THE MAGNETIC FIELD ADJUSTMENTS ON THE D-TYPE ELECTROMAGNETS OF A PROTON ACCELERATOR THROUGH EM SIMULATION

L. A. Rabelo\(^1\) and T. P. R. Campos\(^2\)

\(^1,2\) Department of Nuclear Engineering, Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627 – Pampulha, Belo Horizonte, Minas Gerais - 31270-901 - Brazil.  
\(^2\) Email: tprcampos@yahoo.com.br

\(^1\) Corresponding autor  
L. A. Rabelo  
Department of Nuclear Engineering,  
Universidade Federal de Minas Gerais,  
Av. Antônio Carlos, 6627 – Pampulha, Belo Horizonte,  
Minas Gerais – 31279-901 – Brazil  
E-mail: luisa.rabelo@outlook.com

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ABSTRACT  
The aim of this study was to present the methods to unify the magnetic field of the electromagnets of a circular proton accelerator. Also, it is addressed the definition of the magnet’s material and the geometric changes into the magnet’s shapes to match synchronism in the particle motion internal to the accelerator. This equipment will be design to accelerate protons from 15 MeV up to 64 MeV. The electromagnet simulations were made in CST STUDIO® 3D 2015 software for simulating electromagnetic fields (EM). The simulation results show a regular distribution of the magnetic field in the compact electromagnets after insertion of homogenizer’ shims and coils, as auxiliary structures. As conclusion, the proposed electromagnets proved to be viable for proton circular accelerator and comply with the requirements of synchronization.

Keywords: Electromagnetism, Circular Accelerators, Simulations, Proton, CST.
1. INTRODUCTION
A magnetic field perpendicular to the motion of the particles is applied in circular accelerators, provided by magnets. This field makes these particles circulate inside the equipment returning to an acceleration’s region. Thus, the particles are accelerated when they cross an oscillating electric field induced inside of a cavity. Generally, this potential oscillator is achieved by a constant radio frequency (RF).

One of the major difficulties to design a circular accelerator of high energy is to achieve harmony between the electric field and the time of revolution of the particles inside the equipment, using a constant RF. As soon as the proton kinetic energy increases up to 1.5% to 2.0% of the energy of the proton rest mass, relativistic mass’s change arises and variation in the angular velocity of these particles is observed (McMillan, 1945; Strijckmans, 2001; Kleeven, et al., 2011). Due to these effects, the protons begin to lose energy passing through the acceleration cavity, because the period of the movement of the protons is desynchronized with the oscillation of the electric field. Another factor that compromises the synchronism is the lack of uniformity of the magnetic field inside the electromagnets that affects the axial and radial beam focusing (Rose, 1938).

This study addressed a new model of electromagnet-shape for proton acceleration with energy range between 15 MeV up to 64 MeV (Rabelo & Campos, 2013). Herein, the goal was to present the adjustment’s methods of the magnetic field in order to guarantee uniformity of the magnetic field in the accelerator’s electromagnets and synchronism.

2. MATERIALS AND METHODS
CST STUDIO® 3D 2015 software was used for the preparation of the electromagnet’s design and for the simulations of the magnetic field.

2.1 Definition of the electromagnet material
The first step was to simulate the appropriate material for the magnets. Library materials of CST STUDIO® 3D 2015 software were used. High magnetization can be obtained for even weak magnetic fields, reaching relative permeability in the order of $10^6$, depending on the material choice (Bastos, 2009). The unpaired dipoles align readily with the applied magnetic field for some ferromagnetic materials.

As first choice, the iron was used in this simulation. This material possesses ferromagnetic properties that provide superior magnetic field line distribution. The CST STUDIO® 3D 2015 software offers several options with variations in some electrical properties of the material. For this study two property-types, normal and non-line, irons (CST, 2015) were considered. Thus, irons assuming normal or linear isotropic proprieties were simulated. For linear behavior, the parameters of the dielectric and magnetic materials follow the relation:

$$D = \varepsilon E \quad e \quad B = \mu H$$  (1)

where $D$ is the electric flux density, $\varepsilon$ is the dielectric constant or electric permittivity, and $E$ is the electric field strength; and, $B$ is the magnetic field, $\mu$ is the magnetic permeability and $H$ is the magnetizing field (CST, 2015), respectively. Thus, the pairs: electric field and the electric flux density, and the magnetic field and the magnetic flux density are related, respectively.

