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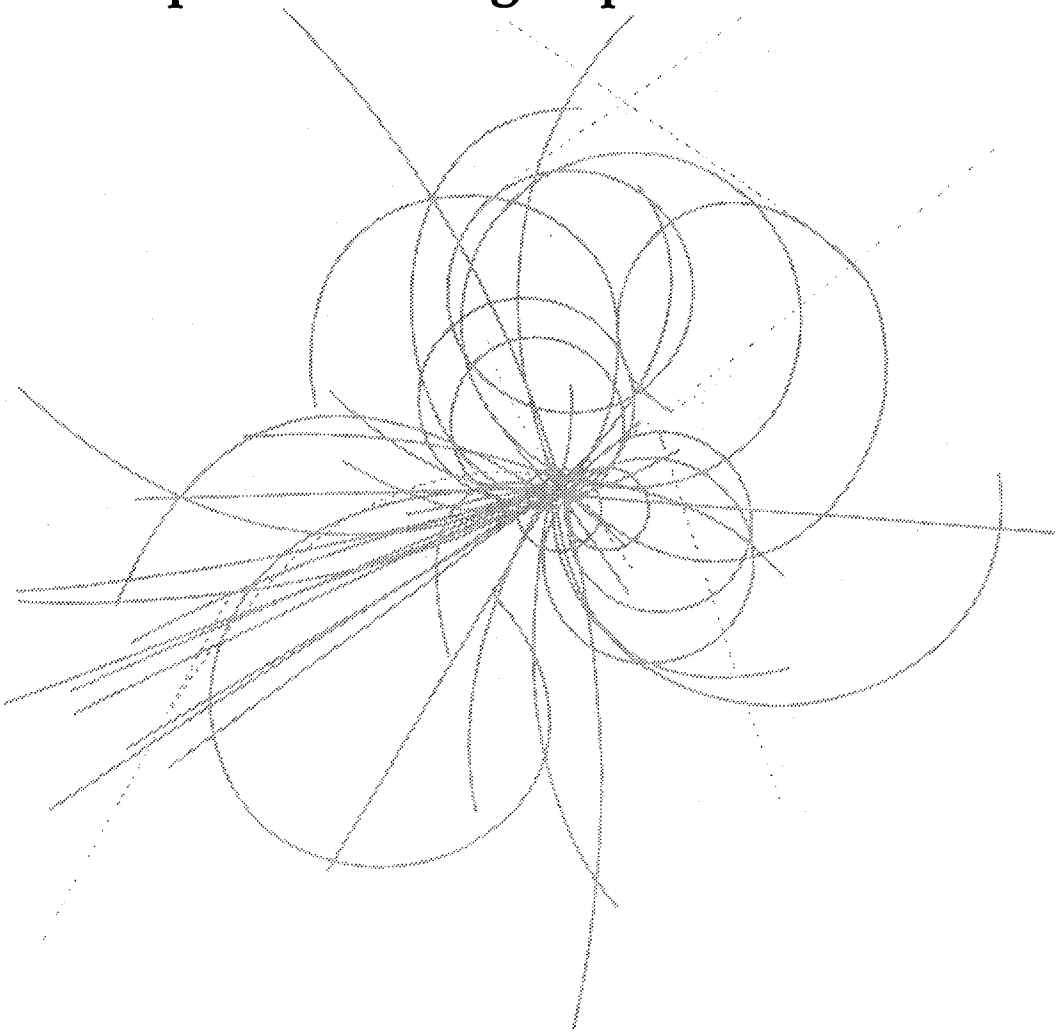

Possibilities of SSC Device Testing at the Serpukhov 70-GeV Accelerator

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Sergei Cherny

Abstract

The possibilities for the testing and measurement of different physical facilities related to the Superconducting Super Collider (SSC) are considered. The Institute for High Energy Physics (IHEP) accelerator complex at Serpukhov, Russia, is described, and technical parameters are presented. Generally, the beam extraction and beam line systems are described because both systems constitute the environment in which the physicist finds himself, and most often these systems define the final possibilities of experimental set-up for a fixed-target run. Three groups of SSC problems may be examined at the existing 70-GeV accelerator at IHEP: the study of radiation resistance of various devices, the study of beam monitor performances, and the testing and investigation of modules of collider detectors.

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1.0 INTRODUCTION

The Superconducting Super Collider (SSC) project has reached the stage at which many devices need to be tested using particle beams. Discussions at working meetings suggest several possibilities in the areas of accelerator physics and collider detectors. Some groups of SSC problems may be studied at the existing 70-GeV accelerator at the Institute for High Energy Physics (IHEP) near Serpukhov, Russia.

The first is the study of radiation resistance for various devices used in accelerators and in experimental set-ups.[1–3] Sooner or later all laboratories begin to investigate radiation resistance of their devices, some components of electronics, and so on. The existing dose rates of the radioactive sources and nuclear reactors may be at least 1.0 Mrad/h. But accelerators offer the possibility of studying radiation resistance under the conditions of local irradiation and the developing shower of particles, or under the condition of mixed secondary irradiation. The CERN experience and IHEP data show that it is very important to study electronic components, for example, where the difference in output performance of electronics between nuclear reactor irradiation and accelerator irradiation may vary in several times among different experimental groups. One requires very accurate measurements of doses in both cases and correct comparison of the irradiation condition.

