# PROGRESS OF RF-KNOCKOUT EXTRACTION FOR ION THERAPY

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## *Abstract*

At HIMAC, the RF-knockout slow extraction method has been utilized to treat cancers moving with the respiration of the patient owing to a faster response of the transverse RF field. Considering the usage of the slowly extracted beam through the RF-knockout method for the beam scanning irradiation method, a lower ripple of the beam spill and a faster response to the beam on/off are necessary. From this point of view, the source of the spill-ripple was investigated. As a result, the beam ripple was successfully suppressed less than ±20% through the advanced RF-knockout method. In addition, the fast beam switching is carried out. This paper reports the progress of the RF-knockout extraction at HIMAC for the ion therapy.

## 1 INTRODUCTION

Heavy-ion beams have attracted growing interest for cancer treatment due to their high dose localization at the Bragg peak as well as high biological effect there. At HIMAC (Heavy Ion Medical Accelerator in Chiba) [1], clinical trials of heavy ion therapy started on June 1994, and treatments of more than 1100 patients had successfully been completed by April 2002. The RF-knockout slow extraction method makes treatments possible for cancers moving with the respiration of the patient owing to a faster response of the transverse RF field [2]. However, this method brings a huge ripple with a frequency around 1 kHz related to the repetition of the frequency modulation (FM). Considering the usage of the slowly extracted beam through the RF-knockout method for the beam scanning irradiation method [3], on the other hand, the beam spill should have a low ripple less than ±20%, because the spill-ripple may disturb the lateral dose distribution in the irradiation. In addition, the response time of the beam off should be smaller than at least 1% of the shortest irradiation time of one spot.

From above-mentioned requirements, we have studied the source of the spill-ripple in the RF-knockout extraction in order to suppress the ripple [4]. In addition, the extracted beam after turning off the transverse RF field have also been studied to reduce the unwanted dose in the scanning technique [5]. As the results of these studies, it was consequently found that the tune oscillation due to the horizontal chromaticity and the synchrotron oscillation contributes to beam extraction as well as an amplitude growth due to the transverse RF field. Also the source of the spill-ripple during one period of the FM became clear. The advanced RF-knockout method that can supply a lower ripple less than ±20% was proposed and verified [6].

A new beam cut-off method was realized by turning off the transverse and longitudinal RF fields at the same time. This method allows us to obtain a very fast response of the beam off around 50 μsec. The fast beam switching based on the fast beam cut-off method was also tested. This paper reports the progress of the RF-knockout extraction at HIMAC for the ion therapy with experimental results.

## 2 RIPPLE IMPROVEMENT

### *2.1 Source of the spill-ripple*

Owing to the amplitude dependence of the horizontal tune in the third-order resonance, there are two tune regions in the extraction process through the RF-knockout slow extraction with FM: (1) Extraction region; when the frequency of the transverse RF field matches with the tune region near to the boundary of the separatrix, the particles there can be spilled out from the separatrix due to the betatron-amplitude growth through the resonance of the transverse RF field. (2) Diffusion region; when the RF frequency matches with the tune region deeply inside the separatrix, the particle there are diffused toward the boundary of the separatrix.

At HIMAC, therefore, the frequency of the transverse RF field was modulated with saw-tooth wave to cover those two regions of the tune spread. The frequency of the transverse field was swept from 1118 kHz to 1133 kHz, corresponding to the horizontal tune of 3.676 and 3.685. Other experimental conditions are summarized at Table 1. Considering the two tune regions, when the frequency of transverse RF field matches the tune of the

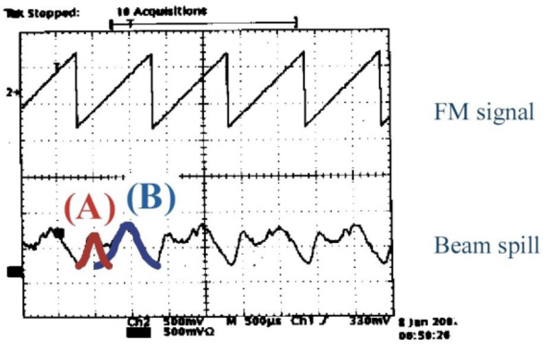

Figure 1: The beam spill in the case of large chromaticity ~ -3.2.

