DEVELOPMENT STATUS OF BEAM-MONITOR SYSTEM AT XFEL/SPRING-8 (ITS TEMPORAL RESOLUTION ISSUE)

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Abstract

In XFEL/SPring-8, the most important issues is to generate a highly-quality electron beam, having a low slice emittance of 0.7 πmm- mrad, a pulse width of 30 fs, and a peak current of 3 kA. Monitoring the temporal structures of an electron beam and a laser beam are an indispensable function in order to tune the machine to obtain such a beam and to maintain stable X ray laser operation. For this purpose, various instruments, such as a beam position monitor (BPM), a HEM11-mode rf beam deflector, a screen monitor (SCM), and an in-vacuum photo diode monitor have been developed. The BPM has a position resolution of less than 1 μm. The SCM used to observe the deflected beam image has a position resolution of 2.5 μm, which corresponds to a temporal resolution of 0.5 fs, when it is installed at a position 5 m downstream from the HEM11-mode deflector. A phase reference cavity of the BPM has an additional function of providing beam arrival timing information. An experimental test for the BPM showed a temporal fluctuation of 46 fs in the beam arriving timing at the SCSS test accelerator. An in-vacuum photo diode was also prepared to roughly measure the laser arrival timing with 1 ps resolution. These monitors with high temporal resolutions allow us to achieve the fine beam tuning demanded for the XFEL.

INTRODUCTION

An X-ray free electron laser (XFEL/SPring-8) comprises an 8 GeV linear accelerator (400 m long) and eighteen undulators of a short period and in-vacuum design (5 m long). The machine is now under construction at SPring-8, aiming at generating first light in 2011[1]. In order to maintain stable SASE-FEL operation, an electron beam should have a transverse size of 50 μm (rms) with a 40 fs (rms) bunch length, a peak beam current higher than 1 kA, a slice emittance of 1 πmm-mrad in an undulator section of 90 m[1]. Furthermore, a beam energy stability of 1 x 10^{-4} (rms) and a beam timing stability of less than 50 fs (rms) are demanded[2]. Therefore, monitors to observe the electron beam should have a spatial resolution of less than 1 μm, and a temporal resolution of under 10 fs. We developed these beam monitors, and already presented their spatial resolution at EPAC08[3]. The temporally constant longitudinal structure of the beam bunch is very important for FEL, because it conducts the stable peak current that directly connects to stable non-linear amplification of SASE for the undulator section. The bunch structure is mainly formed by a velocity bunching process by multi-sub-harmonic cavities at the injection part[4] of the accelerator, and the bunching process by a magnetic chicane with the beam energy chirped along its longitudinal direction. For these reasons, measurements of the temporal structure and the beam timing (phase) to an acceleration rf signal are very important to tune and to obtain a stable peak current. For the measurements, we newly developed a HEM-11 mode C-band rf beam deflector (RFDEF)[5], a high-resolution screen monitor (SCM)[6], a cavity-type beam-position monitor (BPM)[7], a very fast current transformer (CT) to be able to measure rough timing around 1ps[8], and an in-vacuum fast photo diode (PD) system to observe SASE light and to also observe rough timing. Their temporal resolutions are mainly described in this paper.

RF DEFLECTOR PART BEAM MONITOR SYSTEM

There are many beam monitors at the XFEL. We cannot explain everything in the short space of this paper. Therefore, we intensively explain representative beam monitors in an rf deflector part as an example.

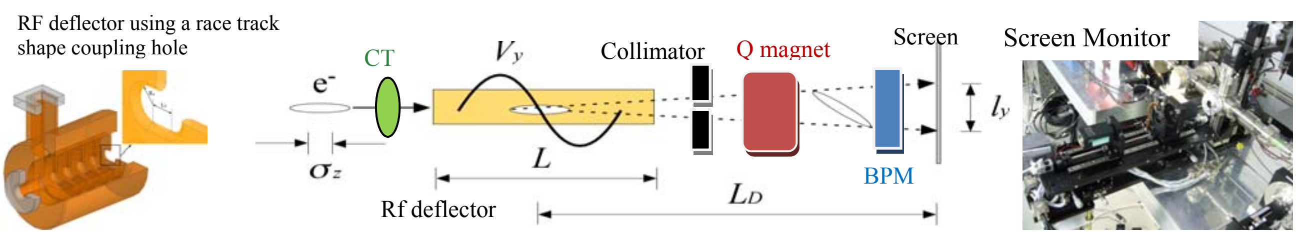

Figure 1: Beam-monitor layout at the rf deflector part (center), RFDEF cavity shape (left), and SCM (right).

