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Obtaining a Proton Beam with 5-mA Current in a Tandem Accelerator with Vacuum Insulation

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Abstract—Suppression of parasitic electron flows and positive ions formed in the beam tract of a tandem accelerator with vacuum insulation allowed a more than threefold increase (from 1.6 to 5 mA) in the current of accelerated 2-MeV protons. Details of the modification are described. Results of experimental investigation of the suppression of secondary charged particles and data on the characteristics of accelerated proton beam with increased current are presented.

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At present, boron neutron capture therapy (BNCT) [1] is considered to be a promising method for the treatment of malignant tumors. Broad implementation of the BNCT method in clinics requires compact sources of epithermal neutrons based on charged particle accelerators generating proton beams with energy of 2–3 MeV and no less than 3-mA current. To solve this task, an electrostatic proton accelerator of the new type—a tandem accelerator with vacuum insulation—has been proposed and developed at the Institute of Nuclear Physics (Novosibirsk). The new source is characterized by high ion acceleration rate and the insulator remote from the ion acceleration channel [2]. Upon decreasing the dark current down to an acceptable level [3] and optimizing the input of hydrogen ions into the source [4] and their stripping in a gas target [5], the proton beam current was increased from the initial value of about 140 μA [6] up to about 1.6 mA [7] and remained stable for more than 1 h.

In attempts to elucidate factors responsible for the limitation of current in the channel of acceleration of negative hydrogen ions, we have detected and measured a significant flow of accompanying electrons and counterflow of positive ions formed in the acceleration channel and in the stripping gas target [8]. For suppression of these undesired flows, we have proposed and implemented some ideas and approaches that are new for the physics of particle accelerators. This Letter describes details of this modification and results of experiments on the suppression of secondary charged particles and increase in the proton beam current.

Figure 1 shows a schematic diagram of the modified tandem accelerator with vacuum insulation. A beam of negative hydrogen ions with 23-keV energy and up to 6-mA current from source *1* is rotated by 15° in a magnetic field, focused by magnetic lenses *2*, injected into accelerator *3*, and accelerated to 1-MeV energy. Gas stripping target *7* arranged inside high-voltage electrode *6* converts the accelerated negative hydrogen ions into protons, which are accelerated by the same 1-MeV potential difference up to 2 MeV. The potential to high-voltage electrode *6* and five auxiliary accelerating electrodes *5* is supplied from high-voltage power source *9* (sectioned rectifier, not completely depicted) via feedthrough insulator *8* with an ohmic divider. The gas is pumped by turbomolecular pumps *10* (situated at the ion source and accelerator output) and by cryogenic pump *4* through high-voltage electrode louvers.

The accelerator was modified as follows. Input vacuum volume *14* was increased in length so as to accommodate cooled metal diaphragm *13* with a 20-mm diameter hole, which could be center-adjusted with respect to the beam axis. This diaphragm was intended to reduce the flow of gas and UV radiation out from the source of negative hydrogen ions to the accelerating channel. A DU 250 port on the upper flange of the input vacuum volume was used to mount additional cryogenic pump *11* (On-Board 10, CTI-Cryogenics, United States) capable of pumping argon and hydrogen at a rate of 2500 and 5000 L/s, respectively, so as to improve vacuum conditions in the tract of beam transport and accelerating channel. Metal

