THE STUDY AND DESIGN OF SPIRAL INFLECTOR AND CENTRAL REGION FOR CYCIAE-100 CYCLOTRON

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Abstract

CYCIAE-100 is a compact proton cyclotron with the maximum energy of 100MeV; it was designed at CIAE (China Institute of Atomic Energy) as a main part of BRIF (Beijing Radioactive Ion-beam Facility). A spiral inflector and central region were designed to reduce beam loss and inject good quality beam into CYCIAE-100 from an external H^- ion source. The behavior of beam with the fourth harmonic RF mode in central region was studied through numerical calculations, including accelerated centering beam, transverse and RF acceptances and so on. The radial motion study was carried out to minimize the centering error; and the acceptance of central region was calculated. The design procedure and results will be presented. Results show that this design can meet the requirements of 100MeV compact cyclotron.

INTRODUCTION

CYCIAE-100 [1], being constructed at CIAE, is a compact, four straight sectors isochronous cyclotron, designed to accelerate H^- ions to a maximum energy of 100MeV and extract proton beam by stripping foil. The two 36° wide dees with the increasing voltage along the radius from 60kV in the central region to 120kV in the extraction region are placed on two opposite valleys, so the acceleration takes place four times per turn at the gaps. The RF frequency is 44.4 MHz and the harmonic number is four.

The 40keV H^- ions, produced in an external multi-cusp ion source which is located underneath the cyclotron, will be injected to the CYCIAE-100 cyclotron axially by an injection line upwards to the spiral inflector which bends beam 90° into the central region at the median plane. The central region and spiral inflector were designed to meet the requirement of the CYCIAE-100 cyclotron. The detailed results are reported in this paper.

ORBIT CALCULATIONS

The program CYCLONE [2] is used for orbit calculations in the central region. The calculations were carried out based upon magnetic field values obtained by a 3D infinite element code and electric field files generated using the program RELAX3D [3] for solving 2- or 3-dimension Laplace and Poisson equations.

The electrodes shapes in the central region for CYCIAE-100 cyclotron were drawn by AUTOCAD, shown in Fig. 1 including the key sizes for calculations; the geometry information was introduced to RELAX3D by the program of Pre-R3D [4], which generated the input file for RELAX3D with the boundary conditions included. The first two gaps crossing was calculated using CYCLONE-PART I with RF time as the independent variable, the electric field shape was obtained with RELAX3D in an area of 12cm×18cm, the grid spacing is 0.03cm×0.03cm×0.04cm in x-, y- and z-direction; orbit calculations in the large region with an area of 40cm×40cm were performed using CYCLONE-PART II with particle angle as the independent variable, the grid spacing is 0.1cm×0.1cm×0.1cm. The actual area for orbit calculations is smaller than the areas used in electric field calculations.

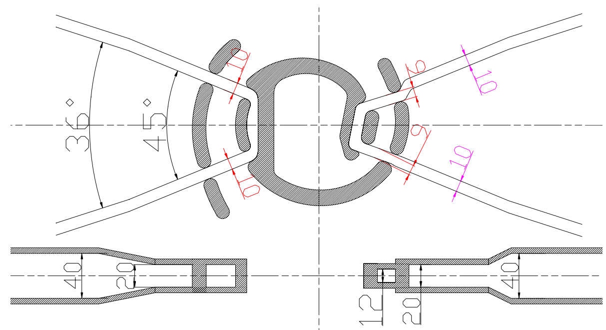

Figure 1: Two sections schematic (up- horizontal; down- vertical) of the electrode structure for the CYCIAE-100 central region (unit: mm)

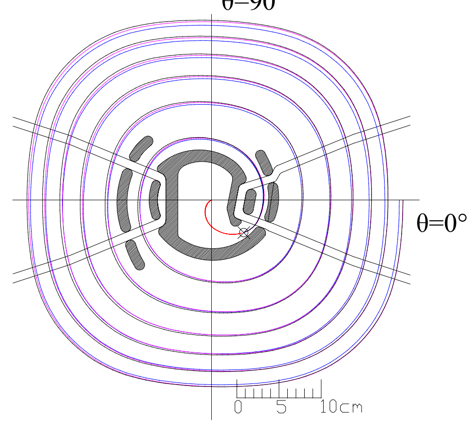

Figure 2: Central rays of three particles with different initial phases in central region, the phase width is 40°; with the central ray through the inflector together

