RELIABLE BEAM-INTENSITY CONTROL TECHNIQUE AT THE HIMAC SYNCHROTRON

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Abstract

Short extraction called preliminary extraction has been added before irradiation in order to avoid an overshoot of the beam spill. A fast beam shutter was developed and installed in the extraction line to prevent the beam delivering to the patient during preliminary extraction. The fast shutter enables us to switch from preliminary extraction to irradiation in 100 ms, and the reliability of the beam-intensity control system was drastically improved by the preliminary extraction technique.

INTRODUCTION

In raster scan irradiation for charged particle cancer therapy, an upper limit of the beam intensity depends on the magnetic scan speed. The beam intensities beyond the limit cause extra dose deposition, which must be avoided for reducing the damage to normal tissues. Some therapy facilities, therefore, employ the feedback control system of the extracted beam intensity [1], and National Institute of Radiological Sciences (NIRS) in Japan is also one of them.

NIRS has carried out carbon-ion therapy with beam scanning [2] since May 2011. The carbon-ion beam is slowly extracted from the Heavy Ion Medical Accelerator in Chiba (HIMAC) synchrotron using the third-order resonance with the RF-knockout method [3]. The intensity of the extracted beam is kept constant by controlling the amplitude of the transverse RF-field with the feedback system [4]. 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. Their magnets are also 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. At the HIMAC synchrotron, it was often induced by a slight variation of the beam emittance in operation cycles. A typical figure of the spill overshoot is shown in Fig. 1. The high overshoot of the beam spill is capable of bringing dose hot spot inside the target volume, because the tolerable beam-intensity in scanning irradiation is low.

It is impossible to avoid the spill overshoot with the feedback control of the transverse RF-field amplitude, because the spill overshoot occurs even if the transverse RF-field remains turned off. Although the fundamental solution of this problem is the improvement of the operation repeatability, it is difficult to maintain the beam emittance with high accuracy on a long-term basis.

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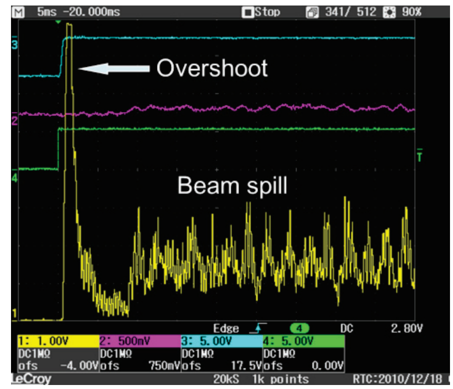

Figure 1: Typical overshoot of the beam spill at the start of extraction.

Accordingly, the required solution is a repeatability-independent way, such as the one which removes the uncontrollable spilled particles selectively.

We have added short extraction, called preliminary extraction (pre-extraction), as a technique for avoiding the spill overshoot. Before irradiation, the particles causing the spill overshoot are removed unfailingly from the synchrotron by pre-extraction. It is necessary to prevent the beam delivering to the patient during pre-extraction. In addition, for reducing the dead time, it is desirable that the switching between pre-extraction and irradiation performs in a short time. Therefore, a fast beam shutter was developed and installed in the HIMAC extraction line.

The spill overshoot was prevented in the experiment at the HIMAC, and the reliability of the beam-intensity control system was drastically improved by the pre-extraction technique. In this paper, we describe the pre-extraction system including the developed fast shutter and the experimental results.

PRE-EXTRACTION SYSTEM

System Layout

The pre-extraction system has been incorporated into a beam-intensity control system of the HIMAC synchrotron. A block diagram of the beam-intensity control system is shown in Fig. 2. An RF-knockout controller works as the generator and feedback amplifier of the low-level RF voltage. The reference and actual values of the beam intensity are provided from an irradiation control unit to this controller. The actual value is measured by an ionization chamber.

The pre-extraction control unit is a Programmable Logic Controller. This unit carries out the control of the

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beam shutter and the pre-extraction gate while receiving a gate signal, which indicates permission for extraction, from the HIMAC timing system. It also sends an irradiation enable signal to the irradiation control unit.

A schematic timing chart of the pre-extraction control is shown in Fig. 3. The beam is accelerated to the flattop energy, and the pre-extraction is performed with the beam shutter closed. The pre-extraction time is set to 200-400 ms. The beam shutter is opened as soon as the pre-extraction is finished. While driving the shutter, the beam extraction is paused. The irradiation to the patient is started when the beam shutter is completely opened. The irradiation is also turned off at the end of the flattop, and the beam shutter is closed.

