Recent Achievements in Studies of Negative Beam Formation and Acceleration in the Tandem Accelerator at Budker Institute

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Abstract. The source for epithermal neutron production, based on vacuum insulated tandem accelerator (VITA) is under operation at the Budker Institute of Nuclear Physics since 2006. The accelerator provides a high current DC proton beam with energy up to 2 MeV. Numerous improvements to achieve stable tandem work and increase the accelerated proton current were made in more than a decade of experimental operation. These improvements include reduction of the accelerator dark current, modifications for the secondary particles suppression in the tandem gaps, vacuum improvement, upgrades of negative ion source, introduction of additional diagnostics to control and adjust the beam injection and transport. These measures provide the upgraded tandem operation with the accelerated proton current of up 9 mA. Two new schemes of negative ion injection into the tandem were designed and tested. New schemes use the upgraded version of a Penning surface-plasma negative ion source with DC H^- beam current of up 15 mA and beam pre-acceleration before injection to tandem. The recent experimental results and its comparison with numerical modelling are presented and discussed.

INTRODUCTION

Accelerators producing particle beams in the energy range of 2 MeV with high average current are required for applications like radiography and medical therapies. Tandem accelerators are preferred due to the compact size and low cost. The reported results and projects [1-3] demonstrate the operation in the range of 1-4 mA. However current capability exceeding 10 mA for continuous operation is still not reached for commercially available accelerators.

BINP ACCELERATOR-BASED NEUTRON SOURCE

The concept of an accelerator-based neutron source, using particle acceleration in a tandem with vacuum insulation (VITA) was proposed in Budker Institute of Nuclear Physics in 1998 [4]. The scheme of vacuum isolation was chosen to provide reliable high-current DC operation of the tandem. The layout of the accelerator-based neutron source with vacuum insulated tandem is shown in Fig. 1. A negative ion source and a neutron-producing target are both at ground potential. The accelerator operating voltage is one half of the full energy gained by accelerated protons. A Penning surface-plasma negative ion source is attached to the 15° tilt chamber with differential pumping. The beam enters a 50 mm diameter transport channel where a solenoidal magnetic lens is placed. The lens focuses the diverging beam and directs it to the tandem entrance. Beam steering is enabled by two electromagnetic correctors. An electrostatic lens in the first accelerating gap of the tandem produces beam focusing, while the applied high acceleration rate minimizes the beam space charge effects. The enlarged tandem entry volume weakens the electric field at the entrance, thus minimizing the effect of beam focusing by the electrostatic tandem lens. The high voltage insulators of the VITA electrodes, embedded one into another, are placed far from the ion beam acceleration zone (see Fig. 1). The negative hydrogen ions are injected from the ion source, transported through the low-energy beam transport line (LEBT) and

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accelerated to ~1 MeV energy at the high voltage terminal of the tandem, where a stripping target is placed. The protons produced by H^- ion stripping in the target are further accelerated to double the energy at the tandem exit. The protons with an energy of 2 MeV are transported through a high-energy beam transport line (HEBT) and directed to a lithium target for neutron production.

