# THE IHEP ACCELERATOR - STORAGE COMPLEX
# STATUS REPORT

## 1. Introduction

The IHEP Accelerator - Storage Complex (UNK) is being developed as a basis for further deepening and advancement of high-energy physics research.[1-4] A 3-TeV superconducting proton synchrotron with a prospect for colliding beams in the future has been chosen as a basis of the UNK.[4] Presently the design study of the UNK has been completed.

The basic parameters of the accelerator are listed in Table I.

Table I. The Main Parameters of the UNK.

| | Name | Unit of measurement | 1st stage | 2nd stage |
|---|---|---|---|---|
| 1. | Total length | m | 19288 | 19288 |
| 2. | Injection energy | GeV | 70 | 400 |
| 3. | Maximum energy | GeV | 400 | 3000 |
| 4. | Injection field | T | 0.117 | 0.670 |
| 5. | Maximum magnetic field | T | 0.670 | 5.0 |
| 6. | Cycle duration | sec | 78 | 78 |
| 7. | Pulse intensity | p /cycle | $6 \times 10^{14}$ | $6 \times 10^{14}$ |

It is a two-stage accelerator. The first stage is a proton synchrotron with conventional magnets and is designed to stack and preaccelerate protons up to 400 GeV. Acceleration up to the maximum energy is to be achieved in the second stage, where superconducting magnets are to be utilized. Both accelerators are located in a common tunnel. The presently existing IHEP 70-GeV accelerator (U-70), whose intensity is planned to be increased up to $5 \times 10^{13}$ ppp, is to be used as an injector into the UNK.

The two-stage system enables us to facilitate the superconducting accelerator operating mode substantially. Beam preacceleration in the first stage makes it possible to reduce the effects of residual fields. Due to the decrease in the beam dimensions, the requirements imposed on the field quality of the superconducting magnets are made less severe. Single-turn beam injection onto the central orbit of the second stage is employed for the same reason. Beam stacking is performed in the first stage; this also offers the opportunity to free the superconducting accelerator from inevitable particle losses.

There are other advantages of the two-stage system. It allows the maximum use of the injector intensity, and therefore achieves the maximum mean intensity of the accelerated beam. The two rings available in the same tunnel provide an option for a 0.4 TeV and 3-TeV proton-proton colliding-beam facility, with 2.2-TeV energy in the c. m. s. The ring of the first stage can also be used to stack beams of electrons, antiprotons, etc.

Figure 1 shows the layout of the UNK. The location of the UNK tunnel is chosen taking into account a preliminary study of geologic conditions. The ring center is within 6.5 km of the U-70 accelerator center. The UNK tunnel dimensions are chosen to allow the future possibility of installing a superconducting storage ring. This will enable us to stack a 3-TeV proton beam and to collide it with a beam of the same energy accelerated in the pulsed superconducting ring. As a result, the pp-collision energy can be increased up to 6 TeV in the c. m. s.

The UNK project is designed with a view for its future development. Six straight sections, each 485 m long, are introduced into the structure of both stages (Fig. 1). The U-70 beam is injected into section 1, in which the beam transfer system into the second stage is also located. The accelerated particles are extracted from Section V. The accelerating systems are placed in Section II, and the beam abort systems in Section IV. Sections III and VI are reserved for colliding beams. The layout of the accelerator and storage rings in the tunnel and the construction of the straight sections are chosen so that the intersections of the maximum energy beam would be subsequently obtained more easily. In designing the long straight sections, all measures eliminating the influence of ring intersections on the $\psi$-function and the momentum compaction factor were taken. Figure 2 presents a schematic view of the UNK tunnel cross section and the position of the magnets therein.

## 2. The Characteristics of the UNK

The scheme of the UNK operation is shown in Fig. 3. A $5 \times 10^{13}$ proton/cycle beam is recaptured in the U-70 accelerator by an rf field with a frequency of 200 MHz, equal to the UNK accelerating voltage frequency. Stacking of $6 \times 10^{14}$ ppp during 71.5 sec is achieved by successive injection of 12 pulses from the U-70. The UNK circumference is exactly 13 times that of the U-70, therefore a part of the first stage circumference is not filled with a beam. This makes it possible to arrange "time slots" between the beam pulses, necessary to facilitate the operation of injection and extraction devices and thus to reduce particle losses. On completion of stacking, the beam is accelerated in the first stage up to 400 GeV and single-turn transferred into the second stage of the UNK. The cycle of the second stage comprises a 20-sec acceleration, a 38-sec beam extraction, and a 20-sec field decay time.

The basic parameters of the UNK magnetic structure are given in Table II.

