Repetitive Rate Operation Mode of Magnetically Isolated Diode with Dielectric Anode

A.V. Stepanov, V.S. Lopatin, G.E. Remnev, and E.N. Melnikova*

High Voltage Research Institute, 2a, Lenina av., Tomsk, 634028, Russia
Phone: 8(3822) 41-85-40, E-mail: StepanovAV@mail.ru
**Tomsk Polytechnic University, 30, Lenina av., Tomsk, 634050, Russia*

Abstract – A magnetically isolated diode with Br - magnetic field and nanosecond generator based on a double forming line with matching transformer were used in this study. The metal anode had concentric grooves filled with various dielectrics. Altogether ten hydrogen-containing dielectric materials were tested. The accelerating voltage was up to 400 kV, with pulse duration of 60 ns. The pulse repetition rate varied up to 6 Hz. The energy transfer efficiency from the forming line to the ion beam reached 0.7, when operating near the matched mode, which corresponded to the diode impedance of 32–35 Ω.

The measurement of the gas quantity released from the anode dielectric filling, and the ion current amplitude, indicated their proportionality to one another. The volt-ampere characteristics of diode, energy and of ion beam did not depend on the pressure value within the range of $P = (2 \times 10^{-5} \div 10^{-2})$ Torr.

1. Introduction

High-power ion beams (HPIB) find a wide application for the modification of construction material surfaces and for the deposition of metal and semi-conductive films [1]. High effectiveness of these technologies stimulates the study of magnetically isolated diodes (MID). The diodes with radial magnetic field (Br-field) possess a row of advantages [2, 3]. The important aspect of practical application of MID is the increase of MID pulse repetition rate.

To create plasma on the anode, basically, two approaches are used. The first one is pulsed gas introduction in area of the anode with its subsequent ionization [4]. The second one is plasma formation on the surface of dielectric filling on the anode [5].

The increase of diode operation frequency is related to the pressure alteration in the working chamber and stability of MID parameters at that. Earlier [6] we reached a rather high life time of MID operation with dielectric anode without a significant degradation of anode coating after 104 pulses. In these studies MID with ballistic focusing and passive plasma source was used.

2. Experimental equipment and technique

The studies have been performed at the pulsed nanosecond accelerator [7]. The accelerator is assembled by the following scheme: marx generator, double forming line (DFL) with de-ionized water and step-up transformer. The DFL energy switching is provided by the discharger with compressed gas. The auto-transformer increases the voltage at the load from 220 kV up to (400÷450) kV; at that the impedance of nanosecond generator is $Z = 40\ \Omega$, and voltage pulse duration at the half-height is $\tau = 50$ ns. The charging of marx generator capacitors with the frequency up to 10 Hz was used for realization of frequency mode of accelerator operation. The amplitude of the accelerating voltage at the diode varied from 330 kV up to 450 kV, at that the total diode current Id changed within the range of 12 kA to 6 kA.

Functional diagram of MID vacuum diode is shown in Fig. 1. The diode anode is made of aluminum possessing low specific electric resistance. The anode surface has annular grooves 5 mm in width and 1 mm in depth. The grooves are filled by the hydrogen-containing dielectrics: epoxide compound (EC), polyethylene and conducting epoxide compound (DEC).

The total area of the dielectric coating of anode is $S = 100$ cm^2. The conical surface inclination of aluminum anode to surface, normal to the configuration axis, is $\alpha = 15°$. The external C_1 and internal C_2 cathode are made of nickel-clad brass 0.25 mm in thickness with specific resistance of $\rho = 40\ \mu\Omega \cdot$ cm.

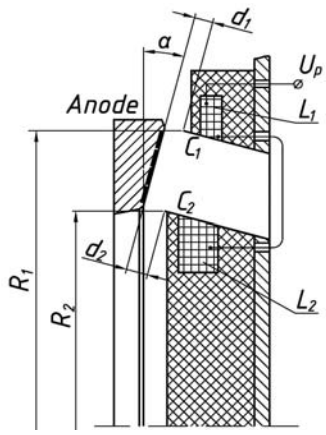


Fig. 1. MID configuration with radial magnetic Br field

The radii of external and internal cathode are $R_1 = 100$ mm and $R_2 = 75$ mm, correspondently.

In most experiments the external cathode C_1 was placed at the distance $d_1 = 6$ mm from the anode surface, the inner cathode C_2 was at the distance $d_2 = 8$ mm.

The distance d_1 was increase up to 6 mm in order to reduce the critical value of magnetic filed inductance Bcrit. The reduction of A-C gap values leads to the decrease of diode impedance Z and increase of magnetic field energy. This is not acceptable for the frequency operation mode. The reduction of d_1 and d_2 distances led to decreasing of diode impedance, and necessity to increase magnetic field energy appeared. To shift the diode operation mode to higher impedance Z the gap value d_1 was increased to 7.5÷8 mm.

