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THE DESIGN OF NONLINEAR REGENERATIVE EXTRACTION IN 250MeV PROTON SUPERCONDUCTING SYNCHROCYCLOTRON

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Abstract

The objective of this article is to apply the regenerative extraction system to a 250MeV proton superconducting synchrocyclotron. The parameters of the regenerative extraction system are determined by iteratively calculating the appropriate magnetic field and particle trajectory in the region where the magnetic field and particle trajectories interact. This is then combined with the magnetic channel system to achieve the extraction of the beam from the accelerator. In the article, the particle orbit dynamics analysis and the design of relevant parameters for the regenerative extraction system were successfully implemented using Matlab programming. The simulation results showed that the stability in the vertical direction has the greatest impact on the extraction efficiency and determination of the regenerative magnetic field parameters. In order to maximize the particle extraction efficiency, the radial displacement of particles in the last few turns should pass through two identical nodes.

INTRODUCTION

Proton therapy is an effective treatment for cancer with minimal side effects. In recent years, due to the development of superconducting technology, superconducting synchrocyclotron has compact structure and low design difficulty to meet the needs of medical treatment of cancer. The extraction problem is very important in the design process of superconducting synchrocyclotron, and the common extraction methods include electromagnetic deflection system, target scattering beam and regenerative extraction system [1]. The electromagnetic deflection system utilizes deflecting plates to apply a radial electric field force on particles, causing an increase in their orbit radius. The electromagnetic deflection system is suitable for accelerators with large particle orbit spacing, and the particle orbit spacing in the superconducting synchrocyclotron is small, so the application of the electromagnetic deflection system in the superconducting synchrocyclotron will cause some particles to hit the deflection plate and cause unnecessary losses. The target scattering beam method involves scattering the beam into a magnetic channel using a material with a high atomic number. However, this method generally exhibits low extraction efficiency. The regenerative excitation system generates the required magnetic field by adding iron blocks between the edges of the magnetic poles. The generated magnetic field disturbs the particles and causes an increase in their radial amplitude while maintaining stable operation in the vertical direction, thereby achieving the goal of extracting particles from the accelerator [2]. The extraction efficiency of the regenerative excitation system can reach between 50% and 70%, indicating a high level of extraction efficiency. In order to promote the development of proton therapy in China, the Key Laboratory of Radiation Physics and Technology, Ministry of Education, has designed an extraction system for a 250MeV proton superconducting synchrocyclotron. The main parameters of the accelerator are shown in Table 1.

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Table 1: The Main Parameters of 250MeV Superconducting Synchrocyclotron

Extraction beam energy	250MeV
Magnetic pole radius	53cm
Central magnetic field	5.57T
Ampere-Turn Number	533A-3000turns
RF Cavity Voltage	20kv
RF frequency ranges	58-85MHz

The regenerative extraction system was initially proposed by Tuck and Teng [2] and further improved by Le Couteur [3,4]. The initial regenerative system is linear regeneration, which is a method of increasing the number of "peeler" and the" regenerator" two local magnetic fields on the magnetic pole edge. As shown in Figure 1 (a), these two local magnetic fields are reduced and increased by linear methods in a linear way. Then the study found that only a single increase in the magnetic pole edge of the magnetic pole could also achieve the resulting effect. As shown in figure 1 (b), where the magnetic field of "regenerator" increases nonlinearly with the radius, the magnetic pole utilization rate of this method is higher.

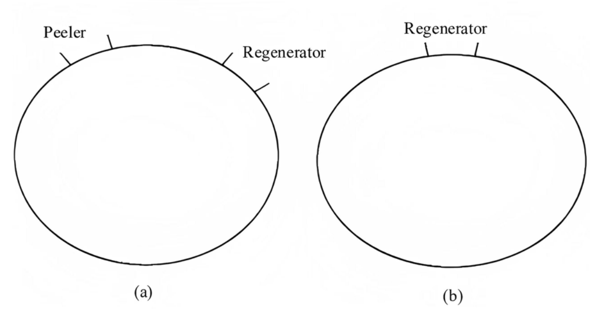

Figure 1: (a) is schematic diagram of linear regenerator extraction, (b) is schematic diagram of nonlinear regenerator extraction.

Appropriate regenerative magnetic field parameters can result in a rapid increase in the radial amplitude of particles while maintaining stability in the vertical direction. When

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particles are running near the vicinity of a magnetic field drop-off exponent of n=0.2(νz=2νr), the resonance effect can cause a rapid increase in the vertical displacement of particles, leading to particle loss. Therefore, to avoid the resonance effect, the starting position of the regenerative magnetic field should be located before n=0.2.

