ISBN: 978-3-95450-199-1 doi:10.18429/JACoW-SAP2017-MOPH04

SOME INITIAL RESULTS OF CENTRAL REGION ORBIT TRACKING FOR SUPERCONDUCTING CYCLOTRON CYCIAE-230*

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Abstract

CYCIAE-230 superconducting cyclotron, a medical accelerator for proton therapy, is designing and constructing at CIAE now [1]. An internal PIG source was adopted to attain a compact and simple design. Central region electric and magnetic field design will directly affect the beam quality and reliability of the cyclotron in terms of phase selection, beam loss and beam stability. Moreover, a favourable central region will ensure single-turn extraction efficiency. The central region study was based on detailed orbit tracking results, including the beam behaviour in the push-pull RF mode and phase selection and axial focusing in the latest magnetic field and electrical field distribution from calculation. The physical design results of central region beam dynamics are presented here.

INTRODUCTION

CYCIAE-230 is a compact isochronous cyclotron with four spiral pole sectors and four spiral Dees in the valleys given the central field of 2.33 T and Dee voltage of 72 kV. This machine is designed to accelerate proton beam from the ion source to extraction energy of 230 MeV. Aims for clear single-turn extraction by electrostatic deflectors, second harmonic acceleration as well as push-pull RF mode was employed to get enough turn separation, which also benefits the central region design for larger energy-gain in the first turns. Internal ion source was adopted to simplify the machine, lead to a compact central region. Protons at the opening slit of the ion source was considered nearly zero energy, extracted by the puller at proper RF phase and accelerated in the first gap subsequently. Under the circumstances of internal ion source, the beam behaviour is strongly sensitive to the initial parameters of particles and the electric field distribution at the first gap. Meanwhile, without the injection beam line it is hard to satisfy all the demands of beam input properties (including energy, RF phase, radial phase space matching and vertical focusing) only by adjusting the position and opening direction of ion source. The general solution is to abandon the radial phase space matching in central region and rectify the radial oscillation by trim-rods or trim-coils located in the accelerator region. In our machine, four sets of trim-rods will be installed to provide radial beam alignment, but difficulties still remain in the ion source and central region design.

* This work was supported by the National Natural Science Foundation of China under Grand Nos.11375273 and 1146114103
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ORBIT CALCULATION

The calculation was conducted by single-particle tracking code CYCLONE [2] with the magnetic field in the symmetric plane and 3-dimensional electrical potential map in central region. The magnetic field calculations were carried out by 3-dimension finite element method code and the electric field was calculated by 2- or 3-dimension Laplace and Poisson equations solver RELAX3D [3]. The shape of central region electrodes was drawn in AutoCAD and imported to RELAX3D as boundary condition of electric potential.

Two electric field maps were used in CYCLONE. The small field, only covered the first gap, was fine meshed to make a more accurate orbit-tracking result, the field area is 1.6×1.6 cm and the grid size is 0.01×0.01×0.01 cm, The large field in CYCLONE has an area of 20×20 cm and grid size of 0.05×0.05×0.05 cm, contains about first 5 orbit turns. Simulation results implied such small grid in the small field region is necessary and the number of nodes in the large field is suitable for rapid iteration.

The initial coordinates of reference particle was chosen at the zero-potential surface in the opening of ion source, as recommended by Forringer's thesis [4] to provide accurate radial phase-space prediction. And the initial energy and RF phase of reference particle were scanned and determined in orbit-tracking.

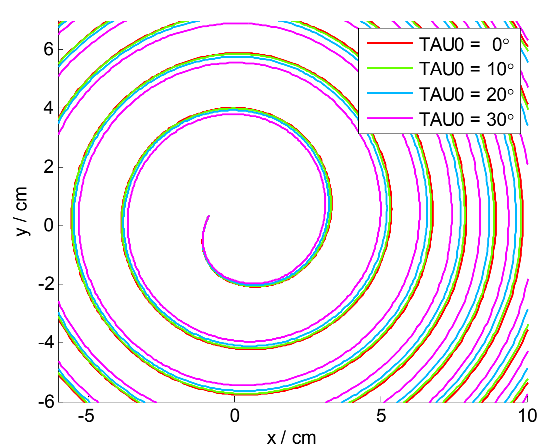

Figure 1: Orbits of particles with different initial RF phase.

