BEAM OPTICS STUDY OF A FRAGMENT SEPARATOR FOR THE PLANNED RARE ISOTOPE BEAM FACILITY IN KOREA

W. Wan, Lawrence Berkeley National Lab., Berkeley, USA
Y.H. Park, J.W. Kim*, National Cancer Center, Gyeonggi-do, Korea

Abstract

A heavy-ion accelerator facility based on a linear accelerator is planned in Korea. The facility is designed to provide high-current radioisotope beams, and they will be utilized in the fields of nuclear, material and biomedical sciences. The primary beam energy is in the range of a few hundreds of MeV/u. A major mechanism to produce isotope beams is in-flight fragment separation. The separator system should have high mass resolution and particle identification method to separate and identify rare isotopes of interest, and also large momentum and angular acceptances for maximal utilization of produced isotopes. We are considering improved beam optics design to realize such a system, where second order aberrations are corrected. The study has been performed mainly using COSY Infinity.

INTRODUCTION

A plan to construct a heavy ion accelerator facility has been announced by the Korean government in January 2009. The primary accelerator is a superconducting linac to accelerate U ions to 200 MeV/u at a maximum beam power of 400 kW. It is planned to utilize both ISOL and in-flight fragmentation methods to produce rare isotope beams. In fact, considering the difficulties of using ISOL methods for some refractory elements and short-lived ions, in-flight fragment method is complementary in producing rare isotope beams [1].

The designs of two separators, which are in operation and under design, have been referred: the BigRIPS at RIKEN [2] and the separator design for the FRIB at Michigan State University [3]. BigRIPS is a two-stage fragment separator, which is actively utilized to search for new rare isotopes using heavy-ion beams from the cyclotron complex. We have studied the beam optics of a two-stage separation similar to that of the BigRIPS, also the possibility of symmetric lattice employing larger number of higher order multi-pole components.

The separator design for the FRIB facility, which is aimed to operate with the beam power of 400 kW while the beam power for BigRIPS is 100 kW, adopts a pre-separator to accommodate heavy shielding and remote handling capability. The primary beam not used for reaction is dumped in this area. The design of the FRIB separator includes vertical bending to account for the level difference between the accelerator and the beam lines for experiments. Our separator is designed to be at the same elevation considering technical and maintenance difficulties caused by the vertical bending.

*jwkim@ncc.re.kr

The use of wedge degrader is essential to separate the isotope with the same q/A ratio by Z-dependent energy loss. The wedge is located in the dispersive focal plane, and then the energy loss makes the beam achromatic at the focal point with appropiate wedge shaping. However, the effect of the wedge is not considered in the present work.

DESIGN OF A FRAGMENT SEPARATOR

The use of 400-kW beam power requires significant enhancement in radiation shielding compared to the usual nuclear science facility handling less than a few tens of kW. A pre-separator is needed to separate the primary beam and most of the unwanted isotope beams so as to dump them into water-cooled shielding structure. The design of pre-separator should consider radiation damage and shielding structures [4].

Configuration of the separator under consideration is given in Fig. 1 together with the beam envelope in the dispersive plane. The entire separator is located at the same level, and the locations of beam dump and shielding walls are schematically indicated. To accommodate the space for the shielding walls, we leave a long drift space of roughly 4 m in the middle of the pre-separator, a 2 m long drift space after the first dipole and a 1 m long drift between the pre- and the main separator.

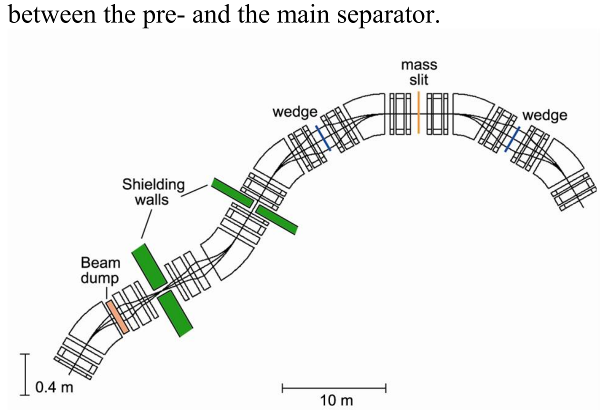

Figure 1: Configuration of a separator under consideration.

The optics of the separator was studied using COSY Infinity [5], including the pre-separator and the following main separator. The use of a matching section in between was considered but eventually dropped due to limited benefit and additional cost it brings.

OPTICS OF THE PRE-SEPARATOR

The pre-separator contains 2 dipoles and 12 quadrupoles, and its maximum magnetic rigidity is 8 Tm.

The dipoles bend to the opposite directions and the quadrupoles are symmetric about the centre. The dispersion is zero at the centre, which ensures the whole beamline is achromatic as shown in Fig. 2. An image in the horizontal plane is formed at the midpoint of the drift after the first dipole where the beam dump is located. Furthermore, in the first half, it is point-to-parallel in both planes and parallel-to-point in only the vertical plane. The one free parameter, the first quadrupole in our case, is used to adjust the ratio of the horizontal and vertical acceptance so that they are roughly the same.

