A DIRECT MEASUREMENT OF THE LONGITUDINAL PHASE SPACE FOR A LOW ENERGY ELECTRON BEAM USING ENERGY DEPENDENT ANGULAR DISTRIBUTION OF CHERENKOV RADIATION*

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Abstract

Particle distribution of the electron beam extracted from a thermionic RF gun in longitudinal phase space is essential for electron bunch compression. Because space charge effects in the RF gun are not fully understood, an efficient bunch compression scheme employing magnetic chicane or alpha magnet is not easily designed. In order to measure the distribution in the longitudinal phase space of relatively lower energy electrons (below 2 MeV), we have studied a novel method for direct observation of electron energy employing velocity dependence of opening angle of Cherenkov radiation. Intrinsic energy and temporal resolution are discussed by showing a numerical ray-trace simulation.

ITC-RF GUN AND FEMTO-SECOND ELECTRON PULSE

An intense terahertz light source based on an electron accelerator has been under development at Tohoku University, and is called the t-ACTS project [1]. Stable production of very short electron bunches is an important issue for the t-ACTS project. Photocathode injectors have already successfully generated femtosecond pulses with considerable bunch charge. However, we have chosen thermionic cathode for the RF gun because of stability, multi-bunch operation, and cheaper cost. The thermionic RF gun consists of two independent cavity cells to manipulate the longitudinal phase space, so it is named the ITC (Independently-Tunable Cells) RF gun [2]. The bunch charge will be small (a couple of tens of pC), and then coherent enhancement of the radiation is not so strong, the space charge effect may not be a very serious concern, and the thermionic cathode should have good stability, so excellent beam quality would be expected. Moreover, high repetition operation in multi-bunch mode will open another aspect of application experiments.

PROPERTIES OF CHERENKOV RADIATION

The beam energy from the ITC-RF gun is not so high (kinetic energy T ~ 1.7 MeV) and velocity is still slower than light, which means the particle distribution in the phase space may vary even in drift spaces due to the space charge force. Consequently a conventional analyzer magnet is not proper for measurement of the particle energy because a considerable path length is inevitably required.

Cherenkov light is widely used for beam diagnostics and particle counters. It is well known that the Cherenkov angle θ_c is inversely proportional to the particle velocity β as

$$\cos\theta_c = 1/n(\omega)\beta, \qquad (1)$$

where $n(\omega)$ is the refractive index of the Cherenkov radiator medium at a radiation frequency ω [3]. The Frank-Tamm formula gives the energy dissipation of Cherenkov radiation with a frequency region from ω_1 to ω_2 as,

$$\frac{dE}{dz} = \frac{q}{4\pi}\int_{\omega_1}^{\omega_2} \mu(\omega)\omega\left(1-\cos^2\theta_c\right)d\omega, \qquad (2)$$

where z is the radiator length, q is the charge of the particle and $\mu(\omega)$ is the permeability of the medium. Assuming no frequency dependences of n and μ in a narrow band, the number of photons between wavelengths λ_1 and λ_2 emitted from an electron is expressed as

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

where α is the fine structure constant.

As one notices from Eqs. (1) and (3), the refractive index is an important parameter for detection of the particle energy. In order to secure sufficient energy resolution in the measurement system, a derivative of Cherenkov angle $d\theta_c/d\beta$ is preferred to be large. Meanwhile the number of photons is proportional to $sin^2\theta_c$. Figure 1 shows the Cherenkov angle and the value

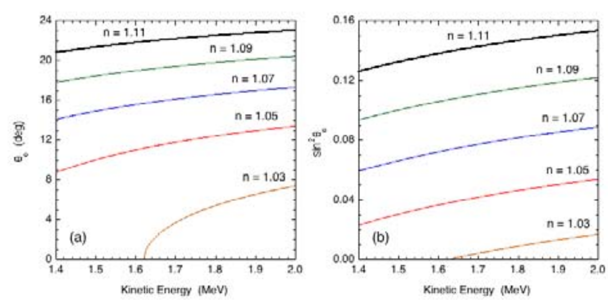

Figure 1: (a) The Cherenkov angle and (b) the value of $sin^2\theta_c$ for various refraction indexes, plotted as a function of the kinetic energy.

