STUDY ON A LONGITUDINAL QUADRUPOLE-MODE BUNCH OSCILLATION IN THE KEK PHOTON FACTORY STORAGE RING

S. Sakanaka, T. Obina, and T. Mitsuhashi, Institute of Materials Structure Science,
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

Abstract

In order to understand the beam behavior under rf phase modulation, which has been used to improve the beam lifetime[1-3], we studied the response of induced bunch oscillations. By applying phase modulation at frequencies around two-times the synchrotron frequency, both quadrupole-mode and dipole-mode longitudinal oscillations were excited. We found that the bunch oscillated resonantly at two separate frequencies, which could be assigned to the coherent quadrupole-mode frequency and twice the coherent dipole-mode frequency, respectively.

1 INTRODUCTION

An rf phase-modulation technique at a frequency of two-times the synchrotron frequency[3] has been found to be useful both for improving the beam lifetime and for suppressing the longitudinal beam instabilities in synchrotron light sources. In this method, a longitudinal quadrupole-mode (bunch shape) oscillation, which is excited by phase modulation, is utilized. In order to control this oscillation, it is important to understand the beam response to an applied phase modulation.

A theoretical analysis on a single particle motion[4,5] predicts that: (i) two fixed points (two steady-state oscillations) arise when the modulation frequency is set at a frequency of two-times the synchrotron frequency, and (ii) three fixed points (two oscillating states and one non-oscillating state) arise when the modulation frequency is set slightly lower. Each electron can take one of such oscillation states. The above prediction has qualitatively been supported by an experiment[5]. However, we also found that the response of the bunch oscillation to the applied phase modulation largely depended on the beam intensity per bunch. This research was intended to clarify this beam intensity effect.

2 EXPERIMENT

2.1 Experimental Method

An experiment was carried out in the 2.5-GeV Photon Factory (PF) storage ring at KEK. The principal parameters of the ring during this experiment were as follows: E = 2.5 GeV, $f_{\rm rf}$ = 500.10724 MHz, h = 312, V_c = 1.7 MV, α = 0.0061, f_s = 23.55 kHz, τ_ε = 3.9 ms, where E is the beam energy, $f_{\rm rf}$ the rf frequency, h the harmonic number, V_c the rf voltage, α the momentum compaction factor, f_s the synchrotron frequency, and τ_ε the longitudinal damping time.

A setup for the experiment is shown in Fig. 1. While storing single electron bunch, we modulated rf phase by a sinusoidal waveform at frequencies around two-times the synchrotron frequency. Induced longitudinal bunch oscillations were then monitored with a button-type electrode signal, using a spectrum analyzer. In order to investigate the beam response, we scanned the modulation frequency. At every modulation frequency, we recorded the beam spectrum, which was observed near the second harmonic ($2f_{\rm rf}$) of the rf frequency. By analyzing the amplitudes of several synchrotron sidebands beside this frequency, the longitudinal bunch oscillations could be deduced, at least, qualitatively.

In order to avoid any hysteresis effect in the bunch oscillation, we reset the oscillation at every frequency. This was done by turning off the phase modulation gradually, changing the modulation frequency, and then, restoring the modulation amplitude to a fixed level. We found from several measurements that this procedure was essential to obtain well reproducible data. The above measurement was carried out automatically by using a personal computer.

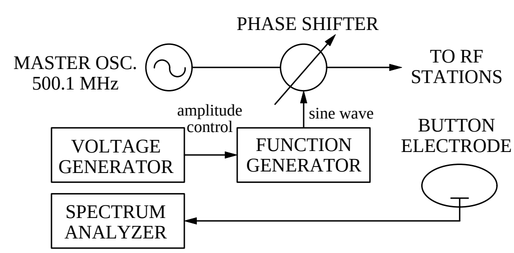

Figure 1: Experimental setup.

2.2 Results

Figure 2 shows the typical responses of the beam spectrum to the phase-modulation frequency, which were measured under different bunch currents. It can be seen that the bunch oscillated resonantly at two separate frequencies; this was especially clear in the cases of (b)-(e). At the lower peak (about 45.9 kHz in the case (c)), the amplitude of the second synchrotron sideband (indicated by triangles) was comparable to that of the first synchrotron sideband (indicated by closed circles). This suggests that the bunch oscillated in a mixture of both quadrupole- and dipole-modes, where the quadrupole mode was dominant. At the upper peak (about 46.9 kHz in the case (c)), on the other hand, the first synchrotron sideband was much larger than the second one. This suggests that the dipole-mode oscillation was dominant at this frequency.

