11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO3C3

PULSE-BY-PULSE PHOTON BEAM POSITION MEASUREMENTS AT THE SPring-8 UNDULATOR BEAMLINE*

H. Aoyagi†, H. Osawa, K. Kobayashi, T. Fujita, S. Takahashi
Japan Synchrotron Radiation Research Institute (JASRI/SPring-8), Hyogo, Japan

Abstract

A pulse-mode X-ray beam position monitor that enables pulse-by-pulse position measurement in the synchrotron radiation beamline of the synchrotron radiation facility was improved, and evaluation tests were performed. The monitor was equipped with blade-shaped detection elements utilizing diamond heatsinks to reduce stray capacitance, and a microstrip transmission line to improve high-frequency characteristics. The detection elements operate as photocathodes and generate single unipolar pulses with a full width at a half-maximum of less than 1 ns. This operation allows pulse-by-pulse measurement of the synchrotron radiation beam. To ensure operations at the undulator beamline in SPring-8, where the synchrotron radiation power is very intense, further improvements were introduced to the detecting elements to enhance heat resistance. The evaluation results of sensitivity and resolution in the pulse-by-pulse photon measurement and observation of beam oscillation during beam injection are discussed herein.

INTRODUCTION

We developed a pulse-mode X-ray beam position monitor (PM-XBPM) that enables pulse-by-pulse position measurements in the synchrotron beamline of SPring-8, a synchrotron radiation facility, and are working on practical applications. To improve the high-frequency characteristics, this monitor is equipped with diamond heatsinks to reduce the blade-shaped detecting elements' stray capacitance and a microstrip transmission line to match the impedance. The detection principle is the same as conventional X-ray beam position monitors (XBPMs), in which four blade-shaped detection elements are arranged vertically and horizontally, with the photon beam axis as the center of symmetry, and the current signal ratio of each detection element is read out as position information. The prototype was installed in a bending-magnet beamline (BM-BL), and evaluation tests were conducted. Thus, a unipolar pulse signal with a pulse length of 0.7 ns FWHM was generated, and a pulse-by-pulse beam position of the synchrotron radiation beam was observed [1].

To ensure the stable operation of the monitor in the insertion device beamline (ID-BL), where the synchrotron radiation power is extremely high, we aimed to enhance the heat resistance by modifying a diamond heatsink and a water-cooling holder [2]. By doubling the size of the diamond heatsink in the beam axis direction to 16 mm compared with the prototype, the contact area with the cooling base was increased to enhance the thermal resistance. This improvement increased the photon-receiving area, which led to an increase in the current signal. Furthermore, the heat-transfer efficiency was enhanced by adopting a wedge-shaped copper plug.

We confirmed the basic performance of the modified pulse-mode XBPM at a BM-BL (BL02B1), which has a maximum power density of 1.5 kW/mrad^2 and an actual irradiation power density of approximately 0.1 W/mm^2). Subsequently, it was transferred to the ID-BL (BL35XU), which has a maximum power density of approximately 500 kW/mrad^2 and an actual irradiation power density of approximately < 25 W/mm^2), and evaluation tests were performed. This paper discusses the position sensitivity, resolution, and observation of the beam oscillation during a top-up injection.

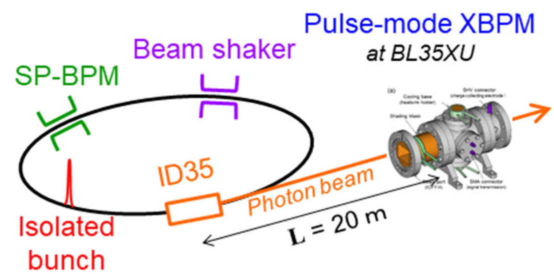


Figure 1: Setup of position sensitivity measurement.

