BUNCH-BY-BUNCH PHASE MEASUREMENT at KEKB

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Abstract

A fast gate module has been developed at KEKB, which can pick up the signal of one bunch from a train of bunches. The gate module is attached to a turn-by-turn beam position monitor, where the beam phase is detected by an orthogonal phase technique. Characteristics of the gate module have been investigated. We have measured the bunch phase along a long train followed by a gap. The phase shift in the train was compared with a calculation based on the transient beam loading. Longitudinal displacement of the collision point was estimated from this phase shift.

1 INTRODUCTION

KEKB[1] is a high intensity multi-bunch collider. The collider consists of two storage rings, the Low Energy Ring (LER) for the 3.5 GeV positron beam and the High Energy Ring (HER) for 8 GeV electrons. Both rings store more than 1000 bunches, where the harmonic number is 5120 with an rf frequency of 509 MHz. The separation between successive bunches is so narrow that bunch parameters would not be strictly the same for all bunches due to wake fields and other collective effects. Thus the measurement of bunch-by-bunch parameters is required to understand the beam properties. The bunches are actually stored with a 4-bucket spacing (8 ns), forming a single train of bunches. The train of bunches is followed by an empty gap. The gap, which occupies 10 percent of the circumference, is required not only for using the abort kicker, but also for clearing ions and photo-electrons. Two bunches, called *pilot bunches*, are intentionally placed inside the gap for tuning the machines. It is predicted that the gap causes a bunch-by-bunch phase shift due to the transient beam loading [2,3]. The phase shift is related to the longitudinal displacement of the collision point, which not only reduces the luminosity but also may create serious problems for KEKB.

2 TRANSIENT BEAM LOADING

The beam-loading of cavities is one of the most important issues in a high-current and multi-bunch storage ring such as KEKB. The amplitude and phase of the accelerating voltage is modulated by the gap, since the beam-loading effect is different between the gap and the beam. As a result, the synchronous position is shifted bunch-by-bunch along a train. Assuming that the cavity is operated at the optimum tuning, that the filling time of the cavity T_f is much longer than the revolution time T_0, *i.e.* $T_0 / T_f << 1$, and that the synchronous phase $\varphi_s \approx 0$, the amount of beam phase shift between the head and the tail bunches in a train is approximately given by [2]

$$\Delta\varphi \approx \frac{I_t}{2V_c}\frac{R_s}{Q}\omega_{rf}\Delta t\,, \tag{1}$$

where I_t is the beam current, V_c the accelerating voltage, R_s the shunt impedance, Q the Q-value of the cavity, ω_{rf} the angular rf frequency and Δt the length of the gap. In the case of KEKB, however, this simple formula cannot be applied: T_0 / T_f =0.54 for the normal-conducting (NC) cavities in the LER and two different types of cavities (normal- conducting and super-conducting (SC)) are operated in the HER. Consequently, the phase shift of each bunch is calculated using a simulation code, which was developed to study the beam-cavity system of KEKB including feedback loops [3]. The result is compared with the measurement, which will be discussed in section 4. Since the phase shift along the train is different in both rings, it gives rise to a longitudinal displacement of the collision point along the train, as given by

$$\Delta L_{CP} = \frac{c}{\omega_{rf}}\frac{(\varphi_{HER} - \varphi_{LER})}{2}\,, \tag{2}$$

where c represents the speed of light.

3 DETECTOR

Two methods were considered to measure an individual bunch in multi-bunch mode. The first method finishes the signal processing before the next bunch comes. This technique used in the bunch-by-bunch feedback system [4] has the merit that all bunches are processed together. However, it is hard to obtain a normalized signal. The other method is to gate a bunch using a high-speed switch. A gated bunch allows the execution of signal processing over a revolution period. Thus a precise measurement is expected. The requirements for bunch-by-bunch measurements using the gated method are:

- Gate duration is less than the interval between neighboring bunches;
- The switch has a wide linear dynamic range and low noise with high isolation.

Considering the transient response of an electric switch, the rise and fall times do not show the same response. Thus a ringing waveform with exponential decay is frequently observed at a transition from *on* to *off* states. In order to improve the switching response, two switches are connected in series [5] as shown in Fig. 1. Commercially available switches (Macom, SW-209) have

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been used. Two pulses are prepared for each switch, which are complementary to each other, but are shifted by cable delay. The delay time determines the gate duration. The length of delayed cable was adjusted to determine the optimum duration of the gate. A gate duration of 6 ns was obtained with an insertion loss of 3 dB, which is used for normal operations with 4-bucket (8 ns) bunch spacing.

