DEVELOPMENT STATUS OF A BEAM-DIAGNOSTIC SYSTEM WITH A SPATIAL RESOLUTION OF TEN MICRON-METERS FOR XFEL

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Abstract

An about10 micron-meter stability of an electron beam is required along the undulator section of XFEL to stably generate an X-ray laser. To obtain the beam stability, measurements of the spatial and temporal beam structure are very important. We have developed an electron beam-diagnostic system with a measurement resolution of less than 10 micron-meters. The system comprises a cavity-type beam-position monitor, an optical transition radiation screen monitor, a beam-current monitor, an rf beam deflector to diagnose femto-second order temporal structure, and beam slits to appropriately shape the beam spatial structure. The arrangement of these instruments was decided based on requirements of the beam position and size measurements based on the design of the electron-beam optics. This paper describes the development status of the beam-diagnostic system. The test results and design of the instruments showed sufficient performance to attain the measurement resolution mentioned above.

INTRODUCTION

In an apparatus using the self amplified spontaneous emission (SASE) method as an X-ray free electron laser (XFEL) being under construction at SPring-8, a 8 GeV linear accelerator of 400 m in length and 18 short period in-vacuum undulators of 5 m each in length are employed[1]. In this case, an electron beam passing through an udulator section of 89 m in effective length should be almost completely overlapped with X-rays radiated by interactions between an undulated beam and a periodic magnetic field; otherwise, electron-beam micro-bunching derived by the radiated X-rays and the electron undulation motion is not evolved well toward SASE saturation. The allowable orbit deviation between the beam and the X-rays is less than 4 μm[2]. In order to maintain stable SASE generation, the beam should have a size of several tens of micron-meters, a peak beam current of several kilo-amperes, a micro-bunch length comparable to the X ray wavelength, an emittance of less than 1 πmm mrad, and an energy stability of 10^{-4} (a time stability (rf phase) of femto-second order)[3]. At RIKEN/SPring-8, we are now constructing

Table 1. Electron-beam quality for the undulator section demanded for generating a stable SASE.

Energy	~8 GeV
Charge amount	~ 0.3 nC (A peak current of 1 kA)
Emittance	~ 1 πmmmrad
Size	~ 50 μm (rms)
Pulse width for serving SASE generation	~ 40 fs (rms)

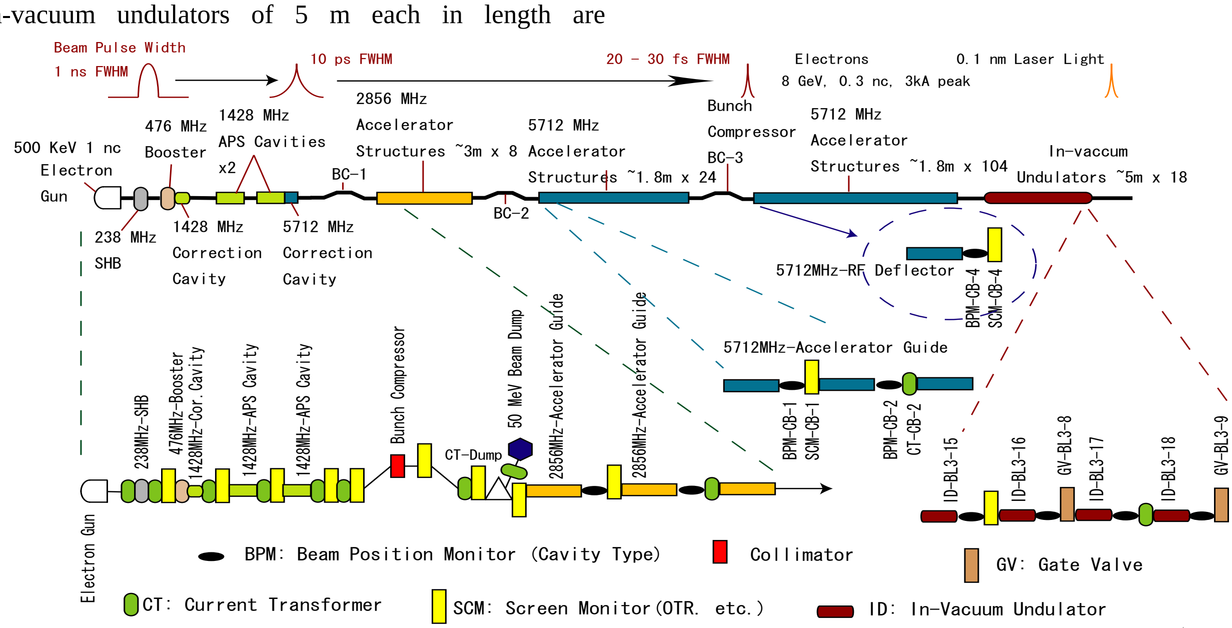

Figure 1: Planned layout of an accelerator (upper) and the example layout of monitors (lower) for XFEI

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Table 2. Kinds and numbers of beam monitors.