During studies the total diode current I_d was measured by Rogowski coil while the accelerating voltage U_d was measured by capacity divider. The energy released in the diode was calculated as follows:

$$Q_d = \int_t U_d I_d dt. \tag{1}$$

The total energy transported by MID was measured by calorimeters based on the copper absorbent the mass of which was from 80 up to 200 g and diameter was $\varnothing = 160$ mm. The ion current density J and mass composition of MID were determined by a couple of collimated faraday cups (FC) with magnetic cutoff of the accompanying electrons. For the measurement of the ion beam profile the films of radiation-colored polymer were used. All measurements of MID ion characteristics were done at the beam axis.

Figure 2 shows the typical oscillograms of accelerating voltage U_d, total diode current I_d, and diode impedance Z.

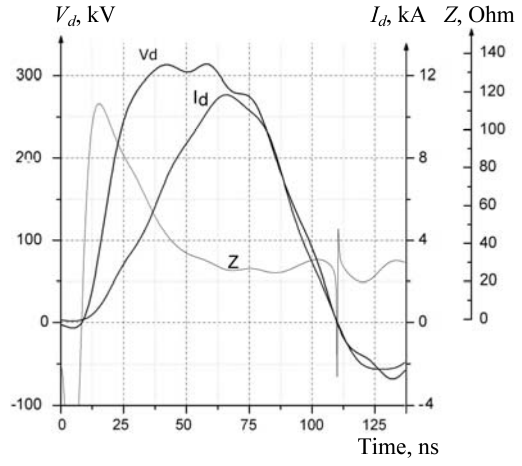


Fig. 2. The oscillograms of accelerating voltage U_d, total diode current I_d, and diode impedance Z (operation frequency $f = 0.5$ Hz)

During the experiments the total diode current varied within a range $I_d = (8.5÷10.5)$ kA, at that the ion current density reached the values $J_i = (35÷40)$ A/cm^2 and stayed during 40÷100 pulses for polyethylene coating and during 10÷20 pulses for epoxide coating EC and then went down.

The electron flux was controlled by radial Br – magnetic field from the diode cathode edges. Br – magnetic field was created by a couple of in-phase-connected coils L_1 and L_2, the number of windings were WL1 = 8 and WL2 = 14. The windings of magnetic field were maximally close to the emitting edges of cathodes for more complete use of magnetic flux. For creation of current in coils L_1 and L_2 the discharge of storage capacitor of pulsed power source was used, the capacity value of which was 200 μF. The discharge current pulse duration in the magnetic field coils was 180 μc. The maximal voltage of magnetic field power source reached $U_p = 3.2$ kV, the pulse repetition rate of power supply was $f = 10$ Hz. The maximal source energy supply was $Q_p = 1$ kJ.

The pumping of the vacuum volume $V = 0.25$ m^3 was done by the diffusion pump with the productivity 2 m$^3 \cdot$ s^{-1}. The measurement of residual and pulsed pressures in the working chamber was performed by the ionization gauge PMI-51 placed on the side-wall on the vacuum chamber with the output to oscillograph. The threshold pressure in the chamber was $\sim 6 \cdot 10^{-5}$ Torr.

3. Gas release and limitation of operation frequency by pressure

Due to the gas-release of the MID configuration details under the action of accelerated electrons and ions in A-C gap and storage of gaseous products in the pumping volume a row of auxiliary experiments were performed. During these experiments it was found out that the main source of gas was anode dielectric.

As the result that the electrons accelerated in A-C gap fell to the anode the anode plasma was formed and the extracted gas which was the product of dielectric decomposition appeared. The number of gas particles was determined basing on the pressure pulse amplitude and chamber volume and varied from $2 \cdot 10^{18}$ to $2 \cdot 10^{19}$ particles per shot depending on the experimental conditions. The amplitude of pressure pulses P in the shot series varied within a range $P = (2 \cdot 10^{-4} ÷ 10^{-3})$ Torr, and reached $P = 3 \cdot 10^{-3}$ Torr in separate shots.

It should be mentioned that the average value of pressure in the chamber in the pulse series did not change from pulse to pulse. Fig. 3 shows the oscillogram of pressure pulses for polyethylene coating in the pulse series with a repetition rate of $F = 1$ Hz. By the moment of the next shot the pressure in the chamber restored and its level was $P = 2 \cdot 10^{-4}$ Torr.

The means of pumping allowed realizing long MID operation at the frequency up to $F = 3$ Hz. With this frequency the speeds of pumping and of gas introduction were congruent. This is shown by oscillograms presented in Fig. 4.

