EXTRA DOSE REDUCTION BY OPTIMIZING RF-KO SLOW-EXTRACTION AT HIMAC

K. Mizushima#, T. Shirai, T. Furukawa, S. Sato, Y. Iwata, K. Noda,
National Institute of Radiological Sciences, Chiba, Japan
H. Uchiyama, T. Fujisawa,
Accelerator Engineering Corporation, Chiba, Japan

Abstract

A 3D scanning method gated with the patient's respiration has been developed for the HIMAC new treatment facility. The RF-knockout slow-extraction method has been used during scanning irradiation, because of the quick response to beam on/off switching from the synchrotron. However, a small amount of beam that remained just inside the separatrix spill out even without the transverse RF field, which brings the extra dose. We have proposed a method which applies another RF-frequency component matched with the betatron frequency of the particles near the stopband in addition to the original transverse RF field. The particles just inside the separatrix can be selectively extracted during the irradiation; as a result, the extra dose can be also reduced. We measured it with an ion chamber, and could reduce to around 0.4 % compared to the original method.

INTRODUCTION

A 3D scanning irradiation [1-3] using carbon ion beams gated with the patient's respiration [4] was developed at HIMAC in NIRS, and can provide the high-dose concentration and relative biological effectiveness, even for irregularly shaped tumors. The irradiation requires the high irradiation accuracy and the quick response to beam on/off switching from the synchrotron. To meet the requirements of the irradiation, the RF-knockout (RF-KO) slow-extraction method [5] has been used. The method extracts the beam using the third-order resonance and the diffusion by the transverse RF field with frequency modulation (FM) which is matched with betatron frequency bandwidth in the separatrix. However, particles near the separatrix spill out even without the transverse RF field due to the momentum oscillation by the synchrotron motion [6] with the chromaticity, the emittance growth by the scattering with residual gas, and the current ripple of magnet power supplies. The particles induce the uncontrollable spilled beam [7], and bring the extra dose.

We have proposed to apply another transverse RF field with a single-frequency component (Mono-RF field) that is matched with the betatron frequency of particles near the stopband in addition to the original transverse RF field with FM (FM-RF field). The particles near the stopband can be selectively extracted using the proposed method during the irradiation. As a result, the particle density around the separatrix is lowered, and the extra dose can be reduced.

PARTICLE SIMULATION

The effect of the Mono-RF field is evaluated using the particle-tracking simulation. The parameters are summarized in Table 1. The FM-RF field functions to diffuse the beam which has the tune spread inside the separatrix by nonlinear field of sextupole magnets. The bandwidth corresponds to the horizontal betatron tune between 3.676 and 3.680.

Table 1: Simulation parameters

Beam	$^{12}C^{6+}$ 350 MeV/n
Betatron tune	(3.680, 3.113)
Momentum spread (1σ)	2.5×10^{-4}
Horizontal chromaticity	-0.5
Revolution frequency (f_{rev})	1.589 MHz
Longitudinal RF-frequency	6.355 MHz = 4 × f_{rev}
Frequency of FM-RF field	1.074 to 1.080 MHz
Frequency of Mono-RF field	1.069 MHz
Max kick angle by RF-KO	4.0 μrad

The simulation is carried out with the following conditions. First, the beam is extracted for 100 ms in stage (1), and is stopped for 30 ms in stage (2) by turning off the RF-KO voltage and exciting fast quadrupole magnets, which rapidly move away the horizontal tune from the resonance to prevent the beam from spilling out. The same scheme is used for the operation at HIMAC. Only the fast quadrupole magnets are turned off in stage (3). The simulation result is shown in Fig. 1 (a) using only the FM-RF field. It is found that particles spill out in stage (3), and the pulse width is 0.7 ms, which corresponds to the synchrotron frequency of 1.55 kHz owing to the momentum oscillation. The distribution of those particles in the normalized horizontal phase space just before stage (2) is seen as Fig. 2 (a). The particles remain just inside the separatrix. The Fourier spectrum of the horizontal position is shown in Fig. 2 (b). The simulation result applying the Mono-RF field is shown in Fig. 1 (b). The frequency of the Mono-RF field is matched with 1.069 MHz corresponding to the peak of Fig. 2 (b). As seen in Fig. 1 (b), the amount of the extra dose is reduced to 4.5 % of the case with only the FM-RF field.

