

# Beam Tracking Simulation Study Using Three Dimensional Field Map of Multipole Magnets at the HEBT in the KHIMA Accelerator System

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The Korea Heavy Ion Medical Accelerator (KHIMA) project of Korea Institute of Radiological & Medical Sciences (KIRAMS) is engaged in designing synchrotron-based ion beams treatment facilities for cancer treatment and various nonclinical scientific research. Designed machines can accelerate proton beams from 60 MeV to 230 MeV and carbon beams from 110 MeV/u to 430 MeV/u in fine energy variation steps. The beam extracted from the Synchrotron is transferred to each treatment room via a dedicated high energy beam transport (HEBT) line. The HEBT line lattice design was confirmed with beam optics code, MAD-X and WinAgile. The beam tracking code TRACK having the completed HEBT lattice is performed in order to confirm the beam loss in the HEBT line. In order to apply the realized multipolar magnet to the TRACK code, a three-dimensional field map obtained by the Opera3D program was used. By applying a realistic field map to the TRACK code, the beam width for the beam energy was deformed compared to the estimate by optics code. In this analysis, corrections made to eliminate the difference between the reconstructed beam width by TRACK and the estimated beam width by optical code are performed on each dedicated beam line.

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## I. INTRODUCTION

The Korea Heavy Ion Medical Accelerator (KHIMA) project of Korea Institute of Radiological & Medical Sciences (KIRAMS) has developed an accelerator system based on a synchrotron equipped with multiple ion sources for various cancer treatments. The synchrotron is designed to accelerate a protons (carbon ions,  $^{12}\text{C}^{6+}$ , beam) from 60 MeV (110 MeV/ $u$ ) to 230 MeV (430 MeV/ $u$ ). Fig. 1 shows the schematic layout of the accelerator center. The electron cyclotron resonance ion source (ECRIS) generates ions with charge-to-

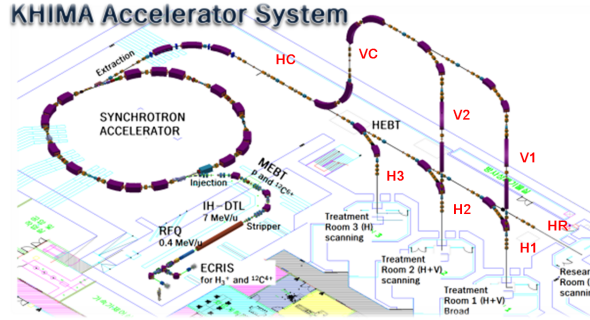


FIG. 1: (Color online) Schematic layout of the KHIMA accelerator system.

mass ratio  $q/m = 1/3$ , in particular  $\text{H}_3^+$  or  $^{12}\text{C}^{4+}$ , with energies up to 8.0 keV/ $u$ . These two ions are accelerated to 7 MeV/ $u$  via the radio frequency quadrupole (RFQ) linac and the interdigital H-mode drift tube linac (IH-DTL). At the beginning of the medium energy beam transport (MEBT), each accelerated ion is fully ionized to either protons or a  $^{12}\text{C}^{6+}$  and transported to the entrance of synchrotron to maintain a constant rate. Each ion is injected into a synchrotron having a multi-turn injection mechanism and is accelerated by the switching frequency on a radio frequency (RF) system. The accelerated ion beam is extracted to the high energy beam transport (HEBT) line using the slow resonance extraction method[1–3]. The beam extracted from the synchrotron is transported to each treatment room via a dedicated HEBT line as described in Sec. II. In Sec. III, two different beam tracking algorithms are introduced to realize beam dynamics in the HEBT line. Finally the results and conclusions are given in Sec. IV.

