Design Study of Regenerative Extraction System for Superconducting Proton Synchrocyclotron

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Abstract

Superconducting synchrocyclotrons exhibit an ultra-compact structure with reduced cost, rendering them particularly suitable for proton therapy systems deployed in hospital environments. Compared with existing proton therapy systems, those utilizing superconducting synchrocyclotrons offer lower per-treatment costs for tumor therapy, demonstrate substantial application potential, and have consequently attracted considerable attention from accelerator research institutions and commercial enterprises. The regenerative extraction system constitutes a critical subsystem of superconducting synchrocyclotrons and represents both a pivotal and challenging aspect of their design. This study presents the design of a regenerative extraction system for a 230 MeV proton superconducting synchrocyclotron intended for proton therapy applications. Owing to the intimate coupling between the regenerative extraction system and the main magnetic field, the initial section of this paper addresses the main magnet design and presents associated dynamics calculation results. Existing cyclotron design software lacks dedicated functionality for designing synchrocyclotron regenerative extraction systems; therefore, this work has developed a specialized program for regenerative extraction system design. The design results demonstrate that the regenerative extraction system for the 230 MeV proton superconducting synchrocyclotron satisfies the extraction requirements and can serve as a reference for the design and engineering implementation of other systems in superconducting synchrocyclotrons.

Full Text

Design Study of a Regenerative Extraction System for a 230 MeV Proton Superconducting Synchrocyclotron

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Abstract

Superconducting synchrocyclotrons feature an ultra-compact structure and lower cost, making them particularly suitable for proton therapy systems deployed in hospital environments. Compared with existing proton therapy systems, those employing superconducting synchrocyclotrons offer significantly lower per-treatment costs for tumor therapy, presenting tremendous application prospects that have attracted considerable attention from accelerator research institutions and industry. The regenerative extraction system represents both a critical subsystem and a key technical challenge in superconducting synchrocyclotron design. This paper presents a systematic design study of the regenerative extraction system for a 230 MeV proton superconducting synchrocyclotron intended for proton therapy applications. Since the extraction system is intimately coupled with the main magnetic field, the first part of this paper addresses the main magnet design and presents relevant dynamic calculations. Existing cyclotron design codes lack dedicated functionality for synchrocyclotron regenerative extraction system design, prompting the development of a specialized program for this purpose. The design results demonstrate that the 230 MeV proton superconducting synchrocyclotron regenerative extraction system satisfies all extraction requirements, providing a valuable reference for the design and engineering implementation of other systems in superconducting synchrocyclotrons.

Keywords: superconducting synchrocyclotron; ultra-compact structure; regenerative extraction system design; main magnet design

0 Introduction

Conventional radiotherapy employs photon beams to irradiate tumor tissue. However, the energy deposited by photon beams in human tissue decreases with increasing penetration depth, resulting in greater energy deposition along the beam path and less energy delivered to the tumor region. This characteristic leads to severe side effects in traditional radiotherapy. In contrast, the energy deposited by proton beams is inversely proportional to the square of their velocity, concentrating primarily at the end of their range to form the characteristic dose "Bragg peak." By controlling proton energy and trajectory, the radiation dose can be precisely deposited within the tumor volume, substantially reducing side effects [**?**].

The three primary accelerator types currently used in proton therapy systems are synchrotrons, isochronous cyclotrons, and synchrocyclotrons. Among these, synchrotrons are relatively large and expensive, limiting their widespread adoption. Isochronous cyclotrons, with their compact structure and lower cost, represent the mainstream accelerator type in commercial proton therapy systems.

Synchrocyclotrons operate in pulsed mode with average beam currents far lower than those of cyclotrons. However, their simple magnet structure, when combined with superconducting technology, enables dramatic reductions in size and weight, allowing direct installation on rotating gantries and thereby significantly reducing the construction cost of beam transport systems. This makes them strong contenders for proton therapy applications. Numerous design and development efforts for superconducting synchrocyclotrons have been undertaken worldwide [?], with Mevion [?] having already achieved commercial production of superconducting synchrocyclotron-based proton therapy systems.