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of $sin^2\theta_c$ calculated for a kinetic energy region from 1.4 to 2.0 MeV. The number of photons increases with n; meanwhile the slope of the Cherenkov angle is gradually decreasing. Silica-aerogel has been presumed to be the radiator medium. We insist on the energy resolution and the angular resolution, so a refraction index of 1.05 has been chosen for further study.

OPTICAL ELEMENTS IN MEASUREMENT SYSTEM, LFC-CAMERA

Design Concept

Since the Cherenkov angle contains information of the particle energy, the photons having the same Cherenkov angle has to be focused on a certain position of a detector. If the focus points of different energies are aligned on a straight line, the energy distribution of the beam can be observed at once by using a semiconductor sensor. Furthermore, if information on relative arrival times into the aerogel for each particle can be preserved, we shall perform direct observation of the longitudinal phase space distribution by using a high-resolution streak camera. The estimated photon number emitted from a single electron passing through a radiator medium of n = 1.05 with a thickness of z_R = 1 mm is approximately 0.04 for 1% bandwidth at a wavelength around 500nm. The number of electrons in a single bunch extracted by the ITC-RF gun is typically about 20 pC. Figure 2 shows a tentative optical apparatus design of the detection system we call the Linear Focal Cherenkov ring camera (LFC-camera). A turtle-back mirror gathers a part of the Cherenkov ring and confines onto the s-axis.

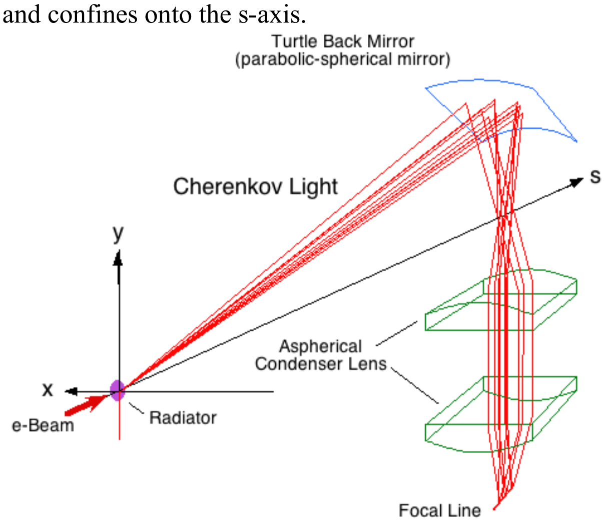

Figure 2: Schematic apparatus of the LFC-camera. The system consists of a specific (parabolic-spherical) mirror and two aspherical condenser lenses. Angular distribution of the Cherenkov radiation is imprinted onto a straight focal line.

The photons are transported and confined again by aspherical lenses. The Cherenkov angle is therefore converted into a position on a focal line.

Turtle-back Mirror

The reflecting surface of the mirror able 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, which looks like a turtle-back carapace. The mirror surface can be represented by the following equation,

$$x^2 + y^2 - \left(-\frac{1}{2A}s^2 + \frac{A}{2}\right)^2 = 0 \quad \left(A \equiv \sqrt{y_0{}^2 + s_0{}^2} + y_0\right) \qquad (4)$$

Here, the base point 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 s_0= 0.3 m (then θ_c=11.8° and y_0 = 0.063 m).

Since the turtle-back mirror gives a focal line on the s-axis, indeed the beam axis, the photons have to be transported to outside of the beam pipe and confined again. We have intended to employ optical lenses for transport of the light and a normal incidence band-pass filter for wavelength selection because of convenience.

Aspherical Condenser Lens

Because a conventional formula of aspherical surface for the optical lenses contains many parameters, if one would like to eliminate aberration considerably, it may take a very long time to optimize the lens surface. For the moment we have designed a simple condenser lens consist of a flat surface and a one-dimensional aspherical surface, as shown in Fig. 2. The formula used to determine the surface is

$$x^2 + \left(y + gx^2\right)^2 - \left(\frac{R}{\eta - 1} + gx^2\right)^2 = 0, \qquad (5)$$

where g is an aspherical coefficient, R is a base spherical curvature radius. The relative refractive index η of the lens is chosen to be 2.0, and R = 4 cm is employed in order to keep the system compact. Consequently it has turned out that the maximum acceptance can be obtained at g = 23, and approximately 10 % of the Cherenkov light emitted into the azimuthal angle of 2π is confined on the focal line 100 μm in width.

