Effect produced by a space charge and spherical aberration of lenses on a negative hydrogen ion beam injected into a vacuum-insulated tandem accelerator

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ABSTRACT: A source of epithermal neutrons based on a vacuum-insulated tandem accelerator and a lithium target is developed for the technique of boron neutron capture therapy. A stationary proton beam of 2 MeV with a current of up to 5 mA was obtained in the accelerator. With a view of increasing the current, the transport of a beam of negative hydrogen ions from the ion source to the accelerator is studied using a wire scanner and an emittance meter. The dependence of the ion beam profile and the current on the residual gas pressure is measured and the influence of the space charge is detected. We measured the phase portrait of the beam in the radial and azimuth directions and discovered the effect produced by the aberrations of the focusing magnetic lens. We also gaged the value of the normalized beam emittance. Recommendations are given on the modernization of the beam transport path in order to increase the proton current.

KEYWORDS: charged particle accelerator; wire scanner; emittance meter.

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1. Introduction

An accelerating source of epithermal neutrons was proposed and created at the Budker Institute of Nuclear Physics [1] for the further development of a promising technique for the treatment of malignant tumors - boron neutron capture therapy [2, 3]. Neutron generation results from ^{7}Li(p,n)^{7} threshold reaction initiated by directing a 2-MeV proton beam with a current of up to 5 mA produced in a vacuum-insulated tandem accelerator [1, 4] to a 10-cm diameter lithium target [5]. With a view of increasing the current, the transport of a beam of negative hydrogen ions from the ion source to the accelerator is studied using a wire scanner and an emittance meter.

2. Experimental facility

Fig. 1 schematically shows a fragment of the experimental facility used in these experiments. Negative hydrogen ions with an energy of 22 keV are generated by a surface plasma source *1* using the Penning discharge with hollow cathodes. The beam of negative hydrogen ions leaving the source rotates through an angle of 15° in the source magnetic field, passes through the aperture of a conical diaphragm with a diameter of 28 mm (*2*), is focused by a pair of magnetic lenses *5* and is injected into the vacuum-insulated tandem accelerator. The gas is pumped out by two turbomolecular pumps TMP-3203lm (Shimadzu, Japan) *4* and *13* at a hydrogen pumping rate of 2400 l/s. The residual gas pressure is regulated by the leak valve *12*. The residual gas pressure is measured by a vacuum lamp Pfeiffer vacuum d-35614 *3*.

The current and profile of the negative hydrogen ion beam injected into the accelerator are measured by the wire scanner OWS-30 (D-Pace, Canada; under the license of TRIUMF) [6] *7* placed before the cooled diaphragm *8*. In the scanner, there are two orthogonal tungsten wires 0.5 mm in diameter, 49 mm long and fixed on a common rod, which is deflected from the axis crossing the center of the ion beam by an angle of 13.5°, and when it is used for measuring, it rotates to an angle of -13.5° and comes back. The rotation axis of the rod is at a distance of 190 mm from the center of the ion beam. When the rod moves, the current is measured (with an error of 10^{-10}A) as well as the deflection angle of the rod; these values with the beam diameter less than 30 mm allow one to reconstruct the transverse profile of chordal measurements of the ion beam current in two orthogonal planes and to determine the value of the total current [7]. The secondary emission of electrons from the scanner wires, which was measured to be 1.61 ± 0.08, was suppressed by applying a potential of -300 V to two metal rings *11* installed before and after the scanner.

The scanner was also used to measure the current profile of the ion beam when, at a distance of 225 mm, a diaphragm made from a 1 mm thick tantalum plate with a 0.8 mm diameter opening was introduced into the beam. The opening was countersunk on the both sides of the plate. Moving the diaphragm at an angle of 45° to the axis of the scanner made it possible to measure the phase portrait of the beam in the radial and azimuthal directions and to determine the emittance of the beam.

