ASYMMETRICAL SPECTRUM OBSERVED AT THE KEKB HIGH-ENERGY ELECTRON RING

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Abstract

It was observed that the vertical tune-spectrum of an electron bunch showed an asymmetrical distribution biased to a higher tune in normal colliding operations. The asymmetry depended on the structure of the fill pattern of bunches and the vacuum pressure in the electron ring. We found that a beam-beam interaction affected the asymmetry in the tune spectrum, although a measured bunch did not collide. The observations imply that the distortion in the spectrum is related to the field due to ions produced by colliding bunches placed forwards to a measured bunch. A tune-shift measurement supported the presence of ions.

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 store more than 1,000 bunches, where the harmonic number is 5120 with an RF frequency of 509 MHz. KEKB is usually operated with a single train of bunches, followed by an empty gap for aborting the beams. Bunches are spaced by 6 ns or 8 ns in a train. The maximum luminosity of $1.5 \times 10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ has been achieved at KEKB, which is the best in the world.

The betatron tune is one of the key parameters to make high luminosity. We measure the betatron tune of a non-colliding bunch, called a *pilot bunch*, placed just after a colliding bunch-train using a swept-frequency method.

In addition to measuring a tune itself, the tune spectrum gives useful information on beam diagnostics [2]. We can obtain information on the threshold of beam instability from sidebands [3]. A broad spectrum suggests an incoherent tune spread. Moreover, we might estimate effects of trapped ions [4] and of the electron cloud from distorted spectra.

We have observed a curious distortion in the vertical tune-spectrum in the HER, as shown in Fig. 1. Figure 1 shows that the distortion is biased to a higher tune. On the other hand, the horizontal spectrum is symmetrical and sharp. In general, there are several mechanisms that affect a distribution of the beam spectrum: (1) tune spread due to a finite chromaticity; (2) forced damping due to transverse feedback, since the damping rate is related to the width of the spectrum; (3) ions trapped in an electron bunch; (4) electron cloud coupled with positron bunches; (5) beam-beam force; and (6) quadrupole and higher-order wake fields.

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The observed asymmetrical spectrum was investigated under various beam conditions.

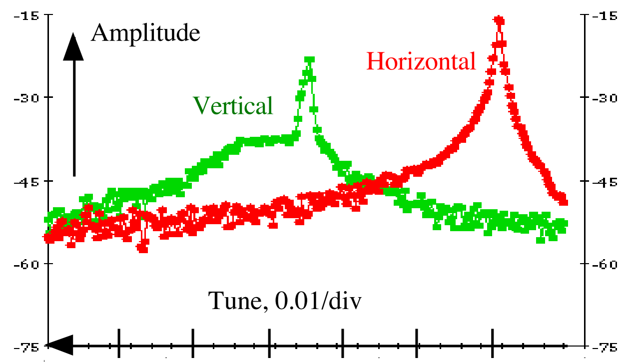

Figure 1: Tune spectra of a pilot bunch observed at the HER under normal colliding operations; the horizontal scale is the tune going right to left with a full scale of 0.07. Vertical is the amplitude with log-scale in dB. The red curve is the horizontal spectrum with a fractional tune of 0.511 and green is vertical with a tune of 0.582.

GATED TUNE MONITOR

The gated tune monitor [5] is operated under a bunch-by-bunch transverse feedback system [6], as shown in Fig. 2. The gated tune monitor can measure a bunch-by-bunch tune using a gate module (gate-1). A detected signal of the pilot bunch is analysed using a tracking analyser (Anritsu, MS420K). The feedback loop can turn on/off the signal of a specific bunch using the gate-2 indicated in Fig. 2. The feedback loop is usually off for the pilot bunch to avoid any effect due to feedback damping in the tune measurement.

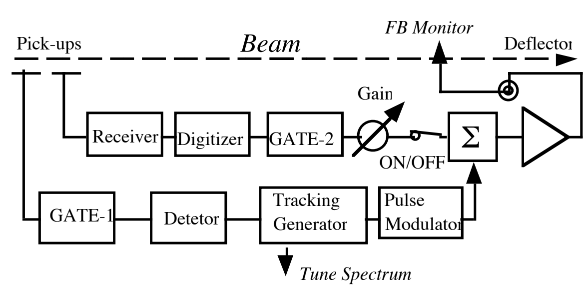

Figure 2: Schematic diagram of a gated tune monitor and a transverse feedback system.

