DEVELOPMENT OF A MULTI-STRIPLINE BEAM POSITION MONITOR FOR A WIDE FLAT BEAM OF XFEL/SPRING-8

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Abstract

A multi-stripline beam position monitor (BPM) has been developed for the x-ray free-electron laser facility at SPring-8 (XFEL/SPring-8). This BPM is used at the energy dispersive part of a bunch compressor, where the transverse beam profile is very flat and wide, maximally 50 mm. The position measurement of the flat beam is usually difficult with an ordinary beam position monitor having cylindrical symmetry, such as a four-electrode stripline BPM. Therefore, we designed a multi-stripline BPM that is equipped with five stripline electrodes on each of the top and bottom surfaces of a rectangular BPM duct having a cross section of 70 mm width and 10 mm height. These electrodes provide a rough charge profile and the beam position is calculated from the gravity center of the profile. We tested a prototype of the multi-stripline BPM at the SCSS test accelerator. The position sensitivity of the BPM was estimated to be 0.1 mm for the horizontal direction and 0.01 mm for the vertical direction.

INTRODUCTION

In general, an x-ray free-electron laser (XFEL) machine has bunch compressors, since a high peak-current beam is necessary. A bunch compressor (BC) consists of four bending magnets making a chicane trajectory, in which a higher energy electron travels with a shorter time-of-flight. When a time-dependent energy slope is applied to an electron beam with head electrons having lower energy, the bunch length of the beam is compressed by the BC. The energy slope is given by the rf voltage of an accelerating cavity at an off-crest phase. Therefore, the bunch length is sensitive to the acceleration rf phase.

An rf phase fluctuation of the off-crest accelerating cavity can be monitored by a beam position monitor (BPM) at the energy-dispersive part of the BC, since the beam energy strongly depends on the rf phase. In the case of the XFEL facility at SPring-8 (XFEL/SPring-8) [1], the position resolution is demanded to be 0.1 mm for stable lasing. This value comes from the required energy stability of 0.1% [2, 3], which is achieved by the energy feedback control with this BPM, and from a dispersion value of about 100 mm.

Another requirement for the BPM at the dispersive part is that the horizontal aperture must be large enough to accept the horizontal beam size of maximally 50 mm due to the large energy chirp. This aperture is larger than the rf cavity BPM [4], which is employed at the non-dispersive part of the XFEL.

An ordinary four-electrode stripline BPM (4S-BPM) is also unsuitable for such a wide beam. A 4S-BPM signal is affected by the beam profile in addition to the beam position, if the aperture of the 4S-BPM is comparable to the horizontal beam size. In this case, a non-linearity response and a degradation of the position resolution can be caused. To reduce the beam-profile effect, a cylindrical 4S-BPM should have more than 100 mm diameter, when the beam size is 50 mm. However, such a large BPM forms an rf resonating cavity, when it is connected to the beam duct of our BC, which has a rectangular cross section of 70 x 25 mm^2. In this case, the BPM generates a beam-induced rf background together with a BPM signal.

Therefore, we newly developed a multi-stripline BPM (MS-BPM) with a wide rectangular duct similar to the beam duct of our BC. Since stripline electrodes of the MS-BPM are closer to the beam than those of the 4S-BPM, the number of electrodes is increased. In this case, a rough beam profile can be obtained and the beam position can be calculated from the gravity center of the profile. In addition, no beam-induced rf background is generated, since the MS-BPM does not form an rf cavity.

In this paper, we describe the design, including the electro-magnetic simulation and the readout electronics, and beam test results of the MS-BPM.

DESIGN OF THE MULTI-STRIPLINE BPM

Dimensions of the Multi-stripline BPM

A schematic drawing of the MS-BPM is shown in Fig. 1. The cross-section of the beam aperture of the MS-BPM has dimensions of 70 (x) x 10 (y) mm^2. On each top and bottom surface, five stripline electrodes are arranged with a 10 mm interval. Since the vertical opening of the MS-BPM is 10 mm, most of the electric field from a single electron is confined to within 10 mm. This means that each electrode is sensitive to electrons only within 10 mm. Therefore, the resolution of the horizontal charge profile is expected to be 10 mm, which is the same as the

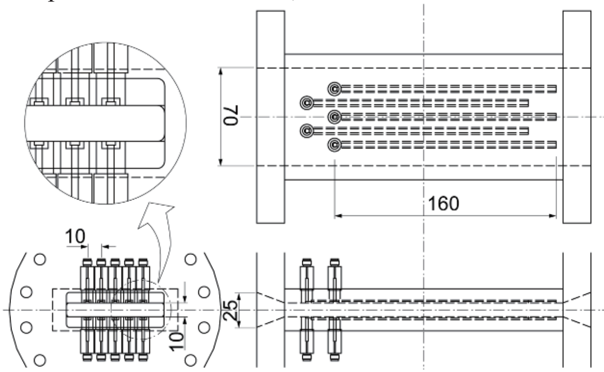

Figure 1: Schematic drawing of the multi-stripline BPM.

