Design of a Superferric Quadrupole Magnet with a High Field Gradient

Alexander Kalimov, Egbert Fischer, Roman Kurnyshov, Gebhard Moritz, Carsten Muehle, and Petr Shcherbakov

[1]Abstract—**FAIR, a new international accelerator complex is now being developed by GSI (Darmstadt, Germany). The synchrotron SIS 100 is a part of this complex and will be equipped exclusively with fast-cycling superferric magnets. The magnet system of this accelerator includes 168 identical quadrupoles with a maximum gradient of 33.4 T/m in an elliptical useable aperture of 120 mm × 65 mm. An important requirement of the quadrupole design is a field gradient uniformity better than ±0.06% for the flux density variation range of 0.2 T – 2 T. This goal is achieved by introducing slots in the central part of the magnet poles, creating the effect of artificial saturation. Simultaneously, these slots reduce the eddy currents in the yoke, induced by the current ramp in the magnet coil. This is important because the whole magnet will be operated near 4.2 K, so the power loss in the yoke should be minimized. Additionally, the shape of the quadrupole pole ends was optimized to provide the necessary integral field quality.**

***Index Terms*— Ion beam applications, magnetic fields, superconducting magnet.**

I. Introduction

A fast-pulsed superferric quadrupole magnet was designed at GSI, Darmstadt for the new international accelerator facility FAIR (Facility for Antiproton and Ion Research)[1], in close collaboration with JINR, Dubna. The synchrotron SIS 100 will be part of this new facility, which will be equipped with superferric dipole [2] and quadrupole magnets. These magnets were designed to be similar in concept to those of the NUCLOTRON accelerator at JINR [2]. In both cases the whole magnet, including yoke, superconducting coil, and beam pipe, is cooled down to helium temperatures (~4.5K). The new requirements for the SIS 100 magnets are substantial ac loss reduction, improved field quality, and stable operation for up to $2\cdot10^{8}$ cycles during a 20 year lifetime. Here, we will describe the design principles and expected properties of the SIS 100 superferric quadrupoles. The main magnet parameters and field quality requirements are summarized in Table I.

TABLE I
SIS 100 Quadrupole Magnet Parameters

Parameter	Units	Value
Maximum gradient	T/m	33.4
Minimum gradient	T/m	4.0
Maximum field in the aperture	T	2.0
Field gradient quality		$\pm6\times10^{-4}$
Useable horizontal aperture	mm	±60
Useable vertical aperture	mm	±32.5
Pole tip radius	mm	46
Maximum pole tip field	T	1.65
Cable inner diameter	mm	4.0
Cable outer diameter	mm	7.0
Number of turns		4
Maximum current	kA	8.0
Effective length	mm	1000
Magnet width	mm	150
Magnet height	mm	150
Magnet length	mm	1080

II. 2D Design of the SIS100 Quadrupole

A. Conductor

The coil of the SIS 100 quadrupole will be fabricated from a hollow superconducting cable, designed at JINR, Dubna [3]. The cable consists of 31 strands of 0.500 mm diameter and with the Cu/NbTi ratio of 1.4. The critical current of the cable at the flux density of 3.0 T is 11.5 kA. Such cable parameters are sufficient to build a winding consisting of 4 turns per pole. The maximum current in such a coil will reach 8.0 kA, while the maximum flux density in the coil area is about 2.6 T.

B. The magnet cross section

The cross section of the iron yoke and the position of the superconducting coil were optimized to provide the required field quality inside the elliptical good field area. The optimized cross section of the magnet is shown in Fig. 1.

For small excitation currents the maximum flux density gradient deviation along the elliptical border of the aperture satisfies the formulated requirements and stays within the margins of ±6×10-4 relative units, as is shown in Fig.2.

