Linear Focal Cherenkov-ring Camera for Direct Longitudinal Phase Space Measurements

A. Lueangaramwong*, F. Hinode, S. Kashiwagi, T. Muto, I. Nagasawa, S. Nagasawa, K. Nanbu, Y. Shibasaki, K. Takahashi, K. Yanagi and H. Hama
Electron Light Science Centre, Tohoku University

Abstract

A test accelerator for the coherent THz source (t-ACTS) has been constructed at Tohoku University, in which the generation of intense coherent THz radiation from sub-picosecond electron bunches will be demonstrated. The distribution in the longitudinal phase space extracted from an electron gun is crucial to achieve extremely short electron bunches. For relatively low electron energy, to avoid a space charge effect during measurement is required. Employing velocity dependence of the opening angle of Cherenkov radiation, combined use of a streak camera and a "turtle-back" mirror which resolves and confines the Cherenkov light with different opening angle onto a line may allow us to observe the longitudinal phase space distribution directly. Energy resolution can be improved by the "4f" imaging system consisted of two off-axis parabolic cylinder mirrors, and more practical experimental setup has been investigated. The sufficient energy and time resolution was derived by the numerical ray tracing. The current status of this development will be presented.

INTRODUCTION

Intense relativistic electron beam with short bunch length is a key for coherent radiation production in the terahertz (THz) 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 THz radiation from sub-picosecond electron bunches will be demonstrated [2]. An advanced independently tunable cells (ITC) thermionic RF gun consisting of two uncoupled cavities was proposed for the t-ACTS project.

Electron beam is generated by the ITC RF-gun and introduced into an alpha magnet and an accelerating structure as the bunch compression system with velocity bunching. The final electron bunch from the compression system strongly depends on the longitudinal phase space distribution at the RF-gun exit. Proper longitudinal phase space distribution can be manipulated by the ITC RF-gun adjusted relative RF phases and field strengths of the two cavities.

Longitudinal phase space measurement is crucial for extremely short bunch production. Linear focal Cherenkov-ring (LFC) camera was proposed as a novel method for directly measure the longitudinal phase space [3]. The practical measurement system based on LFC camera has been developed.

* anusorn@lns.tohoku.ac.jp

LINEAR FOCAL CHERENKOV-RING CAMERA

The measurement of electron energy (or momentum) employing velocity dependence of the opening angle of Cherenkov radiation was proposed for relatively low energy electrons (1.8 - 2.4 MeV/c momentum region). A "turtle-back" mirror is shaped to a parabola on ys-plane, whose line of symmetry equation is $y = 0$ and radiation point is the origin, rotated around s-axis in Fig.1. The mirror surface defined a base position $(0, y_0, s_0)$ can be expressed as Eq. 1, where the parameter A is defined as twice the focal length of the parabolic curve.

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

The turtle-back mirror was designed to resolve the Cherenkov rays with the different opening angles, and confine them to focal positions along a focal line. By using combination of a streak camera and the turtle-back mirror, the longitudinal phase space distribution could be directly observed, where the focal position corresponds to electron energy [3, 4]. The focal position s_f at the Cherenkov angle θ_c can be derived as Eq. 2.

$$s_f(\theta_c) = A(-\tan\theta_c + \sqrt{\tan^2\theta_c + 1}) \tag{2}$$

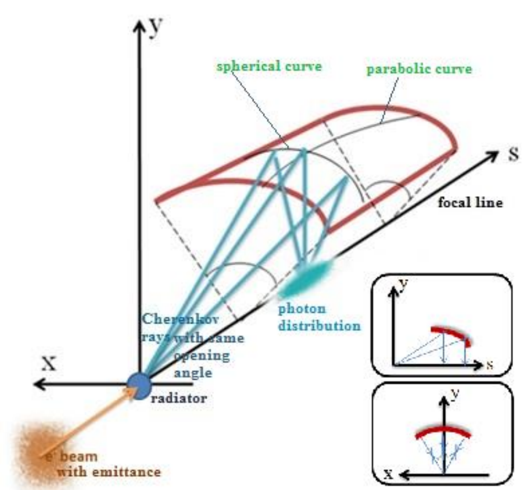

Figure 1: Design of the turtle-back mirror.