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electrode interval. The horizontal beam position is calculated to be the gravity center of the obtained charge profile.

The length of the stripline electrode is 160 mm. This length corresponds to λ/4 of 476 MHz, which is the second harmonic of the 238 MHz pre-buncher cavity of XFEL/SPring-8. If this frequency component is picked up from a detected signal by using a band-pass filter, a synchronized detection method with the acceleration rf signal can be used.

Each electrode is placed in a groove in order to reduce the electrical coupling with the other electrodes. The characteristic impedance of the stripline is tuned to be 50 ohm by using an electro-magnetic simulation (described in the next section). The BPM signal is extracted from an SMA vacuum feed-through connector, which is matched to the stripline impedance. The other side of the stripline is shorted to the beam duct.

Electro-magnetic Simulation

We performed an electro-magnetic simulation by using Ansoft HFSS 11 [5]. The electric field distribution from a small electron beam is shown in Fig. 2. The electric field exists only within 10 mm around the beam. The coupling between electrodes was calculated to be less than –30 dB.

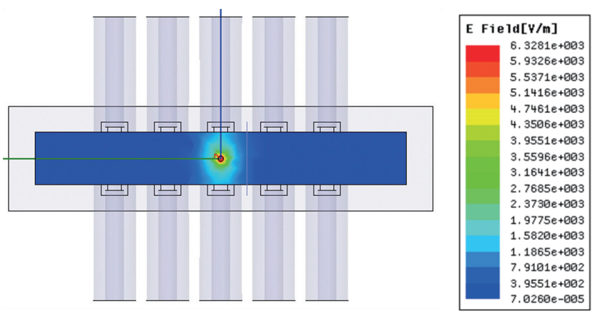

Figure 2: Simulation of the electric field generated by a small beam.

Readout Electronics

Figure 3 is a block diagram of the readout electronics of the MS-BPM. We employ 476 MHz IQ (In-phase and Quadrature) demodulators and VME-ADC boards, since these electronics have been developed for the rf monitor of the accelerating rf cavity [3]. The BPM signal has a negative impulse, followed by a positive one. The interval between the positive and negative pulses has a half period

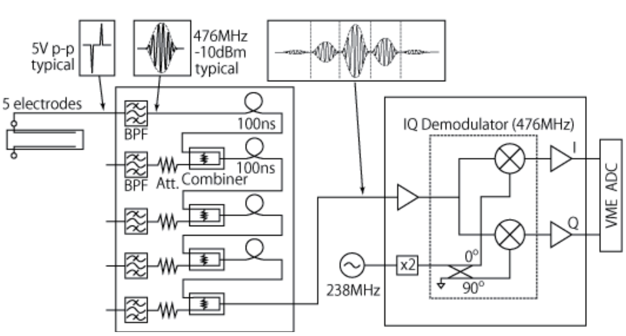

Figure 3: Block diagram of the readout electronics of the multi-stripline BPM.

of 476 MHz (1.05 ns). This signal is fed into a cavity-type band-pass filter and converted to a 476 MHz rf pulse with a 50 ns FWHM. To reduce the number of IQ demodulators, five signals are sequentially multiplexed into one channel by using 100 ns delay lines and 3dB power combiners. Thus, all ten signals from a MS-BPM can be processed by two IQ demodulators.

BEAM TEST

To confirm the performance of the MS-BPM, we manufactured a prototype of the MS-BPM, and tested it at the SCSS test accelerator [6]. Figure 4 shows a photograph of an installed prototype MS-BPM. This prototype has the same vertical opening of 10 mm, but the number of electrodes is reduced to six (three for each of the top or bottom surface), because of the dimensional limitation of a beam pipe. The prototype MS-BPM was mounted on a motorized stage for a position-sensitivity measurement.

The beam energy of the SCSS test accelerator is 250 MeV and the bunch charge is approximately 0.3 nC per pulse. Although a wide beam profile is better for the MS-BPM, the beam profile has a round shape during the usual FEL operation, since the prototype MS-BPM is installed at a non-dispersive part. Therefore, some quadrupole magnets are tuned to squeeze the beam profile, as shown in Fig. 5. The beam core was horizontally stretched to approximately 4 mm.

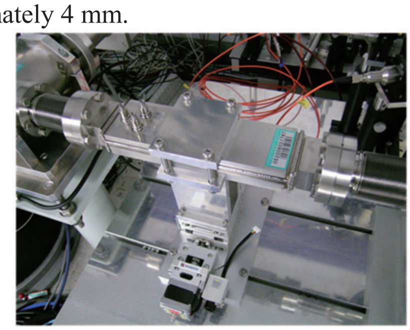

Figure 4: Photograph of the prototype of the multi-stripline BPM installed in the SCSS test accelerator.

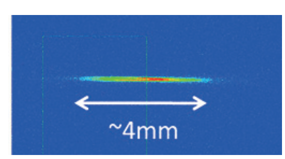

Figure 5: Beam profile near the MS-BPM taken by an OTR screen monitor.

