DESIGN AND CONSTRUCTION PROGRESS OF A 7MEV/U CYCLOTRON

B. Wang, H.F. Hao, J.Q. Zhang, M.T. Song, Q.G. Yao, L.Z. Ma, S.H. Zhang, X.W. Wang, A.M. Shi, Z.M. You, X.T. Yang, D.Q. Gao, X.Q. Zhang, K.D. Man, Y. Cao, H.W. Zhao
Institute of Modern Physics(IMP), Chinese Academy of Sciences, Lanzhou, 730000, China

Abstract

The 7MeV/u cyclotron accelerates carbon ions with mass number 12, 5+ charges, the extraction energy of carbon ions is 7MeV/u, and the beam current density is designed to be 10eμA. It designed as injector for the HITFiL(Heavy Ions Therapy Facility in LanZhou) synchrotron, which accelerates carbon ions to the energy 300MeV/u for tumors treatment. Computer modeling results on the axial injection, magnetic, accelerating and extraction systems of the cyclotron are given. Design of the main systems of the cyclotron and the results of beam dynamic simulations are introduced [1], [2], [3], [4]. The construction progress including the ECR ion source, the axial injection beam line, the magnet, the RF system, the vacuum system etc. will be described respectively

INTRODUCTION

The 7MeV/u cyclotron is designed as a commercial cyclotron which is operated in a hospital where the operators of the cyclotron may not be the expert in cyclotron field. At the phase of designing the cyclotron, we aimed to design a compact cyclotron to reduce the cost and a simply operational cyclotron that can be well done by staff in hospital. For these purposes, we designed the extraction average radius to be 0.75 m, the maximum magnetic induction density was about 1.9 Tesla that can be safely achieved with the pure iron material. The magnet of the cyclotron is 4 fold in azimuzal direction with 4 straight edge sectors, the sector's angle is 56 degree. The diameter of the magnet is 2.8 m and the height of the magnet is 1.6 m. We optimized the magnet pole to form the isochronous magnetic field with no trim coils to be used. In two valleys of the magnet, tow 30 degree rf Dees are located. There were eight holes in the magnet four valleys to install vaccum pumps and rf stems. The ion source was designed as a permanent magnetism ECR ion source to remove injection and extraction coils for the ECR ion source. For the axial injection line and extraction system of the cyclotron, we used as less as possible components to simplify the design and construction.

The phase of constructing the cyclotron started in December 2009. The permanent magnetism ECR ion source, the axial injection line, the rf amplifiers and rf cavity are fabricated in plants now. The schedule of the magnetic field measurement is in July 2011, the assembly of the cyclotron is in October 2011, the commissioning of the cyclotron is in December 2011.

DESIGN RESULTS

General Description

As a injector of the HITFiL synchrotron, the 7 MeV/u cyclotron was required to extract $C^{5+}{}_{12}$ beam, while the beam energy was 7 MeV/u, the energy spread was less than 1%, the beam emmitance is about 20 π mm.mrad, the beam current intensity was greater than 10 eμA. The cyclotron was designed as a compact cyclotron with fixed magnetic field and rf frequency, its magnet was 4 fold symmetry with 4 straight edge sectors. The beam produced by permanent magnetism ECR ion source was injected axially into the central region, then accelerated to 7 MeV/u energy by tow 30° Dees located in the tow opposite magnet valleys, finally extracted through a electrostatic deflector(E1) and a magnetic deflector channel(M2).

ECR Ion Source

The permanent magnetism ECR ion source was designed to produce $C^{5+}{}_{12}$ beam solely, the beam current was designed to be 200 eμA with 120 π mm.mrad emmitance, the extraction voltage of the ion source was 22.3kV. The configuration of the ion source is illustrated in Fig. 1.

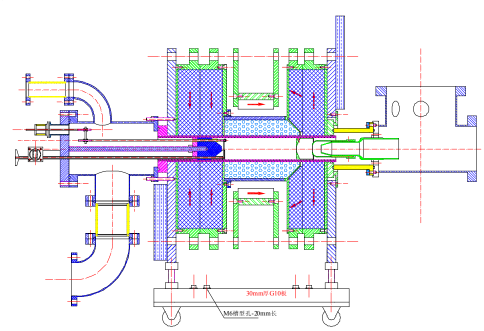

Figure 1: The configuration of the ion source

Magnet

The conceptual design of the 7 MeV/u cyclotron magnet has been performed using OPERA-3D softwar. The B-H magnetization curve of the sectors was measured on the samples, then used in the calculations. The specification of the magnet is given as following. To form the isochronous magnetic field, we cut iron on each sector's surface near the cyclotron median plane, then put a 5 mm thick cover on the sector's surface, changed the quantity of cut iron and the edge shape of cover. The 1/16 model of the magnet is shown in Fig.2. The calculated magnetic field was analysed, the difference of average field between calculated magnetic field and the ischronous field was less than 10 Gauss in the acceleration zone, the working path of the accelerating particle didn't cross some dangerous resonances. The reults are shown in Fig. 3 and Fig. 4.

