STATUS OF PNPI PROTON SYNCHROCYCLOTRON

N.K.Abrossimov, A.A.Vorobyov, G.A.Riabov

1. Introduction

One of the main experimental facilities of PNPI is the proton synchrocyclotron (SC) for acceleration of protons up to 1 GeV kinetic energy [1,2]. SC is constructed for research in nuclear physics, elementary particle physics, solid state physics, as well as for the applied research. Also, SC is intensively used for medical treatments. The start-up of SC was in November 1967, and the routine operation began from April 1970. Since 1975 the regular proton therapy was initiated. The history of design, construction and start-up of the accelerator is described in details in Ref. [3] which was dated to the 25th PNPI anniversary. The milestones of the SC up-grade program are given also in that article. The PNPI SC, being the world's largest synchrocyclotron, has some peculiarities related to its high energy. The progress in the accelerator technology and in the accelerator physics has been taken into account under its design and up-grading. The design and construction of the accelerator required some new and original technical decisions, such as high quality shimming of the magnetic field, a new scheme of the frequency variator with a system of symmetric coupling and feed back of the high frequency generator, a high efficiency beam extraction system, a new C-shape system which can be used for both a long burst operation and one turn deflection of the internal beam onto the neutron production target, a new scheme of the electrostatic focusing in the central region. From April 1970, SC has been put in routine operation with running time of 5000–6000 hours per year.

2. Basic SC parameters

The design features of the Gatchina SC as well as the description of its subsystems are presented in the bibliography [4]. Let us mention SC features which distinguish it from other synchrocyclotrons (Dubna, Berkley) and some parameters which make SC competitive with other accelerators in physics research.

.

2.1. Magnet and magnetic field

The Gatchina SC has a record energy for this type of accelerators – 1000 MeV. The world's largest one piece electromagnet with a pole diameter of 7 m and iron weight of almost 8000 t was designed and constructed for this accelerator [5]. The basic magnet and magnetic field parameters are presented in Tables 1, 2.

A program of careful magnetic measurements and field corrections has been carried out. The magnetic measurements have been performed using a specially developed automatic measuring machine. The computer controlled measuring machine consisted of a nuclear resonance magnetometer, thermostatic Hall probes and a scanning machine for positioning the field probes at a given point of the magnet gap. The relative accuracy of the magnetic field measurements was $5\cdot 10^{-5}$. To find the position of the median plane, a special probe (so called "Russian pendulum") was used [6]. The proper field distribution has been achieved by using the ring-shaped iron shims attached to the upper and lower pole faces [7]. The magnetic field of SC has been corrected to make possible also acceleration of polarized protons.

2.2. Vacuum system

The vacuum chamber has a volume of 35 m^3 with the operating pressure $2\cdot 10^{-6}$ mm Hg. The supporting structure of the vacuum chamber is made of stainless steel and attached to the magnet poles. The side walls of the chamber are made of 30 mm thick duraluminum. The walls have rubber vacuum sealing with the stainless steel frame. All the chamber mechanisms like Dee, the C-shape electrode, target drivers, probes, and vacuum pumps are attached to the vacuum chamber walls. High vacuum in this chamber of large volume and surface area is provided by using a pumping system with record productivity of about 40 000 liters per second [8].

Table 1

Basic parameters of the PNPI SC magnet

Pole diameter	6.85 m
Gap without shims	0.5 m
Field in the centre	1.9 T
Maximum field in the steel	up to 2.2 T
Number of turns in the coil	264 (22 × 12)
Conductor of the main coil	Al, 83 × 83 mm^2 / 30 mm
Resistance of the main coil	0.038 Ω
Inductivity of the main coil	5 H
Current of the main coil	4600 A
Power supply voltage	200 V
Number of turns in the additional coil	48 (2 × 24)
Current of the additional coil	600 A
Stability of the power supply current	10^{-5}
Weight of iron	7800 t
Weight of the main coil	120 t
Consumption of cooling water	30 m^3/h
Overall dimensions of a magnet	16.5 × 7.8 × 10 m^3

Table 2

Basic parameters of magnetic field

Magnetic field at the center	1.9 T
Extraction radius	3.167 m
Pole utilization factor	0.924
Magnetic field at the extraction radius	1.786 T
Magnetic field index n at the extraction radius	< 0.1
First harmonic of magnetic field	$< 2\cdot10^{-4}$
Average deviation of the median plane	< 5 mm
$K-$ coefficient of phase stability	4