Manuscript received September 19, 2005.
A. Kalimov is with the St.Petersburg State Polytechnic University, 195251, Polytechnicheskaya, 29, St.Petersburg, Russia (e-mail: kalimov @sptu.spb.su).
E. Fischer, G. Moritz, C. Muehle, are with GSI, Abteilung BTE, Planckstrasse 1, D-64291, Darmstadt, Germany. (emails: E.Fischerr@gsi.de; G.Moritz@gsi.de; C.Muehle@gsi.de, phone: +49-6159-712368, fax: +49-6159-712043).
R. Kurnyshov is with "Electrozavod", Moscow, Russia
P. Shcherbakov is with IHEP, Protvino, Russia

However, if the field gradient exceeds a level of about 20 T/m, the saturation of the yoke steel affects the field distribution in the aperture noticeably and the maximum deviation of the flux density gradient reaches values of more than $\pm 30 \cdot 10^{-4}$ relative units. This is 5 times worse than the acceptable margin (Fig. 2).

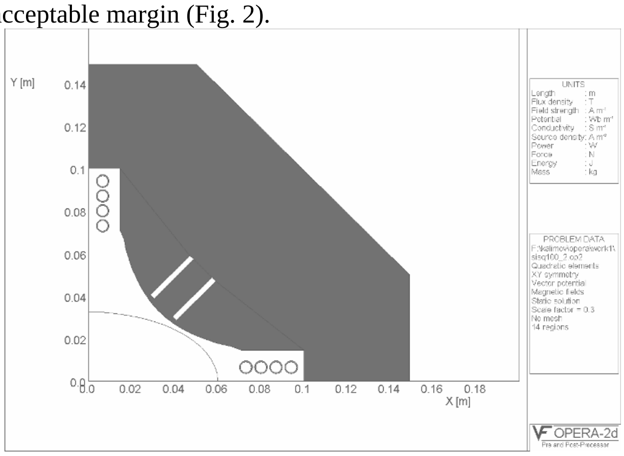


Fig.1. Cross section of the SIS 100 quadrupole magnet. Elliptical line indicates the border of the good field area.

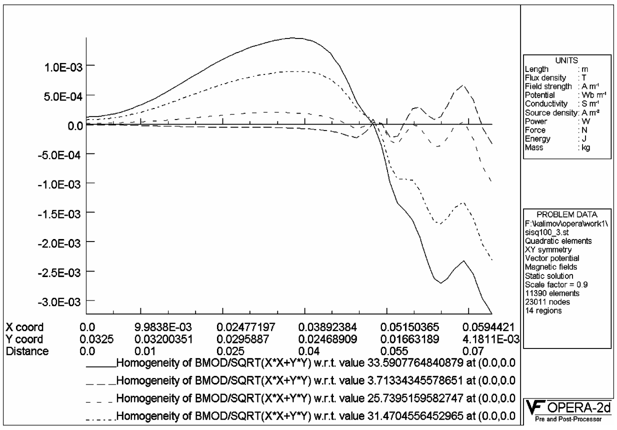


Fig.2 Average field gradient distribution along the border of the elliptical good field area for different field gradient values for the quadrupole without air slots in the yoke.

The negative effect of the yoke saturation may be partly compensated by introducing air slots in the pole [4]. These slots imitate the saturation of the pole's central part at high flux density levels and homogenize the field distribution in the aperture. As a result, we have increased the upper limit of the field gradient, for which the field quality corresponds to the requirements, up to value of 33.5 T/m. The influence of the air slots on the field distributions along the elliptical border of the good field area is demonstrated in Fig.3.

The next plots, shown in Fig. 4, illustrate the dependence of the main higher order field harmonic amplitudes on flux density gradient in the aperture. These data were obtained for a circular line with a radius of 40 mm. One can see that the higher order harmonics do not exceed 0.01% of the main quadrupole field. All the presented results have been obtained using the program OPERA-2D.

