MEASUREMENT OF THE TRANSVERSE QUADRUPOLE-MODE FREQUENCIES OF AN ELECTRON BUNCH IN THE KEK PHOTON FACTORY STORAGE RING

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Abstract

In order to extend our knowledge on the collective beam behavior, we measured the transverse quadrupole-mode frequencies of an electron bunch in the Photon Factory storage ring at KEK. The transverse quadrupole oscillations were excited by applying oscillating quadrupole magnetic fields. The responses of the excited oscillations were recorded by detecting visible synchrotron light using a photo multiplier and a spectrum analyzer. As a result, we found remarkable dependences of the horizontal and the vertical quadrupole frequencies on the bunch current.

INTRODUCTION

According to the perturbation formalism [1] for the collective beam dynamics, the motion of a bunched beam can be described by a superposition of many normal-modes of oscillation. The coherent frequency of each oscillation mode can be affected by some collective effects due to wake forces or to other mechanisms.

It has been reported in many electron storage rings [2, 3] that the transverse dipole-mode (barycentric oscillation) frequency shifts down as the bunch current increases. This effect has been explained by the following mechanism [4]. When an electron bunch passes some components with a transverse offset, the particles generate a transverse wakefield behind them. The succeeding particles in the same bunch are kicked by the short-range wakefield in the same direction to the bunch offset. Then, an integrated kick gives a defocusing force to the motion of the bunch center.

On the other hand, there have been few measurements on the coherent, quadrupole or higher-mode oscillations in the electron storage rings. We expect that such a measurement will extend our knowledge on the collective beam behavior. In this paper, we report our measurement results of the coherent quadrupole frequencies, which were carried out in the 2.5-GeV Photon Factory (PF) storage ring at KEK.

EXPERIMENTAL METHOD

Basic technique for exciting the transverse quadrupole oscillation was described in references [5, 6]. Our setup for the measurement is shown in Fig. 1. While storing a single bunch of electrons in the PF storage ring, we applied a small tune modulation using a high-frequency quadrupole magnet (HFQM). An excitation signal for the HFQM was produced by a spectrum/tracking analyzer (Advantest R3162). In order to measure the horizontal quadrupole frequencies, we swept the excitation frequency around a frequency of $2\cdot f_{\beta x}$, where the $f_{\beta x}$ is a fractional horizontal betatron frequency (i.e. fractional tune times the revolution frequency). For the other measurement of the vertical quadrupole frequency, we used a slightly different setup as described later.

Excited bunch oscillations were then detected using an optical monitor system. Visible synchrotron light from the bunch was imaged on a slit. A fast photo multiplier (Hamamatsu H5783) behind the slit detected the quadrupole oscillations as the intensity modulation of the synchrotron light from the central part of the bunch. A signal from the photo multiplier was analyzed by the spectrum/tracking analyzer. At the same time, we used a dual-sweep streak camera (Hamamatsu C5680) in order to confirm that the excited oscillations were really the transverse quadrupole mode.

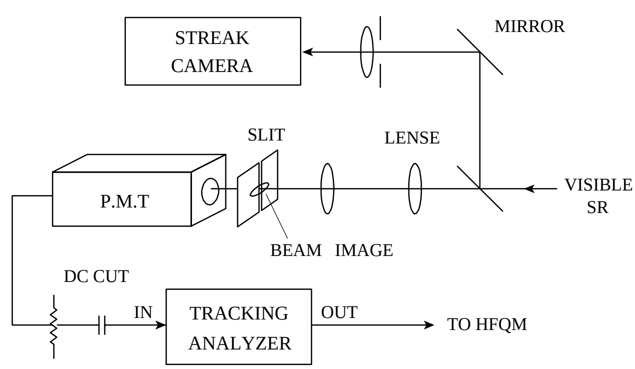

Figure 1: Experimental setup for measuring the transverse, coherent quadrupole frequencies. P.M.T.: photo multiplier.

MEASUREMENT RESULTS

Horizontal Quadrupole Frequency

We swept the excitation frequency around a frequency of about 1.915 MHz ($\approx 2\cdot f_{\beta x}$), where a fractional horizontal betatron frequency ($f_{\beta x}$) was about 957.5 kHz at low currents. The responses of the bunch oscillations were then measured using the spectrum/tracking analyzer. A peak excitation current of the HFQM was about 3.96 A, which gave an estimated horizontal-tune modulation of about 5.2×10^{-5}. An estimated growth rate of oscillation was about 260 s^{-1}, which was about twice the radiation damping rate of 128 s^{-1}. Other parameters were the beam energy of 2.5 GeV, the revolution frequency of 1.602904 MHz (harmonic number: 312), and a fractional vertical betatron frequency of 456 kHz (at low currents),

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respectively. Octupole magnets were almost turned off.

Some of the measured beam responses are shown in Fig. 2. Each trace showed a peak where the quadrupole oscillation was excited most strongly. Then, we could consider that the frequency of each peak indicated the coherent quadrupole frequency. During this measurement, we checked using the streak camera that the quadrupole oscillations were really excited at around the peak frequencies; an example of the measurement is shown in Fig. 3. We could clearly observe the quadrupole oscillations at low currents (below 10 mA), while the quadrupole oscillations were not very clear at high currents (more than about 10-15 mA).

