Nuclear Instruments and Methods in Physics Research A 637 (2011) S7–S11

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Advanced diagnosis of the temporal characteristics of ultra-short electron beams

Yuji Otake *

XFEL Joint Project/SPring-8, RIKEN, 1-1-1, Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan

A R T I C L E   I N F O

Available online 10 February 2010

Keywords:
Beam Monitor
Ultra-fast electron beambeam
Bunch length
Femto-second
Free-electron laser
X-ray

A B S T R A C T

Monitoring the temporal structure of an ultra-short electron beam is an indispensable function in order to tune a machine to obtain a highly qualified beam for a recent sophisticated accelerator, such as an X-ray free electron laser (XFEL), and to maintain stable X-ray laser operation. For this purpose, various instruments, such as an HEM11-mode RF beam deflector (RFDEF), a screen monitor (SCM), an electro-optic (EO) sampling method that uses a ZnTe crystal, and a beam position monitor (BPM) have been developed. The SCM that is 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 and it is installed at a position 5 m downstream from the RFDEF. The EO sampling method showed the ability to observe an electron bunch length for up to 300 fs (FWHM) at the SCSS test accelerator. The phase reference cavity of the BPM has an additional function of providing beam arrival timing information. A test for the BPM showed temporal fluctuation of 46 fs on the beam arrival timing at the test accelerator. These monitors with high temporal resolutions allow us to achieve the fine beam tuning demanded for the XFEL. The above-mentioned activities are described in this paper as a review article.

1. Introduction

The temporal beam characteristic in recent sophisticated accelerators, such as time-sliced emittance along a bunch width of several ten femtoseconds, is one of the most indispensable parameters to define beam quality. For example, a further bunch peak current of more than 1 kA, which is strongly correlated to an ultra-short electron bunch length compressed by a bunch compressor and a smaller sliced emittance of less than 1π mm mrad, can effectively reduce the gain length of self-amplified spontaneous emission (SASE) amplification along an undulator beam line of an X-ray free electron laser (XFEL) [1]. Of course, our project, XFEL/SPring-8 [2], is not exempted from these conditions. However, it is difficult to measure the temporal structure of an ultra-short bunch, such as the energy to time (E–T) distribution, which reflects the sliced emittance measured by the quadrupole magnet scan method and the bunch width. To overcome this difficulty, a method to observe the above-mentioned parameters with a resolution of at least a few femtoseconds is necessary [3]. Several methods for measuring these parameters while maintaining an ultra-short bunch have been developed to achieve an extremely stable beam, meaning a constant degree of intensity, energy, bunch length, emittance, and timing, which allows a stable SASE process.

Measurement methods for an ultra-short electron beam are roughly categorized as (1) a temporal bunch structure measurement to realize the requirements mentioned above and (2) a measurement of the beam timing that reflects the velocity bunching condition of an injector linac and a magnetic bunching condition related to an R56 parameter in the magnetic chicane [3,4]. Since these two parameters strongly influence the performance of recent sophisticated accelerators, like the XFEL, they should be measured to perform optimum beam tuning to generate a stable SASE.

This paper is a review article that gives rough introductions of the above-mentioned measurement methods for an ultra-short electron beam, based on development activity for XFEL/SPring-8, and provides recent results that satisfy the demanded temporal resolution of a femtosecond region.

2. Temporal structure-measurement methods

The most promising method to measure the beam temporal structure of several ten femtoseconds is an RF deflector system, which pitches the electron beam to project its longitudinal temporal image on a screen. The next bunch length measurement method is EO sampling using an electro-optical (EO) crystal to

* Tel.: +81 791 58 2929; fax: +89 791 58 2840.
E-mail address: otake@spring8.or.jp

0168-9002/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2010.02.010

detect the relativistic electric field of a beam. This electric-field distribution reflects the longitudinal bunch structure of the beam.

2.1. RF deflector system

The RF deflector system [5] comprises a transverse RF deflector cavity (RFDEF) [6], a beam slit, and a high-precision beam screen monitor (SCM) [7] with a position resolution of several micrometers. Fig. 1 shows the beam-monitor layout at the RF deflector part of XFEL/SPring-8 as an example. The function of this part is described as follows. The RF deflector cavity pitches the beam bunch around its center to project an image of the longitudinal bunch structure on the screen of the SCM. The relation between the beam kick 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 space between the center of the RFDEF and the screen surface of the SCM, k_a the wave number of the RFDEF, σ_z the bunch length, and p_z the longitudinal momentum of a bunch. On putting the parameters of the RFDEF cavity listed in Table 1 in Eq. (1), V_y should be 40 MV in the planned case of L_d=5 m and l_y=1 mm, as calculated. Using the developed SCM with a spatial resolution of less than 2.5 μm [7], as mentioned below, we can examine the bunch structure with a resolution of 0.5 fs from an energy vs. time image of the electron beam. The image shown in Fig. 2 is a mere simulated example in the case of XFEL/SPring-8. Since this system is under development, unfortunately, we cannot show an experimental image of the beam bunch structure.

