

LINEAR FOCAL CHERENKOV CAMERA FOR THE t-ACTS INJECTOR*

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Abstract

Thermionic RF gun has a potential ability for producing very short electron bunch. However, because space charge effects in the RF gun are not fully understood, an efficient bunch compression scheme has been not well designed so far. In order to measure the distribution in the longitudinal phase space of relatively lower energy electrons extracted from the thermionic RF gun, we have been developing a novel method to observe the energy spectrum employing a velocity dependence of opening angle of Cherenkov radiation. We have performed numerical ray-trace simulations and discuss intrinsic energy and temporal resolution of the system.

t-ACTS PROJECT

A test accelerator system for production of intense terahertz light has been under development at Tohoku University, called the t-ACTS (test Accelerator as Coherent THz Source) project [1]. We have chosen thermionic cathode for the RF gun because of stability, multi-bunch operation and cheaper cost. Since bunch charge in a microbunch will be small depending on acceptable energy spread, then coherent enhancement of synchrotron radiation is not much strong. However, high repetition operation in multi-bunch mode will open another aspect of application experiments. In Fig. 1, the source layout is shown. An undulator ($\lambda_u = 10$ cm, 25 periods) may provide coherent THz radiation at a wavelength range from 0.18 mm to 0.38 mm stably owing to a very short bunch length less than 100 fs.

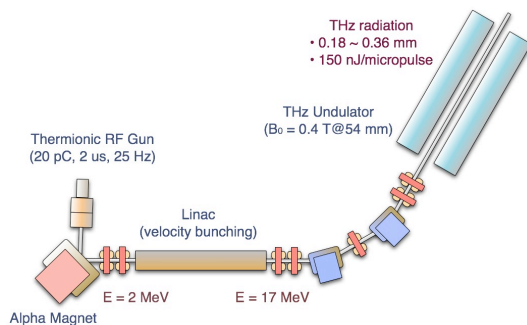


Figure 1: Schematic layout of t-ACTS for coherent THz undulator radiation. The bunch is compressed to less than 100 fs by means of the velocity bunching. The expected form factor at the wavelength around 0.3 mm is more than 0.8.

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ITC-RF GUN FOR FEMTO-SECOND ELECTRON PULSE

We have developed a thermionic RF gun consists of two independent cavities to manipulate the longitudinal beam phase space (see Fig. 2(a)), named the ITC (Independently-Tunable Cells) RF gun [2]. Particle distribution in longitudinal phase space is crucial for efficient bunch compression. The ITC-RF gun has been designed so as to produce appropriate longitudinal particle distribution by changing the relative RF phase and field strengths, as shown in Fig. 2(b).

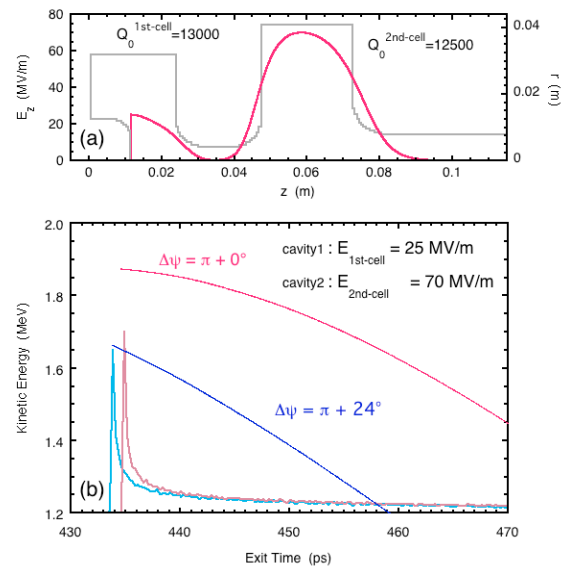


Figure 2: (a)Cavity structure and field distribution in the ITC-RF gun. A small size ($\phi = 1.85$ mm) cathode of single crystal LaB₆ is employed, which can provide a current density of more than 50 A/cm². (b) Particle distribution in the longitudinal phase space simulated by an FDTD code [3]. One for the phase difference of $\pi + 0^\circ$ (usual RF gun) leads higher energy (red dots). Meanwhile linear chirped particle distribution can be obtained by detuning the RF phase (blue dots). Those projections on the time axis are plotted solid lines.

