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REGULAR ARTICLE

The Experimental Setup for the Study of Sources of Positive and Negative Ions

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In modern medicine, accelerator technology, semiconductor production, there is a need to develop ion sources of various elements capable of generating currents in a wide range of values from 1 μA to 100 mA. Before using the created ion sources in specific applied cases, it is necessary to study them in detail, optimize the operating parameters and study the main characteristics of the ion beam. Current, emittance, brightness, energy distribution and mass composition, stability of the beam output signal are important for obtaining a quality result. The article presents a stand for testing ion sources developed at the IAP of NASU. The developed installation allows researching various sources of metal and gas ions, both negative and positive ions. The installation has all the tools for a detailed study of such parameters of the ion current as the distribution of ions by energy, by mass, emittance, beam profile, working gas consumption. The developed device for measuring the distribution of ions by mass allows studying the elemental composition of the beam. Measurement of the distribution of particles by energy is necessary to study the source for the possibility of its use with specific accelerators of charged particles and implantation technologies. The emittance meter allows you to study the emittance of the beam and obtain its profile. At the installation, a series of studies of the sputtering source of metal ions, the duoplasmatron, and the source of negative ions were carried out, the characteristics of the ion beams created by them were studied in detail, and the values of emittance and mass distribution of particles were determined. The developed facility allows for detailed research of almost any type of ion sources for ion implantation technologies.

Keywords: Ion sources, Experimental setup, Ion beam, Emittance, Particle mass and energy distribution.

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1. INTRODUCTION

Ion sources are a key part of the experimental base of charged particle beam physics. These are devices capable of generating beams of positive and negative gas and metal ions, which are used:

- in radiation materials science [1] to modify the structure of structural steels in order to increase their resistance to negative processes (increased brittleness, swelling, loss of strength, etc.) that develop under the influence of constant neutron irradiation;
- in the production of multicomponent semiconductors [2] to create various types of modern materials for electronics;
- in medicine [3] for proton and carbon therapy, boron-neutron therapy, for the production of a wide range of isotopes;
- at research accelerator complexes and etc.

For their launch, testing and optimization of operating parameters, special equipment is required, which allows safe operation with high voltage, obtaining a high operating vacuum, forming, focusing and conducting ion beams, performing various measurements of operating parameters of both the sources and the beams created by them.

In the Institute of Applied Physics of the National Academy of Sciences of Ukraine in Sumy has developed a setup for testing various types of ion sources. The vacuum system of the installation is capable of creating a vacuum at the level of 10^{-3}-10^{-4} Pa, which is sufficient for working with ion beams with minimal probability of parasitic breakdowns in the working chamber.

The development of this setup is an urgent task, as the demand for ion beam technologies in Ukraine and the world is high and constantly growing. The created stand has a number of advantages, among which it is important to note the possibility of working with sources of both positive and negative ions. It has the possibility of easy control of all necessary operating parameters of the ion source, such as operating voltage, current on system electrodes thanks to the use of Rogowski coils and measuring transformers. The setup also has all the necessary diagnostic tools for monitoring the size and parameters of the ion beam and accompanying particle beams, such as electrons. For Ukraine, this stand is unique and has no analogues, it opens up wide opportunities for testing new ion sources created for various tasks.

2. GENERAL DESCRIPTION OF THE SETUP

The main goal of the development was to create a simple and functional setup capable of working with the widest possible range of ion sources of different types.

Wide possibilities for obtaining experimental data are

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provided: a differential manometer for estimating the consumption of working gas, an energy and mass analyzer for studying the elemental composition of the beam, an emittance-meter, which can be used to measure the profile of the beam. In addition, the installation has the possibility of measuring various operating currents in a wide range of values: 0.001-100 A using Rogowski coils, a Faraday cup, a measuring transformer, and an oscilloscope. The system includes high-voltage voltage sources for powering the discharge voltage $U_{dis} \leq 1$ kV, the extraction voltage $U_{extr} \leq 30$ kV, the focusing lens $U_f \leq 20$ kV.

The scheme of the setup in its general form is presented in Fig. 1.

