ESTIMATION OF ELECTRON-CLOUD DENSITY BY MEANS OF MEASURING BETATRON TUNE AT KEKB LOW ENERGY RING

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Abstract

The KEKB Low Energy Ring suffers from blowup in the vertical size of positron bunches due to an electron cloud. Solenoids are installed around the ring to confine the electrons to the vicinity of the chamber. The density of the electron cloud can be estimated from a change in the betatron tune of an individual bunch. Tune-shift measurements were performed while the solenoid field, the bunch spacing and the bunch current changed.

1. INTRODUCTION

KEKB [1,2] is a multi-bunch, high-current, electron/positron collider for *B* meson physics. 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 electrons. Both rings store more than 1,000 bunches, where the harmonic number is 5120 with an RF frequency of 509 MHz.

The LER has suffered from blowup in the vertical beam size since the early stage of commissioning [3]. The blowup is caused by an electron cloud. In order to confine electrons to the vicinity of the chamber wall, solenoids were installed in the arc sections in September 2000, and it was confirmed that they were effective to weaken the blowup. Thus, we added solenoids in the straight sections. The total length covered by the solenoids, including the permanent magnets, is about 2300 m [4], where the circumference of the LER is 3016 m.

Though the solenoids have contributed to increasing the luminosity, blowup in the vertical beam size is still observed at high beam currents and for narrow bunch spacing. It is required to investigate the properties of the electron cloud and the effects of the solenoids. We have estimated the electron cloud acting on positron bunches by measuring the coherent betatron tune of individual positron bunches.

2. TUNE SHIFT DUE TO ELECTRON CLOUD

Since the effect of photoelectrons was first identified at the Photon Factory [5,6], many efforts have been made to clarify the mechanism of the instability. Analytical work and simulations have provided an image of an electron cloud. A model showed that the blowup in the vertical beam size observed in the LER was caused by a strong head-tail instability [7]. Using a two-particle model, the threshold of the electron density in the cloud for the blowup is given by

$$\rho_{\rm th} = \frac{2\gamma\nu_s}{\pi r_e L\langle\beta_{x,y}\rangle}, \qquad (1)$$

where γ is the relativistic factor, ν_s is the synchrotron tune, r_e is the classical electron radius, $\langle\beta_{x,y}\rangle$ is the average value of the horizontal or vertical betatron function and L is the longitudinal length of the cloud. Experimentally, the density of electrons in a cloud can be estimated from a shift of the betatron tune under the hypothesis that the electric fields due to the electron cloud result in a shifting of the coherent betatron tune of positron bunches. The tune shift due to the cloud is given by [8]

$$\Delta\nu_{x,y} = \frac{r_e}{2\gamma}\cdot\langle\beta_{x,y}\rangle\rho_0\cdot L, \qquad (2)$$

under the condition that the majority of the electrons in the cloud are not disturbed during the passage of a positron bunch. Here, ρ_0 is the average density of the electron cloud. Combining Eqs. (1) and (2), the threshold for the blowup in the tune shift is simply given by

$$\Delta\nu_{th} \approx \frac{\nu_s}{\pi}. \qquad (3)$$

This expression shows that the threshold is determined by the synchrotron tune alone. This condition is similar to that for the strong head-tail instability in a single bunch. A synchrotron tune of 0.025 results in a threshold of 0.008 in the tune shift.

3. MEASUREMENT OF TUNE SHIFT

The betatron tune is measured based on a swept frequency method. A bunch signal picked up by a button electrode is selected by a gate module [9] and its peak is detected. The noise level on a detector is less than the rms vertical beam size at the pickup electrode. The resolution of the tune measurement is mainly determined by the bandwidth of an analyser and is estimated to be ±0.0004 in the present configuration [10].

The measurement was performed without any collisions, where bunches were placed with an equal spacing in a train and each bunch in a train had almost the same intensity. Since each train was separated sufficiently, a leading bunch in a train would not be affected by the cloud. Thus, we regarded the tune of the leading bunch as a standard. The synchrotron tune was 0.0249 and the chromaticity had slightly positive values, ξ_x =0.7 and ξ_y =2.2. The average values of the betatron function were 10.5 m horizontally and 11.0 m vertically.

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3.1 Effect of Solenoids

Under the current solenoid system, the effect of solenoids was investigated. Note that some permanent magnets are active regardless of the solenoids being on/off. The betatron tune increases along a train and tends to saturate at the rear part of a train, as shown in Fig. 1. The saturated tune shift is about 0.009 horizontally and 0.015 vertically without any solenoid fields. When all solenoids are active, the tune shift is reduced to 0.002 horizontally and to 0.006 vertically. Thus, the reduction in the tune shift by the solenoids is about 0.007 horizontally and 0.009 vertically. The measured tune shifts are different between the horizontal and vertical directions. This result suggests a different distribution and/or mechanism in producing the cloud between two directions.

