

# OBSERVATIONS OF BEAM-BEAM TUNE SPECTRUM AND MEASUREMENT OF COHERENT TUNE SHIFT AT KEKB

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## Abstract

KEKB is a double-ring electron/positron collider with a horizontal crossing angle. The crab cavities achieved an effective head-on collision and gained a higher specific luminosity. For a crabbing collision, tune spectra of a colliding bunch were observed on a spectrum analyzer. The beam-beam spectrum showed strong nonlinear resonant phenomena. Considering this nonlinearity, the coherent beam-beam tune shift was measured as a function of the bunch current. It was confirmed that the vertical beam-beam parameter estimated from the coherent beam-beam tune shift agreed with the value obtained from a bunch-by-bunch luminosity monitor. The estimated vertical beam-beam parameter attained a saturation level of approximately 0.05, which is termed a beam-beam limit. We found that the bunch current corresponding to the beam-beam limit was considerably lower than that used in usual operations.

## INTRODUCTION

KEKB [1] consists of two storage rings: a low-energy ring (LER) and a high-energy ring (HER) employed for a 3.5-GeV positron beam and 8-GeV electrons. Both rings store more than 1500 bunches, where the harmonic number is 5120 with an RF frequency of 509 MHz. Bunches forming a single bunch train collide at one interaction point (IP) with a horizontal crossing angle of 22 mrad. An effective head-on collision occurred because of the installation of the crab cavities [2]. The collision resulted in an increase in the specific luminosity, however, which reduced with an increase in the bunch current. The maximum current is limited by the lifetime of both beams. KEKB now operates with a current product of bunches of 0.5 to 0.6 mA<sup>2</sup> with a bunch spacing of 6 ns.

Assuming that both beams are Gaussian, the luminosity can be expressed using the coherent beam-beam parameter  $\Xi_y^\pm$ , as

$$L \approx \frac{f_0}{r_e} \left( \frac{N^+ \gamma^+ N^- \gamma^-}{N^+ \gamma^+ + N^- \gamma^-} \right) \left( \frac{\Xi_y^+ + \Xi_y^-}{\beta_y^*} \right) R_L, \quad (1)$$

where  $f_0$  is the revolution frequency,  $r_e$  is the classical electron radius,  $N^\pm$  is the number of particles in a positron/electron bunch,  $\gamma$  is the relativistic factor,  $\beta_y^*$  is the vertical beta function at the collision point (IP) and  $R_L$  is the luminosity reduction factor resulting from the hourglass effect. Here,  $\beta_y^+ = \beta_y^-$  and a flat beam  $\beta_x^* \gg \beta_y^*$  are assumed. However, the energy transparency condition  $N^+ \gamma^+ = N^- \gamma^-$  is not satisfied in actual operations. A coherent beam-beam parameter is defined as

$$\Xi_q^+ + \Xi_q^- = \frac{\kappa(v_0^+, v_0^-)}{Y} \Delta v_{bb}, \quad (2)$$

where  $\kappa(v_0^+, v_0^-)$  is a coefficient determined by unperturbed tunes and the *Yokoya* factor  $Y$  is introduced on the basis of a coherent tune measurement. In the relation  $\Xi_q^+ + \Xi_q^- = \bar{\xi}_q$ ,  $\bar{\xi}_q$  is an average incoherent beam-beam parameter. The beam-beam interaction generates two modes of oscillations, a higher ( $H$ -) mode and a lower ( $L$ -) mode; both modes are affected by the beam-beam force. The coherent beam-beam tune shift is defined as  $\Delta v_{bb} = v_H + v_L - v_0^+ - v_0^-$ , where  $v_H$  and  $v_L$  are tunes of the  $H$ -mode and  $L$ -mode, respectively. We can estimate the horizontal emittance from the horizontal beam-beam parameter, assuming  $\beta_x^+ = \beta_x^-$ , as

$$\Xi_x^+ + \Xi_x^- = \frac{r_e}{2\pi(\epsilon_x^+ + \epsilon_x^-)} \left( \frac{N^-}{\gamma^+} + \frac{N^+}{\gamma^-} \right) R_x^*, \quad (3)$$

where  $\epsilon_x^\pm$  is the horizontal emittance of the positron or electron beam and  $R_x^*$  is the reduction factor resulting from the hourglass effect.

