BEAM DIAGNOSTIC SYSTEM OF XFEL/SPring-8

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Abstract

We present the design and the performance of the beam diagnostic system of XFEL/SPring-8. The XFEL facility requires sub-μm resolution beam position monitors (BPM), screen monitors with less than 10 μm resolution, high-speed beam-charge monitors and a temporal structure measurement system with less than 10 fs resolution. We developed an rf cavity BPM system that uses the TM110 mode at 4760 MHz. The estimated position resolution was 0.2 μm. For the screen monitor, we designed a custom lens system having 2.5 μm resolution and variable magnifications from 1 to 4. For the charge measurement, we developed a high-speed differential current transformer (CT). The rise time of the CT signal was 0.2 ns and common-mode noise was considerably reduced. To measure the temporal beam structure, we developed a C-band (5712 MHz) transverse deflecting cavity that has a disk-loaded backward traveling wave structure. This cavity can resolve a beam into a few fs fragments. Thus, the beam-diagnostic system satisfies the demands of the XFEL accelerator.

INTRODUCTION

An x-ray fre-electron laser facility at SPring-8 (XFEL/SPring-8) [1] is under construction to generate coherent and extremely intense x-rays, where various new applications are expected in life sciences, material sciences, etc. The target wavelength is less than 0.1 nm. The XFEL light is generated by a self-amplified spontaneous emission (SASE) process.

A schematic layout of the XFEL facility is illustrated in Fig. 1. An electron beam with a normalized emittance of 0.6 π mm mrad is generated by a thermionic electron gun. The beam is accelerated to 8 GeV by the following series of rf accelerator cavities: 238 MHz pre-buncher, 476 MHz booster, L-band (1428 MHz), S-band (2856 MHz) and C-band (5712 MHz) accelerators. In the mean time, the bunch length is shortened from 1 ns to 30 fs by using a velocity bunching process of the sub-harmonic acceleration cavities and a bunch compression process of the three magnetic chicanes. Finally, the peak current becomes 3 kA without substantial emittance growth. The electron beam is finally fed into in-vacuum undulators, and an XFEL light is generated. The undulator period is 18 mm and the maximum K-value is 2.2.

In order to maintain the high gain SASE process at an x-ray wavelength, we need to monitor the beam position, the transverse beam profile, the beam charge, the beam arrival timing and the temporal bunch structure at each acceleration stage. The resolution of the beam-position monitor in the undulator section is required to be less than 0.5 μm so as to maintain an overlap between the electron beam and radiated x-rays with 4 μm precision. The transverse beam profile should be measured with a spatial resolution of less than 10 μm. The required resolution of the temporal bunch structure is less than 10 fs.

In this paper, firstly we show an overview of the beam diagnostic system, and then we describe the design and the performance of each diagnostic device.

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OVERVIEW OF THE BEAM DIAGNOSTIC SYSTEM

The diagnostic system of XFEL/SPring-8 [2,3] consists of high-resolution rf cavity beam position monitors (RF-BPM), precise screen monitors (SCM), high-speed differential current transformers (CT) and a transverse rf deflector system. The quantities of these monitors are summarized in Table 1, and are shown in Fig. 1. A detailed description of each monitor is given in the next section.

Table 1: Summary of the Number of Beam Monitors

	Number of Monitors
RF cavity BPM	56
Screen Monitor	43
Current Transformer	30
Transverse RF Deflector	1

DESIGN AND PERFORMANCE OF EACH DIAGNOSTIC DEVICE

RF Cavity BPM

Since the details of the RF-BPM are reported in Ref. [4], we summarize the performance of the RF-BPM. The RF-BPM cavity consists of two cylindrical cavity resonators: a TM110 dipole resonator for the position detection and a TM010 monopole resonator for the phase reference and the bunch charge measurement. We designed an RF-BPM cavity with a resonant frequency of 4760 MHz and a detection electronics equipped with an IQ (In-phase and Quadrature) demodulator. We tested the RF-BPM system in the SCSS test accelerator [5] with a 250 MeV electron beam and a 0.3 nC bunch charge. The position resolution was 0.2 μm and the beam arrival timing resolution of the TM010 cavity was 25 fs.

Screen Monitor

The transverse beam profile is monitored by a SCM. We use a fluorescent screen, such as Ce:YAG for a low-