The beam extraction system constitutes both a critical subsystem and a key technical challenge in superconducting synchrocyclotrons. On one hand, during particle acceleration in a superconducting synchrocyclotron, the RF electric field frequency must vary according to changes in the particle cyclotron frequency, resulting in a much lower quality factor for the RF cavity compared to fixed-frequency cavities and consequently lower accelerating voltage. On the other hand, superconducting synchrocyclotrons operate in strong magnetic fields around 5 T. These two factors combine to produce extremely small orbit separations, making traditional electrostatic deflector extraction impractical [?]. Additionally, the strong main magnetic field causes stripping losses for negative ions, rendering stripping extraction unsuitable for superconducting synchrocyclotrons, which generally can only accelerate positive ions. Regenerative extraction, proposed in the 1950s as an extraction scheme specifically for synchrocyclotrons, was eventually developed and refined by Couteur Le [?] and successfully applied in the IBA 230 MeV proton superconducting synchrocyclotron [?] and the Mevion S250i proton accelerator [?]. This paper presents a comprehensive dynamic study of the regenerative extraction system for a 230 MeV proton therapy superconducting synchrocyclotron and provides the regenerator design.

Since existing cyclotron design codes lack functionality for synchrocyclotron regenerative extraction system design, we have developed a dedicated program for this purpose. Furthermore, as the extraction system design is intimately coupled with the main magnetic field, the first part of this paper describes the main magnet design for this synchrocyclotron, along with relevant orbital dynamics characteristics and key accelerator parameters. The second part of the paper presents the regenerative extraction system design for this accelerator, optimizing the regenerator structure through orbital dynamics analysis and culminating in an extraction system design that meets all requirements.

1 Main Magnet Design

The main magnetic field of a superconducting synchrocyclotron is similar to that of a classical cyclotron, exhibiting rotational symmetry about the central axis and mirror symmetry about the central plane z=0, with a simpler pole structure than the sector magnets of isochronous cyclotrons. To minimize accelerator size, the maximum magnetic field strength was determined to be 5.71 T at the magnet center, referencing the design of the IBA 230 MeV superconducting synchrocyclotron.

Based on requirements for transverse motion stability of charged particles in rotationally symmetric magnetic fields [**?**], the magnetic field in a superconducting synchrocyclotron must decrease gradually from center to pole edge, with the magnetic field fall-off index n satisfying 0<n<1. Considering magnet utilization efficiency, n«1 in the primary acceleration region. Since superconducting synchrocyclotrons generally operate with relatively low acceleration voltage, protons execute numerous turns, making them more susceptible to resonance effects. The main magnet design must therefore carefully consider the influence of resonances on motion stability [**?**], ensuring protons traverse unavoidable resonance lines as quickly as possible. This design considered resonances up to fifth order. When protons approach resonance lines, the pole face is adjusted to cause rapid magnetic field decrease, minimizing the number of turns spent crossing resonance lines to reduce resonance effects. Through optimization, the quarter-section structure of the main magnet is shown in Figure 1 [Figure 1: see original paper], with key parameters listed in Table 1 .

Figure 2 [Figure 2: see original paper] presents the central plane average magnetic field and magnetic field fall-off index n as functions of radius, obtained through CST simulations. The radial variation of the magnetic field is achieved primarily through optimization of the pole face structure. The field is 5.71 T at the magnet center, decreasing monotonically to 5.32 T at the beam extraction radius (r=44 cm). The magnetic field fall-off index exhibits three rapid increases with radius: within 8 cm radius, n increases rapidly from 0 to 0.017 to enhance vertical focusing force and improve proton beam capture efficiency; between 26 cm and 37 cm radius, n increases sharply from 0.026 to 0.065 to accelerate passage through the _z=1/5 and _z=1/4 resonance lines; the rapid increase at the pole edge results from magnetic leakage.