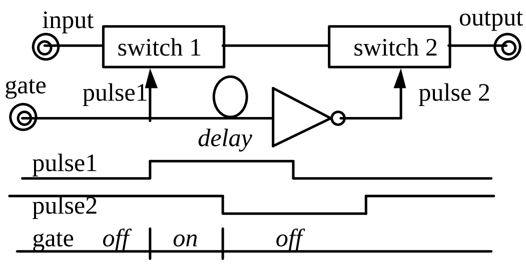

Figure 1: Schematic gate module.

The gate module was attached to the turn-by-turn beam position monitor [6] which employs an I/Q (In-phase and Quadrature phase) demodulator working at the rf frequency of 509MHz. A beam signal picked up by a button electrode is gated by a pulse synchronized with the revolution frequency. The 509 MHz component of the beam pulse is divided into two orthogonal components and the phase of each component is compared with the 509 MHz rf phase. The detected signals represented by $V_{\sin}$ and $V_{\cos}$ as shown in Fig. 2 are sampled by the revolution pulse and stored in the memory of an ADC. The intensity of the beam pulse is given by $|V| = \sqrt{V_{\sin}^2 + V_{\cos}^2}$. The amplitude ratio of two orthogonal components gives a phase difference between the beam and the rf as

$$\varphi_b - \varphi_{rf} = \tan^{-1}\left(-\frac{V_{\sin}}{V_{\cos}}\right), \quad (3)$$

where φ_b and φ_{rf} are the beam and the rf phases, respectively. Assuming the rf phase is constant, the beam phase is obtained from Eq. (3). Since the amplitude data are detected using a 14-bit ADC every turn ($10\mu s$) and are averaged over 32,000 turns, a high resolution is expected in the phase measurement. We have determined that average values were settled within ±0.1 degree. The phase resolution corresponds to the time resolution of less than 1 ps. A drift of the phase, however, was observed over a long time, which may be caused by a drift of the rf phase used for reference.

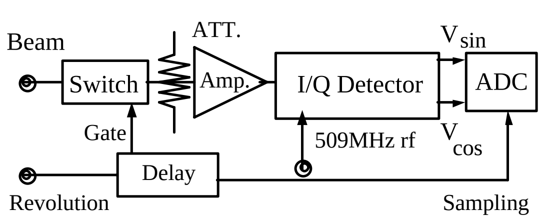

Figure 2: Schematic beam phase detection.

The dynamic response of the gate module was tested using a real beam pulse. The intensity response of the gate shows good linearity with bunch current. Measured phase, however, indicated a large variation as the current increased and the direction of the variation depended on the polarity of the input pulse. It was also confirmed that the phase response of the I/Q detector itself was small compared with that of the gate module. Thus the variation of the phase is related to nonlinear characteristics of the switch. The phase variation should be carefully compensated by monitoring the bunch intensity.

A relatively large switching noise was observed. The noise can be canceled out by subtracting common data in the measurement. The on/off isolation of the gate module was investigated using the bunches in the HER. While keeping the bunch intensity constant, timing of the gate was shifted bucket by bucket and the intensity was measured for two cases. One is for bunches in a train and the other for an isolated bunch in the gap. The results are shown in Fig. 3. If the gate timing is separated by three buckets from an isolated bunch, an S/N ratio of more than 32 dB is obtained. The gate module itself can cut off the neighboring buckets of a train.

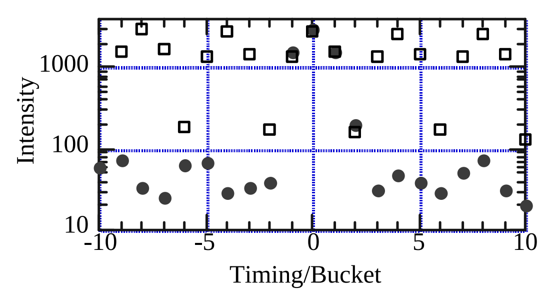

Figure 3: Variation of intensity as a function of timing of the gate, where timing "0" is optimum. Dots are intensity of an isolated bunch, and squares are that for bunches in a train.

4 MEASUREMENT

The bunch phase was measured along a train during collision. The train contains 1153 bunches with a 4-bucket spacing. Figure 4 shows variations of the measured phase shift (dots) together with a simulation result (solid line) as a function of the bucket id. Signals from four pick-up electrodes are averaged at each bucket of the measured data. The intensity-dependent phase error of the gate module is less than 0.3 degree since individual bunch intensity is uniform within ±5%. It is seen that the measured phase shift rapidly increases until the bucket id of around 201 (written as #201 hereafter). After #601, it gradually increases up to the last bunch of the train (#4609). The phase of pilot bunches located in the gap decreases and forms a periodic structure in one revolution. The measured phase shift and the simulation result are quantitatively in good agreement, except at the leading part of the train before about #401. Figure 5 shows the difference of the bunch phase between bunches #401 and #4609 as a function of the beam current, compared with a simulation result. Again, they are in good agreement. Thus the measured phase shift after about #401 is consistent with transient beam-loading due to the gap. The reason for the rapid increase in the leading part of the train is not clear so far. There are two possible causes: (1) it may be due to some longitudinal wake with a range of shorter than 400 buckets, which is not taken into account in the simulation; (2) it may be due to insufficient isolation or other imperfection of the gate module.

