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Stripping extraction calculation and simulation for CYCIAE-100*

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Abstract A 100 MeV H- compact cyclotron is under construction at China Institute of Atomic Energy (CYCIAE-100). The proton beams of 75 MeV-100 MeV at an intensity of 200 μA will be extracted in dual opposite directions by charge exchange stripping devices. The crossing point at the switching magnet center is fixed inside the magnet yoke and the stripping points for various extraction energies are calculated by the code CYCTRS. With the code GOBLIN, we can calculate the transfer matrix including the dispersion effects from the stripping point to the switch magnet. The beam distribution just after stripping foil can be obtained from the multi-particle tracking code COMA and the extracted beam parameters after the switch magnet such as emittance, envelope, dispersion, energy spread, bunch length, etc. are given by the extraction orbit simulations.

Key words H^- stripping extraction, crossing point, transfer matrix, dispersion

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1 Introduction

A 100 MeV H- compact cyclotron is under construction at China Institute of Atomic Energy (CYCIAE-100)[1]. The proton beams of 75 MeV-100 MeV at an intensity of 200 μA will be extracted in dual opposite directions by charge exchange stripping devices. Two stripping probes with carbon foil are inserted radially in the opposite directions from the hill gap region and the two proton beams after stripping are transported into the crossing point in a switch magnet center separately under the fixed main magnetic field. The switch magnet is fixed between the adjacent yokes of main magnet in the direction of valley region. The optical trajectories of the extracted beam are studied in detail until the switch magnet.

The stripping points with various energies have been calculated with the code CYCTR[2] and checked by the codes GOBLIN[3] and Strip-ubc seperately. The transfer matrix from the stripping point to the switch magnet is obtained numericaly by using the code GOBLIN. The phase space distributions at the stripping foil are obtained from the multi-particle trackings by the code COMA[4]. The extracted beam parameters are given by the extracted optics calculation.

2 Method to calculate extraction trajectories and transfer matrix

In a magnet with median plane symmetry, the linearized equations of motion are given[5]:

$$\frac{\mathrm{d}^2x}{\mathrm{d}s^2}=-\frac{1-n}{\rho^2}x+\frac{1}{\rho}\frac{\Delta p}{p}, \qquad (1)$$

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$$\frac{\mathrm{d}^2 z}{\mathrm{d}s^2} = -\frac{n}{\rho^2} z, \tag{2}$$

$$\frac{\mathrm{d}(\Delta l)}{\mathrm{d}s} = \frac{1}{\gamma^2}\frac{\Delta p}{p} - \frac{x}{\rho}, \tag{3}$$

where $\Delta l = \beta c \Delta t$ and n is the field index:

$$n = -\frac{\rho}{B_z}\frac{\partial B_z}{\partial x}. \tag{4}$$

The extraction trajectory can be calculated by integrating Eq. (1)-(3). Assume the beam transport is linear here, for the paraxial particles we have:

$$(x, x', z, z', \Delta l, \delta)^{\mathrm{T}} = R(x_0, x'_0, z_0, z'_0, \Delta l_0, \delta_0)^{\mathrm{T}} \tag{5}$$

where $\delta = \Delta p/p$ and R is the 6×6 transfer matrix. By using five particles with different initial conditions: particle 1 with (x, x', z, z', δ) of (1,0,0,0,0), particle 2 with (0,1,0,0,0), ..., particle 5 with (0,0,0,0,1) and the symplectic condition, we can obtain numerically the full 6×6 transfer matrix R. With the transfer matrix R, the beam parameters at the switch magnet can be calculated.

3 The positions of stripping foil

The positions of the stripping points for different energies are calculated with the code CYCTR. The main magnetic field used to calculate the extraction trajectories is assumed to have mid-plane symmetry for the CYCIAE-100 that is a compact isochronous cyclotron with 4 separate sectors. The extracted beam energy is chosen by the corresponding static equilibrium orbit, which is calculated with the code CYClOP[6].

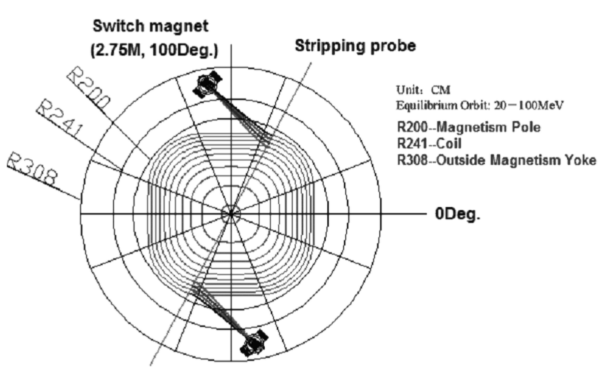

Fig. 1. Stripping probe and position of switch magnet.