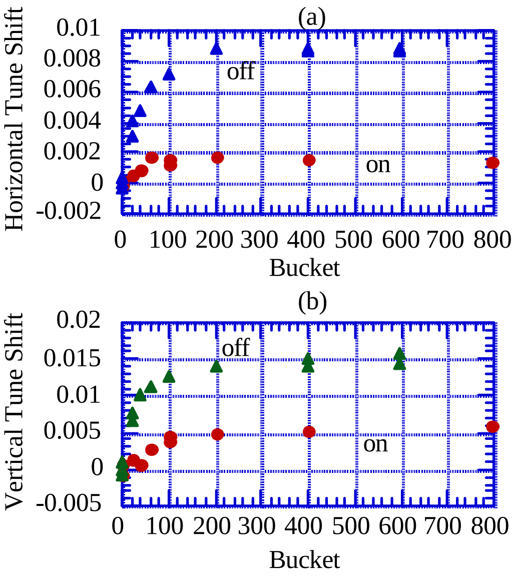

Figure 1: Horizontal (a) and vertical (b) tunes along a train, the dots are tunes with solenoid field and the triangles are without a solenoid field. The bunch current is 0.5 mA and the bunch spacing is 8 ns.

3.2 Bunch Spacing and Current Effects

The effect of the bunch spacing was measured under a constant solenoid field of 45 Gauss. Figure 2 shows the tune shift with different bunch spacing of 4, 6 and 8 ns at a bunch current of 0.5 mA. The horizontal and vertical tune shifts behave similarly at 6 ns and 8 ns spacing. However, the tune shift is extremely large at 4 ns spacing in both directions. The result suggests that the current solenoids system is insufficient to repel the electron cloud at 4 ns bunch spacing.

Next, the current dependence of the tune shift was measured under a constant bunch spacing of 8 ns. Figure 3-(a) shows the tune shift as a function of the bunch current with the solenoids off. The horizontal and vertical tune shifts linearly increase with the bunch current. According to a beam size measurement using an interferometer [11], the threshold bunch current for blowup in the vertical beam size was 0.35 mA, which corresponded to a tune shift of 0.011. This tune shift for blowup is higher than the expected value of 0.008 using Eq.(3). Figure 3-(b) shows the current dependence with the solenoids being on. The horizontal tune shift is suppressed by the solenoids. However, the vertical tune shift increases with the bunch current, even if the solenoids are active. We found a kink in the curve, where a vertical coherent oscillation of bunches was observed at the rear part of a train. The threshold bunch current for blowup is 1.4 mA, which corresponds to a tune shift of higher than 0.012. These results are roughly consistent with the expectation, though the measured tune shift is slightly higher than the expectation.

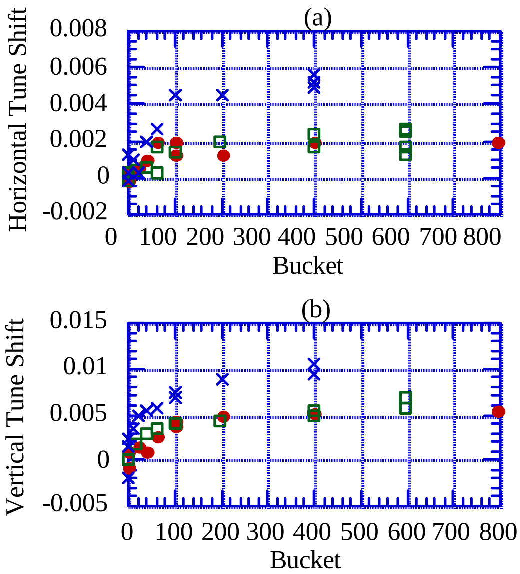

Figure 2: Horizontal (a) and vertical (b) tunes along a train. The dots are tunes with a bunch spacing of 8 ns, the squares are with 6 ns and the crosses are with 4 ns. The bunch current is almost constant, 0.5 mA.

