

STUDY OF REFLECTIVE OPTICS FOR LFC-CAMERA*

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Abstract

A Linear Focal Cherenkov ring (LFC)-Camera is studied to observe the longitudinal phase space distribution of the beam extracted from a low energy RF gun. The LFC-Camera employing refractive optics employing aspherical lens was studied so far. In this work, the LFC-Camera using reflective optics is numerically investigated. Performing numerical ray-trace simulations, we discuss characteristics of the LFC-Camera using reflective optics.

INTRODUCTION

A test accelerator system for a terahertz source project (t-ACTS) using isochronous accumulator ring and bunched free electron laser has been under development at Tohoku University [1, 2]. Stable production of very short electron bunches is critical issue for the t-ACTS project. We have developed a thermionic RF gun consists of two independent cavities so as to manipulate the longitudinal beam phase space, named the Independently-Tunable Cells (ITC) RF gun [3]. Particle distribution in longitudinal phase space is crucial for efficient bunch compression. The ITC RF gun has been designed to produce appropriate longitudinal phase space distribution by adjusting relative rf phases and field strengths of the two cavities. The longitudinal phase space distribution at the exit of the rf-guns may govern the final bunch length of electron beam after bunch compression process. Therefore, the understanding of the longitudinal phase space is indispensable for efficient bunch compression.

In order to measure the longitudinal phase space distribution of non-relativistic electron beam, we have been developing a novel method using the characteristic that the opening angle of Cherenkov light depends on the speed of incident charged particle. The LFC-Camera employing refractive optics with aspherical lens had been studied previously [4]. In this paper, the LFC-Camera using the reflective optics is investigated. We have carried out numerical ray-trace simulations and discuss the energy and temporal resolutions of the LFC-Camera using reflective optics.

LFC CAMERA

Property of Cherenkov Light

Cherenkov light is widely used for beam diagnostics and particle counters for high energy physics. It is well known that the Cherenkov angle θ_c is inversely

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proportional to the particle velocity β as

$$\cos\theta_c = \frac{1}{n(\omega)\beta}, \quad (1)$$

where $n(\omega)$ is the refractive index of the Cherenkov radiator medium at a radiation frequency.

Estimated number of the Cherenkov photons emitted from a single electron passing through the radiator with index $n = 1.05$ thickness $t = 1$ mm is about 0.4 for 1% bandwidth at a wavelength around 555nm. For example, a 1 pC electron bunch can produce more than 2.2M photons. We have anticipated that the charge of the extracted beam from the ITC RF gun with a reasonable energy spread of 2 % is about 20 pC, so that total photon number is 45 M/micropulse. Detection threshold of an image intensifier is more than 1.3k photons/sec. Similarly, photons more than 10k photons/micropulse is required for observation using high resolution streak-camera.

Design Concept

Since the Cherenkov angle contains information of the particle velocity, the photons with the same Cherenkov angle has to be focused on an identical position of a detector. When the focal points are placed on a straight line, the energy distribution of the beam can be observed at once by using semiconductor linear image sensor. Furthermore, if information on relative arrival times onto the Cherenkov radiator for each particle can be preserved, we are able to perform direct observation of the longitudinal phase space distribution by using a high-resolution streak camera. Figure 1 shows a tentative apparatus of the optical transport system. In this study, we have chosen an optical system for LFC-Camera employing reflective optics. The LFC-Camera consists of a "turtle-back" mirror, explained in the following section, a two parabolic mirrors and a Cherenkov radiator. The turtle-back mirror gathers some part of photons emitted in the Cherenkov ring and confines onto the longitudinal axis (see Fig. 2(a)). The reflective optics using parabolic mirrors makes it possible to transport the Cherenkov light onto a detector excluding path length difference.

Turtle-Back Mirror

The reflecting surface of the mirror to gather the photons of the Cherenkov ring and confine them onto a focal line is parabolic in the s-axis and spherical in the x-axis (shape of mirror looks like a turtle-back carapace). The mirror surface can be described by the following equation,

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

Here, the base point (0, y₀, s₀) has been chosen so as to make the system compact, i.e., the Cherenkov light from the electrons with a kinetic energy of 1.7 MeV hits the mirror at s₀ = 0.3 m (then θ_c = 11.8° and y₀ = 0.063 m).

Since the turtle-back mirror gives a focal line on the s-axis, the photons have to be transported to outside of the radiator chamber and confined again.