POSITION SENSITIVITY

Perturbation by Beam Shaker and Amplitude Measurement by SP-BPM

Figure 1 illustrates the measurement system used for evaluating position sensitivity. A single isolated bunch was injected into the storage ring, and the bunch current was 0.95 mA. Betatron oscillations were excited horizontally and vertically using the bunch-by-bunch feedback (BBF) kickers at Cell 04 in the horizontal direction and a 0.9-m kicker at Cell 30 in the vertical direction. The perturbation frequency was set to 28.9 kHz (ν_x = 41.1382) in the horizontal direction and 60.0 kHz (ν_y = 19.3257) in the vertical direction. The excitation of the betatron oscillation was locked by a phase-locked loop (PLL) to automatically follow the tuning changes caused by the opening and closing of the ID gap and the bunch current. The perturbation amplitude was adjusted by the Dimtel iGp12 DAC output, and when the amplitude at the BPM of cell 21 reaches 100 µm, the DAC output is called "nominal kick power 100%." The kick angles corresponded to θx = 0.033 µrad and θy = 0.047 µrad under this condition. The stationary perturbation amplitude excited by radio frequency knockout

* Work supported by Japan Society for the Promotion of Science through a Grant-in-Aid for Scientific Research, No.18K11943 and No.21K12530.
† aoyagi@spring8.or.jp

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO3C3

(RFKO) at any single-pass BPM (SP-BPM) can be converted to the amplitude at the PM-XBPM point. Figure 2 presents the estimated amplitude at the PM-XBPM (BL35XU) position 20.3 m from the source, which is converted from the amplitude observed at the SP-BPM (cell 21). The following values were used as conversion coefficients [2]:

$$\frac{|y_{XBPM}|}{|y_{BPM}|} = \frac{\sqrt{\left(\sqrt{\beta_{ID}} - \frac{\alpha_{ID} L}{\sqrt{\beta_{ID}}}\right)^2 + \frac{L^2}{\beta_{ID}}}}{\sqrt{\beta_{BPM}}} = 3.90 \,/\, 1.90 \text{ (hor. / ver.)},$$

where $\alpha_{ID} = -1.195\times10^{-5}$, $\beta_{ID} = 31.16$ m, $\beta_{BPM} = 31.21$ m in the horizontal direction and $\alpha_{ID} = +4.61\times10^{-6}$, $\beta_{ID} = 5.04$ m, $\beta_{BPM} = 5.73$ m in the vertical direction. The perturbation amplitude was adjusted by the iGp12 DAC output, and "nominal kicker power" was set to 100%, 75%, 50%, 25%, and 0%. The photon beam amplitude is linear to the DAC output value.

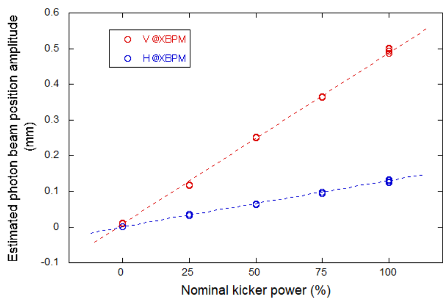


Figure 2: Photon beam position amplitude at PM-XBPM estimated from SP-BPM data.

Amplitude Measurement by PM-XBPM

Each pulse signal from the four detector elements (UL: upper-left, UR: upper-right, LL: lower-left, LR: lower-right) of a PM-XBPM was measured with an oscilloscope (4 GHz b.w., 50 GS/s, High Res. Mode, 12 bit). The horizontal and vertical beam positions were calculated using the integrated waveforms. Figure 3 shows a connecting diagram of PM-XBPM. To protect the oscilloscope, each signal cable was connected to a divider with a terminator of 50 Ω at one end instead of connecting it directly to the oscilloscope.

Figure 4 shows the oscillation during 40 consecutive turns observed by this monitor and the fitting curves of sine waves when the "nominal kick power" is changed. Here, the vertical and horizontal directions exhibit linearity (Fig. 5).

