DEVELOPMENT OF THE RF CAVITY BPM OF XFEL/SPRING-8

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Abstract

We describe the design and performance of the rf cavity beam position monitor (RF-BPM) for the x-ray free-electron laser project at SPring-8 (XFEL/SPring-8). The required position resolution is less than 0.5 μm. To achieve this demand, we designed an RF-BPM that has a TM110 cavity to detect the beam position and a TM010 cavity to obtain the beam charge and phase reference. The resonant frequency is 4760 MHz for both cavities. We designed a detection circuit equipped with IQ (In-phase and Quadrature) demodulators. We installed the BPM system into the SCSS test accelerator and performed a beam test. We observed a position sensitivity of approximately 0.1 μm and a position resolution of less than 0.2 μm at a 0.3 nC bunch charge. We evaluated the resolution of the beam arrival timing measurement with the phase being between the TM010 resonator and a reference rf signal. The temporal resolution was 25 fs. These results are sufficient for the beam tuning of XFEL/SPring-8.

INTRODUCTION

The x-ray free-electron laser project at SPring-8 (XFEL/SPring-8) [1] is underway to open a new era of life sciences, material sciences, etc. The XFEL/SPring-8 facility consists of an electron injector with a thermionic cathode, C-band high-gradient accelerators and short-period in-vacuum undulators. XFEL/SPring-8 is designed to generate a coherent x-ray beam at an angstrom wavelength by a self-amplified spontaneous emission (SASE) process.

One of the most important technical issues is to overlap the electron beam with radiated x-rays throughout the undulator section with high precision. The position difference between the electron beam and the x-rays must be less than 4 μm [2]. Therefore, we require the resolution of the beam position monitor (BPM) to be less than 0.5 μm. Among various types of BPMs, only an rf cavity BPM (RF-BPM) can achieve this demand, because of its high beam-cavity coupling. There exist some past experimental reports with nanometer-level resolutions [3-5].

It is also important to monitor the time difference between a beam and a reference rf signal. The temporal precision of the XFEL accelerator is demanded to be less than 50 fs [6]. An RF-BPM has a capability to detect beam arrival timing from the phase of an excited rf signal.

We designed a BPM system comprising an RF-BPM cavity and a detection circuit in order to achieve the required resolution. This system was installed into the SCSS test accelerator, which was built to demonstrate the feasibility of XFEL/SPring-8, and has been operating as FEL at extreme ultraviolet (EUV) FEL since 2006. Our BPM system was tested with a 250 MeV electron beam. In this paper, we describe the design of this system and the results from beam tests.

DESIGN OF THE RF-BPM SYSTEM

The RF-BPM uses a TM110 dipole resonant mode in a cylindrical cavity to measure the beam position. The longitudinal electric field, E_z, of TM110 is expressed as

$$E_z = E_0 J_1\left(\frac{\chi_{11} r}{a}\right) \cos\varphi \; e^{j\omega t}, \qquad (1)$$

where E_0 is a constant that represents the field amplitude, J_1 is a first-order Bessel function of the first kind, $\chi_{11} \simeq 3.8$ is the first root of $J_1(r) = 0$, a is the cavity radius and ω is the resonant angular frequency. Since $J_1(r)$ can be approximated by a linear function near the axis, the amplitude of the TM110 field excited by an electron beam is proportional to beam displacement.

The voltage amplitude of the output signal from the TM110 cavity can be written as [7]

$$V = V_1 q x + jV_2 q x' + jV_3 q + V_n, \qquad (2)$$

where q, x and x' are the beam charge, the beam position and the slope of the beam trajectory, respectively. $V_1 q x$ is the in-phase component proportional to the beam position, $jV_2 q x'$ is the quadrature-phase component coming from the beam slope, $jV_3 q$ is also the quadrature-phase component due to leakage of the parasitic TM010 monopole mode and V_n are the other components, such as a thermal noise. To obtain beam position information, we have to scale the signal with the beam charge and determine the sign with a phase reference. Therefore, we prepared an additional TM010 mode cavity in the same cavity block to provide charge and phase information.

Based on concepts mentioned above, we designed the RF-BPM illustrated in Fig. 1. For the TM110 cavity, the rf signal is picked up through a coupling slot that is decoupled to the TM010 monopole mode in order to minimize the third term of Eq. 2 ($jV_3 q$). The resonant

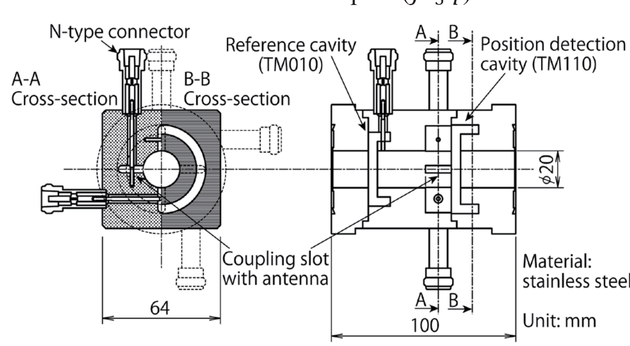

Figure 1: Drawing of the RF-BPM cavity.

