ISSN 0020-4412, Instruments and Experimental Techniques, 2017, Vol. 60, No. 1, pp. 70–73. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © E.V. Domarov, A.A. Ivanov, N.K. Kuksanov, R.A. Salimov, I.N. Sorokin, S.Yu. Taskaev, V.G. Cherepkov, 2017, published in Pribory i Tekhnika Eksperimenta, 2017, No. 1, pp. 77–81.

ELECTRONICS AND RADIO ENGINEERING

A Sectioned High-Voltage Rectifier for a Compact Tandem Accelerator with Vacuum Insulation

E. V. Domarov[a], **A. A. Ivanov**[a, b], **N. K. Kuksanov**[a], **R. A. Salimov**[a], **I. N. Sorokin**[a]*, **S. Yu. Taskaev**[a, b]**, and **V. G. Cherepkov**[a]

[a] *Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences,*
pr. Akademika Lavrentieva 11, Novosibirsk, 630090 Russia

[b] *Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090 Russia*

**e-mail: i.n.sorokin@inp.nsk.su*

***e-mail: s.yu.taskaev@inp.nsk.su*

Received December 25, 2015; in final form, February 11, 2016

Abstract—A prototype of a compact sectioned high-voltage source for the modernization of a tandem accelerator with vacuum insulation has been created at the Budker Institute of Nuclear Physics. In contrast to the existing voltage source, it is possible to specify the potential at the accelerating electrodes directly from the rectifier sections, as well as to decrease the accelerator height. This paper presents a new source design and the test results.

DOI: 10.1134/S0020441216060130

An epithermal-neutron source has been designed for boron neutron capture therapy of malignant tumors at the Budker Institute of Nuclear Physics [1]. It is based on a tandem accelerator (TA) with vacuum insulation and a lithium neutron-producing target [2–4]. In the TA with vacuum insulation (Fig. 1), first, negative hydrogen ions are accelerated; inside the high-voltage electrode in the stripping target they then turn into protons that are accelerated by the same potential to twice the energy.

A sectioned rectifier of an industrial electron accelerator of the ELV series was used as a high-voltage source [5]. To ensure the focusing stability and ion beam acceleration, it was suggested to determine the potential of intermediate electrodes directly from rectifier sections rather than by using a resistive divider [6].

This work describes the rectifier design, which makes it possible to feed the potential to intermediate electrodes of the accelerator directly from its corresponding sections, which should reduce the effect of dark currents and transient processes on the accelerator operation. In addition, the rectifier test results are presented.

The new design allows the arrangement of a part of the bushing insulator of the accelerator, which is under sulfur hexafluoride pressure, directly inside the sectioned rectifier. The rectifier design is shown in Fig. 2; the appearance of the high-voltage column is shown in Fig. 3. The vessel, *1,* is mounted on stay, *2.* Primary winding, *3,* rests on supports, *4,* which are mounted on the lower flange of the vessel shell. The elements of

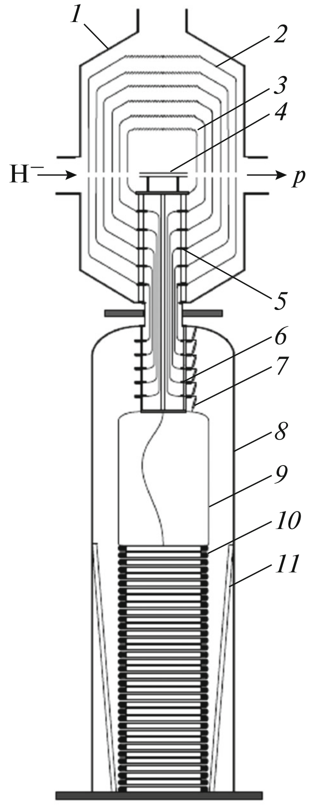

Fig. 1. The layout of the tandem accelerator with vacuum insulation: (*1*) the tank of the tandem accelerator; (*2*) intermediate accelerating electrodes; (*3*) high-voltage electrode; (*4*) gas charge-exchange target; (*5*) the vacuum part of the bushing insulator; (*6*) the gas part of the bushing insulator; (*7*) resistive divider; (*8*) the tank of the high-voltage source (sectioned rectifier); (*9*) the high-voltage electrode of the rectifier; (*10*) rectifier sections; (*11*) the primary winding of the rectifier. H^- is the beam of negative hydrogen ions and p is the proton beam.

