ADVANCES IN THE DEVELOPMENT OF A VACUUM INSULATED TANDEM ACCELERATOR AND ITS APPLICATIONS*

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Abstract

A compact accelerator-based neutron source has been proposed and created at the Budker Institute of Nuclear Physics in Novosibirsk, Russia. An original vacuum insulated tandem accelerator (VITA) is used to provide a proton/deuteron beam. As a result of scientific research and modernization, the power of the ion beam was increased, an operation mode without high-voltage breakdowns was achieved, and the operation of the accelerator in a wide range of changes in the energy and current of ions was ensured. The proton/deuteron beam energy can be varied within a range of 0.6 – 2.3 MeV, keeping a high-energy stability of 0.1%. The beam current can also be varied in a wide range (from 0.3 mA to 10 mA) with high current stability (0.4%). VITA is used to obtain epithermal neutrons for the development of boron neutron capture therapy, thermal neutrons for the determination of impurities in ITER materials by activation analysis method; fast neutrons for radiation testing of materials; 478 keV photons to measure the ^{7}Li(p,p'γ)^{7}Li reaction cross section, etc. VITA is planned to be used for boron imaging with monoenergetic neutron beam, for characterizing of neutron detectors designed for fusion studies, for in-depth investigation of the promising ^{11}B(p,α)αα neutronless fusion reaction, for studying the crystal structure of materials by neutron diffraction, etc.

INTRODUCTION

To develop a promising procedure for treating tumors (boron-neutron capture therapy, BNCT [1]), an accelerator-based epithermal neutron source has been prepared and designed in the BINP [2]. Neutrons are generated as a result of the ^{7}Li(p,n)^{7}Be threshold reaction by directing a proton beam, which is produced in an original design tandem accelerator, onto the lithium target.

Significant progress in the development of the accelerator and a significant expansion of its applications have been achieved recently. The report provides a description of the accelerator and its operating parameters, highlights the features of the accelerator, gives the examples of its application and declares plans.

EXPERIMENTAL FACILITY

The neutron source comprises an original design tandem accelerator, solid lithium target, a neutron beam shaping assembly, and is placed in two bunkers as shown in Fig. 1. The facility has the ability to place a lithium target in 5 positions; they are marked as positions *A*, *B*, *C*, *D*, *E*.

The original design tandem accelerator, which was named as Vacuum Insulated Tandem Accelerator (VITA), has a specific design that does not involve accelerating tubes, unlike conventional tandem accelerators. Instead of those, the nested intermediate electrodes (*1b*) fixed at single feedthrough insulator (*1d*) is used, as shown in Fig. 1. The advantage of such an arrangement is moving ceramic parts of the feedthrough insulator far enough from the ion beam, thus increasing the high-voltage strength of the accelerating gaps given high ion beam current. A consequence of this design was also a fast rate of ion acceleration—up to 25 keV/cm.

RESULTS AND DISCUSSION

The potential is supplied for the high-voltage electrode and five intermediate electrodes of the accelerator from a sectioned rectifier (*1e*) through a feedthrough insulator (*1d*) in which a resistive voltage divider is mounted. For the compactness of the accelerator, the average electric field strength on the insulator was chosen to be 14 kV/cm, which is 1.5 times higher than the recommended one. This led to breakdowns along the surface of smooth ceramic insulators with a height of 73 mm, from which the feedthrough insulator was assembled. Such breakdowns occurred approximately once every 10 – 20 min; they did not lead to a decrease in the electric strength of the accelerator, but required 15 s to restore the parameters of the ion beam. To eliminate breakdowns along the vacuum surface of insulators, smooth ceramic insulators were replaced with corrugated insulators of the same height.

A beam of negative hydrogen ions with an energy of 20 – 30 keV is injected into the tandem accelerator. Since VITA is characterized by a fast ion acceleration rate, the entrance electrostatic lens is strong. For this reason, the injected ion beam must be refocused to the entrance to the accelerator. To focus the ion beam at the entrance of the accelerator, we used a magnetic lens. Since the transport and focusing of a relatively low energy ion beam is accompanied by a spatial charge, a wire scanner OWS-30 (D-Pace, Canada) is used to control the position and size of the ion beam at the entrance to the accelerator.

The position and size of the ion beam in the accelerator are controlled by two pairs of video cameras overseeing the input and output diaphragms of the external accelerating electrode. Cameras register visible radiation caused by interaction of ions with residual and stripping gases, and heating of diaphragms.

