Technical Paper

Optimization Study for the CRC PIXE System Beam Transport Line

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Abstract - Proton Induced X-ray Emission (PIXE) is a MeV ion beam analysis method for use with particle accelerators. PIXE uses low-energy charged particles as an excitation mechanism to generate characteristic x-ray emission from each element in a target. In PIXE analysis, the beam current used is from a few nA to several tens of nA. Chosun University (Cyclotron Research Center) designed a 50 μA beam line from the 13 MeV cyclotron for use with a PIXE analysis system, as well as performing beam transport line optimization research. In this study, the beam line operation conditions for the optimization process of beam transport and beam characteristics are shown.

Key words : PIXE analysis, Cyclotron, Beam transport line, Degrader, Beam optic

INTRODUCTION

Proton Induced X-ray Emission (PIXE) is a MeV ion beam analysis method for use with particle accelerators. It can also be classified as an X-ray emission analysis method. Charged particles with an energy of 1～4 MeV are used in PIXE experiments, and the emitted X-rays are detected by energy dispersion Si(Li) detectors (KR-90-3C-4 1990). In a PIXE analysis, a beam current of just a few nA to several tens of nA is used.

PIXE can analyze about 20 elements simultaneously. In addition, the analysis can completed within 10～20 min, including the beam irradiation time. Therefore, it is widely used for solid sample tests as a non-destructive method for analysis. However, some disadvantages remain for PIXE analysis. for example, the accelerator cost is high and users must design and manufacture the system independently.

In this study, a cyclotron, which was developed by KIRAMS with 13 MeV protons for F-18 and C-11 production, was used. Cyclotrons are rarely used for PIXE analysis, because they generate wide energy spreads. In spite of this, a beam transport line was designed and manufactured for simultaneous operation fo both RI production and PIXE analysis. The beam line operation conditions and installation method were recommended by the optimization results on the designed beam transport line.

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MATERIALS AND METHODS

A 13 MeV cyclotron, which was installed inside the Cyclotron Research Center (CRC), was used as an accelerator. The specifications for this cyclotron are shown in Table 1 (Kim 2011). The beam transport line has three optical design parameters. First, the beam line size must fit within the given space of the cyclotron vault. Second, the nozzel design must minimize initial beam loss. Third, the beam momentum dispersion of should be zero to focus the beam at the center of the nozzle. Additionally, the beam optics design and optimization were considered to reduce the cost on the construc-

tion of the system to be within the given CRC budget.

The initial beam conditions for the optimal optics design were defined as follows the beam emittance for the PIXE analysis was defined by the beam transport setup. This is arranged such that the generated 13 MeV proton beam passes through the defined collimators and analyzing magnet. The thickness of the collimator was set to 5 mm for easy handling and to stop the 13 MeV proton beam. The beam diameter used was 20 mm, which is the same diameter used with a target for RI production. The distance between the defined collimators was 1,330 mm, which is the measured distance between the cyclotron and analyzing magnet. The beam emittance was calculated from the given conditions, and the results are shown in Table 2, for an initial beam. The beam optics design was processed based on the calculated initial beam parameters. The beam shape after the defined collimator, obtained with WinAGILE software, is shown in Fig. 1.

Table 1. General specifications of the 13 MeV cyclotron [3]

Beams of ion	Proton
Injected particle	H^-
Output energy/current	13 MeV/ 50 μA
Magnet type	H-type
# of sectors	4
Pole diameter	0.96 M
Hill/valley gap	4 cm/12 cm
Magnet nr/nz	1.025/0.3 ~ 0.36
Bmax (hill)/Bmax (valley)	1.99 T/ 0.99 T
RF frequency	77.3 MHz
RF harmonic number	4
Dee angular width	39 deg.
Dee voltage	45 kV
Radial and vertical effective emittances	29/6π mm mrad
Extraction radius	0.406 M