2.3. Accelerating system

The most serious problem in the SC design was development of the high frequency (HF) accelerating system with a very high frequency span ratio corresponding to the final proton energy of 1 GeV. The 1 GeV energy seems to be the ultimate limit for this kind of accelerators because of the problem in implementation of the HF system with such a wide frequency range. The half-wave resonance system has been used for the PNPI SC. It consists of one Dee and two rotating capasitors. The factor of effective capacity overlapping is equal to 40 and the factor of frequency overlapping of the whole system is reached 2.3. These values were achieved due to introduction of non-uniformity in the Dee-chamber wave line and a rather sophisticated variator scheme with additional inductivity elements [9]. Creation of the high frequency system for the SC with the ultimate energy of 1 GeV became possible only after a number of innovations [10], some of them being protected by the certificates: the scheme and design of the rotating condenser, the symmetric feed back system which provided effective suppression of the unwanted transversal oscillations [11], the methods of accelerating voltage optimization [12]. The basic parameters of the accelerating system are given in Table 3.

Table 3

Basic parameters of SC high-frequency system

Operating frequency range	f_i = 28.88 MHz f_f = 13.18 MHz
Macro duty cycle	0.5
Amplitude of the accelerating voltage	8 kV
Repetition rate	50 Hz
Power consumption	150 kW

For the 30 years operation period, the HF system has shown sufficient reliability. The period of trouble-free operation between the time scheduled inspections is around 2000 hours.

2.4. Ion source and central region

The central region of the accelerator determines to a great extent the intensity and beam quality of the accelerator. In a traditional synchrocyclotron, the open ion source geometry can be used due to low accelerating voltage. For the PNPI SC, a special electrostatic focusing in the central region has been developed to increase the intensity and to improve the beam quality [13]. In the central region of $r < 50$ cm, two additional (central and lateral) electrodes were installed opposite to the main Dee. A positive potential of 20 kV feeds the central electrode for a short period of the beam capture and, as a result, the additional electrostatic focusing force is appeared. Unfortunately, the additional electrostatic focusing force gives rise also to an unwanted effect of reduction of the proton revolution frequency. Application of the electrostatic focusing in combination with the correction of the acceleration frequency in the central region provides the essential increase of the beam intensity. The number of protons accelerated in one cycle reached 3.8×10^{11}, the average current of the internal beam being about 3 μA [14].

2.5. Extraction of the proton beam

It was usual practice for synchrocyclotrons to operate with the extraction efficiency of the order of 5% because og a poor internal beam quality and problems with compensation of the magnetic field perturbations introduced by the magnetic channel and the regenerator. A traditional regenerative extraction system which consists of a regenerator and a magnetic channel was used at the PNPI SC. Extensive computer calculations of beam trajectories in the real magnetic field of the synchrocyclotron were carried out, and the dependence of the extraction efficiency on the internal beam quality and on the extraction system parameters was investigated. Following the calculations, the effective vertical aperture of the regenerator and the magnetic channel had been significantly increased. Also, the focusing gradients in the magnetic channel had been introduced and optimized. During implementation of the new extraction system, special attention was paid to the field shimming in order to cancel the channel influence on the magnetic field in the region of particle acceleration. As a result, after careful tuning of all accelerator systems, the highest for the synchrocyclotrons extraction efficiency of 30% was achieved [15]. The high extraction efficiency has made possible to use only external targets for generation of the secondary beams. The external target has some advantages over the internal one. The external target is more convenient for the design of the secondary meson beams and permit to lower the vacuum chamber irradiation and, as a consequence, the radiation dose for the staff.

2.6. Extraction of an additional low-intensity proton beam

The low-intensity proton beam of the order of 10^{10} s^{-1} (< 1% of the main beam) is extracted from the vacuum chamber and can be used simultaneously with the main beam. This beam has been developed for the purpose of proton therapy to produce the patient treatments simultaneously with the physical research program, as far as for proton therapy the proton beam intensity of the order of 10^8–10^9 s^{-1} is sufficient. The idea to extract the low-intensity beam was emerged after analysis of the particle trajectories in the extraction system. Some of the trajectories in the beam extraction procedure are going outside the magnetic channel and are lost for the main beam. By introducing an additional magnetic channel it is possible to extract this low-intensity beam from the vacuum chamber and to direct it to the existing hole in the magnet joke. The additional proton beam of low-intensity has proton density of 1.4×10^9 cm^{-2} s^{-1} in the intermediate focus and can be used both for physical and applied purposes, in particular for proton therapy [16].

