SINGLE PARTICLE TRACKING SIMULATION FOR A COMPACT CYCLOTRON*

H. W. Kim, Y. S. Lee, B. N. Lee, K. R. Nam, H. S. Song, J. S. Chai#, WCU Department of Energy Science / School of Information & Communication SungKyunKwan University, Suwon, 440-746, Korea

Abstract

Low energy compact cyclotrons are needed for the production of radioactive isotopes. To develop a radio isotopes producing system for Positron Emission Tomography (PET), Sungkyunkwan University has started to design the system of compact cyclotron in 2010. In the design of the cyclotron, single particle tracking simulation after the magnet design is important to check the quality of designed magnetic field.

In this paper, the single particle tracking simulation for cyclotron magnet was done with commercial program 'OPERA-3D TOSCA' and the process of simulation is also described. Model of 9 MeV proton cyclotron magnet was used for example of simulation and pseudo electric field gaps are designed to accelerate or decelerate reference particle. 3D CAD program 'CATIA P3 V5 R18' was used to designe the magnet and pseudo electric field gaps. All magnetic and electric field calculations had been performed by 'OPERA-3D TOSCA' and the own-made program 'OPTICY' is utilized for other calculations - phase slip, radial and axial tune.

INTRODUCTION

A 9 MeV H- compact cyclotron for Positron Emission Tomography system is being designed at Laboratory of Accelerator and Medical Engineering, Sungkyunkwan University. It will provide 9 MeV proton beams for generating radioactive isotopes for example ^{18}F. A process of single particle tracking simulation of 9 MeV H- cyclotron magnet is described in this paper.

The simulation process includes magnet design, generating of pseudo electric field gaps and particle tracking by using combined magnetic and electric field. Figure 1 shows the whole steps of this simulation. The example cyclotron has a normal conducting magnet with 4 sectors so that it becomes Azimuthally Varying Field and fixed RF frequency cyclotron [1]. The diameter of magnet is 1.25 m and the pole is 0.35 m. The maximum designed field strength on the mid-plane is 1.9 T. Other magnet parameters are shown in Table 1 and the 1/8 model of designed magnet is shown in Figure 2. With this magnet model, calculation of magnetic field was done. After this step, pseudo electric field gaps are designed. This pseudo electric field gap model comes from a cyclotron RF cavity model. It has angles that are aligned with magnet valley angles. The models of gaps are displayed in Figure 5. The outcomes of magnetic and electric field calculations are combined in the same grid on the next phase and this combined field is used to single particle tracking.

3D modelling process was done by 3D CAD system, CATIA [2]. To reduce the magnetic and electric field calculation times, batch files were developed which can import the 3D models, generate mesh and draw field map automatically in TOSCA [3] modeller and post-processor. The calculation of the tunes have been done by own made beam dynamics program OPTICY [4].

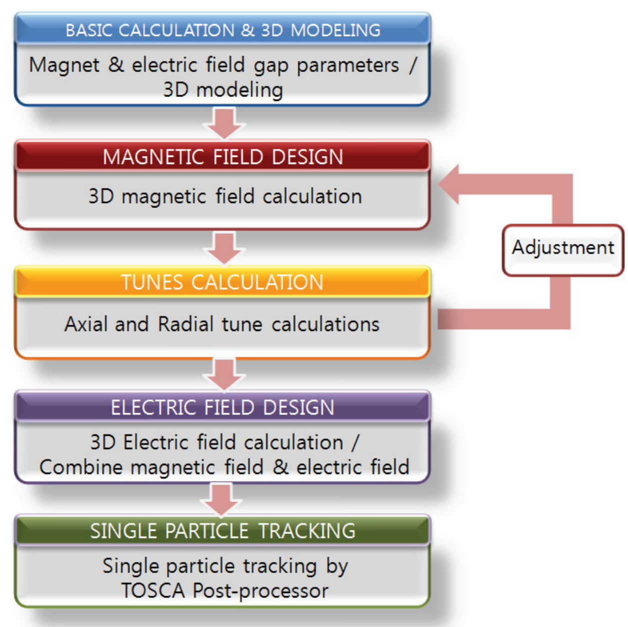

Figure 1: Steps of simulation process.

MAGNETIC FIELD SIMULATION

There are three steps to design isochronous cyclotron magnet. Basic parameters calculations were done firstly to determine the size and field strength of magnet by using simple first-order theory of beam optics [5]. Simulation model was sketched after the deliberation of basic parameters. The three-dimensional magnetic field calculation is necessary to consider the consequence of azimuthally non-symmetrical characteristic of the geometry [5]. Hence the three-dimensional magnetic field simulation is done with the sketched model.

