MEASUREMENT OF THE LONGITUDINAL WAKE POTENTIAL IN THE PHOTON FACTORY ELECTRON STORAGE RING

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Abstract

We tried to determine the longitudinal wake potential in the Photon Factory electron storage ring by measuring the longitudinal bunch structure with a photon counting method. A train of test bunches whose currents were small enough to neglect the interaction among them were injected behind a bunch with a large current. Deformation and the shift of the test bunches in the longitudinal direction due to the wake field generated by the large current bunch were measured, and the wake potential was estimated. We found the wake potential consists of two components: one is the short range wake which vanishes outside the bunch, and the other with the medium range of successive several bunches. The photon counting method is not always suitable for the multi-bunched beam. Development of a fast light shutter with a Pockels cell which enables us to measure the structure of a bunch in the multi-bunch mode is under way.

1 INTRODUCTION

According to the damping time of the wake field, we classified the wake into three types. The first is the short range wake which exists within a bunch only, the second is the medium range wake whose damping time is longer than the minimum bunch spacing but shorter than the revolution time of the bunch. The last is a long range wake which lasts longer than the revolution time. The short and medium range wakes are transient, but the long range wake is sometimes piled up and gives rise to beam instabilities. Although the long range wake has been widely studied theoretically and experimentaly, there are few experimental studies of the short and medium range wake so far. In this paper, we present the experimental results and discussion on the longitudinal wake of short and medium range.

We measured the longitudinal bunch structure with a single photon counting system[1] insalled in beamline 21 in the Photon Factory electron storage ring (PF-ring). Since the short range wake generated by a bunch affects only itself, we investigated the wake by measuring the longitudinal distribution of electrons in the bunch in the single-bunch mode as a function of the bunch current. In order to measure the medium range wake, we developed the test bunch method in which a main bunch with a large current and a train of small current test bunches as probes of the wake potential are stored simultaneously. The principle of the test bunch method is described in Sec.2. The short and medium range wakes are discussed in Sec.3.

We have been developing a fast light shutter with a Pockels cell which can select a light pulse out of successive light pulses radiated from the multi-bunched beam. A preliminary result of the beam test of the shutter is presented in Sec. 4.

2 PRINCIPLE OF TEST BUNCH METHOD

The test bunch method was developed for the measurement of the medium range wake. Making use of the wide dynamic range (>10^5) and the excellent time resolution (<10ps) of the photon counting method, we measured the change in bunch lengths and the longitudinal shifts of the test bunches following a large current main bunch, and estimated the longitudinal wake potential generated by the main bunch.

When the phase shift from the synchronous phase of the k-th test bunch in the presence of the wake potential $V_w(t)$ is ϕ_{sk}, the total acceleration voltage V_{tot} and its gradient $\dot{V}_{tot}$ are represented as

$$V_{tot}(t) = V_{RF}\sin(\omega_{RF}t + \phi_{sk}) + V_w(t) \quad (1)$$

and

$$\dot{V}_{tot}(t) = \omega_{RF}V_{RF}\cos(\omega_{RF}t + \phi_{sk}) + \dot{V}_w(t). \quad (2)$$

The bunch length is given by

$$\sigma_t = A\Big/\sqrt{\dot{V}_{tot}} \quad (3)$$

where A is a constant. Using eq. (2), the deviation of the bunch length $\Delta\sigma_t$ from its natural length is given by

$$\frac{\Delta\sigma_t}{\sigma_t} = -\frac{\dot{V}_w(t)}{2\dot{V}_{RF}(\phi_{sk})}.$$

When the wake potential and the radiation loss U_{rad} is small compared with the RF voltage, the deviation of the synchronous phase $\Delta\phi$, which corresponds to the shift of the bunch center Δt, is given by

$$\Delta\phi \cong \omega_{RF}\Delta t = \frac{V_w(t)}{V_{RF}}.$$

The longitudinal shifts of the centers and the deviations of the lengths are proportional to the wake potential and its gradient, respectively. Therefore, by measuring the lengths and the centers of the test bunches, we can sample the wake potential and its gradient with the sampling period of the bunch spacing (2ns).