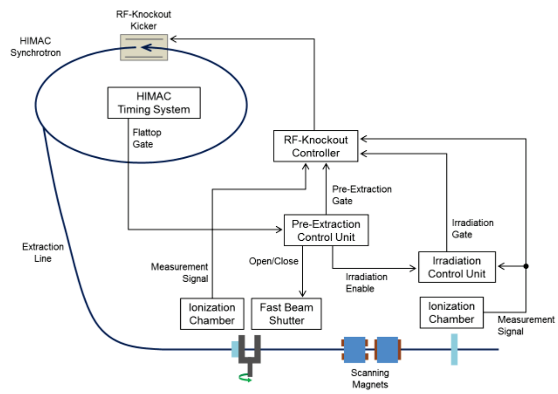

Figure 2: Block diagram of the beam-intensity control system at HIMAC.

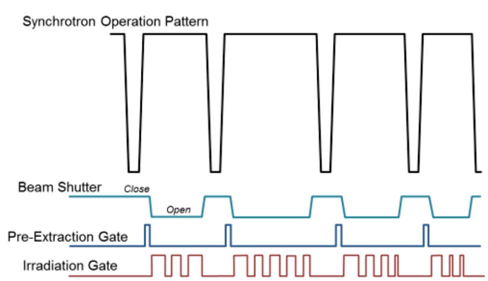

Figure 3: Schematic timing chart of the pre-extraction control.

Fast Beam Shutter

The fast beam shutter was developed to reduce the dead time produced by switching from pre-extraction to irradiation. The open/close-mechanism of this beam shutter is constructed with two parallel plates on a 90 degree rotary table, as shown in Fig. 4. The shutter plates and rotary table are made in integral structure by cutting an aluminum block. The magnetic fluid seal is used as a vacuum seal for a shaft which drives the rotary table. The driving mechanism of the shaft is a pneumatic rotary actuator. The space between the parallel plates on the rotary table is the beam aperture when the shutter is open.

An ionization chamber is mounted on one of plates in order to measure the beam intensity during the shutter closed period. Using the measured value with the ionization chamber, the beam intensity is controlled by the RF-knockout controller even during pre-extraction. The driving shaft is hollow, and the cables for the signal readout and high-voltage supply pass through the hollow shaft. The shutter plate and rotary table also have a through hole to connect the cables to the ionization chamber. The inside of the ionization chamber and hollow shaft is filled with air. The internal air is confined within the ionization chamber by closing an air valve, which is equipped on the middle of the shaft.

The driving time, which means all time spent on the open or close controls of the fast beam shutter, is estimated at about 100 ms from the specifications of the rotary actuator. The beam shutter enables us to switch from pre-extraction to irradiation with this driving time. It was installed in the HIMAC extraction line, as shown in Fig. 5.

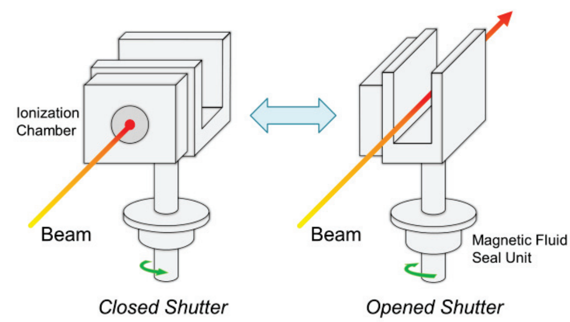

Figure 4: Schematic drawing of the fast rotary beam shutter.

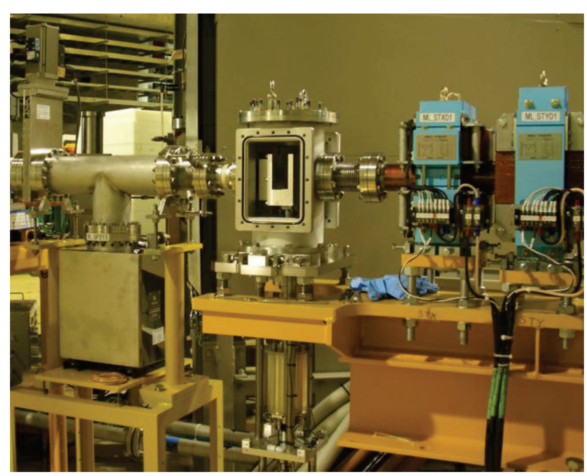

Figure 5: Photograph of the fast beam shutter installed in the HIMAC extraction line.

