Particle Accelerators, 1990, Vol. 28, pp. 181–187
Reprints available directly from the publisher
Photocopying permitted by license only

STUDY OF THE SUPERCONDUCTING DIPOLE MAGNET FOR THE UNK

A.I.Ageyev, N.I.Andreyev, V.I.Balbekov, V.I.Dolzhenkov, K.F.Gertsev, V.I.Gridasov, K.P.Myznikov, A.P.Orlov, N.L.Smirnov, V.V.Sytnik, N.M.Tarakanov, L.M.Tkachenko, Yu.V.Vanenkov, L.M.Vasiliev, V.A.Vasiliev, V.V.Yelistratov, A.V.Zlobin
Institute for High Energy Physics, 142284, Serpukhov, Moscow region, USSR

Abstract The basic element of the superconducting (SC) dipole magnet for the UNK is a 80 mm in diameter shell-type two-layer coil. The current carrying element is a Rutherford-type SC cable consisting of 19 strands with 9 coated with a Sn+5% Ag alloy. The magnets are wound from a multifilamentary, each filament is 6 μm thick, SC wire having a critical current density of at least $2.3 \cdot 10^5$ A/cm^2 in the 5 T field at 4.2 K. This work presents some results on training, mechanical stability, ac losses, static heat leaks, ramp rate characteristics and coil heating when a SC dipole quenches. The measurements and calculations of the transfer function and bore field nonlinearities are also given.

INTRODUCTION

To substantiate the choice for the serial design of SC magnets for the Accelerating and Storage Complex (UNK) IHEP has studied two types of SC dipoles, with a warm and cold iron[1,2]. The analysis of the obtained results has shown that the basic characteristics of the dipoles of the two types satisfy the requirements imposed. But still, the cold-iron design exhibited a number of advantageous features important for the serial production of SC magnets. The most important are a decrease of static heat leaks in the helium vessel, a cut in the amount of the superconductor used and a simpler cryostat design. With these considerations taken into account, the cold-iron design was favoured over the warm-iron one for the development of serial SC magnets for the UNK. The short and full-scale models of SC dipole magnet for the UNK have been designed and tested proceeding from the results on the tests of SC dipole models with a cold iron and reduced consumption of the superconductor[3].

MAGNET DESIGN

The basic element of the SC dipole magnet for the UNK is a 5800 mm long shell-type two-layer coil with an inner diameter of 80 mm and a 5600 mm long cold iron. Figure 1 shows the cross-sectional view of a SC dipole for the UNK and Table I presents its basic characteristics.

Tables II and III present the basic characteristics of the current carrying element of a SC dipole for the UNK.

The SC cable is insulated with the help of two layers of kapton tape 20 μm thick and a layer of fiberglass-epoxy tape 100 μm thick and 10 mm wide wound with a 1 mm gap.

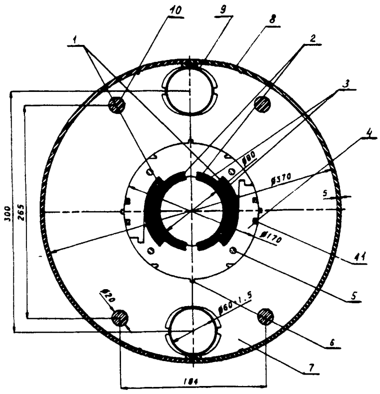

FIGURE 1. Cross section of a UNK dipole: 1 - outer layer, 2 - inner layer, 3 - spacers, 4 - collars, 5 - pin, 6 - rectangular lug, 7 - iron, 8 - helium vessel, 9 - two-phase helium pipe, 10 - stud, 11 - key.

TABLE I. The Basic Parameters of a SC Dipole for the UNK

Parameter	Inner layer	Outer layer
Number of turns	2 x 34	2 x 21
Turn width, mm	8.7	8.7
Medium turn thickness, mm	1.63	1.63
Angular layer dimension, deg	2 x 75.96	2 x 44.34
Angular spacer dimension, deg	4.25	7.24
Angular dimension of medium spacer, deg	2 x 0.10	2 x 0.5
Inner layer radius, mm	40	49.2
Maximum layer - to - bore field ratio	1.096	0.806
Quench temperature for 5 T bore field, K	5.4	6.3

TABLE II. Conductor Specification

1.	Superconducting alloy	Nb + 50% wt.Ti (NT-50)
2.	Conductor diameter, mm	0.85 + 0.03
3.	Number of filaments	8910
4.	Filament diameter, μm	6
5.	Twist pitch, mm	10
6.	Matrix material	Cu
7.	Copper-to-superconductor ratio (packing factor)	1.38 ± 0.12 (0.42 ± 0.02)
8.	Copper residual resistivity ratio	≥ 70
9.	Critical current at 5 T and 4.2 K, A	≥ 550
10.	Critical current density at 5 T and 4.2 K, A/mm^2	≥ 2300

The coil of SC dipoles is formed at a stress of 500-800 kg/cm^2 and then cured at a temperature of 150^{o}C during 5 hours. The coil layers are connected in series with the help of interlayer joints 75 mm long. To connect SC dipoles into a string, the coil has a bus conductor in the medium plane of the outer layer insulated with 6 layers of kapton tape and a layer of fiberglass-epoxy tape.