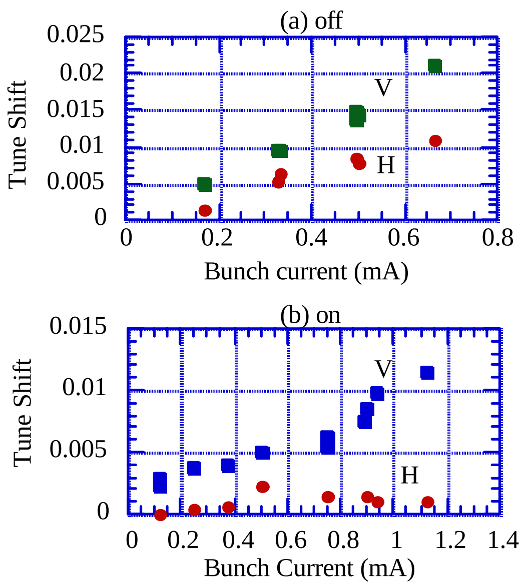

Figure 3: Difference in the tune between the leading and last bunches in a train as a function of the bunch current, (a) with the solenoid Off and (b) with the solenoid On. The dots are horizontal tune and the squares are vertical one.

4. DISCUSSION

4.1 Comparison with a Simulation

The electron cloud density can be estimated from the tune shift using Eq. (2). The cloud builds up at the front part in a train and tends to saturate at the rear part, as shown in Fig. 4. The build-up time with a linear approximation is 70 to 80 ns in both axes. However, a difference between the horizontal and vertical axes seems to enlarge at the rear part in a train. The horizontal tune shift is 0.009, which corresponds to a cloud density of $1.3\times10^{12}(m^{-3})$, assuming L=3000 m. On the other hand, the vertical one is 0.015 at the tail. A slow increase in the vertical tune is observed at the saturation region.

A simulation can evaluate the cloud density, assuming the yield of photoelectrons, (Y) and the reflection coefficient, (R) of the synchrotron light. Assuming Y=0.02 and R=0.4 [12], the central cloud density linearly increases along a train and tends to saturate, where the beam conditions between the simulation and the measurement are almost equal. The linear build-up time is about 70 ns and the saturated density is evaluated to be $1.2\times10^{12}(m^{-3})$, which corresponds to a tune shift of 0.0084 with L=3000 m. The simulation agrees with the tune shift on the horizontal axis.

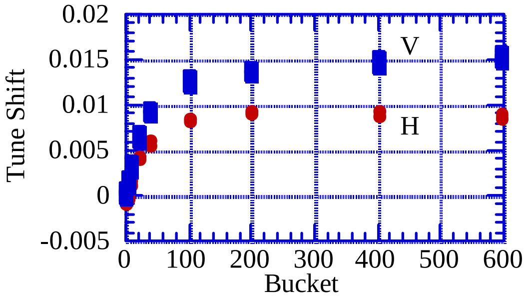

Figure 4: Tune shift along a train with the solenoid field Off. The dots are the horizontal tune and the squares are the vertical one. The bunch current is about 0.5 mA and the spacing is 8 ns.

4.2 Where is the Cloud?

Though the horizontal tune shift was almost suppressed by the solenoids, about one third of the vertical tune shift remained. Where was the remaining cloud? The existence of a cloud controlled by the solenoids might be investigated by partially switching off the solenoids wound around the ring. The LER can be simply divided into 8 parts, 4 arc and 4 straight sections. The arc sections are 2.5 times longer than the straight sections. The tune shift was measured, when one fourth of the solenoids at the arc sections were On to Off and when the solenoids at all straight sections were On to Off. Each change in the tune shift indicates how much the cloud was suppressed by the solenoids located there. The results are summarised in Table 1, assuming that contributions from four arc sections were the same. While the contribution from the arc sections is isotropic, that from the straight sections is not. For the vertical tune shift, about half of the effect comes from the straight sections. The asymmetric tune shift due to the remaining cloud might come from the asymmetric contribution of the cloud at the straight sections.

Table 1 Contribution of the tune shift, measured with a bunch spacing of 6 ns and the bunch current of 0.5 mA. The remains mean the tune shifts with all solenoids on.

	Horizontal	Vertical
Arc Sections	0.006 ~ 0.008	0.006 ~ 0.008
Straight Sections	0.0035	0.008
Remains	0.001 ~ 0.002	0.0055
Total (estimation)	0.011 ~ 0.014	0.020 ~ 0.022

5. SUMMARY

- The horizontal and the vertical tune shifts are asymmetrical at the KEKB LER, i.e. the vertical tune shift is larger than the horizontal one, except for the leading part in a train.
- The horizontal tune shift and its build-up time agree with a simulation.
- The vertical tune shift at the blowup is roughly consistent with the threshold for blowup with the head-tail model.
- Half of the vertical tune shift suppressed by the solenoids comes from the straight sections.
- The current solenoid system is insufficient at a bunch spacing of 4 ns in both directions.

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