IMPROVEMENT OF 18 MeV CYCLOTRON MAGNET DESIGN BY TOSCA CODE

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Abstract

According to an increasing need to cyclotrons in the world, designing and manufacturing of these machines are considered. Therefore, designing of 18 MeV cyclotron magnet has begun at Amirkabir University Of Technology. The magnet is one of the most important parts of the cyclotron, so in designing of magnet, all other components of cyclotron which influence on magnet, should be considered. Since the achievable energy for particle is determined 18MeV, designed magnet has AVF structure. TOSCA (Opera-3D) code was selected for simulation and analysis. First of all, theoretical calculations and estimations were done and magnetic field data according to radius were achieved. After that, simulation with initial estimations and a simple model of the magnet was begun and optimization process continued until magnetic field results from the simulation coincided with the theoretical one. Different shimming was used for better coincidence. Some results contain the magnetic field on middle plane and Betatron oscillations were checked. Also working points of the cyclotron with resonance regions were checked. According to use reliable mesh, the accuracy of simulation results is sufficiently high.

INTRODUCTION

According to the importance of cyclotrons in the world, development and advancement about these machines are increasing. One of the most important applications of cyclotrons is in medical, so design of 18 MeV cyclotron magnet has been begun for medical purposes at Amirkabir University of Technology. In cyclotron particle can move in a spiral path by applying a magnetic field which is produced by the magnet. Therefore, designing of magnet is one of the most important parts of the cyclotron design. By considering final 18 MeV for particles, construction of designed magnet is Azimuthally Variable Field (AVF). This kind of magnet has 4 hills and valleys. Three important purposes have been followed in this paper are: At first, initial estimations about different dimensions of the magnet, then how to achieve to best coincidence between theoretical result and simulation one and at the end checking the validity of the results.

INITIAL CALCULATIONS AND ESTIMATIONS

Some important parameters of the magnet should be calculated before beginning of the simulation. According to last design [1], RF frequency has been selected 64.3 MHz, With following relation between magnetic field and radius, curve of magnetic field versus radius which is theoretical curve has been achieved.

$$B_{iso} = \frac{B_0}{\sqrt{1-\left(\frac{300ZB_0r}{E_0}\right)^2}} \qquad (1)$$

By applying the most important equation in cyclotrons, radius poles have been obtained 63 cm [2].

In an AVF cyclotron, there are 2 coils which are the most main source of magnetic field in the magnet. Estimation of ampere-turn of coils has done with ampere law [3]. But during the optimization process it should be changed, finally 58000 Ampere-turn was selected for each coil in designed magnet.

After first estimations, magnet simulation was begun with a simple model of magnet in CST code. Then the STP file was exported and imported in OPERA-3D (TOSCA code) [4].

For achieving best coincidence between theoretical results and simulation one, some methods can be applied. One of them is decreasing pole gap as a function of radius [3]. So in designed magnet pole gap is 3.6-5.6 cm.Another way is shimming of pole edges.

SHIMMING OF POLE EDGES

There are many methods for shimming in magnet design. Shimming can be horizontal or vertical. Also, sometimes, some parts of poles can be cut or extra slice can be added. In the previous model, vertical shimming was applied. But this kind of poles is not affordable in manufacturing. So all shimming were changed and the magnet was redesigned [5].

In the design process, horizontal cuttings were created on pole edges and a small slice was cut at the initial part of the pole for decreasing magnetic field in initial radiuses.

In addition, for improving the magnetic field at the final positions, tow triangle with 11 angle put at the end of each pole. All these methods were applied for achieving isochronous magnetic field.

Figure 1 shows all applied shimming methods on poles.

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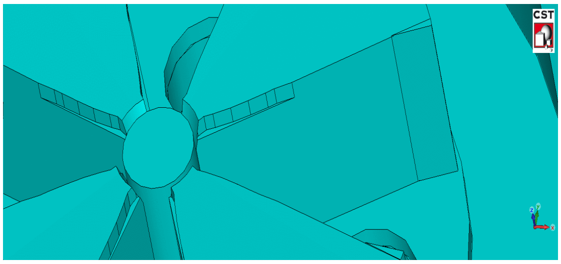

Figure 1: Shimming of pole edges.