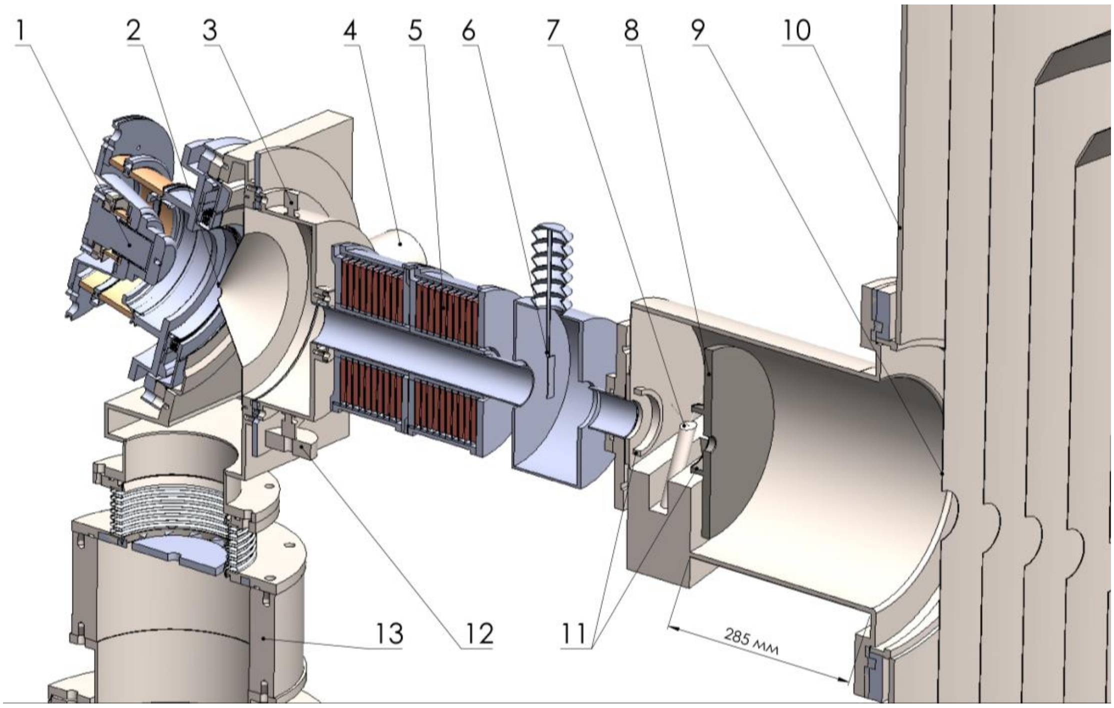

Fig. 1. Experimental facility: *1* – source of negative hydrogen ions, *2* – conical diaphragm, *3* – vacuum lamp, *4* and *13* – turbomolecular pumps, *5* – magnetic lenses, *6* – movable diaphragm, *7* – wire scanner OWS-30, *8* – cooled diaphragm, *9* – the first electrode of the accelerator, *10* – vacuum tank of the accelerator, *11* – metal rings, *12* – leak valve.

3. Measurement results and discussion

Fig. 2 shows the graphs of the current, cross-sectoral area, and current density of the negative hydrogen ion beam versus the pressure of the residual gas regulated by the leak valve. Here, the cross-sectional area is understood as a quantity calculated by the formula of ellipse area where each side of the ellipse is equal to the width, the current area under which is 95% of the total current. Fig. 3 presents profiles of chordal measurements of the ion current and reconstructed radial current distributions.

