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Study of Cherenkov Radiation from Thin Silica Aerogel

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Abstract

A beam diagnostics system employing Cherenkov radiation from a thin silica aerogel has been studied at Research Center for Electron Photon Science (ELPH), Tohoku University. We are developing a Linear Focal Cherenkov ring Camera (LFC-Camera) to observe longitudinal phase space distribution of the beam extracted from a low energy RF-gun. A thin silica aerogel plate with water-free hydro-phobic treatment is being used as Cherenkov radiator. We performed the beam test of the thin silica aerogel using a 50 MeV electron beam from t-ACTS (test accelerator as coherent terahertz source), and also we have examined performance of the thin silica aerogel for Cherenkov radiator.

Keywords

Cherenkov radiation, Beam diagnostics system, Thin silica aerogel

Introduction

Cherenkov radiation is widely used for particle detectors in nuclear physics and particle physics. We have aware that it must be a powerful tool for beam diagnostics in accelerator technology. The t-ACTS has been developed for generation of intense coherent THz radiation using ultra short electron beam at ELPH, Tohoku University [1,2]. To generate the coherent THz light, the electron bunch length is required to be shortened to a few hundred femtosecond or less. The t-ACTS employs velocity bunching scheme in an accelerating structure for bunch compression [3,4]. In the scheme, the longitudinal phase space distribution at the entrance of the accelerating structure dominates the final bunch length. The LFC-Camera will be used to diagnose the proper electron beam prior to the injection into the accelerating structure [5-7]. Cherenkov radiation from thin radiator made of silica aerogel is going to be applied for beam diagnostics of energy spread, transverse beam profile and bunch length. Preliminary results of the beam test of thin silica aerogel radiator are described in this article.

LFC-Camera

Principle and concept

The LFC-Camera employs velocity dependence of opening angle of Cherenkov light produced by electron beam to observe its energy distribution. Since the emitted time of Cherenkov light contains time information of electrons if the radiator medium is thin enough, so we can deduce the longitudinal phase space distribution by measuring both time and energy spectra simultaneously using a high resolution.

Test of Thin Silica Aerogel Radiator

Thin silica aerogel radiator

The Cherenkov radiator, which is one of the most important components in the LFC-camera system, is required to have high-transparency, low refractive index and sufficient mechanical strength. The thickness of radiator is preferred thinner, because the energy loss was diminished when passing through the radiator medium. The refractive index is also important parameter to identify the energy of the electrons. A derivative of Cheren-

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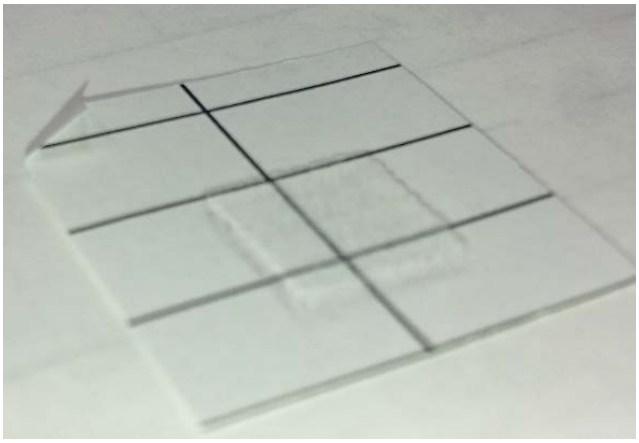

Figure 1: Photograph of thin hydrophobic silica aerogel. The dimension of this aerogel is 10 mm × 10 mm × 1 mm.