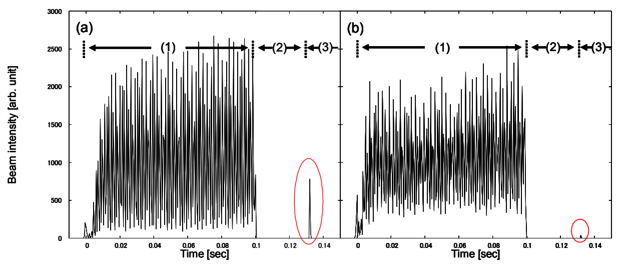

Figure 1: Simulation result of the extracted beam spill (a) with only the FM-RF field and (b) with the Mono-RF field in addition. Stage (1): Beam extraction for 100 ms. Stage (2): The beam off duration of 30 ms by turning off the RF-KO voltage and exciting fast quadrupole magnets. Stage (3): Only the fast quadrupole magnets are turned off.

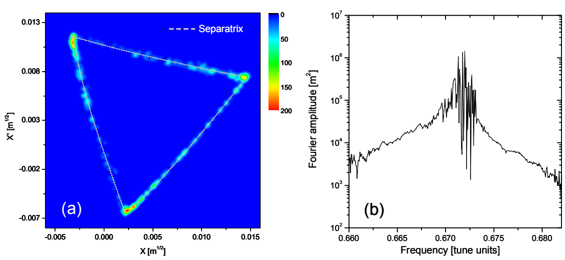

Figure 2: (a) Distribution of extra dose particles in the normalized horizontal phase space with the separatrix line of $\Delta p/p$ = 0 and (b) Fourier spectrum of the turn-by-turn horizontal position of those.

BEAM EXPERIMENTS AT HIMAC

In reality, the emittance growth due to the scattering with residual gas and the current ripple of the magnet power supplies also affect, but it is difficult to evaluate the effects by the simulation. Therefore, the beam experiments were carried out with $^{12}C^{6+}$, 350 MeV/n at HIMAC. The stored particle number was 1 × 10^{10} in the ring, and the extracted beam rate was 5 × 10^8 particles per second (pps). Just like the simulation, after the beam extraction gate of 1 s in stage (1) and the beam off duration of 1 s in stage (2), the fast quadrupole magnets were turned off remained the transverse RF field off in stage (3). The frequency of the FM-RF field ranged from 1.079 MHz to 1.082 MHz. The other conditions were equal to the parameters given in Table 1. The block diagram is shown in Fig. 3. There were two ion chambers at the end of the beam line used to measure the beam spill of the extra dose and for the feedback control of extracted beam intensity [8]. The extra dose beam was measured for 100 ms in stage (3). The measurement result of the beam spill extracted with only FM-RF field is shown in Fig. 4 (a). The beam rate of the extra dose was 7.6 × 10^8 pps. The feedback system kept the extraction beam rate constant in stage (1) by controlling the RF-KO voltage. In addition, we measured the beam profile utilizing a non-distractive 2D beam profile monitor [9] in the HIMAC synchrotron in order to investigate the effect of the Mono-RF field on the beam density distribution.

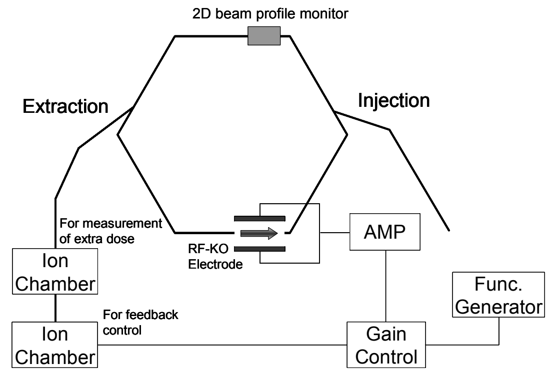

Figure 3: Block diagram of the measurement setup.

