DEVELOPMENT AND PERFORMANCE TEST OF THE BPM SYSTEM FOR THE SPring-8 UPGRADE

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Abstract

For the low-emittance upgrade of SPring-8, a new BPM system is under development. Principal requirements for the BPM are long-term stability of the electric center within 5 µm to maintain the photon beam axis of each beamline, high single-pass resolution of 100 µm rms for a 100 pC single-bunch and accurate electric center of 100 µm rms with respect to the magnetic center of an adjacent magnet for first-turn commissioning. We designed a molybdenum button electrode and a stainless steel BPM head so as to satisfy the requirements and produced these prototypes with sufficient electric and mechanical accuracy. Beam test of a prototype BPM was carried out in order to confirm the design performance. Sufficient signal intensity for a single-pass measurement was obtained and long-term stability was evaluated to be 1 µm for three months. Thus, the new BPM system satisfies our requirements.

INTRODUCTION

Hardware developments are in progress for a low-emittance upgrade of the SPring-8 storage ring (SPring-8-II) [1]. The natural emittance after the upgrade will be approximately 140 pm rad with 5-bend achromat lattice, which will further be reduced to about 100 pm rad by radiation damping in insertion devices. The horizontal source size and the angular divergence of undulator radiation are approximately 20 µm and 5 µrad, respectively, which are significantly smaller than the present storage ring. Therefore, the pointing stability of the photon beam is quite important. In order to maintain the photon beam axis within its divergence, the electron beam position should be stabilized within 5 µm. Thus, highly stable electron beam position monitor (BPM) for a closed-orbit distortion (COD) measurement is mandatory.

Since the new lattice after the upgrade reduces the dynamic aperture, a high-resolution single-pass (SP) BPM is required for beam commissioning to achieve the first beam storage. The electric center of each BPM head should be aligned within 100 µm from the magnetic center of adjacent quadrupoles and the position resolution should be better than 100 µm rms for an injected single-bunch with a charge of 100 pC. Consequently, the BPM is demanded to have both high electric sensitivity and high mechanical precision (10 µm level).

In this article, we describe the design concepts and prototype development of the BPM system for SPring-8-II and report results of a beam test in the present storage ring.

DESIGN CONCEPTS AND PROTOTYPE DEVELOPMENT

We first briefly summarize the design concepts of the BPM system for SPring-8-II and describe the prototype development. Details of the design concepts of the BPM system have been reported in Ref. [2-4].

BPM Electrode

The BPM button electrode consists of a molybdenum electrode, a ceramics insulator and a stainless steel sleeve, as illustrated in Fig. 1. Main reasons for choosing molybdenum as the button material are non-magnetic material not to affect the magnetic field of adjacent magnets, high conductivity (small ohmic loss) to reduce trapped-mode heating and similar thermal expansion coefficient with insulator ceramics for brazing between the electrode and the ceramics.

We produced two types of prototype electrodes (Fig. 1). The first one has a copper washer on the brazing part between the molybdenum electrode and ceramics insulator in order to avoid any imperfections. However, copper is a corrosive material, which could cause a degradation of the electric performance. Therefore, we produced second prototype in which the molybdenum electrode was directly brazed with ceramics. Both types were successfully manufactured and no vacuum leak was detected around the brazing part. The machining accuracy was confirmed to be 10 µm level, which was sufficient for our requirement. A heat cycle test between the room temperature and the baking temperature of 150 °C and a destructive tension test were performed and enough mechanical toughness was confirmed.

BPM Head

Figure 2 shows a schematic drawing of the BPM head. The cross section of the beam duct has an octagon shape with 20 mm-wide flattops and with a side room to extract synchrotron radiation. Four button electrodes are placed on the flattops. A water-cooling channel is formed beside the electrodes to reduce temperature rise.

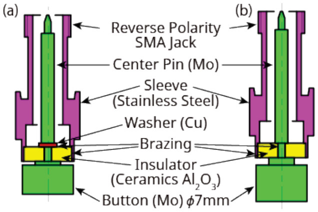

Figure 1: Schematic drawings of the cross-sections of the first prototype electrode (a) and the second one (b).

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The geometry of the BPM head is determined so that the sufficient signal intensity for the SP measurement is obtained and that the position sensitivities for both horizontal and vertical directions are optimized. The diameters of the button electrode and its hole are 7 mm and 8 mm, respectively, and hence the button gap is 0.5 mm. The horizontal and vertical span of the electrodes are 12 mm and 16 mm, respectively. The horizontal (vertical) position sensitivity, k_x (k_y), are calculated to be 6.8 mm (7.7 mm), where the beam position is obtained from the formula,

$$(X,Y) = \left(k_x \frac{V_1 - V_2 - V_3 + V_4}{V_1 + V_2 + V_3 + V_4}, \ k_y \frac{V_1 + V_2 - V_3 - V_4}{V_1 + V_2 + V_3 + V_4}\right).$$

Here, V_1, V_2, V_3, V_4 are the signal intensities of top-right, top-left, bottom-left, bottom-right electrodes, respectively.

