CENTRAL REGION DESIGN FOR A SUPERCONDUCTING CYCLOTRON IN THE HUST PROTON THERAPY FACILITY*

Zhiyuan Mei,Xiaofei Li,Zhijie Zeng, Lige Zhang, Shengwei Hu,Kuanjun Fan†
Huazhong University of Science and Technology, Wuhan 430074, China

Abstract

A 250 MeV isochronous superconducting cyclotron is being studied for a proton therapy facility at the Huazhong University of Science and Technology (HUST). One of the most difficult problems to solve is the central region design due to the very compact structure. Much effort has been made to the design and optimization of the central region in order to obtain a qualified proton beam for treatment. An internal proton PIG source with constant arc current is used to ensure high stability of the beam. A puller followed by an adjustable slit to select the beam phase width. To meet the requirement of the intensity modulated proton therapy (IMPT), a vertical electro-static deflector and a collimator are implemented. The central region structure is optimized iteratively with the simulation codes OPERA3D and CYCLONE. An optimum central region configuration with RF phase acceptance of around 24° has been obtained. This paper presents the design of the central region and the resulting proton beam behavior.

INTRODUCTION

Proton therapy is one of the most precise, advanced radiation treatment modalities for cancer. The number of proton therapy centres is rising rapidly recently. China has the greatest cancer patients in the world, which leads to a very fast growing demand for proton therapy. A superconducting cyclotron based proton therapy facility was supported by the National Key Research and Development Program in the thirteenth five-year plan for science and technology development. This project are jointly developed by several institutes, among which Huazhong University of Science and Technology (HUST) plays a crucial role in this program. The facility adopts a 250 MeV isochronous superconducting cyclotron(HUST-SCC250) to provide the proton therapy beam. Since the proton beam quality is greatly affected by the parameters of the central region, much effort has been given to the design and optimization of the central region. A cold-cathode PIG internal ion source is adopted to generate the stable proton beam required by treatment. OPERA3D code is used to calculate the electromagnetic field of the central region, and CYCLONE code is used to study the beam trajectory. An optimum central region configuration with RF phase acceptance of 24° has been obtained finally by using this iterative process. Besides, a test bench has been designed to examine the extraction beam quality of the internal PIG source for further improve the PIG source practically.

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† E-mail:kjfan@hust.edu.cn

COLD INTERNAL PIG SOURCE DESIGN

Most high energy cyclotrons used for proton therapy, such as the superconducting cyclotron COMET made by Varian/ACCEL, a cold-cathode PIG internal ion source is often adopted for its simplicity and low-cost [1]. Internal ion sources have disadvantages of low beam intensities, no beam manipulation, simple ion species, however, its excellent maintainability and compactness makes it more suitable for the superconducting cyclotron in the proton radiation therapy. An internal cold cathode PIG source is designed for the 250 MeV superconducting cyclotron, which is shown in Fig. 1.

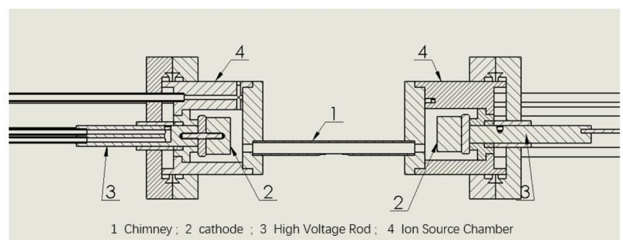

Figure 1: Structure of the PIG source.

The internal ion source consists of two halves anode cathode pairs. The cathodes are made of tantalum for its excellent physical properties. The anode cathode arcs are used to ionize the hydrogen gas. Both halves are connected via a chimney with diameter of 7 mm, which is very easy to be put in the central region. A beam extraction slit of 5.5 mm × 0.3 mm is opened in the middle of the chimney where the protons are extracted from the plasma by the puller dee voltage. The whole PIG source is cooled by water, and the high voltage rod is designed to be hollow for the cooled-water circuit.

Beam Exit Slit

The structure of the chimney's slit has great influence on the initial boundary condition of plasma at exit slit, which in turn affects the proton beam trajectories from the ion extraction slit [2]. Slits with different geometry and dimensions are studied extensively using COMSOL code for the parameters optimization as shown in Fig. 2.

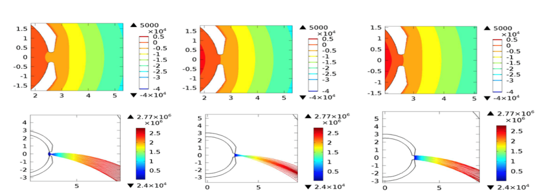

Figure 2: Exit slit effects on extraction beam.