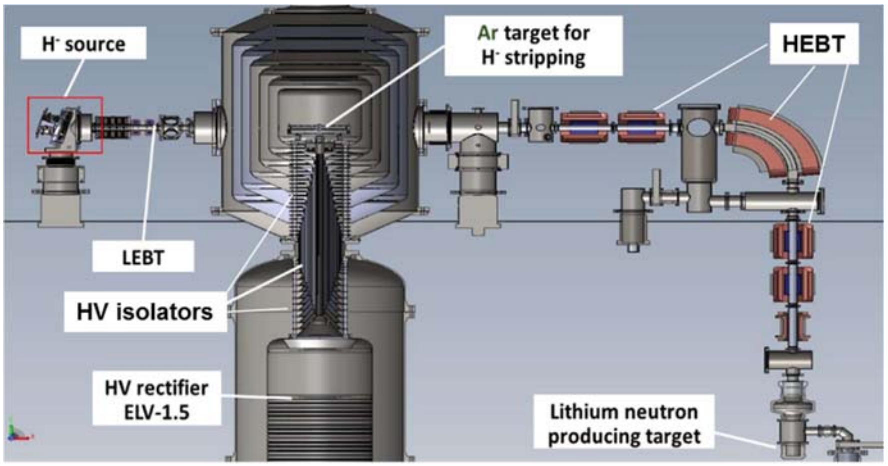


FIGURE 1. Scheme of accelerator-based neutron source with vacuum insulated tandem (VITA).

TANDEM UPGRADES AND PROGRESS IN OPERATION

The systematic operation and studies of the accelerator-based neutron source began in 2006 [5]. The first accelerated protons were obtained in 2008 [6]. The following step-by-step improvements in the tandem operation and the progress in the accelerated proton current are listed in the Table 1.

TABLE 1. Progress in 2 MeV proton beam production and improvements.

Date	Proton beam, mA	Improvements
2008	1	First experiments on beam acceleration up to 1.8 MeV [6].
05.2014	1.6	Minimization of the high energy x-ray radiation from the tandem; overheated input aperture was eliminated [7].
12.2015	5	Suppression of secondary charged particles: cooled aperture at the tandem entrance; improved pumping of the LEBT and tandem entry box; negatively biased ring in front the input aperture; negatively biased meshes on the input and output apertures [8].
01.2018	8	Beam positioning and focusing using wire scanner; in situ beam position monitoring with the help of CCD cameras [9, 10].
12.2018	9	Negative ion source boosting to higher output current (>10 mA).

Tandem Improvements

Proton beam current with an intensity of 1 mA and energy 1.8 MeV was produced at the initial stage of tandem operation [6]. The decrease of the accelerator dark current, optimization of the input to the accelerator and stripping of hydrogen ions in the duct resulted in extension of the stable operation to more than 1 hour with proton beam current up to about 1.6 mA in 2014 [7].

The first major increase in accelerated current to 5 mA was done in 2015 after suppression of secondary electrons, produced by accelerated argon ions flowing from the gas target and ionized by the beam [8]. The upgrade improved the accelerator operational stability as well. Details of the accelerator modification are shown in Fig. 2. An additional cryopump was mounted at the tandem entrance box to improve LEBT and tandem pumping. A negatively biased ring was placed behind the transport channel output to block the accompanying electrons entering the tandem. A water-cooled tandem entrance electrode with a 20 mm aperture was installed to reduce the gas flow and UV radiation from the transport channel to the accelerator. The diaphragm was covered from the tandem side by a negatively biased tantalum mesh, which diminishes the secondary electron production by back streaming argon ions. A similar biased electron suppression grid was also installed at the accelerator exit (not shown in Fig. 2).

In the beginning of 2018 an improved matching of the injected beam with the tandem axis was achieved using wire scanner beam position diagnostics [9]. The scanner is located near the tandem entrance and monitors the two perpendicular profiles of beam current density. The scanner signals were transformed into the beam current density profiles by using BINP developed software. The scanner enables optimization of the beam position and angle at the tandem entrance.

