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Gas emission of anode polymer coating and its influence on applied – B_r magnetically insulated ion diode characteristics

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Abstract

The paper presents the result of investigation gas emission from anode polymer coating of applied – B_r magnetically insulated ion diode. The gas pressure value for any polymer type was determined. The investigations of the pressure variation were carried out during the pulse repetition rate of ion beam from 1 to 4 pps. The residual gas pressure value variation inside the vacuum chamber influenced on the ion beam parameters. The mass content of ion beam injected into the transition area did not depend on the residual gas pressure value. The breakdown of residual gas pressure by eddy electric field of magnetic coils was investigated.

Keywords: Ion beam; Plasma source; Gas pressure; Ion beam characteristics

1. INTRODUCTION

High intensity ion beams (HIIB) of light ions (H^+, C^+) have found wide application in a number of applied researches (Remnev *et al*., 2009). The applied – B_r magnetically insulated ion diodes for the generation of such beams, which are usually used. Their efficiency can reach as high as 80% (Greenly *et al*., 1988). A hydrogen-bearing polymer coated on the anode surface was used as a plasma source in applied – B_r ion diode. In the ion diodes, polymers have been employed as a major source material attaching onto the anode for generating HIPIB of light ions, such as proton and carbon ions (Nakagawa *et al*., 1994; Yatsui *et al*., 1995; Yatsuzuka *et al*., 1995; Wood *et al*., 1998), because of its capability of producing dense plasma under high-voltage pulse discharge.

The polymer coating was exposed to bombardment by the electrons emitted from cathode edges. As a result of electron charge accumulation in polymer subsurface layers, electric breakdown occurred. It resulted in dendrites formation on the polymer surface. A strong correlation has been found in the diode experiments between electron loss to the anode and ion beam generation. This correlation and the presence of in-depth dendrites indicate electron bombardment of the polymer material, which plays an important role in plasma formation for anodes with large-scale polymer irregularities (Sweeney *et al*., 1984). Production of discharges along the surface by local, inhomogeneous charging of a polymer surface from electron impact agrees with old models (Jacobs *et al*., 1952) of a field-enhanced secondary electron emission that is similar to the "Townsend avalanche" occurring in a gas discharge. It consequently caused the formation of dendrites. The researches (Johnson *et al*., 1985) showed that in epoxy polymer resin used as anode coating dendrites penetrated into the depth of 90–225 μm. At the ends the dendrites are surrounded with bubbles. It is assumed by the authors that bubbles are filled with gas which is present in the polymer. Such gas bubbles were found at the depth of 90 μm. Also the bubbles could be formed during the process of anode grooves filling with an epoxy polymer resin. However, in this case the bubbles can be found at any depth. As a result of electric breakdown, subsurface polymer layer evaporation leads to gas emission from the polymer surface, actually from dendrites and bubbles. Increase of pressure in the vacuum chamber can lead to dysfunction of ion diode operation. The properties of the anode polymer for ion beam generation degraded under high-voltage pulse discharge (Zhu *et al*., 2007). It changes the surface morphology, leading to a noticeable decrease in the output of ion beam intensity, that is, ion current density and diode voltage, accompanied with an increase in instability of the parameters.

2. EXPERIMENTAL CONFIGURATION

The applied – B_r diode used for these experiments was described (Lopatin *et al*., 2004), and, therefore, we describe it only briefly here. This diode was connected to the high-voltage

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accelerator (Furman *et al*., 2004). The diode schematic diagram is shown in Figure 1.

The operation conditions for the experiments reported here were as follows: 400 kV diode voltage, 10 kA total diode current, and 100 ns pulse duration. This diode was placed in the 0.25 m^3 accelerator vacuum chamber. The vacuum oil–vapor pump for degassing vacuum chamber volume up to $\sim 6 \times 10^{-5}$ Torr was used. The anode of diode had a conic surface with a half angle of 15° to axis. The emission surface had the trapezoidal ring grooves with a depth and width of 1.5 and 3 mm, respectively. During the research work, the ring grooves were filled with different polymer containing hydrogen and carbon. The anode effective area was 90 cm^2. The distance from the external cathode edge to the anode surface was about 6 mm in most experiments. Internal and external cathodes with the corresponding diameters of 170 and 200 mm were made from 0.25 mm-thick white copper. The construction and ion diode parameters are described more detailed (Furman *et al*., 2007; Stepanov & Remnev, 2009).

