Journal of the Korean Physical Society, Vol. 67, No. 1, July 2015, pp. 96∼102

A Comparison Study of the Ridge Filter Parameter by Using FLUKA and GEANT4 Simulation Codes

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(Received 8 December 2014, in final form 6 March 2015)

We investigated the parameter optimization of the ridge filter's thickness for carbon-ion therapy by using a Monte Carlo simulation. For this study, a ridge filter was designed for the spread-out Bragg peak (SOBP) by considering the relative biological effectiveness (RBE). The thickness, height, and width of the ridge filter were designed by using the FLUKA and the GEANT4 codes, and we analyzed and compared the results of the physical dose distributions for the FLUKA and the GEANT4 codes. The results showed that the minimum width of the groove for the ridge filter should be at least 0.5 cm for an appropriate biological dose. The SOBP sections were 8 cm, 9 cm, and 10 cm, respectively, when the heights were 3.5 cm, 4.0 cm, and 4.5 cm. The height of the ridge filter was designed to be associated with the SOBP width. Also, the results for the FLUKA and the GEANT4 codes showed that the average value of the difference was 3% and that the maximum error was 5%; however, the trends were similar. Therefore, the height and the width of the groove for the ridge filter are important parameters for deciding the length and the plateau of the SOBP.

PACS numbers: 29.85.+c, 29.50.+v
Keywords: FLUKA, GEANT4, Ridge filter, Broad beam
DOI: 10.3938/jkps.67.96

I. INTRODUCTION

Carbon-ion therapy is a very effective method for the treatment of cancer because of its very high relative biological effectiveness (RBE) around the peak and excellent dose distribution. Carbon-ion therapy was started in 1994 when the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) in Japan [1]. Since then, it has been researched for clinical trials on light-ion therapy at Lawrence Berkeley National Laboratory, USA (LBNL) [2]. The Heidelberg Ion Beam Therapy Center (HIT) in Germany has also been treating patient since 2009 [3]. Due to its high therapeutic efficiency [4], several countries plan to establish a carbon-ion therapy treatment facility. The Korea Institute of Radiological and Medical Sciences (KIRAMS) is currently under construction, with an objective of starting clinical trials in 2017 at Busan Gijang in Korea.

The ion beam should be modulated when treating patients. One methods for beam modulation is broad-beam modulation, which extends the Bragg peak to the size of the tumor. The broad-beam modulation method can be either active or passive. The active modulation method is used at Helmholtzzentrum für Schwerionenforschung GmbH (GSI), and the passive modulation method is adapted at NIRS. In the passive modulation method, a special component must be added on the broad-beam line; its ridge filter consist of a small groove. The filter is made of aluminum fabricated in small steps and is used to create a pristine spread-out Bragg peak (SOBP). The design of this ridge filter was developed by Kanai *et al.* [5], Akagi *et al.* [6] and Hata *et al.* [7].

The SOBP is made by inserting bar ridge filters in the beam's path [8]. At the NIRS, the ridge filter is made of aluminum. The spacing of each bar ridge is 5 mm, and the ridge filter does not move during irradiation. Due to multiple scattering in the ridge filter and the angular dispersion of the wobbling beam, the shading due to the bar ridge is smeared out at the irradiation site. In clinical trials, aluminum ridge filters with widths from 2 cm to

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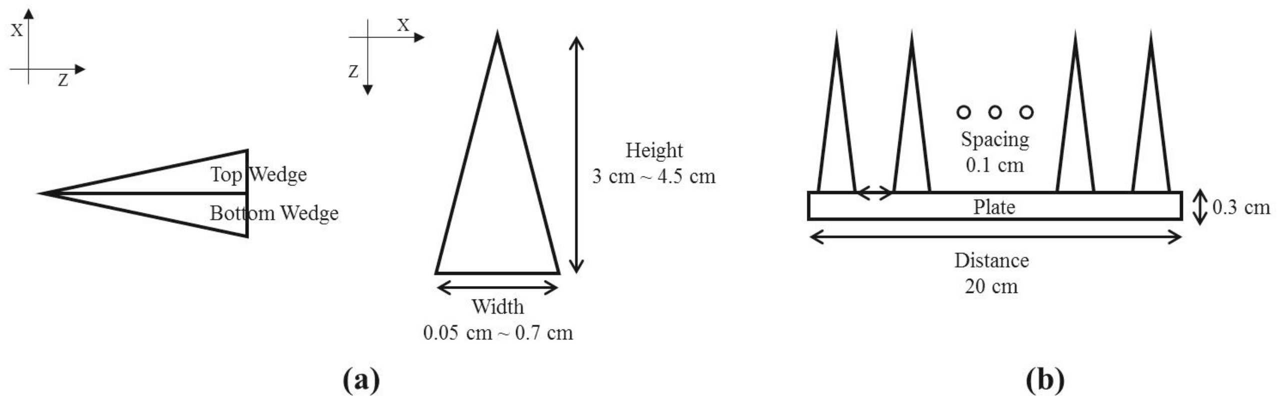