MAGNETIC FIELD RESULT

The most important result from the magnet simulation is a magnetic field diagram according to radius [6]. At first results were not acceptable. By applying different methods same as changing ampere-turn and pole gaps, shimming, reliable results were achieved. As shown in Fig. 2, there is an acceptable coincidence at most radiuses.

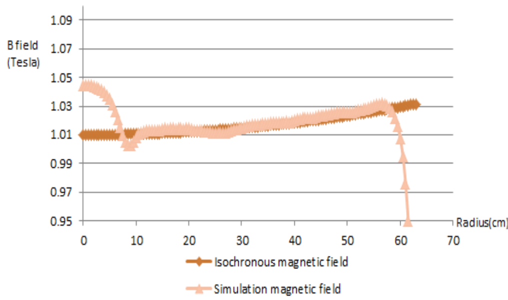

Figure 2: Magnetic field diagram according to radius.

MAGNETIC FIELD DISTRIBUTION

Checking the distribution of magnetic field in middle plane is necessary after each simulation. Figure 3 shows the maximum and minimum of magnetic field on middle plane. The maximum value should not be more than the saturation point of the magnet material. Designed magnet material is AISI 10-10 with 1.85 Tesla saturation point. As shown in Fig. 3, maximum magnetic field on middle plane is 1.70 Tesla [7].

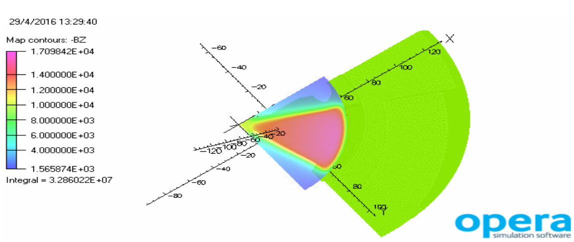

Figure 3: Magnetic field distribution on middle plane.

BETATRON OSCILLATIONS

In cyclotron motion (special in final orbits) some oscillations in vertical and horizontal direction occur. These are Betatron oscillations. Because of particle motion sensitivity in final tracks all these oscillations should be checked. From the following equations Betatron oscillations factors in tow direction are achieved [3]:

$$\upsilon_z^2 = 1 - \gamma^2 + \frac{N^2}{N^2-1}F \qquad (2)$$

$$\upsilon_r^2 = \gamma^2 + \frac{3N^2}{(N^2-1)\times(N^2-4)}F \qquad (3)$$

For increasing particle stability in cyclotron motion, vertical oscillation factor should not be negative and the horizontal (or radial) value should not be less than one.

Figure 4 shows the Betatron oscillation factors which are in an acceptable range.

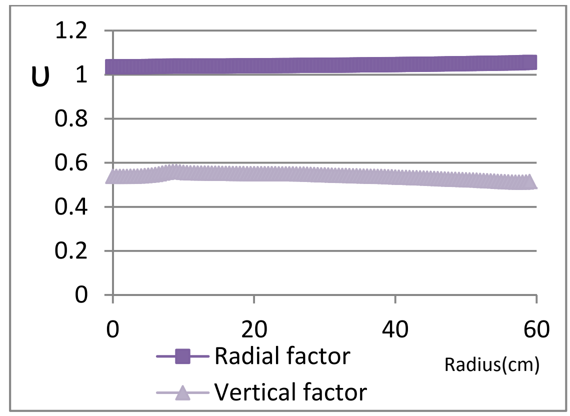

Figure 4: Betatron oscillations factors.

PAHSE SHIFT

The difference between simulated magnetic field and isochronous one can cause particle motion phase shift proportion to RF phase. Phase shift is calculated by the following equation [8]:

$$d(\sin\varphi) = 2\pi h \frac{dB}{B_{iso}} n \qquad (4)$$

Figure 5 shows the particle phase shift during acceleration. The acceptable value for this parameter is 20-25 degree, as shown, the maximum phase shift in designed magnet is about 25 degrees [7].

