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Increasing the Electric Strength of a Vacuum-Insulated Tandem Accelerator

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Abstract—The electric strength of ceramic insulators was tested at a dedicated high-voltage vacuum facility and the electric strength of a vacuum-insulated tandem accelerator with redesigned feedthrough insulators was studied. Based on the results of the investigations and the upgrade the voltage in the accelerator was increased from 1.00 to 1.15 MV; the operating mode was achieved without high-voltage breakdowns.

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INTRODUCTION

A source of epithermal neutrons was developed by the Budker Institute of Nuclear Physics (BINP) on the basis of the vacuum-insulated tandem accelerator with a lithium target [1]. This source is intended for the development of a promising method for treating malignant tumors, i.e., boron neutron capture therapy [2]. A stationary proton beam with an energy of 2 MeV was obtained at the facility, generation of neutrons was performed and the effect of neutron radiation on cell cultures [3] and laboratory animals [4] was studied. However, the necessity to produce a therapeutic neutron beam with the required parameters for the treatment of deeply located tumors requires that the proton energy be increased to 2.3 MeV [5].

The purpose of this work was to modify the feedthrough insulators of the accelerator to achieve the voltage required to produce a proton beam with an energy of 2.3 MeV.

THE ACCELERATOR DESIGN

The diagram of a vacuum-insulated tandem accelerator is shown in Fig. 1. A proton beam with an energy of 2 MeV and a current of up to 9 mA is produced as follows. A beam of negative hydrogen ions with an energy as high as 25 keV is extracted from the surface-plasma source *1*. The beam is bent through an angle of 15° in the magnetic field of the ion source and then is focused by magnetic lens *2* to the entrance of the accelerator *11*, where it is accelerated to an energy of 1 MeV. Negative hydrogen ions are converted into protons in the gas stripping target *7* mounted inside the high-voltage electrode *5* of the accelerator, and protons are accelerated by the same potential of 1 MV to an energy of 2 MeV.

The potential is supplied for the high-voltage electrode *5* and five intermediate electrodes *6* of the accelerator from the high-voltage source *10* through the feedthrough insulator *9* in which an ohmic voltage divider is mounted. Gas is pumped out by turbomolecular pumps *8* that are installed near the ion source and at the accelerator output and by cryogenic pump *4* through the louvers of the electrodes.

The vacuum part of the high-voltage feedthrough insulator (Fig. 2) is composed of 24 ring glass insulators with a diameter of 394 mm and a height of 35 mm, which are tightly trussed via vacuum with intermediate electrodes. The gas-filled part of the insulator is enclosed in a tank of the high-voltage rectifier. It consists of 14 ceramic rings with a diameter of 394 mm and heights of 30 and 60 mm, which are glued to the electrodes. The inside of the feedthrough insulator is filled with insulating gas SF_6 at a pressure of 0.3 MPa. The tank of the high-voltage rectifier is filled with SF_6 gas at a pressure of 0.8 MPa.

The total resistance of the resistive voltage divider of the feedthrough insulator is 1.8 GΩ. Resistors located around the lower gas-filled part of the feedthrough insulator distribute the potential among the intermediate accelerating electrodes through the electrodes of the gas-filled part of the insulator, thin-walled metal pipes that have different lengths and diameters and are coaxially located inside the feedthrough insulator, and the electrodes of the upper vac-

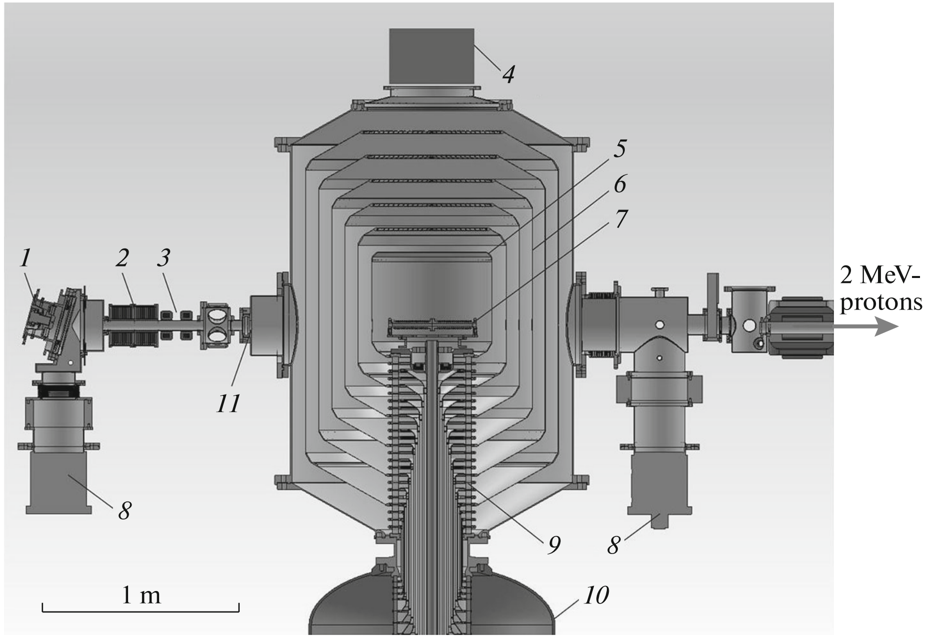


Fig. 1. The vacuum-insulated tandem accelerator: (*1*) source of negative hydrogen ions, (*2*) magnetic lenses, (*3*) correctors, (*4*) cryogenic pump, (*5*) high-voltage electrode, (*6*) intermediate electrodes, (*7*) gas stripping target, (*8*) turbomolecular pump, (*9*) feedthrough insulator, (*10*) high-voltage power supply, and (*11*) the location of the entrance diaphragm of the accelerator.

