BEAM ANGLE MEASUREMENT USING CHERENKOV RADIATION

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Abstract

A simple beam angle monitor utilizing observation of far-field Cherenkov radiation is being developed. The monitor is independent of beam energy as well as position and requires modest camera sensitivity. The angular resolution is determined by beam scattering in a radiator and diffraction from a finite size radiation source. Numerical analysis shows that the angular resolution with a 100-μm thickness fused silica radiator is 800 μrad. The experiment results with 2-mm and 100-μm thickness fused silica agrees with the numerical result qualitatively, but still small error due to misalignment of optics remains. The possibility of non-destructive measurement is also discussed.

INTRODUCTION

The measurements of angular trajectory/distribution have been successfully implemented. The most straightforward way is to measure beam positions at two screens with a drift space in between. One of the other methods is to observe far-field of optical transition radiation with or without interference between two foils [1]. An rf cavity monitor has also been employed [2].

One of purposes of the monitor using Cherenkov radiation is to measure beam angle of microbunches excited via FEL/IFEL processes. When an electron pulse propagates inside an undulator collinearly with laser radiation, transverse motion of electrons is coupled with transverse field of electromagnetic wave of the radiation. The electrons can then be accelerated/decelerated according to the phase with respect to the beat wave composed of the wiggler and radiation fields. Eventually electrons are microbunched at the same wavelength as the radiation. Not only the radiation but also the microbunched pulse has been deduced for other experiments, such as staged IFEL acceleration, STELLA [3]. When one wants to pick up a single or a couple of microbunches from a train of microbunches, for instance, one of straightforward ways may be to apply energy modulation on it, followed by a magnetic field that presumably separates microbunches one by one. In order to diagnose it, it is necessary to observe spatial separation after long distance of drift space or angular trajectory after the magnet. In the IFEL microbunching, at Brookhaven National Laboratory Accelerator Test Facility (BNL-ATF), each microbunch has an electron charge of a few pC and the distance between them is 33 fs, the period of CO2 laser. Hence it is required to detect a small charge without being affected by high repetition rate. For the purpose, a scheme based on far-field, or wavefront, measurement of Cherenkov radiation (CR) was proposed [4]. The scheme observes the far-field CR emitted by an electron pulse from a radiator, e.g., a fused silica. Therefore the angular trajectory can be observed without a long drift space. Since a wavefront of CR is not spherical but planar, the far-field image is infinitely small, which may result in high angular resoluation. The intensity can be adjusted according to the electron charge and the sensitivity of a detector as far as the thickness does not distort the angular resolution, because the number of CR photons emitted by an electron is proportional to the thickness of a radiator. Further the measurement does not depend on the repetition rate of microbunches. No significant effect of e-beam energy upon the measurement is also important, especially when the electron energy varies independently with each other according to the FEL/IFEL process. In the paper, the angular resolution in a practical experiment is discussed via numerical analysis and experiment. The possibility of non-destructive measurement is briefly discussed as well.

ANGLE MEASUREMENT

When an electron moves with velocity larger than speed of light in a dielectric medium, CR is emitted as a shock wave, or an optical cone with opening angle given by the ratio between the electron velocity and the light velocity, $\cos^{-1}(c/nv)$. Another characteristic of the shock wave is the wavefront; it is no longer spherical like transition radiation. One-dimensional wavefront can be regarded as a plane wave. Accordingly CR is focused onto infinitesimal image by far-field optics in one-dimensional geometrical optics, or equivalently an infinitely thin optical ring in three-dimensional geometrical optics. Since the angle of the wavefront of CR is linearly rotated as the beam angle is changed, the beam angle can be measured by observing the far-field CR image. Figure 1 illustrates a schematic setup of the measurement. In order to avoid internal total reflection, a radiator is tilted. Then some part of an optical cone can escape the radiator without reflection, only with refraction. Once the angle of electron trajectory changes by $\Delta\theta$, then the position of far-field CR image on a detector is shifted by

$$\Delta x = f \cdot tan\Delta\theta' , \qquad (1)$$

where

$$\Delta\theta' = sin^{-1}\left(n \cdot sin\Delta\theta\right) \qquad (2)$$

and n is the index of refraction. The characteristics of the scheme are as follows; First the measurement is not influenced significantly by the energy jitter/drift of electrons even at moderate energy: the energy deviation of 5 % from 60 MeV corresponds to 3.4 μrad. Second, the radiation intensity can be increased by making a radiator thicker. Third, the wavelength can be chosen depending on the detector. Fourth, only basic experimental apparatus such as a dielectric medium, an optical lens, a CCD camera and reflective optics are required.

