MEASUREMENT OF WAKEFIELD EFFECTS CAUSED BY ELECTRON CLOUD AT KEKB

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Abstract

In order to study the wakefield effects of an electron cloud, a test bunch was placed behind a bunch train, where the cloud density rapidly varied. A current-dependent tune shift and the tune spread of the test bunch were measured as a function of the bunch current while varying the bucket position of the test bunch. The vertical tune shift indicated a strong defocusing force together with a widened tune spread in a region of relatively low cloud density and low bunch current. However, the vertical defocusing disposition changed to a focusing force at a high cloud density and a high bunch current. The horizontal and vertical tune spreads also demonstrated nonlinear, as a function of the bunch current. The current at the maximum horizontal tune spread was approximately equal to the threshold current of the vertical size blowup. The variation in the horizontal tune spread suggested a new index for the vertical instability threshold caused by the electron cloud.

INTRODUCTION

Electron cloud instabilities are a great concern for the KEKB [1], an asymmetric electron/positron double-ring collider. The collider consists of two storage rings: a low-energy ring (LER) for a 3.5-GeV positron beam and a high-energy ring (HER) for 8-GeV electrons. The newly installed crab cavity can be used for achieving effective head-on collisions at the interaction point while maintaining a crossing orbit. Therefore, bunches circulate around the rings with a horizontal tilting of the head and the tail. The LER suffers from a vertical instability caused by an electron cloud. The solenoids field mitigates the instability [2], however, the vertical size blowup is still observed in the case of short bunch spacing. A betatron sideband was observed in the tune spectrum, which indicated a blowup of the vertical beam size [3]. A short-range wake induced by the electron cloud causes fast head-tail instability. However, a coupling between synchro-betatron modes cannot be observed in the process of reaching the threshold, unlike the instability due to the conventional impedance. How does a bunch behave in the case of a vertical instability, when the density of electron cloud and the bunch current increase? A measurement of the variations in the tune spectrum was carried out in the LER with a test bunch placed behind a bunch train. The tune shift and the spectrum width were measured, while changing the cloud density. Although a similar measurement has already been reported [4, 5], the crab cavities were newly installed afterwards. The effect of the crab kick is demonstrated.

TUNE SPECTRUM

Assuming that coupled-bunch instability is suppressed, we find that two types of forces that can induce dynamic variations in the tune should be considered; one is the short-range wake force from the impedance and the other is the space charge force due to the electron cloud. The dynamical change in the tune is influenced by these wakefields and can be expressed as

$$\Delta\nu_q = \frac{T_0 I_b \langle\beta_q\rangle}{4\pi E/e}\Big(\sum_i k_{qi\_imp} + \sum_j k_{qj\_ec}\Big). \tag{1}$$

Here, T_0 is the revolution time, I_b the bunch current, E the beam energy, $\langle\beta_q\rangle$ the average betatron function and k_{qi_imp} (V/Cm) 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 total kick factor over a ring from the slope of the current-dependent tune shift, $\Delta\nu_q/\Delta I_b$. The parameter $\Delta\nu_q/\Delta I_b$ is termed as the tune slope. When the tune slope is negative, a defocusing wake force is expected. Since the impedance effect is common for all bunches, we can extract the cloud effect by measuring the bunch-by-bunch tune slopes and 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 is given as follows by using the two-dimensional model;

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

Here, r_e is the electron classical radius and γ the relativistic factor. Using the strong head-tail model, we can simply express the threshold for the vertical instability as

$$\rho_{th} \approx \frac{2}{\pi r_e}\frac{\gamma\nu_s}{\oint \beta\cdot ds}. \tag{3}$$

The betatron tune is measured with a swept-frequency method by using a spectrum analyzer. The method is equivalent to obtaining a frequency response function of the beam. The spectrum width is related to the tune spread. Since the effect of an electron cloud is different from bunch to bunch, the spectrum width caused by the electron cloud can be estimated by comparing the widths of the different bunches, by assuming that the feedback damping effect is negligible. The width can be estimated as

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

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

MEASUREMENT

Four long bunch-trains were stored in advance and they were separated by a time interval of 940 ns. A test bunch was placed behind one of the trains, as illustrated in Fig. 1. The parameter "*Distance* or *D*" was defined as the bucket interval between the last bunch of the train and a test bunch. During each injection, the tune spectrum was measured as a function of the current of the test bunch under a constant train current. The excitation amplitude for measuring the tune spectrum was constant. The measurements were carried out without solenoids fields under the conditions as listed in Table 1. During the measurements, a transverse bunch-by-bunch feedback system was active for the bunch-train and cured the coupled-bunch instability. However, the feedback was turned off only for the bunch to be measured.