We can see from Fig. 2 that the horizontal quadrupole frequency shifted up as the bunch current increased. Figure 4 shows a summary of the measured quadrupole frequencies as a function of the bunch current. Fitting these data linearly (except for the first two points) gave the following current dependence:

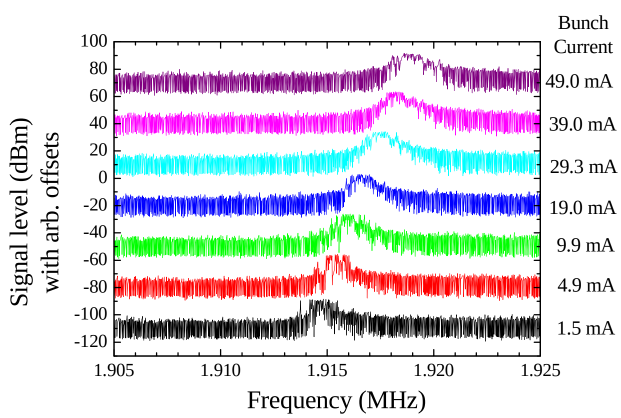

Figure 2: Frequency responses of the horizontal quadrupole oscillation, which were measured under different bunch currents. Abscissa: excitation frequency, ordinate: spectrum intensity of the photo-multiplier signal. The neighboring traces were separated by adding an offset of 30 dB. The excitation frequency was swept upward.

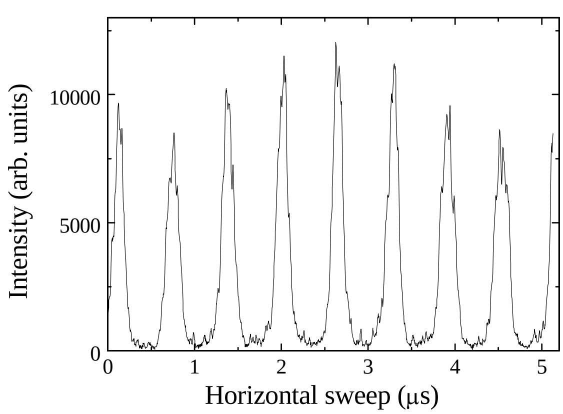

Figure 3: Measured turn-by-turn change in the horizontal beam profile due to a horizontal quadrupole oscillation. Bunch current: 1.5 mA.

$$f_{qx}[\text{kHz}] \approx 1915.2 + 0.0769\times I_b[\text{mA}], \qquad (1)$$

where the f_{qx} is the horizontal quadrupole frequency and the I_b is the bunch current, respectively.

During the above measurement, we also measured the dipole-mode frequencies using an rf knockout method. The results are shown in Fig. 5 (in horizontal) and in Fig. 6 (in vertical), respectively. Linear fits of these data

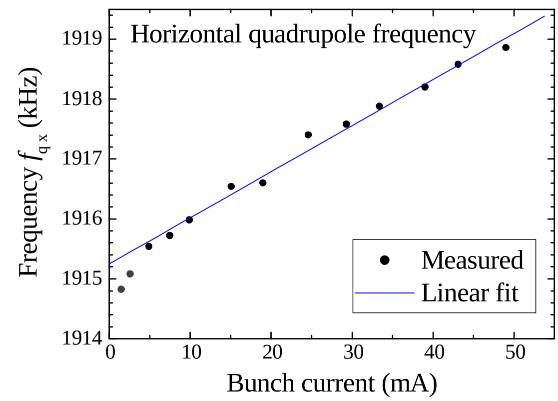

Figure 4: Measured coherent frequencies of the horizontal quadrupole oscillation. Peak current of the HFQM: 3.96 A.

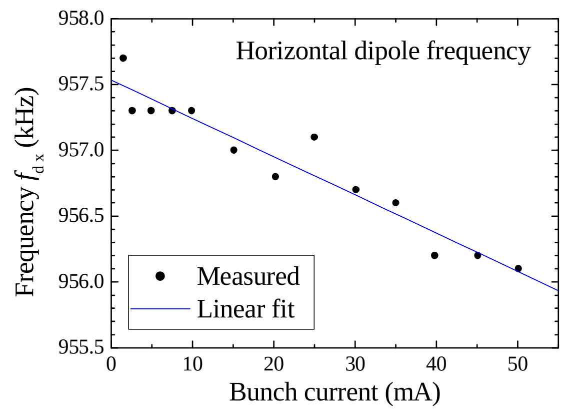

Figure 5: Measured frequencies of the horizontal dipole oscillation as a function of the bunch current.

