THEORY AND TECHNOLOGY OF PARTICLE ACCELERATION

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A SIMPLE SOURCE OF METAL AND GAS IONS FOR ION BEAM TECHNOLOGICAL INSTALLATIONS

V.A. Baturin, P.A. Litvinov, O.Yu. Roenko, S.O. Yeryomin
Institute of Applied Physics of the National Academy of Sciences of Ukraine, Sumy, Ukraine
E-mail: baturin49@gmail.com

At the stand of the Institute of Applied Physics of the National Academy of Sciences of Ukraine, a small-sized spattering source of metal and gas ions was developed, manufactured and tested. Ionization of sputtered atoms occurs by fast oscillating electrons in a longitudinal magnetic field. A beam containing ions of plasma-forming gas and metal is output through an emission hole in the anticathode. The source has high ion current stability, is easy to maintain, and can generate ions from any conductive solid. Modeling and manufacturing of an ion-optical system for this source, which is part of the injector of the implanter of the Institute of Applied Physics of the National Academy of Sciences of Ukraine, was carried out.

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INTRODUCTION

The problem of efficient and high-quality implementation of technological processes in installations for ion-beam processing of materials in a vacuum requires the creation and use of a universal ion source and an injector based on it [1]. This source should generate a wide range of ions of various elements, in both gas and solid states. In addition, the use of an ion source in technological installations increases the requirements for its operational characteristics: it must have a simple and reliable design, small dimensions, simple power supply and a long period of continuous operation.

PURPOSE OF WORK

1. Development of a small-sized source that generates a wide range of metal and gas ions.
2. Conducting bench tests of the created source in order to optimize the geometry and thermal operating conditions of its individual elements, as well as conducting studies of the mass and charge composition of the beam generated by this source.

Known sources of metal ions can be divided into two groups depending on the method of obtaining the concentration of atoms of a given material in the volume of the discharge chamber [2]. The first group is evaporation sources, which, depending on the evaporation temperature, can be divided into low-temperature (with an operating temperature t < 600 °C), medium-temperature (t = 600…1200 °C) and high-temperature (t > 1200 °C). The second group is spattering sources.

The use of evaporation sources in technological ion-beam installations, especially when producing ions of refractory metals, is not always justified. The fact is that the production of working medium vapors in these sources occurs, as a rule, in an external evaporator with their subsequent direction to the discharge chamber. Ensuring efficient transportation of vapors through a steam pipeline, as well as the need to use high-power heaters and heat shields, leads to a more complex design of the source.

These problems are absent in the spattering type source we developed. Sputtering processes, in contrast to the formation of metal atoms by evaporation, occur in the near-surface layers of a solid under conditions far from thermal equilibrium [3]. Thus, this method of creating a working environment makes it possible to form an atomic concentration of metals with any melting and evaporation temperature in the discharge chamber.

When creating sources of metal ions, the effective organization of the following main stages of their working process is required: generation of a sufficient concentration of atoms of a given substance in the volume of the discharge chamber, ionization of the resulting working medium, acceleration and primary formation of the ion beam.

The design of the ion source was based on the formation of a plasma emitter containing metal ions using a Penning glow discharge. The oscillations of electrons in it make it possible to use low pressure in the discharge chamber and thereby maintain the necessary vacuum regime in the working chamber of the technological installation.

DESIGN OF THE SOURCE

Before constructing the ion source, model calculations of its individual elements, in particular the configuration of the magnetic field, were carried out. The type of magnet, the approximate dimensions of the source and its power system are also selected.

Simulation of the magnetic field of the ion source was carried out using the Trak program [4]. The simulation result is shown in Fig. 1. The magnetic field in the cathode-anti-cathode gap was set at a level of 0.1…0.2 T. Simulation showed that when using a permanent magnet NdFeB (ring size D100 × d70 × h20 mm), the magnetic field strength in the gap hollow cathode 4, anode 3 and the anti-cathode 2 reaches a value of B = 0.16…0.2 T, which is acceptable for the created ion source.

Taking into account the completed modeling, the source was constructed. Its design is shown schematically in Fig. 2.

