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DESIGN OF THE BEAM DIAGNOSTIC SYSTEM FOR THE NEW 3 GeV LIGHT SOURCE IN JAPAN

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Abstract

We designed and developed the beam diagnostic system for the new 3 GeV light source project in Japan. To achieve the performance goals of the light source, we need to precisely measure various beam parameters of the storage ring, such as beam position, stored current, beam size, betatron tune, etc. We developed a button-type beam position monitor (BPM) with a single-pass resolution of less than 0.1 mm for a 0.1 nC injected bunch and with sub-µm closed-orbit distortion resolution for more than 100 mA stored current. The BPM stability was evaluated to be 5 µm for more than one month. The stored current is monitored by two DC current-transformers, which are attached to a vacuum chamber designed to have small beam impedance and small temperature rise. The beam size is measured by an X-ray pinhole camera with a 10 µm resolution. We will install a 3-pole wiggler as a radiator for the X-ray pinhole camera and diagnostics with visible light. Since the resistive wall impedance is expected to be high in the storage ring, we developed a bunch-by-bunch feedback (BBF) system to suppress the beam instability. We tested FPGA-based high-speed electronics for BBF and confirmed sufficient damping performance. A realtime betatron-tune monitor is also implemented in the BBF system. Thus, the beam diagnostic system is ready for the construction of the new light source.

INTRODUCTION

A new 3 GeV light source is now being constructed in Sendai, Japan [1], and will be completed in 2023. It will generate highly brilliant X-rays more than 10^{21} photons/s/mm^2/mrad^2/0.1%BW around 1 keV photon energy. These X-rays are emitted from a brilliant electron beam having a small natural emittance of 1.1 nm rad and a high beam current of 400 mA. This electron beam performance will be realized with a double double-bend achromat lattice on a 16-cell storage ring with a circumference of 349 m.

To provide the brilliant and stable X-rays to users, the electron beam needs to be stored stably with the design performance. Therefore, the various beam parameters, such as the beam orbit, current, size, etc. have to be monitored precisely and stably. Since a low-emittance storage ring has a narrow dynamic and physical aperture, the electron beam should be precisely steered within the aperture in the commissioning stage by using beam monitors and by tuning various magnets. Consequently, we have designed a precise and stable beam diagnostic system based on the development results of the beam monitors for the SPring-8 upgrade project [2]. In the following sections, we describe the design and test results of the beam monitors for the new 3 GeV light source.

OVERVIEW OF THE BEAM DIAGNOSTIC SYSTEM

In the commissioning of the storage ring of the new light source, the trajectories of a 0.1 nC bunch from the injector linac need to be measured with a resolution of 0.1 mm std. by the single-pass (SP) mode BPM. To adjust and keep the beam orbit to the ideal one in the user operation, a sub-µm resolution is necessary for the closed-orbit distortion (COD) mode BPM for a stored beam of more than 100 mA. The BPM should also be stable within 5 µm in one operation cycle (~1 month). The total stored beam current and each bunch current must be precisely monitored to keep the stored current and the bunch filling pattern constantly in the top-up injection mode. The bunch phase should also be monitored to inject a beam at an appropriate timing in the RF bucket. A precise realtime betatron-tune monitor is necessary to correct the tune shift caused by the gap changes of the insertion devices. Since the storage ring is equipped with narrow aperture vacuum chambers, the beam impedance will excite the beam instability. Therefore, a bunch-by-bunch feedback control system is also required to cure the beam instability.

