DEVELOPMENT OF NON-INVASIVE ELECTRON BEAM POSITION MONITOR BASED ON COHERENT DIFFRACTION RADIATION FROM A SLIT*

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Abstract

Diffraction radiation is emitted when a charged particle passes through in the vicinity of a boundary between two media with different dielectric constants. An aperture, a slit, and an edge are used for diffraction radiation target. It is theoretically suggested that an asymmetry of a spatial distribution of diffraction radiation appears by changing the beam trajectory with respect to the center of a rectangular slit. We have developed the beam position monitor using the coherent diffraction radiation generated when a sub-picosecond electron beam passes through the rectangular slit. A theoretical background of the diffraction radiation emitted from the slit and experimental results will be reported.

INTRODUCTION

Generation of an ultra-short pulsed electron beam with a bunch length of few hundreds of femtoseconds and below 100 fs is key technique of accelerator science; that are generation of intense terahertz radiation [1] and x-ray free electron lasers (X-ray FEL) [2]. Many techniques for beam diagnostic have been developed so far.

Diffraction radiation (DR) is used as a non-invasive beam diagnostic and can be used to measure beam energy, transverse size, divergence, and position [3]. DR is generated when a charged particle moves in the vicinity of a boundary between two media with different dielectric constants with a condition of $d < \gamma\lambda/2\pi$, where d is the distance between the edge of the medium and the electron, γ is the Lorentz factor of the electron beam, and λ is the observed wavelength of DR [4]. An aperture, a slit, and an edge can be used as DR devices.

Recently, three-dimensional electron bunch charge distribution (3D-BCD) monitor has been proposed for the X-ray FEL by H. Tomizawa [5-6]. It is based on Electro-Optical (EO) multiple sampling (multiplexing) with a manner of spectral decoding. Here, three hollow EO detectors surround the electron beam axis azimuthally and are installed at three detection points on the beam axis. To simplify the monitor system of the 3D-BCD, the basic concept of the DR beam position monitor was proposed [5]. The electron bunch's center of mass and incident angle at the central EO detector of 3D-BCD is defined by the EO detectors of both ends. We investigated the feasibility of the concept of this novel monitor.

Our facility, S-band compact electron linac at the National Institute of Advanced Industrial Science and Technology (AIST) [7] is the beam energy of 40 MeV. If we observe an optical diffraction radiation with the wavelength of 500 nm, the distance d must be smaller than 6 μm. This value will be much smaller than the beam size. Therefore it is necessary to observe the longer wavelength of DR for realistic measurements.

Coherent radiation emits when the wavelength of the radiation is comparable to or longer than the electron bunch length. The frequency spectrum of coherent radiation is mainly depended on a bunch form factor described as

$$f(\omega) = \left| \int_{-\infty}^{\infty} \rho(t) \exp(i\omega t) \mathrm{d}t \right|^2 , \qquad (1)$$

where ω is the angular frequency of coherent radiation, $\rho(t)$ is the particle distribution, and t is time. If $\rho(t)$ is assumed to a Gaussian particle distribution of bunch length σ (rms), the form factor is expressed as

$$f(\omega) = \exp(-\sigma^2\omega^2). \qquad (2)$$

Consequently, the frequency spectrum of coherent radiation is strongly depended on the bunch length σ. For example, if the bunch length is 200 fs, coherent radiation up to the frequency of 2 THz (wavelength of 150 μm) is coherently enhanced. If we observe the wavelength of 150 μm of the CDR, the distance d must be less than 2 mm. This condition is useful for the CDR measurement. Therefore, CDR can be used to measure electron bunch length, energy, transverse size, divergence, and position.

In this paper, we focus on the measurement of the beam position using the CDR emitted from a rectangular slit. A theoretical background and experimental results will be reported. We have successfully detected the beam position by measuring the asymmetry of the spatial distribution of CDR.