2.7. Time structure and energy resolution of the proton beam

The time structure of the accelerator beam determines to a great extent the efficiency of the accelerator use for physical experiments. Normally, the synchrocyclotron gives the pulsed beam with the macro duty-cycle of order of 1.4%. However, for the electronics methods of registration it is optimal to have the uniform time distribution. To increase the macro-duty cycle of the PNPI SC from 1.4% up to 50%, a method was applied of slow accelerating of the beam by using an additional acceleration system [17]. This system is protected by a certificate [18].

An additional C-shape electrode is installed in the region of the final radii of the acceleration. After the beam bunch is accelerated up to the final energy, the main accelerating system is switched off, and the new system slowly reaccelerate protons to the extraction radius during the fly-back time of the frequency variator (~50 % of the repetition period). A slow extraction system was developed at the PNPI SC with the frequency and phase lock between the main and the C-electrode generators. The implementation of the frequency and phase lock provides high efficiency of the beam capture in the slow acceleration and also gives opportunity to use a low power supply system for the C-electrode (~ 3–5 kW) and a ferrite frequency variator This method is protected by a certificate [19].

Energy spread of the proton beam is a very important parameter for the precision spectrometric measurements. Usually, the energy spread of the extracted proton beam is of the order of 1%, or 10 MeV for the 1000 MeV final energy. However, the computer simulation of the beam behavior in the extraction system and the subsequent experiments at the operating accelerator have shown that the beam energy is continuously increased over the macropulse duration, and this phenomenon is correlated with betatron oscillations in the internal beam. If one measures in the experiment the extraction time in the beam macropulse and takes into account the energy change over the macropulse duration, then the instant energy spread becomes about 0.03% only. With this method of effective monochromatization of the extracted beam, comprehensive investigations of the nuclear matter density in nuclei were performed using a magnetic spectrometer with the energy resolution of 0.1%. The method of the effective monochromatization is protected by a certificate [20].

Microstructure of the extracted beam. In the duration of the beam macropulse, the particles are extracted from the accelerator by short (7−10 ns) bunches with a period of 77.5 ns that corresponds to the extraction frequency of 13.2 MHz. For experiments using time-of-flight (TOF) methods, it is very important to have short micropulse duration. This defines the start pulse for time-of-flight measurements. It is highly convenient for some experiments to have a large duration between micropulses, allowing observation of the short-lived particle decay in the interval of 77.5 ns between micropulses. By special accelerator tuning, it was developed a regime with 7 ns micropulses and low background between the micropulses at the level of 10^{-6}. Using this methodology, the precision lifetime measurements of π^+ and K^+ mesons have been carried out. This data were included in the handbooks of the elementary particle properties.

2.8. One turn beam deflection on the neutron production target

A system for one turn beam deflection of the internal beam onto the neutron production target was developed at the PNPI SC for the TOF neutron spectrometer GNEIS [21]. An electrostatic deflector with the pulsed voltage up to 150 kV is used to generate a 10 ns neutron start pulse. The deflection of the beam occurs in the vertical direction onto the target located below the median plane. As the deflector, a C-electrode is used in which the upper and lower plates are conductive divided from each other. A special system of electronics switching provides simultaneous operation as in the mode of slow extraction so in the mode of the one turn deflection, *i.e.* any of the 50 acceleration cycles following each second can be directed either to the extraction channel, or to the neutron production target.

3. Experimental complex and SC beams

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, ventilation), beam transport lines, biological protection, beam dampers and the experimental installations (see Fig. 1).