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Figure 1 shows the beam-monitor layout at the rf deflector part lining up the CT, the RFDEF cavity, the BPM, and the SCM. The function of this part is as follows. The deflector cavity pitches the beam bunch around its center to project the image of the longitudinally compressed bunch structure on the screen of the SCM. The relation between the deflection voltage, V_y, and the projected bunch length on the screen, l_y, is given by

$$V_y = \frac{l_y}{L_d} \frac{cp_z}{ek_a\sigma_z}\,, \tag{1}$$

where L_d is the drift length between the RDFEF center and the SCM, k_a is the wave number of the RFDEF, σ_z is the bunch length, and p_z is the longitudinal momentum of a bunch. Putting the RFDEF cavity parameters in Table 1 into Eq. (1), V_y must be 40 MV in the planned case of L_d = 5 m and l_y = 1 mm. By using the developed SCM with a spatial resolution of less than 2.5 μm [6], we can examine the bunch structure at a resolution of 0.5 fs.

Table 1: RFDEF Cavity Specifications

Total Deflecting Voltage	V_y	40	MV
RF deflecting phase	φ_a	0	degree
Fractional bunch length for X-ray oscillation	σ_z	200	fs
Beam energy at the deflector	p_z c	1.45	GeV
Resonant frequency	f_a	5712	MHz
Type of structure		CZ	
Resonant mode		HEM11	
Phase shift per cell	βD	$5\pi/6$	rad
Group velocity	v_g /c	-2.16	%
Filling time	T_f	0.27	μs
Unloaded Q	Q_a	11500	
Transverse shunt impedance	z_y	13.9	MΩ/m

RFDEF

The RFDEF cavity[5], which has a race-track shape rf coupling iris to prevents rotation of the deflection plane of the HEM11 mode, is under development. Table 1 gives the parameters of the RFDEF cavity.

SCM

The SCM[6], as shown in Fig. 1, comprises a vacuum chamber, an in-vacuum stainless-steel foil (100 μm thick) with a small radiation loss to radiate OTR, focusing lenses with 3 groups and 4 pieces, and a CCD camera system. In order to accomplish a bright 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 effective to reduce the airy radius of a near-field image and to obtain a wide numerical aperture. The calculated 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 an optical target film, as shown in Fig. 2. The results taken by observing the target film suggests a comparable resolution to that of the calculation.

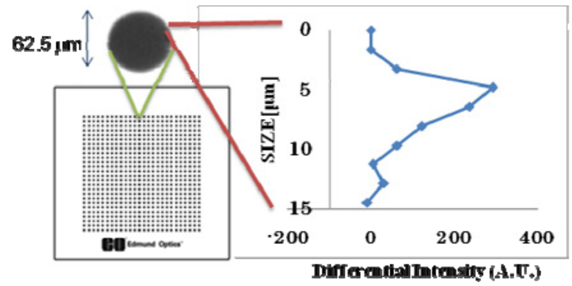

Figure 2: Resolution of the optical system of the SCM. The dot diameter is 62.5 μm. The graph shows that the sharpness (resolution) of the dot edge is about 4 μm (FWHM). The edge sharpness is obtained by differential operation of the dot contrast.

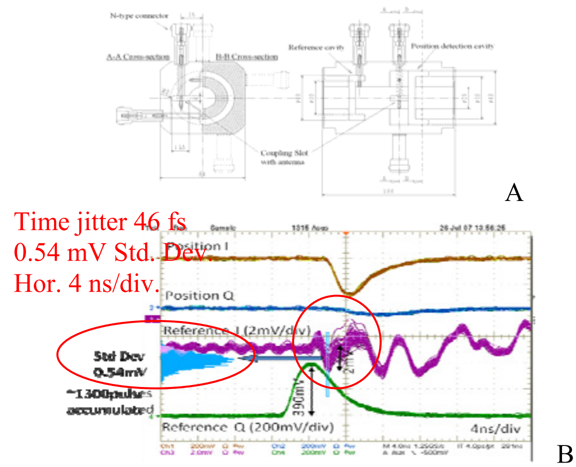

Figure 3: A. Cross-sectional view of the BPM cavity. B. Beam arrival time jitter measured with the BPM intensity cavity. The Std. Dev. of 0.54mV corresponds to a 46 fs jitter (rms). The BPM detection circuit uses the IQ method.

