VARIATIONS IN BEAM PHASE AND RELATED ISSUES OBSERVED IN KEKB

T. Ieiri#, K. Akai, M. Tawada, and M. Tobiyama, KEK, Ibaraki, Japan

Abstract

Newly installed crab cavities realized an effective head-on collision, while maintaining finite-angle crossing orbits. Electron and positron bunches form a single train followed by a beam abort gap. We observed a beam phase advancing along a train because of transient beam loading. Since there is a difference in the beam phase between the two beams, a bunch-by-bunch longitudinal displacement of the collision vertex is expected. Estimated longitudinal displacement agreed with those directly detected by the Belle. A displacement in the horizontal beam position was observed in correspondence with the variations in the beam phase. We found that the horizontal displacement was caused by a transverse kick of the crab cavities to phase-shifted bunches. Moreover, a rapid phase change was observed at the leading part in a train in the LER. Some longitudinal wakes with low Q values in accelerator components are considered responsible for causing the rapid change in the beam phase.

INTRODUCTION

KEKB [1] is a multi-bunch, high-current, electron/positron collider for *B* meson physics. The collider consists of two storage rings: a low energy ring (LER) for a 3.5-GeV positron beam and a high energy ring (HER) for 8-GeV electrons. Both rings store about 1600 bunches, where the harmonic number is 5120 with an RF acceleration frequency of 509 MHz. Bunches are stored in two rings with a 3-bucket (6 ns) or 4-bucket (8 ns) spacing, forming a bunch train followed by empty buckets that occupy approximately 5% of the circumference. The empty buckets are required to abort the beams safely within one revolution time of 10 μs. The two beams collide at one interaction point (IP) with a horizontal crossing angle of 22 mrad. Newly installed crab cavities can provide horizontal tilt to a bunch without changing the central orbit using a horizontal kick operating at the RF frequency [2].

TRANSIENT BEAM LOADING

In a high-current and multi-bunch beam, the amplitude and phase of the accelerating voltage is modulated by the existence of the abort gap, since the beam loading is different between the abort gap and the bunch train. As a result, the synchronous position is shifted bunch to bunch along the train. Assuming that the cavity is working at the optimum tuning, that the filling time of the cavity T_f is much longer than the revolution period, *i.e.* $T_0/T_f << 1$, and that the synchronous phase $\phi_s \approx 0$, the beam-phase difference between the head and tail bunches is approximately given by [3]

$$\Delta\phi_{ht} = \frac{I_t}{2V_c}\frac{R_s}{Q}\omega_{rf}\Delta t_g, \quad (1)$$

where I_t is the total beam current, R_s the shunt impedance, Q the Q value of the cavity, ω_{rf} the angular RF frequency and Δt_g the length of the gap. The phase response in a train with a constant bunch current depends on the filling time of cavities. The phase response is almost linear for $T_0/T_f << 1$ because a cavity with a slow response time works as an integrator for a step pulse of a bunch train. For the inverse case of $T_0/T_f >> 1$ the phase quickly follows a bunch train and approaches a constant value for a pulse of a bunch train [3]. In the case of KEKB, the LER uses the normal conducting (NC) cavities, and the HER uses two different types of cavities, the NC and the superconducting (SC) cavities. The properties of the accelerating cavities are summarized in Table 1. Since the filling time of both cavities does not satisfy the above simple conditions, a precise phase shift of each bunch should be measured and/or needed for simulation experiments [4]. When the beam phase variation along a train is different between the two rings, it gives rise to a bunch-by-bunch longitudinal displacement in the collision vertex. Assuming that the hourglass effect is negligible and that the longitudinal displacement is much smaller than the bunch length, the displacement can be approximately given by

$$\Delta L_{IP} \approx \frac{c}{\omega_{rf}}\frac{(\phi_{HER} - \phi_{LER})}{2}, \quad (2)$$

where c is the speed of light.

Table 1: Properties of accelerating cavities

Parameter	LER	HER
Cavity Type	NC	NC/SC
Number of Cavities	20	12/8
Cavity Voltage (MV)	8	3.5/9.5
Filling Time (μs)	19	19/35
R/Q (Ohms)	14.8	14.8/93

NC: Normal conducting cavity, SC: Superconducting cavity.

MEASUREMENT

Button type electrodes are used for picking up a beam pulse, which is placed in a dispersion-free section, where the horizontal betatron functions are β_x=22 m and 43 m in the LER and the HER, respectively. The beam signals from 4 buttons are fed into each gate module attached to a turn-by-turn beam-position monitor (BPM). The system called a gated beam-position monitor (GBPM) can select an electron or a positron bunch and uses a common

takao.ieiri@kek.jp

detector [5,6]. The GBPM employs an in-phase and quadrature phase (IQ) detector operating at the acceleration frequency of 509 MHz to extract two orthogonal signals, $V_{\sin}$ and $V_{\cos}$ for each bunch. The two orthogonal components are sampled at a rate of the revolution frequency and put into 8-channel ADCs with a resolution of 12 bits. The sampled data are stored each turn in a memory. The beam phase φ_{beam} of a specific bunch, with respect to the RF reference phase φ_{RF}, is calculated from the two orthogonal components as

$$\varphi_{beam} - \varphi_{RF} = \tan^{-1}(-\frac{V_{\sin}}{V_{\cos}}). \quad (3)$$

The GBPM can detect the relative beam phase as well as the transverse beam position. When the GBPM data were averaged over 2,000 turns, a resolution of 0.10 degrees in the phase measurement was obtained including the jitter of the RF reference signal.