Figure 3 [Figure 3: see original paper] shows the proton working diagram in the superconducting synchrocyclotron, where diagonal lines represent two-dimensional coupling resonances, horizontal lines represent one-dimensional resonances, and red dots indicate the working point evolution from radius 0 to 44 cm. The region beyond 44 cm radius is the extraction region and therefore requires no consideration. Since adding the regenerator produces a radius-dependent magnetic field that increases _r and decreases _z, the final red dot in Figure 3 moves away from the _z=1/3 resonance line toward _z=1/4, making the _z=1/4 resonance have minimal impact on proton motion in the primary acceleration region. The figure shows that protons experience relatively weak coupling resonance effects but are affected by one-dimensional high-order resonances. The _z=1/3 resonance lies in the pole edge region outside the primary acceleration region, and protons traverse it rapidly with minimal impact. The _z=1/4 and _z=1/5 resonances may affect proton beam motion, requiring magnetic field reduction to accelerate passage. Higher-order resonances have negligible effects and need not be considered in main magnet design. Detailed proton motion in the magnetic field, of course, depends on comprehensive dynamic analysis.

2 Transverse and Longitudinal Dynamics Analysis

Protons in electromagnetic fields experience the Lorentz force and obey Newton' s second law:

$$\frac{d\vec{P}}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$$

where $\vec{P} = \gamma m_0 \vec{v}$ is the proton mechanical momentum, $\vec{v}$ is proton velocity, $\gamma = 1/\sqrt{1-(v/c)^2}$ is the relativistic factor, c is the speed of light in vacuum, m_0 is the proton rest mass, $\vec{E}$ is the electric field intensity vector at the proton location, $\vec{B}$ is the magnetic flux density vector, and q is the proton charge.

Although three-dimensional electromagnetic field calculation software can produce high-precision three-dimensional magnetic field distributions, practical magnetic field measurements can only obtain two-dimensional field distributions on the magnet pole central plane. Therefore, cyclotron and synchrocyclotron orbit calculations typically utilize magnetic field symmetry to derive three-dimensional field distributions from the central plane two-dimensional distribution [**?**]:

$$B_z(r,\theta,z) = B_z(r,\theta) - \frac{z^2}{2}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial B_z(r,\theta)}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 B_z(r,\theta)}{\partial \theta^2}\right]$$

where $B_z(r,\theta)$ is the two-dimensional magnetic field distribution on the central plane, and r, θ, z are the particle coordinates in a cylindrical coordinate system with the magnet rotational symmetry axis as the z-axis and magnet center as origin. This three-dimensional field expression retains only the quadratic term in the vertical displacement z; higher-order terms can be included using similar expansion methods if greater precision is required. For this design, expansion to the quadratic term in z proves sufficient for particle orbit calculations in the extraction region, even when considering nonlinear effects.

In synchrocyclotrons, particles experience electric fields only in the acceleration gap. This electric field can be obtained through numerical calculation of the resonant cavity to determine the central plane field distribution, then extended to three dimensions using methods analogous to those for the magnetic field.

2.1 Transverse Dynamics Analysis

Without considering extraction system effects, particle orbits in synchrocyclotrons are relatively simple, with static equilibrium orbits being circular. Non-reference particles oscillate about these static equilibrium orbits, with oscillation frequencies determined by the magnetic field fall-off index. Under linear approximation, the orbits satisfy:

$$\frac{d^{2z}}{d\theta^2} + nz = 0$$

$$\frac{d^{2r}}{d\theta^2} + (1-n)r = 0$$

where z is particle displacement relative to the central plane, r is displacement relative to the reference particle, θ is the azimuthal angle, and n is the magnetic field fall-off index. Equations (5) and (6) show that non-reference particles oscillate in the radial and vertical directions with frequencies $\sqrt{1-n}$ and $\sqrt{n}$, respectively.

