DEVELOPMENT STATUS OF A STABLE BPM SYSTEM FOR THE SPring-8 UPGRADE

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Abstract

We are developing a stable and precise BPM system for the low-emittance upgrade of SPring-8. Key requirements for the BPM system are: 1) long-term stability of the radiated photon beam direction well within the intrinsic photon divergence, 2) single-pass resolution better than 100 µm for a 100 pC single-bunch for first-turn steering in the beam commissioning, and 3) BPM center accuracy better than 100 µm rms with respect to an adjacent quadrupole to achieve the design performance of the upgraded storage ring. Based on these requirements, a button-type BPM head and a readout electronics are being developed. Some prototypes of the BPM head were manufactured and the machining accuracy was confirmed to be sufficient. For the readout electronics, a MTCA.4-based system and an upgrade of a commercial BPM electronics are under study. Since radiation damage to the signal cable of the present BPM system was found to be a cause of humidity-dependent drift of BPM offset, measures against the radiation damage are considered for the new BPM cable. The preparation of a beam test of the new BPM system is in progress to confirm the overall performance.

INTRODUCTION

A low-emittance upgrade of SPring-8 was recently proposed in order to provide much more brilliant x-rays to experimental users [1]. The natural emittance of an electron beam after the upgrade is estimated to be 140 pm rad without any radiation damping by insertion devices (IDs), while the emittance of the present SPring-8 storage ring is 2.4 nm rad. The emittance can be further reduced to 100 pm rad by operating IDs thanks to radiation damping. This low emittance value is realized by using 5-bend achromat lattice and by reducing the beam energy from 8 GeV to 6 GeV. As a result, the brilliance of x-ray radiation is expected to be more than one orders of magnitude higher than the present SPring-8.

Since the horizontal beam size becomes smaller, the stability of the beam position should also be improved. The beam size at the center of an ID is approximately $25 \times 5\ \mu m^2$ rms. Therefore, the beam position stability is required to be 1 µm level. Although the vertical beam size is comparable to the present SPring-8, the present BPM system has some drift problems of more than 10 µm [2]. Thus, we plan to replace the present BPM system with new one, which goes for the stability of 1 µm level.

Since the upgraded SPring-8 can provide brilliant x-rays with a small source size, small divergence and a high coherent flux, the stability of the photon beam axis is the most important. The upgraded SPring-8, for example, enables a direct nano-focusing scheme wherein primary x-ray radiation from an undulator can be directly focused to a nanometer spot without any secondary virtual sources by using downstream apertures [3]. In this beamline, the stability of the photon beam axis is critical and it should be well within the intrinsic photon divergence. The required stabilities are sub-µm and sub-µrad for the photon beam position and direction, respectively. Consequently, a stable electron BPM and a photon BPM are necessary [4].

In addition to the stability issue, the BPM system is indispensable to the beam commissioning of the upgraded SPring-8. For the first-turn beam steering, single-pass BPM measurements with high accuracy and high resolution (100 µm rms) are demanded, since the dynamic aperture becomes significantly narrower (< 10 mm) than the present storage ring [1]. After the success of beam storage, the beam orbit is adjusted to the center of each multi-pole magnets in order to achieve the design performance of the upgraded SPring-8. Thus, a BPM system with high single-pass resolution (100 µm rms) and high position accuracy (10 µm rms) is necessary.

In this article, we describe an outline of the BPM system for the SPring-8 upgrade, such as the development status of a BPM head and a readout electronics, and the improvement of the BPM stability. The design of the BPM head is detailed in Ref. [5].

BPM SYSTEM FOR THE SPring-8 UPGRADE

BPM System Overview

The SPring-8 storage ring consists of 48 unit cells and each cell is equipped with 7 BPMs after the upgrade. In total, 336 BPMs will be utilized for the machine operation. The BPM electrode was selected to be a button type [5]. The readout electronics for each BPM is designed to have measurement functions of both closed-orbit distortions (COD) and single-pass (SP) trajectories with sufficient precision and accuracy.

Required Performance

As mentioned in the introduction, the BPM system for the SPring-8 upgrade should have sufficient stability, high-resolution and high-accuracy. Main specifications of the BPM system are summarized in Table 1.

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Table 1: Main Specifications of the BPM System

COD measurement resolution	0.1 µm rms (100 mA, 1 kHz bandwidth)
COD measurement stability	5 µm maximum (1 month)
COD measurement accuracy after beam-based alignment	10 µm rms
SP measurement resolution	100 µm rms (100 pC single-bunch)
SP measurement accuracy with respect to an adjacent Q-magnet	100 µm rms (±200 µm maximum)

The most stringent requirement for a COD measurement is sub-µm position stability and resolution coming from a direct nano-focusing beamline. Therefore, the resolution is set to 0.1 µm rms at 1 kHz bandwidth. Although the stability of 5 µm maximum is not sufficient for a direct nano-focusing beamline, it is still challenging and is enough for most of the conventional beamlines. Nevertheless, we plan to pursue the improvement of the photon beam stability by developing a photon BPM.

