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ION INJECTOR OF A COMPACT SCANNING NUCLEAR MICROPROBE. NUMERICAL SIMULATION

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Numerical simulation of ion beam dynamics in the injector of a compact nuclear scanning microprobe has been carried out. The injector consists of a low-power RF ion source with a micrometer-sized extractor hole and a Wien filter with permanent magnets. It is shown that the injector under consideration effectively separates ions H_1^+, H_2^+ and H_3^+. The voltage required to power the electrostatic deflection plates during proton separation has been determined provided that the beam deviates from the injector axis <10 μm. The error in the voltage value for the permissible beam deviates from the axis provided that the proton beam passes through an aperture with a diameter of 2 mm has been established.

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INTRODUCTION

Focused light ion beams with energies of several megaelectronvolts are widely used in a local microanalysis of various origins samples [1-5]. A setup for focusing ion beams with a resolution in the micrometer range is a scanning nuclear microprobe. The microprobe is one of the end stations of analytical complexes based on general-purpose electrostatic accelerators [1, 2, 5-10]. The classical scheme of a state of the art microprobe includes an object and aperture collimators located at a distance of 3...6 m, a scanning system and a focusing system consisting of a multiplet of magnetic or electrostatic quadrupole lenses [5–7, 11–13]. The entire length of the microprobe from the object collimator to the target is 4...9 m. The collimators form a phase volume of a beam with a current from ~1 fA to ~1 nA, which is focused on the target into a spot with dimensions from several tens of nanometers to one micrometer. The beam at the entrance to the microprobe is created by a general-purpose electrostatic accelerator and after the analyzing magnet the current of the selected ion species is ~10 μA. It should be noted that the accelerator does not take a direct part in the process of forming the microprobe, and the use of the output beam current is also obviously not efficient.

The concept of a compact scanning nuclear microprobe is presented in [14–16], in which a specialized electrostatic accelerator is used as part of an immersion probe-forming system, which allows several times to reduce the size of the microprobe and significantly improve spatial resolution. The main point of the concept is the use of a specialized ion source with a proton current of 0.1...1 nA and an energy spread of <10 eV [17]. The source should have an extracting micrometric hole (20...50 μm) to ensure the spatial resolution of the compact scanning nuclear microprobe at the level of 0.1 μm in the local microanalysis using techniques such as PIXE and RBS. To separate the working ion type, it is necessary to use a compact Wien filter, which is a part of the injector. The Wien filter consists of permanent magnets and a pair of electrostatic deflecting plates.

The main goals and tasks of numerical simulation of the motion of an ion beam in the injector of a compact scanning nuclear microprobe are to calculate the beam envelope to determine the dimensions of the aperture that serves to cut off the second and third masses (H_2^+ and H_3^+) and the distance of its location behind the Wien filter. It is also necessary to determine the potential on the deflecting plates in the filter and the error of its installation in order to pass the beam of the first mass (H_1^+) through the cutting aperture without losses. In the ion source, the problem of beam dynamics is axisymmetric, and in the Wien filter, the problem is flat in the *xOz* plane. Therefore, the problem of numerical simulation of the motion of an ion beam in the injector is divided into two stages. The first stage is to determine the motion of the ion beam in the source, and the second in the Wien filter. The diagram of the ion injector is shown in Fig. 1.

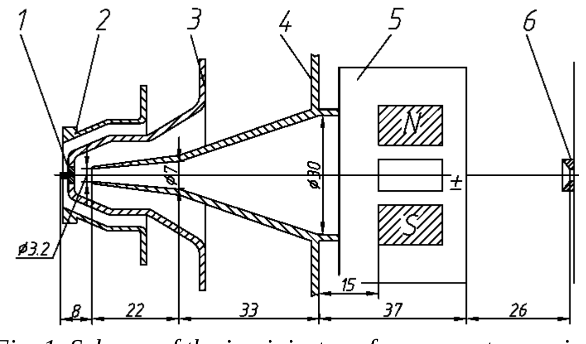

Fig. 1. Scheme of the ion injector of a compact scanning nuclear microprobe: 1 – extractor; 2 – anode (potential 6 kV); 3 – accelerating electrode of the ion source (potential 5.9 kV); 4 – focusing electrode (potential 0 kV); 5 – Wien filter; 6 – aperture with a diameter of 2 mm for cutting off ions of the second and third masses

