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BEAM EXTRACTION SIMULATION FOR A 230 MeV SUPERCONDUCTING CYCLOTRON

Ming Li†, Tianjue Zhang, Tao Cui, Tao Ge, Chuan Wang, Dongsheng Zhang, Jiuchang Qin, Sumin Wei, Shizhong An
China Institute of Atomic Energy, Beijing

Abstract

Introducing superconducting technologies, China Institute of Atomic Energy has designed a cyclotron to extract 230 MeV proton beam for cancer therapy. Extracted beam loss is one of the very crucial parameter in this machine. A low beam loss has benefit in reducing the dose level inside the cyclotron and preventing device damage, and consequently keeps the machine operate stable in long time. Two electrostatic deflectors are installed in the adjacent magnet hills to deflect the beam for extraction. The ν_r =1 resonance and precession motion are introduced in extraction region to enlarge the turn separation. After the deflectors, passive magnetic channels provide radial focusing force to restrain the beam dispersion in the edge field. In this paper, the design process and simulation results will be presented in detail.

INTRODUCTION

Proton therapy is an effective way for cancer treatment with minimal side effect and widely investigated recent years. Due to the progress of superconducting techniques, very compact cyclotron can be manufactured with lower cost and less power consumption, which could be very suitable to be installed in hospital. In order to promote the development of proton therapy in china, CIAE (China Institute of Atomic Energy) has designed a superconducting cyclotron to extract 230 MeV, 300 nA proton beam [1]. The overall structure of the cyclotron is listed in Fig.1. The diameter and height of the magnet is 320 cm and 140 cm respectively, and the weight of the magnet is about 70 ton. The main parameters of the cyclotron are listed in Table 1 in detail. The excitation and field mapping of the coil has completed, the results of which shows the system operates stable and could generate the desired field. Meanwhile, the rough machining of the magnet is finished and the precision machining is ongoing.

As a proton therapy machine installed in hospital, beam extraction efficiency is very critical to reduce the dose level, which could prevent the devices from damage and hence increase the reliability of the machine in long time operation. There are four sectors in this machine. Spiral structure of the pole is adopted to increase the vertical focusing. Unlike the normal temperature magnet, the edge field of pole is very soft, i.e. the field drops slowly at the edge, leading to a long drift before extracted to the outside of the cyclotron. In order to drag the beam from acceleration, two deflectors placed at the adjacent hills are adopted to accelerate the beam deflection. Moreover, many magnetic channels are used to prevent the beam from blowing up resulted from the long drift in edge field.

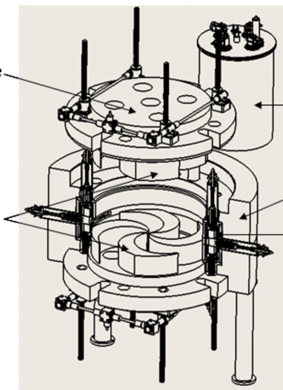

Figure 1: The overall structure of the cyclotron.

Table 1: The Main Parameters of the Cyclotron CYCIAE-230

Beam	
Extracted beam energy	240 MeV
Extracted beam current	300 nA
Magnet	
Pole structure	Spiral
Pole radius	85.0 cm
Outer radius of yoke	160.0 cm
Hill gap	5.0 cm
Central field	2.3 T
Coils	
Coil type	NbTi low temperature superconducting
Ampere-Turn Number	~600000 A.T×2
RF Cavity	
Number of cavity	4
RF frequency	72.0 MHz
Harmonic Mode	2
Cavity Voltage	80～110kV

BEAM PRECESSION

Beam precession with off center injection is always used to enlarge the turn separation in separated sector cyclotrons. A particle travel in the cyclotron with radial oscillation, the position of which at nth turn can be expressed as:

$$r = r_{seo} + x \sin(n(\nu_r-1)\theta+\varphi) \tag{1}$$

Where r_{seo} is the according position of the static equilibrium, x and φ is the oscillation amplitude and phase, ν_r is the tune value in radial direction and θ is the azimuth of the particle. Then the turn separation can be deduced,

†email address 393054642@qq.com

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$$\Delta r = \Delta r_{seo} + \Delta x \sin(n(\nu_r - 1)\theta + \varphi) + n(\nu_r - 1) x \cos(n(\nu_r - 1)\theta + \varphi) \quad (2)$$

Where Δr_{seo} is the separation from energy gain, the second term is from blow up of the amplitude taken from the resonance crossing, and the last term is from precession. From the formula we can know a large enough coherent oscillation amplitude is the precondition for the precession to generate a turn separation. Moreover in superconducting cyclotron, the compact structure results in beam overlap of neighbouring turns and precession in long time of acceleration could increase the effective emittance, thereby off center injection is not allowed in this cyclotron. Actually, beam centering is a very critical work in the commissioning of this cyclotron to improve the extraction efficiency. A clever solution is to introduce the precession in the last many turns instead of the whole acceleration process, where mixing of the phase space is far from sufficient to overlap together.

