THE STATUS OF THE ACCELERATOR COMPLEX NRC KI - PNPI

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Abstract

The main accelerators are concentrated in the accelerator department of PNPI. First of all this is the 1000 MeV synchrocyclotron (SC). It is widely used for fundamental research in the field of elementary particle physics, nuclear physics, and the physics of nuclear reactions, in solid state physics and in radiobiology. The role of the SC is also wide in a variety of applied research on radiation and nuclear tests, including specific medical research.

Second of all this is the isochronous cyclotron C-80. It allows obtaining proton beams with energy from 40 to 80 MeV and current up to 100 μA. The cyclotron is intended for production of a wide assortment of radioisotopes including radiation generators (Sr - Rb, Ge - Ga) for medicine, proton therapy of ophthalmic diseases, tests of radioelectronic components for radiation resistance and studies in the field of nuclear physics and radiation material science.

SYNCHROCYCLOTRON SC-1000

Since the start-up of the SC in 1970, a new generation of the intermediate-energy accelerators has appeared in the world. These are in particular modernized synchrocyclotrons after cardinal reconstruction of all their systems and meson factories. Thanks to intensive and original improvements programs at the SC, about the same beam intensities were obtained at the SC, as in other synchrocyclotrons after their reconstruction. In spite of the fact that modern "meson factories" exceed considerably the PNPI SC in the beam intensity, nevertheless, due to some accelerator features, mainly due to the higher energy, which is important in a number of cases for experiments on proton, meson and neutron beams, and an extensive and successful application program, there is a significant area for the research at the SC which is not overlapped by other facilities.

Simultaneously with physical experiments on SC, an intensive program was carried out to improve the beam parameters and to develop new experimental capabilities. Briefly the main features of 1000 MeV synchrocyclotron facility can be formulated as follows.

1. *Long burst operation system* [1]. To increase the effectiveness of electronic methods of registration, an original long burst operation system using a Cee-electrode was developed. Unlike similar systems, the SC uses a ¾ wave resonance line with ferrite frequency variation and synchronization of the Cee–voltage in frequency and phase with the main dee voltage. The use of a resonance scheme made it possible to reduce the Cee power supply and to increase the beam macro duty cycle from 1.4 to 50 % and more. The originality of the technical solutions is confirmed by an author's certificate.

2. *Electrostatic focusing system in the SC centre* [2]. In the central region of the accelerator, a new three-electrode focusing system was put into operation to increase the vertical focusing and to compensate the space-charge forces that limit the accelerator intensity. The new focusing system made it possible to increase the intensity by about 5 times and to reach 3.5 μA beam inside the vacuum chamber, and the intensity of the extracted beam to 1 μA. The originality of the technical solutions is also confirmed by an author's certificate.

3. *New variators*. To improve the reliability of the accelerator and to facilitate the maintenance work of the HF system, new variator rotors with Al plates, manufactured at PNPI, were introduced instead of the old ones with stainless steel plates. After installation of the new two variators, the accelerator operating time achieved 6000 hours per year.

4. *The experimental complex of the PNPI SC* consists of the accelerator, buildings and experimental halls with the systems of engineering maintenance (power supplies, water cooling, and ventilation), beam transport lines P1, P2, P3 and P4, biological protection, beam dampers and the experimental installations. When the proton mode is in operation, the extracted beam is transported through the accelerator hall and then directed by the bending magnet SP-40 into the experimental hall through one of the collimators. The beam for the proton therapy is transported by the beam line P2 in the special medical building [3]. The magnetic spectrometer with 10^{-3} energy resolution [4] is using the P1 beam. Its effective use became possible after an invention of a way of monochromatization of the SC proton beam. With this spectrometer, an extensive series of researches on the study of the nuclear matter structure by means of elastic and quasi-elastic proton-nucleus scattering was performed. The beam line P3 provides the proton beam to the IRIS laboratory where short-lived isotopes are investigated by using a mass-separator and the laser technique [5]. There is second proton beam with small intensity P4 (about 1 %) that acts in parallel with a main beam. It can be used as for physical so for applied purposes. For an example using this beam for proton therapy will essentially decrease the cost of patient irradiation.

