MEASUREMENT OF THE BEAM RESPONSE TO QUADRUPOLE KICK BY USING STRIPLINE PICKUP MONITOR AT J-PARC MAIN RING

Y. Nakanishi, A. Ichikawa, A. Minamino, K. G. Nakamura, T. Nakaya, Kyoto University, Japan
T. Koseki, H. Kuboki, M. Okada, T.Toyama, KEK, Japan

Abstract

In high intensity proton synchrotrons, linear and nonlinear betatron resonances cause beam loss. When the betatron tune spreads over a resonance line, the betatron oscillation amplitude will get larger, causing large beam loss. Our study aims for a direct measurement of the betatron tune spread by using a quadrupole kicker and a four-electrode monitor. The monochromatic RF signal is transfered to the kicker and we induce an oscillation by kicking the beam. The amplitude of the quadrupole oscillation will depend on the number of particles having a certain tune. In the beam test at J-PARC MR, the dipole kicker was used as a quadrupole kicker by exciting the two facing electrodes in-phase. We measured the response to the kick at several frequencies. We observed that the amplitude of the quadrpole oscillation depends on the kicker frequency and the number of particles per bunch. This demonstrates that the quadrupole oscillation can be induced by a kicker and the possibility of measuring the number of particular tune particles from the response. We will present the result of the beam test and our prospect and the comparison between the experimental result and a numerical calculation.

INTRODUCTION

J-PARC, Japan Proton Accelerator Research Complex, has a high intensity accelerator. J-PARC accelerator consists of three parts, LINAC (Linear accelerator), RCS (3 GeV Synchrotron) and Main Ring (30 GeV Synchrotron).

It is important to consider the beam loss upon increasing the beam power [1,2]. The beam loss is caused by the coherent motion and the incoherent motion of the beam. The incoherent motion is mainly induced by space charge, and this effect make the incoherent tune spread. In J-PARC, tune spread has estimated by not a direct measurement but a simulation. If tune spread can be measured, we can know a betatron bare tune which makes tune spread smaller than under current operation.

We aim for measuring tune spread caused by the space charge effect in this measurement. The response by a normal quadrupole kicker was measured in J-PARC MR.

When the beam run under an unideal operation, for instance the injection mismatch and the error field effect, the beam circulates involving the small quadrupole oscillation. After the injection, the beam width gradually increases until it becomes stable. Kickers, which use monochromatic RF signal and make the normal quadrupole force, kick the beam and induce the quadrupole oscillation.

THE METHOD OF MEASUREMENT

This measurement was carried out on J-PARC MR. Table 1 shows the parameter of the used beam.

Table 1: Beam Parameter

Horizontal tune	22.40
Vertical tune	20.75
Revolution frequency	185743.5Hz

Table 2: Kicker Setting Parameter

Maximum power	3kW×2
RF frequency	222854 Hz, 215854 Hz, 208854 Hz, 201854 Hz, 194854 Hz, 247615 Hz
Kicker angle	102μrad / m / turn

Table 3: Beam Intensity

	The number of protons per bunch
(I)	$0.99(\pm0.01)\times10^{13}$
(II)	$1.28(\pm0.01)\times10^{13}$
(III)	$1.39\ (\pm0.02)\times10^{13}$

Two power amplifier are connected to kickers. The maximum power is 3 kW for each amplifier. Three kickers are arranged in series. The kicker consists of two electrodes in the vacuum pipe. We use it as a dipole kicker in the usual operation, but in this measurement, as a quadrupole kicker by exciting the two facing electrodes in-phase [3]. The beam passes through the kicker, particles having a certain tune oscillate larger. The relationship between a resonance tune of particles and the kicker RF frequency is given by Eq. (1), (2). [4]

$$2\nu_x = n_x \pm f_{RF}/f_{rev} \qquad (1)$$

$$2\nu_y = n_y \pm f_{RF}/f_{rev} \qquad (2)$$

$\nu_{x,y}$ is betatron tune in x and y direction, $n_{x,y}$ is an integer, f_{RF} is the kicker RF frequency, and f_{rev} is revolution frequency in MR.

The response is measured by four-electrode monitor [5]. Table 2 shows the parameters of kicker operation. Maximum power is sum of three kicker power. Two means the number of electrodes in each kicker. The angle gradient per turn is 102 μrad/m in this quadrupole kicker. The beam was kicked after 1s from the beam injection. This is because the beam is affected by the injection mismatch and the beam largely oscillates just after the injection. Figure 1 shows the schematic view of kicker setup. The signal from a signal generator, AFG3252 Textronix, was separated by power splitter, Mini-circuits ZFSC-2-6+. The signal was amplified by R&K A101 K101- 6565R RF Power Amplifier. Data was taken in 0.2s by an oscilloscope, LECROY-HDO6104-MS. The measurement starts before 0.04s from the beginning of kicker operation. Sampling rate was 2.5×10^8Hz, and ADC bit was 12bit. 8329-300 w/Blower made by Bird Electronic Corporation was used for an attenuator.

