Beam-Position Monitor System for the KEKB Injector Linac

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Abstract. About 90 stripline-type beam position monitors (BPMs) have been newly installed in the KEKB injector linac. These monitors easily reinforce handling beam orbits and measuring the charge of single-bunch electrons and positrons which are injected to the KEKB rings. The design value of the beam position resolution is expected to be less than 0.1 mm. A new data-acquisition (DAQ) system has been developed in order to control these monitors in real time. The hardware and software of 18 front-end computers were tuned for the linac commissioning. This report describes the hardware and software system, the monitor calibration, and preliminary beam test results.

INTRODUCTION

The KEK *B* Factory (KEKB) project (1) is in progress in order to test CP violation in the decay of *B* mesons. KEKB is an asymmetric electron-positron collider comprised of 3.5 GeV positron and 8 GeV electron rings. The PF 2.5 GeV linac (2) is also being upgraded to the KEKB injector linac in order to inject single-bunch positron and electron beams directly into the KEKB rings. The injected beam charges are required to be 0.64 nC/bunch and 1.3 nC/bunch, with a repetition rate of 50 Hz, for the positron and electron beams, respectively. High-charge primary electron beams (~10 nC/bunch) are required in order to generate sufficient positrons. Therefore, it is important to easily control the orbits of the beams; most importantly, the beam positions and charges of the primary high-current electron beams have to be controlled so as to suppress any beam blowup generated by large transverse wakefields. A BPM system has been developed to perform this function since 1992. The goal of the beam position measurement is to detect the charge center of gravity with a resolution of 0.1 mm. The amount of the beam current needs to be precisely controlled in order to maximize the positron production and the beam injection rate to the KEKB rings. This facilitates a well-controlled operation of the injector, allowing us to reach an optimum operational condition with as a short a tuning time as possible and maintain such a condition through a long-term operation period. A new DAQ system based on VME/OS-9 computers, which are connected with the linac control system, has also been developed in order to control these monitors in real time. The performance of the new system has been tested using electron beams at an extended linac beam line during its commissioning.

HARDWARE SYSTEM

Design of a Beam Position Monitor

A conventional stripline-type BPM made of stainless steel (SUS304) was designed with a $\pi/2$ rotational symmetry. A drawing of the monitor geometry and a photograph are shown in Figures 1 (a) and (b), respectively. The total length (195 mm) was chosen so as to make the stripline length (132.5 mm) as long as possible, so that it can be installed into limited space in the new beam line of the linac. Each electrode is comprised of a 50 Ω transmission line. The angular width of the electrode is 60° in order to avoid strong electromagnetic coupling between the neighboring electrodes. A 50 Ω SMA vacuum-feedthrough is connected to the upstream side of each electrode, while the downstream ends are short-circuited to a pipe in order to simplify the mechanical manufacturing. Quick-release flange couplings (manufacturer's standard KF flange) are used at one end of the monitor for easy installation into the beam line. More detailed descriptions are given elsewhere (3–6).