Table II. The Basic Parameters of the Magnetic Structure of the First and the Second Stages of the UNK.

| | Parameter | Unit of Measurement | Value |
|---|---|---|---|
| 1. | Number of superperiods | | 6 |
| 2. | Total number of periods | | 180 |
| 3. | Length of a period | m | 91 |
| 4. | Length of a matched straight section | m | 484.67 |
| 5. | Total number of dipoles | | 2160 |
| 6. | Total number of quadrupoles including matched straight sections | | 402 |
| 7. | Dipole length | m | 5.8 |
| 8. | Length of a standard quadrupole | m | 4 |
| 9. | Magnetic bending radius | m | 1993.89 |
| 10. | Ratio of the quadrupole gradient to the dipole field | $m^{-1}$ | 14.75 |
| 11. | Betatron frequencies | | 40.75 |
| 12. | Momentum compaction factor | | $5.83 \times 10^{-4}$ |
| 13. | Transition energy | GeV | 38.8 |

The lattices of the magnetic structure of the first and the second stages are identical. They comprise 180 periods of the FODO type with separated functions, each having 12 dipoles and 2 quadrupoles. The requirements on the magnetic characteristic spread and on the accuracy of the dipole and quadrupole positioning are listed in Table III.

Table III.

|  |  |  |
|---|---|---|
| 1. | r. m. s. spread of dipole fields (horizontal and vertical components) | $5 \times 10^{-4}$ |
| 2. | r. m. s. accuracy of horizontal and vertical survey of the optic axes of quadrupoles to the geodetic survey marks. | 0.1 mm |
| 3. | r. m. s. misalignment of adjacent lenses (vertical and horizontal) | 0.05 mm |

Since the dipoles are to be installed after taking into account the magnetic measurement results, the tolerance stated in the first line of the table signified the uncertainty due to magnetic measurement errors and field variation in the cycle and from cycle to cycle. An orbit correction is envisaged in either oscillation plane. With use made of 180 correctors in each plane and with 0.5 mm r. m. s. orbit measurement resolution, the design correction accuracy is ± 2 mm. Considering all the factors above, the maximum beam dimensions at injection into the first stage are 50 mm in the vertical direction and 70 mm in the horizontal plane. During injection into the second stage, the corresponding dimensions are 42 mm and 50 mm. The dimensions of the vacuum chamber of the first stage are of two types, $47 \times 87$ mm$^2$ and $65 \times 65$ mm$^2$; the chamber of the second stage has an elliptical cross section of $60 \times 70$ mm$^2$.

The vacuum requirements in the chambers of the UNK two stages are determined by proton losses due to the residual gas. The mean pressure of the residual gas in the first stage should not exceed 3 × $10^{-7}$ Torr in nitrogen equivalent and 2 × $10^{-8}$ Torr in the second stage. Preliminary calculations show that with the 20 - 40 ° K temperature of the chamber walls of the superconducting ring a 2 × $10^{-11}$ Torr vacuum can be obtained for hydrogen and ~ $10^{-13}$ Torr for the other gases.

The UNK accelerating system should provide a 12 MV total amplitude at 20 MHz for the first stage and 17 MV for the superconducting ring. The maximum powers consumed by the beam are 6.6 MW and 18 MW, respectively. At present, scientists of IHEP, MEPI, and MRTI are doing theoretical and experimental research aimed at choosing waveguides or cavities for the UNK accelerating systems. Synchronization of rf fields of the U-70 accelerator and the first stage of the UNK may be difficult due to the large length of the injection line, which is about 6 km. Therefore, fast rf phase correction by the information on bunch phase position is presumed on completion of each injection pulse. The rf field of the UNK second stage will be synchronized similarly.

The injection line is a strong focusing channel of the FODO type with lenses installed within every 50 m. The maximum beam dimension in the channel does not exceed 35 mm. Over the whole length of the channel, within every 1 km there are correction stations of the beam trajectory in either plane. They consist of beam position pick-ups and three correction magnets. With the 0.2 mm r. m. s. tolerance for lens misalignment with respect to the channel axis, the beam trajectory distortion should not exceed 5 mm over the whole length. The final correction station should provide matching of the channel axis and the UNK orbit to within 1 mm. The beam is injected into the first stage and transferred into the second in the vertical plane.

Three extraction modes are foreseen: single-turn extraction, ~ 30 sec slow resonance extraction, and fast resonance extraction of 10 pulses spaced at 3 second intervals with each pulse yielding $6 \times 10^{13}$ protons in ~ 1 msec. For single-turn extraction, a kicker magnet 30 m in length with a rise time of 1.5 μsec to 0.9 kG is intended to be used. For slow and fast resonance extractions, the $3\ Q_r = 122$ resonance will be employed. To gain maximum extraction efficiency, the structure of a matched straight section is arranged in such a fashion that the maximum of the horizontal amplitude function can be obtained in its center. With the maximum value of the amplitude functions in the straight section approximately a factor of 10 larger than that in the accelerator lattice, one can obtain a 20 mm step-size at the ES septum for a maximum excursion in the normal cell-dipoles of 2 cm. The tolerance for relative values of the magnetic field nonlinearities at the chamber edge should be $10^{-4}$ and ~ $10^{-3}$ for odd and even components, respectively. With these requirements, the value of the extraction efficiency will be 99%. To achieve a good duty factor of the beam with a 30-sec extraction duration, the tolerance for the relative value of current ripple in the sextupoles is to be $10^{-6}$ and about $10^{-9}$ in the magnets of the superconducting ring.

The average electric power consumed by all the UNK systems is about 100 MW. The maximum peak power does not exceed 300 MW. Such loadings are acceptable for the 220-kV mains available. To reduce oscillations of the mains voltage due to UNK pulsed components to acceptable levels, regulators of reactive power are foreseen.