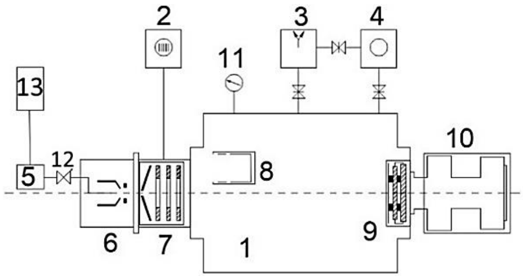

Fig. 1 – Scheme of the experimental setup for the study of ion sources: 1 – vacuum chamber, 2 – turbomolecular pump, 3 – forevacuum pump, 4 – diffusion pump, 5 – differential manometer, 6 – ion source, 7 – ion-optical system, 8 – Faraday cup, 9 – mass-analyzer, 10 – emittance-meter, 11 – ionization lamps for vacuum measurement, 12 – needle inlet valve, 13 – gas cylinder

The results of measurements of all necessary parameters of the ion sources are displayed on the digital oscilloscope.

Table 1 presents the main operating parameters of the experimental setup, allowing for a wide range of studies of ion sources of various types.

Table 1 – Operating parameters of the setup for studying ion sources

Setup components	**Subcomponents**	**Operating Parameters**
Vacuum system	Forevacuum pump 3NVR-1D	$P \leq 10^{-4}$ Pa
	Diffusion pump NVDM-250	
Power supplies	Discharge power supply	$U_{dis} \leq 1$ kV
	Beam extraction system power supply	$U_{extr} \leq 30$ kV
	Focusing lens power supply	$U_f \leq 20$ kV
Operating current measurement	Rogowski coils	$I \approx$ 1-100 A
	Faraday cup	$I \geq 1$ mA
Measuring instruments	Energy analyzer	$\Delta E \geq 0.1$ V
	Mass-analyzer	$\Delta M \geq 1$ u
Pulse gas valve	Gas pulse length	$\tau_v = 0.2 \div 1.4$ ms
	Frequency	ν = 1-5 Hz

2.1 The Vacuum System

The vacuum chamber is pumped in two stages: by a forevacuum pump and by a vapor-oil diffusion pump NVDM-250. To increase the working vacuum, an additional turbomolecular pump can be used, which is connected directly to the ion-optical system of the source. Different types of working gases are used for plasma ignition in the studied ion sources, most often Ar, H. The gas is supplied using the needle nozzle of the differential manometer, the possibility of measuring the gas consumption is provided. It is possible to supply gas with a pulse electromagnetic valve. For example, a valve with an opening time $\tau_v = 0.2 \div 1.4$ ms is used to work with a source of negative hydrogen ions. Depending on the needs of the experiment, the work can be carried out at a vacuum level of $2 \div 7 \times 10^{-3}$ Pa. The vacuum is measured by ionization lamps, VIT-3, VMB-14 vacuum gauges.

2.2 The Instruments for Measurements Operation Currents

When studying any ion source, the ability to control all discharge parameters, the distribution of operating currents in the discharge chamber, for example, between the magnetron anode and the emission electrode, is of great importance. For this purpose, there are 3 Rogowski coils on the setup, with the help of which it is possible to measure alternating currents under a high potential in a wide range of values: 1 mA-100 A. This allows to observe the operating parameters of the ion source, to study not only the magnitude of the current of the formed beam, but also other important characteristics: currents on the electrodes of the discharge system, on the ion-optical system, parasitic currents, for example, of electrons, when working with a source of negative ions, etc.

In addition, the ion beam current is measured using a Faraday cup, created in the IAP NASU, the image of which is shown in Fig. 2.

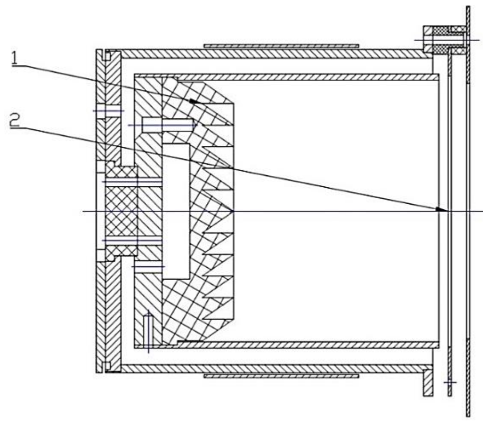

Fig. 2 – Faraday cup for measuring ion current: 1 – graphite bottom of the cylinder, 2 – electrode for trapping electrons