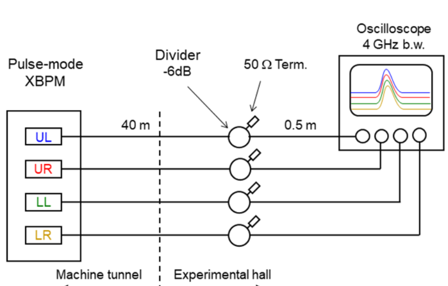
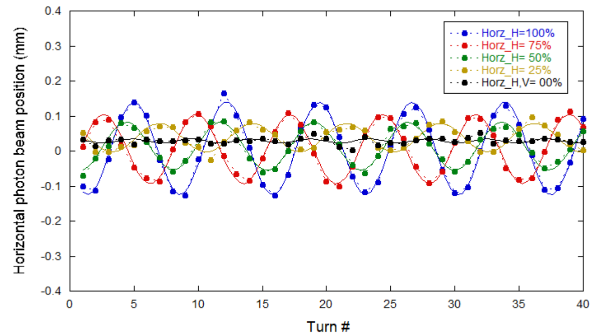
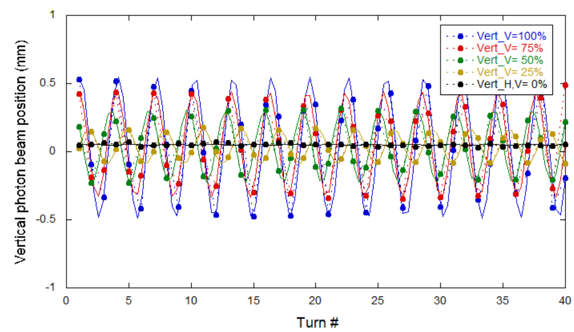


Figure 3: Connecting diagram of PM-XBPM.



(a) Horizontal



(b) Vertical

Figure 4: Photon beam amplitude measured by PM-XBPM.

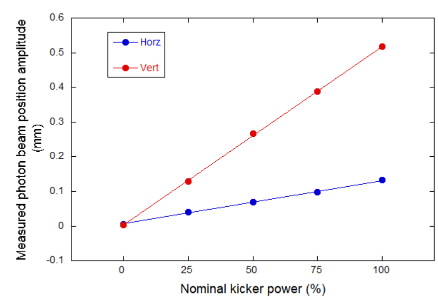
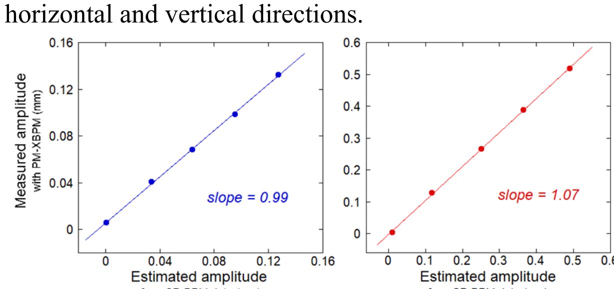


Figure 5: Amplitude of PM-XBPM readouts.

Comparison of SP-BPM and PM-XBPM

Figure 6 shows the correlation between SP-BPM and PM-XBPM data. The horizontal axis represents the amplitude at the PM-XBPM estimated from the amplitude observed by the SP-BPM (Fig. 2), and the vertical axis represents the amplitude measured by the PM-XBPM (Fig. 5). Sufficient linearity for practical uses was confirmed in both horizontal and vertical directions.



(a) Horizontal (b) Vertical

Figure 6: Correlation between XBPM and SP-BPM.

11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO3C3

RESOLUTION

Using the connection diagram described above (Fig. 3), we evaluated the resolution depending on the bunch current. The bunch current was set to 0.5, 1, 2, 3, 4, and 5 mA/bunch, as shown in Fig. 7. To reduce an influence of the pulse tails on the next pulses, a bunch interval was set to 24 buckets (47.2 ns) and low-current bunches were arranged from the front. The bunch current in each bucket was kept constant during this measurement by top-up injection. Figure 8 shows the superimposed waveforms of each bunch.