Waveform from the Multi-stripline BPM

Some waveforms from the MS-BPM taken by an oscilloscope are shown in Fig. 6. Negative and positive impulses with an interval of 1.05 ns were observed. In addition to the BPM signals, there was a small ringing noise. The source of this noise is considered to be a beam-induced rf field in a MS-BPM duct, or a signal reflection at the connection between the SMA connector and the stripline. However, the noise level is not so large as to deteriorate the BPM performance.

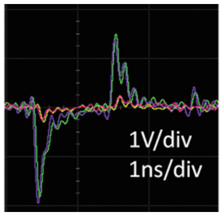

Figure 6: Waveforms of MS-BPM signals.

Position Sensitivity Measurement

To measure the position sensitivity, we scanned the MS-BPM position by using the motorized stage. The beam position was not moved in this measurement.

Figure 7 shows the gravity center of the MS-BPM signal as a function of the horizontal position. The position was varied from –8 mm to +8 mm with a 1 mm pitch. The gravity center, X_{center} , was calculated by

$$X_{center} = \frac{\sum_i x_i v_i}{\sum_i v_i}, \quad (1)$$

where x_i is the horizontal position of the electrode and v_i is the peak voltage measured by an oscilloscope. This plot indicates that the gravity center is almost proportional to the MS-BPM position. The slope of the fitted function was 0.91, while this value should be unity. A small sinusoidal shape was also observed. These deviations came from the geometrical condition of the electrodes; they can be corrected by using calibration data. After correcting these deviations, the rms fluctuation of the gravity center was 0.1 mm. Consequently, the horizontal position sensitivity was considered to be less than 0.1 mm.

Figure 8 shows the vertical gravity center as a function of the vertical BPM position. The position was scanned from –1 mm to +1 mm with a 0.2 mm pitch. The vertical gravity center, Y_{center} , was calculated by

$$Y_{center} = \frac{\sum_i v_i \mathrm{sgn}(y_i)}{\sum_i v_i}, \quad (2)$$

where $\mathrm{sgn}(y_i)$ is the sign of the vertical position of each electrode and v_i is the peak voltage. This plot shows good linearity. The rms fluctuation of the data was approximately 0.01 mm. Therefore, the vertical position sensitivity was estimated to be less than 0.01 mm.

Waveform from Band-pass Filter

We checked the performance of the band-pass filter at the input of the readout electronics, as shown in Fig. 3. The waveform from the band-pass filter is shown in Fig. 9. A 476 MHz rf pulse signal with 50 ns FWHM was observed, as expected. The peak rf power was approximately –10 dBm. Although some higher order modes can be seen in the early stage of the signal, these modes can be removed by a low-pass filter.

SUMMARY

We designed a MS-BPM that has ten stripline electrodes in a wide rectangular duct for a wide flat beam at the energy dispersive part of XFEL/SPring-8. The prototype of the MS-BPM was tested at the SCSS test accelerator. A linear relation between the detector

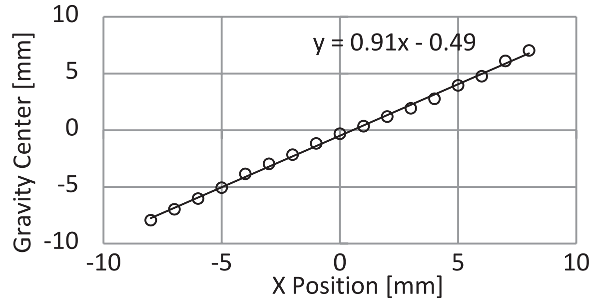

Figure 7: Horizontal position dependence of the gravity center of the MS-BPM signal. A linear function fitted to the data is also plotted.

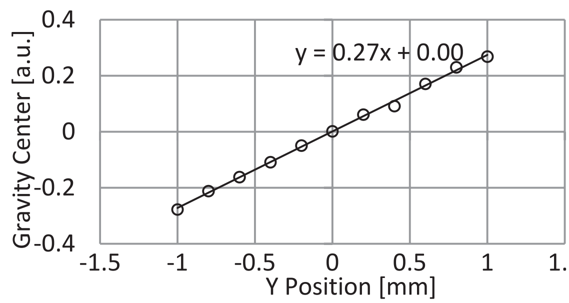

Figure 8: Vertical position dependence of the gravity center of the MS-BPM signal. A linear function fitted to the data is also plotted.

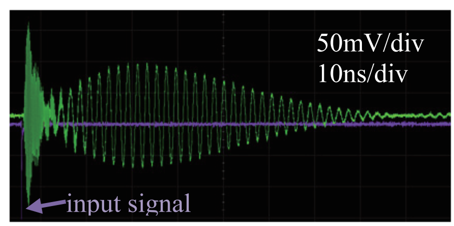

Figure 9: Waveform of the band-pass filter output (green) and input signal (purple).

position and the gravity center of the MS-BPM signal was observed. The position sensitivities of the horizontal and vertical directions were 0.1 mm and 0.01 mm, respectively. The energy resolution at the BC is expected to be 0.1% when the dispersion value is 100 mm. These results are satisfactory for our purpose.

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