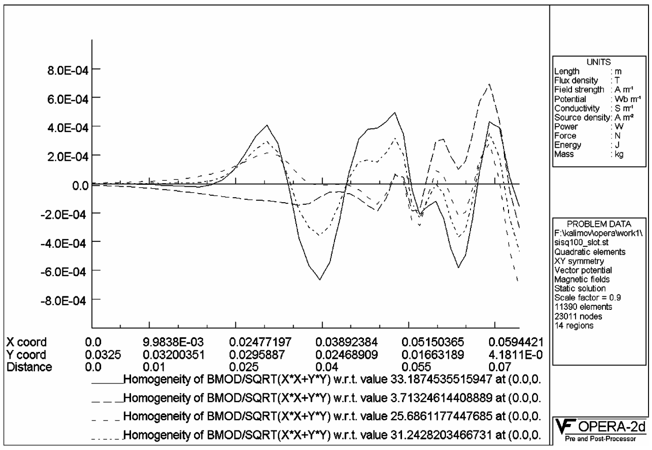


Fig.3 Average field gradient distribution along the border of the elliptical good field area for the different field gradient values for the quadrupole with the air slots in the pole.

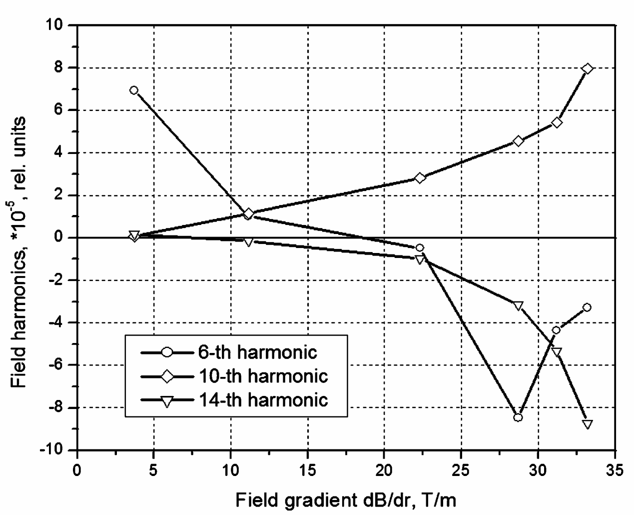
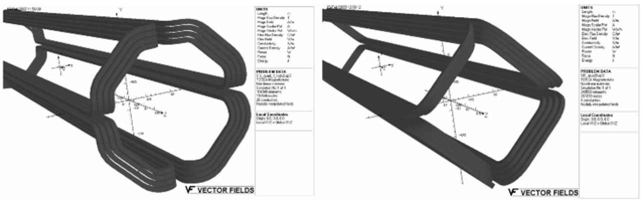


Fig.4. Dependence of the main flux density harmonic amplitudes on the field gradient in the aperture. Harmonics are calculated along a circle of 40 mm radius and normalized to the amplitude of the main quadrupole harmonic.

III. INTEGRAL FIELD QUALITY OF THE SIS100 QUADRUPOLE

The described quadrupole design provides the desired field quality only in the middle part of the magnet. The integral focusing effect of the magnet depends also on the field distribution near the end parts of the magnet. That is why the integral properties were also investigated for different 3D models of the SIS100 quadrupole. As the main criterion for the integral field quality, we used a distribution of the average flux density absolute value along the good-field-area elliptical border. Average field characteristics were calculated as B_{av} = ?Bdz / ? z. A total integration length was chosen to ? z = 0.6 m and includes the half-length of the magnet and additional 0.1 m, where the edge fields could not be neglected. The Fourier harmonics of the average field gradient B_r / r along a circle of 32.5 mm radius were also monitored.

The magnet yoke in the first 3D model was built by simply extruding the 2-D cross section model (Fig.1). The magnet winding was approximated by independent coils of rectangular cross section. Two different types of coil end shape were compared. The first one corresponds to a saddle shape, the second to a race track shape of the coils (Fig. 5).



(a) (b)

Fig.5. Two different types of the quadrupole coils - saddle shape (a) and race track (b).