The second group of problems involves the study of the beam monitor performances. The IHEP has limited capability for the testing of the beam instrumentation for circular accelerators, but these capabilities are sufficient for the Linac beam instrumentation, the Linac to Low Energy Booster (LEB) transfer line, and the LEB to Medium Energy Booster (MEB) transfer line. We should take into account that for the SSC the Linac particle energy is 600 MeV, output emittance is approximately 0.3π mm-mrad in both directions, X-beam sizes are 3–47 mm in the transfer line, Y-beam sizes are 3–25 mm, the output MEB particle energy is 11 GeV, emittance for the collider run is approximately 0.6π mm-mrad, beam sizes in the transfer line are 1.5–6 mm, beam intensity is 10^{12} protons per cycle, and the cycle is 0.1 s.[4]

The third group of questions that can be decided for the SSC at the Serpukhov accelerator relates to the testing and investigation of modules of collider detectors.[5,6] The average energy of particles in the 10–70 GeV range is enough for many applications in calorimeter detector measurements:[7]

- study of the module mapping
- study of the detector response next to the boundaries of metal absorbers, spacers, and module edges
- measurement of the electron/pion response
- choice of the working point from the high-voltage power supply
- charting of the response of module assembly versus the pseudorapidity and angles
- study of muon chamber performance
- and others.

The IHEP accelerator complex is located approximately 60 miles south of Moscow, in a small city called Protvino. The larger city of Serpukhov is 12 miles away. The IHEP accelerator is the largest base in Eastern Europe for investigations in the field of high-energy physics. The commissioning of the accelerator in 1967 and the first physics investigations in 1968 marked the beginning of a whole series of scientific studies in the USSR. Below we will consider the IHEP accelerator performances that can be useful in understanding possible applications to the aforementioned problems at the SSC.

2.0 THE IHEP COMPLEX

The IHEP accelerator complex (Figure 1) consists of a chain of three accelerators: a linear accelerator to energy of 30 MeV, a booster to energy of 1.5 GeV, and the main accelerator with final working energy of 70 GeV. The beam extraction systems ensure operation not only of the internal target set-up in the vacuum chamber of the accelerator but also of external targets where, as a rule, more intense secondary particle beams can be produced than in internal targets. The systems of beam lines form beams with required performances and transfer them to the experimental facilities located in Buildings 1BV, 2, 2A, BC-1, and BC-2.

The main piece of information for experimental physicists is the performance of particle beams that may provide experimental set-ups. In consideration thereof, a close look at the technical devices of accelerators and their parameters is not essential to the content of this report; therefore, they will be described briefly. We will pay more attention to the beam extraction systems because they determine not only beam parameters for detectors, but also the physical environment of the experimental area, the possibility of simultaneous runs of several detectors, and the changes of beam parameters in different combinations of beam extraction. Also, the beam lines will be considered as obvious factors in determining the possibility of experiments.

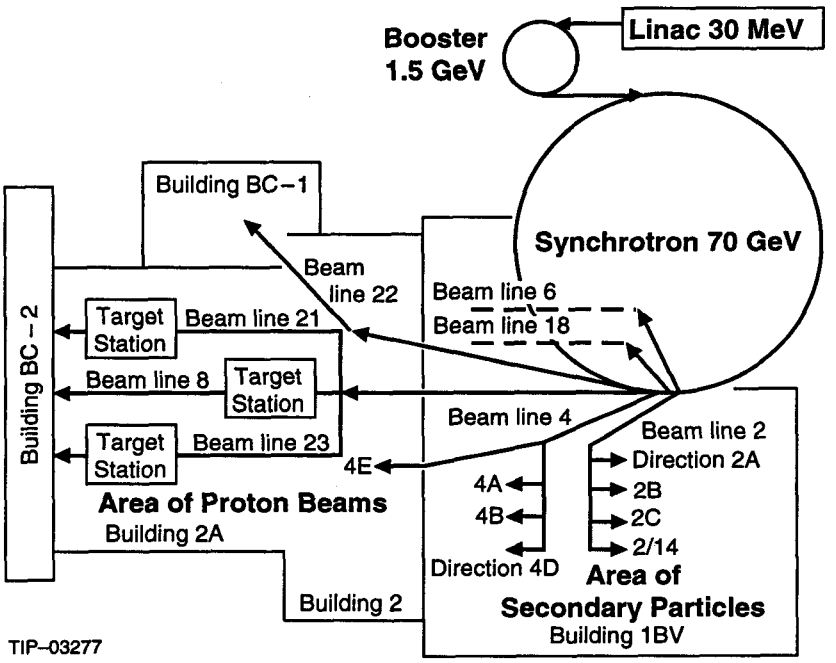

Figure 1. Schematic Arrangement of the IHEP Accelerator Complex.

3.0 THE LINEAR ACCELERATORS

The Institute has two linacs. The first accelerator, I-100, is a linear proton accelerator with a particle energy of 100 MeV and a current of approximately 100 mA. It was previously used as the injector[8] for the main 70-GeV accelerator. This linac has been replaced by the new accelerator, URAL, and it is now used for various application problems. This facility has advanced systems for beam and radiation monitoring.

The second proton accelerator, URAL-30, is used as the injector. It has a particle energy of 30 MeV at its exit and a working value of current up to 100 mA. The accelerating system consists of an ion gun with output energy of 100 KeV;[9] the initial part of the accelerator, up to energy 2 MeV; two sections of the main part of the accelerator, to 16 and 30 MeV; and a beam debuncher.

