CENTRAL REGION DESIGN OF THE HUST SCC250 SUPERCONDUCTING CYCLOTRON

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Abstract

Recently, the development of a 250 MeV cyclotron for advanced cancer therapy has been carried out by Huazhong University of Science and Technology(HUST) . It has four sector magnet and RF cavity which resonance frequency is 74.69 MHz. The internal ion source was adopted and the central region was designed to accommodate the starting beam. In this paper, the design of the central region to optimize the initial circumstances for H+ beam were described. The electric and magnetic field distribution were designed by electrostatic and magnetic solver in OPERA-3D TOSCA. The beam characteristics including the beam orbit, motion of the center of orbit, energy gain was investigated for central region was simulated by means of computer code Z3CYCLONE.

INTRODUCTION

A cancer therapy superconducting cyclotron is modelled to produce a low cost, dependable proton beam. The present calls for the production of 250MeV protons with currents up to 500nA. The magnet was designed with a central field of 2.45T giving an orbital frequency of 74.69MHz. A four sector, four dee in the valleys configuration was chosen and afford a large energy-gain-per-turn towards the end of single turn extraction. To simplify the RF drive system (and reduce cost) the RF will be run in second harmonic with a peak dee voltage of 60kV. The peak magnetic field in the hills of the magnet is approximately 3.9T and the minimum valley field is 2T. The central region design studies were carried out by way of beam orbit tracking. Studies were made of the source placement required to produce well centred beams with good vertical focusing.

DESIGN CONSIDERATIONS OF THE CENTRAL REGION

The main parameters of the SCC250 central region are listed in Table 1. The beam is extracted form an internal cold cathode PIG source. Without beam manipulation provided by the external beam injection line, such as beam phase matching with the cyclotron eigen-ellipse and bunching, the central region of internal source cyclotrons is more sensitive and should be carefully designed. The main goals of central region design is a. horizontal centring of the beam with respect to the cyclotron centre; b. vertical centring of the beam with respect to the median plane; c. Optimizing the phase acceptance; d. minimizing the vertical beam loss in the central region [1].

Table 1: Basic Parameters

Parameters	Value
DEE width	50°
DEE voltage	60 kV
Harmonic mode	2
RF frequency	74.69 MHz
Injection radius	1.18 cm
Injection radius	122°
Central magnetic field	2.45 T

PIG SOURCE

The ion source used in the present study is a cold cathode PIG ion source. The source is similar to the source used in PSI. Fig. 1 shows a cross section view of the cathode-anode region of the source. This source used in the magnetic field as high as 3.9 Tesla that the magnetic field is parallel to the chimney. The rates of the hydrogen gas flow is 1.6 to 6.0 cubic centimetres per minute. The potential difference between the anode and cathode to cause the arc to strike is 3kV. When the plasma is established, the power supply shifts to current limited operation and the potential between the anode and cathode drops to the value required to sustain this current. It has a water-cooling system inside the steel use stainless (SUS) pipes. The anode material is chosen as tungsten-copper. The slit for extracting the hydrogen gas has 0.5mm in width and 5mm in height[2-3].

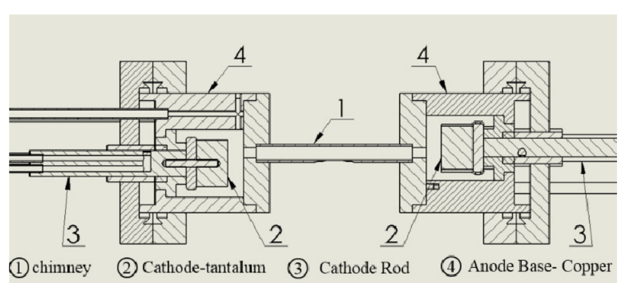

Figure 1: Structure diagram of the PIG source.

PIG EXPERIMENT PLATFORM

The condition of the beam which affects the entire acceleration characteristics. A DC PIG source experiment platform is designed as shown in Fig. 2. The magnetic field is produced by a C-type dipole magnets. The central field strength is 1 Tesla. High voltage is supplied to the dee by a power supply which is rated at 60kV and 2mA.

The puller provides the electric field that extracts the beam from the ion source. The part of the beam that hits the slit probe or the beam shield is blocked. Some other diagnostic facilities were also designed as show in Fig. 3.