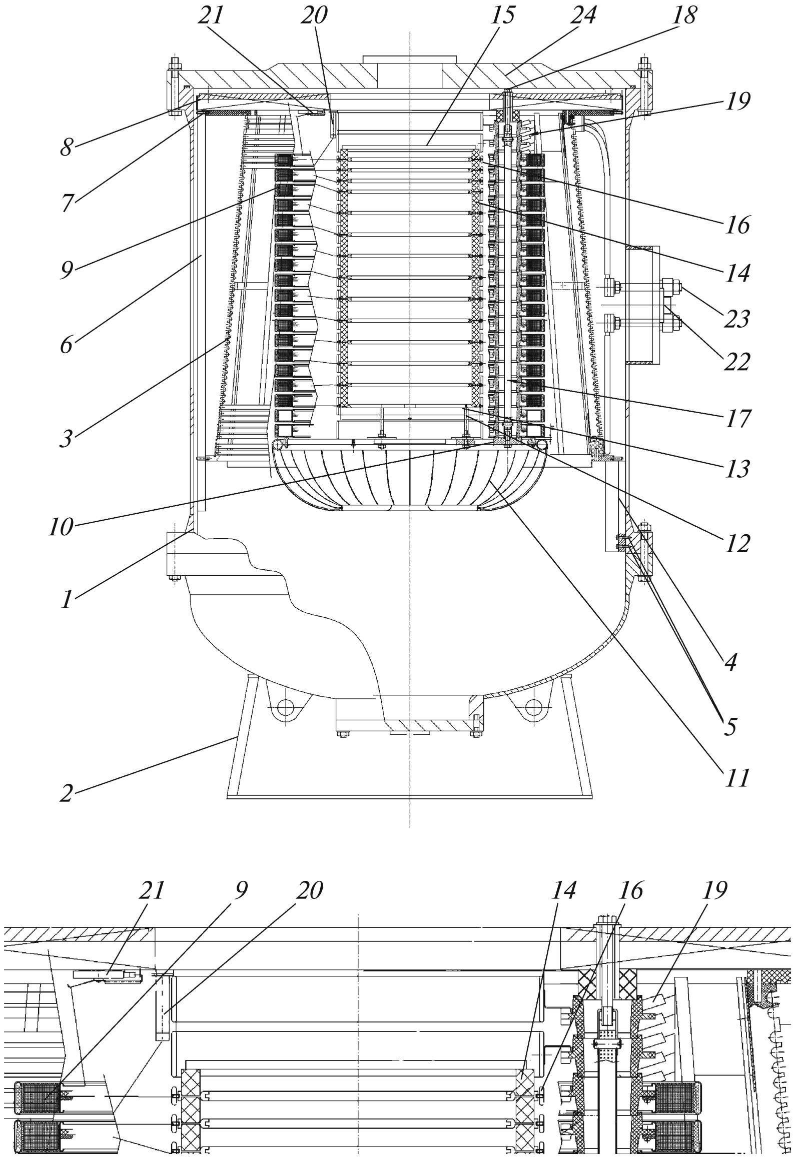

Fig. 2. The design of the rectifier: (*1*) high pressure vessel; (*2*) stay for the high-pressure vessel; (*3*) primary winding; (*4*) support of the primary winding; (*5*) screws to fasten the supports of the primary winding; (*6*) the magnetic conductor of the primary winding; (*7*) the fastenings of the magnetic conductor of the primary winding; (*8*) bottom magnetic conductor; (*9*) rectifier sections; (*10*) textolite base; (*11*) high-voltage electrode; (*12*) the legs of the high-voltage electrode; (*13*) duralumin disk electrode; (*14*) gas part of the bushing insulator of the accelerator; (*15*) disk duralumin electrode; (*16*) copper short-circuit rings; (*17*) rods of the high-voltage column; (*18*) fastening nuts of rods; (*19*) divider of energy; (*20*) divider of the first section; (*21*) current sensor; (*22*) connector for measuring signals; (*23*) inputs of the primary winding; and (*24*) bottom of the vessel.

the cylindrical magnetic conductor, *6*, are fixed directly to the base of the primary winding. The rectifier column, which consists of 17 sections, *9*, was assembled on a reinforced glass-textolite basis, *10*, of the high-voltage electrode, *11*. On the same basis, the gas part, *14*, of the accelerator bushing insulator is mounted on the legs, *12*, and duralumin disk electrode, *13*, in alignment to the column. From above, the insulator is closed with a disk duralumin electrode, *15*.