In accelerator URAL-30, accelerating systems of two types are used that differ from the traditional Alvarez accelerating system. In the initial section of the accelerator there is a structure with electrodes formed by a long four-lead line with spatially homogeneous quadrupole focusing.[10] In the main sections of the accelerator,

structures with double accelerating gap and focusing rf field are used.[11] In both types of structure, the rf field at the electrodes is produced by an H-resonator.[12] These accelerating structures have a number of advantages over the traditional Alvarez-Blewett accelerator, the scheme of which was followed in the former injector, I-100. An accelerator based on the Alvarez-Blewett scheme (cylindrical resonator excited in the wave E_{010} and loaded with drift tubes with quadrupole magnets built into them) requires a high-voltage injector and is of considerable size. The injection energy is determined by the possibility of arranging along the length of a period the structures of quadrupole magnetic lenses in drift tubes. The shorter the tubes, the lower the energy of the accelerated particles. Thus, the construction sizes introduce restrictions on the energy of injection into the accelerator. In addition, the lower injection energy in an Alvarez accelerator leads to larger Coulomb effects, which significantly lower the limiting beam current. Therefore, an accelerating structure with spatially homogeneous quadrupole focusing offers possibilities of lowering the injection energy (to about 100 KeV) without significant loss of beam intensity. Basis performances of the linear accelerator URAL are shown in Table 1.

TABLE 1. BASIS PERFORMANCES OF LINEAR ACCELERATOR URAL-30.

Output energy, MeV	30
Beam current, mA	Up to 100
Momentum spread of particle $\Delta p/p$,%	0.3
Emittance (90% of current), cm-mrad	0.6 π
Duration of current pulse, μs	Up to 10
Number of pulses in packet	32
Repetition frequency of pulses in packet, Hz	20
Repetition frequency of packet, Hz	0.2

4.0 THE BOOSTER

The booster is the first in the cascade of IHEP cyclic accelerators. The need to build the booster in order to raise the beam intensity in the main accelerator arose from the development of a program of neutrino research at the IHEP. If one is studying the interactions of particles with small cross sections, the beam intensity may determine the very possibility of conducting an experiment during a reasonable time period. Restrictions on the intensity of the accelerated beam in the 70-GeV accelerator are imposed by the permissible shift of the betatron frequencies under the influence of the beam self-field at the initial energy of the particles in the accelerator, *i.e.*, the injection energy. For the existing parameters of the main ring, the injection energy of more than 1 GeV corresponds to the required intensity of 5×10^{13} protons/cycle of the accelerated beam. Different possibilities of high-energy injection into the 70-GeV accelerator were analyzed,[13] and preference was given to a rapid booster to 1.5 GeV, *i.e.*, to a small-radius synchrotron operating with high repetition rate and filling the main accelerator with protons during a few of its cycles.

For the chosen multiplicities of the radio frequencies of the booster and the main accelerator (1 and 30, respectively), each bunch accelerated into the booster is injected into one separatrix of the main accelerator, the filling of which thus requires 30 injection cycles. For this method of injection, 1.7×10^{12} particles must be accelerated in each booster cycle. The maximum repetition rate of the booster is chosen to be 20 Hz. Basic parameters of the ring injector booster[14] at the IHEP are shown in Table 2.

TABLE 2. PARAMETERS OF IHEP RING INJECTOR BOOSTER.

Energy of Protons, MeV	30–1500
Pulse intensity (projected), proton/cycle	1.7×10^{12}
Intensity achieved by 1991, proton/cycle	0.9×10^{12}
Number of cycles in packet	Up to 29
Cycle repetition frequency, Hz	Up to 20
Type of magnetic structure (M: magnet; F: focusing magnets; D: defocusing magnets; O: free gap)	MOFODOFOMO
Number of periods of magnetic structure	XII
Radius of orbit in bending magnet, m	5.73
Perimeter of orbit, m	96.16

5.0 THE 70-GEV ACCELERATOR AT IHEP

The main IHEP accelerator, the 70-GeV synchrotron, is the largest accelerator in the country. The idea of building such an accelerator was first advanced in 1956 by V. Vladimirskiy, E. Komar, and A. Mints[15] and was supported by leading physicists in the country. In 1958, the government of the USSR decided to build the accelerator complex, and in 1961 construction commenced at Protvino. Because experience with developing such machines had not yet been obtained in the USSR, a decision was made to build at the Institute of Theoretical and Experimental Physics in Moscow the first strongly focusing accelerator (to 7 GeV) in the country, the aim being to test on it the technical decisions adopted for the Serpukhov accelerator. This accelerator was commissioned in October 1961. The physical commissioning of the IHEP synchrotron, at that time the largest in the world, occurred on October 14, 1967.

The Serpukhov accelerator is built in an underground concrete ring tunnel of cross section 8.4×8.4 m. Part of the accelerator ring passes through an experimental hall, where protons are extracted from the accelerator together with beams of secondary particles from internal targets of the accelerator.

Main parameters of the 70-GeV synchrotron are shown in Table 3.

TABLE 3. PARAMETERS OF THE IHEP 70-GEV SYNCHROTRON.