Considerable amount of charge concentrates on to the head part of the beam, which means the space charge effect is so strong that the particle distribution in the longitudinal phase space is very likely distorted.

Velocity bunching in the accelerator structure for the lower energy beam ($\beta < 1$) is very much effective in a compact injector system [4]. However the bunching process is much sensitive to the initial particle

distribution. In order to establish an adequate bunch compression system toward femto-second electron pulse, observation the particle distribution in the longitudinal phase space extracted from the RF gun is quite significant.

CHERENKOV ANGLE

The beam energy from the ITC-RF gun is less than 2 MeV so that the velocity is still slower than the speed of light. Cherenkov light is widely used for beam diagnostics and particle counters in the high energy physics. It is well known that the Cherenkov angle θ_c is inversely 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 ω [5].

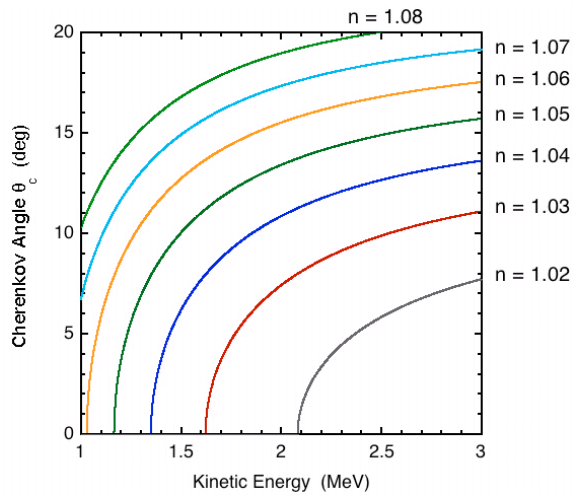


Figure 3: The Cherenkov angle plotted as a function of the kinetic energy for various refractive indexes.

The Cherenkov angle reaches to $1/n$ as increasing the particle energy. In case of that a derivative of the Cherenkov angle $d\theta_c/d\beta$ is sufficiently large, the particle velocity, viz. the energy, can be measured. Taking look at below 2 MeV in Fig. 3, we know $d\theta_c/d\beta \approx 1 \text{ mrad}/10 \text{ keV}$. This is not so small for a angle-resolved detection.

Silica-aerogel of a refraction index of 1.05 has been presumed to be the radiator medium in this study. Assuming no frequency dependence of n in a narrow bandwidth, the number of photons between wavelengths λ_1 and λ_2 emitted from an electron is calculated from Frank-Tamm formula as

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

where α is the fine structure constant. Using a second-order expansion, we obtain the number of photons at a visible wavelength per an electron, 1 % bandwidth and 1 mm radiator thickness,

$$N \approx 0.917\theta_c^2 \left[/n_e/1\%b.w./1mm \right] @500 \text{ nm}. \quad (3)$$

Since the Cherenkov angle is around 10 deg (~ 0.17 rad), the number of photons emitted 1 pC is approximately 1 M photons/1%b.w./mm. Estimated charge of the extracted beam with a reasonable energy spread of 2 % is about 20 pC, so that total photon number of 20 M/pulse, which may be not insufficient but not satisfactory sufficient. Since the Cherenkov light is emitted to 2π in the azimuthal angle, detection efficiency is desired to be as high as possible.

LINEAR FOCAL CHERENKOV RING (LFC) CAMERA

Since the Cherenkov angle contains information of the particle velocity, the photons having the same Cherenkov angle has to be focused on an identical position of a detector. When the focal points are aligned on a straight line, the energy distribution of the beam can be observed at once.

Figure 4 shows a tentative optical apparatus design of the detection system, and we call the Linear Focal Cherenkov ring camera (LFC-camera). A parabolic-spherical (Turtle-back) mirror gathers some part of photons in the Cherenkov ring and confines onto the s-axis.