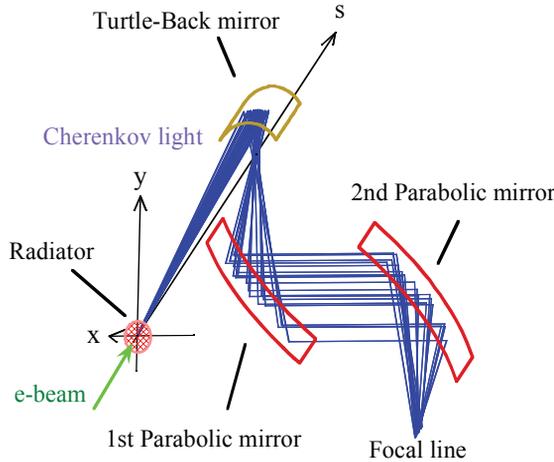


Figure 1. Schematic apparatus of the LFC-Camera.

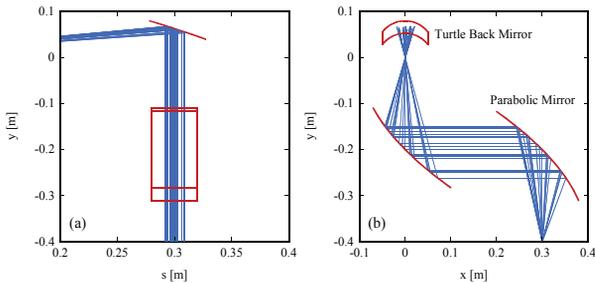


Figure 2: (a) Side view and (b) rear view of the transport of Cherenkov light in the LFC-Camera. Blue lines are light trajectories calculated by a ray-trace code assuming a point source.

Transport of Light

Parabolic mirror is widely used such as astronomical observation, spectrometric analysis and lighting equipment, etc. It is well known that the parabolic mirror is employed to produce a parallel beam when the light source is placed at its focal point or to collect parallel beam onto focusing point. The focal position of 1st parabolic mirror is matched to the focal position of the turtle-back mirror. An axis of 2nd parabolic mirror for the optical detector is adjusted to fit the axis of 1st parabolic mirror. Thus the difference in the path length of lights

from focal line of the turtle-back mirror to final focal line on optical detector is 0 (see Fig. 2(b)).

A reflective optics has no chromatic aberration, so that the optical system can cover a wider wavelength range without path length difference, then photon intensity on the detector can be increased.

INTRINSIC RESOLUTIONS FOR ENERGY AND TIME

Energy Dependence of the Focal Position

From the numerical studies, the energy dependence of focal position at the optical detector is approximately 30 keV/mm in a kinetic energy region of electron beam around 1.7MeV. To achieve a high energy resolution, it is necessary to observe a Cherenkov light on the focal line with a high spatial resolution. Resolution of image intensifier is about 20 μm, and it is sufficient for detection with an energy resolution of 0.6 keV.

Energy Resolution

Though transverse emittance of the beam from the RF gun is expected to be small, the finite spatial and angular spread of the beam may affect the energy resolution of the LFC-Camera. In order to evaluate the effect of the beam size at the radiator for energy resolution, the ray-trace calculations were performed for mono-energetic beam conditions characterized by horizontal and vertical beam size.

As shown in Fig.3, the dependence of the horizontal beam size on the energy resolution is comparatively small. We found dependence of the vertical beam size on the

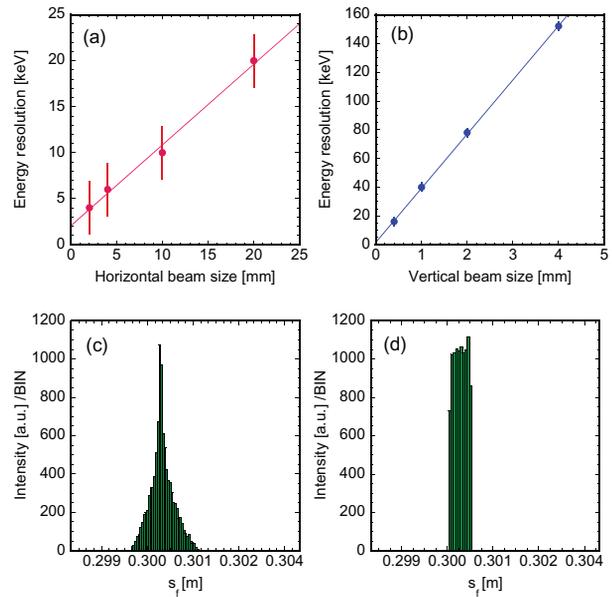


Figure 3: (a) Horizontal beam size dependence of the energy resolution and (b) vertical beam size dependence of the energy resolution. (c) Spatial profile for horizontal beam size of 4 mm and (d) one for vertical beam size of 0.4 mm.

