where $I=0.5I_{\text{total}}$ in Fig. 2). A calculation of the magnetic induction, based on a factor that takes into account the geometry of the diode, gives similar values.[5] The analysis shows that the electron drift velocity in the second pulse is low (less then 4 mm/ns) (see Fig. 7). Therefore, the drifting electrons make a negligible contribution to the total diode current during the second pulse.

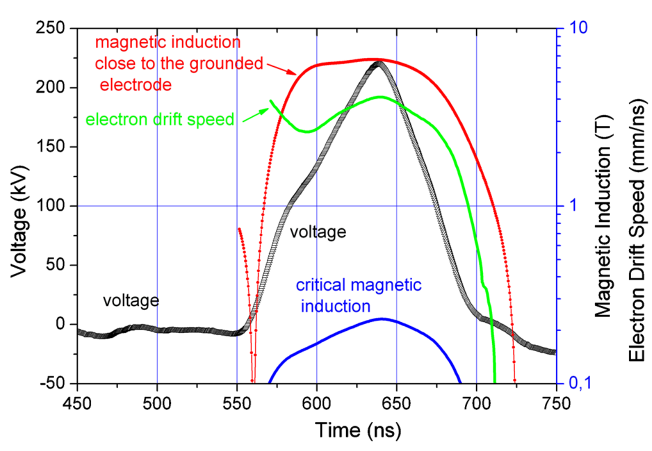

FIG. 7. (Color online) Change of accelerating voltage, critical magnetic induction, induction in anode-cathode gap, and electron drift speed during ion beam generation.

Calculations show that, during the entire pulse of accelerating voltage, the magnetic induction in the anode-cathode gap exceeds the critical value. Therefore, the emitted electrons, from the grounded electrode, drift to the top of the diode (see Fig. 1), providing magnetic isolation. Then, electrons cross to the potential disk of the diode, leaving a specific track. Some of the electrons drift into the anode-cathode gap in the region occupied by the ion space charge, providing its additional compensation and an increase in ion current density. When the amplification coefficient is equal to 6–8, the ion current density is determined by the condition of compensating the ion space charge with a flow of magnetized electrons moving along the potential electrode surface. In crossed electric and magnetic fields, the electrons from the end of the diode drift almost the entire length of the diode, providing a uniform compensation of space charge.

It was found experimentally that the generation of the ion beam occurs uniformly across the entire surface of the potential electrode. The distribution of ion current density through the cross-section was recorded by the impression formed on the surface of a copper plate installed outside the grounded electrode. The amplification of ion current inside the diode by magnetic self-insulation provides a more uniform distribution of the ion current density across the beam section even when the anode-cathode gap is adjusted.

VI. CONCLUSION

The analysis of a pulsed ion diode with a passive anode in double-pulsed mode shows that the influence of magnetic isolation of electrons is significant only during the generation of the ion beam (second pulse). During the initial period, at the stage of forming and developing explosive-emission centers on the potential electrode surface of the diode, the plasma dynamics are similar to processes taking place in the electron diode of a pulsed electron accelerator. After a solid plasma surface forms on the passive anode, the only effect of magnetic insulation is to reduce the rate of expansion of the plasma across the gap. The electron current, which constitutes more than 90% of the diode's total current, is well described by a model of space charge limitation. The electron drift time in crossed electric and magnetic fields during the formation of the plasma on the passive anode does not exceed more than a few nanoseconds. After the polarity of the voltage applied to the potential electrode reverses, a significant suppression of the electronic component of the total diode current takes place. The electron drift velocity reduces to a level below 4 mm/ns and the drift time exceeds the duration of the voltage pulse. As a result, during the second pulse, the diode impedance increases by a factor of 2–4 compared to the calculation (based on the Child–Langmuir ratio). A nonuniform magnetic induction along the diode with magnetic self-insulation provides additional compensation of the ion space charge by magnetized electrons. The compensation factor amounts to 70%–80% and significantly reduces the restriction of ion current density.

An ion diode with magnetic self-insulation is a convenient tool for studying the processes of high-power ion beam generation. The dynamics of explosive-emission plasma can be controlled by the voltage-current characteristics of the diode and by the process of ion generation (by the ion current density). Both independent diagnostics use measurements of the voltage-current characteristics, which provide very high temporal resolution.

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