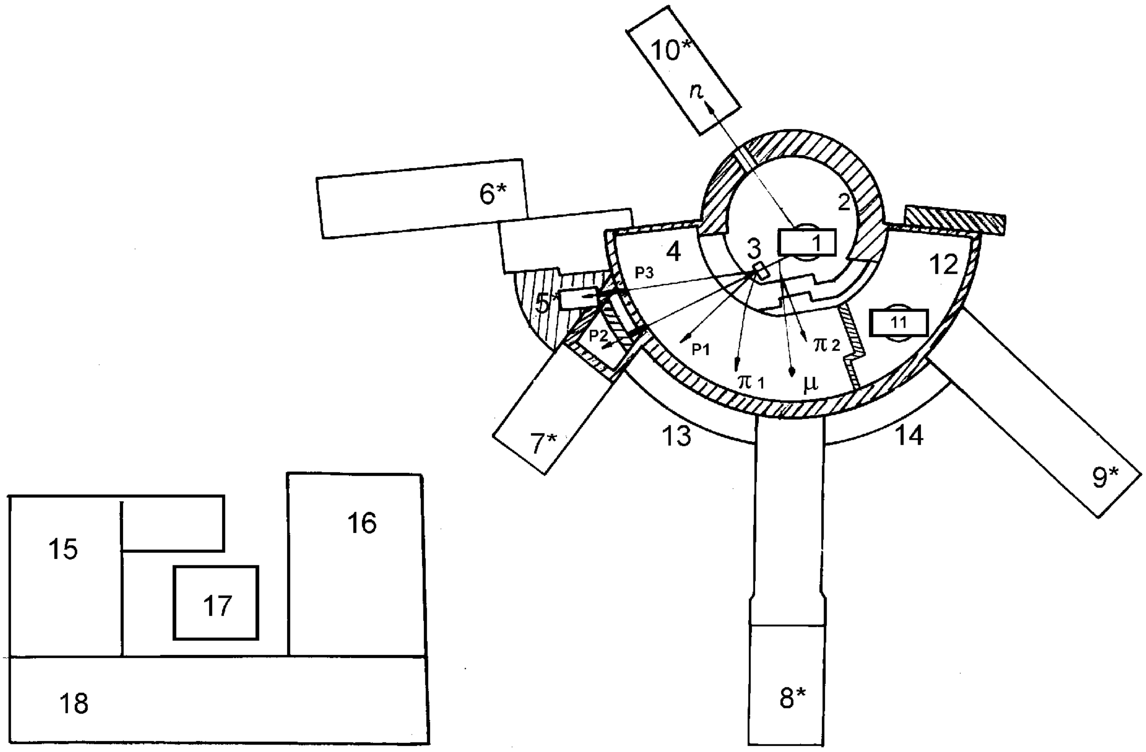

Fig. 1. General view of the synchrocyclotron building complex and beam lines. The blocks which were built after the synchrocyclotron start up are marked with *. 1 – the synchrocyclotron; 2 – the main hall; 3 – the beam distributing magnet SP-40; 4 – the experimental hall; 5 – the trap-damper of the proton beam; 6 – IRIS; 7 – the medical block; 8 – the block of technical maintenance; 9 – the computer centre; 10 – GNEIS; 11 – the isochronous cyclotron under construction; 12 – the cyclotron hall; 13, 14 – the counting rooms; 15 – the equipment test hall; 16 – the power supply hall; 17 – the electrical power supply station; 18 – the administrative block and the synchrocyclotron control room

SC is installed in a round hall of 32 m in diameter. The thickness of the wall made of heavy concrete is ~ 8 m, the thickness of the floor is 4 m. The experimental hall is of a half-ring shape (25 m in width) with the experimental area of 2500 m^2 . Collimators in the concrete wall between the accelerator and the experimental halls allow to transport beams to experimental setups. There are several modes of operation of the proton beam. In the proton mode of operation, the beam with intensity $\leq 10^{11}$ s^{-1} can be transported in the experimental hall to experimental setups. Also, the proton beam can be transported to the specialized areas such as the laboratory for short-lived isotope investigation IRIS (full intensity beam) or the medical building for the patient treatment (low intensity well focused beam). In the meson mode of operation, the proton beam is directed onto a meson-production target which is installed in the accelerator hall behind the thick concrete wall. The proton beam lines are terminated by 4 m long iron beam dampers to cut down the background in the experimental hall. According to the operation regulation the non-used collimators in the wall between the accelerator and the experimental halls are closed down by the remote handling iron blocks. This collimator shielding with the remote handling helps to decrease the background and the irradiation dose for the staff.

3.2. Main proton beams

The experimental hall and the transport beam lines are presented in Fig. 2. 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 [22]. The magnetic spectrometer with 10^{-3} energy resolution is also using the P2 beam. The beam line P3 provides the proton beam to the IRIS laboratory where short-lived isotopes are investigated using a mass-separator and the laser technique. Parameters of the proton beams are presented in Table 4.

