ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2018, Vol. 15, No. 7, pp. 819–822. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © A.V. Vanin, Yu.N. Gavrish, 2018, published in Pis'ma v Zhurnal Fizika Elementarnykh Chastits i Atomnogo Yadra, 2018.

CYCLOTRONS AND LINEAR ACCELERATORS OF INTERMEDIATE AND LOW ENERGIES

Present-Day Cyclotron Systems Designed and Built at NIIEFA

A. V. Vanin[a] and Yu. N. Gavrish[a, *]

[a]*AO Efremov Research Institute of Electrophysical Apparatus, St. Petersburg, 196641 Russia*

**e-mail: gavrish@luts.niiefa.spb.su*

Received November 1, 2017

Abstract—A number of cyclotrons and cyclotron systems for the generation and use of accelerated proton beams within energy ranges from 1 to 80 MeV have been designed at AO NIIEFA. Some types of cyclotrons are intended for the production of accelerated deuteron beams. The cyclotron systems intended for operation at medical centers are equipped with targetry systems for the production of radionuclides in gaseous, liquid, and solid states.

DOI: 10.1134/S1547477118070683

INTRODUCTION

At AO Efremov Research Institute of Electrophysical Apparatus (NIIEFA), a number of cyclotrons have been developed for the acceleration of negative hydrogen and deuterium ions yielding accelerated proton and deuteron beams by charge exchange on thin graphite foils. The basic characteristics of the cyclotrons are presented in Table 1.

The operation of the cyclotrons and cyclotron systems is fully automatically controlled. The ACSs with a distributed architecture are comprised of controllers and computers; each of them is responsible for the control of one or several systems of the cyclotron complex.

CYCLOTRON SYSTEM FOR ANALYTICAL STUDIES

The SS1-3 cyclotron system [1, 2] ensures the production of proton beams with unique parameters, viz., the energy range from 1 to 3 MeV with a spectral width that does not exceed 0.1% and energy determination accuracy no worse than 1 keV; it is intended for analytical studies by X-ray spectrometry, gamma-ray spectrometry, and Rutherford backscattering spectrometry.

To achieve the above beam parameters, a variant of the system was selected that comprises a compact cyclotron and a beam-shaping and -transport system (Fig. 1). The cyclotron electromagnet is equipped with a shell-type magnetic core that serves simultaneously as the vacuum chamber; the median plane is horizontal. The resonance accelerating system is positioned in the vacuum chamber space. The external negative hydrogen ion injection system is placed under the electromagnet. The accelerated proton beam is extracted using a stripping device equipped with three graphite foils.

The beam-shaping and -transport system ensures the proton beam parameters in terms of the spectral width and the energy determination accuracy nonstandard for the cyclotrons. The system comprises a matching, a switching, and a correcting electromagnet and two quadrupole doublets. The basic unit of the system is the magnetic analyzer comprised of an electromagnet with a rotation angle of 270° and two collimators installed at the electromagnet vacuum chamber inlet and outlet.

The equipment of the cyclotron system was assembled and adjusted at the Vinča Nuclear Institute in

Table 1

Cyclotron	Energy, MeV (p/d)	Current, μA	Auxiliary equipment of the system
SS-1-3	1–3	20	Analyzer: $\Delta E/E < 10^3$
SS-12	12	100	Targetry system for production of USL (^{11}C, ^{13}N, ^{15}O, and ^{18}F) nuclides
SS-18/9	18/9	100/50	Targetry system: USL and SL (^{81}Rb, ^{123}I, ^{111}In, ^{201}Tl, ^{67}Ga, ^{87}Y, etc.) nuclides
SS-18/9M	12–18/6–9	150/50	Targetry system: USL and SL (^{81}Rb, ^{123}I, ^{111}In, ^{201}Tl, ^{67}Ga, ^{87}Y, etc.) nuclides
SS-30/15	18–30/9–15	100/50	Targetry system: USL, SL, and LL (^{22}Na, ^{57}Co, ^{109}Cd, and ^{139}Ce) nuclides
Ts-80	40–80	100	Beam-shaping channel for proton-beam therapy

