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OPERATIONAL PERFORMANCE OF NEW DETECTION ELECTRONICS FOR STRIPLINE-TYPE BEAM POSITION MONITORS AT THE SuperKEKB INJECTOR LINAC

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Abstract

SuperKEKB injector linac delivers four different beam modes modulated pulse by pulse at 50 Hz, which have 100-times different beam charges, and a pulse may contain two bunches only 96-ns apart. Required low-emittance beams for SuperKEKB rings would need precise beam orbit controls in order to suppress the transverse wakefield in the accelerating structures. A new detection electronics with a wide dynamic range of 40 dB with a high resolution based on a 180-MHz narrow-band detection technique for stripline-type beam position monitors (BPMs) has been developed for the SuperKEKB injector linac. Position resolutions of 5-7 micrometer in one standard deviation were successfully achieved in a normal operation. The self-calibration system is also installed in order to monitor or compensate gain drifts for each input channel with accuracy down to 0.1%, by using test pulses going through stripline heads between 50-Hz beam pulses. The design concept of the new detection electronics is described, as well as operational performance of synchronized measurement with 100 BPMs for injection beams to four electron/positron storage rings.

INTRODUCTION

The linac is required to inject electron/positron beams with bunch charge of 4 nC and normalized emittance of $(\varepsilon_x,\varepsilon_y)$=(40,20) µm for e^-, (100,15) µm for e^+, to SuperKEKB HER/LER circular accelerator [1] and 0.3 nC/bunch beams into PF/PF-AR rings. Thus, there are multiple beam modes that can be switched ever 20 ms [2, 3]. Because beam injection energies for those rings are different, 64 pulsed magnets with dedicated power supply system with energy recovery circuit have been installed [4].

To deliver the low emittance e- beam which is generated by an rf-gun[5] to the HER, suppressing emittance growth in the linac is very important. The main source of the emittance growth is transverse wakefield generated in misaligned quadrupole magnets and accelerating structures[5], and it can be mitigated by an orbit correction. For this purpose, a high resolution, less than 10 µm, beam position monitor had been required. Then, we have developed a stripline BPM read system with high position resolution, high dynamic range and self-calibration system [6, 7]. Because the linac has double bunch operation with 96 ns spacing, a full width of the signal output from bandpass filters, 4th-order Butterworth and 2nd-order Bessel filter, used in the readout board less than 90 ns. The dynamic range can be ensured by attenuation of the of the BPM signal for every beam modes. The attenuator value of each BPM board is determined by the beam mode and the amount of the bunch charge passing through, and a calibration coefficient is given for each attenuator value. There are about 100 BPMs in the linac, and all readout systems were updated in 2017.

PERFORMANCE OF THE BPM SYTEM

Position Resolution

The BPM readout system has a position resolution of 3 µm if the attenuator is set optimally [6], but in the current operation, the strength of the attenuation is set so that it has a wide dynamic range with respect to position and the position resolution is 10 µm or less. Position resolutions of BPMs are shown in Fig. 1 with the linac layout. The resolution is estimated by 3-bpm method using data obtained by changing strength of a quadrupole at the A-sector. Except for points, J-Arc and a chicane in 3-sector, with a large dispersion function because energy jitter and variation of the energy distribution affect the measurement at that point, the position resolution is much better than the requirement. Since stripline BPMs in 3-sector to 5-sector has small inner radius, resolutions are better than others.

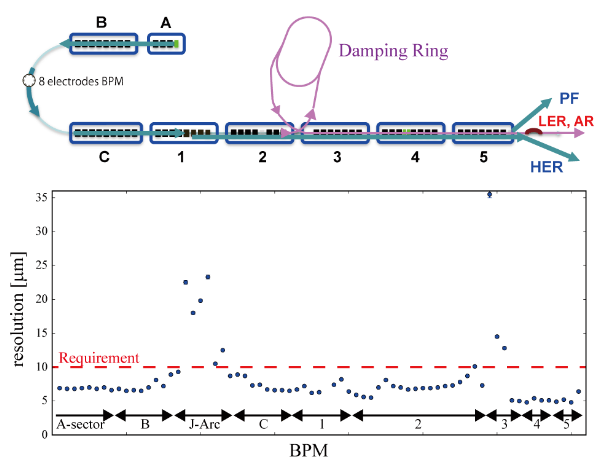

Figure 1: Linac layout and position resolution.

