DEVELOPMENT OF FAST-CYCLING SUPERCONDUCTING QUADRUPOLE AND CORRECTOR MAGNETS FOR THE SIS 300

L. Tkachenko, I. Bogdanov, S. Kozub, P. Shcherbakov, P. Slabodchikov, V. Sytnik, V. Zubko
Institute for High Energy Physics, Protvino, Moscow region, 142281

Abstract

IHEP participates in the development of superconducting fast-cycling magnets for the FAIR project. In the frame of this project IHEP has developed a prototype of the main quadrupole, assigned for using in the SIS300 ring. The main parameters of the quadrupole are: 45-T/m central gradient in 125-mm ID of the coil with the useful aperture of 105 mm; the gradient ramp rate is 10 T/m/c and the length of the prototype is 1 m. The main characteristics of the designed quadrupole magnet are discussed here. The correction system consists of multipole magnets, resonance and chromaticity sextupoles and steering dipoles. The multipole magnet contains octupole, sextupole and quadrupole coils and the steering magnet involves horizontal and vertical dipoles. Geometries of corrector and steering magnets are presented as well as their main magnetic parameters.

INTRODUCTION

During the past several years IHEP has took part in the FAIR project [1]. At the moment, IHEP's main tasks are to develop a design of the main quadrupole [2], [3], [4], as well as designs of the corrector and steering magnets [3] for the SIS 300 ring. The optimized 2D and 3D geometries of the quadrupole and the main magnetic characteristics of the magnet are presented. The preliminary designs of the corrector and steering magnets for the SIS 300 as well as their main characteristics are presented too. All magnetic characteristics were calculated with a help of computer programs MULTIC [5] and HARM-3D [6].

QUADRUPOLE; REQUIREMENTS

Main quadrupole requirements are: the central gradient (G_0) is equal to 45 T/m; the inner beam pipe diameter is 105 mm; the gradient ramp rate is 10 T/m/s; the injection gradient is 10 T/m. The region of good field quality is r_0 = 40 mm and the effective length of the magnet is 1 m. The temperature margin has to be at least 1 K. Alterations of lower multipoles of the integral field at r_0 should be less then 2×10^{-4}. Additional requirements are: minimal geometric length; simple and reliable design; low AC losses in the magnet; minimum risks; cost reduction.*

QUADRUPOLE; 2D GEOMETRY

The main characteristics of the superconducting wire are: 0.825-mm strand diameter; 3.5-μm filament diameter; a 5-mm filament twist pitch, a Cu/superconductor ratio of 1.4, a critical current density of J_c = 2.7 kA/mm^2 (at 5 T, 4.2 K). Ratio of ρ_{300}/ρ_{10} is more than 70. Superconducting strands will have Staibrite coating.

Numerical simulations showed that it is enough to have a cable with 19 strands in order to meet given requirements for the quadrupole. Such type of cable was used for the UNK magnets [4]. The cable will be fully keystone with a width of 8.45 mm and an average height of 1.56 mm (with insulation). The cable will be insulated by polyimide tape in three layers. The radial thickness of the insulation after assembly and cool down is 125 μm and azimuth thickness is 98 μm. It is estimated that the cable will have contact crossover resistance in 0.02 mΩ and transverse resistance in 20 mΩ [6].

The 1-layer coil is divided by three blocks, allowing suppress the first three multipoles in the approximation of an infinitely high permeability in an iron yoke with the inner cylindrical surface. The geometric parameters of the coil are presented in Table 1, where *N* is a number of turns; *φ, α* are the initial and final angles of the block. The operating current is 6.262 kA. The ID of the iron yoke, made from 2212 electric steel, is 190 mm and the iron thickness is 52 mm. The iron yoke has four notches with 17×30 mm^2 dimensions for location of bus bars placed symmetrically under 45° as well as four adjusting bolts for quadrupole arrangement in the cryostat (Fig. 1).