DIFFRACTION RADIATION GENERATED FROM A RECTANGULAR SLIT

Theoretical equations concerning with the DR emitted from the rectangular slit are described in Ref. [4]. The DR field generated by a charged particle passing through a rectangular slit opening in a rectangular screen can be described as

$$E^{\mathrm{DR}}_{x,y}(a_{\mathrm{out}}, b_{out}) = E^{\mathrm{TR}}_{x,y}(a_{\mathrm{out}}, b_{\mathrm{out}}) - E^{\mathrm{TR}}_{x,y}(a_{\mathrm{in}}, b_{\mathrm{in}}) . \qquad (3)$$

where the indices x and y are the horizontal and vertical polarization components at the detector coordinates, a_{out}

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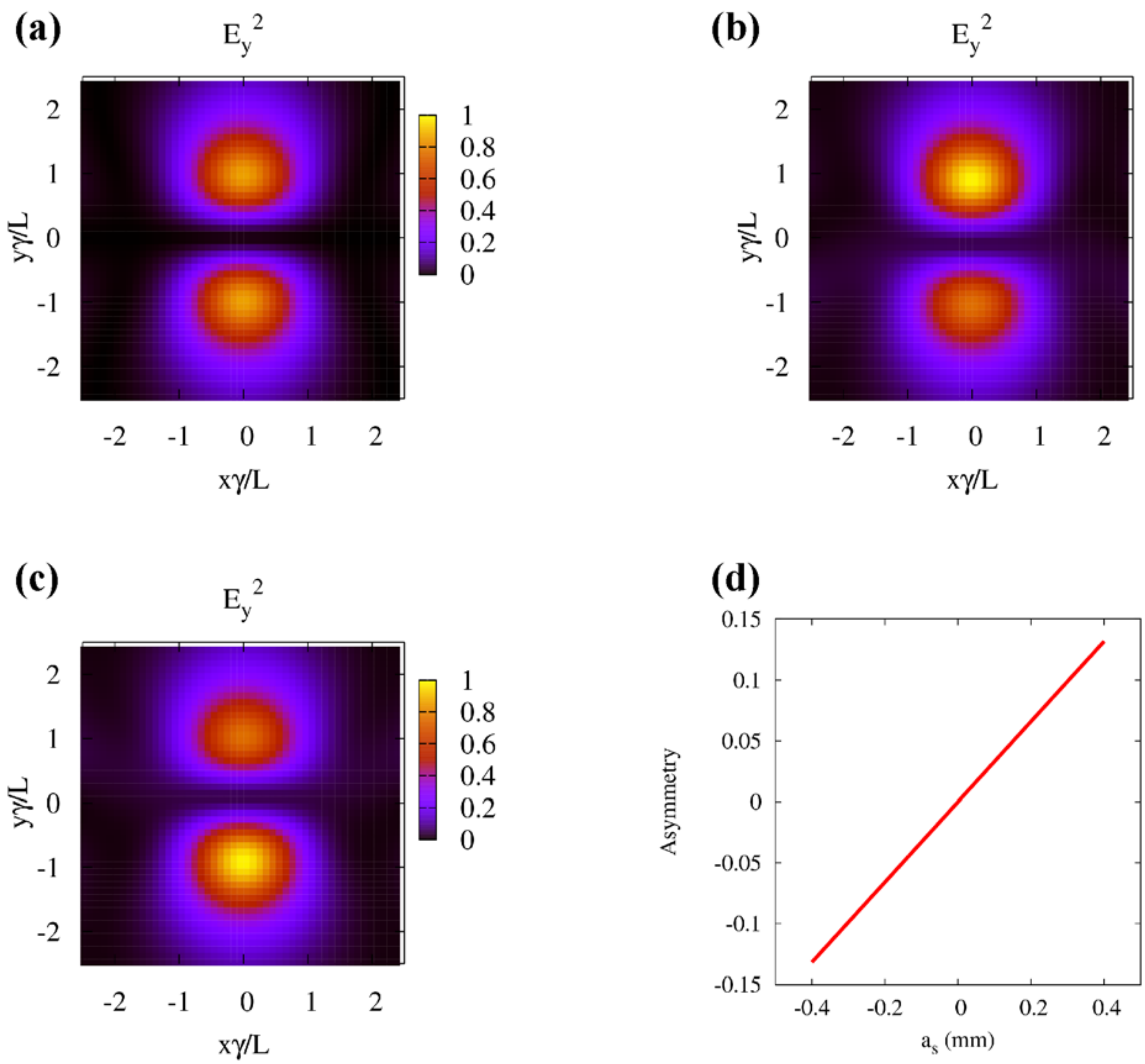