To increase the accuracy of measuring the current of the received ions in the developed cylinder, a shaped bottom of a toothed shape was specially created from graphite. Due to the small coefficient of secondary emission of electrons [4], this solution allows to minimize the impact of secondary electrons on the measurement of the target current. Electrode (2) is under a potential of – 200 V, whereby it effectively prevents the exit of secondary emission electrons from the cylinder into the chamber, which also allows to increase the accuracy of measurements, especially at small ion currents.

2.3 Energy and Mass-Analyzer for Studying the Elemental Composition of the Beam

Distributions of extracted ions by mass and energy are one of the main characteristics important for further use of the ion beam. The energy spectrum of the beam particles must be minimal for its successful focusing, acceleration, and transportation through the accelerator tube [5]. In order to measure the energy distribution of ions and estimate the mass composition of the beam, a special analyzer developed on the setup, schematically shown in Fig. 3.

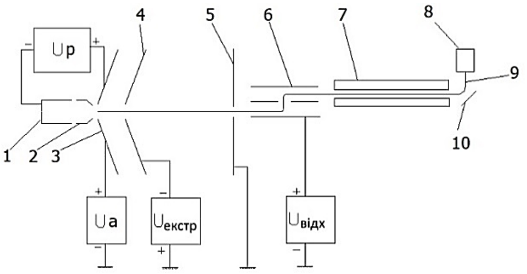

Fig. 3 – Scheme of the energy and mass-analyzer of the experimental setup: 1 – ion source cathode, 2 – intermediate electrode, 3 – anode, 4 – extracting electrode, 5 – grounded diaphragm, 6 – energy filter, 7 – monopole mass-analyzer, 8 – SEM, 9 – beam trajectory, 10 – deflector

The ion beam is extracted from the investigated source, passes through the grounded diaphragm, energy filter, then through the monopole mass spectrometer, deflect with the help of a deflector and enters the SEM. A computer and specially developed software control the mass spectrometer.

The mechanism for estimating the mass spectrum of the beam consists of a 2-slit system, passing through which a paraxial strip beam is cut from the ion beam, which has all mass fractions in its composition [6]. Next, it is passed through the magnetic field of the mass analyzer with an induction value of $B = 0.2$ T. Each ion fraction in the magnetic field deflects from a rectilinear trajectory by an amount proportional to the ratio of its charge to the mass M/Z. Knowing the values of the charge and mass of the ions, the induction of the analyzer's magnet, the distances traveled by the particles in the magnetic field, it is possible to calculate the displacement that will correspond to different fractions of the beam.

$$X = \left[qL_1B\left(\frac{L_1}{2} + L_2\right)\right]/Mv \qquad (1)$$

Where, X is the displacement of ions of different fractions (mm), q – the charge of the ion, M – mass of the ion, v – the velocity of the ion, B – the induction of the magnetic field of the analyzer, L_1 – the length of the path of the ion in the magnetic field, L_2 – the length of the path from the boundary of the magnetic fields to the measuring wire collector. The collector can move in steps of 0.1 mm, which provides a high resolution of measurements.

2.4 The Emittance-Meter for Measuring the Beam Profile

An emittance-meter [7] is used on the experimental setup, which allows obtaining the profile of the beam and measuring the numerical value of its emittance. Part of the ion beam is passed through a diaphragm chamber and measured by a wire probe. The emittance is measured according to the position of the diaphragm slit and the probe, the ratio of which is characterized by the angular and spatial coordinates of the ion beam [8]. The scheme of the device shown in Fig. 4.

