Status Report on the R&D of a 5 T/m Normal Conducting Quadrupole Magnet for the 10-MeV Beam Line of the Electron Linac of the Mexican Particle Accelerator Community

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Abstract. The Mexican Particle Accelerator Community (CMAP) has endeavoured the development of a 100 MeV electron Linac (eLINAC) that will have three beam lines at 10, 60 and 100 MeV. The Linac, at present under design, will make use of four normal conducting quadrupole magnets for the 10-MeV beam line. The quadrupoles follow a standard type geometry and they will operate using Cu conductors at room temperature. This work reports the progress on the overall quadrupole design, analytic, magnetic, thermal and mechanical studies. In addition, the selection of varied materials for the Yoke and how affects the multipole content and gradient uniformity is explored. A winding strategy is discussed as well as the CMAP plan for the development of the first prototype.

1. Introduction
A preliminary design on the first Mexican electron Linac (eLINAC) is being developed by the Mexican Particle Accelerator Community (CMAP). The eLINAC consists in a sequence of three 2-m in length focusing defocusing cells (FODO) composed of four quadrupoles. Three radiofrequency cavities (RF) cavities are interspersed among the three cells. To minimize the beam size along the line, a 60° phase advance per FODO cell is selected, thereby minimizing the maximum value of the beta functions; the emittances are assumed to be constants.

The 10-MeV beam line of the Mexican eLINAC will be the first step of the accelerator complex of the 100-MeV eLINAC. Magnetic gradients for the three pairs of quadrupoles for the 10, 60 and 100 MeV lines are computed based on the required magnetic flux density at the tip of the poles, and
the aperture radius. The 10-MeV line requires a magnetic flux density of 0.09 T at the tip of the pole, assuming a 0.02 m bore radius, the desired gradient is 4.5 T/m.

The quadrupoles were designed bearing in mind infrastructure, materials, cost-effective development techniques (air cooled design) and equipment available at the University of Guanajuato. The current design makes use of regular copper wire (AWG 12) for the windings and allows future energy (current) upgrades, ranging from 4 T/m up to 19 T/m while preserving field quality and thermal stability. In the following sections, we are going to describe the quadrupole design for the 10-MeV beam line. However, thanks to the optimized geometry and the parametrized design, small modifications will be needed for the quadrupoles to be employed in the 60-MeV and 100-MeV beam lines. A thermal model driven by Joule-Lenz law and heat conduction in solids was modeled using the commercial software COMSOL Multiphysics® [1] for finite element analysis. A mechanical model of the Lorentz force distribution was studied as well as the fringe field effects at the end of the quadrupole.

2. Quadrupole design
The 10-MeV beam line has an aperture radius of 0.02 m and requires a flux density of 0.09 T at the tip of the pole, i.e. a 4.5 T/m gradient. The use of standard copper wire AWG 12 for winding suggested the use of a “standard-type geometry” for the quadrupole design. 126 turns per pole were used and a 6.6 A current was applied. The pole shape was modeled following an optimization method described in [2, 3]. In this method, the pole geometry follows a truncated hyperbole and field quality is related to pole thickness. Parallel simulations using COMSOL Multiphysics® were done to determine the optimum value for pole thickness vs. field quality (see Figure 1). According to beam dynamics requirements, the 1% uniformity in field quality is achieved when pole thickness, which can be expressed in terms of the distance from the pole to the axis “A”, is \( A = 0.0061 \) m. Analogously, a shimming strategy was added to the pole tip geometry to boost field uniformity [3]. Main quadrupole parameters are listed in Table 1.

| Parameter                  | Value | Units |
|----------------------------|-------|-------|
| Wire OD [m]                | 0.002 | m     |
| Iop [A]                    | 6.60  | A     |
| Turns per pole             | 126   |       |
| Bore Radius [m]            | 0.02  | M     |
| Bnorm at Pole Tip          | 0.09  | T     |
| Gradient                   | 4.71  | T/m   |
| Power Dissipated           | 31.8  | W     |
| Gradient upgrade suggested limit | 15.0 | T/m   |
| Current upgrade recommended limit | 19.00 | A     |
| Quadrupole length          | 0.10  | m     |
| Quadrupole mass            | 20.85 | m     |

Magnetic relaxation calculations where done using Finite Element Analysis software COMSOL Multiphysics®. Figure 1 shows the optimized geometry. For assembly purposes, the poles will be wind separately and installed at the iron yoke. This process allows us to use the available interpole space.

2.1. Thermal model
Normal-conducting magnets use non-superconductor materials for windings, because of their characteristic non-vanishing resistivity (\( \rho = RA/L \), \( \rho \) resistivity [Ωm], \( R \) electrical resistance [Ω], \( A \) cross-section are of conductor [m²], and \( L \) the conductor length [m]) the Joule-Lenz Law takes place, increasing the temperature of the system proportionally to the square of the current passing through the conductor.
Considering standard copper wire AWG 12, the number of turns per pole, the length of the quadrupole and the resistivity of pure copper (1.68x10^-8 Ωm [4]), we estimated 31.8 W of dissipated power for a 4 T/m gradient. Bearing in mind thermal properties of pure iron as the “iron yoke” material, and using heat equation, it is possible to estimate the increment in temperature produced by that amount of heat. The finite element analysis simulation estimates a temperature rise of 2 °C, assuming the quadrupole is in a 20 °C room. The gradient upgrade case was studied, the amount of current needed to produce a 19.27 T/m gradient is 19 A per wire, which produces a 263 W power. For that case, the temperature increments 3.6 °C, which does not affect the actual air cooling method.

