NUMERICAL INVESTIGATION OF THE INFLUENCE OF THE MAGNETIC FIELD IN THE ION SOURCE WITH THE PENNING DISCHARGE OF A GAS-FILLED NEUTRON TUBE ON THE ION CURRENT PULSE*

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Abstract

The report examines the influence of the distribution and intensity of a magnetic field in the ion source with the Penning discharge of a gas-filled neutron tube on the shape and amplitude of the ion current pulse. The study was carried out by means of numerical modelling using the KARAT code. The ion source has a length of 1.1 cm, the length of the anode is 0.6 cm with its diameter of 1.1 cm. Atomic deuterium is used at a pressure of 1 mTorr as the residual gas. A ring-shaped hot cathode with an internal diameter of 4 mm and an external diameter of 6 mm with an electron current of 10 mA is considered as the discharge trigger. The anode voltage pulse has an amplitude of2.5 kV and a front of 0.5 µs. The magnetic field is created by a 1.1 cm long solenoid with a diameter of 2.3 cm, the magnetomotive force of which ranged from 2 kA to 4 kA. The change in the distribution of the magnetic field was achieved by moving the solenoid along the longitudinal axis. The base case with respect to which the magnetic field ranged has an ion current pulse amplitude of 700 µA at a rise time of 2.5 µs. The displacement of the solenoid towards the cathode entails an increase in the ion current pulse amplitude up to 1 mA, but at the same time it leads to its spreading. The transfer of the solenoid toward the anticathode shortens the front of the ion current pulse, but leads to a decrease in its amplitude to 350 µA. At the low magnetic field intensity, the current pulse front becomes steeper, but the pulse itself has a more sinusoidal shape with an amplitude of 600 µA. An increase in the magnetic field intensity entails an increase in the duration of the pulse front and an increase in its amplitude up to 450 µA, while retaining a pulse shape close to rectangular.

INTRODUCTION

At present time, the method of the neutron logging of oil-and-gas wells requires the new generation of gas-filled neutron tubes capable of generating the neutron pulses with the short fronts [1]. The form of the neutron pulse in the modern gas-filled neutron tubes (GNT) is determined mainly by the operating mode of the ion source that generates and delivers the directed deuterium ions beam towards the neutron-generating target. The rising front of the ion current pulse is bound to be less than 1 µs, and the value of the ion current is to be of the order of 400 µA. It is appropriate to search for methods of an achievement of such an operating mode of GNT with the help of the numerical simulation.

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SETTING A NUMERICAL MODEL

The numerical simulation has been conducted by means of code KARAT [2] in the axially symmetric geometry with the dimension 2.5D. Figure 1 shows the model of a gas-filled neutron tube with the ion source of the Penning type [3] for code KARAT and the ion current pulse, generated with it. The cylindrical anode voltage is equal to 2.5 kV and its front duration is 0.5 µs. The cone-shaped electrode in the right part of the model has potential equal to –2.5 kV and simulates potential of the accelerating electrode that has potential equal to –100 kV. The coil 1.1 cm long creates the magnetic field and 2.3 cm in average diameter, which magnetomotive force varies from 2 to 4 kA that corresponds to the average value of the magnetic field induction equal to 1 – 2 kGs. The source is filled with the atomic hydrogen at the pressure 1 mTorr. The ring electron beam, emitted from the cathode surface that is enclosed by circles with radii equal to 2 and 3 cm, is used as the initiator of discharge.

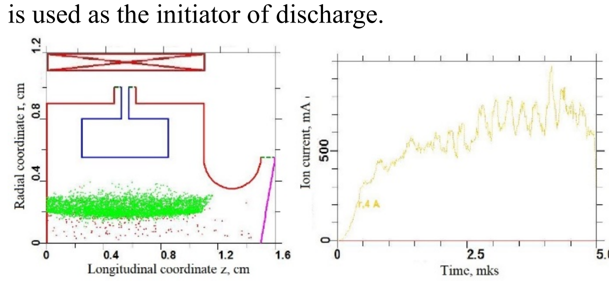

Figure 1: Model of the ion source of the Penning type (on the left) and extracted ion current (on the right).

At the numerical simulation of the plasma processes, the crucial issue is the spatial mesh size. A numerical model has to take into account the action of the electromagnetic field on the plasma particles; therefore, the size of the computation cell has to be much less than the Debye layer or the skin depth. The Debye radius is determined only for the thermalized plasma whereas the skin depth is the dynamic parameter. Initiation of discharge takes place due to the directed electron beam; the continuous generation and loss of ions and electrons occur. At the same time, when the volume density of the charged particles is equal to 10^{10} – 10^{11} cm^{-3} and their energies are

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about ~500 eV, the collision frequency of electrons among themselves is extremely small. All these statements indicate that the deciding plasma parameter is the depth of the collisionless skin layer:

$$\delta = \frac{c}{\omega_e} = \sqrt{\frac{\varepsilon_0 m_e c^2}{ne^2}} = \frac{5.31 \cdot 10^5}{\sqrt{n\left[cm^{-3}\right]}}\left[cm\right]$$

The skin depth in the given problem does not take the value less than 1 cm; it allows to use the computation mesh containing 101×131 cells.

