Requirements to Magnetic Field Configuration of Ion Diode and the Power Supply System of Coils of a Magnetic Field

E. G. Furman, A. V. Stepanov, V. A. Makeev, V. S. Lopatin*

High Voltage Research Institute, 2a Lenina ave., Tomsk, 634050, Russia, 41-85-40,
E-mail: stepanov@hvd.tpu.ru
Engineering-Physics Center, 2a Lenina ave., Tomsk, 634050, Russia

Abstract − The pulse power supply system of coils of a magnetic field of the ion diode with external magnetic isolation (IDM) which is capable to ensure the functioning of the diode in a frequency mode is considered. Requirements are formulated: to the magnetic field (IDM) which provides formation of an electron cloud which is the cathode in the diode, to the conditions of accumulation of a negative charge in the magnetic field for neutralization of an ion beam in the space of ion beam drift. The basic calculation ratios necessary for engineering calculation of coils IDM and the pulse power supply system in a frequency mode are summerized.

1. Introduction

Powerful ion beams are generally used for surface modification, production of thin films from ablation plasma. The special attention to ion beams is given in connection with practical realization of thermonuclear synthesis. For this purpose ion beams of high energy density, and in a frequency mode are required. In [1, 2] systems of ion diodes in which there are no systems of a preliminary plasma formation are considered, this is its main difference from others. In [2] for the first time the operating mode of the diode similar to the idling mode is realized. It has provided a frequency operating mode with efficient transformation of electric energy of forming lines to kinetic energy of an ion beam more than 60 %.

The mechanism of operation of the ion diode is connected to formation of an electron cloud in an accelerating gap of the diode. Accumulation of a negative charge in an electron cloud occurs in the crossed electric and magnetic fields (E⊥B). The negative charge makes the closed azimuthal drift on a cycloid at a surface of the anode and a radial drift on radius to an axis X along a surface of the anode [2].

2. Functional scheme of ion diode

Figure 1 shows functional scheme of ion diode. The design of the diode has a ballistic focusing of ion beam. The diode has ring cone-shaped cathodes 1, 2 with radii R_1=98 mm and R_2=80 mm. Cathodes are made of stainless steel (thickness 0,8 mm). Cathodes

1,2 and skeletons of coils 3, 4 fasten on a disk 5. The anode A and a disk 5 are made of well conducting material, aluminum, that damp the pulse magnetic field in the area of an accelerating gap which is created by a positive charge on a surface of the anode and an electron cloud [3]. Cathodes 1, 2 are continued by electrodes 7 and the neutralizing grid 8 is located. The principle of operation and results of an experimental research of the similar diode are considered in details in [2]. The basic power ratios necessary for engineering calculation IDM are summarized below.
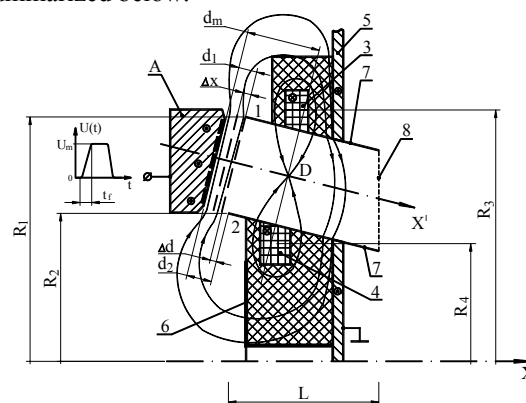

Fig. 1. Functional scheme of ion diode. 1, 2 are cone-shaped cathodes; 3,4 are coils of magnetic field; 5 is disk; 6 is collector; 7 are electrodes, 8 is grid.

3. Requirements to configuration of magnetic field

The magnetic field configuration concerning edges of cathodes 1, 2 and a surface of the anode A should meet the following requirements.

1. The minimal value of an induction of a magnetic field B_{min} in the region of an emission edge of the cathode 1 (region Δx) should be

$$B_{min} \geq \sqrt{3} \cdot E / c, \qquad (1)$$

where E is the average value of electric force in an accelerating gap: anode – cathode edge 1, E=U/d_1, c is a light speed.

2. Point D of a branching line of a magnetic field, where $B \equiv 0$, should be on an axis of symmetry X^1 an ion beam, Fig. 1. It needs realization of the following ratio

$$R_3 \cdot W_3 = R_4 \cdot W_4 , \qquad (2)$$

where W_i is a number of coils' 3, 4 windings, R_i is a radius of the center of ampere turns of windings of coils 3 and 4.