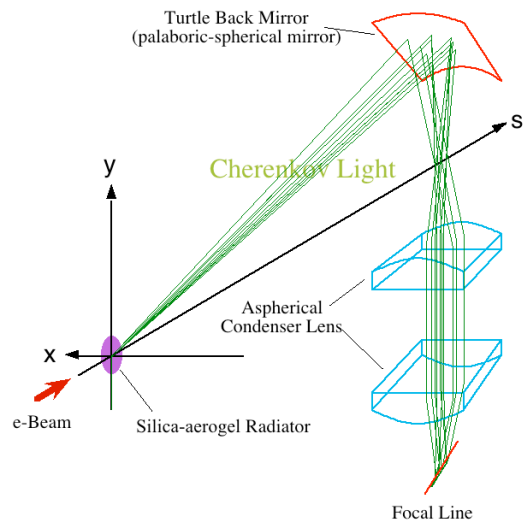


Figure 4: Schematic apparatus of the LFC-camera. The system consists of a specific (parabolic-spherical) mirror and two aspherical condenser lenses. Angular distribution of the Cherenkov radiation is imprinted onto a straight focal line.

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

The turtle-back mirror surface can be expressed by the following equation

$$x^2 + y^2 - \left(-\frac{1}{2A} s^2 + \frac{A}{2} \right)^2 = 0, \quad (4)$$

where $A \equiv \sqrt{y_0^2 + s_0^2} + y_0$. The base point $(0, y_0, s_0)$ 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 $\theta_c = 11.8^\circ$ and $y_0 = 0.063$ m).

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 for the other side, as shown in Fig. 2. The formula used to determine the surface is

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

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. It has turned out that the maximum acceptance can be obtained at $g = 23$, and approximately 10 % of the azimuthal angle of 2π is covered.

Using Eqs. (1) and (4), one can derive the focal position s_f as

$$s_f(\beta) = An\beta \left[1 - \sqrt{1 - (1/n\beta)^2} \right]. \quad (6)$$

We derived the derivative of the focal position with respect to the energy to be $\sim 50 \mu\text{m}/\text{keV}$. Pixel size of recent CMOS photosensor is smaller than $10 \mu\text{m}$. That is sufficient for detection with an energy resolution of keV order.

INTRINSIC ENERGY RESOLUTIONS OF LFC-CAMERA

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 2.5×10^{-7} mrad for the ITC-RF gun. In order to evaluate the effect for the position resolution, the ray-trace simulation

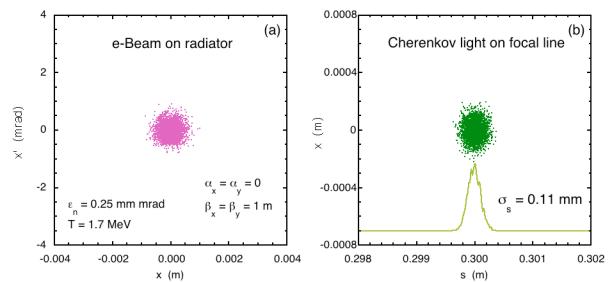


Figure 5: Electron distribution in the transverse phase space at the radiator medium (a) and photon distribution at the focal line (b).

were performed for two different monoenergetic beam conditions characterized by a beta function of the Twiss parameter.

Position spread at the focal line is 0.11 mm for the tight focused electron beam ($\beta = 1$ m) as shown in Fig. 5. This value of the position spread corresponds to ~ 3 keV, which is quite acceptable. We have also investigated the position spread caused by radiator thickness, source position dependence in other word. We, however, recognized that the parabolic mirror (in the s -axis of the turtle-back mirror) confines the parallel lights, so that a longitudinal shift of the source position is not significant. Results of the ray-trace show that the position spreads are 0.1 mm and 0.2 mm for the radiator thicknesses of 1 mm and 10 mm, respectively.

PROSPECT

We have designed a novel system for measurement of the longitudinal phase space of the low energy electrons extracted from a thermionic RF gun. The system, the LFC-camera, consists of a turtle-back mirror to confine the Cherenkov ring onto a focal line and two aspherical lenses for the light transportation. The numerical ray-trace shows the intrinsic energy resolution of the optical system to be less than 5 keV when the electron beam is well focused on the radiator.

We are going to continue optimization of the optical element without optical lenses to eliminate higher-order aberration.

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