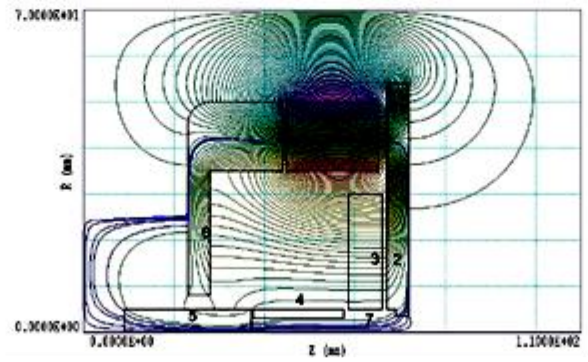

Fig. 1. Results of magnetic field modeling: 1 – permanent ring magnet NdFeB; 2 – emission electrode (anti-cathode); 3 – anode; 4 – hollow cathode; 5 and 6 – magnetic circuit; 7 – magnetic field lines. The source geometry is axially symmetric, the axis of symmetry is at the bottom of the figure

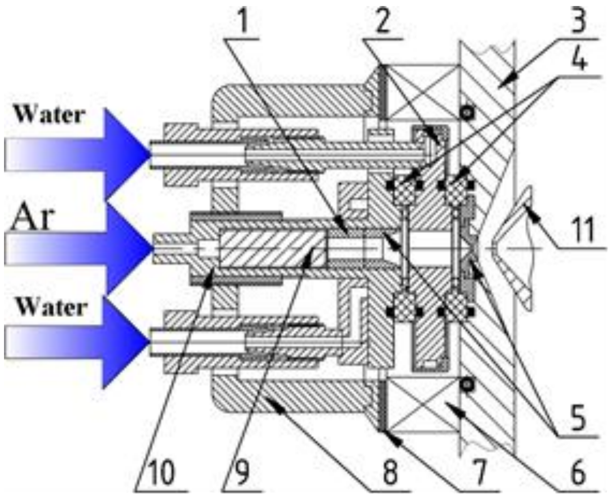

Fig. 2. Design of the metal ion source: 1 – hollow cathode; 2 – anode; 3 – anti-cathode; 4, 7 – insulators; 5 – spattering inserts; 6 – NdFeB magnet; 8 – body; 9 – ferromagnetic insert; 10 – cathode unit; 11 – extraction electrode

The gas discharge chamber of the source consists of a hollow cathode 1, anode 2, anti-cathode 3 and housing 8, forming a Penning discharge geometry. A uniform magnetic field in the gas-discharge chamber is created by NdFeB magnet 6 and magnetic cores 3, 8, 9. Gas (Ar) to ignite the plasma and maintain the combustion of the discharge is supplied to the rear part of the cathode 1 of the discharge chamber. To avoid binding the discharge to the hole for gas entry into the discharge chamber, this source is provided with a gas distribution cavity. Gas enters the discharge through a narrow (0.5 mm) annular slot in the peripheral region of the cathode assembly 10.

Overheating of the electrodes in contact with the discharge can lead to a change in the discharge burning mode. To eliminate this phenomenon, the cathode assembly 10 and the anode 2 of the ion source are cooled with water.

To effectively form the working medium in the discharge chamber of the source, sputtered inserts 5 are pressed directly into the hollow cathode and anti-cathode. Spray inserts are made of the material from which the ions are to be obtained. Cathode 1 is made of molybdenum.

Due to the incomplete ionization of sputtered atoms in the discharge, a significant part of them from the plasma falls on the walls of the emission chamber, where they are either desorbed again (from the anode) or sputtered again (from the end walls), but in both cases they fall back into the discharge. Thus, losses of the working substance in this source are minimized.

To increase the reliability of the source's operation, all kinds of heaters were fundamentally excluded from its design, and the required temperature regime of the discharge chamber electrodes was achieved by distributing the discharge power between its individual elements.

ION-OPTICAL INJECTOR SYSTEM

The ion-optical system (IOS) is an important structural part of the ion injector, responsible for the selection of particles from the plasma boundary and the primary formation of the beam.

In Fig. 3 shows the design of the IOS ion injector.