3. Distribution of density of magnetic field lines $B_1(R)$ concerning a surface of the anode A and an edge of the cathode 1 is described by an inequality:

$$B_1(R) > \frac{B_{min}}{R \cdot \ln\left(R_1 / R_2\right)} , \quad R_1 \geq R \geq R_2 , \qquad (3)$$

where R is actual radius, R_1 and R_2 are radii of edges of cathodes 1 and 2. That is the induction of magnetic field $B_1(R)$ with reduction of radius R should grow faster than function 1/R. In this case there is a radial drift of electrons to an axis X. The speed of radial drift electrons is:

$$V(R) \approx \frac{V \cdot r_e \cdot \Delta B}{B \cdot R} , \qquad (4)$$

where r_e is larmor radius of electron, ΔB is a change of an induction B on radius R on distance equal $2r_e$.

Propagation paths of electrons from an edge of the cathode 1 look like slowly turned off spirals which come to an end on a collector 6, Fig. 1. These electrons during rise of a pulse of accelerating voltage U(t) should provide surface density of a charge of the electron cloud simulating a cathode surface in the diode. This surface density of charge is necessary for acceleration of ions from the anode.

4. The edge of the cathode 2 should stand from a surface of the anode A on distance $d_2 > d_1$, $d_2 = d_1 + \Delta d$. Density of magnetic field lines $B_2(R)$ in area Δd should fall down more slowly than function f(1/R), i. e. the sign in (3) for $B_2(R)$ should be opposite. In this case during rise time of a pulse of an accelerating voltage negative charge Q should collect in area of a branching line of a magnetic field. Charge Q is necessary for compensation of a space charge of an ion beam which is injected from the anode. Thus the following condition should fulfill:

$$Q / j_i \cdot V_i = \varepsilon_0 \cdot Z / 2 d_1 \cdot L , \qquad (5)$$

where j_i is current density, V_i is speed of ion beam, $\varepsilon_0 = 8,85 \cdot 10^{-12}$ F/m, L is a length of magnetic drift, Z is impedance of the diode according to the law "3/2" for protons. The low "3/2" in a considered case looks like (U in [MV]):

$$I_P = 5,3 \cdot 10^{-2} \cdot \frac{\pi\left(R_1^2 - R_2^2\right)}{\left(d_1 - r_e\right)^2} \cdot U^{3/2} \text{ [kA]}. \qquad (6)$$

When formation of an electron cloud is finished the injection of electron from the cathode 2 practically stops. The edge of the cathode 2 will become "shielded" by a charge of an electron cloud. If during rise time of a pulse of an accelerating voltage in area L necessary charge Q does not collect, the part of energy of ion beam is required for creation of ablating plasma on a surface of cathodes 1, 2 and exhaustion from its

electrons that to compensate a charge of an ion beam. This process considerably reduces coefficient of efficiency of the ion diode.

5. The energy of a magnetic field as a first approximation can be estimated as

$$Q_m = \pi \cdot B_{min} \cdot I_{3m} \cdot W \cdot R_1 \cdot d_m , \qquad (7)$$

where W is total number of windings of coils 3, 4, I_{3m} is a amplitude of current in coils, R_1 and d_m are the sizes in Fig. 1.

4. The power supply system of coils of a magnetic field

The power supply system of coils 3, 4 of a magnetic field forms a pulse magnetic field. This pulse can be considered to be constant during time of a pulse of accelerating voltage U(t). The power supply system is designed according to one of circuits described in [4].

Figure 2 shows the principle electric circuit of power supply system of coils and diagrams of currents and voltage.
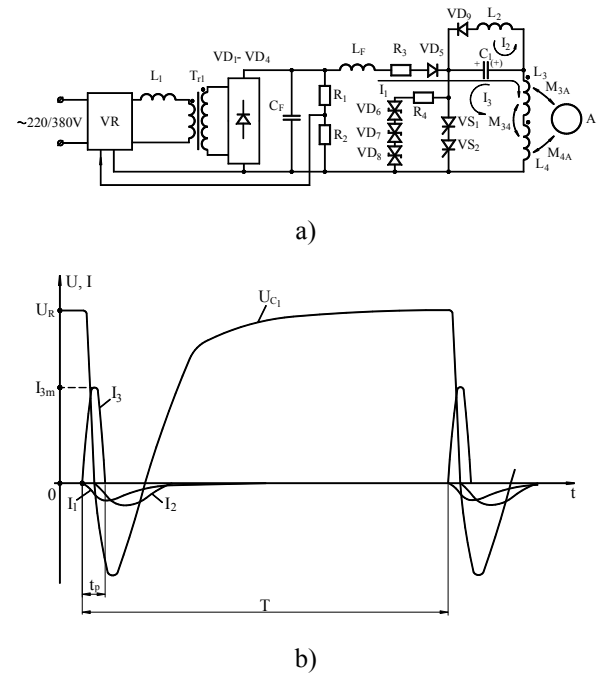

a)

b)

Fig. 2 The principle electric circuit of power supply system (a) and diagrams of currents and voltage (b).