1. EQUATION OF BEAM MOTION IN AN ION SOURCE

Since the electrodes of the ion source have axial symmetry, the equation describing the motion of ions in the source has the form [18]

$$r'' = \frac{\left(E_r(r,z) - r'E_z(r,z)\right)\left(1 + r'^2\right)}{2\left(p_0^2/2mq + \varphi(r,0) - \varphi(r,z)\right)}, \quad (1)$$

where p_0, m, q – initial momentum, mass and charge of the beam particle; $p_0^2/2m$ – initial kinetic energy of the particle at the entrance to the extraction hole of the source; E_r and E_z – field components of the ion-optical structure of the source, the potential φ in the presence of axial symmetry of the electrodes has the form [18]

$$\varphi(r,z) = U(z) - U''(z)r^2/4 + U^{IV}(z)r^4/64, \quad (2)$$

the field is expressed through the potential

$$\vec{E}(r,z) = -grad(\varphi),$$

$U(z)$ – distribution of electric potential on the source axis.

2. EQUATION OF BEAM MOTION IN A WIEN FILTER

The geometry of the Wien filter is shown in Fig. 2. Here the ion beam H_2^+ and H_3^+ is deflected in the xOz plane.

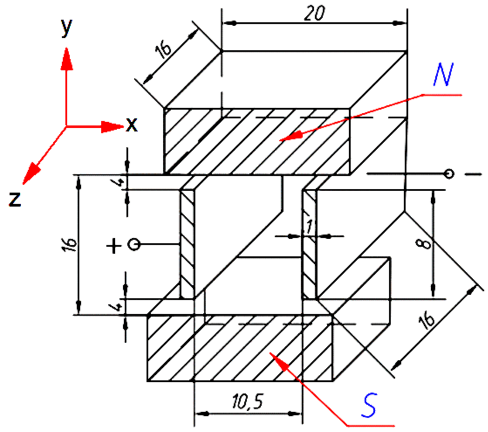

Fig. 2. Scheme of the Wien filter

The equations describing the beam dynamics in this plane have the form [18]

$$x'' = \frac{\left(E_x(x,z) - x'E_z(x,z)\right)\left(1 + x'^2\right)}{2\left(p^2/2mq + \varphi_C(x,0) - \varphi_C(x,z)\right)} -$$

$$-B_y(z)(1 + x'^2)^{3/2}\sqrt{\frac{q}{2m(p^2/2mq + \varphi_C(x,0) - \varphi_C(x,z))}}, \quad (3)$$

where $p^2/2m$ – kinetic energy of the ion at the entrance to the Wien filter; E_r, E_z – components of the electric field between the deflecting plates of the Wien filter;

$$\vec{E}(x,z) = -grad(\varphi_C),$$

for bipolar powering of deflecting plates the planar field potential

$$\varphi_C(x,z) = -U_1(z)x + U_1''(z)x^3/6, \quad (4)$$

$U_1(z)$ – field strength distribution on the axis between the deflecting plates; B_y – component of the magnetic field, $B_y(y,z) = -\frac{\partial \varphi_B}{\partial y}$,

$$\varphi_B(y,z) = -W_1(z)y + W_1''(z)y^3/6, \quad (5)$$

$W_1(z)$ – distribution of magnetic induction on the axis.

Since the problem is solved in a plane xOz, that $B_y(0,z)=B_y(z)=W_1(z)$. It is worth noting that equations (1) and (3) are exact trajectory equations in electromagnetic fields, taking into account their symmetry.

3. SIMULATION OF FIELD DISTRIBUTION IN AN ION SOURCE AND WIEN FILTER

From (2), (4), and (5) it is clear that to solve the problem of field distribution it is necessary to know the distribution of potential $U(z)$, electric field strength $U_1(z)$, magnetic induction $W_1(z)$ and their higher derivatives. The calculation of these distributions was carried out using the boundary element method in the representation of the Laplace equation in integral form. This approach allows the derivatives of the function with high accuracy at the analytical level due to the differentiation of the kernel of the integral equation to be determined.

