BEAM POSITION MONITOR AT THE SCSS PROTOTYPE ACCELERATOR

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Abstract

This paper presents the design and the performance of the beam position monitor (BPM) in the prototype accelerator of the X-ray free electron laser (XFEL) project at SPring-8. An RF cavity-type BPM has been developed, since it has the capability to achieve the required position resolution, which is less than 1 μm. The TM110 mode of a beam-induced field is extracted and its amplitude and phase yield the beam position. Conversion coefficients were determined by beam-based calibration. The position resolution was also evaluated by a beam-based method. The preliminary result was obtained to be approximately 5 μm, or better. This result is sufficient for tuning the beam of the prototype accelerator to generate the vacuum ultraviolet (VUV) FEL, and a FEL amplification has been observed. However, XFEL requires better resolution. Therefore, we are planning to perform more precise measurements and to develop a new detection circuit.

INTRODUCTION

The XFEL project, SCSS (SPring-8 compact SASE[!] source) [1], is in progress, and the prototype accelerator [2] is in operation. One of the most important subjects to produce XFEL is that the electron beam must overlap with the radiated X-ray throughout the undulator section. The position difference between the beam and the X-rays is required to be less than 4 μm [3]. Therefore, the resolution of the BPM is necessary to be less than 1 μm. The cavity type RF-BPM has a capability to achieve the required performance, since past experiments, such as Ref. [4], showed resolutions of a few tens of nanometers. Another advantage is that the agreement between the electrical center and the mechanical center is fine, since the cylindrical shape of the RF-BPM enables a precise lathe process. We describe the design and the performance of the RF-BPM used at the prototype accelerator.

MEASUREMENT PRINCIPLE

Suppose that there is a cylindrical RF cavity in a beam line. When a short bunch of charged particles passes through the cavity, it excites electromagnetic oscillations resonating with the cavity. Since the electric field of a dipole mode, such as TM110, linearly varies with the transverse offset near the cavity axis, the amplitude of the beam-induced field strongly depends on the beam position. On the other hand, the electric field of a monopole mode, such as TM010, has axis symmetry at the cavity center. Accordingly, the amplitude is almost independent of the beam position, and is sensitive to only the beam charge. Thus, dipole modes are available for beam-position measurements. Since the TM110 dipole mode is the lowest order, we consider this mode hereafter.

The complex amplitude of the TM110 frequency is expressed as [5]

$$V_{RF} = A_1 qy + iA_2 qy' + iA_3 q + V_N \,. \tag{1}$$

Descriptions of each term are:

- $A_1 qy$: Beam position signal. The amplitude is proportional to the beam displacement, y, and the beam charge, q.
- $iA_2 qy'$: Beam angle signal, which is induced by the beam angle, y'. The phase is 90 degrees different from the first term, which is the reason why the imaginary unit i is multiplied.
- $iA_3 q$: Contamination from the tail components of the frequency distribution of monopole modes. Even if the eigenfrequency is different, the finite Q value causes a measurable effect on the TM110 frequency. The phase of this term is also 90 degrees apart from the first term.
- V_N: The other components, such as thermal noise.

Here, A_1, A_2 and A_3 are proportionality coefficients. Thus, we can obtain the beam position when we know the amplitude and the phase of the TM110 signal together with the beam charge. To measure the charge, it is effective to prepare another TM010 cavity whose resonant frequency is the same as that of the TM110 cavity. In this case, the TM010 cavity provides a phase reference of the TM110 signal in addition to charge information.

HARDWARE SETUP

The drawing of the RF-BPM installed in the prototype accelerator is shown in Figure 1. The RF-BPM consists of two cavities, a position-detection cavity (TM110) and a reference cavity (TM010). The resonant frequency is

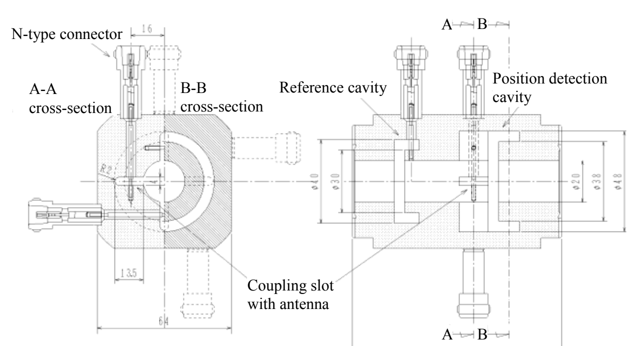

Figure 1: Drawing of the RF-BPM.