For CYCIAE-100, the outer radius of magnet yoke is 3.08 m and the switch magnet is located inside the yoke (R=2.75 m, θ=100°). Fig. 1 shows the position of switch magnet and the extracted beam trajectories from the stripping foil to the switch magnet center for different energies. The red lines are the equilibrium orbits, corresponding to the energies from 20 MeV to 100 MeV and the circles R200 and R241 are the outer radii of the pole and the coil. Table 1 shows the positions of stripping foil with the extraction energy between 70 MeV and 100 MeV. The results from the code CYCTRS, GOBLIN, STRIP-UBC agree very well with each other.

Table 1. Position of stripping foil with different extraction energy with code CYCTRS.

energy/MeV	CYCTRS	
	R/m	θ/(°)
100	1.8755	59.626
90	1.7962	58.959
80	1.7086	58.388
70	1.6120	57.806

4 Calculation results of extraction trajectories

4.1 Transfer matrix of the extraction path

For the calculations of the stripping extraction trajectories, the magnetic fields of both the main magnet and switch magnet are included. The extracted beam trajectories can be calculated with the transfer matrix including the dispersion effects, which is got from the code GOBLIN. For the extracted beam with the energy of 100 MeV, the full 6×6 transfer matrix for the stripping extraction is:

$$M_s = \begin{pmatrix} 0.992 & 0.206 & 0 & 0 & 0 & 0.656 \\ -0.431 & 0.918 & 0 & 0 & 0 & 4.080 \\ 0 & 0 & 0.503 & 0.192 & 0 & 0 \\ 0 & 0 & -2.619 & 0.988 & 0 & 0 \\ -0.433 & -0.024 & 0 & 0 & 1 & 1.607 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

4.2 Reference trajectories for different extraction energies

The field of switch magnet is different for different extracted energies and the bending angle is ±5°. The field is zero for the extracted energy of 85 MeV. Fig. 2 shows the extraction trajectory including the fields of switch magnet for different extracted energies. With the different fields, the extracted beam with different energies after stripping foil will go through the crossing point of the switch magnet center and extracted along the same direction after the crossing point.

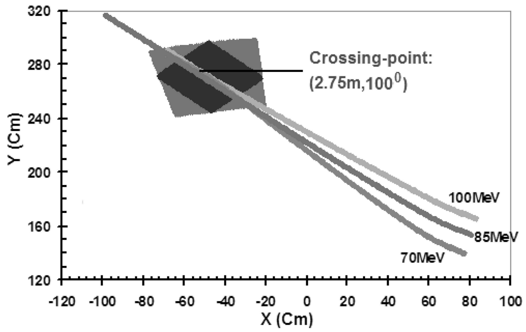

Fig. 2. The extracted trajectories with the switch magnet fields for different energies.

4.3 Dispersion effects

The dispersion due to the main magnet field together with the switch magnet field along the extraction path can be obtained from GOBLIN. The dispersion will lead to the emittance growth in x direction. Fig. 3 shows the dispersions for the energy of 70 MeV and 100 MeV along the extraction path. The symbol of star in the plots is the position of the switch magnet and the symbol of triangular is the position of (3.3 m, 106°) after the switch magnet.

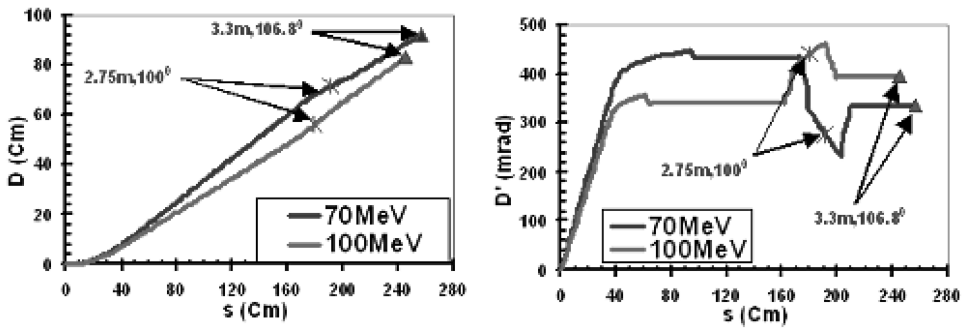

Fig. 3. The dispersions for the switch magnet located at (2.75 m, 100°).