## MEASUREMENT

### Measurement System

The betatron tune was measured by a swept-frequency method using a spectrum analyzer (Advantest, R3132) and a tracking generator: the measurement of the betatron tune is equivalent to the measurement of the frequency response function of the beams. A gated tune monitor [3] is employed, which can excite a selected bunch and detect the oscillation of the excited bunch in a multi-bunched beam. In order to eliminate a forced damping effect due to beam feedback, the transverse feedback of the bunch to be measured is turned off. The resolution bandwidth (RBW) of the spectrum analyzer is 100 Hz with a swept-time of 1.9 s. The measurement resolution is about  $2 \times 10^{-4}$  using a fitted resonant curve. The noise level corresponds to an amplitude oscillation of 0.3  $\mu\text{m}$  at the pickup. The dynamic range is greater than 60 dB. A bunch-by-bunch luminosity monitor termed a zero degree luminosity monitor (ZDLM) [4] is used to monitor the relative luminosity for a specific bunch with an accuracy of 10 %. The absolute luminosity can be estimated by means of slow luminosity monitors [5].

### Observations of Tune Spectra

The spectrum was observed under the condition that the tunes of both beams were almost identical. We observed two peaks in the vertical spectra of both the beams: the peak in the symmetrical spectrum indicated a lower tune and the peak in the asymmetrical spectrum indicated a higher tune as shown in the left panel of Fig. 1. We supposed that the symmetrical spectrum is the  $L$ -mode and the asymmetrical spectrum is the  $H$ -mode. When an

excitation level was slightly increased by 3 dB in the gated tune monitor system, the peak of the asymmetrical spectrum shifted to a lower tune side by 0.005, although the peak in the symmetrical spectrum remained almost constant as shown in the right panel of Fig. 1. The nonlinear beam-beam kick curve causes the amplitude-dependent of the tune. Since the beam-beam parameter is based on a linear portion in the kick curve, the coherent tune shift should be determined either by the edge of the highest tune in the asymmetrical spectrum or by the minimum amplitude response. A similar measurement was carried out in the horizontal plane, which also showed an amplitude-dependent tune-shift.

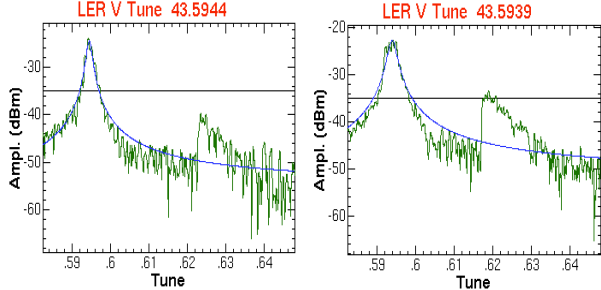


Figure 1: Vertical tune spectra of a colliding positron bunch, denoted by the green curve. The blue line is a fitted resonant curve for a single peak. The left peak corresponds to the  $L$ -mode spectrum and the  $H$ -mode is represented by the right triangle spectrum and is measured at excitation levels of -28 dB (left), and -25 dB (right).

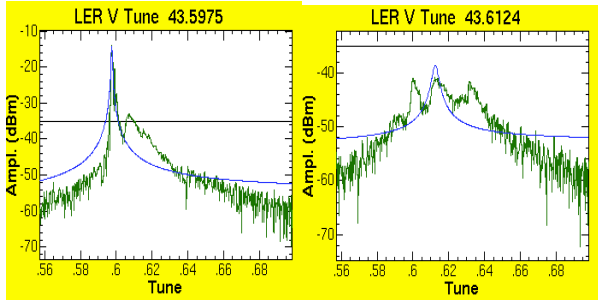


Figure 2: Vertical tune spectrum of a positron bunch during an increase in the electron bunch current. This spectrum is denoted by the green curve. This spectrum is measured for a positron bunch current of 0.82 mA with an electron current of 0.38 mA (left) and 0.58 mA (right). The blue line is a fitted resonant curve for a single peak.