Figure 1: Normalized spatial distribution of vertically polarized DR calculated for different offsets of the electron beam trajectory with respect to the slit center derived from Eqs. (3) – (5). (a) a_s = 0.0 mm, (b) a_s = -0.4 mm, and (c) a_s = 0.4 mm. (d) Asymmetry in the plane $x = 0$.

and b_{out} are the screen dimensions along the y-axis and x-axis, respectively, a_{in} and b_{in} are the slit dimensions along the y-axis and x-axis, respectively. E^{TR} is the transition radiation (TR) field including pre-wave zone effect generated by a rectangular screen and is described as

$$E^{TR}_{x,y}(a_{out},b_{out}) = -\frac{R_{x,y}}{4\pi^3}\frac{ek^2}{\gamma L}\int_{-a_{out}/2+a_s}^{a_{out}/2+a_s} dy_s \int_{-b_{out}/2+b_s}^{b_{out}/2+b_s} dx_s \times \frac{x_s, y_s}{\sqrt{x_s^2+y_s^2}} K_1\left(\frac{k}{\gamma}\sqrt{x_s^2+y_s^2}\right) \times \exp\left\{\frac{ik}{2L}(x_s^2+y_s^2) - \frac{ik}{L}(x_s x + y_s y)\right\} \quad (4)$$

Here R_x and R_y are the Fresnel reflection coefficients, e is the elementary charge, k is the wave number, L is the distance from the slit to the detector plane, a_s and b_s are the offsets of the electron trajectory with respect to the slit center along the y-axis and the x-axis, respectively, x_s and y_s are the coordinates of the target surface, and K_1 is the modified Bessel function of the second kind, respectively.

The spectral angular distribution of the DR energy is calculated to be

$$\frac{d^2W^{DR}}{d\omega d\Omega} = 4\pi^2 L^2\left(\left|E_x^{DR}\right|^2 + \left|E_y^{DR}\right|^2\right). \quad (5)$$

Here, $d\Omega = dxdy/L^2$. We can calculate the spatial distribution of DR emitted from the slit by using Eqs. (3) - (5).

Figure 1 show the normalized spatial distribution of vertically polarized DR calculated for different offsets of the electron beam trajectory with respect to the slit center derived from Eqs. (3) - (5) and spatial distribution asymmetry as a function of the offsets. The asymmetry of

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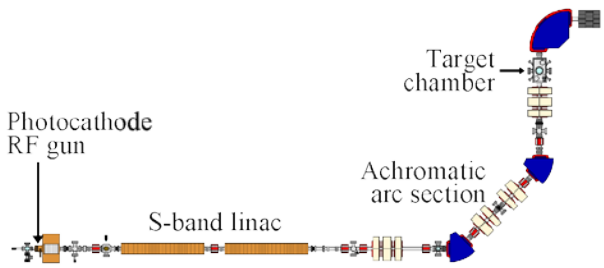

Figure 2: Schematic illustration of the S-band compact electron linac at AIST.