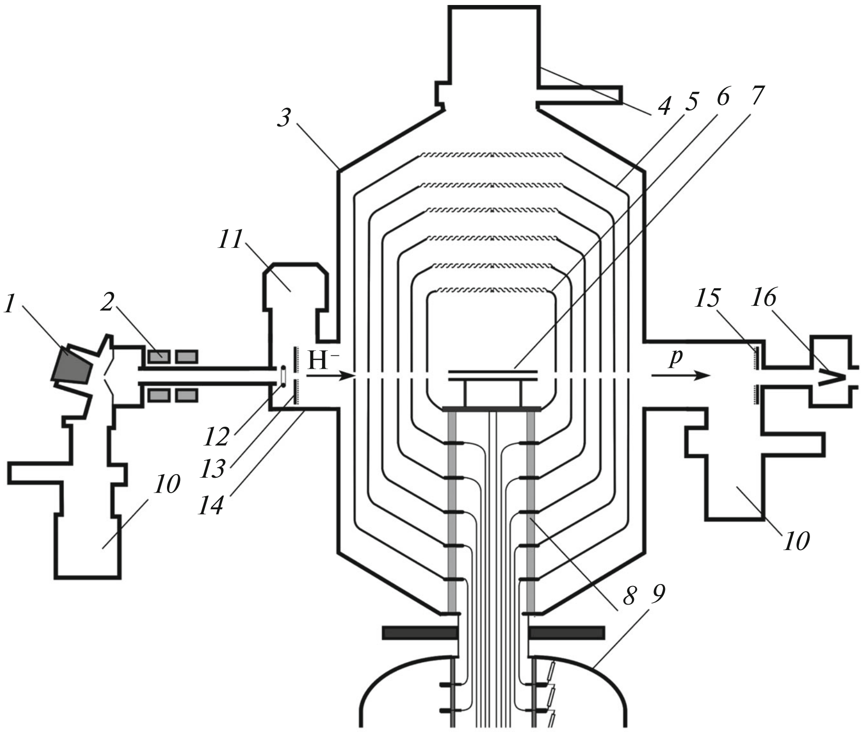

Fig. 1. Tandem accelerator with vacuum insulation: (*1*) source of negative hydrogen ions, (*2*) magnetic lenses, (*3*) accelerator, (*4*) cryogenic pump, (*5*) auxiliary electrodes, (*6*) high-voltage electrode, (*7*) gas stripping target, (*8*) feedthrough insulator, (*9*) high-voltage power source, (*10*) turbomolecular pump, (*11*) cryogenic pump, (*12*) ring, (*13*) cooled metal diaphragm and edge grid detector, (*14*) input vacuum volume, (*15*) edge grid detector, and (*16*) Faraday cup. Arrows indicate the directions of motion of the beam of negative hydrogen ions (H^-) and protons (*p*).

ring *12* was arranged between the beam transport output and cooled metal diaphragm. Negative potential applied to this ring must block the flow of electrons accompanying the beam of negative hydrogen ions. The surface of cooled diaphragm *13* from the source side was covered by a tantalum grid that blocked secondary electrons generated by positive ions bombarding of the vacuum chamber walls. Insulated metal disk arranged between the grid and diaphragm was used to measure the current. Analogous metal grid and disk *15* covered the vacuum chamber surface at the accelerator output.

Figure 2a shows that the application of potential to a grid at the accelerator input significantly decreases the dose of bremsstrahlung radiation generated by 1-MeV electrons absorbed in the metal [9]. The current–voltage characteristic of the edge (grid–disk) detector at the accelerator input (Fig. 2b) shows that the coefficient of secondary electron emission under the action of positive ions is about 10 (high value of this coefficient is characteristic of many-electron ions and atoms with energies above 100 keV [10]). Introduction of the diaphragm, cryogenic pump, ring, and grids provided a significant decrease in parasitic currents of charged particles. In particular, the flow of electrons accelerated to full voltage was decreased 20 times (down to about 0.5% of the ion beam current). The contribution from argon flow in the stripping target to this current decreased from 80 to 30%.

The suppression of parasitic currents of charged particles in the accelerator improved the stability of accelerator operation with respect to full voltage breakdown and allowed the proton beam current to be significantly increased (from 1.6 to 5 mA). Figure 3 shows waveforms of the proton beam current and energy measured in one experimental run. The proton beam current (measured by Faraday cup *16*, Fig. 1) for a period of about 1 h exceeded 5 mA, having an average value of 5.12 ± 0.06 mA and a maximum value of 5.327 mA. It should be noted that fluctuations of the current were caused by unstable operation of the source of negative hydrogen ions in ultimate regimes. At a proton beam current of 3 and 4 mA, the system operated for about 1 h at a current stability of 0.5% without high voltage breakdowns. As can be seen from Fig. 3, there were two breakdowns at a current of above 5 mA and the current was restored on the preceding level within 35 s, which is a quite acceptable situation. In regimes with high beam current, the output voltage of the high-voltage power source decreased so that the proton beam energy declined from 2 MeV at 4 mA to 1.93 ± 0.01 MeV at 5 mA. It is suggested that this effect can be eliminated by modifying the high-voltage

