EXTRACTION BEAM ORBIT OF A 250 MeV SUPERCONDUCTING CYCLOTRON

Haijun Zhang, Kuanjun Fan, Yan Yan, Lige Zhang

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Hubei, China, HUST, Wuhan, China

Yi-nong Rao, TRIUMF, Vancouver, Canada

Email: kjfan@hust.edu.cn

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Abstract--A superconducting cyclotron based on proton therapy facility is being developed at Huazhong university of science and technology （HUST）. Due to the compact size of the main magnet, the beam orbits at the extraction region are distributed densely, which creates difficulties for beam extraction leading to severe beam loss. In order to deal with these challenges, the orbit precession method has been employed in the extraction system design. In this paper, we introduce a method of employing a first harmonic field near the $\nu_r = 1$ resonance where the beam energy is about 248 MeV to adjust the amplitude of beam orbit oscillation. The optimum amplitude and phase of the first harmonic field are designed to obtain a large turn separation in the extraction region. Three different ways of generating the first harmonic field are compared for optimization.

I. INTRODUCTION

The superconducting cyclotron HUST-SCC250 based on proton therapy facility has excellent advantages of economy and compactness, but it also complicates the electromagnetic structure, and makes the extraction efficiency very low. Precession extraction is always employed to enhance the distance between successive turns and facilitate extraction of the beam.

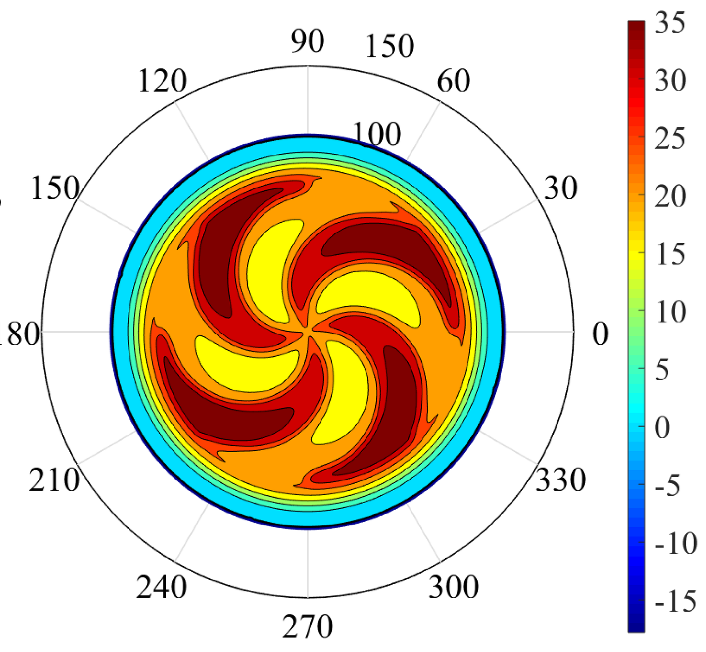

Figure 1: Magnetic Field Map of Superconducting Cyclotron

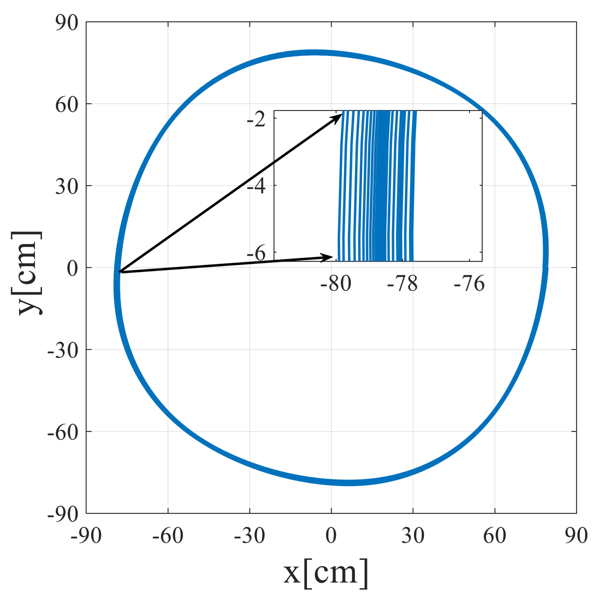

Figure 2: The acceleration orbit without harmonic field.:

