Applied Radiation and Isotopes 106 (2015) 53–56

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Modification of the argon stripping target of the tandem accelerator

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HIGHLIGHTS

- To increase the proton beam current at the vacuum insulation tandem accelerator and to improve reliability of the accelerator it is proposed to modify the gas stripping target creating a transverse magnetic field in front of the target and after the exit.

ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form
19 June 2015
Accepted 25 July 2015
Available online 29 July 2015

Keywords:
Tandem accelerator
Charge exchange
Stripping target

ABSTRACT

The tandem accelerator with vacuum insulation has been proposed and developed in Budker Institute of Nuclear Physics. Negative hydrogen ions are accelerated by the positive 1 MV potential of the high-voltage electrode, converted into protons in the gas stripping target inside the electrode, and then protons are accelerated again by the same potential. A stationary proton beam with 2 MeV energy, 1.6 mA current, 0.1% energy monochromaticity, and 0.5% current stability is obtained now. To conduct Boron Neutron Capture Therapy it is planned to increase the proton beam current to at least 3 mA. The paper presents the results of experimental studies clarifying the reasons for limiting the current, and gives suggestions for modifying the gas stripping target in order to increase the proton beam current along with the stability of the accelerator.

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1. Introduction

The Vacuum Insulated Tandem Accelerator (VITA) was proposed (Bayanov et al., 1998) and developed in Budker Institute of Nuclear Physics to produce epithermal neutrons for Boron Neutron Capture Therapy (BCNT) in the ^{7}Li(p,n)^{7}Be reaction. Fig. 1 shows the accelerator. Coming from the source (Belchenko and Savkin, 2004) the 23 keV negative hydrogen ion beam is rotated in a magnetic field at an angle of 15 deg; it is focused by a pair of magnetic lenses injected into the accelerator and is accelerated up to 1 MeV. In the gas stripping target, which is installed inside the high-voltage electrode, negative hydrogen ions are converted into protons. The stripping target is made as a 400-mm long tube of 16 mm in diameter with the supply of the stripping gas (argon) in the middle (Fig. 2). Then protons are accelerated to the 2 MeV energy by the same 1 MV potential. The potential for the high-voltage and five intermediate electrodes of the accelerator is supplied by a high-voltage source (the most part of the source is not shown) through the insulator, wherein the resistive divider is set. The evacuation of gas is performed by turbomolecular pumps mounted at the ion source and at the exit of the accelerator and a cryogenic pump via jalousies in the electrodes. Neutron generation is carried out by the proton beam bombardment of the lithium target (Bayanov et al., 2006; Kuznetsov et al., 2009).

2. Experimental results

The stationary proton beam with 2 MeV energy, 1.6 mA current, 0.1% energy monochromaticity, and 0.5% current stability is obtained now (Kasatov et al., 2014). With these parameters, the breakdowns at full voltage do not happen more than once per hour, and they do not interfere with work. After the breakdown all the beam parameters are recovered within 20 s.To conduct BNCT it is necessary to increase the proton beam current to at least 3 mA. Attempts to increase the proton beam current by increasing the injected current or increase in the stripping target gas puffing inevitably lead to frequent breakdowns, making the work impossible. To determine the reasons of breakdowns and causes of current limiting an experiment was carried out with a smooth increase in the supply of gas to the stripping target. Fig. 3 shows the dependence of the current in the accelerating gap on the gas

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http://dx.doi.org/10.1016/j.apradiso.2015.07.046
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puffing into the stripping target. The amount of gas puffing is indirectly manifested in the measured residual gas pressure at the accelerator exit. Without a supply of gas to the stripping target residual gas pressure has a value of 2.6×10^{-4} Pa while the cryopump enabled, and the current in the accelerating gap has a value of 1850 μA. When a cryogenic pump is off residual gas pressure has a value of 3.9×10^{-4} Pa, and the current in the accelerating gap is 1770 μA. When the gas is supplied to the stripping target the residual gas pressure is increasing and the current is growing in the accelerating gap. Fig. 3 shows that the current increases almost linearly with increasing pressure of the residual gas. When the cryopump is enabled it becomes possible to increase the gas flow rate to a value that provides 90% proton yield. In this case, as seen from Fig. 3, the current in the accelerating gap amounts to 2100 μA, that is 250 μA more that the value with no gas supply to the stripping target. A further increase in the gas supply leads to frequent breakdowns, making the work impossible. When the cryopump is off it is possible to increase the gas flow only to the value that provides 50% yield protons. In this case, the current in the accelerating gap amounts to 2250 μA, which is 480 μA greater than without stripping gas delivery into the target.