energy resolution is considerably large. From these reasons, the electron beam should be focused vertically at the radiator for better resolution. If the vertical beam size of electron beam on the radiator is 0.6 mm, the energy resolution of the LFC-Camera becomes about 20 keV.

Time Resolution

The turtle-back mirror has been designed to eliminate path length difference of the rays from a point source to the 1st focal line (on the s-axis). Similarly, the optical transportation system has been designed so as to eliminate path length difference of the rays from a single source to the final focal line. However, spatial spreading of the source point at the radiator causes deviation of the path length in the light transport, thus there is a finite time of the LFC-Camera. We estimated the dependence of the beam size on the time resolution, the ray-trace calculations were performed for mono-energetic electrons characterized by horizontal and vertical beam size. As can be seen from the Fig.4, although the horizontal beam size does not much affect on the time resolution, the vertical beam size is crucial. Target time resolution of the LFC-Camera is ~ 0.2 ps, because the time resolution of streak-camera is less than 0.2 ps. Therefore the horizontal beam size has to be less than 2.5 mm and vertical beam size is limited to 0.3 mm. If the time resolution is allowed to be 0.5 ps, the limits of horizontal and vertical beam size would be 5 mm and 0.7 mm, respectively. From these reasons, the electron beam should be focused vertically at the radiator for good resolution.

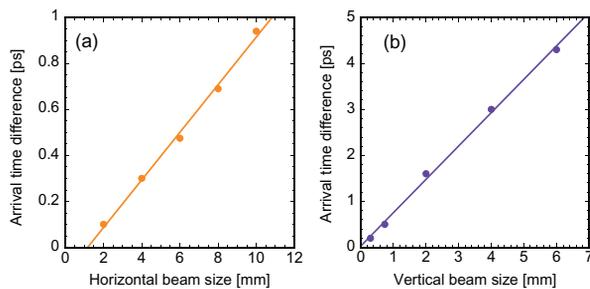


Figure 4: (a) Horizontal beam size dependence of the arrival time difference and (b) that for vertical beam size.

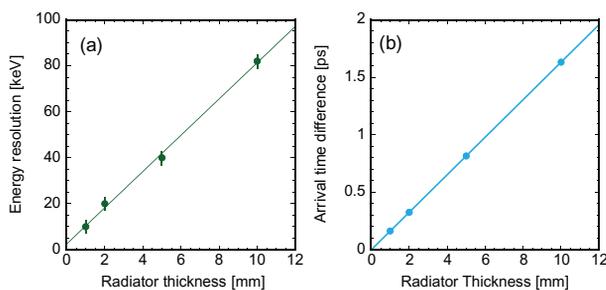


Figure 5: Effect of radiator thickness for (a) energy resolution and (b) arrival time difference.

Effect of Radiator Thickness

The longitudinal position of source point is important factor for energy and time resolution. Figure 5 shows a thickness of radiator dependence of the energy and time resolutions. The radiator thickness of $Z_R = 1$ mm is significant to observe the Cherenkov light. When using the radiator with a thickness of 1mm, the energy resolution becomes around 10keV and the time resolution is less than 0.2 ps. From these reasons, the radiator should be thinner for good resolution as much as possible. An issue brought by the thinner radiator is Cherenkov photon yield. However we anticipate sufficient number of photons can be transported on to the final focal line.

SUMMARY

We have been studying a novel system for measurement of the longitudinal phase space of the non-relativistic electron beam. The LFC-Camera, which employs reflective optics consists of a turtle-back mirror to confine the Cherenkov ring onto a focal line and two parabolic mirrors to transport the light onto the final focal line, has been investigated. The numerical ray-trace shows the intrinsic energy and time resolution of the optical system to be around 20 keV and 0.2 ps, respectively. However, the resolution of the reflective optics is inferior to the refractive optics [4]. Especially, the effect of the radiator thickness is comparatively large, so that thinner Cherenkov radiator has to be prepared.

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