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COHERENT TRANSITION RADIATION SPATIAL IMAGING AS A BUNCH LENGTH MONITOR

J. Wolfenden*, C. P. Welsch, University of Liverpool and the Cockcroft Institute, Liverpool, UK
T. H. Pacey, ASTeC STFC and the Cockcroft Institute, Warrington, UK
B. Kyle, University of Manchester and the Cockcroft Institute, Manchester, UK
E. Mansten, S. Thorin, M. Brandin, MAX IV, Lund, Sweden
R. B. Fiorito, RBF LLC, Bellingham (WA), USA
A. Shkvarunets, University of Maryland, Maryland, USA

Abstract

High-resolution bunch length measurement is a key component in the optimisation of beam quality in FELs, storage rings, and plasma-based accelerators. Simulations have shown that the profile of a coherent transition radiation (CTR) image produced by a charged particle beam is sensitive to bunch length and can thus be used as a diagnostic. This contribution presents the development progress of a novel bunch length monitor based on imaging the spatial distribution of CTR. Due to the bunch lengths studied, 10 fs-100 fs FWHM, the radiation of interest was in the THz range. This led to the development of a THz imaging system, which can be applied to both high and low energy electron beams. The associated benefits of this imaging distribution methodology over the typical angular distribution measurement are discussed. Building upon preliminary multi-shot proof of concept results last year, a new series of experiments have been conducted in the short pulse facility (SPF) at MAX IV. Single-shot measurements have been used to measure the exact point of maximum compression. Analysis from the proof of concept results last year, and initial results from the new measurements this year are discussed.

INTRODUCTION

Transition radiation (TR) is produced when the electric field of a charged particle traverses the boundary between two dielectric constants, e.g. an electron impinging upon the surface of a metallic target [1]. TR has a broadband spectral distribution, of which a specific bandwidth is typically studied. CTR is produced when this bandwidth contains wavelengths comparable to or exceeding the bunch length of the TR source particle bunch.

Previous studies have shown that the Angular Distribution (AD) of similar coherent radiation is sensitive to RMS bunch length [2]. The AD, I^a_{bunch}, for an electron bunch is calculated using the AD from a single electron, I^a_e, multiplied by the longitudinal bunch form factor, F_z, integrated over the applicable bandwidth [3]. Explicitly this is:

$$\frac{dI^a_{\text{bunch}}}{d\Omega} \approx N_e^2 \int_{\Delta\omega} \frac{d^2 I^a_e}{d\omega d\Omega} \left|F_z\left(\rho\left(z\right),\omega\right)\right|^2 d\omega, \quad (1)$$

where $d\Omega$ is the solid angle of observation, N_e is the number of electrons in the bunch, $\rho(z)$ is the longitudinal bunch profile, ω is the frequency of the emitted TR, and $\Delta\omega$ is the specified bandwidth. This formulation assumes a large $\Delta\omega$ and a large N_e, in order to neglect the incoherent contributions to the AD.

Equation (1) demonstrates that the AD produced by the integration over $\Delta\omega$ is simply the summation of the individual spectral components AD's, modulated by the longitudinal form factor of the source bunch. Therefore, changes in $\rho(z)$ will be apparent in the AD produced, if $\Delta\omega$ is chosen such that it captures the spectral range over which F_z varies.

CTR SPATIAL IMAGING

The AD of a radiation source can be collected by placing a detector in the focal plane of a focusing element. This configuration focuses all rays from the source plane with the same angular properties, as well as upstream sources sharing those same properties, to the same point in the focal plane. However, this method has been shown to provide interference issues for coherent wavelengths [4]. When multiple radiation sources are within the coherence length, $L = \gamma^2\lambda$ (γ is the Lorentz factor and λ is wavelength), of one another they can destructively interfere and distort the expected AD of a single source [5]. In an ideal AD system, any two sources of coherent radiation would be kept separated by a distance, d, such that $d >> L$. At mm-wavelengths this becomes impossible in practise, as often $L >> 10$ m. Interference occurs amongst the various upstream sources, and the resulting AD can become incompatible with diagnostic requirements.

Virtual photon theory states that radiation produced through the interaction of relativistic particles with other media has properties similar to that of real photons [1]. This theory can be applied in the case of CTR to draw on optical theory; the spatial distribution (SD) of CTR in the image plane of a focusing element is related via Fourier transform to the AD of CTR in the focal plane of the same focusing element. It follows that the image of CTR must also be dependent upon a longitudinal bunch profile, as Eq. (1). The benefit of using the SD rather than the AD is that the imaging system is now focused on the TR source plane, rather than all upstream sources. Although upstream sources will still be collected, they will be de-focused in the image plane. By maximising the distance from the focusing element to the image plane, upstream sources can be reduced to a near-uniform background. This removes the interference effects

* joseph.wolfenden@cockcroft.ac.uk

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which would otherwise compromise the AD. The CTR bunch image can be calculated, with a similar method to Eq. (1), as [6]:

$$\frac{dI^i_{\text{bunch}}}{dr} \approx N_e^2 \int_{\Delta\omega} \frac{d^2 I^i_e}{d\omega dr} \left|F_z\left(\rho\left(z\right),\omega\right)\right|^2 d\omega, \quad (2)$$

where I^i_{bunch} and I^i_e are the bunch and single particle image distributions, respectively.

