# MEASUREMENT OF QUADRUPOLAR TUNE SHIFTS UNDER MULTIBUNCH OPERATIONS OF THE PHOTON FACTORY STORAGE RING

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*Abstract*

Measurement of quadrupolar tune shifts can provide us information on the incoherent tune shifts due to beam-induced fields. For this purpose, we measured both dipolar and quadrupolar tune shifts under multibunch operations of the Photon Factory (PF) electron storage ring at KEK. As a result, we observed dipolar tune shifts of 0.0041 $A^{-1}$ (in horizontal) and -0.0050 $A^{-1}$ (in vertical), as well as quadrupolar tune shifts of 0.0081 $A^{-1}$ (in horizontal) and -0.0082 $A^{-1}$ (in vertical), respectively.

## INTRODUCTION

The transverse motions of particles in storage rings can be perturbed by wakefields, as well as by self or image fields. Such perturbations can shift the betatron tunes as a function of the beam current. By measuring the tune shifts with the beam current, we can obtain some information on such perturbations.

The tune shifts are commonly measured for dipolar (beam centroid) oscillations. Using smooth approximation, the coherent dipolar tune is approximately given by [1]

$$\left(\nu_{\mathrm{coh}}^{\mathrm{d}}\right)^2 = \nu_y^2 - \frac{1}{m_0 \gamma \omega_0^2}\left[\left.\frac{\partial F_y}{\partial y}\right|_{y=y_0=0} + \left.\frac{\partial F_y}{\partial y_0}\right|_{y=y_0}\right], \qquad (1)$$

where $\nu_y$ is the unperturbed vertical tune; $m_0$, the rest mass of the particle; $\gamma$, the Lorentz factor; $\omega_0$, the angular revolution frequency; $F_y$, the vertical force due to beam-induced fields; $y_0$, the offset of beam centroid; and $y$, the offset of an individual particle. The horizontal tune shift is given by the same equation by replacing $y$ with $x$. The other tune of an individual particle inside the beam is called the incoherent tune, which is approximately given by

$$\nu_{\mathrm{inc}}^2 = \nu_y^2 - \frac{1}{m_0 \gamma \omega_0^2}\left.\frac{\partial F_y}{\partial y}\right|_{y=y_0=0}. \qquad (2)$$

In order to estimate both partial derivatives of $F_y$ on $y$ and $y_0$, we need to know both tunes of $\nu_{\mathrm{coh}}^{\mathrm{d}}$ and $\nu_{\mathrm{inc}}$.

Direct measurements of incoherent tunes are generally difficult. Alternatively, we can estimate the incoherent tunes by measuring the coherent tunes of quadrupolar (beam envelope) oscillations. This technique was first developed by Chanel [2] to study the space charge forces for antiproton beams at LEAR, and it was applied to the other proton or heavy-ion rings [3].

The first measurement [4] of quadrupolar tunes in electron storage rings was carried out at the 2.5-GeV Photon Factory storage ring at KEK under a single-bunch operation. Then, we observed remarkable quadrupolar tune-shifts with the beam current per bunch. It was explained that these tune shifts should be caused by a quadrupolar component of short range wakefields which were induced in axially asymmetric structures.

Following the above-mentioned measurements, we conducted the first measurement of quadrupolar tune shifts under multibunch operations of the PF storage ring.

## EXPERIMENTAL SETUP

The PF storage ring is a 2.5-GeV synchrotron light source, having an rf frequency of approximately 500.1 MHz and a harmonic number of 312. Typical operating point is ($\nu_x$, $\nu_y$) = (9.613, 5.265), and a typical rf voltage is 1.7 MV. The PF storage ring is usually operated with the maximum beam current of 450 mA in sequentially filled 280 bunches. To avoid transverse beam instabilities at high currents, a bunch-by-bunch feedback system is routinely used. An rf phase modulation at twice the synchrotron frequency is also used to improve the beam lifetime as well as to suppress longitudinal coupled-bunch instabilities. The tune measurements were carried out under above-mentioned conditions, while a part of the measurement was carried out at lower rf voltage of 1.4 MV or without the phase modulation

We measured the dipolar tunes using a setup shown in Fig. 1. Output signals from a spectrum analyzer, having frequencies of about $(\Delta\nu + h)f_r$, were converted down to the frequencies of about $\Delta\nu \cdot f_r$, and then, they were used to excite dipolar oscillations of beams. Here, $\Delta\nu$ is the fractional betatron tune; $h$, the harmonic number; and $f_r$, the revolution frequency (≈1.6029 MHz). The dipolar oscillations were detected with differential signals from button-type electrodes. The detection frequency was chosen at the frequencies of about $(\Delta\nu + h)f_r$. Responses of the oscillations were recorded while sweeping the frequency.