To protect the electrodes of the insulator from an alternating magnetic field, the insulator is screened with 14 copper short-circuit rings, *16*, with a diameter of 400 mm and a height of 46 mm. Insulator rings are connected by contact conductors with sections of the rectifier column.

The assembled column is suspended on the bottom magnetic conductor by three rods, *17*, which are placed inside the supports of the rectifier sections.

To measure the total voltage of the rectifier, U_0, a resistive divider, *19*, consisting of 121 resistors with a resistance of 100 MΩ each, is placed in the column. The voltage of the first section U_s is measured with the resistive divider of the section, *20*, with a total resistance of 1 GΩ. The total current of the rectifier, I_0, was measured through the sensor, *21*. All of the measuring circuits U_0, U_s, I_0 are led out through connector, *22*, which is located at the side flange of the vessel. The supply voltage of the primary winding, *3*, is fed through the standard inputs, *23*.

A 180° turn of the rectifier (compared to the initial design) led to a change of the supporting points of most of the construction units. As a result, all of the rectifier units (primary winding, rectifier column, and bottom magnetic conductor) are mounted in the vessel shell on supports, *4*. Each support is fixed to the vessel shell flange. Calculations showed that at a total weight of all of the rectifier units of 560 kg, the safety margin factor of this construction is 6.4.

The primary winding of an accelerator of the ELV-05-03 type was used in the high-voltage source. This has 28 loops of double copper tube wound on a bobbin. The bobbin height is 993 mm, and the maximum screen diameter is 1010 mm. The inner vessel diameter and height of the vessel are 1200 and 1900 mm, respectively. The primary winding mounted in the vessel was tested for serviceability at a maximum permissible voltage of 400 V at a frequency of 426 Hz and a current of 250 A during 12 min. The test showed the full functioning of the primary winding at loads within the operating range.

Evaluation of the strength of acrylic resin rods of the high-voltage column at a mass of the assembled high-voltage column with the insulator, copper rings, and high-voltage electrode of 336 kg (Fig. 3) showed a margin of two. The rectifier remained in the assembled state for 3 months. Inspection of the rods upon its dismantling showed the absence of visible deformations. When assembled and tested in air, the rectifier was placed in a hermetically closed vessel and tested in sulfur hexafluoride (SF_6) at pressures of up to 0.5 MPa.

The voltage induced at the coil of the rectifier section in the column was measured using a ring measuring coil with 30 loops, which was placed at the distance h from the bottom magnetic conductor. The coil diameter is 695 mm, which corresponds to the diameter of the middle loop of the coil of the rectifier section. The voltage distribution was measured both with mounted copper screening rings and without them.

Figure 4 shows the diagrams of the dependence $U = f(h)$ measured at an effective voltage at the primary winding of $U_1 = 100$ V. The domain corresponding to n sections of the rectifier columns is located between the ordinates U_{n1} and U_{n17}. The assessed values of the voltages in the rectifier column are as follows: the voltage in the first section U_{s1} is 12.4 kV at $U_1 = 100$ V; the average voltage of section $U_{s\ av}$ is 12.7 kV at $U_1 = 100$ V, 35.3 kV at $U_1 = 600$ V, and 41.2 kV at $U_1 = 700$ V; the maximum voltage $U_{s\max}$ is 13.5 kV at $U_1 = 100$ V, 37.5 kV at $U_1 = 600$ V, and 43.7 kV at $U_1 = 700$ V; the overall voltage of the source $U_0 = 217.1$ kV at $U_1 = 100$ V; the average loop voltage of a coil of a section is $U_{\text{loop}} = 1.51$ V at $U_1 = 100$ V; and the $U_{1\text{loop}}/U_{\text{loop}}$ ($U_{\text{loop}}/U_{1\text{loop}}$) ratio is 2.36 (0.42).