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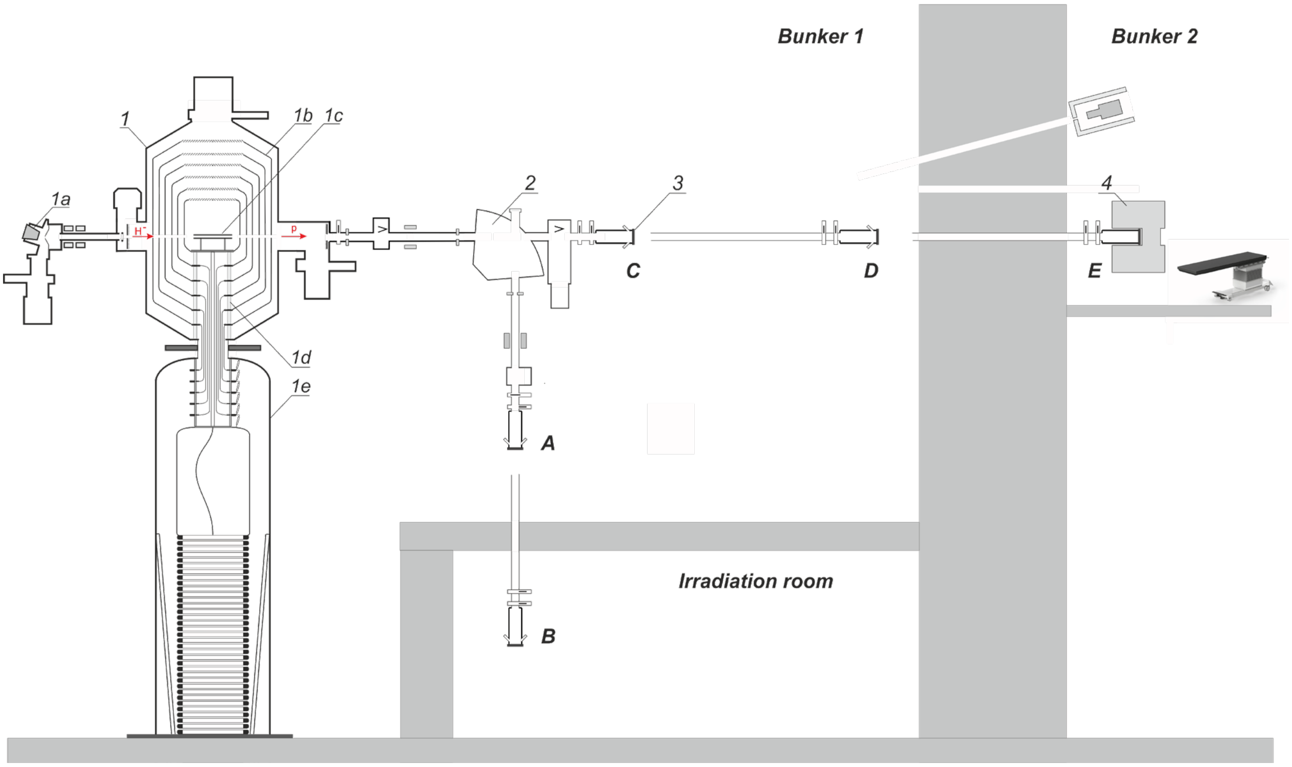

Figure 1: Layout of the experimental facility: 1 – vacuum-insulated tandem accelerator (1a – negative ion source, 1b – intermediate- and high-voltage electrodes, 1c – gas stripper, 1d – feedthrough insulator, 1e – high-voltage power supply), 2 – bending magnet, 3 – lithium target, 4 – beam-shaping assembly. A, B, C, D, E – lithium target placement positions.

A gas stripper *(1c)* is used for stripping negative hydrogen ions into protons. The stripper is a cooled tube with argon inlet through a hole in the middle. The presence of a gas stripper in a tandem accelerator is often considered a disadvantage. We managed to neutralize the disadvantages and turn the use of a gas stripper into an advantage. The additional gas flow makes it possible to visualize the beam for diagnostics of its position and size and improves the high-voltage strength of the accelerating gaps. Of course, additional gas injection increases the undesirable flux of secondary charged particles, but this flux is reduced to an acceptable level by improving vacuum pumping and suppressing secondary electron emission from the walls of the vacuum chamber. The flux of positive argon ions formed inside the gas stripper and penetrating into the accelerating gaps turned out to be extremely low: it was 2000 times less than the proton beam current.

Typically, a gas stripper provides 95% conversion of negative ions to positive ones. Although a larger injection of argon leads to an increase in the proton current, the current of secondary charged particles grows much more strongly. Inside a stripping tube 16 mm in diameter, the ion beam has a size of about 5 mm and a divergence of ±2 mrad. The size of the ion beam and the divergence were determined from measurements of the phase portrait of the neutral flux measured with a cooled diaphragm scanning the beam and a wire scanner located behind the scanning diaphragm and a bending magnet turned on to deflect ions.

The proton beam obtained inside the stripper is focused by an electrostatic lens due to the penetration of the electric field through the diaphragm into the high-voltage electrode, is accelerated in the accelerating gaps, and is slightly defocused by the output electrostatic lens. At a distance of 1.86 m from the center of the accelerator, the proton beam has a characteristic size of 11 mm, a divergence of ±1.5 mrad, and a normalized emittance of 0.23 mm mrad. The peculiarity of the proton beam, which is attractive for its transportation, lies in its sharp border – there is no beam at a distance of 2σ from the beam axis. This is due to the effect of the space charge during the transport and focusing of a beam of negative hydrogen ions and the small size of the diaphragms – 10 mm in the entrance and 20 mm in the accelerating gaps.

