ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOPO009

STUDY ON THE EXTRACTION OF A COMPACT CYCLOTRON FOR BNCT

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Abstract

An 18 MeV, 1 mA H^- compact cyclotron is under design at China Institute of Atomic Energy (CIAE). The proton beam bombards a beryllium target, producing high-flux neutron beam for Boron Neutron Capture Therapy (BNCT). Stripping extraction is adopted in this cyclotron. The position of the stripping point affects the trajectory and beam quality of the extracted beam. In this paper, we use orbit-tracking method to simulate the beam trajectory and emittance with different positions and tilt angles of stripping foil, and adopt the extraction point whose radius is 53.6 cm, azimuth is 57° and the tilt angle of the stripping foil is 15°.

INTRODUCTION

BNCT is one of the most advanced cancer treatment technologies in the world because of its advantages of less toxic and relatively low cost [1]. Because the neutron beam of the accelerator has the characteristics of adjustable energy, and the accelerator also has the safety advantage that the reactor does not have, the accelerator-based BNCT (AB-BNCT) has been paid more and more attention by all countries [2].

CIAE has been developing clinical cyclotron since 2010. In 2012, PET cyclotron CYCIAE-14 was successfully developed, which can provide 14 MeV, 200 μA proton beam [3]. The 14 MeV, 1 mA BNCT high-intensity proton cyclotron developed by CIAE was installed in Sept. 2020, and in Jan. 2022, the extracted beam current reached 1 mA. At present, neutron target experiment and accelerator stability test are under way. In order to improve the neutron flux and product medical isotopes, we plan to develop a new cyclotron, increasing the extraction energy to 18 MeV.

THE POSITION OF THE STRIPPING FOIL

External H^- ion source and stripping extraction are adopted in this cyclotron. The 35 keV H^- beam is produced by a multi-cusp ion source [4] and vertically injected into the cyclotron by an electrostatic inflector. Accelerated over 100 turns, H^- beam is stripped by a carbon foil then extracted to the beam line. When accelerated to 18 MeV, the beam can be extracted at this energy by a stripping foil at any azimuth. However, considering the construction cost and compatibility with other systems, the following restrictions are proposed for the position of stripping foil:

(1) The stripping probe is installed on the magnet pole.
(2) The extracted beam passes through the valley of yoke.
(3) The extracted beam doesn't pass through the RF cavities.

The two RF cavities are installed in the valley at 0° and 180°, so the beam can be extracted in the valley at 90° and 270°. Due to the symmetry of the cyclotron, the extraction designs of the two valleys are the same. Here, the extraction design at 90° valley is taken as an example.

By orbit-tracking program, the reference particle is tracked from 1 MeV to the extraction region. The orbits after extraction are shown in Fig. 1. Compared with the radius of stripping foil, the azimuth has a greater impact on the trajectory. The azimuth should be within 52°-60° to make the beam pass through the valley of yoke.

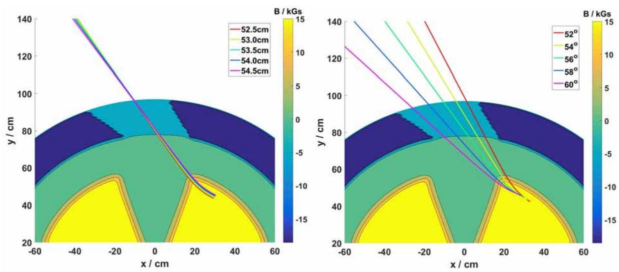

Figure 1: Extracted beam trajectory with different radii (left) and azimuths (right) of the stripping foil.

MULTI-PARTICLE SIMULATION FOR STRIPPING EXTRACTION

Distribution on the Stripping Foil

In the physical design of extraction, the emittance and beam envelope of the extracted beam are expected to be as small as possible, which is beneficial to reduce beam loss and provide higher quality beam. The multi-particle tracking method is used to simulate the emittance, beam envelope and other parameters of the extracted beam to optimize the position of stripping foil.

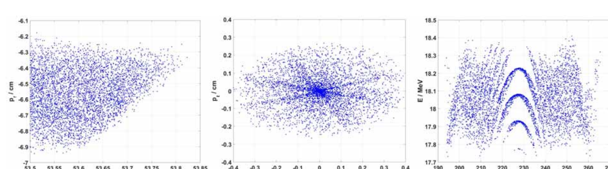

Figure 2: The particle distribution on the stripping foil in radial (left), axial (middle) and longitudinal (right) phase space.