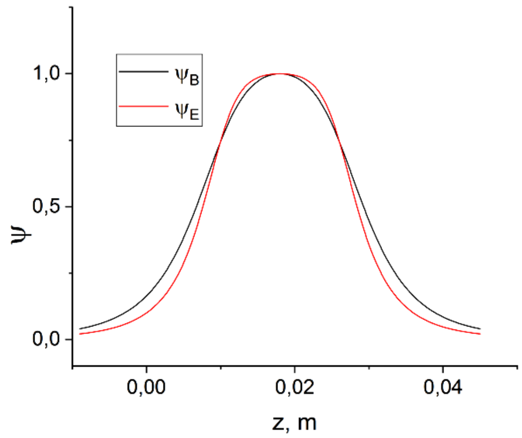

Fig. 3 Distribution of electric ψ_E and magnetic ψ_B field profiles in the Wien filter

Since the task of determining the distribution of electric and magnetic fields is linear, these distributions in the Wien filter were determined from the form of the longitudinal distribution profiles (Fig. 3) as

$$U_1(z) = E_C\psi_E(z),\quad U_1'(z) = E_C\psi_E'(z),$$
$$U_1''(z) = E_C\psi_E''(z),\quad U_1'''(z) = E_C\psi_E'''(z),$$
$$W_1(z) = B\psi_B(z).$$

From experimental data B=0.3 T, then

$$E_C = kB\sqrt{2q(T_0/q + U(0) - U(z_{Wf}))/m}, \quad (6)$$

where T_0 – average ion energy in the plane of the source extraction hole; $U(0)$, $U(z_{Wf})$ – potential on the axis in the plane of the extracting hole of the source and at the entrance to the Wien filter, respectively.

Here the coefficient k is introduced because the profiles ψ_E and ψ_B are not the same (see Fig. 3) and it is necessary to correct the magnitude of the electric field. The magnitude of the potential on the deflecting plates was determined from the relation $V_{\pm}=E_Cd/2$, where d is the distance between the deflecting plates (see Fig. 2).

4. RESULTS OF BEAM MOTION SIMULATION IN AN ION SOURCE AND WIEN FILTER

Equations (1) and (3) were solved numerically, using the Everhart difference scheme [19] of the seventh order approximation. In the simulation, the coefficient k (6) was chosen provided that the axial trajectory of the proton beam at a distance of 126 mm from the extracting hole of the ion source deviated from the z axis within <10 μm. For an ion beam energy of 6 keV k=1.0756.

The initial phase volume of the beam in the plane of the extraction hole was represented as a crossover, with the parameters of a straight ellipse r_0=25 μm, r'_0=5 mrad. The average energy of ions in the beam at the entrance of the extraction hole was T_0=100 eV, the energy spread was ΔT_0=±5 eV [17]. The phase coordinates of the particles were represented by 1000 points on the phase ellipse. The initial energy of the ions was determined randomly taking into account the average energy and spread. The simulation results are shown in Fig. 4.

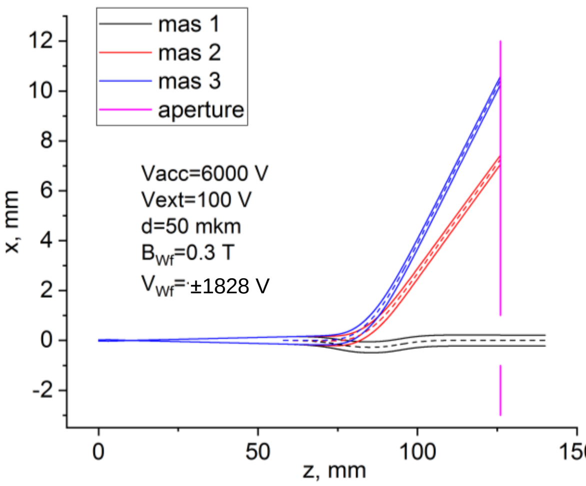

Fig. 4. Results of simulation the motion of the first, second and third mass ion beam in the ion source and Wien filter for the extracting (100 V) and accelerating (6 kV) voltages and the extraction hole size of 50 μm