Figure 9 shows the fluctuations in Diff/Sum from the pulse heights of the four detection elements. The vertical axis in Fig.10 indicates the value (units: mm) obtained by multiplying the standard deviation of Diff/Sum by the correction factor. In both the horizontal and vertical directions, the fluctuation, that is the resolution, is likely to decrease as the bunch current increases. The minimum resolutions were obtained at a bunch current of 5 mA/bunch and were 4.5 μm std horizontally and 4.5 μm std vertically. Figure 10 also shows the fluctuations when the bandwidth is digitally narrowed to 200 MHz using the built-in oscilloscope function. The minimum resolutions were also obtained at a bunch current of 5 mA/bunch and were 1.7 μm std horizontally and 1.2 μm std vertically. Using a low-pass filter extends the pulse length; however, if the bunch interval is wide, the pulse information will be easier to read with a high-speed ADC. The resolution was low at lower bunch currents under these measurement conditions. Still, by optimizing the range of the oscilloscope, we achieved the design goal of a resolution of 10 μm std.

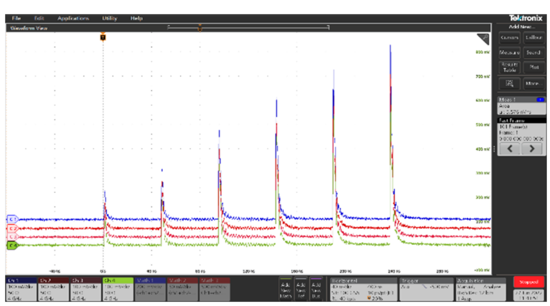


Figure 7: Screen capture of the oscilloscope. Applied voltage of the charge collecting electrodes (HV) is +300 V. ID gap is 6.7 mm.

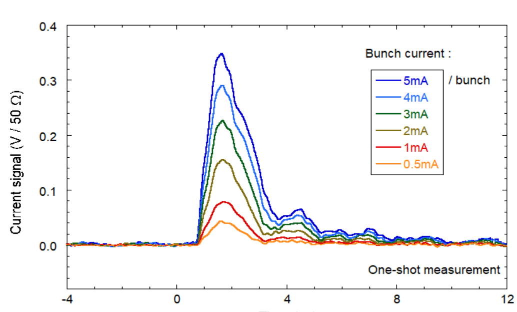


Figure 8: Waveforms of PM-XBPM. HV is +300 V. ID gap is 9.6 mm.

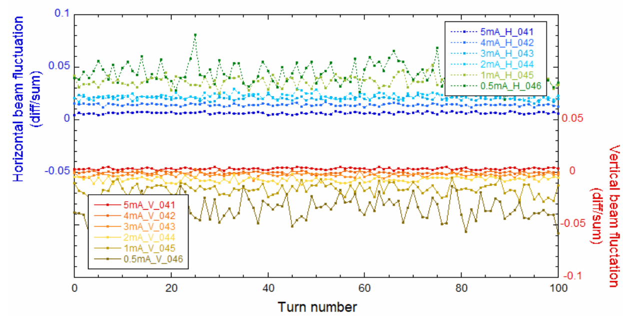


Figure 9: Fluctuation in diff/sum of the PM-XBPM data.

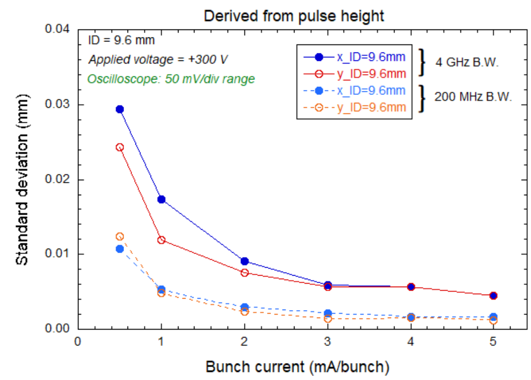


Figure 10: Bunch current dependence of the fluctuations.