## II. LATTICE DESIGN

Beams extracted from the synchrotron must be safely transported to the isocenter in their own treatment rooms or research room. To satisfy this requirement, the lattice design was confirmed with two beam optics codes, WinAgile[4, 5] and MAD-X[6]. Meanwhile, the distorted trajectory for several reasons was corrected by the beam optical tool[2]. The common module of the horizontal common (HC) line is interleaved to control the beam size at the isocenter. This module has important advantages for commissioning and operation. The vertical beam size of transverse beam plane at the isocenter is controlled by the vertical  $\beta$  function,  $\beta_y$ . The module can be adjusted to provide a variable value between  $2 < \beta_y < 27$  m with  $\alpha_y = 0$  at the isocenter. As a variable component, the module includes six successive quadrupole magnets in a common line. The horizontal beam size of transversal beam plane was limited by changing the phase advance as described in ref.[2]. As the shortest of the horizontal lines (H3, H2 and H1), Fig. 2 shows transverse envelope distribution by the horizontal H3 line to the isocenter of the third treatment room. The full width at half maximum (FWHM;  $\Gamma$ ) at the isocenter can be varied with respect to the beam energy according to treatment conditions. Thus, the lattice design reflects these conditions by arranging the corresponding lattice components which are bending, focusing and correcting magnets.

## III. BEAM TRACKING SIMULATION

A beam transport system such as the HEBT line is completed using a detailed beam dynamics code. Due to many advantages, the ray tracing code TRACK[7] was adopted to describe the beam dynamics of the HEBT line. In the beam tracking simulation by the TRACK code, firstly two different methods are used by the encoding algorithm, and secondly, a realistic three-dimensional field map of the electromagnet is applied.

### A. Encoded in TRACK Code

In the hard-edge model of electromagnet, the fringe field falloff of the dipole and multipole magnet elements is not included. On the other hand, the TRACK code implements the encoded 6 parameter Enge function[8] and describes the parasitic fringe field component.

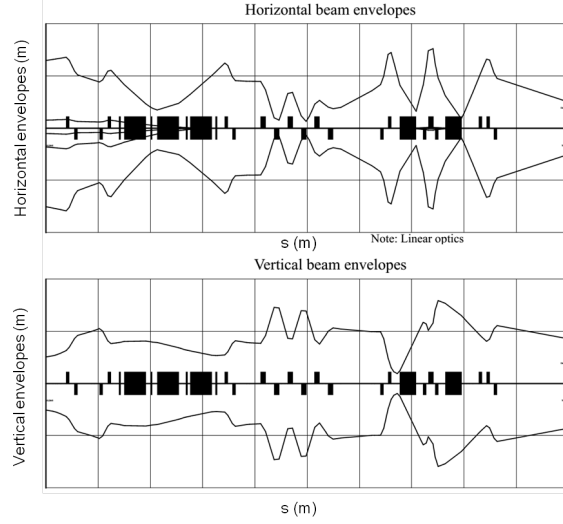


FIG. 2: Beam envelope distribution of the third horizontal (H3) line. There are restrictions when  $\Gamma_y = 9$  mm with an isocenter using a carbon beam with  $E = 110$  MeV/u.

The Enge function is described as[9]:

$$F(z) = \frac{1}{1 + \exp(a_0 + a_1(z/D)^1 + \dots + a_5(z/D)^5)}$$

where  $z$  is the distance along the line perpendicular to the effective boundary line and  $D$  is the full air-gap of element. Fig. 3 shows the beam envelope distribution for the reference trajectory in both horizontal and vertical planes. As shown in the distribution diagram on the lower right side of Fig. 4, FWHM  $\Gamma_y = 2.355 \times \sigma_y = 6.7$  mm was obtained and the result by the matrix based optical code WinAgile was 9 mm. Therefore, the difference between the two methods is large and needs to be considered for additional correction.

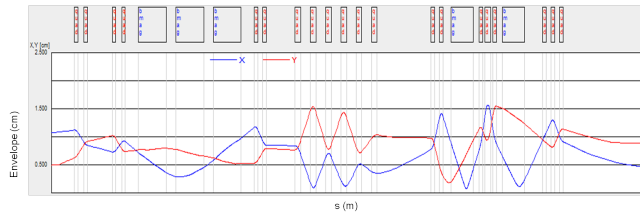


FIG. 3: (Color online) Beam envelope distributions for the 3rd Horizontal (H3) line by using the encoded fringe field fall-off with TRACK, where  $\Gamma_y = 9$  mm with  $E = 110$  MeV/u carbon beam at the iso-center is estimated by optics code.