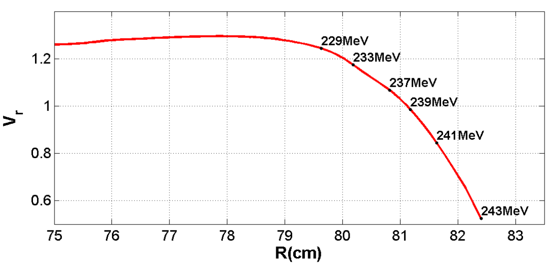

Figure 2: νr vs R at the extraction region.

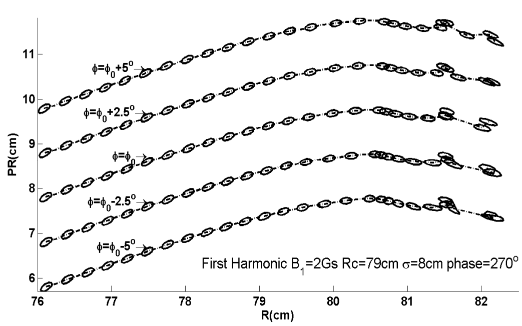

Figure 3: Phase space during the acceleration with different initial RF phase ($Ø_0$ is the central RF phase) , where a first harmonic distribution with maximum B1=2 Gs, center position Rc=79 cm, width σ=8 cm, phase =270°.

In CYCIAE-230, beam is accelerated near the pole edge where field is not isochronous and ν_r drops quickly as shown in Fig.2. A first harmonic near ν_r=1 is added through Trim Rods [2] to excite a coherent oscillation, i.e. the x in formula (2), when the beam passes the resonance. Then procession near the ν_r=0.75 could generate enough turn separation for the electrostatic deflector to extract the beam. We start the simulation from 200 MeV, selecting points on the radial phase space ellipse with normalized emittance of 0.5 πmm·mrad, which are accelerated to high energy, and then we can observe the precession near extraction. Figure 3. records the phase space during acceleration with different initial RF phase. From Fig.3 we can see the position and turn separation of beam with different initial phase is more or less overlapped, meaning beam loss at the entrance of the deflector is inevitable with large phase width beam. Figure 4 clearly shows the particles numbers along radius by simulation, which stars from 2 MeV with particle in an ellipse of 0.5 πmm·mrad, so the first electrostatic deflectors can be placed at r = 81.8 cm, where less particles is at the entry of septum and the beam envelop in the deflector is relatively small.

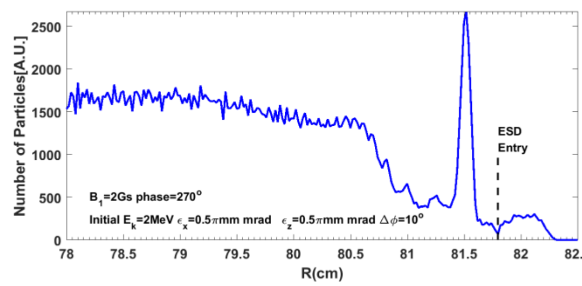

Figure 4: Particles numbers along radius. The entry of the first electrostatic deflector could be placed at r = 81.9 cm.

EXTRACTION DESIGN

Extraction Trajectory

Particle circulates in the cyclotron due to the effect of centripetal force coming from the magnetic field. In order to deflect the particle out of cyclotron, it is essential to drag the particle out as fast as possible, preventing a sharply blow up of the beam in a long drift. As the valley is occupied by the four cavities, two electrostatic deflectors (ESD) are placed in the adjacent hills, pushing the beam deviate from the pole. Then the sharply dropped edge field decreases the centripetal force to the particles, which are extracted after traveling about half turn. Besides, the magnetic channels, which are used to focus the beam, have a negative dipole field component [3], helping to accelerate the beam deflection. Figure 5 gives the trajectories of the particles. In this simulation, many particles are selected in the phase ellipse with emittance of 0.5 πmm·mrad at 200 MeV and the RF phase width is 10°. The electric fields of the ESD are 85 kV/cm and 75 kV/cm respectively.

In the extraction process, the beam has to pass the gap of ESD, MC and also the gap between the joint board of DEE and liner after the second the ESD. The joint board links the top and bottom DEE in large radius. Moreover, the beam can not touch the board in the DEE after the first ESD. The extraction position and electric field in the two ESDs can be changed here to adjust the beam path through the gaps. The increase of the electric field is restricted due to the high voltage discharge in such a compact space. A shimming bar at the outer edge of the pole is added, providing a method to adjust the local field and further change the extraction position.