Let us compare the measured residual vacuum pressure with the calculated one. In order to provide a 90% recharge of the beam of negative hydrogen ions into protons an argon target with a linear density of 1.7×10^{16} cm^{-2} is required. The gas consumption is expected to be 0.1 Torr l s^{-1} (Kuznetsov et al., 2012). At an evacuation rate of 3000 l/s performed by a cryogenic pump, which is limited by jalousie system of the electrodes, the pressure in the high voltage electrode is expected to be 5×10^{-3} Pa. The fact that a lamp near the turbomolecular pump shows a better vacuum (2×10^{-3} Pa) at this moment is explained by the placement of the lamp. The estimation performed reveals the absence of contradictions and makes it possible to consider the gas pressure in the interelectrode space of the accelerator to be 2–3 times higher than the measured pressure when gas is puffed into the recharging target.

To study the current in the accelerating gap a special detector was designed and mounted at the inlet into the accelerating gap (11 in Fig. 1). The detector (Faraday cup) consists of two concentric annular disks (the internal one with the diameters of 52 and 90 mm, the outer one with the diameters of 92 and 136 mm) and a frame with a stretched mesh to suppress secondary electron emission. The detector measures only the current flowing from the high voltage electrode. Fig. 4 shows diagrams of the current on the detector at the injection of the negative hydrogen ion beam with a

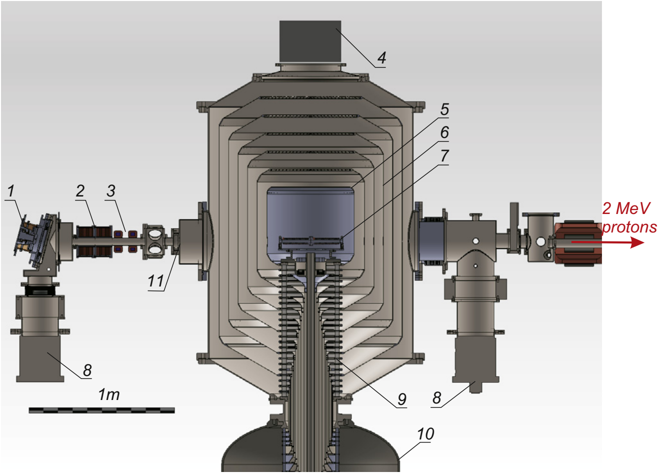

Fig. 1. Tandem accelerator with vacuum insulation: 1 – negative hydrogen ion source, 2 – magnetic lenses, 3 – corrector, 4 – cryogenic pump, 5 – high voltage electrode, 6– intermediate electrodes, 7 – gas stripping target, 8 – turbomolecular pump, 9 – insulator, 10 – high voltage power supply, 11 – inlet diaphragm or detector.

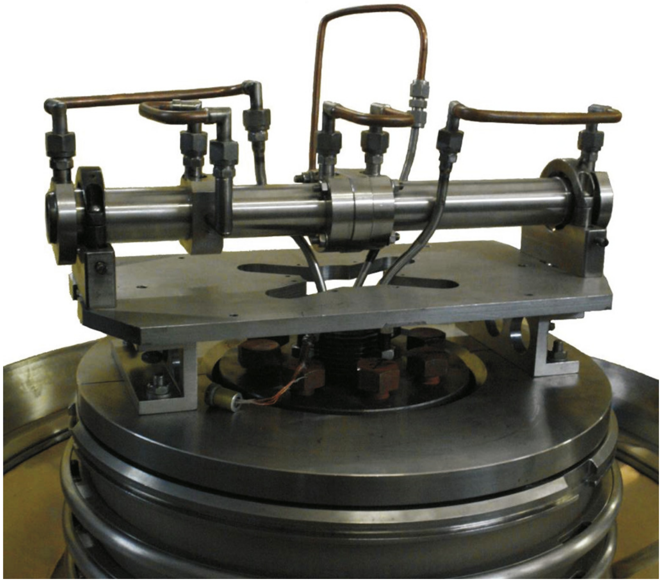

Fig. 2. Photo of the stripping target placed on the feedthrough insulator.