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! Self Amplification of Spontaneous Emission

4760 MHz for both cavities. Although the acceleration frequency is 5712 MHz, the BPM frequency is intentionally shifted so as to avoid any background from the dark current synchronized to the acceleration RF. The position-detection cavity has four coupling slots with antennas, two for x direction and the others for y direction. The slot is designed to couple with the TM110 mode selectively and to be insensitive to the TM010 mode. The loaded Q factor is approximately 100. The voltage of the signal into a 50 ohm cable is calculated to be 16 mV/nC/μm [1].

Figure 2 shows a photograph of the RF-BPM system. The RF-BPM cavity is mounted on the XY stage so that the BPM center can be adjusted to the radiated photon path. A removable iris is attached to the RF-BPM for precise alignment using a HeNe laser [1]. The RF-BPM system is installed on a stable support made of cordierite ceramics. These alignment components are designed to achieve a position accuracy of 4 μm.

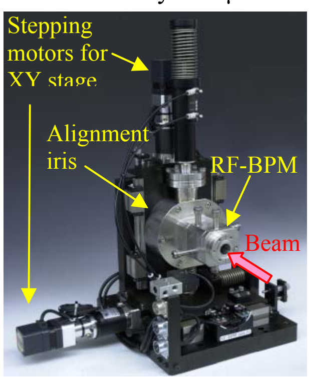

Figure 2: Photograph of the RF-BPM system.

The RF-BPM has three outputs: two from the position-detection cavity (X and Y) and the other from the reference cavity. The signal of each channel is processed by an electric circuit (Figure 3). The raw signal is mixed down to 476 MHz by a heterodyne method and fed into two sections. One is a log amplifier to obtain the logarithm characteristic of the amplitude, and the other is the phase detector after a 100 ns delay line. The amplitude and phase are finally merged with a solid-state switch and recorded with a VME waveform digitizer (ADC) [1,6]. The switch is turned to the log amplifier by default. When a sufficiently large RF amplitude is detected, the switch is flipped to the phase detector. Therefore, one digitizer channel can read out both the amplitude and the phase. By using a log amplifier, the dynamic range is extended to 80 dB and a small signal is magnified to maximize the position resolution around the BPM center.

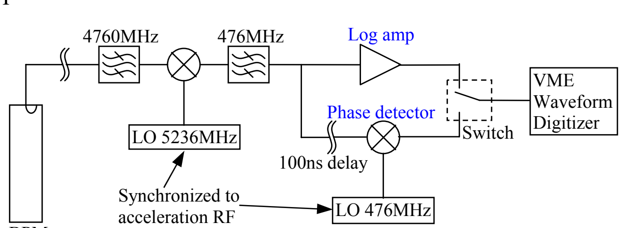

Figure 3: Detection circuit of the RF-BPM signal.

MEASUREMENTS

The amplitude and the phase of a BPM signal are obtained as two sampled voltages from ADC. The absolute value of the beam position is calculated by

$$|y| = \alpha \exp[\beta(V_y - V_q)] , \quad (2)$$

where V_y and V_q are amplitude data of the position-detection cavity and the reference cavity, respectively, and α and β are conversion coefficients. The exponential representation comes from logarithmic compression by the detection circuit. The beam charge is normalized by subtracting V_q from V_y. The sign of y is determined by the phase signal, since the phase is inverted by 180 degrees, depending on the sign, as shown later in Figure 4 (b).

Calibration

The conversion factors in Eq. 2 were determined by a beam-based calibration. During data taking, the beam was kept unchanged and the XY stage was moved. The calibration procedure was as follows:

1. Move the XY stage to the origin.
2. Adjust the beam trajectory to the BPM center by using corrector magnets. This is done by looking for the point that the BPM signal is minimized.
3. Move the XY stage by 0.1mm step, and take 100 events for each step.
4. Fit Eq. 2 to the amplitude data.

When the BPM calibration was carried out, the beam energy was 250 MeV and the beam charge was 0.2 nC. The calibration data are shown in Figure 4. The amplitude was properly fitted by Eq. 2. The phase data indicates that the phase flipped by 180 degrees at 0.0mm. Thus, the calibration was appropriately done.