The upper figure shows the distribution of the electric field with different shapes of slit, which results in concave, flat and convex plasma boundary conditions respectively. The resulting beam orbits are shown in the lower of the Fig. 2, which are over-focusing, focusing to defocusing. Simulation results show that the shape of the plasma boundary has a strong effect on the property of extraction beam.

In order to study and optimize the ion source practical-ly, a multi-purpose experimental test bench has been designed as shown in Fig. 3. Both the ion source and the electrostatic deflector for beam extraction can be tested in the same test bench, which makes the test bench much cost effective.

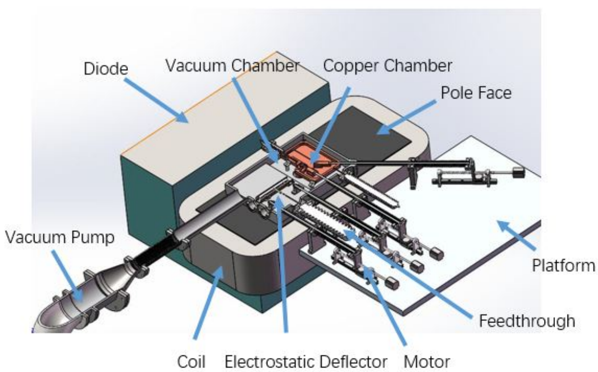

Figure 3: Structure of the ion source test bench.

Fig. 4 shows the ion source inside the testing vacuum chamber in detail. A slit probe and a wire probe is used to measure the beam current intensity and the beam emittance. The high voltage of the puller is set between 3 kV to 4 kV. The whole ion source testing platform is enclosed by a copper chamber to shield stray electric field.

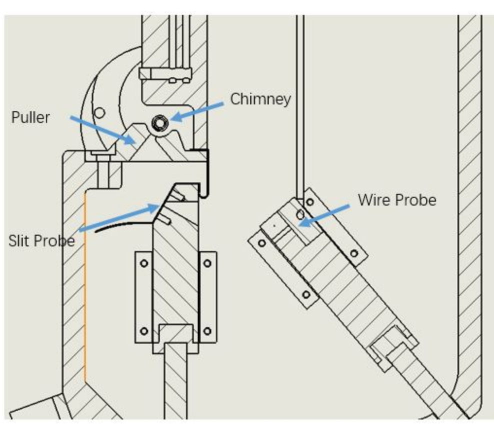

Figure 4: Structure of the ion source testing chamber.

CENTRAL REGION DESIGN

Since beam manipulation of the internal PIG source is not available, considerable efforts have been made to the design and optimization of the central region to achieve good beam quality, such as orbit centering and beam emittance matching, which has significant impact on the distribution of the extraction beam orbits. Table 1 lists the main parameters in the central region.

Table 1: Main Parameters

parameters	value
dee voltage	60 kV
Dee width	50°
Harmonic mode	2
RF frequency	74.3 MHz

Central Region Configuration

In the central region of the HUST-SCC250 cyclotron, the magnetic field flutter is so small that it is difficult to achieve the beam axial focusing. A special shape of electrode in the central region should be well-designed to provide axial focusing. Since the initial proton kinetic energy from the ion source is very small the source-puller electric fields will have great impact on the proton beam quality. The structure of the puller electrode is required to be designed and calculated iteratively and elaborately[3].

The central region structure and the schematic ion orbit is shown in Fig. 5, which consists of a puller, Dees, dummy Dees , a phase slit and a vertical electrostatic deflector. The vertical deflector is used to modulate the beam intensity rapidly for proton therapy.

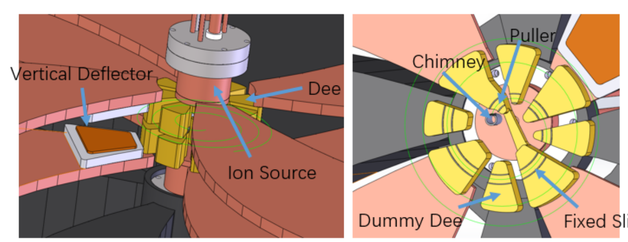

Figure 5: Central region configuration.

OPERA-3D is used to calculate the electric field precisely as shown in Fig. 6 [4]. The phase slit is used to shape the beam length and the corresponding energy spread. The vertical gap is set to 6mm for the vertical oscillation limitation.