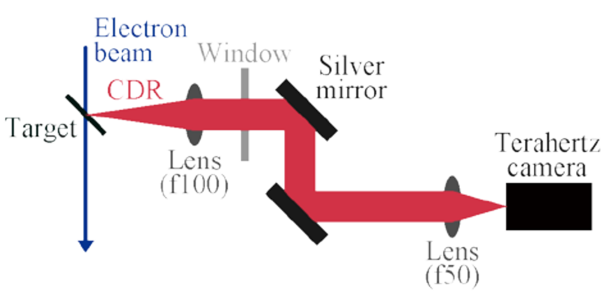

Figure 3: Schematic illustration of the spatial distribution measurement of CDR generated from the rectangular slit using the terahertz camera.

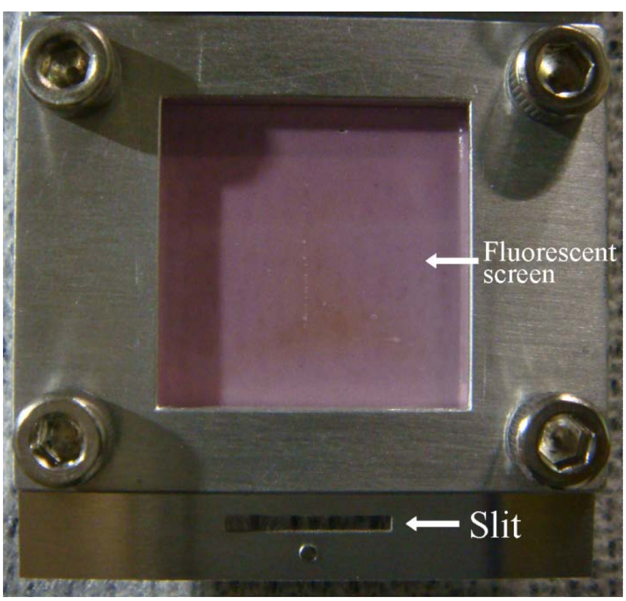

Figure 4: Slit target for CDR.

the spatial distribution was calculated by the following equation:

$$A = \frac{I_{\max}^{y<0} - I_{\max}^{y>0}}{I_{\max}^{y<0} + I_{\max}^{y>0}}. \quad (6)$$

Here $I^{y<0}_{\max}$ and $I^{y>0}_{\max}$ are the maximum intensity in the range of $y < 0$ and $y > 0$ in the plane $x = 0$. The calculation parameters are as follows: $\gamma = 80$; $\lambda = 150$ μm; $L = 790$ mm; $a_{out} = b_{out} = 20$ mm; $a_{in} = 1$ mm; $b_{in} = 10$ mm; $b_s = 0$ mm; and $R_x = R_y = 1.0$. One can see that the asymmetry appears by changing the offsets and reaches 0.13 at the offsets of ± 0.4 mm.

EXPERIMENTAL SETUP

We have developed a non-invasive beam position monitor using a rectangular slit at an S-band compact electron linac (Fig. 2) at AIST. The S-band compact electron linac consists of a Cs_2Te laser photocathode RF gun, a linear accelerator, and an achromatic arc section. Electron beam of 20 micro-bunches separated by 10.5 ns was generated in the RF gun. The bunch charge is 0.6 nC/bunch. Then the electron beam was accelerated up to 40 MeV at two accelerating tubes and passed through the achromatic arc section for bunch compression. The achromatic arc section consists of two 45-degree bending magnets and four quadrupole magnets. The electron beam was compressed to less than 300 fs at the achromatic arc section and then passed through the slit target inside a target chamber shown in Fig. 2.

We measured the spatial distribution of CDR using a terahertz camera (NEC, IRV-T0831) as shown in Fig. 3. The target mounted on a linear manipulator was inclined 45-degree to the electron-beam axis. Backward CDR was emitted perpendicularly to the electron beam axis and extracted into the atmosphere from the vacuum through a z-cut quartz window.

The terahertz camera contains an uncooled micro-bolometer focal plane array (FPA). The structure of focal plane array and the absorption mechanism of the terahertz radiation are explained in detail in Ref. [8]. Specifications of the terahertz camera are as follows [9]: pixel format, 320 x 240; pixel pitch, 23.5 μm; frequency range, 1 - 7 THz; frame rate, 30 Hz; and Noise equivalent power (NEP), <100 pW.