Table 4

Proton beams

Particles	Energy, MeV	*ΔE/E*, %	Intensity, s^{-1}	Beam line	Notes
p	1000	1	6×10^{12}	P1, P2, P3	Main beam
p	1000	1	10^{8}	P2	Medical beam
p	1000	0.1	10^{10}	P2	Monochromatic beam
p	1000	1	10^{10}		Additional beam

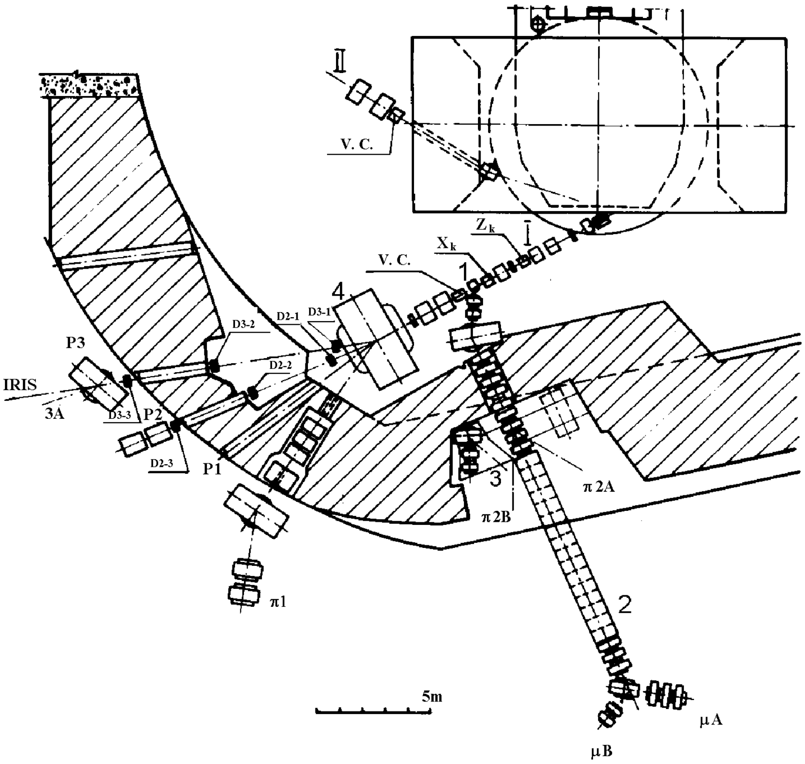

Fig. 2. The beam lines of the PNPI synchrocyclotron. I – the main proton beam 6×10^{12} s^{-1}; II – the supplementary proton beam 10^{10} s^{-1}. 1 – the meson-production target; 2 – the μ -meson channel; 3 – the platform with the second magnet of $\pi2$ channel; 4 – the bending magnet SP – 40; P1, P2, P3 – proton beam lines; D2-1, D2-2, D2-3, D3-1, D3-2, D3-3 – movable beam dampers; $\pi1$ – high energy π-meson channel; $\pi2$A, $\pi2$B – directions of low energy meson beams; μA, μB – directions of μ-meson beams; Z_k – the vertical magnet-corrector; X_k – the horizontal magnet-corrector; V.C. – the vacuum collimators

The last line in Table 4 presents the additional proton beam extracted through the magnet joke to the accelerator hall (see Fig. 2).

3.3. Low-intensity proton beam with energy variation from 200 to 900 MeV

The PNPI synchrocyclotron allows to accelerate protons up to the fixed energy of 1000 MeV. However, for some physical and applied researches, a variable energy beam is required. This can be achieved by using a calibrated copper degrader at the beam line P3. This beam line consists of a degrader, two collimators, a deflecting magnet to separate the beam from the background, and two doublets of quadruple lenses to focus the beam in the spot of small size (~ 20 mm in diameter) in the experimental hall. The range of possible varying the proton energy is from 1000 to 200 MeV, the main beam intensity at 1000 MeV being 1.56×10^{12} s^{-1}. The momentum resolution $\Delta P/P$ is about 1.3% in the worst case. The parameters of the proton beam with variable energy are presented in Table 5.

Table 5

The parameters of the proton beam with variable energy

E, MeV	P, MeV/c	Intensity
1000	1700	1.56×10^{12}
900	1580	1.55×10^{11}
800	1460	4.52×10^{9}
700	1340	6.69×10^{8}
600	1220	3.13×10^{8}
500	1090	2.07×10^{8}
400	954	1.17×10^{8}
300	808	5.58×10^{7}
200	644	1.84×10^{7}

The variable energy proton beam was used for the fission cross-section measurements of heavy elements in the ISTC-1405 project and for radiation tests of electronics components.

