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OPTICAL DIAGNOSTICS OF 1 MeV PROTON BEAM IN ARGON STRIPPING TARGET OF A TANDEM ACCELERATOR*

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Abstract

A neutron source for boron neutron capture therapy based on a vacuum-insulated tandem accelerator has been developed and operates at Budker Institute of Nuclear Physics. Conducting a ~10 mm proton beam with a power of up to 20 kW through a system of accelerating electrodes and 16 mm argon stripping tube is not an easy task. Any mistake made by operator or a malfunction of the equipment responsible for the correction of the beam position in the ion beam line can lead to permanent damage to the accelerator when a powerful beam hits the surface of the stripping tube or diaphragms of the electrodes. To determine the position of the proton beam inside the argon stripping tube, optical diagnostics have been developed based on the Celestron Ultima 80-45 telescope and a cooled mirror located at an angle of 45° to the beam axis in the straight-through channel of the bending magnet. The cooled mirror, in addition to the optical function, also performs the function of measuring the neutral current due to the electrical isolation of the mirror and the extraction of secondary electrons from its surface. The luminescence of a beam in the optical range, observed with the help of the developed diagnostics, made it possible for the first time to determine beam size and position inside the stripping tube with an accuracy of 1 mm. The light sensitivity of applied optical elements is sufficient for using a shutter speed from 2 to 20 ms to obtain a color image of the beam in real time. This makes it possible to realize a fast interlock on the event of a sudden displacement of the beam.

INTRODUCTION

Boron neutron capture therapy (BNCT) is currently considered as a promising technique for treatment of malignant tumors [1, 2]. Two clinics using accelerator based BNCT technique began treating patients in 2020 and four more BNCT clinics are ready to start. An accelerator neutron source developed [3] at Budker Institute of Nuclear Physics serves as a prototype for a facility constructed in 2021 for a BNCT clinic in Xiamen (China). It is planned to equip the National Medical Research Center of Oncology (Moscow, Russia) and National Oncological Hadron Therapy Center (Pavia, Italy) with the same vacuum-insulated tandem accelerators (VITA). Safety and durability of the new type of the accelerator are very important in case of 24/7 clinical operation and have not been studied in detail yet. One of the possible reasons that can lead to permanent damage of the accelerator and interrupt normal operation is the situation when a powerful ion beam hits the surface of the stripping tube or diaphragms of the accelerating electrodes. Since 2008, the year we obtained first neutrons at the accelerator [4], the stripping tube and diaphragms were damaged several times by the beam (Fig. 1).

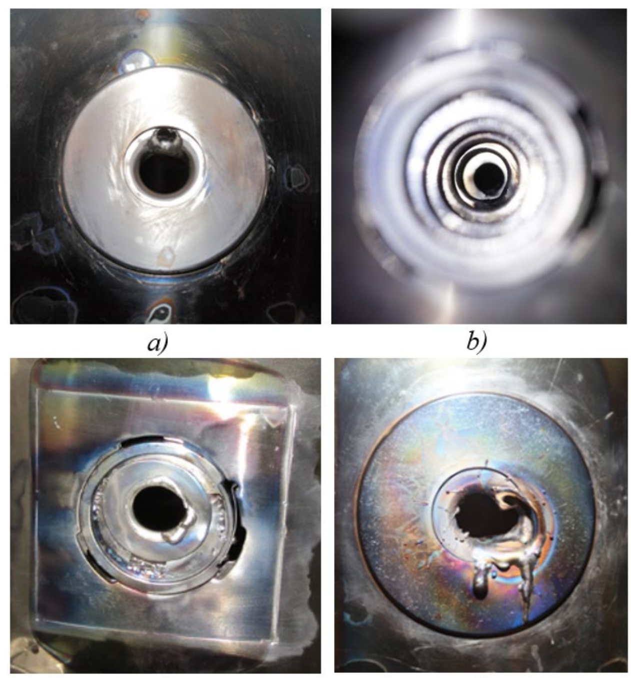

Figure 1: Photos of accelerator diaphragms (diameter is 20 mm) melted by the beam in different times: a) 12.2011, b) 03.2013, c) 03.2015, d) 06.2016.

