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First experimental results from 2 MeV proton tandem accelerator for neutron production[a)]

A. Kudryavtsev, Yu. Belchenko, A. Burdakov, V. Davydenko, A. Ivanov, A. Khilchenko, S. Konstantinov, A. Krivenko, A. Kuznetsov, K. Mekler, A. Sanin, V. Shirokov, I. Sorokin, Yu. Sulyaev, and M. Tiunov
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

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A 2 MeV proton tandem accelerator with vacuum insulation was developed and first experiments are carried out in the Budker Institute of Nuclear Physics (Novosibirsk). The accelerator is designed for neutron production via reaction $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ for the boron neutron-capture therapy of the brain tumors, and for explosive detection based on 9.1724 MeV resonance gamma, which are produced via reaction $^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$, absorption in nitrogen. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2802280]

The device comprises a 20 keV, 5 mA negative ion source, low energy beam line with a set of lenses and correctors, accelerating structure, argon stripping cell at high voltage terminal, high energy beam line, and a set of beam diagnostics including neutron and gamma detectors (Fig. 1).

Arrangement of high voltage electrodes in the tandem differs from traditional accelerating tube.[1] There is a set of nested closed electrodes made of polished stainless steel. Each electrode has two opposite openings through which the ion beam enters and emerges from the electrode. The openings in the electrodes are arranged coaxially and form a channel for the beam acceleration and passing through.

The electrodes are mounted on a high voltage feedthrough, on which insulators located far from the beam passage, thus preventing their exposing to secondary particles and photons. The stripping gas cell is placed inside the central electrode under highest potential (Fig. 2).

This article reports on the first results obtained in the study of the beam transport in the low energy line and further beam acceleration in tandem.

The negative ion beam is extracted by three electrode ion optical system across the magnetic field and acquires turning angle about 0.25 rad. Besides, the beam has an angle of divergence about 0.1 rad. Low energy beam line (about 1 m in length) is used for beam transport and matching with tandem accelerating structure (Fig. 3).

It consists of separately pumped vacuum channel of 5 cm in diameter, pumping and beam diagnostics chambers, and is equipped by two short solenoidal magnetic lenses and two magnet correctors. The calculated beam envelope is shown on Fig. 4 for one set of the optimal beam line parameters.

The large diameter bellow and magnet correctors are used to align the beam axis with the axis of the accelerator. To facilitate the alignment procedure, the beam position monitors (BPMs) were installed at the low energy beam line (LEBL) input and output, where the beam diameter is about 25 mm or less. BPM consists of 5×5 electrically insulated tantalum wires of 7 cm length and 100 μm in diameter; gaps between wires are 5 mm. As our experiments showed, there is no possibility to measure the beam current striking the wire directly because of relatively large density of secondary plasma in the vicinity of BPM and large electron secondary emission from the wires. So, to find the beam radial profile, the increase of wire resistance, ΔR, caused by the beam heating was measured. It can be shown that for our case when beam diameter is sufficiently less than the length of wire and power absorbed by the wire is reemitted by radiation only, the value of current I striking the wire is proportional to $(\Delta R)^2$. The beam current profiles among horizontally stretched wires are shown in Fig. 5. The wire number 3 is stretched along the LEBL diameter.

The low energy beam line is equipped also with movable Faraday cup combined with two-dimensional current profile monitor. The beam current profile was measured by an array (8×8) of small electrodes placed behind the small holes properly perforated in cup bottom. The hole diameter is 0.5 mm and spatial step is 4.5 mm. This system is placed in the middle plane of diagnostic chamber. It was used for net current measurements and for preliminary beam line alignment (Fig. 6).

