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DESIGN AND ANALYSIS OF THE 230 MeV CYCLOTRON MAGNET FOR THE PROTON THERAPY SYSTEM

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Abstract

This paper demonstrates the design and analysis of 230 MeV cyclotron magnet of the proton therapy system. The magnet is the core of the 230 MeV cyclotron, which can keep the beam orbit and limit beam divergence. The magnetic field calculation and modification are analyzed in detail, with the isochronous error of the magnetic field less than 0.2%. Meanwhile, the thermal analysis of the coil has been calculated by the empirical formula.

INTRODUCTION

The overall model of the C230 cyclotron and the structure of the accelerator is shown in Fig. 1.

The proton cyclotron magnet is mainly composed of magnetic pole, magnetic yoke and pad. In order to achieve the design goal of 230 MeV proton energy, a helical sector focusing structure, four blade poles and four harmonic accelerations are adopted (Fig. 1). To compensate for the increasing energy with radius and the increasing defocusing by the main field, the angle by which the hill-valley boundary is crossed increasing by making the hill-valley structure spirally shaped [1]. This kind of magnet structure is relatively simple and more compact. A replaceable tuning block is installed in the edge of the magnetic pole, and the isochronicity of the magnetic field can be adjusted by changing the tuning block size. In order to ensure isochronous acceleration conditions, the design goal is to limit isochronous error less than 0.2%.

The main magnet model of the accelerator was established in Opera3D, whose yoke material is low carbon steel. The magnetization curve was shown as the Fig. 2 below. The acceleration frequency and energy curves of the initial model are present respectively. Final particle energy can meet the design requirements, indicating that the profile is basically correct. However, the acceleration frequency fluctuation is large in the initial model, which does not full-fill the condition of iso-chronicity.

The change of the phase, stipulated by the change of the frequency of the accelerating voltage the electric intensity [2]. When the RF frequency is large, it indicates that the ideal reference particle is ahead of the acceleration voltage.

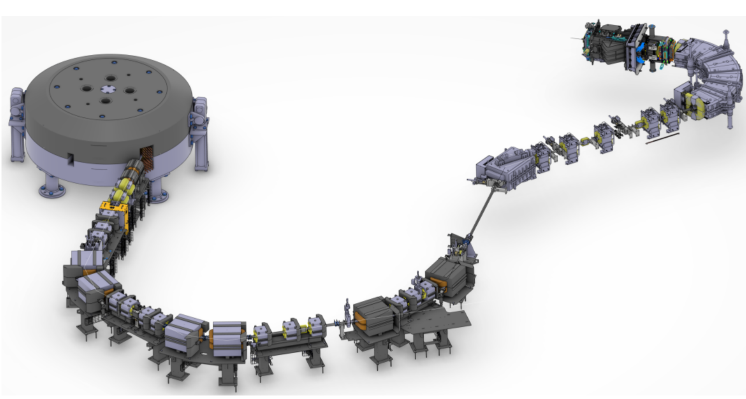
The cyclotron frequency of the particle will be reduced, through changing the magnetic field by adjusting the angle of the magnetic pole at the radius. Instead, it is necessary to increase the magnetic field, through increase the angle of the magnetic pole also. Finally, the particle energy can reach 232 MeV at the radius of 1060 mm, which meets the design requirements. The final optimized magnetic field has been shown in Fig. 3.

The custom oxygen-free copper wire with inner circle and outer square is selected, whose specification is 9.5 × 20.9 × 20.5 mm, further more total resistance of the coil is 298 mΩ. There are 352 turns of single coil totally, inner diameter of 2,360 mm, outer diameter of 3,340 mm, height of 350 mm.

Through the simulated resulting, the coil current density is 1.525 A/mm², and the ampere-turns 261,537.5 A. The coil current is about 743 A, and the power consumption is about 165 kW.

It is generally believed that the inlet temperature of coil cooling water is about 20 °C, and the outlet temperature is below 45 °C.

The total water flow $q = \frac{P}{c_p \cdot \rho \cdot \Delta T}$ is 94 L/min. The calculated pressure loss of cooling water in the coil is 1.149 MPa. The cooling system is set to cooling water pressure of 1.5 MPa, coil cooling flow of 99.2 L/min.



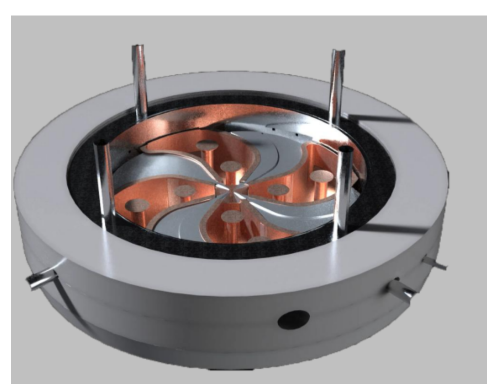


Figure 1: Overall model of C230 cyclotron and internal structure of the accelerator.