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frequency is 4760 MHz for both TM110 and TM010 cavities. Although the acceleration rf frequency is 5712 MHz, the BPM frequency is intentionally shifted so as to avoid any background due to the dark current synchronized with the acceleration rf. Some other parameters of the RF-BPM are summarized in Table 1.

The RF-BPM signal is processed by an IQ (In-phase and Quadrature) demodulator (IQ-DEM), as shown in Fig. 2. In order to improve the resolution in the SCSS test accelerator, where a different electronics with a logarithmic amplifier is used [8], we newly developed IQ-DEM type electronics. The rf signal from the RF-BPM is fed into an attenuator switch so as to extend the dynamic range, because the required value is 100 dB (sub-μm – a few mm), while the dynamic range of the IQ-DEM is 60 dB. The baseband signal from the IQ-DEM is recorded by a 12-bit VME A/D converter [9]. The basic performance was verified with a CW rf signal. The amplitude linearity error was less than 1% and the phase error was less than 1 degree when the input rf voltage was more than 10% of the full scale (100 mV). The obtained performance is sufficient for beam-position measurements in XFEL/SPring-8.

RESULTS FROM THE BEAM TEST

We tested the RF-BPM system in the SCSS test accelerator. A photograph of the installed RF-BPM is shown in Fig. 3. The cavity was mounted on a movable stage to align the cavity along the beam axis and to confirm the beam position dependence of the signal. The beam energy was 250 MeV and the beam charge was 0.3 nC. The transverse beam diameter was approximately 0.2 mm (FWHM). We measured the position sensitivity, the position resolution and the beam arrival timing resolution. We describe the results in the following subsections.

Position Sensitivity

We obtained the position sensitivity by moving the BPM position while the electron beam trajectory was fixed. One of the plots of ADC counts versus BPM positions is shown in Fig. 4. The sensitivity was measured to be more than 20 ADC counts per 1 μm. Since the ADC noise is a few counts, the position sensitivity is approximately 0.1 μm.

Position Resolution

The position resolution can be measured by using three adjacent RF-BPMs. The first and third BPMs predict the position at the second BPM, assuming a straight beam trajectory. The position resolution is determined from the residual, which is the difference between the detected position of the second BPM and the expectation.

A resolution measurement was performed with the three BPMs illustrated in Fig. 5. All of the electromagnets between the BPMs were turned off so that the beam trajectory would be straight. The distribution of the residual in the horizontal direction is shown in Fig. 6. The width of this histogram is the convolution of the position

Table 1: Parameters of the RF-BPM Cavity

	TM110 cavity	TM010 cavity
Resonant Frequency	4760 MHz	4760 MHz
Loaded Q factor	50	50
Number of ports	4 (X: 2, Y: 2)	1
Signal amplitude at the 50 ohm port	14 mV/μm/nC (peak)	200 V/nC (peak)

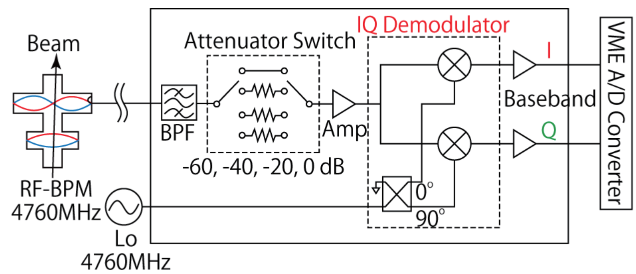

Figure 2: Block diagram of the RF-BPM electronics.

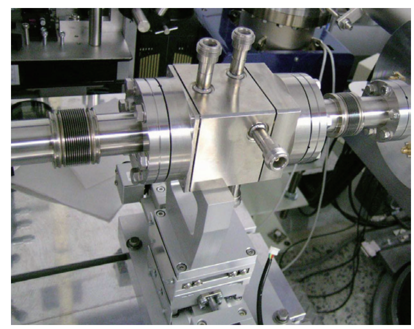

Figure 3: Photograph of the RF-BPM cavity.

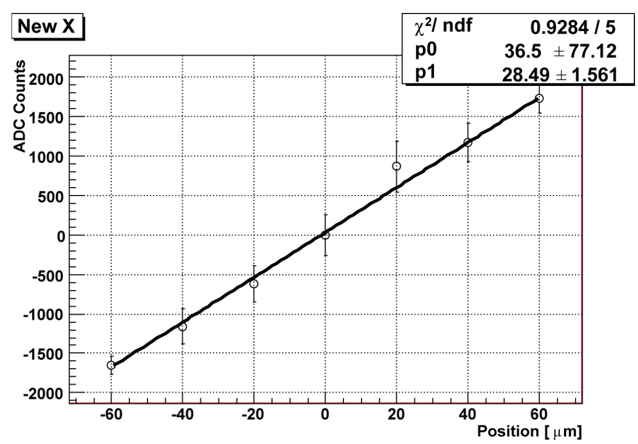

Figure 4: ADC count of the RF-BPM at each position. The error bars show the standard deviation of the histogram of the ADC data. A linear function fitted to the data is also plotted.

