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ENVELOPE CONTROL OF THE EXTRACTED BEAM FROM COMPACT CYCLOTRON

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Abstract

Along with the fast development of cyclotrons, more and more compact cyclotrons are used in the medical treatment and the scientific research. Because of the compact structure, the magnetic field in the extraction area is complex and there is no room for the focusing elements, the new methods to control beam envelope in extraction area are needed. In this paper, the influence of envelope caused by the angle between the foil and the beam has been studied, the experiment on a 10 MeV compact cyclotron that construct in CIAE (China Institute of Atomic Energy) has been done, the result is well agrees with the theoretic design. For the small medical cyclotrons, this method can be used to adjust the beam spot on the liquid target which installs just on the exit of the cyclotron.

INTRODUCTION

A majority of the medical cyclotrons for the radiopharmaceuticals production are compact cyclotrons, 10 MeV-30 MeV proton beams are extracted to produce radioactive nuclide for diagnosis such as F-18[1]. Usually, these kinds of cyclotron accelerate H- and extract proton beam by stripping foil because of the compact structure. Stripping is one of the most important methods in beam extraction of compact cyclotron because of the simple mechanical structure, the high extraction efficiency, the low cost, and the adjustable extraction energy.

For compact cyclotron, the dispersion caused by fringe field on the extract region will be obviously because of the small gap of the magnet, on the other hand, the energy dispersion of beams extracted by stripping foils usually large, which caused large increase in beam envelope and emittance, beam loss will be increased too. The extracted beam from these compact medical cyclotrons usually hit liquid target directly without long beam transfer line to produce short lifetime radioactive nuclide, there is no room for the focusing elements such as quadrupole, so we can't control beam envelope at this area and beam spot on target by focusing elements. The influence of envelope caused by the angle between the foil and the beam has been studied to control beam characteristic, both theoretical study and experiment study have been done. The results shows that one can control beam envelope effectively at extraction area only by adjusting the foil angle, it is of great significance for beam spot control on target, increasing the yield of radioactive nuclide and increasing of target lifetime.

For other cyclotrons with small extraction region that hard to install focusing elements, this method can be used to control the extracted beam envelope, which is very important for the later beam transport, especially for high current cyclotron.

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ANGLE EFFECT OF THE FOIL

Normally, the foil is perpendicular to beam direction and bring no influence for beam envelope. When there is an angle α between foil and the normal direction of beam, as shown in Fig. 1, it will bring a increment on x' after foil, could be expressed as formula 1.

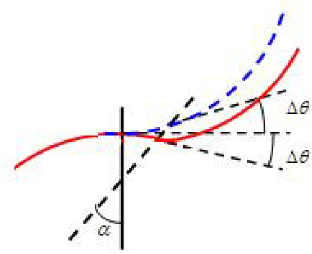

Figure 1: The angle between the foil and the beam.

$$\begin{aligned}\Delta x' &= 2\int \frac{B_z}{B\rho} ds \\ &= \frac{2}{(1+\delta)}\int \frac{B_0 + \frac{\partial B}{\partial x}x}{(B\rho)_0} ds \\ &= \frac{2}{(1+\delta)} \frac{1+\frac{\partial B}{\partial x}\frac{x}{B}}{\rho} x\tan\alpha \\ &= \frac{2}{\rho}(1-\frac{n}{\rho}x)(1-\delta)x\tan\alpha \\ &= \frac{2\tan\alpha}{\rho}x - \frac{2n\tan\alpha}{\rho^2}x^2 - \frac{2\tan\alpha}{\rho}x\delta\end{aligned} \quad (1)$$

In which α is the angle between foil and the normal direction of beam, ρ is the bending radius of the particles, δ is the momentum dispersion, n is the field-gradient index. Ignore higher order terms, the formula 1 can be wrote as:

$$\Delta x' = \frac{2\tan\alpha}{\rho}x \quad (2)$$

Which means when there is an angle between foil and the normal direction of beam, it is a focusing effect in x direction, such as the pole-face rotation angle of the bending magnet.

Similarly, for z direction, the increment on z' after foil can be shown in formula 3.

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$$
\begin{aligned}
\Delta z' &= 2\int \frac{Bx}{B\rho} ds \\
&= \frac{2}{(1+\delta)} \int \frac{\frac{\partial Bx}{\partial z} z}{(B\rho)_0} ds \\
&= \frac{2}{(1+\delta)} \int \frac{\frac{\partial By}{\partial x}}{(B\rho)_0} dsz \\
&= -\frac{2}{(1+\delta)} \frac{n}{\rho^2} xz \tan\alpha \\
&= \quad \frac{2\tan\alpha}{\rho^2} n(1 \quad \delta) xy \\
&= \quad +\frac{2n\tan\alpha}{\rho^2} xz \quad \frac{2n\tan\alpha}{\rho^2} xz\delta
\end{aligned} \tag{3}
$$

Ignore higher order terms, $\Delta z' = 0$, which means there is no angle change in z direction, so the angle between foil and the normal direction of beam brings no change of transfer matrix in z direction, the vertical envelope has no change.