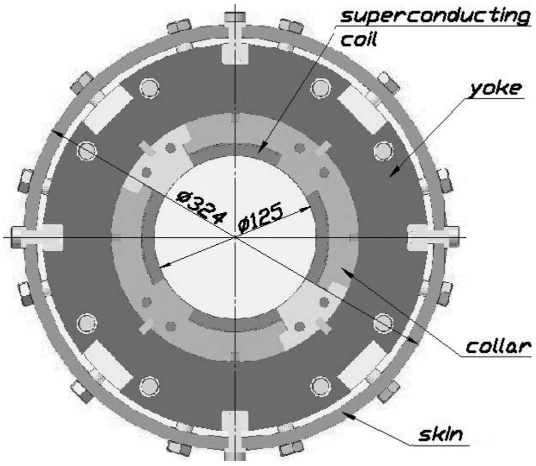

Fig. 1: General view of the cross section.

Table 1: Main Geometric Parameters of Coil Block

	N	*φ*	*α*
1	8	0.129	11.413
2	7	11.959	21.831
3	5	26.604	33.656

Field dependences for the normalized gradient and

---

[*] This work was completed with financial support from Rosatom, contract H4e45.03.10.1027

multipole b_6 are presented in Fig. 2, 3. The initial parts of the curves show an influence of the coil magnetization and the final parts present the effects of the iron yoke saturation.

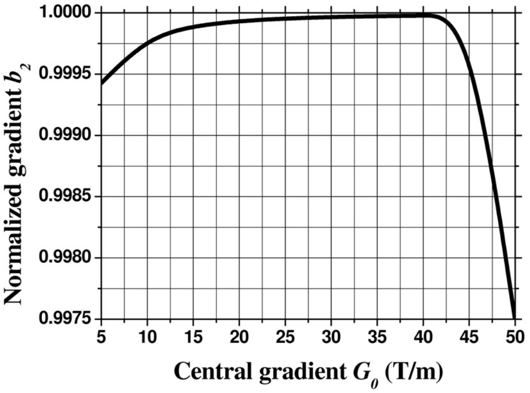

Fig. 2: Field dependence of normalized gradient.

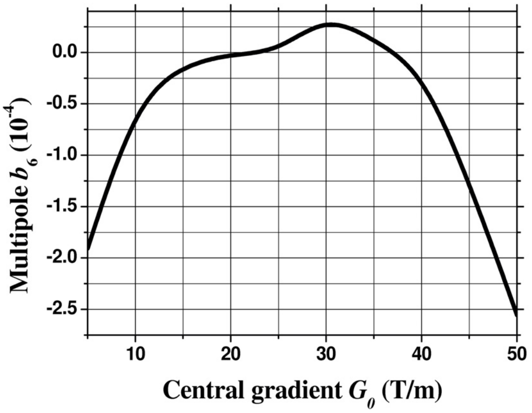

Fig. 3: Multipole b_6 versus central gradient.

QUADRUPOLE; 3D GEOMETRY

The end parts of the quadrupole have a shape that had been developed for the UNK magnets [7]. Turns in this geometry on the end parts are installed perpendicular to the generatrix of the cylinder. The geometric length of 1000 mm for the coil block was chosen because of technological considerations. The locations of spacers in the end part are chosen as a continuation of the spacers in the straight part of the coil. The thickness of the spacers in the end parts in the optimized geometry are: S_1 = 21.56 mm; S_2 = 9.42 mm. Fig. 4 shows an involute of the optimized end parts in the $\rho\theta$-Z plane.

In order to reduce the ratio of operating current I_{op} to the critical current I_C that provides a better value of the minimal quench energy, the length of the iron yoke is shorted in the end parts by 130 mm with each end. At the length of the iron yoke of 740 mm B_{max} in the end parts is equal to the maximal field in the cross section and equals 3.505 T. The temperature margin at this field is 1.54 K. The load line of the quadrupole is shown in Fig. 5. The current margin is 44%.

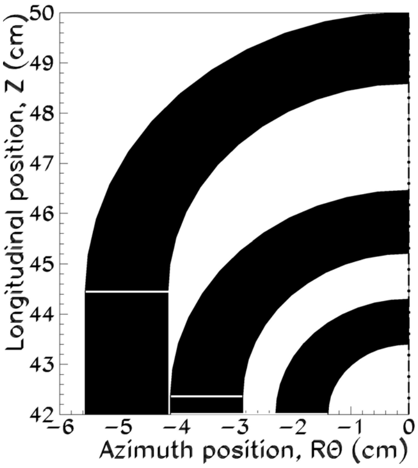

Fig. 4: Involute of optimized end parts.