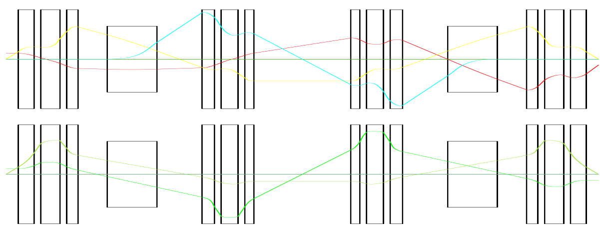

Figure 2: The sine-like, cosine-like and dispersive rays in the pre-separator. Upper envelop is for horizontal plane and the lower one is for vertical plane. The slope of the sine-like rays is 40 mrad; the amplitude of the cosine-like rays is 1.75 cm (beam radius 1 mm) and the momentum deviation of the dispersive ray is 9%. The total arc length is 26.3 m, and the radius of quadrupole aperture is 15 cm for all cases of this paper. The bending angle and arc length of the dipoles are 30° and 2.2 m, respectively.

The 4.3 m long drift in the centre of the pre-separator is to be occupied by the shielding wall. The beam dump is located in the 2 m drift space after the first dipole. A wedge can be placed in the symmetric position to the beam dump across the middle. There is a 1.3 m drift after the second bend magnet where additional shielding can be placed. The 1.1 m drift space at the end of the pre-separator is reserved for the second shielding wall shown in Fig. 1.

During the study, we have also considered the option of same bending direction with a large dispersion in the middle so that a wedge can further purify the beam. By splitting the dipoles, we achieved imaging in the horizontal plane between the split dipoles while keeping the entire pre-separator achromatic as displayed in Fig. 3. Hence the beam dump will be placed between the first two dipoles. Other constraints are the same as the above mentioned s-shaped pre-separator. The drift spaces at the middle, after the last bend and at the end of the c-shaped pre-separator are the same as those in the s-shaped one. In comparison, the c-shaped pre-separator has smaller dispersion at the beam dump (0.4 m in momentum deviation as oppose to 1.06 m). On the other hand, the large dispersion at the centre (1.0 m) makes it possible to either further reduce the momentum spread with a second slit or purify the beam with a wedge.

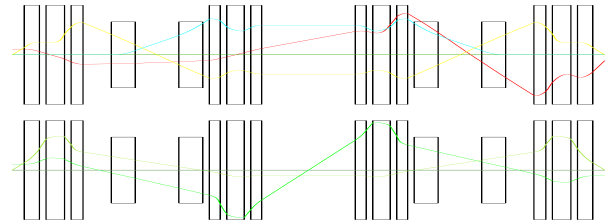

Figure 3: The sine-like, cosine-like and dispersive rays in the c-shaped pre-separator. The conditions of the rays are the same as those of Fig. 2. The total arc length is 27.2 m. The bending angle and arc length of the dipoles are 15° and 1.1 m, respectively.

If only linear dispersion is taken into account, the c-shaped pre-separator clearly has larger momentum acceptance. Yet the advantage vanishes when fringe field and high order aberrations are included. For ±40 mrad angular acceptance, the momentum acceptance for the c-shaped and the s-shaped pre-separators are ±1.5% and ±1.4%, respectively. The sizes of the image at the end are also similar. As a result, only the tracking result of the s-shaped pre-separator is shown in Fig. 4. Attempts to correct aberrations using multipoles have not been successful. It's clear that the size of the image at the end is dominated by aberrations. Furthermore, we found that the aberrations come mainly from the extended fringe field which is based on measured field data of the PEPII magnets [5, 6]. Therefore, magnets designed to limit the extent of the fringe field will help reduce aberrations.

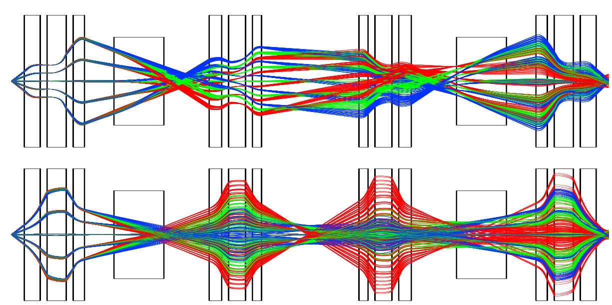

Figure 4: The element-by-element tracking result of the s-shaped pre-separator using 7^{th} order Taylor map. Upper envelop is for horizontal plane and the lower one is for vertical plane. The maximum slope of rays is 40 mrad; the amplitude is 1 mm and the momentum deviation is 1.4%.

