Development and Study of the UNK Superconducting Quadrupole Magnet

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Abstract

IHEP has developed and tested full-scale prototypes of superconducting quadrupole magnet for the regular part of the UNK main-ring lattice. This paper presents description of design and technological features of these magnets, and the results of their tests.

1 INTRODUCTION

The superconducting ring of the second stage of UNK consists of 474 superconducting quadrupoles [1]. During proton beam acceleration from 400 GeV to 3000 GeV the field gradient in the main SC quadrupoles increases from 13 T/m to 97 T/m, quadrupole magnetic length being 2967 mm. Variation of the main quadrupole gradient through the cycle has to be properly tied to the field rise in the main dipole magnets.

Four full-scale prototypes of the UNK main SC quadrupole have been manufactured and tested. These magnets allow one to examine the design solutions and materials chosen, to establish production technology and to study the reproducibility of the quadrupole major parameters. The magnetic measurement equipment and procedure were also examined. The obtained results are in a good agreement with the calculated ones. They allow one to make the conclusion on acceptability of the developed design of quadrupoles from the viewpoint of their operating parameters and acceptability to mass production.

2 SC QUADRUPOLE DESIGN

The design of the UNK main SC quadrupole has been described elsewhere in papers [2], [3]. Major elements of the design are a two-layer coil with 80 mm bore and a cold iron yoke.

The quadrupole coil consists of four two-layer blocks. Inner and outer layers of each block are made of a one-piece SC cable without any interlayer joint. To provide the required bore field quality, the inner layer of each block has two spacers.

The quadrupole coils are collared with stainless-steel collar laminations. The geometry of the quadrupole collars is such that the coil could be collared following the technology and using the equipment for dipole collaring. The collars are fixed by means of pins and holes in the collars and the keys put into the grooves.

The iron yoke is assembled around the collared coil. The position of the collared coil inside the yoke is fixed by four lugs. The main SC dipoles and quadrupoles are to be connected in series. Therefore, the dimensions of the iron yoke in SC quadrupole were chosen so as to provide the constant ratio of the quadrupole field gradient to dipole field throughout the operating cycle. The yoke length in the quadrupole is equal to the coil one.

The cable for the UNK SC quadrupoles is a Rutherford-type SC cable the same as for the UNK SC dipoles [4]. It consists of 19 strands. The cable transposition pitch is 62 mm. The cable has a keystone cross-section with the bases 1.30 mm and 1.62 mm for the inner layer and 1.33 mm and 1.59 mm for the outer one. The cable width is 8.5 mm.

The cable is manufactured of composite SC wires 0.85 mm in diameter, containing 8910 Nb-Ti filaments, each 6 μm in diameter, and embedded into a copper matrix. The packing factor is 0.42. The twist pitch of SC filaments is 10 mm. The minimal critical current density at 5 T and 4.2 K is $2.3 \cdot 10^5$ A/cm^2.

Beam pipe and collars are made of a stainless steel which has a low and constant magnetic susceptibility at helium temperatures in the range $0-5$ T of magnetic field. Each collar lamination is 2 mm thick. The magnetic shield is made of a 3-mm sheet low-carbon steel. The chemical content and magnetic properties of the above steel at helium temperatures are described in paper [5].

The quadrupole cryostat consists of a vacuum vessel, thermal shield and helium vessel with the coil assembly and magnetic shield placed inside it. The helium vessel is fixed to the vacuum vessel by means of titanium vertical suspensions and horizontal extension rods placed in two cross sections along the magnet. Longitudinal displacements of the helium vessel are avoided with anchor extension rods fixing the central cross section and allowing a free motion of the magnet ends in thermal cycles. The thermal shield is manufactured of aluminum and cooled by 80 K liquid nitrogen flow. The helium vessel and nitrogen shield are covered by 10 and 40 layers of superinsulation, respectively.

The SC quadrupole magnets are cooled by a $4.4-4.6$ K single-phase helium flow. A part of this flow goes through the coil while another one is by-passed through the channels inside the magnetic shield. There would be no heat exchange between single- and two-phase helium flows in the UNK SC quadrupole.

3 TECHNOLOGICAL FEATURES

Four full-scale prototypes of the main UNK SC quadrupole were manufactured. All magnets were made of 19-

strand SC cable of "zebra" type, 9 of which were coated by $Sn + 5\% Ag$ alloy, while the rest ones had a natural oxide on their surfaces. The cable for SPKM1, SPKM2 and SPKM4 was insulated by two layers of 20 μm thick polyimide film and by a layer of fiberglass tape impregnated with an epoxy compound. The cable for SPKM3 was insulated by three layers of 30 μm thick polyimide film. The outer layer of the polyimide film had a gluey coating of $5 - 10$ μm thickness on both sides.

