COMPARISON OF THREE DESIGNS OF A WIDE APERTURE DIPOLE FOR THE SIS300 RING

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INTRODUCTION

The new accelerator complex being developed at GSI [1] includes the SIS300 machine, which requires the following parameters for superconducting (SC) dipoles: magnetic field amplitude of 6 T, 1 T/s field ramp rate, and 100-mm coil aperture. A high ramp rate produces large AC losses in the magnet, which reduce magnet temperature margin, leading to complications of magnet design, as well as raising operating costs. Increasing the coil diameter from 80 [2, 3] to 100 mm required considerable detailed design analysis. In the frame of collaboration between IHEP and GSI, three new dipole designs have been considered, with the main goal being to reduce heat losses in magnet. The principal difference in these designs is the coil support collar width, which determines the distance between iron yoke and coil. Decreasing this distance raises the magnetic field contribution from the iron yoke, so it is possible to reduce the volume of required superconductor and therefore also decrease AC losses in the coil. But decreasing this distance increases magnetic field quality distortions due to saturation effects of the iron yoke. **Design I** has the maximum collar width, which allows the collars to restrain all electromagnetic forces acting on the coil. The collars in **design II** have a lesser width and are intended to provide coil restraint only for magnet assembly. The iron yoke will take up forces arising during magnet cool-down, as well as during dipole energizing. **Design III** has no collars; the iron yoke is placed near the coil and also fulfils all function of the collars. A comparative analysis will be made for these designs, allowing one to choose the optimal geometry.

CONDITIONS OF OPTIMISATION

Furthermore, we will use the field representation:

$$B_y + iB_x = B_0 \sum_{n=1}^{\infty} w_n(r,z)\left(\frac{r}{r_0}e^{i\theta}\right)^{n-1}.$$

Here, B_0 is a normalizing factor; r_0 is a reference radius, which is chosen equal to 40 mm for the GSI wide aperture dipole; $w_n = b_n + ia_n$; b_n and a_n present normal and skew field harmonics of the (n–1)-th order; z is the longitudinal axis of the magnet. The point of origin is placed in the center of the magnet. Usually, the factor B_0 is set equal to the central field of a dipole. It is convenient to choose B_0 as the magnetic field for the approximation of an infinitely large magnetic permeability in the iron yoke. Then, the difference b_1-1 shows effects of iron saturation. Integrating the field series over z, we get integral field decomposition:

$$\hat{B}_y + i\hat{B}_x = \hat{B}_0 \sum_{n=1}^{\infty} W_n(r)\left(\frac{r}{r_0}e^{i\theta}\right)^{n-1}.$$

Here $\hat{B}_0(0,0)$ is the integral of the axis field over z. With the analogy to w_n the values of $W_n = b_n + ia_n$; $\hat{b}_n$ and $\hat{a}_n$ present normal and skew integral field harmonics of the $(n–1)$-th order. The value of $\hat{B}_0 / B_0$ determines the magnetic length of the magnet.

The conditions of geometry optimisation in the cross section and end parts are:

1. Critical temperature ≥ 5.3 K.
2. Minimization of heat losses in the coil and iron.
3. Minimization of field enhancement in end parts.
4. Field and integral field harmonics must independently satisfy the following conditions:

$$\int_{B\min}^{B\max} b_n(B)dB = 0; \quad \int_{B\min}^{B\max} \hat{b}_n(B)dB = 0.$$

The last conditions mean zero integral equality for harmonics during accelerating time. As the coil consists of two layers with inter-turn spacers, it is possible to satisfy this equation for n = 3, 5, 7, 9 in field harmonics. The inner layer also has two spacers in the end parts, which allow one to suppress two (n = 3, 5) integral field harmonics, as well as to minimise field enhancement in the end parts. For total minimisation of field enhancement in the end parts up to the cross section level, it is also necessary to shorten the iron yoke length.

MAIN CHARACTERISTICS

It is assumed the coil will be made with SC strand, having 0.65-mm diameter, 3.5-μm filaments and 4-mm twist pitch. Copper/SC ratio is 1.38 and critical current density is 2.7 kA/mm^2 at standard operating conditions (5 T, 4.2 K). Presently, a possibility of increasing strand diameter to 0.825 mm is under consideration, to increase the magnet temperature margin to 1 K. Heat losses in the iron yoke can be reduced by a suitable selection of material. As the result of a study of electrical steel magnetic properties (for application in fast cycling magnets of SIS100 and SIS300 rings [4]) the material of 2212 steel quality was chosen. A low enough coercive force of 72 A/m, 0.5-mm thickness of lamination, and resistivity of 0.15 μΩ×m allow one to decrease total heat losses in the iron by more than a factor of 2, in comparison with previously used steels.

A general view of the three designs in cross section is shown in Fig. 1-3.