Next, the intensity dependence of the tune spectrum was observed. Figure 2 compares two spectra of a positron bunch having almost the same bunch current under a constant excitation level. As shown in the left panel of Fig. 2, at a low current of an electron bunch, two peaks in the spectrum appear, one represents the  $L$ -mode with a high peak and the other represents the  $H$ -mode indicated by a broad spectrum with a long tail toward a higher tune. The edge of the  $H$ -mode spectrum is regarded as the tune of the  $H$ -mode. However, at a higher electron current, it is observed that the  $H$ -mode spectrum splits into several peaks. Simultaneously, the amplitude of

the  $L$ -mode reduces and a broad spectrum or a large tune spread is formed. The widening spectrum was also observed at a high bunch current in the horizontal plane.

The tune spectrum can be observed along a train. Since the positron bunches are affected by an electron cloud, a change in the vertical tune is observed along a bunch train and the vertical tune is shifted by 0.01 at a beam current of 1600 mA without the collisions [3]. The vertical tune spectrum of a leading bunch is compared to that of a backward bunch in a bunch train during the usual colliding operations. Figure 3 shows two spectra in which the difference between the vertical tunes of both beams is approximately 0.015. The beam-beam force would be superimposed on the effect of the electron cloud. Moreover, another peaks are observed at a backward bunch of a train in the right panel of Fig. 3. The second peak could represent the  $H$ -mode, because a similar spectrum was observed in the electron beam. The difference in the spectrum suggests a difference in collision state. However, the bunch-by-bunch luminosity monitor did not show a change in the specific luminosity along a bunch train.

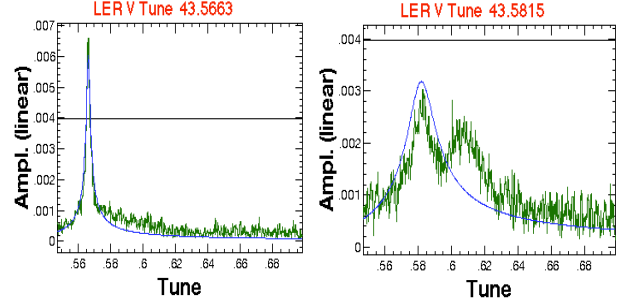


Figure 3: Vertical tune spectra of a positron bunch at #0 bucket shown (left) and at #4753 bucket (right). The bunch currents of the positron and electron are 0.93/0.45 mA, respectively. The total currents of the positron and electron are 1600/850 mA, respectively.

### Beam-beam Tune Shift

After the machine is tuned under the condition of a large bunch spacing of 192 ns, an additional bunch is injected into an empty bucket. The beam-beam tune shift and the luminosity were measured, while increasing the injected bunch charge step by step. The major optical parameters are listed in Table 1.

Table 1: Beam and Machine Conditions

	LER	HER
Emittance (nm)	24	24
Beta@IP (cm)	80/0.59	80/0.59
Betatron Tune: $\nu_x$	45.507	44.510
Betatron Tune: $\nu_y$	43.595	43.595
Synchrotron Tune: $\nu_s$	-0.0249	-0.0216
Crab Voltage (MV)	0.94	1.43

The vertical beam-beam parameter is estimated by two methods: one method is to use the coherent tune shift and the other is to use the luminosity. Figure 4 shows the beam-beam parameter estimated by the measured

luminosity and the coherent beam-beam tune shift as a function of the product of the bunch currents. The coefficients of  $Y=1.21$  and  $R_L = 0.83$  are used in the estimation [6]. The beam-beam parameter increases in a low current region, however, both values tend to be saturated at a level of approximately  $\xi_y \approx 0.05$ , which is termed the beam-beam limit. The corresponding current product is  $0.14 \text{ mA}^2$ .

