VARIATIONS OF BETATRON TUNE SPECTRUM DUE TO ELECTRON CLOUD OBSERVED IN KEKB

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Abstract

In order to investigate the characteristics of electron clouds, the wake effects were measured at KEKB using a test bunch placed behind a bunch-train, where there was a rapid decay in the electron cloud density. The current-dependent tune-shift of the test bunch exhibited nonlinear behaviour in the vertical plane [1]. By observing the tune spectrum, we found that the spectrum width expanded and this was accompanied with a large negative tune slope at a low cloud density and at a low bunch current. However, as the cloud density increased, the spectrum width shrunk and this was accompanied with a positive tune slope. These experimental results suggested that a high electron cloud density caused an anti-damping effect in the tune spectrum. We believe that the variations in the tune slope and spectrum width might be related to the wake field in the resonator model, where the wavelength is comparable to the bunch length.

INTRODUCTION

The low-energy ring (LER) of KEKB [2] suffers from an increase in the vertical beam size due to the electron cloud. The solenoids are wound in all spaces that allowed the installation. A solenoids field of about 40 Gauss covers 73% of the circumference [3]. Although the solenoids have significantly contributed to an increase in the luminosity, an increase in the vertical beam size is still observed at a high beam current and in a narrow bunch spacing. A betatron sideband was observed in the tune spectrum, which is related to blowup of the vertical size [4]. It is believed that the vertical instability is caused by a fast head-tail instability due to a short-range wake induced by the electron cloud. A resonator-like wake is proposed to explain the instability. Is there any other evidence that characterizes the cloud effect?

Since the space charge of an electron cloud causes a positive tune shift, the density of the cloud could be estimated from a coherent tune shift. The measured tune shift along a train [5] was consistent with the simulation studies [6]. On the other hand, the current-dependent tune shift of a specific bunch is used to evaluate the wake force caused by the transverse impedance. This technique could be used to estimate the wake force due to the electron cloud. Since a tune measurement with the swept-frequency method is equivalent to measuring the frequency response of a beam, the tune spectrum would have useful information on the damping or the tune spread and on the nonlinear electromagnetic fields acting on a bunch. How does the tune spectrum behave under the existence of an electron cloud?

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TUNE SPECTRUM

In a high-intensity machine such as that in the LER, the tune is affected by various electromagnetic forces acting on a bunch. We consider two typical forces that can induce variations in the tune; one is the force due to a short-range wake force induced in a positron bunch and the other is the space charge force due to the electron cloud. When the positron bunch coexists with the electron cloud, the wake field due to electron cloud should be considered in addition to the conventional wake fields caused by the transverse impedance. Therefore, the change in the tune is influenced by these wake fields and can be expressed as

$$\Delta\nu_q = \frac{T_0 I_b}{4\pi E/e}\left(\sum_i \beta_{qi} k_{qi\_imp} + \sum_j \beta_{qj} k_{qj\_ec}\right). \qquad (1)$$

Here, T_0 is the revolution time, I_b the bunch current, E the beam energy, β_q the beta function and k_{qi_imp} (V/Qm) the dipolar kick factor of the i-th impedance component and k_{qj_ec} the j-th component of the kick factor induced by the electron cloud. We can estimate the average kick factor over the ring from a slope of the current-dependent tune shift, $\Delta\nu_q/\Delta I_b$. The parameter $\Delta\nu_q/\Delta I_b$ is termed as a tune slope. When the tune slope is positive, a focusing wake force is expected. The kick factor k_{qi_imp} usually shows a negative value. Since the impedance effect is common for all the bunches, we can extract the cloud effect by subtracting the impedance effect.

Let us consider a bunch passing through an electron cloud with a uniform density ρ_e. The tune shift due to the electron cloud in the two-dimensional model is given as

$$\Delta\nu_{q-ec} = \frac{r_e}{2\gamma}\oint \rho_e \beta_q ds. \qquad (2)$$

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 and results in a positive tune shift. Assuming that the coupled-bunch instability is stabilized, the density of the electron cloud can be derived by comparing the bunch-by-bunch tunes to a reference tune under the same bunch current.

