SUPPRESSION OF CONCOMITANT FLOW OF CHARGED PARTICLES IN THE TANDEM ACCELERATOR WITH VACUUM INSULATION*

S. Yu. Taskaev[†], D. Kasatov, A. Makarov, Yu. Ostreinov, I. Shchudlo. I. Sorokin,
Budker Institute of Nuclear Physics, Novosibirsk, Russia

Abstract

A source of epithermal neutrons based on a tandem accelerator with vacuum insulation for Boron Neutron Capture Therapy of malignant tumors was proposed and constructed. Stationary proton beam with 2 MeV energy, 1.6 mA current, 0.1% energy monochromaticity and 0.5% current stability was obtained. The flow of charged particles accompanying the accelerated ion beam was detected and measured. To suppress this concomitant flow cooled diaphragm, cryopump and the electrostatic ring were installed in the input of accelerator. The surface of the vacuum vessel was covered with netting to suppress secondary electron emission. These steps have reduced the flow of charged particles 25 % of the ion beam to 0.5 % and to increase the current proton beam 3 times up to 5 mA.

INTRODUCTION

Boron neutron capture therapy (BNCT) is currently considered as a promising technique for treatment of malignant tumors [1]. For the widespread introduction of this technique in practice compact epithermal neutron sources based on charged particle accelerators are required. A new type of the accelerator – a tandem accelerator with vacuum insulation – was proposed and constructed in BINP [2]. The accelerator is characterized by fast ion acceleration and a large distance between the ion beam and the insulator (on which electrodes are mounted). After the dark current was decreased to an acceptable level [3], the injection of a negative hydrogen ion beam into the accelerator [4] and stripping in the gas stripping target was optimized [5], the proton beam current was increased from the initial values of about 140 µA [6] to 1.6 mA [7], which was stable for more than one hour. In the elucidation of the reasons for the limitation of the current in the tube for accelerating negative hydrogen ions, a significant electron flow and a counter-flow of positive ions generated in the acceleration tube and in the stripping target were found and measured [8].

EXPERIMENTAL RESULTS

Figure 1 shows the accelerator. Coming from source *1* the low-energy negative hydrogen ion beam is defected in a magnetic dipole field by an angle of 15 degrees, focused by a pair of magnetic lenses *2*, injected into accelerator *3* and accelerated up to 1 MeV. In a gas (argon) stripper *7*, which is installed inside a high-voltage electrode *6*, negative hydrogen ions are converted into protons. Then pro-

tons are accelerated by the same 1 MV potential to an energy of 2 MeV. The potential for the high-voltage electrode *6* and five intermediate electrodes *5* of the accelerator is supplied by the high-voltage power supply *9* (most the source is not shown) through insulator *8*, wherein the resistive divider is set. Gas evacuation is performed by turbomolecular pumps *10* mounted on the ion source and at the accelerator exit and a cryogenic pump *4* via jalousies in the electrodes.
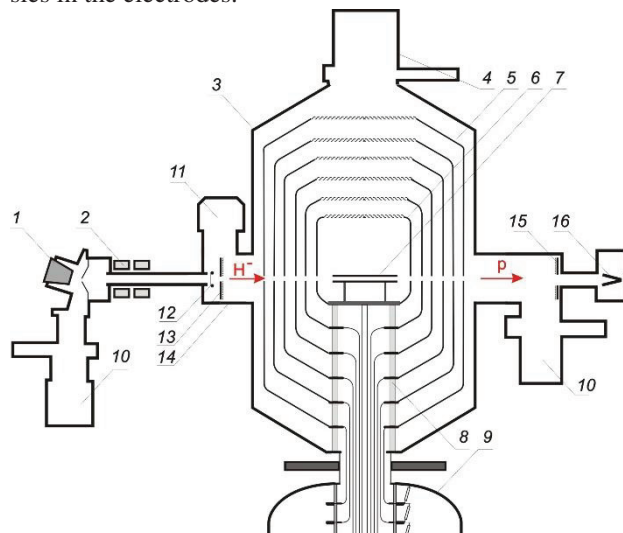

Figure 1: Modernized tandem accelerator with vacuum insulation: *1* – negative hydrogen ion source, *2* – magnetic lenses, *3* – accelerator, *4* – cryogenic pump, *5* – intermediate electrodes, *6* – high-voltage electrode, *7* –gas stripper, *8* – insulator, *9* – high-voltage power supply, *10* – turbomolecular pumps, *11* – cryogenic pump, *12* – ring, *13* – cooled metallic diaphram and end detector with a grid, *14* – intake vacuum volume, *15* – detector with a grid, *16* – Faraday cup.

