3D STATIC AND DYNAMIC FIELD QUALITY CALCULATIONS FOR SUPERCONDUCTING SIS 100 CORRECTOR MAGNETS

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Abstract

The superconducting synchrotron, SIS 100 is the core component of the FAIR accelerator complex. Most of the magnets in the accelerator ring, designed as a superconducting magnets, are based on the Nuclotron technology. The corrector magnets utilize the advantages of the Nuclotron cable as well as of the main dipole magnet. The 2D and 3D designs of the corrector magnets and the field qualities are presented. Some issues to be solved for the realization are also discussed.

INTRODUCTION

The Facility for Antiproton and Ion Research (FAIR), which is an accelerator complex, will be constructed at GSI, Darmstadt, Germany [1]. The superconducting synchrotron SIS 100, which provides various beams to storage rings and beam lines to fit requirements, is the core of this complex. The main dipole magnet, based on the Nuclotron magnet, have been designed and successfully tested. The corrector magnets, namely multipole corrector, steerer, and chromaticity sextupole, are planed to be installed in the ring [2, 3]. The multipole corrector and the steerer were designed as a longitudinal-space-saving nested magnet, namely, a quadrupole, a sextupole and an octupole in the multipole corrector and horizontal and vertical dipoles in the steerer. These magnets are of the $cos\theta$ type. The chromaticity sextupole was designed as a superferric magnet.

MAIN DIPOLE FIELD ERRORS

The static and dynamic field quality was calculated using Opera/TOSCA and Ansys. The reliability of the static field quality results was proven by comparison of the obtained results to the measurements [4, 5]. The calculated static and dynamic field quality is given in Fig. 1. One can see that the eddy currents induced in the vacuum chamber create a significant sextuple, when the ramp starts after injection. Its magnitude is owed to the original design of the chamber [6] but can be reduced by the alternative presented in [7]. Still a correction of this sextupole shall be possible at the start of the ramp, thus the associated correctors strength must be changed considerably faster than the main magnets one.

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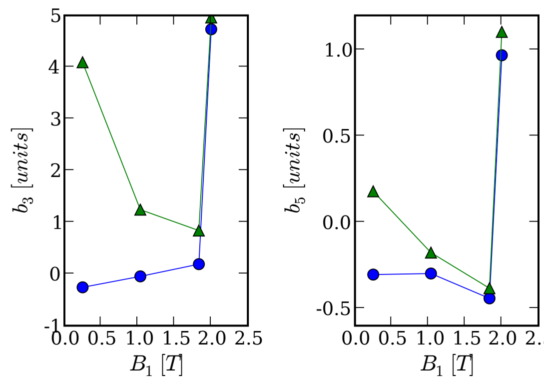


Figure 1: The sextupole and the decapole versus the main field for the static field without vacuum chamber (circles) and on the ramp with the vacuum chamber inserted (tripods). One can see that at injection all multipoles on the ramp are much larger on the ramp than in the static case.

CORRECTOR MAGNET DESIGN

2D and 3D Design

The requirements for the SIS 100 superconducting correctors are shown in Table 1. These correctors have their own current leads, therefore to minimize the heat load from warm-cold transition, low current (less than 300 A) copper leads are adopted. Utilizing the advantages of the Nuclotron type cable on cooling and mechanical stability, the corrector coils are also wound with the Nuclotron type cable. It is, however, necessary to operate them with low current, therefore each wire of the cable is insulated and all wires are powered in series, thus reducing the current by