With the proper matching point and injection parameters, the centered trajectory was obtained; the

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detailed procedure will be given in the next section. In the orbit calculations, injection energy of 40keV and the RF voltage of 60kV were used. Figure 2 shows the central rays of reference particle with three different initial RF phases (Φ_0, $\Phi_0\pm20°$). The phase history at the position of θ=90° for three particles with different initial phases is shown in Fig. 3.

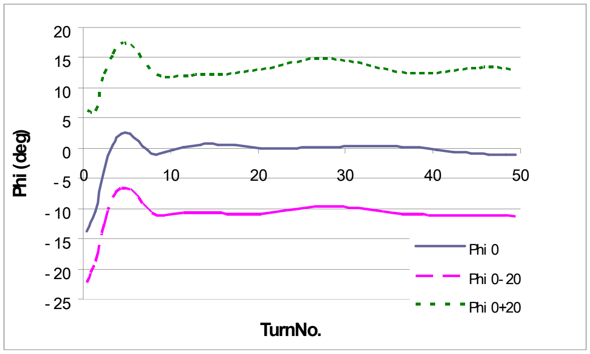

Figure 3: Phase history as a function of turn number at the position of θ=90° (see Fig. 2) for three particles with different initial phase

RADIAL MOTION

Beam Centering

In order to obtain a well centered beam, the accelerated equilibrium orbit was obtained tracking back from 100MeV to about 1.5MeV using COMA [5] with the varying dee voltage, adjusting the radius and radial momentum (i.e. r and Pr at 100MeV) to minimize the centering error, i.e.. trying to reduce the displacement between the accelerated orbit and the static equilibrium orbit at the same energy. We defined the phase space (x, Px), where $x=r-r_{seo}$, $Px=Pr-Pr_{seo}$. When x is small enough compared with the incoherent amplitude of beam in the cyclotron, the AEO is obtained. The radial phase space of AEO for the CYCIAE-100 cyclotron is shown in Fig. 4, the plot was got at the position of θ=0° which is the centre line of the first dee.

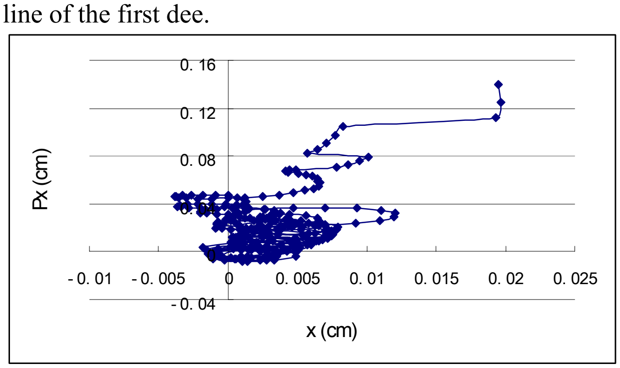

Figure 4: Radial phase space of AEO plotted at the position of the center line of the first dee (θ=0°), where x= r-reo, $P_x=P_r-P_{reo}$

Based upon the values of AEO, the particle was tracked backwards, using the electric field file obtained by RELAX3D, from a certain point located on the AEO corresponding to the energy of between 1.5 to 2 MeV to the injection energy at a proper position. The iterative calculations were performed to get the matching point parameters which will produce the well centered beam and provide the reasonable conditions to the injection line and spiral inflector as well. The results calculated for the CYCIAE-100 cyclotron show that the beam centering error is about 0.03cm, which can be easily corrected using the first harmonic magnetic field produced by the centering coils located in the central region.

