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FIELD AND COST OPTIMIZATION OF A 5 T/m NORMAL CONDUCTING QUADRUPOLE FOR THE 10-MeV BEAM LINE OF THE eLINAC OF THE MEXICAN PARTICLE ACCELERATOR COMMUNITY*

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Abstract

The Mexican Particle Accelerator Community is currently designing the first Mexican RF eLINAC composed of three beam lines at 10, 60 and 100 MeV. In this work, we present an optimized design in terms of field quality and production cost for the 5 T/m normal conducting quadrupoles of the 10 MeV beamline. Several candidate materials for the yoke were studied in terms of the availability and machinability, with the aim to optimize in-house production cost (Mexico) while restricting a low multipole content.

INTRODUCTION

The Mexican Particle Accelerator Community (CMAP) is composed of a group of young scientists and students that have the common goal of developing science and technology of particle accelerators in Mexico. Since foundation, in 2015, CMAP has been boosting the development of the area by promoting fundamentals schools and workshops for students all around from Mexico and, recently, with a project to develop of a 100 MeV electron linac, currently under design. The lattice linac design will be using 2 m focusing-defocusing (FODO) cells, and each of it is formed of two quadrupoles [1]. This work presents an optimized design for the normal conducting quadrupoles that will make part of the Mexican linac FODO Cells. The design is based on a cost optimization model, in terms of production cost and field uniformity, developed to promote in-house manufacture.

PARAMETRIZATION MODEL

The development of accelerator technology represents a challenge, on one hand the technological and on the other hand economical perspectives [2–4]. To merge both concepts, a comprehensive design of a normal conducting quadrupole must consider a large number of parameters to fulfill beam requirements, and it should provide a feedback of how this affect the total production and operation cost. A schematic model of one quarter of the "standard type" quadrupole geometry is shown in Fig. 1, that relates the field requirement with the geometry parameters, providing a direct path for field and cost optimization.

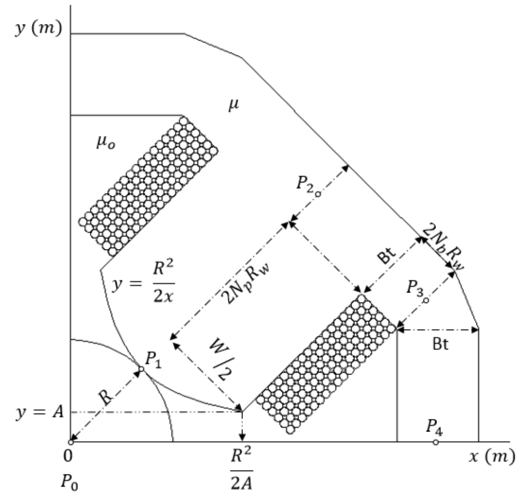

Figure 1: Geometry parameters for a quarter section of a standard type geometry of normal conducting quadrupole.

The main parameters that defines the geometry of a quadrupole are: R the aperture radius, W the width of the hyperbola pole-profile, and A, the latter defined as in terms of the minimum pole distance [5]. This last parameter has a strongly influence of the field quality at the good region of the aperture. By geometric construction one can express the width of the pole as:

$$W = \sqrt{2}A \left| 1 - \frac{R^2}{2A^2} \right| \qquad (1)$$

On the other hand, the length of the pole can be expressed in terms of the number of wires Np, laying on the pole face of a block-coil distribution, which depends on the conductor radius Rw. The thickness of the flux return Bt, depends on the field saturation, and can be defined on the magnetic relaxation model. This model provides a correlation between the main geometric parameters and the beam requirements, and it could be easy extended to Collins and Panofsky geometries [6], or to higher order normal conducting electromagnets.

COST OPTIMIZATION

To produce an optimized quadrupole, in terms of minimum production, operation cost, and optimum field performance, we have merged the latter parametrization model,

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with the cost optimization procedure given by Brianti and Gabriel [7], and extended to normal conducting quadrupoles.

The total cost is divided into two main components: the equipment cost M_e, and the running cost, M_r. The first takes into account the cost of the power supply and associated equipment M_1, cost of finish coil mounted on the yoke M_2, cost of the finished yoke M_3, cost of a.c. and d.c. distribution M_4 and cost of cooling M_5, shown in Eq. (2). The latter, considers the operation cost for a given running time and involves the cost of electricity for the power supply.

$$M_{tot} = M_r + \sum_{i=1}^{5} M_i \tag{2}$$

We have chosen to normalize the cost components M_i with respect to power supply cost, to avoid fluctuations in cost and economy. This normalization relates the cost between different components and leaves undetermined the actual money. The values and the functional dependence of the M_i coefficients with the main parameters are given on Table 1.

