INSENSITIVE METHOD TO POWER SUPPLY RIPPLE IN RESONANT SLOW EXTRACTION

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Abstract

The betatron tune fluctuation due to the current ripple of power supplies brings the beam spill ripple through the separatrix area variation in the resonant slow extraction. The amount of the separatrix area variation due to the tune ripple depends on the difference between the bare and the resonant tune, and the strength of the multipole magnet producing the separatrix. We proposed a method based on the theoretical calculation in order to suppress the effect induced by the tune ripple. The method is to set the bare tune away from the resonance while keeping the separatrix area. We measured the correlation between the beam spill ripple and the bare tune by adding the tune ripple generated artificially. We confirmed the reduction of the beam spill ripple by the proposed method.

INTRODUCTION

The resonant slow extraction method [1,2] has been used for the various purposes which need the beam current over several seconds. The method is often required to keep the beam rate constant during the extraction as well as the beam position and size. The RF-knockout slow extraction method [3] has been used for the raster scanning irradiation [4] in the cancer therapy at the Heavy Ion Medical Accelerator in Chiba (HIMAC) because of the quick response to the beam on/off switching, the stability of the beam position and size. The raster scanning irradiation method requires the low beam rate extraction for several ten seconds and the stable beam spill structure with the lower ripple. But, the power supply ripple of the magnets in the synchrotron ring prevents to meet the requirements. The betatron tune fluctuation due to the ripple brings the beam spill ripple through the separatrix area variation. The separatrix area depends on the difference between the bare and the resonant tune, and the strength of the multipole magnet producing the separatrix; therefore, the amount of the separatrix area variation due to the tune ripple also depends on those. In order to suppress the beam spill ripple due to the effect of the power supply ripple, a method based on the theoretical calculation using the simplified model and the particle-tracking simulation was proposed. The method is to up the multipole magnetic strength, while keeping the separatrix area, by setting the bare tune away from the resonance. We quantitatively measured the correlation between the beam spill ripple and the bare tune using the third-order resonance and the RF-knockout slow extraction method by the experiment at HIMAC. The experiment was carried out by means of the artificially generated tune ripple with low and high frequency components of 67 Hz and 1167 Hz near those of the real current ripple: 50 Hz and 1200 Hz. We verified the reduction of the beam spill ripple by the proposed method. The experimental results were compared to those of the theoretical calculation and the simulation.

THEORETICAL CALCULATION

The separatrix area A produced by the third-order resonance and the sextupole magnetic field [5] is defined as

$$A = 48\sqrt{3}\pi \frac{q^2}{S^2} \tag{1}$$

$$q \equiv Q_x - Q_{res} \tag{2}$$

where Q_x is the horizontal bare tune in a linear lattice, Q_{res} the resonance tune, S the sextupole magnetic strength. It assumes that the betatron tune fluctuates with the ripple frequency f and amplitude $a \geq 0$.

$$q(t) = q_0 + a\sin(2\pi f t) \tag{3}$$

If the condition $(\Delta q/q)/(\Delta S/S) >> 1$ is satisfied, the separatrix area also varies by the tune fluctuation as

$$\frac{dA(t)}{dt} = 96\sqrt{3}\pi \frac{q(t)}{S^2}\frac{dq(t)}{dt}. \tag{4}$$

The beam is extracted with the rate of b particles per second (pps) using the RF-knockout slow extraction method and the beam rate is kept constant without the tune ripple effect. We can define the speed v_a of the fluctuated separatrix line and the diffusion speed v_b of the beam by the transverse RF field as

$$v_a = \frac{1}{l}\frac{dA(t)}{dt} \tag{5}$$

$$v_b = \frac{b}{\sigma l} \geq 0 \tag{6}$$

where l is the length of the separatrix line, and σ the average particle density near the separatrix. The beam spill ripple is generated due to the separatrix area variation through the tune ripple. If the condition $v_b \geq v_a$ is satisfied, the extracted beam current $N(t)$ fluctuates as the following.

$$N(t) = q_c e(v_b - v_a)\sigma l \tag{7}$$

where $q_c e$ is the charge of the beam particle. The tune ripple amplitude a is usually quite small compared to q_0. Therefore, we can write as

$$N(t) = q_c e\left(b - 4\pi\sigma A_0 \frac{fa}{q_0}\cos(2\pi f t)\right) \tag{8}$$

$$A_0 \equiv 48\sqrt{3}\pi \frac{q_0^2}{S^2}. \tag{9}$$

The power spectrum intensity Y of the tune ripple frequency f component in the beam spill is written as

$$Y \propto \left(\frac{\sigma A_0}{q_0} fa \right)^2 \tag{10}$$

In many real cases, the separatrix area A_0 is determined by the initial distribution of the revolution beam in the horizontal phase space and the extraction condition. Therefore, the method which is to set the bare tune away from the resonance while keeping the separatrix area is effective for the reduction of the beam spill ripple.