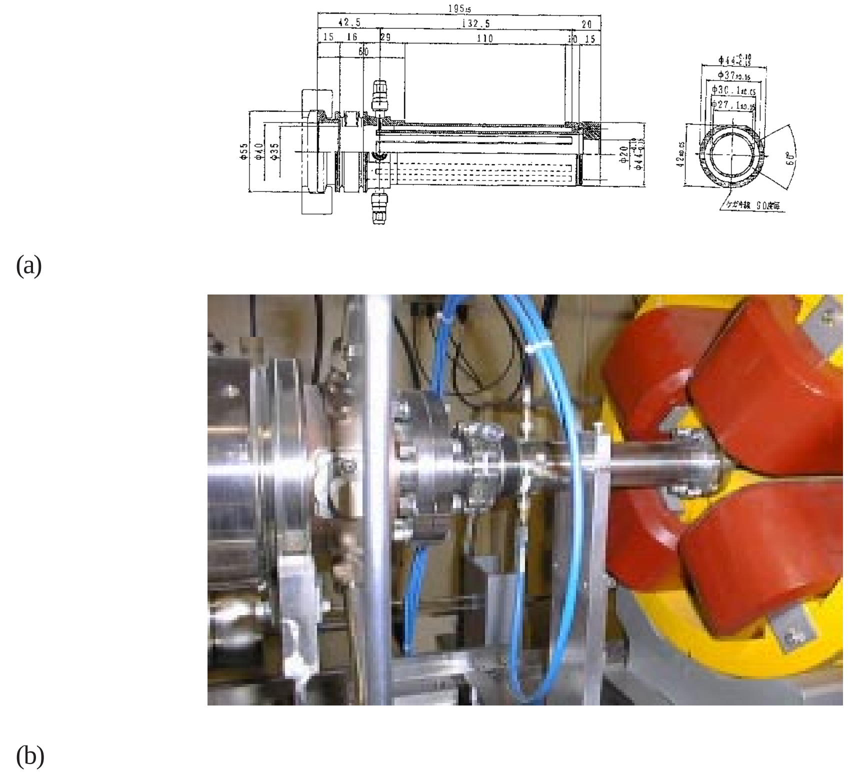


FIGURE 1. Geometrical drawing (a) and photograph (b) of the stripline-type beam position monitor installed in the new beam line.

Data-Taking System

All analog signals of the BPMs are connected with monitor stations in conjunction with those of wall current monitors (WCMs). Eighteen monitor stations, each of which is comprised of a front-end computer (VME/OS-9 with a MC68060 microprocessor at 50 MHz), a signal digitizing system (an oscilloscope), and a signal-combiner box, are located on the linac klystron gallery at nearly equal intervals along the beam line. Each monitor station can control a maximum of twelve BPMs. A schematic drawing of the monitor station is shown in Figure 2. Four signals of a BPM are sent directly to a signal-combiner box through 35 m-long coaxial cables. The frequency response and characteristics of the coaxial cable are given elsewhere in detail (5). Two signal combiners combine the horizontal and vertical signals from each BPM, respectively. In the combiner box, one of two horizontal (vertical) signals is delayed with a time of 7 ns in order to reject its signal-mixing. The two signals from the signal combiners are fed to two input channels of a digital sampling oscilloscope (Tektronics TDS680B) with a sampling rate of 5 GHz and a bandwidth of 1 GHz. The Unix workstations and the front-end computers communicate with each other through a network system. As shown in Figure 3, all of the front-end computers are linked to a switching-hub with a star topology. Fiberoptic cables are used for physical connections in order to avoid electromagnetic interference from high-power klystron modulators. The hub has a link to the linac control network, where Unix workstations (WSs) and man-machine interfaces (PCs and X-terminals) are connected.

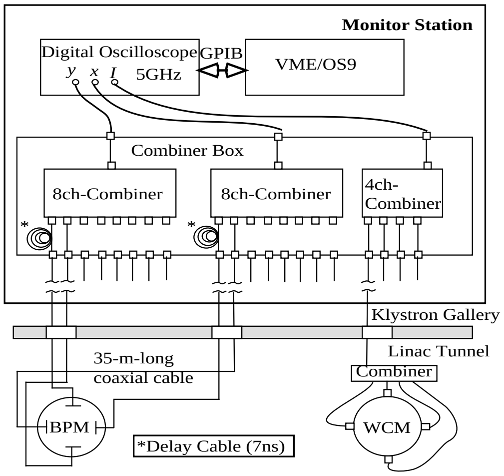


FIGURE 2. Schematic drawing of the data-taking system in a monitor station.

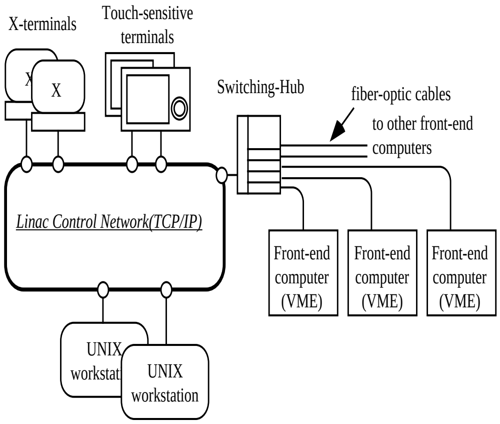


FIGURE 3. Block diagram of the linac control network and the new network (right side) system.