BEAM OSCILLATION DURING BEAM INJECTION

A top-up injection is regularly performed during user time to supply stable beams to user experiments at SPring-8. However, the photon beam oscillated briefly during beam injection once every 20–40 s. Therefore, we attempted to observe the pulse-by-pulse behavior of the synchrotron radiation beam using PM-XBPM, synchronizing with the injection timing. Figure 11 shows the connecting diagram. The signal from each detection element was connected to a combiner (labeled "Divider" in the figure) through an attenuator (-10 dB). Therefore, the influence of reflected pulses can be attenuated. To observe the horizontal position, the combined signal from the UR and LR was connected to Channel 1 of the oscilloscope, and the combined signal from the UL and LL was connected to Channel 2. The cables were reconnected when switching to the vertical measurement.

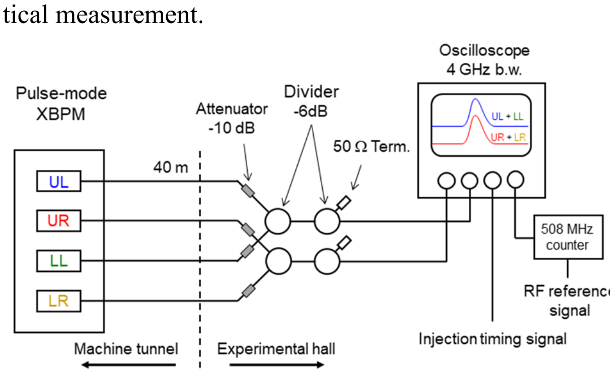
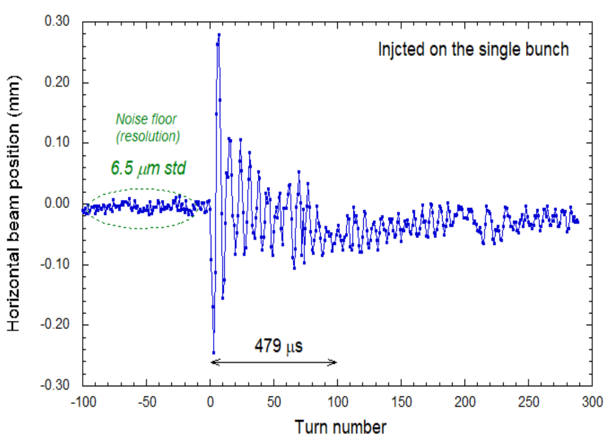


Figure 11: Connection diagram of PM-XBPM.

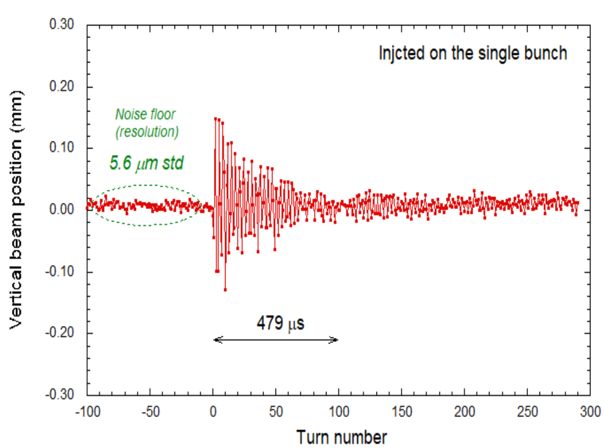
11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MO3C3

We observed the oscillation of the isolated bunch (5 mA/bunch) during the user time ("11/29-bunches + 1 bunches" mode [3]). As illustrated in Fig. 12, different behaviors were observed in the horizontal and vertical directions, suggesting that the PM-XBPM detects the horizontal and vertical directions independently. Here, the standard deviation of the beam fluctuation before the timing of beam injection can be interpreted as the resolution of this measurement system. Both the horizontal (6.5 μm std) and vertical resolution (5.6 μm std) are lower than the resolutions driven in the previous section. This is because that the pulse-height reduced by an additional divider (-6 dB) as a combiner and an attenuator (-10 dB).