With a DC current of up to 10 mA and energy of 2 MeV it takes only a few seconds for the beam to melt a diaphragm. In this case, one second of beam displacement will cost 2 weeks of repairing the accelerator. Reasons of sudden beam displacement from the axis can be different: it can be a mistake made by operator, or a malfunction of the equipment responsible for the correction of the beam position, or fast variation in conditions of a gas discharge in the H^- ion source. In this paper we describe an optical diagnostics that is capable to determine the position and size of the proton beam inside the accelerator with an accuracy better than 1 mm in real time. Such diagnostics can improve the reliability of the accelerator in clinical use. Available beam diagnostics, such as optical diagnostics at the entrance to the accelerator [5], calorimetric diagnostics

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of a charge-exchange tube, and measurement with a wire scanner [6] do not allow *in situ* estimation of the position, size, and shape of the beam inside the stripping tube. The speed of operation and the accuracy of these diagnostics also do not allow the implementation of fast interlock on the event of a sudden displacement of the beam.

EXPERIMENTAL SETUP

Figure 2 shows the VITA and the high-energy beam transporting channel where the new optical diagnostics is installed. Coming from source *1* the low-energy negative hydrogen ion beam is injected into accelerator *2* and accelerated up to 1 MeV. In argon stripping tube *3* negative hydrogen ions are converted into protons. Then protons are accelerated by the same 1 MV potential to an energy of 2 MeV. Accelerated proton beam is transported through the high-energy beam line and received by the lithium target *5* when the bending magnet *4* is switched on. In this case, thanks to the straight-through channel of the bending magnet, uncharged particles and visible light can pass directly into the vacuum chamber *6*. This property is used to register the glow in the stripping tube. With the help of a cooled mirror installed inside chamber *6* at an angle of 45° to the axis of the accelerator, visible light is directed into telescope *7* Celestron Ultima 80-45.

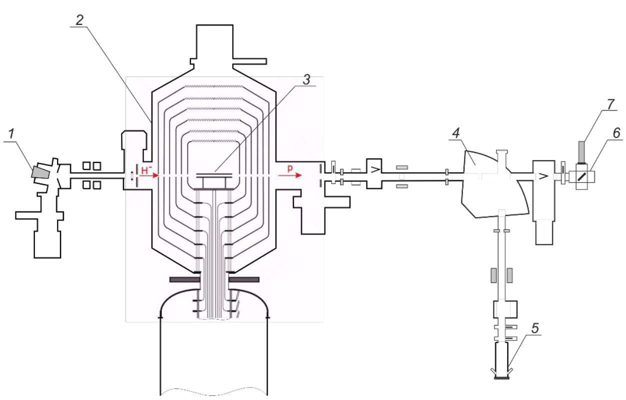
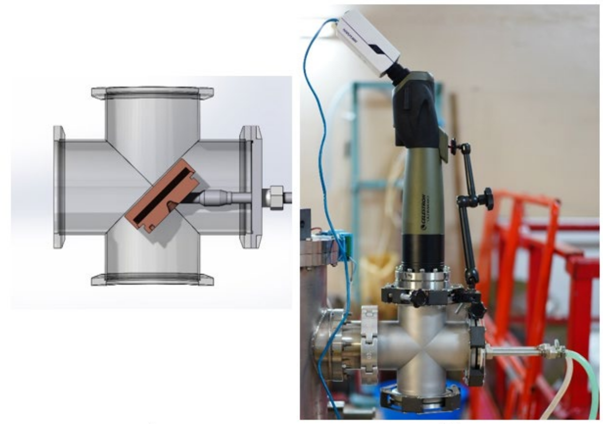


Figure 2: Experimental setup: *1* – negative hydrogen ion source, *2* – accelerator, *3* – argon stripping tube, *4* – bending magnet, *5* – lithium target, *6* – vacuum chamber with cooled 45° mirror, *7* – telescope.