Table 1 Main parameters of the RF-knockout extraction

| | |
|---|---|
| Energy of $C^{6+}$ | 400.0 MeV/u |
| Tune (Qx/Qy) | 3.681/3.130 |
| Frequency of FM | 977.5 Hz |
| Max. Kick angle of RF kicker | 2.0 μrad |
| Field strength of sextupole field | |
| $K_2$ (SXFr1/2) | 1.644 $m^{-3}$ |
| $K_2$ (SXDr1/2 | 1.978 $m^{-3}$ |
| Revolution frequency | 1.653 MHz |
| Voltage of longitudinal RF field | 4 kV |
| Frequency of synchrotron oscillation | 1.455 KHz |
| RF bucket-height (Δp/p) | $\pm 1.06 \cdot 10^{-3}$ |

extraction region, the particles will be extracted. This was verified in the small horizontal chromaticity around +0.2. In the large horizontal chromaticity around –3.2, however, the beam was also extracted even when the frequency of the transverse field does not match the extraction region as shown peak (B) in Fig. 1. From this point of view, it is considered the chromaticity and the synchrotron oscillation contribute to the beam extraction as well as transverse heating through RF-knockout. It was clearly observed, further, that the tune oscillation play an important role to reduce the spill-ripple. This effect was clearly seen in fast beam cut-off method described in section 3.

### *2.2 Advanced RF-knockout method*

Applying an RF field with mono-frequency that matches with the extraction region, the spill has no ripple in neglecting current ripple of the main power supply, because the amplitude growth rate is taken as almost constant due to satisfying the resonance condition. On the other hand, we should diffuse the particles deeply inside the separatrix in order to extract all particles in the ring during a single flattop. Therefore, the frequency bandwidth for the diffusion of the particles in the diffusion region is generated through the dual FM method [6], and the RF field having the mono-frequency that matches with the extraction region is additionally applied for the beam extraction. The typical frequency spectrum of the transverse RF field is shown in Fig. 2, and typical beam spill in this method in Figs. 3. We can supply a beam with a low ripple of less than ±20% as shown in Fig. 3 (b). Further details about this new method will appear in ref. [6]. The global beam spill as shown in Fig. 3 (a) will be easily flattened by the usage of the feedback control.

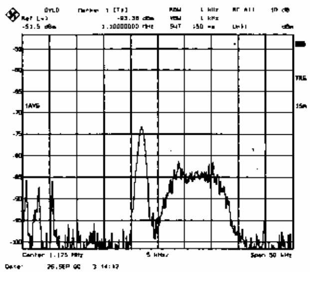

Figure 2: Typical spectrum of the transverse RF field in the advance RF-knockout method.

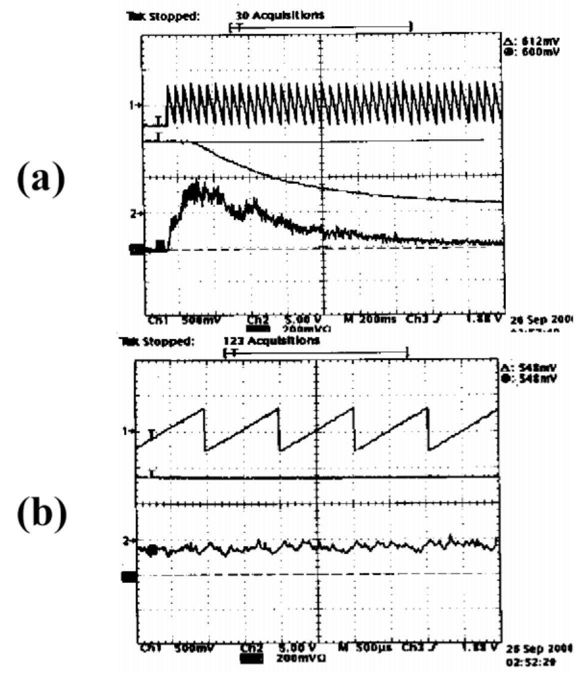

Figure 3: Typical beam spill in the advanced RF-knockout method. (a): 200 msec/div, (b): 500 μsec/div.

## 3 FAST BEAM CUT-OFF METHOD

In a synchrotron ring with slow extraction, a particle spilled out from a separatrix needs a few hundred turns to reach the extraction channel. Therefore, the cut-off time is mainly limited by this excursion time. At the HIMAC synchrotron, the cut-off time is estimated around 60 μsec, corresponding to 100 turns, by analytic approach [7]. In turning off only the transverse RF field, however, the cut-off time has been observed to be 700 μsec, corresponding to around 1100 turns, at maximum. The cause of this difference became clear as mentioned below.

As mentioned in section 2.1, it was found that the tune oscillation contributes to the beam extraction. Based on the result of the study, a new beam cut-off method has been proposed and realized by turning off the transverse and longitudinal RF fields at the same time. The typical experimental result, as shown in Figs. 4, is in good agreement with the simulated result. When only the transverse RF field is turned off, as can be seen Fig. 4 (a), the cut-off time is estimated to be around 700 μsec, corresponding to one period of the synchrotron oscillation. On the other hand, when both the transverse and longitudinal RF fields are simultaneously turned off, as can be seen in Fig. 4 (b), the cut-off time is estimated to be around 50 μsec. Description of this new method is discussed in ref. [5].