The pulsed pressure measurements in the vacuum chamber were carried out using ionization manometric converter (PMI-51). PMI-51 was placed on the vacuum chamber wall at the distance of 150 mm to the anode, as shown in Figure 1. The operation principle of PMI-51 is based on residual gas molecules ionization by the flow of electrons emitted from the heated cathode. During the experiments, the current passing though the collector of PMI-51 converter, which changed proportionally to pressure, was measured. To calculate the value of current to pressure, a conversion factor equal to 1, which corresponds to atmospheric air, was chosen. The PMI-51 converter was preliminary calibrated at constant pressure conditions within the range of 5×10^{-5}–2×10^{-3} Torr. The ion beam mass content was determined by using of two collimated Faraday cups with magnetic cut-off of the accompanying electrons. The scheme of the experiment is shown in Figure 1.

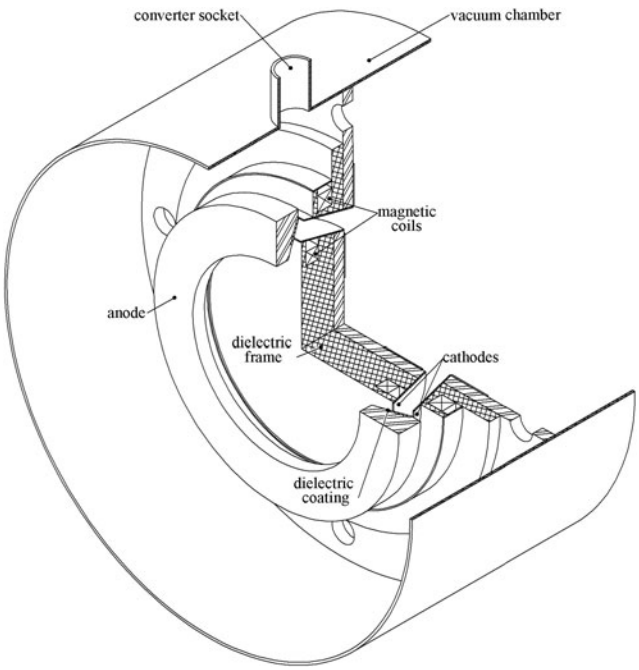

Fig. 1. Schematic view of the applied – B_r magnetically insulated ion diode.

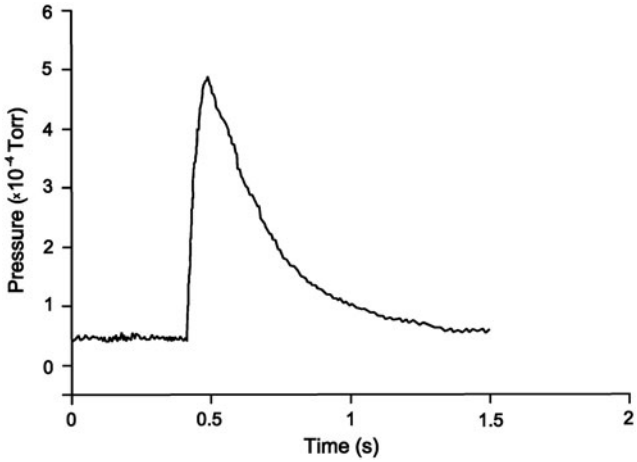

Fig. 2. The pulse of gas pressure inside the vacuum chamber during ion beam current pulse formation. The anode polymer coating – epoxy resin.

