Design and Tests of UNK Superconducting Correction Magnet Models

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Abstract

At present NIIEFA is designing superconducting correction magnets for UNK. UNK magnetic field correction system includes about 1500 various correction windings: dipole, quadrupole, sextupole and octupole. The magnet consisting of 3 concentric saddle type multipole coils with common iron yoke ("*spool-piece*"type) was selected as basic one. Each of the correction coils has the next optical force: sextupole—600 (T/m^2)·m, quadrupole—5.5 (T/m)·m, dipole—0.68 T·m. Total length is about 1.6 m, operating current $\leq$20 A. The 4 full scale models of the basic correction magnet with different types of conductors and various technique of winding have been built. This report describes the main design parameters of models and the particulars of their construction. The results of manufacturing and tests (quench behavior and magnetic field measurements) are discussed.

I. INTRODUCTION

The basic element of magnetic field correction system of second UNK stage is a superconducting corrector with 70mm diameter aperture. It has 3 correction windings: dipole is to correct the orbit, quadrupole is to correct the betatron frequencies and sextupole is to correct the chromaticity and to compensate the sextupole errors from the main dipoles. These windings has optical forces of 0.68 T·m, 5.5 (T/m)·m and 600 (T/m^2)·m accordingly. The "*spool-piece*" conception [1] was chosen as basic. A gabarit size limitations and, particularly, low operating current ($\leq$ 20A) had led to the necessity of preliminary modelling. Four full-scale models of the correction magnet SCM-1 (2 models), SCM-3 and SCM-4 with different construction of the coils has been designed, built and tested. About 400 correction magnets will be made for the second UNK stage and therefore the big attention was paid to the fabrication technique in series production conditions.

II. THE MAIN PARAMETERS AND ASSEMBLY OF MAGNET

Except the difference of coils design, all three models were the same arrangement and similar construction. They consist of 3 concentric saddle shaped windings enclosed in the common cylindrical laminated iron yoke with helium channels on its outer surface. The 4mm stainless steel shell makes outer wall of helium vessel and serves, at the same time, as mechanical bandage. The cross-section of the models is shown in figure 1.

Superconducting wire parameters are given in table 1.

Table 1: Parameters of wire

Diameter of wire (mm)	0.3
Superconductor	NbTi alloy
Matrix	Cu
Cu / NbTi ratio	1.7
Number of filaments	150
Diameter of filament (m)	15
$R_{300}/R_{4.2}$ ratio	>100
Critical current density at 5 T (A/m2)	(2.0–2.2)·10^9
Critical current at 5 T (A)	52-57

Chosen wire has a big margin of the critical current (operating current of all models is between 12–20 A in the field, up to 1.3 T). It had been done to avoid the training up to operating current that was one of the main requirements.

The main dimensions of models are given in table 2.

In table 2 the turns density is a number of turns per unit of the coil cross-section. The meanings of the short sample

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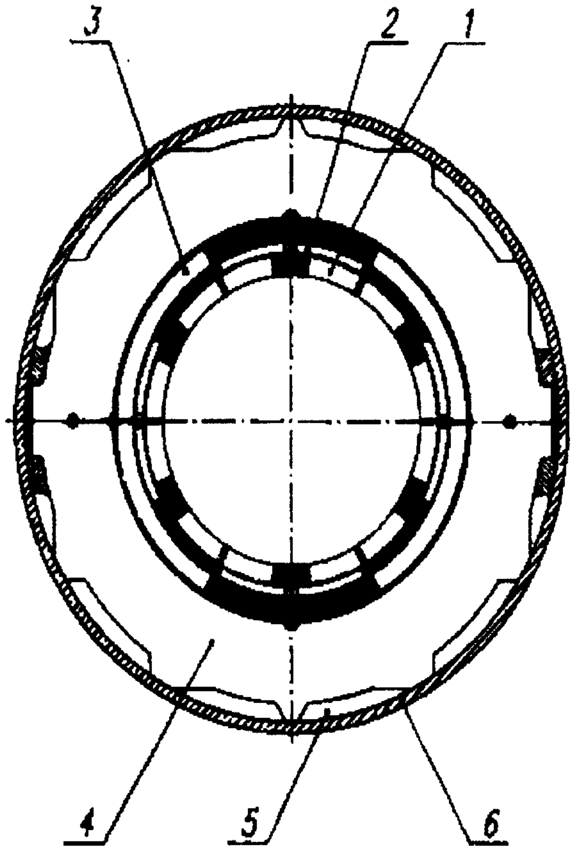

Figure 1: Cross-section of SCM models. 1—sextupole coil, 2—quadrupole coil, 3—dipole coil, 4—laminated iron yoke, 5—helium channels, 6—helium vessel shell

Table 2: Main dimensions of models (mm)

Dimension	Sextupole	Quadrupole	Dipole
COILS:			
Inner radius	40.0	46.5	49.9
Outer radius	46.2	49.6	56.1
Angle dimension (grad)	20.8	27.8	58.9
Total length	1370	1290	1190
Straight length	1320	1220	980
Coils per magnet	6	4	2
Sections per coil (SCM-1 only)	2	4	8
Layers of ribbon per coil (SCM-3 only)	37	58	131
Turns per coil:			
SCM-1	624	408	1760
SCM-3	592	464	1965
SCM-4	384	266	1260
Turns density ($1/cm^2$)			
SCM-1	7.3		
SCM-3	6.2		
SCM-4	3.8		
IRON YOKE:			
Inner radius	56.9		
Outer radius	84.0		
Total length	1400		
MAGNET:			
Total diameter	176		
Total length	1440		

limit are given for the joint ramping of all three windings (in more detail see below).

The electrical and magnetic parameters are presented in table 3.