Basic elements of the power supply are capacitor storage C_1, coils L_3 and L_4, the anode A and switching devices: thyristors VS_1 and VS_2. The capacitor energy C_1 is used for creation of a radial magnetic field with the specific configuration in a gap of the diode, Fig. 1, 2. The configuration of magnetic field generated by coils L_3 and L_4 is defined by geometrical location of the anode A and coils L_3 and L_4, and its parameters [5], Fig. 1.

The charge voltage U_{C1} of storage C_1 is regulated by a voltage regulator VR in a range $0 \div 3$ kV. The

maximal reserved energy in C_1 at $C_1=200$ μF makes $Q_{C_1 \max} = 900$ J.

Storage C_1 from a ac voltage network through the rectifier $VD_1 \div VD_4$ and filter L_F C_F (current I_1) is charged up to voltage U_R. Throttle L_1 excludes a short-circuit conditions during the first moment of time of charge C_1 and limits speed of increase of a current dI_1/dt. The voltage regulator VR stabilizes a voltage on the filter condenser C_F, using a feedback signal from a potential divider R_1, R_2. When thyristors switches on, storage C_1 begin to discharge (current I_3). To protect thyristors from the pulse overvoltage during discharging C_1, the voltage limiters $VD_6 \div VD_8$ and resistors R_4 are used. Storage C_1 is overcharged through the recuperation circuit: inductance L_2, diode VD_9 (current I_2). The diode VD_5 precludes from coursing of return half wave of a current I_3 in a charge circuit, thus recuperation of energy in storage C_1 is improved.

To generate a magnetic field the first half wave of a current I_3 is used. When value of current I_3 becomes equal to the maximal value I_{3m}, the accelerating pulse of voltage U(t) is put to the ion diode. Pulse duration of acceleration voltage U(t) is 80 ns. The effective value of a current I_3 in coils 3 and 4 is equal:

$$I_{3\text{eff}} = \frac{I_m}{\sqrt{2}} \cdot \sqrt{t_p \cdot N}, \qquad (8)$$

where $t_p \approx \pi\sqrt{L_\Sigma \cdot C_1}$ is pulse duration of current I_3, L_Σ is equivalent inductance, N is number of pulses in a second. Inductance L_Σ at the account mutual inductances coils 3, 4 and anode A is equal:

$$L_\Sigma = L_3 + L_4 + M_{12} - M_{1A} - M_{2A}. \qquad (9)$$

The value of inductance L_Σ is 60 μH. Parameters of a current pulse I_3 when the storage C_1 is discharged: $I_{3m}=5$ kA и $t_p=280$ μs, Fig. 3.
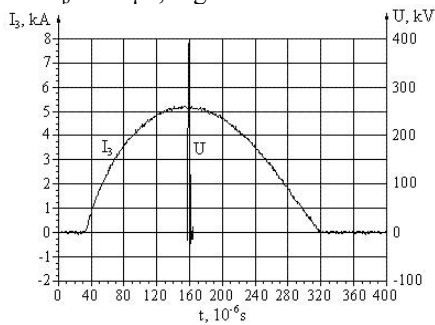

Fig. 3. Current I_3 of discharge C_1 and acceleration voltage U(t).

At frequency N=10 Hz the effective current $I_{3\text{eff}}$ in coils is equal to $I_{3\text{eff}} = 187,6$A. Energy stored in magnetic field, at the account mutual inductances coils and anode A, is equal:

$$Q = 0,5 \cdot L_\Sigma \cdot I_{3m}^2. \qquad (10)$$

and makes Q = 750 J. Thus, transformation efficiency electric energy of storage C_1 in energy of a magnetic field makes 83,3 %.

To provide selection of constant power P from industrial network the time constant of charge circuit (R_3, L_F, C_1, L_3, L_4) is less than period of time of pulses T=100 ms and makes 20 ms. The power consumption by power supply from industrial network is equal P=9 kW.

5. Experimental research of a magnetic field

In an experimental research of a magnetic field configuration the edges of cathode 1 and 2 were on distance $d_1=5^{\pm0,1}$ mm and $d_2=7,5^{\pm0,1}$ mm from the anode surface. Average value of electric field strength in gap of diode at amplitude of a pulse accelerating voltage U_m = 350 kV was equal E=70 kV/mm. In experiments voltage on the storage C_1 was equal 3 kV, and reserved energy in coils was equal 750 J. Number of windings of coils 3, 4 were equal $W_3=8$ and $W_4=14$, and its average radii of windings R_3 = 11 cm, R_4 = 6,5 cm.