The displacement of the electron beam from the field center of a multipole magnet should be 10 µm level to achieve the design performance [1]. This requirement comes from the alignment tolerance of multipole magnets (a few 10 µm). Therefore, the offset of the BPM center from an adjacent quadrupole magnet should be measured by a beam-based alignment (BBA) with 10 µm accuracy.

In the early stage of the beam commissioning, a SP trajectory measurement is necessary to guide an injected electron beam throughout the storage ring. The SP resolution is required to be less than 100 µm rms for an injected single bunch of 100 pC charge [1]. Furthermore, the displacement of a BPM electric center with the field center of an adjacent quadrupole magnet is demanded to be within 100 µm rms and ±200 µm maximum [1], in order to reduce any unwanted kick from multipole magnets.

BPM Head

Figure 1 shows a schematic drawing of the BPM head and the button electrode. The beam duct has 20 mm-wide flat-tops and the vertical aperture is 16 mm. Two button electrodes are attached on each flat-top with a horizontal span of 12 mm. The button diameter is 7 mm, which is large enough to obtain required signal intensity for the SP resolution [5]. In order to reduce the error on the electric center position, the machining accuracy is set to a few 10 µm for both the electrode and its lodging hole in the BPM head. The displacement error on the electric center with respect to the reference plane is estimated to be less than 50 µm.

The material of the button electrode and the central pin was selected to be molybdenum, since the material should be non-magnetic to avoid any field interference with adjacent magnets and highly conductive to minimize trapped-mode heating by ohmic losses. The beam duct is made of stainless steel, which is the same material with the other vacuum chambers. The heat input from the 100 mA stored beam was estimated to be 1.1 W maximum [5], which is small enough to suppress the mechanical distortion within a few µm. The BPM connector was selected to be a reverse-polarity SMA jack, because the spring strength of the inner socket of a normal female SMA connector might be lost after a thermal process for brazing the ceramic and the metals of the button electrode.

The BPM head is supported from the same girder as magnets and vacuum chambers. In this case, the relative position between the BPM head and an adjacent quadrupole magnet is not changed after a realignment of the girder. The displacement between the reference planes of a BPM head and a quadrupole magnet is measured by a laser tracker survey within 50 µm rms accuracy. The total error on the BPM electric center position is approximately 70 µm rms by taking a quadratic sum of the machining error and the survey error. There remains a margin in the BPM alignment error and it is reserved for the calibration error of the readout electronics etc.

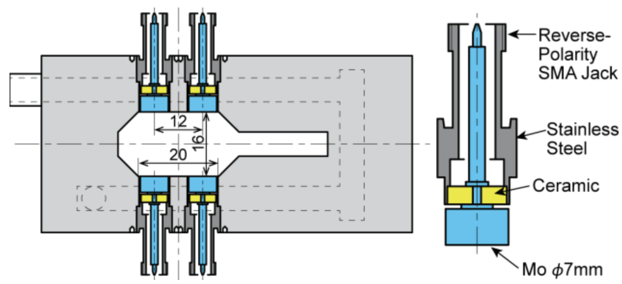

Figure 1: Schematic drawings of the cross-sections of the BPM head (left) and the button electrode (right).

BPM Electronics

We are considering two candidates for the BPM electronics, our original design and the new generation of Libera Brilliance+ [6]. They are developed in parallel and the final decision will be made before the mass-production.

The original design is based on the new digital low-level RF (LLRF) system [7], which utilizes the MTCA.4 standard [8]. A schematic diagram of the BPM electronics is illustrated in Fig. 2. Single-ended signals from 2 BPMs (8 channels in total) are fed into a rear transition module (RTM). The signals are conditioned by band-pass filters, step attenuators and amplifiers, and converted to balanced differential signals. These signals are transferred to an advanced mezzanine card (AMC) and recorded by fast analog-to-digital converters. Since a direct under sampling scheme (~300 MSPS) of a 508 MHz acceleration signal is chosen for the RF detection method of the LLRF system, the same scheme is used for the BPM system. The noise figure of the electronics was estimated to be approximately 14 dB including the power loss of the signal cable (~2 dB). We are considering to use calibration tone, having a slightly shifted frequency from a BPM signal, for the gain calibration of the electronics.