After winding the coils were pressed to the design dimension and were cured at the temperature of 160° C . The fixation of the windings one about another was achieved with the advance assembly of the coils in the semi-blocks consisting of three sextupole, two quadrupole and a dipole coils. Complete coils were assembled in the semi-block on the cylindrical mandrel with epoxy impregnated ground insulation. Then semi-blocks were pressed relatively to the middle plane of the package, were cured again and assembled in the winding package. The top view of the winding package are displayed on figure 2.

Laminated iron yoke was made of the stamped magnetic steel sheets, which in advance were set up in the 100 mm long semi-packages and were welded on outer surface. Semi-packages of the iron yoke were assembled on the complete winding package, pressed along the vertical axis by the pressure of 150 kg/cm^2 and then welded with two seams in the middle plane of the package. Coil connections were made at the top flange of the magnet after assembly. Separate wire were twisted together, wrapped with the thin copper wire and then soldered.

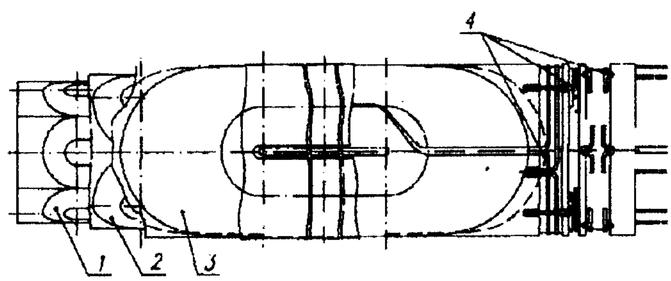

Figure 2: Top view of the winding package. 1—sextupole coil, 2—quadrupole coil, 3—dipole coil, 4—current leads

The coil resistance measurements and testings of the ground insulation had made after each operation during of the manufacturing and assembly.

Table 3: Electrical and magnetic parameters of models (SCM-1/SCM-3/SCM-4)

Parameter	Units	Sextupole (N=2)	Quadrupole (N=1)	Dipole (N=0)
Optical force	$(T/m^N)\cdot m$	600	5.50	0.68
Centre field (gradient)	T/m^N	448	4.37	0.59
Operating current	A	12.2/13.0/20.0	11.7/10.4/18.5	13.1/12.5/20.8
Short sample limit	A		54/56/69	
Constructive current density	$\cdot 10^8$ A/m^2	0.90/0.80/0.80	0.96/0.66/0.67	0.96/0.73/0.75
Inductance (calculated)	H	3.7/3.2/1.4	1.4/1.9/0.6	15.5/18.8/6.8
Active resistance at 300 K (measured)	kΩ	3.4/3.4/2.4	1.5/0.9/1.1	3.2/3.8/2.5
Stored energy	kJ	0.27	0.10	1.4

III. PARTICULARITIES OF THE COIL DESIGN

A. *SCM-1*

The coil consists of the several sections with square cross-section. This approach allows to receive the more regular distribution of the turns in the coil. Each section was random wound by the single wire with 25 μm polyamidimide enamel insulation in the separate flat mandrel. During the winding the wire was put through the bath with epoxy resin. After the winding the section was pressed to the design dimension, formed on the cylindrical mandrel and cured. After that the complete sections were assembled together around the central G-10 former. Then separate sections were connected seriesly.

The experience of the two models SCM-1 shown that this technique, on the whole, allows to make the magnets corresponding to presented requirements. However, it is sufficiently complicated and difficult. Besides, it was no possible to avoid completely of the turn shorts, which were observed in approximately 10% of sections.

B. *SCM-4*

In the model SCM-4 for the elimination of the turn shorts was used the wire with combined insulation—15 μm polyamidimide enamel and 50 μm fiberglass braid. The coil was all random wound in the cylindrical mandrel around G-10 former. In other respects the winding and assembly process was just the same as in the model SCM-1.

Application the add insulation allowed to exclude the turn shorts. Unfortunately, in this case we had to decrease the turn density comparing with the model SCM-1 (see table 2) and to increase the operating current till the limited meaning of 20 A. Besides the random winding brought to the nonuniformity of the turns distribution on the coil cross-section (especially in dipole coil), therefore even after pressing and curing the coil is very friable and needs in vacuum impregnation and special equipment for it.

C. *SCM-3*

One of the ways to reach the regular turns distribution is a winding with the ribbon conductor [2]. Ribbon has the width equal to the radial coil thickness and consists of several parallel secured wires which are connected seriesly on the coil end. In the model SCM-3 the coils were wound with the ribbon conductor that was made in original method. The ribbon was made with the binding a number of parallel wires by the polyimide thread with following impregnation with the small number of polyamidimide varnish and curing for making ribbon stability during of the winding. The ribbon wires has the increasing diameter from the inner to outer edge of the ribbon to compensate increasing of the coil angle length from the inner radius to outer. The ribbon for the dipole and sextupole coils consisted of 16 wires, and for quadrupole—of 8.

The coils of the model SCM-3 were made like its of model SCM-4. After the curing the separate wires were joined seriesly. The construction of series connection is similar to the described in above.

The use of the ribbon conductor speeds up the winding process much and allows to increase the turns density in about 1.6 times as compared with the random winding. Polyimide thread securing the separate wire in the ribbon, make the additional insulating distances between its, that allows to exclude the turns shorts. At the same time they make the coils "*transparent*" for the penetration of epoxy resin. One can suppose that it will make possible to receive the monolithic coils without vacuum impregnation. On the whole, one can say that the winding of the coil with the ribbon conductor is, perhaps, the most preferable of all testing variants.

IV. THE TESTS

The models were tested in a 3 meter long vertical cryostat at 4.2 K. SCM-1 and SCM-4 models were cooling twice and SCM-3—one time.