The shape of the tune spectrum contains important information on the beam dynamics. When an external forced oscillation is applied to a beam, the damped oscillation possesses a finite width in the frequency spectrum. The damping rate or the tune spread can be estimated from the spectrum width. Since various damping mechanisms should be considered in a real accelerator, the measured width is given as

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$$W_m = \sqrt{W_b^2 + W_h^2 + W_0^2}\,, \qquad (3)$$

where the parameter W_b is the width based on the beam properties, including the radiation damping, the head-tail damping with a finite chromaticity, beam-beam effects and an electron-cloud effect. The beam-related width depends on the chromaticity and the beam current. The parameter W_h is the width caused by the hardware of the machine, including the width due to feedback damping, nonlinear magnetic fields and fluctuations in magnetic fields. The parameter W_0 is the width due to the resolution bandwidth of the spectrum analyzer and has a constant value. The width due to the electron cloud can be estimated by comparing the widths of different bunches, by assuming that the electron cloud is reset within one revolution. The width due to the electron cloud is given as

$$\Delta W_{ec} = \pm\sqrt{\left|W_m^2 - W_{m0}^2\right|}\,, \qquad (4)$$

where W_{m0} is the width measured without the electron cloud effect. In Eq. (4), the plus sign denotes the damping effect and minus sign denotes the anti-damping effect.

MEASUREMENT

The measurement of the tune spectrum was carried out for a bunch structure as illustrated in Fig. 1. A long bunch-train was stored in advance and a test bunch was injected as the probe behind the train. The parameter "*Distance* or *D*" is defined as the bucket interval between the last bunch of the train and the test bunch. A test bunch was injected one by one from a larger distance. During each injection, the tune spectrum was measured as a function of the current of the test bunch under a constant train current. The measurements were carried out without solenoids fields under the conditions as listed in Table 1. During the measurements, the transverse bunch-by-bunch feedback system was active for the bunch-train and cured the coupled-bunch instability due to electron cloud. However, the feedback was turned off only for the bunch to be measured.

Figure 1: Measurement method.

Table 1: Machine and beam conditions

Bunch Structure	4/200/4
Bunch Current in a Train	0.5 & 0.7 mA
Bunch Current of a Test Bunch	1.2 mA max.
Solenoid Field	OFF
Synchrotron Tune	0.025
Chromaticity ξ_x, ξ_y	1.6, 4.6

Note that values n/m/s shown in the row of the bunch structure are the number of trains, the number of bunches in the train and the bucket spacing respectively.

EXPERIMENTAL RESULTS

The tune spectrum of the test bunch was measured under a constant train current. Figure 2 shows the current-dependent tune and a spectrum width measured at a large distance of D=60. We found a linear decrease in the tune and a linear increase in the width, with increasing the bunch current in the horizontal and the vertical directions. The negative tune slope is roughly equal to that measured in a single bunch. We believe that the tune slope is caused by a short-range wake field due to the transverse impedance and that the effect of the electron cloud is small. On the other hand, the change in the spectrum width should be caused by the head-tail damping due to the positive chromaticity of ξ_x=1.6 and ξ_y=4.6 and the change is proportional to the bunch current and the chromaticity. It is confirmed that the tune and the spectrum width are independent of the excitation amplitude varying over 20 dB. The head-tail damping rate is related to the real part of the transverse impedance, on the other hand, the tune slope depends on the imaginary part of the impedance. These data are used as reference values for measuring the cloud effects.

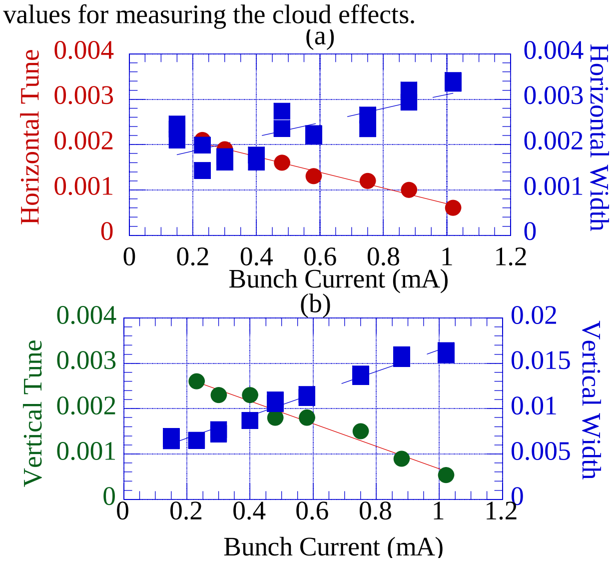

Figure 2: Horizontal tune and spectrum width (a) and vertical tune and the width (b) as a function of the bunch current measured at D=60. The tune is indicated by red or green dots and the spectrum width by blue squares. The tune of the head bunch of a train is used as the reference.

