THE STATUS AND DEVELOPMENT OF THE UNK PROJECT

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The project of the IHEP Accelerating and Storage Complex (UNK) [1-5] envisages the possibility of accelerating protons up to 3 TeV with the beam extracted onto the fixed target and of the collision mode at 6 TeV in the c.m.s. The 1st stage of the UNK incorporating the 3 TeV machine with the system extracting the beam onto the fixed target is presently under construction.

The UNK is placed in the Ø 5.1 m underground ring tunnel having a circumference of 20.77 km. Figure 1 shows the ring cross section with the equipment layout. The presently existing 70 GeV proton synchrotron, whose intensity is planned to be upgrades up to $5 \cdot 10^{13}$ ppp, will be the injector into the UNK. The 1st stage of the UNK, UNK-1, i.e., the 400 GeV conventional machine, is the booster for the 2nd, supersonducting stage, UNK-2, but it can also run as a storage ring. Another superconducting ring, UNK-3, is intended for 3x3 TeV proton-proton collisions. The orbits of the 1st and 2nd stages actually coincide, whereas those of UNK-2 and UNK-3 interchange periodically going from the inner wall of the tunnel to the outer one or vice versa to intersect in 4 points of Matched Straight Sections (MSS) 2, 3, 5, 6, where the detectors for colliding beams may be placed. In addition to these MSS's (2, 3, 5, 6), for the experimental setups, each 490 m long, the project also envisages another two 800-m technological sections, MSS1 and MSS4. MSS1 will house the injection, loss localization and beam abort systems as well as the accelerating stations for all the stages. MSS4 is intended for the systems of extraction and beam transfer from UNK-1 into UNK-2 and UNK-3. A part of the MSS6 space is to be occupied by the reverse beam injection from U-70 into UNK-1 in the pp-colliding beam mode.

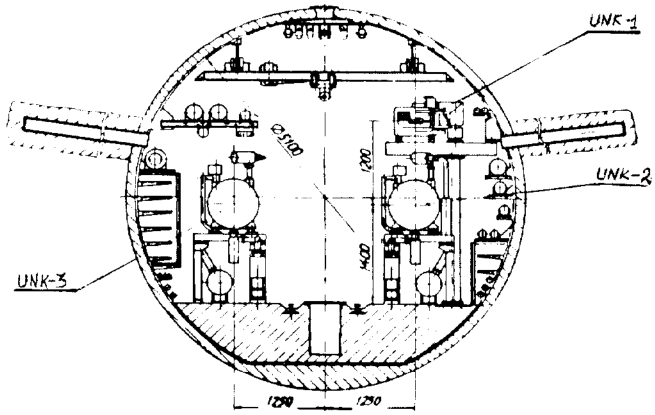

Fig. 1. The ring cross section with the equipment.

OPERATION IN THE ACCELERATION MODE

On rebunching at a frequency of the accelerating field of the UNK, 200 MHz, the U-70 beam is injected into UNK-1. Here an intensity of $6 \cdot 10^{14}$ ppp is stasked within 72 s by multiple, up to 12 times, injection. After 20-s acceleration on UNK-1 up to 400 GeV the beam is transferred into UNK-2 by single-turn injection to be accelerated further up to 3 TeV. The cycle of the superconducting stage, UNK-2, is as follows: 40-s field rise, 40-s flattop and 40-s drop. This cycle provides a mean intensity of $5 \cdot 10^{12}$ p/s. Three extraction modes from UNK-2 are foreseen: 40-s slow extraction, fast resonant extraction of 10 pulses, each lasting 2-4 ms, at an interval of 3 s and fast single-turn one for neutrino experiments. Fast resonant extraction can be carried out simultaneously with slow one. The 3d-order resonance at sextupole nonlinearity has been chosen as the operating one of the slow extraction system. The basic parameters of the fixed-target mode are presented in Table 1.