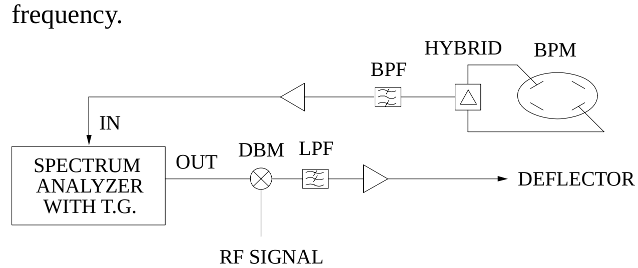


Figure 1: Setup for the dipolar tune measurements.

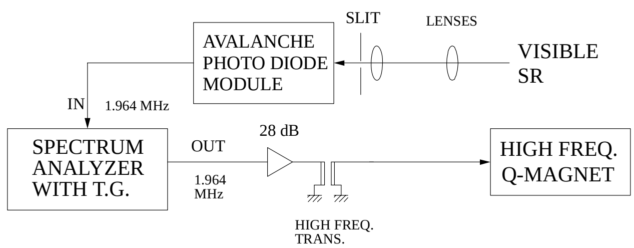


Figure 2: Setup for the quadrupolar tune measurements.

A setup for the quadrupolar tune measurement is shown in Fig. 2. We excited a high-frequency quadrupole magnet (HFQM) at frequencies of about $2\Delta\nu_x \cdot f_r$ (for horizontal measurement) and of about $(3 + 2\Delta\nu_y)f_r$ (for vertical measurement), respectively. Since both excitation frequencies were above the revolution frequency, it could excite quadrupolar oscillations of higher-order multibunch mode. A tune modulation applied by the HFQM was approximately $5.3\times10^{-5}$ at peak in both planes. To detect the quadrupolar oscillations, we made beam images of visible synchrotron radiation (SR) on a slit, and detected intensity modulations of the transmitted light through the slit. The beam images were rotated by 90° between the horizontal and the vertical measurements. To detect pulses of visible SR which repeated at the rf frequency, we used an avalanche photodiode module (Hamamatsu, C5658) which has a wide bandwidth from 50 kHz to 1 GHz. A narrow diameter (0.5 mm) of the sensor imposed additional aperture stop for the light.

## MEASUREMENT RESULTS

We measured the responses of dipolar and quadrupolar oscillations at different beam currents while storing 280 bunches. Typical responses of dipolar oscillations are shown in Figs. 3 and 4, whereas those of quadrupolar oscillations are shown in Figs. 5 and 6. The abscissas of Figs. 3-6 indicate an excitation frequency. Note that the data in Figs. 6 were taken on a different day than that in Figs. 3-5, and thus, unperturbed betatron tunes were slightly different.

Figures 3 and 4 indicate that the horizontal dipolar tune increased with the beam current whereas the vertical tune decreased. We also observed that a single peak at the coherent dipolar frequency split into double peaks when the beam currents were higher than about 250 mA. The cause of this splitting has not been understood yet. Figures 5 and 6 indicate that the horizontal quadrupolar tune increased with the beam current while the vertical quadrupolar tune decreased.

Measured tune shifts are summarized in Figs. 7 and 8, where the dates of the measurements are also indicated. Although the data shown in Figs. 3-8 were taken on different days, we confirmed that the tune shifts reproduced well. By fitting lines to the data in Figs. 7 and 8, we obtained the tune shifts shown in Table 1. Our previous measurements under single-bunch operations are also shown in Table 1. Note that we fit the lines to the dipolar tunes below the beam currents of 200 mA, where only single peaks could be identified.