The longitudinal displacement of the collision point is obtained from the difference of the phase shift at each bucket between both rings, as given by Eq. (2). An example is shown in Fig. 6. It is within 0.5 mm except for several bunches in the leading part of the train and the pilot bunch. Since it is much smaller than the bunch length of 7 mm, no significant luminosity reduction would be expected. The result is consistent with data of the vertex detector [7] installed at the collision point. At the design beam current of 2.6 A in the LER and 1.1 A in the HER and the design bunch length of 4 mm, however, the displacement will cause luminosity reduction. It is desired that the gap length be reduced from 10% to 5% for the future.

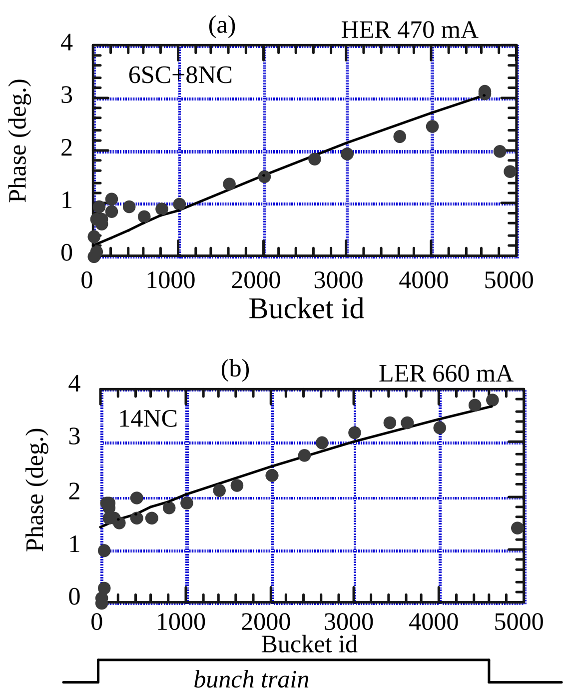

Figure 4: Bunch phase along a bunch train: (a) HER at a beam current of 470 mA and (b) LER around 660 mA. Dots are measured data and solid lines are simulation results.

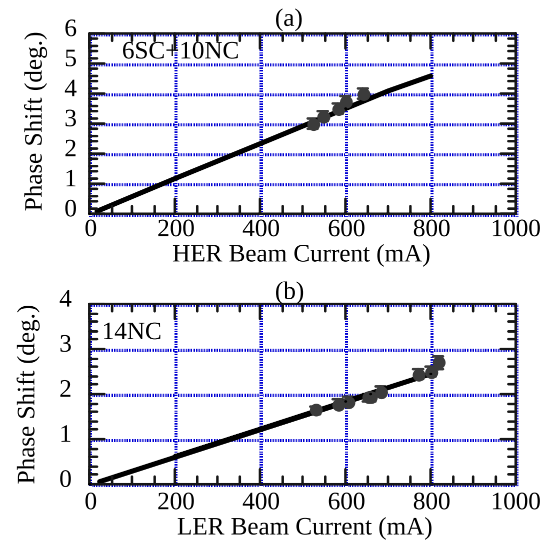

Figure 5: Bunch phase difference between bucket #401 and the last bunch (#4609) as a function of beam current in the HER (a) and the LER (b). Dots are measured data and solid lines show simulation results.

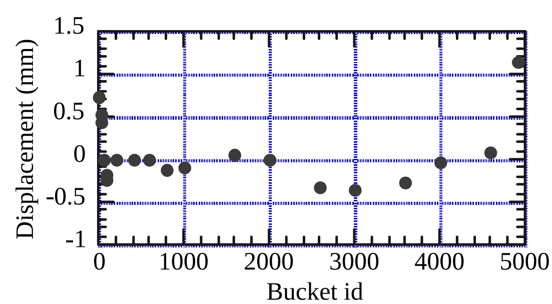

Figure 6: Displacement of longitudinal collision point calculated from the relative phase difference between the two rings, measured at 470 mA in the HER and around 660 mA in the LER.

5 SUMMARY

We have measured the bunch-by-bunch phase along a long bunch train in order to investigate the transient beam loading effect. The measured phase shift in a train agrees with the calculated one except in the leading part of the train. A rapid change in the phase was observed there. More investigation is required to understand this behavior. Authors would like to thank Prof. K.Oide for his support.

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