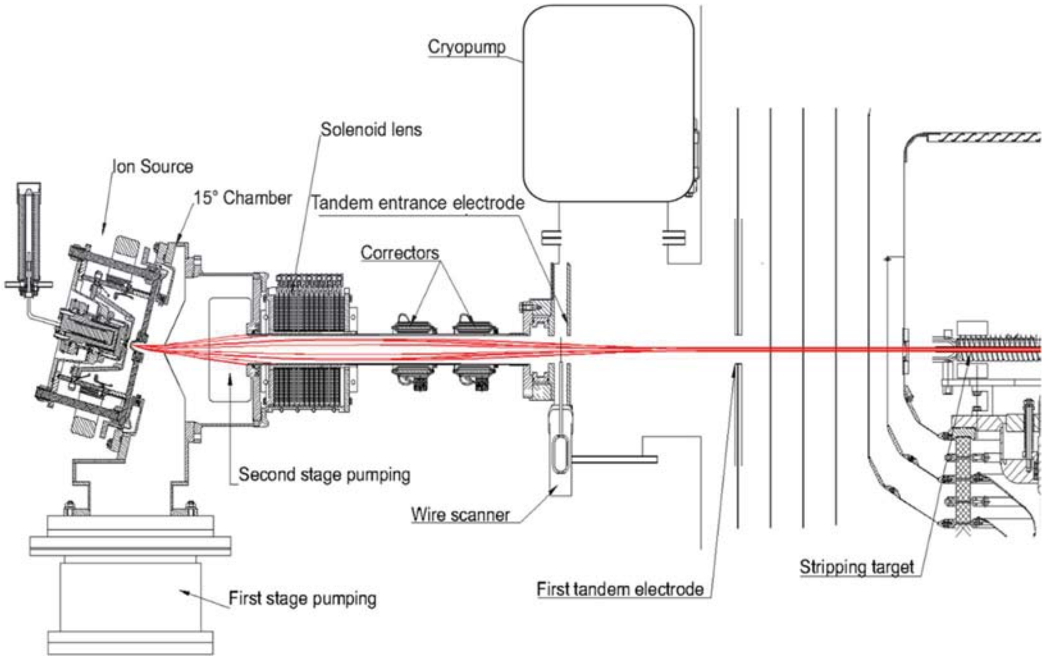


FIGURE 2. Upgrade of LEBT and tandem elements. H- ion trajectories calculated by COMSOL shown in red.

Upgrades of Ion Source at the Tandem

The first version of the DC Penning negative ion source for the tandem was made in 2004 [10]. The source uses a high-current Penning hydrogen-cesium discharge with plasma injection from hollow cathodes. A triode source ion-optical system (IOS) with circular apertures was used for beam extraction and acceleration. The dipole magnetic field in the ion source discharge and nearby IOS area was generated by an external electromagnet. H^- ions are produced on the cesiated anode surface at constant caesium feed of ~5 mg/h with hydrogen pressure in the discharge chamber of ~4 Pa. The DC H^- beam with current up to 8 mA and energy of 25 keV was produced at the source output. The beam regular divergence was ±80 mrad and measured normalized 1 RMS emittance was 0.2 π·mm·mrad [11]. The H^- ion trajectories calculated by COMSOL are shown in Fig. 2 by red lines, without space charge effects.

Several upgrades of the DC Penning negative ion source to increase output current were made [12]. NdFeB magnet inserts were introduced to increase the magnetic field in the discharge up to 0.1 T. An upgrade of the source acceleration power supply allowed an increase of beam energy and optimized beam transport through the IOS. Several modifications were made to improve the source operation stability, to increase lifetime and to simplify maintenance. A detachable cathode heater, replaceable high voltage insulators and extraction electrode insert were introduced [12]. An improved differential pumping system equipped with two high-performance turbomolecular pumps with pumping speed of 2200 l/s was introduced, which permitted an increased DC H^- beam output of 10 mA.

The source operational statistics at the tandem are presented in Table 2. Both the first and the upgraded source versions have operated for total more than 4281 hours with average daily run ~ 5 hours. An average source start time is about 50 minutes.