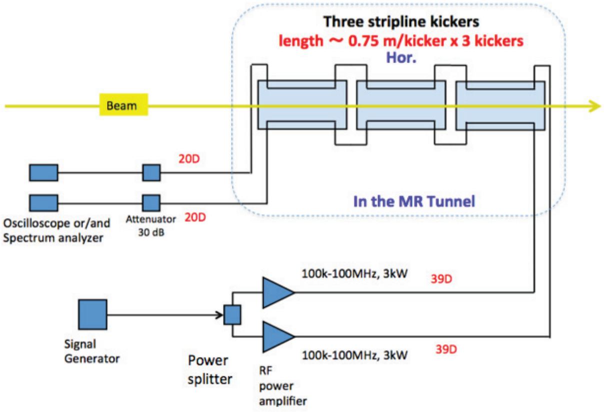

Figure 1: Schematic view of kicker setup.

Data was taken three times in each parameter setting. The value in Table 3 is the number of particle in starting to measure the data. The beam loss was existed, and particles vanished by $0.02 \times 10^{13} protons$ in the condition (I), $0.05 \times 10^{13} protons$ in (II), $0.08 \times 10^{13} protons$ in (III). This change realized by changing the thinning ratio [6]. This measurement was carried out on six RF frequencies indicated in Table 2. The parameter was corresponded to the blue line in Figure 2. The RF frequency of quadrupole kicker can be transferred to tune by Eq. (1) and (2). Tune spread is represented by the black area in Figure 2 [7]. The tune spread is calculated by Space Charge Tracking Program. The condition is shown in Table 4. The six frequencies were chosen not to cross over the RF kicker resonance line in both x and y direction.

Other Measurements

We measured on the two conditions:

(a) Beam was not injected, and kicker RF turns on.
(b) Beam was present in the ring, and kicker RF turns off.

The measurement in the (a) condition is for checking whether there is an unpredicted path through which the kicker RF signal propagates to electrodes.

Table 4: Beam Parameter in the Simulation

Power	200kW
The number of particles	1.33×10^{13} protons per bunch
Emittance in x direction	$16\,\pi\, mmmrad\ (2\sigma)$
Emittance in y direction	$24\,\pi\, mmmrad\ (2\sigma)$
Bunching factor	0.2
Betatron bare tune	(22.4, 20.75)

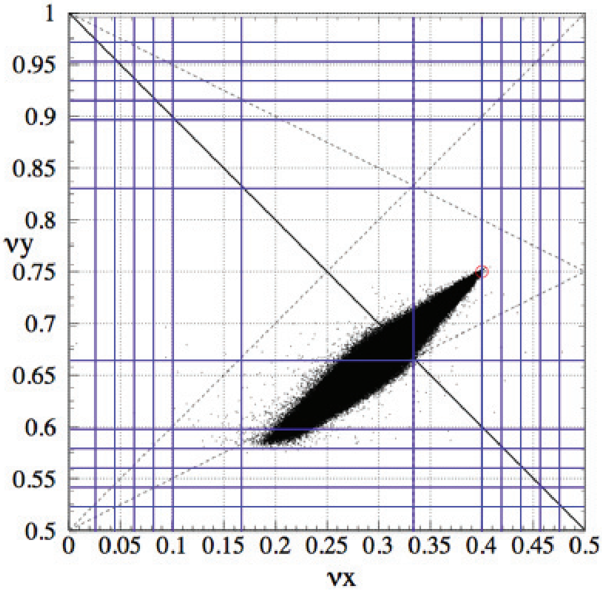

Figure 2: Tune spread diagram and the kicker RF resonance line. Horizontal axis is tune in x direction, and vertical is in x direction.

THE SIGNAL PROCESSING

One set of the data includes four channels, 371476 pulses per pulse included in the data from the oscilloscope. First, the data is divided into a bunch. The period is 5.384μs for a turn. Each data has 37147 turns. Second, the data was changed by Fourier transform. The time window is 5.384μs, the period for sampling is 4ns. We got the Fourier spectrum and the peak is existed and $V_i (i = 1,2,3,4)$ is defined by the height of the peak. Normal quadrupole moment is calculated by Eq. (3) [8]. V_1, V_2, V_3 and V_4 correspond the signals of right, left, up, down.

$$Q = (V_1 + V_3 - V_2 - V_4)/(V_1 + V_3 + V_2 + V_4). \qquad (3)$$

The sensitivity factor is $K_Q = 237.4[1/m^2]$ in this monitor, where $Q = K_Q \times (<x^2> - <y^2>)$.