The periodic transfer matrix for a periodic system is:

$$M = \begin{pmatrix} \cos(2\pi\sqrt{K}) + \alpha\sin(2\pi\sqrt{K}) & \beta\sin(2\pi\sqrt{K}) \\ -\gamma\sin(2\pi\sqrt{K}) & \cos(2\pi\sqrt{K}) - \alpha\sin(2\pi\sqrt{K}) \end{pmatrix}$$

For multi-particle simulation analysis, transverse beam matching is calculated through the periodic transfer matrix (8), where $K = 1-n$ for the radial transfer matrix and $K = n$ for the vertical transfer matrix. With $\beta = 1/\gamma$ and $\beta = \rho/\sqrt{K}$, the phase ellipse parameters for transversely matched beams at radius ρ satisfy: $\beta_r = r_{\max}/r'_{\max} = \rho/\sqrt{1-n}$ and $\beta_z = z_{\max}/z'_{\max} = \rho/\sqrt{n}$.

We calculated particle orbits using a self-developed program employing the fourth-order Runge-Kutta algorithm with time as the independent variable. The magnetic field was obtained using the expansion methods of equations (2), (3), and (4), with first and second derivatives of $B_z(r,\theta)$ with respect to r and θ calculated by finite differences. Azimuthal and radial step sizes of 1 degree and 1 cm were selected, as either too small or too large step sizes introduce significant errors.

Figure 4 [Figure 4: see original paper] shows the particle betatron oscillation frequencies as functions of radius. The dotted lines represent frequencies calculated by the orbit program, which first determines the proton static equilibrium orbit, then calculates radial and vertical oscillation frequencies by perturbing the proton transverse position or velocity direction. The solid lines represent frequencies obtained by direct differentiation of the central plane average magnetic field radial distribution. The excellent agreement between orbit integration results and theoretical values confirms the program' s accuracy. Although the magnetic field is expanded to quadratic order in z, nonlinear effects remain small because particle transverse velocities are much smaller than azimuthal velocities.

2.2 Longitudinal Dynamics Analysis

For longitudinal dynamics calculations, we assume an acceleration gap width of 1 cm with uniformly distributed electric field varying temporally as:

$$\vec{E}(t) = E_0 \cos(\omega_{rf}(t)t + \varphi_s)\hat{e}_\theta$$

where E_0 is the peak electric field intensity in the acceleration gap (numerically equal to the peak acceleration voltage divided by gap width), ω_{rf} is the accelerating field angular frequency, and φ_s is the particle acceleration initial phase (the reference proton synchronous phase). Since the phase slip factor $\eta = \alpha_c - 1/\gamma^2$ remains positive throughout acceleration, the equilibrium phase φ_s must be greater than zero.

Assuming a reference proton synchronous phase of 30 degrees and acceleration voltage of 20 kV to provide constant energy gain per gap crossing, the program uses time t as the independent variable with non-constant time steps between 10^{-13} s and 10^{-10} s. By calculating the times when the reference proton reaches the acceleration gap center, and requiring the accelerating field phase to follow $\pi/6$, $\pi/6 + \pi$, $\pi/6 + 2\pi$, etc., the temporal phase variation is obtained. Since the program cannot directly capture the exact time when the reference proton arrives at the gap center, linear interpolation is performed between the time points immediately before and after gap crossing. The first time derivative of the electric field phase yields the electric field frequency variation.

Figure 5 [Figure 5: see original paper] shows the reference proton revolution frequency and gap crossing phase as functions of time and radius, covering acceleration from 5 cm to 49.5 cm radius. Beyond 49.5 cm, protons are essentially extracted and require no further consideration. The reference proton requires approximately 0.106 ms to accelerate from 5 cm to 49.5 cm radius, with RF frequency decreasing from 85.86 MHz to 60.61 MHz and electric field phase increasing from $\pi/6$ to $\pi/6 + 15249\pi$, corresponding to 7624.5 turns.