uum part of the insulator. The potential distribution at the electrodes of the vacuum part of the insulator, which are galvanically isolated from the coaxial tubes, is set by the resistors located inside the vacuum part of the feedthrough insulator.

The use of the feedthrough insulator provides a voltage of 1 MV and guarantees a long service life. Nevertheless, it is possible to increase the voltage U to 1.15 MV (see Fig. 3). Accelerating gaps are trained by keeping at an applied high voltage, and residual pressure P_{vac}, dark current I_{dark}, and X-ray dose rate D decrease over time.

At the same time, the dark current in the accelerating gaps remains significant. As a result, a redistribution of the potential of the intermediate electrodes occurs in a low-power resistive voltage divider, which leads to an increase in the electric field strength in individual accelerating gaps and to high-voltage breakdown over the surface of the insulator.

The greatest damage consisted in the burnout of resistors in the voltage divider (Fig. 4) that was located inside the feedthrough insulator, which results from the sagging of resistor chains due to the significant heat release in a limited space. Replacing the resistances was a lengthy process, since it required a complete disassembly of the accelerator and the feedthrough insulator.

The proposed solution to the problem of resistor burnout consisted in doubling the height of individual insulators and eliminating the part of the ohmic divider that was located inside the feedthrough insulator. In other words, only electrodes that were electrically connected to the electrodes of the lower gas-filled part of the feedthrough insulator by internal coaxial metal pipes had to be left in the upper vacuum part of the feedthrough insulator. Since a number of insulator electrodes were also removed from the feedthrough insulator, it was necessary to increase the height of individual insulators from 35 to 73 mm to maintain the overall height of the feedthrough insulator. This led to an increase in the voltage across a single insulator from 50 to 100 kV and required experimental verification.

INVESTIGATION OF THE ELECTRIC STRENGTH OF INSULATORS

A test facility was designed and manufactured for an experimental study of the electric strength of insulators. The test insulator, which was tightly vacuum trussed between the grounded and high-voltage electrodes, was located inside the vacuum volume of the high-voltage facility. A high voltage was applied to the test insulator through a high-voltage bushing. The X-ray dose rate was measured with a dosimeter.

The examined ceramic rings had a height of 73 mm, an external diameter of 394 mm, an inner 336 mm, and smooth (Fig. 5a) and ribbed (Fig. 5b) vacuum surfaces. The residual gas pressure during the experiment was 2×10^{-4} Pa.

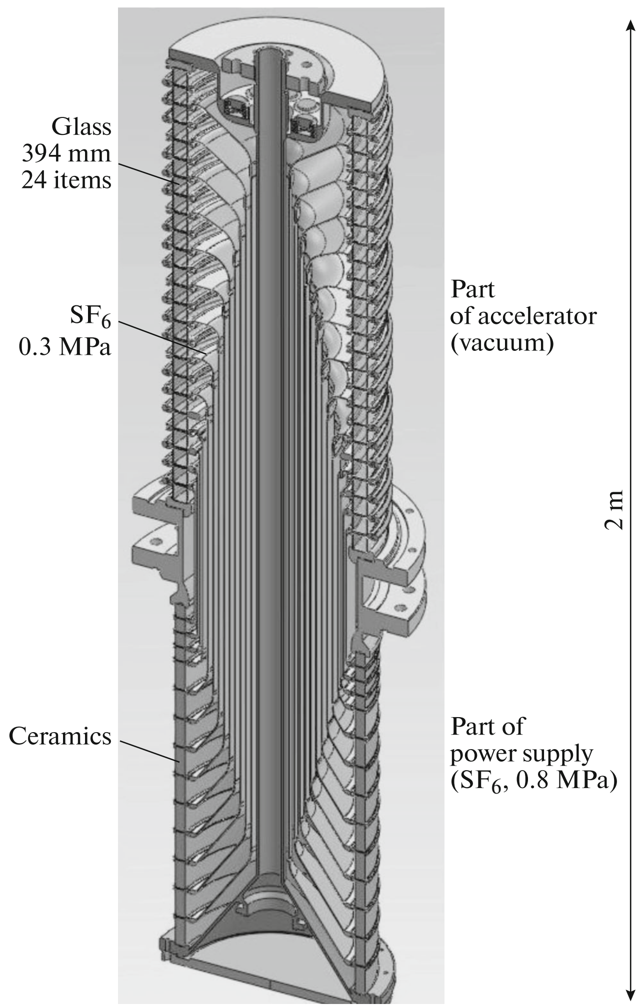


Fig. 2. A diagram of the feedthrough insulator of the accelerator.

