

## Design of Turn-by-Turn BPM in KEKB

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### Abstract

A turn-by-turn beam position monitor (BPM) system is proceeding in the KEKB. The system employs an I/Q demodulator which detects each beam pulse from each button electrode at the accelerating rf frequency of 509 MHz. Not only a transverse oscillation but also a longitudinal oscillation can be detected owing to the I/Q technique. An analog gate would be used for selecting a few bunches from a multi-bunched beam.

### 1 Introduction

The KEKB[1] is an asymmetric e+ e- collider with two storage rings named LER and HER. Bunches are injected from the Linac through transport lines. A positron bunch with 0.6 nC is injected into the LER and an electron bunch with 1.2 nC into the HER. About 5000 bunches will be stored with 2 ns spacing in each ring, where the harmonic number is 5120. Total current is 2.6 A in the LER and 1.1 A in the HER.

Two projects to measure a beam position are now proceeding in the KEKB. One is the BPM system[2] which measures the closed orbit distortion (COD) by switching each electrode signal using a common detector. The COD BPM manages about 900 sets of button electrodes located around the rings. Though the system has a high resolution of less than 1  $\mu\text{m}$ , it cannot measure the betatron oscillation and a transient change of the orbit. The other project is the bunch-by-bunch feedback system.[3] The feedback system has high speed electronics with great memory capacity and can measure an individual bunch position with 2 ns spacing. However, the resolution of measured data is limited by 8 bits. The system would demand a tight phase stability for the rf signal because of using its 4-th harmonics. In order to cover the weak points of the above systems, a turn-by-turn BPM system is required.

### 2 Technical Consideration

#### 2.1 Required specification

A turn-by-turn BPM system is useful for monitoring transverse oscillations during an injection. Especially when a first beam is injected into the KEKB, the system may be indispensable. The system should be sensitive for a small current and detect a beam position of 0.1 nC charge or 10  $\mu\text{A}$  current to use the system instead of screen monitors at commissioning the next year. The damping rate and the betatron tunes measured from injection oscillations are useful for tuning the machines.

Detection of charge amounts is also useful for tuning injection efficiency. The system can be used during a stored state. When an external kick is applied to a beam, the betatron oscillations are excited. The betatron phase is measured by several monitors located around the ring, which helps to estimate an error of the Twiss parameters. Resolution of 10  $\mu\text{m}$  is required to exchange the system for the COD BPM.

A beam signal is picked up by a button electrode which is common to the COD BPM. Since the rms bunch length is so short that the pulse width of a picked-up signal is less than 100 ps. A peak value of the beam pulse is reduced and the pulse width is widened by passing through a cable from 50 m to 100 m in length. Estimated voltage would be about 1 to 2 V with a duration of 1.5 ns when one may observe a bunch current of 0.5 mA using a 800 MHz low-pass filter (LPF) installed at the end of a cable. Since the bunch spacing is 2 ns, the fundamental component of the beam is in 509 MHz. Thus, the fundamental frequency is chosen as the beam detection.

An estimated signal level was  $\pm 7.6$  mV at the beam current of 0.1 mA using a band-pass filter (BPF) of 509 MHz center frequency and 60 MHz bandwidth. The bandwidth of 60 MHz widens signal duration to 20 ns. On the other hand, the thermal noise level depends on the bandwidth. It can be estimated to be -86 dBm assuming the bandwidth of 60 MHz and the noise figure of 10 dB. Therefore, the S/N ratio of 54 dB is obtained. An estimated position resolution is to be about 50  $\mu\text{m}$  at 0.1 mA. An averaging technique would improve the resolution. The resolution depends on the beam current and it would be 0.5 mm when a single bunch of 10  $\mu\text{A}$  is detected.

#### 2.2 Signal processing

There are two approaches to process a beam pulse signal. One is processed in a time domain, where a peak value of a pulse is sampled. A jitter of a sampling pulse causes an error in the detection. When an acceptable jitter is assumed to be 10 ps, the detected pulse width should be larger than 5 ns to keep the resolution of less than  $1 \times 10^{-5}$  at which the jitter error will be neglected. This method is useful for a single shot measurement. On the other hand, the signal process in a frequency domain is useful to reject an external noise. The bandwidth of the detection determines the response time. Thus, this system adopts a hybrid technique of the two methods to achieve the requirements of both fast detection and high resolution. Frequency components around 509

MHz are picked up and demodulated with a 20 MHz LPF. The pulse width of the demodulated pulse is 40 ns, which would be free from a jitter error.