Since this was the first experimental campaign at tandem proton accelerator, and the new tandem construction (VITA) was tested for the first time, the accelerating electrode current was deliberately limited to the value of 0.2 mA by ballast resistors to minimize possible consequences of breakdowns. Therefore, these experiments were performed with accelerated beam current of 1 mA or less. Besides, relatively small output beam power (~2 kW) does not require special arrangements for power density decreasing at the beam dump. The VITA volume was pumped by cryopump and turbovac with total effective rate of 3500 l/s, and stripping gas flow was varied from 0.015 to 0.050 Torr l/s, thus generating effective target thickness nL up to 3×10^{16} cm^{-2}.

Final stage of the tandem high voltage conditioning in presence of the 0.4 mA beam and stripping gas is shown on Fig. 7. Upper curve presents the potential of inner electrode measured with a resistance divider, and lower curve the residual gas pressure (about 1×10^{-5} Torr). One can see only

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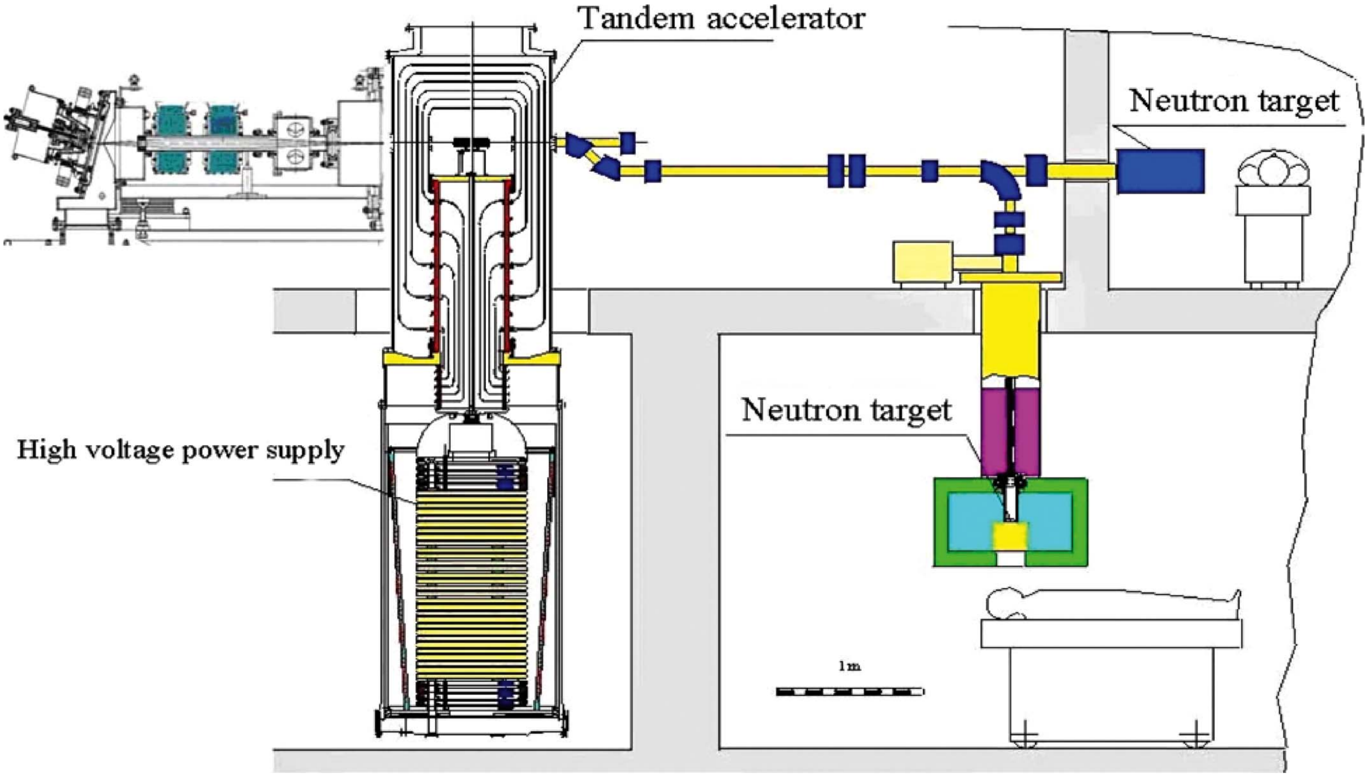

FIG. 1. (Color online) Layout of the installation.

five short breakdowns (and four technical shutdowns accompanied by slight vacuum improving) during almost 5 h run.