## 3. Field Quality Requirements

The superconducting dipole field has relatively large nonlinearities due to real and ideal coil differences. This results in Q-shifts dependent on oscillation amplitudes and particle momenta. To ensure a lossless beam acceleration in the superconducting ring, the working point in the frequency lattice of betatron oscillations was chosen in the area most free from strong resonance lines ($Q_r \approx Q_z \approx 40.7$), and tolerances for systematic field nonlinearity in the dipoles are established so that betatron frequency spread in the beam would not exceed 0.02 within the whole acceleration cycle. This permits us to avoid intersections of low-order resonances lines. The requirements for fabrication of the dipoles are such that the neighboring strong resonances would cause beam dimension modulation not greater than 10%.

Since the values of nonlinear field components are minimal in the aperture center of the dipoles, measures are taken to hold the beam close to the central orbit during the whole acceleration period in the UNK. This is facilitated by a decrease in the beam dimensions with the help of pre-acceleration in the first stage, single-turn injection into the central orbit of the superconducting accelerator, and a precise correction of the orbit within the whole acceleration cycle.

The question of residual field effects of the dipoles, which is closely related to a choice of the injection energy into the second stage, is very important. Figure 4 shows the calculated dependence of residual field nonlinearities on the field level in the center of the UNK dipoles. Relative

2nd, 4th and 6th order nonlinearities at a distance of 35 mm from the chamber axis are shown. Quadratic nonlinearity, which is supposed to be corrected by the sextupoles, is the most influential one. The total spread of betatron frequencies is a function of the dipole nonlinearity and of the number of the correction system sextupoles and their positioning. The magnitude of the dipole nonlinearity and the strength of the correction element make it necessary to take into account terms in $(\Delta H_z/H)_2{}^2$. With 360 sextupoles used, the permissible value of quadratic nonlinearity of the dipole is $1.5 \times 10^{-3}$, corresponding to the field of 4 kG in the dipole center as indicated by Fig. 4. Considering the poor data on spread of residual fields and their reproducibility, the value of the injection field into the second stage was chosen to be 6.7 kG. This corresponds to an energy of 400 GeV. With a $\pm 1 \times 10^{-3}$ relative momentum spread of the beam injected into the second stage, it is necessary to correct chromaticity in order to satisfy the requirements for betatron frequency spread. This will be done with the help of the same sextupoles.

Systematic nonlinearities of low even orders can be suppressed by an appropriate choice of the dipole construction. Analysis showed that a dipole with a two-shell coil meets the imposed requirements quite well. Choosing the angles of the shells, one can suppress 2nd and 4th order nonlinearities. The remaining higher order ones have a weaker effect, and tolerances for tune spread are satisfied in the region filled with the beam. The value of higher order harmonics can be decreased, if necessary, by calibrated spacer positioned in the first shell of a coil. Therefore, correction systems for systematic nonlinearities higher than the 2nd order are not foreseen in the UNK second stage.

Inaccuracies in the superconducting dipole fabrication lead to a random spread of even nonlinearities and appearance of odd ones. The requirements for the dipole fabrication precision stem from tolerances for r. m. s. spreads of nonlinearities exciting resonances near the working point. The admissible value of r. m. s. spreads for quadratic nonlinearity is $3 \times 10^{-4}$, $6 \times 10^{-4}$ for cubic nonlinearity, and $10^{-3}$ for the 6th order one. The precision of dipole fabrication and assembly needed to ensure such an accuracy is about 0.1 mm and seems to be attainable. That is why correction of nonlinear resonances is not foreseen in the UNK second stage.

With the stated fabrication precision, the relative value of the constant components of cubic nonlinearity and the skew gradient may turn out to be inadmissibly large. Therefore, provision is made for the relevant correction stations to be installed in the long matched straight sections. To adjust betatron frequencies, chromaticity, and the equilibrium orbit, the universal superconducting correctors placed near the main quadrupoles are to be used. These universal correctors contain dipole, quadrupole, and sextupole coils.

## 4. Space-Charge Effects

Each successive injection into the UNK second stage of $5 \times 10^{13}$ protons is followed by nonchoherent Q-shifts, $\Delta Q_r = 0.017$ and $\Delta Q_z = -0.013$ (Fig. 5), which are practically identical for all particles. Therefore applying magnetic field gradient correction, one can maintain noncoherent betatron frequencies within the given position with an accuracy better than 0.01, though the total noncoherent Q-shifts at the $6 \times 10^{14}$ proton cycle intensity can reach large values, $\Delta Q_r^{\text{noncoh.}} = 0.21$ and $\Delta Q_z^{\text{noncoh.}} = -0.15$. The field nonlinearity from space charge will result in ~ 0.01 betatron frequency spread, which is not a serious limitation.

At this intensity, coherent betatron frequencies of protons will differ from noncoherent ones: $\Delta Q_r^{\text{coh.}} = -0.3$ and $\Delta Q_z^{\text{coh.}} = -0.26$. The limiting intensity, determined by an intersection of one of the coherent frequencies with the integral resonance, is 1 to $2 \times 10^{15}$ protons/cycle.

