IOP Conf. Series: Journal of Physics: Conf. Series **1115** (2018) 022005 doi:10.1088/1742-6596/1115/2/022005

Study of plasma formation in a planar type ion diode with self-magnetic isolation

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Abstract. One of the sources of high-power ion beams is an ion diode with isolation by external or self-magnetic field. Due to the simplicity and reliability of the design, this type of diodes is widely used in applied research. The explosive plasma generation on the anode surface under a bipolar voltage pulse is accompanied by a loss of the electron current from the anode-cathode region of the diode. The electron current characteristics depending on the operation mode of diode and the energy supplied are presented. Investigation of the cathode emission surface and distribution of the ion current density at the output of the diode along the anode surface were carried out. The ion current density reaches 15-25 A/cm^2 at the outer edge of the anode, and 5-8 A/cm^2 – in the central region. The area of emission surface of the anode is approximately 25-30% of the total anode area. Electron loss current in the matching mode of diode reaches 6.5 kA.

1. Introduction

The ion diode with isolated anode-cathode (A-C) gap by self or external magnetic field is one of the well-known powerful ion beam (PIB) sources [1, 2]. Given diode type is widely used at applied researches due to the simplicity and durability of construction [3-6]. The efficiency of similar diode systems is not so high in comparison with ion diode with closed electron drift and isolation by external radial magnetic field (B_r – diode) [7, 8]. Ion diodes with a dielectric anode coating and external magnetic field are more efficient [9]. One of the most powerful self-magnetic isolation ion diodes is the ion diode [10] with emitting dielectric anode coating of 238 cm^2. Energy conversion efficiency reaches up to 30% provided by positive voltage pulse 0.9 MeV and value of total current 52 kA, respectively. However, the operation life of present diode is restricted by durability of dielectric coating anode, which is only 40 pulses of ion current.

Graphite is the most suitable material of the anode to carry out the applied research. The construction of self-magnetic isolation ion diodes with graphite anode is similar to [2, 11], nevertheless, their efficiency is slightly lower than the efficiency of similar diodes with dielectric emitting coating. The formation of plasma in these diodes is carried out under the exposure of a voltage prepulse of negative polarity, which additionally complicates the accelerator construction. The use of the graphite electrode as material for anode substantially increases the ion diode operation life.

Taking into account the foregoing, of the present work is to provide research of the self-magnetic isolation ion diode with graphite electrode in order to increase energy conversion efficiency by the optimization of ion diode operating mode. The construction of the self-magnetic isolation ion diodes is typical for most diodes of this type [4, 12]. The electrodes of such diodes, usually, have a plane or focusing geometry to provide ballistic focusing of ion beam. The electrode cross section is square with

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a small fillet radius at the edges. The proportion of A-C gap $d_{A\text{-}C}$ to anode width r for given diodes is as follows: $d_{A\text{-}C}/r<1$. The ion current and voltage to Child-Langmuir’s law [13].

2. Experimental Technique

In the investigated diode, the anode is a graphite focusing electrode of rectangular cross-section with a width of 60 mm, a length of 250 mm and a surface area of 100 cm^2, and a focusing length of 150 mm. The diode cathode is designed in the form of a grid made of stainless steel of 3 mm thickness, width 40 mm and optical transparency 80%. Value of $d_{A\text{-}C}$ in the region of the electron current closing from the cathode to the anode is equal to 8 mm, while the in the opposite side $d_{A\text{-}C}$ value is 9 mm. The ion diode was positioned vertically; the cross section of A-C assembly with diagnostic location is shown in figure 1a. The experiments were carried out using TEMP accelerator [14].

