THE INJECTION LINE AND CENTRAL REGION DESIGN OF CYCIAE-70*

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Abstract

A 70MeV compact cyclotron is under design at CIAE, which is aimed to provide both proton and deuteron by stripping two electrons from H^- beam and D^- beam respectively. Both of the negative charged beams are produced in a single external multi-cusp ion source, injected axially by a low energy beam injection line and bent onto the median plane through a spiral inflector. In the central region, the electrode structures and the shape of Dee tips are constructed and optimized to achieve matching at the inflector exit and to maximize the acceptance of the central region. The preliminary design results of the injection line, the spiral inflector and the central region are elaborated in the paper.

INTRODUCTION

China Institute of Atomic Energy (CIAE) is carrying out the physics design of a multi-purpose 70MeV compact cyclotron, CYCIAE-70[1], which will be applied in radioactive ion-beam production and nuclear medicine. This machine adopts a compact structure of four straight sectors. It will be capable of accelerating both H^- and D^- beam and extracting proton and deuteron beam in dual opposite directions by charge exchange stripping devices. The energy of the extracted proton beam is in the range 35~70MeV with a beam intensity up to 700μA. The energy of the extracted deuteron is 18~35MeV and the required beam intensity is only 40μA. For both particles, the energy is continuously adjustable.

As is well known, the internal PIG ion source is incapable of providing the high intensity beam of milliampere level, therefore the external ion source, and accordingly, the beam injection line and inflector are essential for this cyclotron. Considering the fact that a single multi-cusp ion source is capable to provide both H^- beam and D^- beam by filling with H_2 gas and D_2 gas respectively, only a single ion source and a single beam injection line are needed. After extracted by the ion source located underneath the cyclotron, the beams are injected into the cyclotron axially by an injection line upwards to the spiral inflector which bends beam by 90° onto the median plane of the central region. The detailed design methods and results of the central region, the spiral inflector and the injection line are reported in the following sections.

CENTRAL REGION DESIGN

The central region is one of the most challengeable sub-systems of a compact isochronous cyclotron. The principle of the design is that the central region is capable of accepting both 40keV H^- beam and 20keV D^- beam without replacing any components.

The approach for central region design is as follows:

(1) Build a 3D finite element model of the cyclotron main magnet and create the isochronous field maps on the median plane for both H^- and D^- particles respectively. The conversion between the two isochronous fields can be achieved by moving 8 additional shimming bars and tuning the ampere-turns of the main coils. Orbit centering in the central region is achieved by tuning the ampere-turns of the centering coil.

(2) Draw a preliminary geometry of the central region in AUTOCAD, which is then imported into RELAX3D[2] with the help of the pre-processing code Pre_Relax3D[3], that can read the geometry information and generate the finite difference grid with the boundary conditions. Then the 3D electric potential map around the median plane can be calculated. The central region structure must be compatible with the main magnet and the electrode of inflector. In order to avoid voltage breakdown, the accelerating gap was chosen not smaller than 6mm.

(3) Search the AEOs of a given energy points W_0 at the high energy region for H^- and D^- beam. Then do the backtracking from the AEOs of high energy towards the central region.

(4) Observe and analyze the backtracking results of H^- and D^- particles and check whether the following conditions are fulfilled: (a) The two orbits cross just before entering the first accelerating gap, the crossing point is the matching point (MP1) with inflector; (b) the energy of H^- and D^- particles at MP1 are approximately equal to 40keV and 20keV respectively; (c) in the central region the distances between the H^- orbit and the posts of two sides are approximately equal.

(5) In case the above conditions in item (4) is not fulfilled, try to do the following changes in sequence: (a) adjust the starting energy W_0; (b) adjust the structure of central region; (c) adjust the magnetic fields by adjusting the magnet structure or tuning the ampere-turns of main coils.

(6) Once the above conditions in item (4) is fulfilled, track the H^- and D^- particles of different phases. Check that whether the phase acceptance of central region is larger than 40º for H^- beam and 20º for D^- beam, and the normalized axial acceptance for both beams are larger than 0.5π mm-mrad. Otherwise optimize the structure of central region.