3 WAKE POTENTIAL IN PF-RING

3.1 Short range wake

We measured the dependece of the longitudinal distribution on the bunch current in the single-bunch operation with the photon counting method. The longitudinal distributions below the threshold current of the microwave instability are shown in Fig.1. The vertical bars in the figures show the statistical errors. The left hand side of the horizontal axis shows the head of the bunch. The distributions at the bunch current up to about 4 mA are nearly Gaussian, but those at larger currents become asymmetric due to the wake potential generated by the bunch itself.

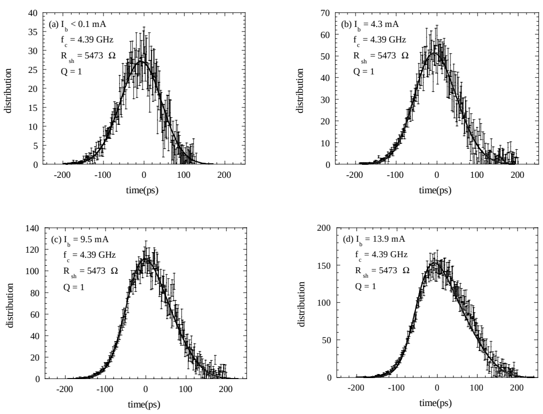

Fig. 1 : Longitudinal distribution of electrons in the bunch in single-bunch mode.

In order to explain the wake potential, we employed the broadband impedance model. The broadband impedance model is represented by a wideband resonator whose quality factor Q is unity. It contains the contribution of all the vacuum chamber components of the ring. We reconstructed the wake function of the broadband impedance and solved the Haissinski equation [2] iteratively. When we assume the shunt impedance and resonant frequency to be 5500Ω and 4.4GHz, respectively, which gives the coupling impedance |Z/n| of about 2Ω, the calculated distributions (solid lines in Figs. 1) are well fitted to the experimental distributions. These parameters are consistent with other studies [3,4].

3.2 Medium range wake

In order to investigate the medium range wake, we employed the test bunch method. Influence on the test bunches with a beam current of 1mA each was observed as a function of the beam current of the main bunch. If the wake fields produced by the main bunch excite longitudinal coherent oscillations of the bunches around the synchronous phases, the gross bunch lengths measured with the photon counting system become longer than the real lengths, because the system measures the averaged longitudinal distribution of the bunch. We determined amplitude of the longitudinal coherent oscillations of the test bunches, measuring a beam signal from a button-type pickup electrode with a histogram function of an oscilloscope (HP54121A and 54120B). The r.m.s. amplitudes of the oscillation were less than 10 ps. Since their contribution to the measurements of the bunch lengths are less than 1 ps, we concluded that the effect of the coherent oscillation is negligible in the test bunch method.

We stored the test bunches in one of regions listed below:

Region 1: just before the main bunch,
Region 2: just after the main bunch,
Region 3: opposite side of the ring with respect to the main bunch,

and estimated the damping time of the wake by measuring the length and the shift of the center of each test bunch. Considering the reproducibility of the bunch length measurement (±0.4ps) and that of the bunch center measurement (±5ps), the variation of the bunch lengths and the shifts of the bunch centers in Region 1 and 3 were meaningless. We therefore investigated the wake in Region 2 in detail. Examples of the variation of the bunch lengths and the shift of the bunch centers in Region 2 are shown in Figs. 2. The main bunch with a beam current of

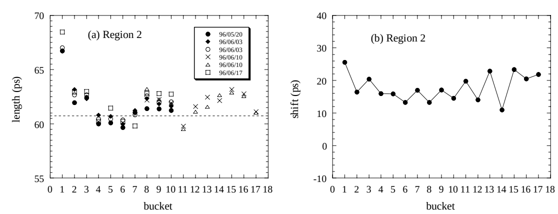

Fig. 2 :Results of the test bunch measurement. (a) variation of the lengths and (b) shifts of the centers of the test bunches stored just after the main bunch.

