
NUCLEAR EXPERIMENT
TECHNIQUE

Diagnostics of the Efficiency of a Gas Stripping Target of a Tandem Accelerator with Vacuum Insulation

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Abstract—Diagnostics have been developed for measuring the efficiency of stripping a beam of negative ions in a gas stripping target of a tandem charged particle accelerator. The coefficient of ion-electron emission during the bombardment of copper by protons with an energy of 1 MeV was measured. A bending magnet with a horizontal nozzle was installed, which made it possible to place a Faraday cup and receive a stream of neutrals formed on it as a result of incomplete stripping of negative ions in the stripping target. Diagnostics of the efficiency of the gas stripping target were put into operation on the basis of measuring the current of electrons emitted from the surface of a Faraday cup during its bombardment by a directed stream of neutrals and the proton current by a non-contact current sensor.

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An accelerating source of epithermal neutrons [1–3] was created at the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences. The source was proposed and developed for the development of boron neutron capture therapy – a promising method for the treatment of malignant tumours [4, 5]. The source consists of a tandem accelerator with vacuum insulation to produce a proton beam with an energy of 2 MeV and a beam current of up to 9 mA, a lithium target for neutron generation as a result of the ${}^7\text{Li}(p, n){}^7\text{Be}$ threshold reaction and epithermal neutron beam shaping assembly [6].

The accelerator is intended for biological research in the field of boron-neutron capture therapy [7, 8], measurement of the content of undesirable impurities in boron carbide ceramic samples developed for ITER [9], and radiation testing of optical fibers of CMS calorimeter laser calibration systems to ensure the operation of the Large Hadron Collider (CERN) in high luminosity mode.

The need to provide long-term stable neutron generation requires the development of diagnostic techniques that display real-time information from various subsystems of a neutron source.

The purpose of this work was to create diagnostics of the efficiency of stripping an ion beam in a gas stripping target of a tandem accelerator with vacuum insulation.

MATERIALS AND METHODS

The neutron source scheme is shown in Fig. 1, its detailed description was given in [3]. A proton beam with an energy of 2 MeV and a current of up to 9 mA is obtained as follows. From a surface plasma source 1, using a Penning discharge with hollow cathodes, a beam of negative hydrogen ions with an energy of up to 25 keV are pulled. The beam in the magnetic field of the ion source is rotated through an angle of 15° and then focused with a magnetic lens 2 accelerator input 3 [10] and accelerated to an energy of 1 MeV.

In a gas stripping target 4 installed inside the accelerator's high-voltage electrode, negative hydrogen ions are converted into protons, which are then accelerated by the same potential of 1 MV to an energy of 2 MeV. The stripping gas target is made in the form of a cooled cylindrical tube with a hole diameter of 16 mm and a length of 400 mm with a gas inlet in the middle [11].

Gas supply to the target is carried out from a 5-liter cylinder with a GCE gas reducer placed in the high voltage electrode of the power source through the buffer volume. The flow of gas into the volume is controlled by the opening frequency electromechanical valve, which is typically 0.04 Hz. From the buffer volume gas enters the stripping target through a precision needle leak via a 2-m-long tube with an inner diameter of 4 mm located inside the feedthrough insulator.

At the exit from the accelerator, the proton beam has a transverse size of ~1 cm [12].