Main Parameters

Both components of the capital cost, M_e and M_r depends on the active power, the volume of the conductor and the volume of the yoke, as described in [7]. The power P, defined by the Joule-Lenz law [8], can be express in terms of the main beam requirements: field gradient K, current density S_f, magnet length L, aperture radius R and the field quality (A), setting the magnet length and the current density as the two scaling parameters. To determine the power P, we define the number of wires per pole in terms of the field gradient and aperture radius. The former is determined by the electrical excitation in the coils according to Ampere's law [9]. If the integration path connecting the segments: $\overline{P_0P_1}$, $\overline{P_1P_2}$, $\overline{P_2P_3}$ and $\overline{P_3P_0}$ on Fig. 1 is used, one can estimate the field gradient in terms of the operational current I_{op}, as:

$$I_{op} = \frac{KR^2}{2\mu_0} \tag{3}$$

The number of wires per pole, is obtained as the ratio between the operational current, and the total current per wire, in terms of the current density passing through a conductor of radius R_w:

$$N = \frac{KR^2}{2\mu_0(S_f \pi R_w^2)} \tag{4}$$

If a conductor of radius R_w and resistivity ρ_c is used, the resistance is:

$$R = \frac{\rho_c L}{A} = \frac{\rho_c}{\pi R_w^2}\left[L + W\right] 8N \tag{5}$$

The power P defined by the length of the magnet, the resistance of the conductor and the current density, can be expressed as:

$$P = \frac{4K\rho_c S_f R^2}{\mu_0}\left(L + \sqrt{2}A\left|1 - \frac{R^2}{2A^2}\right|\right) \tag{6}$$

One can estimate the volume of conductor as:

$$V_c = \frac{4KR^2}{\mu_0 S_f}\left(L + \sqrt{2}A\left|1 - \frac{R^2}{2A^2}\right|\right) \tag{7}$$

From Fig. 1, the volume of the iron yoke is calculated as a function of the quadrupole length L. Assuming that the cross-sectional area of pole is approximately $2N_pR_WW$, one can write the volume of the yoke as given by:

$$\begin{aligned} V_y = L\Big[&8B_tN_pR_W + 4B_tW + 16B_tN_bR_w + \\ &\sqrt{2}B_t^2 + 8B_t\left(A + \sqrt{2}R_W\left(N_p - N_b\right)\right)\Big] \end{aligned} \tag{8}$$

From $N = N_pN_b$ one can express N_b as:

$$N_b = \frac{KR^2}{2\mu_0\left(S_f\pi R_w^2\right)}\frac{1}{N_p} \tag{9}$$

Table 1: CMAP Quadrupole Parameters and Values

Parameter	**Symbol**	**Value**
Field Gradient	K	3.2 T/m
Aperture radius	R	0.025 m
Field at pole tip	B_{tip}	0.080 T
Minimum pole distance[1]	A	0.0074 m
Flux return thickness	B_t	0.013 m
Wires along pole	N_p	18
Wires along base	N_b	6
Total Wires/pole	$N = N_bN_p$	108
Conductor radius	R_w	0.002 m
M_1	$M_1 = M_{01} + m_1(\alpha P)$	
Power Supply & Equip.	M_{01}	1.5161
Power cost/kW	m_1	$1.22x10^{-5}$
Power factor	α	0.99
M_2	$M_2 = m_2V_c$	
Conductor cost/m^3	m_2	114.744
Volume of finished coil	V_c	
M_3	$M_3 = m_3V_y$	
Cost of finished yoke/m^3	m_3	5.458
Volume of finished yoke	V_y	
M_4	$M_4 = m_4P$	
a.c. distribution/kW	m_4	0.3058
M_5	$M_5 = m5$	
Cost of cooling/kW	m_5	0.002
M_r	$M_r = m_6T(\beta P)$	
Running time	T	36500 h
Cost of electricity/kWh	m_6	$1.22x10^{-5}$
Power Correction factor	β	0.5

Case Study: CMAP Quadrupoles

The latter procedure is applied to case of the normal-conducting quadrupoles using the values described on Table 1. For the optimization procedure, several candidate materials for the yoke were considered in terms of the availability and machinability. The steels: A-1010, A-1008, A-1006 and A-1018 are available and at low cost. A preliminary

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study of the multipole content, considering the latter materials [10], revealed negligible difference between them in terms of performance. Steel A-1010 was selected for the iron yoke. As far as machinability, laser-cut milling offers a 10x cheaper production, while maintaining tolerances, in comparison with Computer Numerical Control (CNC) milling, for a laminated quadrupole design.