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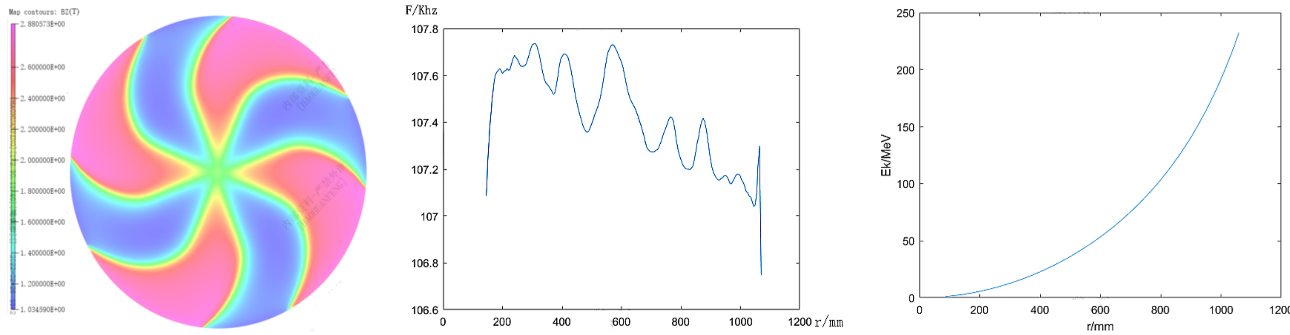

Figure 2: Initial iteration version cloud image of C230 magnetic field distribution, the acceleration frequency fluctuation is large in the initial model, particles of different radii accelerate in energy.

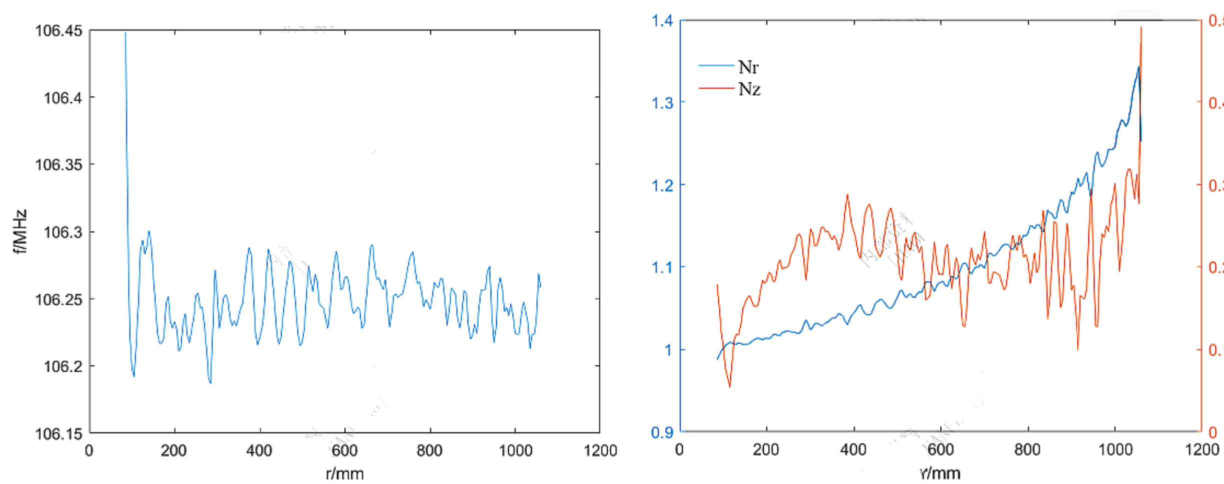

Figure 3: After model iteration, the acceleration frequencies of different radii tend to be stable.

By the formula:

$$\frac{1}{\sqrt{f}} = -2\lg\left[\frac{k_s}{3.7\cdot d} + \frac{2.51}{Re\cdot\sqrt{f}}\right], \quad (1)$$

$$\Delta P = 0.01\cdot f\cdot\frac{L\cdot v^2\cdot\rho}{2\cdot d} + \left[0.131 + 0.163\cdot\left(\frac{d}{R}\right)^{3.5}\right]\cdot 4\pi\cdot\frac{v^2\cdot\rho}{2\cdot 10^5}\cdot k, \quad (2)$$

The theoretical pressure loss of cooling water in the coil is 1.149 MPa. In order to preserve the margin and other factors, 1.5 MPa cooling water was selected and coil cooling single flow rate was 6.2 L/min, a total of 99.2 L/min.

CONCLUSION

In this paper, the electromagnetic field analysis software Opera3D is used for modeling and analysis of the cyclotron magnet, and by comparing with isochronous field, the magnetic model is modified accordingly.

Through the magnetic field calculation and modification, the isochronous error of particles is less than 0.2%. The magnetic field at a small radius has a negative gradient through adding a permanent magnet in the center area, which could provide an axial weak focusing force, so as to meet the axial stability condition. Finally, the ideal model of proton cyclotron magnet has been obtained. Meanwhile, the temperature rise and pressure drop of the coil have been calculated.

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