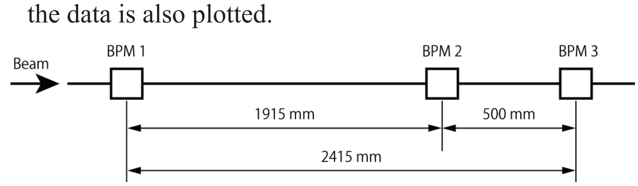

Figure 5: Arrangement of the three BPMs for the resolution measurement.

uncertainties of the three BPMs. Assuming that the resolutions of the three BPMs were same, the position resolution, σ_{BPM} , was calculated by the following equation by means of an appropriate error propagation:

$$\sigma_{\mathrm{BPM}} = \frac{L_1+L_2}{\sqrt{2(L_1{}^2+L_1L_2+L_2{}^2)}}\,\sigma_{\mathrm{res}} \simeq 0.773\,\sigma_{\mathrm{res}}\ , \qquad (3)$$

where L_1 and L_2 are the distance between the BPM 1 and 2 and that of the BPM 2 and 3, respectively, and σ_{res} is the standard deviation of the residual distribution. Since we found that the conversion coefficient of the ADC counts to the beam position had a systematic error of 10%, we increased σ_{BPM} by 10%. Finally, the position resolution of the RF-BPM was measured to be less than 0.2 μm, as tabulated in Table 2.

Beam Arrival Timing Resolution

The beam arrival timing can be measured by the phase of the TM010 resonator. In the SCSS test accelerator, the beam arrival timing jitter was measured to be approximately 50 fs [6] with this method. However, the temporal resolution of the RF-BPM, itself, was not evaluated at that time. Therefore, we measured the temporal resolution by using the two neighboring BPMs (the BPM 2 and 3 in Fig. 5).

Figure 7 shows the distribution of the phase difference between the two TM010 cavities. The standard deviation is 0.0459 degree of 4760 MHz, corresponding to 27 fs. The temporal resolution is $1/\sqrt{2}$ of this value if the resolutions of the two BPMs are same. We found that the beam arrival timing jitter of the BPM 2 was 30% different from that of the BPM 3. Therefore, we increased the resolution by 30% as a systematic error. Consequently, the temporal resolution of the RF-BPM was obtained to be 25 fs (= 27 fs / $\sqrt{2}$ × 1.3).

CONCLUSIONS

We designed an RF-BPM system to achieve a sub-μm resolution required for the XFEL facility. The performance of the RF-BPM system was confirmed by an electron beam of the SCSS test accelerator. The position sensitivity was 0.1 μm and the position resolution was less than 0.2 μm. The temporal resolution on the beam arrival timing was evaluated to be 25 fs. These results are sufficient for the XFEL facility.

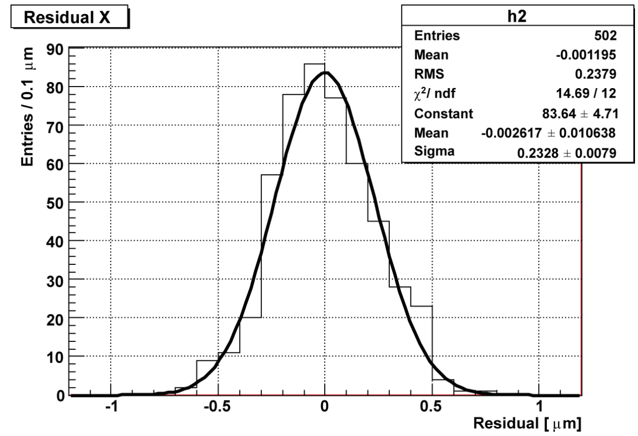

Figure 6: Residual distribution of the position resolution measurement. The histogram was fitted by a Gaussian.

Table 2: Position Resolution of the RF-BPM

	Horizontal	Vertical
Position resolution	0.198 μm	0.171 μm

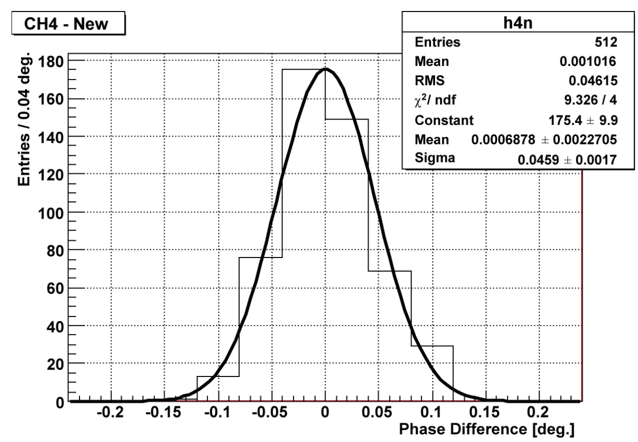

Figure 7: Phase difference between the TM010 cavities of the BPM 2 and 3. The histogram was fitted by a Gaussian.

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