DIAGNOSTICS OF AN ELECTRON BEAM USING COHERENT CHERENKOV RADIATION*

R. Tikhoplav#, P. Musumecci, J. Rosenzweig, S. Tochitsky, UCLA, Los Angeles, CA 90095
G. Gatti INFN/LNF, 00044 Frascati (RM) Italy

Abstract

The use of coherent Cherenkov radiation as a diagnostic tool for longitudinal distribution of an electron beam is studied in this paper. This method will be employed for the 7th harmonic bunching experiment at Neptune linear accelerator facility at UCLA. Coherent Cherenkov radiation is produced in an aerogel with an index of refraction close to unity.

THEORETICAL BACKGROUND

Radiation due to a relativistic electron beam traversing a medium, such as transition radiation (TR), has proved itself to be a powerful tool for beam diagnostics, e.g., determining the transverse distribution and position of an electron beam as in TR screen technique. Such radiation could also be used for reconstruction of the longitudinal profile of the electron beam if the coherent part of such radiation is known [1].

Regardless of the source of radiation (Cherenkov (CR), Synchrotron (SR), or TR), the spectral response of the electron bunch can be represented as following [2],

$$T(\lambda) = S(\lambda)\left(N + N(N-1)\left|F_{3D}(\lambda)\right|^2\right) \quad (1)$$

where $S(\lambda)$ is the spectrum of a single particle, λ is wavelength, N is the number of particles in the bunch, F_{3D} is the 3-D Fourier transform of the bunch particle distribution, called the form factor,

$$F_{3D}(\lambda) = F(\lambda)F_T(\lambda) \quad (2)$$

where F and F_T are longitudinal and transverse form factors respectively. Coherent part of radiation is proportional to the number of emitters squared, thus it gives a much stronger signal than the incoherent part. It is also a function of a form factor which depends on the shape of the bunch. If a longitudinal modulation of a certain period λ_0 (micro-bunching) is introduced to the bunch with longitudinal Gaussian distribution of rms size σ, such modulation would change the form factor resulting in enhancement of a corresponding frequency of radiation and its harmonics.

$$F(\lambda) = \exp\left(-2\pi^2\sigma^2/\lambda^2\right)\left(1 + \sum_n h_n(\lambda_0)\right) \quad (3)$$

where $h_n = a_n \exp\left(-2n^2\pi^2\sigma^2/\lambda_0^2\right)\cosh\left(4n\pi^2\sigma^2/\lambda\lambda_0\right)$ is the modulation factor, n and a_n are the harmonics number and its weight respectively. Such radiation would be analyzed and a temporal distribution of the electron beam could be deducted.

Coherent Cherenkov Radiation in the Aerogel

Cherenkov radiation induced by a single particle can be expressed in terms of number of photons per unit frequency,

$$\frac{\partial N_{ph}^{Ch}}{\partial k \partial \theta} = L\alpha\theta_c^2\delta(\theta - \theta_c) \quad (4)$$

here α is the fine structure constant, θ_c is Cherenkov angle, L is the length of the electron path in the medium. In the case of a bunched electron beam, the total number of photons for Coherent Cherenkov Radiation (CTR) can be expressed as the following,

$$N_{ph}^{Ch} \approx \sqrt{\pi}LN^2\frac{\alpha}{\sigma}a_n^2\theta_c^2\left|F_T(\lambda)\right|^2 \quad (5)$$

We are particularly interested in using the aerogel as a medium for CTR. Aerogel, or 'frozen smoke' is a low-density solid-state material made by high temperature and pressure-critical-point drying of a gel composed of colloidal silica structural units filled with solvents [3].

Table 1: Aerogel Parameters

Parameter	Value
Material	SiO_2
Density	20 kg/m^3
Refractive Index, n	1.008
Cherenkov Angle, θ_c	7.25^O
Melting Point	1200^{O}C

Its low density provides nearly non-destructive tool for the electron beam diagnostics (see Table 1) and its small refractive index $n=1+\Delta$ gives a small Cherenkov angle $\theta_c \approx \sqrt{2\Delta}$.

The form factor (and consequently, the enhancement of coherent radiation) depends on the transverse shape of the electron beam as well. A Gaussian transverse distribution $f(\rho) \propto \exp(\rho^2/2\sigma_T^2)$ leads to suppression of shorter wavelengths (see Fig. 1), unless the transverse size σ_T is infinitely small. The corresponding form factor is given by the following:

$$F_T(\lambda) = \exp\left(-2\pi^2\theta_c^2\sigma_T^2/\lambda^2\right) \quad (6)$$

This could be overcome if other transverse shapes are employed. For example, transverse hard-edge distribution