The foregoing effects and related beam losses are important in the UNK first stage only. In the second stage, noncoherent Coulomb shifts are negligibly small and coherent ones, at the 400-GeV energy and $6 \times 10^{14}$ ppp intensity, are about -0.02.

To suppress transverse coherent beam instabilities, dampers with feedback from ~ 1 MHz band position pick-ups will be used. A peculiar feature of the UNK is an extremely fast development of wall instability. At the $6 \times 10^{14}$ ppp intensity, the time interval for instability to develop is 60 μsec in the first stage; i. e., it approximately coincides with the revolution time. This difficulty seems to be overcome, though it may lead to making the damping system more complicated. In the second stage this time is about 5 times larger and instability suppression is made easier.

A study of longitudinal instabilities arising during beam interaction with the resonant elements of the vacuum chamber merits serious consideration. Design of elements of the vacuum chamber (pick-up electrodes, vacuum branch pipes, flange fittings, etc. ) calls for a thorough control of their resonance frequencies and impedances.

## 5. Irradiation Problems of the Superconducting Ring

Estimates of high-energy radiation effects due to beam losses on the UNK superconducting coils showed that radiation heating can become a factor limiting the beam intensity.[5] Instantaneous beam losses lead to coil temperature increase and may initiate a quench. Heat energy flow, loading the cryogenic system, is a limiting factor for time-distributed losses. The admissible value for it should not exceed 1 W per 1 m of the superconducting magnet. Instantaneous beam losses are a most severe limitation under these conditions. The value of admissible losses is dependent on the particle energy and the nature of their time and space distribution. At the initial period of acceleration in the UNK second stage, the bound for admissible beam losses is $10^{10}$ ppp in order of magnitude.

With a $6 \times 10^{14}$ ppp accelerated beam, this level of irradiation of the superconducting magnets can be ensured only when taking special measures. The UNK project attaches a great importance to developing such measures; 70-GeV beam stacking and beam preacceleration take place in the first stage. This will afford an opportunity to decrease substantially the space-charge effects in the second stage. Besides, various methods of beam halo scraping and introduction of gaps in the beam azimuthal distribution will be employed in the first stage. This will enable an effective, close to 100%, beam transfer into the second stage. To localize possible beam losses during acceleration, in both UNK stages beam scraping stations are arranged in the long straight sections. Their large length makes it possible to put a sufficient number of collimators after these stations to suppress particle fluences to the level suitable for the normal operation of the superconducting magnets. In case of inadmissibly large beam losses, the accelerated beam will be extracted from the accelerator during one turn with the help of beam-abort systems into the outer stoppers.

There arise serious extraction problems since the radiation fluences due to the extraction septum losses cause intolerable energy releases in the superconducting magnets located downstream. A beam deflection at an angle of a few mrad with respect to the central orbit before the extraction septum is a most effective protection technique against these fluences. Due to the large length of the straight sections this allows a substantial decrease of superconducting element irradiation. The residual fluences can be suppressed to the required level by protection collimators.

Observation of the whole variety of measures makes the UNK superconducting magnet irradiation problems solvable.

## 6. Stages of the UNK Developments

For economic reasons, the first step of the UNK construction intends to achieve an operating mode with the field rise and fall time increased to 40 sec in the superconducting stage. At the price of decreasing the mean intensity, this will allow a substantial cut in the cost for the cryogenic system, rf accelerating system, the power supply system of the magnets, and of the whole complex. However, the complex of the engineering facilities is being designed keeping in mind the further development of the above-mentioned systems and increase of the mean intensity of the accelerator up to the maximum value.

Subsequent stages of the complex development intend to realize in the superconducting ring the storage mode of the maximum energy proton beam.

Collision of this beam with another proton beam accelerated in the opposite direction in the first stage of the UNK will permit an energy in the c. m. s. up to 2.2 TeV at a luminosity value of $10^{32}$ $\text{cm}^{-2}$ $\text{sec}^{-1}$.

A further energy step in p-p collisions up to 6 TeV in the c. m. s. can be obtained by construction in the tunnel of a 5 T constant field superconducting storage ring. At a $6 \times 10^{14}$ ppp intensity in each beam the luminosity value will be about $10^{32}\text{cm}^{-2}$ $\text{sec}^{-1}$. The length chosen for the straight section enables us to meet all the experimental requirements.

A possibility to achieve a 6-TeV energy in the c. m. s. without an additional superconducting storage ring is also under study. It is related to realization of proton - antiproton colliding beams in the UNK and application of the electron-cooling method. A preliminary study[6] showed that with a reasonable antiproton storage time one can achieve a luminosity of $10^{30}$ - $10^{31}$ $\text{cm}^{-2}$ $\text{sec}^{-1}$. Yet, a number of technical problems does not permit, at the moment, a firm conclusion on the advisability of undertaking the project. The UNK scheme is, however, such that additional elements necessary to produce, store, and preaccelerate antiprotons can be introduced into it in the future.