II. STATIC ORBIT PROPERTIES ANALYSIS

The isochronism of the given magnetic, which varies around zero over the energy range, provides essential information for calculating the phase shift by the well-known phase-energy equation:

$$\Delta(\sin\phi) = \sin\phi_f - \sin\phi_i = \frac{2\pi h}{\Delta E}\int_{E_i}^{E_f}\left(\frac{\omega_0}{\omega} - 1\right) dE$$

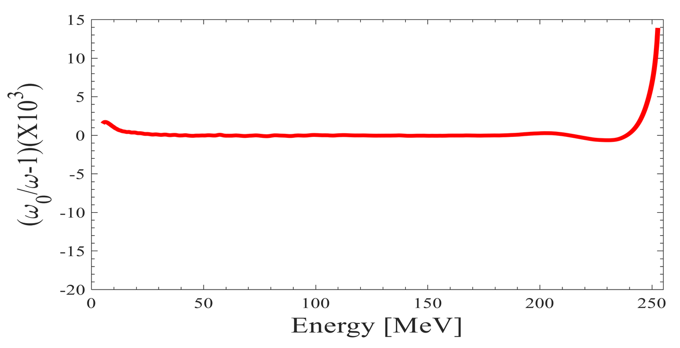

Figure 3: The isochronism parameter $(\omega_0/\omega - 1)$ vs. energy. The ω_0 and ω are the nominal rf angular frequency and the revolution angular frequency of particle along the SEO, respectively.

The initial phase $\phi_i = 32.8^{\circ}$ is chosen such that the integral of $\sin\phi$ equals to zero, so as to minimize the energy spread of beam at the extraction region.

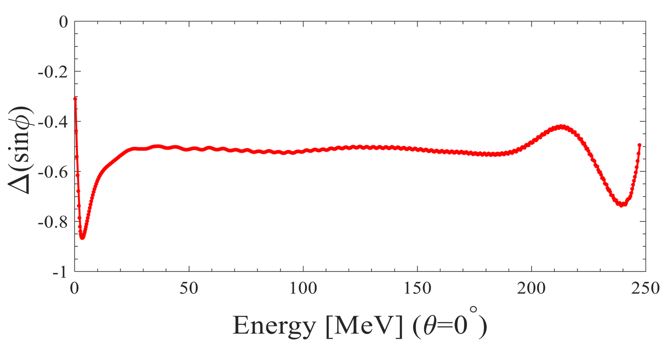

Figure 4: the phase shift $\Delta\sin(\phi)$ vs. energy.

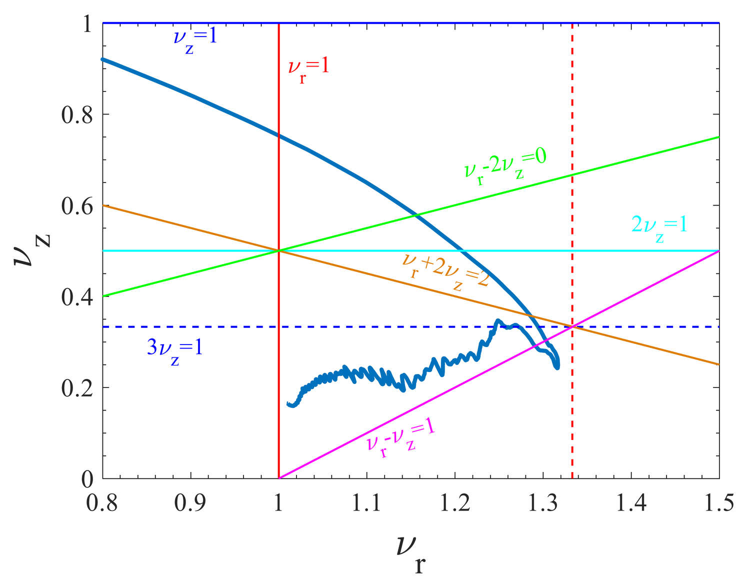

Figure 5: The turn diagram.