BPM

The BPM[7] as shown in Fig. 3 comprises a position detection cavity (TM110-mode) and a reference cavity (TM010-mode) operated at a resonant frequency of 4760MHz. 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 C-band 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 intensity of the rf field is proportional to the beam position. The detection sensitivity of the BPM is 16 mV/nC/μm. This BPM can also measure the time jitter between an acceleration-rf signal and a beam-induced field at the reference cavity with a detection circuit using the IQ method. An experiment to measure the jitter at the SCSS test accelerator was carried out. The result of a time jitter measurement, as shown in Fig. 3, was 46 fs in rms.

CT

A fast CT[8], as shown in Fig. 4, which has a function to reduce any common mode noise by differential outputs, was developed to measure the beam current. On the other hand, a rough timing determination of the beam-arrival time can be also made with this CT, because of its fast pulse response. The pulse wave form outputted from the CT, as shown in Fig. 4, was taken by using a beam of the test accelerator. The rise time of the pulse was about 200 ps (10-90%). This value is sufficient to determine the rough beam arrival timing of 1 ps resolution.

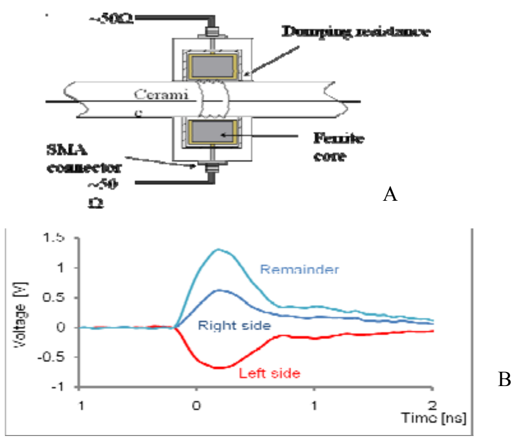

Figure 4: A. Cross-sectional view of the differential output-type CT monitor. B. CT output wave forms induced by the electron beam.

In-Vacuum Photo Diode

To measure the intensity and rough arrival timing of EUV light (e. g. 60 nm), a fast photo diode (IRD Inc.) used within a vacuum was employed. Figure 5 shows the in-vacuum photo diode and the coaxial cable, and the output pulse wave form of when an experiment to observe the EUV light with this PD was carried out at the test accelerator. A 5712 MHz time reference signal for acceleration of the electron beam is also displayed as a time mark. The rise time of the pulse is about 90 ps (10 – 90 %). The measured time jitter of the light referred to the rf signal was 2,5 ps in rms. The actual time jitter was 46 fs as mentioned in the above BPM section. The resolution of this time jitter measurement was close to 1 ps. This PD is still useful to determine the rough arrival timing of the EUV light, because the other timing jitter measurement method under less than a 1ps resolution for the EUV light is not well developed.

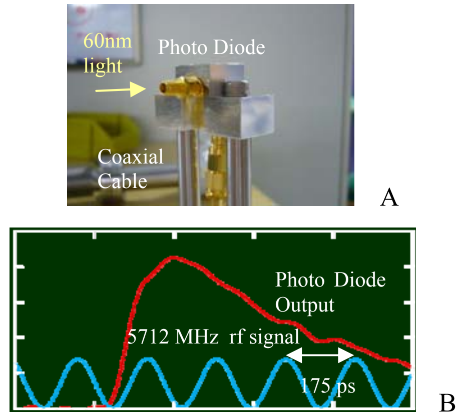

Figure 5: A. EUV in-vacuum photo-diode detection system. B. 60 nm EUV light pulse detected with the PD.

SUMMARY

The development of an XFEL beam monitor system is going well. The developed monitor devices were tested at the SCSS test accelerator, and satisfied our demand of temporal resolution for the XFEL, such as a femto-second region time resolution and a rough timing of around 1 ps. On the other hand, there are some monitors still under development, such as a bunch-length monitor using a THz signal generated by an electron beam. Therefore, we must continue to develop the beam-monitor system, so as to accomplish our XFEL project. We appreciate help from the XFEL project members for this development.

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