Simulation of beam optics for $^{12}C+^{12}C$ scattering of RCNP by using Monte Carlo method *

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Abstract: The Monte Carlo method is used to simulate the beam optics of the WS beam line of RCNP, Osaka University in order to know the effect of collimators on the beam line to control the beam spot. According to the simulation, we do not need to use the collimator to cut the beam and the beam angular resolution can be better than 0.05° in achromatic mode. In the present paper, the actual beam condition during the beam adjustment is listed. The accelerator can provide a ^{12}C beam in achromatic mode and the angular resolution σ=0.7775 mrad ±0.0030 mrad.

Key words: achromatic matching, simulation, orbit4, datadesk, collimators

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1 Introduction

Recent theoretical developments have suggested the experimental study of the repulsive nature of optical potential due to the three body force. Thus, it is important to measure the angular distribution of elastic scattering of reaction system, such as 100–400 MeV/u $^{12}C+^{12}C$. Through observing a change of diffraction pattern of angular distribution, the repulsive nature of optical potential can be studied [1–3]. A 100 MeV/u $^{12}C+^{12}C$ reaction has been proposed to measure the exactly angular distribution of elastic and inelastic scattering by using the magnetic spectrometer "Grand Raiden" at RCNP (Research Center for Nuclear Physics), Osaka University. In the experiment, in order to accurately obtain the angular distribution, it is required that the angular resolution is better than 0.1° and the beam spot is smaller than 3 mm. Since the momentum dispersion on target will result in a bad momentum resolution of the magnetic spectrometer, we expect that the smaller the momentum dispersion on target is, the better it is. A ^{12}C beam is not often used at RCNP and, consequently, there is no exact data. Therefore, we have tried to simulate the ^{12}C beam transportation on the WS (West South) beam line.

Usually, when the beam momentum (energy) of an accelerator increases, the beam momentum (energy) spread also increases. It is clear that at higher energies the large momentum spread Δp of the beam can severely limit the resolution of momentum spectra measured by magnetic spectrometers. In order to use the full potential of a high-resolution spectrometer (i.e. to measure a good-quality spectrum on the focal plane detectors), it is important to match the beam characteristics at the target position with those of the spectrometer to compensate for the deterioration of large Δp. There are several kinds of matching methods between accelerator and spectrometer, one is achromatic matching and the other is dispersion mode. Although the dispersion mode has a higher energy resolution, the achromatic mode can achieve a good angular resolution and no momentum dispersion on the target. Consequently, according to the requirements of our experiment, we chose the achromatic mode.

A 100 MeV/u $^{12}C+^{12}C$ experiment was performed on the WS beam line of RCNP. It consists of five sections with dipole and/or quadrupole magnets, as well as one special quadrupole magnet QM9S. The details are described in Ref. [4].

2 Calculation and simulation processes

The beam transport passes from one point to another

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point through the transport matrix one by one. The beam transport equation is shown by

$$\begin{pmatrix} x \\ a \\ y \\ b \\ l \\ \delta \end{pmatrix} = M_1 \times M_2 \times M_3 \times \cdots \times \begin{pmatrix} x_0 \\ a_0 \\ y_0 \\ b_0 \\ l_0 \\ \delta_0 \end{pmatrix},$$

where x, a, y, b, l and δ denote horizontal position, horizontal angle, vertical position, vertical angle, drift distance and beam momentum spread, respectively. M_1, M_2, $M_3 \cdots$ represent the matrix of every unit during the beam transportation, such as quadrupole magnets, dipole magnets, drift space and so on. x_0, a_0, y_0, b_0, l_0 and δ denote horizontal position, horizontal angle, vertical position, vertical angle, drift distance and beam momentum spread at the original position, respectively.

In our simulation, we have used the "orbit4" program, which was written to facilitate an automatic parameter optimization in an ion-optical system and repetition of optical calculation with varying parameters involved in the optical system. Special care has been paid to achieve high versatility of the program in dealing with the parameter optimization problems with various optimization purposes. The calculation is based on the transfer matrix theory and the third order matrix formulations [5]. We can get the matrix according to our requirement up to the third order.

In the first order approximation, the horizontal angle at (after) the target can be obtained from the horizontal angle at the focal plane where the detectors are setup, and the particle momentum can be obtained from the horizontal position at the detector. Here the horizontal width of the beam is assumed to be zero. Thus a finite beam width deteriorates the momentum resolution, as well as the horizontal angular resolution. The effect can be estimated by using the first order ion-optical parameters of the "Grand Raiden" spectrometer.