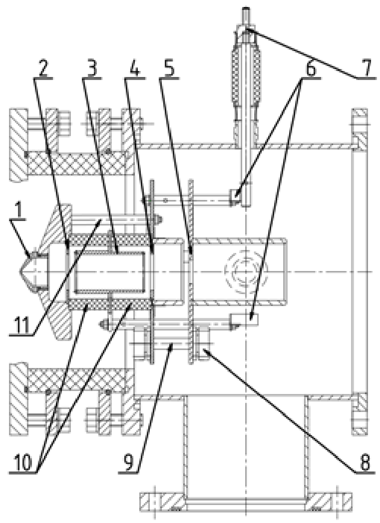

Fig. 3. Ion-optical injector system: 1 – extraction electrode; 2–4 – electrodes of a single-potential electrostatic lens; 5 – slowing electrode; 6 – contact plates; 7 – sealed lead-in; 8 – collet clamp; 9 – ceramic rod; 10 – ceramic centering rings; 11 – tightening pin

The ion source is at +20 kV and the lens is at -10 kV relative to the high voltage platform which is at +100 kV. Thus, the ion extraction voltage from the source is 30 kV. The retarding electrode 5 is under the platform potential. This design of the injector made it possible to use the existing magnetic mass separator to separate ions weighing up to 65 a.e.m. and at the same time extract ions from the source at a high accelerating voltage. This system largely determines the emittance of the ion beam, which must be consistent with the acceptance of the specific accelerator installation in which the source is planned to be used. The geometric dimensions of the ion-optical system were selected based on computer modeling. For modeling, the IBSimu library of the C++ programming language was used, designed to simulate the extraction of positive and negative ions, as well as electrons from plasma in injectors [5]. One of the results of this simulation is shown in Fig. 4.

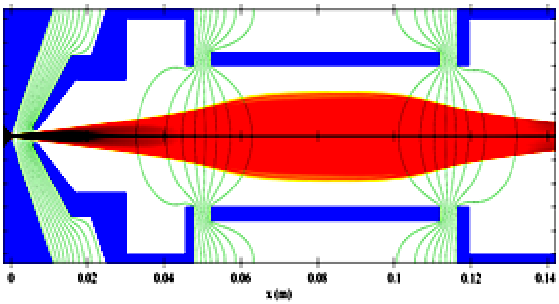

Fig. 4. Trajectories of ions extracted from plasma in the ion-optical injector system

The elements of the ion-optical system are made of stainless steel 12X18H10T and high-vacuum ceramics Al_2O_3. Collet clamps 9 for ceramic insulating rods 10 are used for precision adjustment of the size of the gaps between individual optical elements and for alignment of ion optics as a whole.

A photo of the metal ion injector is shown in Fig. 5.

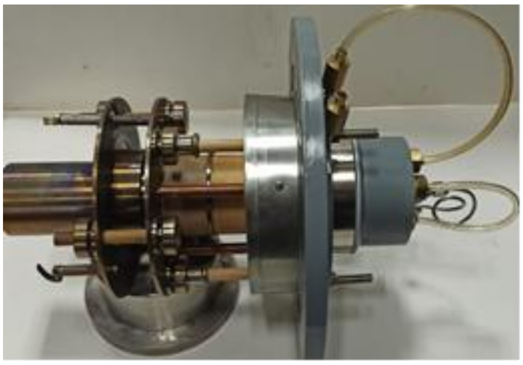

Fig. 5. Injector of metal ions

EXPERIMENTAL STUDIES

At the stage of debugging the ion source and selecting its operating modes, the sputtering inserts (cathode and anti-cathode) were made of Al. The ion extraction voltage from the source was maintained in all experiments at a level of 30 kV, and the ion energy after acceleration in the implanter was maintained at a level of 100 keV.

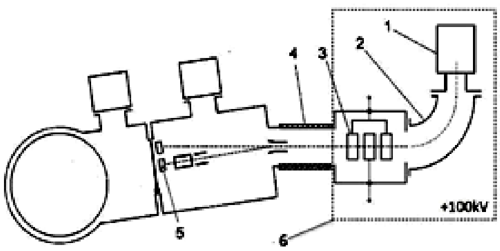

Fig. 6. Ion source as part of the implanter:
1 – ion source with a primary formation system;
2 – magnetic mass separator; 3 – second single electrostatic lens; 4 – accelerating tube;
5 – Faraday cylinder; 6 – high voltage platform

Testing of the design of an ion source with a primary formation system and a study of its operating characteristics were carried out on an ion implanter of the Institute of Applied Physics of the National Academy of Sciences of Ukraine, shown schematically in Fig. 6 [6].