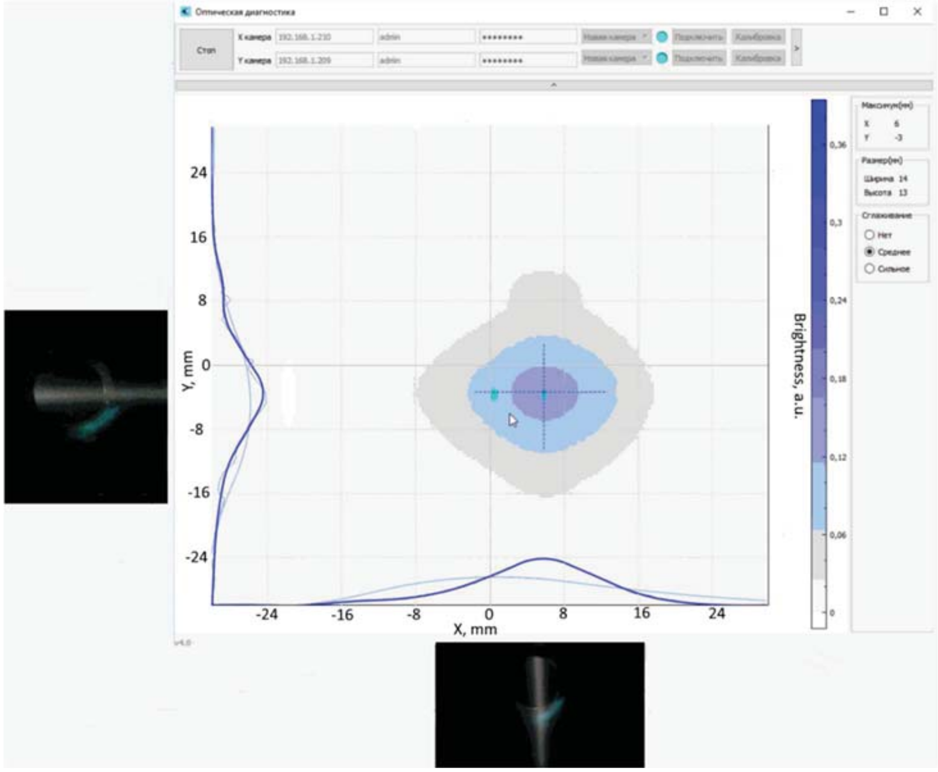
TABLE 2. The ion source annual operational statistics.

Year	Operation days	Source operation hours
2006-2014	358	1693
2015	53	265
2016	70	341
2017	121	658
2018	92	516
2019	77	431
2020*	40	377
Total	820	4281

* now in operation

LEBT Upgrades

The LEBT was equipped with several beam position and current control diagnostics [13]. They simplify beam targeting and focusing at the tandem entrance, and support reliable operation of the tandem accelerator at the increased current level. Four CCD cameras were installed to observe the residual gas glow on the entrance and exit apertures of the first tandem electrode from two perpendicular directions. Software was written to visualize the beam profile in situ, giving its transverse position at the input and output apertures during the tandem operation. An example of beam profile visualization is shown in Fig. 3.



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Максимум(мм)
X 6
Y -3

Размер(мм)
Ширина 14
Высота 13

Сглаживание
○ Нет
● Среднее
○ Сильное

FIGURE 3. Beam profile visualization at the input tandem aperture.

The ion source upgrades and optimization of the beam transport allow to achieve the reliable operation with the accelerated 2 MeV proton current of up to 9 mA. The negative ion source was boosted higher compared to the regular output current (>10 mA) in the last case.

NEW INJECTOR STUDIES

Several limitations of the existing injection scheme prevented further increase of tandem operational current. The accelerated current could not be significantly increased and it was limited by the ion source arrangement. The magnetic lens and low energy transport channel have small apertures and intercept the beam peripheral parts. The H^- ion stripping in the ion source chamber and transport channel can be reduced by improved pumping. The high current beam acceleration could be improved by optimization of the tandem entrance lens. To overcome these problems, two new injectors were designed and studied. Both injectors use an upgraded version of the Penning surface-plasma source [14] with production of H^- current up to 15 mA. A photo of the 15 mA source is shown in Fig. 4.