We checked the hardware with a gating method that is relevant to observe the asymmetrical spectrum of the tune. The isolation of the gate itself was 60 dB at 1 GHz in a bench measurement. However, a beam signal of forward bunches actually leaked backward with a long tail. The signal level of a previous bunch was below -40 dB at the pilot bunch separated by 8-buckets, or 16 ns from the last bunch in a colliding bunch-train. The leak effect would be negligible even with the case of a shorter spacing, since we detect only specific low-frequency components of a beam signal selected by the spectrum analyser. The tune measurement can be measured with a short bunch spacing of 4 ns.

OBSERVATIONS OF SPECTRUM

Definition of asymmetry

Before we discuss the spectrum in detail, the asymmetry in the tune-spectrum is defined as shown in Fig. 3. The asymmetry is given by $A = a1/a2$, where a1 and a2 are the widths on both sides at 20 dB below from the peak. When a spectrum is biased to a higher tune, A is larger than 1.0. This value indicates the level of distortion of the spectrum.

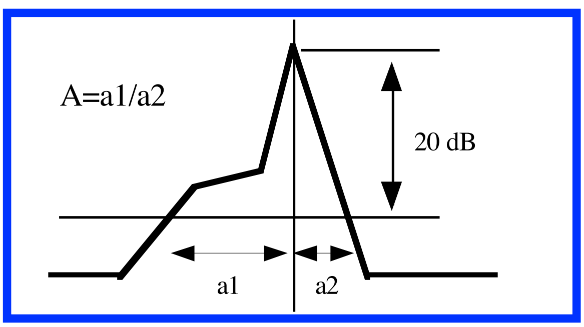

Figure 3: Definition of asymmetry in the spectrum.

Observation in single beam

A large asymmetry of 2.0 to 3.0 was observed during normal colliding operations, as shown in Fig. 1. In order to avoid beam-beam effects, we measured the tune spectrum under a single beam, while changing the beam conditions at the HER. First, the asymmetry kept a range of 1.0 to 1.5, when the vertical beam size changed by a factor of 3.5. Next, the vacuum pressure was artificially made worse by turning off the ion pumps; the asymmetry was still about 1.3. Therefore, a large asymmetry in the vertical spectrum is a different phenomenon from simple ion-trapping and fast-ion effects observed with poor vacuum pressure in an electron storage ring [4,7].

Effect of collisions

In order to confirm that a large asymmetry is caused by collisions, we made two beams vertically separated at the IP under normal operations. The luminosity decreased due to the separation. It was observed that the asymmetry was also reduced from 2.2 to 1.5 in the electron pilot bunch, while the luminosity was about 1/10, as shown in Fig. 4. On the other hand, the vertical tune spectrum of a positron pilot bunch kept a constant value at A=1.0.

Effect of a bunch-train structure

The colliding bunches usually formed a single bunch train, which contained 1186 bunches with a bunch spacing of 6 or 8 ns. The non-colliding pilot bunch for the tune measurement was placed just after a train. In this structure, a high asymmetry of 2.0 to 3.0 was observed at the electron pilot bunch. The asymmetry was enhanced under a bad vacuum condition. During a relatively bad condition in the vacuum, we changed the structure of a bunch-train from a single long train into 8 bunch-trains. Each train was separated by gaps with 60 empty buckets. The total number of bunches was slightly reduced to 1083. The beam current was almost the same between two structures of trains. We found that the gaps inserted in a bunch-train reduced the asymmetry of from 3.25 to 1.9.

Moving place of a pilot bunch in an abort gap

The asymmetry was measured while shifting the position of the pilot bunch. The pilot bunch is usually placed at 8 buckets after the last bunch in a bunch-train. When the position of the pilot bunch approached a bunch-train, as shown in Fig. 5, the asymmetry further increased to 3.0 to 5.0. Note the reduction of the asymmetry at 3 bucket spacing is because the spectrum widened into both sides. When the pilot bunch was far from more than 20 buckets from a bunch-train, the asymmetry was almost the same as that in a single beam.

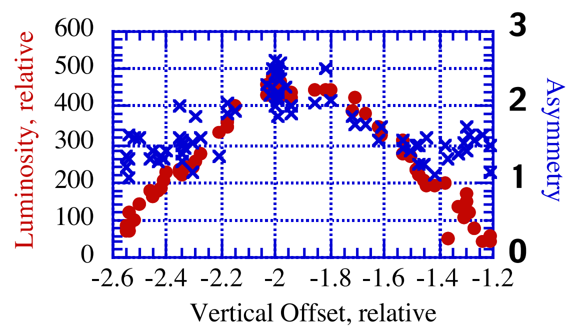

Figure 4: Relative luminosity (red dots) and the asymmetry (blue crosses) in the spectrum as a function of the vertical separation.