Tabel 1: magnet specifications

Outer Radius of the Magnet	1440mm
Height of the Magnet	1600mm
Radius of the Pole	840mm
Mumber of Sectors	4
Sector Angle	56°
Gap between the Hills	50mm
Gap between the Valleys	360mm
Field in Hills	1.87T
Total Weight of Iron	70 t
Ampere-Turn Number of the Main coils	70 kAT

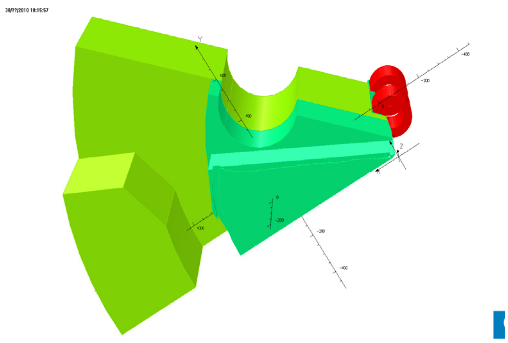

Figure 2: The 1/16 model of the main magnet

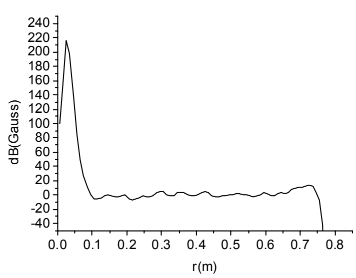

Figure 3: The difference of average field between calculated magnetic field and the ischronous field

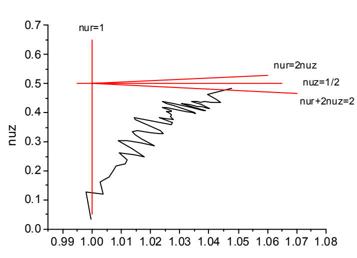

Figure 4: The resonance diagram for the acceleration of C^{5+}_{12} particle

RF System

The 7 MeV/u cyclotron operated on 4 harmonic numbers, the rf frequency of it is 31.02 MHz. The main parameters of the rf system is described in Tabel 2.

Tabel2: Parameters of rf system

rf Frequency	31.02MHz
rf Voltage	70 kV
Harmonic Number	4
Number of Dee	2
Angle of Dee	30°
Outer Radius of Dee	770 mm
Number of Cavity	2
Q Value of Cavity	7800
Dissipated Power per Cavity	18 kW

Tow half wave length cavities were installed into the valleys of the magnet, tow capacitance coupler near the outer radius of Dees imported rf power into cavities, tow 50 kW rf amplifiers connected the couplers with coaxial transmission lines respectively. Near the short plane of cavities, we installed frequency tune device and rf sampling device to tune the cavities tinily.

Fig.5 illustrates the model of one cavity of the cyclotron. The design of rf cavities used the CST Microwave Studio software.

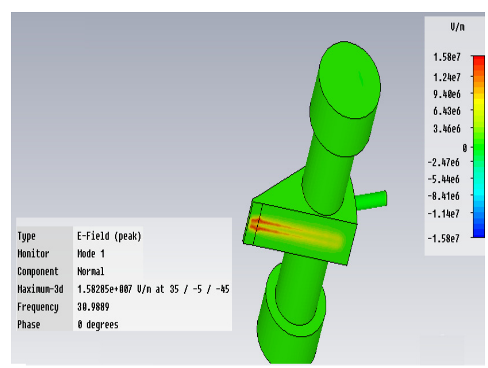

Figure 5: The model of one cavity

The calculation result indicated that the resonant frequency can changed from 30.51 MHz to 31.51 MHz with different position of short plane, the 31.02 MHz frequency could be achieved. The Dee voltage changed from outer radius to inner radius, it was 76 kV at outer radius and 64 kV at inner radius. To extract good quality beam, we requested the stability of rf system to be: rf voltage amplitude stability was $\pm 5\times10^{-4}$/24h, rf frequency stability was $\pm 1\times10^{-6}$/24h, rf phase stability was ±1°.

Vacuum System

The 7 MeV/u cyclotron used upper and lower iron yoke as vacuum seal, the principle vacuum chamber was divided into tow parts above the cyclotron medine plane. The vacuum system was composed of four cryogenic pumps of 5000l/s. The vacuum of priciple chamber was 5×10-7 mbar and the vacuum of injection line was 1×10-7mbar.