To achieve the best energy resolution, a radiator and the turtle-back mirror should be put inside of the vacuum chamber, called "radiator chamber" [5]. A thin aerogel film with reflective index of 1.05 is considered as the Cherenkov radiator to achieve higher energy and time resolution.

However, the transverse beam emittance significantly degrades the momentum and time resolution. The previous concept must be developed to improve resolution of measurement result.

RESOLUTION ENHANCEMENT

The "4f" imaging system consisting of two off-axis parabolic cylinder (OAPC) mirrors transfers the Cherenkov light through a quartz window to outside of the vacuum system and enhances energy resolution of the system as well. It allows the turtle-back mirror to focus the Cherenkov light (radiated by monoenergetic beam) to a spot size at the new focal line.

The additional "4f" imaging systems consisting of two off-axis parabolic (OAP) mirrors and two flat mirrors can be used to transport the Cherenkov light to the streak camera and preserve both energy and time resolutions [6]. So the streak camera can be protected from radiation at the accelerator.

The experimental setup was proposed. Thus, we examined the setup with reflective optics by a numerical ray tracing to optimize parameters of optical elements and configuration as shown in Fig.2.

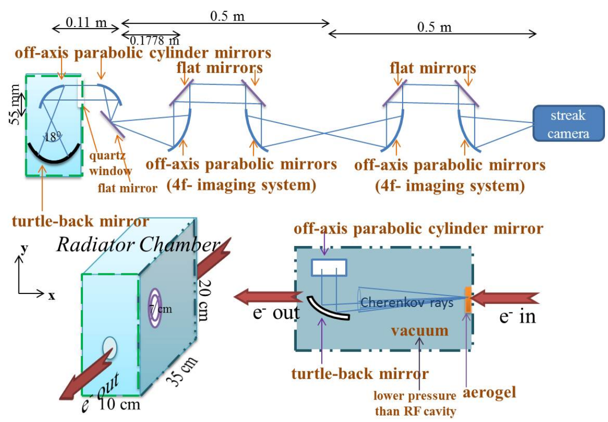

Figure 2: Proposed scheme of experimental setup.

SIMULATION RESULT

To estimate the momentum and time resolution, monoenergetic election beam is considered in the ray tracing calculation. The numerical ray tracing was carried out to investigate photon spatial distributions shown in Fig.3 and standard deviations of the distribution in s direction corresponding to the momentum resolution.

Fig.3(a) and (b) show that the "4f" imaging system consisting of OAPC mirrors enhances the momentum resolution, due to the smaller photon distribution at the new focal line. Moreover, Fig.3(b) and (c) prove that the "4f" imaging systems consisting of OAP mirrors can transfer image

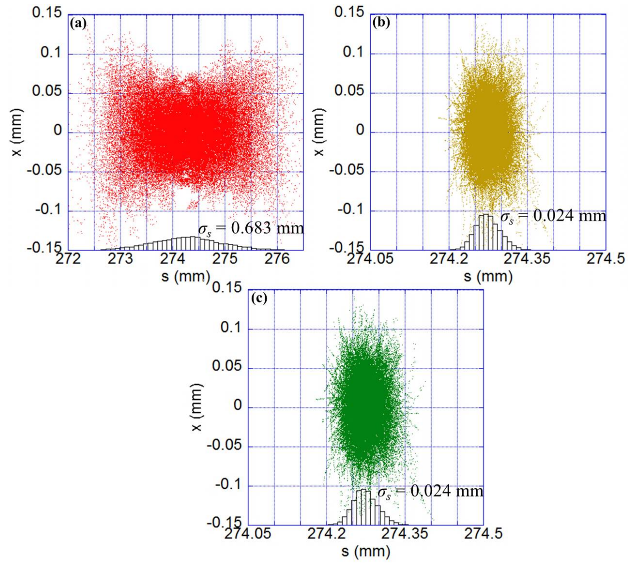

Figure 3: Photon distribution at the three focal line (a) at the original focal line (after the turtle-back mirror with parameter A of 350 mm), (b) at the new focal line (after the OAPC mirrors with effective focal length of 55 mm), and (c) at the entrance slit of streak camera.

from the new focal line to the streak camera and also preserve the resolution.

