DEVELOPMENT OF BEAM DIAGNOSTIC SYSTEM FOR THE SPring-8 UPGRADE

H. Maesaka†, T. Ohshima, Y. Otake, RIKEN SPring-8 Center, Sayo, Hyogo, 679-5148, Japan
H. Dewa, T. Fujita, M. Masaki, K. Kobayashi, S. Matsubara, T. Nakamura, S. Sasaki, S. Takano, Japan Synchrotron Radiation Research Institute, Sayo, Hyogo, 679-5198, Japan

Abstract

For the upgrade of SPring-8, the design and development of the beam diagnostic system are in progress. The pointing stability of the photon beam is essentially important. The demands for the position and angular stabilities of the source electron beam are less than 0.5 μm and 0.2 μrad, respectively. To fulfill the stringent demands, both an electron beam position monitor (BPM) and an x-ray photon beam position monitor (XBPM) with sufficient accuracies, resolutions and stabilities are necessary. We are developing a high-resolution button-type BPM system having enough long-term stability. For stable user operation, precision diagnostics of beam current, beam size, etc. and control of collective beam instabilities are also crucial. The diagnostic instruments other than the BPM and the XBPM have been already implemented at the present SPring-8 storage ring with sufficient performances for the upgraded ring.

INTRODUCTION

For the upgrade of SPring-8, a new fourth-generation ring-based x-ray source is now under design and development [1, 2]. The natural emittance is approximately 140 pm rad by using 5-bend achromat lattice without extra radiation damping, and the emittance for user experiments can be further reduced to 100 pm rad by operating insertion devices (IDs). The x-ray brilliance of the upgraded SPring-8 is enhanced by a factor of 20 for the photon energy below 60 keV [1]. In order to fully utilize the brilliant x-ray radiation, cutting-edge beam diagnostic instruments are demanded for stable operation of the upgraded ring [3].

The enhanced brilliance and coherent fraction of the upgraded SPring-8 enables several kinds of breakthroughs on beamline x-ray optical systems, such as a direct nano-focusing scheme, in which primary x-ray radiation is directly focused to a nanometer-size spot without any secondary virtual sources by means of downstream apertures [4]. One of the most stringent requirements from direct nano-focusing is the photon beam axis stability: sub-μm for the source beam position and sub-μrad for the beam direction. Therefore, the developments of an electron beam position monitor (BPM) and an x-ray photon beam position monitor (XBPM) with sufficient stabilities are critical for the success of the SPring-8 upgrade.

Other high-performance beam diagnostic instruments are also necessary for beam commissioning and stable operation. Since the storage ring after the upgrade has a significantly narrow dynamic aperture (< 10 mm) [2], for first-turn beam steering in the commissioning phase, single-pass measurements of beam trajectories with high accuracy and high resolution are required for the BPM system. A high-resolution beam profile monitor is necessary for ultra-low emittance diagnostics. A bunch-by-bunch feedback (BBF) system is also indispensable for suppressing beam instabilities due to enhanced coupling impedance of narrow vacuum chambers for the upgraded ring.

In this article, we describe the outline of the beam diagnostic system for the SPring-8 upgrade and the design and development status of the BPM system.

BEAM DIAGNOSTIC SYSTEM FOR THE SPring-8 UPGRADE

The beam diagnostic instruments for the SPring-8 upgrade are listed in Table 1. In each of the 48 unit cells of the upgraded ring, 7 button-type BPMs are placed. In total, 336 BPMs will be installed and utilized for machine operation. Each BPM can measure both closed-orbit distortions (COD) and single-pass (SP) trajectories. An XBPM is provided for each beamline to monitor the photon beam axis. DCCTs, a pinhole camera and a BBF system are also prepared for beam current measurements, beam profile monitoring and control of beam instabilities, respectively.

Main specifications of the BPM system are given in Table 2. The direct nano-focusing requires the source beam position and angular stabilities of 0.5 μm and 0.2 μrad or less, respectively [4]. While the COD BPM resolution of 0.1 μm is enough for the requirement, the drift issues [5] of 5 μm maximum are yet to be solved. Therefore, we consider that the photon beam axis should be stabilized by the combination of the BPM and the XBPM. The offset of the BPM electric center from the magnetic center of an adjacent quadrupole magnet should be corrected with accuracy better than 10 μm in order to achieve the designed beam performance of the upgraded SPring-8 [2]. The COD resolution can be achieved by a button-type BPM head with recent electronics technologies. Therefore, one of the most important R&D issues is to eliminate the BPM drifts.