Axial Injection Line

The axial injection line was installed on the upper yoke of the cyclotron, beam extracted from ECR ion source transported downstream to the machine central region. The injection line were composed of four solenoids, a double 90^o magnetic dipole, a quadrupole, a buncher and a chopper. Beam diagnostical devices contained a double direction slit and a Falady cup. A solenoid behind the ECR ion source, a double 90 ^{o} magnetic dipole, a quadrupole and a slit formed a charge analysis system. The injection line was designed by TRACE-3D code, at the entrance of spiral inflector, the emittance of the beam was waist in tow horizontal planes, where the envelope of the beam is 2.5 mm. The scheme of axial injection line is shown in Fig. 6, the beam envelope through the injection line is shown in Fig.7.

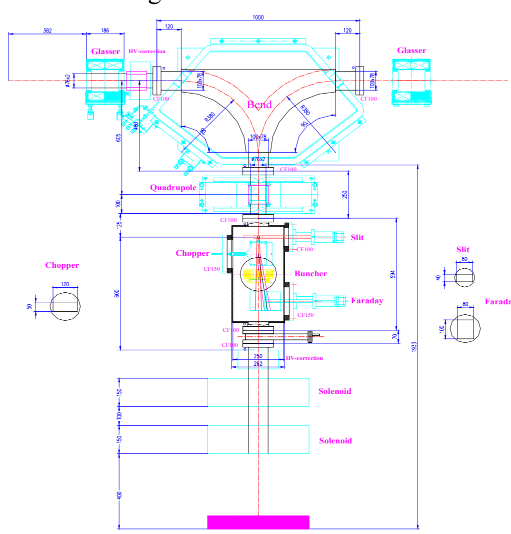

Figure 6: The scheme of axial injection line

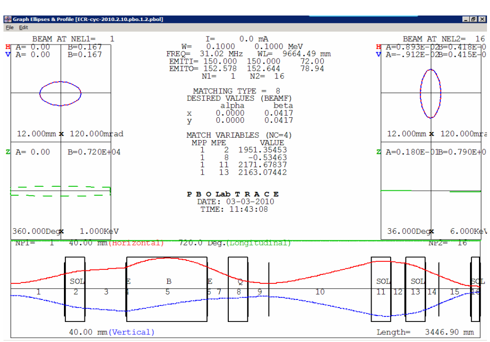

Figure 7: The beam envelope of the injection line

The Central Region

At the beginning of central region design, we found the accelerated equilibrium orbit at large radius, which could be backtraced after the first accelerating gap and matched to a special kind spiral inflector's central particle trajectory. In the calculation, we optimised the geometry of the Dee tip to get matching of energy, position and direction between the backtraced orbit and central trajectory of spiral inflector. So we defined the parameters of the spiral inflector. The chosen parameters of the inflector are described in Table 3.

Table 3: The parameters of spiral inflector

Electric bend radius	30 mm
Magnetic bend radius	27 mm
Electrod spacing	8 mm
Electrod width	16 mm
Orientation angle	-54^o
Voltage of electrods	±5.5 kV

To reduce the effect of fringe field of inflector, we cut 3 degree at the exit of the spiral inflector. The electric field of the inflector was calculated by MAFIA code, the model of the inflector is illustrated in Fig.8.

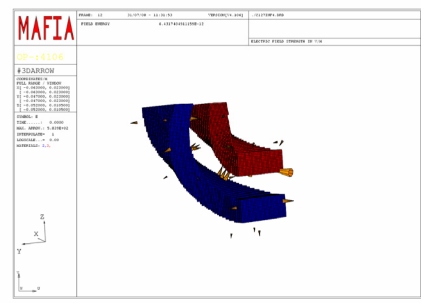

Figure 8: The model of the inflector use by MAFIA

To study beam dynamics in central region, we created 3D model of Dee tip in central region by MAFIA code, and calculated the electric field of the Dee tip. Using the data and magnetic field calculated by OPERA-3D softwar, we studied the orbit motion in the central region. Again we optimised the Dee tip model, espically for the vertical foucus of the injection beam and the centralization of the orbits. The potential lines in the medine plane of the Dee tip electric field is ploted in Fig.9. The orbits that started from inflector exit with different positions and directions, and accelerated six turns were illustrated in Fig.10.

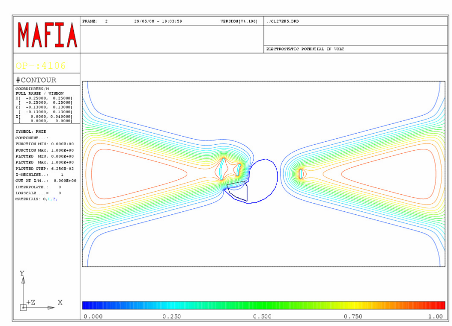

Figure 9: The potential lines in the medine plane of the Dee tip electric field

The Extraction System

The extraction system was composed of a bump coil, a electrostatic deflector(E1), and a a magnetic deflector channel(M2). We could increase the turn separation from 7 mm to 14 mm using the bump field before the entrance of E1. The maximum voltage of E1 was 85 kV with 10 mm gap. The maximum magnetic field of M2 was 1.1 T, its direction was oppsite to the cyclotron's main magnetic field. To improve the horizontal focus of M2 and reduce its effect to sector's magnetic field in the outer radius, we optimised the M2's design to add a gradient field to it and make its yoke to be magnetic saturation. The scheme of extraction system is shown in Fig. 11.