The program also evaluates the momentum and time resolutions (1.15 keV/c and 0.74 ps) for electron momentum of 2.4 MeV/c with normalized transverse emittance of 0.25 mm mrad. The momentum and time resolutions seem sufficient for this study.

However, surface roughness of the turtle-back mirror has been investigated for the effect on the energy and time resolutions by the ray tracing, which is shown in Fig.4.

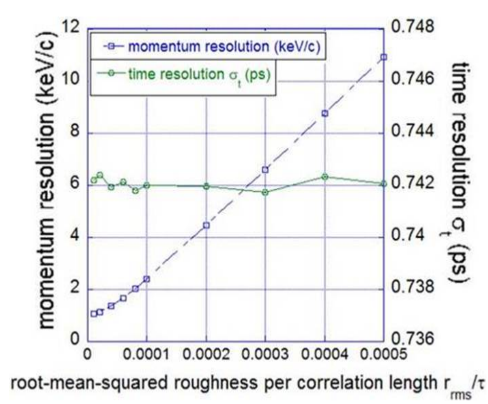

Figure 4: Effect of the turtle-back mirrors roughness on momentum and time resolution for electron momentum of 2.4 MeV/c in the optimized setup.

In Fig.4, the root-mean-square roughness per horizontal correlation length should not exceed 0.0001 to achieve sufficient momentum resolution.

OPTICAL PERFORMANCE TEST

The turtle-back mirror was fabricated for the first time. A large aluminium block was machined by the parabolic curve (of turtle-back mirror's surface with the parameter A of 350 mm) around the central axis of the block as shown in Fig.5. It was divided to 8 sectors equally by wire cutting machine.

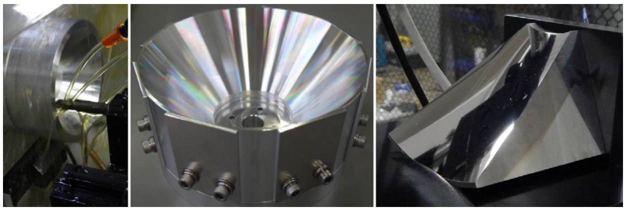

Figure 5: (left,middle) aluminium block machined by the parabolic curve, and (right) the fabricated turtle-back mirror.

The 1-D surface profiles of the turtle-back mirror (Fig.6(left)) were measured by the contact profilometer and analyzed by discrete Fourier transform (Fig.6(right)).

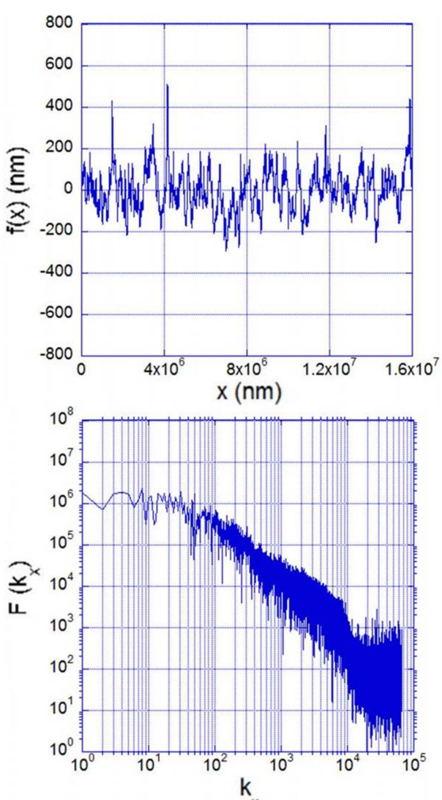

Figure 6: (left) Example of 1-D surface profile of turtle-back mirror, and (right) its spectrum.

