

# INVESTIGATIONS CONCERNED WITH DEVELOPMENT OF SC DIPOLE FOR THE SIS 300 ACCELERATOR

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## Abstract

GSI, Darmstadt, is planning to build FAIR (Facility for Antiproton and Ion Research). This facility will include the SIS300 stage, a fast-ramping heavy ion synchrotron with a rigidity of 300 T-m, based on 6-T, 100-mm coil aperture superconducting (SC) dipoles, ramped at 1 T/s. This article presents investigations concerned with development of the SC dipole for the SIS 300 accelerator. Measured characteristics of the most suitable steels for the iron yoke as well as of SC cable are presented. The results of a study of experimental and calculated differences between straight and bent dipole coils are shown. Optimization of geometries from the viewpoint of magnetic and mechanical characteristics was carried out.

## INTRODUCTION

At present GSI, Darmstadt, Germany plans to build the new international Facility for Antiproton and Ion Research (FAIR) [1]. In frame of IHEP-GSI collaboration IHEP realizes development of SC dipole magnet with 100 mm aperture, 6 T field and 1 T/s field ramp rate as a main element of the magnetic structure of the second stage SIS300. The UNK dipole design [2] was chosen as a base model for the SIS300 dipole. The operating field of these dipoles was 5.11 T, at 0.11 T/s ramp rate. Sizeable temperature and current margins allowed one to reach a magnetic field of up to 6.5 T, with field ramp rate of 0.8 T/s during magnet tests [3]. This article presents main results of developments, made in IHEP, allowing one to reach to modeling SC dipole magnets for the SIS300.

## STUDY OF MATERIAL PROPERTIES

### Electrical Steels

A number of silicon electric steels, both isotropic and anisotropy, with thickness  $\leq 0.5$  mm have been studied extensively from viewpoint of yoke loss minimization and guarantee of field quality in the dipole. Its magnetic properties, including B-H curve, coercive force  $H_C$  and losses in quasistatic mode were measured at 300, 77 and 4.2 K [4]. On the base of this study following steels were chosen for the needs of fast cycling FAIR SC magnets: steels of grade 3411 and 3413 for SIS100 and M250-50A for SIS300 magnets. The last steel was chosen due to minimum hysteretic losses, in spite of the steel 2212 has better magnetic properties. For these steels Si content and the values of magnetization of saturation  $M_s$ , measured in IHEP at two temperatures, are presented in Table 1.

Table 1: Magnetization  $M_s$  of silicon steels.

| Steels   | Si, % | $M_s$ , T (4.2 K) | $M_s$ , T (300 K) |
|----------|-------|-------------------|-------------------|
| M250-50A | 3.3   | 2.09              | 2.04              |
| 3413     | 2.4   | 2.11              | 2.06              |
| 2212     | 1.3   | 2.18              | 2.13              |

### Superconducting Cable

The SC cable for SIS300 dipoles must have low losses and produce acceptable field distortions during the fast ramp. Cable with high resistive core and strands covered by stabrite satisfies to such requirement. We measured the crossover resistance  $R_c$  and adjacent resistance  $R_a$  in a cored cable. Cable consists of 36 strands with 100-mm transposition pitch and has the core made with 25- $\mu$ m thick stainless steel foil. Strands with diameter 0.825 mm have 0.5  $\mu$ m thick AgSn coating. In order to form the oxide layers on the strands surface (i.e. to increase the inter-strand resistance) the preliminary heat treatment at 200°C was done on air in free state. Then stack of cable pieces was cured into fixture under pressure of 90 MPa at temperatures 220°C during 10 minutes or 120°C during 2 hours that imitates polyimide or epoxy adhesive gluing for Kapton insulation, accordingly. It was found that high temperature curing regime for polyimide adhesive gives few times lower  $R_a$  values than the regime for epoxy adhesive, see Table 2.

Table 2. Adjacent resistance  $R_a$  in 36-strand cored cable.

| Preliminary heat treatment | Curing regimes | $R_a$ , $\mu\Omega$ |
|----------------------------|----------------|---------------------|
| 200°C, 2 hours             | 220°C, 10 min  | 46                  |
| 200°C, 2 hours             | 120°C, 2 hours | 109                 |
| 200°C, 2 hours             | 120°C, 2 hours | 83                  |
| 200°C, 4 hours             | 220°C, 10 min  | 16.7                |
| 200°C, 4 hours             | 120°C, 2 hours | 118                 |

Measurements of  $R_c$  were performed on the small pieces of SC cable. Side ridge of cable were cut. Current flowed across cable through the area of  $13 \times 12$  mm<sup>2</sup> (~120 crossover joints). Pressure applied to this area at 4.2 K was varied from 0 to 90 MPa. Above 20 MPa the pressure dependence of  $R_c$  have gentle dip. For the cables exposed by 4-hour heat treatment the crossover resistance  $R_c$  at 50 MPa and 4.2 K (operating condition) was equal 450 and 120 m $\Omega$  for polyamide or epoxy adhesive gluing regimes correspondingly.