Energy of accelerated protons, GeV	
maximum	76
working	70
Intensity	
designed, proton/cycle achieved	5×10^{13}
by 1991, proton/cycle	1.6×10^{13}
Cycle repetition period, sec	9.5
Frequency of accelerating voltage, MHz	5.56–6.1
Critical energy, GeV	Approx. 8.9
Mean radius of orbit, m	Approx. 236

6.0 BEAM EXTRACTION SYSTEMS

The extraction of the beam from the accelerator and formation of the beam with the parameters needed for the physics experiments are among the most complicated problems in accelerator practice. Up to now, four methods of beam extraction have been developed for the IHEP accelerator. Each of them covers a certain range of energies and intensities of the extracted beams. Historically, beam extraction from internal targets was the first method that permitted physics experiments in a wide range of energies of secondary particles of 10–60 GeV and designed for fluxes of the secondary particles up to 10^7 particles/cycle. Nonresonant slow extraction of protons elastically scattered by an internal target was developed in recent years in order to meet the need for beams with intensity of 10^6–10^{10} protons/cycle. Rapid extraction was formulated as a method to meet requirements of the experiments with bubble chambers, where a beam of protons is directed onto an external target with energy of approximately 70 GeV, intensity of 10^{11}–10^{13} protons/cycle, and extraction duration up to 5 μs. Finally, slow extraction provides high-intensity beams of 10^{11}–10^{13} protons/cycle with an energy of about 70 GeV for experiments by the electronic method with the extraction of particles lasting up to 1 sec. The sequence of operation of the extraction systems is as follows. At the end of the acceleration cycle, rapid extraction of a bunched beam can be carried out; then, after debunching of the beam in the flat part of the magnetic cycle, there can be slow extraction or extraction of particles from internal targets, or these methods can be used in succession.

6.1 Extraction of Particles from Internal Targets

In the IHEP accelerator, the method of obtaining beams of secondary particles from internal targets is realized as follows. On completion of the acceleration of the particles to the final energy, the proton beam is shifted radially (±5 cm) from the central orbit by means of magnetic systems that produce a local distortion of the orbit (bump). Before this, a target fixed to a support is introduced in the region of the local disturbance. Some of the particles produced on the target pass through a magnetic field of the dipole and can be formed into a beam by the next magneto-optical system in the transfer beam line. By a slow increase in the amplitude of the local perturbation, the remaining beam of protons is guided in subsequent revolutions onto the target, thus ensuring a duration of the beam of secondary particles up to 2 sec. By means of this method, the IHEP accelerator can be operated simultaneously with up to three targets[16] in several magnetic dipoles of the accelerator. The momentum of the particles collected into the beam line depends on the radial position of the target relative to the optic axis of the beam line, since the field of the accelerator magnet plays a part in the preliminary magnetic analyzer. The size and material of the target are chosen on the basis of the required efficiency of interaction of the accelerated beam with the target and the parameters of the transporting beam line. Targets made of light metals are most often used, because as a result of multiple passages of the beam through a target, the dimensions of the primary proton beam are increased more strongly by Coulomb scattering processes, and the heavier is the matter of the target. Targets made of beryllium and aluminum, which have high relative yields of secondary hadrons, are widely used. In the case of slow guiding of the beam onto a target, beams that are sufficiently uniform in time and elimination of the modulation that arises from the influence of the instabilities of the beam parameters in the accelerator and the pull-stations of the current in the power sources of the magnetic systems can be achieved only by introducing into the guiding system a feedback with respect to the current of the particles from the target. A signal from the sensor of the beam current from the target is sent to a circuit that controls the currents in the additional coils of the magnetic blocks of the accelerator that produce the perturbation of the orbit. The feedback closed in this way maintains the intensity of the extracted beam in the case of operation with one target with fluctuations at the level of 10–20%. If two or more targets are operated, the fluctuations of the beam intensity are, as a rule, larger. However, by using thin targets (approximately 50 mg/cm^2), one can obtain better results and ensure modulation of the intensity at the level of 7–10%.[17] The frequency range of the system makes it possible to treat intensity fluctuations in a frequency band up to several hundred Hz. For effective use of the duration of the flat part of the magnetic cycle of the accelerator, one uses successive operation of targets with different

bumps. In this regime, the dead time is largely determined by the rise time of the current in the additional coils of the blocks (approximately 0.15 sec).

Among the advantages of this method of beam extraction are the high efficiency of interaction of the accelerated beam with the target (about 90%) and the comparative ease with which beams of secondary particles extended in time can be obtained. However, with increasing intensity of the primary beam on the target (more than 10^{12} protons/cycle), the problem of activating the accelerator equipment becomes very serious. Therefore, the main method of using high-intensity beams is to extract them from the accelerator with high efficiency and to generate secondary particles on the external targets.

6.2 Rapid Extraction of Protons from the Accelerator

This method is based on extraction of one or several bunches of the beam by a powerful pulsed magnet (kicker magnet) in a straight section of the accelerator, with the growth and decay of the field in the magnet taking place in the time interval between the passage of neighboring bunches of the beam.[18] Having received an angular deflection in the kicker magnet, the proton beam passes through deflecting septum magnets that are common to the rapid and slow beam extraction methods (Figure 2). To shift the beam into the opening of the deflecting magnets, an additional perturbation of the beam orbit (a bump) is created by switching on addition coils of several magnets of the accelerator. Depending on the current in the last magnet (DM-30), the beam is directed either along the track of beam line No. 8 or of beam line No. 22.

At the present time, rapid beam extraction operates only in one direction of beam line No. 8, permitting experiments with the experimental set-ups Neutrino, Neutrino Detector, and the bubble chamber SKAT. As a result of investigations aimed at achieving the projected intensity in the beam line of 3×10^{13} protons/cycle, the parameters of the extracted 70-GeV beam are being improved, and for reference we may give the main parameters: at a beam intensity of 10^{13} protons/cycle, the extraction efficiency is 95%, the emittance in the horizontal and vertical plans is 2π mm-mrad, the momentum spread is about $\pm 1.5 \times 10^{-3}$ at the 95% intensity level, the number of extracted bunches is between 1and 30, and the maximum intensity of the extracted beam is approximately 1.6×10^{13} protons/cycle.