Figure 4 shows a rectangular slit target. A target was made the hole of 10 mm x 1 mm in a 0.5 mm thick aluminium plate. Horizontal size of the hole is much larger than the vertical size. In order to observe the CDR with the terahertz camera, the beam trajectory and the beam size of the electron beam have to be adjusted. First, we checked the spatial distribution of coherent transition radiation (CTR) emitted from the fluorescent screen and metal screen. The beam parameters were adjusted to obtain the ring profile of CTR [10]. Then, we measured the spatial distribution of CDR using the slit. The slit position was moved at 100 μm step in the vertical direction in the range of ± 400 μm from the slit center.

RESULT AND DISSCUSSION

Figure 5 shows the spatial distribution of CDR measured with the terahertz camera for two electron beam trajectory offsets with respect to the slit center and the line intensity distribution. The spatial distribution was clearly changed by changing the electron beam trajectory with respect to the slit center. A total count of a

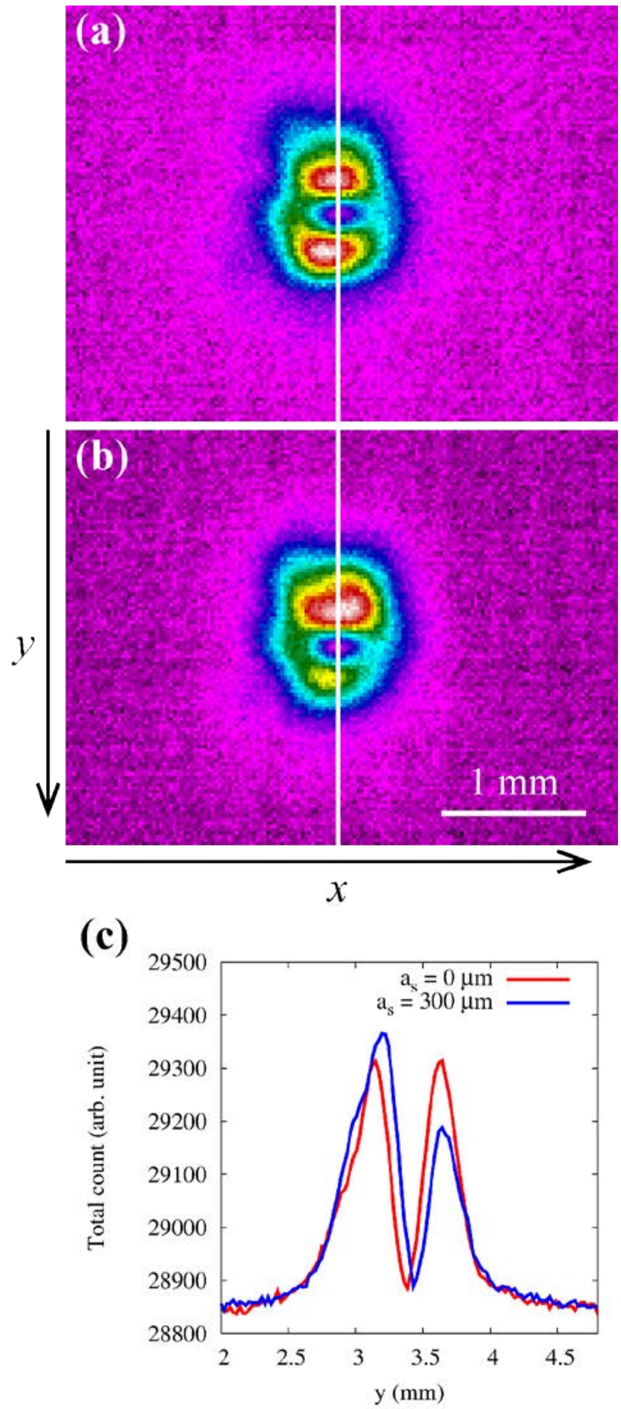

Figure 5: Spatial distribution of CDR measured with the terahertz camera. The electron beam trajectory offsets with respect to the slit center as (a) 0 µm and (b) 300 µm, respectively. (c) The line intensity distribution given in (a) and (b), respectively.

background, where y < 2.5 mm and 4.5 mm < y, is not reduced to zero as shown in Fig. 5 (c). This is due to the NEP of the FPA.

