BEAM-BEAM EFFECTS MEASURED USING GATED MONITORS AT KEKB

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Abstract

In normal beam operations, the luminosity of KEKB is maximized with a finite orbit offset at the interaction point in the horizontal direction. On the other hand, in the case of wider bunch-spacing than usual, zero horizontal offsets are needed to achieve the maximum luminosity. These observations suggest that some wake fields, which might come from electron cloud effects, play a role in the beam collision in normal operations. The horizontal beam size estimated from a beam-beam kick is less than the unperturbed size. The horizontal emittance estimated from the beam-beam tune shift is somewhat larger than expected. These results suggest the presence of dynamic effects.

INTRODUCTION

KEKB [1] 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 with a circumference of about 3,000 m store more than 1,200 bunches, where the harmonic number is 5120 with an RF frequency of 509 MHz. The two beams collide at one interaction point (IP) with a horizontal crossing angle of 22 mrad. The luminosity achieved at KEKB is 1.39×10^{34} cm^{-2}sec^{-1}, which is the best in the world.

Unlike conventional single-ring colliders, the beam parameters are different between the two rings, which complicates collision tuning. Since KEKB is operated at the horizontal betatron tune just above a half integer, the beam-beam collision changes the emittance and the beta function due to dynamic effects.

The orbit at the IP is controlled with a set of dipole magnets near the IP, called "iBump" magnets. The strength of the horizontal iBump magnets is adjusted to make the luminosity maximum, while keeping the vertical size of the positron beam constant. We have found that the collision is best carried out with a non-zero horizontal position offset in normal operations, and that the luminosity is asymmetric with respect to bump height in an iBump scan [2].

In order to investigate the asymmetric beam-beam effects, the beam parameters between colliding and non-colliding bunches were compared using gated monitors. This type of a monitor can easily detect the beam-beam effects and is not affected by a global orbit change. A turn-by-turn beam-position monitor can measure a bunch-by-bunch position utilizing a gate function [2].

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When two beams collide with a position offset, they are kicked by the space charge of the opposite beam and the orbit is distorted around the ring. A position monitor located at a phase advance of $\Delta\varphi$ from the IP detects an orbit change due to collision. A position shift at a detector is given by

$$\Delta X_{\mathrm{det.}} = \frac{\sqrt{\beta_{\mathrm{det.}} \beta_x^*}}{2 sin(\pi\nu)} \theta_{b-b} \cos(\pi\nu - |\Delta\varphi|) .$$

Here, $\beta_{\mathrm{det.}}$ and β^* are the beta functions at a detector and the IP, respectively and ν is the betatron tune and θ_{b-b} is the beam-beam kick angle. Since the position shift at a detector is proportional to the beam-beam kick, assuming the beta function is unchanged, we can estimate a relative beam-beam kick from a position shift. Assuming a rigid Gaussian bunch, the beam-beam kick for a bunch is given by [3]

$$\theta_{b-b}(\Delta_x,\Delta_y) = \frac{-2r_e N_b}{\gamma} \Delta_x \int_0^\infty \frac{\exp(-\frac{\Delta_x^2}{(t+2\Sigma_x^2)} - \frac{\Delta_y^2}{(t+2\Sigma_y^2)})}{(t+2\Sigma_x^2)^{3/2}(t+2\Sigma_y^2)^{1/2}} dt .$$

Here, Δ_x and Δ_y are the horizontal and the vertical position offsets, r_e the classical electron radius, N_b is the number of particles in a bunch, γ the relativistic factor and $\Sigma_{x,y} = \sqrt{(\sigma_{x,y}^+)^2 + (\sigma_{x,y}^-)^2}$ is the effective beam size. The superscript ± denotes positron and electron bunches. The slope in the beam-beam kick around zero-offset depends on the beam size, which gives information on the beam size. Since the beam-beam kick has a maximum value at an offset of $1.32\Sigma_x$, we can also estimate the beam size from the maximum kick. The calculated horizontal beam sizes without the dynamic effect are σ_x^+ = 103 μm and σ_x^- = 121 μm. Therefore, the effective beam size is estimated to be Σ_x=159 μm.