Figure 6 [Figure 6: see original paper] shows the kinetic energy deviation relative to the reference proton for five protons entering the acceleration field with initial phases of 30°, 0°, -29°, 65°, and -35°. The proton entering at the reference phase of 30° shows nearly zero energy deviation. The proton entering at 0° phase, though offset from equilibrium phase, accelerates with the reference proton throughout, with its phase oscillating about the 30° equilibrium phase and a maximum kinetic energy deviation of approximately 0.7 MeV. The proton entering at -29° phase similarly oscillates about the 30° equilibrium phase with a maximum deviation of about 1.05 MeV. Protons entering at 65° and -35° phases eventually enter the deceleration region and are lost, indicating they lie outside the phase stability region. This demonstrates that larger initial phase differences from the reference phase produce greater kinetic energy spread. With an equilibrium phase of 30°, the phase stability region extends from -30° to 60°, and only protons entering within this region will accelerate to completion.

Multi-particle simulation phase space evolution during acceleration is shown in Figure 7 [Figure 7: see original paper]. To satisfy extraction requirements of radial turn separation exceeding 1.5 cm and vertical beam size constraints imposed by the accelerating cavity, the initial beam bunch has radial dimensions of 1.4 cm and vertical dimensions of 2 cm. The bunch enters the acceleration gap at 5 cm radius with initial transverse phase space satisfying $\beta_r \approx 0.0503$ and $\beta_z \approx 0.4226$, longitudinal phase distribution between 5° and 55°, and initial momentum spread of 5‰. Subfigure (a) shows the initial matched transverse and longitudinal phase space distributions at 5 cm radius. Subfigure (b) shows distributions at 22.9 cm radius (2000 turns), (c) at 33 cm radius (4000 turns), and (d) at 45 cm radius in the extraction region (6700 turns). The transverse phase space remains elliptical throughout acceleration due to uniform focusing forces. The radial beam size changes little because ν_r varies only slightly, while the vertical size decreases from 2 cm to 1.1 cm due to larger variations in ν_z. Transverse divergence angles decrease continuously, with maximum radial and vertical angles reducing from 139 mrad and 23.66 mrad to 14.84 mrad and 4.98 mrad, respectively. Longitudinal momentum spread decreases from 5‰ to 1.8‰, with all proton phases oscillating about the 30° equilibrium phase. No protons are lost during acceleration.

Based on this analysis, the main parameters for the 230 MeV proton superconducting synchrocyclotron are finalized in Table 2 .

3 Regenerative Extraction System Design

With an accelerating voltage of 20 kV, the orbit calculation program yields a reference proton turn separation of only about 40 m. Using electrostatic deflectors would cause massive beam loss from protons striking the electrodes, making such extraction impractical. Superconducting synchrocyclotrons typically employ regenerative extraction, which involves adding local iron shims at the pole edge to produce a nonlinear, radius-dependent magnetic field. This utilizes the $\nu_r = 1$ resonance to shift the proton orbit center in one direction while increasing radial turn separation and maintaining stable vertical motion. A regenerator design is considered adequate if the reference proton achieves radial turn separation exceeding 1.5 cm with stable vertical motion at 230 MeV.

Without a regenerator, protons encounter the $\nu_r = 2\nu_z$ resonance during acceleration, causing energy exchange between radial and vertical motion that can reduce radial oscillation amplitude while increasing vertical amplitude, leading to beam loss. The regenerator should therefore be positioned to extract protons before they enter this resonance. Regenerator design involves iterative calculation between structure adjustment and dynamics analysis. As regenerator shim thickness increases, the generated magnetic flux density and reference proton turn separation increase. However, beyond a certain thickness, while turn separation continues increasing, vertical motion amplitude grows rapidly until protons strike the pole and are lost. The design must meet extraction requirements while maximizing regenerator aperture to allow passage of as many protons as possible.

Through iterative optimization, the final regenerator structure is determined. Figure 8 [Figure 8: see original paper] shows the final regenerator structure: a quarter-section view along the radial direction and an azimuthal cross-section at 48.5 cm radius, with the red outline indicating the regenerator cross-section. Key parameters are listed in Table 3 .