![Optimized quadrupole design](image)

Figure 1. Optimized quadrupole design. Four hyperbolic truncated poles house 126 turns per pole of standard copper wire AWG 12. 18 layers, 7 wires each are wound around each pole. The pole tip was optimized varying pole thickness as a function of multipole content. A shimming strategy allow to boost the gradient uniformity at the fard end of the aperture.

2.2. Mechanical model

If Lorentz forces are large, they could cause permanent damage or even affect magnet performance. The present magnetic requirements are small to produce large Lorentz forces. Although this statement is true, it must be validated. A finite element analysis study was performed to estimate the magnetic forces produced while energizing the quadrupole at full field.

The model considers contributions from each turn at the pole, assuming no-ends effects, which in a first approximation is valid. In the 2D model, the wires are aligned parallel to beam direction. The estimated overall contribution along the total length of the quadrupole (0.1m) is 1.2 N toward the base of the pole. This amount of force gets redistributed along the iron yoke and does not represent a damage to the wires nor the mechanical structure of the quadrupole.

2.3. Materials for Iron Yoke and winding strategy

Original field relaxation model assumed LHC type steel [5], which has an extended performance over the 2 T saturation limit. This is related to the carbon content in the alloy. For low field purposes, as in this case (0.09 T at pole tip), an evaluation of the multipole content must be study for candidate materials to determine how smaller magnetic permeabilities affect quadrupoles overall performance.

A field relaxation study will be done varying different materials, i.e. changing the B-H curves at room temperature, see Figure 2. The study of the materials will consider the most common steel alloys that can be readily obtained in Mexico [6, 7]. The materials used were: Pure Iron, Pure Iron Annealed, Steel 1018, Steel 1020, Cast Iron, Cold drawn Low Carbon Steel. Hot Rolled Low Carbon Steel, Mu-Metal, Magnet Steel and LHC Steel. The goal of the study will be to preserve the field quality.
requirements (less than 1 unit for the allowed multipoles) at full field in both cases, the desired operation gradient and for future upgrades, in which the maximum recommended gradient will be 19 T/m.

Analytic, thermal, mechanical and material studies confirm that, for the present field requirements, the current design satisfies the expectations. The next step is to develop a winding strategy for a model quadrupole. A barrel-winding procedure [8] will be used to wind the 18 layers (7 wires each) on each of the poles, starting inside-out of the base of the pole. Winding tables and special tooling is being develop for the first prototype.

Figure 2. Magnetic permeabilities for different materials. Notice the saturation point for most materials falls behind the 2 T limit. The desired effect is to reach saturation at higher fields. For our purposes, the field at the tip of the pole is 0.09 T, which implies that almost every material could be use. Taking into account future energy upgrades, it is recommendable to select a cost-effective material with high saturation field. Pure Iron, or Steel 1020 are good candidates.

2.4. Fringe field for sensitive electronics
Fringe field lines were computed on a 3D model at several magnetic flux density values, starting at 5 G (five times earth’s magnetic flux density field). Due to small field values and quadrupole geometry, the field at the body of the magnet is completely enclosed by the iron yoke. Naturally, the remaining component is at the ends of the magnet, in which there is no iron yoke. According to the International commission on non-ionizing radiation protection (ICNIRP, 2009) [9], prudent practice requires posting warnings at the 5 G line, and limit access to areas with more than 10 to 20 G to knowledgeable staff. The 5, 20, 50 and 100 G lines were computed, (see Figure 3). The estimated 5 G line is located at 0.14 m from the centre of the quadrupole while the 20 and 50 G lines are at 0.11 and 0.09 m respectively.

Figure 3. Fringe field distribution along the axis of the quadrupoles. The quadrupoles axis is oriented along the Z axis. In A, B and C), the gauss lines equipotential surfaces were computed for the 5, 20 and 100 G. The 5-G line is located at 0.14 m from the center of the quadrupole, while the 20 and 100-G are at 0.11 and 0.09 m respectively.
3. Conclusions
An optimized geometry and design for the quadrupoles of the 10-MeV beam line of the CMAP eLINAC has been presented. A basic analytic model, based on general requirements and limitations, showed that a 637 A current must be applied to each pole to produce a ~4.5 T/m gradient in a 0.02 m bore radius. The quadrupole is designed in such a way that allows future energy updates, ranging from 4 to 19 T/m while preserving gradient uniformity. To improve field quality and keep gradient uniformity below 1%, the end of the hyperbolic poles was strategically shimmed. The mechanical model showed that a net force of 1.2 N is directed towards the base of each pole. The basic thermal model revealed that when a current at 6.6 A per wire is applied, the power dissipated barely increases the copper temperature by about a 2°C. The 19 A scenario was modelled, producing a temperature increment of 3.6 °C over the 6.6 A model. In both cases, the quadrupoles can be cooled using natural air convection.

The iron yoke fully encloses the magnetic field at the body of the quadrupole, adding no contribution to the fringe field. At the end of the quadrupole, there is a small region in which the winding around the pole is not covered by the iron yoke. This region contributes to the fringe field that extends out of the quadrupole. According to the International Commission on Non-Ionizing Radiation (ICNIRP, 2009), prudent practice requires posting warnings at the 5 G line. The magnetic model computes the 5, 10 and 50 G lines, being the first at 0.14 m from the centre of the quadrupole. Special tooling is being designed and it will be developed shortly.

Thermal, mechanical and electromagnetic studies have shown that the quadrupole fulfill the requirements for the quadrupoles of eLINAC, low-cost production and air-cooled. In addition, thanks to the parametrized design only small modifications will be needed for the quadrupoles to be employed in the 60-MeV and 100-MeV beam lines.

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