The beam-beam interaction produces a new set of two betatron tunes by mixing two unperturbed tunes. Assuming a rigid Gaussian model, the resultant tunes are represented by [4]

$$\cos\mu_H + \cos\mu_L - (\cos\mu_0^+ + \cos\mu_0^-) = 2\pi\{\Xi_q^+ \sin\mu_0^+ + \Xi_q^- \sin\mu_0^-\},$$

where μ_H and μ_L are the perturbed betatron phases and $\mu_0^\pm$ is the non-collision betatron phase of each beam and $\Xi_q^\pm$ is the coherent beam-beam parameter [4]. The coherent beam-beam parameter is just half of the

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incoherent beam-beam parameter, ξ_q; when both of the sizes are equal; it is $\xi_q \approx \Xi_q^+ + \Xi_q^-$. Both of the perturbed tunes are shifted to higher values as the beam-beam parameter increases. By measuring the coherent beam-beam tune shift, defined as $\Delta\nu_{bb} = \nu_H + \nu_L - \nu_0^+ - \nu_0^-$, we can obtain the sum of the coherent beam-beam parameters, $\Xi_q^+ + \Xi_q^-$, as

$$\Xi_q^+ + \Xi_q^- = \frac{\kappa(\nu_0^+, \nu_0^-)}{Y} \Delta\nu_{bb} .$$

Here, $\kappa(\nu_0^+, \nu_0^-)$ is a coefficient determined by unperturbed tunes and the Yokoya factor [5], Y is introduced, considering coherent tune measurement. The relation between horizontal emittance and the coherent beam-beam parameter is expressed as

$$\varepsilon_x^+ + \varepsilon_x^- = \frac{r_e}{2\pi} \cdot \left(\frac{N^+}{\gamma^-} + \frac{N^-}{\gamma^+}\right) \cdot \left(\Xi_x^+ + \Xi_x^-\right) .$$

Here, $\beta_x^+ = \beta_x^-$ is assumed. We can estimate the sum of the horizontal emittance from the tune shift. The calculated emittance without the dynamic effect is $\varepsilon_x^+ = 18$ nmrad and $\varepsilon_x^- = 24$ nmrad.

GATED MONITORS

KEKB is usually operated with a single train of bunches followed by an empty gap. Bunches are spaced either 6 ns or 8 ns apart in a train with an average bunch spacing of 7.4 ns. Additional bunches, called *pilot bunches*, are placed just after the train, at different location in each ring so that they do not collide with each other. We can evaluate the beam-beam effects, by comparing the beam parameters of colliding bunches in a train with those of the pilot bunch. The measurement has the following features: we do not need to install a detector near the IP; imbalance in gains of the detector is cancelled out due to subtraction; and, the measurement is not affected by global orbit correction.

Gated beam-position monitors [2] are installed about 600 m away from the IP in each ring. The monitors detect not only the transverse position, but also the beam phase. One of the monitors is located at an optimum phase advance from the IP with a high horizontal beta function of 73 m and is suitable for detecting a horizontal beam-beam kick.

A gated tune monitor can measure bunch-by-bunch tune with a minimum bunch spacing of 4 ns. The tunes are measured by a swept frequency method and can be read from the resonant frequency in the spectrum.

MEASUREMENT

The horizontal position at the IP was scanned using the iBump magnets under the conditions as shown in Table 1, while the vertical orbit and the betatron tune were kept constant. The bunch current used in the experiment is about half of the maximum current. The position of each beam at the IP was estimated using the position monitors [6] near the IP. The difference is the position offset.