Table 1. The UNK Parameters in the Fixed-Target Mode

	UNK-1	UNK-2
Maximum energy, GeV	400	3000
Injection energy, GeV	65	400
Orbit length, m	20771.9	20771.9
Maximum field, T	0.67	5
Injection field, T	0.108	0.67
Total cycle duration, s	120	120
Acceleration time, s	20	40
Harmonic number of accelerating field	13860	13860
Total amplitude of accelerating voltage, MV	7	12
Maximum energy gain per turn, MeV	2.1	4.5
Transition energy, GeV	42	42
Betatron frequency (without special section of lattice taken into account)	36.7	36.7
Total intensity	$6 \cdot 10^{14}$	$6 \cdot 10^{14}$
Mean intensity, s^{-1}	$5 \cdot 10^{12}$	$5 \cdot 10^{12}$
Invariant transverse beam emittance, mm·mrad, not more than	150	200
Invariant longitudinal bunch emittance, MeV·m/s, not more than	100	120

In addition to beam extraction onto the external target of the experimental area, the 1st stage of the UNK envisages the experiment at the internal jet hydrogen target to be performed in MSS3 in the circulating beam of both UNK-1 and UNK-2.

COLLIDING BEAMS IN THE UNK

The further upgrading of the UNK is related to operation in the collider mode. Three different schemes of colliding beams in the UNK have been investigated: 0.4x3 TeV pp beams from UNK-1 and UNK-2 [2], 3x3 TeV $p\bar{p}$ beams in the ring of UNK-2 [4-6], and 3x3 TeV pp beams from the superconducting rings of UNK-2 and UNK-3 [3-5].

In the pp collider mode, particles are stacked according actually to the same scheme as in the acceleration mode. One of the requirements imposed on the colliding beams is that the bunch-to-bunch distance should be at least 9 m (30 ns). This can be accomplished by having inU-70 another 33 MHz recapture system (the harmonic number is 165). The frequency of the accelerating field in the UNK still remains equal to 200 MHz. Therefore when the beam is transferred into UNK-1, every sixth bucket will be filled. After UNK-2 is filled, the beam is retained there at the injection field. In UNK-1 the field polarity is reversed and other operations necessary to accelerate particles in the opposite direction are performed. After that the ring

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magnet is trained. According to the data available, 10-20 cycles are sufficient for that. Then the stacking procedure is repeated but the beam is injected into UNK-1 in the opposite direction with the help of the MSS6 injection system. On acceleration up to 400 GeV the beam can either be transferred into UNK-3 or used to arrange 0.4x3 TeV collision. Figure 2 shows the UNK operational scheme in this mode.

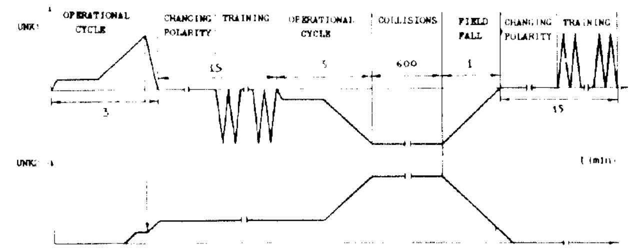

Fig. 2. Operational scheme of the 0.4x3 TeV UNK collider.

As in the accelerator mode, the U-70 beam is injected into UNK-1 12 times and is stacked there at an injection energy of 65 GeV. After that it is accelerated up to 400 GeV and injected into UNK-2 to be accelerated additionally up to 487.5 GeV and retained there for the time period required. Within this period of time field polarity reversal and other operations needed for beam acceleration in the opposite direction are carried out in UNK-1. After that a few magnetic cycles of the reverse polarity are performed to train the ring electromagnet, then the beam is injected from U-70 into UNK-1 in the opposite direction and stacked at its central orbit till the required intensity is reached. Then the beams of UNK-1 and UNK-2 are accelerated synchronously up to the maximal energy so that the ratio of their momenta at any time instant be 1:7.5. At this energy the optics of the collision ints is returned to obtain a low β-function, the beams are matched whereupon the collision mode starts. In this mode, the luminosity attainable in MSS6 can reach $1\cdot10^{33}$ $cm^{-2}s^{-1}$, where the underground experimental hall for the physics setup MMS (MultiMuon Spectrometer) is planned to be constructed. The MMS experiment is aimed primarily at the search for the t-quark at a pp-collision energy of 0.4x3 TeV (2.2 TeV in the c.m.s.). To guarantee the beam parameters required for this experiment, a special magnetic optics of MSS6 (fig.3). The chosen optics is such that the β-function in the collision area be 0.2 m in UNK-1 and 1.5 m in UNK-2. This is accomplished with the help of strong superconducting lenses Q_{39} and Q_{40}, whereas the distance between the edge ones is determined by the detector dimensions and is reduced to 16 m. To avoid having a large value of the beam envelope during injection in the lenses placed in the neighbourhood of the collision areas, the so-called "rubber optics" is applied, i.e., the gradients of the lenses are varied during the magnetic cycle.

