# NOVEL SINGLE SHOT BUNCH LENGTH DIAGNOSTIC USING COHERENT DIFFRACTION RADIATION

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*Abstract*

Current beam bunch length monitors that measure the spectral content of beam-associated coherent radiation to determine the longitudinal bunch form factor usually require wide bandwidth detection, Fourier transformation of spectral or interferometric data, phase retrieval algorithms and multiple beam pulses to obtain the bunch length. In this paper we discuss progress in the development of a novel single shot method that utilizes the frequency integrated angular distribution (AD) of coherent diffraction radiation (CDR) to measure the RMS bunch length directly. We also present simulation results that show how the AD changes with bunch length for two electron beam linacs, where we are planning to test this new method, our single shot measurement technique and plans for comparison to other bunch length monitors.

## INTRODUCTION

Conventional RF accelerators as well as plasma wakefield accelerators have the ability to generate very short pulses of electrons (~10fs), and schemes are being developed to produce even shorter pulse lengths. A number of techniques have been developed to measure bunch length and even the longitudinal distribution of bunches down to ~10 fs in duration. These include Fourier transform interferometry, direct spectroscopy and various electro-optic techniques that sample either the Coulomb field of the bunch itself or the radiation field produced by the bunch interacting with a physical structure or an electromagnetic field. However, the experimental techniques required are usually complex and difficult to implement particularly for single shot measurements.

Frequently, measurement of the rms bunch length rather than the detailed longitudinal profile of the bunch is sufficient for tune up and accelerator monitoring. To meet this need we propose to develop a novel rms bunch length method that is noninvasive, easy to implement, simple to analyze, capable of bunch length measurements over a very wide range and has the potential for single-shot measurements.

## BACKGROUND

For most cases of interest, the AD of the CDR can be calculated as the integrated spectral angular density of DR from single electron multiplied by the longitudinal form factor of the pulse:

$$\frac{dI_{bunch}^{CDR}}{d\Omega} \approx N_e^2 \int_{\Delta\omega} \frac{d^2 I_e^{DR}}{d\omega d\Omega} S_z(\sigma_z,\omega) d\omega \qquad (1)$$

The single electron spectral angular density, the first term of the integrand depends on the shape and size of the radiator as well as the frequency. This can be calculated for any size/shape radiator [1]. The second term of the integrand is the longitudinal bunch form factor, which is a function of the bunch length ($\sigma_z$). Assuming a model (e.g. a Gaussian) for the longitudinal bunch form factor and an appropriate frequency band, Eq. (1) can be integrated and fit to the measured AD data to produce the rms bunch length [1].

The method has been validated experimentally in a proof of principle experiment done at the Paul Scherrer Institute using repetitive picosecond electron beam pulses with energy E=100 MeV and a Golay cell to scan the angular distribution of the CDR in both the horizontal and vertical directions [2]. However, the measurement was time integrated, i.e. averaged over many repetitive macro-pulses and provided only 1D scans for the fit.

We propose to measure the entire AD projected onto the plane of an imaging detector to improve the accuracy of the measurement and to demonstrate single shot capability. The method will be tested at two accelerators with widely different bunch lengths and beam energies: the ALICE accelerator at Daresbury Laboratory and the FACET accelerator at SLAC.

## EXPERIMENTS

### *ALICE*

The beam parameters that are planned for our initial CDR AD imaging experiments on ALICE are: E=26 MeV, $\tau_{rms}$ = 0.7-1.3 ps, Q = 100 pC/micro-bunch, 1-4000 micro-bunches per macro-pulse and macro-pulse repetition rate $f_{rep}$ = 10 Hz.

CDR will be created as each picosecond micro-bunch passes through a simple circular annular aperture inclined at $45^0$ to the velocity of the electron beam. The CDR will emerge at $90^0$, passing through a vacuum window and be imaged onto a pyroelectric array.

We have calculated the frequency integrated AD of CDR for an annular radiator (outer radius = 8mm and inner radius = 4mm) over the wavelength band 18-200 μm, which corresponds to a frequency band 0.15 - 2 THz, for different bunch lengths. In this band the longitudinal bunch form factor is most sensitive to changes in the bunch size. The results of our calculations are shown in Figure 1. The widths of the three distributions correspond to rms bunch widths: 0.7, 1.0 and 1.3 ps. The intensities are normalized to their respective peak values.