5. *All meson beams at the PNPI SC* are generated at the same target installed in the accelerator hall behind a thick wall. It is possible to perform two experiments simultaneously. In total, there are three meson channels: π1-channel, π2-channel of lower energy, and μ^- channel. The π1-channel selects $\pi^\pm$ mesons generated in the

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forward direction. In this channel one can get beams with the maximum for the SC-1000 meson energy up to 700 MeV. The π2-channel selects π^- mesons with the production angle of 60°. This channel provides pion beams with lower energy. At the π2 channel, a special vacuum target can be installed to obtain the so called μ^+ "surface" mesons with the momentum of ~29 MeV/*c* .The muon channel can provide separated $\mu^\pm$ mesons and an assortment of mixed π and μ meson beams [6].

6. *Neutron beam and neutron TOF spectrometer GNEIS* [7]**.** A one-turn deflection of the proton beam to the neutron production target generates on the target a short (7 ns) flush of neutrons with the intensity of (2 – 3) 10^{14} s^{-1}. The time-of-flight (TOF) neutron spectrometer GNEIS has a 48.5 m flight base. Due to the high beam intensity and the short pulse duration, the spectrometer GNEIS is competitive with other well known spectrometers like WNP–LAMPF (Los-Alamos, USA), ORELA (Oak-ridge, England) and GELINA (Gel, Berlin). The neutron beam is used for investigations of neutron-nucleus interaction cross sections. The cross sections for inelastic neutron-nucleus interaction in the case of heavy nuclei were measured in collaboration with Japan scientists. In addition, GNEIS is widely used for tests of electronics components.

7. *Proton beams of variable energy.* At first it was assumed that the SC would accelerate the protons only to a fixed energy of 1000 MeV. However, proton beams of variable energy are necessary for some physical and applied experiments. For these purposes it was developed possibility to change the beam energy since ~60 to 900 and 1000 MeV. The beams diameters are ~ 25 - 50 mm, Δp/p are in the range 1.3 – 14 % and intensity are between $10^7 \div 10^{12}$ s^{-1} [8]. Such a beam was achieved by using a calibrated copper degrader with remote change of its thickness. This beam line consists of a degrader, collimators, a deflecting magnet to separate the beam from the background, and two doublets of quadrupole lenses to focus the beam in the experimental hall.

Progress of space and aviation technique is connected with using of micro- and nano-electronics. One of the main conditions of their reliable work is their ability to effectively operate in the radiation field of space and higher layer of atmosphere. Now standards of Russia and international ones include the obligatory tests of radiation resistance for electronic gear using in space and aviation. In 2015 at the NRC KI-PNPI synchrocyclotron the special center for tests of proton radiation resistance began to work. Energy of used protons is variable in diapason ~60-900 and 1000 MeV. Center includes two stands with the beam diagnostic, modern devices dosimetry, system of automatic data treatment and infrastructure for users.

Now the leading countries standards oblige to test an electronic gear using in space and aviation in neutron fields too. International document named «JEDEC STANDARD» orders to test these gears using neutrons that energetic spectrum is equal to atmospheric one. In 2015 at the neutron source GNEIS the stand for such tests were created by collaboration of the group of nuclear fission from neutron division and accelerator department. As a result in NRS KI-PNPI since 2015 the universal center for radiation resistance tests is in operation. It permits to do tests as using protons so using neutrons that energetic spectrum is equal to atmospheric one [9].

In recent years, the accelerator operating time SC achieved ~3000 - 3500 hours per year. The exemplary distribution of the work time on the beams of SC is shown on Fig. 1.

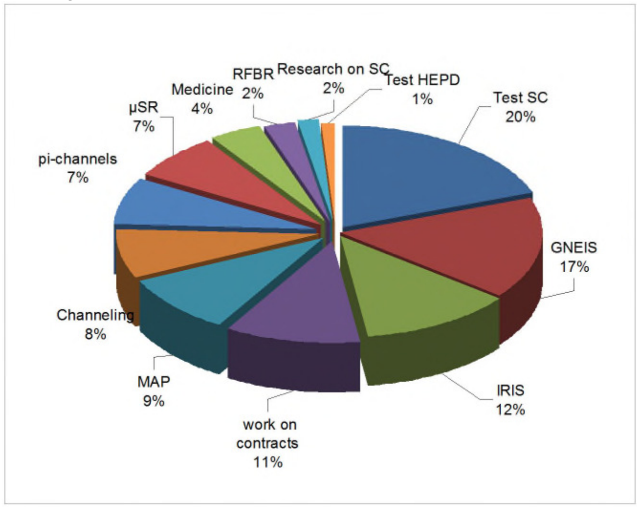

Figure 1: Works and researches usually carried out every year on the beams of SC.

