PECULIAR VARIATIONS IN BUNCH LENGTH OBSERVED AT KEKB

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Abstract

KEKB, an asymmetric electron/positron double-ring collider, utilizes the crab cavity to perform the head-on collision at the interaction point. Peculiar phenomena related to the beam size at the transition from the collision to the non-collision state were observed. The bunch length changed slightly, even though the beam current and the RF-related parameters were almost constant. It was also observed that the transverse beam size of both beams changed at the transition. An experimental study was carried out to investigate whether the bunch length changed, when the vertical beam size was changed intentionally. The bunch length was measured by using an rms bunch-length monitor with a resolution of 0.01 mm. It was found that under a non-colliding condition, the bunch length changed with a change in the vertical beam size. We expect that the change in the bunch length is not caused by the colliding effects, but is related to the longitudinal space charge transformed from the transverse plane. Since the longitudinal space charge effect is negligible for the relativistic beams, some tilting effect of a bunch is suspected.

INTRODUCTION

An accidental phenomenon occurred during the luminosity run at KEKB, an asymmetric electron/positron double-ring collider [1], when one of the beams was abruptly lost and the other beam survived without any beam loss. The beam that survived underwent a transition from a collision to a non-collision state. We observed some changes in the parameters of the survived beam parameters at the transition. Figure 1 shows the changes in the bunch length and in the vertical size before and after the transition observed in the low-energy ring (LER), when the high-energy ring (HER) beam was aborted. The bunch length decreases by 0.03 mm at the transition, and the vertical beam size at the interaction point (IP) increases from 2 μm to 5 μm. The slow decrease in the bunch length after the transition is due to the decay of the beam current. Although the change in the vertical beam size can be explained by the beam-beam effects and by the intentional size control, we do not understand why the bunch length changes. It was confirmed that the RF-related parameters such as the accelerating voltage and the beam phase did not show any variation at the transition. A slight change in the beam orbit change was observed, however, this change was not related to the change in the bunch length. What made the bunch length change at the transition from the collision to the non-collision state? The change in the bunch length might be related to the change in the transverse beam size.

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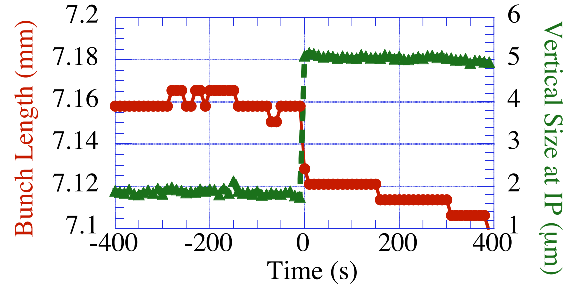

Figure 1: Variations in the bunch length and in the vertical size observed in the LER, at the transition from the collision to the non-collision state, when the HER beam was aborted unexpectedly during the luminosity run at the time "0". The red dots indicate bunch length and the green triangles indicate vertical size.

RMS BUNCH-LENGTH MONITOR

The bunch length measurement based on the beam spectrum is useful in the storage rings. This type of monitoring has advantages with respect to real-time measurement and easy handing. However, an absolute value should be calibrated with a known bunch length (the natural bunch length, for instance). By detecting the amplitude of two frequency components $V_1(\omega_1)$ and $V_2(\omega_2)$ in the beam spectrum under the condition $\sigma_z\omega/c < 1$, we can calculate the rms bunch length [2] as

$$\sigma_z = c\sqrt{\frac{2}{(\omega_2^2-\omega_1^2)}\ln(\frac{V_1(\omega_1)}{V_2(\omega_2)})}\,, \tag{1}$$

where c is the velocity of light. The expected bunch length is σ_z =4 mm to 10 mm in the KEKB. Since Eq. (1) does not require a special distribution function such as a Gaussian distribution of a bunch, we can obtain the rms bunch length for any distribution under the condition of $\sigma_z\omega_2/c < 1$. The detected beam spectra are the harmonics of the accelerating frequency, since these frequency spectra are not affected by the bunch patterns. The fundamental RF frequency is not used as a lower-frequency component because of a noise problem from the strong RF power. The upper frequency is limited by the cut-off frequency of the beam pipe for the waveguide modes. Therefore, the detected frequencies are chosen to be the 2nd harmonics (1.0GHz) and the 5th harmonics (2.5GHz) of the accelerating frequency.

The resolution of the bunch length is determined by the voltage ratio of two beam spectra $R = V_1(\omega_1)/V_2(\omega_2)$, and is expressed as

$$\frac{\Delta\sigma_z}{\sigma_z} = \frac{1}{2\log(R)}\frac{\Delta R}{R}. \tag{2}$$

The voltage ratio is determined by the resolution of the detector. From the variations of each detected voltage, the resolution is expected to be 0.02 mm at a bunch length of

6.0 mm. A continuous measurement obtains a standard deviation of 0.01 mm at the bunch length of 6.7 mm, which corresponds to a time resolution of 33 fs. This high resolution could not be obtained by the measurement in a time domain. A streak camera that is widely used for the bunch length measurement has a resolution of the order of picoseconds.