Based on the above requirements, we designed a beam diagnostic system for the 3 GeV storage ring, as listed in Table 1. We use button-type BPMs for the beam orbit measurement. Seven BPMs are distributed in a unit cell and 112 BPMs are used in total. The stored beam current is measured by two DC current transformers (DCCTs), which are installed into a short straight section (SSS) for beam monitors (SSS-MON1). A 3-pole wiggler is also installed in SSS-MON1 for an X-ray pinhole camera to monitor the beam size. Visible light from the wiggler is also extracted

Table 1: List of Beam Monitors

Diagnostic instruments	Number of units
Beam position monitor (BPM)	112 (7 per cell)
Beam current monitor (DCCT)	2
Stripline BPM	2
Beam size monitor	1
Betatron tune monitor	1 (in BBF)
Beam instability control (BBF)	1

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for other measurements, such as a streak camera for the bunch length, an optical interferometer for the beam size, etc. Two stripline BPM pickups and a stripline kicker are integrated into another SSS (SSS-MON2) for a bunch current and phase monitor, betatron-tune measurement, beam instability feedback control, etc.

DESIGN AND PERFORMANCE OF EACH BEAM MONITOR

Beam Position Monitor

We employ button-type BPM pickups originally developed for the SPring-8 upgrade project [3, 4]. A schematic drawing of the BPM pickup is shown in Fig. 1. The vacuum chamber is the combination of an octagonal beam duct and an antechamber made of stainless steel. Four button-electrodes are attached to the top and bottom planes of the beam duct. The electrode is made of Molybdenum and the diameter is 7 mm. The horizontal spacing of the electrodes is 12 mm and the vertical aperture is 16 mm. The hole diameter for the button electrode is 8 mm and, therefore, the gap of the electrode is 0.5 mm. The beam position sensitivity factor was estimated to be approximately 7 mm for both horizontal and vertical directions. These dimensions were carefully designed to suppress the beam impedance and heat generation [3]. A water-cooling channel is also equipped to the BPM chamber to reduce the temperature rise. The BPM signal is extracted from a reverse-polarity SMA connector since the normal SMA jack connector has a spring part, the force of which can be lost by a high-temperature brazing process of the electrode.

BPM signals are transferred to the readout electronics through coaxial cables. Since cables near the BPM chamber are exposed to a large dose of radiation, radiation-resistive coaxial cables are necessary. We tested several candidates in the SPring-8 storage ring. The cables are placed on an X-ray absorber, where the dose rate is more than 10 kGy per day. As a result, semirigid cables with dielectric materials of SiO_2 and PEEK were confirmed to have sufficient radiation resistivity. Therefore, we use one of these semirigid cables to extract the BPM signal from the BPM head. Since the radiation-resistive semirigid cable is expensive, lossy, and hard to make a long cable, we use a corrugated coaxial cable to transfer the signal from the accelerator tunnel to the outside. We confirmed that a corrugated coaxial cable is not damaged by radiation if it is more than 1 m apart from the electron beam.

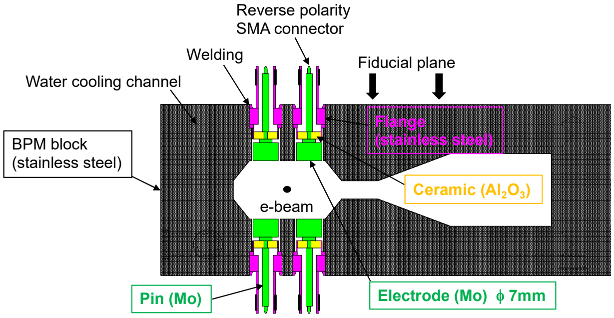

Figure 1: Cross-section of the BPM vacuum chamber with button electrodes.

As described in the previous section, the BPM readout electronics are required to have both the SP and COD detection functions with sufficient precision, accuracy, and stability. For the COD measurement, several data rates are needed: slow data with 10 Hz, fast data with 10 kHz, and turn-by-turn data with 859 kHz. The slow data is used for COD monitor and correction. The fast data is for abnormal orbit alarm to protect beamline components, etc. The turn-by-turn data is for the analysis of fast phenomena. To implement these functions, we employed the MTCA.4 platform [5] for the readout electronics [6]. The BPM signal is fed into a BPM rear transition module (RTM) of the MTCA.4 standard and a 509 MHz signal synchronized to the acceleration frequency is extracted. The signal is transmitted to a digitizer advanced mezzanine card (AMC), which has 10 channels of ADCs with a sampling frequency of 370 MHz and a vertical resolution of 16 bits. The beam position is calculated by an FPGA on the digitizer AMC. Since the MTCA.4 has a high-speed backplane, large BPM data from the digitizer AMC can be easily transferred to a CPU module.