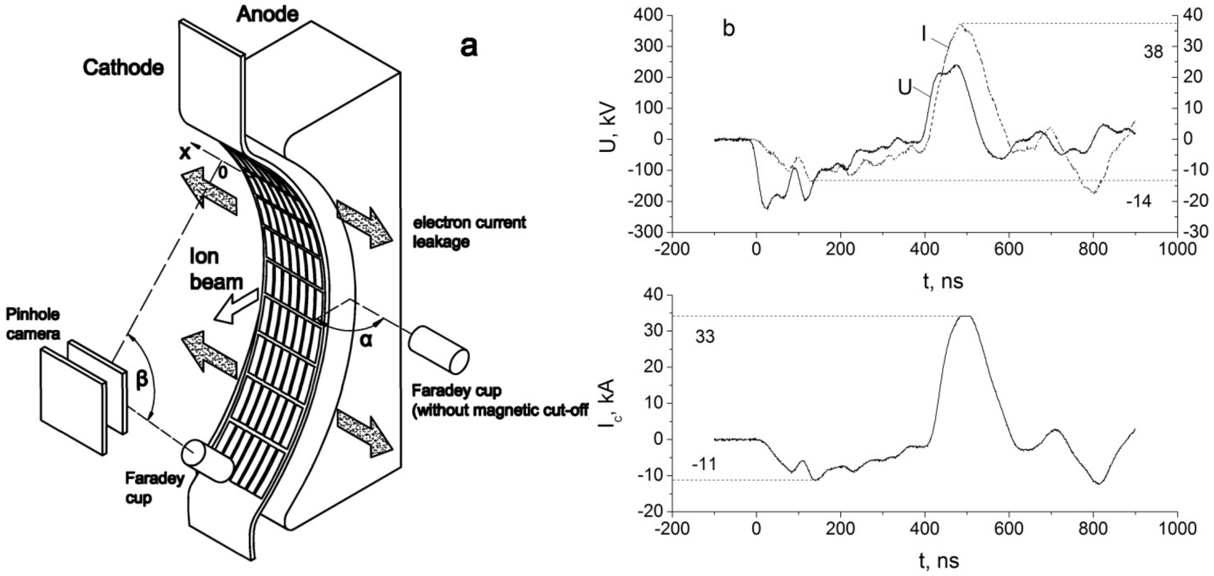

Figure 1. The ion diode with self-magnetic isolation during experiments (a); oscillograms of ion diode (b): U – pulse voltage, I – diode current, I_c – cathode current.

A significant increase in the electric field strength at the anode periphery is typical for planar electron diodes when $d_{A\text{-}C}/r<1$ whose anodes have a sharp edges [15]. As a consequence, the non-uniform electric field leads to inhomogeneous plasma formation along the entire surface of the anode [16, 17]. For given geometry of the ion diode is also typical non-uniform distribution of the electric field strength on the anode surface along the cross section of the A-C region. The modeling of electric field distribution was carried out by Elcut 5.5 software program excluding impact of space charge. At an amplitude of $-2.2\cdot10^5$ V at the anode edges with fillet radiuses $r_к$=1.5 mm, the electric field strength increased up to a value of $4\cdot10^7$ V/m, while in the center at the anode surface, the electric field strength was $1.9\cdot10^7$ V/m. Taking into account the amplification of the electric field at the anode micro points, the actual values of the electric field strength on the anode surface are considerably higher.

3. Results and Discussion

Studies of the anode emitting surface by pinhole camera have shown that the formation of explosive plasma on the anode surface under the influence of a bipolar voltage pulse occurred nonuniformly (figure 2a). The emission centers were located mostly throughout the length of the anode edges areas. The emitting surface amounted approximately 25-30% of total anode area. Ion current density measurements provided at 2 cm from the output region of the diode showed that all anode surface emits ions. However, at the anode periphery the ion current density reached its maximum that amounted 15-25 A/cm^2, and in the central area – 5-8 A/cm^2 (figure 2b). By the use of dielectric as emitting surface, the ion emission from the surface is more homogeneous [10].

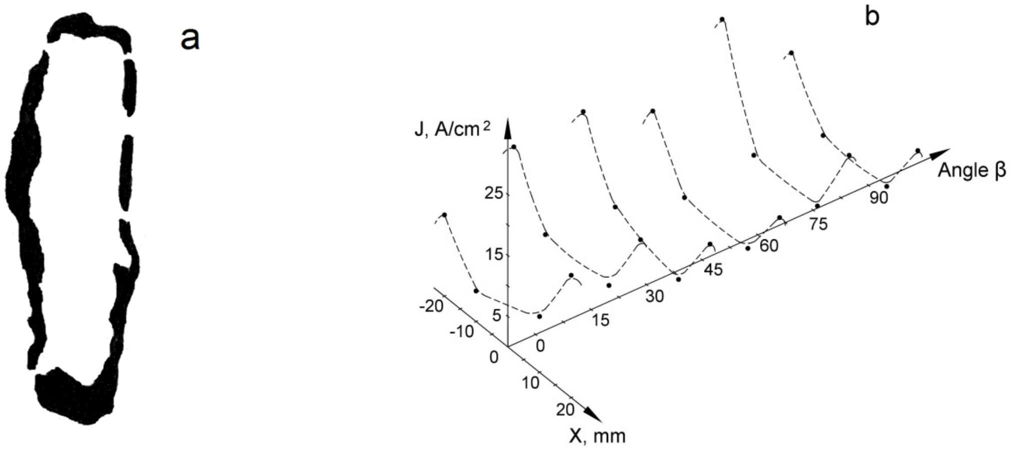

Figure 2. The emitting anode surface picture – single pulse (a), ion beam current density distribution at output space.