3.4. Meson beams

All meson beams at the PNPI SC are generated at the same target installed in the accelerator hall behind the thick wall. It is possible to perform two experiments simultaneously. In total, there are three meson channels: $\pi 1$-channel, $\pi 2$-channel of lower energy, and μ-channel. Parameters of the meson beams are presented in Table 6. The $\pi 1$-channel selects $\pi^{\pm}$ mesons generated in the forward direction at 0°. In this channel one may have beams with maximum for the PNPI SC meson energy up to 700 MeV. The $\pi 2$-channel selecting π mesons with production angle 60° provides pion beams with lower energy. A special vacuum target can be installed in this channel to generate so called μ^{+} "surface" mesons. The muon channel can provide the separated $\mu^{\pm}$ mesons and an assortment of mixed beams of π and μ mesons [23].

Table 6

Secondary particle beams

Particles	Momentum, MeV/c	$\Delta P/P$, %	Intensity, Part./s	Beam line	Notes
π^{+} π^{-}	450 450	6 6	10^{6} 3×10^{5}	$\pi 1$-channel	Achromatic mode
π^{+} π^{-} μ^{+}	250 250 29	2.5–12 2.5–12 12	10^{5}–5×10^{6} 3×10^{5}–10^{7} 3×10^{4}	$\pi 2$-channel	Achromatic mode. "Surface" mesons
μ^{-} μ^{+}	160 170	10 10	9×10^{4} 3×10^{5}	μ-channel	Separated beams

3.5. Neutron beam and neutron TOF spectrometer GNEIS

The one-turn deflection of the proton beam to the neutron production target generates a short (7 ns) flush of neutrons with intensity (2–3)×10^{14} s^{-1}. Majority of the generated neutrons (85%) have the Maxwellian spectrum with an averaged temperature of ~ 3 MeV and approximately isotropic angular distribution. On the basis of the pulse neutron source, the time-of-flight (TOF) spectrometer GNEIS with four neutron guide pipes of 40 m length is constructed [21]. The basic parameters of the neutron beam are presented in Table 7. Due to high 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).

Table 7

Neutron beams

Energy	Intensity*, s^{-1}	Pulse duration, ns	Frequency, Hz
10^{-2} eV–10 MeV	3×10^{14}	10	50

*Total intensity at the neutron production target.

4. Status of experimental program at SC

Even now, after 30 years of successful operation, the Gatchina synchrocyclotron remains a valuable facility especially for various studies in nuclear physics. The proton energy of 1 GeV proved to be ideal for the investigation of nuclear structure with elastic and quasielastic proton scattering off nuclei. Recently, the quasielastic proton-nucleon scattering was used also to show that the nucleon-nucleon interaction is modified by the presence of the nuclear matter. In these experiments, which will be continued in the coming years, an active role plays a group of physicists from Research Center for Nuclear Physics, Osaka (Japan).

A mayor part of the beam is provided now for the IRIS facility for production and studies of the nuclei far from the nuclear stability region. The development of the laser ion source and the high temperature target allowed IRIS to be competitive with the similar facilities like ISOLDE at CERN. A group from Marburg University (Germany) participates in some of the IRIS experiments.

An extensive experimental program is continued in the π-beams. In particular, it concerns the near threshold η-meson production and the $\pi^{-}p$ charge exchange reaction. Scientists from the University of California at Los Angeles and from Abilene Christian University (USA) participate in these experiments.

The neutron time-of-flight facility GNEIS is regularly used for the study of nuclear fission by resonance energy neutrons.

The μSR experiments on the muon channel continue to play an important role in the experimental program at SC.

As in the previous years, the medical proton beam is effectively used for stereotaxic proton therapy.

Considerable amount of the beam time is provided for radiation tests of various materials and equipment as well as for measuring the nuclear spallation cross sections for application purposes. Most of such studies are conducted on the contract basis. In particular, some radiation tests are in cooperation with INFN, Legrano (Italy).

Many experimental methods have been developed at PNPI and tested in the SC beams, before they were used in collaborative experiments at other accelerators (CERN, SACLAY, FNAL, PSI, GSI, DESY, BNL). This tradition is continued. As a recent example, development and tests of the high-temperature target for the on-line mass separator at the Argonne National Laboratory (USA).

