Study of Longitudinal Phase Space Distribution Measurement via a Linear Focal Cherenkov Ring Camera

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Abstract

At Tohoku University, a study of generation of intense coherent THz radiation from sub-picosecond electron bunches has been developing. Initial electron distribution in the longitudinal phase space produced by an electron gun is crucial for extreme short electron bunch production. For relatively lower energy electrons, a novel method for measurement of electron kinetic energy employing velocity dependence of the opening angle of Cherenkov radiation was proposed. Combined use of a streak camera and a "turtle-back" mirror that confines the Cherenkov light on to a linear focal line may allow us to observe the longitudinal phase space distribution directly. An experimental setup was examined with numerical ray tracing, and a radiator placed outside the vacuum chamber was designed to achieve the highest energy resolution. To extract the electron beam from the vacuum, a beryllium thin film was proposed as a beam window. However, a Geant4 Monte Carlo simulation showed that multiple scatterings of the electron beam in the beryllium window significantly affects the resolution of the Cherenkov angle. Detail of examination will be presented in this conference.

INTRODUCTION

Intense relativistic electron beam with very short bunch length is an essential key to coherent radiation in the terahertz frequency region [1]. A test accelerator for the coherent terahertz source (t-ACTS) has been constructed at Tohoku University, in which the generation of intense coherent terahertz (THz) radiation from sub-picosecond electron bunches will be demonstrated [2]. The t-ACTS facility proposed an advanced independently tunable cells (ITC) thermionic RF gun consisting of two uncoupled cavities. The electron beam from the RF-gun would be introduced into an alpha magnet and a linac as the bunch compression system. Proper longitudinal phase space distribution can be produced by the ITC RF-gun adjusted relative RF phases and field strengths of the two cavities. Since the final electron bunch can be dictated by the longitudinal phase space distribution at the RF-gun exit, longitudinal phase space distribution measurement is inevitably significant for extreme short electron bunch production.

Measurement of electron kinetic energy employing velocity dependence of the opening angle of Cherenkov radiation was proposed as a novel method for relatively lower energy electrons. By using combination of a streak camera and a "turtle-back" mirror which confines the Cherenkov light on to a linear focal line, the longitudinal phase space distribution could be directly observed [3, 4]. An experimental setup with reflective optics was examined with numerical ray tracing. For the highest energy resolution of measurement results, a radiator was designed to be placed outside the vacuum chamber. To extract the electron beam from the vacuum, a beryllium thin film was selected as a beam window. However, a Geant4 Monte Carlo simulation showed that multiple scatterings of non-relativistic electron beam in the beryllium window significantly degraded the resolution of the Cherenkov angle.

METHODOLOGY

While required a new method, longitudinal phase space measurement of each single micro-pulse of the beam is potentially useful to optimize beam performance and reliability. The method using coherent Cherenkov radiation as a diagnostic tool was proposed, due to the Cherenkov angle θ_c corresponding to particle velocity β as shown in Eq. 1,

$$\cos\theta_c = 1/n(\omega)\beta, \tag{1}$$

where $n(\omega)$ is the refractive index of the Cherenkov radiator medium at a radiation frequency ω [4]. Since the Cherenkov angle contains information of the particle energy, the particular reflective optics is needed to focus the photons having the same Cherenkov angle on a certain position of a detector, such as a "turtle-back" mirror. Moreover, the "turtle-back" mirror was proposed to focus photons having the different Cherenkov angles on the focal points aligned as a straight line. Thus the energy distribution of the beam can be observed at once by the streak camera. The mirror surface defined a base position $(0, y_0, s_0)$ can be expressed as Eq. 2.

$$x^2 + y^2 - (-\frac{1}{2A}s^2 + \frac{A}{2})^2 = 0 \quad (A \equiv \sqrt{{y_0}^2 + {s_0}^2} + y_0) \tag{2}$$

At t-ACTS the electron kinetic energy extracted from ITC-RF gun is approximately 1.87 MeV with energy spread of about 2% [1]. For instance, the Cherenkov ray from the electron with a kinetic energy of 1.87 MeV strikes the "turtle-back" mirror at s_0 = 47.887 cm (y_0 = 10.890 cm , since θ_c = 0.224 rad). If the entrance slit size of the streak camera is about 3 mm, electron kinetic energy distribution in range of 1.870 $\pm$ 0.034 MeV can be detected at once. Moreover, the "turtle-back" mirror has azimuthal symmetry around s-axis, thus 10% of the Cherenkov cone can be divided to detect by the mirror azimuthal size of 36°.