CALCULATION PRINCIPLE/PHYSICAL MODEL

The parameters of the regenerative extraction system refer to Le Couteur [4]. The distribution of the regenerative magnetic field is:

$$q_0 \frac{r_0}{H_0} H_q = k_1\rho + k_2\rho^2 + k_3\rho^3 + k_4\rho^4 + k_5\rho^5 \tag{1}$$

Where, θ_0 represents the angular width of the regenerative magnetic field region, r_0 represents the starting radius of the regenerated magnetic field, H_0 represents the magnitude of magnetic induction at the starting position of the regenerated magnetic field, H_q represents the difference between the regenerative magnetic field and H_0, ρ represents the particle's displacement from r_0, k_1, k_2, k_3, k_4 and k_5 represents the magnetic field adjustment parameters.

For a complete orbital dynamics analysis, the magnetic field off the central plane needs to be calculated by equations (2), (3) and (4):

$$B_z(r,\theta,z) = B_z(r,\theta) + \frac{1}{2}z^2\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}\right)B_z(r,\theta) + 0(z^4) \tag{2}$$

$$B_r(r,\theta,z) = -z\frac{\partial}{\partial r}B_z(r,\theta) + 0(z^3) \tag{3}$$

$$B_\theta(r,\theta,z) = -\frac{z}{r}\frac{\partial}{\partial \theta}B_z(r,\theta) + 0(z^3) \tag{4}$$

Where, z represents the displacement of the particle away from the vertical direction of the center plane, r represents the radial displacement of the particle away from the equilibrium orbit, Bz(r,θ,z), Br(r,θ,z) and B_θ(r,θ,z) represent the vertical, radial and angular magnetic fields of the desired position in the cylindrical coordinate system, Bz(r,θ) represents the vertical magnetic field distribution on the center plane of the magnetic pole.

Programming beam dynamics analysis is based on Runge Kutta numerical calculation method to accurately calculate particle motion information, time t as an independent variable.The force equation of particles is as follows:

$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{P} = qe\vec{E} + qe(\vec{v}\times\vec{B}) \tag{5}$$

Where，Vector P represents the particle momentum, vector E represents the electric field strength, vector v represents the particle velocity, vector B represents the magnetic induction intensity, and qe represents the amount of charge of the mass particle.

PARAMETER,SIMULATION RESULTS AND DISCUSSION

After repeated iterative calculation between the regenerated magnetic field and particle orbit dynamics, the regenerated magnetic field parameter is finally determined as(The units used in the formula are the International System of Units).

$$q_0 \frac{r_0}{H_0} H_q = \rho(-0.0495 + 35.5\rho - 800\rho^2 + 10500\rho^3 - 50000\rho^4)$$

When adjusting the parameters of the regenerated magnetic field, the utilization rate of the magnetic pole should be increased as much as possible, and the initial radius of the regenerated magnetic field should be increased as much as possible. When the regenerated magnetic field makes the radial gain of the last circle of particles reach about 1.3cm, the trajectory of the last few circles of particles pass through two nodes and maintain stability in the vertical direction, and the radial gain of the particles makes the first magnetic channel located within the magnetic pole, these requirements are met, indicating that the parameter adjustment of the regenerated magnetic field is completed. The local adjustment of magnetic field can be realized according to the main range of influence of k1, k2, k3, k4 and k5. The simulation results show that maintaining the stability of vertical direction is the most demanding parameter selection.

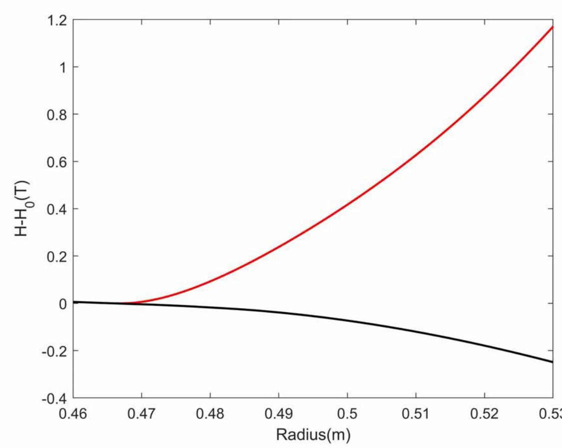

Figure 2: The change of the magnetic field with respect to the radius of H0.