Radial Acceptance

The radial acceptance of the central region was calculated using multi-particle tracking to match the eigen-ellipse of the cyclotron centered on the accelerated orbit at about 10 turns out with the energy of ~2.3 MeV. Because of the radial-longitudinal coupling the radial acceptance is limited by the positive phase, the detailed study is given in Ref [6]. Here we just give the results briefly. With a reasonable assumption of the acceptance of the CYCIAE-100 cyclotron at 4 pi-mm-mrad (normalized), the radial acceptance at the matching point for 40° RF phase width is 0.55 pi-mm-mrad, and increases to 0.9 pi-mm-mrad when the phase width is reduced to 30° .

VERTICAL MOTION

In the center of the CYCIAE-100 cyclotron the flutter of the magnetic field is very small, so the electric field plays a key role in the vertical motion. And the electric focusing is strong phase dependent. The axial electric focusing effect has been analyzed in many literatures, such as Ref [7-8]. In this paper the vertical acceptance of the central region is reported.

From particle tracking results by CYCLONE with the initial parameters of z= 0.1cm, Pz= 0 and z= 0, Pz= 0.1cm, vertical envelope data were obtained and can be used to get transfer matrix R_N and R_{N+1} , corresponding to matrix from injection point to turn number of N and (N+1). Then transfer matrix from turn number N to (N+1) was obtained, as well as the sigma matrix σ_N at the end of turn N. The sigma matrix at the injection point can be derived as follows.

$$\sigma_0 = R_N^{-1}\sigma_N (R_N^{\ T})^{-1} \tag{1}$$

The phase ellipse at the injection point is described by the sigma matrix; particles within the ellipse with the RF phase can be accepted by the cyclotron. Figure 5 demonstrates the vertical acceptance calculations results for three different RF phases, the overlap area is the acceptance emittance for the 40° phase width, the value is ~0.73 pi-mm-mrad with the acceptance of the CYCIAE-100 cyclotron at 4 pi-mm-mrad. The vertical envelops were calculated through tracking the particles that described the boundary of the “overlap” ellipse in Fig. 5. The results show that the uniform envelops for three different phases, and the envelope value is consistent with the incoherent amplitude produced by the finite emittance.

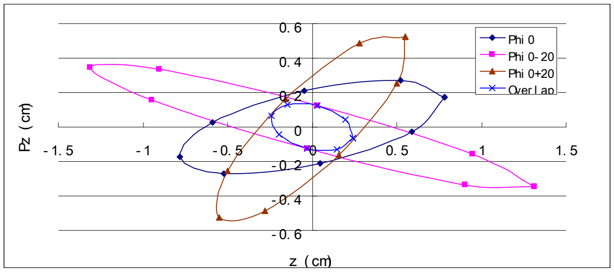

Figure 5: The vertical acceptance results, the “overlap” is the acceptance at the matching point for the CYCIAE-100 cyclotron with the 40° RF phase width

SPIRAL INFLECTOR

The central region calculation provides the matching point closely to the exit of the spiral inflector and the well cantered trajectory, which were used for the inflector design as the confinement conditions. The spiral inflector is determined by three parameters, the electric radius A, the magnetic radius R and the tilt k’. A and R are given by

$$A = \frac{2T_{inj}}{qE} \;,\; R = \frac{mv}{qB} \qquad (2)$$

where T_{inj} is the injection energy, E is the electric field. For the CYCIAE-100 cyclotron T_{inj} is 40keV, R is 3.9695cm. The parameters of A and k’ can be adjusted to make sure that the central particle through the spiral inflector will leave the inflector in the median plane (z=0) with a zero vertical momentum (P_z=0). At the same time it should meet the requirement of the central trajectory through central region, e.g., the radius, radial momentum.

The calculations for the spiral inflector were done by the program CASINO [9], INFLECTOR [10] and RELAX3D. The design results for the spiral inflector of CYCIAE-100 are A= 4 cm, R= 3.9695 cm and k’= -0.58. The central ray through the inflector is shown in Fig. 2 with the trajectories in the central region together.

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