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For Libera Brilliance+, the specification of the position resolution for both SP and COD looks sufficient for our requirement. Therefore, we are considering further improvements of measurement stability. Since the control system of the SPring-8 is MADOCA [9], the control software should be modified to support the MADOCA system.

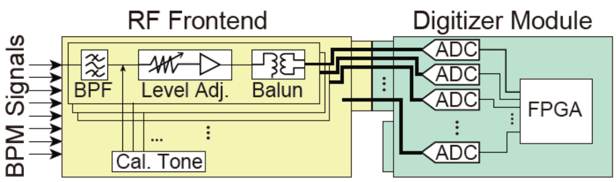

Figure 2: Schematic diagram of the MTCA.4-based BPM electronics. The left half is the RF front end RTM and the right is the digitizer AMC.

DEVELOPMENT STATUS OF THE BPM SYSTEM

BPM Electrode

The design of the BPM electrode has been almost completed [5] and we produced prototype electrodes (Fig. 3). All the total of 24 electrodes manufactured passed a heat cycle test from the room temperature to the baking temperature of 150 ˚C without any vacuum leaks. RF properties and electrical insulation were confirmed to be sufficient. The machining accuracy was also evaluated to be 10 μm level for a precise part and the mechanical strength was checked by a destruction test. Although this first prototype was successfully produced, a copper washer is used at the brazing part. Since copper might be corroded by active gasses generated by radiation, we are trying to produce second prototype without any corrodible metals.

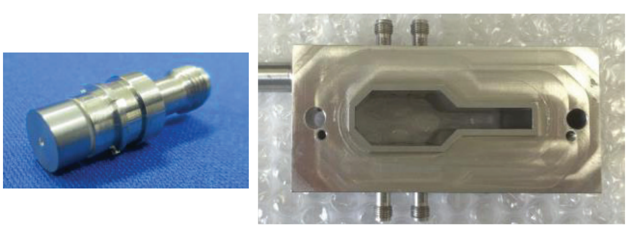

Figure 3: Photographs of a prototype BPM electrode (left) and a prototype BPM block (right).

BPM Block

A prototype of the BPM block was also produced by using prototype electrodes, as shown in Fig. 3 (right). The beam duct was made from stainless steel block bored by wire electric discharging. Since the stainless steel vacuum chamber connected to the BPM has 100 μm-thick copper plating in order to reduce resistive wall impedance, we tried a copper coat of the BPM block. However, it was difficult to manage the accuracy of the inner dimensions of the beam duct with 10 μm level. Since the resistive wall impedance of the BPM block is sufficiently small thanks to its compactness, we chose not to plate copper in the BPM block.

The electrodes were attached to the block by electron beam welding. After the welding, the inner surface of the electrode was slightly pulled out by several 10 μm due to the shrinkage of the welded part. Therefore, the height of the electrode was adjusted at the machining stage by taking the shrinkage into account. As a result, the height of the button surface was controlled within 50 μm.

BPM Electronics

For the BPM electronics based on MTCA.4, we are developing a common AMC digitizer with the digital LLRF system [7], which has 10 AD converters with a 300 MSPS sampling rate and a 16-bit resolution. A general purpose SoC (System-on-Chip) FPGA AMC for fast orbit feedback control is also developed. The digitizer and FPGA AMCs will be delivered in March 2017. The RF frontend RTM is under design and it will be produced in 2017. The other modules such as a CPU module and a MCH (MicroTCA Carrier Hub), are already available.

For Libera, we have been evaluating the performance of the current version of Libera Brilliance+ and we started discussions on the expected improvement of the new generation. An existing BPM head of the present SPring-8 was read out by a Libera Brilliance+ in order to evaluate the position resolution. Although the sensitivity of the present BPM head is different from the new BPM, the result can be scaled to the upgraded SPring-8 by a calculated sensitivity. The SP resolution was obtained to be 50 μm rms for a 100 pC bunch in case of the upgraded SPring-8. This result corresponds to the noise figure of 14 dB including the cable loss, which is comparable to that of the MTCA.4-based design. The COD resolution was less than 0.1 μm rms for 10 kHz throughput data. Thus, both SP and COD resolutions were confirmed to be sufficient.

Signal Cable

Investigations of the drift problem in the present BPM system revealed that one of the most significant causes was radiation damage to signal cables, which gave rise to a humidity-dependent drift [2], as shown in the upper half of Fig. 4. In this figure, we define balance error to evaluate a BPM drift. The beam position can be calculated from 3 electrodes out of 4, and 4 beam position values are obtained from 4 combinations of 3 electrodes. The balance error is defined as the maximum difference among the 4 values.