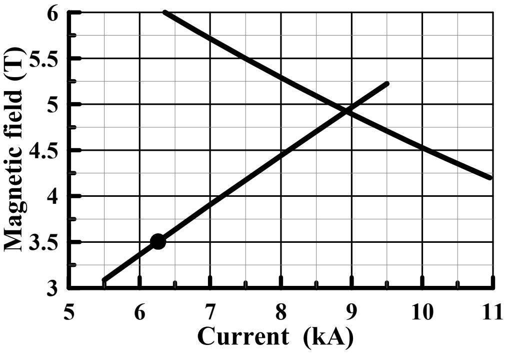

Fig 5: Load line of quadrupole.

The magnetic forces are (in kN/m): F_x = 124.2; F_y = -143.3; $|F|$ = 189.7. The stored energy is 38.0 kJ/m and the inductance is 1.94 mH/m. AC losses in the coil were calculated for the standard triangle cycle for the SIS 300: 10 – 45 – 10 T/m at the ramp rate of 10 T/m/s. The components of losses in the coil are (in J/m): hysteresis - 9.4; matrix - 3.0; cable - 0.3; total losses in the coil are 12.7. Losses in the iron yoke for 2212 steel are: hysteresis - 5.0; eddy current - 0.003, so the total losses in the magnet are 17.7 J/m.

Longitudinal distributions of the lower field multipoles in the end parts of the quadrupole are shown in Fig. 6, 7.

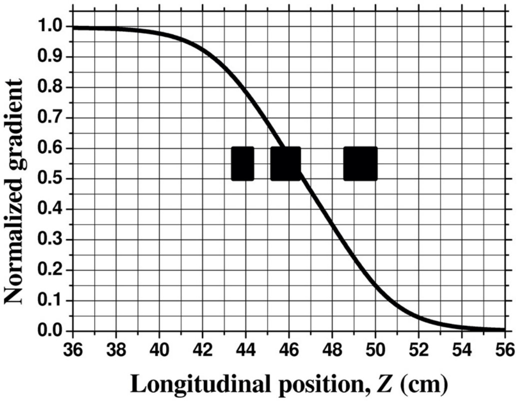

Fig. 6: Longitudinal distribution of normalized gradient. Dark rectangulars show coil blocks in end parts.

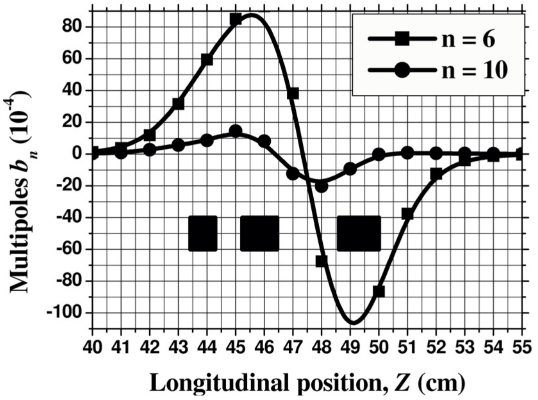

Fig. 7: Longitudinal distribution of lower multipoles. Dark rectangulars show coil blocks in end parts.

CORRECTOR AND STEERING MAGNETS

There are 4 types of corrector magnets:

1. Error compensation multipole corrector, combined magnet, which consists of quadrupole (QM), sextupole (SM) and octupole (OM) magnets;
2. Chromaticity Sextupole (CS);
3. Resonance Sextupole (RS);
4. Steering horizontal (DH) and vertical dipoles (DV), combined magnet.

The main requirements for the corrector magnets are presented in Table 2, where L_{eff} is an effective length of each magnet and t is the current-rise time. The aperture diameter for all magnets is 105 mm and the beam pipe ID is 115 mm. The CS will have series connection; there are 4 magnets in the series. The CS and RS will have bipolar power supplies. The operating current should be less than 250 A. Field quality requirements are not formulated yet, but we assume that an alteration of the first lower integral field multipole should be within 2×10^{-4} and the magnet main field deviation should not exceed 0.2%.

A wire with the following characteristics will be used for the coil winding superconducting NbTi: 0.3-mm diameter; 3-μm filaments, 3-mm twist pitch; Cu/superconductor = 1.7; RRR > 70; $J_c = 2.7$ kA/mm^2 (at 5 T, 4.2 K). The wires will have oxide coating. The superconducting rectangular shape cable consists of 8 strands with a transposition step of 11.9 mm. The cable will be insulated by three layers of a 25-μm polyimide film and has transverse dimensions of 0.6×1.63 mm^2.