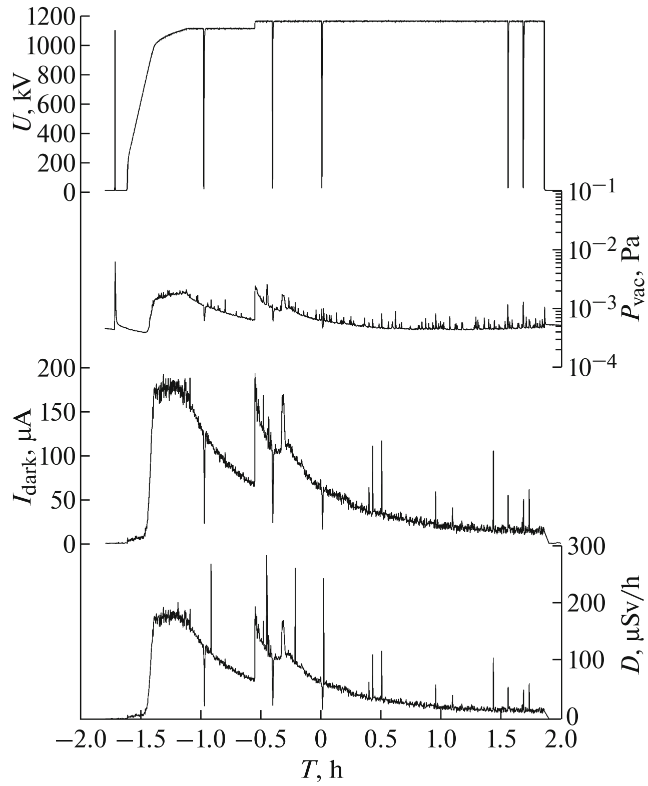


Fig. 3. Graphs of the accelerator-voltage rise.

Figure 6 shows a graph of the voltage rise at the ceramic insulators with smooth (Fig. 6a) and ribbed (Fig. 6b) surfaces. The required voltage of 100 kV was obtained at both insulators and any of them can be used to prevent burnout of resistors located inside the feedthrough insulator.

Ceramic insulators with a smooth outer surface have been selected for use, since they are technologically simpler to manufacture. At the same time, the training of a ribbed-surface insulator was faster; the maximum voltage at which no multiple breakdowns occurred was 140 kV, whereas this value for the smooth-surface insulator was 120 kV.

UPGRADING THE FEEDTHROUGH INSULATOR

The feedthrough insulator was upgraded based on the experimental data obtained in our study of the electric strength of individual ceramic rings. The glass rings in the upper vacuum part of the feedthrough insulator (Fig. 7a) were replaced with smooth ceramic rings (Fig. 7b). Four 35-mm-high rings were used in the first accelerator gap and two 73-mm-high rings were used in the other five gaps.

The insulator of the lower gas-filled part was not modified. The total height of the feedthrough insulator was not changed. A new resistive voltage divider with a total resistance of 1.8 GΩ was also manufactured and mounted outside the lower gas-filled part of the feedthrough insulator.

After the new feedthrough insulator was mounted in the accelerator and a standard training was conducted after opening to the atmosphere, a voltage of 1 MV was attained without any deviations from the previously used procedure. This meant that doubling the voltage across a single insulator ring due to doubling its height did not lead to any limitations in attaining the required voltage or to deterioration in its reliability.

The results of the experiment aimed at obtaining a voltage of 1.15 MV are presented in Fig. 8. The first breakdown occurred at a voltage above 1 MV; the required voltage of 1.15 MV was obtained in the presence of infrequent breakdowns. After this, following a 2-h training the voltage was increased to 1.21 MV and remained at this level for 1 h with one breakdown. The

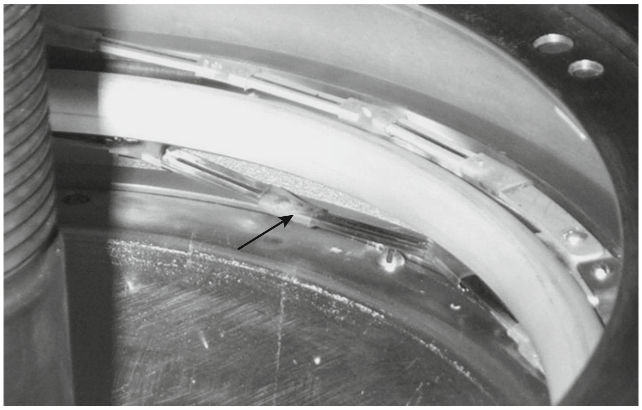


Fig. 4. The sagging and burnout of a part of the voltage divider (shown by the arrow) inside the feedthrough insulator.

voltage was then reduced to 1.15 MV and fixed at this level for 1 h and over, as follows from Fig. 9, which was accompanied by a decrease both in the dark current and in the bremsstrahlung dose.