Chemical analyses of damaged cables revealed that the radiation-damaged insulator of the coaxial cable tends to absorb vapor in the air and the characteristic impedance of the cable becomes sensitive to ambient humidity. Therefore, we replaced the damaged cables and the humidity-dependent drift disappeared, as shown in the lower half of Fig. 4. Thus, we are surveying radiation-resistant coaxial cables and considering radiation shields for the new BPM system.

Beam-based Alignment

In order to precisely obtain the offset of the BPM electric center from the field center of an adjacent quadrupole mag-

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net, we are testing a beam-based alignment (BBA) technique.

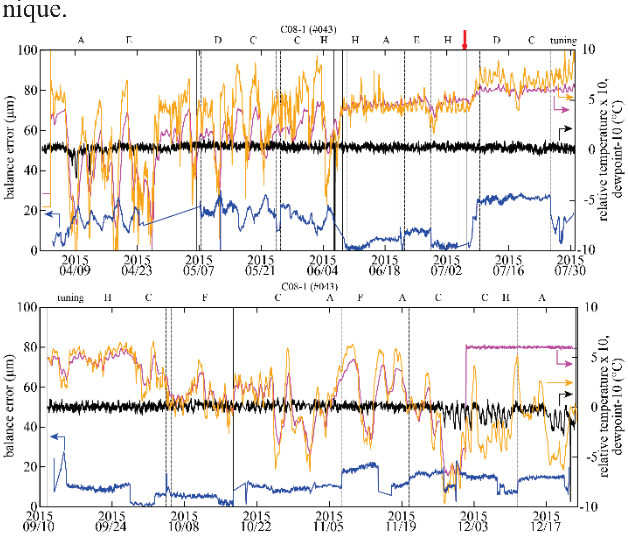

Figure 4: Trend graphs of the balance error of a current BPM (blue lines). The upper figure shows the data before the cable replacement and the lower one is those with new cables. The dew point of the accelerator tunnel (electronics area) is plotted by a magenta (orange) lines. The relative electronics temperature (x10) is shown by black lines.

Figure 5 shows results from a BBA test experiment. The beam position was shifted by generating a local bump orbit and the field strength of an adjacent quadrupole magnet was changed by 1%. Each plot shows a variance of beam position differences for all the BPMs as a function of the height of the bump orbit. The parabolic function was fitted to each data set (solid line). The bottom of the fitted function is the quadrupole magnet center. The reproducibility of the result was 10 μm rms. In the next step, we will confirm the measurement accuracy and optimize the measurement procedure for quick machine tuning.

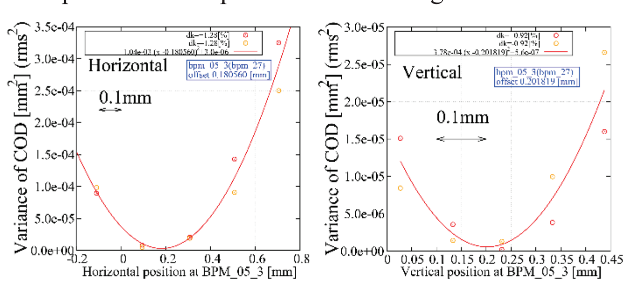

Figure 5: Beam-based alignment data from one of the BPMs. Left and right plots show horizontal and vertical directions, respectively.

Beam Test

We are preparing a beam test setup of the new BPM system in the present SPring-8 and start data taking in this fall. A BPM head with prototype electrodes for the beam test was produced and installed in this summer shutdown. Cables and readout electronics for the upgraded SPring-8 are also evaluated in this test. We will confirm the basic performance of the BPM head, such as signal intensity, waveform and temperature rise, and estimate the long-term stability of the whole BPM system.

SUMMARY

For the low-emittance upgrade of SPring-8, a stable and precise BPM system is necessary. Requirements for the BPM are 5 μm long-term stability and 0.1 μm resolution for COD and high single-pass resolution and accuracy of 100 μm rms. We designed a precise BPM electrode and block to reduce the error on the electric center of the BPM head within 50 μm. Some prototypes of the BPM head were produced and the machining accuracy was confirmed to be sufficient. For the readout electronics, the development of a MTCA.4-based system and the evaluation of Libera Brilliance+ are in progress. Since radiation damage to signal cables was found to be a cause of a humidity-dependent drift, a radiation-hard cable and a radiation shield are under study. A beam-based alignment technique has been tested for the precise orbit tuning with 10 μm rms accuracy with respect to the field center of a quadrupole magnet. We continue the development and perform some beam experiments to complete the BPM system for the SPring-8 upgrade.

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