ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPML062

ACCELERATOR NEUTRON SOURCE FOR BORON NEUTRON CAPTURE THERAPY *

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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. Neutron generation was performed and the flux and neutron spectrum were experimentally measured. A Beam Shaping Assembly was developed and manufactured, which makes it possible to form a therapeutic beam of neutrons to the greatest extent satisfying the requirements of BNCT. It was established that neutron irradiation of tumor cells of human glioma U251 and human glioblastoma T98G, previously incubated in a medium with boron, led to a significant suppression of their viability. Irradiation of mice with grafted human glioblastoma tumor led to their complete cure. In order to increase the beam parameters, the facility was equipped with a wire scanner OWS-30 (D-Pace, Canada), a FLIR infrared camera, an Optris pyrometer, cooled diaphragms with thermistors, telescopic beam receivers with thermoresistors, a new bushing insulator. The investigations established the effect of space charge and spherical aberration of lens on the ion beam transport, the dependence of the heating of the diaphragms of the electrodes and the size of the proton beam on the current of the injected beam of negative hydrogen ions and the pressure of the residual gas in the transport channel.

INTRODUCTION

An accelerating source of epithermal neutrons was proposed and created at the BINP [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]. In the paper, the transport of a beam of negative hydrogen ions from the ion source to the accelerator is studied using a wire scanner and video cameras. The study is necessery due to the consequences that are manifested when the current of negative hydrogen ions was injected into the accelerator increases. First, with increasing injection current for stable operation of the accelerator it was required to change the force of the magnetic lens focusing the ion beam to the entrance of the accelerator. Secondly, as the injection current increased the frequency of high voltage breakdowns increased. Thirdly, when the injection current was increased the diaphragms of the accelerating electrodes are heated up to 1000 °C. It was necessary to find out the reasons for these phenomena before replacing the source of negative hydrogen ions with a new one with a high current and obtaining a beam of protons with a current of more than 10 mA.

* Work supported by Russian Science Foundation (No. 14-32-00006-P)
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EXPERIMENTAL FACILITY

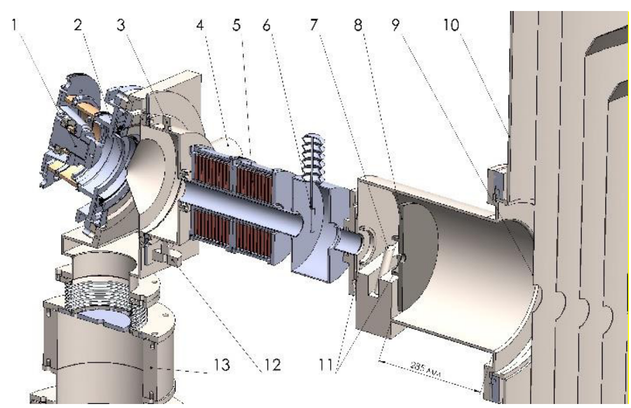

Figure 1: Experimental facility: *1* – source of negative hydrogen ions, *2* – conical diaphragm, *3* – vacuum lamp, *4* and *13* – turbomolecular pumps, *5* – magnetic lenses, *6* – movable diaphragm, *7* – wire scanner OWS-30, *8* – cooled diaphragm, *9* – the first electrode of the accelerator, *10*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

Figure 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*. The beam of ions leaving the source rotates through an angle of 15° in the source magnetic field, passes through the aperture of a conical diaphragm (*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 *4* and *13* at a hydrogen pumping rate of 2400 l/s. The residual gas pressure is regulated by the leak valve *12* added for this experiment. The residual gas pressure is measured by a vacuum lamp Pfeiffer vacuum d-35614 *3*.

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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) *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. The secondary emission of electrons from the scanner wires, which was measured to be 2.61 ± 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. 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.

EXPERIMENTAL RESULTS

Figure 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.

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%. Thus, it became clear that there was no need to improve the gas pumping out in the beam transport path. The optimal beam input is realized at some residual gas pressure, in this case 7.4 mPa, sufficiently small for minor stripping of the ion beam and large enough to compensate for the space charge effect. 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 is able to reduce the undesirable penetration of hydrogen being pumped into the ion source and other particles into the accelerator.