At the beginning of the campaign, the proton beam current was measured at carbon water-cooled target installed at 40 cm distance from the tandem output. It was determined in two ways: as electrical current on the target (with secondary electrons suppression), and through the measurements of heating of the cooling water. Both methods were in reasonable agreement. However, at this distance the proton beam diameter was too small (about 5 mm) and power density was so large that carbon was sufficiently evaporated during 10 min run under 1 mA beam (Fig. 8).

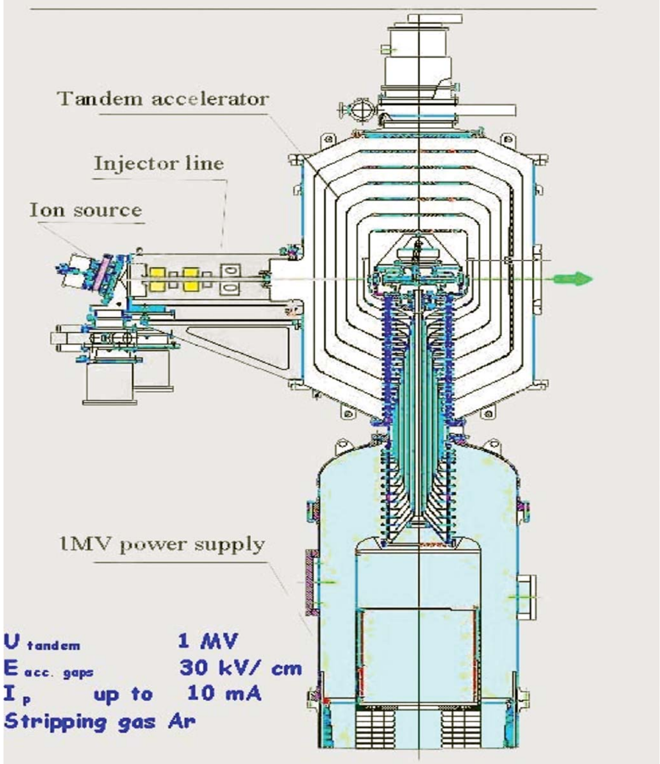

FIG. 2. (Color online) The scheme of vacuum insulated tandem accelerator.

The accuracy of the measurement of proton beam energy (defined as doubled potential of tandem inner electrode) was checked by special measurements of gamma-excitation curve via reaction $^{13}C(p,\gamma)^{14}N$ at thick ^{13}C target. This reaction has large cross section at resonance proton energy of 1.747 MeV (tabulated value of resonance width is 120 eV), and measured flux of 9.17 MeV gamma quanta sharply increases when proton energy reaches resonance energy (Fig. 9, abscissa axis—doubled potential of tandem inner electrode).

Main results of the campaign are as follows:

- The 20 keV negative H source is working stable, the extracted beam of 5 mA current has an angle of divergence about 0.1 radians.
- The H^- beam current measured by Faraday cup near the end of LEBL is about 2.5 mA due to LEBL imperfect acceptance adjustment and ionization losses at residual gas.
- LEBL output aperture of 10 mm diameter was used to protect first tandem electrode against illuminating by the beam halo, and, finally, after beam passing the tandem accelerating channel with argon stripping cell (10 mm in diameter, 400 mm of length), there was obtained a 2 MeV, 1 mA output proton current at the target placed in 40 cm distance from tandem output.