3. MEASUREMENTS

Ion beam current pulse formation was followed by the pressure increase (Lopatin *et al*., 2008) in the vacuum chamber in Figure 2. The pressure increased from 1×10^{-4} to $(4–6) \times 10^{-4}$ Torr for 0.2 s. The pressure pulse front time was determined by spread gas source as well as by diffusion time of decomposed vapors from dendrites in the vacuum chamber. Additional source of vapors in the vacuum chamber was dispersion of adsorbed gas from the cathode area surface and the vacuum chamber internal surface during HIIB transition. The experimental results of applied – B_r diode with aluminum anode (without polymer inserts) showed that evaporation of impurities as a result of accelerated electrons bombardment of the diode metal surfaces did not have any significant influence on the pressure pulse amplitude. The primary source of gas emission was probably the anode polymer coating.

The pulsed pressure amplitude inside the vacuum chamber depended on the type of the anode polymer coating (Table 1). For coatings made from polyethylene and epoxy resin, the pulsed pressure amplitude reached the value of 6×10^{-4} Torr. When blue copperas inclusions were added to the epoxy resin in the volume ratio of 1:3, the pulsed pressure magnitude was about 1×10^{-3} Torr, respectively. Addition of fine iron inclusions in the volume ratio of 1:1 did not influence the pulsed gas pressure amplitude. Such addition resulted in the decrease of ion beam energy in direct relation to impurities concentration. The results of the pressure variation are summarized in Table 1.

The investigations of the pressure variation were carried out inside the vacuum chamber during the pulse train

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Table 1. *The pulsed pressure and ion beam energy for different anode polymer*

Anode coating	Pressure (Torr)	Ion beam energy (J)
Epoxy resin	6×10^{-4}	90
Polyethylene	6×10^{-4}	86
Epoxy resin + $CuSO_4\times5H_2O$	5×10^{-4} (the ratio of volumes 1:1)	86
	1×10^{-3} (the ratio of volumes 1:3)	–
Epoxy resin + fine iron	6×10^{-4}	24

under the pulse repetition rate from 1 to 4 pps. The corresponding results are presented in Figure 3. During the pulse train, the pressure amplitude changed from 2×10^{-4} to 6×10^{-4} Torr within the given pulse repetition rate range. In the given pulse train the pressure average value in the vacuum chamber remained constant, and by the time of regular ion beam current pulse the pressure restored to 2×10^{-4} Torr. During some HIIB pulse trains, the gas emission followed by the increase of pulsed pressure as high as $>1\times10^{-3}$ Torr took place (the pressure peak is specified by an arrow in Fig. 3a). It can possibly be the result of opening the gas cavities formed on the polymer coating surface during production of the coating on the anode.

The experiments with the anode on the basis of epoxy resin with blue copperas in the volume ratio of 1:1 showed that the pressure increase up to 2×10^{-4} Torr corresponded to one pulse. In the HIIB current pulse train with the pulse repetition rate of 1 pps, the increase of residual pressure was observed, as shown in Figure 4a.

The pressure inside the vacuum chamber increased uniformly during the pulse train with the pulse repetition rate of 4 pps (Fig. 4b), which was conditioned by the low oil–vapor pump efficiency. Relative decrease of the pressure from pulse to pulse was constant and its value was about 6×10^{-4} Torr. At the pressure level of 2×10^{-3} Torr the ion diode remained efficient.

With further increase in pressure inside the vacuum chamber, the electric breakdown occurred at anode–cathode gap at residual pressure of over 5×10^{-3} Torr. The residual gas pressure value variation inside the vacuum chamber influenced on the ion beam parameters. By the example of using the epoxy resin as a polymer coating, it was shown that when the residual gas pressure increased from 2×10^{-4} to 1.3×10^{-3} Torr, the ion beam current density at the diode focal plane increased slightly as a consequence of the ion beam transition condition improvement. At the pressure variation within the ion diode working capacity range the energy transported by the beam changed insignificantly owing to additional compensation of positive beam charge by electrons which were formed as a result of ionization by collisions.

