ISSN 1063-7850, Technical Physics Letters, 2015, Vol. 41, No. 2, pp. 139–141. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © D.A. Kasatov, A.N. Makarov, S.Yu. Taskaev, I.M. Shchudlo, 2015, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2015, Vol. 41, No. 3, pp. 74–80.

Recording of Current Accompanying an Ion Beam in a Tandem Accelerator with Vacuum Insulation

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Received August 27, 2014

Abstract—A proton beam (2 MeV and 1.6 mA) has been obtained on a tandem accelerator with vacuum insulation. Experimental results are given that outline the reasons for current limits, and approaches to increasing the current of a proton beam are proposed.

DOI: 10.1134/S1063785015020078

At present, boron neutron capture therapy [1] is considered to be a promising treatment of malignant tumors. For this treatment to be usable widely in clinical practice, compact sources of epithermal neutrons based on a charged particle accelerator need to be provided. Researchers at the Budker Institute of Nuclear Physics proposed [2] and constructed a source of epithermal neutrons based on a unique tandem accelerator with vacuum insulation, characterized by a high rate of ion acceleration and a lithium target for neutron generation.

Figure 1 shows a schematic illustration of a tandem accelerator with vacuum insulation. The beam of hydrogen negative ions with energy of 23 keV and current up to 5 mA exiting from source *1* is rotated in a magnetic field by 15°, focused by a pair of magnetic lenses *2*, injected into the accelerator, and accelerated to 1 MeV. In gaseous (argon) stripping target *7* installed inside high voltage electrode *5*, the hydrogen negative ions are transformed into protons, which are subsequently accelerated by the same potential of 1 MV to an energy of 2 MeV. The potential to high voltage electrode *5* and five intermediate electrodes of accelerator *6* is supplied from high voltage power source *10* (a significant portion is not depicted) via feed-through insulator *9*, where an ohmic divider is installed. The gas is evacuated by turbo-molecular pumps *8* installed near the ion source and at the accelerator output and cryogen pump *4* via an electrode grill.

Using the accelerator, stationary proton beam (2 MeV and 1.6 mA) was obtained with high monochromaticity of 0.1% in terms of energy and current stability of 0.5%. During beam dumping to the lithium target, neutrons have been generated [3] and the influence of neutron irradiation on cell cultures has been studied [4]. In order to perform therapy, the proton beam current needs to be increased to at least 3 mA. This Letter is aimed at understanding the reasons for current limits and includes proposals on approaches to increasing the proton beam current.

Attempts to increase the proton beam current by means of injection of beam of hydrogen negative ions with current of higher than 2 mA or by means of higher gas puffing into a stripping target lead to frequent breakdowns of the accelerator in terms of overall voltage and make it impossible to obtain a stable stationary proton beam.

Within injection of an ion beam by current higher than 1 mA, the current at accelerator output, normalized to the current in accelerator channel, at an increase in gas puffing into stripping target did not rise

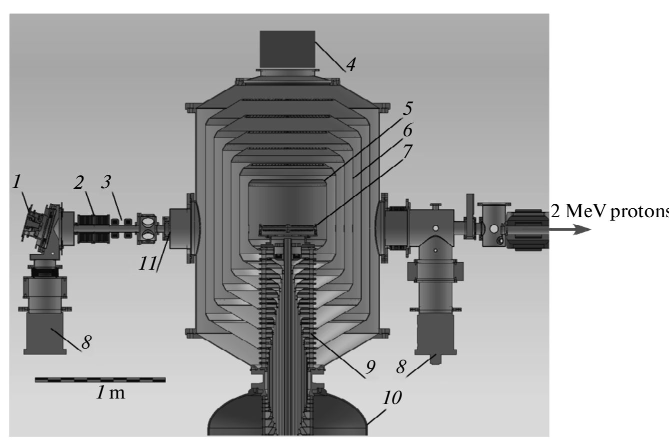

Fig. 1. Tandem accelerator with vacuum insulation: (*1*) source of hydrogen negative ions, (*2*) magnetic lenses, (*3*) correctors, (*4*) cryogen pump, (*5*) high-voltage electrode, (*6*) intermediate electrodes, (*7*) gas stripping target, (*8*) turbo-molecular pump, (*9*) feed-through insulator, (*10*) high-voltage power source, and (*11*) place of diaphragm or detector.