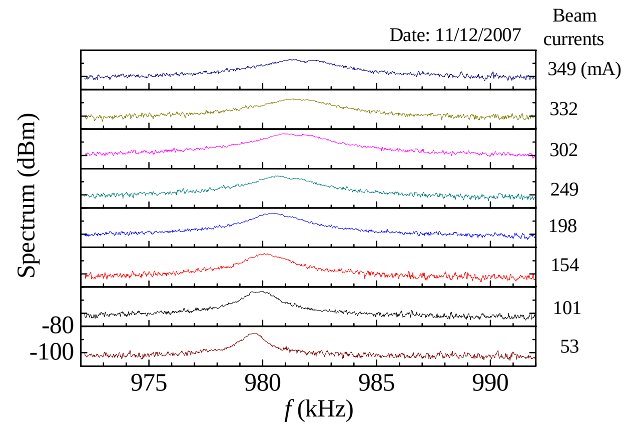


Figure 3: Responses of the horizontal dipolar oscillations.

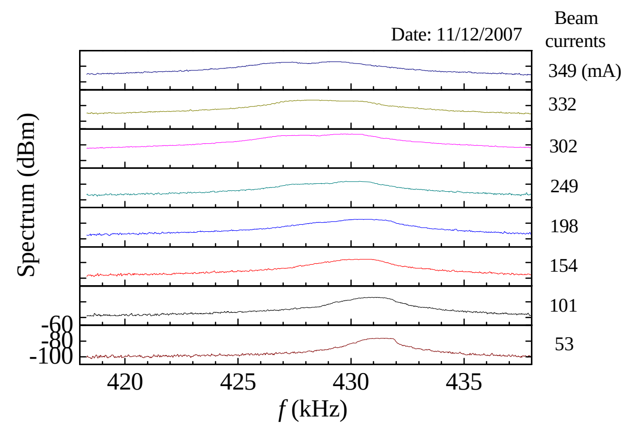


Figure 4: Responses of the vertical dipolar oscillations.

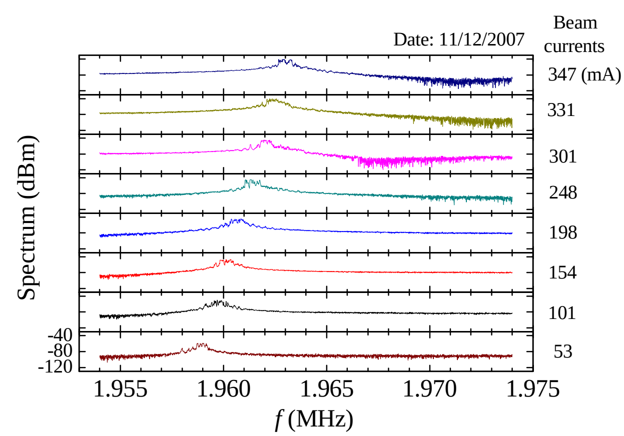


Figure 5: Responses of the horizontal quadrupolar oscillations.

## DISCUSSIONS

Under the multibunch operations, the quadrupolar tune shifts were roughly twice the dipolar tune shifts in both horizontal and vertical planes, as shown in Table 1. The signs of the horizontal tune shifts were both positive, while those of the vertical tune shifts were both negative. The features of the dipolar tune shifts seem similar to those [6] observed at the High Energy Ring of the PEP-II B-factory. Then, the most probable cause of the tune shifts in the PF storage ring is the long-range quadrupolar wakes of noncircular vacuum chambers with finite resistivity [6].

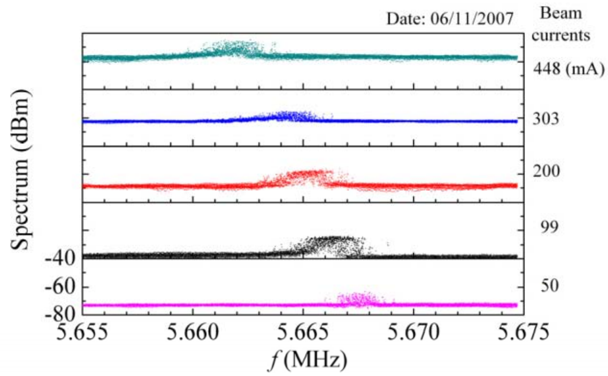


Figure 6: Responses of the vertical quadrupolar oscillations. Ten traces at each beam current were superposed.