For beam commissioning of the upgraded ring, a SP trajectory measurement is necessary, at first, to guide an injected electron beam through the whole ring. The resolution is demanded to be less than 100 μm rms for an injected

Table 1: Beam Diagnostic Instruments for the SPring-8 Upgrade

Instrument	Number of units
Button BPM	336 (7 for each unit cell)
XBPM	1 for each beamline
DCCT	2
Pinhole camera	1
Bunch-by-bunch feedback	1

† maesaka@spring8.or.jp

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Table 2: Main Specifications of the BPM System

COD measurement resolution	0.1 μm rms (100mA, 1 kHz)
COD measurement accuracy after beam-based alignment	10 μm rms
COD measurement drift	5 μm maximum (1 month)
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)

single bunch of 100 pC charge. The allowable alignment error between a BPM electrical center and a magnetic center of an adjacent quadrupole magnet is to be within 100 μm rms and ±200 μm maximum.

In addition to the button BPM, an XBPM is also utilized for diagnostics of the photon beam axis of each ID beamline within 0.2 μrad. Since a conventional blade-type XBPM [6] does not detect the core of undulator radiation but only the peripheral tail part, its position readouts depend on the magnet gap of the undulator and the background radiation from bending magnets. The blade-type XBPM is not fit to use for the upgraded SPring-8. Further investigations are necessary to develop a stable next-generation XBPM that detects the central core of intense undulator radiation.

For beam emittance diagnostics, we use a synchrotron-radiation-based beam size monitor. A spatial resolution of 5 μm is required to measure the emittance around 100 pm rad. An x-ray pinhole camera [7] has a capability to meet the requirement and is one of the strong candidates for this purpose because of its simple and robust setup.

Collective beam instabilities should also be controlled, since resistive-wall and geometrical impedances are enhanced by the narrower vacuum chambers and smaller magnet gaps of IDs of the upgraded ring. The growth rate of the transverse coupled-bunch instability is evaluated to be 4 times larger than present and the instability threshold of the total current is approximately 10 mA. Therefore, a BBF system [8] is indispensable for the user operation with the 100 mA stored beam current.

The beam diagnostic instruments other than the BPM and XBPM systems are already implemented for the current SPring-8 storage ring and the performances are sufficient for the upgraded ring with minor modifications.

DESIGN AND DEVELOPMENT STATUS OF THE BPM SYSTEM

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 set to 7 mm so as to achieve enough signal intensity for the required SP resolution. The button gap is 0.5 mm, which is the same as the present BPM system of SPring-8.

The signal power from a button electrode was computed by three-dimensional electro-magnetic simulations using CST STUDIO SUITE [9] and the power spectrum is plotted in Fig. 2. The signal power of a 100 pC single-bunch is calculated to be –53 dBm at the acceleration frequency of 509 MHz with 10 MHz bandwidth, which satisfies the required power of –57 dBm. The horizontal (vertical) sensitivity factor, k_x (k_y), is evaluated to be 6.77 mm (7.72 mm), when the beam position is defined by

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

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

The material of the button electrode and the central pin was selected to be molybdenum. Main reasons for this decision are as follows: 1) a non-magnetic material to avoid cross-talk with quadrupole and sextupole magnetic fields, 2) thermal expansion close to alumina ceramics of the insulator of the vacuum feed-through, and 3) high conductivity for minimizing trapped mode heating by ohmic losses. The heat dissipation due to a wall current and trapped modes in the button electrode was computed by electromagnetic simulations, as shown in Fig. 3. The calculated heat input to the BPM head was a few watts maximum for the total stored current of 100 mA, if we took the bunch lengthening into account (> 14 ps for 1 mA/bunch, > 10 ps for 0.5 mA/bunch and > 7 ps for 0.04 mA/bunch). The heat input is not small enough for natural air cooling but manageable by cooling water channels in the BPM head. For

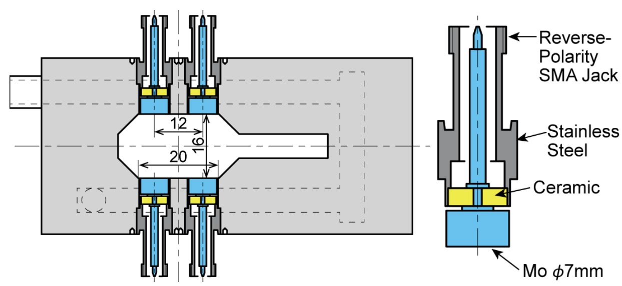

Figure 1: Schematic drawings of the cross-sections of the BPM head (left) and the button electrode (right).