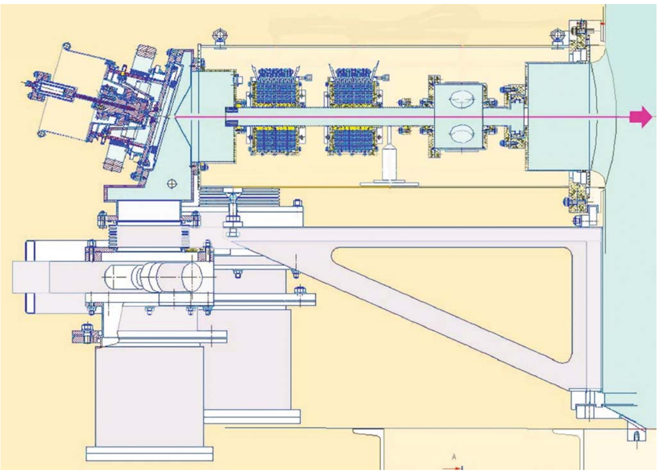

FIG. 3. (Color online) Low energy beam line (LEBL).

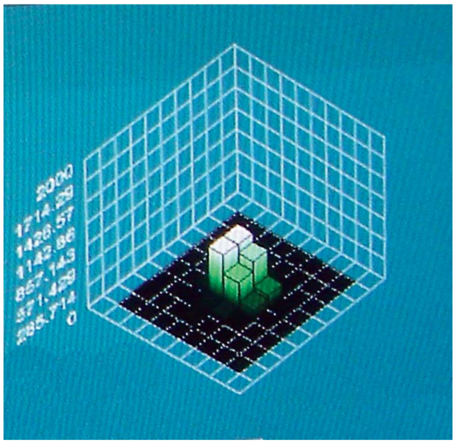

FIG. 6. (Color online) An example of two-dimensional current profile centered near beam line axis.

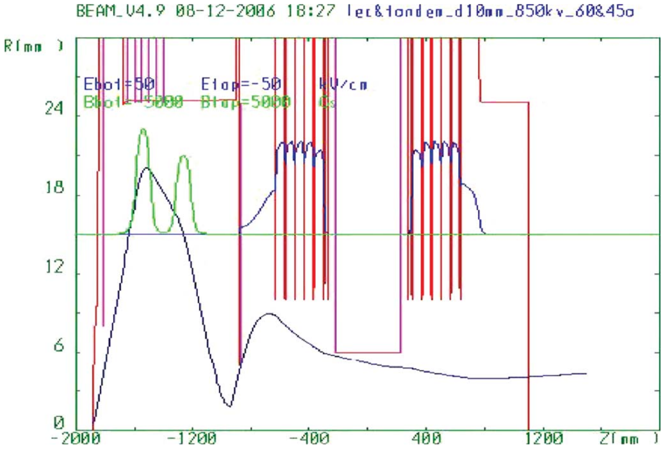

FIG. 4. (Color online) Geometry of limiting beam envelope, output LEBL diaphragm, and accelerating structure electrodes (axial coordinate is scaled down by a factor of 133); the profiles of *B* and *E* fields are also shown.

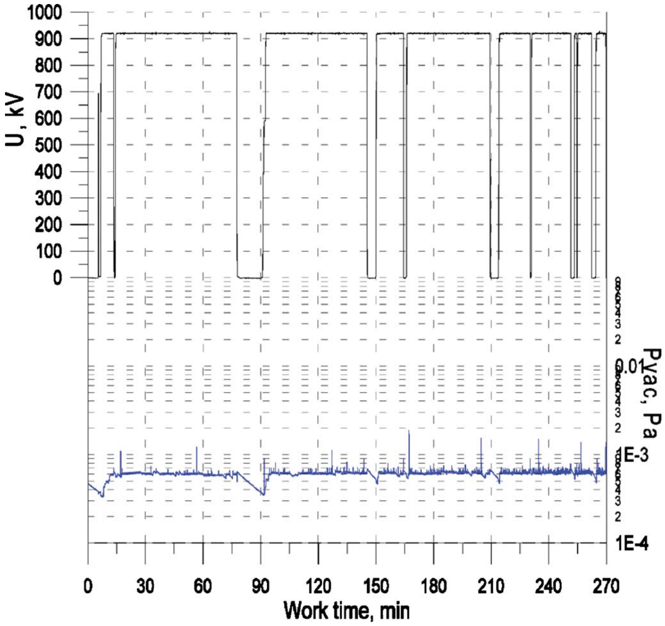

FIG. 7. (Color online) Inner electrode potential versus time at final stage of tandem high voltage conditioning during 5 h run