Fig. 1. Schematic of the groove design of the ridge filter.

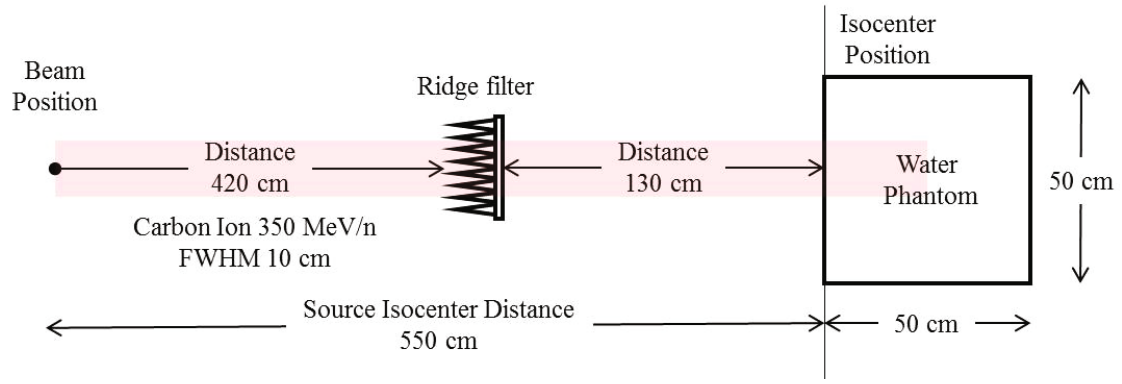

Fig. 2. (Color online) Schematic layout of the broad-beam delivery system used in the Monte Carlo simulation.

12 cm were lined up for SOBP, in which case the height of the aluminum ridge was about 6 cm. For a SOBP of 15-cm width, a brass ridge filter was used [9]. They can select an appropriate ridge filter out of the 8 ridge filters that are mounted on a large wheel. The ridge filter was designed so that the survival fraction of human salivary-gland tumor cells (HSG cells) would be uniform in the SOBP [5].

At the Korea Institute of Radiological and Medical Science (KIRAMS), a carbon therapy facility is under construction, and both broad and scanning modes are being considered now. Thus, the ridge filter design is needed to develop a broad beam irradiation system. In this study, we analyzed the effects of parameters on the dosimetric properties by using MC simulations via the FLUKA and the GEANT4 codes. A comparison study of ridge filter designs was performed.

II. MATERIAL

FLUKA (FLUktuierende KAskade) is a fully-integrated Monte Carlo simulation package for the interaction and the transport of particles and nuclei in matter [10, 11]. FLUKA has many applications in particle physics, high-energy experimental physics and engineering, shielding, detector and telescope design, cosmic-ray studies, dosimetry, medical physics, and radiobiology. A recent line of development concerns hadron therapy.

In order to perform a SOBP simulation of passive modulation, we designed a ridge filter and a water phantom by using the FLUKA 2011.2b code. That ridge filter is reported in the Hyogo Ion Beam Center and Gunma Heavy Ion Medical Center of Gunma University (GHMC)'s papers [6, 12]. These papers compared the measured data with the Monte Carlo simulation results for ridge filters used with carbon and proton beams, respectively. The components were designed by using the FLAIR geometry editor of the FLUKA additional tool. The groove of the ridge filter consists of top and bottom wedges as shown in Fig. 1(a). A spacing is inserted between the grooves, and the same shape is repeated over a distance 20 cm as shown in Fig. 1(b). We also designed a thin aluminum plate with a 0.3-cm thickness. Its purpose was to hold the groove. The heights and the widths of the grooves are important parameters to determine the length and the slope of the SOBP. Due to the size of the patient with a tumor during treatment, different ridge filters are used to modulate the beam, so filters of various types should be designed, and the results of