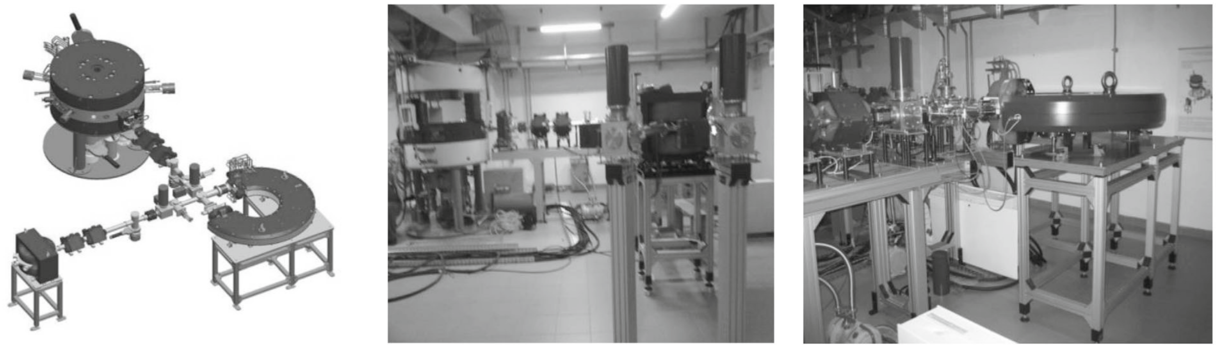

Fig. 1. SS1-3 cyclotron system with the beam-shaping and -transport channel.

Belgrade. The extraction of the proton beam from the cyclotron and the guidance of the beam via the shaping channel have been executed. The system was tested at three matched proton energy values, viz., 1, 1.7, and 2.9 MeV. The cyclotron system with unprecedented parameters is in serviceable condition.

CYCLOTRON SYSTEMS FOR MEDICAL CENTERS

The SS-12, SS-18/9, SS-18/9M, and MSS-30/15 cyclotrons [3–6] are intended for the production of radionuclides directly in healthcare centers. The differences in the accelerated-beam parameters determine the reasonability of using one cyclotron type or another depending on particular conditions.

The above four cyclotron types are based on several common engineering solutions that distinguish the former cyclotrons from cyclotrons manufactured by other companies. The basic shell-type electromagnet has the vertical median plane, which offers easy access to the devices positioned in the vacuum chamber by pushing the movable part of the electromagnet on guide rails. The hydrogen and deuterium ions are accelerated at a fixed frequency using the second and fourth harmonics of the revolution frequency. The radial distribution of the mean magnetic field upon a change in the accelerated-ion type is corrected without applying auxiliary windings by the operative displacement of special-purpose shims. The simultaneous extraction of two accelerated ion beams has been achieved. The cyclotrons are equipped with external negative ion injection systems and the extracted beam transport channels (Figs. 2, 3).

The SS-18/9M cyclotron is equipped with a targetry system also developed and built at NIIEFA for production of radionuclides in gaseous and liquid states [7]. The targets can be installed on both the transport channel pipes and electromagnet outlet pipes directly. The targetry system and its auxiliary systems are integrated into the common cyclotron control system. The targetry system (or individual targets) can be supplied independently for previously commissioned cyclotrons manufactured by NIIEFA or other companies. To date, a robotic device has been developed for operative target replacement.

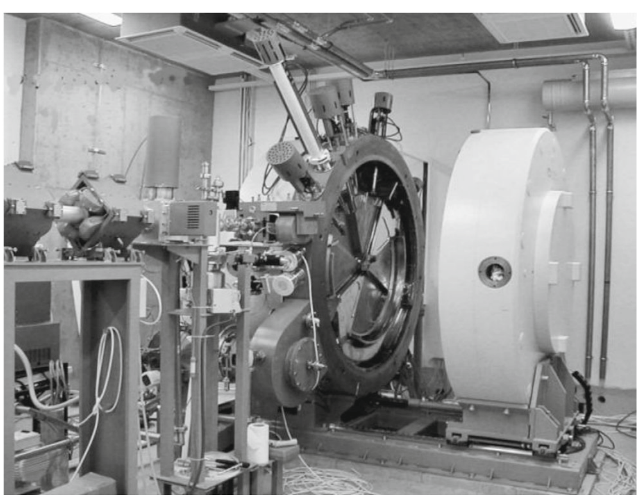

Fig. 2. SS-18/9 cyclotron with an open vacuum chamber.

Fig. 3. SS-18/9M cyclotron with remote targets.

