ISBN: 978-3-95450-199-1 doi:10.18429/JACoW-SAP2017-TUBH4

CENTRAL REGION DESIGN OF THE HUST SCC250 SUPERCONDUCTING CYCLOTRON *

Z. J. Zeng†, K. J. Fan, Huazhong University of Science and Technology, Wuhan, China

Abstract

A superconducting cyclotron based proton therapy system is being developed at Huazhong University of Science and Technology (HUST). The compactness of superconducting cyclotron imposes a challenge to the central region design. This paper describes beam dynamic studies in the central region. Beam performance at the initial 4 or so turns is crucial that determines the beam emittance, energy divergence and extraction efficiency. Therefore, considerable efforts have been made to the central region design and optimization. The electric and magnetic field distribution are numerically calculated by the program OPERA. Particle trajectories are simulated by means of the computer code Z3CYCLONE and the track command in OPERA. Finally, an optimum central region configuration is obtained which meets the stringent requirements and further studies is carried out about the beam radial and axial motion based on the designed central region.

INTRODUCTION

Proton therapy has shown advantages in treating several kinds of cancer and has become a favorable treatment option for patients, which shows considerable advantages over conventional photon therapy. In recent years, there has been a massive growth in the development of proton therapy centers in the world particularly in China. The cancer incidence in China is the greatest in the world, and cancer is the leading cause of death, which has become a major public health problem in China. In order to meet the fast growing demand for proton therapy, Chinese government decided to support the development of a superconducting cyclotron based proton therapy facility in the National Key Research and Development Program at 2016. This project is being taken by several institutes and Huazhong University of Science and Technology (HUST) plays a crucial role in this program.

The superconducting cyclotron HUST-SCC250 has the advantage of minimizing the size, however, it has as a drawback of difficult to design a very compact central region. The central region uses an internal cold cathode PIG source to simplify the structure. The configuration of the central region is optimized by using the OPREA code, which can numerically simulate the electric and magnetic field distribution exactly. The beam dynamics studies in the central region are carried out using the beam tracking codes Z3CYCLONE and the track command in OPERA.

* Work Work supported by national key R & D program, 2016YFC0105303
† zengzhijie@hust.edu.cn

CENTRAL REGION DESIGN

One of the challenging design tasks of a superconducting cyclotrons is the central region, where the initial proton orbits are crucial in determining the properties of the final beam.

To study the beam dynamics in the central region, considerable efforts have been made to optimize the central region geometry. The optimum central region design could be achieved using iterative process. Two main problems concerning the central region are the axial motion and radial motion [1].The main parameters of the central region are listed in Table 1.

Table 1: Basic Parameters

Parameters	Value
DEE width	50°
DEE voltage	60 kV
Harmonic mode	2
RF frequency	75.52 MHz
Injection radius	1.18 cm
Injection angle	122°
Central magnetic field	2.476 T

The design process of central region is illustrated as follows,

1) Assuming a uniform magnetic field in the central region, the initial condition of the beam after circulating one turn is obtained based on the ideal energy gain. Then, the initial condition is revised in order to make beam be centered.

2) Using backward algorithm to determine the position of the ion source.

3) Beam forward tracking algorithm is again used to optimize the electrode structure.

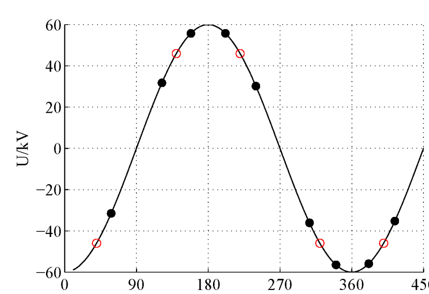

Figure 1: RF phase of the proton crossing the DEE boundary.

Ignoring the transition effect of the accelerating gap, the maximum energy gain on certain RF phases can be obtained, which is shown in Fig. 1 marked as the hollow circles.

ISBN: 978-3-95450-199-1 doi:10.18429/JACoW-SAP2017-TUBH4

In comparison, the RF phases when the proton crosses the DEE boundaries are shown as the solid circles in Fig. 1. The electrode structure is revised precisely to adjust the RF phase in order that the energy gain for beam of a certain initial RF phase can be reasonable. Simultaneously, beam for a certain range of initial phases can have better energy gain when crossing the gaps. The radial acceptance of beam can be adjusted in that way [2–5].

ELECTRIC AND MAGNETIC ANALYSIS

The parameterized model of central region is made using SOLIDWORKS at first, then it is imported into the Finite Element Analysis (FEA) software OPERA to calculate the electric field [6, 7]. Then beam dynamics analysis is carried out by using the track command in OPERA. The parameterized model is in turn revised to meet the requirements for the stable beam radial motion. Finally, the optimized electrode structure in the central region is designed as shown in Fig. 2, and correspondingly the potential map of the central region is shown in Fig. 3.