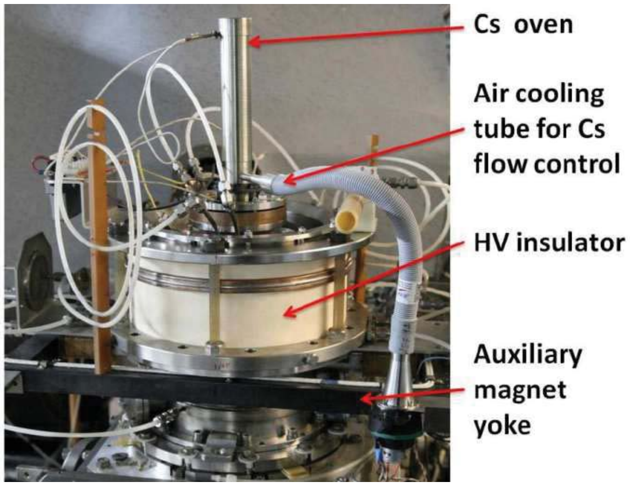

FIGURE 4. The photo of 15 mA negative ion source.

This source has an enlarged magnetic field and emission aperture diameter of 3.5 mm. It produces H^- beam with 1-RMS emittance of 0.2 π mm mrad. A data acquisition system for unattended control of the source has been developed [15]. Various scenarios with fine tuning of the source parameters are supported by autopilot. The source start by autopilot is illustrated in the picture of the control software application window shown in Fig. 5.

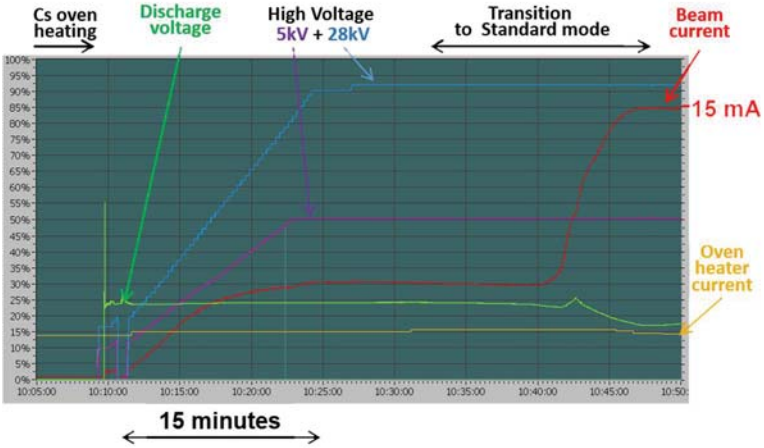

FIGURE 5. Window of the ion source control program. Source start with discharge ignition, IOS electrodes conditioning and negative ion production activation are shown.

Injector with Additional Lens

The scheme of new negative ion injector design for the tandem is shown in Fig. 6. It includes the upgraded version of the Penning surface-plasma source, the additional box for improved differential pumping of the ion source chamber and an additional lens for beam focusing into LEBT channel.

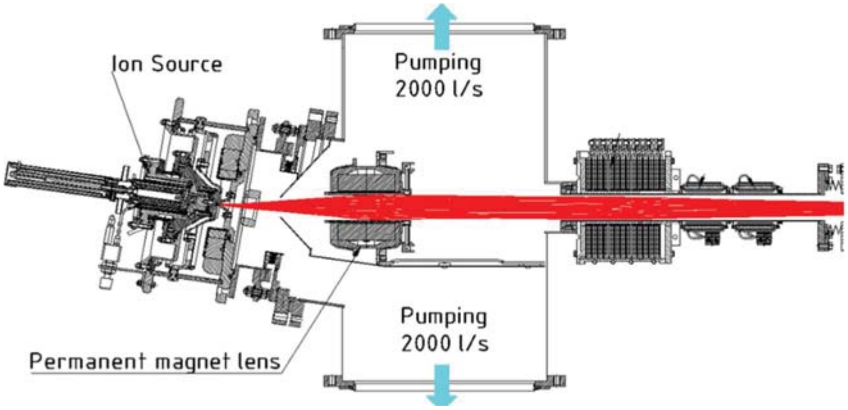

FIGURE 6. Injector with additional permanent magnet lens. H^- trajectories calculated by COMSOL are shown in red.