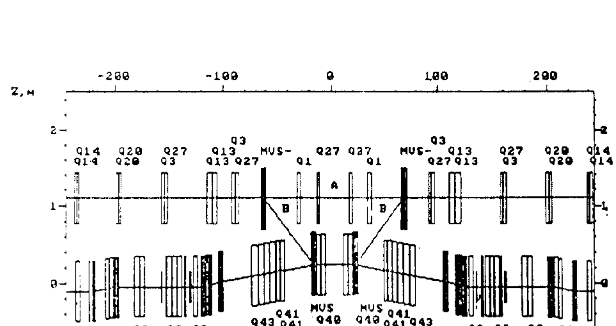

Fig. 3. Optical scheme of Matched Straight Section 6 for colliding beams.

The requirements imposed on the colliding mode are more stringent than those imposed on the fixed-target one. Therefore the UNK project has rather heavy demands on the value of the chamber coupling impedance, the level of noise in the accelerating system, injection and beam transfer mismatches.

Table 2

	UNK-1	UNK-2
Maximal energy, TeV	0.4	3
Injection energy, TeV	0.065	0.4
Number of bunches	348	348
Number of particles per bunch	$3\cdot10^{11}$	$3\cdot10^{11}$
Total number of particles per ring	$1\cdot10^{14}$	$1\cdot10^{14}$
Bunch-to-Bunch distance, m	49.5	49.5
Harmonic number of accelerating field	13860	13860
Maximal amplitude of accelerating field, MV	10	20
Beam acceleration time, s	100	100
RMS invariant beam emittance, mm·mrad	7.5	7.5
Longitudinal bunch emittance, m/ς MeV	120	150
Minimal amplitude function at the collision point, m	0.2	1.5
RMS beam diameter at collision point, mm	0.14	0.14
Bunch length at maximal energy, cm	65	36
Beam-beam tune shift	5.10^{-3}	$5\cdot10^{-3}$
Luminosity, $cm^{-2}s^{-1}$	$1\cdot10^{33}$	
Luminosity lifetime, h	≥ 10	
Total beam stacking and acceleration time, h	≤ 0.3	
Average number of events per collision	30	
Free area for detector, m	±8	

The UNK parameters will depend essentially on the characteristics of the U-70 beam. The fixed-target mode parameters are chosen proceeding from the design characteristics of U-70 and the booster. These characteristics are now somewhat worse than required. Yet, the collider mode requires a noticeable decrease of the bunch phase volume. To attain the parameters required, the following upgrading of U-70 is planned:

- replacement of the corrugated vacuum chamber by a smooth one with a view to bring the longitudinal coupling impedance down to 10 Ohm at least;
- upgrading the power supply system for the ring electromagnet;
- upgrading the field correction system;
- development of the H^- injection system;
- an order of magnitude decrease of the injection and beam transfer mismatches.

DEVELOPMENT OF SUPERCONDUCTING MAGNETS

The superconducting ring of the UNK consists of 2192 dipoles and 474 quadrupoles. The relevant operational conditions in the acceleration and colliding beam modes impose rather stringent requirements on the value and quality of the bore field, heat load on the cryogenic system, temperature reserve necessary for the reliable operation of the UNK which must be met during the development of superconducting magnets. The nominal dipole field is chosen to be 5 T and the gradient of the quads of the regular lattice is 996.11 T/m. To ensure high-efficiency slow and fast resonant extraction the good quality field in the radial direction should be at least ±3 cm. The basic characteristics of the superconducting magnets for the UNK were chosen proceeding from these requirements.