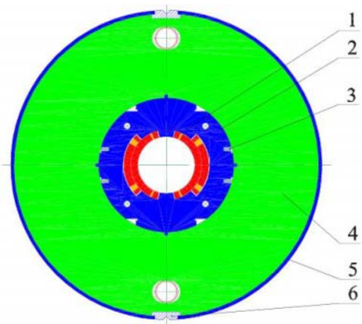

Fig.1. Design I: 1 – coil; 2 – collars; 3 – key; 4 – iron yoke; 5 – outer shell; 6 – staple.

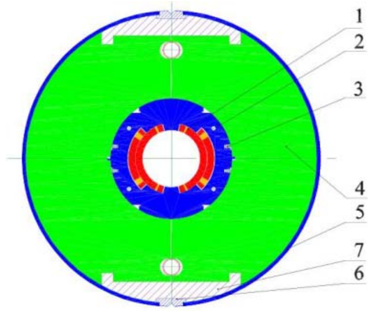

Fig.2. Design II: 1 – coil; 2 – collars; 3 – key; 4 – iron yoke; 5 – outer shell; 6 – staple; 7 – C-clamp.

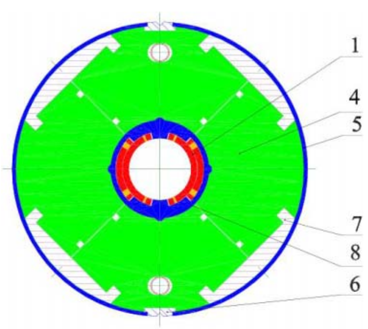

Fig.3. Design III: 1 – coil; 4 – iron yoke; 5 – outer shell; 6 – staple; 7 – C-clamp; 8 - spacer.

The main geometric characteristics of the three designs after optimisation are presented in Table 1.

Table 1. Main Characteristics for Three Designs.

Geometry	I	II	III
Collar thickness, mm	45	30	10
Strand number in cable	38	35	30
Bare cable width, mm	12.80	11.70	9.91
Cable thickness with insulation, mm	1.264	1.273	1.289
Total turn number	91	90	89
Operating current, kA	4.98	4.78	4.48
Inner iron radius, mm	121.4	104.2	80.6
Iron thickness, mm	158	138	140
Coil length, mm	2750	2750	2750
Iron length, mm	2410	2434	2464
Length of cryostat, mm	3180	3180	3180

The extent of iron saturation is shown in Fig. 4 for all designs. Normalised field is the ratio of the central field B_0, calculated with real magnetic permeability, to the value of central field with infinitely large magnetic permeability in the iron.

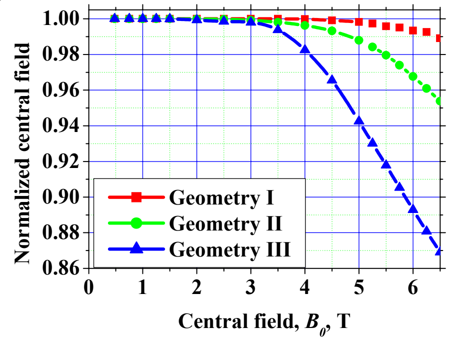

Fig. 4. Normalised field versus central field B_0.

The next three Figures demonstrate behaviour of lower integral field harmonics versus central field. The effects of superconductor magnetization were taken into account.

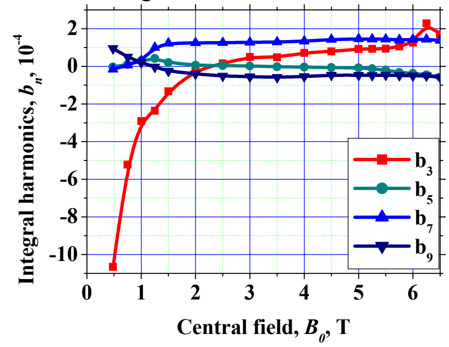

Fig. 5. Integral field harmonics in design I versus B_0.

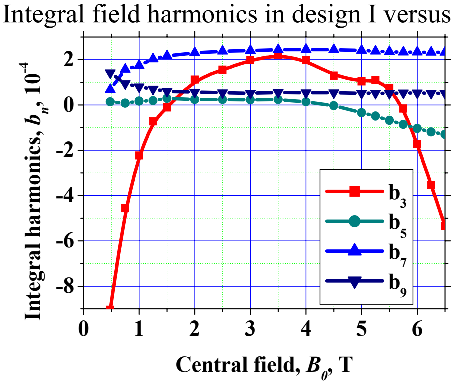

Fig. 6. Integral field harmonics in design II versus B_0.