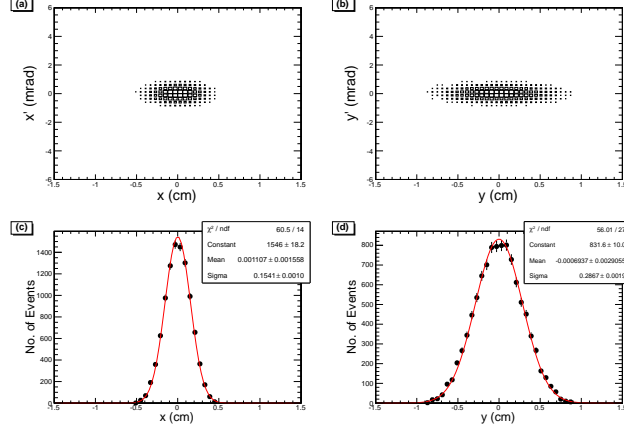


FIG. 4: (Color online) (a) - (b) Particle beam distribution at the isocenter in phase space. (c) - (d) Particle distribution projected on each x, y plane.

## B. Three Dimensional Field Map

Design specifications of dipole and quadrupole determined by beam optics code are realized with Opera3D code. Fig. 5 shows the schematic design and magnetic field distribution of two different quadrupole magnets. Here, the reason for using two different focusing magnets is to respect the wide range magnetic strength of each quadrupole. Fig. 6 shows the distribution of field maps for three different bending angles  $22.5^\circ$ ,  $30^\circ$  and  $45^\circ$  used in the HEBT line. The field map database of multipole magnets from Opera3D code was converted into ASCII text input file of TRACK code. In the TRACK code, two functions, three-dimensional bending and focusing magnet, are provided to read an ASCII text file. The particle beam is transferred via the rewritten TRACK code applied by the field map implementation. Fig. 7 shows the distribution of the particle beam envelope by applying the three-dimensional magnetic field map realized by the multipole magnet to the TRACK code. Even if the realized field map is applied, the isocenter's FWHM value still does not match the field map expected by the beam optics code. Fig. 8 shows the discrepancy of the FWHM distribution between the reconstruction value according to the TRACK code and the estimate by the optics code for various carbon energies from 110 MeV/u to 430 MeV/u. The main reason for disagreement was derived from the fringe field effect in each quadrupole magnet. Various correction methods of the quadrupole magnets are considered to correct the mismatch, but the field scaling factor multiplied to the quadrupole being used