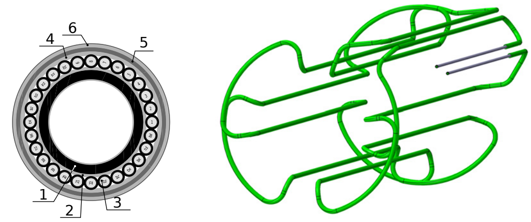
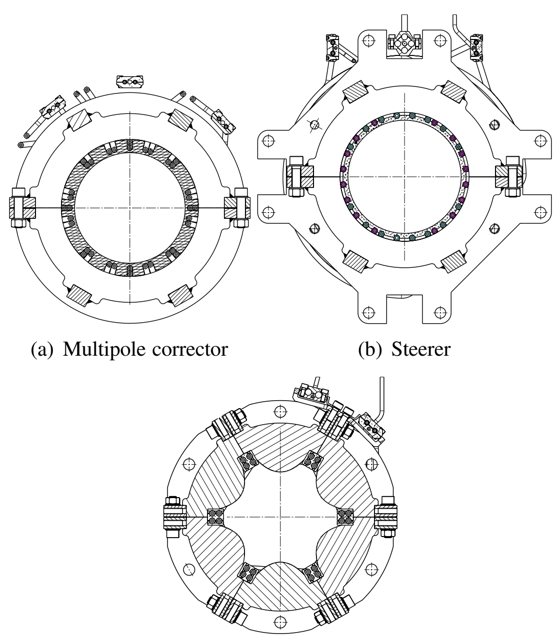


Figure 2: Cross section of the SIS 100 corrector magnet cable; 1. CuNi tube, 2. Ground insulation, 3. Low loss Sc. wire with insulation, 4. Insulation, 5. NiCr wire for fixation, 6. Insulation. And the continuous quadrupole coil winding of the multipole corrector.

Table 1: Parameters of the SIS 100 Superconducting Correctors

		Multipole corrector			**Steerer**	**Chrom. sextupole**
		Quadrupole	Sextupole	Octupole	H/V dipole	Sextupole
Requirements						
Num. of Magnets		12	12	12	84	48
Max. Field strength†	$\mathrm{T/m}^{n-1}$	0.75	25	333.3	0.3	175
Effective length	m	0.75	0.75	0.75	0.5	0.5
Aperture diameter	mm	150	150	150	150	150
Ramp time	sec.	0.15	0.24	0.24	0.2	0.175
Power converter		Bipolar Individual	Bipolar Individual	Bipolar Individual	Bipolar Individual	Unipolar Series
Electromagnetic design parameters						
Num. of Sc. wires		10	22	20	28	28
Current	A	250	246	240	236/232	243
Inductance	mH	0.9	4.6	6.4	21	45
Peak field in cable	T		0.6		0.9	1.4
Margin on the load line	%		46		39	30
Temperature margin	K		2.2		1.9	1.4



(a) Multipole corrector (b) Steerer

(c) Chromaticity sextupole

Figure 3: Cross section of the corrector magnets

the number of wires. Low loss wires are selected to minimize the AC losses as in the dipole magnet. The cross section of the cable is shown in Fig. 2.

The cross section of the multipole corrector and steerer was made to minimize the field errors without mechanical collision of the cables of the nested coils, as shown in Fig. 3. In oder to minimize the risk of the defective wire connection, 3D designs are performed with one continuous cable. The quadrupole coil of the multipole corrector is shown in Fig. 2. Operation parameters are also summarized in Table 1.

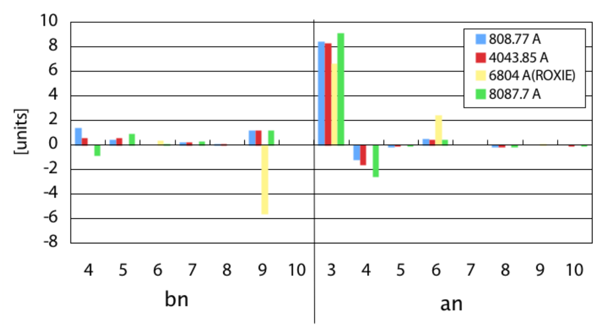


Figure 4: Multipole field error by TOSCA and ROXIE calculations.

Field Quality

The magnet was modeled with all its details in 3D. The obtained integral multipoles‡ are given in Fig. 4 (reference radius $R_{Ref} = 40\,mm$). One can see that Roxie gives only the allowed multipoles next to a large skew sextupole. TOSCA obtained also allowed multipoles, but their sign differs. The obtained skew sextupole differs by 2 units. This difference can be caused by the fact that the coil connection bus bars were only taken into account in the TOSCA model, while the Roxie model made a short cut. Further the TOSCA solver had not yet reached optimal convergence for this model; the TOSCA calculations are rather lengthy (over a week for one single excitation) and still require further improvement of the model.