The iteration of orbit tracking and structure adjusting were performed according to the above approach. Figure 1 shows the final layout of the central region including the electrode structure and accelerating gaps. The

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reference orbits of H^- beam and D^- beam for the first 3 turns are obtained and the results are shown in Fig. 2. The energy increase in the 3 turns is shown in Fig. 3. The parameters of the reference particle after the first 3 turns are listed in Table 1. To obtain these results, RF frequency of the resonator can maintain the same value (56.265MHz) for both beams. Nevertheless, the price we have to pay is that the voltages of Dee tip must be different, i.e., V_{Dee} = 60kV for H^- beam and V_{Dee} = 70kV for D^- beam. Figure 2 shows that the reference orbit for D^- beam is not well centered during the first 3 turns. Since the required beam current for H^- beam is much higher than D^- Beam, H^- beam has higher priority for beam centering in order to diminish the beam loss caused by off-centering injection. However, the centering coil will be capable to construct beam centering for D^- beam after the first turn, where we have enough space to install the components of the trim-coil.

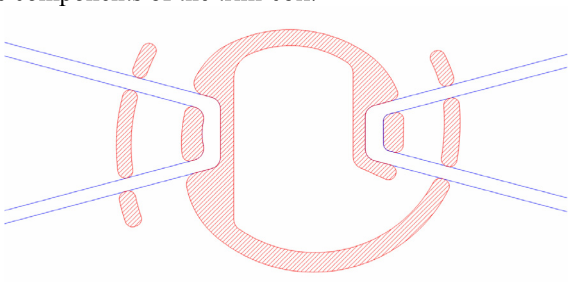

Fig. 1: The layout of the central region including the electrode structure and accelerating gaps

Table 1: Parameters of the Reference Particle after the First 3 Turns (azimuth: 345°)

	H^- beam	D^- beam
Energy E (keV)	652.48	524.57
Radius r (cm)	12.53	17.29
Momentum Pr (cm)	-0.84	-2.09
RF time τ (°)	7.88	41.81

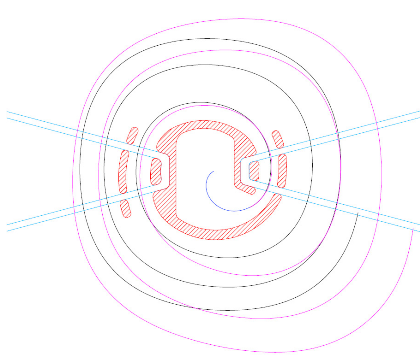

Fig. 2: The reference orbits of H^- particle (black) and D^- particle (pink) in the central region for the first 3 turns, plotted with the projection of the central orbit in the inflector onto the median plane (blue).

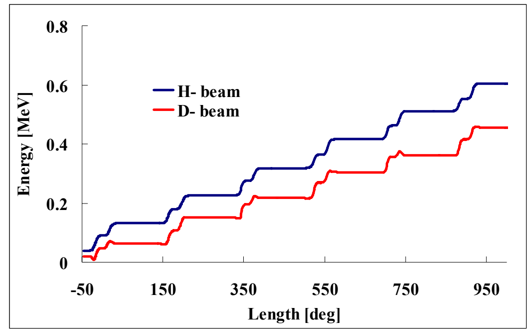

Fig. 3: Energy increase in the first 3 turns

INFLECTOR DESIGN

The central region design provides the matching point closely to the exit of the spiral inflector and the reference parameter at the inlet of central region, which should be used as the confinement conditions for inflector design. Therefore the central region and the inflector must be considered as a whole and the design work must be carried out simultaneously.

The principle of the design is that a single inflector should be capable of bending both H^- and D^- beam onto the median plane by only adjusting the voltage with the transmission efficiency higher than 80%. In order to obtain the same trajectory for the reference particles, the injection energy of D^- beam must be a half of H^- beam. This is because the ratio of charge and mass of D^- beam is only a half of that of H^- beam. For this cyclotron the kinetic energy of the injected H^- and D^- beam are 40keV and 20keV. It is also important that at the match point, both types of reference particles must be accepted by the central region of the cyclotron.

The inflector design was carried out by using CASINO[4] codes. Table 2 shows some key parameters of the inflector. The surface of the inflector electrodes and central trajectory of H^- beam (overlap with and D^- beam) are shown in Fig. 4 The projects of central trajectory onto the r-z plane is plotted in Fig.5 (a). The projection onto the median plane is plotted in Fig. 5 (b) and also in Fig. 2, from which we can see the orbits in the central region and inflector are matching well.