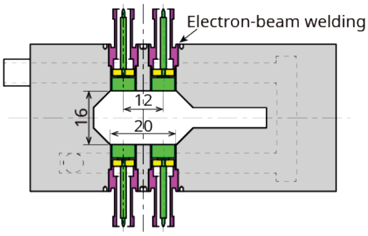

Figure 2: Cross-section of the BPM head.

Several prototypes of BPM heads were manufactured for laboratory tests. For each prototype, all components were precisely machined and the dimension errors were checked to be 10 µm level. The sleeve of button electrode was bonded to a BPM head by electron-beam welding (EBW), since the heat input of EBW is lower and more controllable than TIG welding. The displacement of the electrode due to the shrinkage in the EBW process was studied and the position of the button surface was controlled within 50 µm peak-to-peak tolerance. The error on the electric center was estimated by a three-dimensional rf simulator based on the mechanical tolerance. The simulation showed that the electric center stayed within ±80 µm from the mechanical center, which satisfied the requirement of the electric center position (±100 µm). We are trying to measure the electric center by using an antenna to confirm the simulation.

Electric characteristics of the BPM head was also analyzed in a laboratory, such as time-domain reflectometry (TDR). Figure 3 shows the TDR waveforms of first and second prototypes of button electrodes. The TDR data of the first prototype has a ringing due to a copper washer, which also appears in an rf simulation. This ringing indicates a resonant mode around the electrode, which may cause a trapped-mode heating. The second prototype does not show any suspicious behavior. Thus, the second prototype is better for the new BPM system.

Signal Cables

Signal cables for the BPM system are required to have sufficient rf performances, such as low loss and small reflection, and to be stable under the high radiation environment. The rf performance can be easily satisfied by a commercial coaxial cable. However, the radiation hardness is not guaranteed in general. In fact, drifts of the transmission coefficient of a damaged signal cable were observed in the present SPring-8 BPM system [5]. Therefore, we plan to evaluate several kinds of coaxial cables with radiation-hard insulators, such as SiO2 and PEEK (PolyEther-Ether-Ketone) in the beam test in the present SPring-8 ring. In addition, radiation shielding of the cables is considered so as to reduce the radiation dose.

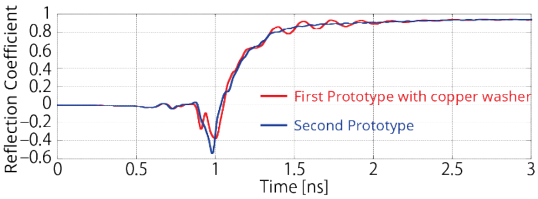

Figure 3: TDR waveforms of first (red) and second (blue) prototypes of button electrodes.

Readout Electronics

We have two candidates for the BPM readout electronics, our original design and the new generation of Libera Brilliance+ [6]. The original design is based on the digital low-level rf (LLRF) system [7], which has also been developed for the SPring-8 upgrade. The LLRF system uses a high-speed digitizer module compliant with the MicroTCA.4 standard [8] to detect rf signals. The same digitizer is utilized to detect BPM signals and an rf frontend is under development. For the new generation of Libera Brilliance+, we started the discussion about required performances and functions. Some units of present Libera Brilliance+ are also evaluated in parallel in the beam test described below.

BEAM TEST IN THE SPring-8 RING

We installed a prototype BPM system in the present SPring-8 storage ring to confirm the design performance for SPring-8-II by beam test. The beam test in the present SPring-8 ring has been conducted in two stages. The first stage was from September to December 2016 and first prototype electrodes (Fig. 1a) were used. The second stage started in April 2017 and second prototype electrodes (Fig. 1b) were tested. Since the second stage has just started, the results from the first stage are shown here.

The BPM head for the beam test has horizontal aperture of 90 mm to fit the beam duct of the present SPring-8 storage ring, while the vertical aperture is the same as the design value (16 mm) of SPring-8-II, as illustrated in Fig. 4. Some holes for thermometers are also made around the electrodes in order to monitor the temperature rise. The BPM head for the first stage was equipped with two BPM sets (4 electrodes for each set), as shown in Fig. 5. Since more than one BPM sets are placed close to each other, the position resolution can be measured by comparing these BPM data. The readout electronics included in the first stage is Libera Brilliance+. A prototype of the original electronics will be set up until the summer shutdown in 2017.

