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MEASUREMENT OF CHERENKOV DIFFRACTION RADIATION FROM A SHORT ELECTRON BUNCH AT t-ACTS

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Abstract

Cherenkov Diffraction Radiation (ChDR) can be utilised as a tool of non-destructive beam diagnostics. The photon flux of ChDR is proportional to the thickness of the dielectric used as the radiator unless its transmittance is small, so that much larger flux can be expected than ordinary diffraction radiation. A basic experimental study about coherent ChDR has been performed at test accelerator facility, t-ACTS, in Tohoku University. The measurements of coherent ChDR from short electron bunches of about 100 fs are reported.

INTRODUCTION

Non-destructive beam diagnostics with single shot is a significant tool for some kinds of accelerators in their operation. For example, laser wake field accelerator can generate quasi-monoenergetic electron beam with GeV class energy, while the beam stability is still the problem which requires a stable and precise control of plasma channel in a gas jet. Recently, development of a new technique called Plasma Micro Optics improved beam quality drastically [1, 2], however, the beam repetition rate is still very low, and thus it would be desirable to use the measured beam itself successively in further application. So far, we have performed the experiments of bunch length measurement using Cherenkov radiation from a thin silica aerogel [3]. In the experiments, the entire ring image of Cherenkov radiation was clearly obtained, and furthermore it was also observed that the ring width depends on the transverse shape of electron beam. Employing ChDR, which is the radiation generated when electrons pass near the dielectric but not inside, it can be utilized as non-destructive beam diagnostics [4]. In this paper, we present an initial measurement result of ChDR generated by a 22 MeV electron beam with short bunches of ~100 fs and demonstrate an intensity dependence of ChDR on the electron beam position.

COHERENT CHDR

ChDR from a Dielectric with a Hole

For a given wavelength, Cherenkov radiation is observed at the specific angle θ_c given by the expression:

$$\cos\theta_{\mathrm{c}} = 1/\beta n, \qquad (1)$$

where n is the refractive index of a dielectric, $\beta = v/c$, and v, c the speed of an electron and light, respectively, in the case of $\beta n > 1$ [5]. The number of photons emitted by an electron within the spectral region confined by the wavelengths λ_1 and λ_2 is also given by

$$N = 2\pi\alpha L\left(1-\frac{1}{\beta^2 n^2}\right)\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right), \qquad (2)$$

where α is the fine-structure constant, and L a dielectric thickness along the electron trajectory [5]. The photon flux N is proportional to the thickness L unless its transmittance is small, much larger flux can be expected than ordinary diffraction radiation. By the way, if the electron is passed near the surface outside the dielectric, one has to take into account an additional attenuation factor K to the photon flux to be observed,

$$K = \exp\left(-4\pi\frac{d}{\gamma\beta\lambda}\right), \qquad (3)$$

where γ is the normalized electron energy, and d an impact parameter which is the distance to the electron trajectory from the dielectric surface [6]. The factor K decrease steeply as the wavelength approaches shorter region. In actually, electron beam travels at an appropriate distance from the dielectric surface comparing with the transverse size of the electron beam, so that the wavelength region of the observed radiation will be longer than sub-millimeter for beam energies around 22 MeV. For the higher energy case (~ a few GeV), the corresponding wavelength would be shifted to MIR region.

Coherent ChDR

The generated number of photons decreases inversely with the wavelength as shown in Eq. (2), while there is suppression in the shorter wavelength region due to the factor K. However, in the wavelength longer than the bunch length of electron bunch, the radiation intensity is enhanced by coherent radiation as,

$$I(\omega) = I_0(\omega) {N_e}^2 f(\omega)\chi, \qquad (4)$$

where I_0 is the intensity for a single electron, N_e the number of electrons in the bunch, $f(\omega)$ the bunch form factor whose inverse Fourier transform gives the longitudinal and transverse density distribution of the electron bunch, and χ a factor of the electron-beam divergence [7].

The spectrum for coherent ChDR can be obtained by multiplying the above equations with a given bunch form factor. Figure 1 shows the coherent ChDR spectrums generated by an electron bunch with the energy of 22 MeV and Gaussian shape of σ_t = 100 fs for different impact parameters. As the impact parameter decreases, the peak height and frequency shift, which eventually corresponds to the coherent Cherenkov radiation (solid line in

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Fig. 1). The peak frequency of the coherent Cherenkov radiation is estimated to be 1.1 THz.

