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THE MAGNETIC FIELD DESIGN OF A 16 MeV VARIABLE ENERGY CYCLOTRON

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Abstract

The development of a 16 MeV H^- cyclotron is in progress at CIM company (Hefei, China). Such machine is designed for radio-isotope production which is used for nuclear medicine. Beam extraction is ensured by means of stripper foils located at different radii to achieve variable extraction energy between 10 and 16 MeV. In this paper, the main magnet design was demonstrated in detail. An AVF magnet with four radial sectors was adopt to get strong axial focusing. The hill angular widths and hill gaps with radius were designed to meet the isochronous magnetic field. The tunes were optimized to avoid dangerous resonance. The result of magnet design was verified by beam dynamics simulations. After the presentation of the magnet design, some results on stripping extraction were also discussed. TOSCA (OPERA-3D) was used to perform 3D magnetic field simulation. An efficient beam simulation code developed by MATLAB was used to do beam dynamics simulations.

INTRODUCTION

In recent years, the Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) and Hefei CAS Ion Medical and Technical Devices Co., Ltd. (CIM) are jointly developing a 10~16 MeV variable energy proton cyclotron, which can be used to produce medical radioisotopes.

Medical radioisotopes, such as ^{18}F and ^{11}C, are in great demand in China. Chinese government issued the Medium and Long term Development Plan for Medical Isotopes (2021-2035) in 2021, vigorously encouraging the application and innovation of nuclear medicine technology. The low energy (10-20 MeV) proton cyclotron has become the main equipment for isotope preparation with its advantages of small size and low cost [1].

ASIPP and CIM have rich experience in the manufacture and commissioning of cyclotrons. The cyclotrons such as SC200 [2] and CIM14-A developed have successfully extracted the beam. In order to further enrich the company's accelerator product series and meet the growing demand for radioisotopes, ASIPP and CIM decided to develop a proton cyclotron with a maximum extraction energy of 16 MeV and a maximum extraction current of 100 µA. Because the extraction method is stripping extraction, the extraction energy can be adjusted from 10 to 16 MeV to produce as many kinds of radioisotopes as possible. The cyclotron accelerates H^- ions. H^- ions whirl in the magnetic field at a frequency of 23.45 MHz. After passing through the stripping foil at the extraction radius (29.9~37.1 cm), two electrons are stripped off and become protons. The magnetic field design and beam dynamics simulation are described below.

MAGNET DESIGN

The cyclotron magnet system is shown in Fig. 1. It is composed of a conventional conductor coil, an iron yoke and 4 pairs of radial sectors. The magnet system is square in shape, 185 cm in side length, 92 cm in height, and 19.7 tons in total weight. It conforms to the characteristics of compactness and flexibility of medical cyclotron, and can be installed in the built hospital. The radius of the magnetic pole is 44.8 cm, which is a flat magnetic pole, and the gap between the magnetic poles is 4.1 cm. The hill-valley modulated magnetic field formed by 4 pairs of magnetic poles can provide axial focusing force for the beam. By shimming the width of the magnetic pole, the isochronism of the magnetic field can be optimized, the phase slip of the beam can be reduced, and the acceleration efficiency can be improved. The central field is designed to be about 1.54 T, which can be realized by conventional conductor coil, and the current density of the main coil is 250 A/cm^2. The main parameters of the magnet system are shown in Table 1.

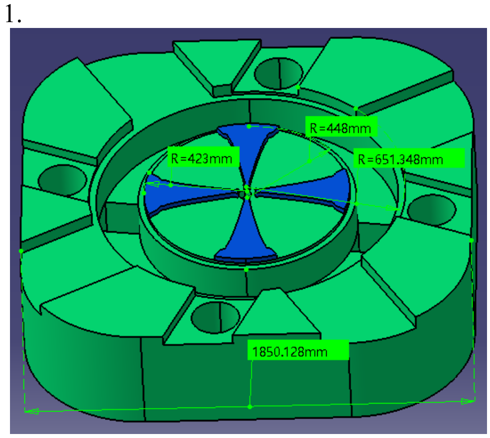

Figure 1: Magnet model of cyclotron.