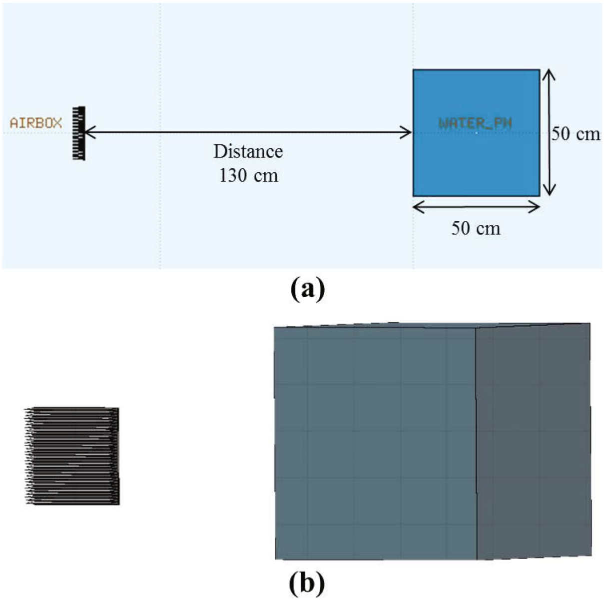

Fig. 3. (Color online) Geometry of the (a) 2D view and (b) 3D view in FLUKA.

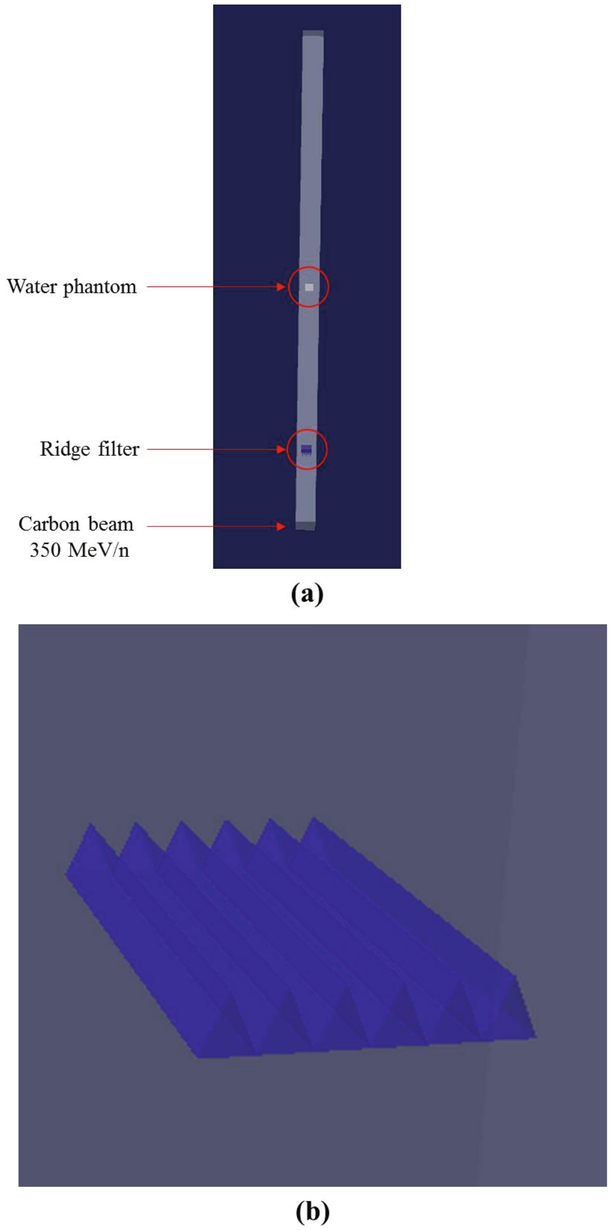

Fig. 4. (Color online) (a) Geometry layout and (b) the ridge filter in GEANT4.

using those filters should be compared. In order to a design 8-cm SOBP for carbon ions, we should design the height of the groove of the ridge filter to be 3.8 cm [12]. In a previous study, we designed ridge filters with various heights and widths of the grooves. The height varied from 3.0 cm to 4.5 cm in intervals of 0.5 cm, the width varied from 0.05 cm to 0.7 cm in intervals of 0.5 cm, and the spacing was 0.1 cm. We designed 56 ridge filters of different designs. The ridge filter's material was mostly aluminum. In this study, the material of the ridge filter was aluminum with a density of 2.699 g/cm^3.