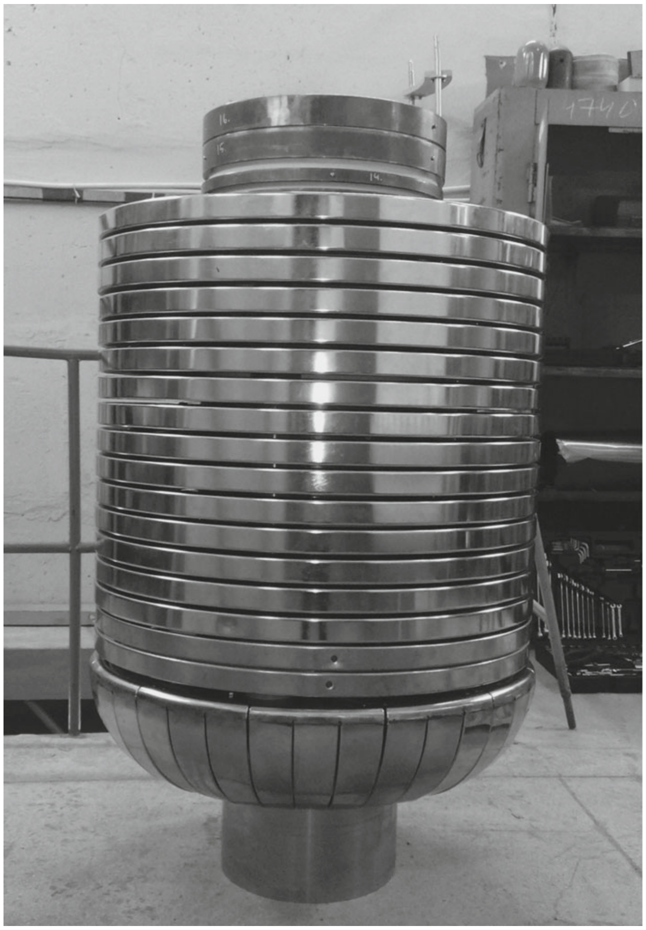

Fig. 3. The appearance of the high-voltage column.

The heating intensity of the copper screening rings was checked at a voltage across the primary winding of 400 V and a current of 288 A during 30 min. It was revealed that the first (from the high-voltage electrode) ring (Fig. 2) was heated to a temperature of 60°C and the current in the ring was 458 A. The remaining screening rings were heated to 40°C. The duralumin disc electrode *15* (Fig. 2) was not heated; its temperature was 25°C. To decrease heating of the first ring between it and the high-voltage electrode, an additional copper screening ring was installed.

When the rectifier was run in air, the measured values agreed with the calculated values from the data of Fig. 4 with an accuracy of better than 3%. Breakdowns at the overall voltage began in air at a voltage of 125 kV.

Figure 5 shows the current–voltage characteristics of the rectifier after tests at an overall voltage of 700 kV at various sulfur hexafluoride pressures. It is seen that

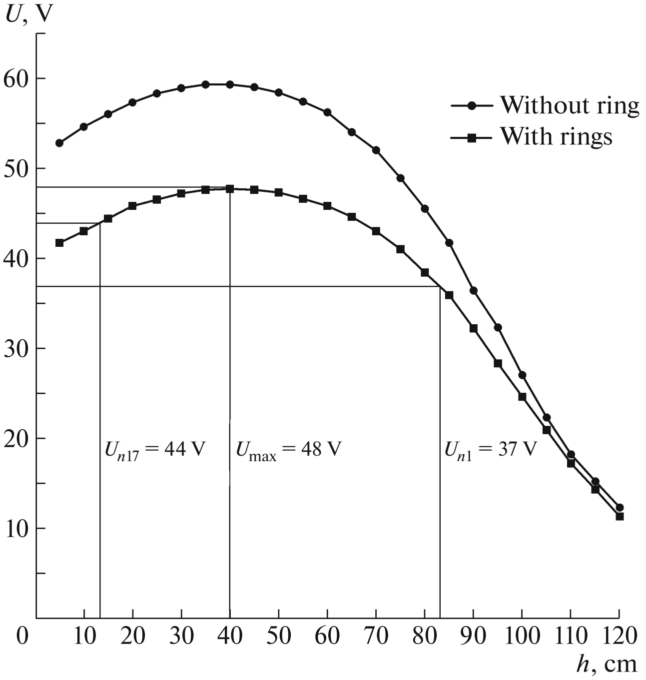

Fig. 4. The dependence of the voltage across the measuring coil on the height h.