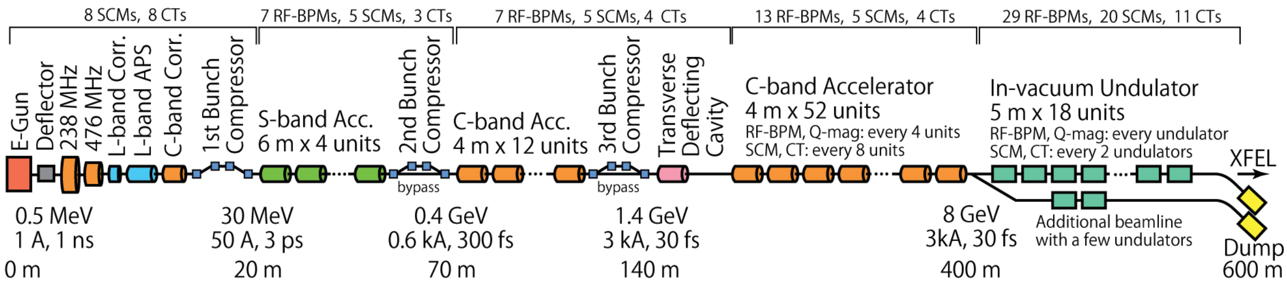

Figure 1: Schematic layout of the XFEL facility. The number of monitors for each section is also shown.

energy beam (less than 100 MeV) and an optical transition radiation (OTR) screen for a high-energy beam.

To achieve the required spatial resolution of less than 10 μm, we newly designed an imaging system [6] comprising a custom lens system and a motorized zoom mechanism from 1x to 4x. Figure 2 shows a photograph of the imaging system. The OTR light from the screen passes through the lens, and forms an image on the CCD camera. The lens and the camera are mounted on motorized stages so that both the magnification and the focus can be adjusted remotely. The optical resolution was 2.5 μm from a measurement of a grid distortion target.

We prepared a thin stainless-steel screen (0.1mm-thick) for an OTR radiator, as shown in Fig. 3, to reduce the radiation damage to other components due to the beam divergence. The central elliptical part is the 0.1mm-thick radiator and it is supported by a 1mm-thick frame. This screen is a stack of ten 0.1mm-thick foils processed by a photo-etching technique, and these foils are unified by a diffusion bonding method. The surface roughness of the screen is several 10 nm and the flatness is 3 μm.

The SCM system was installed into the SCSS test accelerator and tested with an electron beam. Figure 4 (A) shows an OTR image of an electron beam horizontally squeezed by Q-magnets. The horizontal width of this image was evaluated to be 13 μm (standard deviation), which is consistent with the natural divergence due to the beam emittance. Almost the same image as OTR was observed with a Ce:YAG screen, as shown in Fig. 4 (B).

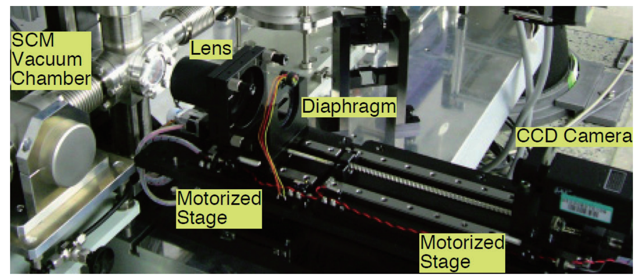

Figure 2: Photograph of the screen monitor.

Figure 3: Thin stainless steel OTR screen.

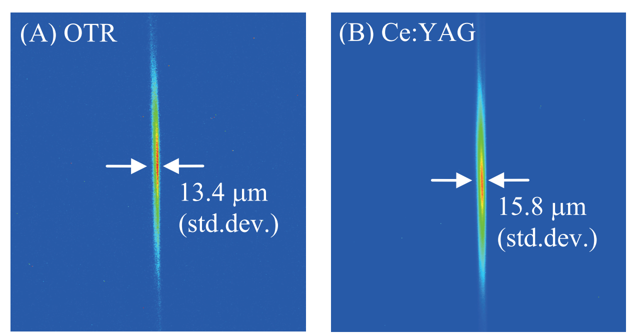

Figure 4: Beam images taken by (A) an OTR screen and (B) a Ce:YAG screen. The magnification of the lens is 4. The horizontal beam size is minimized by Q-magnets.

Current Transformer

The main purposes of the CT are beam charge measurements to monitor the appropriate beam transportation and the beam arrival timing measurement to adjust the timing of accelerator components. In the SCSS test accelerator, some commercial CTs are used for these purposes. However, we found that the CT signal was influenced from substantial noise coming from the thyratron of a klystron power source. Therefore, we developed a high-speed differential CT [7] so as to reduce the noise and to improve the temporal response.

A schematic view of the differential CT is shown in Fig. 5. The CT has four outputs: two are positive and the others are negative. By subtracting a negative signal from a positive one, we can remove any common-mode noise. Since the pickup coil is of single turn, the rise time of the output pulse is expected to be small. The beam-position

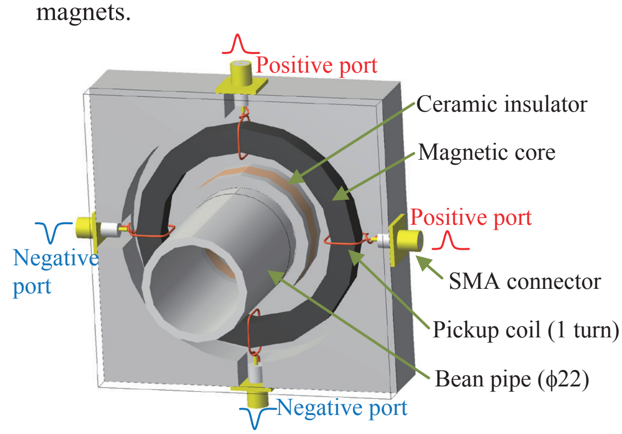

Figure 5: Schematic view of the differential CT.

dependence is eliminated by averaging the signals from all four ports.