Figure 2 shows the geometrical layout for simulating the SOBP. The distance between the source and the isocenter (SID) and the distance from the source to the ridge filter were 550 cm and 420 cm, respectively. The water phantom's shape was square with dimensions of $50 \times 50 \times 50$ cm^3. The distance from the ridge filter to the water phantom was 130 cm. In addition, all of the components were included in an air-filled container in the shape of a $2000 \times 2000 \times 2000$ cm^3 cube.

After the geometry had been designed, in order to debug the geometry, we confirmed the 2D and the 3D component designs, as shown in Fig. 3. Because FLUKA cannot run if a geometry error is found, the geometries of the region and body type must be verified. The designed ridge filter consisted of many grooves because such a design has greater probability of error. We confirmed that no errors in the geometry were present and went to the next step.

The beam-parameter setup cards in FLUKA are BEAM, HI-PROPE, BEAMPOS. The above-mentioned cards can set up the basic beam parameters such as the beam's energy, shape, divergence, initial position, and heavy-ion type. We set up the carbon beam by using these cards. The beam energy was 350 MeV/n, and the FWHM (full width at half maximum) of the beam was 10 cm. In addition, the distance between the beam's initial position and the ridge filter was 420 cm

Scoring was done by using the USRBIN card from among many scoring options in FLUKA. The USRBIN card is a typical scoring card in FLUKA. This card checks the space distribution of the energy and can be used in calculating the total fluence. The list of scoring options of USRBIN includes the deposited energy (GeV/cm^3), dose (GeV/g), activity (Bq/cm^3) and fluence (particles/cm^2). Because the main purpose of this study is to verify the physical dose in a water phantom,

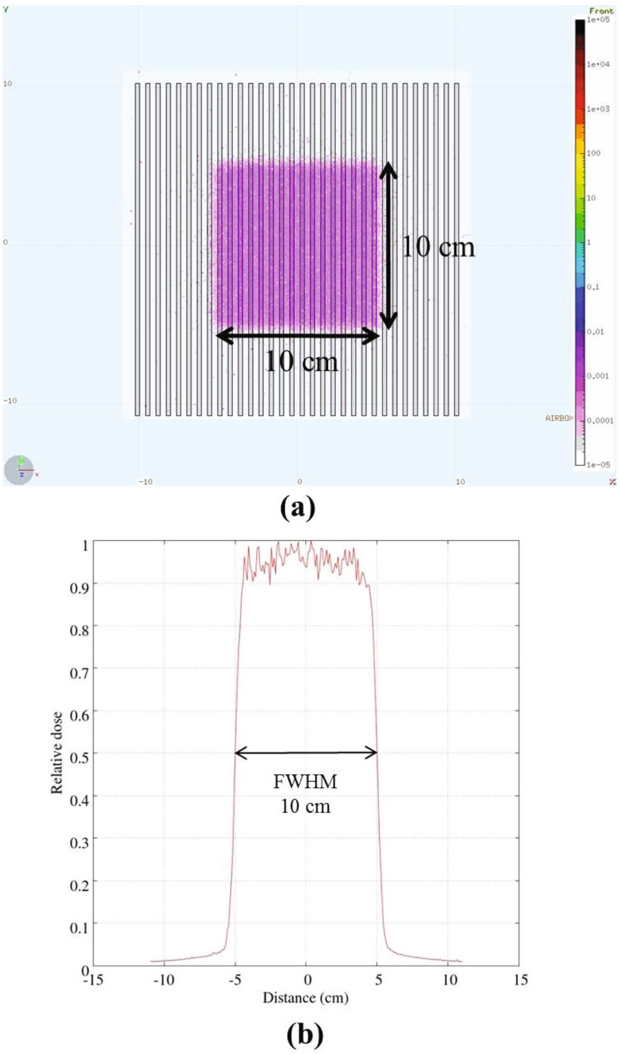

Fig. 5. (Color online) (a) 2D dose distribution of the ridge filter and (b) 1D dose profile.

all of the scoring options were set up the dose. In order to measure the physical dose in a water phantom with the same shape, we added a detector of the same size. To verify the FWHM of the initial beam when it penetrates the ridge filter, we added a covered detector for the ridge filter. In addition, so as to reduce the voxel binning effect, we set up a scoring voxel size of 50 cm $\times$ 50 cm $\times$ 1 cm.