The regenerator consists of four radial sections (45-45.5 cm, 45.5-49 cm, 49-53 cm, and 53-54.5 cm) to adjust the magnetic field radial distribution, and four azimuthal sections (11°, 24°, 30°, 36°) to reduce defocusing from magnetic field depressions in the regenerator' s central and edge regions. In the 45-45.5 cm radius range, three shims extend from far to near the central plane: 36° azimuthal width and 1 cm thickness, 30° width and 0.8 cm thickness, and 24° width and 0.6 cm thickness. In the 45.5-49 cm range, four shims are used: 36° width and 1.05 cm thickness, 30° width and 1.4 cm thickness, 24° width and 1.1 cm thickness, and 11° width and 0.06 cm thickness. Other regenerator modules follow similar patterns.

Figure 9 [Figure 9: see original paper] shows the central plane average magnetic field distribution without the regenerator, the field produced by the regenerator alone, and the total field with the regenerator installed. Figure 10 [Figure 10: see original paper] shows the regenerator magnetic field variation with azimuthal angle at 48.5 cm radius. The regenerator produces a peak field of about 0.8 T, with fields of approximately -0.1 T at 42 cm and 57 cm radii, yielding a total peak field of about 5.98 T. Azimuthally, the field is about -0.04 T at 158° and 202.6°, with a peak of about 0.8 T. The magnetic field depression in radial regions immediately before and after the regenerator causes vertical defocusing, requiring thin shims in small-radius regions to mitigate field reduction. Azimuthal field depressions at regenerator edges and center also cause vertical defocusing, necessitating azimuthally graded edges and thin central shims.

The regenerator' s radius-dependent field increases ν_r toward the $\nu_r = 2/2$ resonance while decreasing ν_z. Figure 11 [Figure 11: see original paper] shows ν_r and $2\nu_z$ versus reference proton kinetic energy with and without the regenerator. Without the regenerator, the reference proton reaches $\nu_r = 2\nu_z$ at 248.2 MeV. With the regenerator, ν_r reaches 1 at 237.1 MeV (radius 43.7 cm) with $\nu_z = 0.278$, representing the maximum achievable proton kinetic energy.

The extraction process can be understood through the radial phase space diagram in Figure 12 [Figure 12: see original paper], which shows r' versus r for protons passing through azimuthal angle 180° where the regenerator is located. The figure depicts radial stability region boundaries for protons with kinetic energies of 226.2 MeV, 231.8 MeV, 234.0 MeV, 235.7 MeV, and 237.0 MeV, plus two unstable orbits at 231.8 MeV. At 231.8 MeV, the radial stability region is about 3.5 cm wide; protons outside this region experience exponentially increasing radial amplitude along asymptotes. As kinetic energy increases, the stability region shrinks, reducing to zero when ν_r reaches 1, after which all protons become unstable and radial turn separation increases rapidly. Therefore, $\nu_r = 1$ defines the maximum achievable kinetic energy, and the extracted beam possesses inherent energy spread. The 3.5 cm stability region at 231.8 MeV is sufficient to capture the vast majority of internal beam, confirming that this regenerator can accelerate protons to 230 MeV.

Figure 13 [Figure 13: see original paper] shows the reference proton' s radial trajectory during the final six turns as a function of azimuthal angle θ (0° to 360°), with the red rectangle indicating regenerator position. Turn separation reaches 1.5 cm at azimuthal angle 101° and radial displacement 48.9 cm, where a magnetic channel could be placed. Passive magnetic channels become magnetized by the main field and affect surrounding fields, requiring iterative position adjustment and dynamics calculations.

Figure 14 [Figure 14: see original paper] shows the vertical trajectory during the final 51 turns for a proton with initial vertical displacement of 1 cm and other parameters identical to the reference proton. Vertical amplitude decreases at small radii but increases near the regenerator, with maximum vertical displacement of 1 cm throughout, demonstrating stable vertical motion.