Table 1: Preliminary Magnet System Parameters

Parameter [unit]	Value
Pole radius [cm]	44.8
Diameter of iron yoke [cm]	185
Hill gap [cm]	4.1
Valley gap [cm]	8.7
Main coil current density [A/cm2]	250
Magnet Height [cm]	92
Magnet weight [t]	19.7

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ANALYSIS OF MAGNETIC FIELD

Through several rounds of iterative optimization of parameters such as main coil current, resonance orbital frequency and magnetic pole width, we finally obtained the physical design magnetic field that meets the requirements of isochronism. The axial magnetic field distribution in the middle plane is shown in Fig. 2. The deviation between the average field and the theoretical isochronous field is within ± 10 G, and the phase slip can be controlled within ± 20 °, as shown in Fig. 3. As shown in Fig. 4, the working diagram of the magnetic field can be seen that the axial working point Qz is greater than 0.05, which can provide sufficient magnetic focusing force and does not cross the dangerous resonance line. Since the 1/4 model is used to calculate the magnetic field, the 1st~3rd harmonic amplitude of magnetic field is less than 0.1 G, and the symmetry is perfect.

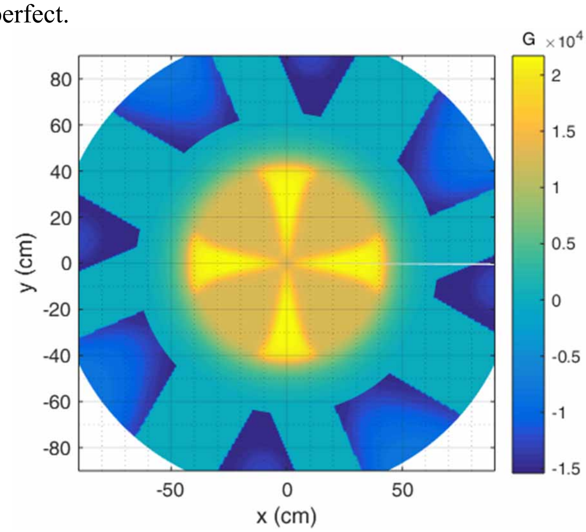

Figure 2: Axial magnetic field distribution in the middle plane.

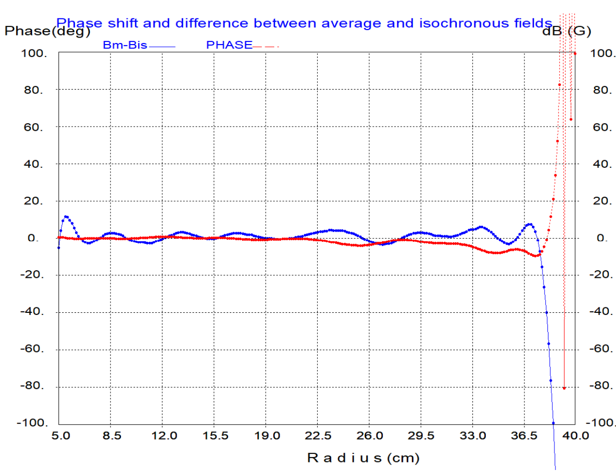

Figure 3: The deviation of the average field from the isochronous field and the slip phase.

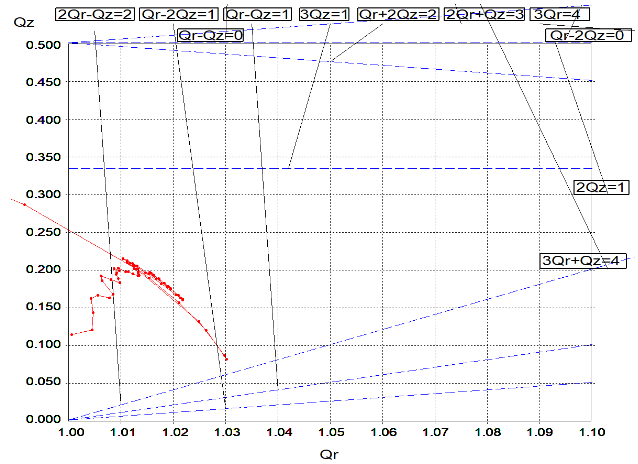

Figure 4: Working diagram and resonance line crossing.