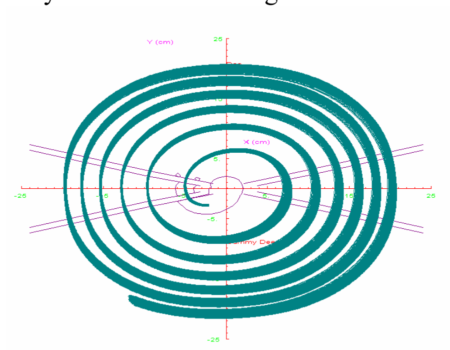

Figure 10: The orbits in the central region

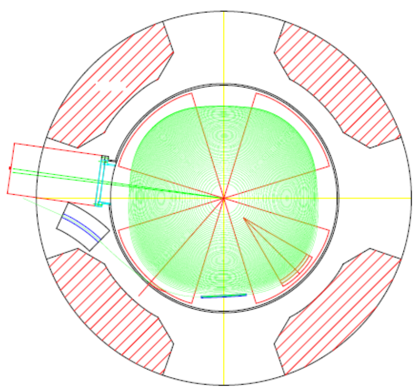

Figure 11: The scheme of extraction system

The Study of Transmission Efficiency

To realize the desiged extraction beam current intesity, we estimated the transmission efficiency of the cyclotron using multi-particles tracing method. Starting from the exit of ECR ion source, with 120 π mm.mrad emmitance beam, we traced this beam to the entrance of inflector, and produced 10,000 particles in the 4D phase space in the horizontal planes, while the energy spread of these particles was ±1%, and rf phase width was ±10° in the longitudinal plane. The calculted bucher efficiency is 45%. Then we traced the particles through inflector, and accelerated them 5 turns, the number of the particles which were not lost was 7997, the injection efficiency was 35%. These 7997 particles were accelerated to be extracted on the end of M2, the calculated extraction efficency was 20%, so the cyclotron's transimission efficency was 7%. It can be satisfy the design requirment. The emmitance of the extract beam was less than 20 π mm.mrad. The energy spread of the extract beam was ±1%. The emmitance of the extract beam is shown in Fig.12.

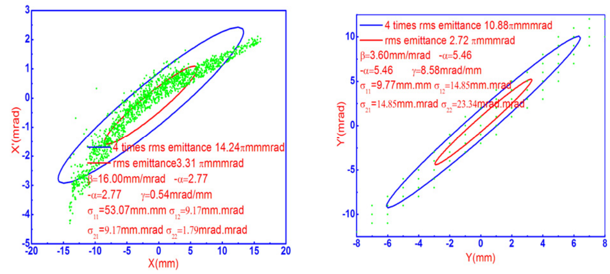

Figure 12: The emmitance of extract beam on the end of M2. Left: the emmitance in (x,x') plane; Right: the emmitance in (y,y') plane

CONSTRUCTION PROGRESS

ECR Ion Source

The concept design and engineering design for the permanent magnetism ECR ion source had been completed. We integrate the permanet magnetism material to form the desinged field now in institude of modern physics. The commissioning of this ECR ion source will be in December 2010.

RF System

The construction design of tow 50 kW rf amplifers had been finished. Fabrication of them will be completed in December 2010. The cavity's engineering design is conducted.

Axial Injection Line

The concept design and engineering design for injection line had been finished except the chopper. Apparatuses of the injection line were fabricated in three corporations and will be finished in December 2010.

The power supplies for the magnet coil, injection and ectraction equipments had been contracted with few corporations. The construction of other items, e.g. the magnet, the vaccum chamber, the spiral inflector, the electrostatic deflector is conducted.

CONCLUSION

The beam dynamic study of the 7 MeV/u cyclotron had been completed. From the result of beam dynamic study, the requirment from synchrotron can be achieved by the concept design. Engineering design of the cyclotron is conducted except ECR ion source and rf amplifers.

REFERENCES

[1] J.Q. Zhang et al. "Axial Injection Beam Line of a Compact Cyclotron", these Proceedings.
[2] L.Z. Ma and Q.G. Yao. "The Isochronous Magnetic Field Optimization of HITFiL Cyclotron", these Proceedings.
[3] S.H. Zhang et al. "The RF System Design of 7 MeV Cyclotron", these Proceedings.
[4] H.F. Hao et al. "Beam Extraction System of Compact Cyclotron", these Proceedings.