Dominant frequencies, excluding noise and very low frequency, represent the surface profile which contains roughness information, and the root-mean-squared roughness per correlation length of 0.00032 was extracted to represent the roughness parameter of the mirror. By using the ray tracing, the momentum resolution is degraded from 1.05 keV/c to upto 7 keV/c. Therefore, the surface roughness of the turtle-back mirror should be reduced and closed to conventional mirror's one.

In the reflection test, the ring-like laser beam with desired opening angle is generated instead of the Cherenkov ring. The experiment was set up to verify that the focal positions s_f correspond to the parameter A of the fabricated turtle-back mirror as shown in Fig.7.

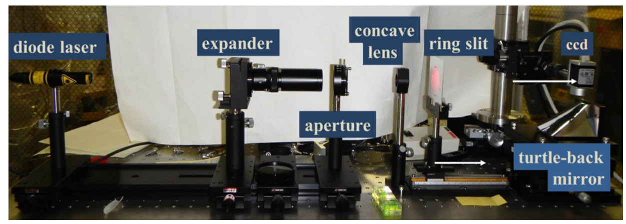

Figure 7: The experimental setup of reflection test using ring-like laser beam.

Fig.8 shows the measurement result of the focal position at the desired opening angle. By the curve fitting illustrated in Fig.8, the measured parameter A_{meas} of 349.50 $\pm$ 0.13 mm is derived, while the design parameter A is 350 mm. It is higher than the design parameter A about 0.11 - 0.18%, due to slight misalignment of the experimental setup and error of surface profile in fabrication process.

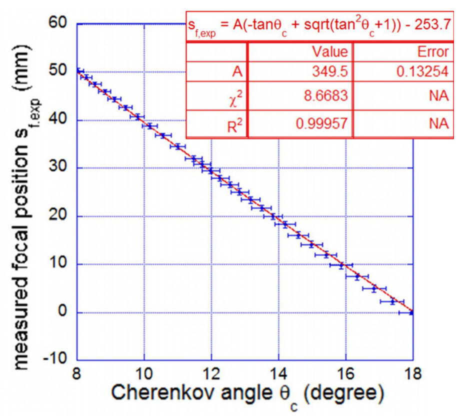

Figure 8: Plot of the measured focal position $s_{f,exp}$ as a function of Cherenkov angle θ_c (The solid line is the fitted curve to Eq.2).

CONCLUSION

Longitudinal phase space distribution measurement via a linear focal Cherenkov ring camera has been studied and developed. The "4f" imaging system consisting of two off-axis parabolic cylinder mirrors can be used to transfer the Cherenkov light to outside of the vacuum through a quartz window and enhance energy resolution of the system. Numerical ray tracing was used to optimize the optical parameters and configuration. Sufficient momentum and time resolutions (1.15 keV/c and 0.74 ps for momentum of 2.4 MeV/c and normalized emittance of 0.25 mm mrad) were estimated. The turtle-back mirror was fabricated, and its qualities of reflection were investigated. It can resolve and confine the Cherenkov light correctly. The measured parameter A_{meas} of 349.50 $\pm$ 0.13 mm is derived, and its surface roughness must be improved.

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REFERENCES

[1] N.Y. Huang, "Advanced Linear Accelerator System for Generation of Femto-second Electron Beam toward Intense Radiation Sources", PhD thesis, National Tsing Hua University, 2013.

[2] F. Hinode et al., Proc. of FEL2012, (2012) 137.

[3] H. Hama et al., Proc. of BIW10, (2010) 79.

[4] K. Nanbu et al., Proc. of FEL2011, (2011) 576.

[5] A. Lueangaramwong et al., Proc. of PASJ10 (2013).

[6] K. Rosbach et al., NIM A, 654 (2011) 580