Carbon ion radiotherapy is known as a less invasive cancer treatment. The radiation quality is an important parameter to evaluate the biological effect and the clinical dose from the measured physical dose. The performance of SOPHIAS detector, which is the SOI image sensor having a wide dynamic range and large active area, was tested by using therapeutic carbon ion beam at Gunma University Heavy Ion Medical Center (GHMC). It was shown that the primary carbon and secondary particles can be distinguishable by SOPHIAS detector. On the other hand, a LET dependence was observed especially at the high LET region. This phenomenon will be studied by using the device simulator together with Monte Carlo simulation.

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1 Introduction

Carbon ion radiotherapy has attracted increasing attention recently as a minimally invasive cancer treatment due to its superior characteristics, such as a high linear energy transfer (LET) and a better dose localization \[1, 2\]. The biological dose can be obtained for the product of the physical dose and relative biological effectiveness (RBE) which depends on the LET \[3\]. The LET distribution is therefore a significant information to evaluate the clinical dose by using the measured physical dose.

A conventional broad beam method is applied to cancer treatment with the therapeutic carbon beam at Gunma University Heavy Ion Medical Center (GHMC) \[4, 5\]. Accelerated carbon ions are passively scattered by various beam line devices to form three-dimensionally dose distribution. Many secondary radiations are generated when primary carbon ions pass through various beam line devices. Thus the radiation quality of the patient-specific irradiation field is very complicated. Figure 1 shows the calculated LET distribution in the water by Monte Carlo simulation, GEANT4. In this simulation, primary carbon ions of 290 MeV/u pass through scatterer made of lead with a thickness of 2.3 mm and then enter water target. This result shows the amount of secondary radiations increase while that of primary carbons decrease in the water. A detailed LET measurement of therapeutic carbon ion beam offers new knowledge and information about carbon ion radiotherapy.

Figure 1: Calculated LET distribution in the water target by Monte Carlo simulation (GEANT4). Left and right represent the LET distribution at depth = 0 mm and depth = 120 mm (in front of Bragg peak), respectively.

SOI image sensor has a high spatial resolution and is relatively resistance to single event effects \[6\]. Especially, the SOPHIAS detector, which has a wide dynamic range and a large active area \[7\], could be a breakthrough dosimetric device in carbon ion radiotherapy. In this report, the experimental result with regard to the response of SOI image sensor to therapeutic carbon ion beam will be presented.
2 Experiment

The beam test of SOPHIAS detector was performed at vertical port of treatment room B in GHMC. Figure 2 shows the experimental setup. A water phantom was located at the upstream position of SOPHIAS detector. The thickness of water can be changed by remote control to measure the LET distribution at any depth easily. Mono-energetic carbon beam of 290 MeV/u with a nominal field size of 110 mm was used and the multi-leaf collimator was adjusted to protect the circuit. Beam intensity was reduced to 1/40 of treatment condition by using attenuator and adjusting the chopper parameters to suppress the multiple events in a single pixel. It was confirmed that the performance of the beam monitor which controls the irradiation dose kept stable even under the low beam intensity.

The back bias voltage and exposure time of SOPHIAS detector were set to 200 V and 100 µs, respectively. The sensor was cooled to around -5 °C by Peltier device. The active area of SOPHIAS with a pixel spacing of 30 µm is 26.73 mm × 64.71 mm (891 pixel × 2157 pixel). In this study, the data for 2/3 of active area was taken due to the limitation of read-out system. As a reference, the data under the same condition except for the beam intensity was taken by the parallel plane ionization chamber (PTW 34045).

![Figure 2: Experimental setup.](image-url)
Obtained images were analyzed with the image processing software, Image J v1.47. The signal above a threshold of 0.02 V was clustered as a "Particle". The "Area" and the "Sum" of pixel values were then extracted for each Particle. Figure 3 shows the example of image analysis.

![Image J example of image analysis](image)

Figure 3: Example of image analysis by ImageJ. Left shows the raw image frame obtained by SOPHIAS detector. Right represents the result of clustering shown in red.