An I(In-phase) and Q(Quadrature phase) demodulator was adopted to detect a beam pulse. The demodulator is also called an rf vector detector. Principle of the I/Q demodulator is shown in Fig. 1. A beam signal is split into two ways with phase difference of  $90^\circ$ . We assume that the two inputs signals are  $V_b = V_b \sin(\omega_b t + \theta_b)$  as a beam signal and  $V_{rf} = V_{rf} \sin(\omega_{rf} t + \theta_{rf})$  as a local signal. Here, it is not required to fix the phase of both signals. The output signals of two mixers are orthogonal. The output signals through a LPF are

$$V_1 = \frac{1}{2} V_b V_{rf} \sin(\theta_b - \theta_{rf}) \quad (1)$$

and

$$V_2 = -\frac{1}{2} V_b V_{rf} \cos(\theta_b - \theta_{rf}). \quad (2)$$

Here,  $\omega_{rf} \approx \omega_b$  is assumed. From eqs. (1) and (2), we obtain an amplitude as

$$\begin{aligned} |V| &= \sqrt{V_1^2 + V_2^2} \\ &= \frac{1}{2} V_{rf} V_b. \end{aligned} \quad (3)$$

Equation (3) gives the amplitude of the beam signal when the amplitude  $V_{rf}$  is constant. A beam position can be obtained from the difference-over-sum ( $\Delta/\Sigma$ ) algorithm using four amplitudes corresponding to the amplitude from each electrode signal named A, B, C and D. Thus, the horizontal position is given by

$$H = k \frac{V_A - V_B - V_C + V_D}{V_A + V_B + V_C + V_D}, \quad (4)$$

where k is the sensitivity of the electrodes. On the other hand, the phase between the beam signal and the rf can be given from the ratio  $V_1/V_2$  of an electrode signal by

$$\theta_b - \theta_{rf} = \tan^{-1}\left(-\frac{V_1}{V_2}\right). \quad (5)$$

We could obtain a change of the beam phase assuming that  $\theta_{rf}$  is constant. The detected phase represents the relative synchronous phase since the detection is carried out at the accelerating frequency.

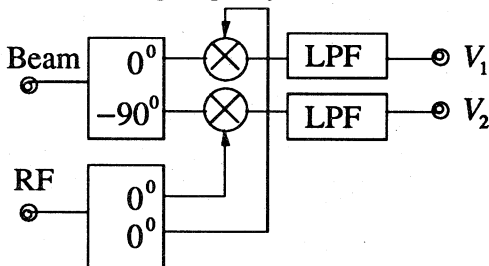


Figure: 1 Principle of I/Q demodulator.

### 3 System

#### 3.1 Overview

Block diagram of the turn-by-turn BPM system is shown in Fig. 2, where only one channel of four channels is drawn. Button electrodes and cables to a control room are common to the COD BPM system. A switch selects a beam signal between the HER and the LER. The feature of the system is that each signal from each electrode is detected by the corresponding detector. This method was adopted in the single-passage BPM of the TRISTAN beam transport lines.[4] In the transport BPM, variations of the position offset were investigated for three years. The result indicates the variations are less than  $\pm 50 \mu\text{m}$ . Thus, the variations of this system would be estimated to be within  $\pm 0.1 \text{ mm}$ , but they are not investigated yet.

A bench test was performed to measure the characteristics of the I/Q demodulator. A short pulse was generated and passed through a BPF with the center frequency of 509 MHz. A ringing wave was divided into two ways and rectified by two I/Q demodulators. A peak value of a rectified pulse with a 20 MHz LPF was sampled by an ADC described next. First, the dynamic response of the demodulator was measured by changing an input amplitude. Figure 3 shows the intensity as the sum of two amplitudes and the normalized position represented by the  $\Delta/\Sigma$  value. The linearity insures a range of more than 40 dB. The normalized position varies with  $\pm 2 \times 10^{-3}$ , which corresponds to the position variations of  $\pm 60 \mu\text{m}$ , where  $k=30 \text{ mm}$  is assumed. The rms noise of the demodulator was about 3 counts for 2k sampling data in the ADC, where the ADC has 14 bits. When a signal level is half of the full scale, the S/N is estimated to be 62 dB.

#### 3.2 Components

An ADC module using a model ADS-945 (DATEL) was developed in VXI C-size. The VXI bus is used for a high-speed transfer of obtained data. The specifications are listed Table 1. The ADC has the memory capacity of 64 kW per channel with 14 bits. Total 8 ADCs are needed for one BPM. The rms noise of the ADC is 2 counts in 2k samplings.

Table 1 Specifications of VXI-ADC.