The return bus used for series connection of the magnets in the machine was installed in the outer layer of SPKM3 and SPKM4. It was made of 19-strand cable having the same cross section as the cable of the coil outer layer. It was insulated by 8 layers of 20 μm thick polyimide film with a bonding coating.

The coils of SPKM1 and SPKM2 were collared by means of the collars having rectangular grooves and keys. The collars with tapered keys and grooves were used in SPKM3 and SPKM4. This allows one to decrease the collared coil deformations and forces during collaring.

To restrict longitudinal motion of the coil ends in the cycle under ponderomotive forces, the 25 mm thick end plates were used in SPKM4. They were pressed to the coil assembly and then welded to the helium vessel.

4 TEST RESULTS

The full-scale prototypes of the UNK SC quadrupoles were tested at a magnet test facility in force-circulating cooling mode with a single-phase helium at 4.4 K. SPKM2 was damaged at the 1-st quench because of short in the coil.

Figure 1 shows the results of training the UNK SC quadrupoles. During the 1-st quench the critical current was approximately the same for all magnets, 6750 A. This value is well above the maximum operating current in the UNK cycle, 5250 A. After a short-term training the critical current of the SC quadrupoles reached the short sample limit. The repeated tests of the magnets after a warmup-cooldown cycle demonstrated that all SC quadrupoles do remember the maximum current attained during training.

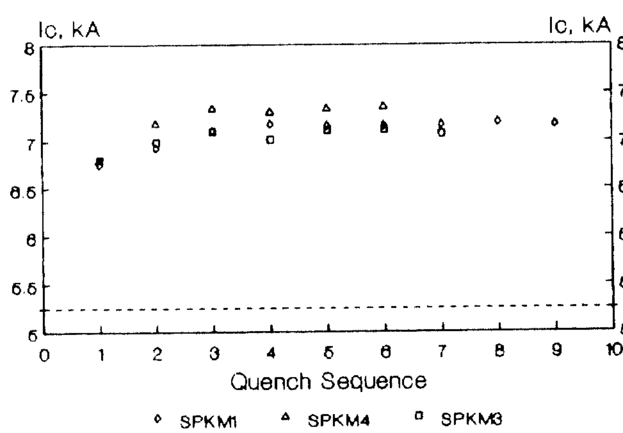

Figure 1: Results of training the UNK SC quadrupoles.

Figure 2 shows temperature dependence of critical current of the UNK SC quadrupoles after training. As is seen, the quadrupole critical current in the measured temperature interval exceeds the maximum operating current in the UNK cycle. The temperature reserve of the main SC quadrupoles at operating temperature in UNK, 4.6 K, is at least 1.2 K.

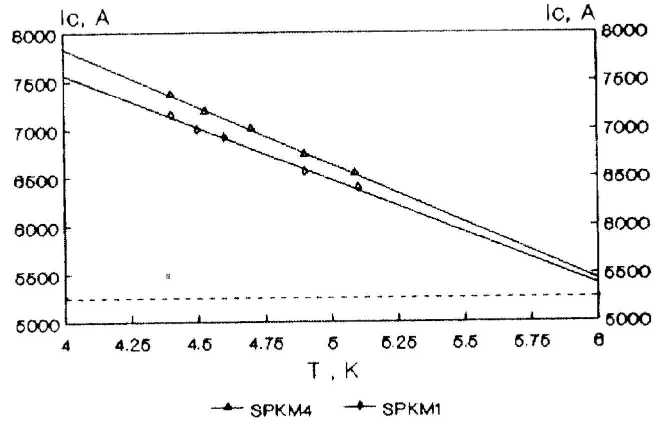

Figure 2: Temperature dependence of the quadrupole critical current.

Figure 3 shows ramp rate characteristics of the UNK SC quadrupoles. The decrease of the quadrupole critical current at a ramp rate of 500 A/s does not exceed 9% of the maximum critical current.

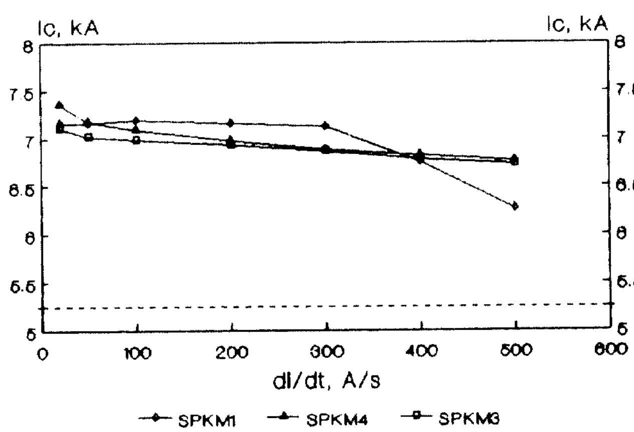

Figure 3: Ramp rate characteristics of the UNK SC quadrupoles.