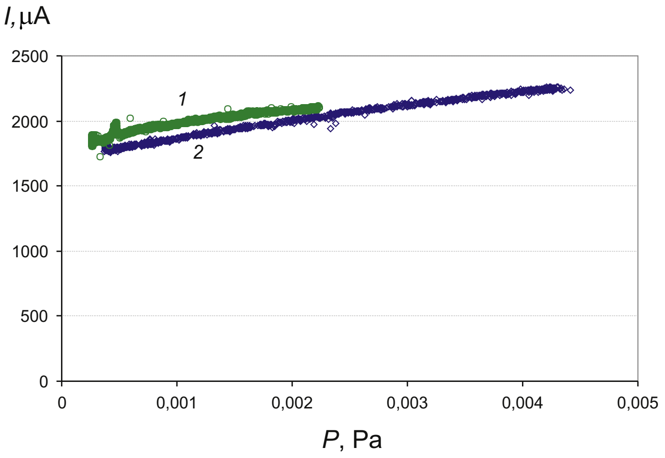

Fig. 3. Dependence of the current in the accelerating gap on the residual gas pressure with an increase in the gas puffing into the stripping target: 1 – cryogenic pumps are switched on, 2 – a cryogenic pump is switched off.

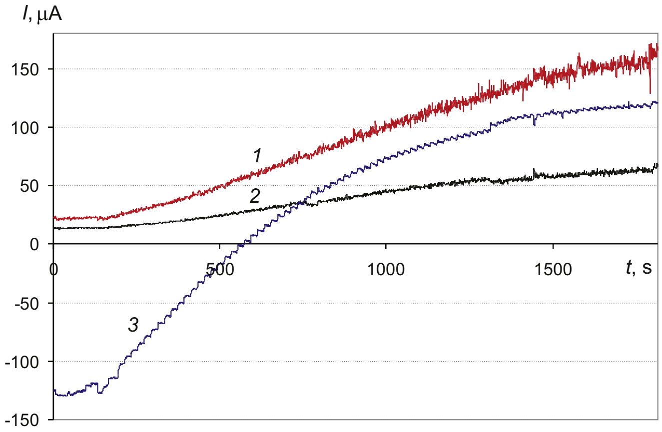

Fig. 4. Diagram of the current to the internal disc of Faraday cup 1 and the external disc of Faraday cup 2 with an increase in the gas puffing into the stripping target. Graph of the current at the output of accelerator 3 is shown (current value is 10 times reduced for convenience).

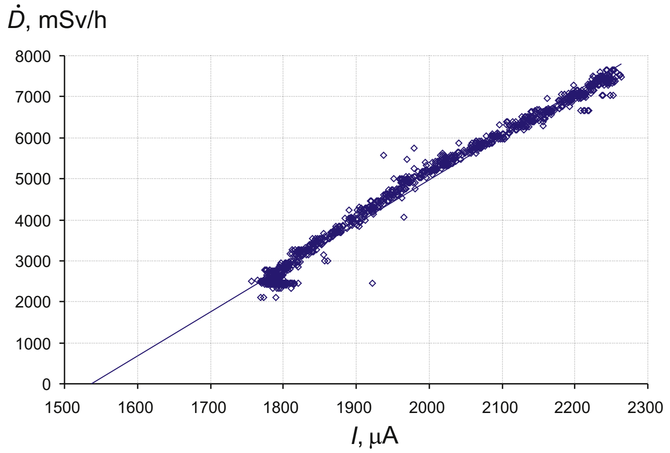

Fig. 5. Dependence of the absorbed dose rate for bremsstrahlung on the current in the accelerating gap.

current of 1.3 mA and after the time instant of 150 s the gas puffing is started to be continuously increased in the stripping target by a short opening of the electromechanical valve for the gas supply at a frequency of 0.05 Hz.

Line 3 in Fig. 4 shows the dependence of the current at the accelerator output by increasing the gas puffing. Until the time 150 s gas was not supplied to the stripping target, stripping of negative hydrogen ions was not carried out and at the output of the accelerator negative current was recorded caused by negative hydrogen ions, which were first accelerated and then decelerated in tandem accelerator. Gas supply to the stripping target leads to conversion of negative hydrogen ions into protons and increasing the current at the output of the accelerator. It is seen that at time 1800 s the current at the output of the accelerator is positive and has a value of 1.2 mA, which corresponds to 90% beam stripping. Note that in this half-hour there was no breakdown of the high voltage.

Lines 1 and 2 in Fig. 4 show almost linear increase in the current to the detector drives up to 140 μA to the internal drive and 50 μA to an external one. Thus, the acceleration of the negative hydrogen ion beam is accompanied by a countercurrent flow of positive ions.