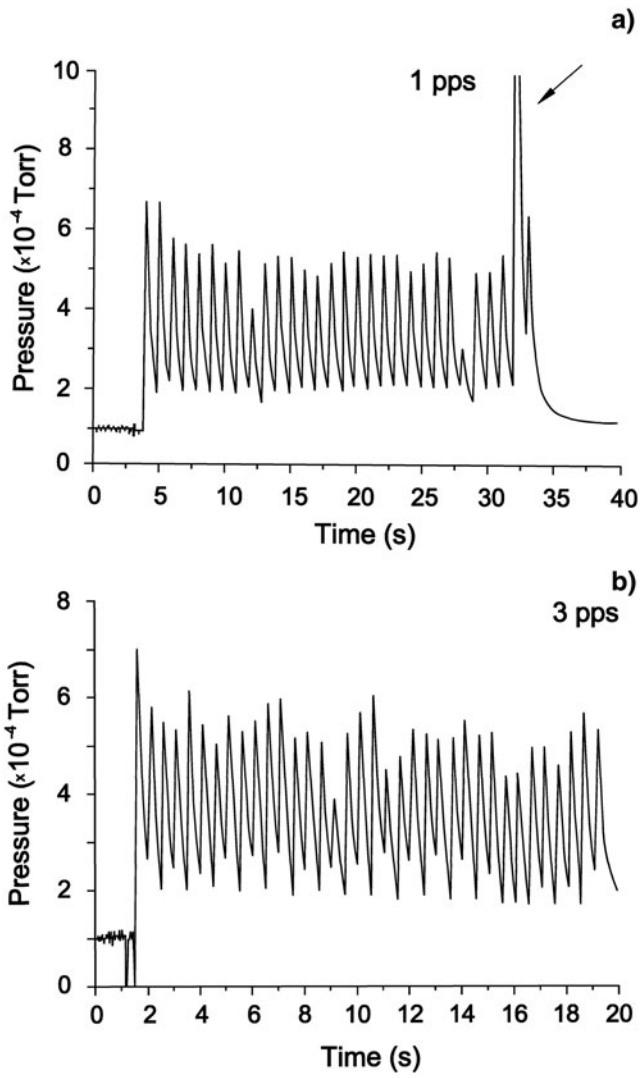

Fig. 3. Pulsed pressure variation during the pulse train inside the vacuum chamber: (a) pulse repetition rate is 1 pps; (b) pulse repetition rate is 3 pps. The anode polymer coating is made of polyethylene.

The mass content of HIIB injected into the transition area did not depend on the pressure value (Fig. 5). The adsorbed vapors of atmosphere air and oil had an insignificant impact on the ion beam content. The ion beam content variation for the other polymer coatings studied in the work is presented in Table 2.

It is found that the relative content of carbon ions increased from 16 to 25% with polyethylene coating and from 13 to 23% with the epoxy resin coating in HIIB. It was caused by the increase in scattering of the ion beam owing to proton leaving from the area occupied by HIIB.

While studying the parameters of the ion beam current, the electric breakdown of residual gas inside the vacuum chamber occurred. It was caused by eddy electric field of magnetic coils. The time moment of electric breakdown was determined at sharp decrease in discharge time of power supply capacitor storage through magnetic field coils (Fig. 6a).

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The breakdown of residual gas pressure by eddy electric field occurred at the pressure of about $>1\times10^{-4}$ Torr. The breakdown delay time relative to high voltage accelerating pulse depended on the pressure inside the vacuum chamber (Fig. 6b). At the inside chamber pressure of $(1.5–2)\times10^{-4}$ Torr the delay time was about 100 μs, at the pressure increase up to 1×10^{-3} Torr the delay time decreased to 30 μs. Thus, in the research pressure range, the gas breakdown did not have any effect on applied – B_r diode operation stability. The relation between breakdown delay time and the pressure inside the vacuum chamber depended on ionization processes of the residual gas.