The ion beam, extracted from the ion source and formed by the primary formation system, was separated by mass in a magnetic mass separator 2. After additional formation by a single electrostatic lens 3, it was accelerated in the accelerating tube 4 and fell on the Faraday cup 5. The vacuum in the receiving chamber was maintained at level $1{\cdot}10^{-4}…5{\cdot}10^{-5}$ Pa.

The metal component of the working substance (Al) in the discharge chamber of the source was formed by sputtering the cathode and anti-cathode inserts with Ar^+ ions. The dependences of the beam current of Al^+, Ar^+ ions on the discharge current were recorded at various pressures of the plasma-forming gas in the range of $(1.1…1.7){\cdot}10^{-3}$ Pa, shown in Figs. 7 and 8.

The Al^+ ion component (see Fig. 7) is almost independent of the operating pressure and increases almost linearly with increasing discharge current over the entire range of pressure changes. This dependence of the ion current can be explained by the fact that the main atomic component of Al is formed in the area of the anti-cathode insert during its sputtering, and here the ionization of atoms and formation into an ion beam takes place.

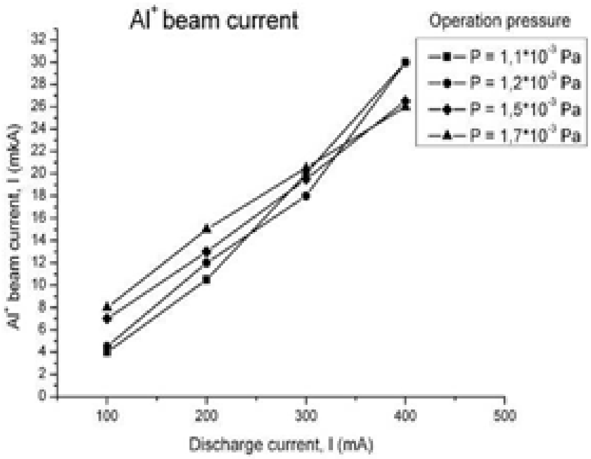

Fig. 7. Dependence of the Al^+ ion beam current on the discharge current at different operating pressures

As can be seen from Fig. 8, the argon ion current increases almost linearly with increasing cathode-anode discharge current and depends on the gas pressure in the source. It is obvious that with an increase in the pressure of the plasma-forming gas in the discharge chamber of the source and, accordingly, an increase in the concentration of sputtered Al atoms, the Ar^+ ion component in the plasma decreases due to charge exchange processes taking place on the neutral component of aluminum atoms.

Subsequently, other metal ions (Fe, Cu, Zr, Mo) were obtained from this source. Figs. 9–13 show the dependence of the beam current of the resulting metal ions on the discharge current.

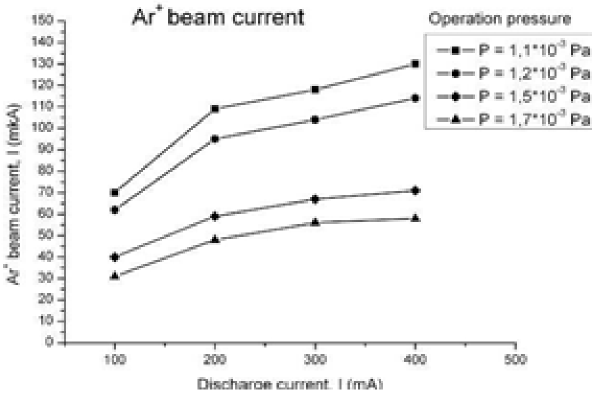

Fig. 8. Dependence of the Ar^+ ion beam current on the discharge current at different operating pressures

The operating pressure of Ar, whose ions sputter cathode and anti-cathode inserts made of these metals, was optimized for each type of metal separately, since they have significantly different sputtering coefficients. Thus, for argon ions with an energy of 300…400 eV, which is characteristic of a discharge in the source under consideration, the sputtering coefficients have the following values: Fe (0.76), Cu (1.59), Zr (0.41), Mo (0. 58). In addition, the sputtering coefficient is influenced by factors such as surface roughness, ion current density, temperature, etc.

