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Design Optimization of a Compact Quadrupole Electromagnet for CLS 2.0

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***Abstract*—**This paper reports a study on the optimal magnetic design of a compact quadrupole electromagnet for the Canadian Light Source (CLS 2.0). The nature of the design is to determine a quadrupole with low relative higher order harmonics and better field quality. The design problem was formulated as an optimization model, in which the objective function is the higher order harmonics (multipole errors) and the variable to be optimized is the material distribution on the pole. The higher order harmonics arose in the quadrupole due to truncating the ideal hyperbola at a certain point to make the pole. In this project, the arisen harmonics have been optimized both transversely and longitudinally by adjusting material on the poles in a controlled way. For optimization, finite element analysis (FEA) has been conducted. A better higher order harmonics amplitudes and field quality have been achieved through the optimization. On the basis of the optimized magnetic design, electrical and cooling calculation has been performed for the magnet.

***Keywords*—**Drift, electrical, and cooling calculation, integrated field, higher order harmonics (multipole errors), magnetic field gradient, quadrupole.

I. Introduction

THIS project aimed to optimize the design of a quadrupole that has coils that do not protrude beyond the magnet yoke. In the case of a conventional quadrupole, the coils stick out beyond the magnet yoke into the drift space between magnets (Fig. 1). Since the new quadrupole occupies none of the drift, it is called a "Zero Drift Quadrupole".

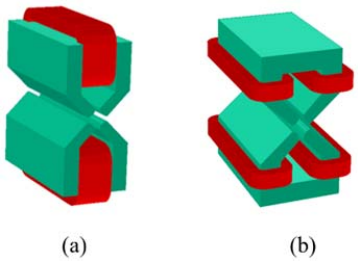


Fig. 1 (a) Zero Drift Quadrupole (Coil does not stick out beyond the magnet yoke), and (b) Conventional Quadrupole (Coil sticks out beyond the magnet yoke)

This quadrupole design is part of the design study for a new storage ring for the Canadian Light Source (CLS 2.0). A preliminary magnetic analysis of this quadrupole was presented at IPAC 18 [1]. The magnet is 240 mm long with a 12 mm aperture radius and has two coils recessed on two top yokes. 2D magnetic models have been performed with POISSON [2]. This code was used to define the field gradient and minimize the transverse multipole errors. To calculate the integrated field and to do some longitudinal multipole optimization 3D simulations were performed with Opera [3].

The main objectives of this project were an optimized integrated field with the least multipole errors and determine the electrical and cooling specifications for the quadrupole based on the optimized magnetic design.

II. Optimization Methodology

Using the 2D code, the pole tips were shaped to reduce the multipole errors. The process was to insert bumps at the asymptotes poles edges to compensate for the subtracted materials from the ideal hyperbola as shown in Figs. 2 and 3.

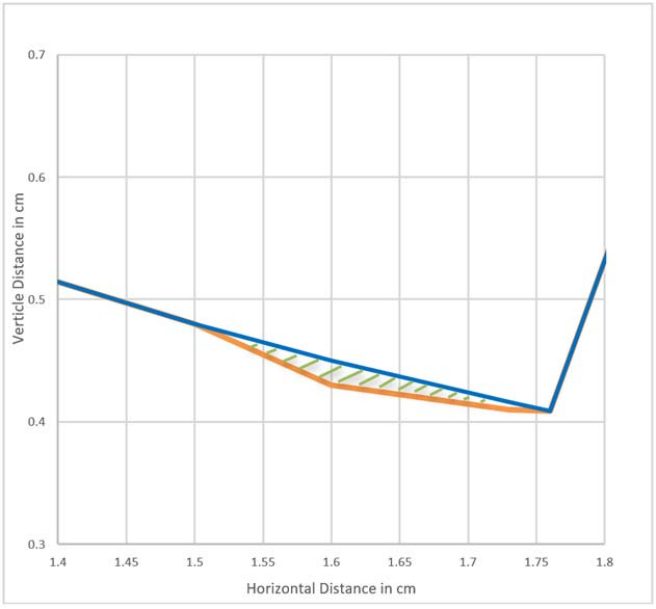


Fig. 2 Comparison of hyperbolic pole (blue line) and optimized pole (orange line) shape showing compensated material (green lines covered zone) on the pole contour. This is symmetric on the other side of the pole which has been indicated in Fig. 3