Table 1: Parameters used in the experiment

No.	Bunch Spacing	I_b^+ / I_b^- (mA)	Number of Bunches	ν_{x0}^+ / ν_{x0}^-
1	7.4 ns	0.56/0.47	1284	0.512/0.514
2	48 ns	0.62/0.52	203	0.510/0.508

First, the scan was performed with the conditions as shown in Case 1. The orbit of the electron beam was moved from the outside of the ring (a positive offset) to the inside. The relative horizontal beam-beam kick, the luminosity and the vertical size of the positron beam were obtained as a function of the horizontal offset as shown in Fig. 1. The center of the horizontal offset was determined by the zero point in the beam-beam kick. Comparing the measured beam-beam kick with the calculated value, we find the beam-beam kick is not symmetrical with respect to the offset. Considering only the positive offsets, the effective horizontal beam size is estimated to be 113 ± 15 μm. Assuming both beam sizes are equal, the rms size of each beam is about 80 ± 10 μm. The maximum deflection occurred at an offset of about 150 μm, which means the effective beam size is about 114 μm. Both values agree with each other. The vertical beam-beam kick and the beam phase were almost constant during the scan.

Figure 1-(b) shows the luminosity and the vertical size of the positron beam as a function of the offset, and shows that the luminosity is maximum not at zero offset, but rather, its peak shifts to the positive side and it falls off rapidly on the negative side. The vertical size of the positron beam increases as the offset goes to the negative region. Since the luminosity is very sensitive to the vertical size at KEKB, the main reduction in the luminosity may be caused by an increase of the vertical size.

We observed two peaks due to the beam-beam effects in the horizontal tune spectrum: one was the *L*-mode, which appeared close to the non-collision tune, the other was the *H*-mode, at a lower amplitude in the spectrum. The coherent beam-beam tune shift is obtained from measuring the four tunes. It was confirmed that the maximum tune shift corresponded to a zero offset in the beam-beam kick. When the offset shifted to a negative side of –50 μm, a coherent instability with a self-oscillation was observed in the vertical spectrum. The instability may be related to an increase of the vertical size and reduction of the luminosity.

Next, similar measurement was performed with a wide bunch spacing of 48 ns. Figure 2 shows the horizontal relative beam-beam kick, the luminosity and the vertical beam size as a function of the horizontal offset. The effective beam size is 127 ± 15 μm from the positive offset part of the fitted curve. A remarkable phenomenon is seen in Fig. 2-(b), where the maximum luminosity moves to the center in the case of a wide bunch-spacing. At the same time, we did not observe a coherent instability in the vertical spectrum at a negative offset of –60 μm.

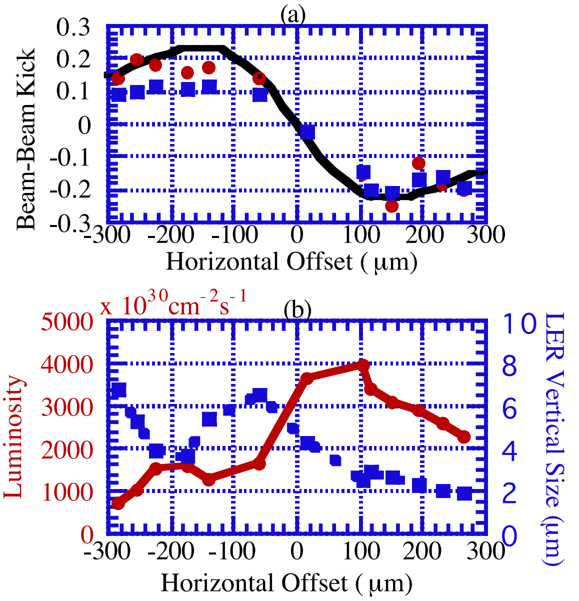

Figure 1: The scan with the normal bunch spacing. In (a), the relative horizontal beam-beam kick from the position shift as a function of horizontal offset. In (b), the luminosity (solid) and the vertical beam size (dashed) of the positron beam. The solid line in (a) is the calculated beam-beam kick, assuming the effective size is 114 μm. Note that the line is fitted only on the positive offset side.