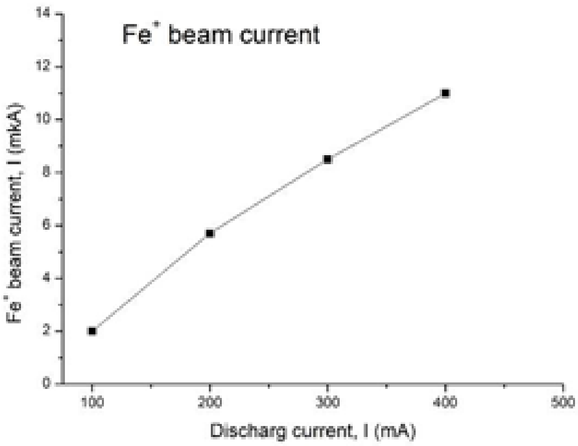

Fig. 9. Dependence of the Fe^+ ion beam current on the discharge current. Chamber pressure $P = 1.5\cdot10^{-3}$ Pa

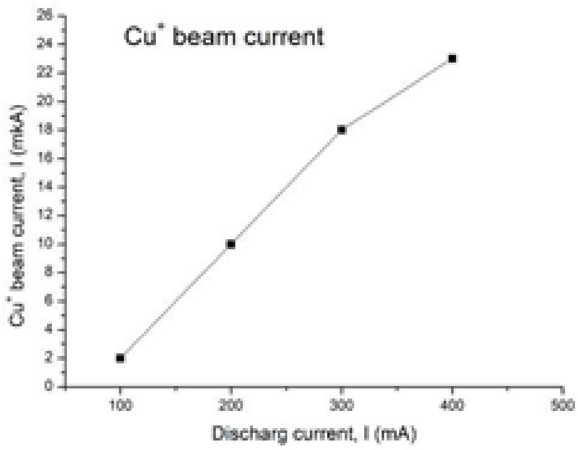

Fig. 10. Dependence of the Cu^+ ion beam current on the discharge current. Chamber pressure $P = 3.8\cdot10^{-3}$ Pa

Due to the fact that the magnetic mass separator of the IAP implanter does not allow recording singly charged ions with a mass of more than 65 a.e.m. Thus, it was decided to switch the operation of the ion source to the generation of doubly charged ions. This allowed us to obtain beams of Zr^{2+} and Mo^{2+} ions at the output of the implanter.

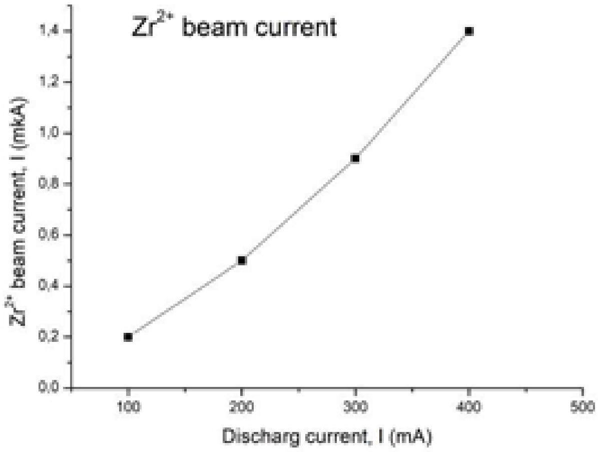

Fig. 11. Dependence of the Zr^{2+} ion beam current on the discharge current. Chamber pressure $P = 1.1\cdot10^{-3}$ Pa

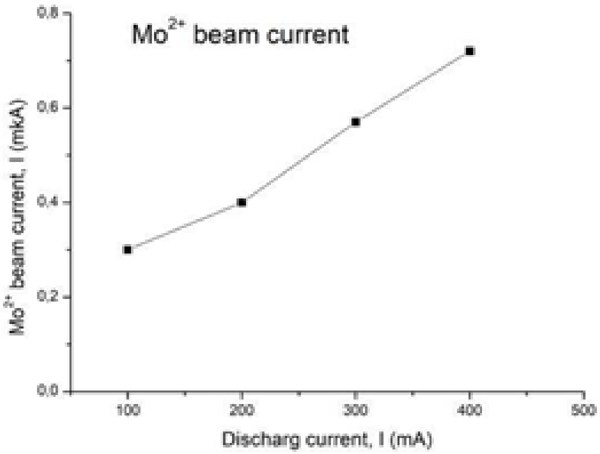

Fig. 12. Dependence of the Mo^{2+} ion beam current on the discharge current. Chamber pressure $P = 1.4\cdot10^{-3}$ Pa