The process of selecting the position of the bumps in the pole contour was an iterative process using the 2D code where the performance function was the first few allowed multipole errors, satisfying the requirement of $\frac{\Delta B}{Bo}$, a certain value within

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the good field region ±10 mm [4]. The bumps required are a small deviation from the truncated hyperbola of the original model. The effectiveness of the bumps is calculated by evaluating the multipole harmonics B_n. The relative deviation from an ideal quadrupole is given by

$$\frac{\Delta B}{B_0} = \frac{\sum_{n=3}^{\infty} B_n X^{n-1}}{B_2 X} \quad (1)$$

where B_2 is the quadrupole gradient. The results of the optimization are shown in Table I and Fig. 4.

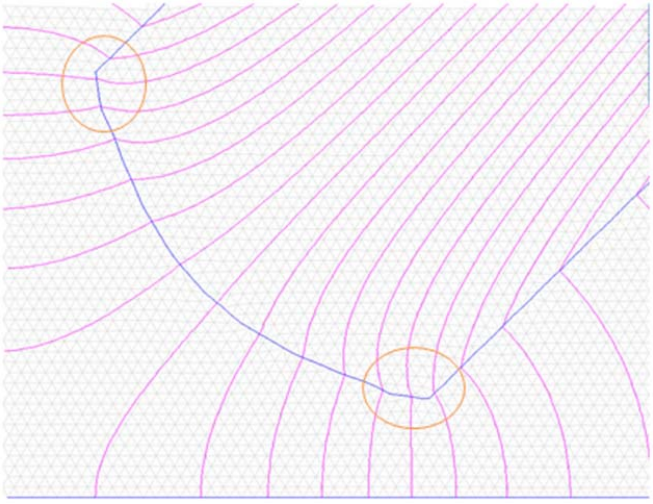


Fig. 3 Optimized 2D field simulation at the pole. The orange circles showed the locations of the bumps at the pole edge

TABLE I
QUADRUPOLE HARMONICS

Harmonics	Uncorrected	Optimized
B_2 (T/m)	54.06	55.80
B_6 (T/m^5)	-0.088408	-0.0033077
B_{10} (T/m^9)	-0.020988	0.0082867
B_{14} (T/m^{13})	-0.010726	-0.0089632
B_{18} (T/m^{17})	0.00064977	0.000046123
B_{22} (T/m^{21})	0.0019474	0.0019432
B_{26} (T/m^{25})	0.0035001	0.0039019