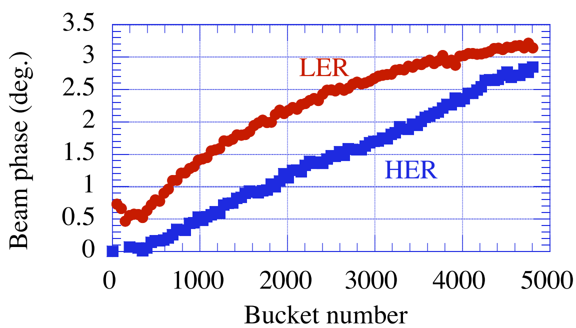

Figure 1: Beam phase along a bunch train as a function of the bucket number (BN) at a beam current of 1530 mA in the LER, and 800 mA in the HER. The beam phase at BN=0 is set to be zero.

The beam phase were measured every 49 buckets along a train during the crabbing collision in both rings, where a train contains about 1600 bunches. Figure 1 shows the beam phase as a function of the bucket number (BN). The beam phase advances relative to the RF reference phase along a train because of transient beam loading. The maximum phase shift between the head and the tail of a train is approximately 3 degrees in both LER and HER, where the total beam current in the LER is approximately twice that in the HER. When the total beam current was the same in both beams, the maximum phase shift in the HER was approximately twice that in the LER. The difference in the maximum phase shift at the same current is due to differences in the R/Q value of the cavities and in the cavity voltage, as listed in Table 1. As shown in Fig. 1, the variations of the phase displacement along a train behave differently between both beams. The phase in the LER significantly increases in the forward part and tends to saturate in the backward part in a train. On the other hand, the phase in the HER almost linearly increases along a train. These behaviours in the beam phase could be qualitatively explained by a difference in the filling time of the cavities, where the filling time of the SC installed in the HER is larger than that in the NC, as shown in Table 1. The phase difference causes a longitudinal displacement at the IP as is given in Eq. (2). Figure 2 shows the longitudinal displacement estimated from the phase measurement as a function of BN. The estimated displacement agreed with direct measurements using the Belle detector [7]. A phase difference of 1.0 degrees in peak-to-peak was observed, which corresponds to a longitudinal displacement of 0.8 mm at the IP. The displacement is so small approximately 1/8 comparing to the bunch length that it does not affect reduction in the luminosity.

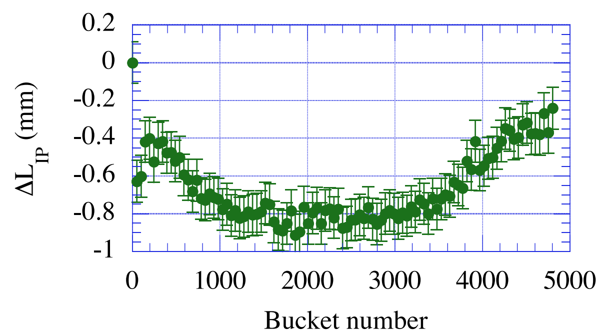

Figure 2: Longitudinal displacement of the collision vertex at the IP estimated from the measured beam phase difference with error bars as a function of BN.

DISCUSSION

As shown in Fig. 1, a rapid increase in the beam phase was observed in a region of BN < 200 in a train of the LER. In order to study the rapid increase in the beam phase in detail, both of the beam phase and the horizontal position were measured using a short bunch train with a large abort gap that occupied approximately 53% in the revolution time. We observed that horizontal position varied in correspondence with the variations in the beam phase as shown in Fig. 3.

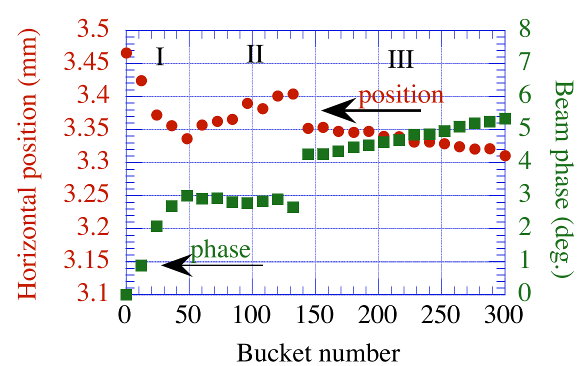

Figure 3: The horizontal beam position and the beam phase as a function of BN, measured using a short bunch train and during crab kick in the LER. The variations in the phase are divided into three regions, I, II and III as marked in the graphs.