### Superconducting Wire

Also the measurement of magnetization of EAS NbTi SC wire with 5 mm twist pitch was done. Magnetization was measured by pickup coils varying the external

magnetic field in region 0–6 T with rate up to 1 T/sec. That allowed us to obtain the expression for effective transverse resistivity of this wire (important value for calculation of eddy current loss in SC wire matrix of fast ramping magnet):  $\rho_{et} = (2.52 + 1.3 \cdot B) \cdot 10^{-10} \Omega \cdot m$ .

## TESTS OF STRAIGHT AND CURVED DIPOLE COIL BLOCKS

Enough small bending radius of the SIS300 ring (50 m) causes anxiety in production of curved magnet, which can lead to a reduction of the critical parameters of a dipole, particularly, the critical current. To define a suitable bending technique, a 1 m long dipole, manufactured in the framework of the UNK project, was chosen. The straight dipole was tested, then bent with 50 m radius of curvature, and retested [6]. The dipole was bent by clamps in a special frame, which supplied the bending of the dipole during test. After bending, the dipole began to retrain. The maximum critical current reached during training of the dipole did not decrease after its bending (Fig.1).

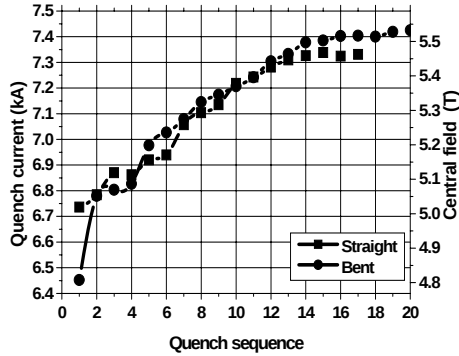


Figure 1: Training of dipole coil block before and after bend.

The dipole was exposed to more than 1000 cycles of 0.5 – 6.8 – 0.5 – 6.8 s (pause – ascent – plateau – descent) with field cycle 0 – 5.0 – 0 T and 0.75 T/s field ramp rate or 1 kA/s, which was the maximum possible current ramp rate for the power supply. Quenches were not observed during magnet cycling and the critical current of the dipole did not decrease after this cycling.

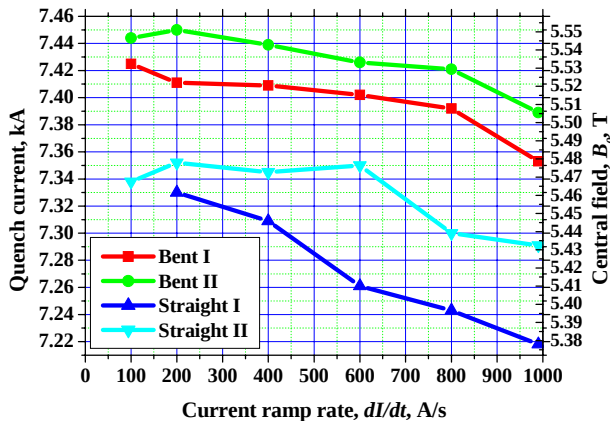


Figure 2: Ramp rate dependences for straight and bent

dipoles, measured before (I) and after (II) 1000 cycles.

The main results of dipole test before and after magnet bending are the following: Bending of the collared dipole coil (50 m curvature radius) did not produce turn-to-turn shorts and did not decrease ground insulation resistance. The dipole began to train afresh after the bending. Characteristics of training and ramp rate dependence of the straight and bent dipoles are similar. 1000 cycles (0 – 5 T – 0 with 0.75 T/s ramp rate) practically did not influence the critical current value and ramp rate dependence in the bent dipole (Fig.2). Cable losses had increased after a storage period of twelve years as the coil turns were under high pressure at room temperature without motion. AC losses were unchanged, after dipole bending. Harmonic  $b_2$  was appeared in curved dipole and this value is in good agreement with calculations.