Nuclear interactions generated by ions are treated through interfaces to external event generators. The heavy-ion interaction models in FLUKA are the dual parton model (DPM), the relativistic quantum molecular dynamics model (RQMD) and the Boltzmann master equation (BME). We selected the RQMD for the nucleus-nucleus interaction model because the RQMD mainly use between 0.125 and 5 GeV per nucleon. In the last stage, we checked all of the cards in FLUKA and determined the number of initial particles. If number of initial particles increased, the error was reduced. Therefore, deciding on the number of initial particle is important. In this study, we carried out a simulation for an initial particle number of 10^8.

In order to verify the results from FLUKA, we also designed a same geometry by using GEANT4 from among the other Monte Carlo simulation codes. In this study, we used the source codes and the data libraries of GEANT4 10.0. The electromagnetic and hadron physics lists were based on a reference physics list. The electromagnetic physics process was set to "EM standard option 3", which is suitable for medical research. The hadron physics process was configured by using the reference physics list "QGSP_BIC_EMY", which included the binary cascade model (BIC). Figures 4(a) and (b) show the broad-beam line layout and the ridge filter in GEANT4, respectively.

III. RESULTS

In order to ensure that the beam was incident correctly on the ridge filter, we designed a detector on the ridge filter and measured the absorbed dose. Figure 5(a) shows the 2D dose distribution on the ridge filter, which looks to be approximately 10 cm $\times$ 10 cm. Because the verification of the beam's FWHM is not accurate, we converted 2D raw data to a 1D profile to confirm the accuracy of the beam. Figure 5(b) plots the 1D beam profile on the ridge filter and confirmed that the FWHM of the beam was exactly 10 cm.

Figure 6 plots the depth distribution of the physical dose in the water phantom. We observed different physical doses for heights of 3.0 cm, 3.5 cm, 4.0 cm and 4.5 cm, widths of 0.05 cm to 0.7 cm, and an interval of 0.05 cm. Each plot was normalized to the maximum value. When a carbon-ion beam passes through the ridge filter and is incident on the water phantom, the doses gradually increases until the beginning of the SOBP. Then, the dose decreases at a constant rate until the beginning point of the tail. When the width is below 0.4 cm, a second peak occurs as shown in Fig. 6. If a plateau for the SOBP is to be created, the second peak should not occur. Therefore, we realize that the minimum width of the groove of the ridge filter should be at least 0.5 cm. Figures 6(b), (c) and (d) show the dose distributions for heights of 3.5 cm, 4.0 cm and 4.5 cm, respectively. When the heights are 3.5 cm, 4.0 cm, and 4.5 cm, the SOBP sections are 8 cm, 9 cm, and 10 cm, respectively. We realized that when the height increased 0.5 cm, the length of the SOBP increased about 1 cm. Therefore, the height and the width of the groove of ridge filter are important parameters for determining the length and the plateau of the SOBP.

In a previous study, we obtained the physical dose with various depths in a water phantom for a ridge filter with broad beam components by using the FLUKA 2011 code. In order to verify the accuracy of the FLUKA results,