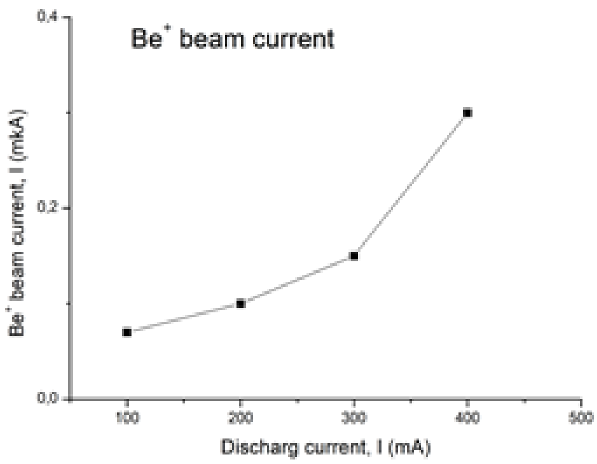

Fig. 13. Dependence of the Be^+ ion beam current on the discharge current. Chamber pressure $P = 1.4\cdot10^{-3}$ Pa

The developed ion injector was also tested for the stability of the output current of metal ions. From the graph shown in Fig. 14, it is clear that the injector has high stability of the extracted current.

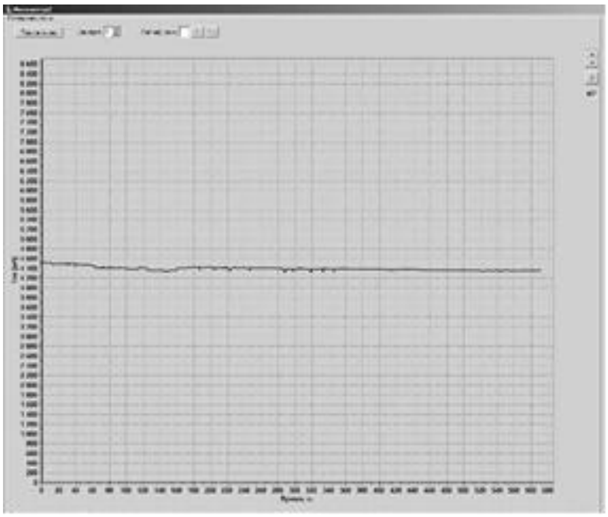

Fig. 14. Dependence of the ion current on the operating time of the source for a beam of Al^+ ions

CONCLUSIONS

The results obtained in this work allow us to note the following:

1. A reliable, inexpensive and versatile metal ion injector based on a sputter source has been developed.
2. For efficient operation of the created source, it is necessary to form a region of concentration of metal atoms in its emission chamber, and to organize the oscillation of ionizing electrons along the axis of this region.
3. The partial ratio of argon/metal ions in the formed beam is in the range of 3–20 and depends on the discharge current and gas pressure in the discharge chamber of the source.
4. Modeling and manufacturing of an ion-optical system for forming an ion beam as part of the injector was carried out.
5. The developed source has high stability of the ion current over time.
6. Tests have shown that the ion source can operate stably for a long time, which is mainly determined by the consumption of material of the sputtered inserts.

It is important to note that source is easy to maintain and versatile in that it can generate ions from any gas and metal without the use of heaters.

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ДЖЕРЕЛО ІОНІВ МЕТАЛІВ ТА ГАЗІВ ДЛЯ ІОННО-ПРОМЕНЕВИХ ТЕХНОЛОГІЧНИХ УСТАНОВОК

В.А. Батурін, П.А. Литвинов, О.Ю. Роєнко, С.О. Єрьомін

В Інституті прикладної фізики НАН України розроблено, виготовлено та випробувано малогабаритне розпилювальне джерело металічних та газових іонів. Іонізація розпилених атомів відбувається швидкими коливальними електронами у поздовжньому магнітному полі. Через емісійний отвір в антикатоді виводиться пучок, що містить іони плазмоутворюючого газу та металу. Джерело може генерувати іони з будь-якого провідного твердого тіла, має високу стабільність іонного струму, легке в обслуговуванні. Проведено моделювання та виготовлення іонно-оптичної системи для цього джерела, яка входить до складу інжектора імплантера Інституту прикладної фізики НАН України.