Q was transformed with Fourier transform. Time window is 0.1599[s].

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RESULT

Figure 3 shows the frequency spectrum of turn by turn Q when the kicker RF frequency is 247615Hz. The horizontal axis is frequency[Hz] and the vertical axis is the Fourier power.

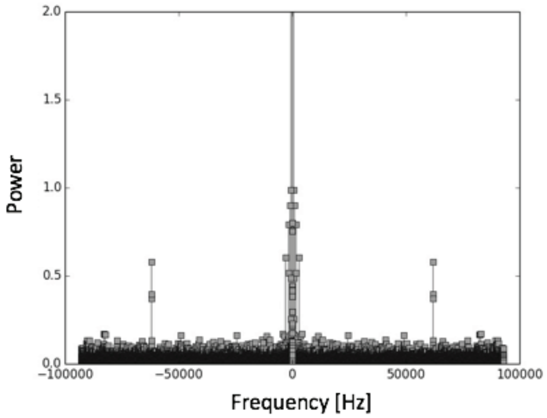

Figure 3: Frequency spectrum of the turn by turn quadrupole moment (29715turn).

In another measurement (a), Q has no mean. The Fourier transformed signal had no peak around the kicker RF frequency. We can conclude that the signal transferred from a kicker to electrodes is small enough not to consider the contribution.

The result of the measurement (b) is shown in Figure 4. From (b) measurement, the signal didn't have a peak around the RF frequency. This can conclude that the peak was induced by kicker RF. Furthermore, it turns out that the quadrupole oscillation occurred by injection mismatch is undetectable.

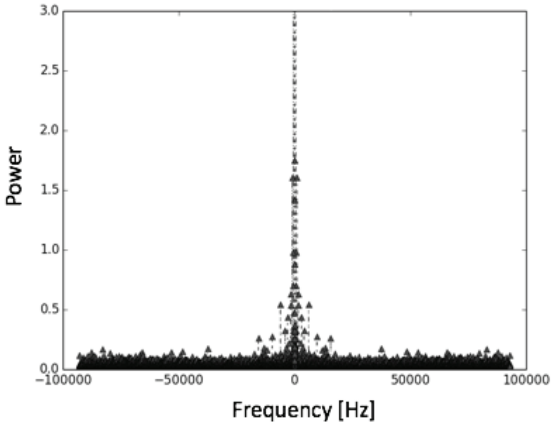

Figure 4: Frequency spectrum of the turn by turn quadrupole moment in measurement (b).

DISCUSSION

The frequency of Fourier peak almost corresponds to the predicted one calculated by Eq. (4).

$$f_{pre} = f_{kicker} - f_{rev} \tag{4}$$

f_{pre} is the predicted frequency of peak in the frequency spectrum. f_{kicker} is the frequency of the kicker RF. f_{rev} is revolution frequency of the beam in the ring.

The predicted frequency calculated by Eq. (4) is 61879.5Hz in the case that the kicker RF frequency is 247615Hz. On the other hand, the frequency in the three measurement is all 61886.8Hz. The measured frequency is larger than predicted value by 7~9Hz. This gap comes from some or one possible reasons, which can be considered unstable kicker RF, unstable revolution frequency, the band width of Fourier transformation ~6.25Hz, the effect of beam optics.

The peak height is defined as q_{peak}. This Fourier power at the frequency spectrum peak corresponds to the amplitude of quadrupole oscillation.

Figure 5 shows the relation of q_{peak} and the frequency of kicker RF in (II).

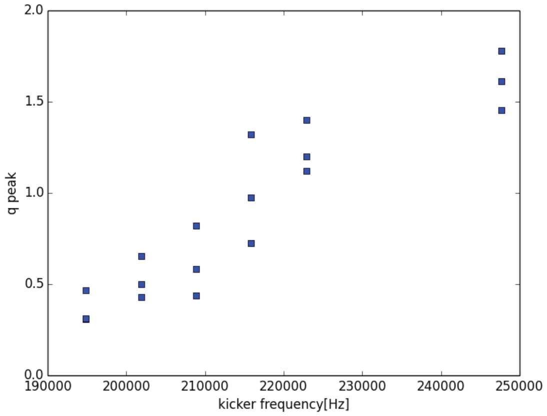

Figure 5: The intensity of quadrupole resonance.