PROOF OF CONCEPT MEASUREMENTS

To test the hypothesis that the image of CTR can be used to measure changes in RMS bunch length, an experimental station on SP02 in the SPF at MAX IV (Lund, Sweden) was established as part of a collaboration between the Cockcroft Institute and MAX IV. The SPF provides access to a 3 GeV electron beam with bunch lengths <100 fs and a bunch charge of ~200 pC. A custom gold coated aluminium target was installed on a linear actuator on the beamline to generate and extract CTR THz radiation; the target was optically flat and had a radius of 12.5 mm. A THz imaging system was designed to measure the CTR image and its bunch length dependence. A schematic of the imaging system is shown in Fig. 1.

The system makes use of a TPX lens; this has a refraction index which is independent of wavelength. This makes the system quasi-achromatic, similar to reflective optics without the associated alignment restrictions. TPX also has a transmission response which is transparent at optical wavelengths. Therefore a HeNe laser could be used to align and focus the imaging system, for direct use with THz signals.

The imaging system is a single lens point-to-point design that maximises the collection efficiency and image resolution. The lens has a focal length, $f = 150$ mm, and is placed at a distance of $2f$ from the source plane; which provides an image plane $2f$ from the lens, and a magnification of 1. The view-port window was chosen to provide a similar transmission response to the TPX lens; the material chosen was Z-cut Quartz. The mirrors between the view-port window and the TPX lens were coated with optically flat gold, providing high reflectivity at THz and optical wavelengths. These mirrors were used to adjust the alignment as required during the measurement program.

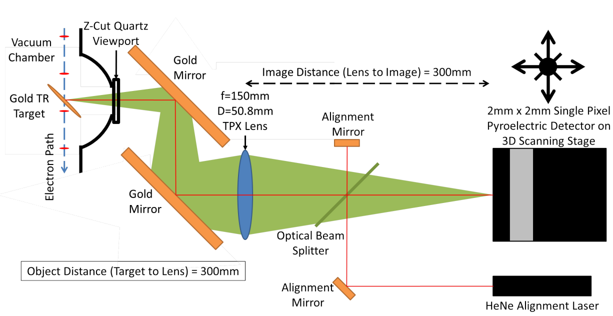

Figure 1: The single TPX lens imaging system installed in the SP02 beamline in the MAX IV SPF.

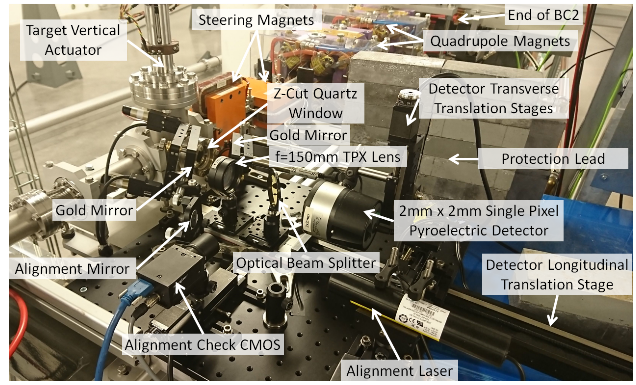

Figure 2: CTR imaging system installed on the SPF beamline at MAX IV.

To maximise the system sensitivity, a single pixel (2 mm×2 mm) pyro-electric detector (Gentec Model THZ2I-BL-BNC) was used. This was scanned over the image plane to produce an image. The system installed in the MAX IV SPF is presented in Fig. 2.

Simulations were conducted to understand the bunch length resolution of this set-up. The results presented in Fig. 3 show the normalised image distributions expected for different Gaussian FWHM bunch lengths. The images have a width which varies with bunch length. The absolute intensities showed shorter bunch lengths produce more intense signals, but using this as a bunch length monitor requires a corresponding high precision measurement of the bunch charge on a shot-to-shot basis, as any fluctuations will be amplified by the N^2 in Eq. (2). A much more reliable method is to use the image shape variation found in Fig. 3.

Therefore, the bunch length resolution of this monitor is directly dependent upon the resolution of the imaging system. However, this system was limited by the scan time of the detector, even in the case of single pixel steps as per Fig. 4 multiple shots were required for statistically valid measurements. For an intense signal (e.g. high charge or shorter bunch lengths), a single-shot method could be used.