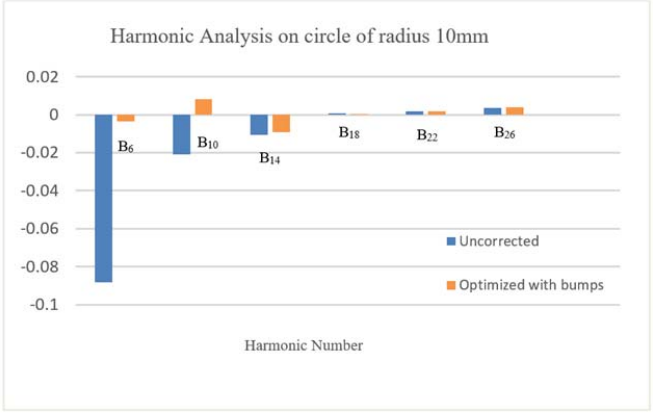


Fig. 4 2D harmonic analysis on a center circle of radius 10 mm

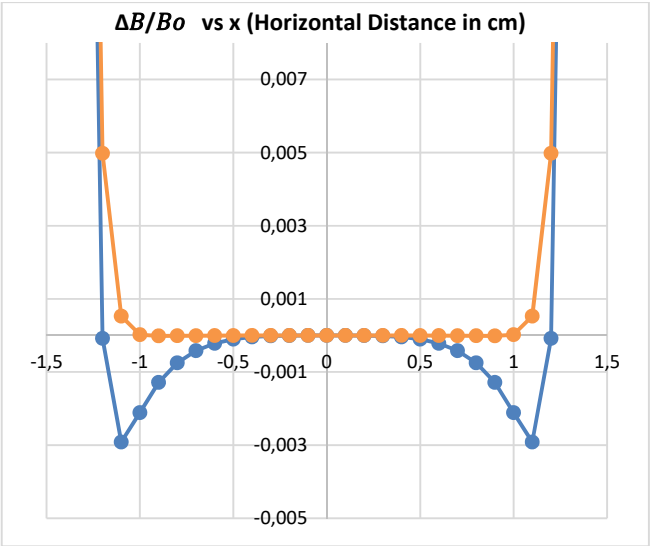


Fig. 5 Field Quality for uncorrected (blue) and optimized pole tip (orange)

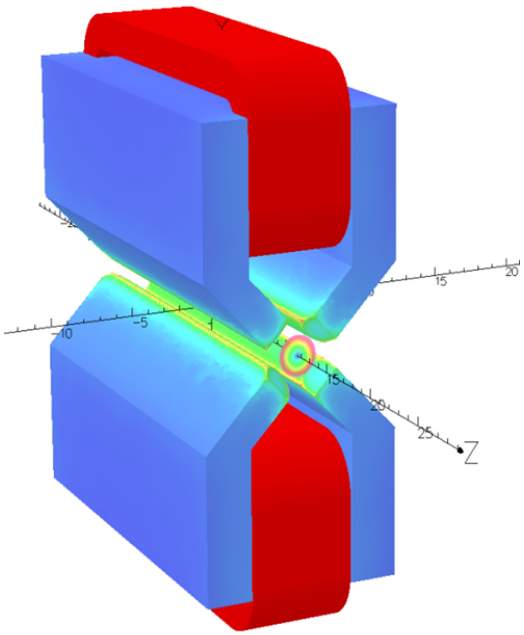


Fig. 6 Opera 3D final model, showing magnetic flux density B, at the end of the magnet on a 10 mm radius circle

The 2D simulation has been performed taking AISI 1010 steel as the magnet material and 4020 amp-turns. The quadrupole gradient B_2 in Table I has increased for the optimized shape due to some geometry adjustment on the top yoke. The gradient for all harmonics was observed on a circle of radius 10 mm at the center of the one quadrants of the full magnet. Field Quality for the uncorrected and optimized shape has been calculated following (1), considering up to harmonic 26. Due to the 2D model symmetry, only harmonics 6, 10, 14, etc. are present.

The improvement of the "good field region" is shown in Fig. 5. With the correction the good field region extends from

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-1 cm to +1 cm.

To analyze the integrated field and end effects, 3D simulation was performed (Fig. 6). For simulation, AISI 1010 steel was used and current density 6.7 A/mm^2 resulting in 4020 Amp-turns. The quadrupole design was evaluated by comparing the integrated field strength of a conventional magnet and the Zero Drift magnet. For both models, the geometry from POISSON has been used. The integrated field is evaluated at a position of X = 10 mm off axis from the center of the magnet.

Further optimization has been done on each pole tip end by removing some material to reduce the field errors arising from end effects [5]. This end chamfer is shown in Fig. 8.

Various dimensions for the end chamfer were evaluated. A satisfactory result was found with a 1 cm cut along the Z-axis and a 0.5 cm cut along the outer surface. The higher order harmonics were calculated from the model by Fourier analysis on a circle of radius 10 mm at the end of the magnet (see Fig. 6). The values are normalized to the same quadrupole gradient. The results are shown in Fig. 9.