## DIPOLE GEOMETRY OPTIMIZATION

### History

The main task of development of high field fast cycle SC magnet is the minimization of the heat loads at good field quality. The concept for the new GSI accelerator facilities was reported [7]. The possibility of using of UNK magnets for SIS300 project has been discussed with the reducing AC losses in 2001 in Proposals of IHEP to GSI. The design of dipole with aperture diameter of 80 mm, made from the cable with the reduced hysteresis, matrix and cable losses and thin sheet silicon steel for the yoke has been developed in 2002 [3]. With the aim of increasing aperture to 100 mm three geometries of possible model of SC dipole have been developed in 2003, they differ mainly by the collar thickness, 45 mm, 30 mm and 10mm [9]. For these designs the questions of material selection [4] and AC losses [10], the behaviour of SC magnets at quench process [11], as well the problems of stability of fast cycling SC dipole [12] have been studied. For increasing of the temperature margin from 0.6 K to 1.0 K and reducing of degradation of the current carrying capacity during the cabling the decision has been approved to use partially keystoneed cable with stainless steel core. The design of large aperture SC dipole with 100 mm aperture and partially keystoneed cable with trapezoidal median insertions has been developed in 2005 and is presented in [14]. The design of short dipole model without the trapezoidal median insertions has been developed in 2006 and will be presented in [15].

### 2D Geometry

The 1-m length dipole model consists of six coil blocks (Fig. 3) and has 100 mm aperture with 80 mm good field region. Central magnetic field is 6 T at ramp rate of 1 T/s. The optimization process in the frames of 2D geometry was carried out from point of view the required magnetic and mechanical characteristics of the magnet model.

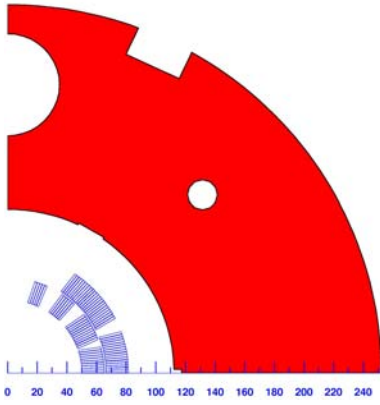


Figure 3: Common layout of the cross section

Table 2 presents main geometrical parameters in cross section, where  $R$  is the inner radius of the layer;  $\varphi$  is the angle of the lower-bottom corner of the block and  $\alpha$  is the initial inclination angle of this block.

Table 3. Geometrical parameters of SC-coil

| Turns | $R$ , mm | $\varphi$ | $\alpha$ |
|-------|----------|-----------|----------|
| 16    | 66.35    | 0.2       | 0        |
| 23    | 66.35    | 26.32     | 31.61    |
| 10    | 50       | 0.2       | 0        |
| 11    | 50       | 19.33     | 24.54    |
| 6     | 50       | 45.73     | 48.38    |
| 5     | 50       | 65.40     | 67.30    |

### 3D Geometry

The optimal azimuthal position of the end coil blocks allows one to suppress field multipoles  $b_n$ ,  $n = 3, 5, 7$ . The layout of the turns at the coil end parts provides the maximum effective length. The selection of the thickness of inter-turn spacers at the end parts and the optimal yoke length allowed one to minimize field in the end parts to the central cross section level.

### AC losses in SC-coil

The calculation of AC losses in the dipole SC coil was carried out for standard magnetic cycle 1.6 - 6 - 1.6 T during the time cycle is 4.4 - 11 - 4.4 - 0 s (ascent - plateau - descent - pause). Following values of contact resistances in the cable were used for cable losses calculation:  $R_c = 20 \text{ m}\Omega$  and  $R_a = 200 \text{ }\mu\Omega$ .

The components of conductor AC losses are: hysteresis losses - 42.7 J/m, matrix - 13.9 J/m, cable - 11.4 J/m. So the total losses is 68 J/m. Losses in the iron yoke are 24.8 J/m and were calculated using measured specific losses [4] so total losses in the magnet are 92.8 J/m.

### CONCLUSION

In the frame of collaboration between IHEP and GSI in 2001-2006 the series of designs of fast cycling SC dipoles for SIS300 accelerator have been developed; the necessary experimental studies and the numerous magnetic, thermal and mechanical calculations of operating characteristics of the magnets were measured.

The next step consists of manufacture and test of the 1-meter SC dipole model with the parameters of the last developed design.

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