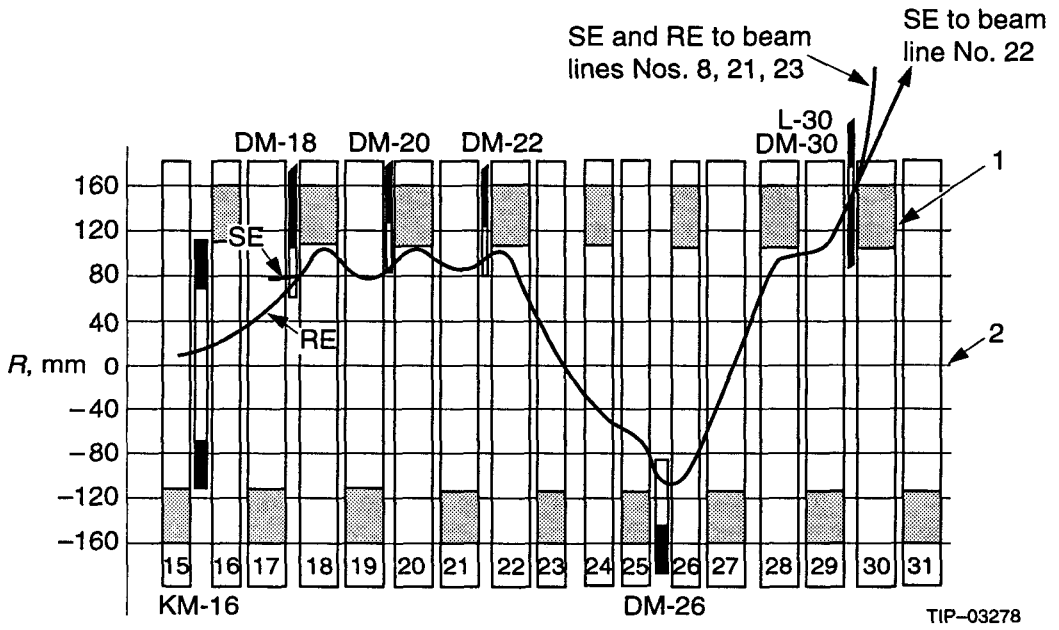

Figure 2. Schemes of the Systems of Rapid and Slow Extraction of the Beam from the 70-GeV Accelerator: 1) Region of Strong Nonlinearity of Magnetic Field; 2) Center of Vacuum Chamber of Accelerator; 3) KM is the Rapid–extraction Kicker Magnet; DM are Deflecting Septum Magnets; L are Quadrupole Magnets; SE is Slow Extraction; and RE is Rapid Extraction.

6.3 Slow Proton Extraction from the Accelerator

The slow extraction system[19] is intended to extract a proton beam with energy from 20 to 70 GeV and projected intensity up to 3×10^{13} protons/cycle for experiments using the counter method. The extraction is done in the flat part of the magnetic cycle of the accelerator, with duration up to 1 sec, in the direction of beam line No. 8 (into beam lines Nos. 21 and 23, too, because they are the branches of line No. 8) and into beam line No. 22. The extraction scheme is based on the excitation of radial betatron oscillation at the third-order resonance $3Q_R = 29$, *i.e.*, the frequency of the betatron oscillations is shifted in such a way that the resonance conditions for the betatron oscillations are satisfied in three complete revolutions of the beam, thus leading—in the presence in the accelerator of harmonics of the magnetic field at this frequency—to an appreciable increase in the amplitudes of the radial oscillations of the beam. The resonance is excited by introducing the 29th harmonic of the quadratic nonlinearity of the magnetic field by means of four sextupole magnets distributed at intervals of 90° in the accelerator azimuth and in the straight sections.

The adjustment to resonance ($Q_R = 9.66\ldots$) is achieved by a quadrupole magnet in the 38th straight section of the accelerator. The extraction duration is determined by the rate of change of the gradient in the magnet. The required rate of change of the frequency of the betatron oscillations on the passage through the resonance band is very small. Parasitic pulsation in the magnetic fields of the accelerator or in the magnets of the system that excites the betatron oscillations will give rise to a density modulation of the beam. In this connection, the requirement of uniform extraction imposes stringent restrictions on the pulsation of the current in the magnetic systems. The existing fluctuations of the parameters restrict the lower limit of the rate of passage through the resonance band, which is determined by the admissible level of beam-density modulation during the extraction time. These factors put a lower limit on the intensity of a slowly extracted beam at a level of more than 10^{11} protons/cycle. A rectangular intensity pulse of the extracted beam is formed by a beam feedback system that consists of a monitor of the extracted beam, an amplifier with regulated gain, and blocks for controlling the currents of the quadrupole magnet of the adjustment to resonance. The efficiency of elimination of the pulsations in the extracted beam by this system has a fundamental restriction with respect to the pulsation frequency due to the finite time of development of the resonance (approximately 1 msec). Therefore, the feedback circuit can effectively deal with pulsations only to frequencies around 100 Hz.

After excitation of the resonance, the particles are transferred into gaps of the septum magnets[20] with successively increasing thickness of the beam-separating septum and, accordingly, an increasing maximum possible field induction. This makes it possible to reduce the losses of the particles in the septum conductor. The extraction efficiency in this part of the track is determined largely by the loss of particles in the first septum and by the effect of the stray magnetic field of the septum on the circulating beam.