PARTICLE SIMULATION

The particle-tracking simulation is carried out with the parameters summarized in Table 1 in order to verify the correlation between the tune ripple effect and the bare tune, and compare the result to that expected by Eq. (10). The longitudinal conditions are those of the bunched beam. The bare tune Q_x is changed from 3.680 to 3.695 so that the separatrix area is kept constant. The resonant tune Q_{res} is 11/3. The effect of the tune ripple is given by the thin lens quadrupole magnets placed every cell. The tune ripple form is the sine wave with the frequency of 50 Hz which is equal to that of the industrial frequency. The ripple amplitudes of the tune are 1×10^{-4} and 2×10^{-4}. The beam is extracted by the transverse RF field using the RF-knockout slow extraction method. The voltage of the filed is determined so that the beam rate is approximately constant without the tune ripple. The simulation results of the extracted beam spill are shown in Fig. 1. The extraction duration is 500 ms. It is found that the ripple amplitude of the beam spill in Fig. 1 is suppressed by setting Q_x away from the resonant tune of $11/3$. The power spectrum intensity of the frequency component of 50 Hz in the beam spill is shown in Fig. 2. The dotted line in Fig. 2 is the damping curve expected by Eq. (10). It is found that the simulation result corresponds with that expected by the theoretical calculation.

BEAM EXPERIMENT AT HIMAC

We carried out at HIMAC experiment using a fully stripped carbon $^{12}C^{6+}$ beam with energy 250 MeV/n. The experimental parameters are summarized in Table 2. The number of stored particles in the ring was 1×10^{10}, and the extraction beam rate was 1×10^8 pps. The bare tune Q_x is changed from 3.677 to 3.689. The block diagram is shown in Fig. 3. We added the tune ripple effect artificially for the quantitatively measurement using the fast quadrupole magnets of two units which were symmetrically placed in the ring. The effect generated with a sine wave function was inputted the power supply of the fast quadrupole magnets. The frequency components of the added ripple were 67 Hz and 1167 Hz because those of the real ripple were mainly 50 Hz and 1200 Hz which were contributed to the industrial frequency and the 24-phase rectifier. The revolution beam was extracted by the transverse RF field using the third-order resonance and the RF-knockout slow extraction method. The field had frequency modulation which was matched with the tune spread of the beam in the separatrix. The ion chamber was placed at the beam line end for the measurement of the beam spill and the feedback control of the extraction beam current. The extracted beam rate was kept constant by the feedback system which controlled the voltage of the transverse RF field. Although the time constant of the feedback control was 0.1 ms, the feedback system controlled using the integration average of the measurement value during 100 ms in order to prevent that the feedback control reacts the beam spill ripple induced by the artificially tune ripple.

Table 1: Simulation parameters

Beam	$^{12}C^{6+}$ 250 MeV/u
Particle number in the ring	1×10^5
Horizontal tune	3.680 – 3.695
Horizontal chromaticity	– 1.0
Momentum spread (1σ)	2.5×10^{-4}
Revolution frequency	1.423 MHz
Frequency of artificially ripple	50 Hz

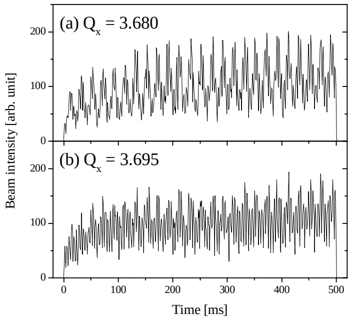

Figure 1: Simulation results of the beam spill extracted by the RF-knockout slow extraction method in the case of (a) $Q_x = 3.680$ and (b) $Q_x = 3.695$. The tune ripple is the frequency of 50 Hz and the amplitude of 2×10^{-4}.