For non-linear iron the magnetic permeability varies by magnetization and by applied magnetic field strength. So, $\varepsilon$ and $\mu$ are dependent on the field strength and turnbuckles that change the direction of the field.
2.2 Geometric changes and gap insertions between and into D-type magnets

It is very difficult to obtain a uniform magnetic field onto the electromagnets of an accelerator. So, geometric changes are required in the structure of the electromagnets for achieving uniformity and also for reaching synchronism between the evolution of proton beam and the electric field oscillation on the acceleration cavity.

A full cylinder electromagnet was split on a half, originating two D-type magnets, separated by a gap, namely central gap. Into each D-type magnets, new space-changes were introduced. lateral gaps in a triangular-type shape was inserted, namely internal-gaps. These gaps were snippets made in the D-type electromagnets with total removal of the magnet-material on that magnet portion. They have specific dimensions in according to each proton orbit, or proton beam energy. The purpose of introducing these empty-regions was to induce changes in the circulation-times and trajectories of the proton beams through the variations of the magnetic fields. In addition, the internal-gaps help in the adjustments of the radial beam motion. It was ideal that the magnetic field achieves near zero and the edge-field is as small as possible into these central gap and internal-gaps. At crossing these gaps, the protons beams may deflect tangentially in a rectilinear path and perpendicular to the electromagnet edge.

The second stage of this study was to define improvements in technical design performing simulations of the magnetic fields in order to hold a 3.0 T general uniform field (defined previously for this accelerator model). Also, an auxiliary coil and different materials of the electromagnets inside the gaps were added to correct the magnetic field. This was done to remove and to divert the magnetic field lines in these gap-regions in a desirable way.

3. RESULTS AND DISCUSSION

The representations of the electromagnets, the coils and the magnetic field were made in the CST STUDIO® 3D 2015. Figure 1 illustrates the design of the electromagnets and the coils.

![Figure 1. Main coils and electromagnets of the accelerator.](image)

3.1 Definition of electromagnet material

Figure 2 (a-b) shows the distribution of the magnetic field into the electromagnets depicted in Figure 1, for two types of iron properties: normal (Figure 2-a) and non-linear (Figure 2-b).
Figure 2. Magnetic field distribution into the electromagnets to normal (a) and (b) non-linear type irons.

The magnetic profiles presented in Figures 3 (a-b) are related to an axial planar magnetic field into the electromagnets made of iron with normal (Figure 3-a) and non-linear (Figure 3-b) properties.

Figure 3. Magnetic field profiles as a function of the electromagnet radial distance to normal (a) and (b) non-linear type irons. Points 1 and 2 represent the electromagnet edges.
The normal iron profile (Figure 3a) shows significant effects of edge-field. This field can distort the orbits and decrease the beam axial stability. The nonlinear iron presented certain advantages, such as: more uniform distribution of the magnetic field and reduction of the edge-fields, represented by the sharp declining of the magnetic field at the electromagnet edge (Figure 3b). The nonlinear iron was set as the preferable material for the D-type electromagnets. It is expected that the effects of the loss of beam focusing are minimized. Initially, the supply current coils and the number of turns have been evaluated empirically for the magnetic field to achieve the 3.0 T proposed field. Thus, the coil properties have been adopted in accordance to the material’s definition. For the normal iron, main coil held copper wires with nine thousand turns and a 24 A supply current. For the non-linear iron, main coil has copper wires with same number of turns; however, with a 12 A supply current. The nonlinear property allowed applying a reduction of the coil supply current and the field lines found to be less dispersed.

3.2 Geometric changes and gaps insertion

The gaps were introduced in the electromagnet design. These hollows increased the proton’s trajectories and changed the proton travelling-time. Indeed, all the orbits held the same travelling-time- to achieve synchronism. If the time of the trajectories was the same for all energy beams, so the frequency of oscillation of the electric field could be set constant. This is equivalent to say that the accelerator’s synchronism was preserved. The electromagnet shape after introduction of the central gap and the internal-gaps is shown in Figure 4. The empty gaps reduced the uniformity in the magnetic field. So, it was necessary to minimize these effects. The magnetic field distribution in the electromagnets after the gaps insertion is shown in Figure 5. Figure 6 presents the magnetic field profiles at radial section.