## 7. The UNK Status

Creation of the UNK superconducting dipole prototypes is one of the main problems. Presently, the Institute for Electrophysical Apparatus, CEN (Saclay) and IHEP are carrying out a joint program on development and production of 1-m long dipole models. Their efforts are aimed at the determination of superconducting cable requirements, and the choice of basic design and technological solutions for construction of magnets. IHEP has manufactured and put into operation a machine for cabling and built the equipment to test short samples. Preparation of the test equipment for 1-m long dipoles in a vertical dewar and in horizontal force-circulating ones is being completed. It is furnished with the necessary devices for critical parameter measurements, cryogenic and magnetic measurements, etc. To shorten test time, a system of data handling with an EC-1010 computer is being developed. The devices are manufactured by joint efforts of IHEP, Saclay, MRTI, and JINR.

The IHEP will produce equipment for magnetic, vacuum, and cryogenic tests of the UNK dipole prototypes. Model work on the UNK cryogenic system is envisaged. For these purposes a refrigerator with 400 W capacity at 4.5 °K will be employed. Joint work on cryogenic test equipment automatization is underway in collaboration with Saclay.

Other systems of the UNK are being developed and prototype work is underway. Equipment is being prepared to test rf accelerating systems, injection and extraction devices, devices for magnetic field correction, magnet power supply systems, etc. The development of the beam recapture station at 200 MHz has been initiated in common with JINR.

In the area of the planned location of the UNK, geologic work is being continued. Studies of the ground long-term stability are in progress.

The purpose of the research being carried out is to choose the most economic and rational solution for the UNK project.

## References

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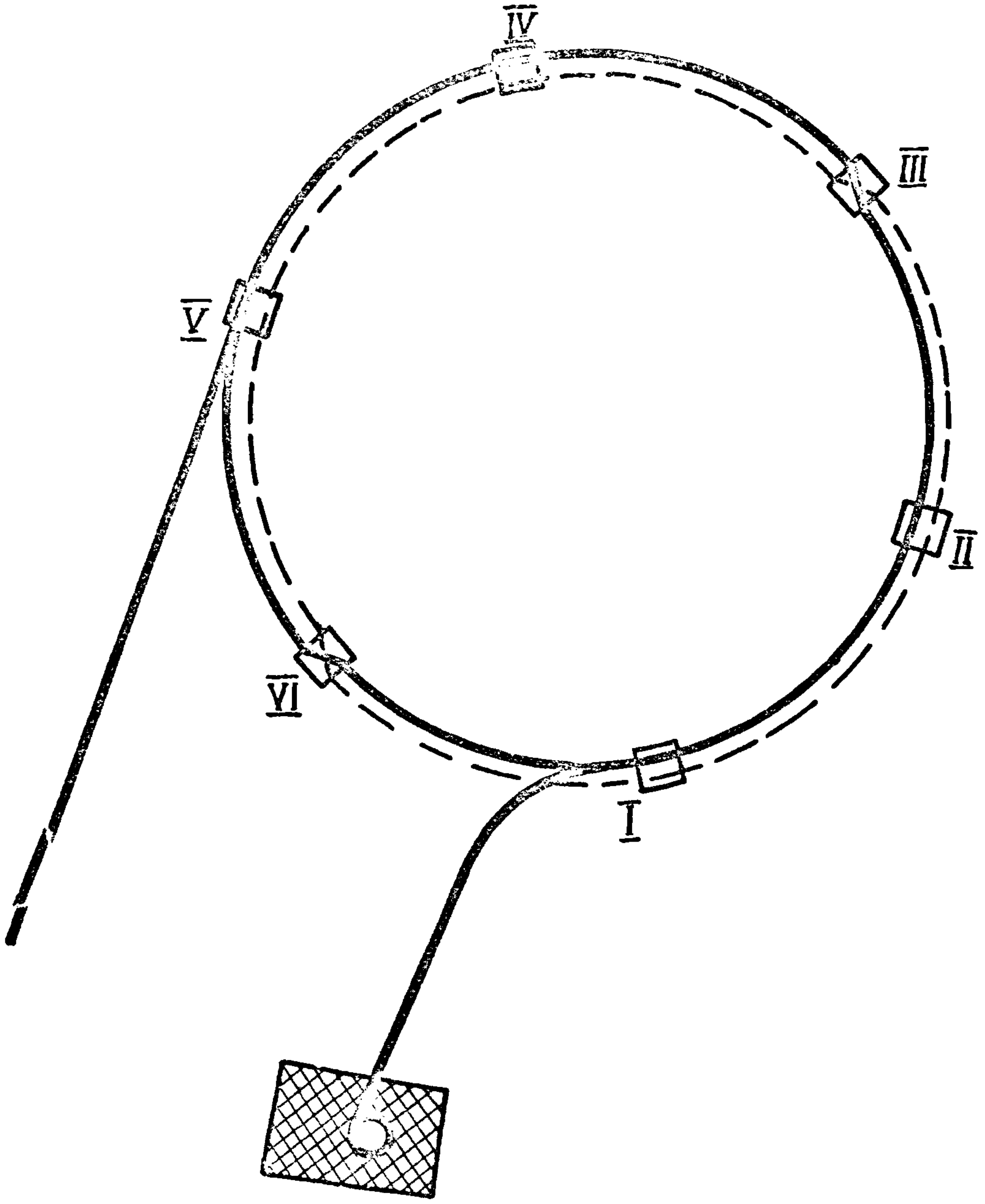

Fig. 1. The layout of the IHEP Accelerating and Storage Complex; the dashed line shows the superconducting storage ring.