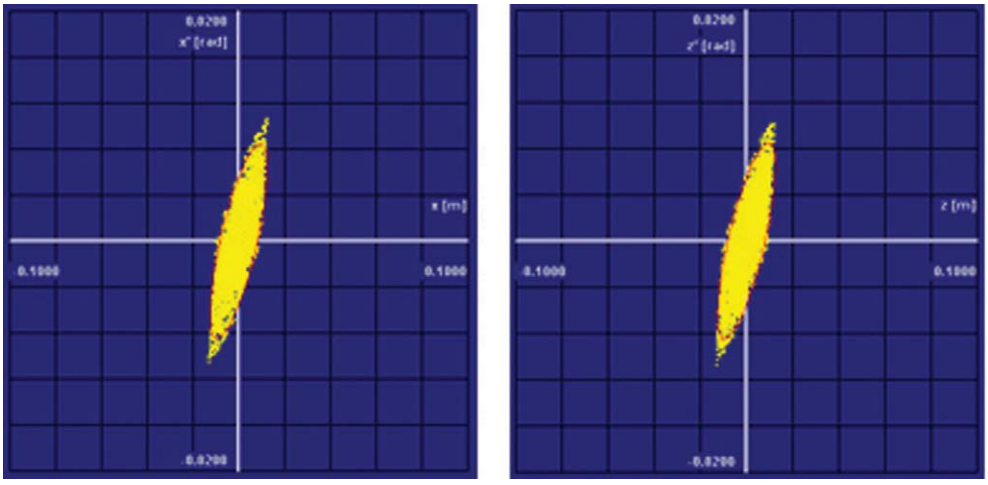
Table 2. Results of beam emittance simulation with WinAGILE software

Initial parameters	Description
Beam spreading	< 500 keV
Horizontal divergence (x′)	3.7 mrad
Horizontal position (x)	4.82 mm
Horizontal transverse emittance (ε_x)	15.56π mm mrad
Vertical divergence (y′)	3.69 mrad
Vertical position (y)	4.84 mm
Vertical transverse emittance (ε_y)	15.44π mm mrad

RESULTS AND DISCUSSION

1. Beam optics

As mentioned earlier, the beam transport line was intended for two uses, i.e., RI production and PIXE analysis. To minimize the worker radiation exposure and background, a 90° bending magnet was included. Therefore, the targets for RI production and beam transport line for the PIXE analysis system cross each other at a right angle. The generated protons at 13 MeV are dispersed after passing through the analyzing magnet. A quadrupole doublet focuses the dispersed beam. Also, to reduce the size of the beam and to ensure zero dispersion at the final nozzle, a quadrupole triplet is installed. In the design of the quadruple magnet, the maximum magnetic field was set to 0.1 T to minimize the magnetic distortion due to magnetic field saturation at the yoke



Horizontal phase space Vertical phase space

Fig. 1. Calculated beam shape after the defined collimator.

the magnets were manufactured as described and a beam optics simulation was performed by WinAGILE. The magnet specifications, which were used in the simulation, are listed in Table 3. The magnetic strength of the quadrupole magnet, which was used for the optics design, is listed Table 4. The simulation results are shown in Fig. 2. The beam focusing at the final nozzle, along the horizontal direction, is also shown in Fig. 2. The beam dispersion was also restrained along the vertical direction.

Table 3. Specifications of beam line magnets

Elements	Description
Analyzing magnet	Radius of rotation: 750 mm Magnetic force: 0.7 T Height of gap: 65 mm
Quadrupole magnet	Max. magnetic force at pole tip: 0.1 T Length of magnet: 300 mm Distance of pole: 65 mm

Table 4. Magnetic strength of quadrupole magnet

Elements		Description
Quadrupole doublet	Q1	5.98/m^2
	Q2	−4.79/m^2
Quadrupole triplet	Q3	−0.19/m^2
	Q4	6.00/m^2
	Q5	−4.08/m^2