Calculations of the magnetic field in the ion source, in the permanent magnet lens and in the solenoidal lens of LEBT have been done by COMSOL software. Figures 6 and 7 show the calculated trajectories of H^- beam transmission through the pumping box and LEBT. No beam interception with the lens aperture and LEBT walls were found and 100% transmission of the beam through the LEBT to the tandem entrance was calculated for the beam with emittance 0.2 π mm mrad. The injector is under preparation for installation to the tandem.

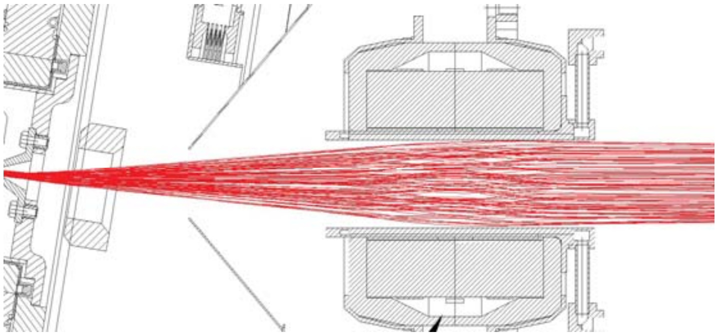

FIGURE 7. Negative ion trajectories for beam transmission through the permanent magnet lens.

130 keV Injector with Preliminary 90° Beam Turn

An injector with negative ion beam 90° bend and pre-acceleration to the energy of up to 130 keV was developed [16]. The scheme and photo of the 130 keV injector and its diagnostics are shown in Figs. 8 and 9. This injector uses the upgraded ion source with 15 mA current yield. The vacuum box with 90° bending magnet is used to separate the 33 keV negative ion beam from accompanying particles before entering the acceleration tube. The box was equipped with a high-speed turbomolecular pump protected from particle streams from the source by a water-cooled jalousie. Accelerating the beam to a higher energy of 130 keV before injection into the tandem reduces the effect of space charge and improves the beam transport through the tandem at a wide range of beam parameters and tandem voltages. Beam focusing by the 90° bending magnet and by the acceleration tube permits operation without the additional magnetic lens in the LEBT. A larger 100 mm diameter of the transport channel and an additional 200 l/s pump in the LEBT support enhanced vacuum and decrease H^- stripping losses during transport.

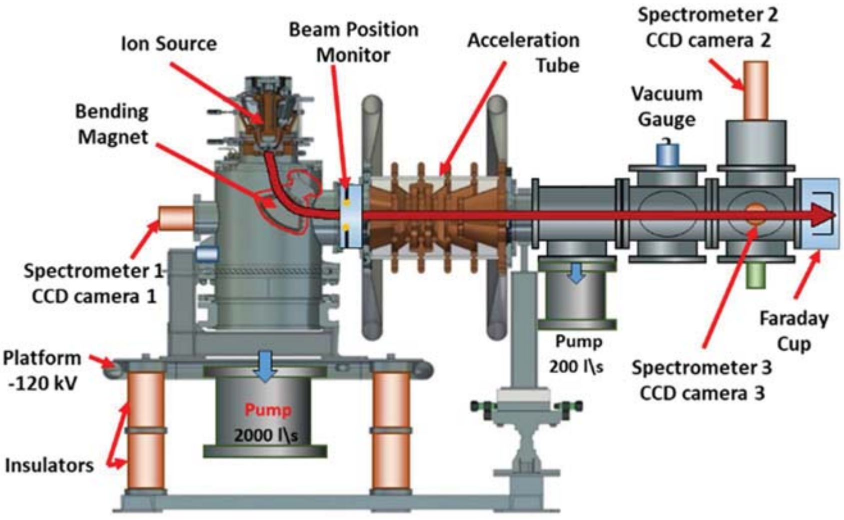

FIGURE 8. Test stand with 130 keV injector and it diagnostics.

