Nb_3Sn ARC QUADRUPOLE MAGNETS FOR VLHC*

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Abstract

Superconducting quadrupoles with a field gradient of 400-450 T/m for a future Very Large Hadron Collider (VLHC) are being studied at Fermilab. To reach the target field gradient in a 40-50 mm aperture, Nb_3Sn superconductor is used at an operating temperature of 4.2 K. Two cases with different magnet functions, beam separation distances and coil arrangements have been analyzed and optimized in order to provide the required field quality and magnet parameters.

1 INTRODUCTION

The magnetic system of the high field stage of VLHC (VLHC-2) is a FODO structure with separate functions. It consists of arc dipole and quadrupole magnets, correctors and special magnets. Conceptual designs of the arc dipole magnets developed for VLHC-2 at Fermilab are described elsewhere [1]. They are based on the 2-in-1 approach but have different coil geometry, bore arrangements and yoke designs.

Design parameters for the arc quadrupole magnets have to be coordinated with the arc dipoles and machine magnetic structure, including IR optics. Obviously the bore separation distance in the quadrupole magnets should match with one in the relevant dipoles.

Based on two possible options of IR optics in VLHC-2, two to different quadrupole magnet functions have been considered. Quadrupoles with a vertical bore arrangement for flat beam optics should provide FF or DD function in each aperture with respect to the relevant beams. Quadrupoles with a horizontal bore arrangement for round beam optics should provide FD or DF functions.

2 MAGNET DESIGN

All quadrupole magnets described below are based on superconducting coils, which utilize the same cable and employs design principles similar to the Nb_3Sn shell-type dipole [2]. The bore diameter is 43.5 mm, the total number of turns is 52 and the coil area is 24.1 cm^2. The inter-layer spacer thickness is 0.28 mm and thickness of an additional mid-plane insulation layer is 2×0.125 mm. Each coil quadrant has a floating pole and wedges in the inner layer, which allows minimizing of the low order field harmonics.

Coil geometry optimization was done using the ROXIE code [3], assuming a round yoke with an inner radius of 72 mm and a constant iron permeability of 1000. Figure 1 presents the optimized coil cross-section with a field quality diagram.

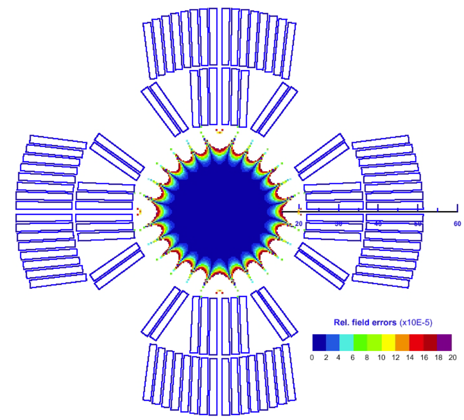

Figure 1: Quarupole coil cross-section.

The coil straight section is prestressed and mechanically supported by means of Nitronic 40 stainless steel collar laminations with minimum thickness of 20 mm. Such a coil support structure will be able to keep the coils under compression with stresses in the coil less than 150 MPa in the operating gradient range [4]. No additional prestress and support from the iron yoke is required. Tapered keys lock collar laminations in two perpendicular directions. Thick aluminum end cans provide prestress and mechanical support of the magnet ends.

2.1 Magnet with vertical bore arrangement

The arc quadrupole with a vertical bore arrangement is designed for use with the common coil dipoles [1]. The dipole design optimized for the “react and wind” technique dictates the bore separation distance of 290 mm. The iron yoke is split vertically into two pieces, allowing assembly of collared coils in the common yoke. The collared coils are aligned inside the yoke with special alignment keys. To eliminate the effect of possible gap variation on the field quality, the vertical gap between two iron pieces is always closed.

The FF/DD quadrupoles are required for the flat beam optics. In this case the coils are powered such that the magnetic flux is tangential to the magnet midplane, imposing negative coupling between the two apertures. Special holes are used to minimize magnetic coupling and the iron saturation effect. The large holes in the magnet midplane have the same diameter and separation distance as the holes in the dipole magnet. One additional hole in magnet center serves for minimization of remaining deviations in field multipoles due to the yoke saturation effect. Figure 2 presents the magnet cross-section numerically optimized using the OPERA2D code. The optimum yoke outer diameter is 530 mm.

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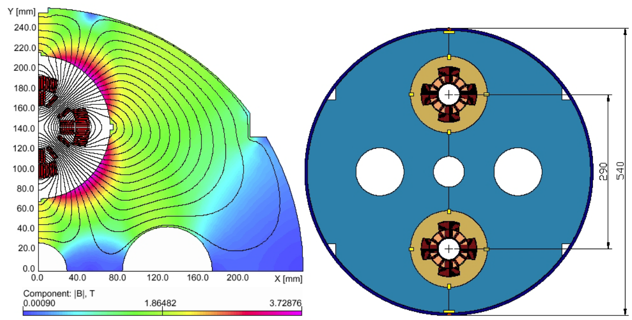

Figure 2: Field map and "cold" mass cross-section of FF quadrupole.