During the negative voltage pulse the total diode current flows through the cathode. Measurements of the diode current were made using two Rogowsky coils. The diode current through the cathode I_c was measured with one of them. The second Rogowsky coil's was installed over the potential electrode and measured the total diode current I. The value of the total current of the diode was 14 kA (figure 1b) while the current flowed through the diode cathode was 11 kA. The difference between the values of I and I_c is due to the plasma formation at the diode accompanies by electron flow through border space of A-C gap (figure 3a).

Electron current flowed from both anode sides and essentially contented several pulses from tens to hundreds nanosecond duration. The electron current pulses count, energy and density outside of A-C gap depend on total energy transmitted to the diode, accelerating gap geometry and time delay between voltage pulses. A negative voltage pulse was applied to A-C gap of diode when the prepulse gas spark of accelerator [18] was switched on. During the negative voltage prepulse occurred mismatch impedances between diode and accelerator, that caused by inhomogeneous plasma formation at the anode surface. At a negative voltage pulse of amplitude 220 kV outside of A-C gap was captured several, generally two, pulses of electron current ≤50 A/cm^2 and time delay relatively to the front edge of negative voltage pulse ≤1.7 µs.

During a positive voltage pulse (figure 3a) the energy transmitting to the diode increased and several additional pulses of electron current (pulses J_{e1} and J_{e2}) appeared. At a voltage of 220 kV the electron current density increased to ≤250 A/cm^2, also the energy of electrons is increased too, and time delay relatively to the front edge of positive voltage pulse shortened to ≥0,3 µs (figure 3a).

The time delay duration between voltage pulses was determined by the ratio of gas pressure in the accelerator's dischargers. The minimum value of time delay duration was 400 ns. In increase the time delay up to 550 ns the energy of the ion beam increased too (figure 3b). This was due to the emitting area of anode surface was changed during time delay. In this case the electron flow through border space of A-C gap was increased too.

Research of angular distribution of electron current density at distance 5 cm from anode showed that electron emission provided by external anode edge (figure 4a). At the position when faradays cup face plane is perpendicular to anode plane (α=0°) the electron density of 100 A/cm^2 and 240 A/cm^2 been fixed.

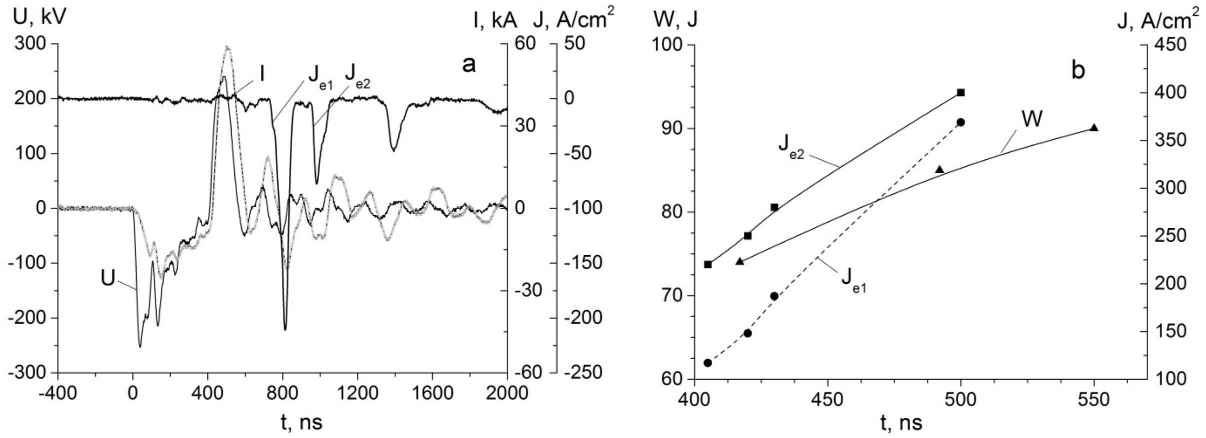

Figure 3. The oscillograms of accelerating voltage U, total current I and electron leakage current J_e outside of A-C gap space (α=0°) (a), the dependence of ion beam energy W and the electron current density J_e from time delay between voltage pulses (b).