BEAM DYNAMICS STUDIES

The optimum of the central region structure can be obtained by the iterative progress of particle tracking and electromagnetic field simulation. The CYCLONE code has been used to calculate the beam trajectory. The beam orbits are calculated using a 4th order Runge-kutta integration method with electric and magnetic field maps. The equation of motion is given by Eq. (1) [5]

$$dE/dt = q \cdot (\partial V/\partial t - dV/dt) \quad (1)$$

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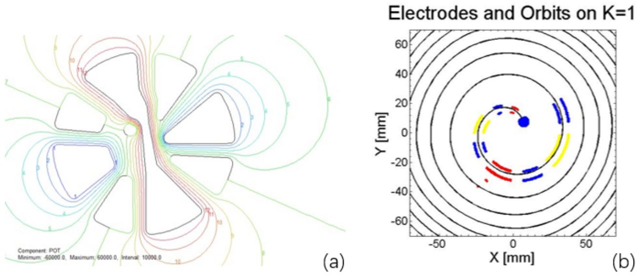

Figure 6: (a):Electric field of the central region;(b)Typical beam orbit.

By moving all the total derivatives to the left hand side, we obtain

$$\mathrm{d}J/\mathrm{d}t = \mathrm{q} \cdot \partial V\,(\mathrm{x}, \mathrm{y}, \mathrm{t})\,/\partial t \tag{2}$$

where we define a variable

$$J = E + qV(x, y, t) \tag{3}$$

By integrating J in Eq. (2) with the Runge-kutta method, the particle trajectory in the central region can be calculate.

The high voltage of the puller is designed to 60 kV, and the optimized slit position is at the radius 18 mm. Fig. 7(a) shows the calculated orbit of three representative particles in the first 5 turns with different starting phase from 147° to 171°. From massive calculating results, the horizontal RF phase acceptance is determined as nearly 24°. Fig. 7 (b) presents the orbit centers motion of the four different initial phase particles.

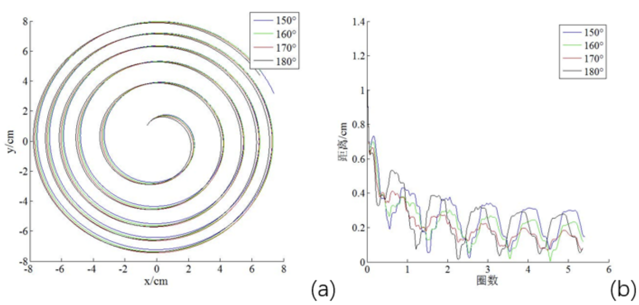

Figure 7: Beam orbit with different initial phase; (a)Particle orbits; (b)Particle orbit curvature center.

The energy gain per the turn by tracking is about 0.35 MeV as shown in Fig. 8, which agrees well with the theoretical calculation. Simulation shows that the uncorrelation between the starting phase and the off-centering of particle is acceptable and the beam trajectory is well horizontal centering.

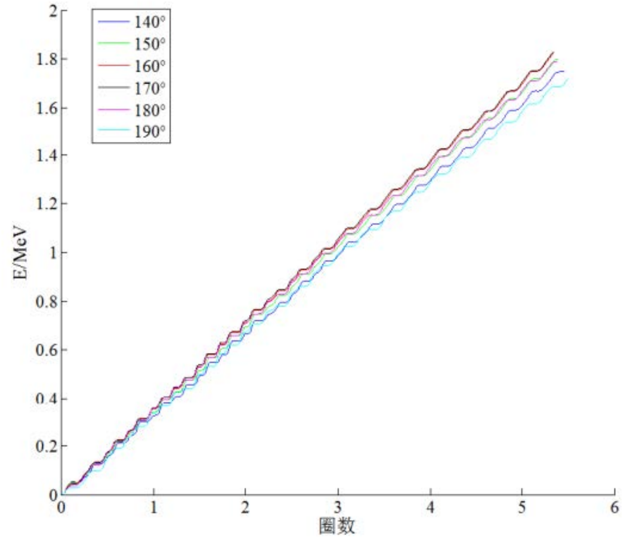

Figure 8: Energy gain diagram.

CONCLUSION

This paper describes the design of the central region of the HUST-SCC250 cyclotron. Both OPERA-3D and the CYCLONE codes have been used extensively to obtain an optimum design of the central region structure, which has a RF phase acceptance of 24°.

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