The design of dipole and quadrupole magnets has been repeatedly described and discussed [5,8]. Its basic part is a two-layer shell-type cold iron coil. Figures 4,5 show the cross sections of the dipole and quadrupole magnet for the UNK, respectively. The magnets

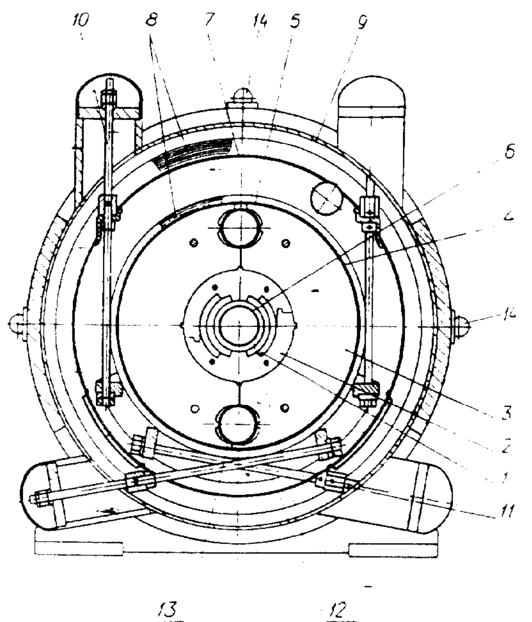

Fig. 4. Cross sectional view of a SC dipole assembled in a force-circulating cryostat: 1 - coil, 2 - collars, 3 - magnetic shield, 4 - helium vessel, 5 - two-phase helium pipe, 6 - ion pipe, 7 - thermal shield, 8 - superinsulation, 9 - vacuum vessel, 10 - suspension, 11 - extension rod, 12 - single-phase helium, 13 - two-phase helium, 14 - geodetic marks.

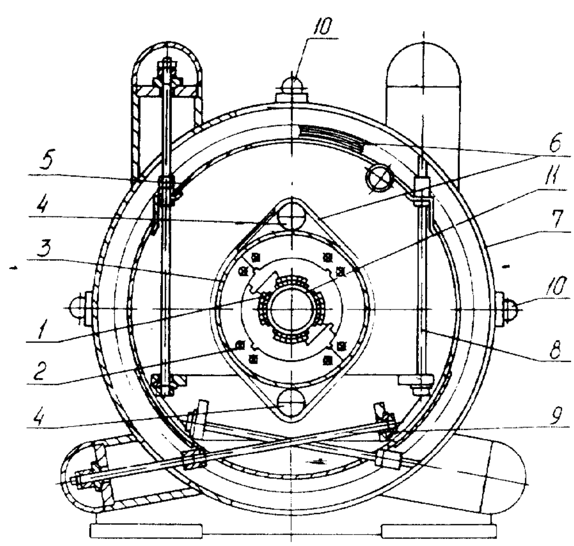

Fig. 5. Cross sectional view of a SC quad assembled in a force-circulating cryostat: 1 - coil, 2 - magnet shield, 3 - helium vessel, 4 - two-phase helium pipe, 5 - thermal shield, 6 - superinsulation, 7 - vacuum shell, 8 - suspension, 9 - extension rod, 10 - geodetic marks, 11 - ion pipe.

are produced from the same superconducting cable of "zebra" type, consisting of 19 0.85 mm in diameter strands, each containing 8910 6 thick Nb-Ti filaments embedded into a copper matrix. The critical current density at 5 T and 4.2 K is at least $2.3 \cdot 10^5$ A/cm^2.

A batch of 10 full-scale SC dipoles has been manufactured and tested. This batch was used to work out the details of the design and technology, to choose and try out the major structural materials. The collars of the magnets were manufactured from 2 mm thick sheet austenitic stainless steel of quality 05X20H15AI6 possessing a low magnetic susceptibility at helium temperatures. The magnet shield was manufactured from 3 mm thick sheet electric steel of quality 2081, havimg a lower coercive force. The collars and laminations of the shield were manufactured with the help of precision press tools of the Swiss company "Feintool".

The study of the SC dipoles manufactured of new structural materials showed the reproducibility of the basic properties from magnet to magnet.