In the case of horizontal angular resolution, $(a|a)$=2.38 and $(a|x)$=1.32 mrad/mm. The numbers are taken from one of the ion optic simulations of the spectrometer. x and a denote the horizontal position and horizontal angle, respectively. The first (second) variable in the bracket denotes the variable at the focal plane (at the target). The horizontal angle at the focal plane is equal to 2.38 × the horizontal angle at the target, which is used to calculate the horizontal angle at the target. However, the horizontal angle at the focal plane=1.32 mrad/mm × the horizontal position at the target, which deteriorates the above calculation. For instance, a beam width of 1 mm corresponds to 1.32 mrad change of the horizontal angle at the detector. This limits the horizontal angular resolution at the target as 1.32/2.38=0.55 mrad. Finally. we get $(a|x)/(a|a)$=1.32/2.38=0.55 mrad/mm, which is the limit of the horizontal (scattering) angle resolution per unit beam width. In order to get 0.1° resolution, we should make the beam size less than 3 mm.

In order to get a small beam size and better angular resolution, we could insert collimators to control the beam size and background. The first set of collimators is used to cut the beam size, however, this results in a higher background. We add another set of collimators to cut the beam halo. The position of the first collimator is discussed later. We try to cut the beam size at the position where the beam size is maximum. From Fig. 1 we see that the maximum horizontal beam size is near QM6. When considering the actual condition, we choose the position of the first collimator to be 2.820 m downstream of BM5 and the second to be 0.530 m downstream of BM7. The position of these two collimators are, respectively, named as collimator 1 and collimator 2, as illustrated in Fig. 1. At the position of each collimator, the 100 MeV/u ^{12}C beam needs to be stopped and it should only go through the gap of each collimator, copper is a good choice here. According to the calculation of energy loss, the thickness of the copper is 5 mm.

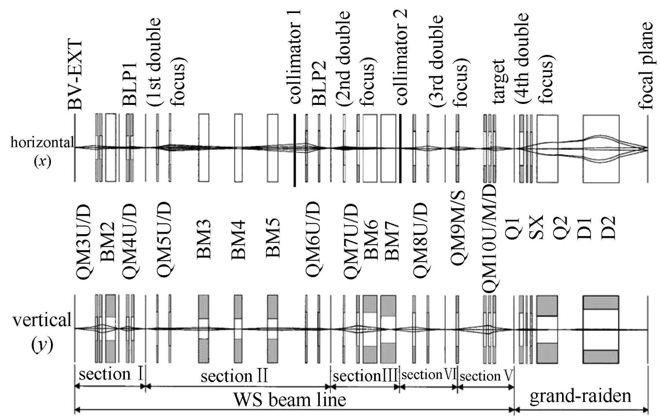

Fig. 1. WS beam line in achromatic mode. Envelopes of achromatic beam in the horizontal and vertical planes from the object point at the exit of the Ring Cyclotron (BV-EXT) via the target location to the focal plane of the "Grand Raiden" spectrometer. Trajectories are shown for particles with $\Delta p/p = \pm 0.3\%$, $\Delta\theta = \pm 2$ mrad and $\Delta\phi = \pm 2$ mrad. The transverse scale is increased for illustration purposes only [4].

By using the "orbit4" program we can get the matrices for six sections of WS beam line, that is from BV-EXIT to BLP1, from BLP1 (Beam line Polarimeter) [6] to Slit1, from Slit1 to BLP2, from BLP2 to Slit2, from Slit2 to Q9S, from Q9S to Target. The collimators do not change the transport matrices, it only gives a selection to the beam. Then, we input the matrix into "datadesk" software. For the initial beam condition, we choose both of the beam sizes at horizontal and vertical directions to be ± 1 mm ($\pm 3\sigma$), both of the beam angular at horizontal and vertical directions are ± 1 mrad($\pm 3\sigma$), and the momentum spread is $\pm 0.3\%$($\pm 3\sigma$) in a Gaussian distribution.