Since the horizontal shift was not observed before the installation of the crab cavity, it would be related to a horizontal kick of the crab cavity. The center of a bunch is not kicked by the crab cavities, if a bunch phase is adjusted to the zero cross of a crab kick voltage. However, this condition is not satisfied for all bunches because of the transient beam loading. When a phase-shifted bunch passes through the crab cavity, the bunch receives a horizontal kick differently between the head and the tail of a bunch as illustrated in Fig. 4. Accordingly, the center of a bunch is kicked and a shift in the horizontal orbit occurs in the whole rings. The GBPM detects a horizontal position shift as

$$\Delta x_{\mathrm{det.}} = \frac{\sqrt{\beta_{\mathrm{det.}}\beta_c}}{2\sin(\pi\nu)}\Delta\phi_c \cos(\pi\nu - |\Delta\varphi_d|), \quad (4)$$

where $\beta_{\mathrm{det.}}$ and β_c are the beta functions at the detector and at the crab cavity, ν the betatron tune, $\Delta\phi_c$ a difference in the crab kick, $\Delta\varphi_d$ the betatron phase advance between the crab cavity and the detector. A difference in the crab kick for a phase shift is estimated to be 4.8 µrad/deg, when the crab voltage is 1 MV in the LER. The phase shift between BN=0 and BN=48 in a train is measured to be approximately 3.0 degrees from Fig. 3, which corresponds to a position shift of 120 µm using Eq. (4). The estimated position shift agrees well with the measurement.

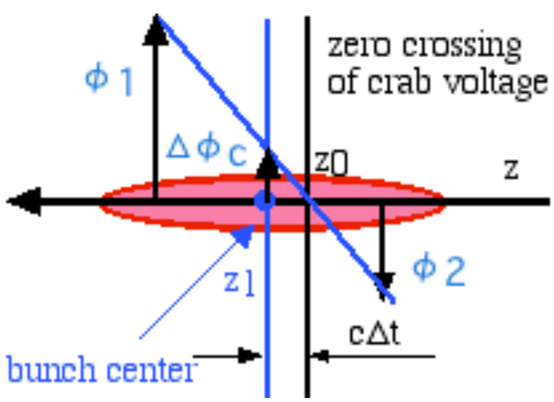

Figure 4: Illustration of an asymmetric crab kick between the head and the tail of a bunch, when a bunch passes through a crab cavity by a timing shift of Δt. Arrows indicate the amplitude of a crab kick. The center of a bunch is kicked by the difference kick $\Delta\phi_c$, to result in a horizontal orbit shift.

As shown in Fig. 3, the phase rapidly increases below BN=50 and almost linearly increase after a step in the phase that occurs around BN=140. It would be reasonable to divide the phase variations to three regions. Region I is a region defined as BN < 50, and region III is a region after the step in the phase. Region II is the intermediate region, where the phase is almost constant. The rapid change in the beam phase occurs at region I. The phase variation in region III is consistent with the estimation for the phase shift caused by the transient beam loading using the properties of the accelerating cavities. We summarize the results obtained from the phase measurements:

- The rise time of the rapid change in the region I is approximately 60 ns.
- The rapid change in the beam phase is independent of the crab kick.
- The phenomena seem to be independent of the effect of electron cloud, because the response time in the phase variation is shorter than electron-cloud build-up time.
- A step of about 1.3 degrees in the beam phase observed around BN=140 is accompanied with a step of about 50 µm in the horizontal position, which is caused by the asymmetric crab kick.
- These abnormal phenomena cannot be explained by the simulation [4] that deals with only the accelerating mode.

Based on the experimental results, it is proposed that the rapid change observed at BN<50 is caused by some longitudinal wakes of low Q values. One candidate is parasitic modes in the NC cavity named ARES [8]. The ARES is a coupled-cavity system consisting of the accelerating, coupling and energy storage cavities to cope with the coupled-bunch instability associated with the accelerating mode under heavy beam loading. It is working in the π/2 mode, while the 0 and π modes are parasitic modes, which are damped by an antenna attached to the coupling cavity. The filling time of the parasitic modes is estimated to be 64 ns, which is consistent with the observations in the phase variations. The ARES is installed in both rings. However, the ARES makes minor contribution to the beam loading in the HER. The source that makes the step around BN=140 in the LER is still unclear. In conclusion, bunch-by-bunch position and beam phase were measured using a GBPM at KEKB. The collision vertex estimated from the phase difference measurement agreed with direct measurements with the Belle detector. It was found that the horizontal position varied along a bunch train, which was caused by a phase-shifted bunch passing through the crab cavity.

REFERENCES

[1] K. Akai et al., Nucl. Instrum. Methods Phys. Res., Sect. A 499, p.191 (2003).
[2] K. Hosoyama et al., Proc. of EPAC08, Genoa, Italy, 2927 (2008).
[3] D. Boussard, Proc. of PAC'91, San Francisco, USA 2447 (1991).
[4] K. Akai, Proc. of EPAC'98, Stockholm, Sweden, 1749 (1998).
[5] T. Ieiri, et al., Phys. Rev. ST Accel. Beams 5, 094402 (2002).
[6] T. Ieiri et al., Proc. of EPAC'08, Genoa, Italy, 1143 (2008).
[7] H. Kichimi et al., private communication.
[8] T. Kageyama et al., Proc. of PAC'97, Vancouver, B.C., Canada, 2902 (1997).