2.1.1. RFDEF

The RFDEF, as shown in Fig. 3, is a backward-traveling wave accelerating structure with a newly devised racetrack-shaped RF coupling iris to prevent any rotation of the deflection plane of an HEM11 mode. Table 1 gives the parameters of the RFDEF. Fig. 4 shows the pass bands of the vertical and horizontal HEM-11 modes. This Brillouin diagram suggests that there is a sufficient band width to transmit the HEM-11 deflection mode, and a sufficient frequency separation between the vertical and horizontal modes by resolving the degeneracy of both modes using a racetrack-shaped iris.

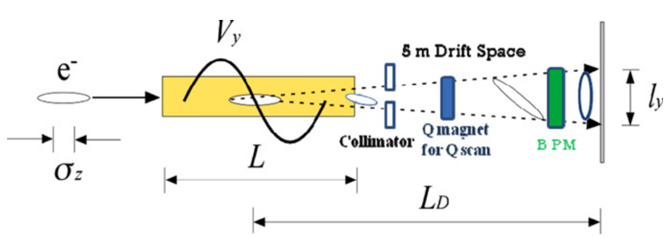

Fig. 1. Beam-monitor layout at the RF deflector part lining up an RFDEF, a collimator, a Q-magnet, a BPM, and an SCM.

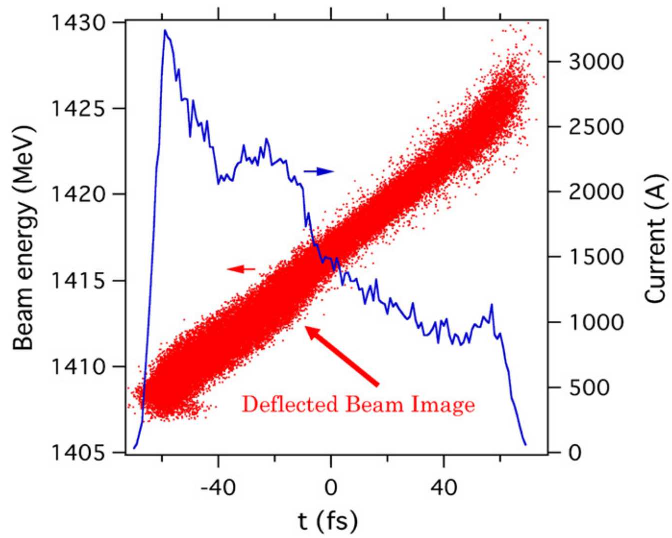

Fig. 2. Simulated beam deflection image (red: energy vs. time) on the SCM by the RFDEF at a position after the bunch compressor. The beam energy is 1.54 GeV.

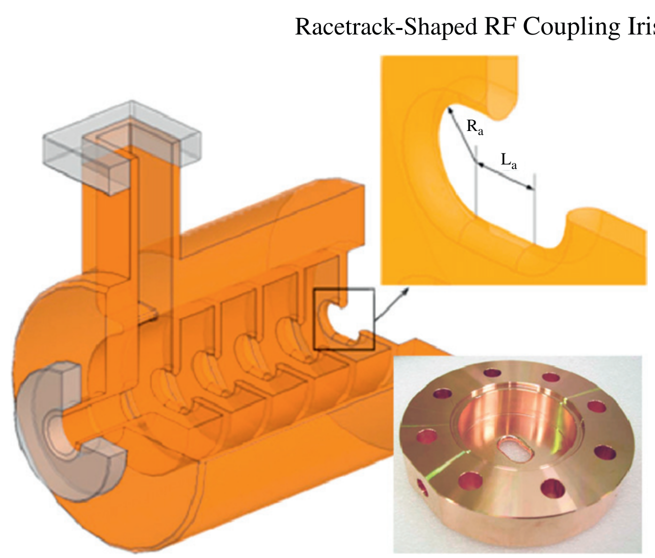

Fig. 3. Cut view of an RFDEF. The RFDEF uses an HEM-11 mode backward wave. It has a racetrack-shaped RF coupling iris, which prevents any rotation of the deflection plane of the mode.

Table 1
RFDEF specifications.

Total deflecting voltage	V_y	40	MV
RF deflecting phase	φ_a	0	deg
Fractional bunch length for X-ray oscillation	σ_z	200	fs
Beam energy at the deflector	p_zc	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	11,500	
Transverse shunt impedance	z_y	13.9	MΩ/m

2.1.2. Screen monitor (SCM)

Fig. 5 shows the screen monitor, which consists of a vacuum chamber, an in-vacuum thin metal foil to radiate optical transition radiation (OTR), a focusing lens comprised of three groups and four pieces, and a CCD camera. The major feature of this monitor is a high-resolution and bright optical system, employing a thin oval foil (material: stainless steel; semi-major axis: X=14 mm; semi-minor axis: Y=10 mm; thickness: 100 μm) to reduce any radiation loss. In order to realize this optical system, the lenses are placed near the foil, with a distance of 100 mm between the surface of the front lens and the foil surface; the lenses have a large aperture of 2 in. This geometrical structure of the optical system is very helpful to reduce an airy radius of a