To attain the bore field quality required for resonance both slow and fast beam extraction, the inner and outer layers have spacers placed in each quadrant between turns 29-30 and 16-17, respectively. These spacers suppress the even structural nonlinearities of the 2nd, 4-th, 6-th and 8-th order. The UNK dipoles will be rectilinear, therefore to satisfy the requirement imposed on the characteristics of the edge field the end parts of SC dipoles have a blockwise layout of turns. The layout of turns was optimized proceeding from a necessity to suppress the structural nonlinearities of the 2nd and 4-th order of the integral field and to decrease the value of the field in the coil end parts as compared with that in the rectilinear section of the coil.

TABLE III. Cable Specification

1. Number of strands	19
2. Cable type	ZEBRA
3. Strand coating	
9 strands	Sn+5% Ag
10 strands	bare
4. Cross section	
inner layer, mm^2	(1.30-1.62) x 8.5
outer layer, mm^2	(1.33-1.59) x 8.5
5. Cable twist pitch, mm	62
6. Cable critical current at 5 T and 4.2 K, A	$\geqslant$9500

The coil is collared with stainless steel collars connected with the help of pins and keys placed from the two sides into the grooves close to the median plane. To make the coil assembly more rigid the geometry of locks and keys has been optimized as well as the position of the pins and also the tolerance was made more stringent. A prestress in the collared coil at ambient temperature is at least 1000 kg/cm^2 in the linear section of the inner layer and not less than 600 kg/cm^2 in that of the outer one. To make the end parts more stable mechanically they are loaded axially with bolted face flanges. A prestress in the coil end parts is at least 500 kg/cm^2. The position of the coil assembly with respect to the iron is fixed with rectangular collar lugs. Then choosing the geometrical dimensions of the iron, the dimensions of the grooves for rectangular collar lugs and of the holes for liquid helium have been optimized as well as the iron thickness in order to reduce the cold mass of magnets and decrease the effect of iron saturation on the value of lower-order field nonlinearity in the central cross section.

To protect magnets against overheating during quenches the outer layer of coils has strip heaters made from 5800 mm long, 50 μm thick and 45 mm wide stainless steel foil. Strip heaters are insulated against the coil with two layers of kapton 80 μm thick and against the collars with a few layers of kapton 0.5 mm thick.

Figure 2 presents the cross sectional view of a SC dipole for the UNK assembled in a force-circulating cryostat. The magnet is cooled with a single-phase helium flow a part of which passes through the ring coil channels and another one goes into the bypass in the iron to exchange heat with the two-phase helium counterflow going through the pipe inside the bypass. The helium vessel is fixed to the warm vacuum jacket with the help of vertical titanium-alloy suspensions and horizontal extension rods placed in two transverse cross sections over the magnet length. The anchor extensions fixing the central cross section and allowing a free motion of the magnet ends in thermal cycles prevent the helium vessel from longitudinal motions.

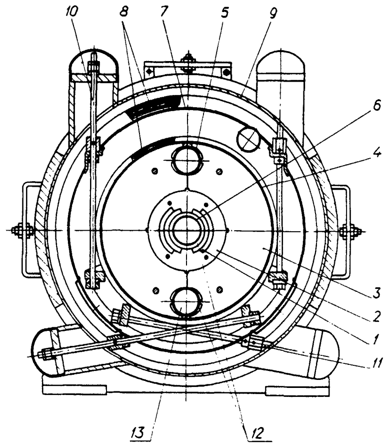

FIGURE 2. Cross section of a SC dipole assembled in a force-circulating cryostat: 1 - coil, 2 - collars, 3 - iron, 4 - helium vessel, 5 - two-phase helium pipe, 6 - beam pipe, 7 - nitrogen shield, 8 - superinsulation, 9 - vacuum shell, 10 - suspension, 11 - extension rod, 12 - single-phase helium, 13 - two-phase helium.

To reduce the radiation induced heat leaks to the helium vessel the cryostat is furnished with an nitrogen shield from aluminium and also multi-layer insulation wound onto them.

MEASUREMENT RESULTS

A few short and full-scale models of SC dipole for the UNK have been manufactured and tested. Short models were tested in a pooling cryostat in free boiling helium at a temperature of 4.25 K. A full-scale model was tested at a force-circulating test facility cooled by 4.3-4.4 K single-phase helium.