The efficiency of proton extraction from the accelerator is about 85%, and the intensity of the extracted beam achieved by 1991 was about 5×10^{12} protons/cycle, with modulation of the beam density in time of about 30–40%.

6.4 Nonresonant Slow Extraction of Protons

As we have already noted, the intensity of the slowly extracted beam is bounded below in the IHEP accelerator by a value around 10^{11} protons/cycle. To extend the possibilities of experiments using the counter method and the formation of beams of lower intensity, use is made of extraction of part of the circulating beam in the accelerator by the selection of particles scattered by a target. This method is based on the use of the slow extraction system for protons scattered elastically by an internal target[21] in the accelerator and extracted in the direction of beam line No. 8 or No. 22. Particles passing through the target acquire an increment in the amplitude of the betatron oscillations, mainly through multiple Coulomb scattering and elastic nuclear scattering of beam particles by the target. The scattering angle depends on the material of the target,its length, and the number of passages of the beam through the target. The track of beam extraction from the accelerator is close to the ordinary track of the slowly extracted beam. This makes possible simultaneous operation, in the cycle, of two facilities with one target.

With 6×10^{11} particles/cycle striking the target, the result was an extracted proton beam in the direction of beam line No. 8, with intensity up to approximately 3×10^{10} particles/cycle and satisfactory beam intensity modulation at the 30% level.

In the direction of beam line No. 22, nonresonant slow extraction was realized using thin targets in the form of carbon tissue with a thickness of about 0.3 mm. Two targets, placed in the dipoles of the accelerator, are targets for the secondary-particle beam lines Nos. 2 and 4. Successive scattering of the beam by two thin targets allows the two main users of secondary beams (beam lines Nos. 2 and 4) and beam line No. 22—in which the beam of protons elastically scattered from the targets is formed—to operate in their usual regime. The use of thin targets in such a regime made it possible to reduce appreciably the modulation of the beam intensity both in the secondary-particle beam lines (as noted above) and in beam line No. 22 with the extracted proton beams, where a beam of protons with intensity fluctuation of about 10% and duration of about 0.8 sec was obtained.

The development and use of the method of nonresonant slow extraction supplied the experimental facilities at the IHEP accelerator with extracted proton beams with energy of 70 GeV extended over about 1 sec and in the intensity range of 10^6–10^{10} protons/cycle with high uniformity in time.

7.0 BEAM LINES FOR TRANSPORTING THE PARTICLES

Physics experiments with the IHEP accelerator are made possible by an extensive complex of beam lines that form particle beams with given parameters. Two groups of beam lines can be distinguished: internal-target, secondary-particle beam lines, which are situated in Building 1BV (see Figure 1), and beam lines with proton beams extracted from the accelerator. The beam lines of the second group pass through Building 1BV and transport the proton beams to the experimental facilities situated in Buildings 2, 2a, BC-1, and BC-2. The regime of operation of the accelerator with the beam lines is usually as follows. At the end of the acceleration cycle, at energy 70 GeV, there is a rapid extraction into beam line No. 8; after 0.2–0.3 sec in the flat part of the magnetic cycle of the accelerator, at particle energy 70 GeV, slow extraction commences for use of the beam in one of the beam lines Nos. 21, 22, or 23, for a duration of approximately 1 sec; after a pause of approximately 0.2 sec, the remaining time of 0.9 sec on the plateau of the magnetic field is used for operation of the internal-target beam lines with simultaneous operation of up to three facilities.

7.1 Internal-target, Secondary-particle Beam Lines

This group includes beam lines Nos. 2, 4, 14, and 18, with a wide possibility of runs;[22] beam line No. 6 has a simple configuration and is used for fault identification of the apparatus. The typical method used to form a beam of secondary particles considers the optical scheme of beam line No. 4B (Figure 3), which transports the beam to the experimental facility GAMS. The negatively charged hadrons generated on an internal target in the magnet of the accelerator are extracted by the magnetic field of the dipole into the head part of the beam line, where a flux of particles in the required interval of angles is taken from the total flux of particles by the vertical and horizontal collimators C1 and C2. The central region of the beam, bounded by the plates of the collimators, is occupied by the doublet of quadrupole magnets Q1 and Q2, which are used for horizontal (so-called pulsed) collimator C3. The necessary dispersion with respect to the momentum in the region of this collimator is produced by the magnet M1. The opening of the plates of the collimator from the beam-line axis determines the momentum interval of the particles in the beam. The next magnet M2 deflects the beam in the direction of the experimental facility and partly compensates the momentum dispersion that has arisen. The doublet of quadrupole magnets Q3 and Q4 fulfills the function of intermediate focusing of the beam. The collimator C4 is used to suppress the background particles that come within the beam halo. The final objective of quadrupole magnets Q5–Q8 is used to form and guide the beam to the experimental facility with the required parameters.