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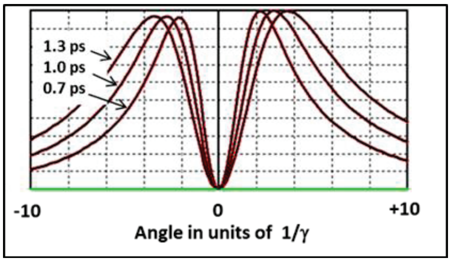


Figure 1: Horizontal line scans of the AD of CDR calculated for the ALICE accelerator parameters.

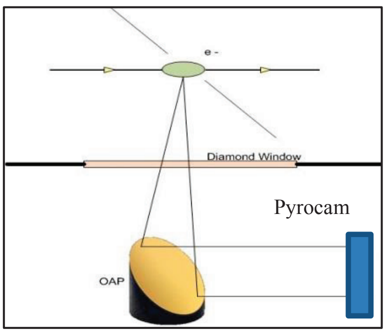


Figure 2: Set-up for direct imaging the AD of CDR passing through an annulus.

The experimental setup is shown in Figure 2. An off-axis parabolic reflector (OAP) with an effective focal length of 50mm will be used to focus the THz CDR AD onto a 12x12 mm, 124 x 124 element pyroelectric array (Pyrocam III). The 85 micron square pixels are sensitive to radiation with wavelengths from 1-3000 microns and have a minimum sensitivity of 7 nJ/pixel. When placed in the focal plane of the OAP the array will subtend an angular field of view $\Theta \sim 0.2$ radians or roughly half of the far field AD pattern shown in Figure 2. A single pixel of the array will be exposed to a calculated peak energy $E_p \sim 3 \times 10^{-6}$ J per micro-pulse per steradian and each pixel subtends about $3 \times 10^{-6}$ sterad. Therefore for 1000 micropulses the signal to sensitivity ratio is about unity. To increase this ratio to ~10 we will use 3x3 binning on the Pyrocam. If more signal is needed we can increase the number of micropulses/macropulse.

The setup to test the proposed optics for our ALICE CDR AD imaging experiment is shown in Figure 3. A HeNe laser beam is first expanded using a two lens system to form a collimated beam. This beam is used to determine the focal plane of the 50 mm focal length OAP, i.e. the collimated laser beam is focused to a point at $f =$ 50mm, where the Pyrocam is placed in order to image the AD of the CDR generated by the electron beam. The 10 X beam expander consists of f/25 and f/250 mm lenses spaced such that the distance between their principle planes is exactly 275mm. In practice this is achieved by varying the inter-lens spacing until a collimated laser beam is observed at several distances after the second (*f*/250mm) lens.

A 50/50 beam splitter (B.S.) directs the collimated beam from the expander to the Pyrocam and also transmits the ALICE internal alignment laser. The latter is setup up separately to follow the electron beam trajectory in the accelerator. When this beam is reflected by the radiator surface out of the vacuum chamber through an optical viewport, it can be used to align the OAP and Pyrocam to the direction of the central ray of the CDR AD pattern that will be observed in reflection from the radiator during the experiment.

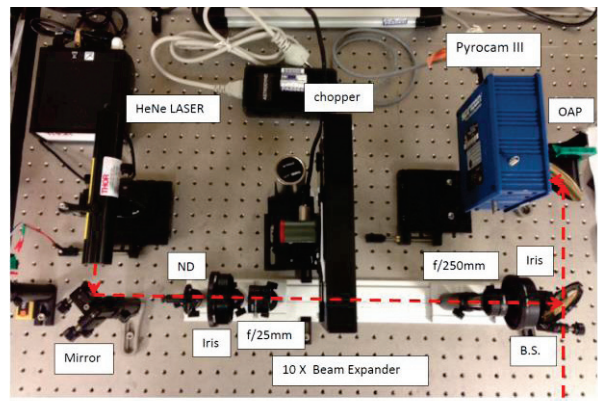


Figure 3: Optics setup to test and align the CDR AD imaging system for ALICE.

## *FACET*

We also are planning CDR AD experiments to determine the bunch length of SLAC's FACET electron beam accelerator. The beam parameters are quite different than ALICE, i.e. E=20 GeV, $\tau_{rms} \sim$ 50-100 fsec and the number of electrons per bunch is $10^{10}$ or Q ~ 0.6 nC per bunch. We estimate the peak energy density of the CDR to be 134 J/sterad in the wavelength band 18-200 microns for a single bunch.