2.2 *Magnet with horizontal bore arrangement*

The arc quadrupole with a horizontal bore arrangement is designed for use with the shell-type dipoles [1]. The bore separation in this case is 180 mm. The collared coils are assembled and aligned inside the common yoke according to the same principles as for the quadrupole with a vertical bore arrangement. No essential difference in mechanical behavior between these two magnets is expected due to the force irrelevance to the bore orientation.

The baseline design of the arc quadrupoles with a horizontal bore arrangement is the FD configuration, suitable for the round beam optics. In this case the coils are powered such that the magnetic flux is normal to the magnet vertical plane, imposing a positive magnetic coupling between the two apertures. The position and size of correction holes were optimized to minimize the iron saturation effect. Figure 3 presents the magnet cross-section numerically optimized using the OPERA2D code. The optimum yoke outer diameter is 420 mm.

3 MAGNET PARAMETERS

The main parameters of the quadrupoles with vertical and horizontal bore arrangements are summarized in Table 1. The nominal current of the quadrupoles is larger than the nominal current of the relevant dipoles, which requires a separate power system. Otherwise the dipole and quadrupole operation current can be adjusted by decreasing the cable thickness in the quadrupole magnets.

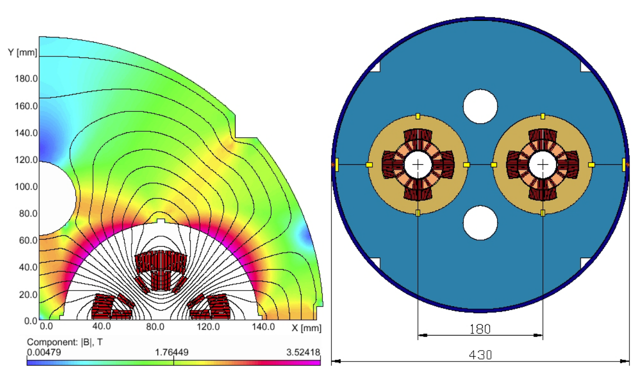

Figure 3: Field map and "cold" mass cross-section of FD quadrupole.

Table 1: Quadrupole magnet parameters.

Magnet function		FF	FD
Nominal gradient G, T/m		400	400
Nominal current I, kA		27.2	27.3
Aperture, mm		43.5	43.5
Aperture separation, mm		290	180
Iron yoke OD, mm		530	420
G/I @ 400T/m, T/m/kA		14.69	14.67
Stored energy @400T/m, kJ/m		2×209	2×209
Inductance @400T/m, mH/m		2×0.565	2×0.562
Forces per first coil octant	F_x	0.993	0.997
@400T/m, MN/m	F_y	1.313	1.318

The calculated maximum gradient in the quadrupoles at 4.2 K vs. the critical current density in the Nb_3Sn coil for two values of the Cu:nonCu ratio is shown in Figure 4. There is no visible difference in the results for the FF/DD or FD/DF designs. For the expected 10% of critical current degradation, the nominal gradient of 400 T/m is achieved with a 10% margin in both designs using strands with J_c(12T,4.2K)=3kA/mm^2 and Cu:nonCu=1.2:1, required for the quadrupole quench protection.

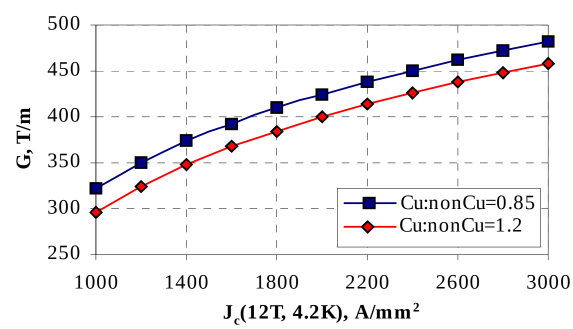

Figure 4: Maximum gradient vs. critical current density.

Magnetic field in the quadrupole bore is described as:

$$B_y(x,y)+iB_x(x,y)=10^{-4}\times B_2\sum_{n=1}^{\infty}(b_n+ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1},$$

where $B_x(x,y)$ and $B_y(x,y)$ are the horizontal and vertical field components, B_2 is the quadrupole field component, R_{ref} is the reference radius, b_n and a_n are the normal and skew harmonic coefficients.

The calculated geometrical harmonics at 1-cm radius and the RMS for ±50µm random coil block displacements are summarized in Table 2, which serves for both designs.