The integrated field at 10 mm off-axis is 127.15 T-mm. The integrated quadrupole field at 10 mm off-axis from the optimized 2D model is BL = 133.9 T-mm where the effective length, L, is taken to be the yoke length. The effect of recessing the coils was to reduce the integrated field strength by 5% which is an acceptable amount. The field errors evaluated in the transverse direction were not adversely affected.

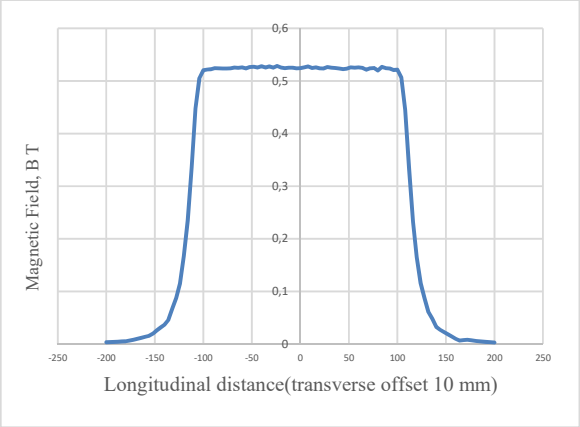


Fig. 7 Magnetic field distribution along the longitudinal coordinate, at a transverse offset of 10 mm

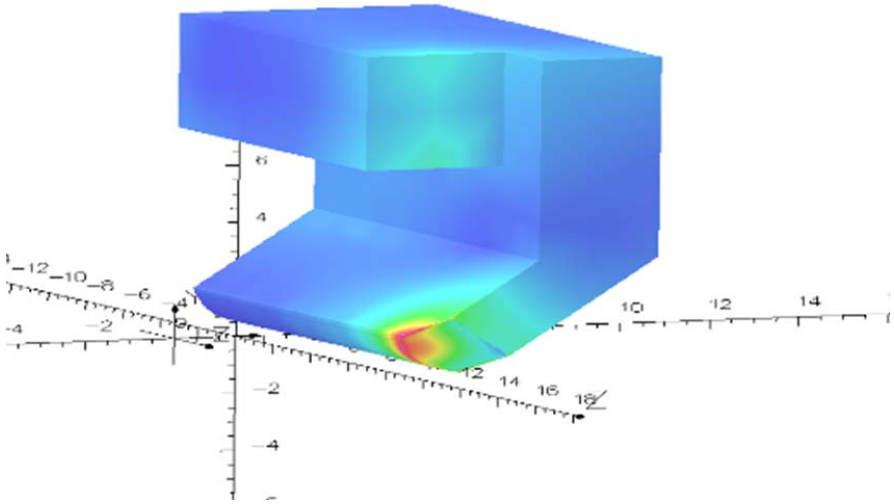


Fig. 8 End chamfer on each pole tip (1 cm cut along the Z axis and 0.5 cm cut along the outer surface)

III. Result

The magnetic properties of the optimized quadrupole are presented in Table II.

TABLE II
QUADRUPOLE PROPERTIES

Unit	Parameter	Value
mm	Yoke Length	240
	Ampere- turns	4020
mm	Aperture radius	12
T/m	Gradient	55.80
T-mm	Integrated Field (@ 10 mm)	127.15
mm	Effective Length	227.9
mm	Good Field Region	±10

IV. Electrical and Cooling Calculations

Electrical and cooling calculations have been performed with a copper conductor of cross-section area 4.76 x 4.76 mm^2 with a cooling duct of diameter 3.19 mm. 48 turns were used for the coil. The total length of the conductor is 52.6 m. Temperature rise through the conductor is due to 83.75 A (I=4020/48) current flow. The velocity of deionized cooling water (Low Conductivity Water) has been calculated keeping the pressure drop, from 155 psi to 35 psi [6]. The calculated electrical and cooling parameters for the magnet are given in Table III.