4. DISCUSSION OF RESULTS

The gas emission from the anode polymer coating is connected with plasma formation processes in the anode–cathode area of the diode. As a consequence of incomplete electric discharge in anode polymer subsurface layer, the dendrites are formed (Sweeney *et al*., 1984; Zhu *et al*., 2007). As the polymer is characterized by low thermal conductivity, the coating heating is possible to the depth of the dendrites formation. It is probable that when the dendrite channel is heated, the gas emits and, as consequence, there is pressure increase inside the channel. It takes significantly longer time for the gas to get out from the dendrite channel than

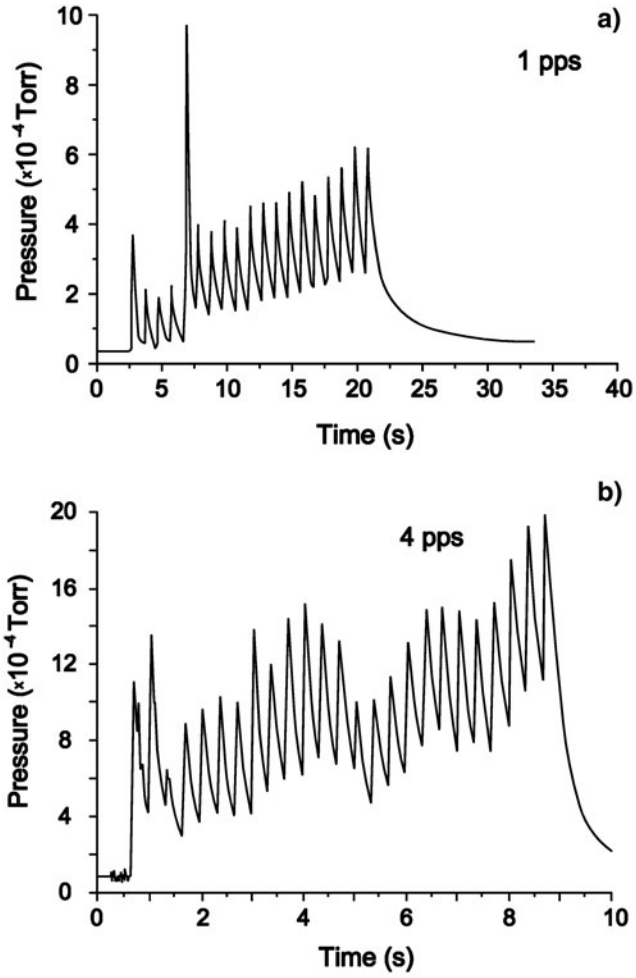

Fig. 4. Pulsed pressure variation inside the vacuum chamber during the pulse HIIB: (a) the anode coating is epoxy resin + $CuSO_4{\cdot}5H_2O$; (b) the anode polymer coating is epoxy resin.