The 3D simulation of the magnetic field demonstrated that the integral field quality of such quadrupoles is considerably worse than required. The corresponding field integral distributions and the main Fourier harmonics for this model are shown in Fig. 6 and Table II. The deviation of the field gradient from the average value reaches $40{\cdot}10^{-4}$ - $60{\cdot}10^{-4}$ relative units. This is about ten times more, than required. The Fourier components of the field distribution are also ten times higher than in the 2D case. The distributions given in Fig. 6 demonstrate that with respect to field quality, the difference between the two investigated coil structures is not significant.

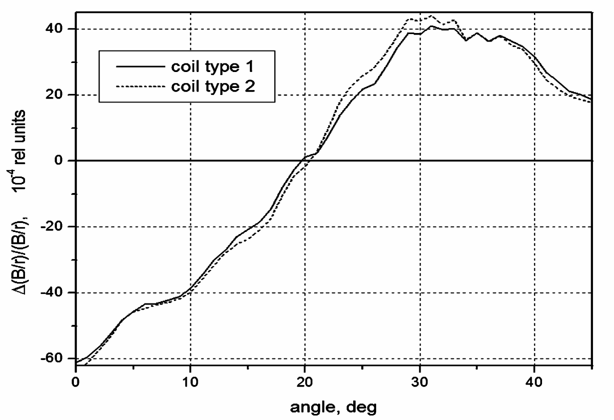


Fig. 6. Average flux density deviation along the border of the elliptical aperture for two types of the coil - saddle shape (type1) and race track (type2).

TABLE II
HIGH-ORDER HARMONIC AMPLITUDES

Harmonics:	6	10	14	18
Coil type 1	$-5{,}975{\cdot}10^{-4}$	$-2{,}093{\cdot}10^{-7}$	$2{,}280{\cdot}10^{-5}$	$-8{,}144{\cdot}10^{-6}$
Coil type 2	$-5{,}758{\cdot}10^{-4}$	$-1{,}763{\cdot}10^{-7}$	$2{,}400{\cdot}10^{-5}$	$-7{,}653{\cdot}10^{-6}$

We have chosen a special shape for the chamfer in the end part of the pole, to improve the integral properties of the SIS 100 quadrupole (Fig. 7). The chamfer angle is 43°. The axial depth is 10 mm. Such a deformation of the pole improves the integral field quality. The deviation of the field gradient integral from the average value generally does not exceed margins of $\pm6\times10^{-4}$ relative units for such a magnet. The amplitudes of the flux-density-gradient higher-order harmonics are only slightly bigger than in the 2D case. For a high value of the flux density gradient (32.2 T/m) the field quality is approximately the same as in the low field case.

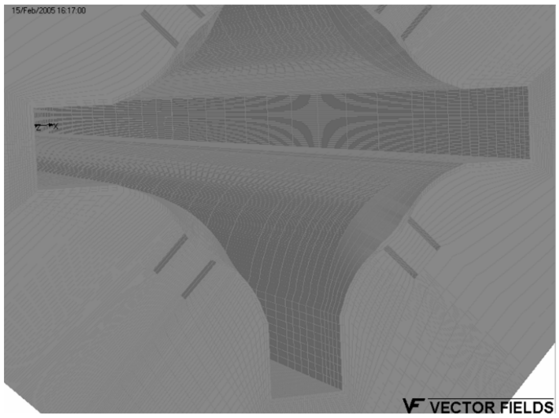


Fig.7. A 3D model of the SIS100 quadrupole yoke (b).

The distributions of the integral field gradient for low and high magnetic fields are shown in Fig. 8. The corresponding amplitudes of the Fourier higher order harmo-nics are given in Table III.