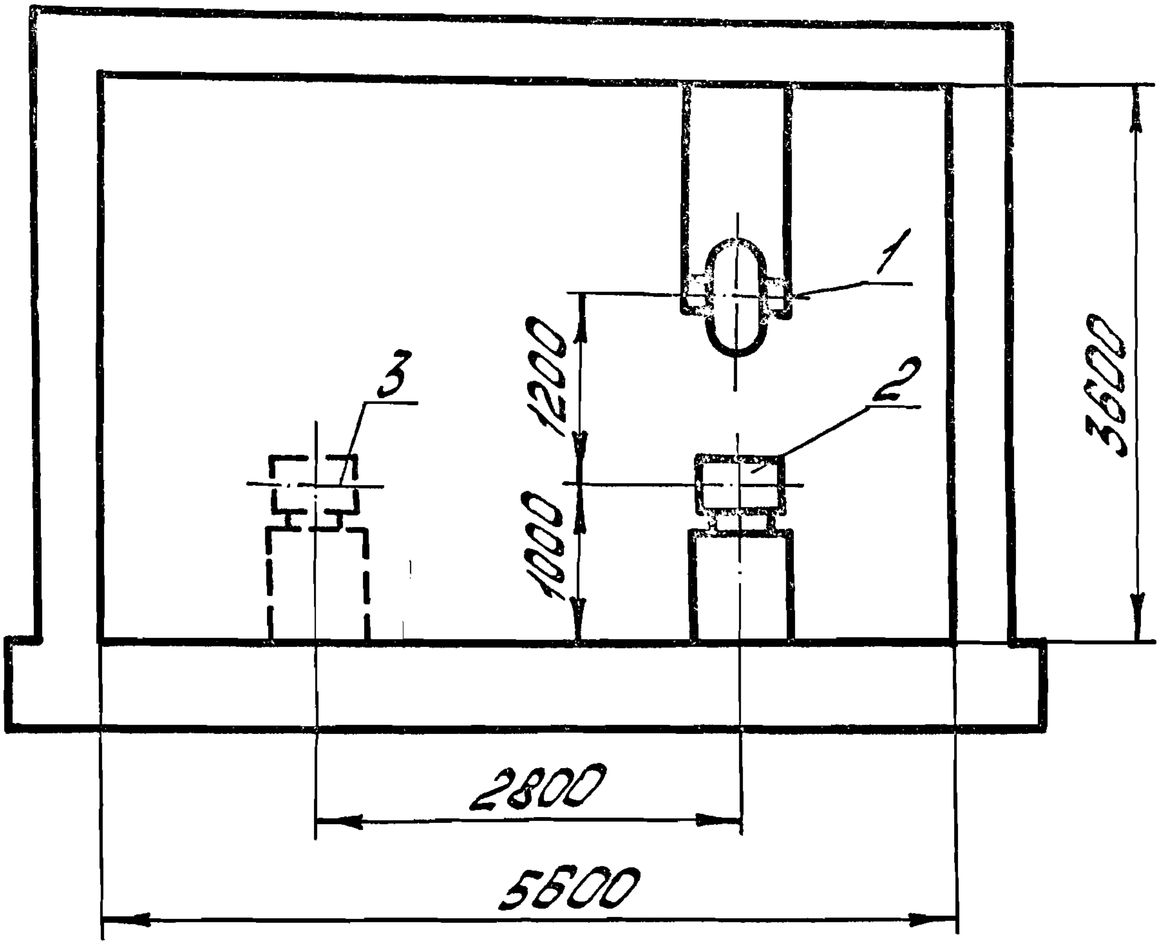

Fig. 2. The view of the UNK tunnel cross section: 1 denotes the first stage of the UNK; 2 denotes the second stage of the UNK; 3 is the storage ring.