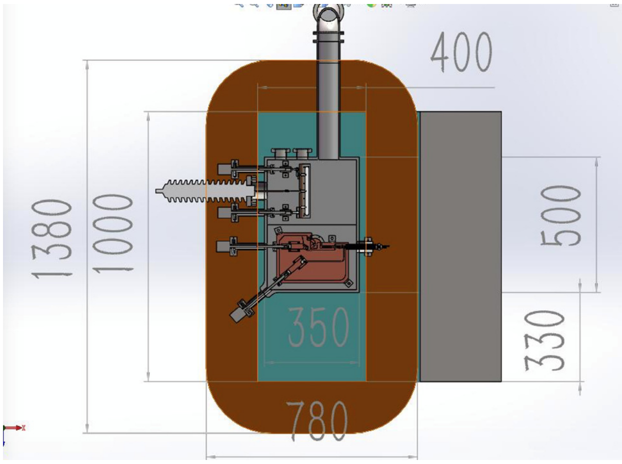

Figure 2: Structure diagram of the PIG experiment platform

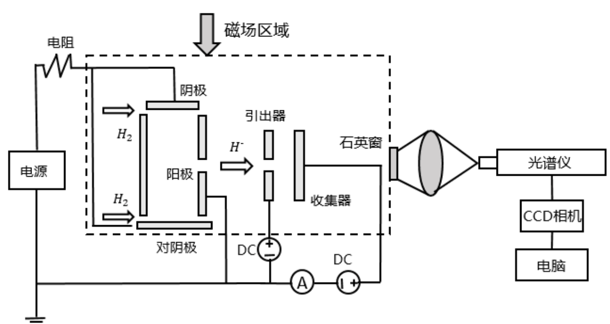

Figure 3: Schematic diagram of the central region electrode.

ELECTRIC AND MAGNETIC ANALYSIS

By containing more details, the electro-magnetic field simulation results using the finite element method (FEM) in 3D models are close to the reality. IBA's experience shows that there exists a 2%-3% difference in the magnetic field when using the OPERA-3D code. After the magnet had been mapped, it was modelled with the TOSCA (TOSCA is part of the Opera-3D software package produced by Vector Fields Inc.) The complex central region structure model which contains the dee, dummy dees, the puller and beam channels. SOLIDWORKS is firstly used to establish the parameterized model, as shown in Fig. 4, which is imported to the Finite Element Analysis (FEA) software OPERA [4] to calculate the electric field. The potential map is shown in Fig. 5[5].

Considering the isochronous requirements of the cyclotron, the radial logarithmic gradient of the magnetic field is bigger than zero, at the same time, the radial dimension of the first 2 turns is about 50mm which is relative small resulting that the magnet flutter can be ignored. Thus, the magnet pole shape is initially designed to optimize the axial focusing of the beam. And the average magnetic field distribution is shown in Fig. 6.

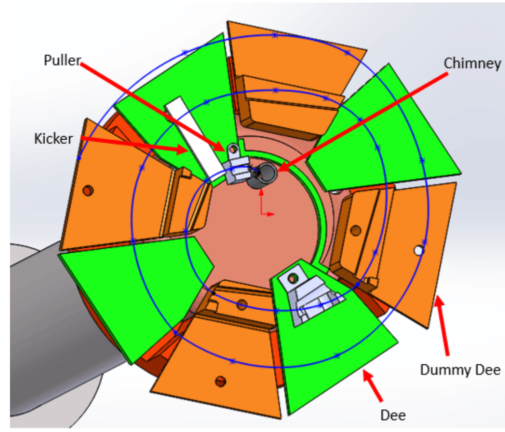

Figure 4: Structure diagram of the central region electrode.

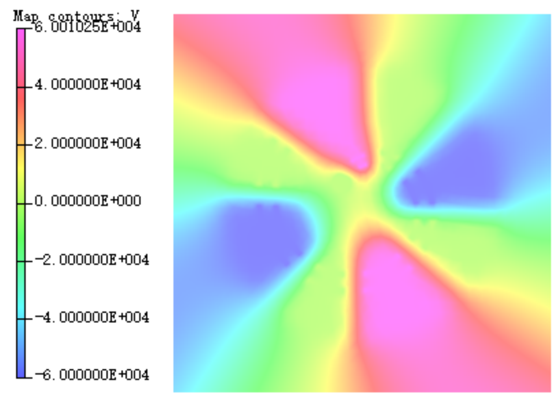

Figure 5: Potential map calculated by TOSCA.

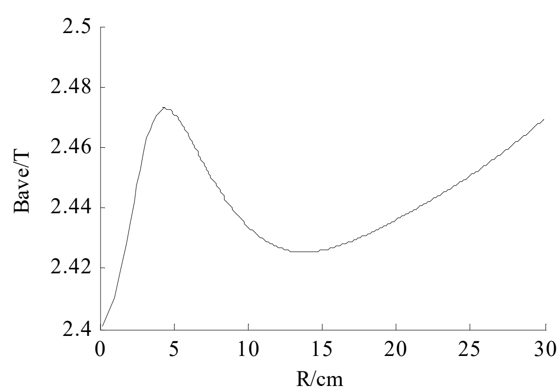

Figure 6: Radial distribution of the average magnetic field in central region.