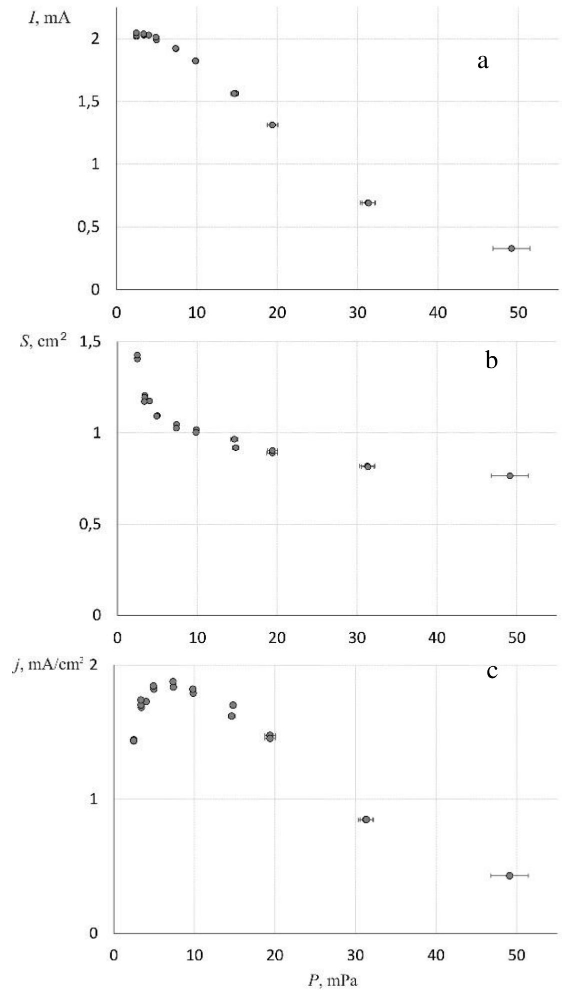

Figure 2: Current I (*a*), cross-sectoral area S (*b*), and current density j (*c*) of the negative hydrogen ion beam versus the residual gas pressure P.

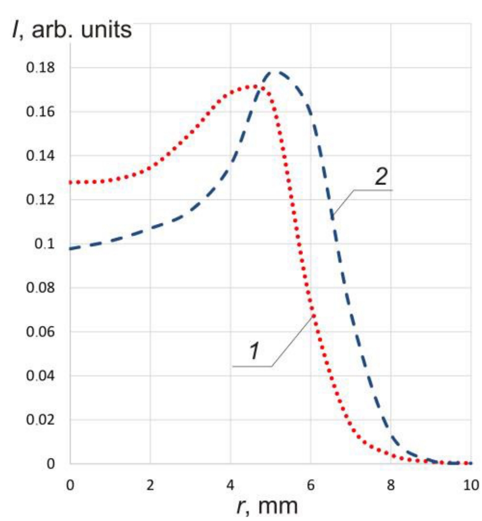

Figure 3: Profile of reconstructed radial distributions of the ion current at different values of residual gas pressure (20 mPa - *1*, 2,5 mPa - *2*).

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Making the Abelian transformation of chordal measurements of the ion current, we obtain the radial distribution of the ion beam current, which is shown in Figure 3. It can be seen that the ion beam is annular, as the pressure of the residual gas decreases its size increases and it becomes more hollow.

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. The results are shown in Figure 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. 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.

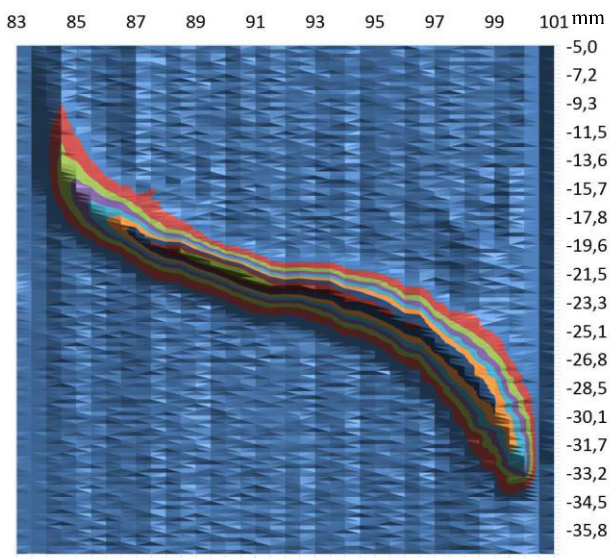

Figure 4: The phase portrait of the ion beam. On the ordinate axis, the values of the diaphragm aperture position are plotted (in mm), along the abscissa axis - the positions of the scanner wires (in mm).

We abandoned the second magnetic lens and increased the current in the first by 1.4 times to increase the ion current and reduce spherical lens aberrations.

Two video cameras Hikvision were installed in the accelerator, which detected the radiation produced by the interaction of the ion beam with the residual and stripping gases, and the radiation from the heated diaphragm of the first accelerating electrode (potential +166 kV). Figure 5 shows the image from the video camera, on which the ion beam is visible in blue, and the diaphragm is red. The image from the video cameras made it possible to monitor the position of the ion beam in two directions in real time.

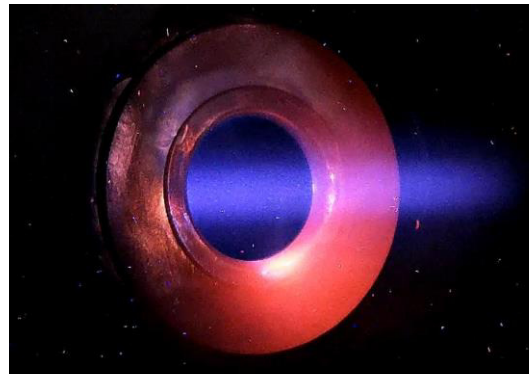

Figure 5: The camera image.

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 by means of a scanner and a movable diaphragm. The effect of a space charge and aberrations of a focusing magnetic lens on a beam of negative hydrogen ions is discovered. 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.

The change in beam focusing mode and the introduction of optical diagnostics of the beam position in the diaphragm of the first accelerating electrode made it possible to significantly improve the stability of the accelerator operation when working with a high current of the proton beam, up to 6 mA.

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