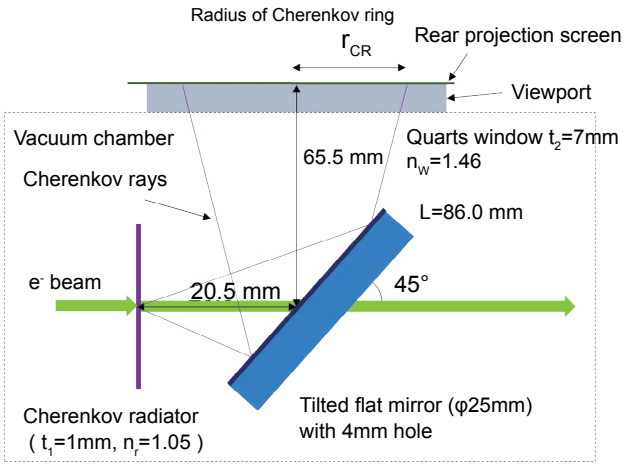

Figure 2: Schematic view of the beam irradiation test system for Cherenkov radiator. Cherenkov radiator and profile monitor are attached on the identical frame to move along the same axis. The tilted flat mirror with a 4 mm hole along the beam axis is installed behind Cherenkov radiator to reflect the Cherenkov light. Those components can be moved in the vacuum chamber by linear actuator with a stepper motor. The vacuum chamber is evacuated by an ion pump together a large conductance duct. The distance between surface of radiator and screen is 86.0 mm.

kov angle respect to energy $d\theta_c/dE$ is preferred to be large value for precise measurements. Meanwhile, small refractive index material is not expected be mechanically strong, and the number of generated photon is smaller than one with the large refractive index. Silica aerogel (synthetic ultra light material) has some suitable characteristics. Those are not only high transparency with low refractive index but also easy processing for small thin plate. One of the candidates of low refractive index material is cryogenic liquids or compressed gases, but it was not easy to install in vacuum. Consequently, we have chosen the thin hydrophobic silica aerogel with ultra-low refractive index (n = 1.05) developed at Chiba University [8,9]. Figure 1 shows a thin silica aerogel sample. Assuming no frequency dependence in both refractive index and the permeability of the Cherenkov radiator medium within narrow band, the number of emitted Cherenkov photons N between wavelengths λ_1 and λ_2 is given as

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

Where z is radiator thickness, α is the fine structure constant and θ_c is Cherenkov angle. For example, a silica aerogel with refractive index of 1.05 and thickness of 1.0 mm is used as the radiator, estimated number of Cherenkov photons generates by a 20 pC electron bunch with E = 2.2 MeV at 1% bandwidth of wavelength 555 nm is approximately 5 Million. Overall efficiency of optical transport of the LFC-camera system is expected to be ~5% of the total Cherenkov photons. Since minimum detectable photon number of the streak camera (HAMAMATSU FESCA-200) is ~1000 photons at the visible wavelength region, the number of photons is sufficient.

Refractive index measurement of thin silica aerogel

Refractive index of the thin silica aerogel is also important factor in a momentum calibration for the LFC-Camera. If refractive index of radiator changes by only 0.1%, deduced electron momentum would be shifted to ~50 keV from original one. In general, refractive index of large silica aerogel blocks for the particle counter is measured by the so-called laser fraunhofer method [9]. However, thin silica aerogel is too small to employ the laser Fraunhofer method, so that we performed measurement of the thin silica aerogel refractive index by detecting an optical path difference using a Mach-Zehnder interferometer with a 632 nm laser diode [10].

Beam test of thin silica aerogel

For precise longitudinal phase space measurement, ring image of the Cherenkov light is required to be not distorted. Moreover, we have to install the thin silica aerogel in ultra-high vacuum to measure the beam at the downstream of the RF-gun. To investigate the performance of the thin silica aerogel for the Cherenkov radiator, we carried out irradiation tests in the beam diagnostics section of the t-ACTS [11]. Figure 2 shows an experimental setup. Cherenkov ring profile on a screen was observed by a gated Charge-Coupled Device (CCD) camera, BASLER acA1300-gc. In the beam test, the silica aerogel radiator was irradiated by the 50 MeV electron beam with peak current of 8 mA with 1 pps pulse repetition. The electron beam focused onto the radiator was measured to be σ_x = 0.23 mm and σ_y = 0.35 mm. The refractive index of silica aerogel is approximately expressed by a formula