30mA was stored in 0th bucket. For the determination of the frequency components of the wake, we performed the discrete Fourier transform (DFT) on the data in Figs. 2. The results are shown in Figs. 3. Since the numbers of data are 17 and the sampling frequency is 500 MHz (RF frequnecy), the resolution of frequency is limited to ±15 MHz. According to the sampling theorem, the highest frequency we can identify is a half of the sampling frequency and the frequencies higher than that cause aliasing. Main components in Figs. 3 are

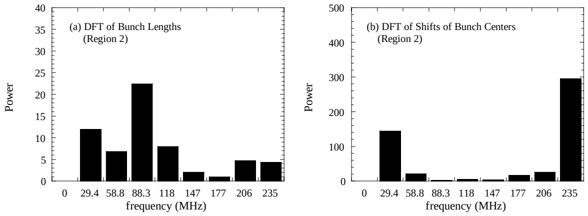

Fig. 3 : DFT's of (a) variation of the lengths and (b) shifts of the centers of the test bunches in Figs. 2

$$f_1 = n_1 \times f_{RF} + 88\text{MHz} \ \text{ or } \ -88\text{MHz}$$
$$f_2 = n_2 \times f_{RF} + 235\text{MHz} \ \text{ or } \ -235\text{MHz}\,.$$

RF cavities are often assumed as the impedance sources because they have many higher order mode (HOM) resonances. We calculated the wake potential in the RF cavities using the code ABCI [5,6], and calculated the lengths and the shift of the centers of the test bunches. This wake potential causes little change of the bunch lengths. On the other hand, it leads to the shifts of about 10ps of the bunch center. In Fig. 4, we show the DFT of

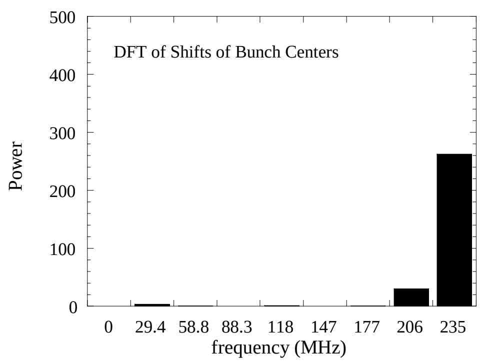

Fig. 4 DFT of the calculated shifts of the bunch centers due to the wake potential in the RF cavities.

the calculated shifts of the bunch centers due to the wake potential in the RF cavities. Although apparent pattern of the shift in the time domain differs from the experimental shifts, the power level of the frequency component of around 235 MHz in Fig. 4 is about the same as that of f_2 in Fig. 3 (b).

In order to explain the variation of the lengths of the test bunches phenomenologically, we intrduce an impedance of a resonator. Considering the cutoff frequency of the beam duct of the PF-ring and the damping pattern of variation of the bunch lengths, we set the resonant frequency and the quality factor to be 2575MHz and 120. Using these value, we determined the shunt impedance which can explain the experimental data to be about 80kΩ. The calculated lengths are shown in Fig. 5.

4. DEVELOPMENT OF FAST LIGHT SHUTTER

In the multi-bunch mode, speedy observation of a particular bunch using the photon counting system is

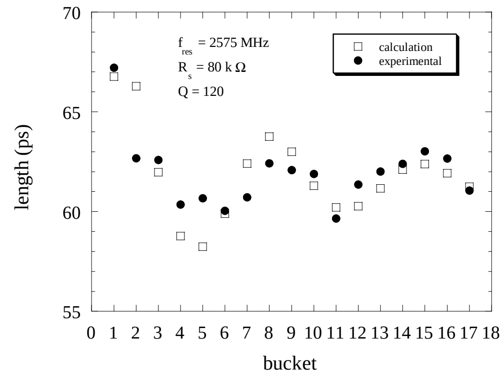

Fig. 5 : Variation of lengths of test bunches.

difficult because of a current limitation of the photomultiplier. A high speed shutter which can open or close within a time scale of the bunch spacing (2 ns in KEK-PF) enables us to observe one particular bunch: the time required to measure the single bunch impurity becomes short, and the longitudinal fine structure of the test bunches which emit less photons than the main bunch can be measured precisely.

The shutter system is composed of two polarizers and a Pockels-cell[7], which changes the polarization of penetrating light when a high voltage is applied. We succeeded to select photons from one particular bunch with the system. Some parameters of the shutter system are shown in Table 2.

We estimate that the extinction ratio makes the time required to measure the impurity down to about 1/100.

driving voltage	550 V
repetition rate	533 kHz
rise time (5 to 95 %)	1.5 ns
fall time (95 to 5 %)	1.6 ns
flat top	0.9 ns
extinction ratio	280

Table 2 : Parameters of the shutter system

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