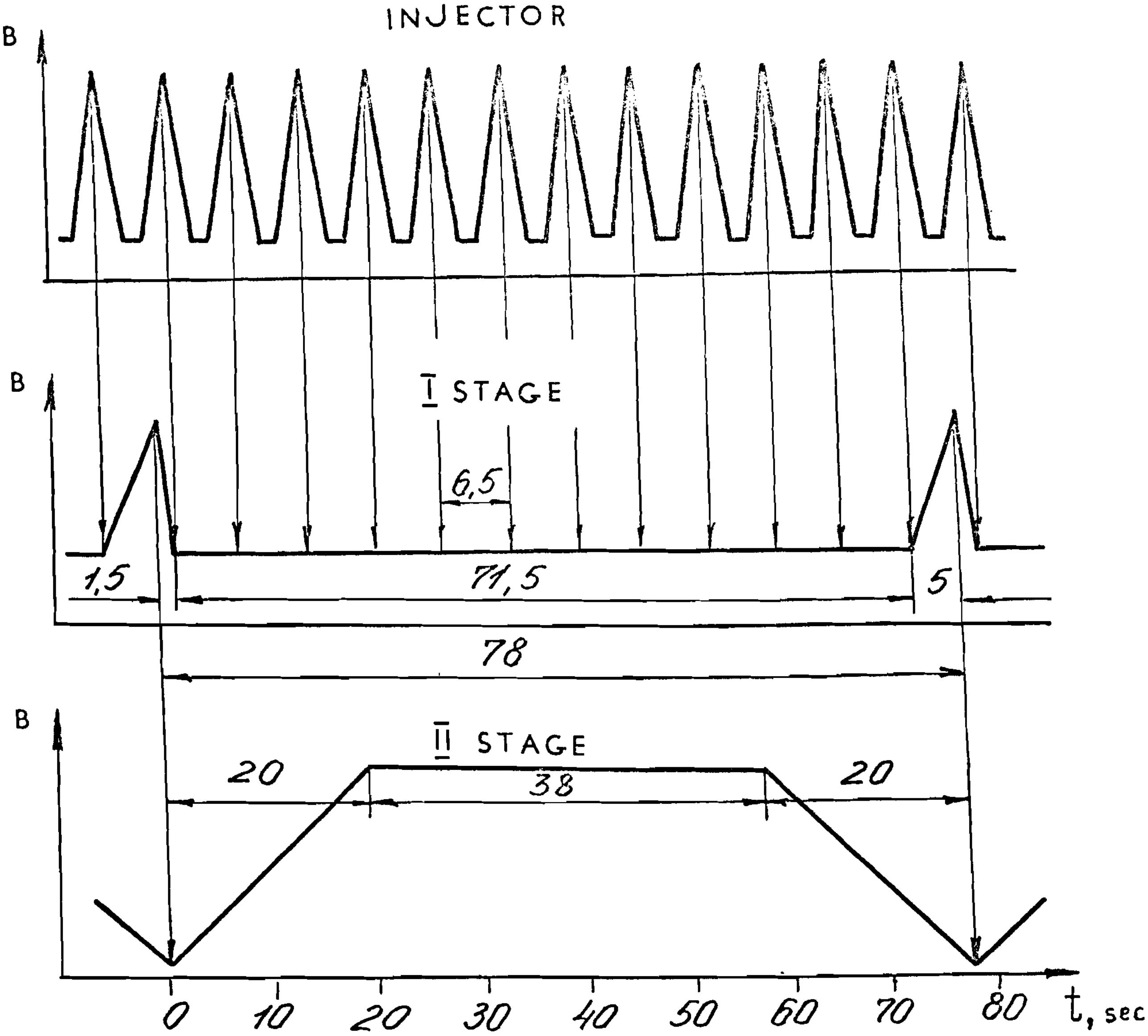

Fig. 3. The magnetic cycle of the U-70 injector and of the UNK first and second stages.