In order to observe discharges and breakdowns, holes were drilled in the vacuum tank of the accelerator and KF branch pipes with windows were welded into these holes. Hikvision cameras (China) were fixed in places on the branch pipes with the windows. Two cameras were aimed at the input diaphragm of the first accelerating electrode, two cameras were directed towards the output diaphragm of the first accelerating electrode, and two cameras looked at the first accelerating gap from above.

A video camera was mounted on one of the branch pipes in the lower cone of the vacuum tank of the accelerator and was aimed at the ceramic insulators with a height of 35 mm. An LFP-10WP-R halogen lamp (Shibuya, Japan) was mounted on the second branch pipe in the lower cone of the vacuum tank for illumination. Another camera was fixed in place at the end of the horizontal proton-beam transport line; it was aimed along the beamline.

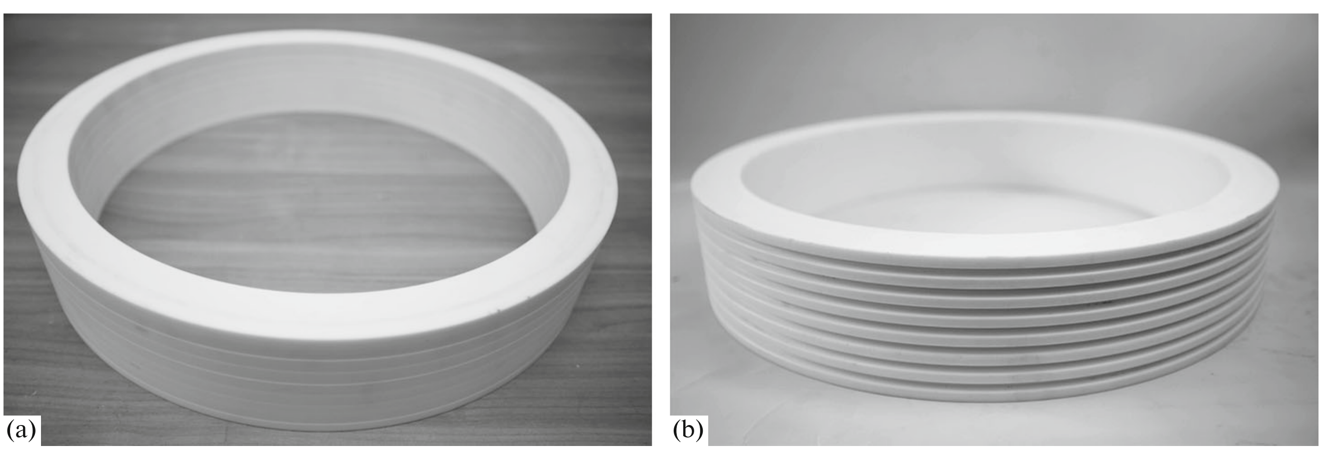
The video cameras recorded discharges and breakdowns. Photos of breakdowns over the surface of the ceramic rings in the feedthrough insulator are shown in Fig. 10. A visible track remains on the surface of the insulator (Fig. 11b) after a breakdown. It should be noted that lightning may pass very close to the earlier track, as can be seen in Fig. 10a.

Observation of the discharges suggests that a discharge with a current of 1–3 mA ignites before a flash of lightning in one of the accelerating gaps. The flow of current in a gap with a value as high as this leads to a decrease in the voltage in this gap and to an increase in the voltage in the other accelerating gaps, since the potential of the intermediate electrodes is set by the low-power ohmic voltage divider of 1.8 GΩ.

It is worth noting that the average electric field strength on the insulator surface is 14 kV/cm, which is higher by a factor of 1.4 than the value recommended for operation without breakdowns. Naturally, when a discharge ignites in one of the gaps, the electric field strength in the other gaps increases even more and breakdown occurs.

When a proton beam is produced and neutrons are generated in the ^{7}Li(p, n)^{7}Be reaction, the software for the system of control and data acquisition automatically restores the accelerator parameters in 10 s after a breakdown. Breakdowns leading to a temporary cessation of neutron generation occur every 3–10 min and, in principle, may not interfere with therapy, but their disposal is desirable.

There are two ways to solve this problem. The first consists in increasing the height of individual insulators by a factor of 1.4, which leads to an increase both in the accelerator size and in the energy stored in the accelerating gaps. The second is to corrugate the surface



(a) (b)

Fig. 5. The ceramic insulators with (a) smooth and (b) ribbed outer surfaces.

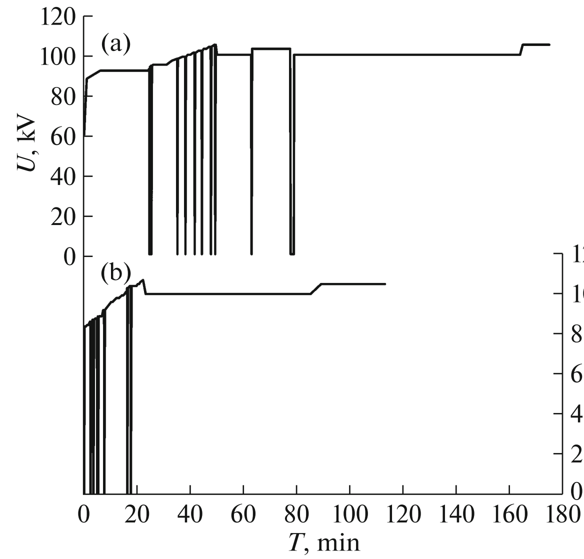


Fig. 6. The voltage rise at the 73-mm-high insulators with (a) smooth and (b) ribbed outer surfaces.