In summary, ignore higher order terms, the angle between foil and the normal direction of beam can be used as focusing/defocusing lens in x direction with no effect in z direction. So the beam envelope can be controlled only by rotate a small angel of the stripping foil, especially for the cyclotrons whose target is at the exit, the beam spot on the target can be adjusted.

SIMULATION RESULTS OF CYCIAE-14

To produce short lifetime medical radioactive nuclide, promote development of medical cyclotron in China, a compact medical cyclotron CYCIAE-14 is designed and constructed in CIAE [2], this cyclotron using a dual stripping extraction system to get proton beam with highest current 400 μA, for each extract direction, the beam with energy 14 MeV and 14.4 MeV are extracted , as shown in Figure 2, in which the beam with energy 14 MeV will hit liquid target directly for F-18 production, beam with energy 14.4 MeV is for solid target to produce radioactive nuclide such as C-11.

As shown in chapter III, the beam envelope in x direction can be controlled by using the angle between foil and the normal direction of beam, which can be used as focusing/defocusing lens. Also the circular beam spot can be got by this angle, which is good for radioactive nuclide production.

The particles distribution on foil is simulated with the multi-particle tracking code COMA [3]. A particle tracking code developed with MATLAB has been done for beam tracking after stripping foil.

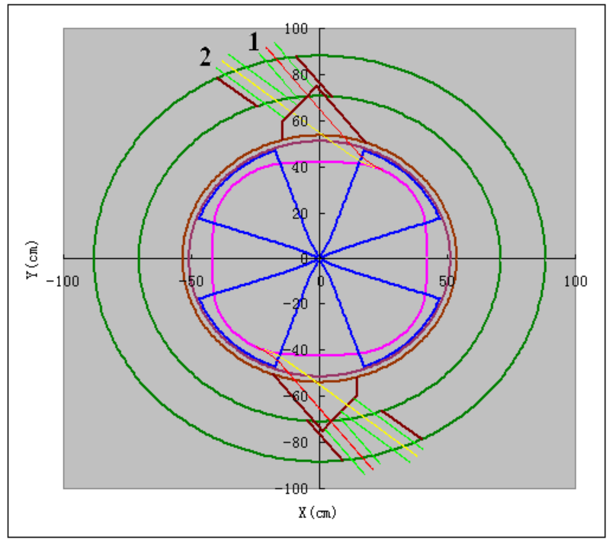

Figure 2: Dual extracted beam of CYCIAE-14.

Figure 3 shows the envelope after foil, in which the upper one is the results of beam 1 (as shown in figure 2), the nether one is beam 2. In the upper figure, the blue lines shows the vertical envelope and red lines shows the horizontal envelope, 2 cases are simulated: foil is perpendicular to beam direction and foil rotated by 20°, simulation shows that the vertical envelopes are same in these 2 cases, but for horizontal, the envelope can be reduced by almost 20%. As the liquid target is installed inside the return yoke of cyclotron, just at the exit, the beam spot can be adjusted as a circular with diameter 8 mm on the target, as shown in this figure. The other beam can be extracted outside cyclotron and transfer into a beam line for solid or gas target. If different beam spots are required, we can rotate the foil by different angles, the beam on target can be adjusted easily.

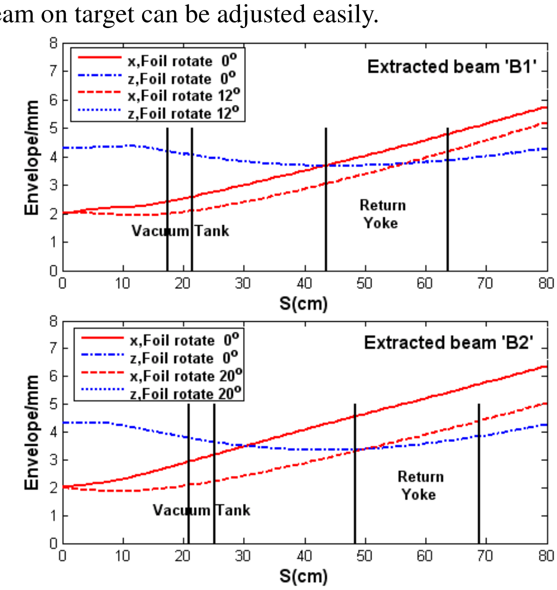

Figure 3: Extracted envelope with foil rotated.

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SIMULATION AND MEASUREMENT ON CYCIAE-CRM

The measurement has been done to prove this method on CYCIAE-CRM, a compact cyclotron build in CIAE. This cyclotron is the first compact medical cyclotron that design and construct all by ourselves in China, with highest beam energy 10 MeV [4].