The results on training and ramp rate properties of the SC dipoles measured in force-circulating mode of cooling with single-phase helium are given in figures 6, 7. As is seen from these figures, the critical current of the SC dipoles trained with ramp rates of up to 500 A/s exceeds the maximum operating current in the UNK cycle, i.e. 5 kA. The maximum bore field after training reaches 6.4-6.6 T.

The a heat releases in the coil and in the elements of the dipole and static heat load on the helium volume were measured. The ac loss measured in the UNK cycle for the 100 A/s ramp rate was 700 J per magnet, corresponding to the mean power in the cycle of 6 W. The total static heat influx was 5 W per magnet, out of which about 1 W accounts for that on the support system. So, the total contribution from a SC dipole into the value of the heat load on the cryogenic system does not exceed 11 W in the acceleration cycle.

Figure 8 presents the results on measuring the transfer function B/I of a full-scale dipole versus the current in the coil. As seen from the measurements, the reduction of the transfer function due to magnet shield saturation at the maximum current of 5 kA is 0.7%, which is in a good agreement with the calculations done with account of the magnet shield properties.

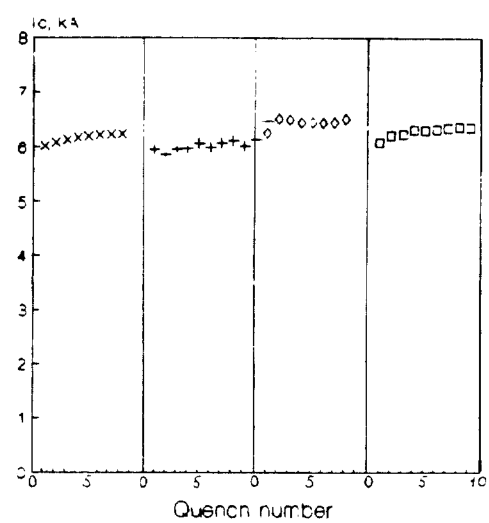

Fig. 6. Training curves for SC dipoles: <- DDXB1, o - DDXB2, Δ- DDXB6.

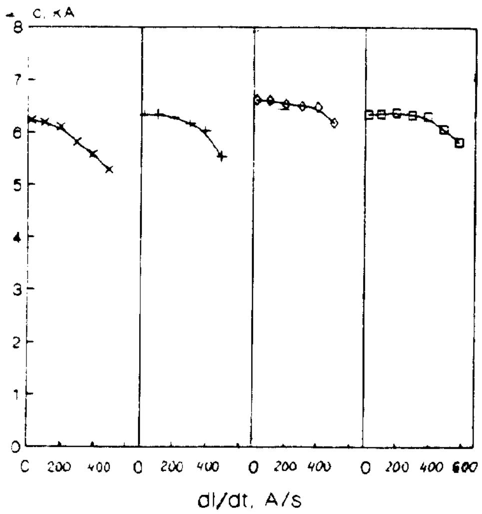

Fig. 7. Ramp rate characteristics of SC dipoles: o - DDXB2, □ - DDXB4, Δ - DDXB6.

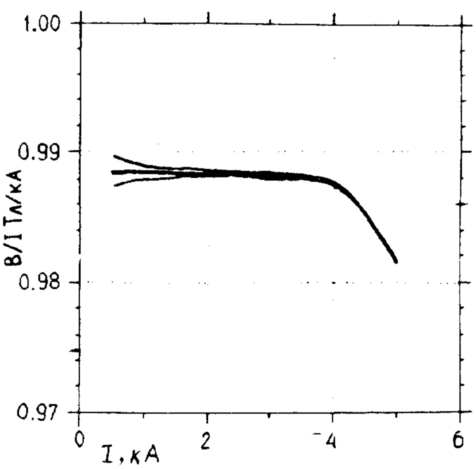

Fig. 8. Transfer function of a SC dipole versus the coil current.