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#jschai@skku.edu

The B-H characteristic of material that was imported to simulation is important to magnetic field simulation. In magnetic field simulation, AISI 1010 steel is used as the main magnet material. AISI 1010 steel has a good B-H characteristic as kinds of low carbon steel.

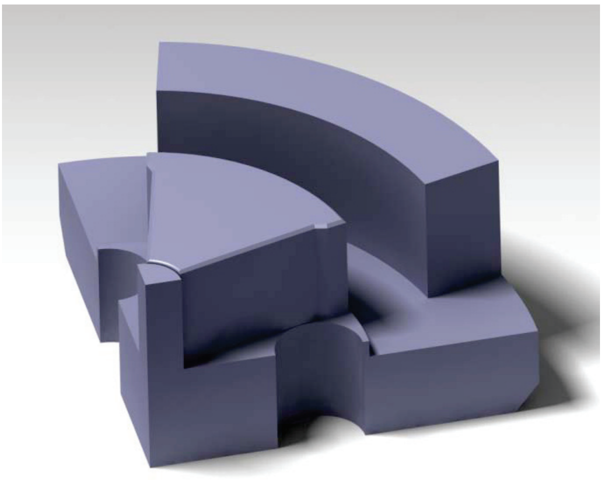

Figure 2: 1/8 model of designed magnet.

Table 1: Parameters of Magnet

Parameters	Values
Maximum energy	9MeV
Number of sectors	4
Central field	1.39 T
Pole radius	0.35 m
Extraction radius	0.31 m
Harmonic number	4
Hill / Valley gap	0.02-0.03 / 0.38 m
Hill angle	60-64°
B-field (min.,max)	0.24, 1.89 T

Local mesh method is applied because it increases the accuracy of simulation and shortens the simulation time. The size of mesh between two magnetic poles is four times smaller than boundary and return yoke part. Total number of calculated meshing elements is 3.3 million and only 1/8 elements were simulated because of the symmetry of model geometry. Dummy vacuum gap is used to check the precise magnetic flux density on mid-gap.

Figure 3 shows the average magnetic field increase along the average radius of the beam as the isochronous field. The average magnetic field at the specific radius means the average of magnetic field values along the equilibrium orbit of that radius. The equilibrium orbits are determined by the solution of linearized equations of motion for the given magnetic fields [6].

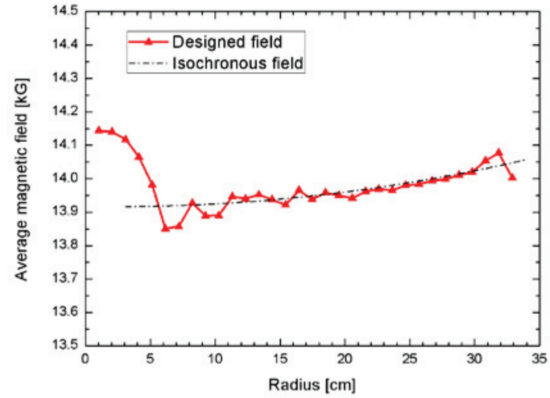

Figure 3: Average magnetic field along the average radius.

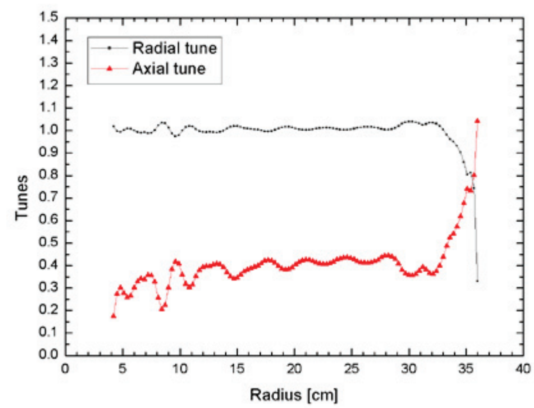

Figure 4: Radial and axial beam tunes.

The own made program OPTICY calculate the tunes and phase error. Figure 4 contains the tune diagrams from OPTICY.

ELECTRIC FIELD SIMULATION

Four pseudo electric field gaps are designed to accelerate or decelerate the reference particle. Each pseudo gap has angles that are aligned with magnet valley angles and 40cm long. They are placed at the same location as the gaps of two double gap cavities and the applied potential difference at each gap is calculated from the energy gain of a beam per turn. The energy gain of the beam per turn is given by

$$\Delta \mathrm{E} = 4qV_{\mathrm{D}} \sin \frac{h\theta_{\mathrm{D}}}{2} \qquad (1)$$

where q is the charge of particle, V_D is the dee voltage, h is the harmonic number and θ_D is the angle of the dee. The variables - q, V_D, h and θ_D are design values of cyclotron RF cavity. In this simulation case, V_D = 45kV, h = 4 and θ_D = 30° so the energy gain per turn is ΔE = 156kV. The total number of turns to reach 9MeV is 58 in ideal case. The potential differences inside of the gaps are scaled during particle tracking simulation to get an ideal number of turns.