3 Results and discussions

Firstly, we use "orbit4"[1)] program to calculate the achromatic beam transport matrix. We use the original matrix to check the beam condition. In achromatic mode, Section 1 has a different setting from dispersive mode. There is a vertically focusing location at the exit of BM2. This vertical focus is realized by the doublet consisting of QM3U and QM3D quadrupole magnets. The following QM4U and QM4D magnets act as the vertically and horizontally focusing elements, respectively. The beam is doubly focused at BLP1. The magnification and dispersion of this section are (M_x, M_y)=(-1.47, 1.36) and D=1.48. Thus, $|D/M_x|$=1.01. In Section 2, one group composed by QM5U and QM6D acts as vertical focus, while the other group consists of QM5D and QM6U acts as horizontal focus. The magnification and dispersion of this section are (M_x, M_y)=(1.00, 1.00) and D=0. Thus, D/M_x=0. Sections 3 and 4 act as one ion-optical unit. The beam is doubly focused. One group composed by QM7U and QM8D acts as a horizontal focus, while the other group composed by QM7D and QM8U act as a vertical focus. The magnification and dispersion of this section are (M_x, M_y)=(0.47, 1.90) and D=0.70. The lateral dispersion produced by Section 1 is compensated in this section, the angular dispersion produced by Sections 1 and 2 is also canceled. The last section consists of QM9S and Section 4 in dispersive mode. In achromatic mode the QM10U quadrupole is not excited. The remaining three quadrupole magnets are grouped in pairs. QM9S and QM10D act as horizontal focus, while QM10M magnet focuses vertically. These quadrupoles are used to focus the beam on both horizontal and vertical directions at the target location. After all of above conditions are satisfied, the final matrix of the whole transportation can be obtained, which is shown in Table 1. Through the transportation matrix and the initial beam condition, the beam condition on target can be obtained.

The Monte Carlo method was used to simulate the beam condition on target. As shown in Fig. 1, the beam line consists of five sections. When the two collimators were inserted, the transportation was divided into six parts that is from BV-EXIT to BLP1, from BLP1 to Collimator1, from Collimator1 to BLP2, from BLP2 to Collimator2, from Collimator2 to Q9S, from Q9S to Target. The matrix for every part was obtained using "orbit4" program and input into "Datadesk". In "Datadesk", five random numbers were generated and present the horizontal beam position, angular, vertical beam position, angular and momentum spread of the initial beam condition. On the basis of the six matrices, the beam condition on BLP1, Collimator1, BLP2, Collimator2, Q9S and Target can be acquired. When the horizontal beam size at Collimator1 and 2 was changed,the beam on target will also change. Then, the analysis of the beam condition of the target can help us to determine the collimator size.

The total matrix can be obtained through the six matrix, which is shown in Table 1. Both of the magnifications on horizontal and vertical directions are about 1, their momentum dispersions are 0. The beam is focused on x and y directions through $(x|a)$ and $(y|b)$ terms. The beam condition on target can be acquired through the matrix. When changing the gap of the collimator, in Fig. 2 we show the beam size on the horizontal and vertical directions, and in Fig. 3 we show the beam distribution on the horizontal direction and the horizontal angle. When the gap is ± 10 mm, it is nearly fully open. This is the original beam condition. In all of the figures, the color from blue to red present the particles whose angular is from -1 mrad to 1 mrad.

Table 1. The whole transportation matrix of WS beam line from BV-EXT to target in achromatic mode. x, a, y, b, δ denote the position and angle of horizontal direction, the position and angle of vertical direction, momentum spread of beam, respectively.

	x	a	δ
x	-0.93498	-0.00002	0.00000
a	-0.18806	-1.06949	-0.68051

	y	b	
y	-1.02813	0.00000	
b	-0.49416	-0.97259	

Secondly, we insert the first collimator and check what will happen. From Fig. 2 and Fig. 3 we can observe that, when changing the gap of collimator from ± 10 mm to ± 0.5 mm, the beam angle does not change much. However, the beam size becomes larger, but is still not obvious. ± 10 mm is nearly full open and the beam can go through the gap of collimator without missing. In Table 2, we show the ratios to ± 10 mm for counts, beam size and beam width with the different gap sizes of the collimator. The beam width is listed by 1σ.

From Table 2 we can see that, with the change of gap size of the collimator, the ratios to ± 10 mm for counts largely change. However, the ratios to ± 10 mm for beam size and beam angular width do not change much.

1) Morinobu S. User manual of program "orbit4", Private communication.