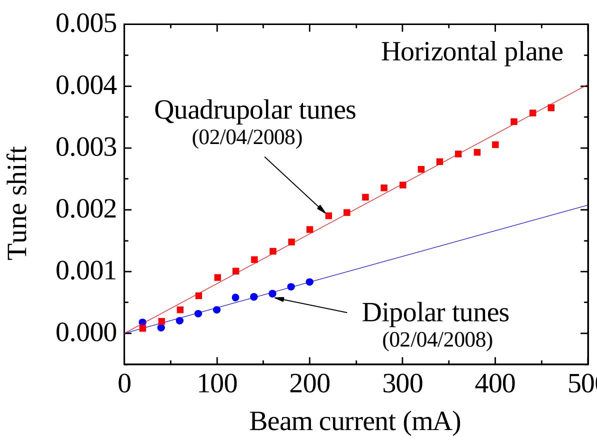


Figure 7: Measured dipolar and quadrupolar tune shifts in the horizontal plane. Lines indicate linear fits to the data.

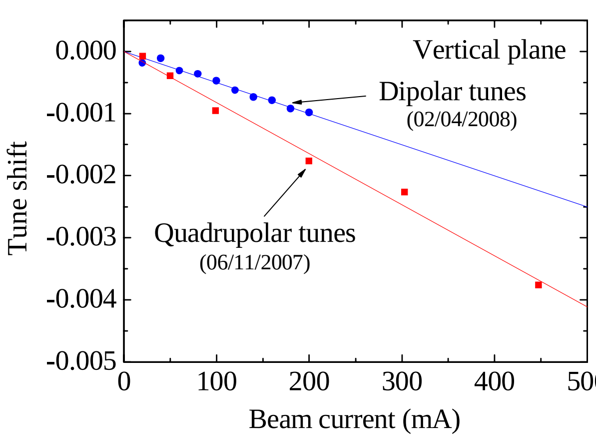


Figure 8: Measured dipolar and quadrupolar tune shifts in the vertical plane. Lines indicate linear fits to the data.

Table 1: Summary of the measured tune shifts under the multibunch and single-bunch operations of the PF storage ring. Units: $A^{-1}$.

| **Oscillation mode** | **With 280 bunches** | **With single bunch** [5] |
|---|---|---|
| Horizontal dipole | $4.1\times10^{-3}$ | $-9.1\times10^{-3}$ |
| Horizontal quadrupole | $8.1\times10^{-3}$ | $1.3\times10^{-1}$ |
| Vertical dipole | $-5.0\times10^{-3}$ | $-1.4\times10^{-1}$ |
| Vertical quadrupole | $-8.2\times10^{-3}$ | $-1.0\times10^{-1}$ |

If we assume that the beam-induced fields are not affected by the beam sizes, an individual particle in the beam receives the same beam-induced force irrespective of the quadrupolar oscillations. Then, the coherent quadrupolar tune-shift will be twice the incoherent tune shift, that is,

$$\delta\nu^{q}_{coh} \approx 2\delta\nu_{inc} . \tag{3}$$

If this assumption is true, we can estimate the incoherent tune shifts to be approximately $4.1\times10^{-3}$ and $-4.1\times10^{-3}$ in the horizontal and the vertical planes, respectively, under the multibunch operation. Since these tune shifts are very close to the measured dipolar tune-shifts, we can guess that the term $\partial F_y / \partial y_0 \big|_{y=y_0}$ in Eq. (1) contributed little to the coherent dipolar tune-shifts.

It can also be seen from Table 1 that the tune shifts under the multibunch operations were much smaller than those under the single-bunch operations. This suggests that the tune shifts under the multibunch operations should be caused by different sources than those under the single-bunch operations.

## CONCLUSIONS

We measured both dipolar and quadrupolar tune shifts under the multibunch operations of the PF storage ring. The measured quadrupolar tune-shifts were roughly twice the dipolar tune-shifts, and they had opposite signs in the horizontal and the vertical planes. The measurement of the quadrupolar tunes will be useful for estimating the incoherent tunes, and thus, for studying the effects of beam-induced forces.

## REFERENCES

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