Table 2: Systematic and random harmonics, 10^{-4}.

n	Systematic, b_n	RMS,σ_{an}	RMS,σ_{bn}
2	10000.0000	4.78	-
3	-	1.82	1.82
4	-	0.82	0.83
5	-	0.38	0.37
6	-0.0003	0.19	0.15
7	-	0.071	0.075
8	-	0.026	0.035
9	-	0.013	0.014
10	-0.0038	0.001	0.01

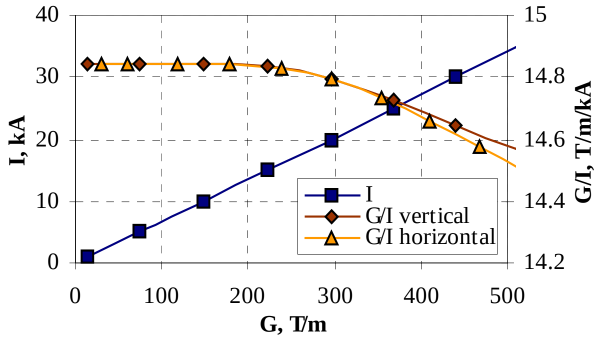

Figure 5: Transfer function and coil current vs. gradient.

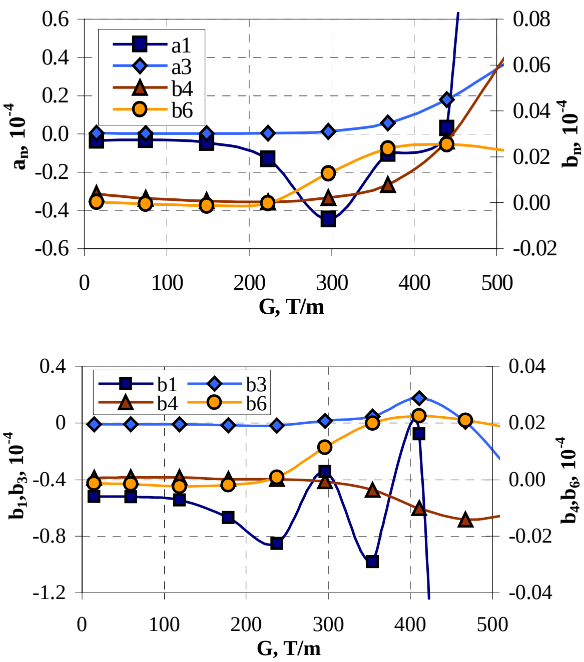

Figure 6: Harmonics in FF (top) and FD (bottom) quadrupoles.

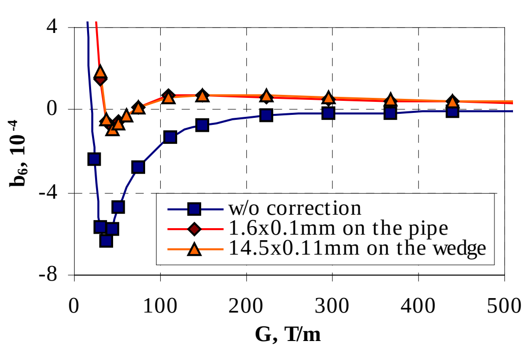

Figure 7: Coil magnetization effect.

The effect of iron saturation at high gradients on the magnet transfer function is shown in Figure 5. The effect is noticeable for gradients larger than 200 T/m. Field multipole deviations due to the yoke saturation effect in both designs are shown in Figure 6. The top-bottom asymmetry in FF quadrupole results in deviations of skew dipole and sextupole, while left-right asymmetry in FD quadrupole turns them into normal dipole and sextupole. Deviations of the higher order multipoles are considerably smaller.

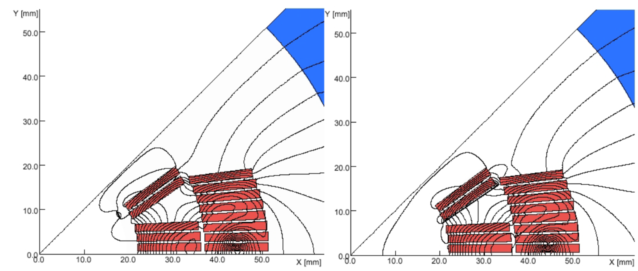

Figure 8: Field correction at injection by strips on the beam pipe (left) and on the wedge (right).

The effect of superconductor magnetization on the field quality is shown by Figure 7. The calculations were performed for the Nb_3Sn strands with J_c(12T,4.2K)=2 kA/mm^2, d_{eff} =100 μm and Cu:nonCu ratio of 0.85. The field quality noticeably deteriorated at low gradients due to the high coil magnetization. A passive correction with 0.1 mm thick iron strips [5], placed as shown in Figure 8 on the wedge upper surface or on the beam pipe, significantly improves the field quality at injection.

4 CONCLUSION

The designs of arc quadrupoles with the horizontal and vertical bore arrangements have been optimized for matching with the relevant arc dipoles. They meet the VLHC-2 requirements, providing an operation gradient range from 45 to 400 T/m with sufficient critical current margin and good field quality. The iron saturation effect on the low order harmonics is suppressed by optimizing the yoke geometry. The coil magnetization effect at low field gradients is effectively reduced by using a simple passive correction based on iron strips.

6 REFERENCES

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