Calibration of the Monitors

All of the monitors were installed into the beam line after bench calibration. The bench calibration system for the BPMs is described in detail elsewhere (7). Here, only the bench calibration and the beam position calculation are briefly described. All of the BPMs have been calibrated by "mapping," which is performed on the test bench with a thin current-carrying wire (500 µmϕ), stretched through the center of the monitor, to simulate the beam. The calibration coefficients of the map function, which relates to the pulse-height information obtained from four pickups for various wire positions, are measured by the bench calibration. The horizontal (x) and vertical (y) beam positions are represented by map functions with a third-order polynomial, as follows:

$$x = \sum_{i,j=0}^{3} a_{ij} (\Delta_x / \Sigma_x)^i (\Delta_y / \Sigma_y)^j , \tag{1}$$

$$y = \sum_{i,j=0}^{3} b_{ij} (\Delta_x / \Sigma_x)^i (\Delta_y / \Sigma_y)^j , \tag{2}$$

$$Q = G \sum_{k=1}^{4} g_k V_k . \tag{3}$$

Here,

$$\Delta_x = g_1 V_1 - g_3 V_3 ,\ \Sigma_x = g_1 V_1 + g_3 V_3 , \tag{4}$$

$$\Delta_y = g_2 V_2 - g_4 V_4 ,\ \Sigma_y = g_2 V_2 + g_4 V_4 , \tag{5}$$

where a_{ij} and b_{ij} are the coefficients of the map functions (derived by fitting the map data to the map functions by using a least-squares fitting procedure); V_1 and V_3 (V_2 and V_4) are the horizontal (vertical) pickup voltages; and g_k (k=1–4) are the gain correction factors. Q is the beam charge, which is calculated by summing four-pickup voltages, and G is a conversion factor used to calculate the beam charge, which can be measured by wall-current monitors. The gain correction factors (g_k), which correct any signal-gain imbalance caused by attenuation losses of the cables and the difference of the coupling strength of the combiners, are measured by using fast test-pulses with a width of 500 ps. These parameters (a_{ij}, b_{ij}, g_k, and G) for each BPM are stored in the Unix workstations as a calibration table, and are loaded into each front-end computer at every startup.

SOFTWARE SYSTEM

Control Software

Several DAQ processes are running concurrently on the front-end computers and on Unix workstations. The processes, with data and control flow, are shown in Figure 4. DAQ processes for the WCM are almost the same as those for the BPM, except for the data format, as shown in the figure. The read-out process resides on each front-end computer. It reads waveforms of BPM signals from the digital oscilloscope, and then calculates the beam positions and currents while taking into account the calibration coefficients described above. Trigger pulses synchronized with the linac beam are provided to all of the oscilloscopes at the 0.67 Hz cycle. This rate is limited by the communication throughput between a front-end computer and a oscilloscope through a GPIB line. The calculated beam positions and currents are transferred to two Unix workstations over the linac control network with the UDP-protocol (8). In order to reduce the network traffic, data transfer is done only when the beam current data at the front-end is renewed. As a result, the total traffic between front-end computers and Unix workstations is always constant (24 packets per second: 0.67 Hz × 18 VMEs × 2 WSs). Unix workstations receive beam currents from eighteen front-end computers and store ten recent data for each front-end on shared-memory regions. The data servers for BPM use the data on the shared memory. It is worth noting that the data requests from applications do not increase the network traffic to the front-end computers.

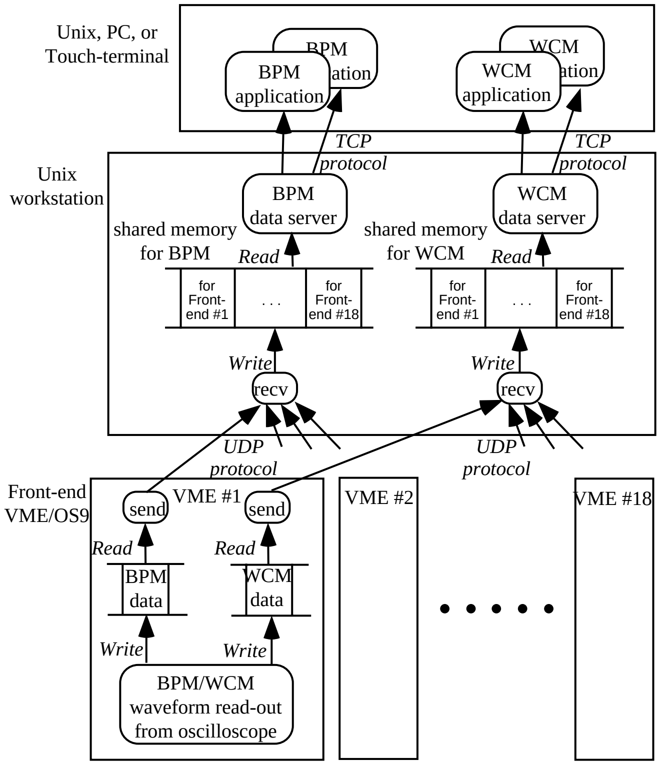


FIGURE 4. Block diagram of the control software and data flow for the data-taking system.