Figure 6 shows the asymmetry of the spatial distribution of CDR in the vertical direction as a function of electron beam offsets with respect to the slit center. It

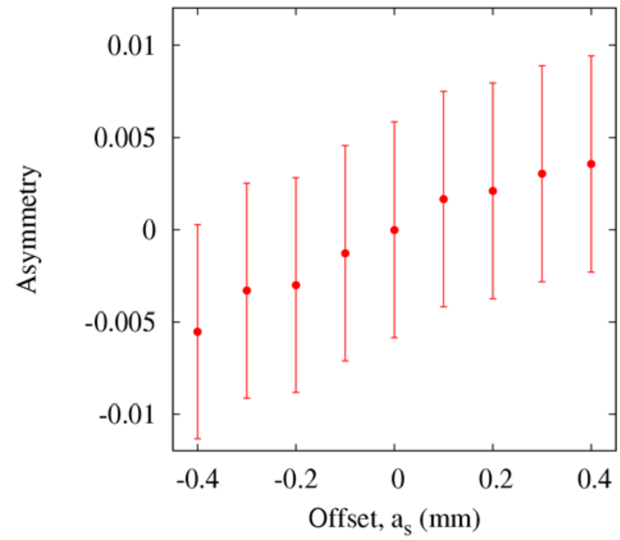

Figure 6: Asymmetry of the spatial distribution of CDR in the vertical direction as a function of electron beam offsets with respect to the slit center.

was clearly observed that the asymmetry depends on the electron beam offsets. Nevertheless, a discrepancy of the asymmetry between the measurement data and the calculated value shown in Fig. 1 (d) was observed. This discrepancy is because of the NEP. If the asymmetry is calculated by considering that the base line of Fig. 5 (c) is zero (the origin), the asymmetry is increased to 0.2 at the offset of 300 µm. This value is twice as much as the calculated value as shown in Fig. 1 (d). However, detailed data analysis has to be performed for a precise comparison.

CONCLUSION

We have developed the non-invasive beam position monitor by observing the asymmetry of the spatial distribution of CDR emitted from the rectangular slit. The spatial distribution was measured with the terahertz camera by changing the slit position with respect to the electron beam trajectory. The asymmetry as a function of electron beam offset with respect to the slit center was clearly observed. This technique can measure the absolute position of an electron beam and can be widely used as a beam position monitor even in high energy electron beam with the energy up to 1 GeV. We will develop the bunch length and beam size measurement technique using the CDR. To improve the contrast of spatial radiation profiles measured with the terahertz camera, we are planning to use a gating THz camera with low NEP for the next step.

REFERENCES

[1] G. L. Carr et al., Nature 420 (2002) 153.
[2] Y. Inubushi et al., Phys. Rev. Lett. 109 (2012) 144801.
[3] R. B. Fiorito et al., Nucl. Instr. Meth. B, 173 (2001) 67.
[4] P. Karataev et al., Phys. Rev. ST- AB, 11 (2008) 032804.
[5] H. Tomizawa et al., Proc. FEL2010 (2010) 445.
[6] H. Tomizawa et al., Proc. IBIC2013 (2013) 1.

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[7] R. Kuroda et al., Nucl. Instr. and Meth. A 637 (2011) S30.
[8] N. Oda, Comp. Rend. Phys. 11 (2010) 496.
[9] N. Oda et al., Proc. of SPIE 8363 (2012) 83630A.
[10] Y. Taira et al., Vib. Spec. in press 2014.

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