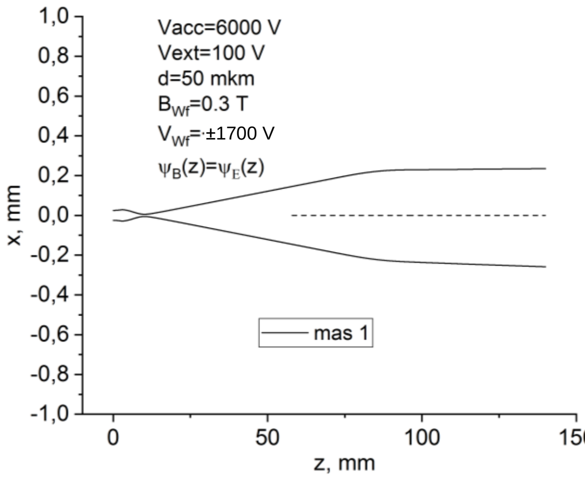

Fig. 5. Envelope of a proton beam in a Wien filter with identical profiles of the axial distribution of the electric and magnetic fields, coefficient k=1

It can be seen from Fig. 4 that in the Wien filter the motion of protons is not rectilinear. This is due to the fact that the profiles of the electric ψ_E and magnetic ψ_B fields (see Fig. 3) are not the same due to their nature and geometric dimensions (see Fig. 2). To confirm this assumption, simulations were carried out with identical profiles ψ_E=ψ_B.

As can be seen from Fig. 5, in this case the motion of the axial proton in the Wien filter is rectilinear. This figure shows that the Wien filter has some focusing properties. This can be explained as follows. Protons with a positive x coordinate have a higher velocity relative to the axial proton (a consequence of equation (4)), therefore, the action of the magnetic field prevails over the electric field, bringing these protons closer to the axis. On the contrary, in the region with a negative x coordinate the protons have a lower velocity, therefore, the electric field will have a greater influence than the magnetic one, thus the protons will again bringing closer to the axis.

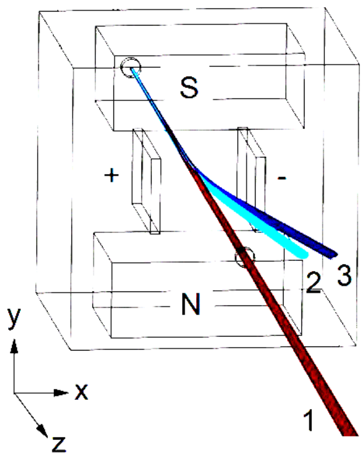

Fig. 6. Results of simulation the motion of an ion beam in a Wien filter obtained using the COMSOL package: 1, 2, 3 – beams of the first, second and third masses are shown, respectively

The motion of the ion beam in the Wien filter was also simulated using the COMSOL Multiphysics package for mathematical simulation of physical problems. The results of this simulation are shown in Fig. 6. The obtained voltage value on the deflecting plates differs by less than 3% from the value obtained when solving equation (3), which is due to the difference in the methods for fields calculating. This relates that the finite element method is used to calculate the distribution of magnetic and electric fields in the COMSOL package.

To assess the accuracy of setting the voltage on the deflecting plates, a simulation was performed when changing the voltage value, provided that the proton beam passes a 2 mm cut-off aperture without loss, which is shown in Fig. 7. This figure shows that for the separation of protons from the general beam, high requirements are imposed on the power source of the deflecting plates, the deviation is allowed within the limits of no more than ±55 V.