EXPERIMENTS

The bunch length was measured in a single beam in order to study why the bunch length changed at the transition from the collision to the non-collision state. Ninety-nine bunches were placed with a bunch spacing of 98 ns with a total beam current of 100 mA, where the average bunch current was approximately 1.0 mA. Since the bunches were separated by a considerable distance, the coupled interaction between the bunches and the effect of the electron cloud would be negligible. We assume that the measured average bunch length was equal to the bunch length of a single bunch.

In general, the bunch length is determined by the RF-related parameters such as the accelerating voltage and the momentum compaction factor of the lattice. The relation between the accelerating voltage and the natural bunch length within a small deviation is expressed as

$$\frac{\Delta\sigma_z}{\sigma_{z0}} \approx -\frac{1}{2}\frac{\Delta V_c}{V_c}. \quad (3)$$

When the accelerating voltage was slightly changed from a nominal value under the condition of a constant bunch current, the bunch length was measured as shown in Fig. 2. The bunch length in the HER was approximately consistent with the value expected on the base of Eq. (3). However, the measured bunch length in the LER indicated a deviation from an expectation. The measurement might be affected by the effects of a finite bunch charge of 10 nC.

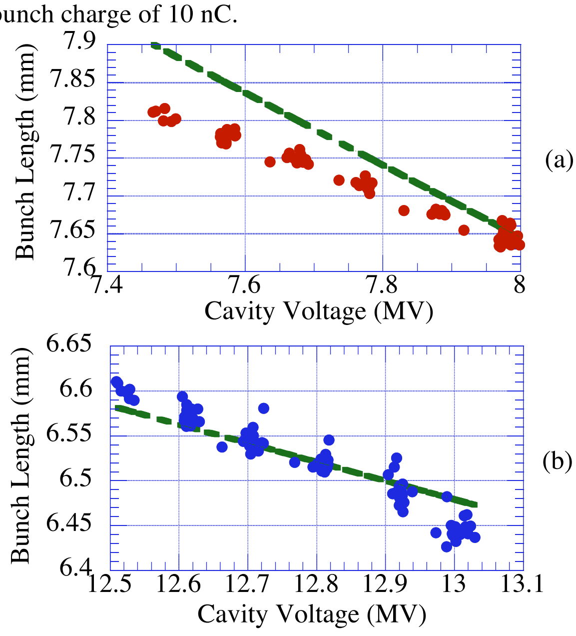

Figure 2: Bunch length vs. accelerating cavity voltage, measured (a) in the LER and (b) in the HER.

As far as a bunch had a finite charge, the bunch shape was affected by the potential-well distortion caused by the longitudinal impedance. The longitudinal impedance could be approximated by the inductive component of the KEKB rings, resulted in bunch lengthening [3]. The bunch lengthening is calculated by using the inductive model as

$$\left(\frac{\sigma_z}{\sigma_{z0}}\right)^3 - \left(\frac{\sigma_z}{\sigma_{z0}}\right) = \frac{\alpha_p}{4\sqrt{\pi}\nu_s^2 E/e}\left(\frac{R}{\sigma_{z0}}\right)^3 \frac{Z_i(\omega)}{n}\cdot I_b, \quad (4)$$

where α_p is the momentum compaction factor, R is the average radius of the ring, $Z_i(\omega)$ is an imaginary part of a broad impedance model, n an integer, ν_s the synchrotron tune, E the beam energy, and I_b the bunch current. The bunch length was measured as a function of the bunch current under a fixed RF-related parameter and a fixed orbit. As shown in Fig. 3, the bunch length increased with an increase in the bunch current. The bunch length was approximated by a linear function at the HER. Since the bunch length changed linearly with a small change in the bunch current, the bunch lengthening could be explained by the potential-well distortion using Eq. (4). However, the bunch length in the LER did not show a linear variation and the measured data were fitted by a third-order polynomial. Both the nonlinear variation and the deviation shown in Fig. 2-(a) were related to the microwave instability. This was because that the measurement was carried out above the threshold of the microwave instability [4]. As shown in Fig. 3, the bunch length changed by 0.03 to 0.04 mm in both rings, even when the bunch current changed by small value of 2%. The current-dependent bunch lengthening was compensated in the experiment.

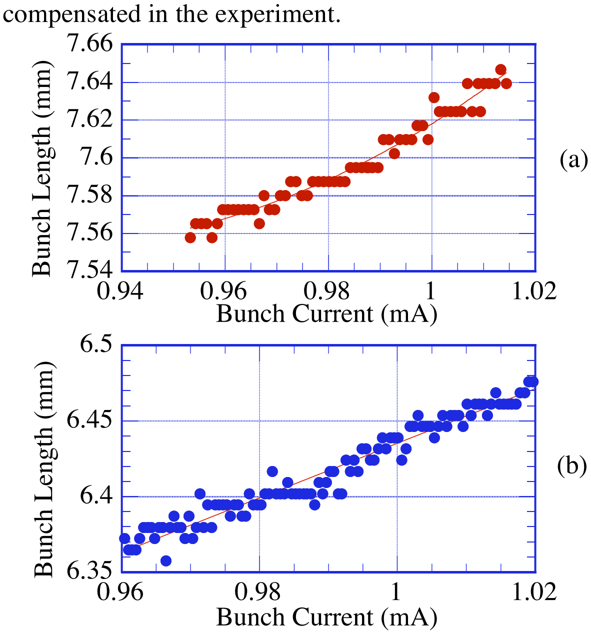

Figure 3: Bunch length as a function of the beam current, measured (a) in the LER and (b) in the HER. Fitting curves are also shown.