BEAM DYNAMICS SIMULATION

In order to calculate the beam trajectory, we developed a beam dynamics simulation code based on MATLAB. The differential equation of motion of particles in the electromagnetic field can be derived from the momentum theorem. As shown in equation (1~3), it is a set of second-order ordinary differential equations with time t as the independent variable. Where, ε stands for electric field, B stands for magnetic field. The fourth order Runge-Kutta (RK4) algorithm is used to solve the differential equation, and the third order Lagrange interpolation is used to obtain the electromagnetic field data of any point, which can make the calculation efficiency and accuracy of the software reach a perfect balance. As shown in Fig. 5, the extraction trajectory of different energy particles calculated by the beam dynamics simulation code shows that the cyclotron can successfully achieve the extraction of 10~16 MeV variable energy beam, with the corresponding extraction radius of 29.9~37.1 cm.

$$\frac{dv_x}{dt}\cdot\frac{m}{q}+\frac{\varepsilon_x v_x+\varepsilon_y v_y+\varepsilon_z v_z}{c^2}\cdot v_x = v_y B_z - v_z B_y + \varepsilon_x \quad (1)$$

$$\frac{dv_y}{dt}\cdot\frac{m}{q}+\frac{\varepsilon_x v_x+\varepsilon_y v_y+\varepsilon_z v_z}{c^2}\cdot v_y = v_z B_x - v_x B_z + \varepsilon_y \quad (2)$$

$$\frac{dv_z}{dt}\cdot\frac{m}{q}+\frac{\varepsilon_x v_x+\varepsilon_y v_y+\varepsilon_z v_z}{c^2}\cdot v_z = v_x B_y - v_y B_x + \varepsilon_z \quad (3)$$

where:
v: speed of particle;
t: time;
m: mass of particle;
q: charge of particle;
ε: electric field intensity;
c: speed of light;
B: Magnetic induction intensity.

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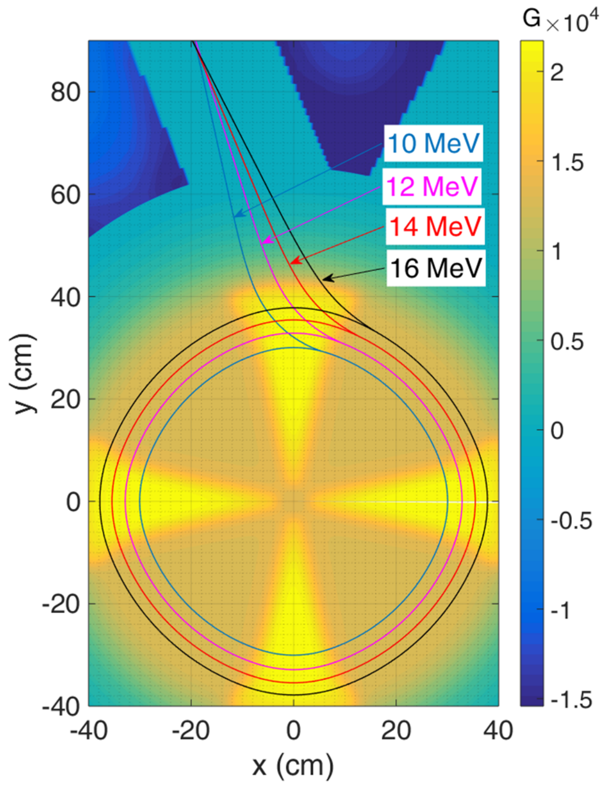

Figure 5: Extraction trajectories of particles with different energies.

CONCLUSION

The magnet of a 10~16 MeV variable energy cyclotron is designed at ASIPP and CIM, which has 4 pairs of radial sectors. The central field is designed to be about 1.54 T. The deviation between average and isochronous field is optimized to be less than 10 G. The working diagram is good as well. No dangerous resonance line is crossed. Beam dynamics simulations show that particles with energy of 10~16 MeV can be extracted at extraction radius of 29.9~37.1 cm.

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