Particles are tracked from 1 MeV. According to the acceptance of this cyclotron, initial horizontal acceptance is 4 π-mm-mrad and phase width is 60°. The result is shown in Fig. 2. τ is the RF time:

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$$V = V_0 \sin \tau \tag{1}$$

We define a momentum unit:

$$\text{Momentum unit} = m_0 c/a \tag{2}$$
$$a = c/\omega_0 \tag{3}$$

where m_0 is the rest mass, ω_0 is the orbital frequency, and a is the cyclotron radius. Thus, all momenta have length units. The beam size on the stripping foil 3.2 mm × 8.0 mm, the size of stripping foil should be greater than it. Because of the serious overlap of neighbour bunches in extraction region, the multiple turns extraction is obvious in the vertical phase space distribution. The rms energy spread is 0.064 MeV.

Distribution at the Entrance of the Beam Line

One of the purposes of the extraction design is to make the beam have a good distribution when entering the beam line, which is beneficial to the beam line design. At the same time, the distribution the entrance of the beam line is obtained as the initial condition of the beam line design. The cyclotron radius is 96.5 cm, and we set the radius of 97.0 cm as the entrance of the beam line. Particles are tracked from the stripping to the entrance of the beam line. The result with the natural coordinate system is shown in Fig. 3. The symbols *x'* and *y'* are the relative rates at which the particle is moving away from the horizontal and vertical axes. The red ellipses are fitted phase ellipses. Because particles are not accelerated after being stripped, the longitudinal distribution is similar to that on the stripping foil.

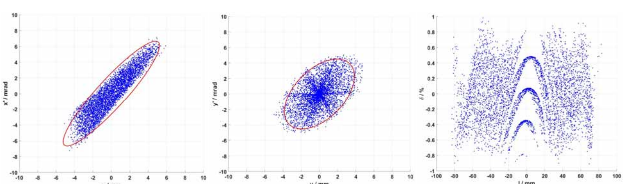

Figure 3: The particle distribution at the entrance of the beam line in horizontal (left), vertical (middle) and longitudinal (right) phase space.

BEAM FOCUSING AT EXTRACTION

As shown in Fig. 1, beam trajectories at the stripping foil with different azimuths are quite different. The radial tune ν_r and the vertical tune ν_z are calculated by Eq. (4) and (5).

$$\nu_r^2 = 1 - n \tag{4}$$
$$\nu_z^2 = n \tag{5}$$

where n is the field index:

$$n = -\frac{r}{B}\frac{dB}{dr} \tag{6}$$

If the stripping point is close to the centre of the magnetic pole, the field index will decrease. Therefore, the closer the stripped foil is to the inside of the magnetic pole, the stronger the radial focusing is, and the weaker the axial focusing is. The simulation results are shown in Fig. 4.

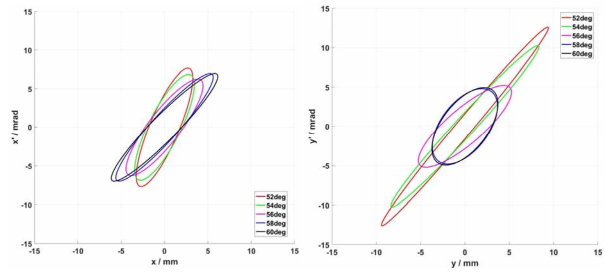

Figure 4: The horizontal (left) and vertical (right) distributions with different azimuths of the stripping foil at the entrance of the beam line.

According to the extraction study on the cyclotron CYCIAE-100, if there is an angle α between the stripping foil and the normal direction of the beam, *x'* and *y'* will increase [5]:

$$\begin{cases} \Delta x' = \frac{2\tan\alpha}{\rho}x - \frac{2n\tan\alpha}{\rho^2}x^2 - \frac{2\tan\alpha}{\rho}x\delta \\ \Delta y' = -\frac{2n\tan\alpha}{\rho^2}xy + \frac{2n\tan\alpha}{\rho^2}xy\delta \end{cases} \tag{7}$$

where ρ is the bending radius of the particle. Ignoring higher terms, Eq. (7) can be written as:

$$\begin{cases} \Delta x' = \frac{2\tan\alpha}{\rho}x \\ \Delta y' = 0 \end{cases} \tag{8}$$

Therefore, the tilt angle of stripping affects the horizontal focusing, which is similar to the inlet and outlet angles of dipoles. The simulation results in Fig. 5 are consistent with the theoretical analysis.