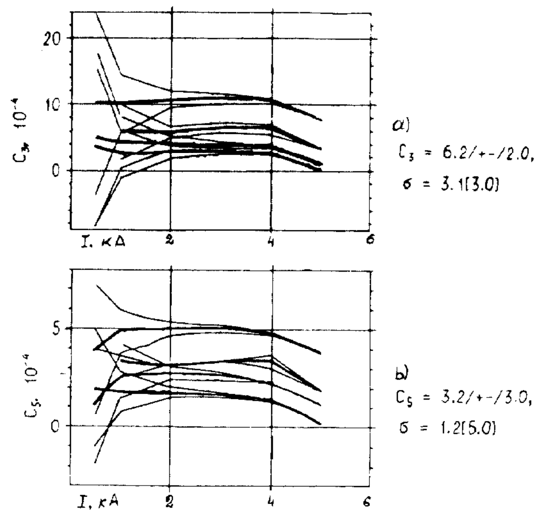

Fig. 9. Bore field nonlinearities of 4 SC dipoles at a radius of 3.5 cm versus the coil current.

The difference in the transfer function and sextupole nonlinearity during current input and output is determined by the hysteresis magnetization of the current element and is in a good agreement with the calculation.

Repeat tests of a full-scale SC dipole were done a year later after the first ones. Their results demostrated a good reproducibility of the major properties of the SC dipole for the UNK.

Three short-scale and two full-scale SC quadrupole prototype were manufactured. All models were produced of new structural materials and the SC cable having the same properties as the one used for SC dipole prototypes. Every short model was 90 cm long, that allowed one to eliminate the influence of saturation effects in the end parts of the magnet shield on the behaviour of field nonlinearities in the central cross sections.

Figures 10, 11 present the results on training and ramp rate property of a full-scale SC quad model, obtained in the force-circulating mode of cooling with single phase helium. As is seen, the critical current of such a quad exceeds essentially the maximum operating current in the UNK cycle.

Figure 9 shows the results on measuring the values of normal constituents of field nonlinearities, sextupole (C_3) and decapole (C_5), in 4 dipoles. The nonlinearities were measured at a radius of 3.5 cm versus the coil current.

As is seen from the curves, the nature of nonlinearity variation versus the value of the current is the same for all the dipoles measured. The effect of magnet shield saturation in the region of high currents corresponds to the calculation. The variation of nonlinearities in the cycle due to ponderomotive forces is within the limits of $(1\text{-}2)\cdot 10^{-4}$ and is guaranteed by the optimal choice of the coil preload and of the collard rigidity. The spread in nonlinearities from magnet to magnet is within the tolerable values.

The nonzero values of C_3 and C_5 is explained by the effect of collars magnetization and deviation of the coil geometry from the design one. Since the additions caused by collars magnetization as well as the systematic errors in the coil geometry are independent of the level of the current, they will be compensated by introducing corrections into the geometry of the coils after the statistics on the results on measuring a series of SC dipoles is accumulated.

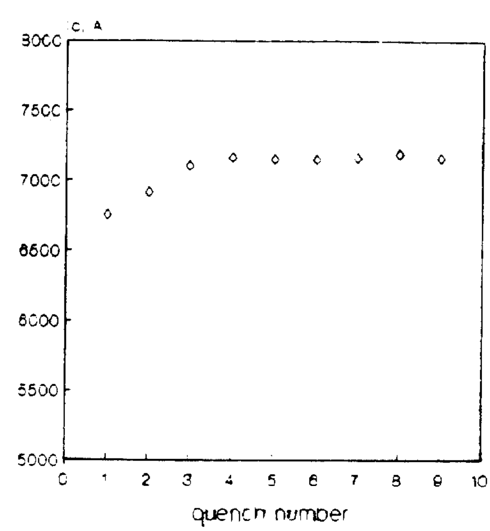

Fig. 10. Training curve of SC quad model.

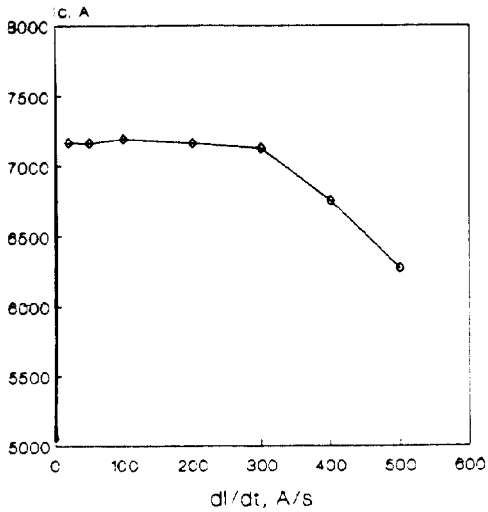

Fig. 11. Ramp rate characteristic of SC quad model.