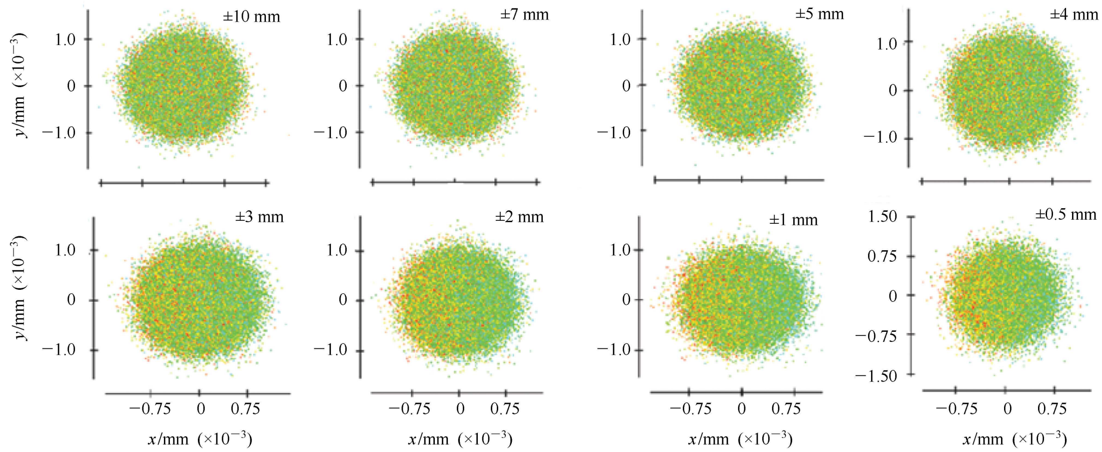

Fig. 2. (color online)The beam size (width=3σ) on horizontal and vertical directions with different gap of collimators. Horizontal and vertical axes represent the beam sizes on horizontal and vertical directions, respectively.

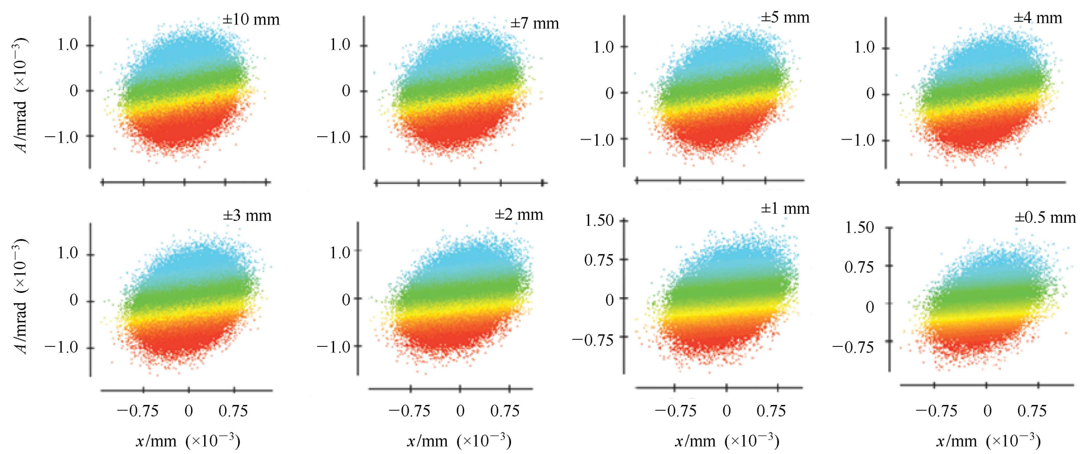

Fig. 3. (color online)The beam distribution on horizontal direction and horizontal angle with changing the gap of collimator. Horizontal and vertical axes represent the beam size(width=3σ) and the beam angle(width=3σ) on horizontal direction, respectively.

Hence, we need not use the first collimator to cut the beam. At this condition, the beam angular width is 0.365 mrad, which corresponds to 0.021°. This value is better than 0.1°. This is enough for the angular resolution of our experiment. Now, the magnification of the beam transport is about 1. According to the reservation law of emittance, if the angular resolution is not enough, then we can adjust the magnification to 2 and the angle will be smaller. The result is shown in Figs. 4(a) and (b). When the magnification is equal to 2, the beam size is about 2 mm and the beam angular width σ is 0.153 mrad. The second collimator only cancels the background produced by the beam on the first collimator, which we will not discuss at this point.