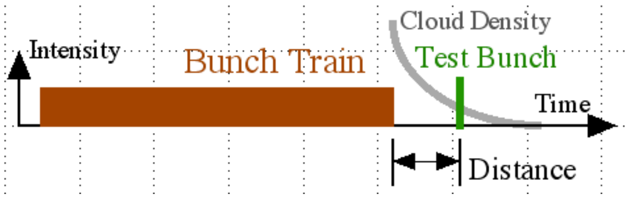

Figure 1: Configuration of a bunch train and a test bunch.

Table 1: Machine and beam conditions.

Bunch Structure n/m/s	4/200/4
Bunch Current in a Train	0.38 to 0.75 mA
Bunch Current of a Test Bunch	1.2 mA max.
Solenoid Field	OFF
Synchrotron Tune ν_s	0.025
Horizontal Emittance ε_x	18 nm
Average Beta Function $\langle \beta_{x/y} \rangle$	10.5/11.0 m
Chromaticity $\xi_{x/y}$	1.0/4.6

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 bunch-by-bunch tune was measured along a train. The horizontal and the vertical tunes rapidly increased until a bucket number of 100, and tended to saturate in the backward region of a train. The variations in the tune shift would approximately reflect the variations in the electron cloud density. Figure 2 shows the maximum vertical tune shift in a train and the vertical beam size measured by the interferometer as a function of the total beam current of a train. The maximum tune shift indicated an approximately linear increase with an increase in the beam current. On the other hand, the vertical beam size was almost constant up to a current of 380 mA, and began to increase with an increase in the beam current. Therefore, the threshold current for the vertical instability is expected to be 380 mA or a bunch current of 0.47 mA. The corresponding tune shift was $\Delta\nu_{th} = 0.008$ for the threshold, as shown in Fig. 2. The cloud density at the threshold was expected to be $\rho_{th} \approx 1.1 \times 10^{12}\ \mathrm{m}^{-3}$ by using Eq. (3). The tune shift and the cloud density were consistent with each other.

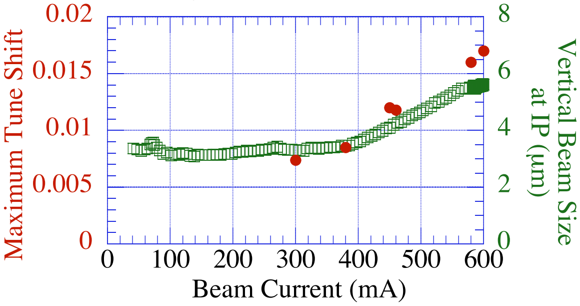

Figure 2: Maximum tune shift in a train and vertical beam size as a function of the beam current. Red dots show the maximum tune shift, and green squares indicate the vertical beam size.

The current-dependent tune shift of a test bunch was measured, when the beam current of a train was constant at 440 mA. When the bunch current of a test bunch was equal to that in a train, the measured tune shift was equivalent to the cloud density behind a train. Figure 3 shows the estimated cloud density as a function of the bucket distance, D. The cloud density decayed rapidly, in a region of D < 10 or 20 ns. The threshold of the vertical instability occurred around D = 6, where the cloud density was expected to be $\rho_{th} \approx 1.1 \times 10^{12}\ \mathrm{m}^{-3}$. As increasing the parameter D, the cloud density decayed slowly. Although the current-dependent tune shift of a test bunch exhibited nonlinear behaviour, a linear approximation was used around a low bunch current of 0.3 mA. The kick factor caused by the electron cloud was estimated, by comparing with that at D = 60, and assuming that the kick factor at D = 60 was only due to the impedance effect. The vertical kick factor around D = 10 exhibited a strong defocusing force as shown in Fig. 3; this force was approximately three to four times larger than the kick factor of the vertical impedance measured at D = 60. When the parameter D moved from 8 to 6, the kick factor abruptly changed into a focusing force with a rapid increase in the cloud density. The rapid variation in the kick factor took place around the threshold of the vertical instability.

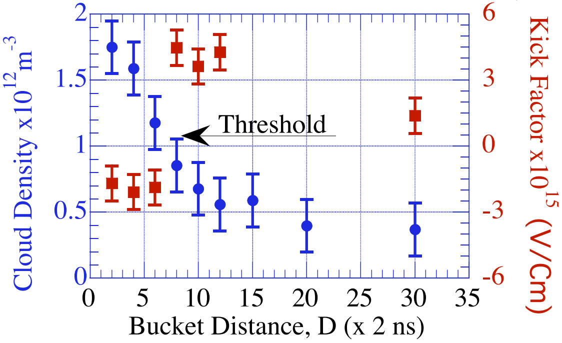

Figure 3: The left axis shows the electron cloud density estimated from the vertical tune shift. The right axis

represents the kick factor due to the electron cloud. Both axes are a function of the bucket distance, D. Here, $\Sigma K_{imp} = 1.5\times10^{15}$ (V/Cm). The positive kick factor denotes a defocusing force.