The orbit tracking result shown in Fig. 1 contains the acceleration orbit of several particles within 30° phase width. In the current single-particle simulation period, the results shown that the phase acceptance of more than 30° is approachable, however a fixed phase slit will be

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mounted in the central region to select particles in about 20° phase width to prevent beam loss at larger energy. The phase history of particles is shown in Fig. 2, in which displays the phase of particles when they across 0 degree azimuth, implies that the phase width of proton beam was compressed from 30° to less than 20° in first one or two gap, moreover, about 8° phase slip in first 5 turns test to be proper to provide electric focusing. Figure 3 gives particle energy with azimuth (turn number), shows four times of accelerations per turn, and the energy-gain per turn of 0.40 MeV is complying with the design parameters. In Fig.4 the acceleration phases of particles at each gap are marked, indicating fast acceleration and vertical electric focusing in the central region.

In the next step, the 3-dimensional computing electric field results of RF system will be import to CYCLONE to make the design more realistic.

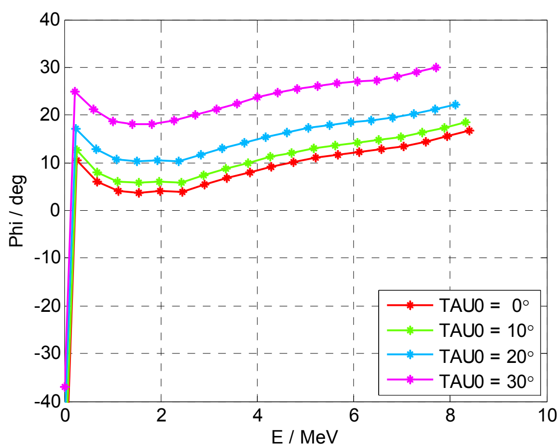

Figure 2: Phase slip of particles in central region.

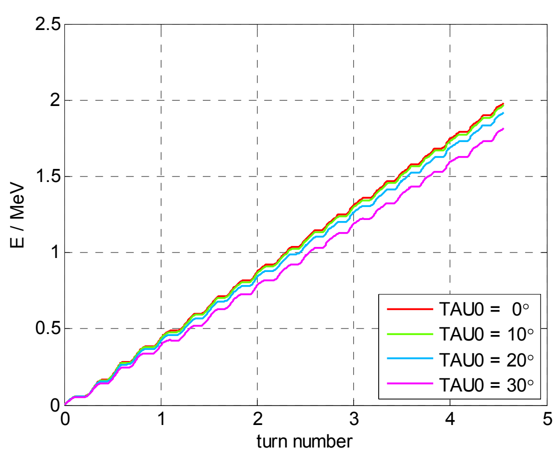

Figure 3: Energy gain diagram.

RADIAL MOTION

Since the internal ion source is adopted in CYCIAE-230, it is hard to reach radial alignment by adjusting the position and opening direction of ion source, the trim-rods in the outer area should provide enough first harmonic to revise the radial oscillation. Moreover, the extraction system stipulates a radial emittance of 2 π mm-mrad within 5° phase width to achieve clear extraction. These claims should be followed in central region design.

Figure 5 shows the radial motion of particles with different initial RF phase but with the same initial coordinates, in which we can easily calculate the radial oscillation amplitude from peaks to illustrate radial alignment. The Y-label ‘x’ is a direct output of CYCLONE, means the radial offset compare to static equilibrium orbit at corresponding energy ($x = r - r_{eo}$). In the iteration steps of central region design, the maximum radial oscillation amplitude was about 0.8 cm. Therefore we provide that the trim-rods should reduce radial oscillation of 1 cm amplitude and arbitrary phase angle. The physical design of trim-rods is completed.

A preliminary multi-particle tracking contain particles in 5° phase width and different initial coordinates in symmetric plane shows that the radial oscillation amplitude range is about 0.22 cm, equivalent to 1.3 π mm-mrad radial emittance, and the radial oscillation amplitude and phase angle is more sensitive to the initial coordinates of particles rather than RF phase. The detailed calculation using a composed magnetic field of main magnet and well-positioned trim-rod is going on.

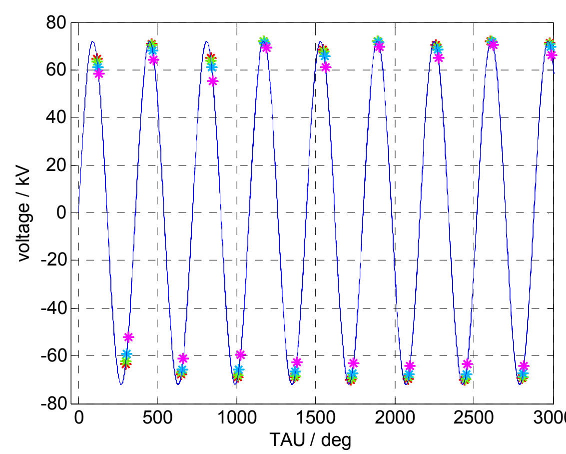

Figure 4: Acceleration phase of particles with different initial RF phase.

