TIME RESOLVED RANGE MEASUREMENT FOR THE SLOW BEAM EXTRACTION

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Abstract

At the National Institute of Radiological Sciences (NIRS), we start cancer treatment with three-dimensional (3D) pencil-beam scanning technique in 2011 [1]. In the scanning technique, the spill ripple will disturb the lateral dose distribution. The RF-knockout (RF-KO) slow-extraction method with frequency modulation (FM) and amplitude modulation (AM) has brought high-accuracy irradiation to the treatment of a moving target with respiratory gating. Further, the spill structures strongly depend on the size of the chromaticity, and are quite difference in the frequency region of the transvers RF field [2]. For improvement of the extraction beam spill structure, sufficient amplitude of the synchrotron oscillation is effective, however the longitudinal distribution and momentum-center of the extracted beam change [3]. In addition to the stable spill, the accuracy of the beam energy/range is required for heavy ion treatment especially for using scanning method. ICRU78 recommend checking the range constancy for daily QA. Recommended relative accuracy of range measurements is less than 0.5 mm [4]. In this study, we have verified the range change caused by the beam delivery especially due to the betatron tune shift with several synchrotron parameters using the scintillator system.

INTRODUCTION

Carbon-ion therapy has been undertaken at various facilities around the world [5–7]. Since clinical trials using the Heavy-Ion Medical Accelerator in Chiba (HIMAC) were started in 1994, treatment for more than 10,000 patients has been successfully carried out with carbon beams. Cancer treatment with three-dimensional (3D) pencil-beam scanning techniques started in 2011 following the performance test of the fast scanning in the physics-experiment course (PH1) at HIMAC in 2008. This irradiation system for 3D pencil-beam scanning can provide treatment for a moving target by fast scanning irradiation. We migrated from hybrid scanning method (HS) to Energy scanning method (ES) in 2015. ES method employs more than 201 multiple beam energies supplied by synchrotron instead of the range shifter [8].

The main advantages of carbon-ion therapy are the reduced total energy deposited in the patient compared to photon techniques, and the finite range of the carbon beam. The range in tissue is associated with considerable uncertainties caused by imaging, the patient setup, the beam delivery and dose calculation [9]. Reducing these uncertainties would allow a reduction of the treatment volume and thus enable a better utilization of the advantages of particle therapy.

The NIRS scanning system makes the dose distribution with raster scanning method. In this method, the delivered dose is controlled in each small spot divided from the irradiation target region; however, the beam extraction is not stopped during shifting a target spot to the next. By keeping the extracted beam-intensity constant precisely, the NIRS scanning system controls the irradiation dose given between the spots. In addition, for fast scanning irradiation, it is desirable that the beam-intensity is modulated in each slice. To meet the requirements, we use a beam-intensity control system [10], which employ the RF-knockout (RF-KO) slow extraction method [11] with the feedback proportional-integral (PI) control.

IRRADIATION SYSTEM

RF-KO beam extraction method

The RF-KO slow-extraction method with frequency modulation (FM) and amplitude modulation (AM) has brought high-accuracy irradiation to the treatment of a moving target with respiratory gating, because of a quick response within 1 ms to beam start/stop. In order to suppress the spill ripple of the extraction beam, Noda et al. have investigated the extraction process through the RF-KO slow extraction with FM [2]. They conclude that the spill structures strongly depend on the size of the chromaticity, and are quite difference in the frequency region of the transvers RF field. For a further improvement of the extraction beam spill structure, Furukawa et al. have studied the contribution of the synchrotron oscillation to the spill ripple [3]. From a result of their study, sufficient amplitude of the synchrotron oscillation and uniform longitudinal phase distribution suppress the spill ripple. However, the longitudinal distribution and momentum-center of the extracted beam change during extraction.

Beam intensity control system

The intensity of the extracted beam is kept constant by controlling the amplitude of the transverse RF-field with the feedback system [12]. The system has a low-level RF generator with amplitude feedback control. The output energy and the reference intensity value are set from an irradiation control system. The actual intensity value is meas-

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ured by ionization chambers. The enable state of beam extraction is informed from an accelerator control system. In the beam-off period, the transverse RF-field is turned off, and the betatron tune is moved away from the resonance by exciting fast quadrupole magnets (QDSs). Their magnets are turned off at the start of extraction. However, then some particles having large betatron amplitude go out of the stable region at a stroke, and they are observed as a spill overshoot.

