COHERENT DIFFRACTION RADIATION IMAGING METHODS TO MEASURE RMS BUNCH

R.B. Fiorito†, C. P. Welsch, Cockcroft Institute, University of Liverpool, Daresbury, UK
A.G. Shkvarunets, IREAP, University of Maryland, College Park, MD USA,
C. Clarke, A. Fisher, SLAC National Accelerator Laboratory, Menlo Park, CA

Abstract

The measurement of beam bunch length with high resolution is very important for the latest generation light sources and also a key parameter for the optimization of the final beam quality in high gradient plasma accelerators. In this contribution we present progress in the development of novel single shot, RMS bunch length diagnostic techniques based on imaging the near and far fields of coherent THz diffraction radiation (CDR) that is produced as a charged particle beam interacts with a solid foil or an aperture. Recent simulation results show that the profile of a THz image of the point spread function (PSF) of a beam whose radius is less than the image produced by a single electron, is sensitive to bunch length and can thus be used as a diagnostic. The advantages of near (source) field imaging over far field imaging are examined and the results of recent high energy (20 GeV) CDR THz experiments at SLAC/FACET are presented. Plans for experiments to further validate and compare these imaging methods for both moderate and high energy charged particle beams are discussed.

INTRODUCTION

In previous studies we have shown that the angular distribution (AD) of CDR from a slit or aperture is sensitive to RMS bunch length [1]. The AD can be calculated from the integrated spectral angular density of DR from single electron multiplied by the longitudinal form factor of the pulse integrated over a frequency band in which the integrand is appreciable [2]. Typically this band is limited at low frequencies by the outer radius or boundary of the radiator. At high frequencies it is truncated by the fall off of the longitudinal bunch form factor and, if the radiator is an aperture, by the aperture size. The AD is given by

$$\frac{dI_{bunch}^{CDR}}{d\Omega} \approx N_e^2 \int_{\Delta\omega} \frac{d^2 I_e^{DR}}{d\omega d\Omega} S_z(\sigma_z,\omega) d\omega$$

where I_e is the intensity of the CDR from a single electron, N_e is the number of electrons, S_z is the longitudinal form factor, σ_z is the RMS longitudinal size of the bunch, $\omega = 2\pi f$ is the angular frequency, and $d\Omega$ is the solid angle of observation.

In a proof of principle experiment, the AD projected on a plane normal to the direction of the CDR from a plate and a slit were observed using a scanning Golay cell at PSI's 100 MeV injector linac for various bunch lengths. The latter was varied by a compressor chicane in the range of 0.5-2 psec. The bunch lengths were inferred fitting scans of the angular distribution obtained from the equation above to the data. The inferred bunch lengths were also compared with those obtained independently with an electro-optical sampling method and were found to be in excellent agreement with the AD measurements in all cases studied.

OBSERVING THE CDR PSF

According to the virtual photon paradigm [3] the properties of radiation produced by relativistic particles interacting with materials or fields follow those of real photon interactions. For example, when a relativistic charged particle passes through an aperture, diffraction radiation is produced with properties similar to those observed when real photons diffract from the aperture. Applying this paradigm to CDR, the spatial distribution of CDR from a transversely coherent source, i.e. the PSF of the radiation from a coherent source such as a bunch of electrons radiating at a wavelength close to the bunch size, should be related by Fourier transformation to the AD of the photons observed. Then since the AD is related to the longitudinal bunch size, the PSF should also be likewise sensitive to the bunch length.

To observe the PSF, i.e. the spatial form of the CDR from a "single" electron, the transverse size of the beam must be much smaller than the PSF observed of a single electron. In this case the CDR is fully transversely coherent and the CDR PSF will be observed. The PSF of coherent transition radiation (CTR) has been similarly observed in the optical band [4], and under similar beam size conditions should be observable in the THz regime as well (note that CDR and CTR for a finite radiator are closely related via Babinet's principle [5]).