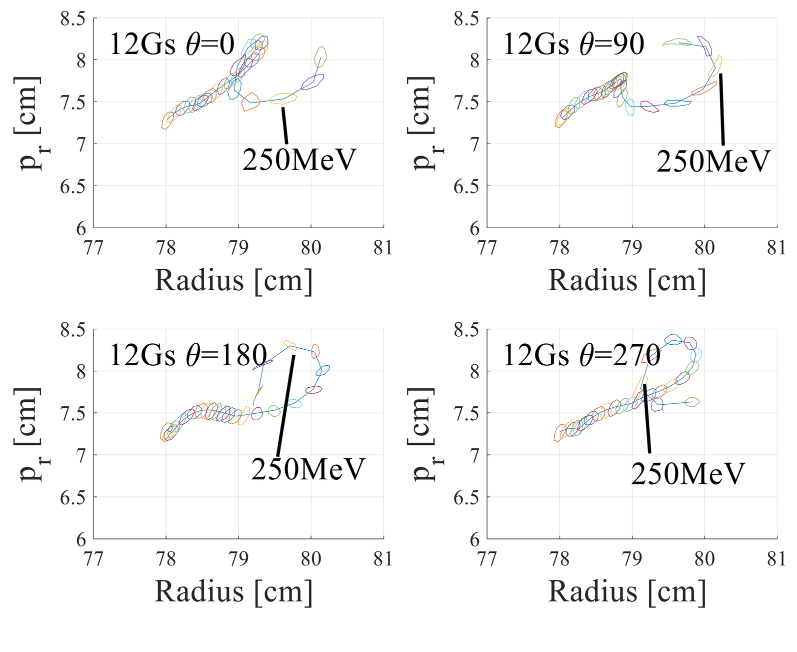

Figure 7: The phase diagrams (12 Gs $\theta = 0^{\circ}\sim270^{\circ}$) near the extraction region.

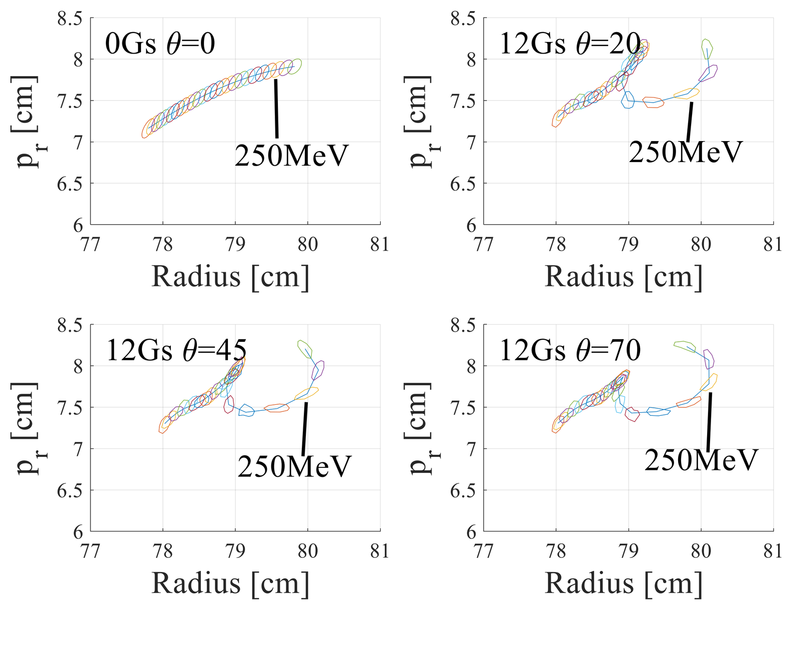

Figure 8: The phase diagrams of the extracting beam under different phase.

For the harmonic magnetic field with phase of $90^{\circ}\sim270^{\circ}$, the orbit is staggered and compressed near the extraction.

As shown in Fig. 9, compared with the orbit without harmonic field in Fig. 2, the turn separation increases obviously for the harmonic field with amplitude of 12Gs and with phase of 45°.