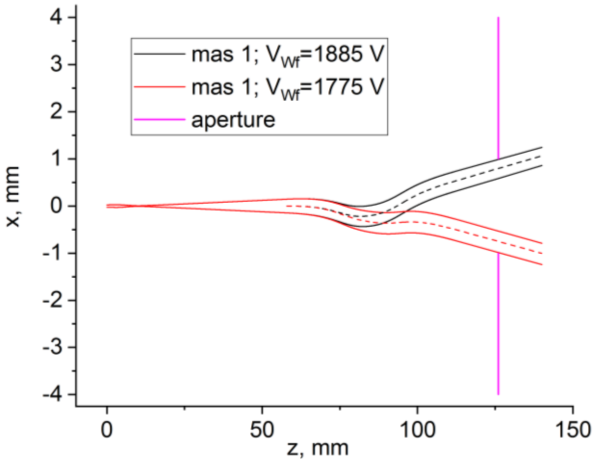

Fig. 7. Variation of the voltage on the deflecting plates in the Wien filter under the condition of free passage of a proton beam with an aperture of 2 mm (see Fig. 1)

CONCLUSIONS

1. The Wien filter effectively separates the beam, separating the second and third masses of ions.

2. The voltage value of 1828 V on the deflecting plates of the Wien filter was determined, provided that the proton beam passes through the cut-off aperture with a deviation from the axis of <10 µm.

3. The limits of voltage change on the deflecting plates of the Wien filter were set to ±55 V, which allow the proton beam through a cut-off aperture with a diameter of 2 mm without loss to be passed.

4. It was shown that the motion of the proton beam in the Wien filter is not rectilinear, due to the difference in the profiles of the longitudinal distribution of the electric and magnetic fields, which leads to the need to correct the ratio between the fields ($E=kvB$, where E, B, v, k are the magnitudes of the electric and magnetic fields, the proton velocity and the correction factor, respectively).

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REFERENCES

1. A.G. Ponomarev, S.V. Kolinko, V.A. Rebrov, D.V. Magilin, I.H. Ihnatiev, V.I. Voznyi, V.F. Salivon. Performance and application of scanning nuclear microprobe at the Institute of applied physics of Natinal academy of sciences of Ukraine // *Nucl. Phys. At. Energy.* 2024, v. 25, p. 289-297; https://doi.org/10.15407/jnpae2024.03.289

2. O. Romanenko, V. Havranek, A. Mackova, M. Davidkova, M. Cutroneo, A.G. Ponomarev, G. Nagy, J. Stammers. Performance and application of heavy ion nuclear microbeam facility at the Nuclear Physics Insttute in Řež, Czech Republic // *Review of Scientific Instruments.* 2019, v. 90, No 1, p. 013701(p. 11); https://doi: 10.1063/1.5070121

3. A.A. Valter, K.B. Knight, G.K. Eremenko, D.V. Magilin, A.A. Ponomarov, A.I. Pisansky, A.V. Romanenko, A.G. Ponomarev. Spatial inves-?igation of some uranium minerals using nuclear microprobe // *Physics and Chemistry of Minerals*. 2018, №45, p. 533-547. https://doi.org/10.1007/s00269-017-0940-z

4. M.B.H. Breese, D.N. Jamieson, P.J.C. King. *Materials Analysis using a Nuclear Microprobe*. New York: John Wiley and Sons Inc., 1996, 428 p.

5. I. Rajta, G.U.L. Nagy, I. Vajda, S.Z. Szilasi, G.W. Grime, F. Watt. First resolution test results of the Atomki nuclear nanoprobe // *Nucl. Instr. And Meth. B.* 2019, v. 449, p. 94-98; https://doi.org/10.1016/j.nimb.2019.03.056

6. G. Nagy, H. J. Whitlow, D. Primetzhofer. The scanning light ion microprobe in Uppsala – Status in 2022 // *Nucl. Instr. And Meth. B.* 2022, v. 533, p. 66-69; https://doi.org/10.1016/j.nimb.2022.10.017

7. A. G. Ponomarev, A. A. Ponomarov. Beam optics in nuclear microprobe: A review // *Nucl. Instr. and Meth. B.* 2021, v. 497, p. 15-23; https://doi.org/10.1016/j.nimb.2021.03.024

8. S.V. Kolinko, A.G. Ponomarev, V.A. Rebrov. Precise centering and field characterization of magnetic quadrupole lenses // *Nucl. Instr. And Meth. A.* 2013, v. 700, p. 70-74; http://dx.doi.org/10.1016/j.nima.2012.10.072