Table 2: Some Key Parameters of the Inflector

Parameter (unit)	Value
Electric bend radius A (mm)	58
Tilt parameter k'	-0.55
Electrode spacing d (mm)	8
Electrode width w (mm)	16
Orientation angle α (deg)	199.40
Voltage V (kV)	±6.90 (H^-) ±3.45 (D^-)

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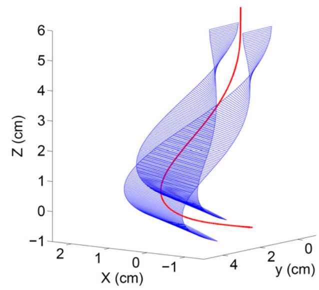
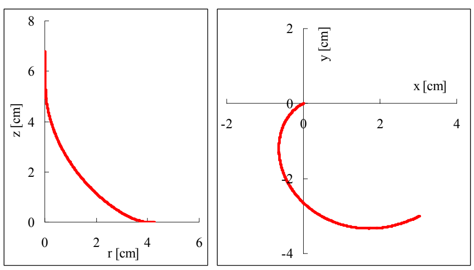


Fig. 4: The surface of inflector electrodes and the central trajectory of H^- beam (overlap with and D^- beam)



(a) (b)

Fig. 5: The project of central trajectory of H^- beam (overlap with and D^- beam) onto the *r-z* plane and median plane

INJECTION LINE DESIGN

The injection line layout of the 70MeV cyclotron obtained by preliminary design is shown in Fig. 6. The DC beam is injected from the ion source located below the magnet of the cyclotron. The injection line utilizes two solenoids and a triplet for transverse focusing and a two-gap buncher for longitudinal bunching. The total length of the injection line is about 2.5m. The effective lengths of two solenoids are 20cm and 40cm respectively, and the aperture diameters are 8cm. The effective lengths of the three quadrupoles are 10cm, 12cm and 10cm respectively, and the aperture diameters of the triplet are 6cm.

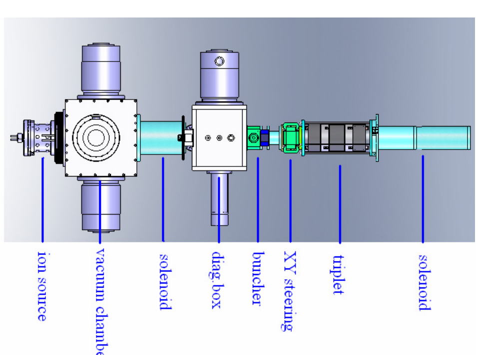


Fig. 6: The layout of the injection line

The ion source will provide the 40keV H^- beam with a current of about 8mA and 20keV D^- beam with a current [7] of about 500μA respectively. Considering the H^- beam space charge effects will be significant, they need to be compensated by neutralization measure. The neutralization of 95% is assumed in the design, which can be achieved with a vacuum of more than 10^{-4}Pa. According to the measured results of phase space at the extraction outlet of the existing ion source[5] at CIAE, we selected the initial parameters of $\varepsilon_r = 48\pi$ mm-mrad, $r_{max} =$ 4mm, $r'_{max} = 22$mrad, $R_{12} = 0.83$.

The beam optics design was performed using TRANSOPTR[6] code. During the design the constraints and fitting conditions were used, including the requirement that the beam sizes should be smaller than the inflector inlet sizes at the inflector entrance and the normalized circulating emittance in the central region should be minimized. Figure 7 shows the beam envelopes from the extraction outlet of the ion source to the first turn in the central region of the cyclotron under the conditions that the cyclotron was approximated by the dipole and the inflector was represented by a transfer matrix. It is indicated that larger envelope size is expected for D^- beam as a result of the larger space charge effects. However, the maximal size of envelope is still smaller than the aperture.

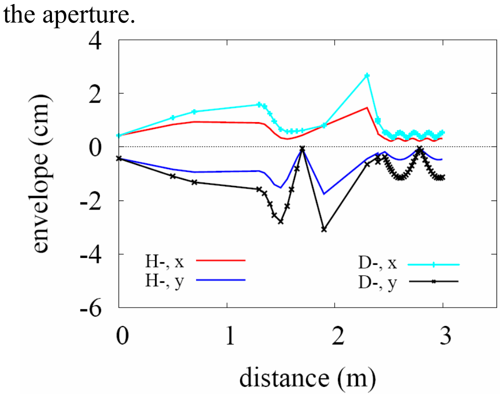


Fig. 7: The beam envelopes for the 8mA H^- beam with 95% neutralization and 500μA D^- beam without neutralization.

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