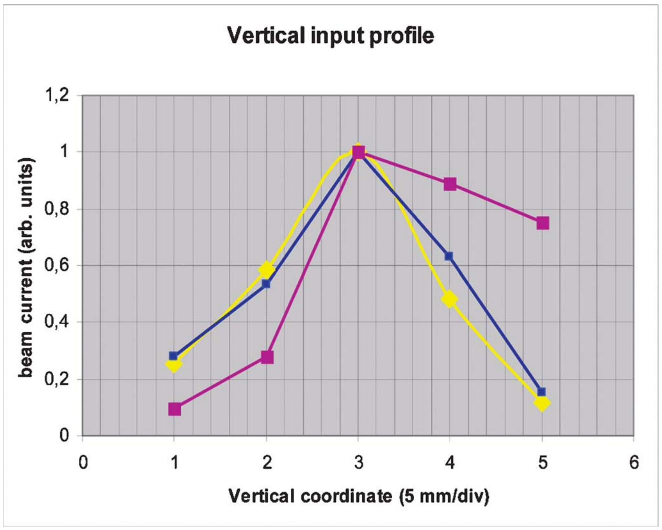

FIG. 5. (Color online) Beam current profiles in vertical direction for slightly different beam turning angles.

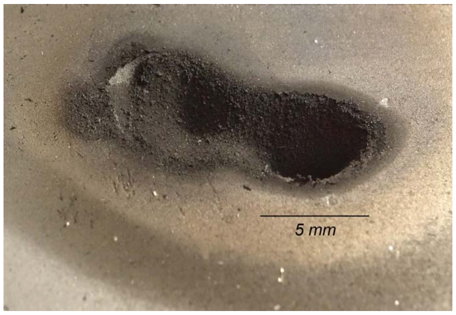

FIG. 8. (Color online) 1.8 MeV, 1 mA proton beam imprints at the carbon target obtained in two runs; exposition time is about 10 min for each run.

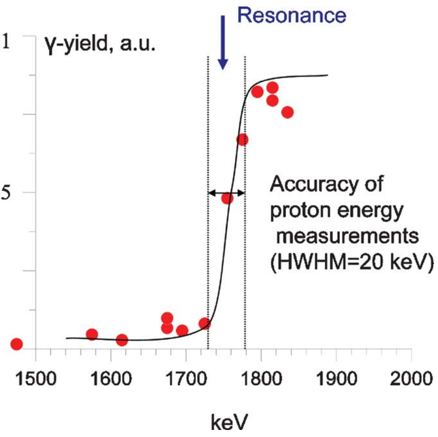

FIG. 9. (Color online) Measured gamma-excitation curve as proton beam energy monitor. Thick ^{13}C target, the curve is averaged over 5 runs; ~1% accuracy is caused by divider thermal stability.

As next steps, we are planning to undertake to increase proton current up to 5 mA:

- to improve LEBL characteristics;
- to increase acceptable current of the first electrode by connecting to a separate power supply instead of to the voltage divider; and
- to reduce beam power density by a beam scanning over target.

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[1] B. F. Bayanov, V. P. Belov, E. D. Bender, M. V. Bokhovko, G. I. Dimov, V. N. Kononov, O. E. Kononov, N. K. Kuksanov, V. E. Palchikov, V. A. Pivovarov, R. A. Salimov, G. I. Silvestrov, A. N. Skrinsky, and S. Yu. Taskaev, Nucl. Instrum. Methods Phys. Res. A **413**, 397 (1998).