In the extended flattop operation, we execute the reinjection, as supplementation of the beam by redoing the injection. We have controlled its timing by setting certain thresholds of two variables. One is the circulating beam-current measured by the DC current transformer (DCCT) and monitored by the sequence controller. This is a simple scheme using the lower limit setting of the current. Another variable is the VCA gain within the feedback control unit in the RF controller.

Transverse Beam Preheating Method

In addition to the feedback control, the pre-extraction action (Preheating: PH) with duration 1000 ms before the irradiation is carried out for the enhancement of the stability and the repeatability of the beam spill in the start of the irradiation. During the PH, the beam dump shutter is closed not to deliver the beam toward the irradiation port while turning off the QDSa; therefore, the ionization chamber installed before the shutter is used for the feedback control of the extracted beam-current.

MEASUREMENT SYSTEM

A photograph of the scintillator system is shown in Figure 1. The system consists of a scintillator block, a Charg-coupled device (CCD) camera, and an opaque (black) box [13]. The light distribution is detected by the CCD camera. The optical path length between the scintillator and lens is 400 mm. The center of the scintillator was placed at the isocenter. An EJ-200 plastic scintillator block was selected as a pure transparent block with density similar to that of the human body, and a matching wavelength of maximum emission for the CCD camera was used. The size of the cylindrical scintillator block was 200 mm dia. × 20 mm thick. For shading the light from the treatment room, the scintillator was wrapped with a light blocking sheet. The CCD camera (Type BH-61M, 1932 × 1452 pixels, Bitran Corp., Japan) was installed on the light-shielding house. The spatial resolution of the system is 0.2 mm/pixels.

Measured two-dimensional images were processed by in-house program developed by c++. Figure 2 is a flow of the range detection. Figure 3 is an example of the two-dimensional depth brightness images. After the background correction and median filter, projection on one-dimensional axis is performed to reduce the noise and avoid the set up error. Figure 4 is an example of the projected distribution. In this work, threshold method (TH) was employed for range determination. The threshold positions set by 80% of maximum value on the projected line are identified. From our investigation, root mean square error of this system is less than 0.1 mm.

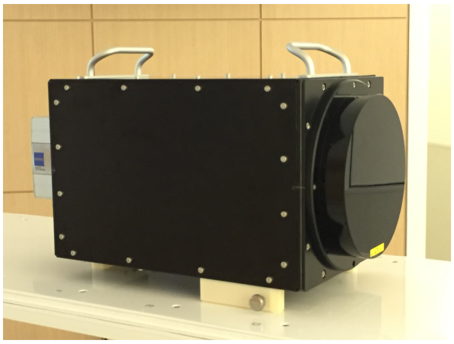

Figure 1: Layout of the scintillator system.

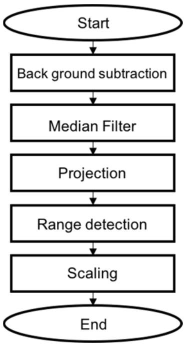

Figure 2: Flow of the range detection.

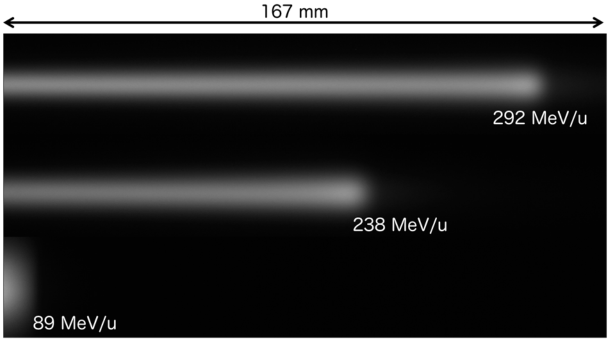

Figure 3: Example of the two-dimensional depth brightness distribution for 292, 238, and 89 MeV/u.

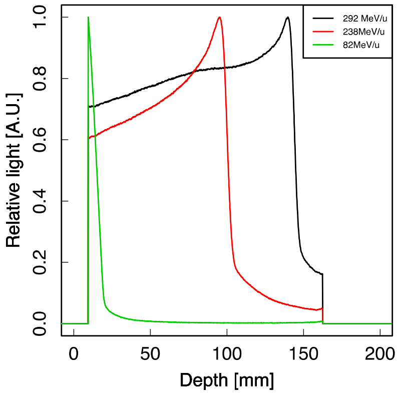

Figure 4: Example of the projected one-dimensional depth brightness distribution for 292, 238, and 89 MeV/u.