The axial focusing force of the magnetic field is small for the radial logarithmic gradient of the magnetic field is higher than zero. To optimize the axial focusing of the beam, the magnet pole shape is initially designed. The average magnetic field distribution is shown in Fig. 4 and the radial distribution of the vertical focusing tunes is shown in Fig. 5.

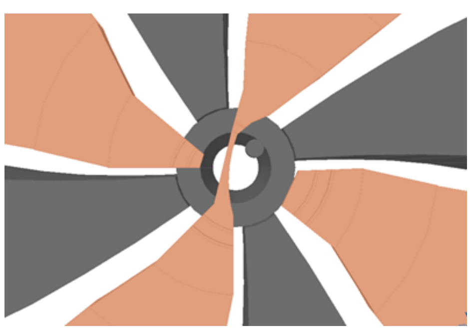

Figure 2: Structure diagram of the central region electrode.

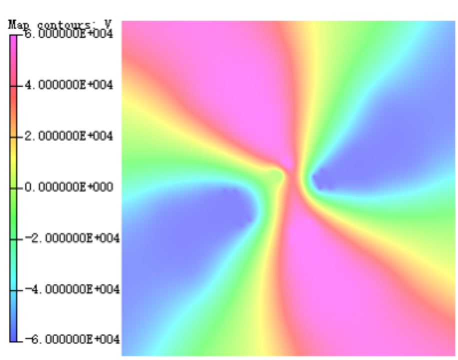

Figure 3: Potential distribution diagram calculated by TOSCA.

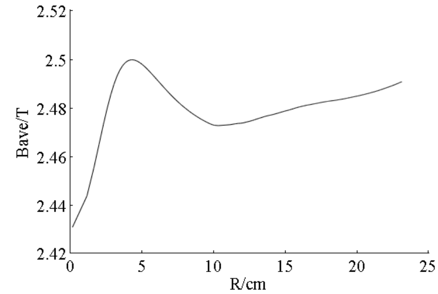

Figure 4: Radial distribution of the central region average magnetic field.

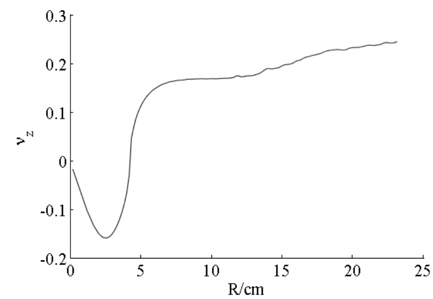

Figure 5: Radial distribution of the vertical focusing tunes.

BEAM DYNAMICS IN THE CENTRAL REGION

Radial Movement Analysis

Z3CYCLONE is adopted to calculate the beam orbit parameters at different initial conditions [8, 9]. The injection radius is 1.18 cm, the injection angle is 122° and several initial RF phases are selected for comparison. As shown in Fig. 6, the radial RF phase acceptance is about 20°, from 242° to 262°.

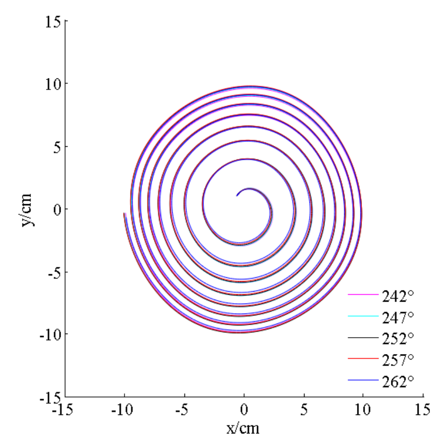

Figure 6: Particle orbit diagram for the initial phase ranging from 242° to 262°.

Ignoring the transition effect in the accelerating gaps, the theoretical energy gain per turn is given,

ISBN: 978-3-95450-199-1 doi:10.18429/JACoW-SAP2017-TUBH4

$$E_{gain} = n \cdot U_m \cdot \sin(\frac{\theta_{DEE} \cdot h}{2}) = 8 \times 0.06 \times \sin(\frac{50 \times 2}{2}) = 0.3677MeV \quad (1)$$

In numerical tracking, the maximum energy gain of one turn is 0.35 MeV, which is 17.7 keV smaller than the theoretical value (as shown in Fig. 7).

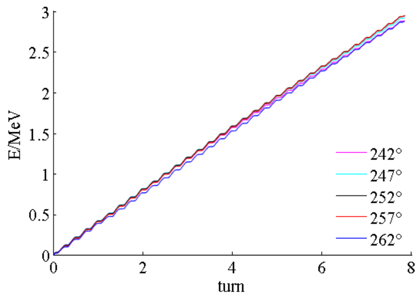

Figure 7: Energy gain diagram.

Figure 8 shows the maximum deviation between the instantaneous beam curvature center and the center of the cyclotron. The deviation is less than 1.8 cm in both x and y direction which is acceptable.