Besides beams of hadrons, pure electron (positron) beams are also obtained in the beam lines.[23] The method of obtaining such beams is based on radioactive decays of short-lived particles, mainly π°-mesons, which are produced in a target by irradiating it with proton beams. The gamma rays from the decay of the π°-mesons produce electron-positron pairs as a result of conversion in the matter of a second target, called the converter. Charged hadrons are removed from the beam by means of an analyzing magnet in the section between the target and the converter. Using electron beams, one can also obtain beams of high-energy gamma rays tagged with respect to the energy.[24]

A new direction in beam formation in this group of beam lines is the method of extracting the proton beam from the accelerator by beam-channeling protons in a single, bent silicon crystal placed in the vacuum chamber close to the periphery of the beam circulating in the accelerator. Such beams were obtained in beam line No. 14. The proton beam was extracted by means of a single crystal bent through an angle of 80 mrad, and the obtained beam intensity was 4×10^6 protons/cycle.[25]

The characteristic parameters of beams realized in beam lines with 10^{12} protons/cycle directed onto the target are given in Table 4. Particle momentum can be changed over a wide range. Table 4 shows typical performances for only one regime.

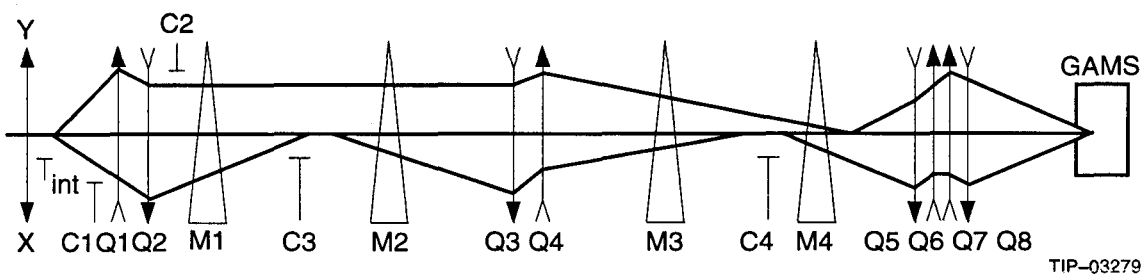

Figure 3. Optical Scheme of Beam Line No. 4B to the Detector "GAMS": C are Collimators; Q are Quadrupole Magnets; M are Dipole Magnets; and T_{int} is the Internal Target.

TABLE 4. TYPICAL CHARACTERISTIC PARAMETERS OF BEAMS IN THE BEAM LINES OF SECONDARY PARTICLES ON INTERNAL TARGETS OF THE ACCELERATOR.

Beam Line	Particle species	Particle momentum GeV/c	Intensity at facility particles/cycle	Momentum interval $\pm\Delta$ p/p, %
2A	h– hadrons	40	2×10^6	1–2
2B	h–	40	2×10^6	2
2C	e–	28	5×10^5	3–4
2/14	h–	40	3×10^6	1–5
	e–	26	6×10^4	1
4A	h–	25	10^7	1–2
	e–, e+	10	2×10^5	1
4B	h–	38	10^7	1
	e–	10	3×10^4	1
4D	h–	38	2×10^6	1
4E	h–	38	5×10^5	1
18	h+	10	10^8	2
	h–	10	10^4	2

7.2 Beam Lines for Extracted Proton Beams

This group of beam lines is based on the systems of rapid and slow extraction of the proton beam from the accelerator. Both types of extraction are used in the case of beam line No. 8. Beam lines Nos. 21 and 23 are branches of beam line No. 8 (see Figure 1). The beam extracted slowly from the accelerator is transported through the head part of beam line No. 8 by means of magnets in Building 2, and the beam is deflected into the track of beam line No. 21 or beam line No. 23. Deflection into beam line No. 21 is by means of pulsed magnets, which permits simultaneous operation of beam lines Nos. 8 and 21 for rapid and slow extraction, respectively. The beam is deflected into beam line No. 23 from the track of beam line No. 8 by a permanent magnet. Simultaneous operation of beam lines Nos. 21 and 23 in the case of slow extraction has now been made possible by means of deflection of part of the beam by a single bent crystal.[26] The beam lines operate as follows. The magneto-optical systems are adjusted to transport the high-intensity beam to beam line No. 23. A bent crystal is introduced into the beam, capturing the protons in the beam-channeling regime and deflecting them through angles of 50–60 mrad; the capture efficiency is about 10^{-4}–10^{-5}. The low-intensity separated beam is directed along the track of beam line No. 21. Beam line No. 22 is the high-intensity beam line for slow extraction; the secondary beams are generated on an external target. Some characteristics of the beams in beam lines Nos. 8, 21, 22, and 23 are given in Table 5.

TABLE 5. SOME CHARACTERISTIC BEAM PARAMETERS IN BEAM LINES OF RAPID AND SLOW EXTRACTION.

Beam Line	Intensity of protons extracted onto target (projected), particles/cycle	Secondary particles	Momentum, energy of secondary particles, GeV/c, GeV	Intensity of secondary particles (at the target 10^{12} protons/cycle)
8	3×10^{13}		5–6	10^{-3} 1/m^2 • proton
21	2×10^{11}	p	70	10^6–10^{10}
	2×10^{12}	h–	35	2×10^7
		h+	35	3×10^8
23	3×10^{13}	h–	35	1.5×10^8
		h+	35	2.5×10^9
22	1×10^{13}	h+	40	2×10^9
	1×10^{13}	h–	40	6×10^7
	1×10^{12}	e–	30	10^6
	2×10^{11}	p	70	10^{10}

7.2.1 Beam Line No. 8

After separation of the systems of beam lines Nos. 21 and 23, beam line No. 8 is intended only for the formation of a neutrino beam for the experimental facilities Neutrino, Neutrino Detector, and the big freon bubble chamber SKAT. By the system for rapid extraction of the beam accelerator, a high-intensity proton beam is directed into beam line No. 8,[27] where it is focused by the magneto-optical system onto a target. The π- and K-mesons produced on the target are formed into a parallel beam by a special neutrino-focusing device and, entering a 120-m-long vacuum tube, they decay, producing neutrino or antineutrino fluxes. The vacuum decay beam line terminates with a massive steel filter that shields the detectors from the hadronic and muonic backgrounds.