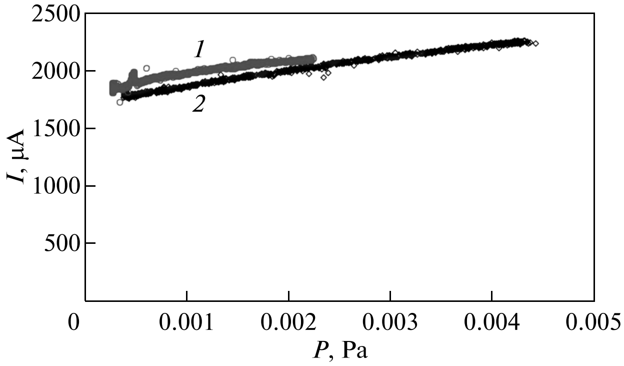

Fig. 2. Current in accelerating gap as a function of residual gas with an increase in gas puffing into a stripping target: (*1*) with activated cryogen pump, (*2*) with deactivated cryogen pump.

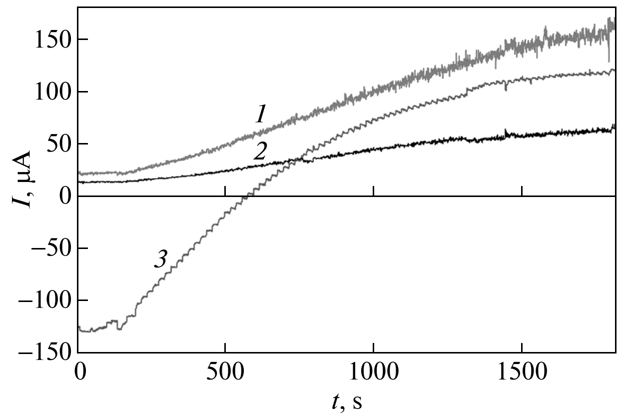

Fig. 3. Plots of current on internal *1* and external *2* disks of detector within increase in gas puffing into stripping target. The plot of current at accelerator output *3 i*s shown (the values of current are reduced by ten times for convenience).

starting from a certain time, but rather dropped. This was in contradiction with the preliminary results obtained with a current that is lower but stable in time [5].

When steady operation of the source of hydrogen negative ions at high currents was achieved, the current in accelerating gap (from input to accelerator to high-voltage electrode) was measured as a function of gas puffing into a stripping target (illustrated in Fig. 2). The current in the accelerating gap equals the difference between the load current measured using the reference resistance of high-voltage power source and the currents measured using the reference resistance of the ohmic divider of a feed-through insulator and Faraday cylinder installed at the accelerator output. The value of gas puffing is indirectly indicated by the measured pressure of residual gas at the accelerator output. It can be seen that, with an increase in gas puffing, the current in the accelerating gap increases by 500 μA with a deactivated cryogen pump and by 250 μA with an activated pump.

The aforementioned phenomena made it possible to assume the existence of a foreign flow of charged particles in an accelerating gap. In order to verify this hypothesis, a dedicated detector was made consisting of two concentric circular disks (an internal one with diameters of 52 and 90 mm and an external one with diameters of 92 and 136 mm) and a frame with a stretched grid for suppression of secondary emission. The detector is installed at the input to the accelerating gap (*11* in Fig. 1); it measures only the current flowing from high-voltage electrode. Figure 3 shows the plots of the current to the detector during injection of a beam of hydrogen negative ions with a current of 1.5 mA and from the time point of 150 s at a smooth increase in gas puffing into a stripping target via short-time opening of an electromechanical gas supply valve with a frequency of 0.05 Hz (the stripping target and gas puffing system have been described elsewhere [6]). Negative values of current correspond to prevailing hydrogen negative ions in the beam, while positive values correspond to prevailing protons. It can be seen that, with an increase in gas density in the stripping target, the rate of beam stripping increases and the current recorded by the detector rises in fact linearly. On the internal disk, it increases by 140 μA, while on the external disk it increases by 50 μA. Therefore, the acceleration of the beam of hydrogen negative ions is accompanied with a counterflow of positive ions.