Next, the oscillation of pulses was observed at 23.6 ns intervals during the user time ("203 bunches" mode [3]). Figures 13 (a)–(c) present the horizontal oscillation, while Fig. 13 (d)–(f) illustrate the vertical oscillation. The vertical axes indicate the Diff/Sum of channel 1 and channel 2, which represents the transverse photon beam position. Each pulse with a bunch separation of 23.6 ns could be observed individually. These oscillations during beam injection are diminished after several 100 μs, and they do not affect user experiments.



(a) Horizontal



(b) Vertical

Figure 12: Turn-by-turn oscillation during beam injection. Revolution time of the storage ring is 4.79 μs. HV is +300 V. ID gap is 9.6 mm.

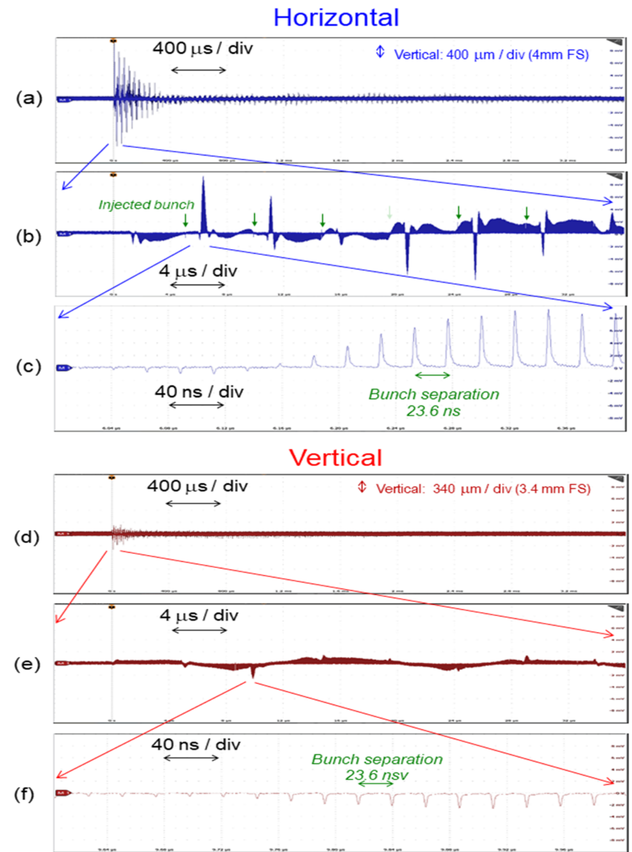


Figure 13: Screen captures of the oscilloscope observing oscillations of pulses with 2.36 ns separation. HV is +300 V. ID gap is 9.6 mm.

CONCLUSION

The evaluation tests of PM-XBPM with enhanced heat resistance were performed in ID-BL at SPring-8. Thus, stable operation in the ID-BL, which has a much higher synchrotron radiation irradiation than the BM-BLs, was verified. Regarding position sensitivity, it was confirmed that the PM-XBPM responds linearly to the perturbation amplitude of the photon beam by applying a stationary perturbation to the electron beam using a beam shaker. Furthermore, we quantified the resolution for different bunch currents and confirmed that a design goal of 10 μm std was achieved. Finally, pulse-by-pulse measurement was demonstrated at the SPring-8 ID-BL by observing the beam oscillation during beam injection. As a next step, introduction of an appropriate fast ADC is required to utilize this monitor in user experiments.

REFERENCES

[1] H. Aoyagi *et al.*, "Pulse-mode x-ray beam position monitor prototype for a synchrotron radiation beam line", *Phys. Rev. Accel. Beams,* vol. 24, p. 032803, 2021. doi:10.1103/PhysRevAccelBeams.24.032803

[2] H. Aoyagi *et al.*, "Toward higher resolution in pulse-mode x-ray beam position monitor", in *Proc. 18th Annual Meeting of Particle Accelerator Society of Japan (PASJ2021),* THP026.

[3] http://www.spring8.or.jp/en/users/operation_status/schedule/bunch_mode/