BPM (Cavity Beam Position Monitor)	Total 61
SCM(Screen Monitor)	Total 32 Desmarquest 3 (for the injector) OTR screen 29 (for regular section)
CT(Current Transformers)	Total 29 1 single end output 28 differential output
Wave Length Spectrometer	3 - 6

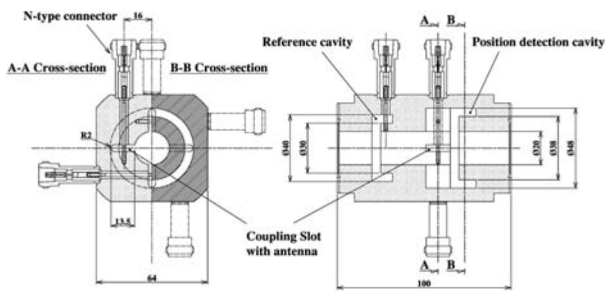

Figure 2: Drawing of the rf BPM.

XFEL with an 8 GeV linac having special features: a highly bright thermionic electron gun, velocity bunching by using multi-sub-harmonic cavities in the low-β section of an injector, and magnetic bunch compression in high-β by using a chicane. The highly elaborated beam demanded for XFEL/SPring-8, as mentioned above, is summarized in Table 1[3]. To tune and realize a high-quality beam with the parameters given in Table 1, beam monitors are also required to have comparable resolution to a spatial structure of less than several tens of micron meters and a temporal structure of several tens of femto-seconds like that the electron beam has. This report describes a summary of an XFEL beam-monitor system and examples of developed beam-monitor instruments.

BEAM MONITOR SYSTEM

Figure 1 shows examples of the planned beam monitors settled along the XFEL accelerator. The total numbers and kinds of the principal beam monitors are listed in Table 2. Representative monitors are a cavity-type beam position monitor (BPM) to measure the beam position, a screen monitor (SCM) to measure the beam profile, and a differential current transformer (CT) to observe the beam intensity. The special features of the monitors are as follows. In the BPM, there are intensity reference and position detection cavities. The reference cavity is also utilized to measures the beam arrival time (beam phase) [4]. The CT [5] has four single-turn detection coils placed along the circumference of a core (finemet HITACH) at each right angle, and a 100 Ω differential transmission line specially designed for reducing any common-mode noise on its coils and signal transmission line. In addition, there is a wavelength spectrometer used as a bunch-length monitor including 5 different size waveguides connected in series and 50 GHz rf detectors for measuring the rough bunch length of a beam by using information obtained from coherent transition radiation or wake fields generated on the surface of the screen monitor[6]. To measure the precise temporal structure of a beam, a longitudinal diagnostic system that includes an rf deflector of a HEM11-5π/6 mode backward travelling-wave structure[7] generating a transverse deflecting voltage over 40 MV, and a high-resolution optical transition radiation (OTR) SCM with a resolution of less than 5 μm is employed. The deflector has a resonant frequency of 5712 MHz, because of the availability of an rf source, which is used for our main accelerator. It has racetrack-shaped beam holes serving cell-to-cell coupling and preventing rotation of the rf polarization, because of easily manufacturing a small cavity at 5712 MHz. A precise measurement resolution of the beam, below 5 μm in size, and under 40 fs in bunch length and timing, is especially demanded in those parts of the bunch compressors and the undulate line that determine the X-ray laser characteristics and stability. Therefore, the measurement accuracy of the above-mentioned monitors placed in these parts is the most important. In this paper, we do not have enough space to describe the details of the monitor system. For this reason, we give a limited report on the position and size measurement resolutions of monitors regarding the BPM and SCM as follows.

Table 3. Results of the BPM resolution measurement tested in the SCSS test accelerator.

	X resolution [μm]	**Y resolution [μm]**
BPM	5.2	4.9

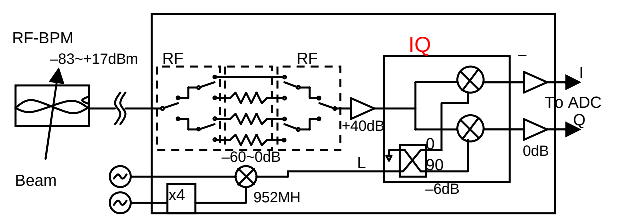

Figure 3: Newly designed rf BPM detection circuit for XFEL. It uses an IQ detector driven with a low-noise power supply (noise -140 dBV at 10Hz) and an attenuator array.