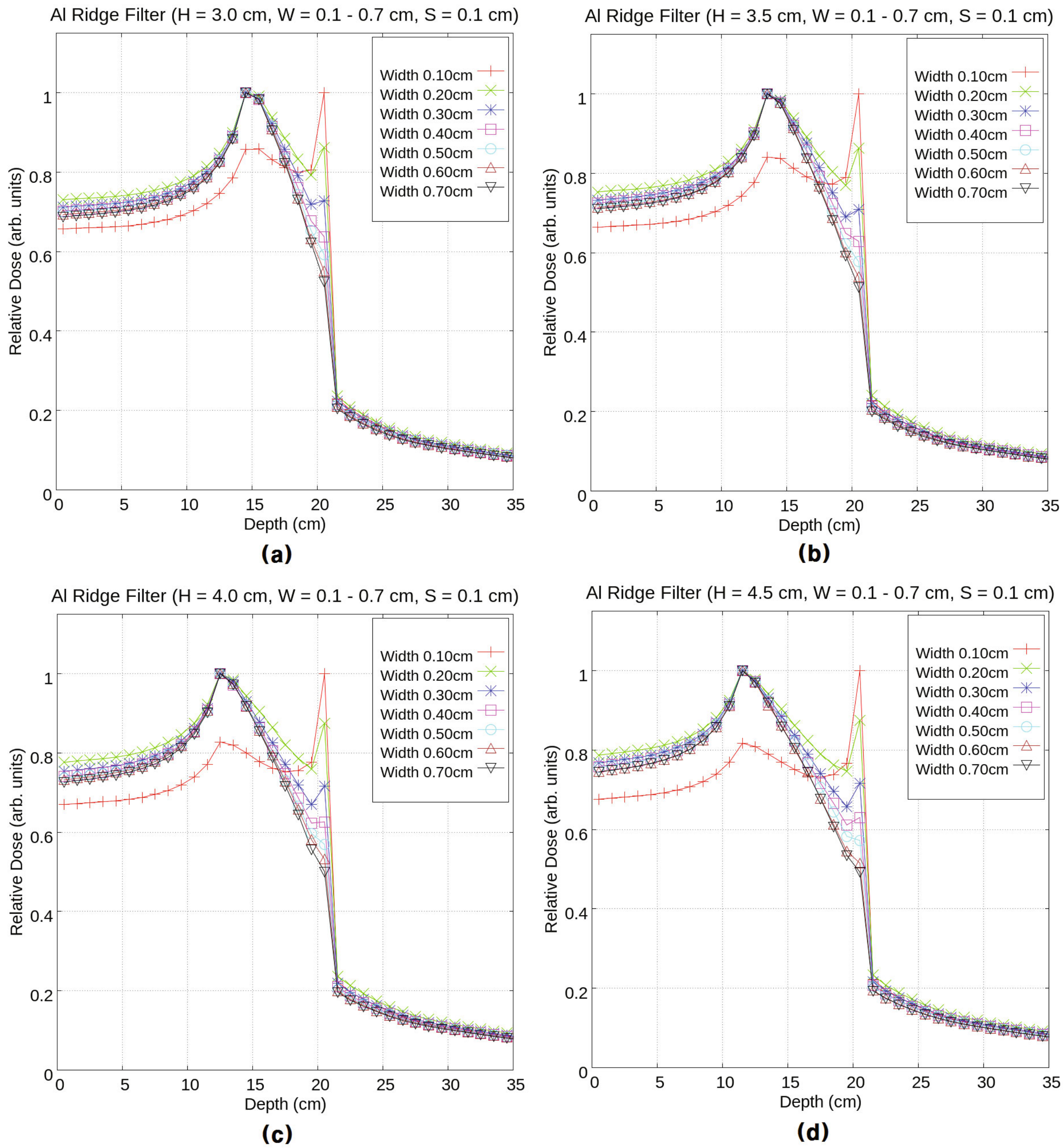

Fig. 6. (Color online) The physical dose distribution in a carbon-ion beam of 350 MeV/n was determined using the FLUKA 2011 code. The heights of the ridge filters are (a) 3.0 cm, (b) 3.5 cm, (c) 4.0 cm and (d) 4.5 cm. The width of the ridge filter was varied from 0.05 cm to 0.7 cm in intervals of 0.05 cm.

we carried out other simulations with the well-known GEANT4 code. The FLUKA and the GEANT4 results were compared. As shown in Fig. 7, the results are for ridge-filter heights of 3.0 cm, 3.8 cm, and 4.5 cm and widths from 0.4 cm to 0.7 cm in intervals of 0.1 cm. The physical doses of FLUKA and the GEANT4 were compared by normalizing the data to the maximum dose. The results showed that the average value of the difference was 3% and that the maximum percent error was 5%.

IV. CONCLUSION

In this study, we designed the major component of a broad beam for the SOBP, which is the ridge filter, by using Monte Carlo simulations with the FLUKA and the GEANT4 codes. Then, we calculated the physical dose distribution in a water phantom. Also we can know that the height and the width of the ridge filter are major parameters. In addition, in order to determine the accuracy of the results, we compared the FLUKA with the