The spectrum width of an electron cloud was obtained by comparing with that at D = 60. The spectrum width indicated peculiar variations as shown in Fig. 4-(a). The horizontal width enlarged and reached its maximum value and then shifted to a lower width, with an increase in the bunch current. These variations shifted to lower bunch current, with an increase in the cloud density. The maximum width was observed at the bunch current of Ib_{max} = 0.6 mA for D = 4, and at Ib_{max} =1.0 mA for D = 8. On the other hand, the vertical width also exhibited similar behaviour to that observed in the case of the horizontal width. However, by comparing Fig. 4-(b) with Fig. 4-(a), we found that there were three different features. First, the maximum width in the vertical plane was observed at a lower current, for instance, Ib_{max} = 0.3 mA for D = 8. Second, the vertical maximum width value was considerably larger than the horizontal one. Third, the vertical width changed its sign and proceeded to anti-damping in the region of a high bunch current. Figure 5 shows the bunch current at the maximum horizontal width, Ib_{max} as a function of the parameter D. The Ib_{max} varied almost linearly as a function of D. On the other hand, the threshold current of the vertical instability was determined by the longitudinal charge density or the bunch current per spacing [6] and could be extrapolated from the measured threshold for different bunch spacings. The measured current, Ib_{max} at the horizontal width was consistent with the expected threshold current of the vertical instability, as shown in Fig. 5.

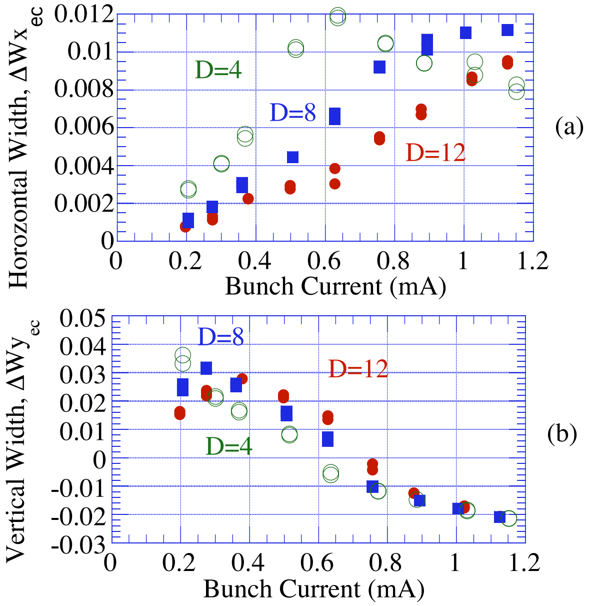

Figure 4: Horizontal (a) and vertical (b) spectrum-widths as a function of the bunch current of a test bunch. The values were obtained at D = 12 (red dots), D = 8 (blue squares) and D = 4 (green circles).

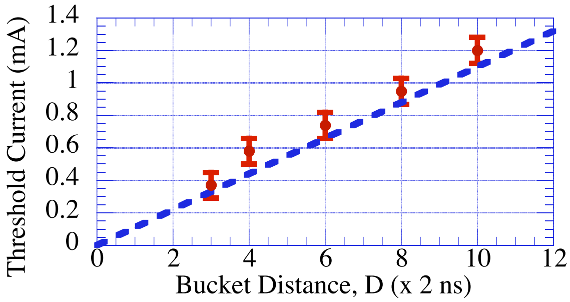

Figure 5: The bunch current at the maximum horizontal width is indicated by red bars and an expected threshold bunch current is indicated by a dashed line as a function of the bucket distance, D.

The horizontal spectrum widths were compared with and without the crab kick as shown in Fig. 6. The horizontal widths were almost the same until the peak in the width was reached: this suggested the threshold of the vertical instability. However, they were separated with the reduction in the horizontal width above the threshold current. The result suggested that the crabbing motion might change a distribution of the cloud density and/or the bunch profile distribution. A simulation is required to verify whether this speculation is correct.

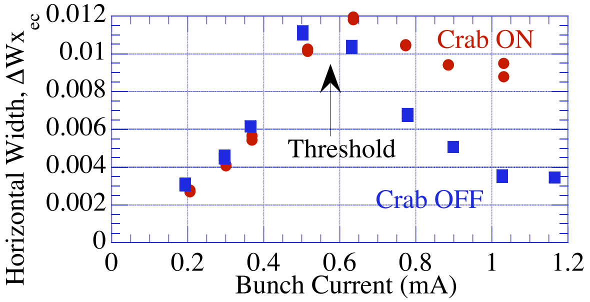

Figure 6: Horizontal width of a test bunch as a function of the bunch current at D = 4, with and without the crab kick. Red dots indicate the width with the crab kick and blue squares indicate that without the crab kick. The train current is 450 mA.

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