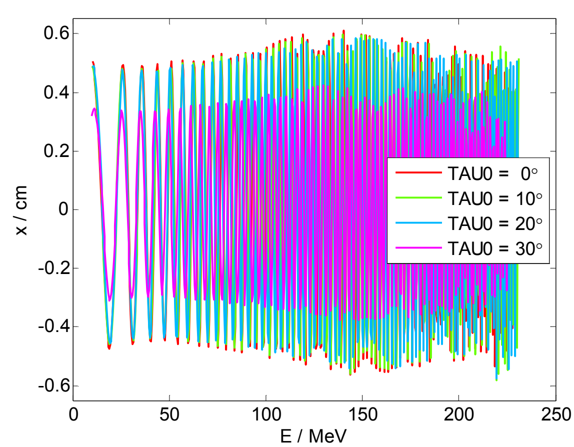

Figure 5: radial oscillation of particles with different initial RF phase.

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VERTICAL MOTION

In the first period of central region design, the position and opening angle of ion source were determined to obtain minimum vertical oscillation amplitude. Then the shape of electrodes is designed to get enough vertical focusing by iterative process.

The vertical motion of particles in central region of CYCIAE-230 combines vertical focusing effect of electric field and magnetic field. In the first 3 turns, the average magnetic field is ascendant and defocusing the beam, while the electric focus effect with proper acceleration phase is strongest in first turns, the vertical oscillation amplitude would not grow much. In the 5rd to 10th turn, beam energy is larger than 2 MeV and the electric focusing effect is rather weak, thus we intentionally build a slowly drop average field to ensure magnetic focusing. In the later turns the magnetic field flutter becomes the main force of vertical focusing and maintains the vertical oscillation amplitude.

The vertical oscillation of particles is shown In Fig. 6 and Fig. 7. In Fig. 6, the particles starting at z-coordinate of 0.1 cm within 30° phase width will not crash on the RF Dees in z-direction. In Fig.7, the particles have the same initial RF phase as reference particle, and the initial axial position ranges from 0.05 cm to 0.20 cm, the amplitude is nearly proportional to the initial z-coordinates.

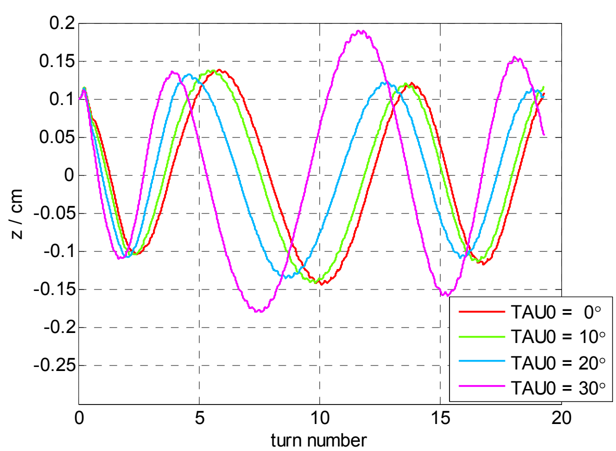

Figure 6: Vertical oscillation of particles with different initial RF phase.

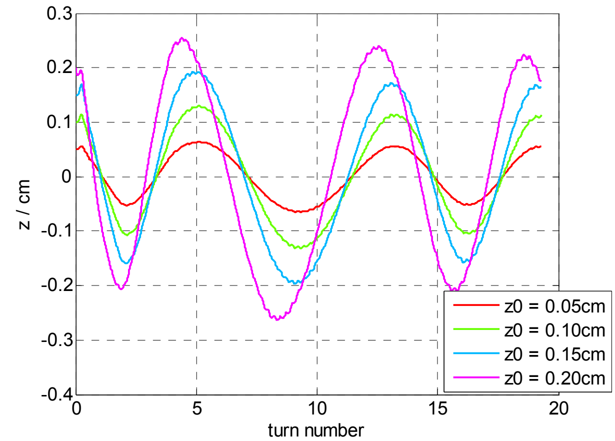

Figure 7: Vertical oscillation of particles with different initial z-coordinates.

CONCLUSION

The physical design results of CYCIAE-230 central region based on single-particle orbit tracking is introduced in this paper. The position of internal ion source and the shape of electrodes are optimized by iterative design process to meet the requirements of extraction system. A detailed simulation using particles of different initial position, momentum and RF phase will proceed in the next step.

ACKNOWLEDGEMENT

We are grateful to thank Jianjun Yang for valuable discussions and experiments in the central region preliminary design stage, and thank Y.N. Rao for helpful suggestions regarding the optimizing goals of CYCIAE-230 central region.

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