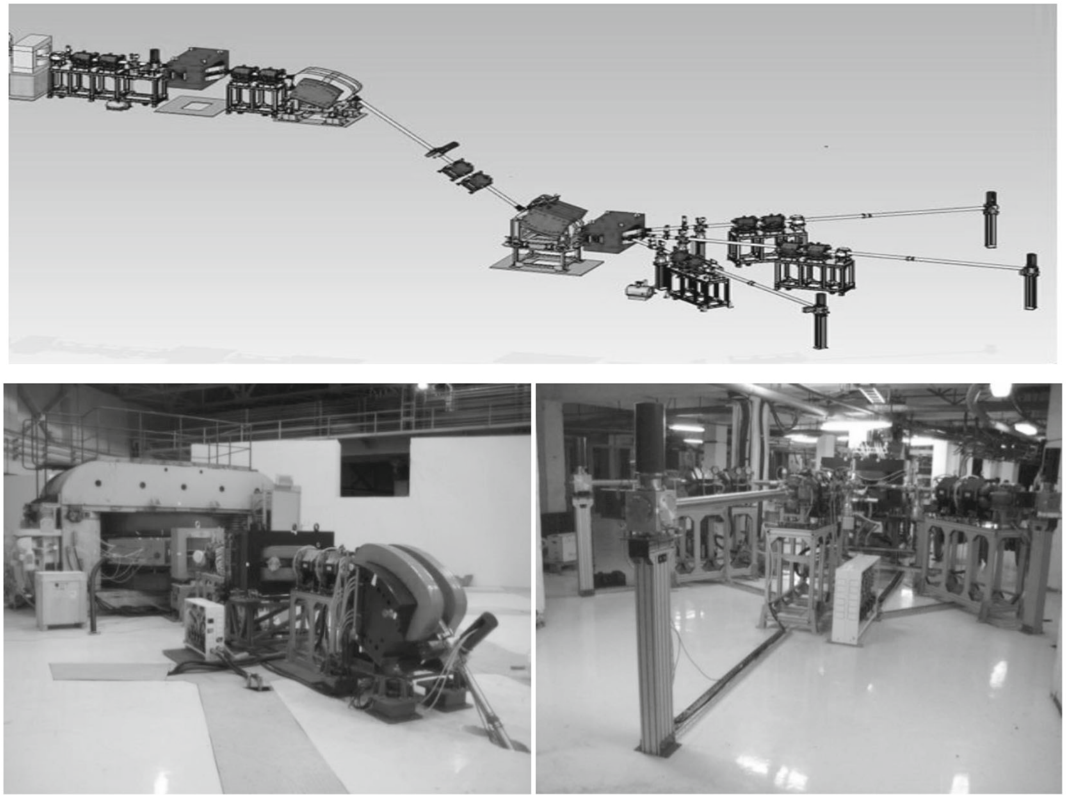

Fig. 4. Layout plan and a photograph of the Ts-80 cyclotron equipment.

Ts-80 CYCLOTRON SYSTEM

The Ts-80 cyclotron system, intended for the production of proton beams with energies in the range 40–80 MeV and a current of at least 100 μA, was developed, manufactured, and supplied to the Konstantinov Institute of Nuclear Physics, St. Petersburg [8, 9]. Beams with such parameters allow the implementation of a number of research and commercial projects, viz.:

• further refinement of the technology for the production of a wide range of medical isotopes, including the radiation generators;

• the commercial-scale production of isotopes;

• proton therapy for ophthalmological diseases;

• longevity investigations of the radiation resistance of radio-electronic equipment using intensive proton and neutron beams;

• experimental studies in the fields of nuclear physics and radiation materials science.

One fundamental distinctive feature of the project is the use of the electromagnet model of an operating synchrocyclotron developed at the St. Petersburg Institute of Nuclear Physics as the basic electromagnet. This solution allowed a reduction in the expenditure but restricted the choice of engineering solutions when developing the cyclotron design:

• The vacuum chamber dimensions and, partially, the number and positions of the linkage equipment pieces have been set.

• The parameters of the magnet's power sources have been set.

• The dimensions of the resonance system have been practically set.

• The external negative hydrogen ion injection system is placed in the basement directly beneath the electromagnet.

• The accelerated proton beams are extracted through one outlet pipe using a positioned stripping device.

• The control range of the energy of the accelerated protons extracted from the cyclotron is restricted by the mutual positions of the stripping device and the resonance system.

• To increase the top energy of the accelerated ions, pole pieces with high-helicity sectors have been redesigned and manufactured.