EXPERIMENTAL RESULTS

The experimental test was carried out with a 140 MeV/n carbon ion beam at HIMAC to confirm the performance of the developed beam shutter. The experimental parameters are given in Table 1.

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Table 1: Experimental Parameters

Energy of $^{12}C^{6+}$	140 MeV/n
Betatron tune (Q_x/Q_y)	3.68/3.13
Stored particle number	6×10^9
Extraction beam-intensity	1×10^8 pps

The beam extraction gates for pre-extraction and irradiation were opened alternately in the experimental test, as shown in Fig. 6. The intervals between the pre-extraction and irradiation gates were the times for driving the beam shutter and sequential processing by the pre-extraction control unit. The actual driving times were 104 ms and 101 ms for the opening and closing of the shutter, respectively.

The beam spill was measured with the two ionization chambers which are mounted on the beam shutter plate and placed in the irradiation port. Both values measured by these ionization chambers are sent to the RF-knockout controller. In Fig. 6, the beam intensity was kept constant at 1×10^8 particles per second (pps) during pre-extraction in addition to irradiation. It means that the two measurement values were successfully used for the feedback control of the beam intensity in the RF-knockout controller. In this experimental test, it was confirmed that the developed shutter prevented the beam delivering to the irradiation port during pre-extraction.

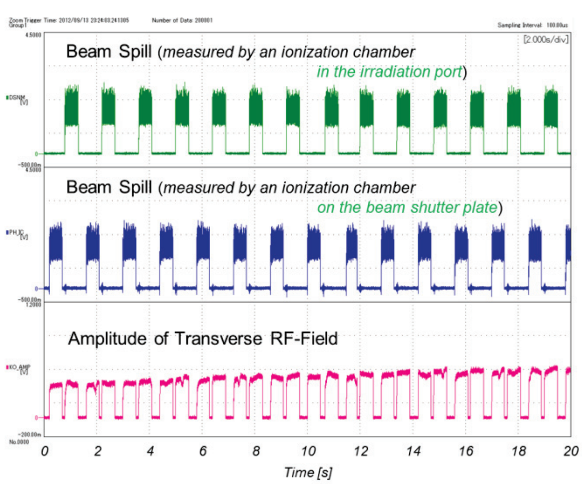

Figure 6: Experimental test of the fast beam shutter equipping the ionization chamber.

The effect of the pre-extraction technique was also verified by the beam experiment at HIMAC. Although the horizontal beam scraper in the synchrotron had been utilized to limit the beam size in the usual condition, it was not used in this experiment to confirm the pre-extraction effect clearly. The spill overshoot was observed without pre-extraction, as shown in Fig. 1. The horizontal beam emittance was surely over the separatrix area at the start of extraction due to the non-use of the scraper. Nevertheless, the generation of the spill overshoot was prevented by the pre-extraction technique, as shown in Fig. 7. The pre-extraction time was 200 ms. We could remove the particles causing the spill overshoot beforehand by pre-extraction. As a result, we could obtain the stable beam spill with a fast ramping.

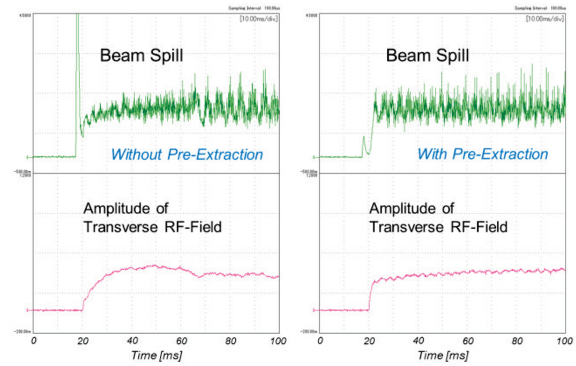

Figure 7: Comparison between the beam spills with and without pre-extraction at the start of extraction.

CONCLUSION

In slow beam extraction for scanned carbon-ion therapy, an overshoot of the beam spill is undesirable because it brings dose hot spot inside the target volume. The pre-extraction system was introduced into the HIMAC synchrotron to remove beforehand the particles inducing the spill overshoot. In addition, a fast rotating beam shutter was developed for the reduction of the dead time due to the pre-extraction technique, and it was installed in the HIMAC extraction line. The switching time, from pre-extraction to irradiation, of 100 ms was achieved by the developed shutter, and the reliable beam-intensity control was realized by the pre-extraction technique. This technique is also effective in the multiple-energy synchrotron operation [5], because it can prevent the spill overshoot induced by the emittance growth due to the stepwise beam deceleration.

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