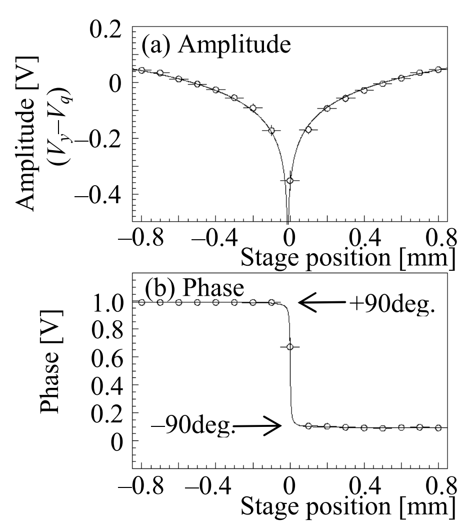

Figure 4: Fit results of the calibration data, (a) the amplitude data after beam charge correction and (b) the phase data.

Resolution measurement

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

We used four BPMs (called A, B, C and D) in the undulator section, as illustrated in Figure 5. The resolution of B (C) was evaluated from A–C (B–D). More than 1000 beam shots were acquired for several minutes. During data taking, electromagnets between BPMs were turned off and the gap of the undulator was fully opened to minimize the magnetic field. The beam energy, charge and profile width were 250 MeV, 0.2 nC and 0.3 mm RMS, respectively.

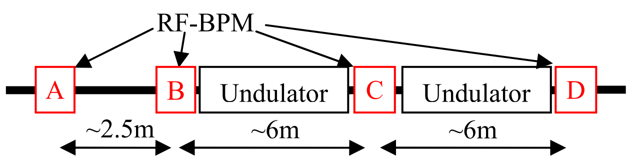

Figure 5: Arrangement of RF-BPMs in the undulator section of the prototype accelerator.

The residual distributions of BPM B are shown in Figure 6. The width of the residual distribution is proportional to the BPM resolution. Under the assumption that the resolutions of three relevant BPMs are the same, the position resolution can be calculated. If BPMs are arranged at even intervals, for example, the position resolution, σ_{BPM}, is

$$\sigma_{BPM} = \sqrt{2/3} \cdot \sigma_{res}, \quad (3)$$

where σ_{res} is the standard deviation of the residual distribution. Analysis results are summarized in Table 1. The resolution was approximately 5 µm, or better.

Discussion

As a result of beam tuning with RF-BPMs, VUV-FEL amplification in the wavelength region of 40–60nm was

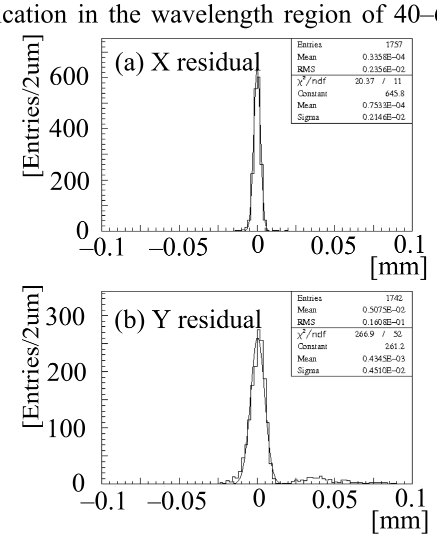

Figure 6: Residual distributions of BPM B for (a) the x-direction and (b) the y-direction.

Table 1: Results of the resolution measurement.

BPM	X resolution [µm]	Y resolution [µm]
B	1.7	3.6
C	5.2	4.9

observed [7]. Thus, the performance is sufficient for the prototype accelerator.

However, the measured resolution is not as good as the design value, which is the requirement of XFEL, less than 1 µm. Since there are undulators and other components between the BPMs, the beam trajectory is not exactly straight due to unignorable magnetic fields. This is thought to be the main reason for the deterioration.

SUMMARY AND FUTURE PLAN

To achieve a precise alignment of the beam trajectory required by XFEL, the RF-BPM was designed and installed in the prototype accelerator. Beam-based calibration was appropriately achieved. The preliminary position resolution was obtained to be approximately 5 µm, or better. This is sufficient for VUV-FEL amplification in the prototype accelerator. Since the data was taken over 1000 beam shots, we may conclude that beam line components in the undulator section were sufficiently stable during data taking, *i.e.* no vibration nor power supply jittering.

However, XFEL requires better resolution. Therefore, we are planning to prepare a BPM triplet to perform more precise resolution measurements. In addition, we are developing a new detection circuit. The present circuit is not effective to distinguish the beam position signal from contaminations of the beam angle and monopole modes, because the recorded amplitude is the sum of these signals. Therefore, an IQ demodulator is used for the new circuit, since it separates the position signal (in-phase) from contaminations (quadrature), by definition.

ACKNOWLEDGEMENTS

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