The basic performance of the BPM system was evaluated in SPring-8 [4, 6]. The prototype BPM chamber having four sets of BPMs was installed in one of the straight sections. Two BPMs from the four were processed by the MTCA.4 electronics. The BPM resolution was estimated by comparing the position data from the two BPMs [6]. The SP resolution was obtained to be 0.02 mm for a bunch charge of 0.13 nC. The COD resolution of the 10 kHz fast data was 0.4 µm for a stored beam current of 30 mA. Long-term stability was also evaluated, as shown in Fig. 2. The vertical axis of this trend graph is balance error, which is defined as the maximum difference among the four values from the three-electrode BPM calculation process [7]. The balance error is constant and independent of the beam position if the gains of all the four electrodes are stable. Variations of the balance error indicate some drifts of BPM hardware. The trend graph shows that the balance error variation was about 5 µm for more than one month, even if the filling pattern was changed several times. Thus, the BPM system has sufficient position resolution and stability.

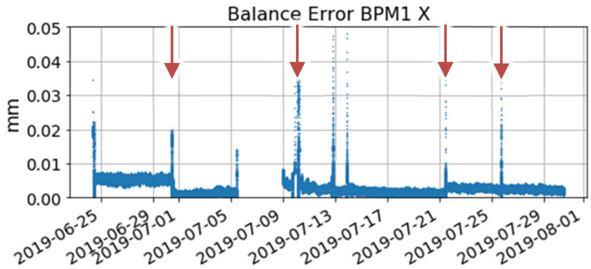

Figure 2: Trend graphs of balance error data (horizontal). Filling patterns were changed several times, which are indicated by arrows.

Stored Beam Current Monitor

The stored beam current monitor will be installed in one of the short straight sections (SSS-MON1). A schematic view of the beam current monitor is illustrated in Fig. 3. The current monitor consists of two DCCTs for redundancy. We employed Bergoz NPCT [8] as a sensor head. It has 1 $\mu A/\sqrt{Hz}$ noise level at the full range of ± 1 A and the full bandwidth of 10 kHz. The RF wakefield from the electron beam is absorbed by SiC around the ceramics gap and the nonlinear response of the DCCT due to the RF wakefield is suppressed. The heat generated in SiC is taken by a copper block with a water-cooling channel. The temperature rise of the DCCT coming from a 400 mA stored beam is estimated to be less than 1 K by using a three-dimensional thermal analysis code, as shown in Fig. 3 (right). Although NPCT has a finite thermal coefficient of 5 $\mu A/K$, the thermal drift is expected to be sufficiently small. Thus, the stored beam current monitor can measure the beam current with the order of 1 μA precision, corresponding to ~1 pC of the stored beam charge. Since the beam charge from the injector linac is the order of 100 pC, the injection efficiency can be evaluated with 1% precision, which is enough for the regulation of radiation safety.

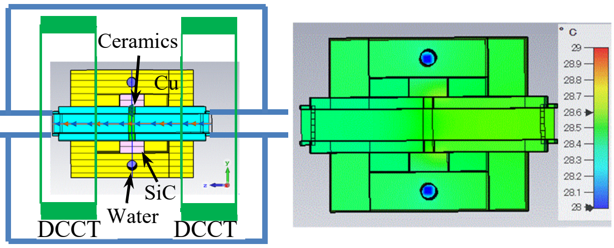

Figure 3: Schematic view of the stored beam current monitor (left) and the thermal analysis result (right).