ORBIT TRACKING

In pursuit of an optimal design of the central and extraction regions in the cyclotron, we have studied optics of a beam starting from the ion source exit to the first 5 turns with Z3CYCLONE[6]. The RF electric field maps used cover the entire beam acceleration region. Based on the requirements for input electric field of Z3CYCLONE, the electric field is divided into two parts, namely, the

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large field and small field. The small field covers the area from the anode to the first puller, the large field is the area from the puller to the first 5 turns. And different mesh size is used based on the accuracy of solution. The mesh sizes of the large field in 3 dimensions are 0.508 mm, 0.508 mm, 0.381 mm respectively; the mesh sizes of the small field are 0.076 2 mm, 0.076 2 mm, 0.190 5 mm。

The injection radial is 1.18cm, with the injection angle of 122 ° and a range of initial RF phase. As shown in Fig. 6, the radial RF phase acceptance is about 24 °, from 147 ° to 171 °. Ignoring the transition effect in the accelerating gaps, the theoretical calculation formula for the energy gain of one turn is as follows,

$$\begin{aligned} E_{gain} &= U_m \cdot \sin\left(\frac{\theta_{DEE} \cdot h}{2}\right) \\ &= 0.06 \times \sin\left(\frac{50 \times 2}{2}\right) = 0.3677\text{MeV} \end{aligned} \tag{1}$$

Fig. 7 gives orbits of the four representative particle in the first five turns with the starting angle perpendicular to the source slit and a zero vertical displacement. The optimized slit position is at the radius 11.8mm. Fig. 8 shows the energy gain of six particles. The maximum energy gain of a single turn is 0.35MeV, 17.7keV smaller than the theoretical value. Fig. 9 shows the motion of the orbit centres of four particles. The maximum deviation of the beam curvature centre from the centre of the cyclotron is about 5mm which is acceptable. From the detail simulation results, the RF phase acceptance is about 24°.

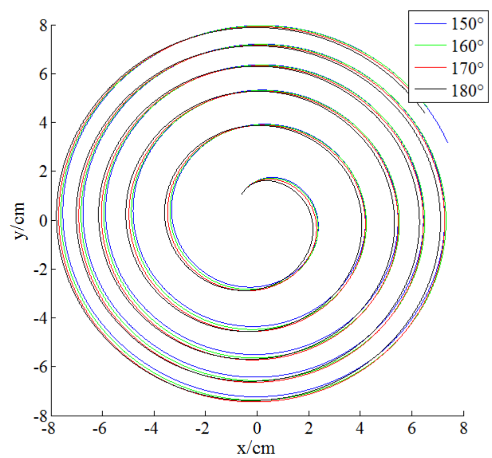

Figure 7: Particle orbit diagram for the initial phase ranging from 150°to 180 °.

CONCLUSION

This paper introduces the design process of the central region of the superconducting cyclotron SCC250 for proton therapy. The cyclotron uses internal cold cathode PIG source, and superconducting coil, which makes the structure very compact. Through the iterative designation, calculation and rectification of the structure with a combine use of SOLIDWORKS, OPERA and Z3CYCLONE, a central region scheme can be put forward which meets the superconducting cyclotron requirements for proton therapy. In this paper, the optimized parameters are as follows, the radial phase acceptance is 24°, the maximum deviation of the curvature center of the beam trajectory from the cyclotron center is controlled within 5mm.

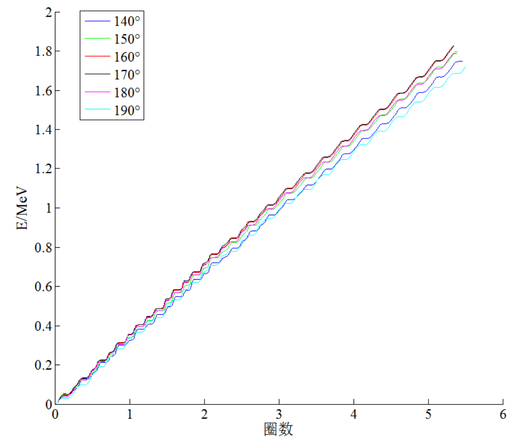

Figure 8: Energy gain diagram.

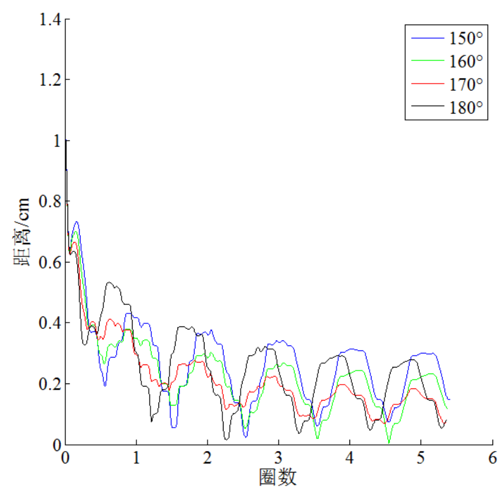

Figure 9: Particle orbit curvature centre diagram.

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