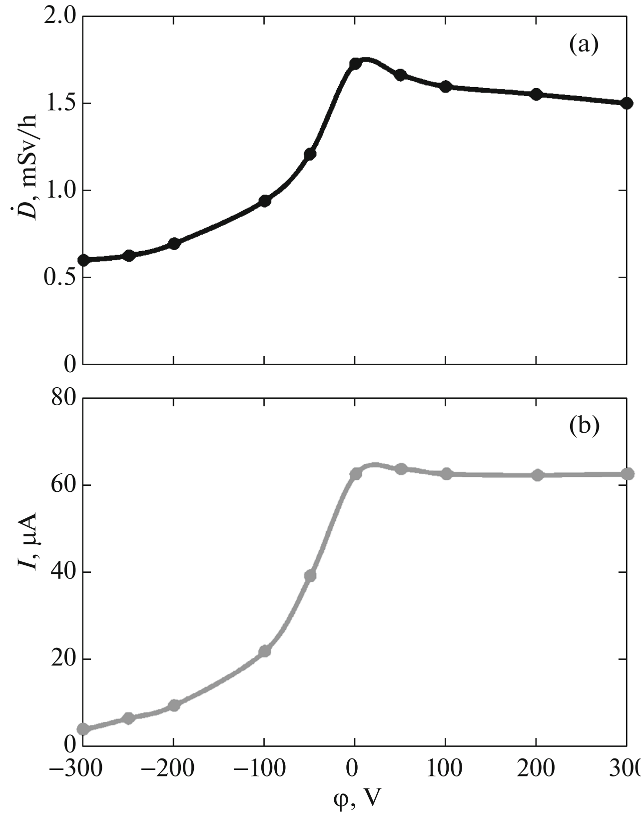

Fig. 2. Plots of (a) γ-radiation dose $\dot{D}$ and (b) current to the edge detector at the accelerator input vs. grid potential φ.

power source, e.g., by introducing an additional rectifier circuit.

Obtaining a stationary proton beam with a 5-mA current in principle solves the problem of neutron sources for BNCT, since the extraction of this beam to a lithium target provides for the required density of epithermal neutron flow. The existing facilities, including the KG-2.5 Kockroft–Walton type accelerator at Obninsk (Russia) [11], Birmingham dynamitron (England) [12], and KURRI cyclotron [13], only provide proton beam currents about 1 mA, which is by no means sufficient for BNCT purposes. It was claimed in 2014 that a 3-mA proton beam was obtained in a Hyperion electrostatic dc accelerator (GR Advanced Technologies, United States) [14], but no results were presented. The required beam current will likely be achieved in the near future with another three accelerators developed for BCNT, including the Hitachi RF linac for the National Oncology Center (Tokyo, Japan) [15], IBA Dynamitron (Belgium) for Nagoya University (Japan) [16], and Mitsubishi RF linac for Tsukuba University (Japan) [17].

The proposed tandem accelerator with vacuum insulation can also be used for the creation of systems detecting hidden explosives and drugs [18], calibration

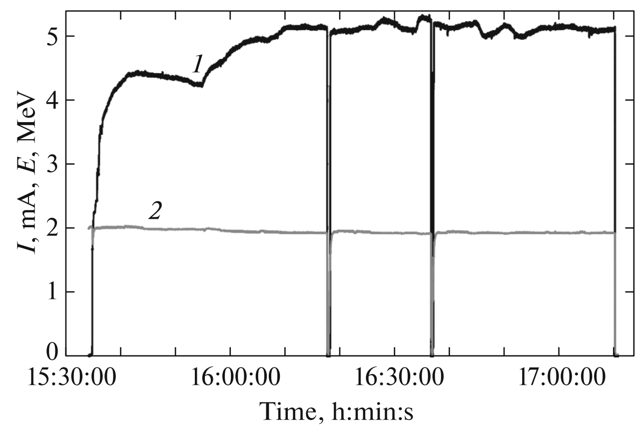

Fig. 3. Temporal variation of (a) proton beam current I and (b) proton energy E.

of weakly interacting dark matter detectors [19], and in some other applications.

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