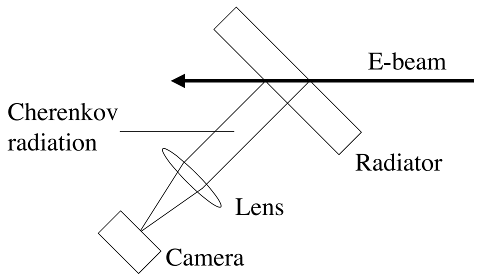

Fig.1 Far-field measurement of Cherenkov radiation

In order to estimate the angular resolution, beam scattering and diffraction of radiation have to be considered. As the thickness of radiator becomes larger, electrons are scattered larger so that the far-field image blurs. On the other hand, the source size eventually becomes larger, which makes the focus size smaller. Hence far-field CR image in a practical experiment forms a ring with finite thickness. These two effects as a function of a thickness of radiator are briefly estimated as shown in Fig.2. Here beam scattering is calculated based on empirical formula for multi-scattering[5] and the diffraction is estimated under assumption of no distortion of wavefront. The electron energy is fixed at 60 MeV, input beam radius is 300 μm and focal length of far-field optics is set to be 100 mm.

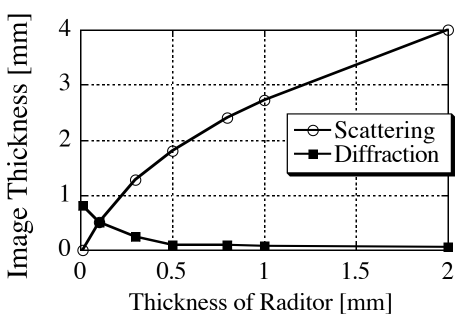

Fig.2 Effects of e-beam scattering and diffraction of CR upon far-field CR image width for 60 MeV beam.

In Fig.2, the thickness of 100 μm gives the thinnest image, which is about 600 μm for either effect. Under assumption that the two effects are independent with each other, which is not practically true though, the total thickness of the image is 840 μm for 60 MeV electrons. When the image has a smooth distribution like Gaussian distribution, the resolution of the peak-position measurement, or resolution of angle measurement of CR, is smaller than the thickness of the image. Supposed that the factor is ten, the resolution of peak-measurement is 84 μm. Since the focal length of the far-field optics is 100 mm, the angular resolution is found to be 840 μrad.

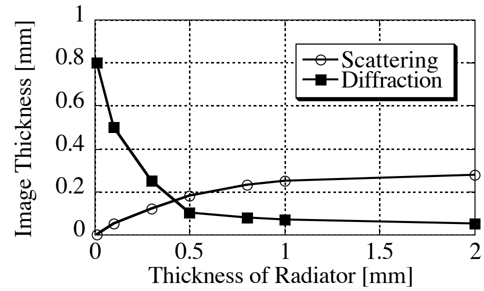

Fig.3 Effects of e-beam scattering and diffraction of CR upon far-field CR image width for 1.0 GeV beam.

It should be noted that the scheme is more effective for higher energy. Figure 3 is calculated in the same way as Fig. 2 but for 1.0 GeV electrons. As the energy goes higher, the scattering effect is suppressed. Then the appropriate thickness goes higher, which is preferable because the number of photon emitted from a radiator is increased. For 1.0 GeV electrons, the best thickness is about 450 μm. Further, the image thickness is decreased by factor of more than three.

EXPERIMENTS

Experiments have been implemented using two thicknesses of radiators; 2 mm and 100 μm. As a radiator, Fused Silica (n=1.46) is employed. Far-field optics consists of a cooled CCD with commercial-base optical lens set. No band-pass filter is used. The electron energy is 60 MeV, charge is 100 to 200 pC, and the pulse duration is 3 ps. Far-field CR image emitted from 2-mm thick Fused Silica is shown in Fig. 4, in which CR image is spread out over the field of view due to the beam scattering effect. In the experiment, the focal length of the lens is 70 mm, diameter of the lens is 30 mm, and the distance from the light source to the lens is 300 mm. Hence the diameter of the field of view, d, is

$$d = f \cdot D / L = 7\ [mm], \tag{3}$$

where d is the diameter of field of view, f is focal length of optics, D is diameter of lens, and L is the distance from light source to the lens. It is roughly consistent with Fig. 2, since the 2-mm thick radiator is placed at 45 degree.