Self-Calibration System

The self-calibration system is used to calibrate gain balance between two signals from opposite electrodes and monitor the gain drift or cable connection stability. Figure 2 shows a gain balance calibration of the x-direction. First, the calibration pulse is sent from the channel Y+

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(see Fig. 1-(A)), and then the calibration pulse induces signals on the adjacent electrodes (X+, X-) shown in Fig 1-(B). The amplitude of those signals are measured. The calibration measurement can be performed every 50 Hz, the x-direction measurement is carried out 6.6 ms after the beam position measurement, and the y-direction measurement is performed after the 13.2 ms. Typically, the gain calibration is performed after board installation or a cable re-connection after some maintenance.

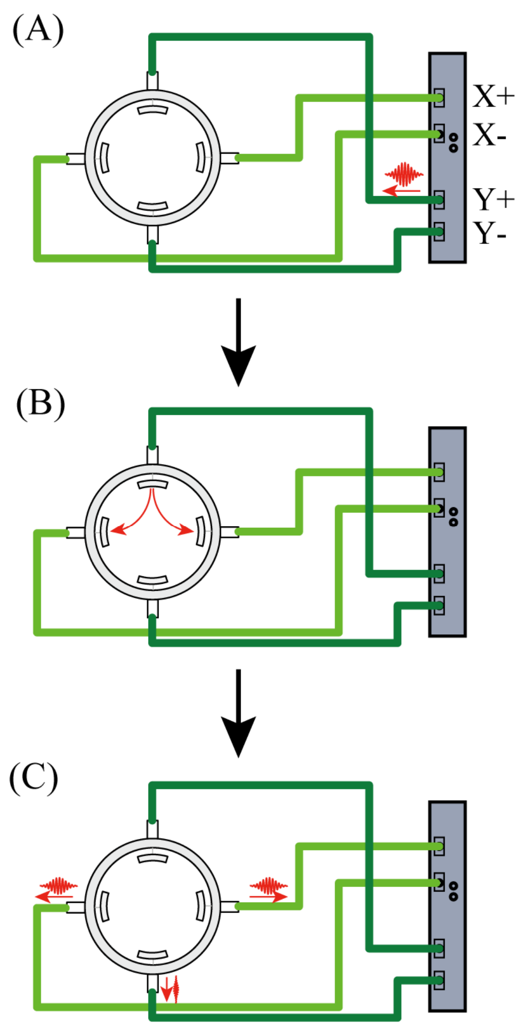

Figure 2: Gain balance calibration in the x direction using the calibration pulse.

Because the signal balance between electrodes affects the beam position measurement, monitoring the balance is important. The calibration pulse measurements are performed twice in an hour. It also runs machine shut downtime. Figure 3 shows transit of the signal balance in a month. The variation of the balance is given by $\Delta r = r - \langle r \rangle$, $r = U_{x-}/U_{x+}$. Where, U_{x+} stands for the signal strength measured on channel X+ and $\langle r \rangle$ means an average of r in a certain period (1 month in this case). The position drift due to the variation of the balance can be approximated by $\Delta x = a\Delta r$. In the linac, a is ~8.5 mm for the sector A-2, ~5.2 mm for the sector 3-5. The most of BPMs were stable like shown in BPM A in Fig. 3. However, some BPMs had sudden gain change or long-term drift, and the reason is not clear yet. The maximum variation of the balance in a month is summarized in Table 1. The beam position shift or drift doesn't affect the beam operation because most of BPMs are stable, balance change of less than 0.3%(~10 μm shift) is 70% of BPMs, and the drift is slow. But we will develop alert or feedback system for sudden gain change or drift of the gain balance.