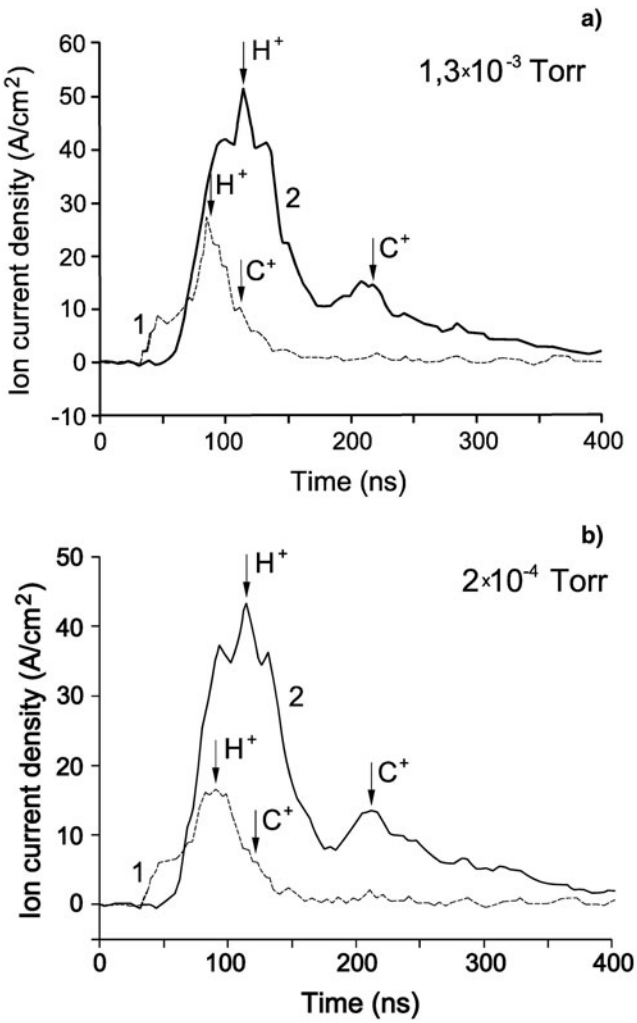

Fig. 5. The ion beam mass content at the pressure inside the vacuum chamber. Curve 1–8 cm from the anode surface. Curve 2–34 cm from the anode surface (at the diode focal plane). The anode polymer coating is epoxy resin.

Table 2. *Ion beam mass content*

Anode coating	Ion type	Ion beam mass content (distance from the anode is 8 cm) (%)	Ion beam mass content (distance from the anode is 34 cm) (%)
Polyethylene	H+	84	75
	C^{n+}	16	25
Epoxy resin + $CuSO_4\times5H_2O$	H^+	87	77.4
	C^{n+}	13	22.6

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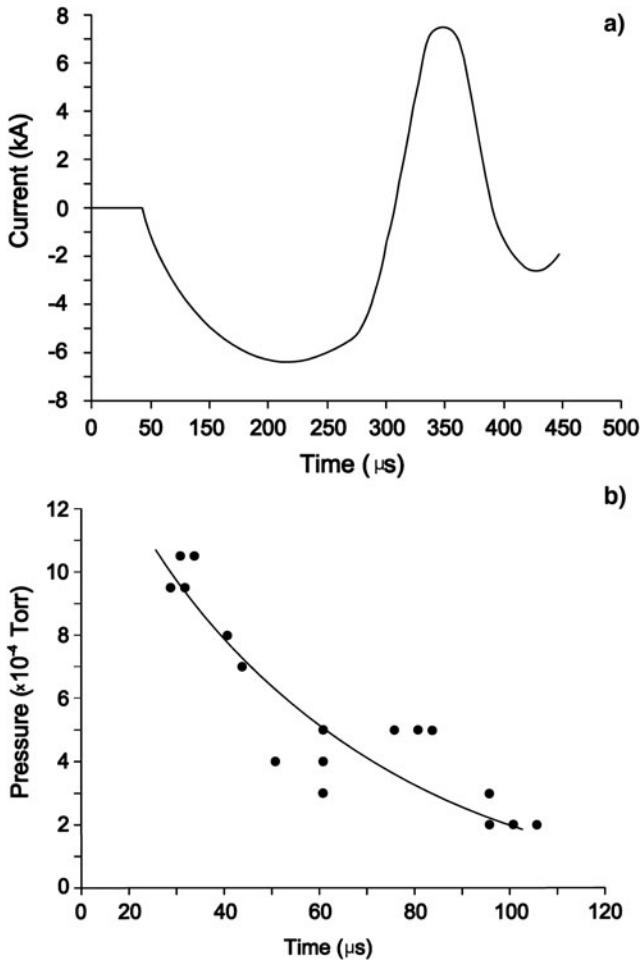

Fig. 6. The current pulse in magnetic coils (a), and the power supply input electric breakdown delay time (b).

the accelerating voltage pulse time. When the pressure increases inside the vacuum chamber from pulse to pulse, the ion beam current density at the diode focal plane increases as well. It is caused by additional neutralization of the ion beam. There is a certain value of residual gas pressure inside the vacuum chamber at which there are no changes in HIIB parameters and applied – B_r diode operation stability is maintained. This value is about $\sim 4 \times 10^{-3}$ Torr for the TEA-500 accelerator (Furman *et al*., 2004).

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