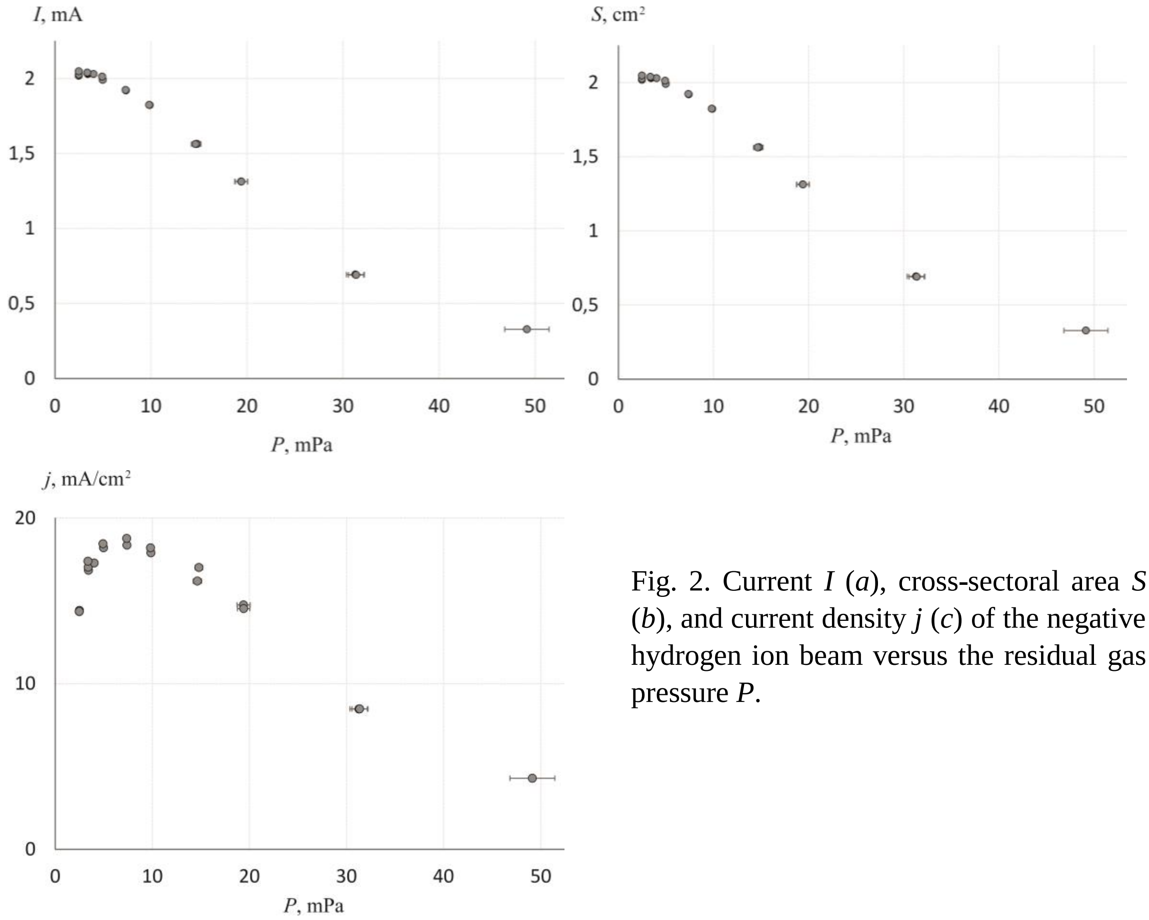

Fig. 2. Current *I* (*a*), cross-sectoral area *S* (*b*), and current density *j* (*c*) of the negative hydrogen ion beam versus the residual gas pressure *P*.

It is seen that the deterioration in the vacuum conditions is accompanied not only by the ion current decrease, which is due to ion stripping on the residual gas but also by the reduction in the beam size, which can be attributed to the weakening effect of the ion charge compensation. The maximum ion current density is attained not under the best vacuum conditions, but at a residual gas pressure of 7.4 ± 0.2 mPa. When the vacuum is improved to the best level of 2.5 ± 0.1 mPa, the ion beam current increases by 5%, and its size grows by 36%, so that the current density decreases by 25%. The injection of a negative hydrogen ion beam into an accelerator with a maximum current density is important for the stable operation of the accelerator since the small aperture of the cooled diaphragm (*8* in Fig. 1) is able to reduce the undesirable penetration of hydrogen being pumped into the ion source and other particles into the accelerator.

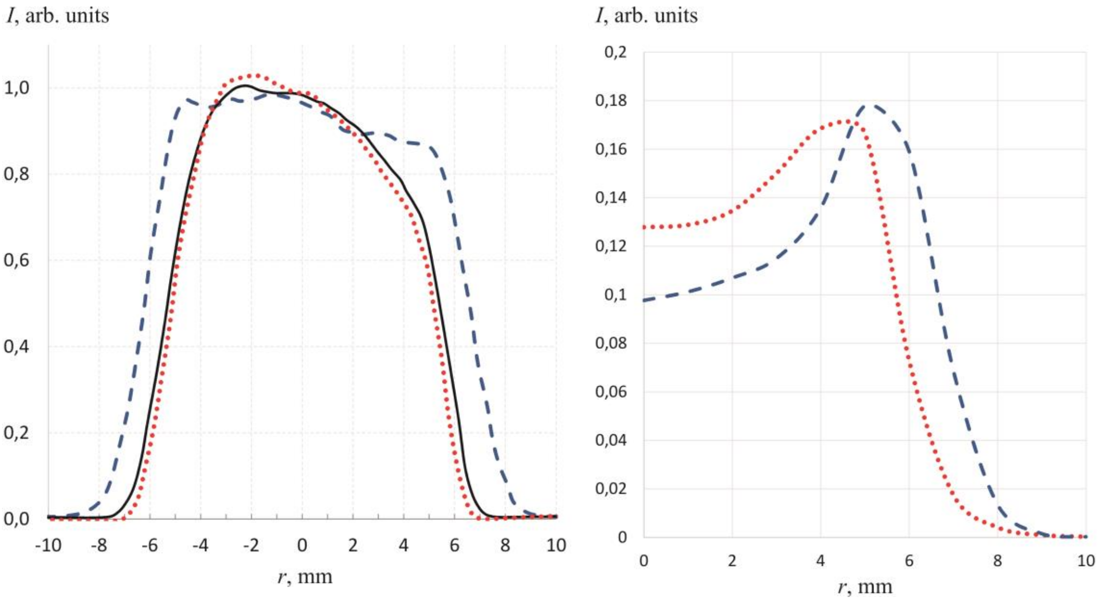

Fig. 3. Profiles of chordal measurements of the ion current (*a*) and reconstructed radial distributions of the ion current (*b*) at different values of residual gas pressure (2.5 mPa - dashed line, 10 mPa - solid line, 20 mPa - dotted line).