Figure 4 shows the results of measuring AC losses in the UNK cycle with the linear current change inside the interval 600 – 5250 – 600 A against the current ramp rate for the full-scale SC quadrupoles. AC losses measured in the UNK cycle with the current ramp rate 120 A/s were 220–280 J, corresponding to an average power in the UNK cycle of about 2 W.

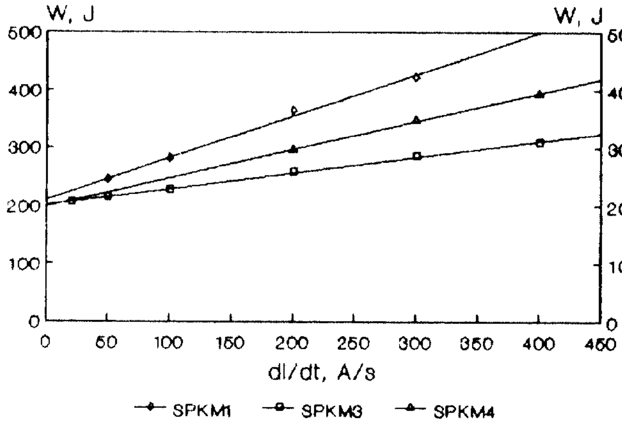

Figure 4: AC losses in the UNK SC quadrupoles.

Table 1 presents the results of measuring normal and skew integral field nonlinearities of the full-scale prototypes of the main UNK SC quadrupoles at a 35 mm bore radius for 3 kA current. These nonlinearities are normalized by the integral dipole field [6], [7].

Table 1: Normal (C_n) and skew (S_n) integral multipole coefficients, 10^{-4}.

	SPKM1		SPKM3		SPKM4	
n	C_n	S_n	C_n	S_n	C_n	S_n
3	0.1	0.4	0.9	0.8	-0.5	-1.9
4	-0.1	-0.3	0.9	-1.0	2.0	-1.1
5	-0.3	-0.3	1.4	-1.9	-2.1	1.6
6	-0.5	-0.1	0.9	-1.0	-0.5	0.8
7	0.2	-0.1	-0.5	-0.1	2.1	0.2
8	-0.3	0.0	-0.6	-0.4	0.7	-2.7
9	0.0	-0.2	2.1	0.0	-4.4	1.0
10	0.0	0.0	3.6	-1.7	10.4	3.0

An analysis of the data presented in Table 1 shows that all major normal and skew nonlinearities of the magnetic field in the quadrupole bore are small enough. They would not have any noticeable effect on particle motion stability in comparison with nonlinearities of the UNK dipoles. This confirms the possibility to ensure the required symmetry of the collared coil with the chosen technology of assembling the UNK SC quadrupoles.

No noticeable effect of the quadrupole design features mentioned above on the quadrupole quench performance and field quality was observed. The developed quadrupole design will allow one to ensure the reproducibility of the magnetic field parameters during mass production.

Magnetization of the quadrupole coil brings contribution only to the values of the field gradient and to C_6 at low current levels. At beam injection its contribution is 1.5 times smaller than the tolerance and is in a good agreement with the calculation. The relative role of the coil magnetization effect rapidly devaluates with current in magnet increasing. The magnetic shield saturation affects only the field gradient at currents above 3 kA. The gradient reduction caused by the iron saturation effect at 5 kA is equal to 0.8%. This is in a good agreement with the calculation as well. Taking into account the results of measuring the SC dipole transfer function ([6], [7]), the variation of ratio of the quadrupole field gradient to dipole field in the cycle would not exceed 0.1%.

The magnetic lengths measured for SPKM3 and SPKM4 at 3 kA current were found to be 2953 mm and 2959 mm, respectively. Finally, the magnetic length of the UNK main SC quadrupole will be chosen proceeding from the results of magnetic measurements of the pilot-industrial batch of the UNK SC dipoles [7] and quadrupoles.

5 CONCLUSIONS

Results of studies of the full-scale prototypes of the UNK main SC quadrupole show that all their parameters in both operating and emergency modes do satisfy the requirements imposed. All quenches induced by mechanical perturbation, AC losses and temperature variations occurred at currents much higher than the operating ones in the UNK cycle. The temperature margin of the magnets allows one to ensure their reliable operation during beam acceleration and extraction, as well as during the emergency removal of the stored energy. The level of AC losses in the magnets satisfies the requirements imposed on the UNK cryogenic system. The bore field quality is acceptable from the viewpoint of the beam motion stability in the UNK cycle. Developed design allows one to ensure the required reproducibility of the major quadrupole parameters during their mass production.

6 REFERENCES

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