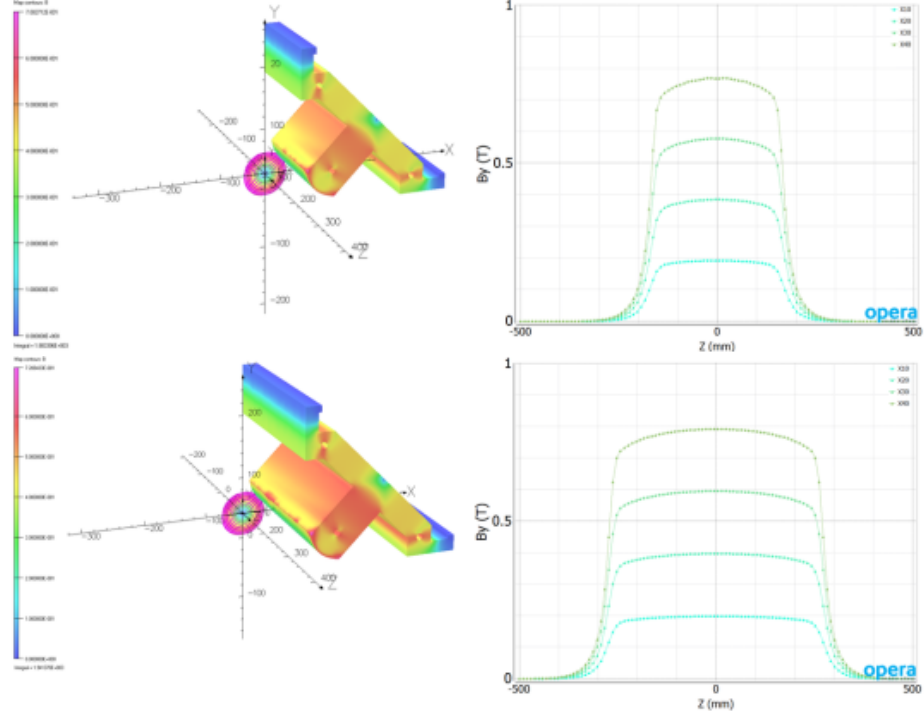


FIG. 5: (Color online) Schematic design output and field distribution over extreme points for short and long distance quadrupole.

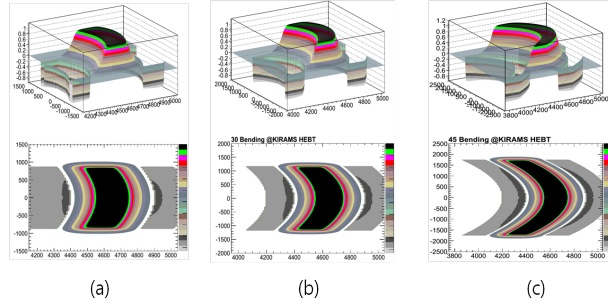


FIG. 6: (Color online) 3-D field map distribution of (a) 22.5°, (b) 30° and (c) 45° bending magnet of Opera3D.

is most appropriate for the H3 line. As an example, Fig. 9 shows the particle distribution projected on  $y$  plane before and after the correction. Here we set  $\Gamma_y = 4$  mm (sigma,  $\sigma_y = \Gamma_y/2.355 = 0.170$  mm) using a carbon beam with  $E = 110$  MeV/u at the isocenter. The fitted sigma ( $\sigma_y = 0.170 \pm 0.001$  mm) value after correction is consistent with the value estimated by the optical code within statistical fluctuation.

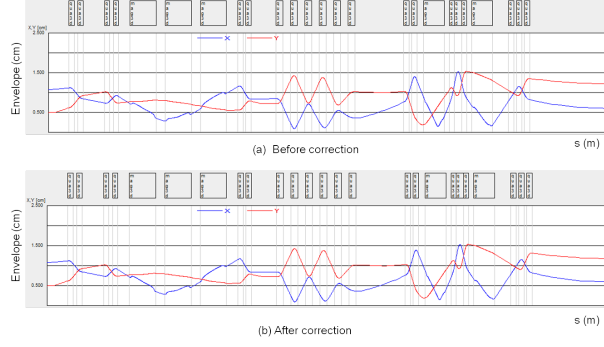


FIG. 7: (Color online) Beam envelope of the 3rd Horizontal (H3) line using the 3-D field map with Opera3D code before and after correction. Here we set  $\Gamma_y = 9$  mm using a carbon beam with  $E = 110$  MeV/u at the isocenter.

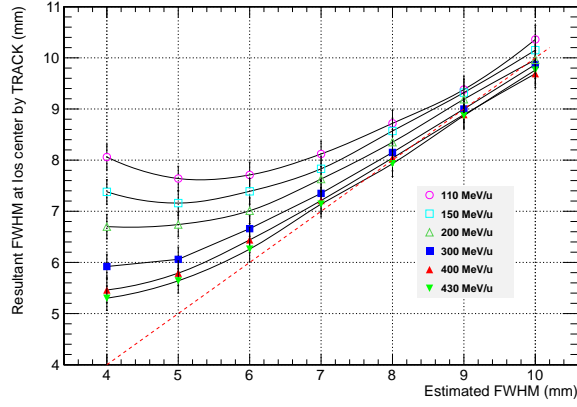


FIG. 8: (Color online) FWHM distribution for the estimated one by the optical code at the isocenter for several energies of the carbon beam.

