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An efficient simulation method of a cyclotron sector-focusing magnet using 2D Poisson code

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ABSTRACT

In this paper we discuss design simulations of a spiral magnet using 2D Poisson code. The *Independent Layers Method* (ILM) is a new technique that was developed to enable the use of two-dimensional simulation code to calculate a non-symmetric 3-dimensional magnetic field. In ILM, the magnet pole is divided into successive independent layers, and the hill and valley shape around the azimuthal direction is implemented using a reference magnet. The normalization of the magnetic field in the reference magnet produces a profile that can be multiplied by the maximum magnetic field in the hill magnet, which is a dipole magnet made of the hills at the same radius. Both magnets are then calculated using the 2D Poisson SUPERFISH code. Then a fully three-dimensional magnetic field is produced using TOSCA for the original spiral magnet, and the comparison of the 2D and 3D results shows a good agreement between both.

1. Introduction

A cyclotron is one of the most important parts in the radiopharmaceutical industry. It has been used for many years to produce radioisotopes such as fluorodeoxyglucose (FDG) as well as for ion beam therapy. A magnet is a core component of a cyclotron machine, and the cyclotron magnet must meet important requirements, such as the production of an isochronous field, with focusing properties in addition to low power consumption. Also, its dimension needs to be optimized in order to fit in the cyclotron, and so it is challenging to design a cyclotron magnet that can produce a stable ion beam from cyclic accelerators. The isochronous conditions must be fulfilled in order to keep the ion beam in phase with the RF system, i.e., in phase with the alternating current (AC) field in the resonator cavity [1].

When a charged particle moves in a circle in a magnetic field, the relativistic cyclotron frequency is

$$\omega = \omega_c \frac{m_0}{m_0 + T/c^2} \tag{1}$$

where ω_c is the classical frequency, T is the kinetic energy, and m_0 is the rest mass of the particle. In order to maintain an isochronism with constant ω, the magnetic field must satisfy a relativistic equation [3,8],

$$B_z = \frac{\gamma m \omega}{e} = \frac{\omega}{ec^2} E(\rho) = \frac{\omega E_0}{ec^2}\left[1 - \left(\frac{\omega \rho}{c}\right)^2\right]^{-1/2} \tag{2}$$

where E_0 is the rest energy, ρ is the radial coordinate of the particle at the energy E [3], ω is the gyro frequency, and e is the electron charge. The isochronous condition can be obtained either by increasing the magnetic field in the radial direction or by increasing the frequency ω with the energy that is increased. Thus, the machines following this principle are referred to as synchrocyclotron.

In a spiral sector magnet, the hills and valleys are shaped as spirals (Fig. 1). Thus, particles crossing the edges of these at a modified angle ζ will have greater focus in the radial direction. One sector edge that the particle crosses will focus, and the other will defocus, but the net effect will be of radial focusing. The magnetic field from the pole must be accurate with a precision on the 10^{-5} order. Also, the RF cavity must fit in the narrow space that is left by the wide magnet gap of the spiral hill and valley [4,5].

In the mid-plane between the magnet poles, the positive field gradient in the radial direction, which is needed for isochronism, will lead to a negative field index, which is the negative radial gradient of the magnetic field, $n = -\frac{r}{B} \times \frac{dB}{dr}$, resulting in vertical defocusing. A negative field index can be neutralized if there is an extra source of vertical focusing, and one way to provide additional focusing is to introduce the azimuthal variations to the bending field [8].

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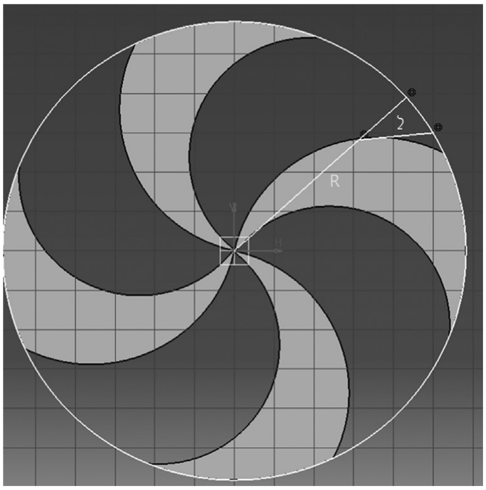

Fig. 1. Geometry of the scalloped orbits in a spiral-sector cyclotron.