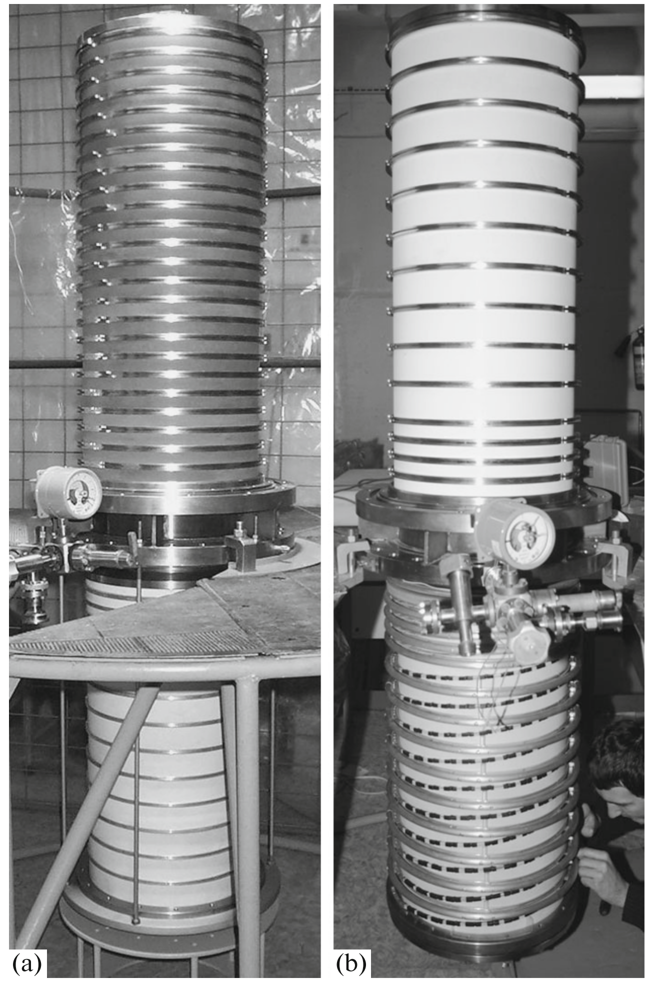


Fig. 7. Photos of the feedthrough insulator with (a) 35-mm-high glass rings and (b) with 73- and 35-mm-high smooth ceramic rings.

of the vacuum part of the ceramic rings, which increases the path along the insulator surface and, therefore, reduce the average electric field strength over the surface. We established previously that, according to the results of the tests at the test facility, the ribbed surface provided an increase in the electric strength of up to 1.5 times relative to the smooth surface [6].

However, corrugation also leads to an increase in the maximum field strength in some places, since the electric field equipotentials in the design of a compact tandem accelerator with the vacuum insulation are not perpendicular to the surfaces of smooth ceramic rings, so it is not obvious which effect will be predominant.

Ceramic rings with a ribbed outer vacuum surface were manufactured (Fig. 12) and mounted in a feedthrough insulator instead of the smooth ceramic insulators. The radius of the ribs and depressions was selected as 1 mm, based on the previous results [6]. The height of the new individual ribbed ceramic insulators was not changed. The overall height of the feedthrough insulator also remained the same.

After the feedthrough insulator with the ribbed outer vacuum surface of its ceramic rings was mounted and the accelerator passed its standard training, a voltage of 1 MV was attained in half the previous time and with a smaller number of breakdowns than in the feedthrough insulator with a smooth ceramic ring surface (Fig. 13). The voltage was then increased to 1.2 MV (Fig. 14), and only two breakdowns occurred over 1 h. The dark current decreased and did not exceed 20 μA.

The operating-voltage level of 1.15 MV was reached without breakdowns (Fig. 15) in the third series of experiments. We note that the average electric-field strength at the insulators with a smooth surface and a ribbed vacuum surface, considering the increase in its length, was approximately 14 and 9 kV/cm, respectively. The latter value is often given in literature sources as the value that provides the required durability.

The operating voltage remained at a level of 1.15 MV for 1.5 h without breakdowns. Thus, the required accelerator operating mode of the accelerator has been achieved. Therefore, the electric strength of the accelerator has been increased by reducing the average electric-field strength on the insulator surface to 8.4 kV/cm; at the same time, the maximum voltage at some points reached a value of 21 kV/cm.