A signal waveform for a single-bunch electron beam is shown in Fig. 6a. A typical bipolar impulse was obtained. Although a small ringing is seen after the impulse, the signal disappears at the next bunch timing (~2 ns later). The amplitude of this waveform was confirmed to be sufficient

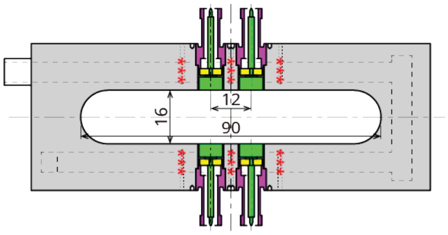

Figure 4: Schematic drawing of the cross-section of the prototype BPM head for a beam test. The temperature sensor position is shown by red "***".

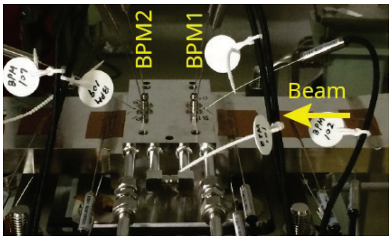

Figure 5: Photograph of the BPM head for the beam test.

for the SP measurement (100 µm rms resolution). The signal intensity for a stored beam (100 mA) was also measured to be –12.6 dBm at the accelerator frequency of 508.6 MHz. This intensity is consistent with the three-dimensional rf simulation (–12.5 dBm).

The COD position resolution was estimated from the correlation between two BPM sets, as shown in Fig. 6b. The difference between the vertical positions of two BPM sets was 12 nm rms. Since this difference is the square root of the square sum of two BPM resolutions, the COD-BPM resolution is approximately 10 nm rms.

The stability of the BPM data was evaluated from the balance error, which was defined as the maximum difference among four position data calculated from four combinations of three-electrode sets [5]. Figure 7 shows the trend graph of the balance error for three months. Most of the data points were within 1 µm peak-to-peak, which was sufficient for our requirement. Outliers in the plot mainly came from abnormal orbit change (~1 mm) together with the error on the conversion coefficient (~0.1%) from the signal intensity to the beam position.

The temperature around the button electrode (Fig. 4) was also monitored throughout the beam test. The temperature rise from no beam condition to a usual 100 mA operation was 0.1–0.5 °C depending on the sensor position and the filling pattern. The temperature rise was also estimated by using a three dimensional temperature simulation software, where the heat input was computed by an rf simulation. The estimated value was 0.1–0.6 °C, which was consistent with the measurement. The temperature simulation showed the maximum temperature of the electrode was approximately 35 °C, which was sufficiently low temperature not to affect thermal deformation etc.

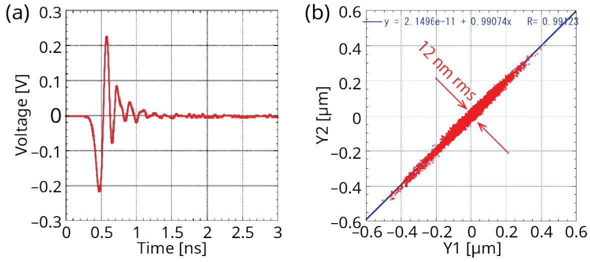

Figure 6: BPM signal waveform for a single-bunch electron beam (a) and correlation between the vertical positions of two BPM sets (b).

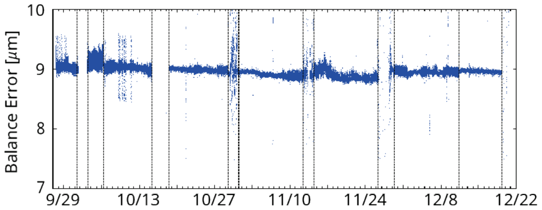

Figure 7: Trend graph of the BPM balance error for three months. Vertical lines indicate changes of filling patterns.

CONCLUSIONS

We have designed a stable and precise BPM system for SPring-8-II. Prototypes of button electrodes were successfully produced and BPM heads were manufactured with sufficient mechanical and electric performance. The displacement of the electric center from the mechanical center was estimated to be within ±80 µm. A BPM head for beam test was installed in the present SPring-8 storage ring and enough signal intensity was observed. The COD-BPM resolution was approximately 10 nm and the long-term stability was within 1 µm for three months. Although there are some ongoing measurements, the obtained results so far are sufficient for our requirements.

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