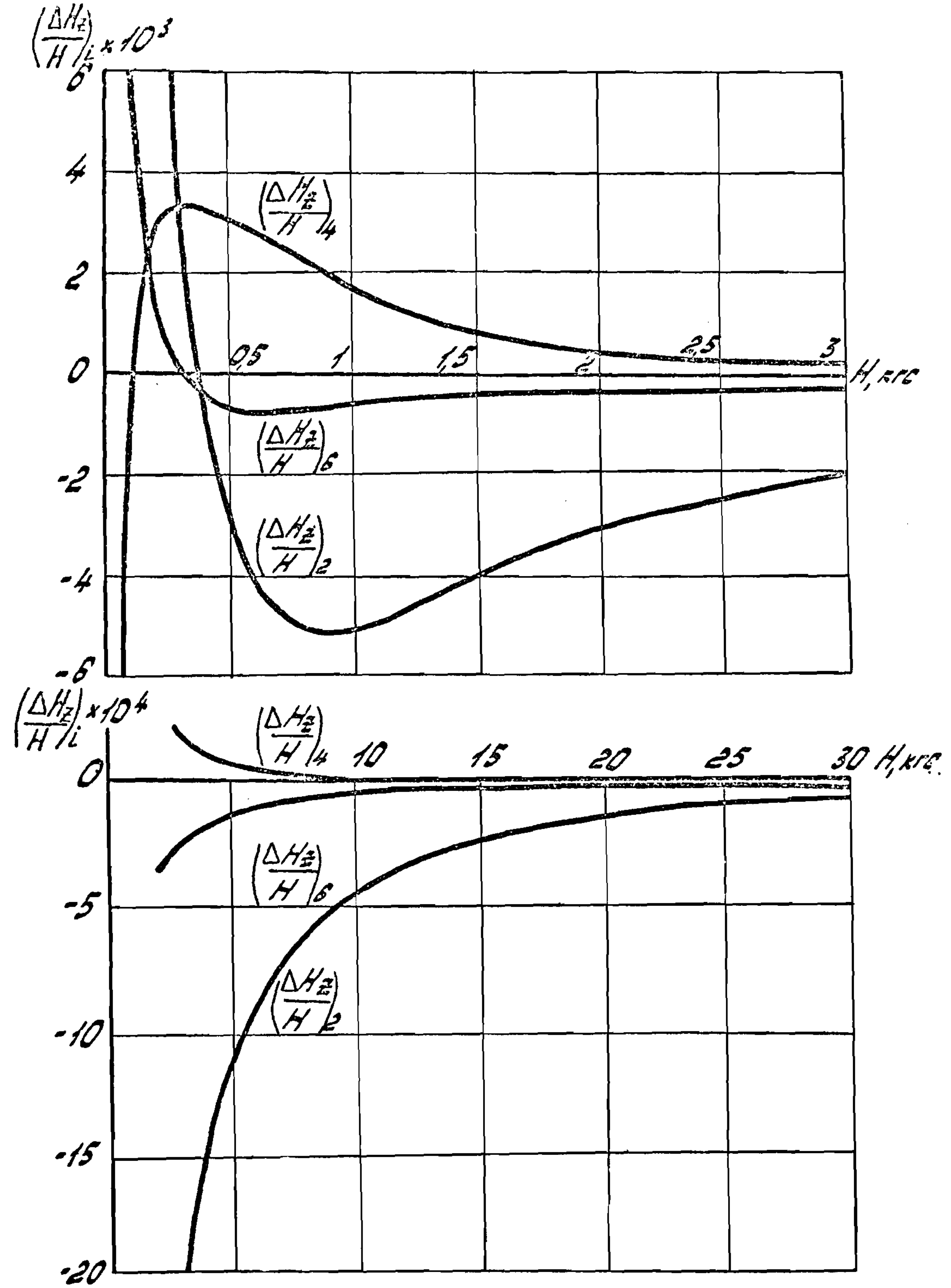

Fig. 4. The residual field nonlinearities as a function of the field value in the superconducting dipole center.

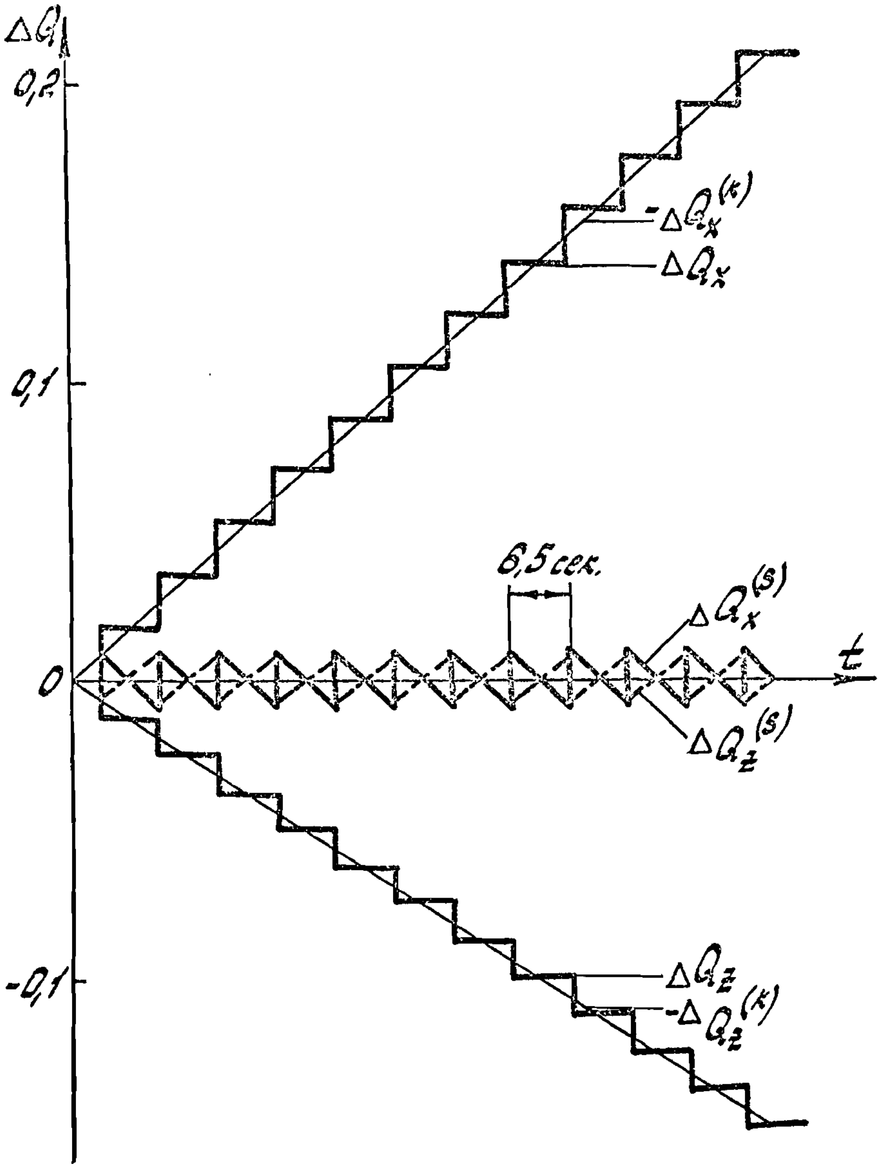

Fig. 5. The change of noncoherent betatron frequencies during beam stacking in the UNK first stage:

$\Delta Q_{r}$, z - noncoherent Coulomb shifts per injection pulse;

$\Delta Q_{r}^{(c)}$, z - betatron frequency correction;

$\Delta Q_{r}^{(s)}$, z - the total Q-shifts.