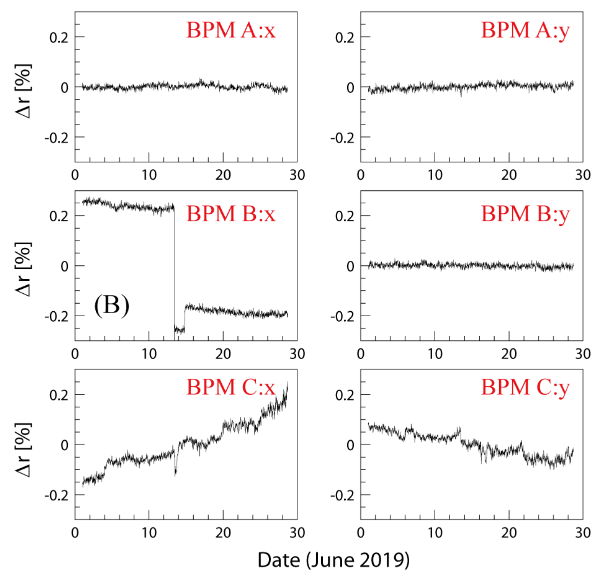

Figure 3: Time trace of the signal ratio between opposite electrodes to the calibration pulse in a month. From the top, stable BPM A, B with sudden change and C with long-term drift are presented. The left and right correspond to direction of x and y balance, respectively.

Table 1: Stability of BPMs in a Month

Maximum variation [%]	<0.1	0.1–0.2	0.2-0.3	>0.3
No. of BPMs	33	23	18	27

Synchronized Data Acquisition

The event timing system [8] allows the beam mode control and synchronized data acquisition of the BPMs, RF monitors [9] and pulsed magnet systems through a shot ID which distributed by an event generator to event receivers. Measurements of each monitors synchronized with the beam is indispensable for improving beam quality and finding problems. Thus, we have developed software to enable synchronized data acquisition of BPMs [10], RF monitors and pulsed magnet systems. Synchronized data and the shot ID are put in process variables of the EPICS.

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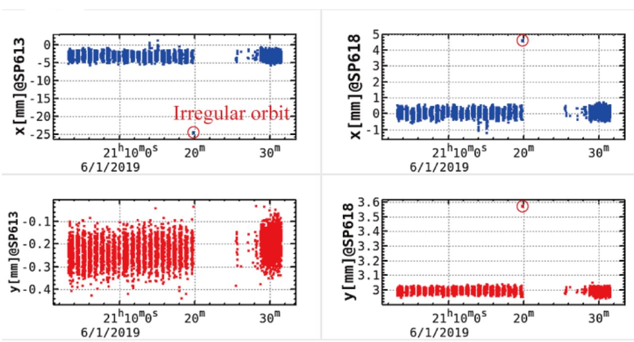

Figure 4: An irregular beam orbit caused a SuperKEKB LER abort. The left and right figures correspond to different BPMs (SP613 and SP618). The SP618 is located in downstream of the SP613 and a vertical bending magnet is installed between them.

Because all of those data are archived, we can analyse correlation of beam position and rf phase, amplitude at the beam timing or currents to the pulsed magnets. Figure 4 shows an irregular beam orbit that caused a LER beam loss abort (most of aborts have another reason); the RF pulse shortening was found at the event.

Quadrupole Moment of the Beam

Monitoring the energy spread of beams during the operation is useful to keep quality of beams. By monitoring the quadrupole moment using 8 electrodes stripline BPM at a large dispersion function point, the change of energy spreads can be diagnosed non-invasively, and feedback system worked in KEKB experiment era [12]. The new high resolution BPM readout system doesn't support 8 electrode BPM, thus we have developed a software EPICS IOC to estimate the quadrupole moment of the beam. The quadrupole moment J_q can be expressed by center of gravity of the charge $<x>$, $<y>$, square half size of the beam $<x>^2$, $<y>^2$ and the pipe radius R, it given by

$$J_q = \left(\langle x^2\rangle - \langle y^2\rangle + \langle x\rangle^2 - \langle y\rangle^2\right)/R^2 = \frac{\sum V_i \cos(2\theta)}{\sum V_i}. \quad (1)$$

Where, V_i and θ stand for pick up voltage and assembly angle of i-th electrode.