Beam Size Monitor

To estimate the beam emittance and the x-y coupling ratio from the beam size, we will use an X-ray pinhole camera, as shown in Fig. 4. A 3-pole wiggler is installed in SSS-MON1 together with the DCCTs as an X-ray radiator. The design of the X-ray pinhole camera is based on that of SPring-8 [9]. The distance from the light source to the pinhole is ~5 m and that from the pinhole to the camera is ~10 m. The optimum pinhole size is estimated to be approximately 13×13 μm^2 when ~50 keV photons are used, and the optical resolution is expected to be approximately 4 μm. The beam radius at the SSS is 80 (H) × 6 (V) μm^2 std. and the design value of the x-y coupling ratio is 1%. Therefore, the beam size monitor has a sufficient resolution for both axes. Since the beam emittance can be estimated from the horizontal size, the beam size monitor is precise enough for the emittance measurement. To measure the x-y coupling ratio precisely less than 1%, we need a more precise method to achieve a sufficient resolution, such as X-ray interferometry [10].

Visible radiation from the 3-pole wiggler is also extracted to measure various beam parameters. The beam size can be monitored by an interferometer and the bunch length can be measured by using a streak camera. Therefore, we extract the visible light to the outside of the accelerator tunnel and guide to a dark room for visible light diagnostics. The detailed setup of the visible light diagnostics is still under consideration.

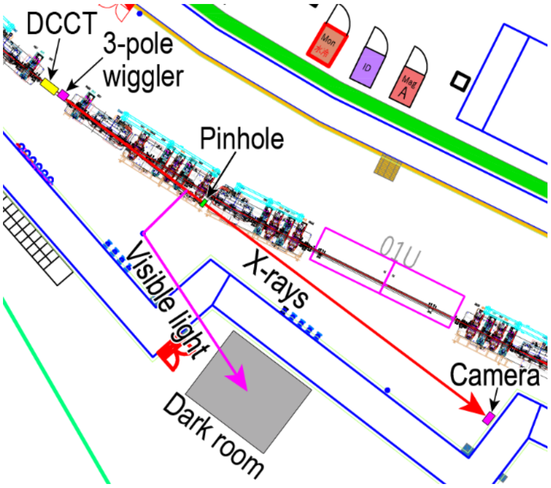

Figure 4: Setup of the beam size monitor and the visible light extraction line.

Bunch Current and Phase Monitor

The bunch current and phase data are necessary to monitor the filling pattern and the injection timing for top-up operation. Electrons should be filled to the bunch that has the largest current deficit. Since the synchronous phase of each bunch is slightly different from each other, the injection timing should be adjusted bunch-by-bunch.

We will use a stripline BPM at an SSS (SSS-MON2) for the bunch current and phase measurement. One of the candidates for data acquisition is an MTCA.4 high-speed digitizer with a sampling rate of around 5 GSPS. The bunch current is obtained from the peak value of the pulse signal from each bunch and the bunch phase is from the rising edge timing. We have another plan to use a high-speed oscilloscope for backup. This method was already applied to the SPring-8 storage ring, and hence no development is needed. However, a commercial oscilloscope does not have high-speed data transfer to our control system. We will decide the data acquisition method in the near future.

Beam Instability Control and Tune Monitor

The suppression of beam instability is necessary to store a high-current electron beam stably since the threshold current for the transverse instability is estimated to be less than 100 mA due to narrow vacuum chambers of the storage ring. Although the instability can be suppressed by a larger chromaticity value, the top-up injection efficiency can be degraded by the chromaticity. Therefore, we use a bunch-by-bunch feedback (BBF) system to suppress the beam instability. The required damping time is estimated to be 0.01 ms for a bunch current of 1 mA.

