THE HIMAC BEAM-INTENSITY CONTROL SYSTEM FOR HEAVY-ION SCANNING

K. Mizushima[#], T. Furukawa, T. Shirai, S. Sato, Y. Iwata, K. Katagiri, E. Takeshita, K. Noda
National Institute of Radiological Sciences, Chiba, Japan

Abstract

Raster scanning irradiation has been carried out at a HIMAC new treatment facility in NIRS. In order to reduce the difference between prescribed and delivered dose distribution, the accurate beam-intensity control with a low ripple and the fast beam-on/off switching are strongly required. For this purpose, we have developed a new beam-intensity control system using the RF-knockout slow extraction. To keep the beam rate constant, this system controls the transverse RF voltage with the feedback proportional-integral control. As a result of the experimental tests, it was verified that this system can modulate the beam-intensity with a low ripple and can switch the beam-on/off with quick responses.

INTRODUCTION

The National Institute of Radiological Sciences (NIRS) has carried out carbon-ion radiotherapy for more than 5000 patients using the Heavy Ion Medical Accelerator in Chiba (HIMAC) since 1994 [1]. To upgrade the treatment irradiation, we have conducted the three-dimensional scanning irradiation [2] at a HIMAC new treatment research facility from May 2011.

The NIRS scanning system makes the dose distribution with a hybrid raster scan method [3] and various thickness polymethyl methacrylate (PMMA) plates, as range shifters. In the NIRS raster scanning, 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. Therefore, the NIRS scanning system controls the irradiation dose given between the spots precisely by keeping the extracted beam-intensity constant. We also require switching the beam-on/off any number of times during the irradiation attendant on in/out of the PMMA plates and the patient's respiration gate. In order to reduce the difference between the prescribed and actual dose, the beam spill ripple should be suppressed as low as possible, and the beam-on/off switching should be executed quickly. In addition, for fast scanning irradiation, it is desirable that the beam-intensity is modulated in each slice. To meet the requirements, we have developed a new beam-intensity control system, based on the past study [4]. This system uses the RF-knockout (RF-KO) slow extraction method [5] with the feedback proportional-integral (PI) control. In the experimental system tests, we could obtain the extracted beam-current with low ripple and the quick response to the beam-on/off switching. It was also confirmed that the system can modulate the beam-intensity in the range of thirty times while maintaining the stable time structure of the beam-current.

BEAM-INTENSITY CONTROL SYSTEM

System Overview

The beam-intensity control system is composed of the two transverse RF controllers, as RFC1 and RFC2 [6], and the sequence controller (SC), as presented in Fig. 1. The both RFCs work as the low-level RF generator and the RF feedback amplifier, as presented in Fig. 2. For the feedback control, the RFC1 and the RFC2 monitor the beam-current measured by the ion chamber and the secondary-electron monitor (SEM), respectively. The two measurement signals are input to the RFCs after digitizing them through the current-to-frequency converter (IFC) near each monitor. The fast quadrupole magnets (QDSs), which have been used to prevent the beam spilling out, are turn off synchronizing with the two RF-on status.

We have utilized multiple energy synchrotron operation with eleven energy-stairs [7] decelerated stepwise from 430 to 140 MeV/n for the scanning irradiation. The variable-energy controller (VE) extends a short flattop at the energy-stair requested by the irradiation control system (NIRR), which performs the scanner magnet control, the beam monitoring and the PMMA plate control, when a treatment irradiation starts.

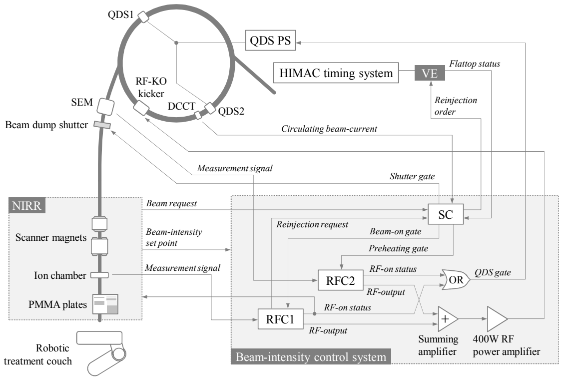

Figure 1: Diagram of a beam intensity control system.

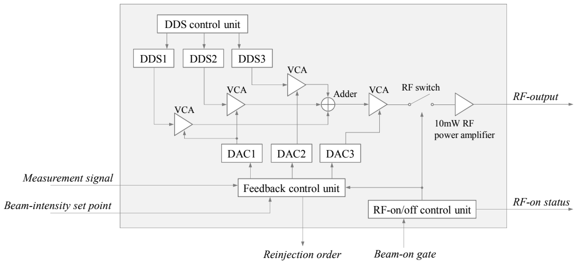

Figure 2: Scheme of transverse RF controller.