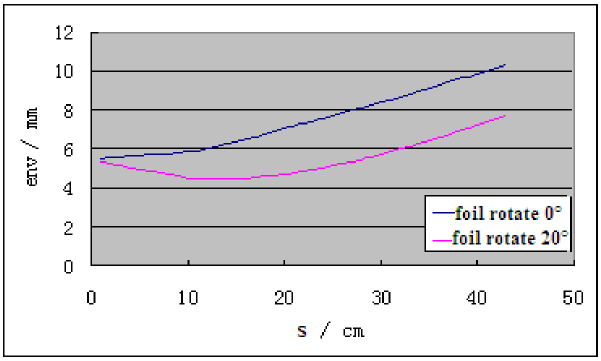

Figure 4: The influence of envelope caused by the foil angle in CYCIAE-CRM.

Figure 4 shows the simulation on influence of envelope caused by the foil angle in CYCIAE-CRM, in the figure, s is the beam trajectory, the blue line shows the envelope which the foil is perpendicular to beam direction, if the foil rotate by 20º, we can get the red line as beam envelope, at target place (where s is 40 cm), the envelope will reduce by almost 3mm because of the foil rotation.

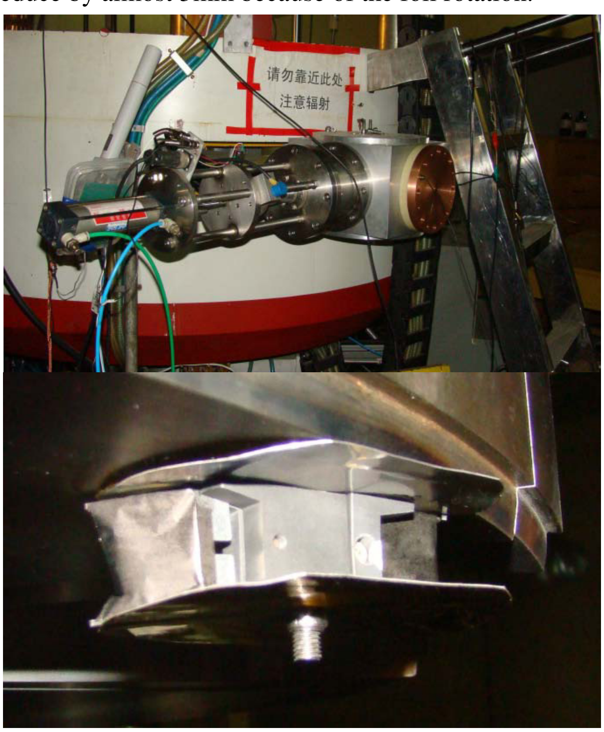

Figure 5: Experimental equipment of influence for foil.

The experiment has been done on CYCIAE-CRM to validate the simulation, the experimental equipment are shown in Figure 5,the cyclotron CYCIAE-CRM can install two stripping foils one time, in this experiment, one of the foil is perpendicular to beam direction, and the other one is rotate by 20º, a wire scanner is installed at the target place to measure the cross section of the beam extracted by two different foils. The result is shown in Figure 6, in which the dotted lines are measured results and the solid lines are the fitting results. The results shows that when the angle between foil and the normal direction of beam is 20º, the beam envelope will reduce by about 3~5mm, which is well agrees with the theoretic simulation.

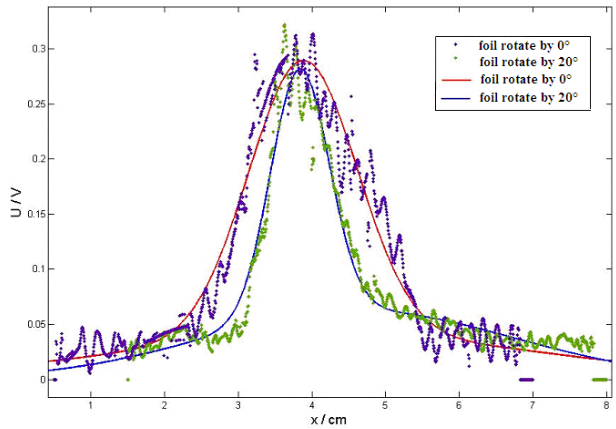

Figure 6: Measurement results of influence caused by different foil angles on CYCIAE-CRM.

SUMMARY

The influence of envelope caused by the angle between the foil and the beam has been studied both by theoretical study and experiment study, the experimental result agreeing well with the theoretic design. This result can not only be used to control beam envelope on the extraction region and beam spot on the target of small medical cyclotron to increasing the yield of radioactive nuclide and increasing of target lifetime, but it can also be used in the improve the envelope in extraction region of high current compact cyclotron without focusing element.

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