As it can be seen on Fig. 2, the total cost has a minimum with respect to the current density at 1.8 A/mm^2, and a minimum with respect to the length at L= 0.1 m. A 1% fluctuation of the cost around the minimum allows to set a current density in the range from 1.2 to 2.4 A/mm^2. If the length of quadrupole increases to next value, 0.15 m, the total cost increases by 2.8%. A dissection of the total cost in terms of the power supply, the magnet, and the cost of electricity, reveals that for the low field gradient and small aperture requirements, the power supply represents the major expense. The magnet cost and the electricity cost merge at current densities of higher than 2 A/mm^2.

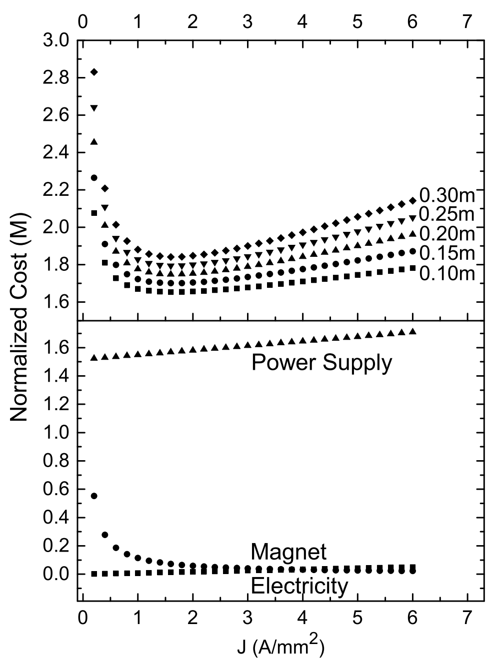

Figure 2: On top, cost Optimization model applied to CMAP quadrupoles. On the bottom, the dissection of the total cost in terms of its main components.

FIELD OPTIMIZATION

The field quality of a quadrupole depends on a number variables such as, the positioning of the coils, the orientation of the poles, the tolerances on the machine parts, and the quality of the magnetic model. To evaluate the magnetic model alone, one can express the magnetic field inside the aperture, in terms of its components B_x and B_y, which can be specified by the multipole expansion, Eq. 10, as described by [1]. Where B_{ro} is the fundamental harmonic at the reference radius R_r (1.8 cm for this calculations), b_n and a_n are the normal and skew multipoles.

$$B_x + iB_y = 10^{-4} B_{ro} \sum_{n=1}^{\infty} (b_n + ia_n) \times [Cos\,(n\theta) + iSin\,(n\theta)] \left(\frac{r}{R_r}\right)^n \quad (10)$$

Applying the parametric model to the geometry shown in Fig. 1 and using Comsol Multiphysics [11] we performed a parametric sweep on the minimum pole distance A. For a 3.2 T/m gradient, the allowed higher order multipoles $b5$, $b9$ and $b13$ [12] are kept within 1 unit when the minimum pole distance A is 7.4 mm, if the pole width slightly increases beyond 7.6 mm, the multipoles rapidly grow, as shown at Fig. 3. This imposes a tolerance limit for machining parts. A tolerances of 76 μm could readily be achieve by laser-cut milling [13], offering safe variation within 7.4 and 7.6 mm.

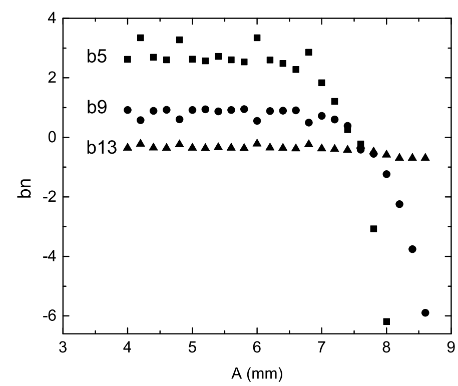

Figure 3: Multipole content as a function of the minimum pole distance A.

CONCLUSION

An optimization procedure, in terms of field quality, production, and operation cost, was applied to encourage the in-house development of the normal conducting quadrupoles in Mexico. The procedure merges a parametrization model with well known cost optimization procedure, and extended it to normal conducting quadrupoles. A 5 T/m quadrupole, was initially proposed, nevertheless, adjustments on the field requirements shifted the field gradient to a new value of 3.2 T/m. The cost optimization expressed in normalized units, considered several steels for iron yoke, being A-1010 the final candidate in terms of availability and low cost. For a 3.2 T/m field gradient, the total estimated cost is 1.66 the cost of the power supply at a current density of 2.2 A/mm^2.

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