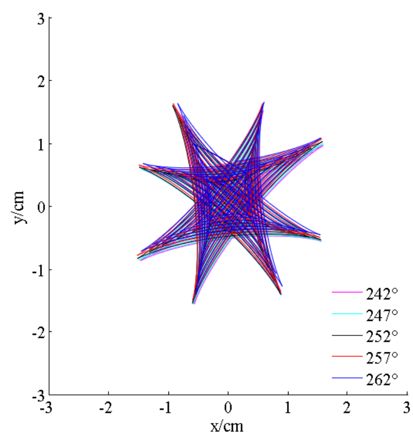

Figure 8: Particle orbit curvature center diagram.

Similarly, the calculated result of energy gain with Z3CYCLONE is cross checked by using the track command in OPERA, which is shown in Fig. 9. The relative error of energy gain for the first 4 turns is less than 1%, which shows the reliability of the orbit dynamics results.

Axial Movement Analysis

The axial movement of the beam is subjected to the electromagnetic force. Considering the half height of the ion source slit is 0.275 cm, axial movements of the beam starting form different initial conditions are analyzed here and shown in Fig. 10 and Fig. 11. The half height of the channel within r=5 cm is about 0.45 cm, thus the beam will not be

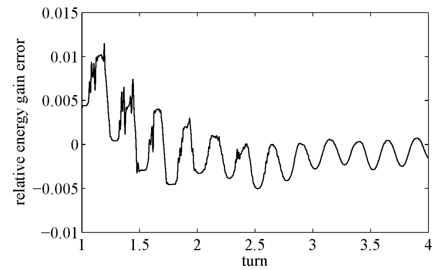

Figure 9: Relative energy gain error for OPERA vs Z3CYCLONE.

lost as shown in the figures. At the same time, the electric focusing force is greater for beam of positive phases which is in good agreement with the theoretical result.

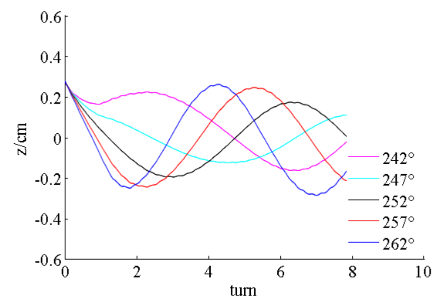

Figure 10: The vertical motion of various RF phase beams starting at z=0.275 cm, p_z=0.

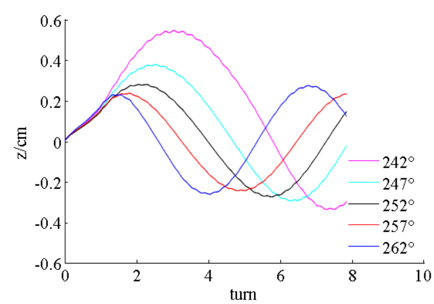

Figure 11: The vertical motion of various RF phase beams starting at z=0, p_z=0.0203 cm.

CONCLUSION

This paper introduces the design process of the central region of the superconducting cyclotron HUST-SCC250 for proton therapy. The compactness of the cyclotron makes the design difficult. The central region is optimized iteratively by using several codes, SOLIDWORKS, OPERA and Z3CYCLONE, which finally meets the requirements for proton therapy. The optimal parameters are as follows, the phase acceptance is about 20°, the maximum deviation between the instantaneous beam curvature center and the center of the cyclotron is controlled within 1.8 cm.

ISBN: 978-3-95450-199-1 doi:10.18429/JACoW-SAP2017-TUBH4

REFERENCES

[1] J. W. Kim, "Magnetic fields and beam optics studies of a 250MeV superconducting proton radiotherapy cyclotron," *Nucl. Instr. Meth*, vol. 582, pp. 366-373, (2007)

[2] V. Smirnov *et al.*, "Design study of an ultra-compact superconducting cyclotron for isotope production," *Nucl. Instr. Meth*, vol. 763, pp. 6-12, (2014)

[3] S. Y. Jung *et al.*, "Central region of SKKUCY-9 compact cyclotron," *Journal of Instrumentation*, 9(04): T04005, (2014)

[4] D. Toprek and L. Milinkovic, in *Proc. EPAC'94*, pp. 2361-2363

[5] D. Campo *et al.*, "Central region and static orbit study for the 300 A MeV superconducting cyclotron," *Cyclotrons and Their Applications*, pp. 391-393, (2007)

[6] Vector Fields Limited, OPERA-3D User Guide & Reference Manual, Oxford, (2006)

[7] H. Houtman, F. W. Jones and C. J. Kost, *Computers in Physics*, 8(4): 469, (1994)

[8] MSU NSCL Accelerator Group, *Z3CYCLONE. Instruction Manual*, Version 4.0., MSU, USA, (1993)

[9] C. Baumgarten *et al.*, "A beam profile measurement in the ACCEL 250MeV medical proton cyclotron," *Nucl. Instr. Meth*, vol. 569, pp. 706-712, (2006)