When operating at the frequency $F > 3$ Hz the pressure in the chamber grew evenly from shot to shot. In the pulse packages with the frequency $F = (4÷6)$ Hz the number of pulses was limited by the pressure increase in the working chamber and did not exceed 20÷30 pulses.

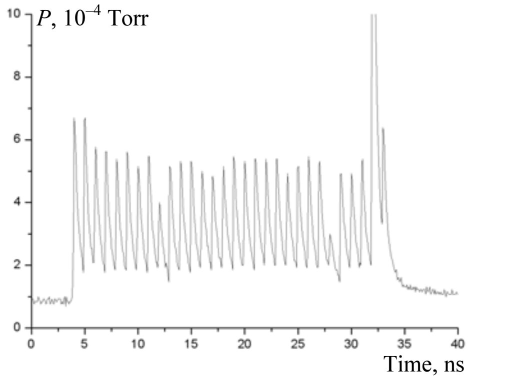
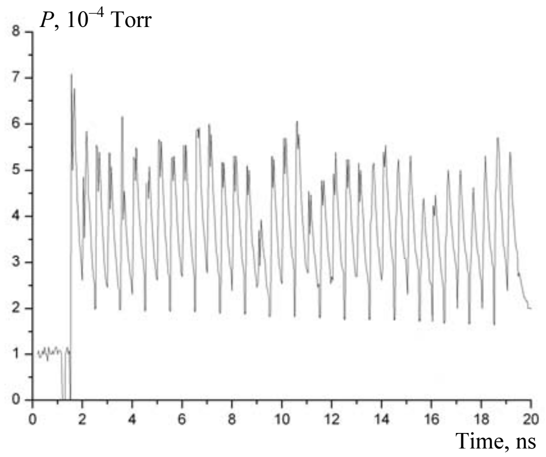
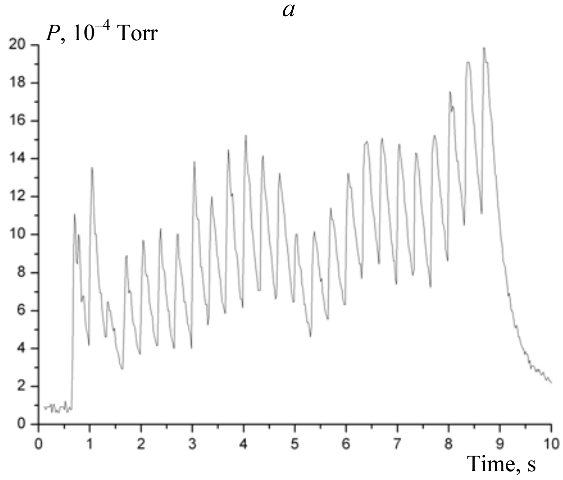


Fig. 3 The gas-release from polyethylene anode coating in the pulse series with $F = 1$ Hz



a



b

Fig. 4 The gas-release from epoxide (EC) anode coating *a*) with the operation frequency $F = 2$ Hz and *b*) with the frequency $F > 3$ Hz

The threshold pressure at which the diode kept operating ability was determined by the speed decrease of working chamber volume pumping to the point when the gas-release of diode anode coating exceeded the pumping speed. The volt-ampere characteristics of diode, energy and mass composition of ion beam did not depend on the pressure value within a range $P = (2 \cdot 10^{-5} \div 10^{-2})$ Torr. Within a range $P = (10^{-2} \div 2 \cdot 10^{-2})$ Torr the accelerating voltage and ion beam generation duration decreased while with pressure $P > 10^{-2}$ Torr in chamber the diode gap bridged.

This result allows stating the possibility of diode operation in the fore-vacuum range of pressures. This is important during practical application of MID sources.

The amplitude of pressure pulse P in the chamber after accelerator response for various types of anode dielectrics did not differ from each other, see the Table. The data of the Table correspond to single pulses.

Table

Anode dielectric	Pressure P, Torr	Diode energy Q_d, J	Ion beam energy Q_i, J
Epoxide compound	$6 \cdot 10^{-4}$	140	62
Conductive EC	$6 \cdot 10^{-4}$	140	90
Polyethylene	$6 \cdot 10^{-4}$	140	86

Ion beam had maximal energy Q_i when using anode coating based on polyethylene and conductive epoxide compound DEC with the value $Q_d = 140$ J. In this case the effectiveness of MID energy Q_d transformation to the energy transported by the ion beam Q_i was $\eta = Q_i/Q_d = 0.7$.

Conclusion

The experimental data indicate the possibility of diode operation at the pressure $P \leq 10^{-2}$ Torr with the saving of MID characteristics. The used means of pumping allowed realizing a long time diode operation at the frequency $f \leq 3$ Hz. The threshold frequency of operation is determined by the speed of working volume pumping.

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