MEASUREMENT OF WAKE EFFECTS BY MEANS OF TUNE SHIFT IN THE KEKB LOW-ENERGY RING

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Abstract

Electron clouds produced by a positron beam induce both single-bunch and coupled-bunch instabilities. The effects of electron clouds limit the performance of KEKB. An effect of the transverse dipole wake-field due to the electron cloud including the impedance effects was tried to measure at the KEKB LER using a tune-shift method. A test bunch was placed behind a bunch-train of a positron beam. The tune shift as a function of the current of a test bunch was measured under a constant train-current, while changing the bucket position of the test bunch. The horizontal tune shift did not quite change as a function of the bucket position. Compared to that, the vertical tune shift indicated a strong defocusing field and changed to a focusing field when a test bunch greatly approached a train. The measurements also indicated an asymmetric contribution of the solenoids between the horizontal and vertical planes.

INTRODUCTION

KEKB [1] is a multi-bunch, high-current, electron/positron collider. The collider consists of two storage rings: the Low Energy Ring (LER) for a 3.5 GeV positron beam and the High Energy Ring (HER) for 8 GeV electron. Bunches are stored in two rings with an average bunch spacing of 7 ns (3.5 buckets) in the usual physics run, forming a single train followed by an empty gap for aborting the beams.

The LER has suffered from an increase in the vertical beam size due to electron clouds. The solenoids used to trap electrons near the wall of the chamber were wound in all spaces that allowed the installation. A solenoids field of about 40 Gauss covers a region of 73% of the circumference [2]. Although the solenoids have greatly contributed to raising the luminosity, an increase in the vertical beam size is still observed at a high beam current and in narrow bunch spacing. A betatron sideband was observed in the tune spectrum, which is related to blowup of the vertical size [3]. It is believed that the vertical instability is caused by a fast head-tail instability due to a short-range wake. A resonator-like wake is proposed to explain the sideband spectrum.

Since the space charge of the electron cloud causes a positive tune shift, the density of the clouds would be estimated from the tune shift. The measured tune shift along a train [4] was consistent with the simulation [5]. On the other hand, the current-dependent tune shift (CDTS) of a specific bunch usually indicates a negative tune shift due to the transverse head-tail wake. How does the CDTS behave under the existence of an electron cloud? The CDTS corresponds to the integrated value of a wake-field over a whole bunch, while the electromagnetic fields of a bunch interact with the electron cloud.

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TUNE SHIFT AND TUNE MONITOR

The betatron tune is determined as the phase advance per turn of the betatron oscillation of a particle in a linear lattice. In an actual machine, however, additional electromagnetic fields acting a bunch cause a tune shift, in addition to nonlinear magnetic fields. When a bunch interacts with the surrounding components, a wake-field generated in the head part of a bunch propagates backwards and the tail part of a bunch would be affected. The transverse head-tail wake shows a negative tune shift given by

$$\Delta\nu_q = -\frac{T_0 I_b}{4\pi E/e}\sum_i \beta_{qi} k_{qi} .$$

Here, T_0 is the revolution time, I_b the bunch current, E the beam energy, β_q the beta function and k_{qi} (V/Qm) the kick factor of an i-th component. We can estimate the transverse effective impedance from the tune shift. The measurement is usually carried out in a single bunch. In a multi-bunched positron beam as in the LER, the electron cloud produced by a positron bunch-train remains even after passing through a train. Let us imagine a bunch passing through an electron cloud with uniform density ρ_e, the tune shift in one-dimensional model is given by

$$\Delta\nu_q = \frac{r_e}{2\gamma}\oint \rho_e \beta_q \, ds .$$

Here, r_e is the electron classical radius and γ the relativistic factor. The space charge due to the electron cloud acts as a focusing field, which results in a positive tune shift. The tune shift is proportional to the cloud density.

The betatron tune is measured with a swept frequency method using a spectrum analyser. The measurement time is 1.9 sec. The system [6] can make a bunch-by-bunch deflection as well as a pickup, and can measure a bunch-by-bunch tune with a minimum bunch-spacing of 4 ns with a resolution of typically $\delta\nu = 1.0\times10^{-4}$. We have two sets of the monitor, which are useful in the tune-shift measurement.

MEASUREMENT METHOD

The tune-shift measurement was carried out under a bunch structure as illustrated in Fig. 1. A long bunch-train was stored, after that, a pilot bunch as a test bunch was injected behind a train. We define the parameter "Distance" as representing the bucket interval between the last bunch of a train and a pilot bunch. A pilot bunch was injected one by one from a larger distance by considering the causality of the wake-field, assuming that the effect of the cloud disappears in the abort gap. During each injection, the tune was measured as a function of the current of the pilot bunch under a constant train current. The current of a pilot bunch was less than 1.2 mA. The measurement was carried out with and without solenoids fields under the conditions as given in Table 1. The transverse bunch-by-bunch feedback system was active for a bunch-train, which might cure the coupled-bunch instability. However, the feedback was turned off only for a bunch to be measured in order to remove the damping effect of the feedback for the tune measurement.