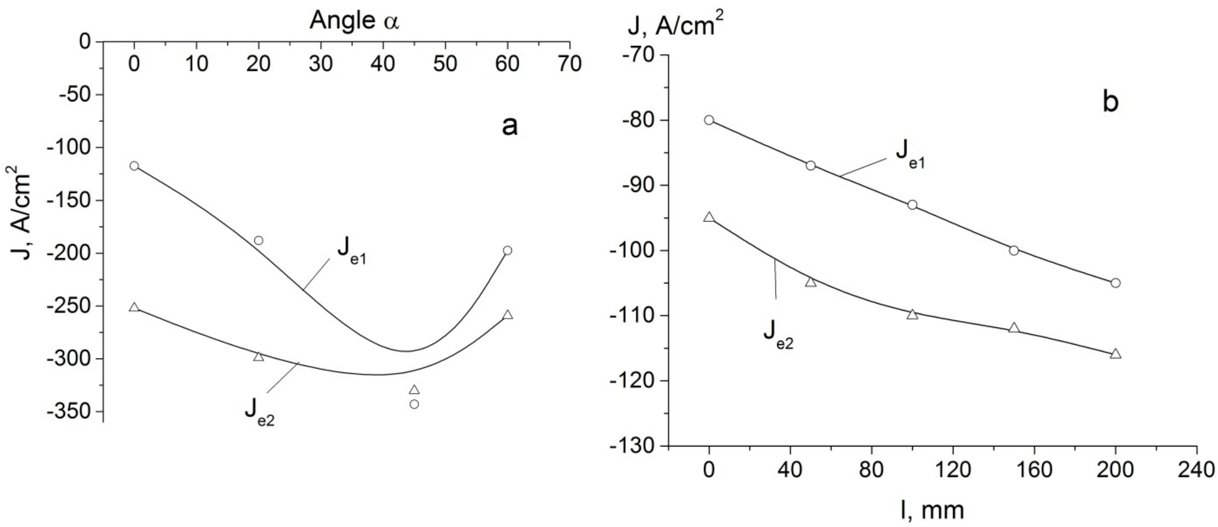

Figure 4. Angle distribution of electron current density (a), distribution of electron current density along anode length (b).

At α=0° the electrons trajectory was codirectional with azimuthal magnetic field power lines therefore electrons did not experience force action. Within α from 0° to 45° the electron current density increased and reached its maximum (figure 4a). With increase of α>45° the electron current density decreased, that caused by magnetization of electrons. The ion current density measurements provided simultaneously with electron current measurements, the faradays cup with magnetic cut-off was used. The ion beam current appeared at α≥75° in anode space area that indicates on angle dissipation of ion beam in A-C gap. Thus, outside of A-C gap the electron flow dissipates and showers on the vacuum chamber inner surface and ion diode parts.

Based on obtained data the leakage electron current outside of A-C gap over two pulses was estimated. The average value of the electron current density (figure 4b) on the first pulse was 100 A/cm^2, on the second pulse – 112 A/cm^2. The area of border space of A-C gap was 40 cm^2 taking into account the electron current flowed on the left and right sides of the anode. As a result the electron current was ~6.5×10^3 A. To evaluate energy of electron flow the copper calorimeter was used. It was placed at the distance 50 mm from lateral area of A-C gap (figure 1). The calorimeter cross-section was round with diameter 26 cm. Energy measurements provided along anode length from both sides, as result the total energy amounted.

4. Conclusion

Thus, the PIB generation by the ion diode with self-magnetic isolation accompanies by electron current leakage beyond the A-C gap. The low efficiency of ion beam generation in such diode systems is due to the non-closed drift motion of electrons in $E \times B_z$ fields. The leakage electron current through border space of A-C gap reduces the value of electrons space charge and it's time of finding in the A-C gap. This also reduces the efficiency of the diode system. The appearance of electron current leakage is due to the inhomogeneous plasma formation during bipolar voltage pulse. Dissipation of electrons leads to decrease the electron component of total diode current in A-C gap. As result, value of self-magnetic field inductance also decreases.

Acknowledgements

This work was supported with the State task science, Ministry of Education and Science of the Russian Federation no. 3.8212.2017/BP.

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