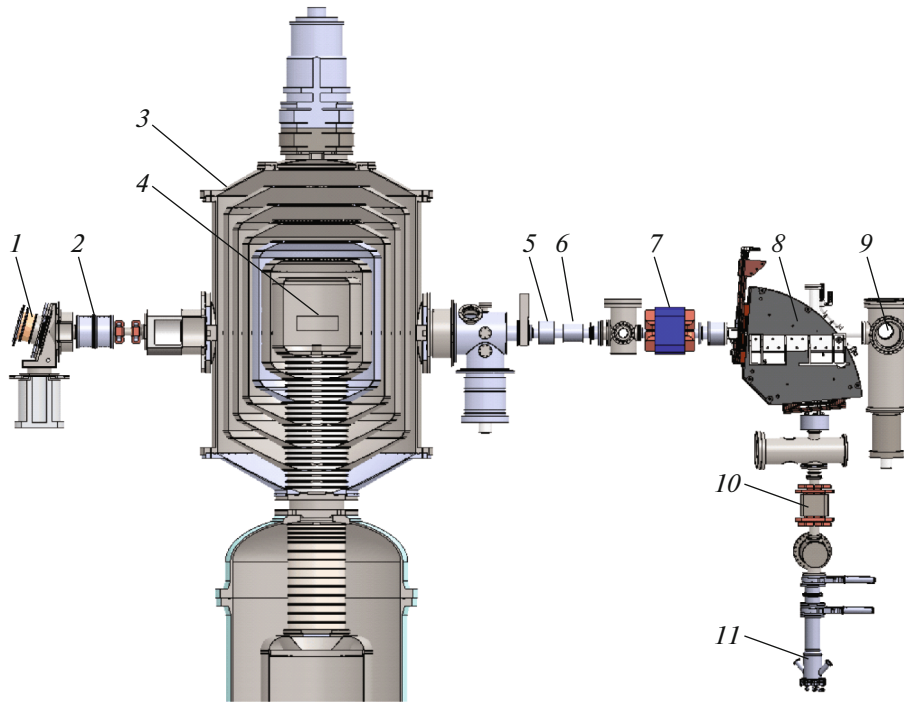


Fig. 1. The scheme of the accelerating source of epithermal neutrons. 1, Source of negative hydrogen ions; 2, magnetic lens; 3, tandem accelerator with vacuum insulation; 4, gas stripping target; 5, cooled copper diaphragm; 6, non-contact current sensor; 7, corrector; 8, bending magnet; 9, a second diagnostic chamber with an introduced Faraday cup; 10, a scanner for scanning the proton beam; 11, neutron generating target.

Transport of protons from the accelerator to the neutron-generating target 11 located horizontally at a distance of 5 m is carried out along the beam transport path. It is equipped with: (1) corrector 7 to adjust the direction of propagation of the proton beam; (2) bending magnet 8 to rotate protons 90°; (3) a scanner 10 for sweeping the proton beam over the target surface; (4) three cooled copper diaphragms with thermocouples to measure the position of the proton beam and to prevent the beam from burning through the vacuum chamber; (5) three introduced Faraday cups with thermocouples to control the current and position of the proton beam; and (6) an NPCT-CF4 contactless current sensor (Bergoz Instr., France) 6 for continuous measurement of the proton beam current.

RESEARCH METHODS AND RESULTS

A proton beam on a tandem accelerator with vacuum insulation is usually obtained in the regime where the gas stripping target provides 95% stripping of negative hydrogen ions, i.e., 95% of the negative hydrogen ions lose both electrons in the target thus producing protons, and 5% of the negative hydrogen ions lose only one electron and fly out of the stripping target in the form of neutrals (hydrogen atoms).

A further increase in the gas inlet is considered impractical, since the parasitic current of secondary charged particles resulting from ionization of stripping

and residual gas by accelerated hydrogen ions increases significantly compared with the proton current [13]. At the same time, incomplete stripping of the beam of negative hydrogen ions provides the ability to measure the degree of stripping of the target by measuring the flow of neutrals. The ability to measure the neutral flux is provided by the ion-optical accelerator system.

The vacuum-insulated tandem accelerator is characterized by a rapid ion acceleration rate and the presence of a strong electrostatic input lens [3]. For this reason, the injected beam of negative hydrogen ions is refocused at the entrance to the accelerator in order to provide its parallelism in the stripping target using the input electrostatic lens. Further, at the exit, the proton beam is slightly defocused by the output electrostatic lens so that if the transverse beam size is 1 cm at the exit from the accelerator it is then 3 cm at a distance of 5 m on the target. The neutral flow is formed in the gas stripping target in the form of a parallel directional beam, which is not affected by the output electrostatic lens, and therefore, its transverse size is kept small at a great distance.