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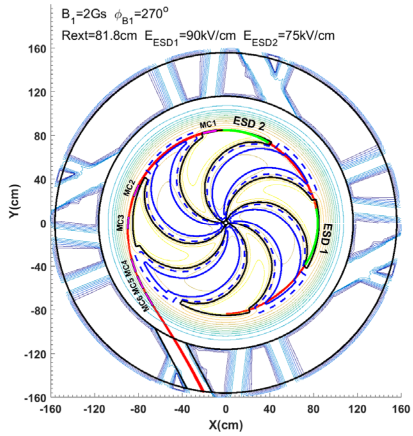

Figure 5: Particle Trajectories in the extraction process passing the electrostatic deflectors (ESD) and magnetic channel (MC) to the outside of the cyclotron.

Extraction Envelop

In the long drift, only the magnetic channel can be used to focus the beam in radial direction. As the space is very limited, passive magnetic channel (MC) are adopted generate a radial field gradient and also with a small dipole field component [3]. The MC is comprised with three iron bars and designed for the beam to pass fitly, so the effect on the main field is relatively weak. Figure 6 gives the cross section of one MC, which has a aperture of 6 mm and can generate a field gradient of 2.6 kGs/cm.

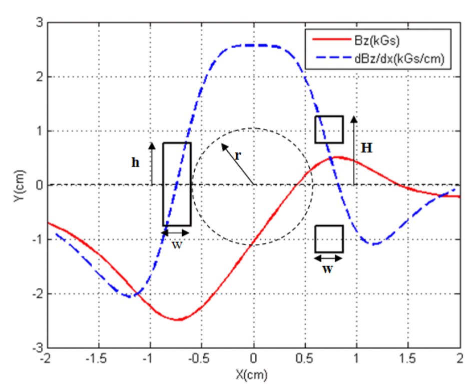

Figure 6: Field distribution in the cross section of the magnetic channel comprised with three iron bars. The size of the bars is given with r=6 mm, w=3 mm, h=8 mm, H=1.25 mm.

Through multi-particles simulation and optimizing the parameters of the six MCs, the beam envelop in the extraction process is illustrated in Fig.7. The radial and vertical envelops at the exit of the cyclotron are 8 mm and 1 mm. Here the start energy of the simulation is 200 MeV and initial emittance is 1πmm·mrad in both directions.

Beam Loss

Following the above the results, the distribution of beam loss is given in Fig.8. Most of the beam lost at the first ESD, especially at the entrance of the septum, which is easy to observe from Fig.4. Due to the thermal effects by the hitting of many particles, the Ti with high melting point is selected as septum material and a cool system is equipped with the first ESD to decrease the temperature of the septum.

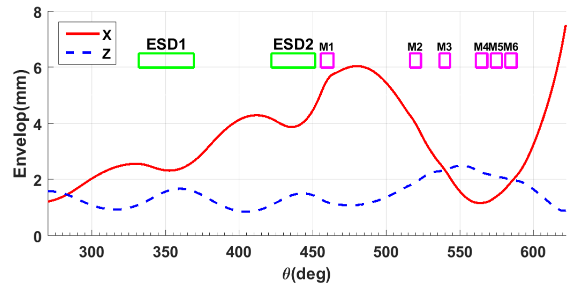

Figure 7: Beam envelop in the extraction process.

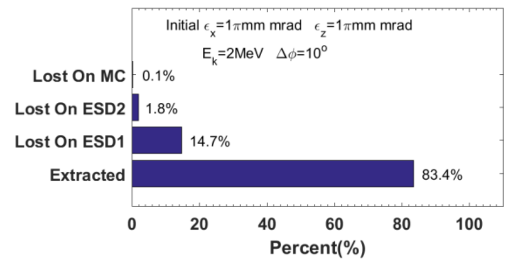

Figure 8: Beam loss distribution in extraction process.

CONCLUSION

The extraction simulation, including the trajectory, envelop and beam loss, is implemented in the CYCIAE-230. Through two ESDs and six MCs, the beam can be extracted to the outside of the cyclotron with reasonable transverse beam envelop. Results show the beam extraction efficiency could achieve 80%, providing a possibility to upgrade the current of cyclotron to about 1 μA in the future. High voltage discharge in the ESD is a critical issue in this machine. A test stand and 1:1 scale model of ESD 1 are designed and under machining to verify the feasibility of the design. Furthermore results on the experiments and the layout of the elements in the extraction process will be illustrated soon.

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