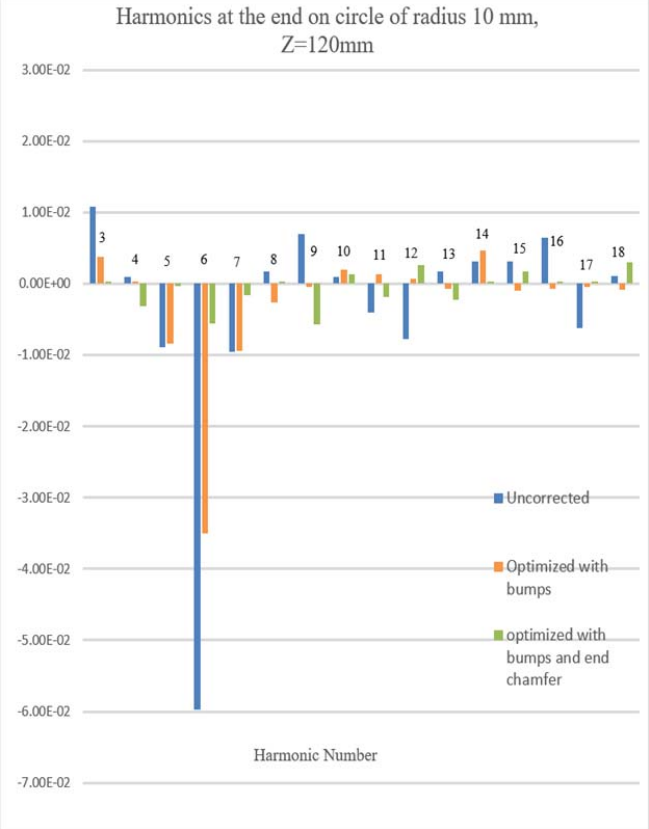


Fig. 9 Normalized harmonics at the end of the magnet

TABLE III
ELECTRICAL AND COOLING PARAMETERS

Unit	Parameter	Value
mm^2	Conductor cross-section	4.76
mm	Cooling duct diameter	3.19
	Windings per coil	48
Ohm	Resistance per coil	0.019987
KW	Maximum power per magnet	1.608
V	Voltage drop per magnet	3.34
^oC	Temperature rise in coil	7.78
m/s	Coolant speed	2.13
bar	Pressure drop per magnet	8.16

V. CONCLUSION

A "Zero Drift" quadrupole has been designed with the coils recessed into the magnet yoke such that the coils do not protrude beyond the magnet steel. Thus, in a magnet lattice, the drift space adjacent to this magnet remains unobstructed. With the coils placed on the outer yokes, the steel can be made thicker in the transverse direction in order to compensate for the loss of material in the longitudinal direction. Consequently, an efficient integrated field can be produced at high quadrupole strengths. Higher order modes in the magnet can be reduced to a level such that field errors are negligible at transverse amplitudes up to 10 mm. Electrical and cooling requirements are comparable to present CLS quadrupole designs.

REFERENCES

[1] Dallin, L.O., Bertwistle, Drew. "Magnet Design Considerations for an Ultralow Emittance Canadian Light Source" 9th International Particle Accelerator Conference (IPAC2018), Vancouver, BC, Canada.
[2] J. H. Billen and M. L. Young. "POISSON/SUPERFISH on PC Compatibles," in Proc. PAC'93, Washington DC, USA, May 1993.
[3] Meng, Wuzheng. "Magnet Design and Simulation", 22 August 2013.
[4] Tanabe, Jack. "Iron Dominated Electromagnets, Design, Fabrication, Assembly and Measurements", Chapter 3-4, pp 57-83, January 06, 2005,
[5] Marks, Neil. "Conventional Magnets for Accelerators", September 2004.
[6] Lin, Linda. "CLS Mechanical Services Design Criteria for System & Components"- 6.1.15.1 – Rev. 2, March 02, 2011

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