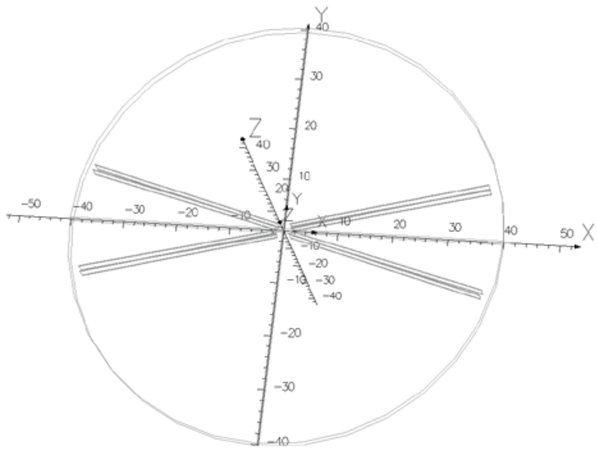

Figure 5: Simulation model of pseudo electric field gaps.

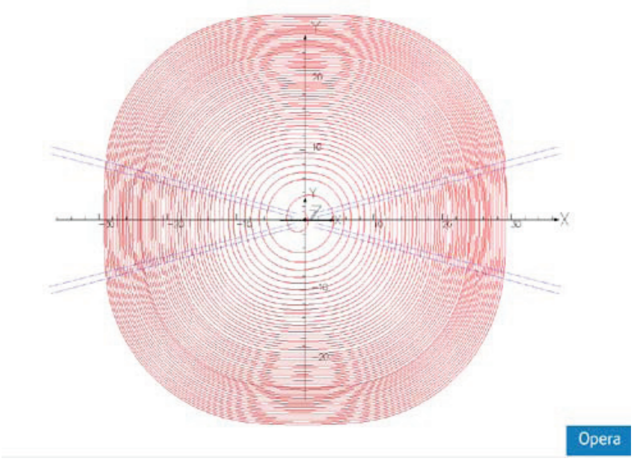

Figure 6: The single particle track of compact cyclotron.

SINGLE PARTICLE TRACKING SIMULATION

The results of field calculations are combined together in the same grid. The simulated magnetic is imported to the database of electric field simulation to use the TRACK command of post-processor. That command calculates the trajectories of charged particles through the electric and/or magnetic fields-including full relativistic correction to single particle tracking [7].

Because the central region field distribution and acceleration are very complex to find an initial point of injection, a beam is transported backward from the larger radius to injection point in the cyclotron [8].

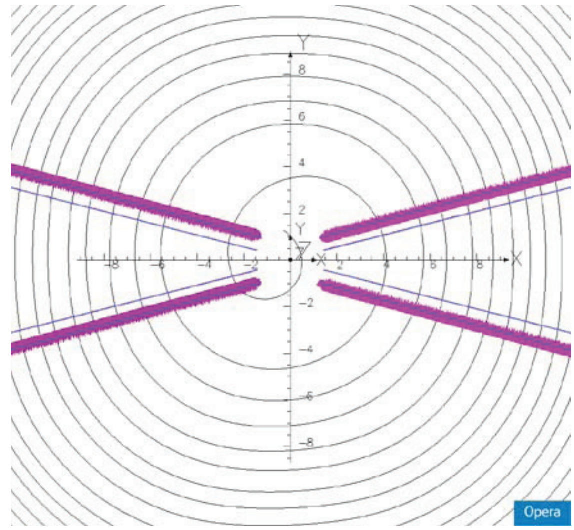

Figure 7: Radial trajectories of single particle for the first 8 turns with electric field vectors.

The single particle track of compact cyclotron is shown in figure 6 and figure 7. The particle starts from the radius of 9 MeV equilibrium orbit to inner radius of cyclotron. After 58 turns, the beam stops and it means that the point can be an initial point of the beam. This result can be used to the precise central region design.

CONCLUSION

The single particle tracking simulation of 9 MeV compact cyclotron is done. Designed magnetic field and electric field are proven to accelerate the single particle effectively. The comparison with other particle tracking simulation codes CYCLONE should be done and multi-particle simulation would be possible taking the space charge effect into consideration.

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