BEAM TESTS

Beam and DAQ System Tuning

DAQ system tuning and the beam tests have been performed (2) using single-bunch electron beams at the extended linac section (sectors A and B). Single-bunch electron beams can be generated by the new pre-injector (9), which is comprised of two subharmonic bunchers, a prebuncher and a buncher. The electron gun can generate a beam charge of about 18 nC/pulse with a repetition rate of 50 Hz. Single-bunch electron beams greater than 10 nC/bunch were stably accelerated from the outlet of the buncher until the end of sector B without any observed beam loss. The beam energies were about 500 MeV and 1.5 GeV, at the end of sectors A and B, respectively. The longitudinal width of the beams was measured by an optical transition radiation monitor to be about 16 ps with a full width at half maximum after tuning of the preinjector. The beam tests during the commissioning were performed at a 5 Hz repetition rate. Figure 5 shows an example of the beam tests at a beam current of 10 nC/bunch, in which the DAQ processes of four monitor stations (22 BPMs) concurrently worked well. It shows the horizontal displacements of the beam from the center (the top drawing), the vertical displacements (middle), and beam charge (bottom), simultaneously with a refresh rate at around 1 Hz after elaborate software tuning. The DAQ system operated stably during the beam tests. Figure 6 shows pickup signals obtained by a beam of 6.2 nC/bunch at the third monitor station.

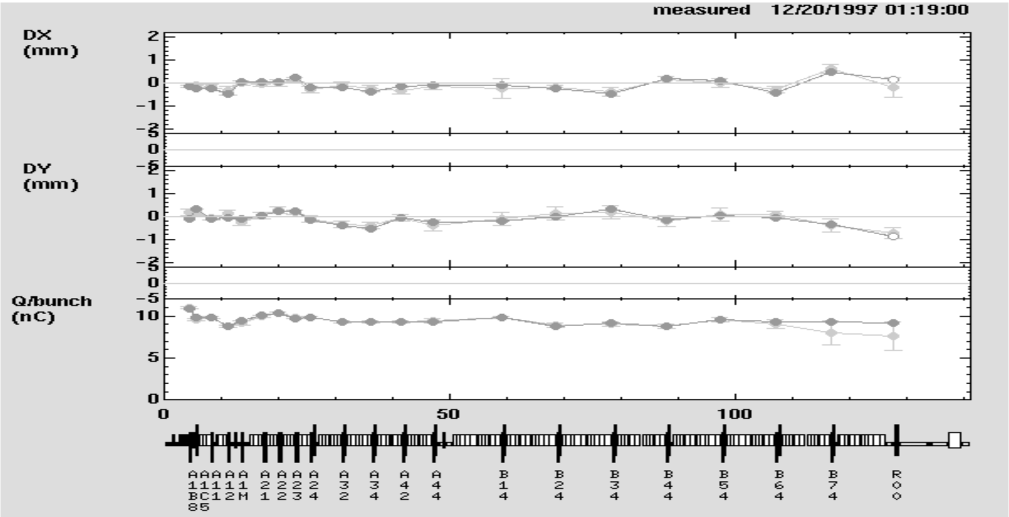


FIGURE 5. Variation of the beam orbits and charge intensity along the linac. The beam current of the single-bunch electrons is 10 nC/bunch.