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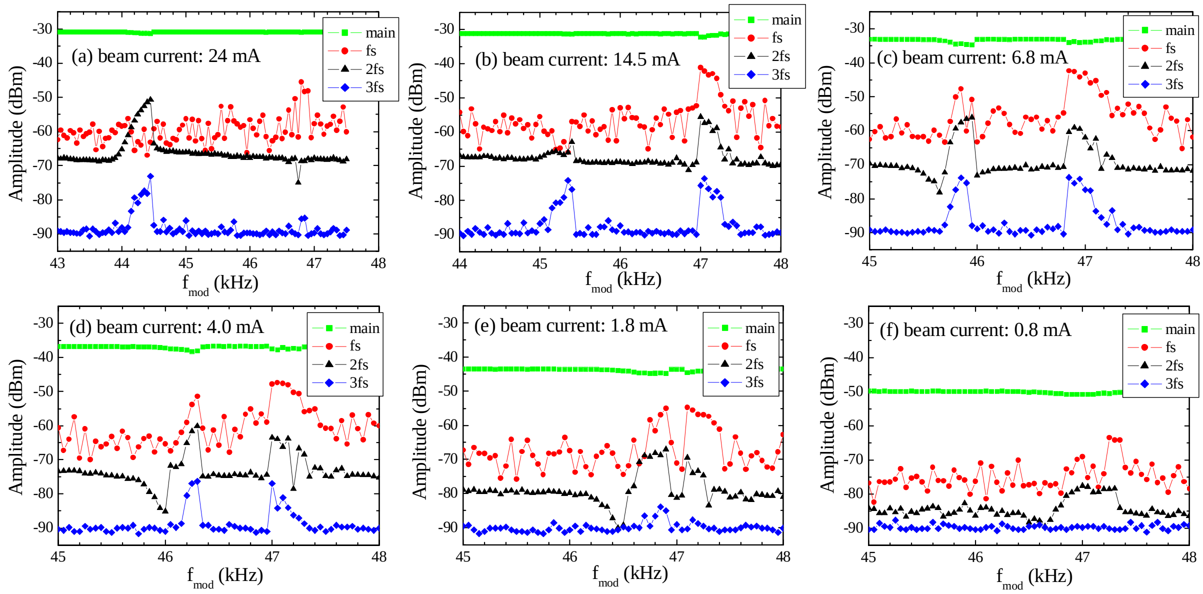

Figure 2: Responses of the synchrotron sidebands to the phase-modulation frequency (f_{mod}). The signal levels of the synchrotron sidebands (up to the third harmonic), as well as that of the main peak (two-times the rf frequency), are plotted. Phase modulation of 11.2°p-p (degrees peak to peak) was applied. The data of (a) and (b), and those of (c)-(f), were measured in different beam-storage runs.

Typical beam images under phase modulation, which were measured with a dual-sweep streak camera, are shown in Fig. 3. The longitudinal beam profile is shown along the vertical axis (500 ps full scale), while its variation is shown along the horizontal axis (101.6 µs full scale). The beam current was 2.0 mA with a single bunch; the modulation amplitude was 11.2°p-p. In the case of Fig. 3(a), the bunch split into three bunchlets. A slight asymmetry in the particle populations of the two oscillating bunchlets can be viewed as a mixture of dipole- and quadrupole-mode oscillations. In the other case of Fig. 3(b), the bunch split into two oscillating bunchlets, however, most of the particles were populated in one of the bunchlets. This was observed as a strong dipole-mode oscillation. Although these data were measured at a different opportunity, they are consistent with the above response measurement.

It can be seen from Fig. 2 that the lower peak was shifted down as the bunch current increased. The measured dependence of the peak frequencies on the bunch current is shown in Fig. 4. The lower-peak frequency depended almost linearly on the bunch current (by about -0.10 kHz/mA), while the upper-peak frequency depended only slightly. Note that the upper-peak frequency (about 47.1 kHz) was very close to twice the coherent dipole-oscillation frequency of 23.55 kHz, which was measured from a small coherent synchrotron oscillation due to an rf noise. We also note that the data in Fig. 4 was measured over two beam-storage runs, which resulted in slight steps in the data between the different runs. We suppose that these steps would be due to a slight difference in some parameters such as an rf voltage.

It is worth noting that when the modulation frequency was swept while keeping its amplitude, we sometimes obtained quite different beam responses. Figure 5 shows one of such examples; the modulation frequency was swept upward while keeping the modulation amplitude to be 11.2°p-p. Comparing Fig. 5 with Fig. 2(c), we can see that the double peaks in Fig. 2(c) was replaced by a single broad peak. We also found that the beam response showed either the single broad peak or the double peaks; this depended on such parameters as the bunch current, the modulation amplitude, and the sweep direction in

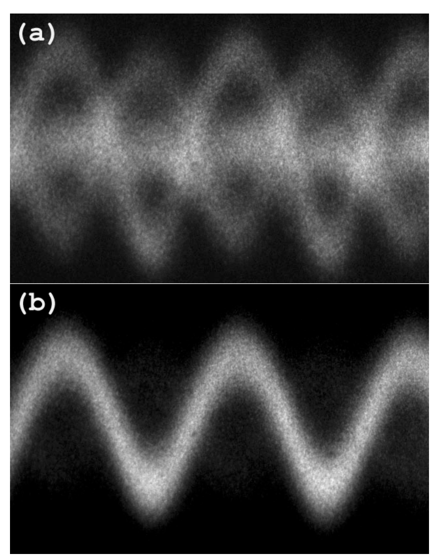

Figure 3: Beam images from the streak camera indicating longitudinal bunch oscillations under phase modulation. Modulation frequency: (a) 46.9 kHz, (b) 47.33 kHz.