In order to understand the processes that are taking place, it is important to plot the absorbed dose rate of bremsstrahlung measured by a spherical ionization chamber installed at a distance of 7.5 m from the accelerator as a function of current in the accelerating gap. The curve is illustrated in Fig. 4. It can be seen that, with an increase in gas puffing and the current in the accelerating gap, the rate of braking radiation also increases.

It should be mentioned that, when the gas is not supplied to a stripping target (at current of about 1800 μA), braking radiation exists and its value is significant. Since the absorption of accelerated ions by engineering materials does not lead to a noticeable absorbed dose rate of braking radiation, then it can be attributed to acceleration of electrons in the accelerator channel. Extrapolating the dependence of the radiation rate on the current to zero, we obtain an intersection at 1.55 mA. This means that a beam of hydrogen negative ions with current of 1.55 mA is injected into the accelerator. The beam in the accelerating gap ionizes the residual gas, which leads to the occurrence of an additional current of 250 μA, which is transferred by electrons toward the high-voltage electrode and by positive ions toward the earthed accelerator tank. The gas supply to the stripping target leads to a further increase in this additional current by 500 μA;

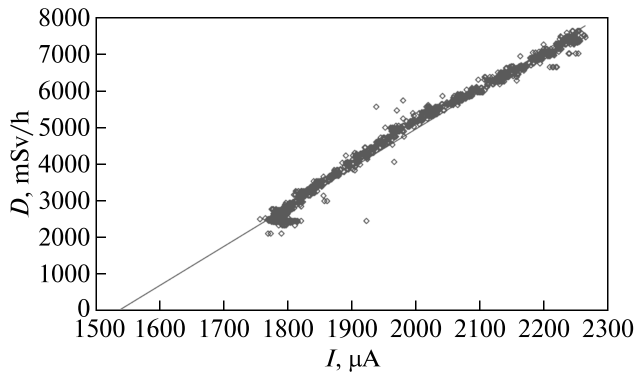

Fig. 4. Absorbed dose rate of braking radiation as a function of current in the accelerating gap.

herewith, a significant portion of it (up to 190 μA), in the form of a flow of positive ions, is transferred to the detector that covers the peripheral region.

Therefore, it has been established that the beam ionization of residual and stripping gas, as well as penetration of a portion of argon positive ions from the stripping target to the accelerator channel leads, to the occurrence of a current accompanying the ion beam. The value of the accompanying current is significant. The flow of this current promotes breakdowns of the accelerator in terms of overall voltage. Without an activated cryogen pump, it is possible to provide 50% stripping of the beam without breakages. Activation of the cryogen pump approximately halves the value of the accompanying current and makes it possible to achieve 90% stripping of the beam. Further increase in the current of the proton beam is possible with improvement of vacuum conditions in an accelerating gap by means of mounting of a cryogen pump onto the input flange of an accelerator and modification of a stripping target. Modification of the target is aimed at decrease in gas flow, ultraviolet radiation and flow of argon positive ions into the accelerating gap. Modification of the target entails its being lifted and inclined with respect to the accelerating channel by means of constant magnets, as well as implementation of differential evacuation by means of a turbo-molecular pump inside the high-voltage electrode.

Acknowledgments. This work was supported by the Ministry of Science of the Russian Federation, unique identifier of applied research RFMEFI60414X0066.

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Translated by I. Moshkin