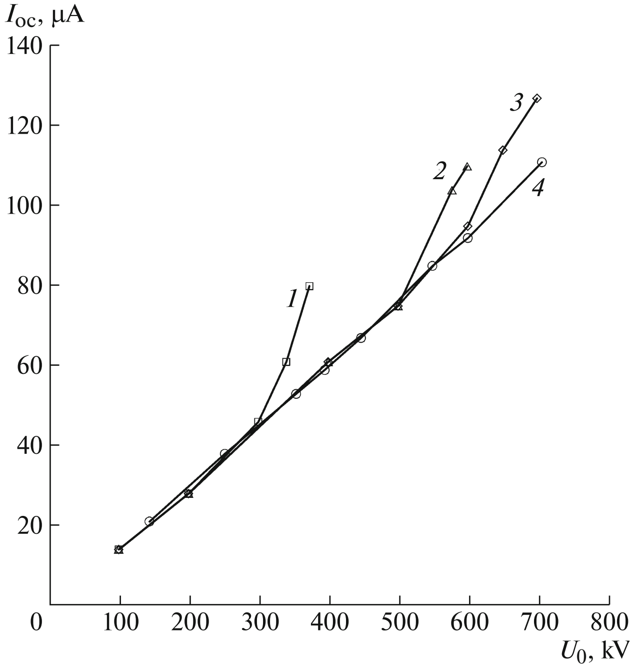

Fig. 5. The dependence of the open-circuit current I_{oc} on the voltage of the rectifier U_0 at P_{SF_6}, MPa: (*1*) 0.2; (*2*) 0.3; (*3*) 0.4; and (*4*) 0.5.

the source can be operated at a sulfur hexafluoride pressure of P_{SF_6} = 0.5 MPa.

Hence, an ELV-type high-voltage sectioned rectifier was developed, inside which the gas part of the bushing insulator of a TA with vacuum insulation can be inserted. This modification makes it possible to feed the potential to the intermediate electrodes of the accelerator directly from the corresponding sections and reduce the effect of dark currents and transient processes, in particular, of beam injection into the accelerator, on the optical properties of the accelerator and, as a result, on the stability of its operation. The use of this rectifier configuration can significantly reduce the height of the entire neutron source, thus making it possible to locate it directly in an oncology clinic.

A rectifier voltage of 700 kV was obtained in the long-term mode. It is planned to modify the rectifier to obtain a voltage of 1.15 MV, which is required to power the accelerator.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Education and Science of the Russian Federation (unique identifier of applied research is RFMEFI60414X0066).

REFERENCES

1. *Neutron Capture Therapy. Principles and Applications,* Sauerwein, W., Wittig, A. Moss, R., and Nakagawa, Y., Springer-Verlag, 2012. doi 10.1007/978-3-642-31334-9
2. Bayanov, B., Belov, V., Bender, E., Bokhovko, M., Dimov, G., Kononov, V., Kononov, O., Kuksanov, N., Palchikov, V., Pivovarov, V., Salimov, R., Silvestrov, G., Skrinsky, A., and Taskaev, S., *Nucl. Instrum. Methods Phys. Res., A,* 1998, vol. 413, p. 397. doi 10.1016/S0168-9002(98)00425-2
3. Kasatov, D., Kuznetsov, A., Makarov, A., Shchudlo, I., Sorokin, I., and Taskaev, S., *J. Instrum.,* 2014, vol. 9, p. 12016. doi 10.1088/1748-0221/9/12/P12016
4. Taskaev, S.Yu., *Phys. Part. Nucl.,* 2015, vol. 46, no. 6, p. 956. doi 10.1134/S1063779615060064
5. Salimov, R., Cherepkov, V., Golubenko, Yu., Krainov, G., Korabelnikov, M., Kuznetsov, S., Kuksanov, N., Malinin, A., Nemytov, P., Petrov, S., Prudnikov, V., Fadeev, S., and Veis, M., *Rad. Phys. Chem.,* 2000, vol. 57, p. 661.
6. Sorokin, I. and Taskaev, S., *Appl. Rad. Isotop.,* 2015, vol. 106, p. 101. doi 10.1016/j.apradiso.2015.06.015

Translated by M. Kromin