Figure 15 [Figure 15: see original paper] presents multi-particle simulation phase space evolution with the regenerative extraction system installed. To improve computational speed without compromising results, boundary protons were selected for simulation. Since regenerator effects are negligible below 30 cm radius, the bunch was started at 30 cm radius. The bunch has radial and vertical dimensions of 1.4 cm and 2 cm, initial momentum spread of 5‰, and initial RF phase between 5° and 55°, with matched transverse phase space parameters. Subfigure (a) shows initial transverse and longitudinal phase space distributions, (b) shows distributions at 34.2 cm radius (1000 turns), (c) at 37.7 cm radius (2000 turns), and (d) at 43 cm radius (3000 turns) with kinetic energy 235.7 MeV, beyond which the radial stability region shrinks to zero and turn separation increases rapidly. Phase space distortion increases during acceleration due to non-uniform focusing from the regenerator-modified field, becoming particularly pronounced beyond 40 cm radius. However, transverse dimensions and divergence angles do not increase significantly, with longitudinal momentum spread decreasing from 5‰ to 2.8‰. All protons remain stable and none are lost, confirming stable acceleration to 235.7 MeV.

Figure 16 [Figure 16: see original paper] shows initial transverse phase space distributions for bunches centered at 43 cm radius with kinetic energy 235.7 MeV, radial dimensions of 1.4 cm and 1.0 cm, and vertical dimensions of 6 mm and 1 cm, with matched parameters. Assuming a magnetic channel entrance at azimuthal angle 105° and radius 48-50 cm, where reference proton turn separation is 1.7 cm, Figure 17 [Figure 17: see original paper] shows the resulting transverse phase space at the channel entrance. The black rectangle indicates the channel entrance position (r=0 corresponds to 49 cm radius). Results are shown for initial conditions with $r_{0\max} = 7$ mm and $z_{0\max} = 3$ mm, $r_{0\max} = 7$ mm and $z_{0\max} = 5$ mm, and $r_{0\max} = 5$ mm and $z_{0\max} = 3$ mm. The regenerator amplifies both dimensions and divergence angles in both planes. Radial dimensions are similar, with maximum displacements of 9.5 mm, 10.0 mm, and 9.7 mm at the channel entrance. Vertical amplification is more pronounced, with maximum amplitudes of 9.5 mm, 13.9 mm, and 8.0 mm. Therefore, constraining vertical beam size is most effective for improving extraction efficiency. Given the regenerator gap of about 3.2 cm, the vertical size at 43 cm radius should preferably be maintained within 5 mm.

4 Conclusion

This paper presents a design study of the regenerative extraction system for a 230 MeV proton superconducting synchrocyclotron. Since the extraction system is intimately coupled with the main magnet, the main magnet design is also presented. Existing cyclotron design codes lack functionality for synchrocyclotron regenerative extraction system design, necessitating development of a specialized program. The main magnet pole structure is designed to be relatively simple and rotationally symmetric about the central plane to facilitate engineering implementation. Dynamic calculations confirm that the central plane magnetic field satisfies radial and vertical focusing conditions, with protons rapidly traversing resonance regions and accelerating normally to the extraction region, validating the main magnet design. Tracking of reference protons during the final turns shows turn separation exceeding 1.5 cm while maintaining stable vertical motion. The main magnet and regenerative extraction system provide adequate radial and vertical stability regions to accelerate internal beam to 235.7 MeV kinetic energy. However, vertical motion amplitude increases significantly during further outward motion; dynamic calculations indicate that vertical amplitude should preferably be maintained within 5 mm when accelerating to 235.7 MeV. Some beam loss at the magnetic channel entrance is unavoidable. Dynamic simulations at the regenerator demonstrate that limiting vertical beam amplitude in the central region can reduce losses in the regenerator region, thereby improving extraction efficiency and minimizing activation from protons striking accelerator structures.

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