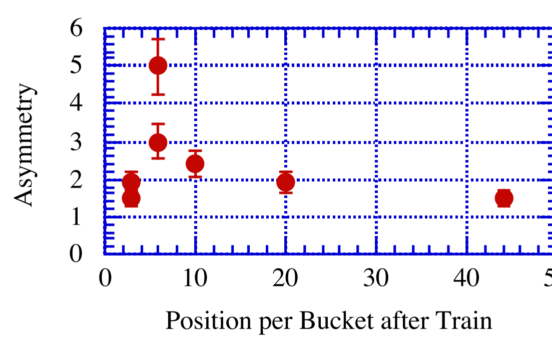

Figure 5: Asymmetry in the spectrum as a function of the bunch location after colliding bunches. One bucket corresponds to 2 ns.

The results observed are summarized as:

- A large asymmetry of more than 2.0 was observed in the vertical tune spectrum of a non-colliding

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electron bunch placed just after a colliding bunch-train.

- The asymmetry was observed regardless of the excitation level.
- In a single beam, the asymmetry was as small as about 1.0 to 1.5, and did not change significantly when the vacuum pressure and the vertical beam size were intentionally changed
- When two beams were separated vertically, the asymmetry reduced together with the luminosity.
- The asymmetry depended on the structure of a colliding bunch train, and was reduced by inserting empty gaps in a train.
- The asymmetry was enhanced under bad vacuum pressure during colliding operations.
- The asymmetry depended on the place of a pilot bunch just after a bunch-train.

Tune shift

The observations suggest that the pilot bunch is somewhat affected by electro-magnetic fields produced by previous colliding bunches. One possible method to estimate the effects of the fields is to measure any current-dependent tune-shift. The tune-shift is related to the derivatives of the electro-magnetic force acting on a bunch and is given by

$$\Delta\nu_{x,y} = \frac{1}{4\pi E}\int \beta_{x,y}(s)\frac{\partial F_{x,y}}{\partial x, y}ds.$$

Here, E is the beam energy, $\beta_{x,y}(s)$ the horizontal or vertical beta function and $F_{x,y}$ the electro-magnetic force. In a single bunch, the tune-shift is related to the wake field of the broadband impedance of a machine. On the other hand, the tune-shift in a multi-bunch is related to various dynamic forces, including the machine impedance. By comparing the tune-shift data measured under different beam conditions, we might estimate the effect of the dynamic electro-magnetic force.

The tune-shift of the pilot bunch was measured under three conditions: in a single bunch, in a single beam and in normal colliding operation. Both in a single beam and in the colliding mode, the measurements were performed under that the total beam current was almost constant at about 1000 mA with the same structure of a bunch-train to avoid any effect of a resistive-wall tune-shift. The current of the pilot bunch was less than 1 mA. The results are summarized in Table 1.

Table 1 Current-dependent tune-shift of the pilot bunch

Condition	Horizontal /mA	Vertical /mA
Single bunch	-0.0004	-0.0039
Single beam	+0.0028	-0.010
Colliding beam	-0.0009	-0.0015

In a single bunch, a large difference in the tune-shift between the horizontal and vertical planes comes from the racetrack shape of the HER vacuum chamber. In a single beam, the horizontal tune-shift increases and the vertical one decreases. These variations might be caused by the quadrupole wake-field of the resistive-wall impedance [8]. When the beams collided, the vertical tune-shift increased from –0.010/mA to –0.0015/mA. The positive change in the tune-shift suggests a focusing field produced by the presence of forward colliding bunches. However, the horizontal tune-shift changed to a negative slope by collisions. The horizontal spectrum did not significantly change between collision and non-collision.

DISCUSSION

From the experimental results, we have found that a large asymmetry is caused by the beam-beam interaction, though the measured bunch does not collide. The effect of parasitic collisions is negligible in this case. It has been observed that collisions make the lifetime of both beams shorten as well as to expand the vertical sizes. Microscopically, it is known that some particles are scattered and lose their energy by Bhabha and radiative Bhabha processes. Thus, the collision rate with residual gas would increase due to the beam-beam interaction. As a result, more ions might be produced and multiplied along a bunch-train. The tune-shift measurement supports the presence of ions. The asymmetrical spectrum might be related to decoherency of ions. If a gap exists in a train, some ions might be lost there, because of the absence of the source. Sequential collisions are required to survive ions through the tail of a bunch-train. This process is similar to single-pass ion effects [9]; however, the source of ions is based on beam-beam collisions in this case, not the electron beam itself. A quantitative analysis remains for future study.

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