From the results, the dispersion will be large for the lower energy and longer distance before the crossing point. The field of switch magnet can counteract the dispersion partly at 70 MeV, but increase the dispersion at 100 MeV. So the switch magnet is helpful in the case of low energy, but harmful to high energy.

5 Multi-particle simulations for the extracted beams

5.1 Beam distribution on the stripping foil

The phase space distribution of the extracted beam just after stripping foil can be obtained by using the multi-particle tracking code COMA. For 100 MeV beam, the stripping efficiency is about 99.96% when the carbon foil thickness is 150 μg/cm^2[7]. The beam emittance increases due to the stripping foil scattering is ignored here.

The H- beam is injected from the symmetry center of a valley with azimuth $\theta = 0°$, and will be tracked through to the stripping foil position for different extracted energies. The initial beam energy is E_0=1.49 MeV at the radius of R=23.1 cm. From the measurements results of IBA-30 and CIAE-30[8], the choice of the initial normalized emittance of $\varepsilon_x = \varepsilon_z$=4 π-mm-mrad for CYCIAE-100 used in the COMA is reasonable. The input phase space distributions are uniform in both transverse and longitudinal directions with the phase extension of $\Delta\phi = \pm 20°$, but with zero energy spread. 10920 macro particles are used. Fig. 4 shows the input beam distribution in phase spaces and Fig. 5 shows the extracted beam distributions on the stripping foil with the energies of 70 MeV and 100 MeV.

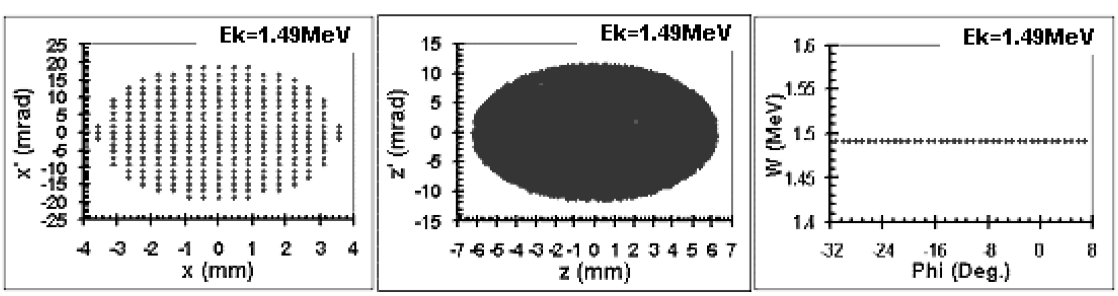

Fig. 4. Initial phase space distribution with the normalized emittance of 4.0 π-mm-mrad.