In conclusion, in spite of reduction of the beam time down to 2000 hours/year, because of the financial limitations, the Gatchina SC remains an active and reliable accelerator allowing to carry out important physical and application programs.

References

[1] N.K.Abrossimov, D.G.Alkhazov, S.P.Dmitriev, V.A.Eliseev, D.M.Kaminker, A.V.Kulikov, Yu.T.Mironov, G.F.Mikheev, G.A.Riabov, N.N.Chernov, V.I.Shalmanov, E.G.Komar, I.F.Malyshev, N.A.Monoszon, V.I.Peregud, B.V.Rozhdestvenskii, I.M.Roife, and E.V.Seredenko. "Leningrad 1 GeV Proton Synchrocyclotron", Zhurnal Tekhn. Fiz. **41**, 1769 (1971) [Sov. Journ. Techn. Phys. **16**, 1399 (1972)].

[2] N.K.Abrossimov and A.A.Vorobiev. "Synchrocyclotron of the Konstantinov's Petersburg Nuclear Physics Institute of AS USSR", Vestnik AN SSSR **11**, 42 (1972), (in Russian).

[3] N.K.Abrossimov, S.P.Dmitriev, V.A.Eliseev, G.F.Mikheev, G.A.Riabov, and N.N.Chernov. "History and Present Status of PNPI Synchrocyclotron", Main Scientific Activities 1971–1996, Gatchina, 1998, p. 6.

[4] "1 GeV Proton Synchrocyclotron of PNPI RAS" (Bibliography), Gatchina, 2000 (in Russian).

[5] B.E.Gritskov, N.N.Indyukov, A.V.Klimov, B.A.Larionov, N.A.Monoszon, B.V.Rozhdestvenskii, N.S.Strel'tsov, and D.G.Shaevskii. "Electromagnet of the 1 GeV Proton Synchrocyclotron", Zhurnal Tekhn. Fiz. **41,** 1776 (1971).

[6] V.A.Eliseev, G.A.Riabov, and I.I.Tkach. "Magnetic Measurements at the 1 GeV Proton Synchrocyclotron", Zhurnal Tekhn. Fiz. **41,** 1787 (1971).

[7] N.K.Abrossimov, V.A.Eliseev, I.A.Petrov, G.A.Riabov, and N.N.Chernov. "Magnetic Field of the Leningrad 1 GeV Proton Synchrocyclotron", Zhurnal Tekhn. Fiz. **41**, 1781 (1971) [Sov. Journ. Techn. Phys. **16**, 1410 (1972)].

[8] I.F.Malyshev, V.I.Peregud, A.V.Popkovich, and V.I.Shalmanov. "Vacuum System of the 1 GeV Proton Synchrocyclotron", Zhurnal Tekhn. Fiz. **41**, 1793 (1971).

[9] I.M.Roife and E.V.Seredenko. "Some Peculiarities of High Frequency System of the 1 GeV Proton Synchrocyclotron", Zhurnal Tekhn. Fiz. **41**, 1797 (1971).

[10] N.K.Abrossimov, D.G.Alkhazov, S.P.Dmitriev, D.I.Egorov, A.V.Kulikov, I.F.Malyshev, G.F.Mikheev, V.I.Peregud, I.M.Roife, E.V.Seredenko, E.P.Khal'chitskii, and N.N.Chernov. "Characteristic Features of the High Frequency System of the 1 GeV Proton Synchrocyclotron", Zhurnal Tekhn. Fiz. **41**, 1222 (1971).

[11] N.K.Abrossimov, S.P.Dmitriev, A.V.Kulikov, G.F.Mikheev, E.V.Seredenko, and N.N.Chernov. "Device of Feed Back of the Generator and Dee at the 1 GeV Proton Synchrocyclotron", Certificate 270131 with priority at 28.04.1969, Bulleten Izobretenii **16**, 62 (1970).

[12] N.K.Abrossimov, S.P.Dmitriev, A.V.Kulikov, G.F.Mikheev, and G.A.Riabov. "Device for the Optimization of the Accelerating Voltage Amplitude at the 1 GeV Proton Synchrocyclotron", Certificate 475948 with priority at 17.09.1973, Bulleten Izobretenii, **27**, 227 (1979).

[13] N.K.Abrossimov, A.V.Kulikov, and G.F.Mikheev. "The Central Region Focusing Device for the Synchrocyclotron", Certificate 743243 with priority 15.12.1977, Bulleten Izobretenii, **23**, 341 (1980).