BPM

The BPM, as shown in Fig. 2, comprises a position detection cavity (TM110) and a reference cavity (TM010) operated at a resonant frequency of 4760MHz[8]. The BPM frequency is shifted from an acceleration frequency of 5712 MHz, in order to avoid the effect of dark current generated in the main accelerating structures. The position detection cavity has four coupling slots with antennas, two for the X direction and the other two for the y direction. The slots are designed to couple with the TM110 mode rf field. The intensity of the rf field is proportional to the beam position. The detection sensitivity of the BPM is approximately 16 mV/nC/μm[8].

The position resolution was measured by using three BPMs aligned along the SCSS test accelerator[9]. The first and third BPMs determine an expected position at the second BPM, assuming a straight trajectory. The position resolution is taken from a residual that is the difference between a position detected with the second BPM and a position expected from the trajectory. The measured results are summarized in Table 3. The resolution is approximately 5μm, or better. This resolution is slightly insufficient compared to the demanded resolution, and should be less than several micron meters. To obtain a further resolution of BPM, a new detection circuit using an IQ detection method, as shown in Fig. 3, is under development.

Screen Monitor

The screen monitor, as shown in Fig. 4, consists of a vacuum chamber, an in-vacuum thin metal foil to radiate OTR and to reduce radiation loss, focusing lenses comprising 3 groups and 4 pieces, and a CCD camera system. The major feature of the monitor is a bright and high-resolution optical system and employing a thin oval foil (material: SUS, semi-major axis: X=14 mm, semi-minor axis: Y=10 mm) with a 100 μm thickness. The foil is surrounded by a thick oblong frame (outer frame size: X=32 mm, Y=17 mm) with a 1 mm thickness. This frame was made by a diffusion bonding process. In order to realize the optical system, the lenses are placed near the foil, with the distance between the front lens and the foil being 100 mm; the lenses have a large aperture of 2 inches. This optical-geometrical structure is helpful to reduce the airy radius of a near-field image and to obtain a wide numerical aperture. Despite the fact that the monitor has a wide optical band width, ranging from 400 to 800 nm for observations, the calculated measurement resolution of an image on the foil is 2.5 μm. An experiment used to evaluate the resolution was carried out by taking an image of many dots with a 62.5 μm diameter on a commercial optical target (dummy) film. The image and resolution data experimentally obtained by using the developed screen monitor are shown in Fig. 5. This result, taken by observing the target film, suggests a comparable resolution to that of the calculation. Recently, a beam image focused on the OTR screen with a Q-magnet was preliminary obtained by this SCM installed in the SCSS test accelerator. The result of this experiment showed that the focused bream size was about 30 μm (rms).

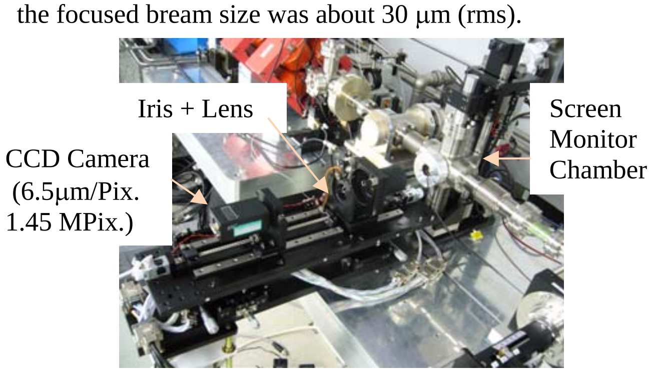

Figure 4: Screen monitor system with OTR.

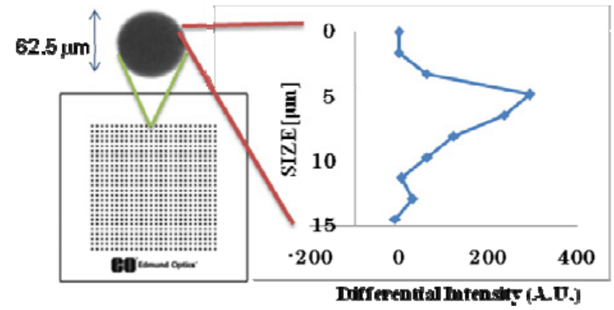

Fig. 5. Resolution of the optical system of the screen monitor. The dot diameter is 62.5 μm. The graph shows that the sharpness (resolution) of the dot edge is about 4 μm (FWHM). The edge sharpness is obtained by differential operation of the dot contrast.

SUMMARY

The construction of XFEL beam monitor system is smoothly in progress. Some of the developed monitor devices were tested by using the SCSS test accelerator, and satisfy our requirement of a several micron-meter position resolution for XFEL. On the other hand, there are monitors still under development. Therefore, we must continue the construction and the development of the beam-monitor system so as to accomplish our XFEL project with fruitful results. We thank the members of the XFEL project for supporting this development.

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