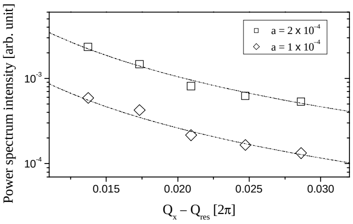

Figure 2: Simulation result of the correlation between the bare tune and the power spectrum intensity of the frequency 50 Hz component in the beam spill. The dotted line is the damping curve expected by Eq. (10).

The experimental result of the correlation measurement between the bare tune and the power spectrum intensity of the frequency component of 67 Hz and 1167 Hz in the extracted beam spill is shown in Fig. 4. The resonant tune Q_{res} was $11/3$. The horizontal tune Q_x was changed from 3.680 to 3.695. The sextupole magnet strength was also changed so that the separatrix area was maintained. The separatrix area was evaluated by the profile of the extracted beam and the theoretical calculation. The statistical errors were measured using some beam spills which were extracted during 6 s. The experimental result corresponded with the dotted which was the damping curve expected by Eq. (10) as well as simulation. The Experimental results of the extracted beam spill are shown in Fig. 5 for the comparison. The frequency ripple amplitude of 67 Hz component in the beam spill was suppressed clearly by the method which is to set Q_x away from the resonance. However, there was an upper limit of the tune Q_x and the sextupole magnet strength to maintain the high efficiency of the beam extraction. Exceeding the limit, the beam loss of the extraction increased suddenly because the separatrix was gotten close to the deflecting electrode owing to the large turn separation every three turns. Therefore, it is preferable from the aspect of the use that the horizontal tune Q_x is set near the upper limit, but below it.

CONCLUSION

The constant beam current from the synchrotron ring are often required in the resonant slow extraction. However, the power supply ripple of the magnets in the ring prevents to meet the requirements by inducing the fluctuation of the separatrix area. We confirmed the ripple effect using the RF-knockout slow extraction method with the third-order resonance and the artificially induced tune ripple at HIMAC experiment. We could suppress the effect by setting the bare tune away from the resonance and upping the sextupole magnetic strength, while keeping the separatrix area. The method is effective for other resonant extraction methods, which use other orders of the resonance and multipole magnetic field, without the improvement of the power supply.

Table 2: Experimental parameters

Beam	$^{12}C^{6+}$ 250 MeV/u
Particle number in the ring	1×10^{10}
Horizontal tune	3.677 – 3.689
Horizontal chromaticity	– 1.0
Momentum spread (1σ)	2.5×10^{-4}
Revolution frequency	1.423 MHz
Frequency of artificially ripple	67 Hz, 1167 Hz
Tune amplitude of artificially ripple	6.0×10^{-6}, 1.2×10^{-5}

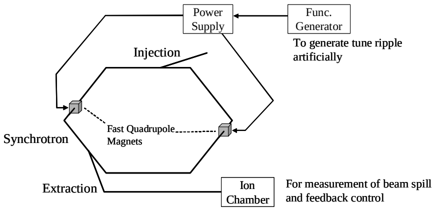

Figure 3: Block diagram of experimental setup.

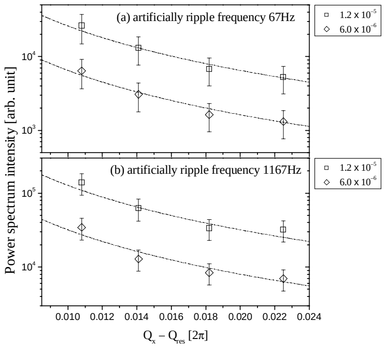

Figure 4: Experimental results of the correlation between the bare tune and the power spectrum intensity of the frequency (a) 67 Hz and (b) 1167 Hz components in the beam spill. The dotted line is the damping curve expected by Eq. (10).

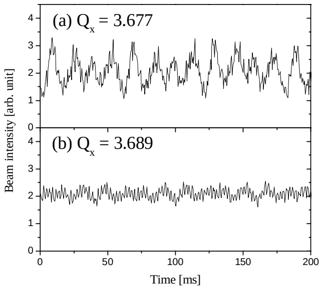

Figure 5: Experimental results of the beam spill extracted by the RF-knockout slow extraction method during 200 ms in the case of (a) $Q_x = 3.677$ and (b) $Q_x = 3.689$. The artificially tune ripple frequency is 67 Hz, and the amplitude is 1.2×10^{-5}.

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