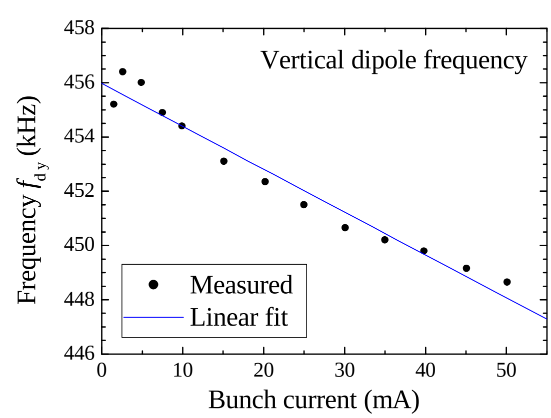

Figure 6: Measured frequencies of the vertical dipole oscillation as a function of the bunch current.

resulted in

$$f_{dx}[\text{kHz}] \approx 957.5 - 0.0290\times I_b[\text{mA}], \quad (2)$$

and

$$f_{dy}[\text{kHz}] \approx 456.0 - 0.158\times I_b[\text{mA}], \quad (3)$$

where the f_{dx} and the f_{dy} are the horizontal and the vertical dipole frequencies, respectively.

Vertical Quadrupole Frequency

Due to limited bandwidth (1.4 - 2 MHz) of the HFQM power supply used in the above experiment, we could not excite it at twice the vertical betatron frequency. Instead, we used another HFQM power supply (bandwidth: 3.3-5.9 MHz), and excited the HFQM at a frequency of ($3f_r$ + $2f_{\beta y}$) ≈ 5.72 MHz, where the $f_{\beta y}$ is the fractional vertical betatron frequency and the f_r is the revolution frequency, respectively.

An initial measurement was carried out using the similar setup to the one in Fig. 1, with a 90°-rotation of the beam image. However, it was found that the measurement was considerably affected by an rf noise from the HFQM. Then, we changed the measurement method; the HFQM was excited by a signal from a function generator at a frequency around ($3f_r$ + $2f_{\beta y}$), and then, an induced beam oscillation was detected at a different sideband frequency of about ($2f_r$ + $2f_{\beta y}$).

The result of our preliminary measurement is shown in Fig. 7. The frequency of the function generator was changed by a step of 0.1 kHz within 10 kHz. For each frequency, we measured a signal spectrum at a center frequency of about ($2f_r$ + $2f_{\beta y}$) ≈ 4.118 MHz within a span of 20 kHz, and then, recorded the maximum (peak) amplitude. Each trace in Fig. 7 indicates the measured peak amplitudes as a function of the excitation frequency.

Although the above measurement was still preliminary, we can see in Fig. 7 that the vertical quadrupole frequency, which was indicated by a peak in each trace, tended to shift down as the bunch current increased. The current dependence was, roughly, -0.095 kHz/mA.

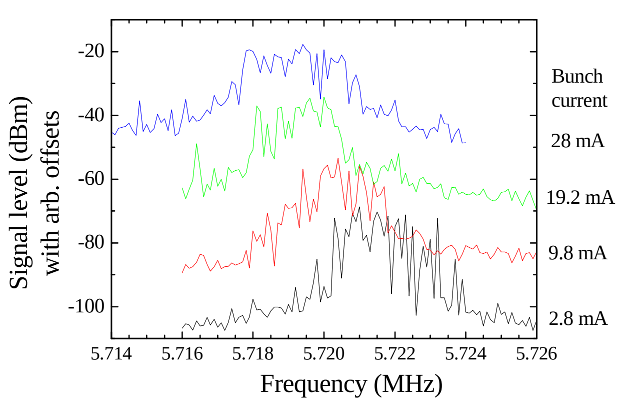

Figure 7: Measured responses of the vertical quadrupole oscillation at different bunch currents. Offsets of 20 dB were added between neighboring traces.

DISCUSSIONS

It can be seen from Figs. 4 and 5 that the horizontal quadrupole frequency was very close to two-times the dipole frequency at the limit of low current. This agrees with a single particle model [6]. As the bunch current increased, the horizontal quadrupole frequency shifted up, while the horizontal dipole frequency shifted down. An absolute slope of the current dependence for the quadrupole oscillation was roughly 2.6 times larger than that of the dipole oscillation. Moreover, the preliminary measurement for the vertical quadrupole frequency indicated that the frequency tended to shift down with the bunch current. The above dependences of the quadrupole frequencies should be due to some collective effects.

In a usual manner, the observed shifts in the dipole frequencies should be attributed to the transverse wake forces [1] which were induced by a dipole (m=1) moment of the charge distribution in the bunch. Similarly, the shift in the quadrupole frequencies may be attributed to the wake forces, which were induced by a quadrupole (m=2) moment of the charge distribution. However, we still have a question why the quadrupole-frequency shift was so large; we usually expect that the effect of the higher-moment wake forces would be smaller than the fundamental mode (m=1, for the transverse case) wakes.

CONCLUSIONS

We measured the horizontal and the vertical quadrupole frequencies in the PF storage ring. The measured quadrupole frequencies showed remarkable dependences on the bunch intensity. The horizontal quadrupole frequency shifted up with the bunch current, while the vertical quadrupole frequency shifted down. These frequency shifts may be attributed to the transverse wake forces of higher moment. However, there remains a question why the quadrupole-frequency shift was so large as compared to that of the dipole-frequency.

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