Figure 4. Illustration of central and lateral gap’s

Figure 5. Magnetic field distribution in the electromagnet after gaps insertions.
Figure 6. Profile of magnetic field as a function of the electromagnet radial distance after gaps insertions.

The Figures 5 and 6 show considerable effects of field-edge at the electromagnet edges and intense magnetic field disperse into the central gap which divided the electromagnet in two D-type portion. These settings affected the proton-motion synchronism. Thus, it was necessary to optimize the electromagnet geometry.

3.2.1 The insertion of homogenizer shims and an auxiliary internal coil
The first correction was made in the level off of the magnet poles into the space that the protons move (Figure 7). This change increases the magnetic field at the edges at the borders of central gap and reduces the effects of field-edges. The addition of homogenizer’s shims in the central borders and in the external ones of the D-type electromagnets reduced the field-edge effects, as shown in Figure 8. The shims were made of iron plates placed near the borders to increase the intensity of the magnetic field at those borders.

Figure 7. The highlighted area shows the magnet’s poles, the space in which beam is present and the radial variation in height (vertical drop).

Figure 8. Homogenizer shims at the borders of the electromagnets.
The magnetic field lines in the gaps were diverted toward the internal mass of electromagnets, so that the field loss the standardization. It was observed variations of the magnetic field in few areas of the electromagnets. The values varied between 2.8 T to 3.1 T. The field was more intense near edges in which it could reach 3.4T. One can observed that these field-edge increasing were important to compensate for the effect of losing of focusing beam due to a general low magnetic field at the edges.

Although the magnetic field was not uniform throughout electromagnets, a suitable proton movement could be achieve based on magnetic field compensations. The present electromagnet configuration generated a non-homogeneous magnetic field. It could be compensated with small variation of the field and with the introduction of an intense field at points in the central edges of the central gap. The high field might compensate the movement-errors generated in regions of low field. To reduce the field into the electromagnet central gap, a rectangular coil with reverse current was added. Figure 11 shows the auxiliary coil.

Figure 9. Magnetic field distribution in the electromagnet after shim added.

Figure 10. Magnetic field profile as a function of the electromagnet radial distance after adding homogenizer shim.

Figure 11. Auxiliary coil with reverse current.
Also, a material considered almost a perfect electrical conductor identified as Lossy Metal on the CST STUDIO® 3D 2015, was added covering the internal-gaps (Figure 12). The Lossy Metal deflected the field lines. This material can simulate solids associated with the use of a model of one-dimensional surface impedance. Electric fields penetrated a very small layer on this material. Such thickness (usually called "skin depth") can be defined by the Equation (2):

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \mu \sigma}}$$

(2)

where $\delta$ is the penetration depth, $\omega$ is the frequency of the pulse field external inductor, $\mu_0$ and $\mu$ are the magnetic permeability of vacuum and of the material; and, $\sigma$ is the electrical conductivity of the material. In this condition $\sigma \gg \varepsilon \varepsilon_0$, in which $\varepsilon$ is the electric permittivity of the material (CST, 2015).

![Figure 12. The design of the electromagnets after adding Lossy Metal.](image)

On the practices, any material which holds perfect electrical conductor proprieties can be defined. Also, future measurements on a real structure shall provide magnetic values that may be easily adjusted by altering geometry and thickness of the shims and the Lossy Metal. The images of the simulation with the auxiliary coil and Lossy Metal are presented in Figure 13 and 14.

![Figure 13. Magnetic field distribution in the electromagnet after insertion of the Lossy Metal in the central gap and lateral gaps.](image)
The Figures 13 and 14 show regions with null magnetic field, held at central area of the central gap and internal-gaps. This result was favorable for attending synchronism. Therefore this solution was an alternative to make this model suitable to accelerate protons.

4. CONCLUSIONS
The magnetic field distribution in the proposed electromagnets proved to be viable for circulating protons with synchronism into a circular accelerator. The magnetic field adjustments were performed and the model meets the requirements for synchronism of the particle beam. In simplified way, it was possible to reduce the intensity of the magnetic field into the gaps and make the correction of the field-edge effects. Future new simulations will involve the trajectory of proton’s beams and the modeling of acceleration cavity.

5. REFERENCES