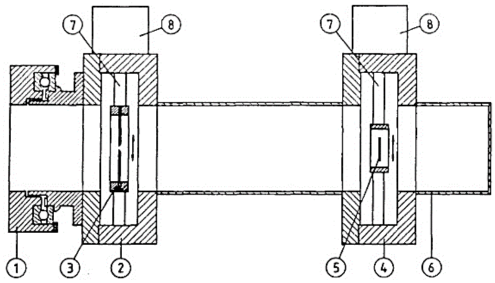

Fig. 4 – Emittance-meter for measuring the ion beam profile: 1 – uniaxial ball bearing, 2 – camera with diaphragm, 3 – moving diaphragm, 4 – camera with wire probe, 5 – moving wire probe, 6 – Faraday cup, 7 – threaded rod, 8 – stepper engine

An axial ball bearing is located in front of the emittance-meter chamber, which, by its rotation, ensures obtaining and maintaining a high working vacuum in the chamber of the device. In the camera, the aperture slit and the wire probe move along special guide rods. Stepper motors are mounted on the camera, which are connected to the rods through a special mechanism and drive the diaphragm and the probe. If it necessary, sensors-switches can be mounted on the slides of these nodes, which ensure that the stepping motors are stopped when the diaphragm or probe comes into contact with the walls of the chamber.

The rods have a thread of 1.5 mm with a step angle of 1.80, which corresponds to a step of the electric engine of 0.0075 mm, whereby a high resolution of the measured signal is achieved. The diaphragm slit, which cuts out the central part of the beam, has a width of 0.4 mm. To prevent heating of the diaphragm as a result of its bombardment with an ion beam, which at a current of only 1 mA and at an accelerating voltage of 30 kV leads to landing on the surface of 30 W of power, a water cooler is used. The height of the aperture is 60 mm, the diameter of the probe is 0.2 mm, its length is 70 mm, the available path for the aperture is ± 20 mm, and the probe is ± 40 mm. If it necessary, there is a possibility to switch the emittance measurement in another plane in the emittance-meter chamber, which corresponds to the rotation of the aperture-probe system by 90° around the longitudinal axis of the beam. At the end of the measuring system, behind the probe, there is a Faraday cylinder for measuring the beam current.

To obtain the emittance, it is necessary to calculate the angular distribution of ions [9] at various points perpendicular to the direction of distribution. The angular distribution of ions is determined relative to the center of the beam. This is achieved by calculating the center of the ion beam at specific points characterized by the position of the diaphragm slit x_s and the wire probe f_s [10]:

$$x_s = \frac{\int_{-\infty}^{+\infty} I(x)x dx}{\int_{-\infty}^{+\infty} I(x) dx} \quad (2)$$

$$f_s = \frac{\int_{-\infty}^{+\infty} I(f)f df}{\int_{-\infty}^{+\infty} I(f) df}, \quad (3)$$

where x is the coordinate of the aperture, f is the coordinate of the probe, $I(x)$ is the ion current measured on the diaphragm, $I(f)$ is the ion current measured on the probe.

3. EXAMPLES OF RESEARCH RESULTS

The setup has been successfully put into operation and is actively used in the study of an ion sources. To date, research has been carried out on the following types of ion sources: a duoplasmatron with a poly cathode, a source of negative hydrogen ions placed in a vacuum, a spray-type metal ion source with a Penning discharge and other. When working with different ion sources, there is a need to change the power supply system of the devices, the method of supplying the working gas, and create transition structures for their connection to the vacuum chamber. All these changes are implemented for the specific source being studied.

In Fig. 5 shows an example of the results of the study of the mass composition of the beam, performed on a metal ion source of the sputtering type with the following parameters: working gas – Ar, gas flow $Q = 1.06 \times 10^5$ Pa $\times$ cm^3/min, discharge current $I_d = 3$ A, discharge voltage $U_d = 350$ V.

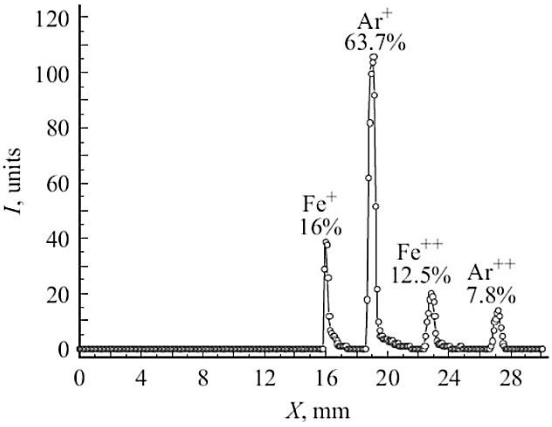

Fig. 5 – An example of measuring the mass spectrum of an ion beam: X – displacement from the axis of the analyzer, mm, I – current of ions of different fractions, units

An example of the result of estimating the energy spread ΔE of He ions on a duoplasmatron with a poly cathode is given in Table 2. The experiment was performed at different discharge voltages and currents. ΔE values are calculated at the level of 0.5 of the maximum current. An example of the experimentally obtained beam profile on a duoplasmatron with a poly cathode is shown in Fig. 6.