CHANGING THE POSITION OF THE MAGNETIC COIL

The behaviour of the electron beam, emitted from cathode, is determined in many respects by distribution of the magnetic field lines of force, because electrons wind on them. In such a way, the displacement of position of the magnetic coil results in the change of location of the electron beam in accordance with the field lines of force (see Fig. 2).

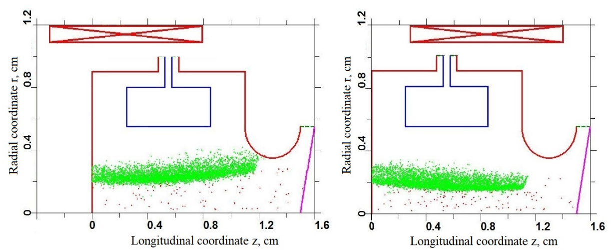

Figure 2: Distribution of electrons (green ones) and ions (red ones) when the magnetic coil is positioned more left than anode (on the left) and more right than anode (on the right).

The dependence of current, extracted from the ion source, is represented in Fig. 3.

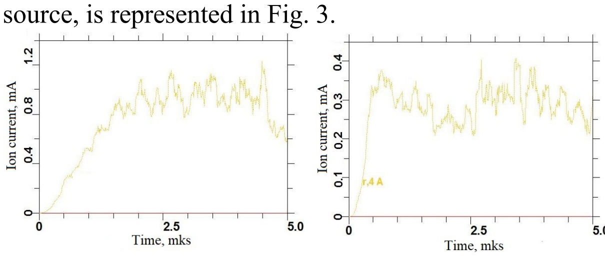

Figure 3: Extracted ion current when the magnetic coil is positioned more left than anode (on the left) and more right than anode (on the right).

In the basic model of the Penning source (see Fig. 1), at the electron current equal to 10 mA, the extracted ion current grows up to 300 μA in time equal to 0.5 μs, and its stationary value is equal to 700 μA. In the case of the displaced to the left magnetic coil, the front of the ion current grows up to 250 μA during 0.5 μs, and its stationary value increases to 1000 μA (see Fig. 3). For the "right" magnetic coil, the inverse changes of the ion current are observed, namely, the front decreases to 330 μA during 0.5 μs and the stationary value of current decreases to 350 μA (see Fig. 3)

The observed behavior of the ion pulse front is connected with the fact that, in case of the "left" coil, electron beam is immediately directed to the anticathode where the great numbers of electrons are being lost (see Fig. 2) and, therefore, the rate of ionization decreases. In case of the "right" magnetic coil, electron beam does not hit the anticathode (see Fig 2) whereas, in the basic case, a small part of the beam falls on it nevertheless (see Fig. 1), and the rate of ionization increases weakly because of it.

As for the stationary value of the ion current, its value changes are connected with the different conditions of extraction of ions that occur due to influence of the negative volume charge of electrons. In the case of the "left" coil, electrons drift from the right region of electron beam onto anode since this region is located closer to it, whereas in the case of "right" coil, the reverse occurs (see Fig. 2). It leads to the asymmetry of the electron volume density about the anode center and to corresponding asymmetry of potential. So, the sizes of the region of ion extraction change. The boundary of this region are located at the maximum of potential that is depicted for different radii in Fig. 4 (the purple line №5 is for r = 0.3 cm where the major part of plasma is located).

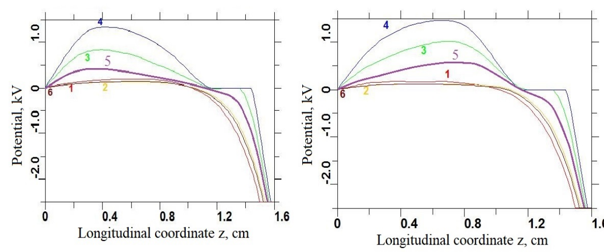

Figure 4: Distribution of potential for different values r when the magnetic coil is positioned more left than anode (on the left) and more right than anode (on the right).

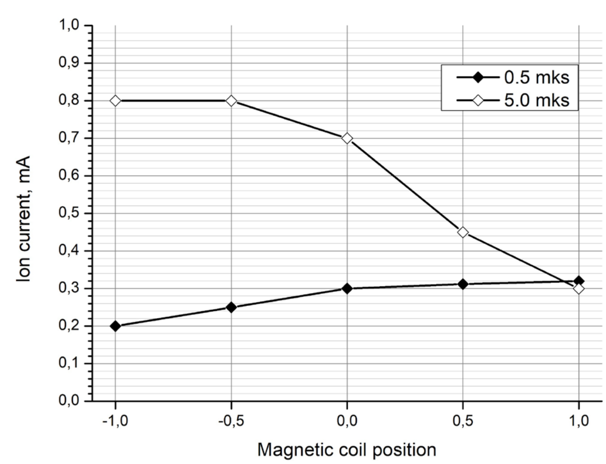

Figure 5: Plot of dependence of the extracted ion current on position of the magnetic coil center about anode: 1 – extreme left position, 0.5 – middle left position, 0 – absence of asperity (the basic case), 0.5 – middle right position, 1 – extreme right position.