CONSIDERATION FOR ENERGY AND TIME RESOLUTIONS OF LFC-CAMERA

Energy Dependence of the Focal Position

The energy dependence of focal position is approximately 0.15 mm/keV in a kinetic energy region from 1.4 to 2.0 MeV. Pixel size of recent CCD or CMOS is surprisingly smaller than 10 μm. That is sufficient for detection with an energy resolution of keV order, even in the 3-MeV region, if the radiation is coming from a point source.

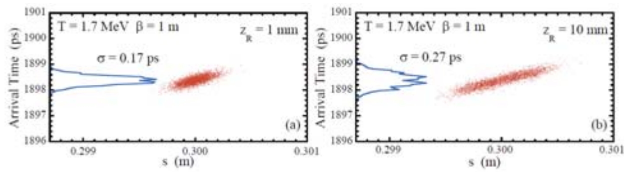

Figure 3: Two-dimensional plots of the arrival time and the longitudinal focal position. radiator thicknesses, z_R = 1 mm and (b) z_R = 10 mm.

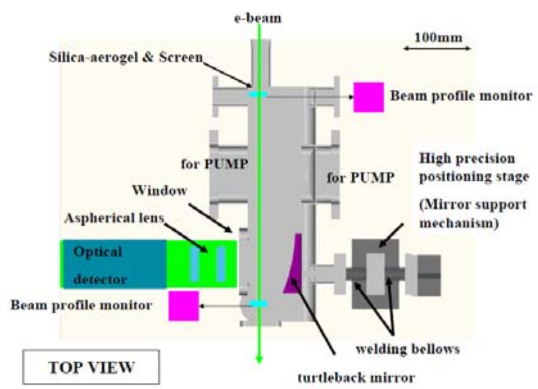

Figure 4: Configuration of the LFC-camera. The turtleback mirror is supported by high precision positioning mechanism. Silica-aerogel is placed in the holder.

Effect of Beam Emittance

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. We have assumed that the minimum normalized slice-emittance is equivalent to the thermal emittance of the cathode that is estimated to be about 2.5 x 10^{-7} m•rad for the ITC-RF gun. In order to evaluate the effect for the position resolution, the ray-trace calculations were performed for two different monoenergetic beam conditions characterized by a beta function of the Twiss parameter, such as tight focused beam on the radiator medium and loose focused one T = 1.37 MeV is 0.037 mm/keV, those values correspond approximately to energy resolutions of 3 and 6 keV, respectively. We recognized that spatial electron distribution at the radiator mainly causes spread of the focal position, but it is less significant than we initially anticipated. We have also examined lower energies such as T = 1.4 MeV, and 1 m obtained energy resolutions of 2 and 4 keV, respectively. It can be concluded that the thermal emittance of the beam does not affect the energy resolution so much if we focus the beam on the radiator somewhat.

Effect of Radiator Thickness

Another important factor to be considered toward the energy resolution is a longitudinal position of the source point. We have supposed that the radiator thickness of R = 1 mm would be enough to produce sufficient number of Cherenkov photons. However, as discussed above, the spread of 1 mm on the focal line gives an energy width of ~ 30 keV at T = 1.7 keV, which is not negligibly small. If we need a thicker radiator than 1 mm, it is a matter of grave concern. Performing the ray-trace calculation, it turned out that the turtle-back mirror gives a longitudinal focusing effect for different longitudinal source positions.

Accordingly, the radiator thickness does not make considerable spread of the focal position.

Time Resolution

The turtle-back mirror has been designed so as to eliminate path length difference of the rays from a single source to the 1st focal line (on the s-axis). However, deviation of the path length in the light transport and the speed of light in the aspherical condenser lenses, as well as the spatial beam distribution at the radiator, cause an intrinsic time resolution of the LFC-camera.

According to result of ray trace calculation, the effect of thickness of radiator is not significant, moreover the light transport via the lenses does not affect the path length deviation so much. The intrinsic time resolution of the LFC camera is a couple of hundred femtoseconds.

PROSPECT

Figure 4 shows a tentative design of the LFC-camera system. The LFC-camera is composed of the beam position monitor, the thin Cherenkov radiator, the turtleback mirror, the aspherical lens, the mirror support mechanism and the photo detector. As a first step, we are planning to measure the energy distribution of the electron beam from the ITC-RF gun.

In addition, we are going to continue optimization of the optical element and prepare for the energy distribution measurement experiments with LFC-camera.

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