Figure 2 describes the change of the main magnetic field and the theoretical regenerated magnetic field with respect to the radius of H0. The red and black lines represent the changes in the regenerative field and the main magnetic field with respect to the radius. Due to magnetic leakage at the edge of the magnetic poles, the actual magnetic field needs to conform to the designed field within a region inside the radius where the magnetic channels are located.

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Radial Motion

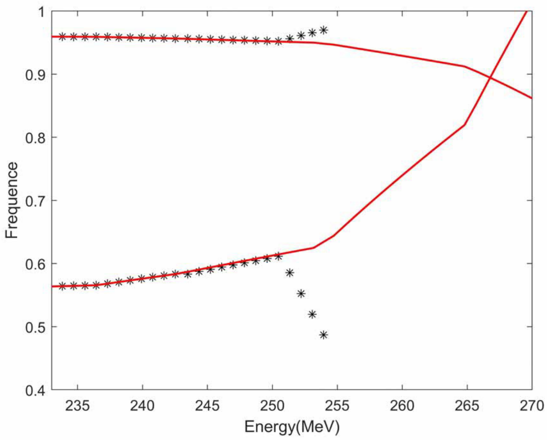

Figure 3: The point and the real line indicate the change in ν_r and $2\nu_z$ with the absence of a regenerative magnetic field.

Figure 3 describes the two solid lines intersect at the energy of 266.8MeV, where n=0.2. When the particle is running close to n=0.2, the radial amplitude of the resonance effect particle will be converted into the vertical amplitude, resulting in the increase of the vertical amplitude and the particle loss. In order to avoid unnecessary loss of particles, the magnetic field of the regeneration region should be placed before n=0.2.

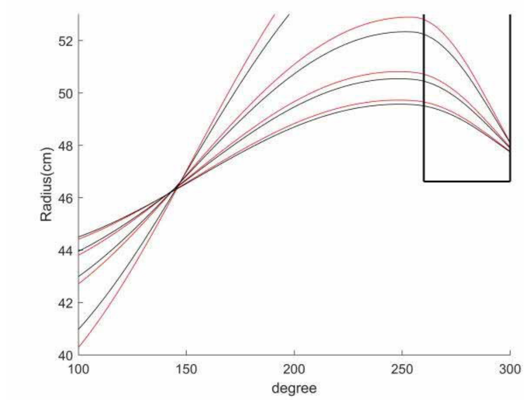

Figure 4: the change of the radius r with the azimuth θ.

Figure 4 describes the trajectory of the radius r of the last four circles of the two radially unstable orbits changing with the azimuth angle, where the value range is from 100° to 300°, and the vertical displacement of the two radially unstable orbits remains stable. Figure 4 shows that the particle trajectory passes through a node, the node at 158°, the azimuth at 206° the particle radial gain can reach 1.3cm, and the magnetic channel can be placed here.

Vertical Motion

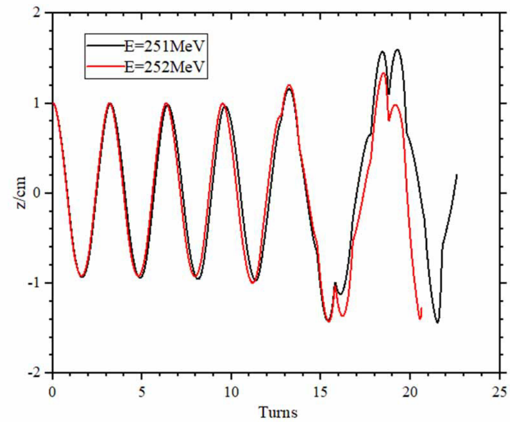

Figure 5: The trajectory of the vertical displacement of particles as the number of runs changes.

Figure 5 describes the trajectory of the vertical displacement of particles with different energies as the number of runs changes. By looking at Figure 5, we can see that the growth factor of the maximum z value decreases from 1.532 at 251MeV to 1.41 at 252MeV. The higher energy particle have a smaller growth factor because the coupling effect is smaller. The initial values of (ρ_0,p_r) are different. The simulation results show that the change of the (ρ_0,p_r) will eventually change the number of rotating cycles for particle into the magnetic channel.

CONCLUSION

The research method used in this paper can be applied to other energy synchrocyclotron beam extraction. According to the simulation results, if the vertical displacement of the particle beam generated by the used particle source is limited, the extraction efficiency of the beam will be improved accordingly, because the loss of particles in the vertical direction during extraction will be reduced. In addition, the activation caused by the increase of the vertical displacement of particles can be reduced.

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