Two CDR radiators will be used to measure the bunch length: 1) an existing circular foil 25 mm in diameter and 2) an annular aperture with an outer radius of 12.5mm and inner radius 2.5mm. In contrast to ALICE we should easily be able to image the entire 2D angular distribution produced by a *single pulse* and analyze it to determine the bunch length. We will do this for a number of different bunch lengths and compare our results to those obtained with other techniques, e.g. a transverse deflecting cavity and an interferometer that are presently online.

A calculation of a horizontal scan of the CDR AD from the annular aperture is shown in Figure 4. Here we have calculated the frequency integrated AD of the CDR for three different bunch lengths over the same frequency band 0.15 - 2 THz used for the ALICE calculation above.

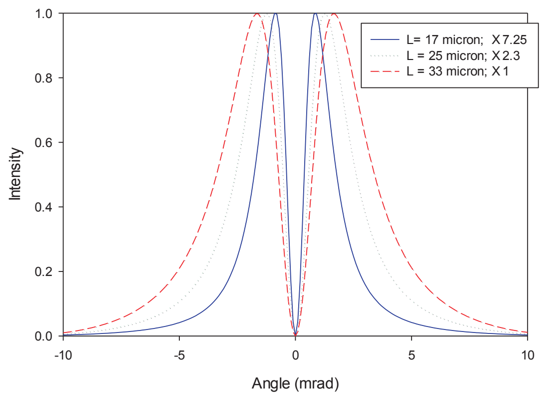


Figure 4: Calculated bunch length dependence of the AD of CDR from FACET for various bunch lengths; intensities are normalized to their peak values.

We will also employ an OAP to focus and image the AD with a Pyrocam III camera. However, since the beam energy is much higher than ALICE, the AD will be highly compressed in angle (cf. Figures 1 and 4). Thus a longer focal length (*f* ~ 1 meter) OAP is required to image the CDR AD. Our estimate for the peak CDR energy that will be seen by a single pixel of the Pyrocam per pulse is ~1 μJ, which is close to the saturation level of the pyroelectric elements, so that attenuation of the CDR may be necessary. Since the FACET pulse repetition rate is 10 Hz, it should be straightforward to capture the CDR AD of a single pulse with the Pyrocam, which can be readout at a 10 Hz rate and triggered to capture the CDR from the FACET electron beam pulse.

## FUTURE PLANS

In follow-on experiments we plan to test an alternative method to perform single shot CDR AD imaging. It is an adaptation of a simple electro-optic (EO) technique that was previously developed to image CDR in the FIR-THz band. It utilizes the fact that the polarizability of an EO crystal is altered by incident CDR THz radiation. The polarization pattern imprinted on the crystal can be imaged on a CCD camera with the help of a polarized laser beam timed to overlap the beam pulse.

The optics that we will use to image the AD of CDR THz radiation is a simple variation of a technique that has been developed to image the source of coherent THz transition radiation (CTTR) [3]. Following the optical setup described above for ALICE, we will place an EO crystal in the focal plane of an OAP to image the THz CDR AD. The setup for the experiment is shown in Figure 5.

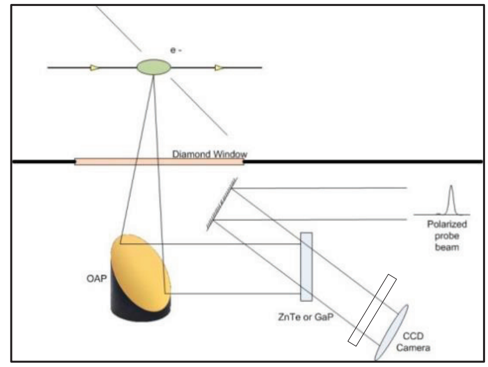


Figure 5: Proposed EO far field CDR AD electro-optic imaging system.

A similar technique has also been successfully applied to image the far field interference pattern of two overlapping AD distribution lobes of CTR produced by a single picosecond pulse. The Fourier transform of the interference pattern yields the autocorrelation and bunch length [4]. Hence the feasibility of far field EO imaging has already been demonstrated.

We will determine the required electric field strength needed to do the direct AD imaging required for our bunch length measurement method. Such a system could in principle be synchronized to select a single pulse from any RF accelerator or plasma wake-field accelerator and would provide a monitor for accelerator tune up and bunch compression.

## ACKNOWLEDGEMENT

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