To measure the current at the accelerator exit, a cooled Faraday cup biased at a positive potential to suppress secondary electrons is used. The difference between the measured load current of the high voltage power supply and the measured proton beam current multiplied by 2 gives the current of associated charged particles. By the associated charged particles we mean negative hydrogen ions that have lost only one electron in the stripper, dark currents, and the electrons and positive ions generated in the acceleration tube and in the striper. In the present experiment we measured the dependence of the proton beam current and the associated particle current on the accelerator voltage at a constant injection current. It is shown in Fig. 2.

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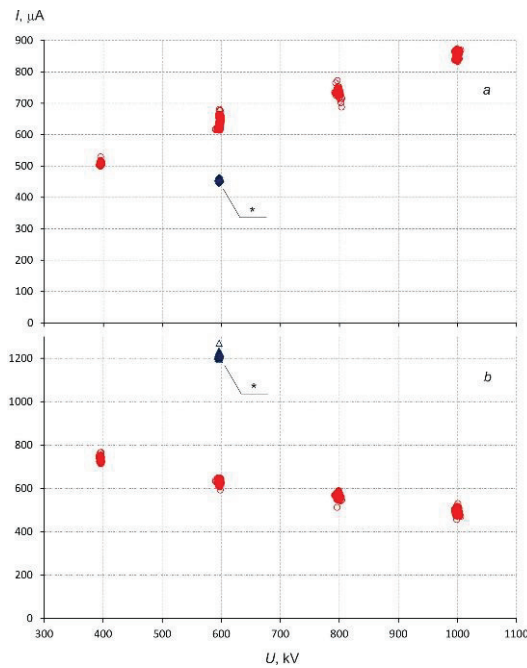
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Figure 2: Dependence of the proton beam current (*a*) and the associated particle current (*b*) on the accelerator voltage. The results obtained with a switched off cryogenic pump are denoted by *.

It can be seen that when the accelerator voltage decreases, the proton current decreases, while the associated particle current increases. This can be due to bad vacuum conditions. This is confirmed by the result obtained when the cryogenic pump was switched off: the proton current decreased even more whereas the associated particle current increased. The major contributors to the associated particle current are the electrons and ions generated because the characteristic dark current in the accelerator is about 10 µA and the current of negative hydrogen ions, which have lost only one electron in the stripper, is less than 100 µA. The accelerator entrance appears to be a critical point: here the injected ions still have a relatively low energy. As a consequence, there is a high probability of their interaction with atoms and molecules of the residual gas. The residual gas pressure at this point can be high because the gas flow from the stripper and the negative hydrogen ion source comes here.

To prevent undesirable ion beam stripping we improved the vacuum conditions at the accelerator entrance by modernization of the accelerator. In the modernized accelerator, an intake vacuum volume (*14* in Fig. 1) was replaced by a new larger one. On the upper flange plate of the volume an additional cryogenic pump *11* was installed (*11* in Fig. 1). With the intent to improve the vacuum conditions within the entrance unit, diaphram *13* was also mounted, which serves as vacuum resistance and limits the penetration of gas and ultraviolet radiation into the acceleration tube. The installation of the diaphram provides the opportunity to move it for centering relative to the ion beam axis. The diaphram is cooled to prevent the secondary electron emission due to its heating by the peripheral part of the injected ion beam. Between the exit

of the beam transport path and the diaphram, metal ring *12* is placed; a negative potential applied to this ring should suppress the flow of electrons accompanying the negative hydrogen ion beam. The entire surface of the diaphram from the accelerator side is covered by a tantalum wire grid to suppress secondary electrons, generated by positive ion irradiation, by supplying a negative potential to it. Between the diaphram and the grid, an insulated metal disk is mounted to measure the positive ion current. A similar disk with grid *15* is mounted within the exit unit of the accelerator.
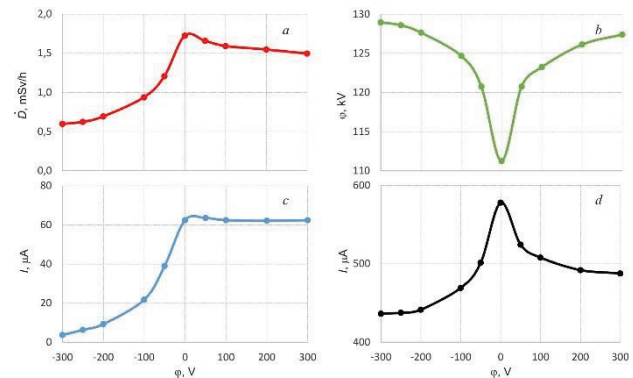

Figure 3: Dependence of the dose rate for bremsstrahlung *D* (*a*), the first electrode potential of the accelerator φ (*b*), the current supplied to the end detector *I* (*c*), and the associated particle current *I* (*d*) on the potential φ simultaneously supplied to the ring and the grid mounted at the accelerator entrance.