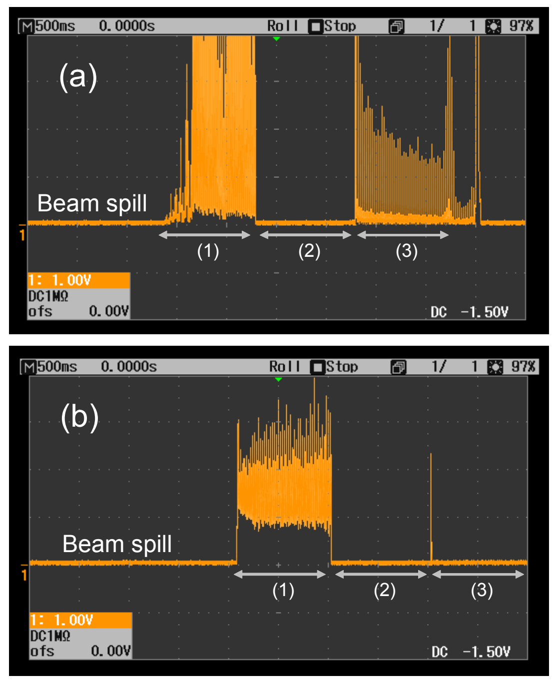

Figure 4: Extracted beam spill and extra dose beam measured by an ion chamber (a) with only the FM-RF field and (b) with applying the Mono-RF field, when the frequency of the Mono-RF field was 1.074 MHz and the voltage ratio between the Mono- and FM-RF fields was 4.

Figure 5 (a) shows the dependence of the extra dose beam rate on the frequency of the Mono-RF field. The frequency ranged from 1.072 MHz to 1.075 MHz corresponding to the horizontal betatron tune from 3.675 to 3.677. The voltage ratio between the FM- and Mono-RF fields was 1:1. The dotted line indicates the beam rate of the extra dose with only the FM-RF field. It was clearly suppressed by the addition of the Mono-RF field. The optimal frequency was 1.074 MHz corresponding to the horizontal tune of 3.676, while the stopband tune was 3.670. Figure 5 (b) shows the dependence of the extra dose beam rate on the voltage ratio, when the frequency of the Mono-RF field was 1.074 MHz. It became 3 × 10^6 pps with the voltage ratio of 1:5.3, which is 0.4 % of that observed in the case of the FM-RF field alone. Figure 4

(b) shows the beam spill with the voltage ratio of 1:4. It is found that the extra dose beam was greatly reduced by using the proposed method compared to Fig. 4 (a).

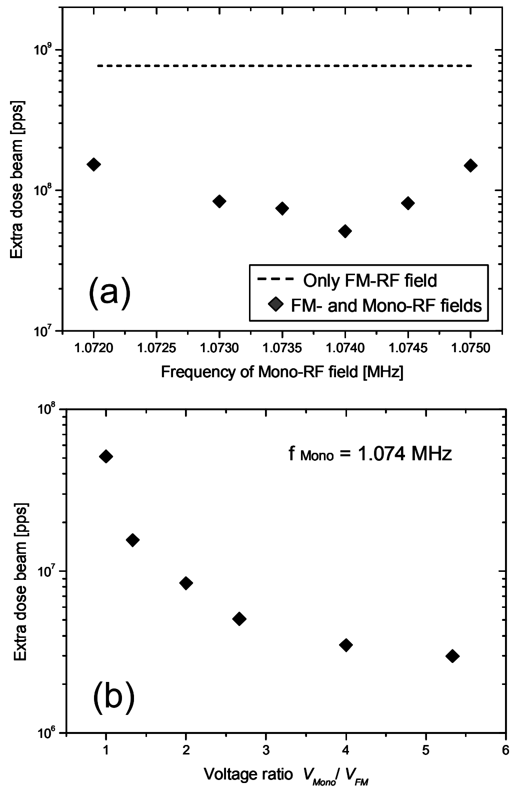

Figure 5: Dependence of the extra dose beam rate on the frequency of the Mono-RF field (a) and on the voltage ratio between the FM- and Mono-RF fields (b).