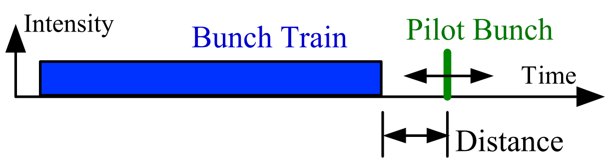

Figure 1: Schematic of a bunch train and a pilot bunch. We define the parameter, “Distance” or “D” as the bucket interval between the last bunch of a train and a pilot bunch.

Table 1: Machine and beam conditions

	Measurement-1	Measurement-2
Bunch Structure	4/200/4	1/1371/3.5
Bunch Current in a Train	0.5, 0.7 mA	1.0 mA
Solenoid Field	OFF	ON
Synchrotron Tune	0.025	0.025
Chromaticity ξ_x, ξ_y	1.6, 4.6	0.9, 3.2

Note that n/m/s in the line of bunch structure means the number of trains, the number of bunches in a train and the bucket spacing.

RESULTS

Without Solenoids Field

The tune shift was measured under the condition of measurement-1 as shown in Table 1. Bunches were spaced with every 4 buckets (8 ns) and formed a train containing 200 bunches with almost equal intensity. The tune was measured along a train as shown in Fig. 2a. We define the tune change as a Bucket-Dependent Tune-Shift (BDTS) under constant bunch current. Both of the horizontal and the vertical tunes rapidly increased in the leading part of a train. The horizontal tune shift was almost saturated after a bucket number of 200, however, the vertical one seemed to slightly increase. Figure 2b shows the tune of a pilot bunch after a train as a function of the distance. The tune shift rapidly reduced to about 1/4 to 1/5, compared to D=3 and D=60.

The CDTS of a pilot bunch was measured, while changing the distance. The results are shown in Figs. 3a and 3b. The CDTSs in both planes were equal to those in a single bunch at D=60. The horizontal CDTS was almost constant except in a short distance. Compared to that, the vertical CDTS indicated a nonlinear behaviour, depending on the bunch current of a pilot bunch. Thus, the CDTS was approximated by two linear fittings. The vertical CDTS showed a higher negative value at a lower bunch current and its slope became flat at a high bunch current at D=9. At D=6 and D=3, the CDST indicated positive values. This dramatic change corresponds to a rapid increase in the tune shift or the cloud density as shown in Fig. 2b.

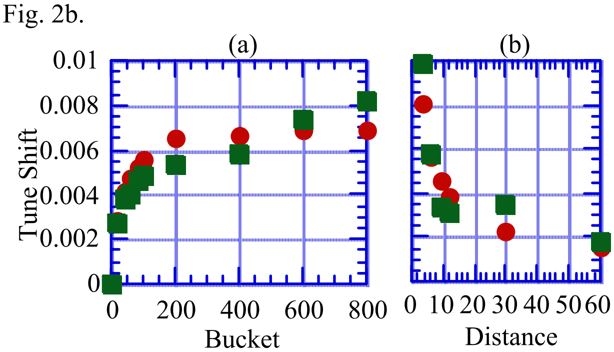

Figure 2: (a) Tune shift along a train. The red dots are horizontal and green squares are vertical with a bunch current of 0.5 mA. The tune of the head bunch of a train is used as a reference. (b) Tune shift of a pilot bunch after a train. The red dots are horizontal and the green squares are vertical with a bunch current of 0.5 mA.

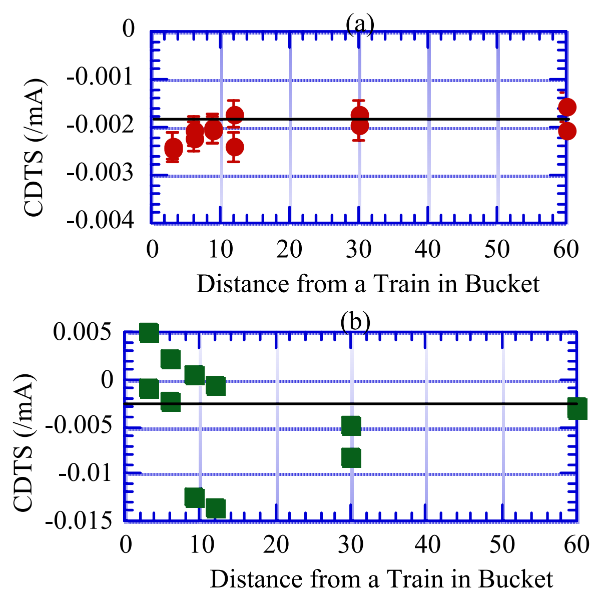

Figure 3: The CDTS as a function of distance from a train, (a) is horizontal and (b) is vertical. Each black solid line indicates a CDTS measured in a single bunch.