The equipment of the cyclotron system is installed in the experimental room of building 2 and its basement. The equipment of the cyclotron and the first transport system section is located on the ground floor; the basement houses the cyclotron's external injection system, the high-frequency generator, and the beam transport system distributed between three receiving targets (Fig. 4). In the future, homogeneous

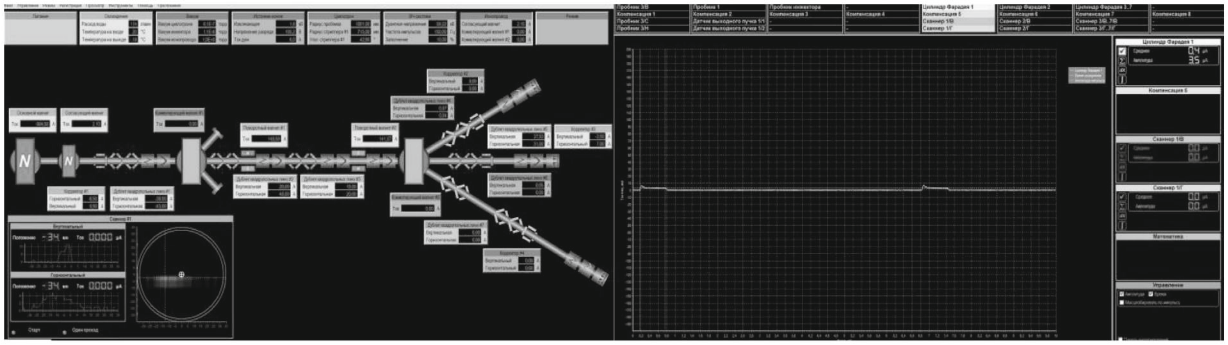

Fig. 5. Display of the parameters of the transport system and the accelerated beam.

beam-shaping equipment for therapy for ophthalmological diseases will be installed on the ground floor.

In June 2016, the physical start-up of the cyclotron system was executed. An accelerated proton beam within the energy range of 40–79 MeV was extracted and the achievement of a design current within the range of 40–60 MeV was confirmed. The beam with matched proton energy of 50 MeV was guided to the final Faraday cylinder over a distance of ~35 m with integrated intensity losses of 12%. The physical start-up and the tests were conducted in the automatic control mode of all cyclotron systems. Information on the conditions and the parameters of the transport-system units during operation is exemplified in Fig. 5.

CONCLUSIONS

A number of up-to-date cyclotrons and cyclotron systems developed and built at AO NIIEFA are intended for the generation of accelerated proton beams with energies in the range 1–80 MeV. Certain cyclotron types can be used both for conducting research in various spheres of science and engineering and the commercial production of radionuclides. One distinguishing feature of NIIEFA is that it ensures the complete lifetime of products, starting from development and through to the manufacture, commissioning, and warranty and postwarranty maintenance.

REFERENCES

1. I. N. Vasilchenko et al., "The CC1-3 cyclotron system," in *Proceedings of the Russian Particle Accelerator Conference RuPAC-2012, St. Petersburg, Russia,* pp. 191–193.
2. A. V. Antonov, et al., "The CC1-3 cyclotron system. Installation and test results," in *Proceedings of the Russian Particle Accelerator Conference RuPAC'2016,* pp. 182–184.
3. P. V. Bogdanov et al., "Development of CC-12 cyclotron design," Vopr. At. Nauki Tekh., Ser.: Elektrofiz. Appar., No. 5 (31), 11–20 (2010).
4. P. V. Bogdanov et al., "Development and realization of CC-18/9 cyclotron project," Vopr. At. Nauki Tekh., Ser.: Elektrofiz. Appar., No. 5 (31), 21–32 (2010).
5. P. V. Bogdanov et al., "Medical compact cyclotron MCC-30/15 with regulated energy of accelerated ions," Vopr. At. Nauki Tekh., Ser.: Elektrofiz. Appar., No. 5 (31), 32–43 (2010).
6. O. L. Veresov, et al., "Cyclotron complex CC-18 / 9M for the production of radioisotope products for the purpose of obtaining diagnostic RFP for PET diagnostics," Vopr. At. Nauki Tekh., Ser.: Tekh. Fiz. Avtomatiz., No. 70, 68–74 (2015).
7. E. N. Abramov et al., "System for remote target replacement of the target system for the CC-series cyclotrons," in *Proceedings of the Russian Particle Accelerator Conference RuPAC'2014,* pp. 415–416.
8. P. V. Bogdanov et al., "Basic technical characteristics of C-80 cycloton complex," Vopr. At. Nauki Tekh., Ser.: Yad. Fiz. Issled., No. 58, 10–14 (2012).
9. Yu. N. Gavrish et al., "Physical start-up of the C-80 isochronous cyclotron," in *Proceedings of the Russian Particle Accelerator Conference RuPAC'2016,* pp. 179–181.

Translated by O. Lotova