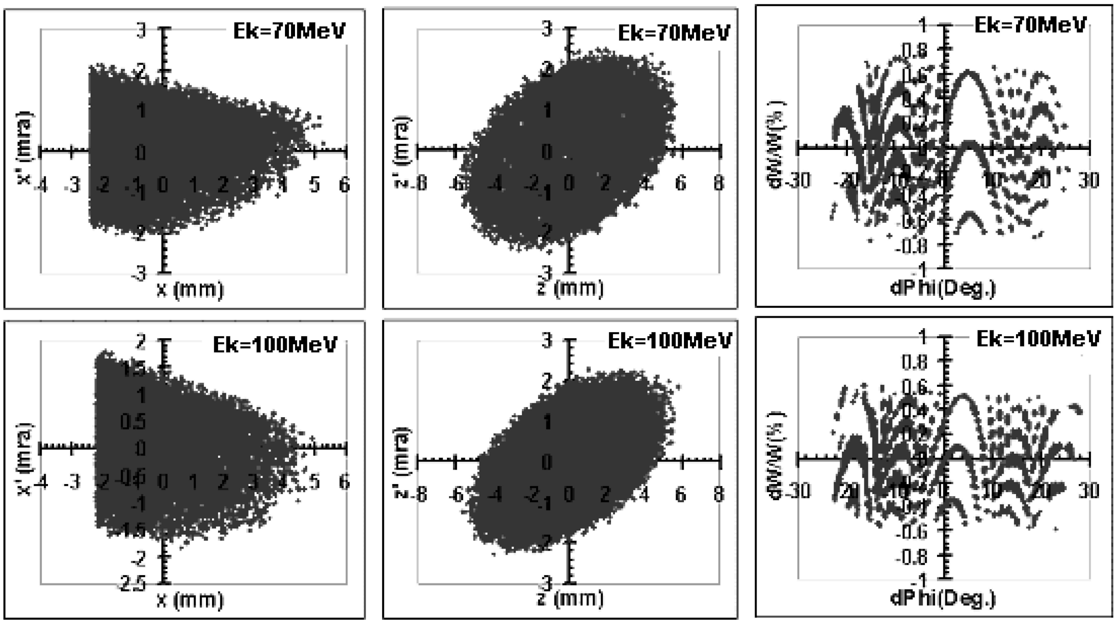

Fig. 5. The extracted phase space distribution for 70 MeV & 100 MeV on the stripping foil.

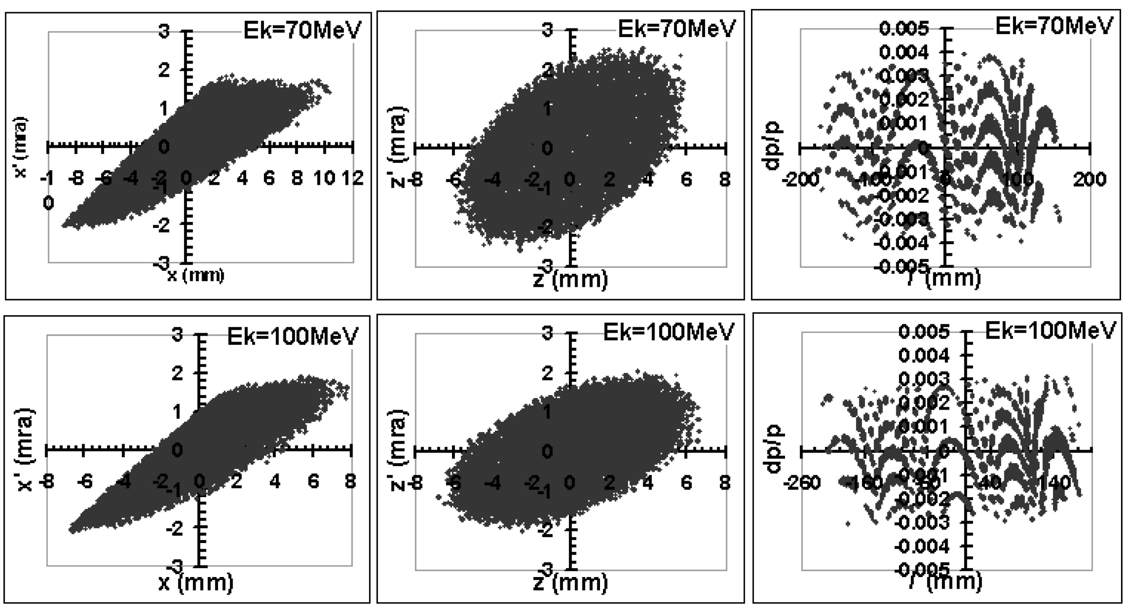

Fig. 6. The phase space distributions at the position of (3.3 m, 106°) for 70 MeV & 100 MeV.

5.2 Extracted trajectories simulation results

From the simulation results by COMA and the transfer matrix by GOBLIN, the extracted phase space distributions at the position of (3.3 m, 106°) after the crossing point are shown in Fig. 6. The emittance increases by about 50% in the z direction due to the fringe field, and by a factor of 2 in the x direction due to the co-influence of fringe field and the dispersion, the energy spread is about ±0.5% for both 70 MeV and 100 MeV energies.

6 Summary

For CYCIAE-100, the stripping points with various energies have been calculated and the results from the code CYCTRS, GOBLIN, STRIP-UBC agree very well with each other. With the transfer matrix obtained numerically by the code GOBLIN and the phase space distribution on the foil obtained from the code COMA, the extraction trajectories for different extracted energies are simulated in detail. From the simulation results, the initial normalized emittance of $\varepsilon_x = \varepsilon_z$=4 $\pi \cdot$ mm $\cdot$ mrad used in the calculation is reasonable and the calculation results are close to the realistic case compared with the measurement results of IBA and CIAE-30. The dispersion effects to the beam are evident in the horizontal direction and contribute to a majortity of emittance growth. The dispersion effects must be considered for the post transfer line matching. The changes of emittance and beam envelope in the vertical direction are very slow.

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