After 50 years of successful operation, the SC-1000 remains one of the active accelerators in Russia. The SC is an multidisciplinary research facility of the institute, on the beams of which a wide range of fundamental and applied research is carried out. The accelerator beams are in demand and are used by many organizations and institutes of our country. There are good prospects for expanding the scope of the work on radiation tests of electronics, proton therapy, on study of rare radioactive isotopes, *etc*.

ISOCHRONOUS CYCLOTRON C-80

At present, the accelerator department, in cooperation with the Institute of Electrophysical Apparatus, has prepared for operation the multipurpose isochronous cyclotron C-80 [10]. Its proton beam have energy in diapason 40-80 MeV and current up to 100 μA. High energy and high intensity of proton beam permit to produce such isotopes and radio pharmacy that producing at commercial cyclotrons is impossible (for an example generators isotopes). Using of generators isotopes permits to conduct positron emission tomography at the medical centers located in remote areas. Beside of this a new method of producing super clean isotopes with a help of magnetic separator is in progress at new cyclotron.

It should be emphasized that almost every C-80 system was pre-calculated and modeled on a computer; see, for example, [11-14]. Then they were manufactured, installed and tuned to a cyclotron.

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The cyclotron has a branched system for transporting proton beams, which is located on two levels. The first section of the beam transport system is located in the experimental hall C-80. The second part of the beam transportation system is located in the basement of the experimental hall, where there are three target stations of different purposes.

In addition, in the experimental hall of C-80, it is planned to place a system for transporting a second (additional) proton beam of low intensity (see Fig. 2) to the procedural location of the PNPI's ophthalmologic center.

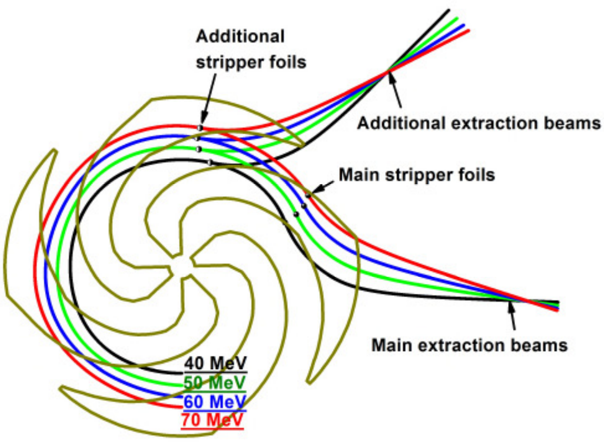

Figure 2: Schematic view of the extraction system of C-80 cyclotron and trajectories of the extracted particles.

It is believed that this additional beam will work in parallel with the main beam of the cyclotron, which is intended, mainly, for the production of radio-pharmaceuticals. To date, exhaustive data have been obtained on the location of the new stripper for different energies within the vacuum chamber, and the way to output the second beam through the available gateway of the probe has been determined. Obviously, its development, fabrication and installation will require upgrading the output system of the main proton beam.

Energetic diapason of proton beam (60-70MeV) at the cyclotron C-80 permits to create ophthalmology center for radiation therapy of eye cancer disease. Now there are no such centers in Russia. This project is developed in accelerator department in cooperation with the Institute of Electrophysical Apparatus. It was simulated the radiation background in irradiation zone for different variants of proton beam formation. It was shown that radiation background to 3 times less if one uses collimators instead of traditional method. More over using of collimator permit to simplify system of beam formation and decrease the quantity of magnetic elements. Equipment for ophthalmology room and soft for planning of irradiation will be created in collaboration with NRC KI-ITEP. It has huge experience in proton therapy of eye as about 1400 patients were treated with a help of this method.

In the nearest future, the following works are planned: building of a special line to form homogeneous proton beams of ultra-low intensity (10^7–10^9 s^{-1}) for proton therapy of ophthalmic diseases; building of a test facility to carry out studies on the radiation resistance of radioelectronic equipment using intensive beams of protons and neutrons.

CONCLUSION

Accelerator Complex at PNPI of NRC "Kurchatov Institute" is maintained in a healthy functional status. The complex has noticeably improved its functionality due to the recent start-up of the isochronous cyclotron C-80 both in the field of fundamental and applied research.

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