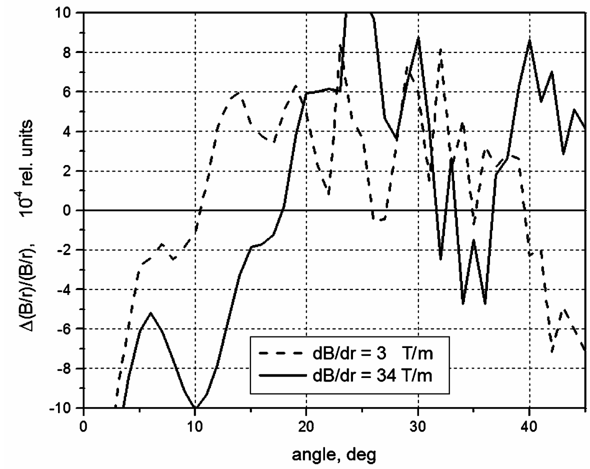


Fig. 8. Average flux-density-gradient deviation along the border of the elliptical good field area for different values of the field gradient, with chamfered pole.

TABLE III
HIGH ORDER HARMONIC AMPLITUDES FOR THE MAGNET WITH THE CHAMFERED POLE.

Harmonics:	6	10	14	18
Coil type 1	$1{,}118{\cdot}10^{-4}$	$-8{,}033{\cdot}10^{-5}$	$2{,}323{\cdot}10^{-5}$	$7{,}775{\cdot}10^{-5}$
Coil type 2	$-2{,}015{\cdot}10^{-5}$	$-6{,}288{\cdot}10^{-5}$	$2{,}613{\cdot}10^{-5}$	$9{,}303{\cdot}10^{-5}$

IV. DYNAMIC PROPERTIES OF THE SIS100 QUADRUPOLE

The designed quadrupole must operate in a pulsed mode. In the most critical case, the flux density in the aperture rises from 0.228 T to a maximum value of 2 T, with a ramp rate of 4 T/s. The magnet yoke is laminated, to reduce eddy currents.

Nevertheless, some noticeable currents can circulate in the lamination plane, due to the longitudinal field components near the magnet ends. The ac loss caused by these eddy currents has to be suppressed because the magnets are operating at helium temperatures and energy savings are important. That is why we compared this longitudinal field component for different coil designs. The corresponding field distributions along different straight lines in the yoke are shown in Fig. 9 and Fig. 10. All 3-dimensional calculations of the static magnetic field were performed using the software OPERA-3D (TOSCA).

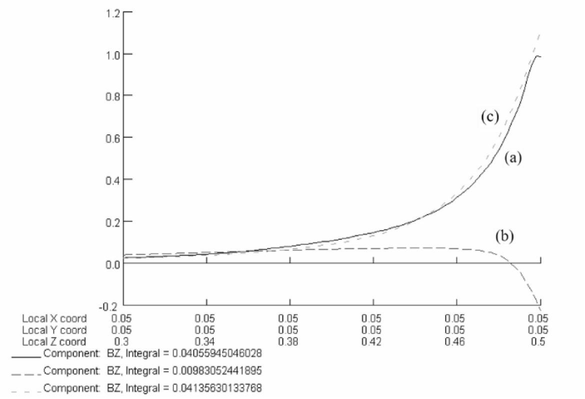


Fig. 9. Distribution of flux density axial component B_z in the yoke along different straight lines for the case of the saddle shape coil: (a) solid line - x = 50 mm, y = 50 mm; (b) long dashed line - x = 70 mm, y = 70 mm; (c) short dashed line - x = 30 mm, y = 30 mm.

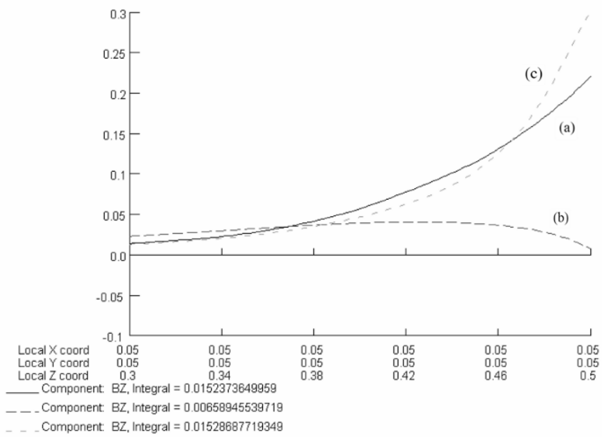


Fig. 10. Distribution of flux density axial component B_z in the yoke along different straight lines for the case of the race track coil: (a) solid line - x = 50 mm, y = 50 mm; (b) long dashed line - x = 70 mm, y = 70 mm; (c) short dashed line - x = 30 mm, y = 30 mm.