The facility was disassembled after 6 months of operation, during which the production of a proton beam and the generation of neutrons were provided without breakdowns. No traces of breakdowns were found on the ribbed vacuum surface of the feedthrough insulator (Fig. 16). Even the rare breakdowns

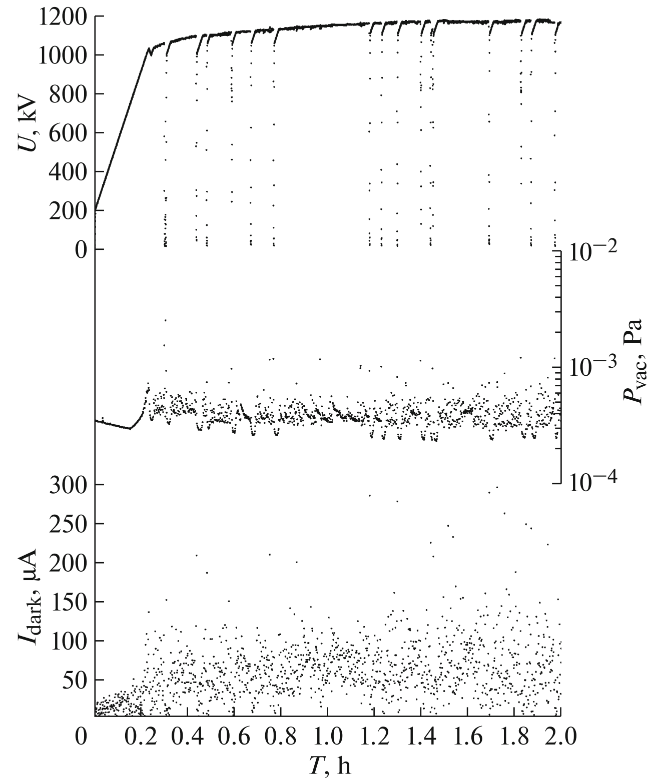


Fig. 8. Graphs of the voltage U, residual pressure P_{vac}, dark current I_{dark} at the accelerator vs. time T during the voltage rise.

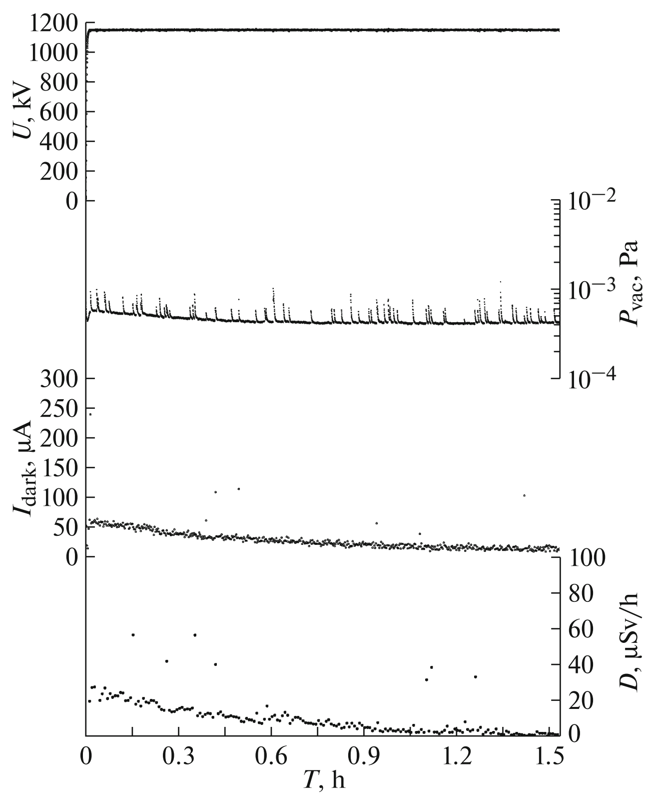


Fig. 9. Graphs of the voltage U, residual pressure P_{vac}, dark current I_{dark}, and the bremsstrahlung dose rate D of the accelerator when the voltage is maintained at a level of 1.15 MV.

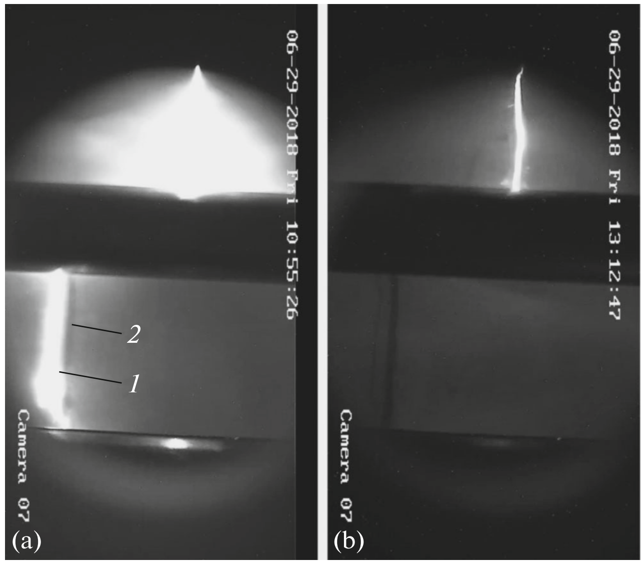


Fig. 10. Photos of breakdowns over the insulator surface: (*1*) current breakdown and (*2*) track formed from a previous breakdown.