Finally, we used the original achromatic mode of beam transport, which is mainly used at RCNP. During our experiment, we used a faint beam and empty target to check the beam spot on focal plane detectors. Through the matrix of spectrometer we can get the beam angle on target. The results are shown in Fig. 5. Fig. 5(a) shows the experimental data of beam distribution on the horizontal angle θ and the vertical angle ϕ, and the fitted

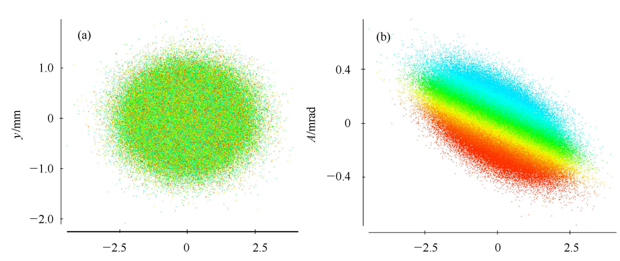

Fig. 4. (color online)Beam distribution when the magnification is equal to 2. (a) The beam size on horizontal and vertical direction. (b)The beam distribution on horizontal direction and horizontal beam angle.

Table 2. Ratios to ±10 mm. The first column denotes the gap size of the collimator. The second column gives how many counts are left. The fourth and sixth columns represent beam width and angular width, respectively. The third, the fifth and the seventh columns show the ratios to ±10 mm for counts, beam size and beam width.

gap sizes of collimator	counts	ratios to ±10 mm	widths (1σ)/mm of beam size	ratios to ±10 mm	beam angular widths (1σ)/mrad	ratios to ±10 mm
±10 mm	499994	1.0000	0.316	1.0000	0.365	1.0000
±7 mm	498478	0.9970	0.315	0.9968	0.364	0.9973
±5 mm	482658	0.9653	0.311	0.9842	0.361	0.9890
±4 mm	454166	0.9083	0.307	0.9715	0.357	0.9781
±3 mm	396996	0.7940	0.302	0.9557	0.353	0.9671

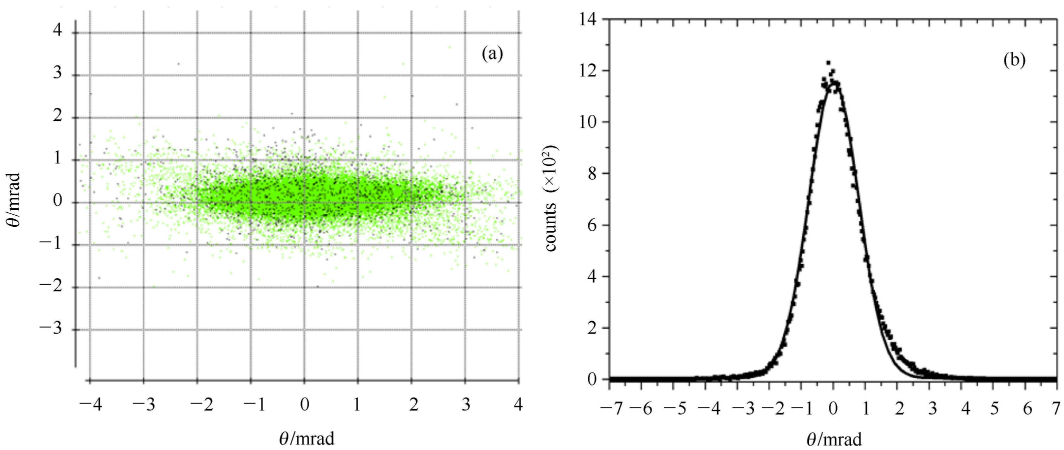

Fig. 5. (a) Beam distribution on horizontal angle θ and vertical angle ϕ. (b) The experimental data and the fitted results (solid line) on horizontal angle θ.

results on horizontal angles θ are shown in Fig. 5(b). The actual beam angular width σ of RCNP is 0.7775 mrad ±0.0030 mrad. This can satisfy the requirement of our experiment.

4 Summary

In order to accurately obtain the angular distribution of elastic scattering for the 100 MeV/u ^{12}C+^{12}C experiment on the WS beam line of RCNP, Osaka University, the ^{12}C beam must be simulated before experiment to give the reference. According to the beam transport optics, we use the "orbit4" program to obtain the matrices of five sections of the WS beam line,. We then input the matrices into datadesk software to simulate the size and distribution of ^{12}C beam with the change of the gap size of the first collimator. It is found that we need not insert the collimator to cut the beam during the experiment. The fully open status of the collimator can satisfy our requirement. We also simulate the beam angular resolution with an increase of magnification. When increasing the magnification, a better angular distribution can be obtained. Through analyzing the experimental data of the beam test, we obtain the actually angular resolution σ=0.7775 mrad ±0.0030 mrad of ^{12}C beam of RCNP. This value can fit the beam angular resolution of our experiment.

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