We tested the differential CT in the SCSS test accelerator. Some waveforms of the signals are plotted in Fig. 6. A sharp pulse signal was obtained, and the rise time was 0.2 ns. External common-mode noise was reduced to 1/10. Thus, the design performance of the differential CT was confirmed.

Transverse RF Deflecting Cavity

We use a transverse rf deflecting cavity (RFDEF) to measure temporal bunch structures of an electron beam, such as the slice emittance and the energy-vs.-time distribution. An electron beam is swept by transverse deflecting rf fields and the temporal profile is converted to a transverse distribution. When we set the center of the bunch to rf phase of zero-crossing, we can linearly stretch the temporal structure.

An RFDEF cavity, named RAIDEN [8], was newly designed as illustrated in Fig. 7. The structure of RAIDEN is a periodically disk-loaded waveguide that has race-track-shaped irises to separate horizontal and vertical modes. The resonant frequency is selected to be the C-band (5712 MHz) so as to fully utilize the C-band accelerator resource and to obtain a higher deflecting voltage. The resonating mode is the HEM11-5π/6 mode of backward travelling-wave type. The basic performance of the RAIDEN cavity was confirmed by a low-level rf measurement of a 7-cell model.

The RFDEF system will be installed downstream of the third bunch compressor. We use two 1.7m-long RAIDEN tubes powered by a 50 MW klystron and generate a deflecting voltage of 40 MV at the crest phase. The 1.4 GeV electron beam can be resolved with a few fs precision by the RFDEF. The transverse distribution of the stretched beam is recorded by the above-mentioned SCM after a 5 m drift space. Although we have the RFDEF at the third bunch compressor only, we can measure the temporal structure at the first and second bunch compressors by using bypass lines of second and third bunch compressors.

SUMMARY AND PROSPECTS

We developed an rf cavity BPM, a screen monitor, a current transformer and a transverse rf deflector for XFEL/SPring-8. The position resolution of the RF-BPM system was 0.2 μm. The optical resolution of the OTR screen monitor was 2.5 μm. The rise time of the CT output pulse was 0.2 ns and common-mode noise was eliminated. The performance of a C-band RAIDEN cavity for the transverse rf deflector system was confirmed by a low-level rf measurement. Thus, the performance of the developed beam-diagnostic system is sufficient to monitor the electron beam of the XFEL facility.

The design work of the beam diagnostic system is almost complete, and mass-production has just started. Installation of accelerator components will start from July 2009. The first XFEL light will be generated in 2011.

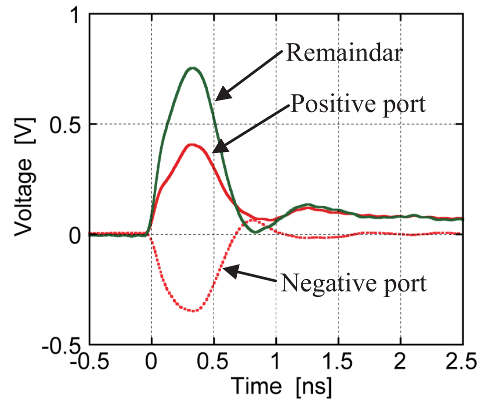

Figure 6: Waveforms of the differential CT.

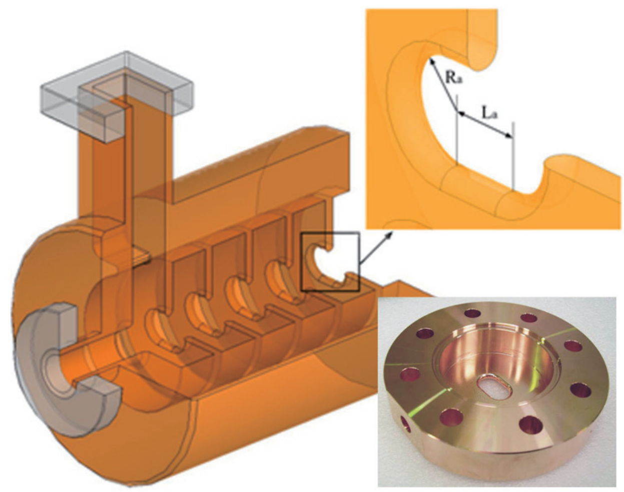

Figure 7: Schematic drawing of the C-band RAIDEN cavity. A photograph of a cell piece is also shown.

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