The tune spectra were measured while shifting the test bunch to the train. The three graphs in Fig. 3 represent the relationship among the tune shift, the tune slope and the spectrum width for a specific distance, D. Figure 3-(a) shows the decay of the tune shift or the cloud density in the horizontal and the vertical planes. The decays are not approximated by a simple exponential decay. The cloud density sharply decays within a short distance of $D \le 10$, however, it slowly decays in the region of $D > 10$. Figure 3-(b) shows the vertical tune slopes. Since the current-dependent tune was nonlinear, the tune slope was approximated by two lines around two bunch currents. A large negative tune slope or strong defocusing wake force is observed around D=10 at a low current. The tune slopes indicate the focusing force for the short distance of $D \leq 10$, where the cloud density is high. Figure 3-(c) shows the variations of the vertical spectrum width. Since the measured width also indicated a nonlinear behaviour as a function of the bunch current, it is plotted for three different currents. At a low bunch current of I_b = 0.3mA, the width increases around D=10 and decreases as the bunch approaches the train. From Fig. 3, we find that the spectrum width or the tune spread decreases and it is accompanied with a positive tune slope or the focusing wake force, when both the bunch current and the cloud density increase.

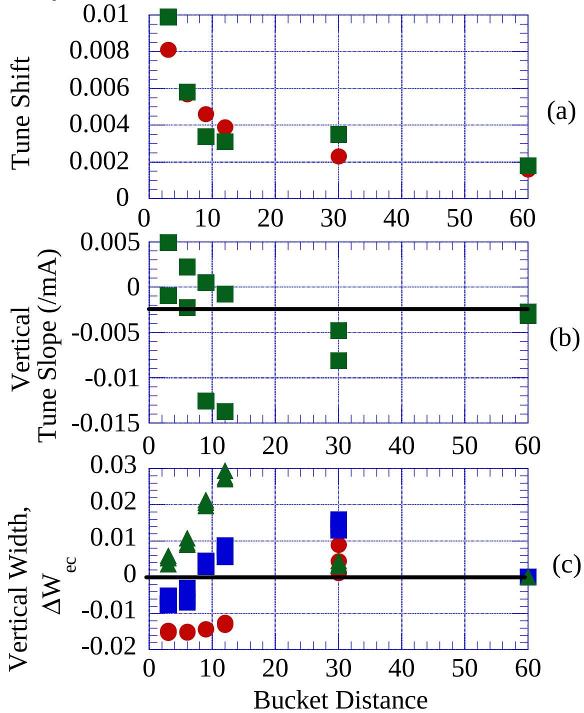

Figure 3: Tune shift, the tune slope and the spectrum width as functions of distance. (a) Tune shift at the bunch current of 0.5 mA, indicated by red dots (horizontal) and by green squares (vertical). (b) Vertical tune slope (/mA), the black horizontal line indicates the measured tune slope at a single bunch. (c) Vertical width at bunch currents of 0.3 mA(green), 0.5 mA(blue) and 1.0 mA(red).

The tune spectrum is measured again, when a bunch current of a train is increased from 0.5 mA to 0.7 mA. The tune shift at the last bunch of the train has a high value of $\Delta\nu_{y-ec} = 0.015$, which corresponds to a cloud density of about $\rho_{ec} \approx 2.0\times10^{12}\,\mathrm{m}^{-3}$. The current is estimated to be above the threshold of the vertical instability from a vertical beam size measurement. As the test bunch approached the train at a short distance of D=3, we observed a double-peak spectrum separated by about 0.005. At that time, the maximum bunch current of the test bunch was limited to below 0.7 mA due to instability. Moreover, some small sideband spectra were observed with a tune separation of 0.04 from the main peak. The sideband phenomenon is similar to the spectrum observed by J. Flanagan [4].

DISCUSSION AND SUMMARY

According to the analysis [7], the transverse wake field due to the electron cloud is represented by a damped resonator model. The wake properties have an alternating feature of defocusing and focusing forces along the longitudinal direction. On the other hand, the electrons transversely oscillate with the characteristic frequency in the potential formed by the positron bunch. The characteristic frequency is estimated to be approximately 30-40 GHz using KEKB parameters. The wavelength of the wake exhibits a size comparable to an rms bunch length of 6-7 mm, and the changes in the wavelength are proportional to the square-root of the charge density of the positron bunch. The dynamic variations of the wake properties might be related to the variations in the tune slope and the spectrum width.

The following experimental results have been obtained.

- A strong defocusing force was observed together with a wide tune spread in the vertical plane in a region, where the cloud density rapidly varied. This result suggests nonlinear fields and/or some change in the cloud distribution.
- As the cloud density grew and the bunch current increased, the tune spread decreased together with a focusing wake force (anti-damping effect). We believe that the phenomena are based on the direct interaction between the bunch and the electron cloud near the bunch.
- The spectrum width is a good parameter to evaluate the nonlinear current-dependent tune-shift.
- A double-peak spectrum was observed above the threshold of the vertical instability.
- We did not observe any wake effects and any variations in the spectrum width in the horizontal plane.

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