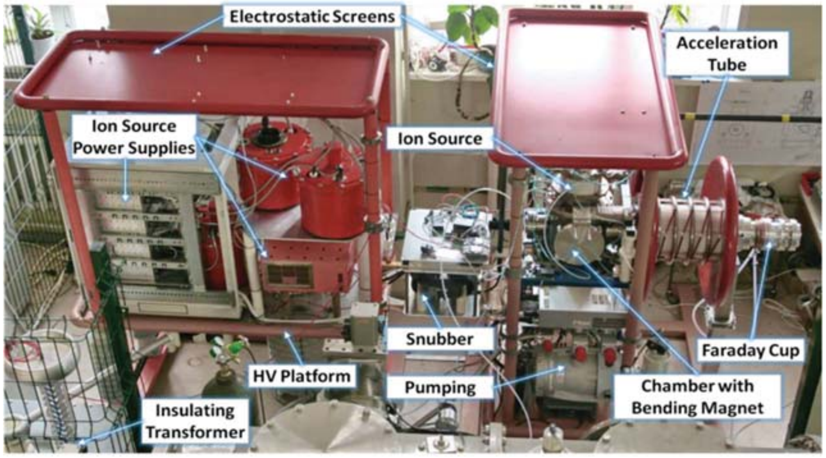

FIGURE 9. Photo of the 130 keV injector with preliminary 90^o beam turn.

Studies of H- beam production, acceleration and transport at different vacuum conditions in the transport channel were performed [16]. About 95% beam transmission was achieved. The presence of secondary electrons with a current of ~0.4 mA was recorded, which were produced in the acceleration tube and co-accelerated with the negative ion beam. The presumable origin of secondary electrons is H^- stripping and secondary emission from the acceleration tube electrodes. The secondary electrons were deflected from the beam by a magnetic filter, installed at the transport tube sides. Reliable operation of the ion injector with ion energy of 133 keV and current of 14.5 mA was achieved.

The influence of gas addition to compensate the ion beam space charge was studied extensively earlier [17, 18]. In the present case, hydrogen, argon and xenon injection into the 0.8 m long transport tube were tested. The resultant transverse size and current of the DC 33 keV negative ion beam transported to Faraday cup were studied using optical diagnostics [19]. A drop of the beam size from 9 to 6 mm was recorded with small $\sim 3 \cdot 10^{-6}$ Torr addition of xenon. A similar decrease of the beam size was obtained with 10 times larger addition of argon and ~40 times larger addition of hydrogen. The measured beam full-width at half maximum (FWHM) was compared with the value calculated by COMSOL for the beam with no space charge effect. They matched well, signifying that the space charge of the beam is fully compensated at the residual hydrogen pressure of $2 \cdot 10^{-5}$ Torr in the LEBT. Further gas addition leads to overcompensation of DC H^- beam space charge and to beam focusing. Xenon addition is more effective for beam focusing and transport. The H^- beam with intensity up to 13 mA was transported and focused to the LEBT exit under a decreased level of the beam losses (<5%).

CONCLUSIONS

An accelerator-based neutron source using a vacuum-insulated tandem has had more than a decade of operation at the Budker Institute of Nuclear Physics. The accelerator provides a DC proton beam with the energy of 2 MeV. Numerous improvements to achieve the stable tandem work and to increase the accelerated proton current were made over the years. Long lasting operation of the tandem accelerator with the proton current of 9 mA was confirmed.

At present, two new injectors of negative ions for the VITA were designed and tested. The injectors use an upgraded version of the Penning surface-plasma ion source with DC H^- beam current of 15 mA and have the decreased H^- stripping losses. Additional elements for enhanced beam focusing, rotation and preliminary acceleration in the low energy beam transport channel before injection into the tandem have been implemented. Numerical calculations and experimental tests of the beam production and transport in the new injectors have been made. The injectors are now prepared for installation on the tandem.

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