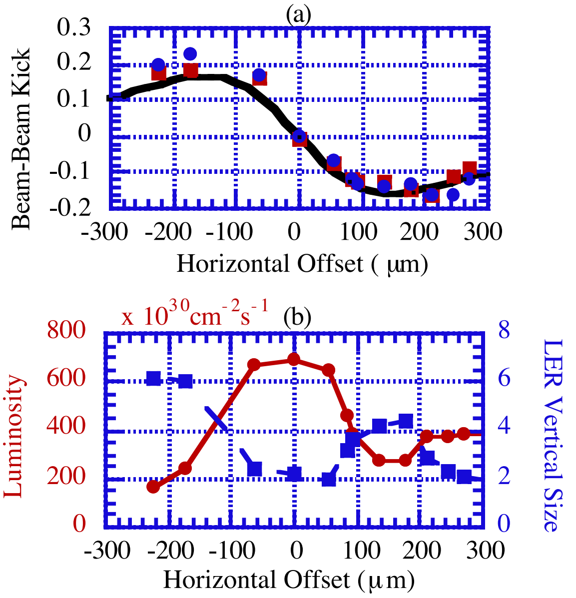

Figure 2: The scan with the wide bunch spacing. In (a), the relative horizontal beam-beam kick from the position shift as a function of horizontal offset. In (b), the luminosity (solid) and the vertical beam size (dashed) of the positron beam. The solid line in (a) is the calculated beam-beam kick, assuming the effective size is 127 μm.

DISCUSSION

We have confirmed that the collision is performed with a horizontal offset to obtain the maximum luminosity with the normal bunch-spacing. A position shift of -100 μm at the detector corresponds to an offset of 50 μm at the IP, using the bunch current shown in Table 1 and the calculated beta function. However, the offset disappeared and the luminosity is symmetrical, when the bunch spacing was expanded to 48 ns. Thus, we believe that the offset in the maximum luminosity and the asymmetrical luminosity are related to an increase of the vertical size of the positron beam in the normal bunch-spacing. These results suggest that the offset and the asymmetry in the luminosity are caused by the wake fields including those due to electron clouds. The electron clouds might play an important role in the beam-beam interaction.

The measured effective beam size was estimated to be about 100 to 140 μm. On the other hand, the calculated effective beam size is 156.6 μm using unperturbed parameters. The measured horizontal beam size is smaller than the calculated value. It is known that the beam-beam effects induce a change in the beta function and in the emittance. The beam size changes, depending on the beam-beam parameter and the tune as shown in. Fig. 3. The size is reduced to 3/4 of the original size due to the collision. The measurement is consistent with the calculation.

The sum of the emittance estimated from the coherent tune shift was about 51 nmrad, assuming that Y=1.31. The calculated emittance without the dynamic effect is 42 nmrad. Though the measured emittance is larger than the calculation, the beam-beam parameter estimated from the enhancement ratio is too small as compared with expectation. Further study is required.

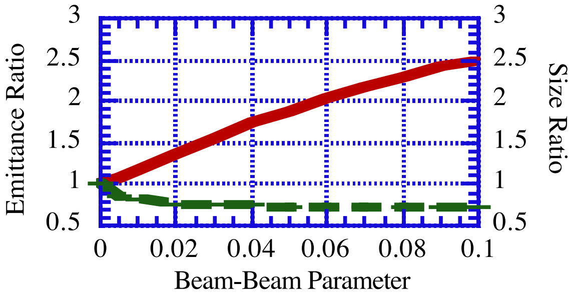

Figure 3: Emittance (solid line) normalized by the natural emittance and beam size (dashed line) normalized by the size at zero current as a function of horizontal beam-beam parameter, assuming that the fractional tune is 0.509.

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