The target station of the neutrino beam line is an extensive complex. A thick concrete-and-metal shielding around the entrance to the target section must suppress radiation to levels that permit personnel to be present in the region behind the shield. The high level of induced radioactivity within the area imposes special

requirements on the construction and reliability of the equipment in the target station. Transition from one part of the experiment to another requires replacement of equipment under conditions when the level of radiation 2–3 months after stopping of the beam line is 2–5 rad/h. Repair of failed equipment 1–2 days after the beam line has stopped operation requires work to be done under conditions of 10–50 rad/h. The main equipment of the target station is the target and the objectives, which consist of pulsed magnets that focus K- and π-mesons. The power-supply system provides currents in the magnets from 350 to 450 kA, depending on the regime for a current pulse that lasts about 160 μsec. If the need arises, the objectives can be remotely disconnected and, with the upper shield of the entrance region removed, that area can be evacuated by means of automatic capture, the presence of which was foreseen in the construction of the equipment. The system of the neutrino-focusing device with three objectives provides intense neutrino fluxes with a wide spectrum at the detector and a mean energy of 5–6 GeV.

The parameters of the beams obtained in beam line No. 8 are as follows. The intensity of the extracted beam achieved by 1991 was 1.3×10^{13} protons/cycle, and the beam diameter at the target was 3–4 mm.

7.2.2 Beam Line No. 21

This beam line was developed as a universal slow-extraction beam line.[28] The program of investigations with the experimental facility includes studies with proton beams as well as with beams of other secondary particles generated on an external target. At the present time, the experimental program can use the following beam line regimes. Proton beams in the intensity range of 10^6–10^{10} protons/cycle are formed from the primary proton beam, which is extracted from the accelerator with an intensity of 5×10^{11} protons/cycle, at which a satisfactory beam density modulation is ensured. The beam can be collimated and reduced in intensity to 10^9–10^{10} particles/cycle. A proton beam with a lower intensity of 10^6–10^9 particles/cycle in the beam line is obtained both by transporting protons that have been elastically scattered on an internal target and extracted from the accelerator and by the diffraction scattering of protons by an external target of the beam line itself. Another way of forming proton beams of moderate intensity is by means of a single bent crystal that traps a beam with an intensity of 10^6–10^7 protons/cycle into the beam-channeling regime. The main part of the proton beam is absorbed in a collimator, and the beam deflected by the signal crystal is transported by the following optics to the experimental facility. Beams of secondary particles are generated in a target in a special collimator. Up to 5×10^{12} protons/cycle can be directed onto the target. The beam line makes it possible to form beams of positive particles with momentum of 7–35 GeV/c and beams of negative particles with momentum of 7–60 GeV/c.

7.2.3 Beam Line No. 23

This beam line[29] forms beams for neutrino investigations with the experimental facility "Tagged Neutrinos." A slowly extracted beam of protons with projected intensity of 3×10^{13} protons/cycle is transported through the head part of beam line No. 8 and is deflected by a permanent magnet into the track of beam line No. 23. A doublet of quadrupole magnets focuses the beam onto a target in the section behind a thick biological shield. Secondary particles with momentum of 5–35 GeV/c are trapped in a beam line that forms a nearly parallel beam. In a vacuum tube of approximately 65 m in length the kaons of the secondary beam decay into muon and electron neutrinos. Estimates show that at the projected intensity at the target of 3×10^{13} protons/cycle, the kaon fluxes in the secondary beam will be at the level of 2×10^9 particles/cycle. According to calculations, this will permit high-precision investigations with both muon and electron neutrinos with energy resolution of the events at the level of 5–10%.

7.2.4 Beam Line No. 22

This line was developed to provide particle beams for two experimental regimes.[22] In the first regime of operation, a high-intensity hadron beam of 10^9 particles/cycle with momentum of 10–60 GeV/c can be formed in the beam line. Another regime of the beam line makes it possible to form for the experimental facility electron beams with intensity of 10^5–10^6 protons/cycle, with about 10^{12} protons/cycle being directed onto the target. The possibility is also foreseen of transporting 70-GeV protons scattered elastically by an internal target of the accelerator.

8.0 CONCLUSION

We would like to conclude with some remarks on the foregoing text. This paper is a technical description of the IHEP experimental facilities[30] and of their possibilities for the performance study of various devices. This paper is not a proposal for an experiment.

The existing agreement between the SSC Laboratory (SSCL) and IHEP foresees the testing at the IHEP complex of Solenoidal Detector Collaboration (SDC) components; the experimental base has been defined for that. One would like to attract the attention of other SSCL experimental groups to the wide possibilities of the IHEP accelerator complex. The accelerator operates four or five runs per year, with each run requiring approximately a month-and-a-half. Good possibilities exist for radiation-tolerance investigation at the linac beams and in the target station areas, internal or external. The developed network of beam lines suggests the possibilities of beam monitor testing and collider detector module study in the momentum ranges of 5–70 GeV and intensity of particles range 10^4–10^{13}. The obvious question is a matter of scheduling. We think that any concrete intent to test at the 70-GeV accelerator can be discussed with the IHEP. In conclusion, one would hope that this paper will be useful for SSCL physicists as they consider their options for beam testing.

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