From the above measurements, it was confirmed that the bunch length monitor had a stability of 0.02 mm for the measurement of an rms value of 6 to 7 mm. The rms bunch length monitor was used, while changing the vertical beam size. The vertical size can be controlled by the height of a local orbit bump produced at the sextupole installed in the horizontal dispersion regions [5]. A horizontal orbit changed the vertical emittance and the vertical size through the x-y coupling. The beam size was measured using the interferometer [6] at the same time. The measurement was carried out with constant RF-related parameters, however, the beam current was slightly changed by the finite lifetime of the beam. In order to compensate the current dependency, the measured bunch length was corrected using a fitting curve of the obtained bunch length data, as shown in Fig. 3.

The bunch lengths as a function of the vertical beam size are shown in Fig. 4. We found that the bunch length actually changed with an increase in the vertical beam size in the HER. The change in the bunch length was approximated using a linear fitting and 0.044 mm/μm with a crab kick. Figure 4 also shows the bunch length measured without the crab kick. By comparing the bunch length with and without the crab kick, we observed that the slight change of approximately 10% in the slope was reduced without the crab kick. The bunch length was slightly reduced with an increase in the vertical size in the LER. There was only a slight difference in the bunch length with and without the crab kick. The reduction in the bunch length with an increase in the vertical size was approximately consistent with the result observed at the transition from the collision to the non-collision state, as shown in Fig. 1.

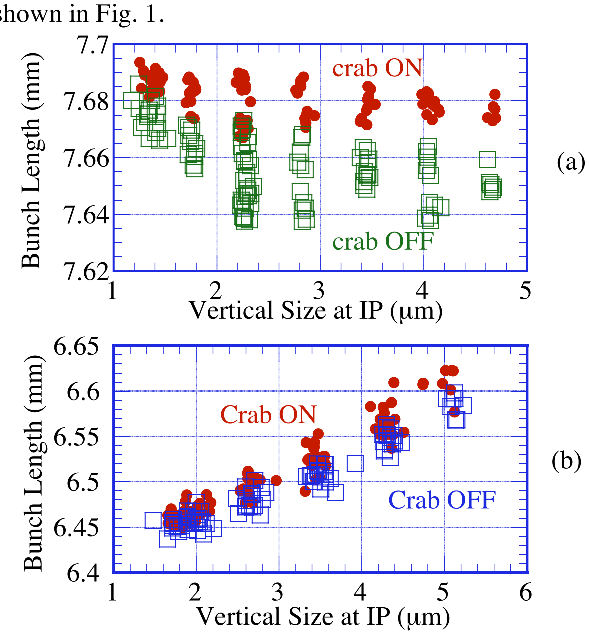

Figure 4: Bunch length as a function of the vertical beam size (a) in the LER and (b) in the HER; measurements were obtained with and without crab kick.

WHAT MAKES BUNCH LENGTH VARY?

Since it was experimentally confirmed that the bunch length changed as a function of the vertical beam size in a non-colliding beam, we understand that the bunch length was not changed by the beam-beam effect. It is known from the Maxwell equation that a change in the transverse size or the space charge induces a longitudinal force. However, in the lab system, the longitudinal space charge force was considerably weaker than that in the transverse direction by a factor of γ^2, where γ, the relativistic factor, was approximately 6800 and 16,000 in the LER and the HER, respectively. However, when a bunch was tilted or had an asymmetric distribution in the longitudinal profile, a longitudinal force component might be produced by a change in the transverse space charge. A crab cavity horizontally kicks a bunch, depending on the longitudinal position. A longitudinal kick of the crab cavity is calculated as [7]

$$k_{II} = -\frac{eV_c}{E}\cos(\phi_s + \frac{\omega z}{c})\cdot\frac{\omega}{c}\cdot x, \quad (5)$$

where V_c is the voltage of crab cavity, and ϕ_s is the synchronous phase angle. The longitudinal kick is proportional to the horizontal position. It was actually observed that the crab kick changed the bunch length as shown in Fig. 4. We observed a slight change of approximately 10% with and without the crab kick in the HER. However, the crab kick did not have a dominant effect on the change in the bunch length. Other dominant effects should be considered. In particular, the large change observed in the HER is a mystery. According to the crab kick measurement, the absolute tilt angle is unclear [8]. It is important to confirm the change in the bunch length by using another method. However, a streak camera cannot have a high resolution in the bunch length measurement. A simulation study on the relation between the bunch tilt and the bunch length is required for future work.

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