The beam signal is picked up by a stripline BPM and the counter kick signal is calculated by a fast signal processor bunch-by-bunch. The kick signal is amplified by a wideband power amplifier and fed into a 4-electrode stripline kicker. The length of the kicker electrode is 0.3 m to kick each bunch with a time interval of 2 ns. The stripline BPM and the stripline kicker will be installed to SSS-MON2. We employ Dimtel iGp12 [11] as a signal processor, which has 509 MSPS ADCs and DACs, high-speed FPGA, and bunch-by-bunch feedback control firmware. The required kicker signal power is estimated to be 250 W for each kicker electrode to achieve the demanded damping time.

A betatron-tune monitor is necessary for the evaluation of the beam optics, automatic tune stabilization, etc. In general, the betatron tune is measured from a frequency response of the transverse oscillation. Since the BBF system has a BPM and a kicker to measure the transverse frequency response, some betatron-tune measurement functions are already implemented to iGp12. The tune can be measured by three methods: (1) A bunch is shaken by a swept sine signal and the tune is calculated from the Fourier transform of the BPM signal. (2) The sinusoidal kick phase is locked to the resonance of the betatron oscillation. (3) The tune value is calculated from a spectral notch under the BBF on. For the methods (1) and (2), the BBF for one of the bunches is turned off and the bunch is shaken by a signal for the tune measurement. Therefore, the tune can be monitored in realtime with sufficiently small perturbation.

We evaluated the BBF and tune monitor performances of iGp12 at SPring-8. The present BPM, kicker, and power amplifiers for the SPring-8 BBF system [12] were used. The grow-damp test result is shown in Fig. 5. A transverse orbit fluctuation was excited by a forced oscillation and the orbit was stabilized by turning on the feedback. The damping time was obtained to be 0.6 ms for a bunch current of 0.5 mA. If we convert this result to the 3 GeV light source by beam energy, beta function, circumference, physical aperture, etc., the damping time is approximately 0.01 ms for a 1 mA bunch, which satisfies the requirement.

The realtime tune monitor was also tested with the same setup. The tune was appropriately obtained with the accuracy of 2×10^{-4} for the swept sine method. The tune measurement precision of the phase lock method was 1×10^{-5} at the acquisition rate of 5 Hz. Since the required tune stability is 10^{-3} level, the tune monitor has enough resolution for the tune stabilization.

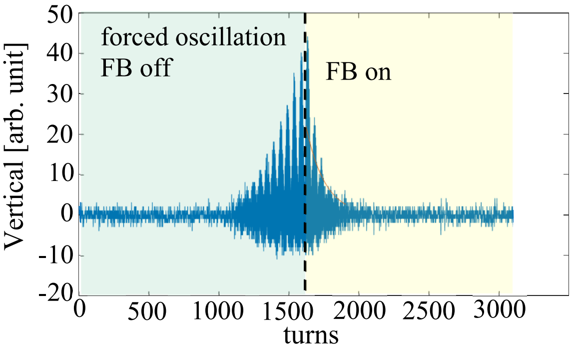

Figure 5: Grow-damp test result of the BBF system.

SUMMARY

The beam diagnostic system for the new 3 GeV light source in Japan has been developed based on the beam diagnostic system design of the SPring-8 upgrade project. The performance of the button BPM was examined in SPring-8. The SP resolution was confirmed to be 0.02 mm for a 0.13 nC single bunch and the COD resolution was 0.4 µm for 10 kHz fast data with the stored beam current of 30 mA. The stability of the BPM was also evaluated to be approximately 5 µm for more than one month. The stored current will be monitored by two DCCTs with 1 µA precision. The beam size will be measured by an X-ray pinhole camera with a 4 µm resolution. Although the detailed designs of the DCCT and the pinhole camera are different from SPring-8, the concepts themselves were already confirmed in SPring-8. The beam instability will be suppressed by the FPGA-based BBF system. This system was also tested in SPring-8 and the sufficient damping performance was confirmed. The realtime betatron-tune monitor is implemented in the BBF system and the resolution was evaluated to be 2×10^{-4} for the swept sine method and 1×10^{-5} for the phase lock method. Thus, the performance of the beam diagnostic system was confirmed to be sufficient for the new light source.

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