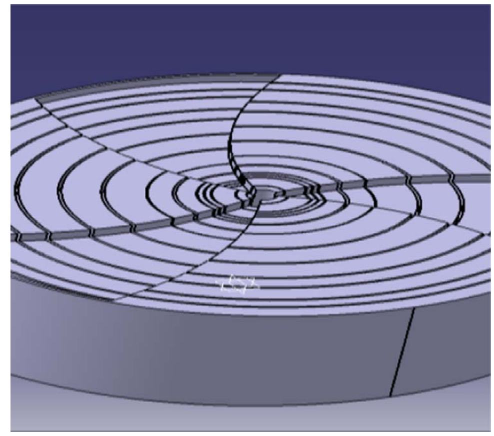

Fig. 2. Layers of the magnet pole.

Table 1
Test Magnet specification.

Pole diameter	100 cm
Injection radius	~5 cm
Sectors	3 spiral
Extraction radius	45 cm
Hill parameters	Gap 72 mm, B (*max*) 1.65 T
Valley parameters	Gap 120 mm, B (*max*) 1.25 T
Spiral angle	33–44°
Energy	18 MeV (*P*)

A spiral magnet with 3 sectors was chosen to perform the numerical experiment based on the fact that the spiral magnet is a more general case than the magnet with straight sectors. This model is supposed to be applicable to the production of variable energy cyclotrons that are capable of accelerating hydrogen up to 20 MeV. The specification for a test spiral magnet is shown in Table 1 below. In order to make the magnet more realistic, a central region has been introduced as part of the injection system.

The time needed for calculations using the PC is proportional to n^3, where n is the number of mesh node points of the geometry of the solution problem. Therefore, 2D code is preferred to obtain solutions of symmetrical cases, such as a cylindrical symmetrical dipole magnet with a third axis that is considered to be infinite or long enough to be treated as infinite.

Traditional cyclotrons with a variable magnetic field at a radial direction or in the azimuthal direction are hard to consider as symmetrical problems. Some tricks are needed in order to use 2D code for such a task. The stacking factor method can be used in regions where the magnet structure differs from the axisymmetric structure, such as in sectors, hills and valleys. The stacking factor *SF* is defined as the fraction of the circle that is occupied by the real ferromagnetic material, and the properties of the pseudo-material filling regions with a stacking factor are given by the *B–H* curve equation [2].

$$B_{pseudo} = \mu_0 H + (B - \mu_0 H) * SF,$$

In this paper, we used a new approach to obtain an approximate solution for the sector-focusing magnet field by using 2D code (POISSON) [9].

2. Independent Layer Method

When using this technique, the surface of the magnet is converted into multi-independent layers. The reason for doing so can be explained by the fact that a magnetic field on the surface of the magnet is perpendicular to the surface [6,7].

The change in the normal component B_n of the magnetic field within the mid-plane can be attributed to the geometric features of the sector magnet. i.e., to a periodic change in the pole gap width between a hill and a valley in the perimeter that causes an azimuthal variation in B_n , but the variation in B_n in the radial direction depends on the ratio of the hill length to the valley length, [6,7].

The analysis of the field tendency at surface is summarized such that the magnetic behavior of the field depends on the pole gap width and the ratio of hill length to valley length at each radial position. By dividing the spiral magnet pole into successive layers in the radial direction, as shown in Fig. 2, the magnetic field at the mid-plane can be independently determined for each layer. Thus, each layer becomes independent of the others due to the absence of a tangential component of the magnetic field (independent layers approximation).

For each layer, we need to determine the magnitude and the variation in the magnetic field in azimuthal direction. For this purpose, we have introduced two magnets that are different from the original sector magnet: one is referred to as the *hill magnet*, and the other is the *reference magnet*.

2.1. Reference magnet and hill magnet

The hill magnet is a dipole magnet with a gap equal to the hill gap. By performing calculations using the 2D Poisson software, we have obtained the magnetic field distribution inside the magnet, as shown in Fig. 3(b). The data that is calculated in the mid-plane is shown in Fig. 3(a), where the hill magnet can be seen to be a pure dipole magnet with the same radius as that of the original sector magnet.

Fig. 4 above shows that the magnetic field near the edge adjacent to the pole tip of the magnet changes drastically and the non-uniformity of the magnet at this area is referred to as the *magnet end effect*. Fig. 3 also demonstrates three contributions into the final magnetic field in the median plane of the cyclotron, and, respectively, these are (1) the magnetic field produced by the magnetized iron of the pole (whose azimuthal average remains unchanged by spiraling), (2) the magnetic field produced by the coils, and (3) the magnetic field produced by the magnetized iron of the yoke. The value of the magnetic field at the Hill-dipole magnet is the same as that of the magnetic field of the 3D field at the hill region in order to introduce a field variation resulting from the presence of a valley, so another magnet was introduced as *the reference magnet*.