[14] N.K.Abrossimov, S.P.Dmitriev, A.V.Kulikov, G.F.Mikheev, and G.A.Riabov. "The Beam Intensity Increasing at the 1 GeV Proton Synchrocyclotron Due to Improvement of Electrostatic Focusing in the Central Region", in *Proceedings of 6th All-Union Conference on Charged Particle Accelerators, Dubna, Russia, 11–13 October 1978* (Moscow, 1979), vol. **1**, p .277.

[15] N.K.Abrossimov, V.A.Eliseev, V.A.Volchenkov, G.A.Riabov, and N.N.Chernov. "A 30% Beam Extraction on the 1 GeV Proton Synchrocyclotron at Gatchina", Nucl. Instr. Meth. **126**, 230 (1975).

[16] N.K.Abrossimov, A.A.Aleksandrov, V.A.Volchenkov, V.A.Eliseev, I.B.Zelichenok, E.M.Ivanov, Yu.T.Mironov, M.S.Perskii, V.Reshetnikov, G.A.Riabov, and B.Z.Sandler. "Extraction of Additional Low-Intensity Proton Beam for the Proton Therapy at the 1 GeV Proton Synchrocyclotron", in *Proceedings of 10th All-Union Conference on Charged Particle Accelerators, Dubna, Russia, 21-23 October 1986* (Dubna, 1987), vol. **2**, p. 174.

[17] N.K.Abrossimov, A.G.Kotov, A.V.Kulikov, G.F.Mikheev, N.N.Chernov, and V.I.Yurchenko. "System Simultaneously Used at the 1 GeV Proton Synchrocyclotron for Long Burst Operation and One Turn Beam Deflection onto the Internal Target", in *Proceedings of 3rd All-Union Conference on Charged Particle Accelerators, Moscow, Russia, 2–4 October 1972* (Moscow, 1973), vol. **2**, p. 277.

[18] A.V.Kulikov and N.N.Chernov. "Device for the Time Stretching of Inner Beam at the Synchrocyclotron". Certificate 370901 with priority at 20.07.1972.

[19] N.K.Abrossimov, A.V.Kulikov, G.F.Mikheev, and N.N.Chernov. "Method of the Beam Loss Reduction when the C-Electrode is Used to Increase the Beam Duty Cycle ". Certificate 497934 with priority at 3.01.1974.

[20] G.D.Alkhazov and S.L.Belostotsky. "The Magnetic Spectrometer for the Measurements of the Secondary Beams of the 1 GeV Proton Synchrocyclotron". Certificate 582709 with priority at 3.05.1976, Bulleten Izobretenii **18**, 294 (1979).

[21] N.K.Abrossimov, G.Z.Borukhovich, A.B.Laptev, V.V.Marchenkov, G.A.Petrov, O.A.Shcherbakov, Y.V.Tuboltsev, and V.I.Yurchenko. "Neutron Time-of-Flight Spectrometer GNEIS at the Gatchina 1GeV Proton Synchrocyclotron", Nucl. Instr. Meth**. A 242**, 121 (1985).

[22] N.K.Abrossimov, V.A.Volchenkov, V.A.Eliseev, E.M.Ivanov, A.V.Kulikov, G.A.Riabov, B.V.Vinogradov, V.Ya. Gertsenshtein, D.L.Karlin, B.A.Konnov, and B.V.Nizkovolos. "New Medicine Proton Beam Line at the 1 GeV Proton Synchrocyclotron", in *Proceedings of 8th All-Union Conference on Charged Particle Accelerators, Protvino, Russia, 19–21 October 1982* (Dubna, 1983), vol. **2**, p. 94.

[23] N.K.Abrossimov, V.A.Volchenkov, V.A.Gordeev, V.A.Eliseev, E.M.Ivanov, V.P.Koptev, S.P.Kruglov, A.V.Kulikov, S.M.Mikirtychiyants, G.A.Riabov, and G.V.Shcherbakov. "Low Energy π and μ Meson Beams at the 1 GeV Proton Synchrocyclotron", in *Proceedings of 8th All-Union Conference on Charged Particle Accelerators, Protvino, Russia, 19–21 October 1982* (Dubna, 1983), vol. **2**, p. 90.

```
ERROR: undefined
OFFENDING COMMAND: ^D^

STACK:
```