The modernization resulted in drastic changes. Fig. 3 depicts the graphs of some measured parameters depending on the potential simultaneously supplied to the grid in the entrance unit of the accelerator and to the ring. The measurements were carried out at an injected current of 800 µA, an accelerator voltage of 900 kV, and the gas supply to the stripping target providing 90 % beam stripping. As can be seen in Fig. 3a, the supply of the potential to the grid at the accelerator entrance significantly decreases the dose rate for bremsstrahlung, which is explained by a decrease in the current of electrons accelerated to the full voltage [9].

The current-voltage characteristic of the end detector (disk with a grid) at the accelerator entrance shown in Fig. 3c indicates that the secondary electron emission coefficient under the effect of positive ions formed is about 10. Such a high secondary electron emission coefficient is typical of many-electron ions and atoms with an energy above 100 keV [10].

The potential supply leads to an increase in the first electrode potential (Fig. 3b) given by a voltage divider and its approach to the equilibrium value of 150 kV obtained in the absence of currents in the gaps. The approach of the potential to the equilibrium value indicates a decrease in the current in the gap between the vacuum tank walls and the first electrode.

Fig. 3d clearly shows that the potential supply results in a noticeable decrease in the associated particle current.

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In total, the inclusion of an additional cryogenic pump, the installation of a diaphram, and the supply of a -300 V potential to the ring and both grids (at the accelerator entrance and exit) cause an increase in the first electrode potential to the equilibrium value, a 3.3 times decrease in the dose rate for bremsstrahlung, and a 10 % increase in the proton beam current. The main factor affecting the first electrode potential is the ring and that affecting the dose rate for bremsstrahlung is the exit grid.

Let us determine an upper estimate of the absolute current of electrons accelerated to the full voltage. Let us assume that the current is carried only by electrons. When both cryogenic pumps are switched off and the grid is grounded, the measured current in the gap exceeds the injected beam current (1.7 mA) by 0.9 mA. This ratio was characteristic of the accelerator and was previously noted in [11, p. 965]. Also, in this case, we observe a noticeable decrease in the first electrode potential, being 0.22 of the equilibrium value. Let us assume that the electrons flow only within the first gap (between the vacuum tank and the first intermediate electrode) and in the acceleration tube up to the high-voltage electrode. Therefore, we assume that the currents are absent between the intermediate electrodes. In this case, the current in the first gap can be easily calculated; it is 465 µA. Correspondingly, the remaining current of 435 µA flows within the acceleration tube. When both cryogenic pumps are switched on and the potential is supplied to the ring and the grids, the total electron current 9 times decreases and the dose rate for bremsstrahlung 20 times decreases. Hence, the total electron current decreased to 100 µA and the current of electrons accelerated to the full voltage decreased to 22 µA. The latter value is about 1 % of the injected beam current. Since the current in the gaps is carried not only by electrons and there is a current between the intermediated electrodes, the electron current is smaller. The analysis of a series of experiments performed gives the current of electrons accelerated to the full voltage of 0.5 % of the injected beam current. It can be said that our actions actually allowed us to remove the associated electron flow from the injected beam.

It is worth noting yet another two points. Firstly, the supply of the -300 V potential to the grid at the accelerator exit decreases the dose rate only by 5 %. Secondly, before the modernization the gas supply in the stripping target resulted in a nearly 4 times increase in the dose rate of deceleration radiation (Fig. 11 in [11]), whereas now it is only 1.5 times increased. These facts indicate that the effect of the stripping gas on the occurring processes ceased to be dominating. The residual gas ionization by the injected ion beam, which leads to the formation of ion-electron pairs in the acceleration tube, plays an important role.

The main result of the modernization is not so much a decrease in the unwanted charged particle flows, as a better high-voltage stability of vacuum acceleration gaps and almost complete disappearance of full-voltage breakdowns. This allowed us to raise the current of the injected negative hydrogen ion beam to the maximum and significantly increase the proton beam current, from 1.6 mA to 5 mA. The measured proton beam current during one hour exceeds 5 mA, with an average value of 5.12 ± 0.06 mA and the maximum of 5.327 mA.

When the proton beam with the 5 mA current generated in a tandem accelerator with vacuum insulation is dumped onto a lithium target, it allows us to obtain the epithermal neutron flow density required for BNCT, which opens the way to use this type of an accelerator based neutron source for BNCT in oncology hospitals [1, 11].

CONCLUSION

The modernization significantly suppressed the unwanted charged particle flows in the tandem accelerator with vacuum insulation. This resulted in the improved high voltage stability of acceleration gaps and enabled an increase in the proton beam current from 1.6 mA to 5 mA. An accelerator with this current can be used in BNCT and other applications.

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