Fig. 10 shows the performance of particle beam width for extremely different beam energies before and after correction. As shown in Fig. 10, the correction factor, which is inversely proportional to the ratio of the figure, in the low carbon energy beam must be greater than that of the high energy beam. In the treatment planning system (TPS), combinations of hundreds of thousands of beam are required, including the number of ion species, different energies, beam size, intensity and extraction time. Based on this analysis with TRACK code, tracking analysis is also successfully performed by other beam lines on the HEBT. Thus, the transportation of the beam to the isocenter through each line works well with

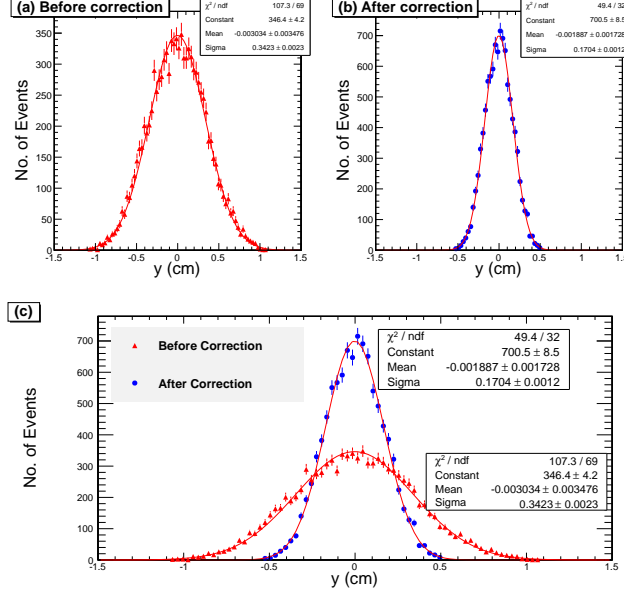


FIG. 9: (Color online) Particle distribution projected on  $y$  plane before and after correction. Here we set  $\Gamma_y = 4$  mm using a carbon beam with  $E = 110$  MeV/u at the isocenter.

suitable and variable magnet components without beam loss.

#### IV. CONCLUSION

The HEBT line is constructed based on a modular design that takes into account the strong asymmetry between two lateral emittances in the lateral beam direction and depends on the trapezoidal distribution of the beam in the horizontal phase space. The KHIMA HEBT line was originally designed using the WinAgile/Mad-X code for the whole beam transport line to each treatment room. Optical code based designs were modified with appropriate correction methods for various treatment conditions. In order to confirm the design based on the optical code and minimize the beam loss in the transport line, tracking analysis using the TRACK code was carried out. TPS requires an enormous amount of beam combinations and needs to be corrected appropriately. In the beam commissioning process, various calibrations and corrections that affect beam performance are performed. Therefore, tracking analysis using the realized three-dimensional electromagnetic field map is very useful for performing correction of each electromagnetic magnet component in the beam commissioning process. Designed beam lines are expected to be built on the basis of



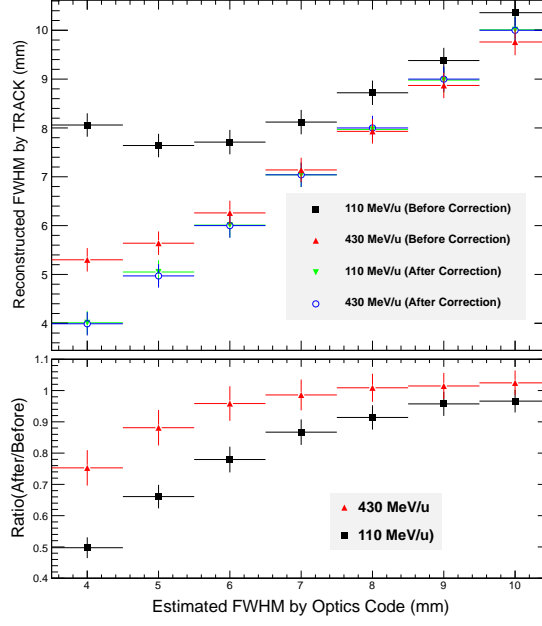


FIG. 10: (Color online) Reconstructed FWHM distribution estimated by optical code (WinAgile) at the isocenter before and after correction of the minimum and maximum energy of the carbon beam.

optical codes and tracking codes in the near future.

## V. ACKNOWLEDGMENT

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