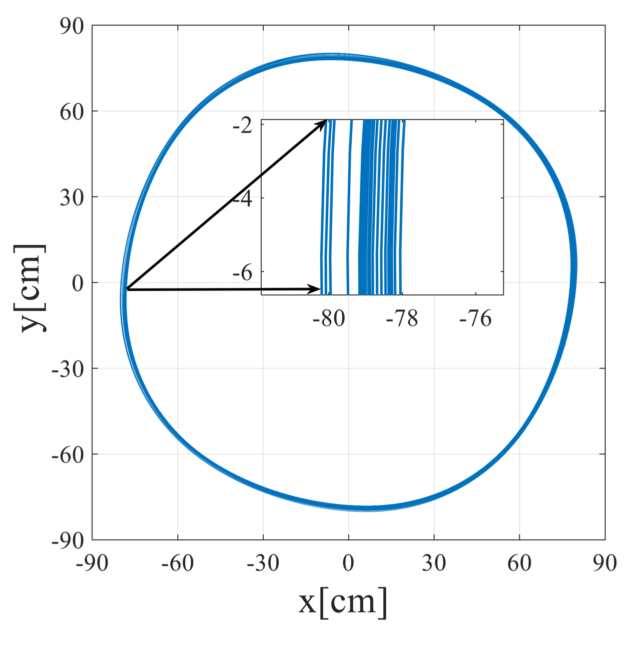

Figure 9: The acceleration orbit For the harmonic field with amplitude of 12Gs and with phase of 45°

III. DESIGN OF EXTRACTION ORBITS

The precession extraction basically is achieved by a perturbation of the first harmonic which provides a driving force in resonance, namely:

$$b(r,\theta) = b_1(r)\cos(\theta - \theta_0)$$

The radial position of particles near the extraction can be expressed as：

$$r = r_0 + A\cos\varphi$$

The oscillation amplitude after the effective duration n_{eff} is as follows:

$$A = \pi R n_{eff}\frac{b_1}{B_0}$$

Where

$$(n_{eff})^{-2} = \left|\frac{d\nu_r}{dn}\right|$$

The turn separation at the extraction region is:

$$\Delta r = \Delta r_0 + A\sin[2\pi(\nu_r - 1)]$$

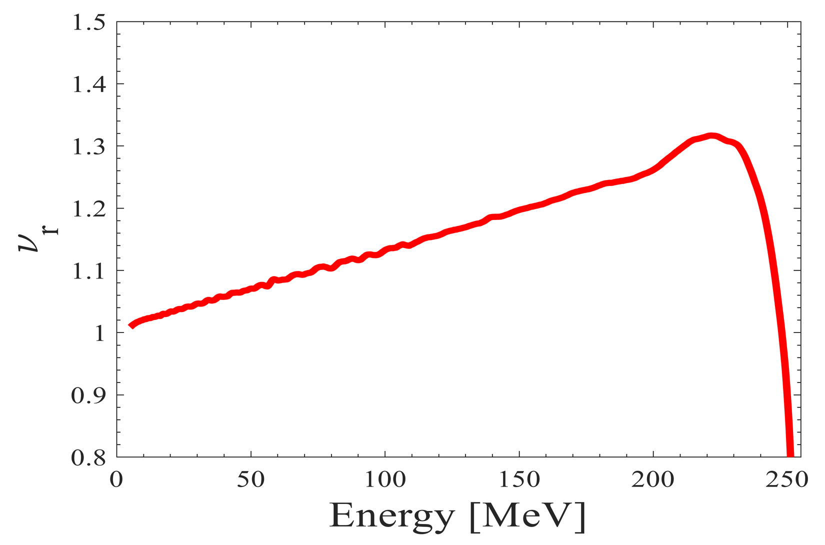

Figure 6: The radial oscillation frequency ν_r vs. energy.

IV. THE WAY OF INTRODUCING FIRST HARMONIC

- ***Trim coil***

  By independently controlling the current of the four coils distributed on the four hills of the main magnet , the continuous and adjustable amplitude and phase of the first harmonic can be obtained.

- ***Trim-rod***

  Compared with the trim coil, the magnetic field generated by the trim-rod is more predictable and stable.

- ***Magnet shimming***

  The beam extraction of the cyclotron accelerating single particle species, is mainly achieved by radial and axial pole shaping.

V. CONCLUSIONS

This paper introduces the design of beam orbit on the extraction of 250 MeV superconducting cyclotron. Utilizing several codes, such as MATLAB, CYCLOPS and CYCLONE, to track the orbit, an optimized first harmonic with the phase of $20^{\circ}\sim45^{\circ}$ is selected, which contributes a turn separation of 4.7 mm. Three ways of generating the first harmonic are introduced, which are trim coil, trim-rod, magnet shimming, respectively.