To diagnose the efficiency of stripping a gas stripping target, it was proposed to develop a new bending magnet equipped with a through horizontal nozzle. In this case, the neutrals that are not deflected by the magnetic field fly through the nozzle and are recorded by the Faraday cup. Such a bending magnet with a

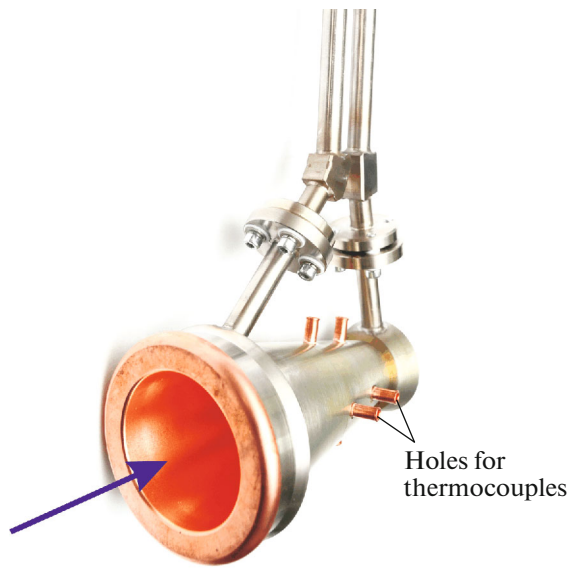


Fig. 2. A photograph of the Faraday cup. The direction of propagation of the ion beam (neutrals) is shown by the arrow.

horizontal nozzle was installed instead of the previous magnet and put into operation.

In addition to replacing the bending magnet, the layout of the nodes of the proton beam transport path was also modernized: a second diagnostic chamber, which was previously placed in front of the bending magnet, was installed after it, behind the horizontal nozzle. The chamber is equipped with a retractable Faraday cup in the form of a cooled copper cone in which nine thermocouples are inserted. A photograph of the Faraday cup is shown in Fig. 2.

An isolated metal ring is placed under a positive potential in front of the Faraday cup mounted on the horizontal axis of the proton beam transport path. It is designed to extract electrons emitted from the copper surface of the Faraday cup when bombarded by neutrals with an energy of 1 MeV.

To determine the electron emission coefficient from a copper surface, the current–voltage characteristic was measured at a proton energy of 1 MeV. This is shown in Fig. 3. According to the figure, when a negative potential of 200 V or more is applied to the ring the secondary electrons are locked inside the Faraday cup. In this case, only the proton current is measured, which is equal to $I_p = 1.005 \pm 0.007$ mA.

When a positive potential is applied to the ring, not only does the proton current flow through the measuring chain of the Faraday cup I_p , the counter current of secondary electrons I_e flows as well. According to Fig. 3, when a positive potential is applied to the ring greater than 400 V the measured current goes to saturation; its value is $I_p + |I_e| = 1.296 \pm 0.009$ mA. From the measured

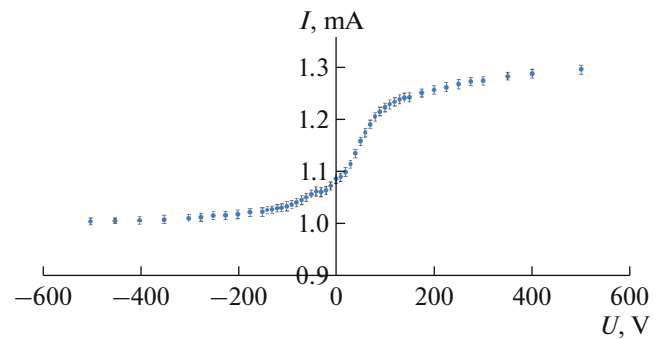


Fig. 3. The current–voltage characteristic of the Faraday cup when it is irradiated with protons with an energy of 1 MeV.

current values we obtain the coefficient of ion–electron emission, which is equal to $k = |I_e|/I_p = 0.29 \pm 0.02$.

Based on these results, diagnostics of the effectiveness of the gas stripping target were developed, which work as follows. The Faraday cup placed in the second diagnostic chamber after the bending magnet takes on a stream of neutrals (hydrogen atoms) with an energy of 1 MeV that form in the gas stripping target of the accelerator and accompany the proton beam to the bending magnet. In a bending magnet, protons are directed downward by a magnetic field toward the target, while the neutrals pass through the magnet without deviating.

The neutrals bombard the copper surface of the Faraday cylinder and knock out the electrons. It is known that the mechanism of potential ejection of electrons is characteristic of energies of bombarding ions of the order of 1 keV. At higher energies, the emission efficiency begins to decrease and tends to zero at energies in the megaelectron-volt range.