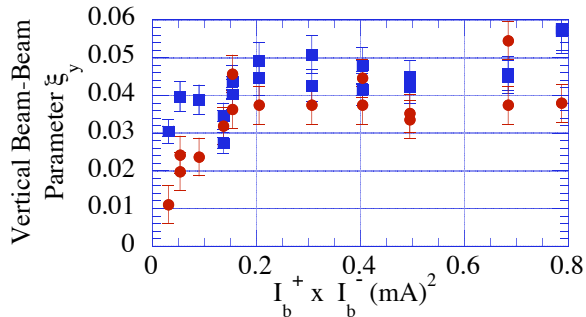


Figure 4: Vertical beam-beam parameter as a function of the product of the bunch current,  $I_b^+ \times I_b^-$ . The red dots represent the average coherent beam-beam parameter estimated from the tune spectrum, and the blue squares represent the beam-beam parameter estimated by the luminosity measurement.

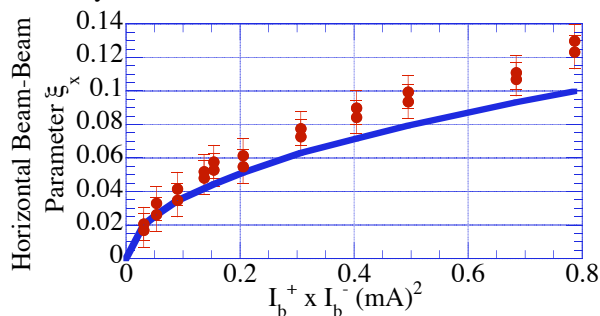


Figure 5: Horizontal coherent beam-beam parameter as a function of the product of the bunch currents. The blue line represents a beam-beam parameter calculated at a constant emittance of  $\varepsilon_x^+ = \varepsilon_x^- = 24 \text{ nrad}$ . A *Yokoya* factor of  $Y=1.31$  and  $R_x^*=0.98$  are used.

We can estimate the horizontal average beam-beam parameter using the coherent beam-beam tune shift, where the *Yokoya* factor  $Y=1.31$  is used. As shown in Fig. 5, the horizontal beam-beam parameter is not saturated above  $\xi_x=0.1$ . Although the estimated beam-beam parameter agrees with a value calculated at a low current, it deviates from that calculated at a constant emittance. The result suggests that the actual horizontal emittance decreases with an increase in the bunch current.

## DISCUSSION

As shown in Fig. 1, the position of the peak in the  $H$ -mode spectrum depends on the excitation amplitude. The dependence is caused by a nonlinear beam-beam kick curve. This nonlinearity causes hysteresis phenomena [7], where a peak of the spectrum shifts depending on the sweep direction in the spectrum analyzer.

As shown in Fig. 4, the average vertical beam-beam parameter  $\xi_y$  tends to be saturated at a bunch current product of  $0.14 \text{ mA}^2$ . On the other hand, the bunch current product is  $0.5$  to  $0.6 \text{ mA}^2$  in the usual operation. The result predicts that the specific luminosity decreases with an increase in the bunch current. In the experiment, the vertical beam-beam parameter is less than  $0.06$ . On the other hand, the peak  $\xi_y$  under most suitable condition is greater than  $0.08$ , which is estimated from the average luminosity monitor [2]. There are two reasons for the discrepancy. First, a measured bunch oscillates coherently because of the excitation applied for measuring the tune spectrum. The vibration might reduce the luminosity. Second, a factor  $R_y$  that accounts for the hourglass effect was used in Ref. [2]; however, this factor was not used in our experiment as shown in Eq. (2). It is found that the measured coherent tune shift agrees with the result of the luminosity measurement.

According to the dynamic beam-beam effect, the horizontal emittance increases with an increase in the beam-beam parameter. However, Figure 5 shows that the  $\xi_x$  is not saturated above  $0.1$  and suggests that the horizontal emittance decreases as the beam-beam parameter increases. The deviation of the emittance from the calculated value increased when the collision occurred with a smaller emittance. The decreased horizontal emittance would increase the vertical emittance and reduce the luminosity. The reason for the emittance reduction is unclear. On the other hand, the tune spectra widen with an increase in the bunch current. Moreover, the horizontal beam profile indicates a deviation from a Gaussian in the peripheral region [8]. These results might be related to lifetime limitation observed in a region of a high bunch current. The authors would like to thank Prof. Ohmi for valuable comments.

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