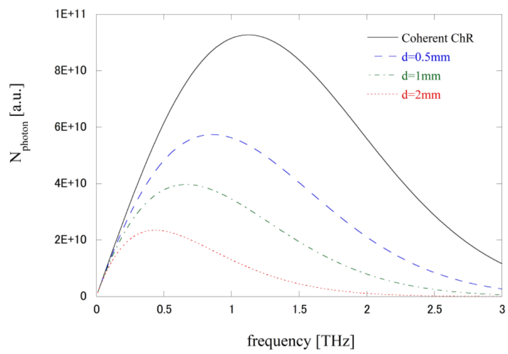

Figure 1: Coherent ChDR spectrum for some impact parameters (0.5, 1, 2 mm), where beam energy of 22 MeV and Gaussian bunch shape of 100 fs (rms) are assumed.

MEASUREMENT OF CHDR

Experimental Set-up

Beam experiment was performed at t-ACTS (test accelerator as coherent terahertz source), Tohoku University. The beam parameters are shown in Table 1. The short electron bunch of about 100 fs is accomplished by the velocity bunching scheme in a 3 m long accelerating structure with a help of specially designed rf-gun [8]. In this experiment, it was first aimed at observing the whole ring image of ChDR. So as to extract the whole ring image through a vacuum window with a reasonable size, the refractive index of the dielectric should be sufficiently small. As the radiator for this purpose, a hydrophobic silica aerogel with an ultra-low refractive index (n = 1.03) was employed [9]. The corresponding Cherenkov angle is 14 ° for the refractive index. The experimental set-up is shown in Fig. 2.

Table 1: Beam Parameters at t-ACTS

beam energy	22 ~ 50 MeV
bunch charge	3 ~ 4 pC /bunch
rms bunch length	~ 100 fs
macropulse length	~ 2.0 µs
number of bunches	~ 5700 bunches/macropulse

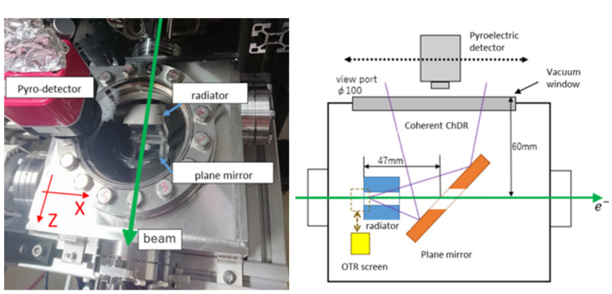

Figure 2: Experimental set-up.

The electron beam passes through the hole inside the radiator, which thickness and hole diameter is 25 mm and 5 mm, respectively. The generated ChDR is reflected by a plane mirror toward upside and then guided outside the vacuum chamber through the fused silica window with a large aperture, while the electron beam passes through a hole of 15 mm diameter inside the mirror as shown in Fig. 2. In order to monitor the position and transverse size of electron beam by generating optical transition radiation (OTR), an aluminum mirror can be inserted to the radiator position. Typical transverse beam size in the experiment was 130 and 150 µm for horizontal and vertical, respectively. The extracted ChDR was then detected by a pyroelectric detector (PYD-1@PHLUXi) with broadband range and high sensitivity [10]. The pyroelectric detector is mounted on a two-axis movable stage and acquires 1D and 2D images of Cherenkov ring by moving in the XZ plane while keeping a distance of 15 mm from the vacuum window. An aperture (2×8 mm for 1D and 4×4 mm for 2D scan) is also attached in front of the detector surface to improve the position resolution.

First Measurement of Beam Position Dependence of Radiation Intensity

First the detector was horizontally scanned along the X direction to obtain the beam position dependence of the radiation intensity. The number of scan steps and the step size are 100 and 2 mm, respectively. Figure 3 shows the measurement results of the 10 scans for each different beam position. The electron beam was steered between -1.65 and +1.85 mm, where the position 0 mm corresponds to the center of the radiator hole. The Cherenkov angle is estimated to be 14˚, and thus the radius of the ring image is deduced to be 30 mm at the detector position. As seen in Fig. 3, the increase of signal amplitude at the position corresponding to the ring radius was clearly observed as the beam position approaches to the wall of radiator hole. There is also a broad peak at the center of the horizontal axis, which is almost independent to the beam position. According to a prior measurement without the radiator, it was shown that this peak is caused by the diffraction radiation generated at the hole of the plane mirror. This diffraction radiation was largely suppressed by increasing the diameter of the mirror hole to 15 mm, but there still remains a considerable contribution.