*Work supported by US Department of Energy
#rodion@ucla.edu

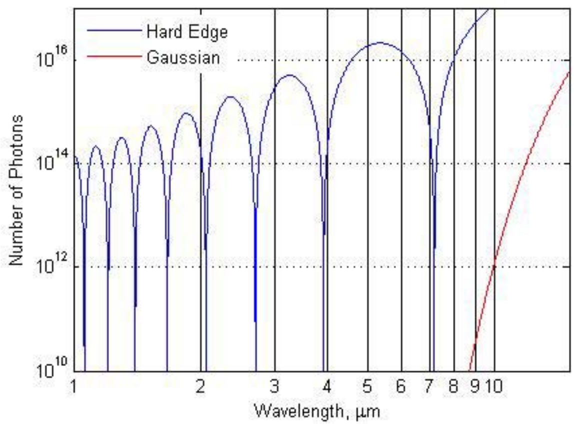

Fig. 3: Number of photons of the Cherenkov radiation induced by 160 pC electron beam for Gaussian and hard edge transverse distributions.

$f(\rho) \propto rect_{\sigma_T}(\rho)$ gives a stronger signal than the Gaussian, see Fig. 1. The corresponding form factor is

$$F_T(\lambda) = \frac{J_1\left(2\pi^2\theta_c^2\sigma_T^2/\lambda^2\right)}{2\pi^2\theta_c^2\sigma_T^2/\lambda} \quad (7)$$

Hard edge distribution is not the only one that gives a good response in the high frequency range. Other techniques such as putting a grid of wires across the beam could be used [4].

Angular Distribution of the Cherenkov Radiation

The delta-function nature of the theoretical representation for the angular distribution of Cherenkov radiation makes unrealistically strict requirements for the transverse emittance of the electron beam. Indeed, spatial coherence of radiation is not achievable unless all the electrons trajectories in the medium are perfectly parallel.

To treat the problem properly, one needs to take into account the fact that the speed of an electron decreases by a small jump every time a photon is emitted. Interestingly, this process is analogues to a spectral line broadening due to finite life of an excited state.

L.I. Schiff [5] treated this problem and got the following distribution for intensity of Cherenkov radiation as a function of an angle between the direction of the motion of an electron and direction of radiation:

$$I(\theta) = I(\theta_c)\frac{\sin^2 y}{y^2} \quad (8)$$

where

$$y = 2\pi\frac{l}{\lambda}(\cos\theta_c - \cos\theta) \quad (9)$$

l is the length of a free path. Distribution (8) has a certain width. Let $\Delta\theta$ to be FWHM of (8), i.e., $I(\theta_c + \Delta\theta/2) = I(\theta_c - \Delta\theta/2) = I(\theta_c)/2$ or $\sin y = y/\sqrt{2}$, and $y \approx 1.4$; therefore from (9) it follows that

$$\Delta\theta \approx 2.8/(2\pi\frac{l}{\lambda}\sin\theta_c) \quad (10)$$

Finding the exact value for the length of the free path l theoretically is challenging due to partial coherence between different elementary waves emitted by different parts of an electron path [6]; but its upper limit is easily set to be the total length of the medium L, which is in our case is 2.5 mm. Hence, the lower limit for $\Delta\theta$ is 14 mrad.

EXPERIMANTAL SET-UP

The Neptune facility at UCLA consists of a 15 MeV Photoinjector linac which can provide a charge of up to 0.5 nC and a CO_2 laser with peak energy of up to 100 J [7]. Using a CO2 regenerative amplifier (10.6 um) with 5-10 MW of power, we expect the electron beam to be fully bunched after traversing a 10 period undulator tuned to the 7th harmonic of the laser [8], see Table 2.

Table2: Neptune Bunching Experiment Parameters

Parameter	**Value**
Undulator Length	33 cm
Undulator Period, λ_u	3.3 cm
Undulator Constant, K_u	1.8
Electron Energy	12.4 MeV
Electron Charge	100 pC
Normalized Emmitance	5 mm-mrad
Laser Energy	1 mJ
Laser Pulse Length	200 ps
Laser Intensity, I	1 GW/cm^2
Laser Beam rms Size	0.65 mm

SUMMARY

A novel method for micro-bunching diagnostics of an electron beam using aerogel has been analyzed and will be tested at Neptune facility at UCLA. By measuring the relative intensities of different harmonicas the whole longitudinal modulation can be reconstructed. The lower limit for the angular width of the Coherent Cherenkov Radiation was found to be 14 mrad which corresponds to the beam parameters available at the Neptune facility.

REFERENCES

[1] R. Tikhoplav, PhD Dissertation (2006).
[2] O. Grimm, *et al.*, DESY April 24, 2006 Internal report (2006).
[3] http://stardust.jpl.nasa.gov/tech/aerogel.html
[4] G. Gatti, *et al*., Proc. of 2007 Part. Accel. Conf. 998 (2007).
[5] L.I. Schiff, Quantum Mechanics (1949).
[6] J.V. Jelley, *Physics-Uspekhi* **58**, 231 (1956).
[7] http://pbpl.physics.ucla.edu
[8] P. Musumeci, *et al*., these proceedings.