9. K.I. Melnik, D.V. Magilin, A.G. Ponomarev. Experimental results of microprobe focusing by quadrplet with four independent lens power supplies // *Nucl. Instr. And Meth. B.* 2013, v. 306, p. 17-20; http://dx.doi.org/10.1016/j.nimb.2013.01.037

10. A.A. Ponomarova, K.I. Melnik, G.S. Vorobjov, A.G. Ponomarev. One-stage probe-forming systems with quadrupole lenses excited by individual power supplies // *Nucl. Instr. And Meth. B.* 2011, v. 269, p. 2202-2205; https://doi:10.1016/j.nimb.2011.02.025

11. A.G. Ponomarev, K.I. Melnik, V.I. Miroshnichenko. Parametric multiplets of magnetic quadruole lenses: application prospects for probe-forming systems of nuclear microprobe // *Nucl. Instr. And Meth. B.* 2005, v. 231, p. 86-93; https://doi:10.1016/j.nimb.2005.01.039

12. V.A. Brazhnik, A.D. Dymnikov, D.N. Jamieson, S.A. Lebed, G.J.F. Legge, A.G. Ponomarev, V.E. Storizhko. Numerical optimization of magnetic nonlinear quadrupole systems in an ion microprobe with given spot size on the target // *Nucl. Instr. And Meth. B.* 1995, v. 104, p. 92-94.

13. S. Matsuyama, M. Miwa, S. Toyama, T. Kamiya, Y. Ishii, T. Satoh. Current status of the Tohoku microbeam system at Tohoku University and other facilities // *Nucl. Instr. And Meth. B.* 2023, v. 539, p. 79-88; https://doi.org/10.1016/j.nimb.2023.03.023

14. V.E. Storizhko, A.G. Ponomarev, V.I. Miroshnichenko. Patent of Ukraine, UA 67341A, G01N23/00, 2003038121 (15.06.2004 Bulletin N6).

15. I.G. Ignat'ev, D.V. Magilin, V.I. Miroshnichnko, A.G. Ponomarev, V.E. Storizhko, B. Sulkio-Cleff. Immersion probe-forming system as a way to the comact design of nuclear microprobe // *Nucl. Instr. and*

Meth. B. 2005, v. 231, p. 94-100;
https://doi:10.1016/j.nimb.2005.01.040

16. D. Magilin, A. Ponomarev, V. Rebrov, A. Ponomarov. High-voltage scanning ion microscope: Beam optics and design // *Nucl. Instr. And Meth. B.* 2015, v. 350, p. 32-35;
https://dx.doi.org/10.1016/j.nimb.2015.03.032

17. V.I. Voznyi, A.G. Ponomarev, D.V. Magilin, D.P. Shulha, V.A. Rebrov. Characteristics of low power RF ion source // *Problems of Atomic Science and Technology.* 2025, №3(157), p. 94-99;
https://doi.org/10.46813/2025-157-094

18. M. Szilagyi. *Electron and ion optics*. Springer. New York, NY, 1988, 556 p.

19. E. Everhart. Implicit single-sequence methods for integrating orbits // *Celestial Mechanics.* 1974, v. 10, p. 35-55; https://doi.org/10.1007/BF01261877

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ІНЖЕКТОР ІОНІВ КОМПАКТНОГО СКАНУЮЧОГО ЯДЕРНОГО МІКРОЗОНДА. ЧИСЛОВЕ МОДЕЛЮВАННЯ

О.Г. Пономарьов, В.І. Возний, В.А. Ребров, В.В. Журакулов, Д.В. Магілін

Проведено числове моделювання динаміки пучка іонів в інжекторі компактного ядерного скануючого мікрозонда. Інжектор складається з ВЧ-джерела іонів малої потужності з мікрометровим отвором екстрактора і фільтра Вина з постійними магнітами. Показано, що розглянутий інжектор ефективно сепарує іони H_1^+, H_2^+ і H_3^+. Визначено величину напруги, необхідну для живлення електростатичних пластин при виділенні протонів за умови відхилення пучка від осі інжектора <10 мкм. Встановлено похибку у величині напруги для допустимого відхилення пучка від осі за умови проходження пучком протонів апертури діаметром 2 мм.