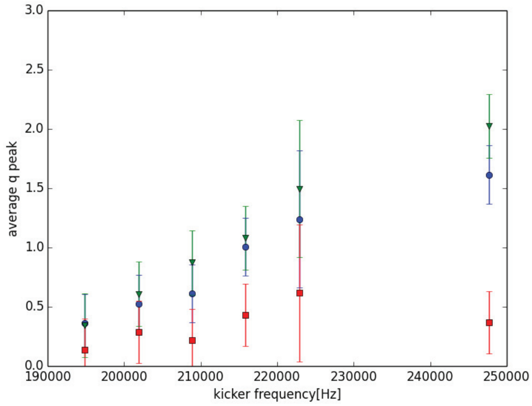

Figure 6: The intensity of quadrupole resonance.

The peak has a large width when the kicker RF frequency is 247615Hz and the number of particles is (II) and (III). A possible reason is that vertical resonance line on tune diagram is covered with the tune spread. So q_{peak} is

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defined as sum of the heights on four points around the peak.

Figure 6 shows the average of three q_{peak} which measured on the same condition. The red square is average q_{peak} in (I). The blue is in (II), and the green is in (III). In Figure 7, the vertical axis is changed to tune by Eq. (5).

$$(f_{RF}/f_{rev} - 1) \cdot 0.5 + 20.5 = \nu_y \qquad (5)$$

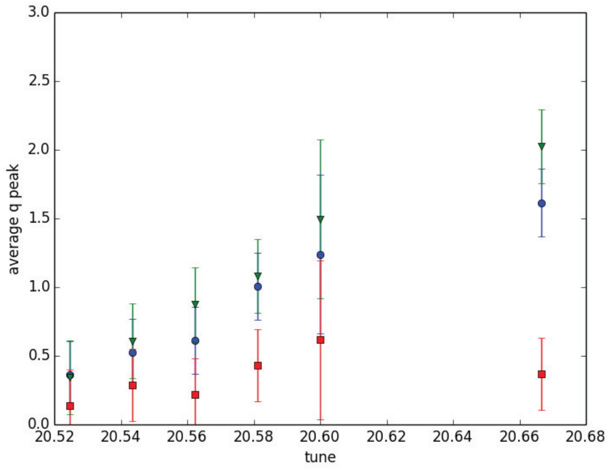


Figure 7: The intensity of quadrupole resonance. The horizontal axis is kicker RF tune. Bare tune is 20.75.

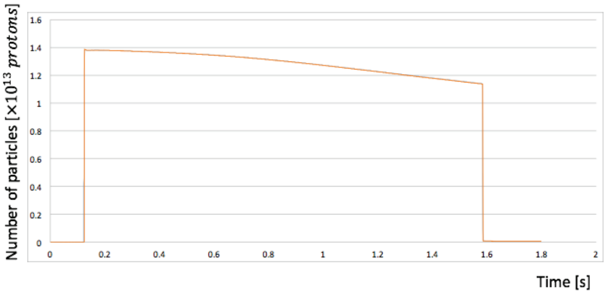
The longitudinal axis represents the intensity of quadrupole oscillation and it depends on the number of particles per bunch and the kicker RF frequency. If the particle which has a certain betatron tune only (or mostly only) can be resonant with kicker RF being satisfied with Eq. (1) and (2), the spectrum in Figure 7 represents the spectrum of tune spread. This result doesn't clearly indicate the change of spectrum due to the change of beam intensity [9]. One reason is that the RF frequency was changed by 7kHz, but this is too rough to get the change of spectrum. Another reason can be that the beam intensity in (II) and (III) could not have a large difference. However, the difference between the spectrum in (II) and (I) can be found and this may be caused by the transition of tune spread.

The Beam Intensity

In Figure 8, beam intensity on two conditions was plotted. Orange line is the average number of particle in three measurements in kicker RF on ($f_{kick} = 247615$ [Hz]). Blue line is in kicker RF off. The difference of the number of particles between RF on and off is 2.65×10^{10} at the end of measurement. The beam intensity during measurement is not different between the two conditions. This means that the beam loss is not clearly caused by the resonance induced by the quadrupole kicker. Figure 8: The number of particles during the measurement.

CONCLUSION

The quadrupole oscillation induced by the RF quadrupole kicker was measured. The resonance arose from the kicker was observed. The amplitude of the resonance oscillation, q_{peak}, depends on the kicker RF frequency. The q_{peak} spectrum depended on the number of particles per bunch.



The additional measurement is planned. The simulation with frozen space charge by transfer matrix approach is now calculated. Vlasov eq. and Maxwell eq. including the external quadrupole RF kick will be also meaningful for our consideration.

APPENDIX

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