The transient processes have been calculated using ANSYS -3D codes for different yoke designs (with and without the slits in the laminations) and coils (race track and saddle shape). The details of the calculation method as well as similar model analyses and comparison to experimental data are given in [5]. Additional fine lamination slits crossing the main direction of the eddy currents can be used for further loss reduction.

The AC losses for the models given here have been determined for an unipolar triangular cycle with a gradient ramp rate of 66 T/(m·s). The time dependence of the loss power due to the axial field in the different yoke modifications are shown in Fig. 11. The overall hysteresis losses were also calculated, using the standard steel properties as given in [5].

The time averaged loss results are summarized in table IV.

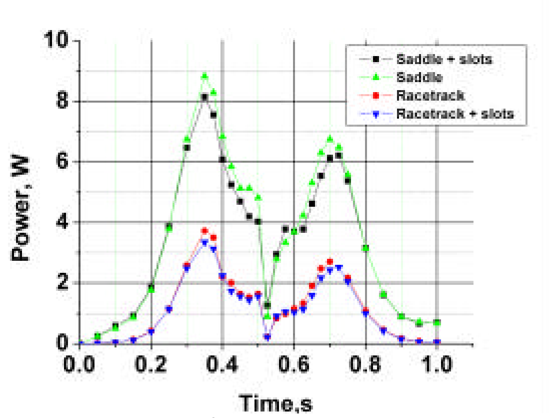


Fig.11 Time dependences of the eddy current loss power due to Bz in laminated yoke.

TABLE IV

SUMMARY OF LOSS CALCULATIONS FOR THE FOUR QUADRUPOLE VERSIONS

coil shape / slots	a) / 0	b) / 0	a) / 2	b) / 2
eddy current loss, W	3.50	1.21	3.25	1.24
hysteresis loss, W	8.65	8.52	8.61	8.96

V. CONCLUSIONS

The design of a superferric quadrupole magnet for the SIS 100 synchrotron developed at GSI is described. A field gradient homogeneity better than ±0.06% over the aperture of 120×65 mm^2 was obtained for a wide range of the maximum magnetic flux density in the aperture (B_{max} = 0.25T – 2.0T). Such field quality for high flux densities is achieved with the help of air slots in the steel yoke, capable of partly compensating saturation effects. A special investigation has been done to define a shape of the magnet end parts, to ensure an integral field gradient homogeneity better than ±0.06%. One profile of the pole end chamfers was chosen for different types of magnet coil ends. The dynamical losses were calculated. Pole air slots not only improve field quality, but reduce eddy currents to a certain extent, as well.

VI. REFERENCES

[1] [1] G. Moritz et. al. "Toward Fast Pulsed Superconducting Synchrotron Magnets," presented at the PAC-2001, Chicago, June 2001.

[2] A.M. Baldin *et. al.* "Superconducting Fast Cycling Magnets of the Nuclotron" *IEEE Trans. on Appl. Superconduct,"* vol. 5, pp. 875 – 877, 1995.

[3] H. G. Khodzhibagiyan et al., "Design of new hollow superconducting NbTi cables for fast cycling synchrotron magnets," IEEE Trans. Appl. Supercond., vol. 13, pp. 3370-3373, June 2003.

[4] A. Chernosvitov, A. Kalimov, H. Wollnik, "Design of an Iron Dominated Quadrupole Magnet with a High Pole-Tip Flux Density," IEEE Trans. Appl. Supercond., vol. 12, pp. 1430-1433, March 2002.

[5] E.Fischer et. al. "3D Transient Process Calculations For Fast Cycling Superferric Accelerator Magnet", MT-19, Genova 2005, THA07PO06