The ac loss in a SC quad measured in the UNK cycle was 60 J/m. This means that the contribution from the ac heat release in a full-scale 3-m quad into the heat load on the cryogenic system in the UNK cycle is 1.65 W per magnet. As estimated from the results on measuring the static heat leaks in SC dipole models, the static heat leak in SC quads will make up 3 W per magnet. So, the total contribution from a SC quad into the heat load on the cryogenic system in the acceleration cycle will be about 5 W.

The measured ratio of the quad field gradient and dipole field is 19.46 m^{-1}. The variation in the ratio of the SC quad field gradient to the SC dipole field in the cycle with account of the coil magnetization and magnet shield saturation does not exceed the admissible value, $\pm 0.1\%$.

The results on measuring the bore field nonlinearities of a SC quad suggest that the effect of magnet shield saturation on variation in the values of G/I and C_6 in the range of high current is not essential and agrees with the calculations. The difference in the value of G/I and C_6 during current input and output is related to the effect of the hysteresis magnetization of the current element and is also in a good agreement with the calculations.

The systematic shift of the measured nonlinearities with respect to the design values does not exceed $2 \cdot 10^{-4}$ for C_6 and $4 \cdot 10^{-4}$ for C_{10} and is within the tolerances. The measured values of the forbidden C_n and skew S_n field nonlinearities do not exceed $\pm 2 \cdot 10^{-4}$ for $n \leq 13$ and are also within the tolerances pointing to a high quality of magnet assembling.

The SC dipoles and quads for the regular lattice of the UNK were developed as a result of the studies performed. The properties of all SC magnets satisfy the requirements imposed on the bore field value and quality, on the level of ac heat releases in the coil and elements of the design and on the value of static heat leaks into the helium vessel of the cryostat.

The analysis of the magnetic measurements show that in the operating cycle of the UNK the values of sextupole and octupole nonlinearities may be corrected by the field correction system. As to higher-order and edge nonlinearities, these are within the tolerances in the beam stacking, acceleration and extraction modes.

According to the measurement results, the heat load on the cryogenic system of the UNK in the acceleration cycle will be about 33 kW. It will be twice as low in the colliding beam mode. This means that the available power of the cryogenic system of the UNK, 60 kW, will allow us to support the operation of one superconducting ring in the acceleration mode or of two superconducting rings in the collider mode. The temperature reserve of the SC magnets allows the reliable operation of the ring SC magnet of the UNK at a liquid helium temperature of 4.4-4.6 K both in the acceleration cycle and during the e ergency removal of the energy stored.

In 1990 the production of a pilot and industrial batch of SC dipoles and quads was started with a view to attain the required reproducibility of magnets when their serial production begins. By now 10 out of 100 have been manufactured and tested. The serial production is planned to be started in 1992.

STATUS OF THE UNK CONSTRUCTION

The construction of the southern part of the ring tunnel and injection beam line is over, the work on the preparation for the equipment is underway. The construction of the surface technological buildings designed to house the power supply, cryogenic and control systems is going on.

The equipment for UNK-1 is presently in serial production. All the electromagnetic and vacuum equipment for the 2.7 km long injection beam line has been manufactured. More than 1000 warm magnets and 11000 m of the vacuum chamber have been supplied, the equipment for the accelerating system and for the power supply system of the ring electromagnet is being manufactured.

There is a special 10000 m^2 building where the equipment is tested and prepared for assembling. The assembling of the electromagnetic equipment in the injection beam line is to start at the end of this year. The rate of the work being carried out confirms the feasibility of having UNK-2 constructed in 1994-1995 and of starting running it in together with the experimental setups in extracted beams in 1995-1996. The 0.4x x3 TeV colliding beams and the MMS setup running in the experimental hall of MSS6 may be ready in 1997.

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