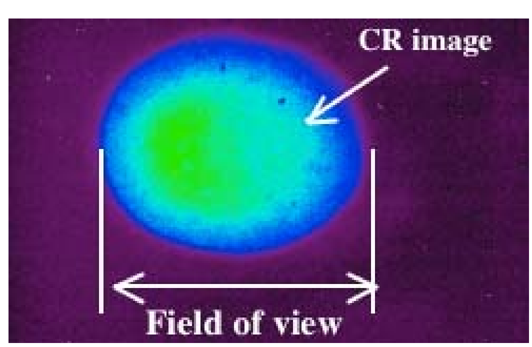

Fig.4 Far-field CR image from 2-mm thick Fused Silica

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In Fig.5, where Far-field CR image from 100-μm thick Fused Silica is taken, the image thickness is much smaller than the field of view (that is larger than the picture frame). The CR image does not form a ring but a vertical line because the image is a part of a ring. It should be noted that the image was taken by a single shot without an intensifier, The number of photons emitted by 100 pC electrons from 100-μm thick Fused Silica (n=1.46) in the range of 300 to 800 nm is 4.4×10^9, while that of transition radiation in the same condition is 1.5×10^7. The intensity distribution of cross section of the vertical line is very close to Gaussian distribution with the rms thickness of 0.5 mm at CCD, which is again consistent with the estimation in Fig.2.

In order to verify the reliability of the scheme, a beam angle was measured by using a pair of beam profile monitors (BPMs) as well as the scheme, kicking e-beams by trim coils. As represented in Fig.6, both measurements are linearly proportional with each other. However, evaluated angles have errors of about 20 %. It was found that the error came from imperfection of optical alignment; the optics setup was not completely far-field.

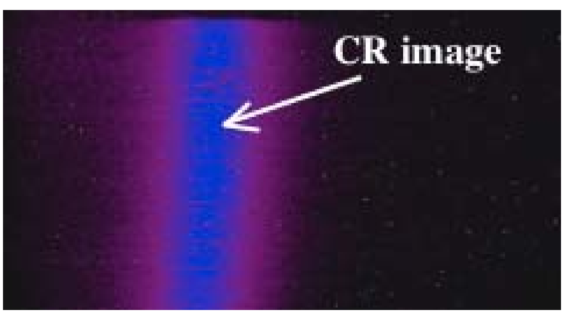

Fig.5 Far-field CR image from 100-μm thick Fused Silica

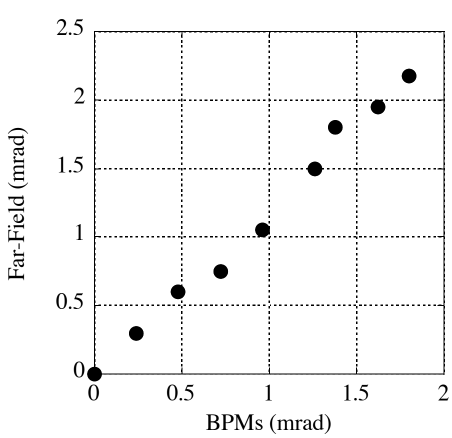

Fig.6 Angle measurements via Far-field CR observation and a pair of beam profile monitors (BPMs).

As regards a non-destructive measurement, it may be possible when dielectric material can be excited by an electromagnetic field around electrons to generate radiation. For high energy electrons such as 1 GeV, it is reasonably possible even in visible regime, since the size of electromagnetic field, $\gamma\lambda$, where γ is Lorentz factor and λ the wavelength of radiation, can exceed electron beam size (~ 30 μm). For moderate energy such as 100 MeV, the radiation of longer length, which is normally addressed as wakefield, needs to be observed. Supposed that the energy is 60 MeV ($\gamma \sim 120$) and the beam size is120 μm peak-to-peak, the wavelength needs to be $\lambda > D/\gamma \sim 120/120 = 1\left[\mu m\right]$.

SUMMARY

A simple scheme to measure electron trajectory angle was studied through numerical analysis and experiments. The numerical analysis gives an appropriate thickness of a radiator; 100 μm for 60 MeV electrons and 450 μm for 1.0 GeV electrons. Accordingly tangular resolutions are respectively estimated to be 840 and 200 μrad. The image thicknesses measured with 2 mm and 100 μm thick Fused Silica and 60 MeV electron beam agreed with the numerical results. The experimental results verified that a single shot measurement is available even for 100 pC 60 MeV electron beam without an intensifier. However, the angular measurement by the observation of far-field Cherenkov radiation did not completely agree with the independent measurement by a pair of beam profile monitors due to imperfection of far-field optics. Since the optical alignment of far-field does not depend on the distance from the light source to the optics, the far-field optics can be adjusted *off-line*. It will be done and the angle mesurement will be conducted.

ACKNOWLEDGEMENTS

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