To test this hypothesis we have developed a simulation code to calculate the CDR PSF and explore its sensitivity to bunch length. The CDR produced as an electron passes through a finite sized radiator is intercepted by a lens positioned in the far field of the source which focuses the radiation onto the image plane of the lens.

Simulation results for a 100 MeV beam, interacting with a simple annular aperture oriented normal to the beam are shown in Figure 1 for various bunch sizes in the range of 1-3 picoseconds in the wave band (1-600 GHz). In this example the transverse beam size of the frequency integrated PSF from a single electron has a FWHM ~ 10-20mm (see Figure 1). Note that each of the PSFs shown is

†ralph.fiorito@cockcroft.ac.uk

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scaled in amplitude by a different factor *A* for each bunch length.

The advantages of observing and using the PSF over the AD of CDR to determine the bunch length are: 1) the former is less susceptible to upstream source contamination than the latter, which is especially important at high energies, where the coherence length of any radiation

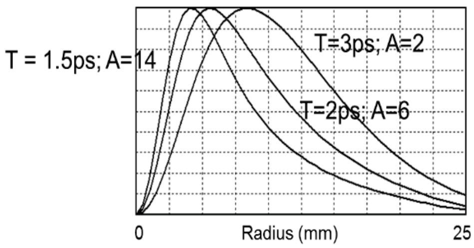

Figure 1: Theoretical CDR PSF distributions produced by a 100 MeV beam interacting with an annular radiator (R_{out}=25mm, R_{in}=5mm) for various bunch lengths.

driven by the beam is very long, i.e. $L \sim \gamma^2 \lambda$ - in this case upstream sources, e.g. CSR synchrotron radiation or another source of CDR within *L* can strongly interfere with and distort the CDR produced by the primary source; 2) the PSF image can be more easily focused to produce a high number of photons per detector pixel for the source image in comparison to the AD image.

Note that the AD is commonly observed in the focal plane of the lens (focus at infinity). However, in this plane the AD from all upstream sources will also be in focus along with that of the CDR. In contrast, the PSF of the designated source is uniquely observed in the image plane when the focal and image plane are well differentiated. Thus, by carefully choosing the focal length of the lens and the object distance, the PSF from the desired CDR source can be readily distinguished from other sources, i.e. upstream sources will be out of focus and will only create a diffuse background in the image plane.

CDR EXPERIMENTS AT FACET

Setup

Observations of the AD and PSF of CDR were made using the FACET facility at SLAC in the first half of 2016 before its shutdown at the end of April.

The FACET electron beam used in our experiments had the following properties: E = 20 GeV, Q ~ 1.1 nC, bunch rep rate f = 10 Hz; transverse beam size ~100 micron, available bunch lengths = 60 - 80 microns FWHM; observed THz wavelength band: 18-200 mm (0.15-2 THz).

A schematic of the experimental setup is shown in Figure 2. A two foil laser based alignment system is used to overlap incoherent OTR generated by the electron beam with a HeNe laser. The laser and OTR are observed using two CCD cameras, which can be remotely inserted into the optical path. The laser is first used to align the optics used to transport the CDR produced by the radiator to two 7 inch focal length off axis parabolic mirrors arranged in a confocal periscope arrangement, then to a flat remotely rotatable mirror and finally to a 250 mm focal length Teflon lens. Two detectors: a Pyrocam pyroelectric array consisting of 128 x 128, 85micron square pixels and a Gentec single, 6 mm square, pyroelectric detector were employed. Each of these detectors can be positioned via a linear translator to the focal plane or the image plane of the final lens in the optical train. Either the AD or PSF could be scanned across the Gentec via the rotating mirror. A one mm diameter iris was inserted in front of the Gentec detector to create a high resolution line scan in either the horizontal or vertical direction.