The minimal coil ID for magnets will be 125 mm. At present only CS, RS, DH and DV magnets have been studied in more details. The coils in all magnets will be of layer type. The magnets will have classical design with an iron yoke serving directly as a supported structure for the coil. The main characteristics of the magnets are presented in Table 3, where φ, α are initial and final angles of the coil; N_w is a number of turns; R_F is the inner radius of the iron yoke; I_{op} is the operating current; L_t is the total length of the coil; S is the straight part of the coil; L_{ef0} and L_{ef} are the required and calculated effective lengths; B_{max} is the maximal field in the coil in the cross section/end parts (T); E is the stored energy (J/m); L is inductance (mH/m); F_x, F_y, $|F|$ are components of magnetic forces (kN/m). All angular dimensions are in deg., linear dimensions are in mm.

Table 2: Main Requirements for Corrector Magnets

	Strength	L_{eff}, m	t, s
QM	1.8 T/m	0.65	2.25
SM	60 T/m^2	0.65	2.18
OM	767 T/m^3	0.65	2.24
CS	130 T/m^2	0.78	0.208
RS	325 T/m^2	1	0.5
DH, DV	0.5 T	0.65	2.27

Table 3: Main Characteristics of the Magnets

	CS	RS	DV	DH
φ	4.485	2.466	12.954	13.425
α	15.186	14.444	41.310	40.263
N_w	2×20	4×23	2×53	2×53
R_F	67.365	71.0	71.0	71.0
I_{op}	234	236	230	231
L_t	800	1040	700	700
S	741.2	973.2	611.2	610.2
L_{ef0}	780	1000	650	650
L_{ef}	780.4	1008.6	666.8	668.3
B_{max}	0.82/0.89	1.69/1.53	1.15/1.42	1.24/1.42
E	582	4358	1033	1126
L	21.3	156.5	39.1	42.2
F_x	2.8	17.6	9.2	0.3
F_y	-1.5	-13.2	-0.8	11.0
$\|F\|$	3.2	22.0	9.2	11.0

CONCLUSION

The design of the superconducting fast-cycling quadrupole magnet for the SIS 300 accelerator has been developed. The quadrupole magnet has a high quality of the field. The compact end parts together with two spacers provide also the high quality of the integral field. The temperature margin is 1.54 K, what guarantees a stability of the magnet. The total losses in the magnet are reduced to 17.7 J/m. The main characteristics of magnets of a correction system are presented.

REFERENCES

[1] [GSI. (2006, Sept.). Baseline technical report. [Online]. Available: http://www.gsi.de/fair/reports/btr.html

[2] L. Tkachenko, S. Kozub, V. Zubko, “Quadrupole for the SIS 300. IEEE Trans. on Appl. Supercond. vol. 19, nr. 3, pp. 1167-1179, 2009

[3] L. Tkachenko, I. Bogdanov, S. Kozub, P. Shcherbakov, V. Sytnik, A. Tchikilev, V. Zubko, “Development of Quadrupole, Steering and Corrector Magnets for the SIS 300”, *to appear in IEEE Trans Appl. Supercon. 20.*

[4] L. Tkachenko, S. Kozub, P. Shcherbakov, V. Sytnik, V. Zubko. “Analysis of the Factors Affecting Field Quality and Heat Releases of the Quadrupole Magnet for the SIS 300”. Presented at ASC-2010, Washington, USA, August, 2010

[5] L.M. Tkachenko. “Code Package MULTIC for Calculation of Magnetic Field with an Arbitrary Configuration”. IHEP preprint 92-28, 1992, (in Russian).

[6] S.V. Purtov and L.M. Tkachenko. “HARM-3D - a Code to Calculate Magnetic Characteristics of SC Magnets”. MT-15, Beijing, China, 1997, Beijing, China, Vol. 1, p.p. 1335-1338.

[7] V.I. Balbekov, L.M. Tkachenko. ”Optimization of the End Parts of the UNK SC dipoles“. *Preprint 82-167*, Serpukhov, 1982 (in Russian)