[#] mizshima@nirs.go.jp

In the extended flattop operation, we execute the reinjection, as the 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 SC. 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 RFC. When the VCA gain exceeds a threshold level over 20 ms, the reinjection request signal is sent to the SC, as presented in Fig. 3. Before conveying the reinjection order to the VE, the SC closes the beam dump shutter. The VE cancels the extension of the flattop through the timing system of the HIMAC, and after the injection, the irradiation is resumed. The reinjection is not executed while the feedback control of the beam-intensity is performed stably. This timing control method of the reinjection is flexible and stable, compared to fixed time control or simple monitoring of the circulating beam-current, even if the amount, the energy and the betatron tune of the beam fluctuate slightly in daily operation.

Transverse Beam Preheating Method

This feedback system takes the slow rise time and needs the long settling time of the extracted beam-current, when the beam-on operation is carried out for the small emittance beam after accelerating from injection energy, as presented in Fig. 4 (a). We had tried applying a feed-forward control in addition to the feedback; however, it was not negligible for our scanning irradiation that the overshoot and the delay of the beam-current generate occasionally, because of the non-repeatability pulse-by-pulse. In the case of the beam with the large emittance, the oscillatory behavior of the beam-current with high peaks lasts for a long time, as presented in Fig. 4 (b), and the beam-rate becomes uncontrollable.

We have introduced the transverse beam preheating method to our beam-intensity control system. This method enhances the stability and the repeatability of the beam spill in the start of the irradiation, by carrying out the pre-extraction action with duration of 500 ms before irradiation, as illustrated in Fig. 5. During the preheating, the beam dump shutter is closed not to deliver the beam toward the irradiation port while turning off the QDSs; therefore, the SEM installed before the shutter is used for the feedback control of the extracted beam-current. The SEM has the aluminum-coated polypropylene with the thickness of 1 micron as the target material. Since it permits the non-destructive measurement of the beam spill, the NIRS scanning irradiation is carried out while staying it in the beam line. We also have applied this method with duration of 200 ms to the beam-on after a long interval more than 5 s from the beam-off, because it sometimes induces the beam-current spike, as shown in Fig. 4 (c), by an emittance growth during the beam-off.

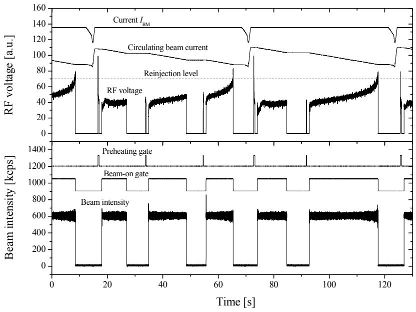

Figure 3: Reinjection timing control.

BEAM EXPERIMENT

We have carried out the experimental tests for the new beam-intensity control system, as summarized in Table 1. Their tests were performed using carbon $^{12}C^{6+}$ beams with energies of 430, 350 and 290 MeV/n. The beams continue to be bunched by the longitudinal RF-field during the flattop. The number of stored particles was 7 × 10^9 in the ring. We extracted them using the sextupole magnetic field and the third order resonance of 11/3.

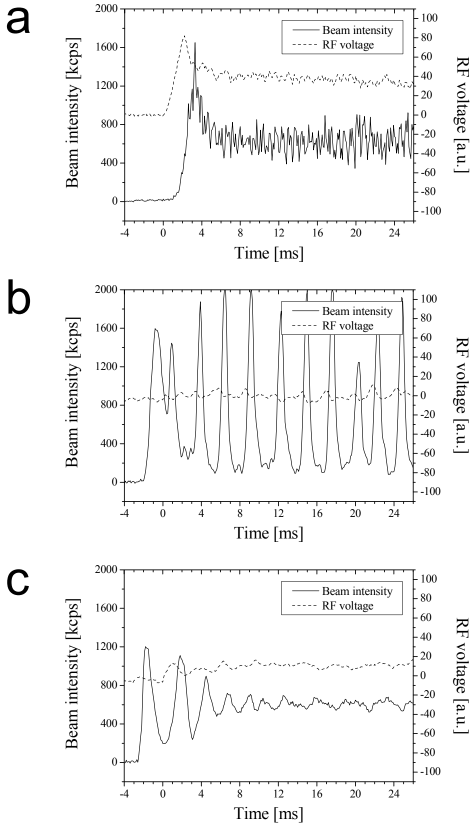

Figure 4: Typical results of beam current spike.

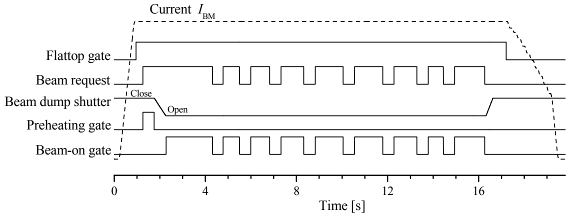

Figure 5: Transverse beam preheating.