2. Beam tracking simulation

To determine the position of the degrader, a beam tracking simulation was performed. The beam separation of spatial distribution in the horizontal direction can be confirmed by the simulation results. The beam tracking simulation results are shown in Fig. 3. The beam tracking results before the 90° analyzing magnet showed that the beam was distributed without a momentum spread. The beam, which passes through the analyzing magnet, diverged depending on the momentum spread along the horizontal direction. The spatial distribution of the beam incident upon the analyzing magnet is shown in Fig. 3(a). The red, green, and yellow dots represent the particles, which have momentum spreads of −0.1%, 0%, and 0.1% respectively. The boundary of beam internal diameter is plotted with blue line. The projection profile of beam distribution along the x- and y-axes is shown as a Gaussian distribution. The spatial distribution after passing through the analyzing magnet is shown in Fig. 3(b). The beam spread in the vertical direction depends upon the beam divergence, not the momentum spread. Therefore, the beam, which has more than ±1% of beam spread, will be dispersed by collisions with the beam line chamber wall. The thickness of the degrader was determined based on these results. In general, the proton energy for PIXE analysis is a few MeV (KR-89-7B-5 1989; KR-90-3C-4 1990). The degrader was

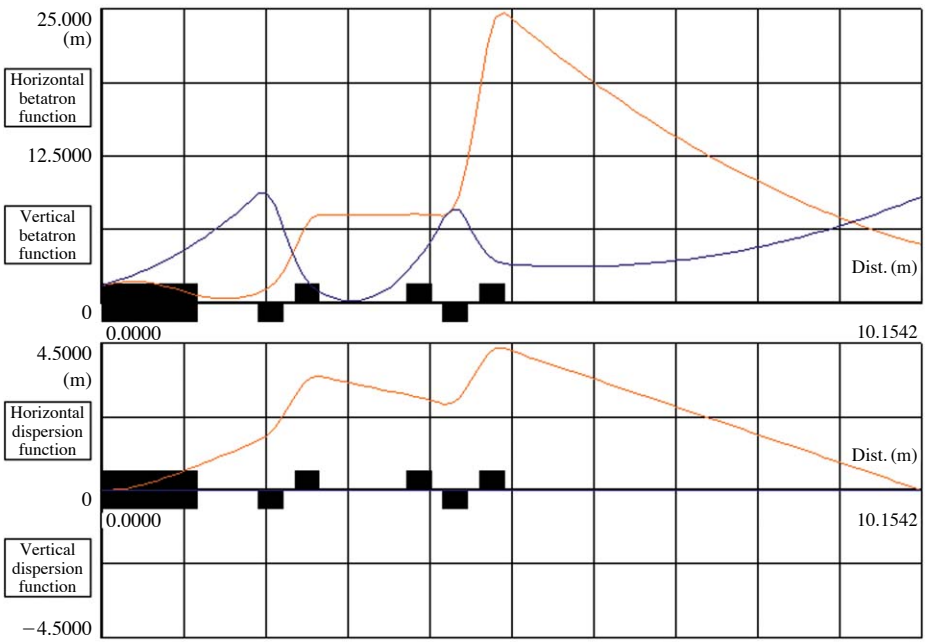


Fig. 2. Results of beam optics simulation.