EXPERIMENTAL RESULT

Experimental setup

The experimental test was carried out with 89, 238, and 292 MeV/u carbon ion beam at HIMAC to confirm the range shift during the beam extraction. The scintillator system was placed at the isocenter of the horizontal beam port. To extract the all of the beam in the ring, flattop extended operation was employ for this measurement and the lower limit of the current for the injection was set to almost zero.

Beam intensity dependence

Measurement was performed at 0.3 and 0.8 ms intervals for high beam intensity and low beam intensity respectively. To conform the performance of the treatment beam, the effect of the PH was also investigate, as shown in Figure 5 and table 1.

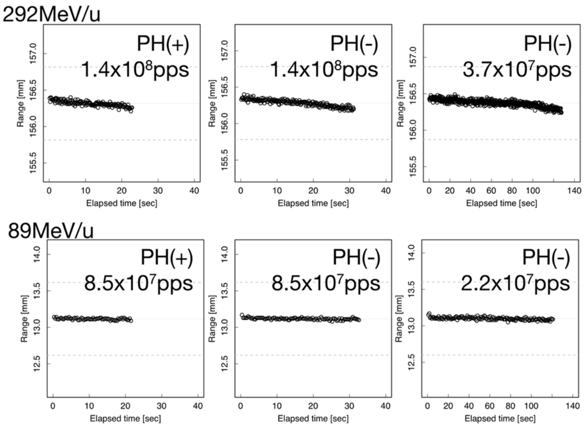

Figure 5: Time change of the beam range with low and high beam intensity.

Table 1: Summary of the Result for the Beam Intensity Dependence

Energy [MeV/u]	Preheat	Intensity [pps]	Min [mm]	Max [mm]	Difference [mm]
292	+	1.4x10^{8}	156.21	156.4	0.19
292	-	1.4x10^{8}	156.17	156.4	0.23
292	-	3.7x10^{7}	156.24	156.49	0.25
89	+	8.5x10^{7}	13.09	13.15	0.06
89	-	8.5x10^{7}	13.08	13.17	0.09
89	-	2.2x10^{7}	13.05	13.17	0.12

Chromaticity dependence

The effect of the chromaticity change for the 238 MeV/u carbon ion beam with beam intensity at 1.2×10^{8} pps was conformed. Measurement was performed at 0.3 ms intervals. Figure 6 shows the time change of the beam range for chromaticity -1, 0, and +1. Effect of the change of the chromaticity is shown in figure 7 and table 2.

CONCLUSION

In scanned carbon-ion therapy, range change during beam extraction is undesirable because it brings dose hot and cold spot inside the target volume. From the result, the amount of the range drift during the beam extraction was less than 0.3 mm. This relative range drift during extraction was according to the beam amount in the ring. The range drift were small for all chromaticity in this study, however, mean range was shifted by the chromaticity change. In practical, a small range drift during the extraction does not affect the dose distribution, however, the mean range shift by the chromaticity change become clinical problem.

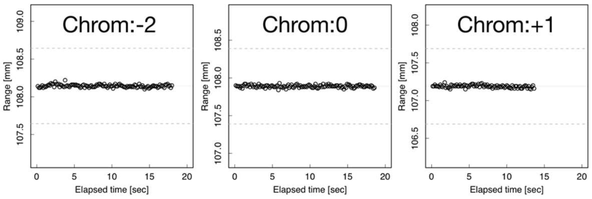

Figure 6: Time change of the beam range for the 238 MeV/u carbon ion beam during the beam extraction.

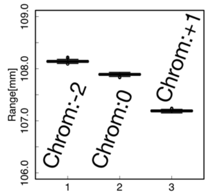

Figure 7: Box plot for the chromaticity dependence test.

Table 2: Summary of the Result for the Chromaticity Dependence

Energy [MeV/u]	Chromaticity	Min [mm]	Max [mm]	Difference [mm]
238	-2	108.09	108.22	0.13
238	0	107.84	107.93	0.09
238	+1	107.15	107.24	0.09

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