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Assuming no frequency dependences of the refractive index and the permeability of the Cherenkov radiator medium in a narrow band, the number of photons N between wavelengths λ_1 and λ_2 emitted from an electron is shown in Eq. 3,

$$N = 2\pi\alpha z(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}) \sin^2\theta_c, \quad (3)$$

where z is radiator thickness and α is the fine structure constant. For example, if an aerogel with refractive index of 1.05 and thickness of 1.0 mm is selected as the radiator, estimated number of the Cherenkov photons produced by 20 pC electrons (in micro-pulse) at 1% bandwidth of a wavelength around 555 nm is about 5.07 million for the electron kinetic energy of 1.87 MeV. In this case, the number of photons is obviously above detection threshold of a high resolution streak camera, despite 10% of the Cherenkov cone split to detect.

Fig. 1 shows the experimental setup. As the "turtle-back" mirror gives a focal line on the s-axis, the two off-axis parabolic cylinder mirrors (such as the focal length = 10 cm) can be used to transport photons outside the radiator chamber and confine again [3]. The focal line of the 1st and 2nd off-axis parabolic cylinder mirror are the 1st and 2nd focal line in Fig. 1 respectively.

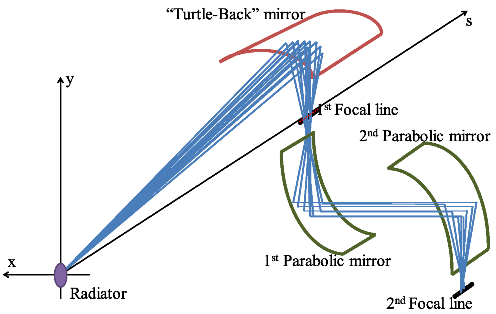

Figure 1: Schematic apparatus of the linear focal Cherenkov ring camera.

By using Eq. 1 and 2, the focal position s_f at particle velocity β can be derived as Eq. 4 [4].

$$s_f(\beta) = An\beta\left(1 - \sqrt{1 - \left(\frac{1}{n\beta}\right)^2}\right) \quad (4)$$

The energy dependence of focal position at the optical detector is about 22.8 keV/mm at electron kinetic energy around 1.87 MeV. The example result on detector screen for point-like beam at various kinetic energy is shown in Fig. 2(a). Furthermore, if resolution of image intensifier is 20 μm, an energy resolution of detector is 0.457 keV.

To investigate effect of beam size on the energy resolution, spatial profiles on the optical detector for uniform beam are illustrated as Fig. 2(b) and 2(c), where the spatial size on the detector is directly proportional to the energy

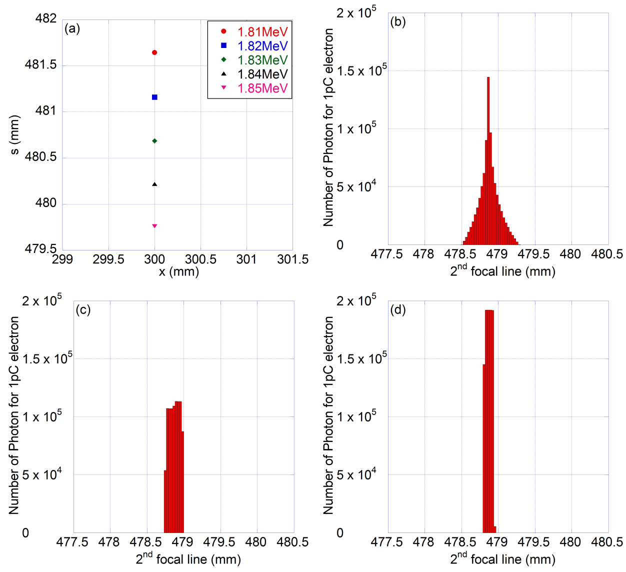

Figure 2: (a)Detector screen for point-like beam at various kinetic energy, (b)spatial profile for horizontal beam size of 4 mm, (c)one for vertical beam size of 0.4 mm, and (d)one for point-like beam by radiator thickness of 1.0 mm.

resolution. In addition, thickness of radiator also affects on the energy resolution as shown in Fig. 2(d).

The radiator was intended to be placed outside the vacuum chamber. However, electron beams passing through a dense material lose energy in collisions with the atomic electrons. For low emittance growth from the multiple scatterings, a beryllium thin film could be chosen as a beam window to extract the electron beam from the vacuum [5].