Table 2 – Data from measurements of the energy spread of ions in a He beam

I_d, mA	20	40	60
U_d, V	300	340	355
ΔE, eV	5,8	6	7,2

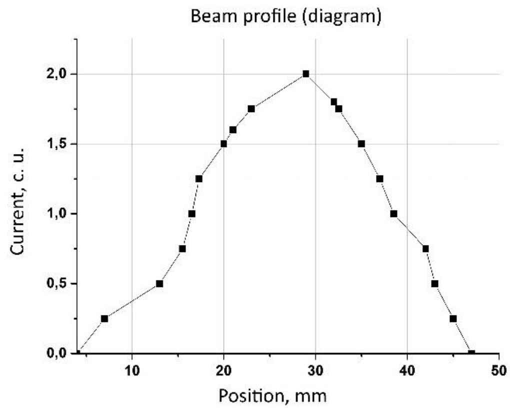

Fig. 6 – Beam profile

The presented setup makes it possible to comprehensively study an ion source of almost any type, evaluate its main operating parameters and the generated beam current. Further implementation of the sources in work on specific applications confirms the high level of accuracy of the research.

4. CONCLUSION

The experimental setup developed at the Institute of Applied Physics of the National Academy of Sciences of Ukraine in Sumy can provide detailed studies of the most types of gas and metal ion sources, both positive and negative ions. Its main advantages are:

- A powerful power supply system with the possibility of raising the working voltage to 30 kV and more.
- All necessary diagnostic devices are present for measuring any parameters of the source of the received beam of charged particles: energy and mass-analyzer, emittance-meter, Faraday cup, Rogowski coils
- Water cooling system, which allows to work with sources with high power at discharge without overheating.

The stand was successfully used when working with different types of ion sources listed above, and showed the ability to accurately assess all the main necessary parameters of these devices. Further use of sources on ion implanters proved the high accuracy of the measurements.

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Експериментальний стенд для вивчення джерел позитивних та негативних іонів

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У сучасній медицині, прискорювальній техніці, виробництві напівпровідників існує потреба в розробці джерел іонів різних елементів, здатних генерувати струми в широкому діапазоні значень від 1 мкА до 100 мА. Перед використанням створених джерел іонів у конкретних прикладних випадках необхідно їх детально дослідити, оптимізувати робочі параметри та вивчити основні характеристики іонного пучка. Струм, емітанс, яскравість, розподіл енергії та масовий склад, стабільність вихідного сигналу пучка є важливими для отримання якісного результату. У статті представлено розроблений в ІПФ НАНУ стенд для випробування джерел іонів. Розроблена установка дозволяє досліджувати різні джерела іонів металів і газу, як негативних, так і позитивних іонів. Установка має всі інструменти для детального дослідження таких параметрів іонного струму, як розподіл іонів за енергіями, по масі, емітанс, профіль пучка, витрата робочого газу. Розроблений прилад для вимірювання розподілу іонів за масою дозволяє досліджувати елементний склад пучка. Вимірювання розподілу частинок за енергією необхідно для дослідження джерела на можливість його використання з конкретними прискорювачами заряджених частинок і технологіями імплантації. Емітансометр дозволяє дослідити емітанс пучка і отримати його профіль. На установці проведено серію досліджень розпилювального джерела іонів металу, дуоплазматрона, джерела негативних іонів, детально вивчено характеристики створюваних ними пучків іонів, визначено значення емітансу та масового розподілу частинок. Розроблена установка дозволяє забезпечити детальне дослідження практично будь-якого типу джерел іонів для технологій іонної імплантації.

Ключові слова: Джерела іонів, Експериментальний стенд, Іонний пучок, Емітанс, Масовий та енергетичний розподіл.