$$n = 1 + k\rho \ , \qquad (2)$$

Where k is a constant number and ρ is its density. In

case of the refractive index of silica aerogel is 1.05; its density is 0.2 g/cm^3 from Equation (2). A Continuous Slowing Down Approximation (CSDA) range of the silica aerogel is estimated to be about 1000 mm for 50 MeV electron beam by its density. The energy loss of electron beam is 68 keV/cm at 50 MeV [12]. The thickness of the Cherenkov radiator used in the experiment is only 1 mm, which is 0.1% equivalent in the CSDA range and 0.14% equivalent in the total energy loss, respectively. Therefore, the effect of beam loss for Cherenkov angle when passing through the Cherenkov radiator is assumed to be negligible small. Figure 3 shows an observed Cherenkov ring on a screen. Measured profile data are analyzed using an ellipse function to evaluate the property of Cherenkov ring profile, and then we derived the radius of 28.4 mm for both the horizontal and the vertical directions. Assuming no alignment error of components, the radius of the Cherenkov ring on screen is given by

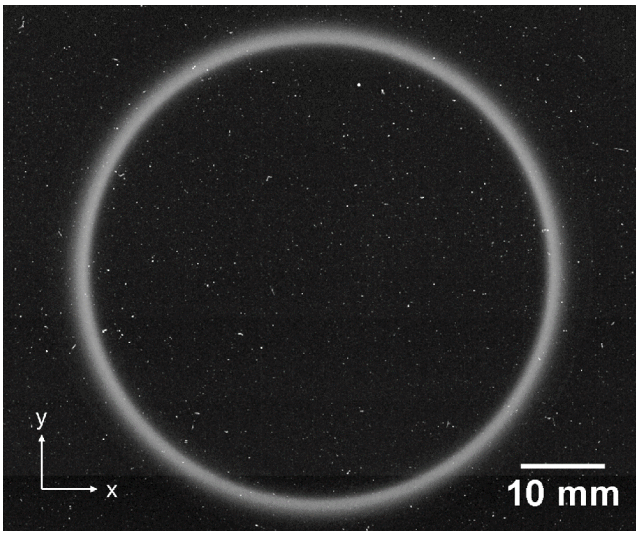

Figure 3: Spatial image of Cherenkov ring on the screen.

$$r_{CR} = t_1 \tan\theta_c + (L - t_1 - t_2)\cdot\frac{n_r \sin\theta_c}{\sqrt{1-(n_r \sin\theta_c)^2}} + t_2 \cdot \frac{n_r \sin\theta_c}{n_w\sqrt{1-\left(\frac{n_r}{n_w}\sin\theta_c\right)^2}} \quad (3)$$