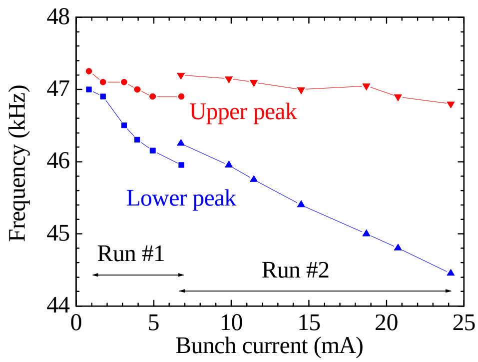

Figure 4: Frequencies of the upper and the lower peaks versus the bunch current. The peaks were read from the response curves of the second synchrotron sideband.

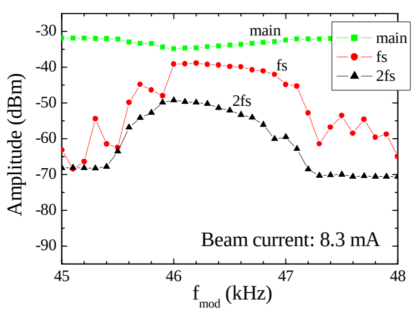

Figure 5: Beam response when the phase-modulation frequency was swept upward while keeping its amplitude.

a complicated manner. Therefore, the measurement with the constant amplitude resulted in very complicated data.

3 DISCUSSIONS

The above experiment showed the following facts: (1) the stored single bunch oscillated resonantly at two modulation frequencies (double peaks) near the frequency of $2f_s$; (2) diagnosing with the beam spectra, the quadrupole-mode oscillation was relatively strong at the lower-peak frequency while the dipole-mode oscillation was dominant at the upper-peak frequency; (3) the upper-peak frequency was very close to twice the coherent dipole-mode oscillation frequency; and (4) the lower-peak frequency shifted down as the bunch current increased while the upper-peak frequency remained almost still.

The above results can be understood by the following explanations: (i) the lower peak corresponds to the frequency of a coherent quadrupole-mode oscillation while the upper peak corresponds to twice the frequency of a coherent dipole-mode oscillation; (ii) the shift in the lower-peak frequency indicates the shift in the coherent quadrupole-mode frequency; and (iii) when the modulation frequency is tuned to a frequency of two-times the coherent dipole-mode frequency, the dipole oscillation is excited strongly by some mechanism.

The perturbation theory on the coherent beam dynamics[6] predicts that the coherent quadrupole-mode oscillation can be shifted down by a longitudinal inductive impedance as the bunch current increases. The above assumption (ii) is consistent with this prediction. If this explanation is valid, the measurement of the quadrupole-mode frequency shift will be useful in estimating the longitudinal impedance of the ring. For this purpose, one should measure both the frequency shift with small amplitudes and the bunch length, at the same time. Although the longitudinal impedance can be estimated from the bunch lengthening or from the transverse mode measurements[7], the above method will provide another means.

The above explanation (iii) presents another interesting subject: how the dipole oscillation is induced when the modulation frequency is tuned to twice the coherent dipole-mode frequency? As shown in Fig. 3(b), this dipole oscillation was due to a large asymmetry in the particle populations in two oscillating states. We observed that this asymmetry lasted for a long time (at least, more than 10 minutes). Since there were some diffusion mechanisms, such as the radiation fluctuation and the Touschek effect, which would equalize the particle populations in the two oscillating states, there should be some mechanism which kept the asymmetric populations. The most probable mechanism is the wakefield effect. Our preliminary tracking simulations, which included both the phase modulation and the longitudinal wake function, showed that an inductive wakefield would play an important role in promoting and keeping this asymmetric population. We are going to investigate it further.

4 CONCLUSIONS

The response of the bunch oscillations to the phase modulation frequency (near the frequency of $2f_s$) was measured under single bunch operation. It was found that the bunch oscillated resonantly at two separate frequencies. These frequencies could be assigned to the coherent quadrupole-mode frequency and twice the dipole-mode frequency, respectively. The dependence of the lower-peak frequency on the bunch current was also found, which can be considered as the shift in the coherent quadrupole-mode frequency due to a longitudinal impedance.

We would like to thank M. Izawa for useful discussions.

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