To understand the processes it is important to derive the dependence of the absorbed dose rate for bremsstrahlung measured by a spherical ionization chamber (an air-filling 0.85 l volume with a polyamide wall thickness of about 1.1 mm, coated with a thin layer of colloidal graphite (Sorokin et al., 2012)) placed at a distance of 7.5 m from the accelerator on the current in the accelerating gap. It is presented in Fig. 5. It can be seen that with an increase in the gas puffing, and correspondingly, the current in the accelerating gap the bremsstrahlung power grows linearly. Note that in the absence of a stripping gas flow to the target (with the current of about 1800 μA) the bremsstrahlung is present and its value is significant. Since the absorption of accelerated ions by constructional materials does not lead to a noticeable increase in the absorbed dose rate of bremsstrahlung, it is explained by the electron acceleration in the accelerating channel. Extrapolating the dependence of the radiation power on the current to zero, we obtain the intersection at a current of 1.55 mA. This means that the negative hydrogen ion beam with a current of 1.55 mA is injected into the accelerator. The beam in the accelerating gap ionizes residual gas, resulting in an additional current of 250 μA, which is carried by electrons towards the high voltage electrode and by positive ions towards the grounded tank of the accelerator. The gas supply to the stripping target increases this additional current still further to 500 μA, with a substantial portion of it (190 μA) as a positive ion flow reaching the detector covering the peripheral region.

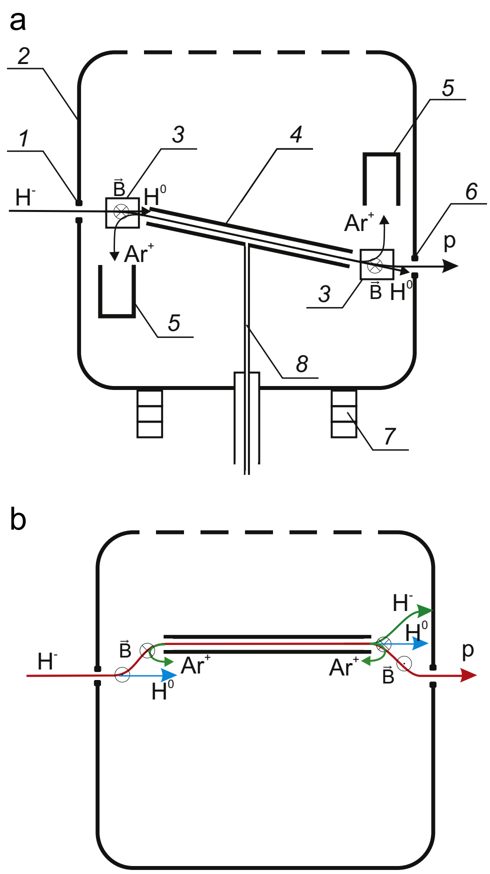

Fig. 6. Variants of the modified gas stripping target: tilted (a), shifted (b).

Thus, it is found that the ion beam ionization of residual and stripping gas as well as the penetration of positive argon ions from the stripping target into the accelerating channel generates the current accompanying the ion beam. The value of the accompanying current is significant. The flow of this current contributes to total voltage breakdowns of the accelerator and therefore requires the suppression.

3. Proposal and conclusion

A further increase in the proton beam current is possible under improved vacuum conditions in the accelerating gap by the planned disposition of a cryogenic pump at the inlet flange of the accelerator and the modification of the stripping target. Options for the target modification are shown in Fig. 6. The modification of the target implies the placement of magnets with the transverse magnetic field before and after the target. The transverse magnetic field almost completely suppresses the penetration of positive argon ions with a characteristic energy of about 10 eV, which formed in the stripping target. Since the magnetic field also affects the ion beam trajectory, it is necessary either to tilt or shift the target with respect to the acceleration path. The target modification can also significantly reduce the flux of gas and ultraviolet radiation in the accelerating gap.

A mode with a shifted target appears attractive because it does not require any changes in the beam line. However, as it was shown by the calculations with the use of the COMSOL Multiphysics software package, the placement of two-pole permanent magnets (NdFeB) in the limited space between the target and the input diaphragm of the high voltage electrode makes it possible to shift the target by no more than 8 mm. Since the input aperture has a high voltage electrode of 20 mm in diameter, the target shift is not sufficient to suppress the gas flux into the accelerating gaps. The substantial suppression of the gas flow into the accelerating gaps in the particular geometry of the accelerator can be implemented with a target inclined at an angle of about 10 deg. The calculations performed show the possible increase in the ion beam emittance with such a target. In this case, it is assumed to shift the electrode aperture of the negative hydrogen ion acceleration path.

Thus, to increase the proton beam current in the vacuum insulation tandem accelerator and to improve the accelerator reliability it is proposed to modify the gas stripping target by generating a transverse magnetic field in front of the target and after the exit.

Acknowledgments

The research is conducted with the financial support of the Ministry of Education and Science of the Russian Federation (a unique identifier for applied scientific research – RFMEFI60414 × 0066).

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