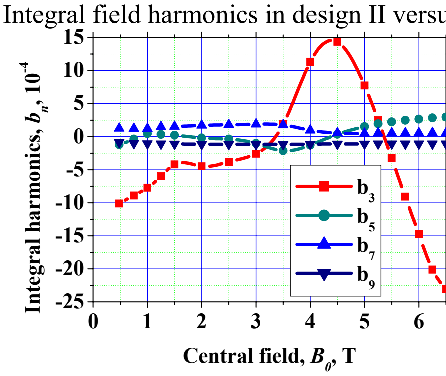

Fig. 7. Integral field harmonics in design III versus B_0.

SUMMARY TABLE

Main physical parameters and estimated costs for three geometries are collected in Table 2.

Table 2. Main Parameters for Three Geometries.

Geometry	I	II	III
Magnetic length (6T), mm	2593	2584	2577
Transversal dimension, mm	559	485	441
b_3 spread peak to peak, 10^{-4}	11.5	12.7	31.3
Linearity loss B_0=kI (6T), %	0.6	3.0	11.5
Horizontal force/quadrant, kN/m	1248	1245	1220
Vertical force/quadrant, kN/m	-626	-550	-418
Total force/quadrant, kN/m	1396	1361	1290
Hysteresis losses/coil, J/m	81	74	57
Matrix losses/coil, J/m	19	18	14
Cable losses/coil, J/m	65	42	23
Total losses/coil, J/m	165	134	94
Losses in iron, J/m	25	31	30
Total losses/magnet, J/m	190	165	122
Stored energy/magnet, kJ/m	245	227	224
Mass of SC/magnet, kg	108.9	98.2	83.4
Mass of collars, kg	500	440	360
Mass of iron, ton	4.99	2.63	2.12
Total mass of magnet, ton	5.98	5.23	4.33
Strand length/magnet, km	42.7	38.5	32.7
Cable length/magnet, km	1.07	1.05	1.04
Relative cost of magnet	1.12	1.07	1.00
Relative operating cost	1.34	1.20	1.00

Geometry I has the largest losses in the coil. Ways to reduce cable loss component are considered in [5]. The stability of these designs influenced by various heat releases arising during operational modes is considered in [6]. A preliminary study of protection system philosophy is presented in [7].

These designs have an as small as reasonable temperature margin ΔT (~0.5 K). It is possible to increase ΔT either by raising the coil critical temperature (increasing the superconductor volume in the cable) or by decreasing the temperature of inlet cooling helium. Fig. 8 demonstrates relative operating costs for both ways. One can see that decreasing the inlet helium temperature is far more effective.

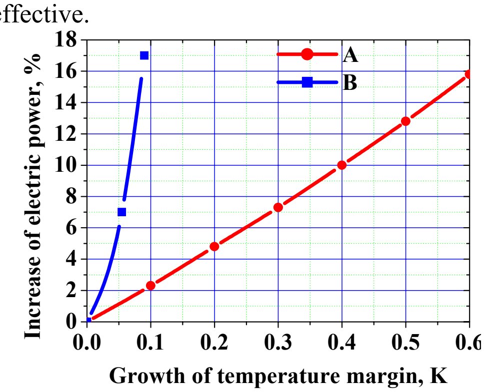

Fig. 8 Dependence of electric power increase for liquid helium production by SIS300 cryogenic system on growth of temperature margin for SIS300 dipole (Design III): *A* is reduction of liquid helium temperature below 4.4 K; *B* is an addition of two and four superconducting wires to 30 wires of cable.

ADVANTAGES OF DESIGN I

So, it is possible to summarize advantages and disadvantages for Geometry I. Of course advantages and disadvantages for Geometry III trade places.

1. Simple and proven design. Designs like this work very well in machines such as Tevatron and HERA. This design was considered for the UNK project and a pilot batch series of 25 full-scale dipoles also showed excellent physical characteristics.
2. Cheaper production and easer assembly;
3. Looser production tolerances on iron yoke;
4. Fail-safe operation;
5. Small deviations of harmonics versus time;
6. Acceptable linearity $B_0 = kI$;
7. Simplification of the correction systems;
8. Maximum magnetic length.

DISADVANTAGES OF DESIGN I

1. Large superconductor expenses and magnet cost;
2. Large overall dimensions and mass;
3. Problems with transportation and installation;
4. Longer time for warming up – cooling down;
5. Large heat losses in the coil;
6. Large operating cost.

CONCLUSION

Taking into account the mechanical complexity of Geometry III, one should choose Geometry II as a starting point for further development. During detailed evaluation of this design, it is necessary to pay special attention to a careful choice of the collar thickness, with the aim of making it with a minimal thickness, which still satisfies all mechanical requirements, including taking into account material fatigue. Also, it is necessary to consider the problem of iron half-yoke connections, with the help of C-clamps. Perhaps it is possible to find a more elegant and effective solution, which still possesses enough simplicity. In order to improve design reliability, the temperature margin will be raised to 1 K, by increasing the strand diameter to 0.825 mm and the strand number to 36 in the final cable design. Minimization of coil heating losses will also be reconsidered at that time.

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