The measurement result by the non-distractive 2D beam profile monitor and the horizontal density distribution are show in Fig. 6. The monitor uses an oxygen gas-sheet target, which is 85 mm in width and 1.3 mm in thickness. The measurement duration was 0.3 ms during the extraction. Figure 6 (a) shows the 2D beam profile with only the FM-RF field, (b) shows that with applying the Mono-RF field with the voltage ratio 1:5.3, and (c) is the horizontal projection of those. The horizontal profile tail of (b) becomes smaller compared to that with only the FM-RF field of (a).

CONCLUSIONS AND OUTLOOK

For the 3D scanning irradiation, the extraction method with the accurate control of the exposure dose has been developed at HIMAC. We improved the RF-KO slow-extraction method by using the proposed approach with the Mono-RF field. Particles which bring the extra dose were reduced by applying the RF-frequency component matched with the betatron frequency of those. We could reduce to around 0.4 % of that observed with the original method by optimizing the parameters. We also confirmed that the horizontal tail of the beam profile during the extraction became smaller.

This method will be also effective for a multiple-level-flattop operation [10], which enables variable energy extraction during one operation cycle of the synchrotron, because it can suppress the beam loss due to the emittance growth that occurs during deceleration.

ACKNOWLEDGMENTS

We would like to express their thanks to the members of the Accelerator Engineering Corporation for their skilful operation of the HIMAC accelerator complex, and are grateful to Dr. Y. Hashimoto in KEK for his support concerning the non-distractive 2D beam profile monitor.

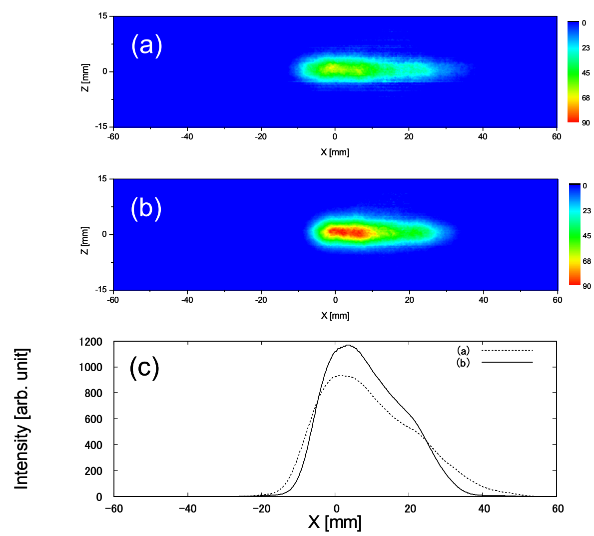

Figure 6: Measurement results by the 2D non-distractive beam profile monitor (a) with only the FM-RF field and (b) with adding the Mono-RF field with the voltage ratio of 1:5.3. The dotted line and the solid line in (c) show horizontal profiles of (a) and (b), respectively.

REFERENCES

[1] T. Inaniwa et al, Med. Phys. 34, 3302-3311 (2007).
[2] T. Furukawa et al, Proceedings of EPAC08, Genoa, Italy, pp. 1794-1799, (2008).
[3] T. Inaniwa et al, Nucl. Instr. and Meth. B 266 (2008) 2194.
[4] S. Minohara et al, Int. J. Radiat. Oncol. Biol. Phys. 47 (4) (2000) 1097.
[5] K. Noda et al, Nucl. Instr. and Meth. A 492 (2002) 241.
[6] T. Furukawa et al, Nucl. Instr. and Meth. A 489 (2002) 59.
[7] K. Mizushima et al, submitted to Nucl. Instr. and Meth. A.
[8] S. Sato et al, Nucl. Instr. and Meth. A 574 (2007) 226.
[9] Y. Hashimoto et al, Nucl. Instr. and Meth. A 527 (2007) 289.
[10] Y. Iwata et al, Proceedings of EPAC08, Genoa, Italy, pp. 1800-1802, (2008).