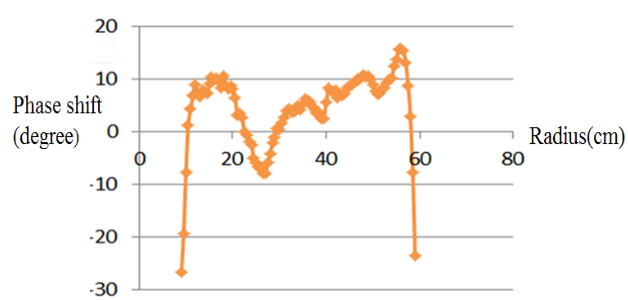

Figure 5: Phase shift diagram.

RESONANCE REGIONS

In each motion same as cyclotron motion maybe some resonances occur. When a perturbation frequency is same as the particle revolution frequency, resonance occurs. Most of these resonances are destructive and destroy the beam. So working points of the cyclotron should be far from the resonance regions or cross quickly from these regions. If working points have many intersections with resonance lines, magnet structure should be revised. Resonance lines are achieved by following equation [9]:

$$K\upsilon_x + L\upsilon_y = in \qquad (5)$$

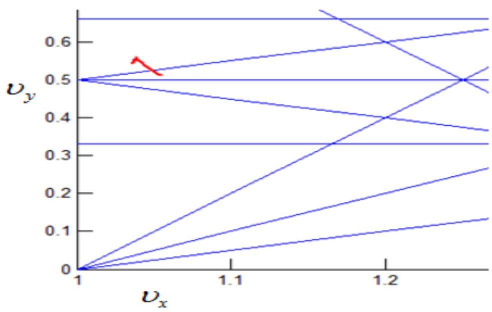

Figure 6: Resonance regions and working points.

In Fig. 6 all resonance lines up to 3rd order (|k|+|L|≤3) were plotted. The red curve is working points of the cyclotron, which is obtained by Betatron oscillations factor. As it is shown working points of the cyclotron cross quickly from the resonance lines, So it will not be dangerous for the beam [6].

Finally, all designed magnet specifications are shown in Table1.

Table 1: Magnet Structure Specifications

Parameter	Value
Total radius	122 cm
Total Height	129 cm
Pole radius	63 cm
Pole height	36.5 cm
Pole gap	3.6-5.6 cm
Hill angle	46
Valley angle	44
Coil dimension	20*22 cm
Number of ampere-turn	58000

Also, for having more current density larger coils applied and wider yokes help to increase the passage of magnetic flux. Figure 7 shows half of the overall structure of designed magnet.

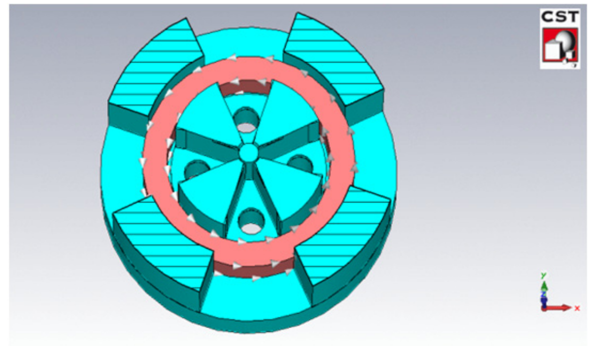

Figure 7: Half of the overall structure of designed magnet.

CONCLUSION

Design and Simulation of 18 MeV cyclotron magnet by TOSCA code has been presented. All basic parameter estimations expressed. Some different methods have been used for achieving better results in a magnetic field diagram. Some checks which ensure the validity of designed magnet (same as Betatron oscillations, resonance regions and magnetic field distribution on middle plane) have been investigated. With considering reliable mesh, the accuracy of results is sufficiently high.

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