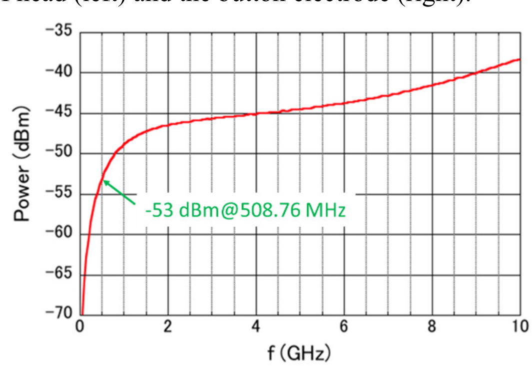

Figure 2: Calculated power spectrum of the button BPM signal from a 100 pC bunch with 10 MHz bandwidth.

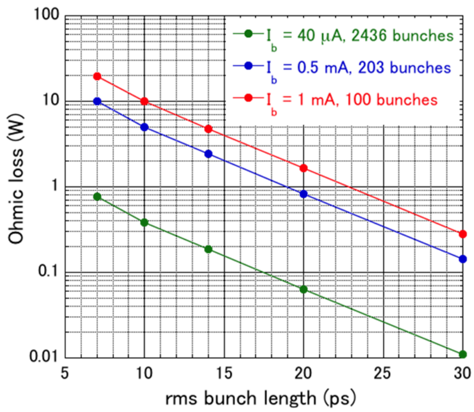

Figure 3: Calculated heat input to the BPM head for the total beam current of 100mA with bunch currents of 0.04 mA (green), 0.5 mA (blue) and 1 mA (red), respectively, as functions of the bunch length.

the BPM connector, reverse-polarity SMA jack was selected, 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.

Some prototypes of the button BPM electrode and the BPM head were manufactured with sufficient machining accuracy (10 μm level). The BPM electrodes did not have any serious problems of the vacuum seal and the rf characteristics (time-domain reflectometry) even after the heat cycle test (room temperature to baking temperature of 150 °C). Now, the prototype BPM buttons are waiting for a beam test at the present SPring-8 storage ring.

The BPM head is supported by a common girder for 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 design of a BPM support from the top of the girder is still underway. Requirements for the support are sufficient stiffness and small thermal expansion to reduce a transverse displacement. Deformations of the girder could result in the displacement of the BPM head. We have to consider minimizing movements of both the girder and the BPM support or monitoring drifts of the BPM head position with sub-micron-order accuracy.

BPM Electronics

We have two alternatives for the BPM electronics, our original design and the new generation of Libera Brilliance+ [10]. The two candidates are developed and evaluated in parallel and the final decision will be made before the start of mass-production. The original design is based on the new digital LLRF system [11], which utilizes the MTCA.4 standard [12]. For Libera Brilliance+, both the single-pass and the COD resolutions were confirmed to be sufficient by beam tests at the present SPring-8 storage ring.

The performance of a signal cable is crucial for stable operation of the BPM system. We have suffered from radiation damages of signal cables for the present SPring-8 BPM system. The radiation damages of cables resulted in significant humidity dependent drifts of BPM offsets [5]. Chemical analyses of damaged cables have 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. We are surveying radiation-resistant coaxial cables and considering radiation shields for BPM cables.

SUMMARY

We have designed and developed the beam diagnostic system for the SPring-8 upgrade project. The most important subject is to stabilize the photon beam axis for each beamline. Therefore, utmost efforts are devoted to the development of a highly stable BPM system. Since the BPM must also have sufficient single-pass resolution for the initial beam commissioning, we tried to maximize the signal intensity in the design of the BPM button electrode. Prototypes of buttons were successfully manufactured and electric and mechanical performances were confirmed to be satisfactory. For other diagnostic purposes, such as beam current, beam size and a bunch-by-bunch instability feedback control, existing instruments at the present SPring-8 storage ring will have sufficient performances for the upgrade project with minor modifications. The development of an XBPM still remains a challenge and further investigations are necessary.

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