Figure 2 shows the dependence of distribution of magnetic field induction on radius R at emission edges of cathodes 1, 2 and on a surface of the anode A. Radius R changed in a range $R_2 \le R \le R_1$.
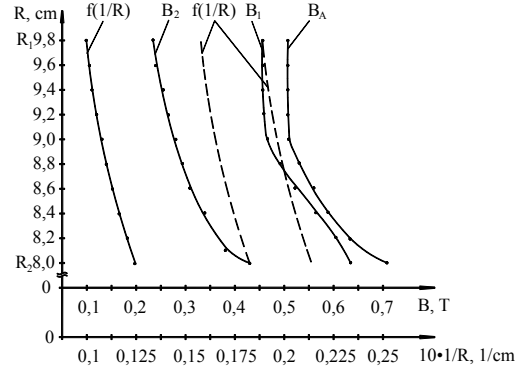

Fig. 4. Distribution of magnetic field induction on radius R at emission edges of cathodes 1 and 2: $B_1(R)$ and $B_2(R)$, and on a surface of the anode A: $B_A(R)$.

The induction of a magnetic field was measured by the search coil (inductive converter). The search coil located at emission edges of cathodes 1, 2 and on the anode surface. The search coil moved in parallel a surface of the anode to planes of Fig. 1. The search coil measured a pulse of electromotive force e(t) which rose at change of the full magnetic flow linked to the search coil. Value of induction B was calculated from ratio:

$$B = \frac{1}{K \cdot \cos\alpha} \int e(t)dt, \qquad (11)$$

where K is a constant of the search coil, $K=W \cdot S=138 \cdot 10^{-6}$ Turn×m², α is a corner between a direction of a vector $\vec{B}$ and a normal to a surface of the search coil. Average diameter of the search coil

Ø=Δx=3,83 mm. Measurements were done at the assumption, that value B was saved to constant on section of the search coil. The mistake of measurements, connected to a corner α, has the maximal value at edges of cathodes 1 and 2 and does not exceed ±10 %.

The value of induction B_1 at an emission edge of the cathode 1 ($R=R_1$=9,8 cm) in region Δx makes $B_1 = 0,46$ T. The minimal value B_{1min} calculated on ratio (1) is equal $B_{1min} = 0,404$ T. According to [2] the height of electrons' cycloid, on conditions that initial speed of electron V_0=0, is equal h=$2r_e$=3,8 mm. In this case the electron cloud makes drift movement at the anode surface in crossed E⊥B fields, and electron cloud not touching anode surface, thus to exclude work of the diode in a mode to short circuit. Value of induction $B_1(R)$ at change R in a range 9,0 cm<R<9,8 cm has a constant value. Average value of speed of azimuthall drift movement of electrons in a range 9,0 cm<R<9,8 cm is equal $V = 9,8·10^7$ m/s. On the same range average value of speed of radial drift, according to (4), is equal V(R) =0 (ΔB=0). Nevertheless radial drift of electrons to an axis X exists, and is caused by electric field strength E in edges of cathodes. Electric field strength E at edges of cathodes has perpendicular component $E_⊥$ and parallel $E_∥$ to lines of magnetic field. Parallel component $E_∥$ is directed to an axis X^I from edges of cathodes 1 and 2, and impose radial drift electrons to an axis X [2]. In this case negative charge Q, which during front of a pulse of an accelerating voltage acts in area of a branching line of a magnetic field, is not enough for compensation of a volumetric charge of an ion beam. Therefore the part of energy of an ion beam is spent in the space of drift L for formation of a negative charge from walls of cathodes 1, 2 and electrodes 7.

6. Conclusion

Infringement of conditions of distribution of a magnetic field induction concerning a surface of the anode and edges of cathodes 1, 2 results in decrease of transformation efficiency of energy of an accelerating impulse in energy of an ion beam. It is connected to installation of coils of a magnetic field concerning the anode and with a choice of ampere turns number of coils 1, 2. Measurement of a magnetic field is executed without taking into account influence of magnetic field of electron cloud charge B_e moving with drift speed V. The self-magnetic field of electron cloud, which moves at a surface of the anode makes approximately 5 % from value of a magnetic field of coils 3, 4 and is located in area the anode - an electronic cloud. The resulting magnetic field at a surface of the anode forms « a magnetic pillow » on which charge electron cloud is located.

References

[1] L. J. Bitteker, B. P. Wood, H. A. Davis, et al., Rev. Sci. Instrum, 71(10), 3677 (2000).

[2] V. S. Lopatin, G. E. Remnev, E. G. Furman, V. A. Makeev, A. V. Stepanov, Instruments and Experimental Techniques, 4, 484 (2004).

[3] G. E. Remnev, E. G. Furman, A. I. Pushkarev, S. B. Karpuzov, N. A. Kondratiev, D. V. Goncharov, Instruments and Experimental Techniques, 3, 394 (2004).

[4] E. G. Furman, Rus. Instruments and Experimental Techniques, 5, 7 (1985).

[5] A. V. Stepanov, *in Proc. of 8th Korea - Russia International Symposium on Science and Technology KORUS 2004*, 2004, pp. 278-280.