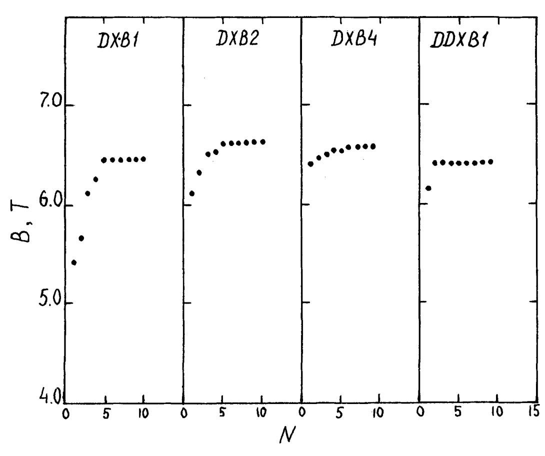

FIGURE 3. Training curves for short (DXB) and full-scale (DDXB) SC dipole models.

Figure 3 presents the results on measuring the training of some short (DXB) and full-scale (DDXB) SC dipole models for the UNK. During the 1st quench the field of all magnets exceeded the maximum operating field in the UNK cycle, 5 T. The maximum bore field after the training was over reached 6.6 T and was determined by the critical current of the short sample with account of the coil temperature and field. The maximum field of a full-scale model, 6.4 T, was attained actually without training in the 2nd quench.

The mechanical stability of the coil assembly was checked from the deformation of the collars due to Lorentz forces and from the measurements of structural nonlinearities in the cycle when the short models were measured without the iron. When the coil current was 6 kA, the increase of collars in the median plane was 140 μm. The variation in the structural nonlinearities did not exceed in this case $|\Delta C_3|=1\cdot 10^{-4}$, $|\Delta C_5|=1.5\cdot 10^{-4}$, $|\Delta C_7|=1\cdot 10^{-4}$, $|\Delta C_9|=0.5\cdot 10^{-4}$. The obtained result points to a sufficient rigidness of the coil assembly within the operating range of fields and currents.

Figure 4 presents a typical ramp rate characteristic of a SC dipole for the UNK. A decrease of the quench current for a SC dipole when the ramp rate was raised up to 500 A/s did not exceed 3%. The ramp rate characteristic of a UNK dipole completely satisfies the requirements both in the operating cycle and during emergency energy removal from the magnet system.

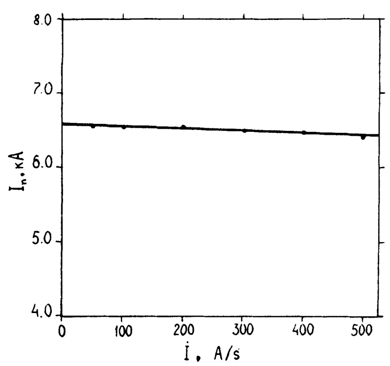

FIGURE 4. Ramp rate characteristic of a SC dipole.

The total static heat leaks were 5 W per magnet, about 1 W accounting for heat influxes across the suspension system. The mean value of ac losses in the UNK cycle with a linear 40-s bore field rise from 0.67T to 5 T, 38-s flattop at 5 T and 40-s linear field drop from 5 T to 0.67 T is 1.1 W per meter of the magnet length, out of which 0.6 W/m fall at the ac losses in the coil and the remaining 0.5 W/m dissipate in the cold iron[4]. Work is being done in order to decrease the values of static heat leaks and ac losses by improving the quality of the superinsulation and decreasing the coercive force of iron.

Table IV presents the basic constituents and total heat releases in the helium vessel of a UNK dipole in the acceleration cycle.

TABLE IV. The Mean Power of Heat Influxes in the Helium Vessel of a SC Dipole in the Acceleration Cycle.

Static heat leaks, W	5.0
AC losses in the coil, W	3.5
Hysteresis loss in iron, W	3.0
Heat loss in the collars, W	0.2
Heat loss in the beam pipe, W	0.02
Total heat load on SC dipole, W	11.72

With account of the results presented in this Table IV, the total heat load on the cryogenic system does not exceed 33 kW in the acceleration cycle. In the collider mode, the mean power of heat releases in the helium vessel of SC dipoles for the UNK are brought down to 5.34 W due to decrease of the power of heat releases in the coil and magnetic shield. This means that the available power of the UNK cryogenic system, 60 kW, will make it possible to run one SC ring in the acceleration mode or two SC rings in the collider mode.

Figure 5 presents the results on measuring and calculating the transfer function for a full-scale UNK dipole versus the coil current. The calculations have been made with account of real magnetic characteristics of iron and collars. Calculational results are in a good agreement with the results on the measurements in the whole range of operating currents in the UNK cycle. According to the measurements, saturation of the iron in the region of high currents leads to 1.03% decrease of the transfer function for the maximum operating current. The calculated decrease of the transfer function of a SC dipole is 0.8%.