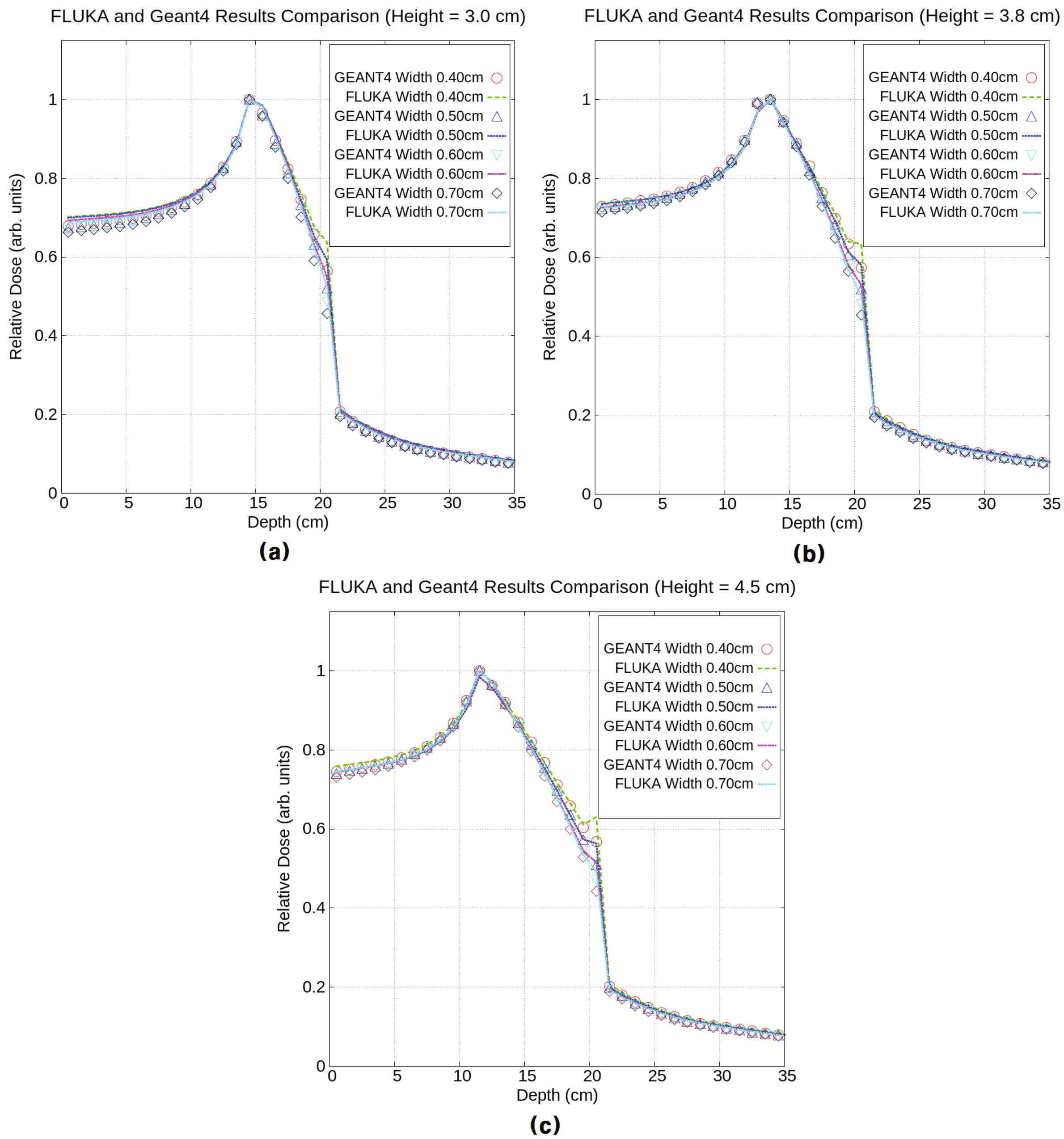

Fig. 7. (Color online) Data calculated by using the FLUKA and the GEANT4 codes are compared to the physical dose calculated. The heights of the ridge filter were (a) 3.0cm, (b) 3.8cm and (c) 4.5 cm.

GEANT4 results. We confirmed the presence of errors of up to 5%. The ridge filter we designed should be applicable to the KHIMA project by changing parameters, such as the height, width and spacing. We plan to simulate the linear energy transfer (LET) and the relative biological effectiveness (RBE) by using the FLUKA code. After we obtain the LET and the RBE, we will attempt to calculate biological dose.

ACKNOWLEDGMENTS

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government's Ministry of Science, ICT and Future Planning (MSIP) (201429534). Also this work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIP) (no. NRF-2014R1A1A3053958).

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