Two cooled copper diaphragms with four thermocouples evenly spaced in azimuth inside are installed before the bending magnet. These diaphragms are used to optimize the production of the ion beam. By a magnetic focusing lens and a corrector in the low-energy beam path, the passage and acceleration of the ion beam are achieved such that the input diaphragm of the first accelerating electrode is heated rather weakly (diagnosed by video cameras) and the cooled diaphragms in front of the bending magnet are also heated weakly and symmetrically. Stronger focusing of negative ions makes it possible to obtain a smaller proton beam at the exit from the accelerator and with a lower divergence, but this mode is accompanied by a greater heating of the entrance diaphragm of the first accelerating electrode due to the broadening of the ion beam here. Weaker focusing of negative ions, on the contrary, does not lead to heating of the entrance diaphragm of the first accelerating electrode, but makes the proton beam more divergent. Since the accelerator operates in a wide range of ion energies and currents, as well as the type of ions—protons or deuterons, this procedure is used to optimize the production of an ion beam.

The spatial charge does not influence the transport of the proton beam, therefore, the proton beam can be transported relatively simply and without loss to a lithium target 10 cm in diameter in whatever position it is installed. So, with the bending magnet turned off, the size of the proton beam on the surface of the lithium target in position *C* is 20 mm, in position *D* – 28 mm, *E* – 38 mm. To direct the proton beam downward, a bending magnet with a decay rate of 0.5 is used, which ensures the same focusing of the proton beam in the direction along and across the magnetic field. The proton beam is transported in the vertical part when its divergence is ±8 mrad. On the surface of the lithium target at position *A*, the transverse dimension of the proton beam is 30 mm and can be increased by turning on the scanner; at position *B*, the transverse dimension of the proton beam is predicted to be 70 mm.

As a result, the facility produces a beam of protons or deuterons, the energy of which can be varied within a range of 0.6 – 2.3 MeV, keeping a high-energy stability of 0.1%. The beam current can also be varied in a wide range (from 1 pA to 10 mA) with high current stability (0.4%).

The facility is capable of producing a powerful neutron flux of various energy ranges: thermal, epihermal, over-epithermal, monoenergetic, and fast; 478 keV photons in ^{7}Li(p,p'γ)^{7}Li reaction, 511 keV photons in ^{19}F(p,αe$^+$e$^-$)^{16}O reaction, α-particles in ^{7}Li(p,α)α and ^{11}B(p,α)$\alpha\alpha$ reactions, and positrons in ^{19}F(p,αe$^+$e$^-$)^{16}O reaction.

APPLICATIONS

The initial application of such an accelerator was to generate neutrons for BNCT, and this application was realized. The developed neutron source commercialized by TAE Life Sciences (USA) is installed in new BNCT Center (one of the first six BNCT clinics in the world) at Xiamen Humanity Hospital in Xiamen, P.R. China in 2020. It is planned to start treatment in early 2022. The manufacture of two more neutron sources began this year: for National Oncological Hadron Therapy Center (CNAO) in Pavia, Italy, and for National Medical Research Center of Oncology in Moscow, Russia. The neutron source in BINP is used for the development of dosimetry methods in BNCT [3,4], testing of boron delivery drugs [5,6], measurements of neutron yield in lithium [7], and it is planned to be used for boron imaging in cooperation with the University of Pavia (Italy) and characterization of the epithermal neutron field in cooperation with the Laboratory of Subatomic Physics and Cosmology CNRS-IN2P3, Grenoble-Alpes University (France) and the Laboratory of Micro-Irradiation, Metrology, and Neutron Dosimetry, IRSN (Cadarache, France).

Another important application of the facility is to gain fundamental knowledge. A ^{7}Li(p,p'γ)^{7}Li reaction cross section and 478 keV photon yield from a thick lithium target at proton energies from 0.65 MeV to 2.225 MeV were measured with high precision [8]. Now an experiment is being prepared to study the energy and angular characteristics of products of the promising neutronless fusion ^{11}B(p,α)$\alpha\alpha$ reaction.

Recently, the source was used to measure the content of hazardous impurities in boron carbide samples developed for thermonuclear fusion reactor ITER [9]. The neutron source is planned to be used for radiation tests of fibers of the laser calorimeter calibration system of the Compact Muon Solenoid electromagnetic detector developed for the High-Luminosity Large Hadron Collider in CERN. The facility is also planned to be used to obtain a beam of cold and ultracold neutrons and to carry out elemental analysis of the surface of materials by backscattered protons.

CONCLUSION

A compact original design tandem accelerator VITA has been proposed and created at the BINP. The accelerator is used to provide the high neutron flux in various energy ranges, from thermal to fast, the 478 keV and 511 keV photons, α-particles, and positrons for research in various fields including boron neutron capture therapy and thermonuclear fusion.

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