MULTIPLE SCATTERINGS OF ELECTRON BEAM

Electron beam suffers significantly from multiple scatterings. At low energies electrons primarily lose energy by ionization, although other processes (Møller scattering, Bhabha scattering, e^+ annihilation) contribute [6]. Moreover, by multiple scatterings of injected particles through the beam window, the root-mean-square deflection angle $\theta_{\rm rms}$ is given for an relativistic particle as Eq. 5,

$$\theta_{\rm rms} = \langle\theta^2\rangle^{1/2} = \frac{21\text{MeV}}{E}\sqrt{\frac{t}{X_0}}, \quad (5)$$

where E is the beam energy, t is the thickness of the material, and X_0 is the radiation length in the material [5]. If the minimum thickness of the beryllium thin film that is strong enough for vacuum is 50 microns, $\theta_{\rm rms}$ is 0.105 rad for electron kinetic energy of 1.87 MeV.

Geant4 is a free software package composed of tools which can accurately simulate the passage of particles through matter by using Monte Carlo methods [7]. To understand multiple scattering effect, Geant4 results, such as the deflection angle and the longitudinal phase space of the electron beam passing through the beam window, can be investigated, as shown in Fig 3.

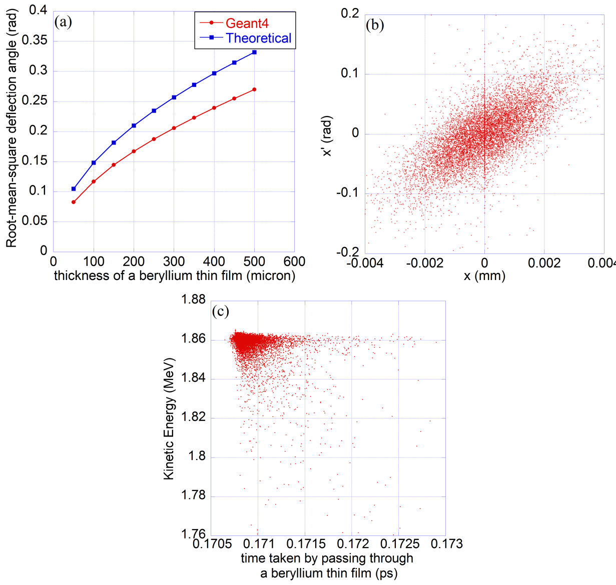

Figure 3: (a)Root-mean-square deflection angle of an injected electron passing through the varied beryllium thin film. (b)Transverse and (c)longitudinal phase space of point-like electron beam through 50-micron beryllium thin film (incident kinetic energy of electron beam = 1.87 MeV).

Fig. 3(a) and 3(b) show that the deflection angle of an injected electron passing through the 50-micron beryllium thin film is high significantly according to derivative of the Cherenkov angle $\mathrm{d}\theta_c/\mathrm{d}\beta$, which corresponds to energy resolution. However, as shown in Fig. 3(c), time deviates slightly in the longitudinal phase space contrary to time resolution of streak camera, and small energy distribution is also negligible for energy resolution. An experimental setup was examined with numerical ray tracing with the Geant4 results, in which the point-like electron beam passes through the beryllium window and the radiator respectively as shown in Fig. 4.

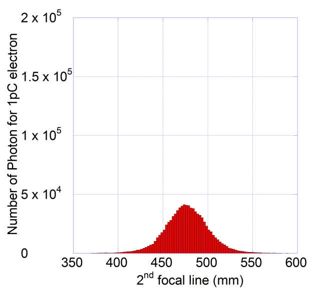

Figure 4: Spatial profile for point-like electron beam with the 50-micron beryllium thin film

Contrary to Fig. 2(b), 2(c) and 2(d), Fig. 4 shows that multiple scatterings of the electron beam in the beryllium window degrades the energy resolution essentially, since the position on the focal line dictates the electron energy. To extract the electron beam from the vacuum chamber to hit the radiator fails the longitudinal phase space distribution measurement via the linear focal Cherenkov ring camera. The radiator and the reflective optics were suggested to be placed inside the vacuum, and the Cherenkov light could be extracted from the vacuum chamber through a quartz window to the detector.

CONCLUSION AND PROSPECT

Longitudinal phase space distribution measurement via a linear focal Cherenkov ring camera has been studied. Due to the numerical ray tracing results combining multiple scatterings effect of Geant4 results, an experimental setup with a beryllium thin film to extract the electron beam from the vacuum degrades the energy resolution of the measurement. However, the experimental setup, in which the radiator and the reflective optics were placed inside the vacuum chamber, was proposed, and the Cherenkov light could be transported through a quartz window out of the vacuum to the detector.

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