At such ion energies, the mechanism of kinetic knockout becomes the determining factor in the emission of electrons, which is based on the process of impact ionization of target atoms. This process is characterized by the presence of a threshold value of ion energy, which depends on many parameters, but usually does not exceed several kiloelectron-volts. With an increase in ion energy above the threshold the pull-out coefficient first increases and then reaches a small plateau, after which it begins to decrease.

It is believed that the maximum emission efficiency for protons lies in the energy region of the order of 100 keV and is more than unity for metal targets. In particular, we previously measured the coefficient of ion–electron emission during the bombardment of tungsten with negative hydrogen ions with an energy of 22 keV, which equaled 2.61 ± 0.08 [10]. For proton energies of 1 MeV, as we have shown above, the coefficient of ion–electron emission $k = 0.29 \pm 0.02$.

Since the kinetic knockout of electrons is based on the process of impact ionization of target atoms, regardless of whether the metal surface is bombarded by pro-

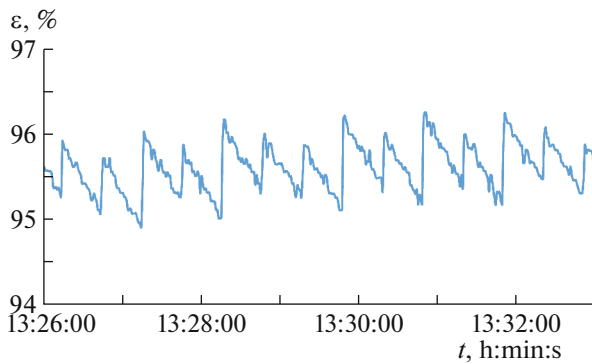


Fig. 4. The dependence of the efficiency of gas stripping target on time.

tons or hydrogen atoms, in the case of the same energy, the emission coefficient will not differ. Therefore, the coefficient of electron ejection under the action of neutrals with an energy of 1 MeV is assumed to be equal to the coefficient of ion-electron emission during bombardment by protons with an energy of 1 MeV.

A positive potential of 500 V is applied to the metal ring installed in front of the Faraday cup from the ULTRAVOLT 1/2AA24-P30-I10 power supply. The current flowing in the chain of the Faraday cup, I_{fc} is measured by an Adam 6024 analog-to-digital converter. The proton current I_p is measured by a NPCT-CF4 contactless current sensor (Bergoz Instr., France). The stripping efficiency ε of the gas stripping target is calculated programmatically with a sampling frequency of 1 Hz as $\varepsilon = I_p / (I_p + I_{fc}/k)$, where $k = 0.29$.

The calculated value of the efficiency of stripping ε of the gas stripping target is output in real time to the monitor of the remote control in the form of a column with information about the current value ε and in the form of a graph of previous values with the abscissa axis adjustable in duration and the ordinate axis in magnitude. An example of the time dependence of the measured efficiency of stripping of a gas stripping target is shown in Fig. 4.

On the graph one can see jumps in the beam recharge level with a period of 25 s, which are due to the opening frequency of the electromechanical valve that regulates the gas supply to the stripping target. According to the schedule the unit operates in standard mode with a stripping efficiency of $95.5 \pm 0.5\%$.

CONCLUSIONS

An accelerator source of neutrons is operating at the Institute of Nuclear Physics SB RAS. It consists of a tandem accelerator with vacuum insulation to produce a proton or deuteron beam with an energy of 2 MeV and a current of up to 9 mA, and a lithium target for generating neutrons.

This paper presents diagnostics of the efficiency of stripping an ion beam in a gas stripping target of a tandem accelerator. The coefficient of the ion-electron emission during the bombardment of copper by protons with an energy of 1 MeV was measured and equaled 0.29 ± 0.02 . A new bending magnet with a horizontal nozzle was manufactured and installed, which made it possible to place a Faraday cup and receive a stream of neutrals with an energy of 1 MeV formed as a result of incomplete stripping of negative hydrogen ions in the gas stripping target of the accelerator. Diagnostics of the efficiency of a gas stripping target were developed and put into operation, using measurement of the current of electrons emitted from the surface of a Faraday cup during its bombardment by a directed stream of neutrals with an energy of 1 MeV and of the proton current by a non-contact current sensor.

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