†Definition: $\mathbf{B} = \sum_{n=1}^{\infty}(B_n + iA_n)(x+iy)^{n-1}$, B_n: normal, A_n: skew, $n = 1$: dipole.

‡Definition: $\mathbf{B} = B_3 \sum_{n=1}^{\infty}(b_n + ia_n)\left(\frac{x+iy}{R_{Ref}}\right)^{n-1} \times 10^{-4}$

AC Losses

AC losses under fast ramp operation were calculated by ROXIE. The superconducting wire specification for the calculations are shown in Table 2. These values were calculated for wires with a Cu and CuMn matrix. The AC loss will be different due to the effective resistivity ρ of the wire, which is given by $\rho = \rho_0 + |\mathbf{B}|\rho_1$, for the inter-filament coupling losses. ρ_0 and ρ_1 of copper and copper-manganese matrices are shown in Table 2, respectively. Iron hysteresis was calculated with an analytical formula [8]. Table 3 shows the averaged AC losses for the triangle excitation. The nested correctors losses are assumed that all coils are excited simultaneously.

In the case of CuMn matrix, the contribution to the losses of one magnet can be reduced from 20% to 2 or 3%, as shown in the table. Consequently, the total loss these correctors decreases by 83% in the SIS 100 accelerator ring.

Table 2: Wire Specification for AC Loss Computations

Wire diameter	mm	0.5
Matrix to Sc. ratio		1.4
Filament diameter	μm	4
Twist pitch	mm	4
ρ_0 (*Cu, CuMn*)	$\times 10^{-10}\Omega$m	0.467, 4.15
ρ_1 (*Cu, CuMn*)	$\times 10^{-10}\Omega$m/T	0.198, 1.90
Sc. filling factor		0.563

Table 3: Averaged AC Losses for Triangle Cycles

(W)	**Multi. corr.**‡		**Steerer**‡		**Chr. sext.**	
	Cu	*CuMn*	*Cu*	*CuMn*	*Cu*	*CuMn*
Int.-fil.	0.85	0.095	1.80	0.20	4.8	0.53
(%)	17.5	2.3	22	3.0	18.4	2.4
Sc.	0.7		0.9		1.1	
Iron	3.3		5.5		20	
Total	4.85	4.1	8.2	6.6	26	22

PRODUCTION PREPARATION

Inspection for Short Turn

As we described above, the insulated strands are connected in series one after the other. A self closed loop by failure of the connection makes degradation of the transfer function and an additional field distortion. In order to find it, we plan to perform warm measurement with rotating coil. Each magnets are excited with 1 A, and detect the transfer function degradation of 3.57% (28 wires) to 10% (1 wires). The ohmic heat induction in the copper-manganese matrix was calculated as within the range of 20-70 W.

A single radial rotating coil is proposed as measurement probe, with the outer windings at $R_2 = 58\,mm$ and the inner one at $R_1 = 0$. The coil probe will be sufficiently mechanically stable even for a length of 1.35 m, which ensures that the whole magnet field is covered. Its sensitivity will be sufficient if equipped with 400 turns. If amplification gains g as given in Table 4 are used, the coil will generate a maximum voltage of roughly 5 V at a rotation speed of 1 revolution per second.

‡All the coils in the nested magnets are excited simultaneously.

Table 4: Strength of the Magnets at RT and Integrator Gains

type	I [A]	$B_m \cdot L$ [Tm @ R_{Ref}]	g
Quad.	1	0.13	100
Sextu.	1	0.25	50
Octu.	1	0.19	50
Steerer	1	0.64	20
Chrom. sext.	1	1.21	10

CONCLUSION

SIS100 corrector magnets have been designed and their field quality is checked in 2D and 3D. As the field homogeneity within the main dipoles varies fast during start of the ramp, the correctors must be ramped with an even higher frequency. The expected AC loss in the correctors was calculated and found to be ≈5 W for the multipole corrector, ≈ 7 W for the steerer and ≈ 22 for the chromaticity sextupole if powered in a triangular cycle with ≈ 2.5 Hz. So, given the cooling power of the cable, cycle frequencies up to a few Hz should be feasible.

In the correctors the wires of the Nuclotron cable are insulated and powered in series; any wrong connection will significantly degrade the transfer function. During production this transfer function can be checked using an rotating coil system.

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