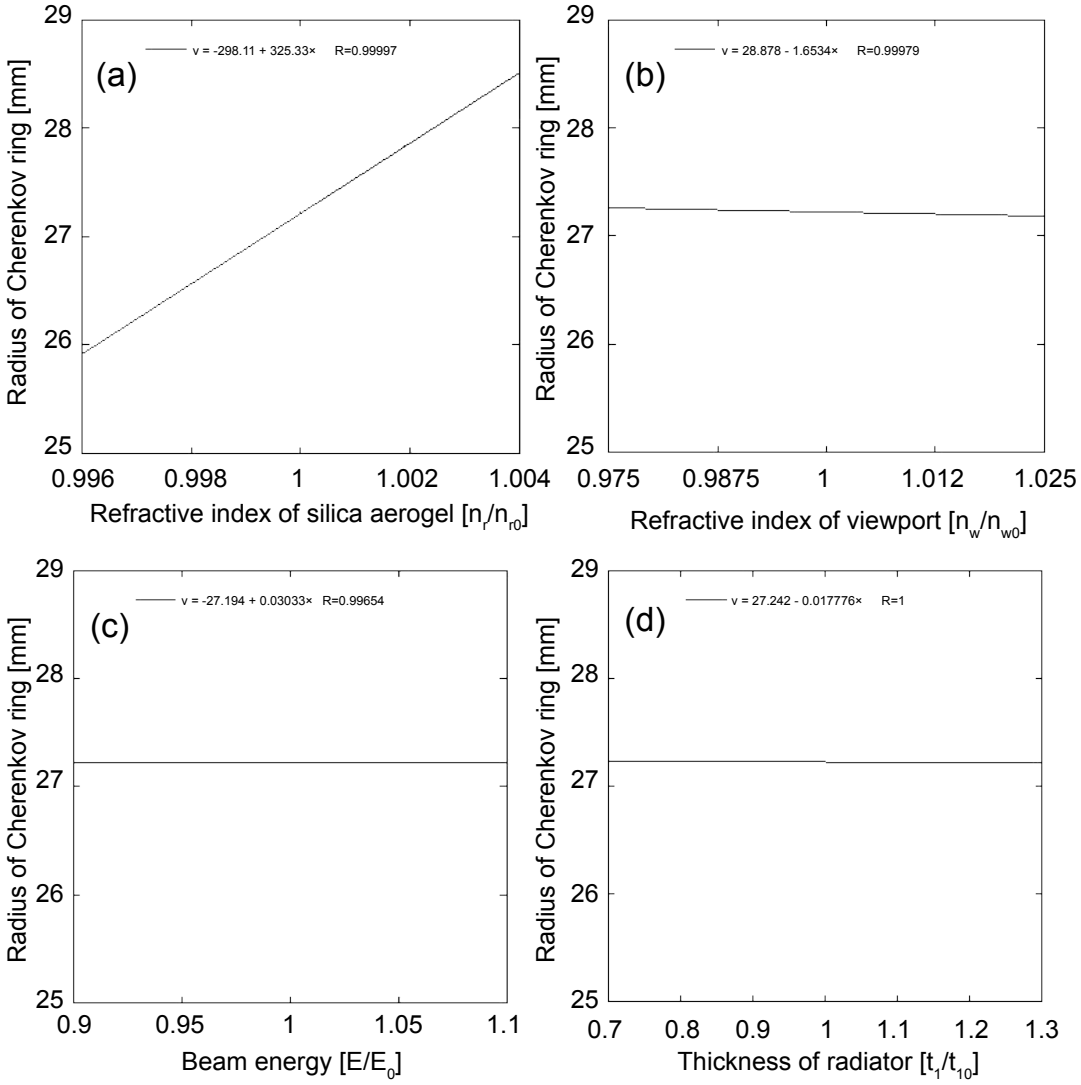

Figure 4: Solid lines denote variation of the radius of Cherenkov ring on the screen for different parameters where n_{r0} = 1.05, n_{w0} = 1.46, E_0 = 50 [MeV] and t_{10} = 1 [mm].

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Where L is total pass length, t_1 is thickness of radiator, t_2 is thickness of window, n_r and n_w are refractive indexes of the radiator and a viewport, respectively. The estimated radius of Cherenkov ring on the screen in this experimental configuration is 28.2 mm from Equation (3). The measured radius of the Cherenkov ring was almost consistent with the expected one. Figure 4 shows possible effects of parameter errors in the experimental configuration. Figure 4 indicates that the radius of the Cherenkov ring depends strongly on the refractive index of Cherenkov radiator, another parameters has little influence on the radius of the Cherenkov ring.

Much outgas from the Cherenkov radiator was observed during the beam irradiation. We have not found significant change on the radiator surface after irradiation. However, there might be a change in a physical property of silica aerogel. A change in refractive index of silica aerogel has a huge impact on the radius of Cherenkov ring. By monitoring of the ring radius, the variation of the refractive index of radiator can be detected that is significant to derive the absolute value of electron momentum.

Conclusion and Prospect

We have been developing the beam diagnostics system at t-ACTS using Cherenkov radiation emitted from the thin silica aerogel. We examined the performance of the thin silica aerogel Cherenkov radiator. The observed Cherenkov ring was not distorted and its radius was almost consistent with the expected one. Since Cherenkov light is two orders of magnitude brighter than an Optical Transition Radiation (OTR), we can detect using the usual gated CCD camera without special device such as an Image Intensifier (IIT). Although we noticed that the vacuum pressure in the radiator chamber was increased by the outgas from the silica aerogel during irradiation, the ultra-high vacuum environment near the RF-gun will be not much affected. It can be concluded that Cherenkov radiation emitted from thin silica-aerogel is very powerful tool for the beam diagnostics system. We continue to develop the LFC-camera, and will try to measure the bunch length as a first step. In addition, it is also planned to develop a real-time profile monitor system employing the thin silica aerogel for high energy beams.

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