Resolution	14 Bits
Bandwidth	20 MHz
Memory	64 kW/ch, 2ch
Clock	5 MHz max.
Input Range	$\pm 1.25 \text{ V}$

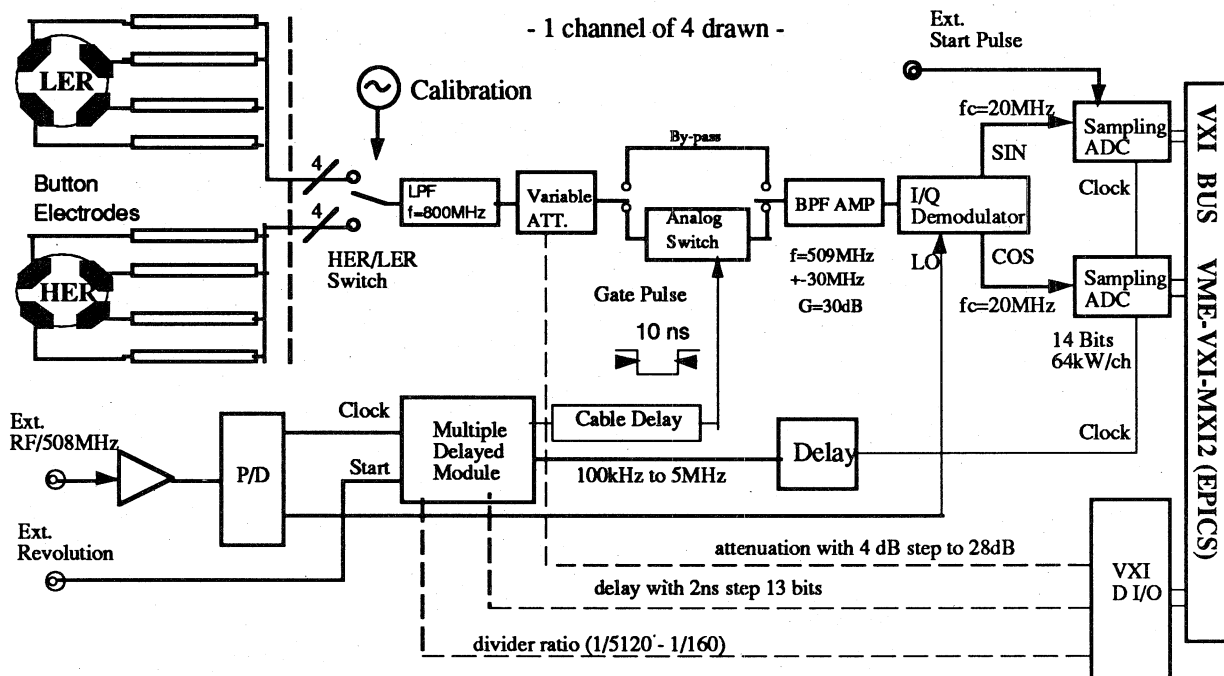


Figure: 2 Turn-by-Turn BPM system.

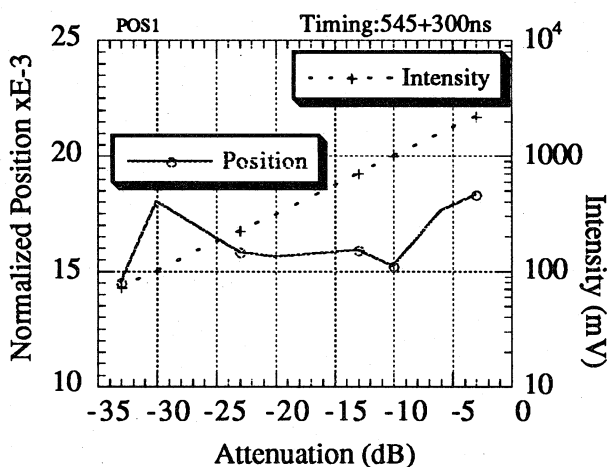


Figure: 3 Dynamic response of I/Q demodulator. The attenuation of 0dB corresponds to the bunch current of 0.28 mA.

An analog gate[5] which has a switching time of 0.2 ns was developed to cope with a multi-bunched beam of 2 ns spacing. However, the gate width will be expanded to 10 ns to reduce switching noise. Thus, five successive bunches (a batch) will be gated.

A delay module TD2[6] was widely used in the TRISTAN. The module outputs a delayed pulse for a revolution period with a 2 ns step. In order to sample several batches within one revolution, the TD2 module was modified. The multiple delayed module outputs equally spaced pulses for a delayed revolution pulse in one revolution as illustrated in Fig. 4. When the multiple factor M is 32, the module outputs 32 pulses in a revolution. Thus, 2000 turns data of 32 batches will be sampled and stored.

The author (TI) wishes to thank the staff of the KEKB beam monitor group, especially Professor S. Hiramatsu for useful comments

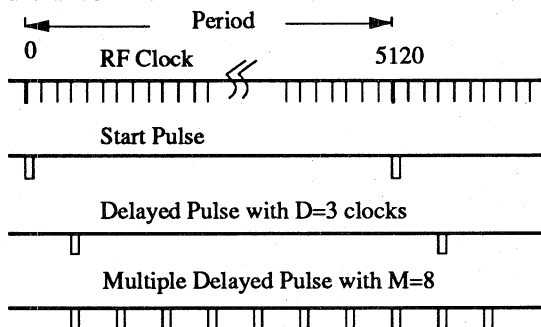


Figure: 4 Multiple delayed module.

Rererences

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