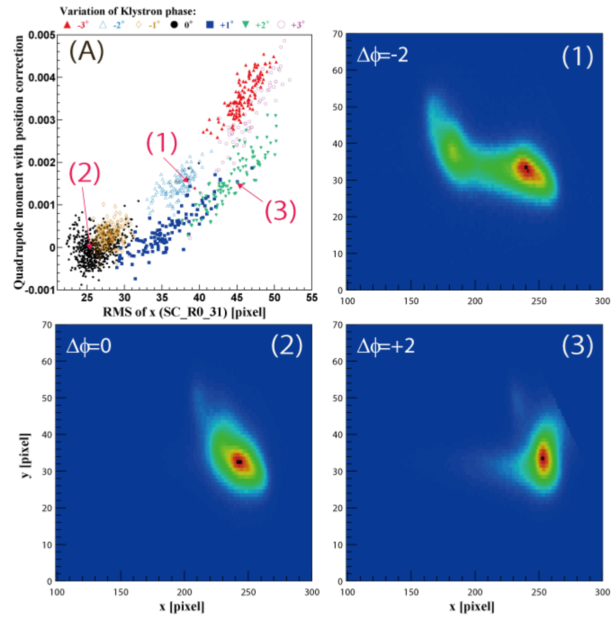

Figure 5: Quadruple moment with position correction and beam size are shown in (A). Beam profiles (1)-(3) correspond to arrowed points in (A).

We have performed synchronous measurement of the quadrupole moment and beam profile at the arc section shown in Fig. 1. The quadrupole moment includes not only beam size terms but also position terms. The position term can be estimated by measurement of beam position and the quadrupole moment. Figure 5 (A) shows quadrupole moment with position correction and beam size estimated by screen monitor. To change energy spread, klystron phases upstream of the arc section were changed, variation from a phase of energy spread minimum are plotted by different symbols. We can find that beam size minimum corresponds to quadrupole minimum. Quadrupole moment proportional to square of beam size, but second-order coefficient depend on beam profile. For example, arrowed points (1) and (3) give same quadrupole moment, but beam size and profile are quite different. However, we can know a change of energy spread by monitoring the quadrupole moment. Figure 6 shows quadrupole moment and klystron phase variation. Although the measurement is about 100 times in a phase set, the quadrupole moment can be evaluated with a sufficiently small error, and the error is very small compared to measurements using the old system.

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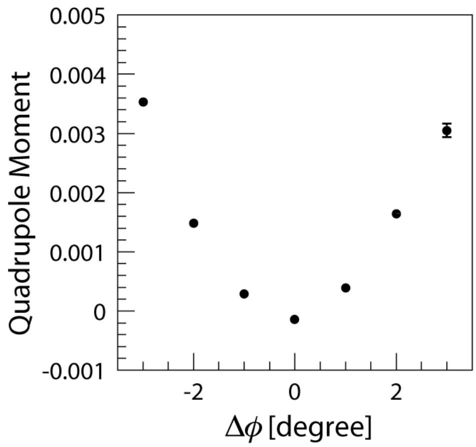

Figure 6: Quadrupole moment and variation of klystron phase. Data points indicate 70-180 shots average.

CONCLUSION

We have developed a BPM readout system with high position resolution and wide dynamic range for the injector for SuperKEKB, and it has been operating stably for about 2 years. The position resolution under operating conditions is 5-7 µm, which satisfies the required resolution of 10 µm. The BPM board is also used for monitoring the energy spread using 8-electrode BPM, and can evaluate the quadrupole moment of the beam with high accuracy. We have developed data acquisition system for BPM, RF monitor and pulse magnet that synchronized with beams, It helps to improve beam performance.

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