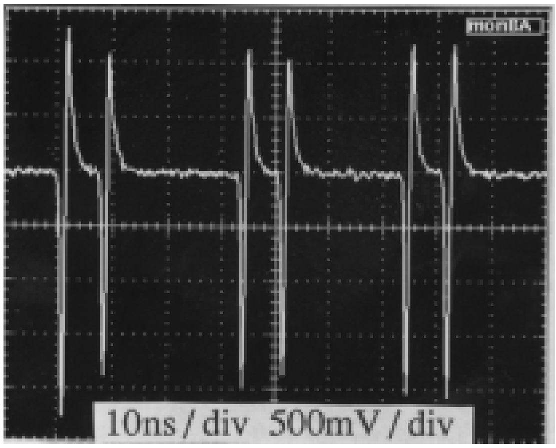


FIGURE 6. Pickup-pulse signals measured by the digital oscilloscope at a beam charge of 6.2 nC.

Position-Resolution Measurement

The position resolution of the BPM has been measured using single-bunch electron beams with a beam charge of 7 nC on the basis of the “three-BPM method”. The principle of this method is simple. The beam orbit of a charged particle through a system with both magnetic lenses and acceleration can be generally represented by a multiplication process of transfer matrices (R) (10). If the beam orbit is represented by a coordinate vector (X), passage of the charged particle through the system can be represented by an equation neglecting the second-order transfer matices:

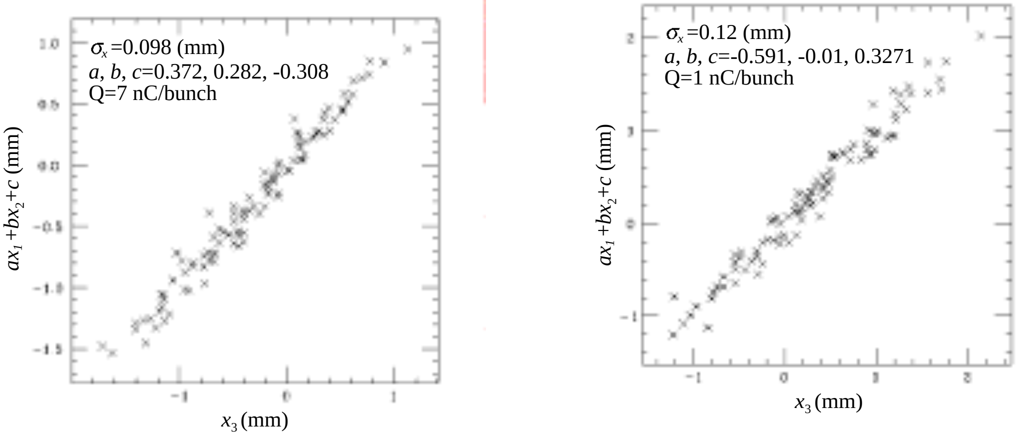
$$X_i(1) = \sum_{j=1}^{i} R_{ij} X_j(0), \tag{6}$$

where $X_i(0)$ and $X_j(1)$ are the components of the initial and final coordinate vectors through the system action, and R_{ij} are the components of the transfer matrix. Here, if any three beam positions (x_1, x_2 and x_3), which are the first components of the coordinate vector X, are measured in the system, the third beam position (x_3) is linearly correlated by the expected beam position ($x^c{}_3$) using the beam positions (x_1 and x_2) as follows:

$$x_3^c = ax_1 + bx_2 + c, \tag{7}$$

$$x_3 = x_3^c. \tag{8}$$

Here a, b, and c are constants obtained by a least-squares fitting of the correlation plot in accordance with Equations (7) and (8). Thus, the position resolution can be obtained by calculating the standard deviation of the correlation plot and assuming that the resolutions of the three BPMs are the same. Beam tests were performed using single-bunch electron beams of 1 and 7 nC. The beam positions were changed within the range of ±2 mm by two correction dipole magnets placed just after the buncher. Figure 7 gives an example.



(a) (b)

FIGURE 7. Correlation plots between the measured and calculated beam positions for the beam charge of (a) 7 nC/bunch and (b) 1 nC/bunch by using the three-BPM method.

CONCLUSIONS

The new beam position monitor system has been installed in the linac in order to reinforce the beam monitoring of the beam positions and currents. The present system was inspected with electron beams in an extended linac beam line. The data-taking rate became 0.67 Hz after elaborate system tuning of the new DAQ. The rate is mainly limited by the data-transfer rate from the oscilloscope through a GPIB line. The present DAQ system has been found to be sufficiently fast and stable. The position resolution has been measured by single-bunch electron beams for beam charges of 1 and 7 nC/bunch to be around 0.1 mm.

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