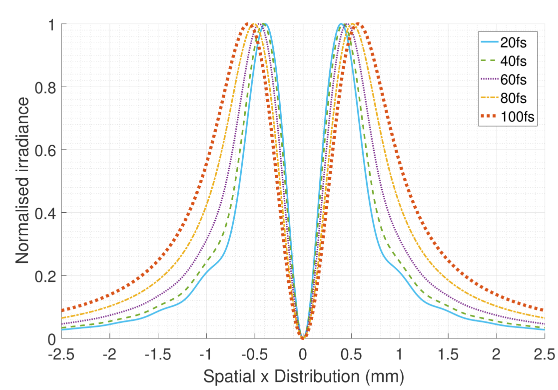

Figure 3: Comparison of the normalised simulated image distribution for different bunch lengths using beam parameters found in the MAX IV SPF.

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PROOF OF CONCEPT RESULTS

Bunch compression in the MAX IV SPF is controlled via two bunch compressors on the accelerator, BC1 and BC2. The first accelerating stage is followed by BC1, which in turn is followed by the second larger accelerating stage and then BC2. The compression is controlled by varying the phase of the klystrons feeding the two accelerating stages; K01 for the first and K02 for the second. Measurements were taken for a range of phase settings, however it was difficult to achieve a true phase scan due to the length of time each individual measurement took (>1 hour each). Example CTR images are presented in Fig. 4.

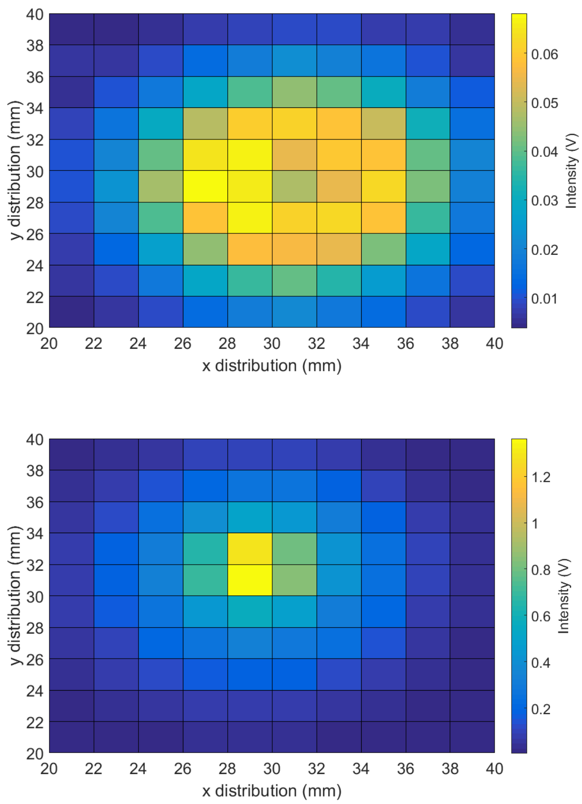

Figure 4: Example CTR images: (above) under-compressed (below) maximum compression.

These images demonstrate qualitatively that the width of the CTR image varies with bunch compression, and hence the bunch length. The limiting factor in these images is the resolution imposed by the binning of the signal by the large format of the single pixel detector. Despite this limitation, by plotting the FWHM of the images with respect to the compression phase (w.r.t. crest), as presented in Fig. 5, a clear relationship between compression and CTR image width can be found. The point of minimum image width coincided with the point of maximum compression found via independent particle tracking simulations.

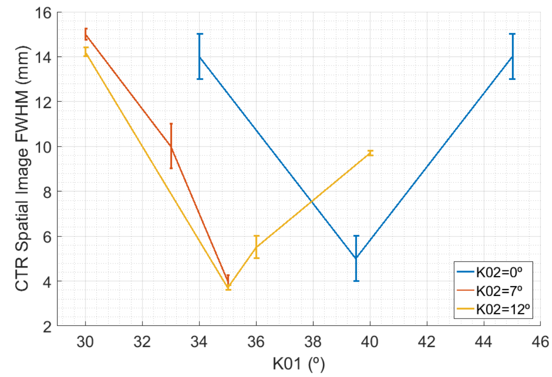

Figure 5: The effect of bunch compression on the FWHM of the CTR images.

DISCUSSION AND FUTURE PLANS

Non-invasive monitoring of bunch properties on a shot-to-shot basis is the ultimate goal for any accelerator diagnostic. Described here is an RMS bunch length monitor which would be a step along that path. Simulations show that established procedures for ADs can be adapted to that of SDs. This dependence has also been demonstrated qualitatively at the MAX IV SPF.

Image comparisons with CTR image simulations will be the next step in transforming this work from a compression monitor to a bunch length monitor. The resolution limits imposed by the detector format mean this data offers little to compare to simulations, due to the relatively large errors on the image widths. Greater image resolution is required to reduce these errors and allow valid comparisons. Therefore, new single-shot measurements have recently been taken with a linear array detector, hosting much smaller pixels (50 µm×100 µm). Analysis of this data is still underway, but initial results demonstrate the same peak intensity increase with compression as found with the single pixel measurements.

ACKNOWLEDGEMENT

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