Let us look in detail at the design of the cooled mirror. A typical proton beam charge-exchange rate is about 95%. This means that the power of the neutral H^0 beam hitting the mirror is 2.5% of the power of the proton beam, i.e. up to 500 W/cm^2 at 10 mA 2 MeV proton beam. Such thermal load requires the organization of effective forced cooling. Plus, significant deformations due to thermal expansion of the metal cannot be allowed for the mirror, as well as deformations as a result of the supply of water pressure to the cooling channels. All these considerations formed the basis for the design of the cooled copper mirror (Fig. 3). The mirror is electrically insulated from the facility body. Due to the electrical isolation of the mirror and the extraction of secondary electrons from its surface, it is possible to measure the current of neutrals and the charge-exchange rate in real time [7]. The vacuum window is made of barium fluoride, so it can be used to install an infrared camera instead of a telescope.

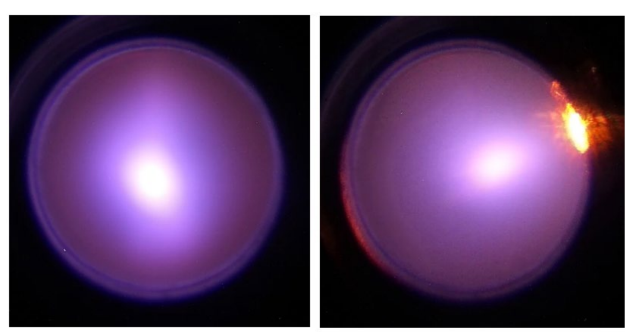


a) *b)*

Figure 3: Construction of the cooled mirror: a) technical drawing, b) photo of the installed diagnostics.

EXPERIMENTAL RESULTS

Before the experimental results were obtained, it was not obvious whether, in principle, it would be possible to get an image of the beam inside the charge-exchange tube. This could be prevented by several phenomena: 1) the glow of the beam in the high-energy beam transporting channel could eclipse the light from the stripping tube, 2) the light sensitivity of the used optical elements could be insufficient. Fortunately, this did not happen and we managed to get an image of the 2 mA beam inside the charge-exchange tube (Fig. 4*a*). At Fig. 4*b*, one can see the moment of displacement of the beam, which occurred due to the breakdown inside the H$^-$ ion source. The beam shifted and returned to its place within less than 20 ms, however, thanks to the fast shutter speed, this moment was captured.



a) *b)*

Figure 4: Photo of the 2 mA proton beam in 16 mm argon stripping tube taken at 1/100 s shutter speed: a) normal operation, b) sudden beam displacement.

Looking at Fig. 4*a*, we get a typical beam size inside the accelerator equal to 3×5 mm. Now we can estimate the minimum time required for the beam to melt the accelerator diaphragm. To heat a part of a stainless-steel

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diaphragm with a thickness of 2 mm up to the melting point, it is necessary to spend energy Q equal to:

$$Q = c\ m\ \Delta T = 154\ \mathrm{J}\ ,$$

where c is the heat capacity, m is the mass, and ΔT is the temperature of the part of the diaphragm heated by the beam. Accordingly, at 10 kW beam power, this will take at least 15 ms. We assume the energy of the beam and, accordingly, its power, relying on our experience: the entrance diaphragm of the central electrode was damaged most often (see Fig. 1), the beam energy in this case is 1 MeV.

To estimate the minimum melting time, we assume the worst-case scenario, namely, that the entire beam hits the diaphragm of the central electrode without touching other diaphragms. And also, we assume that the size of a 10 mA beam does not exceed 3×5 mm. We also neglect heat transfer along the diaphragm and energy losses due to infrared radiation. A relatively large error can be hidden in the assumption that the diaphragm was not heated previously (by the edge of the beam or accompanying particles). In any case, the speed of the developed diagnostics is sufficient to implement interlock, since the longest time is taken by the frame exposure varying from 2 to 20 ms (depending on the beam current, for a large current – it is smaller), other times are shorter.

CONCLUSION

With the help of developed optical diagnostics, it was possible for the first time to see a beam inside the charge-exchange tube of the VITA. Diagnostics makes it possible to determine in real time the shape of the beam, as well as its displacement from the axis of the accelerator with an accuracy of better than 1 mm. The sensitivity of applied optical elements is sufficient to realize fast interlock when the beam suddenly moves. Such diagnostics can improve the reliability of the VITA in clinical use.

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