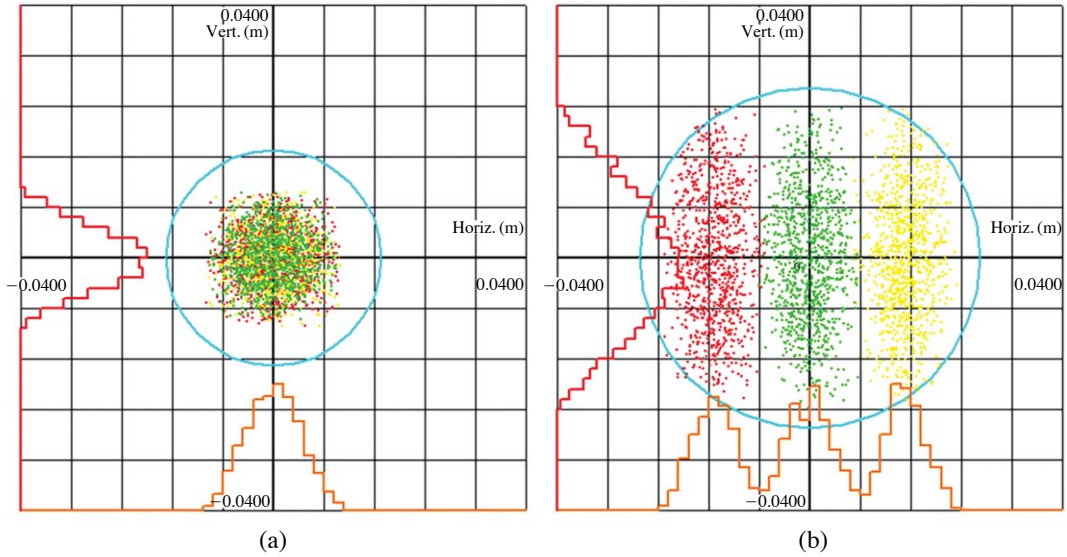


Fig. 3. Results of beam tracking.

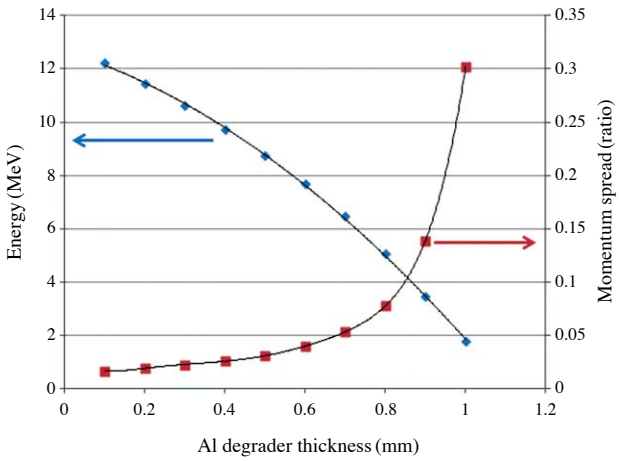


Fig. 4. The simulation results for the energy and momentum spread as a function of the degrader thickness.

designed for extracting protons of a few MeV. Aluminum foil was used as the degrader material. Its thickness was calculated using Geant4 Monte Calro Simulation toolkit. The momentum dispersion and energy of the beam, which depend on the degrader thickness, are shown in Fig. 4. As shown, the beam energy decreases linearly as the degrader thickness increases. In contrast, the momentum spread increases exponentially.

For the general PIXE analysis, a 0.92 mm thick aluminum foil is used to obtain a 3 MeV proton beam. In that case, the momentum spread is considered to be about 17%. We can inferred from this that the beam loss rate will increase as the momentum spread increases for the energy range below 6 MeV. Therefore, the momentum spread rate must be held under 1%. For case of adopting a degrader, the beam survival rate was very low at the PIXE analyzing nozzle, because most of the beam was dispersed by the analyzing magnet. Thus, the beam was forced to pass the analyzing magnet without an initial energy loss and transported to the PIXE analyzing nozzle. The beam energy was decreased just before the PIXE nozzle.