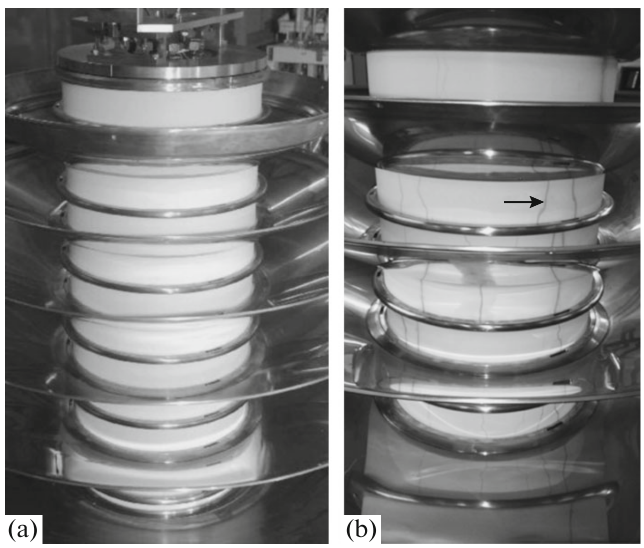


Fig. 11. Photos of the smooth ceramic surface of the insulator (a) before and (b) after the training with traces of breakdowns. The arrow points to one of the tracks formed after the breakdown.

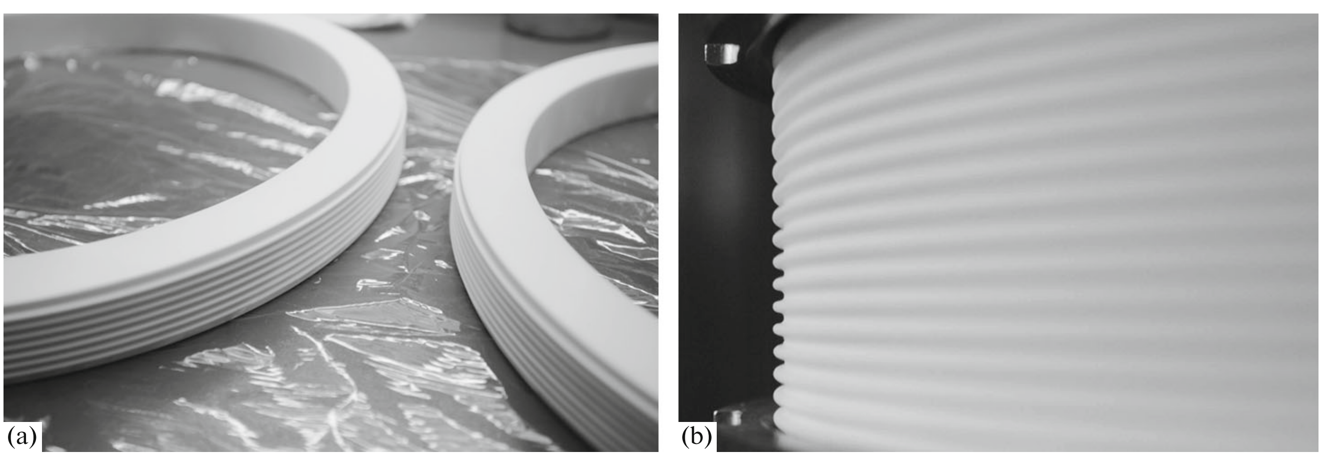


Fig. 12. The ceramic insulators with a ribbed outer surface and a height of (a) 35 and (b) 70 mm.

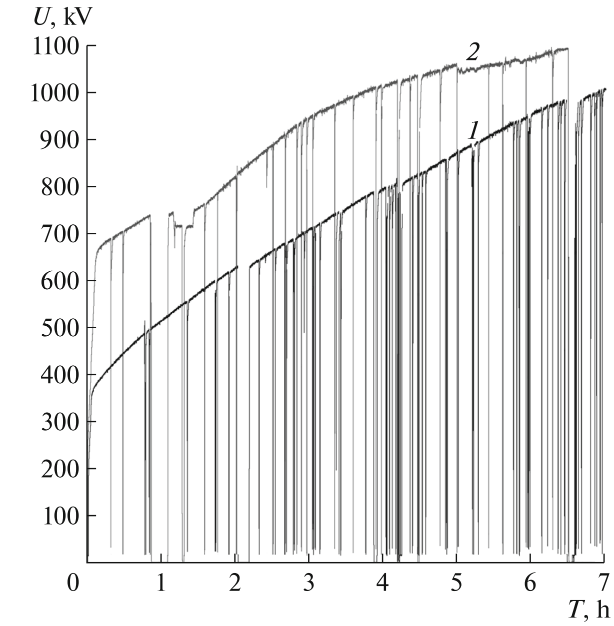


Fig. 13. Graphs of the first voltage rise at the accelerator: (*1*) for the smooth ceramic surface of the insulator and (*2*) for the ribbed ceramic surface.

that occurred during the voltage rise and the training were most likely not related to breakdowns over the insulator surface.