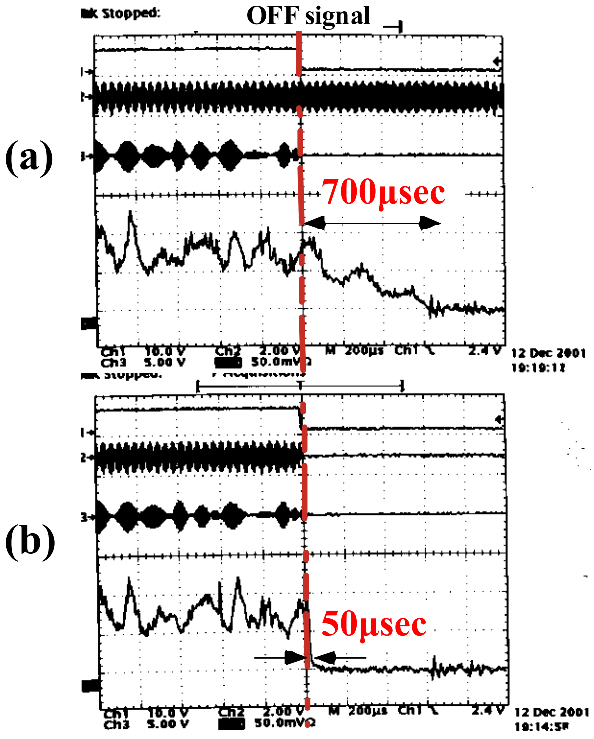

Figure 4: Experimental results of the beam cut-off (a) in turning off only the transverse RF field and (b) in turning off both the transverse and longitudinal RF fields.

## 4 PRELIMINARY TEST RESULTS OF FAST BEAM SWITCHING

It is necessary to turn the beam on/off according to the beam request from a spot-scanning system as many times during a single flattop, and to deposit precise numbers of particles into different spots toward practical usage of the fast beam cut-off technique. In the test, we turned the beam on/off up to 20 times during a single flattop. Concerning the response to the beam on in the proposed method, we have planned an adiabatic recapture with the beam on signal to keep the condition of the extracted beam constant. The voltage of the longitudinal RF field was swept linearly from 0 to 4.0 kV just after the beam on signal. The rising time is set to be 20 msec, corresponding 30 times of the period of the synchrotron oscillation. In the case of adiabatic recapture as shown in Fig. 5 (a), the beam spill changed slowly back into normal, because the longitudinal RF amplitude is slowly increased. On the other hand, in the case of sudden turn-on the longitudinal RF field, the restart of the beam extraction is quite fast as 100 μsec shown in Fig. 5 (b), because the particles near the boundary of the separatrix still stay in the ring owing to the usage of the fast beam cut-off method. We will soon demonstrate to deposit precise number of particles into different spots for precise dose management of the spot-scanning.

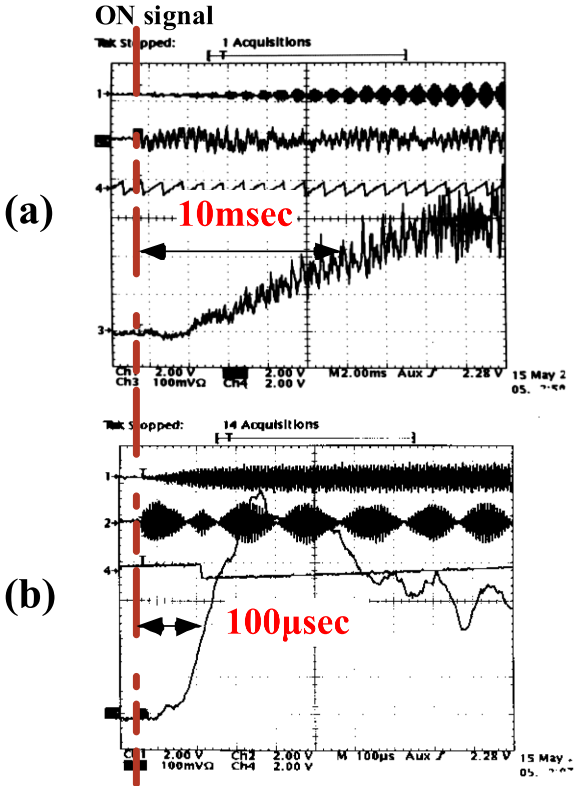

Figure 5: Response of beam on (a) with adiabatic recapture, (b) with sudden turn-on of the longitudinal RF-field.

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