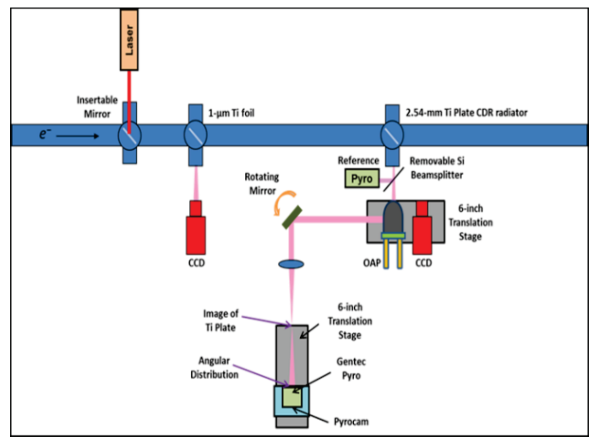

Figure 2: AD and PSF imaging system at FACET.

The CDR radiator is a flat, polished, rectangular Titanium plate (31mm wide, 0.2 inch thick, 4.7 inches long) with a 5 mm circulator aperture located about 2 inches from the bottom of the radiator. Either the flat portion of the radiator or the circular hole could be vertically positioned to intercept the electron beam.

Preliminary Results

Imaging of the PSF of CDR was not possible with the Pyrocam due to experimental difficulties. However, line scans of the radiation observed in the image plane of the Teflon lens were obtained using the Gentec detector with the 1 mm iris.

Figure 3a shows a theoretical horizontal line scan (inverted) obtained using the CDR code described above for a beam with bunch length equal to 60 microns (FWHM), the value measured independently by a transverse deflecting cavity monitor at FACET. The transverse beam size for our experiment was 250 microns, which is much less than the FWHM of the single electron CDR PSF calculated for the FACET parameters.

Figure 3b shows a line scan corresponding to 4a, measured using the rotating mirror and Gentec detector covered with the 1mm iris. Note that this measured scan has the same qualitative shape as the theoretical distribution. However, the measured distribution is about a factor of two wider than the theoretical prediction (see e.g. the peak to peak separation).

The cause of this discrepancy is currently being investigated. It may be due to a calibration error or distortion

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of the CDR distribution due to improper focusing of the THz radiation in the transport optics. The latter is the most likely problem since, in the later stages of the experiment, little time was available to thoroughly test and check the focus of the optics, in particular the image plane of final Teflon lens. We are in the process of comparing our calculations of the PSF with other available codes and studying the effect of defocusing on the image distribution to better understand our results.

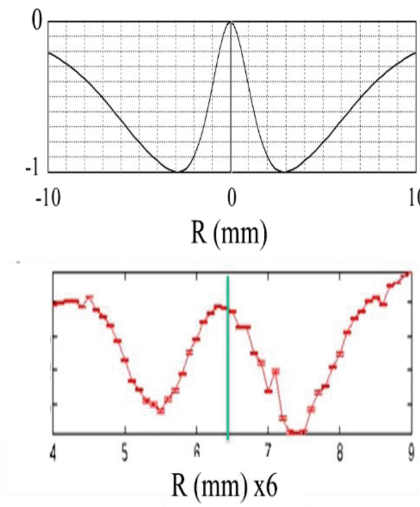

Figure 3: a) theoretical normalized horizontal line scan of the PSF of CDR from a flat rectangular radiator; b) measured normalized line scan of CDR distribution.

CONCLUSIONS

We have developed a new method to measure the RMS bunch length using the PSF of CDR generated in the THz regime. Simulations have shown that the CDR PSF can be observed for a beam with transverse dimensions that are much smaller than the FWHM of the PSF produced by a single electron and thus similar to what has been observed in the optical regime with COTR. A preliminary experiment to image the CDR PSF using the SLAC FACET facility has been done and the results obtained qualitatively agree with predictions. However, a discrepancy of about a factor of two in the scaling of the data is still present and remains to be explained. We are currently examining the issue of image defocusing in the optical system as well as comparing our CDR simulations with other available codes.

Further experiments under more controlled conditions are also being planned at 100 MeV (PSI) and a possible follow up experiment at SLAC using LCLS is under consideration.

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