Thus, it has been experimentally established that the use of single ceramic rings with a double height and a ribbed vacuum surface in the feedthrough insulator and elimination of the part of the resistive voltage divider inside the feedthrough insulator are fully justified: a voltage of 1.15 MV has been obtained and the reliability of the accelerator-based neutron source has been significantly increased.

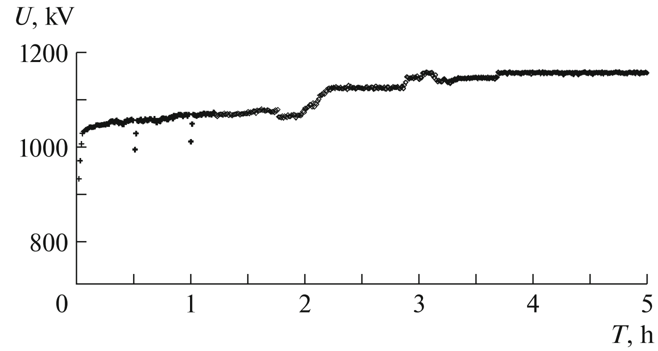


Fig. 15. A graph of the voltage U at the accelerator versus time T when the voltage is increased and maintained at a level of 1.15 MV.

CONCLUSIONS

An epithermal neutron source based on the vacuum-insulated tandem accelerator and a lithium target has been created and used at the BINP. It is intended for development of the boron neutron-capture therapy, which is a promising method for treating malignant tumors, as well as for other applications.

It was necessary to increase the proton energy from 2.0 to 2.3 MeV, i.e., increase the voltage of the tandem accelerator from 1.00 to 1.15 MV to solve the problems of obtaining a therapeutic neutron beam that best meets the requirements of boron neutron capture therapy. For this goal to be achieved, the electric strength of the

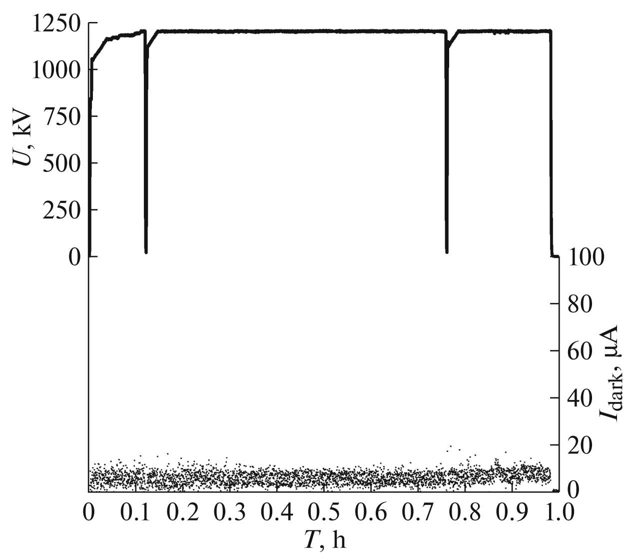


Fig. 14. Graphs of the voltage U and dark current I_{dark} at the accelerator vs. time T.

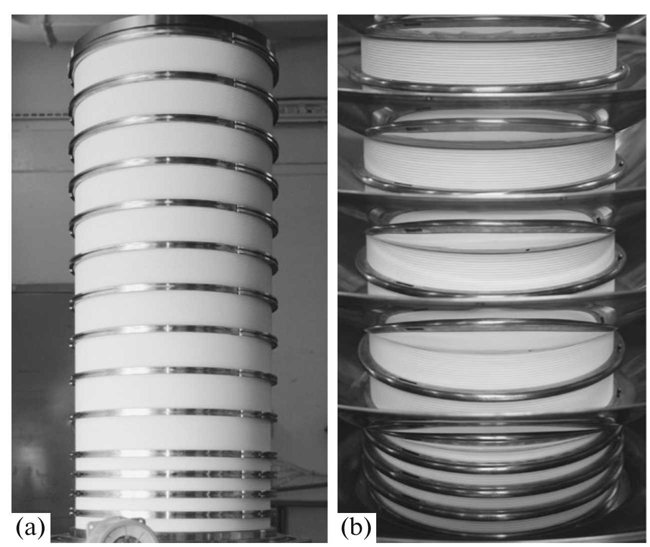


Fig. 16. Photos of the ribbed ceramic insulator surface (a) before and (b) after the training.

ceramic insulators was studied and the feedthrough insulator was upgraded. At the first stage of the upgrading, the glass rings were replaced with double-height smooth ceramic rings, which also made it possible to eliminate the part of the resistive voltage divider inside the feedthrough insulator. At the second stage, the smooth ceramic rings were replaced with ribbed ceramic rings.

As a result of the study, it was established that an increase in the electric strength of the feedthrough insulator is achieved by reducing the average electric field strength over the insulator surface due to the corrugation, although local spots with increased field strength are formed. The required voltage of 1.15 MV was obtained in the vacuum-insulated tandem accelerator after the upgrade. The operating mode without high-voltage breakdowns was maintained, which is important for using a neutron source in therapy and for other applications.

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