Table 1: Experimental Parameters

Energy of $^{12}C^{6+}$	430 MeV/n	350 MeV/n	290 MeV/n
Betatron tune (Q_x/Q_y)	3.679/3.131	3.679/3.128	3.679/3.133
Revolution frequency	1.687 MHz	1.589 MHz	1.497 MHz
Extraction beam rate	7.6×10^6 - 2.3×10^8 pps	8.4×10^6 - 2.5×10^8 pps	9.3×10^6 - 2.8×10^8 pps
FM frequency of transverse RF-field	1.146 - 1.152 MHz	1.080 - 1.088 MHz	1.018 - 1.024 MHz
Single frequency of transverse RF-field	1.138 MHz	1.074 MHz	1.012 MHz

We tested the beam-on/off switching operation including the beam-intensity modulation, as shown in Fig. 6. The beam-intensity set points were varied with the range from 8×10^6 to 3×10^8 particles per second (pps) every 500 ms. Figure 7 represents the standard deviations of the extracted beam-current ripple for each beam-intensity. They were derived from 1 ms averaging value of data recorded with the sampling rate of 50 kHz. To evaluate the effect of the circulating beam-current, we indicate the error bars on Fig. 7 as the range of the standard deviation in the measurement results. The standard deviations of the beam spill ripple were mainly below 20%. In Fig. 8, we describe the fluence map of the measured beam-current on Fig. 6 at the timing of the beam-on/off switching.

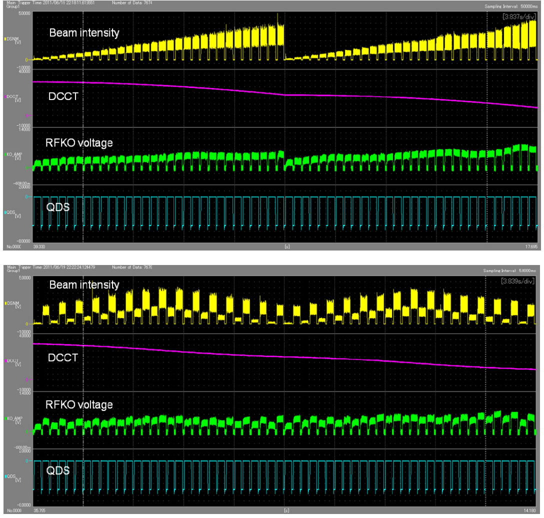

Figure 6: Typical results of beam intensity modulation.

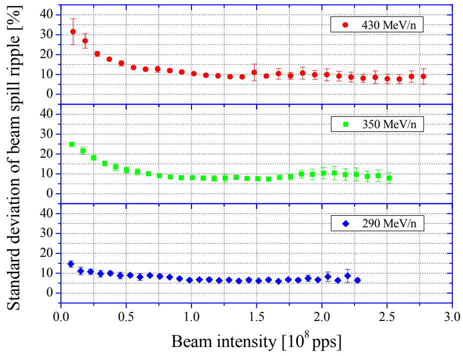

Figure 7: Beam current ripple for each intensity.

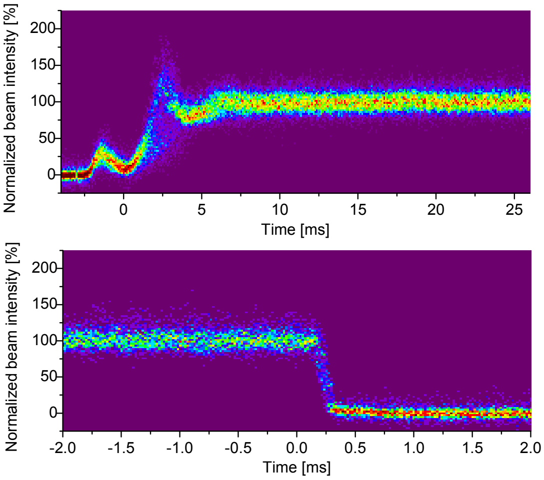

Figure 8: Response to beam-on/off switching.

Each beam-current is normalized with the beam-intensity set point. The rising time of the beam-current was around 3 ms from turning on the transverse RF-field. It was shut off within 0.3 ms from the beam-off order with turning off the transverse RF-field and exciting the QDSs.

CONCLUSION

We have developed a new beam-intensity control system. In the system tests, we could obtain the beam spill with low ripple below 20% while modulating the beam-intensity in the range of thirty times. The switching responses to the beam-on and off were 3 ms and 0.3 ms, respectively. It was allowable for our scanning irradiation.

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