3 Results and Discussion

Figure 4 represent the Area and Sum distribution at plateau and Bragg peak region. No significant peak structure can be found in Area histograms though the Area value increase slightly at Bragg peak. On the other hand, a major peak can be observed in the Sum histograms. The Sum value of the peak increase and the number of events decrease at Bragg peak region. These tendencies seem to be similar to the simulation result shown in Figure 1.

Another approach to investigate this major peak was performed by the estimation of the fluence. For simplicity, the number of events above the threshold set to the local minimum, e.g. 1 V for Figure 4(c) and 3.2 V for Figure 4(d), were evaluated at each depth. Figure 5 shows the evaluated fluence together with the simulation result as a function of depth in the water. The fluence of primary carbon ions decrease in the water while that of the secondary particles increase due to the nuclear reaction. The fluence of primary carbon immediately drop down to zero at the Bragg peak. Comparing the experimental result with simulation result, the major peak shown in Sum distribution can be identified as primary carbon ions.
Assumed that the generated electron by a radiation are corrected without any loss, the signal of each particle should be proportional to the amount of energy deposit. Thus the absorbed dose can be expressed as a sum of each signal. Obtained depth dose distribution normalized at 0 mmWEL is shown in Figure 6. Obviously, the signal reduction can be seen around the Bragg peak where the LET rapidly increase. In contrast, the relative dose beyond the Bragg peak is slightly higher than the result by the ionization chamber. These phenomena indicate the LET dependence of SOPHIAS detector.

Figure 7 shows some signal profiles for various depths and Sum values. It is found that the shape is not similar and maximum output seems to be about 0.25 V. It should be noted that the this output together with the pedestal ( <0.2 V ) is much smaller than the dynamic range. Though it is difficult to explain this phenomenon with this study, the recombination effects might be one possible candidate. More than a hundred million electron-hole pairs are populated in the 500 µm thick Si by the
Figure 5: Fluence as a function of water depth. Left shows the simulation result for primary carbon and major secondaries, helium and proton. Right represent experimental result for carbon candidates. WEL means a water equivalent length.

carbon ion at Bragg peak region. They could be diffused and recombined during the process of collection. The device simulator study is therefore necessary to understand this phenomenon.
Figure 6: Depth dose distribution. The solid line and closed circle represent measurement result by the ionization chamber and SOPHIAS, respectively. WEL means a water equivalent length.

Figure 7: Signal profiles for various depths and Sum values.
4 Summary

The experimental study regarding the response of SOI image sensor, SOPHIAS, to the therapeutic carbon ion beam was carried out. It was confirmed that the primary carbon can be identified with a high spatial resolution. This will be a great advantage for the precise quality assurance and R&D of new irradiation system. The gain reduction was found around the high LET region. This LET dependence will be studied by using device simulator in the near future.

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References

[1] H. Tsujii, and T. Kamada, ”A Review of Update Clinical Results of Carbon Ion Radiotherapy””, Jpn. J. Clin. Oncol. 42, 670-685 (2012).
[2] T. Ohno, ”Particle radiotherapy with carbon ion beams”, EPMAJ, 4, 9 (2013).
[3] T. Kanai, M. Endo, S. Minohara, et al., ”Biophysical characteristics of HIMAC clinical irradiation system for heavy-ion radiation therapy”, Int. J. Radiat. Oncol. Biol. Phys., 44, 201-210 (1999).
[4] M. Torikoshi, S. Minohara, N. Kanematsu et al., ”Irradiation System for HIMAC”, J. Radiat. Res., 48, A15-A25 (2007).
[5] T. Ohno, T. Kanai, S. Yamada, et al., ”Carbon Ion Radiotherapy at the Gunma University Heavy Ion Medical Center: New Facility Set-up”, Cancers, 3, 4046-4060 (2011).
[6] Y. Arai, T. Miyoshi, Y. Unno, et al., ”Development of SOI pixel process technology”, NIM A, 636, S31-S36 (2011).
[7] T. Hatsui, M. Omodani, T.Kudo , et al., ”A direct-detection X-ray CMOS image sensor with 500 µm thick high resistivity silicon”, Proceedings of the International Image Sensor Workshop (IISW), 12-16 (2013).