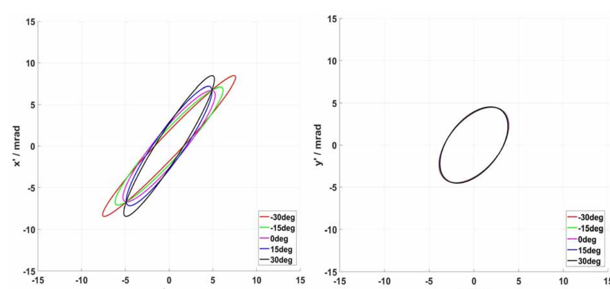

Figure 5: The horizontal (left) and vertical (right) distributions with different tilt angles of the stripping foil at the entrance of the beam line.

In conclusion, there are two methods to adjust the focusing at extraction. The azimuth of stripping foil affects both horizontal and vertical focusing, and the tilt angle only affects horizontal focusing. Therefore, we first choose an appropriate azimuth to obtain good vertical focusing. Then adjust the tilt for better horizontal focusing. The azimuth of 57° and the tilt angle of 15° are adopted, and the beam parameters are shown in Table 1.

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Table 1: The Extracted Beam Parameters at the Entrance of the Beam Line ($\sqrt{6}$×rms value)

Parameters	**Value**
ε_x/π-mm-mrad	13.49
x/mm	4.81
x'/mrad	7.04
α_x	-2.30
β_x/mm·mrad^{-1}	1.71
γ_x/mm^{-1}·mrad	3.68
ε_y/π-mm-mrad	15.00
y/mm	3.82
y'/mrad	4.52
α_x	-0.57
β_y/mm·mrad^{-1}	0.97
γ_y/mm^{-1}·mrad	1.36
l/mm	99.99
δ/%	0.87

THICKNESS OF THE STRIPPING FOIL

The stripping foil with a certain thickness is required for high stripping efficiency. However, a thick foil will increase the energy loss of the beam on the foil, leading to the decline of the lifetime of the carbon foil. Therefore, it is necessary to select the thinnest carbon foil while ensuring sufficient stripping efficiency.

$$\frac{dF_j}{d\pi} = \sum_i \left(F_i \sigma_{ij} - F_j \sigma_{ji}\right) \tag{9}$$

The fraction of ions F_j can be calculated by Eq. (9). Where i and j are charge states, σ_{ij} is the charge exchange cross-section of ions from charge state i to j, and π is the foil thickness. Compared with the electron loss process, the electron capture process is negligible. Therefore, the solution of Eq. (9) is written as:

$$\begin{cases} F_{-1} = e^{-(\sigma_{-10}+\sigma_{-11})\pi} \\ F_0 = \frac{\sigma_{-10}}{\sigma_{-10}+\sigma_{-11}-\sigma_{01}} \left[e^{-\sigma_{01}\pi} - e^{-(\sigma_{-10}+\sigma_{-11})\pi}\right] \\ F_1 = 1 - F_{-1} - F_0 \end{cases} \tag{10}$$

The reaction cross sections of different energies have the relation:

$$\sigma \propto 1/\beta^2$$

where β is the relativistic factor. We adopt the cross-sections measured at 800 MeV [6] and estimate those at 18 MeV. Calculated fractions are depicted in Fig. 6. The carbon foil with a thickness 1.36×10^{18} cm^{-2} (27 µg·cm^{-2}) has a stripping efficiency of 99.9%.

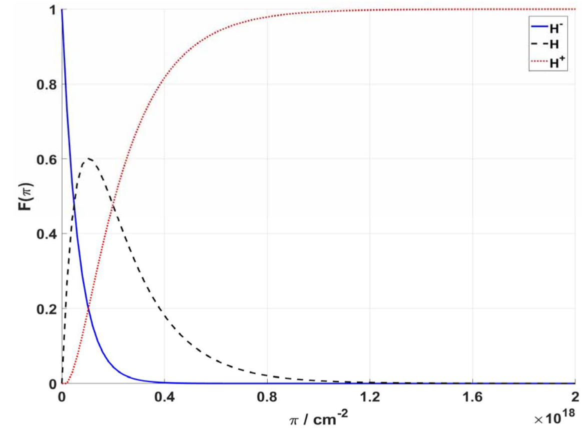

Figure 6: Fractions of hydrogen beam with different thickness of the carbon foil.

CONCLUSION

Orbit-tracking method is used to simulate the extraction of the 18 MeV BNCT cyclotron. The initial normalized emittance of 4 π-mm-mrad is used in the simulation. The azimuth and tilt angle of the stripping foil affect the beam focusing at extraction. The azimuth of 57° and the tilt angle of 15° are adopted. At the entrance of the beam line, the horizontal half size is 4.81 mm and the vertical half size is 3.82 mm.

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