3. Beam transport line layout

In this work, the layout of the beam transport line was also considered. The distance between the analyzing magnet and first quadrupole should be minimized to reduce the beam loss rate. The reason for reducing this distance is to focus the dispersed beam near the analyzing magnet. The distance between doublet and triplet quadrupole should also be maximized because the beam should be transported without dispersion until it reaches the triplet quadrupole after passing through the doublet quadrupole. Then, the focal point of the beam is passed to the PIXE nozzle by the strong focusing of the triplet quadrupole. This arrangement minimizes the beam loss due to collisions with beam line chamber. As such, the calculated beam survival rate is increased to over 1% at the PIXE analyzing nozzle. Based on the above simulation results, the layout of PIXE beam was proposed as shown in Fig. 5. The proposed layout is optimized to utilize

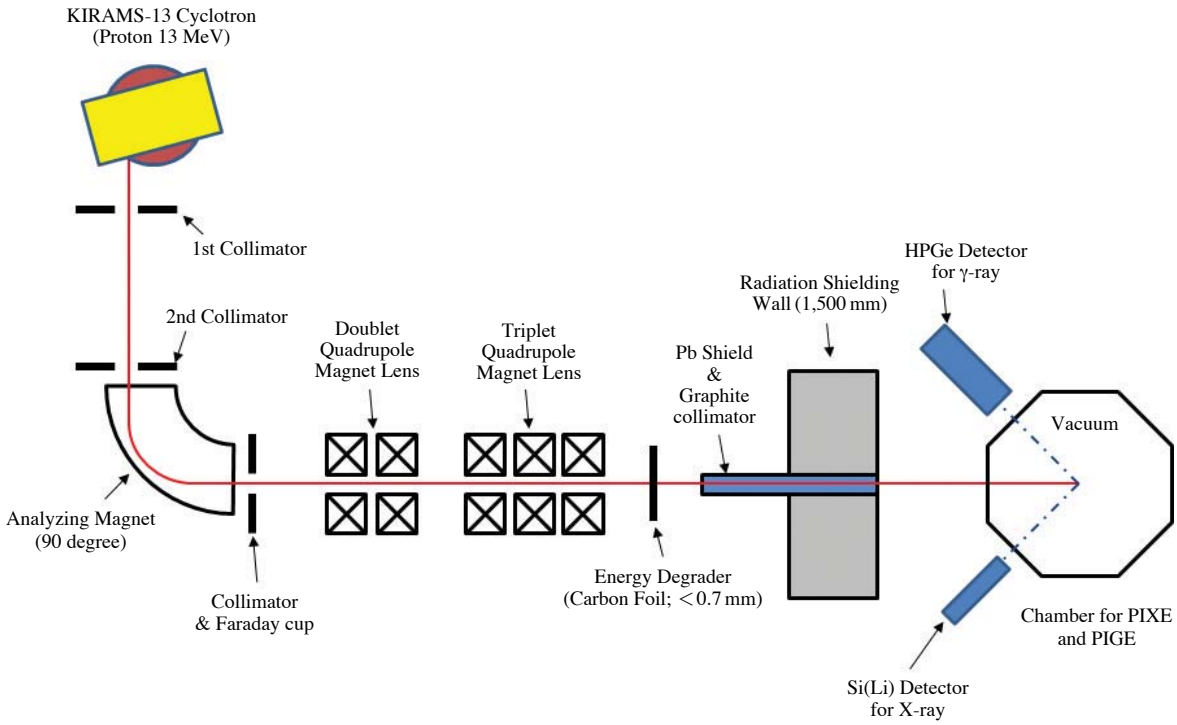


Fig. 5. Schematics of Chosun University's PIXE beam transport line.

the space and components, which have already been manufactured at the Chosun University CRC. The optimal position of the degrader is located directly behind the shielding wall to reduce beam losses.

CONCLUSION

Optimization of a beam transport line for a PIXE analysis system was performed. First, the beam optics parameters were decided. Second, a beam optics simulation was performed based upon the optical parameters. Third, the optics simulation was verified with a beam tracking simulation. Fourth, the optimal layout for the beam line components was proposed. Fifth, an analyzing magnet and quadrupole were manufactured according to the results of this study. Each component will be installed with the proposed layout, and the beam line will be optimized according to these results. Additionally, an adaptable beam line will be built according to the performance improvements and operation of the PIXE system. The system is expected to be used for non-destructive analyses.

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