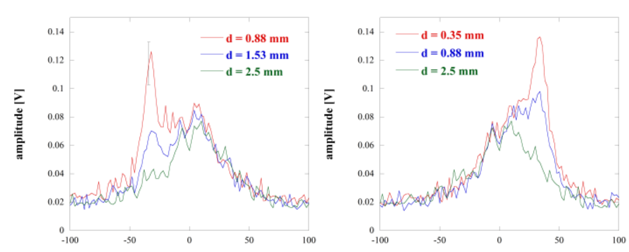

Figure 3: Beam position dependence of the radiation intensity. The beam was steered to -1.05, -1.65 mm (left) and +1.35, +1.85 mm (right). An error bar represents the typical standard deviation of the measured signal.

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The impact parameter dependence of the ChDR signal was extracted from the measured scan data. Although the signal is rather small comparing with the noise level, the opposite side slope of signal was used for background subtraction. After the subtraction, the signal amplitude was integrated over the region corresponding to the Cherenkov angle. Figure 4 shows the impact parameter dependence of the integrated coherent ChDR signal. Solid line shows an exponential fit to the measurement data, and the coefficient was obtained to be B = 0.89±0.22 1/mm. From the fitting results, a radiation frequency was extracted which represents the typical frequency of the observed radiation. The obtained frequency is 0.91±0.22 THz and consistent with the expected peak frequency in Fig. 1.

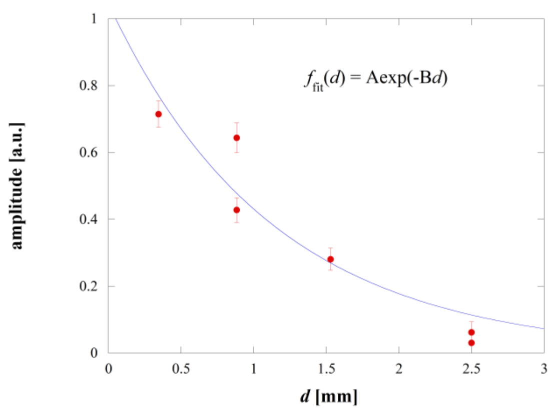

Figure 4: Impact parameter dependence of the coherent ChDR signal.

The detector was also scanned with 4 mm step over 100×88 mm area in XZ plane to obtain the rough image of the Cherenkov ring. Figure 5 shows the observed 2D images of ChDR in THz region. When the electron beam position was steered to ±1.9 mm, the partial ring image was observed in the near side of the radiator.

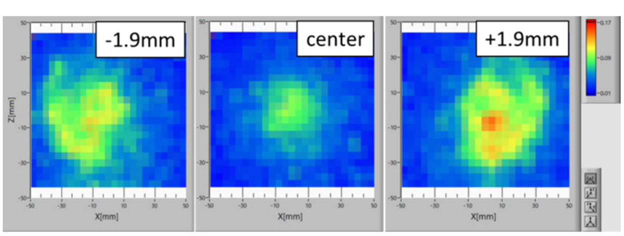

Figure 5: Observed 2D image of Cherenkov ring.

DISCUSSION

So far, the attenuation in the optical system has been implicitly assumed to be small. Prior to the beam experiment, we performed the measurement of the transmission of the silica aerogel in the visible light and NIR region using a spectrophotometer (U-4100@Hitachi Ltd.), and confirmed the good transparency more than 95 %. However the observed signal level is rather small in the beam experiments, so that a non-negligible loss of the ChDR signal in the optical path, i.e. Cherenkov radiator, beam window, etc., should be considered for the THz region. Recently, we also performed a transmission measurement of the hydrophobic silica aerogel in the THz frequency region employing a terahertz optical sampling system (TAS7400TS @ADVANTEST Corp.) [11]. The preliminary results show the significant decrease in the transmission (~90 % loss at ~1 THz), and thus the enhancement of the photon flux by the increase in the thickness of the aerogel radiator has been offset considerably due to this decrease. In order to monitor not only the beam position but also the longitudinal beam shape simultaneously in a further development for the beam instrumentation, it is necessary to observe the entire image of the Cherenkov ring. It would be required to select a more excellent material than silica aerogel with the higher transmittance as the Cherenkov radiator, as well as the beam window (fused silica), concerning the handling of light signals in the THz region.

SUMMARY

The initial beam experiment with respect to the ChDR was performed, and the ring image of the ChDR was partially observed in THz frequency region. The impact parameter dependence of the signal intensity for ChDR was also measured as a basic study for the non-destructive beam diagnostics, which results was consistent with the expected radiation frequency spectrum. Because of the poor transmittance in the current optical system for the THz region, the ChDR signal was too small to extract the beam position accurately at the moment. Besides the improvement of the transmittance in the optical system, we plan for further study to investigate feasibility for the non-destructive beam diagnostics.

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