With Solenoids Field

A similar measurement was carried out with solenoids fields under the condition of measurement-2 given in Table 1. Figure 4a shows the BDTS in a train, where the beam condition was just below the threshold for the vertical instability. It is clearly shown that the horizontal BDTS was completely damped by the solenoids. Compared to that, the vertical BDTS rather increased compared with that in Fig. 2a, even though the bunch current was double. Figure 4b shows the decay of the tune shift after a train, where the vertical decay is slower than that in Fig. 2b. Figures 5a and 5b show the CDTS as a function of the distance. The vertical CDTS indicates a similar structure with and without the solenoids, which suggests an insufficient contribution of the solenoids to the vertical plane.

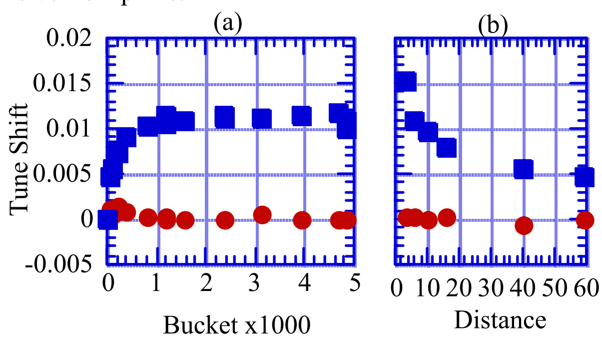

Figure 4: (a) The BDTS, red dots are horizontal and green squares are vertical with a bunch current of 1.0 mA. (b) The tune shift after a train, red dots are horizontal and green squares are vertical with a bunch current of 0.8 mA.

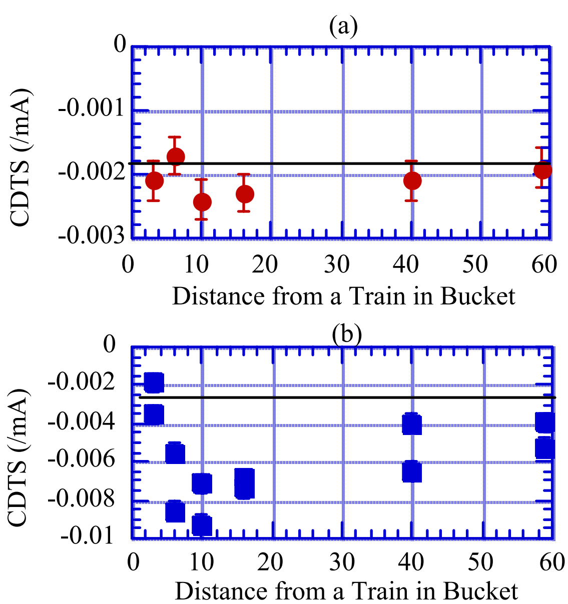

Figure 5: The CDTS (a) is horizontal and (b) is vertical. Each black solid line indicates a CDTS measured in a single bunch.

DISCUSSION

When the solenoids were off, the BDTS showed a symmetrical behaviour between the horizontal and the vertical directions as shown in Fig. 2. However, the vertical CDTS indicated a peculiar behaviour as shown in Fig. 3, which suggested that a bunch train left a strong vertical wake-field. The measurement also suggests that the vertical wake contains both focusing and defocusing forces, depending on the density of the electron cloud. When the solenoids were turned on, the horizontal BDTS was completely suppressed by the solenoids, however, the vertical BDTS was reduced only to about 60%, comparing them under the same bunch current and spacing. We understand from these measurements an asymmetric behaviour in the wake-field and the asymmetric contribution of the solenoids between the horizontal and vertical planes. The results seem to be a discrepancy between the real machine and the simulation [7].

One candidate to make the asymmetry might be a flat shape of a bunch. A strong vertical field of a positron bunch may accelerate electrons passing near a bunch and produce high-energy electrons. A solenoid field of 40 Gauss might be insufficient to trap high-energy electrons of more than several hundreds eV. The other candidate is that the clouds might exist in the dipole magnets, where the solenoids cannot be wound.

The tune spectrum almost showed a single peak corresponding to a betatron tune. However, we observed a distorted spectrum without solenoid fields when the distance was D=3 and the bunch current in a train was 1.0 mA. This condition is expected to be above the threshold for the vertical instability. A two-peak spectrum as shown in Fig. 6b would be a direct effect due to the electron cloud as in the case of a beam-beam interaction. In that case, the CDTS indicated a positive slope.

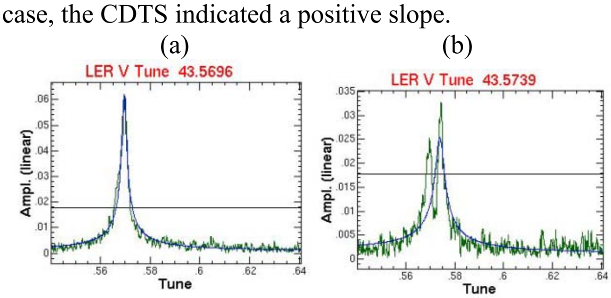

Figure 6: Vertical tune spectrum, observed at D=3 without the solenoids, under a bunch current of 0.5 mA (a) and 0.7 mA (b) in a train.

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