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For the results generalization, let us present the plot of dependence of the extracted ion current on position of the magnetic coil center about anode (see Fig. 5).

CHANGING THE STRENGTH OF THE MAGNETIC COIL

We consider here phenomena connected with changing the magnetomotive force of the coil and corresponding changes of the magnetic field strength when the space distribution remains invariable. In the basic case, it is equal to 3 kA. Below, the magnetomotive force equal to 2 kA and 4 kA cases are considered. The increase of the magnetic field strength leads mainly to the decrease of the radial drift of plasma (see Fig. 6).

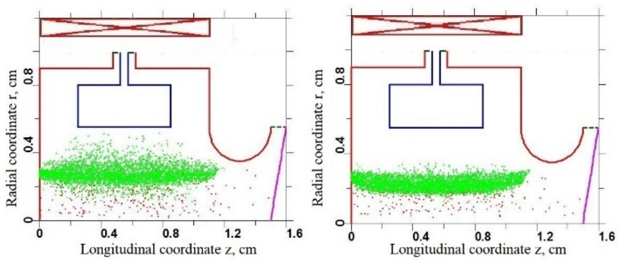

Figure 6: Distribution of electrons (green ones) and ions (red ones) in the cases of the magnetomotive force of the coil equal to 2 kA (on the left) and 4 kA (on the right).

Let us consider currents of the charged particles onto regions of the Penning source (see Fig. 7).

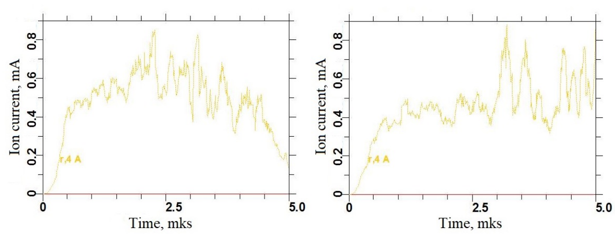

Figure 7: Extracted ion current in cases of the magnetomotive force of the coil equal to 2 kA (on the left) and 4 kA (on the right).

When the magnetic field is weak, the ion current through the extracting electrode grows up to 400 μA during 0.5 μs; when it is strong, the current increases up to 280 μA during 0.5 μs (see Fig. 7). At the same time, in the basic case, the current increases up to 300 μA during 0.5 μs. So, the decrease of the magnetic field strength leads to the decrease of the ion current front. At a later time, in the case of the weak field strength, the ion current attains 600 μA and retains this value up to 3.5 μs; thereafter, it begins to decrease. In the case of the strong magnetic field strength, the value 600 μA is also maximal, but the current attains it only in the point of time equal to 5 μs.

For generalization of results, let us present the plot of dependence of the extracted ion current on the value of the magnetomotive force of the coil (see Fig. 8).

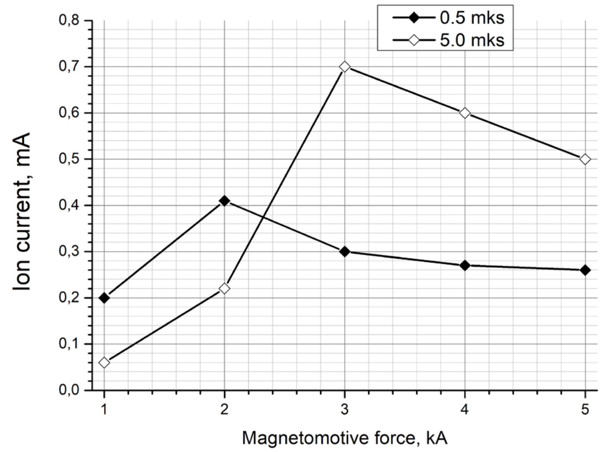

Figure 8: Plot of dependence of the extracted ion current on the value of the magnetomotive force of the coil.

CONCLUSION

The magnetic field distribution is able to influence on position of the electron beam in the space between cathode and anticathode and thereby influence on conditions of extracting of ions from the Penning source. Displacement of the magnetic coil on the left from the center of the Penning source leads to the increase of the ion pulse front and the stationary value of current. Displacement of the coil on the right leads to the reverse effect. The decrease of the magnetic field leads to the short-term increase of the number of electrons in the Penning source volume that results in the corresponding increase of the ionization rate and decrease of the ion pulse front. But the same process leads later on to the rapider decaying of discharge due to the electron losses on the anode surface. On the contrary, the increase of the magnetic field reduces the growth of number of electrons in the system but increases the discharge duration.

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