OPTICS OF THE MAIN-SEPARATOR

The use of high power primary beam allows the production of isotopes with small cross-sections near the drip-lines of the nuclear chart. To separate such isotopes requires more refined method than a single-stage separation using momentum dispersion by magnetic field to purify the isotope of interest. A profiled wedge degrader at the dispersive focal point is used to allow Z-dependent separation in addition to the dispersion by the magnetic field of the dipole. However, the use of a target material in the beam course adds background particles and induces energy straggling. The main-stage separator can indentify isotope beam species by measuring the time of flight and energy loss of the beam as well as the magnetic rigidity.

Since the two stages of the main separator are identical, only one is shown in the proceeding figures. The Gaussian optics is somewhat similar to that of the first stage of the BigRIPS [1] or the c-shaped pre-separator. The main difference is that the first half is point-to-parallel in the horizontal plane as well. Apart from the marginal benefit of higher degree of symmetry, the main advantage is that it lowers the strongest quadrupole strength by about 8% compared to the solution of BigRIPS and reduces the magnification of the dispersive image from 1.7 to 1.3, resulting in higher momentum resolution. The disadvantage is that the angular acceptances of the two planes are no longer the same as shown in Fig. 5. The first-order momentum resolution is around 1760, which is expected to decrease around 15-20% when aberrations are included.

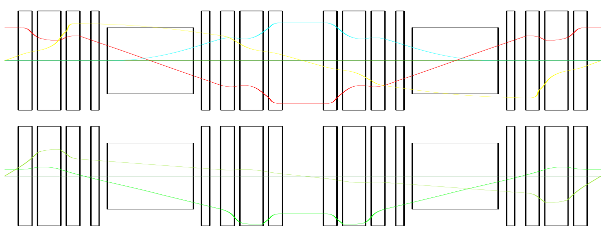

Figure 5: The sine-like, cosine-like and dispersive rays in the main-separator. The slopes of the sine-like rays in the horizontal and the vertical planes are 30 and 50 mrad, respectively; the momentum deviation of the dispersive ray is 5%. The total arc length is 21.8 m. The bending angle and arc length of the dipoles are 30° and 3.14 m, respectively. The four short magnets next to the dipoles are octupoles.

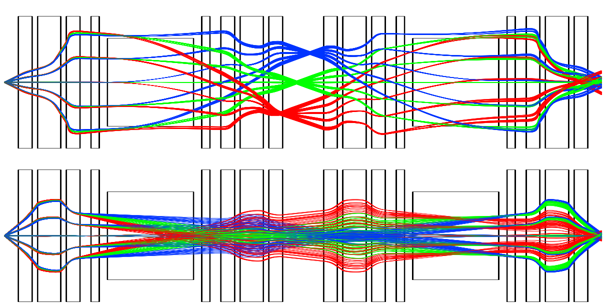

Figure 6: (Top) Effect of aberrations on the horizontal and (Bottom) the vertical planes without multipole correction. The maximum slopes of rays in the horizontal and the vertical planes are 30 and 50 mrad, respectively; the momentum deviation is 3%.

The effects of aberrations were analyzed through element-by-element tracking using the 7th order Taylor for each magnet. As shown in Fig. 6, the aberrations severely degrade the quality of the image both at the middle and at the end. One obvious effect is the change of focal length for different momentum at the middle due to chromaticity. To correct those most prominent terms, we added sextupole coils in the 3rd, 4th, 8th and 9th quadrupoles and octupole coils in the 2nd and 11th quadrupoles, together with four stand-alone octupoles next to the dipoles. The result is presented in Fig. 7, which shows significant improvement.

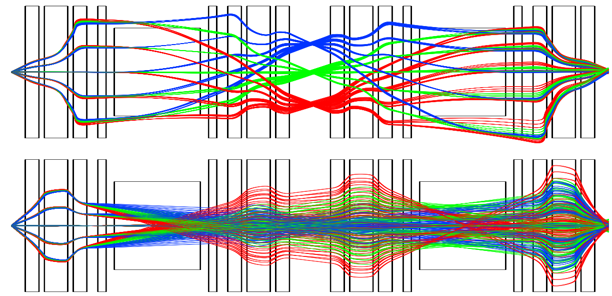

Figure 7: (Top) Effect of aberrations on the horizontal and (bottom) the vertical planes with multipole correction. The maximum slopes of rays in the horizontal and the vertical planes are 30 and 50 mrad, respectively; the momentum deviation is 3%.

CONCLUSIONS

The design of an in-flight fragment separator for the planned Korean heavy-ion beam facility is in the early stage taking into account the designs of existing and future facilities of other places. While the other separator designs have been constrained by the existing facility layout, the Korean facility may provide more freedom in adopting new schemes. Tracking result shows the role aberrations plays in determining the size of the image and the momentum resolution of the separator and the effectiveness of multipoles in aberration correction. Future work includes studying the impact of the wedges and optimizing the beamline based on detailed engineering design.

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