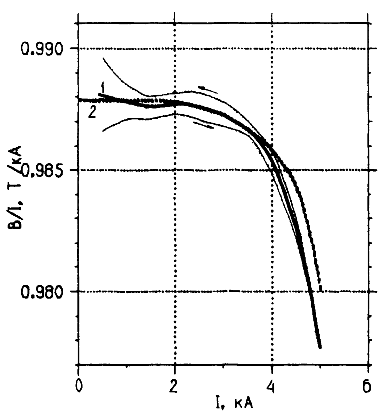

FIGURE 5. SC dipole transfer function versus coil current: 1 - measurements, 2 - calculation.

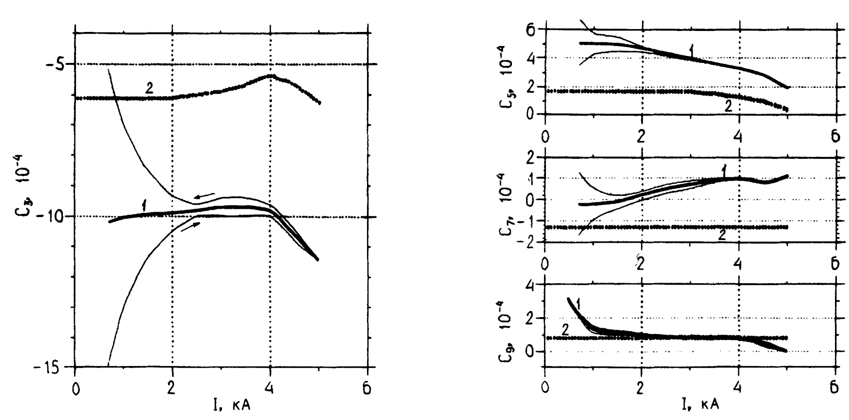

FIGURE 6. C_3, C_5, C_7 and C_9 field constituents versus coil current: 1 - measurements, 2 - calculation.

Figure 6 presents the results on measuring and calculating the integral values of C_3, C_5, C_7 and C_9 in the bore of a full-scale SC dipole at a radius of 3.5 cm versus the value of the coil current. As is seen from the charts, the effect of iron saturation on the value of variation in sextupole C_3 and decapole C_5 constituents of the field in the region of high currents coincides with the calculation actually completely. The nonzero integral values of C_3, C_5, C_7 and C_9 are due to the collar magnetization effect and slight deviations of the coil geometry from the design one. Further, in order to reduce the collar magnetization effect on the bore field, stainless steel having a magnetic susceptibility of 0.005 and possessing stable magnetic properties will be used[5].

The difference between the value of the transfer function of a SC dipole and sextupole nonlinearity during current input and output is determined completely by the hysteresis magnetization of the SC cable[6].

The analysis of the magnetic measurements results shows that in the UNK cycle the values of gradient, quadratic and cubic nonlinearities can be corrected by the envisaged system of field correction. Higher-order and edge nonlinearities are within the tolerances in the acceleration, stacking and extraction modes.

The value of quench integral in a quech initiated by internal heaters has been measured versus the coil current. The maximum value of the quench integral for a SC dipole with the chosen design of the heaters does not exceed $6.5 \cdot 10^6$ $A^2 \cdot s$. In this case, the coil heating due to the stored energy dissipation in it does not exceed 200 K.

CONCLUSIONS

The study of the properties of the UNK dipole shows that the chosen design meets the requirements imposed on the value and quality of the bore field, the level of ac losses and static heat leaks. The available reserve in the critical current, 25÷30%, will ensure a reliable operation of SC dipoles in the UNK cycle at a temperature of liquid helium of 4.4-4.6 K under the conditions of ac and radiation heat releases.

Presently, IHEP is doing work on the preparation for the mass production of SC dipoles for the UNK.

REFERENCES

1. A.I.Ageyev et al. Proceed. of XIII Intern. Conf. on High Energy Part. Accel. - M.: "Nauka" (Novosibirsk), 1987, v. 2, p. 39.
2. A.I.Ageyev et al. Proceed.of Workshop on Superconducting Magnets and Cryogenics. - BNL, 1986, p. 199.
3. A.I.Ageyev et al. Preprint IHEP 89-27, Serpukhov, 1989.
4. A.N.Baidakov et al. Preprint IHEP 89-26, Serpukhov 1989.
5. A.N.Baidakov et al Preprint IHEP 89-59, Serpukhov, 1989.
6. K.F.Gertsev et al. IEEE Trans. on Magnetics. 1988, 24, N 20, p. 812.