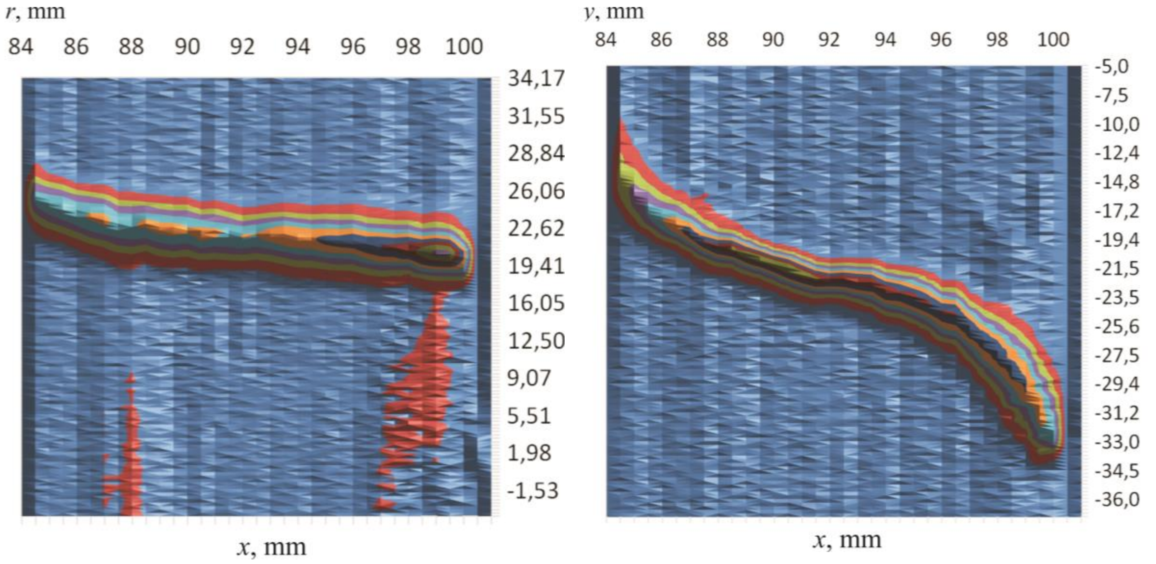

Fig. 4. The phase portrait of the ion beam in the azimuthal (*a*) and radial (*b*) directions. On the ordinate axis, the values of the diaphragm aperture position are plotted, along the abscissa axis - the positions of the scanner wires. For each position of the diaphragm aperture moved by steps of 0.25 mm, distributions of the current measured by the scanner (characteristic values of the current - 10^{-7} - 10^{-6} mA) are constructed. The signal amplitude is presented by uniform partitioning into 10 ranges from the maximum value; the ranges are shown by the same color.

In order to understand the reason for the beam injected into the accelerator being more annular rather than Gaussian, the phase portrait of the beam was measured using a scanner and a movable diaphragm. For reducing the beam size in the diaphragm region, the current of the magnetic lenses was increased from 54 to 65 A. The diaphragm step was 0.25 mm. The results are shown in Fig. 4. The invariant normalized emittance of the beam, in which 2/3 of the current is concentrated, amounted to 1.7 ± 0.1 mm mrad. This emittance is an order of magnitude lower than the acceptance value of the accelerator stripping tube, but clearly visible in Fig. 4b, the difference between the phase portrait of the beam and the ellipse can lead to beam losses in the accelerating path. This curvature of the portrait is due to the spherical aberration of the magnetic lenses caused by the large initial divergence of the generated ion beam. The improvement in the quality of the ion beam injected into the accelerator and, accordingly, the reduction in the ion losses during acceleration requires lessening the effect produced by spherical aberrations of the lenses, which is possible either by increasing the aperture of the lenses or by decreasing the size of the ion beam in the lens region.

4. Conclusion

The OWS-30 wire scanner (D-Pace, Canada) was used to measure the dependence of the profile and current of negative hydrogen ion beam injected into a vacuum-insulated tandem accelerator on the residual gas pressure. The phase portrait of the beam was measured in the radial and azimuthal directions by means of a scanner and a movable diaphragm. We were the first to discover the effect of a space charge and aberrations of a focusing magnetic lens on a beam of negative hydrogen ions. It has been established that the beam profile is close to annular and the maximum beam current density is attained at an intermediate pressure of the residual gas in the transport channel equal to 7.5 mPa. The value of the normalized beam emittance is determined; its value is 1.7 ± 0.1 mm mrad. To reduce ion beam losses in the accelerator, it is recommended to decrease the size of the beam of negative hydrogen ions in the region of the focusing magnetic lenses or to increase the aperture of the lenses.

Acknowledgments

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