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COHERENT DIFFRACTION RADIATION IMAGING AS AN RMS BUNCH LENGTH MONITOR

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Abstract

High-resolution bunch length measurement is of the utmost importance for current and future generations of light sources and linacs. It is also key to the optimisation of the final beam quality in plasma-based acceleration. We present progress in the development of a novel RMS bunch length monitor based on imaging the coherent diffraction radiation (CDR) produced by a non-invasive circular aperture. Due to the bunch lengths involved, the radiation produced is in the THz range. This has led to the development of a novel THz imaging system, which can be applied to low energy electron beams. For high energy beams the imaging system can be used as a single shot technique. Simulation results show that the profile of a CDR image of a beam is sensitive to bunch length and can thus be used as a diagnostic. The associated benefits of this imaging distribution methodology over the typical angular distribution measurement are discussed. Plans for experiments conducted at the SwissFEL (PSI, Switzerland), along with plans for future high energy single shot measurements are also presented.

INTRODUCTION

Diffraction radiation (DR) is produced when the electric field of a relativistic charged particle interacts with a target surface whose boundaries intersect the spatial distribution (SD) of the particles electric field, for example an aperture [1]. The DR produced has a non-uniform broadband spectral distribution; the spectral intensity is controlled by the spatial dimensions of the target surface. Typically a specific spectral range of this distribution is studied. If this range contains wavelengths comparable to or exceeding the bunch length of the particles used to produce the DR, the radiation is said to be coherent, and hence CDR is produced.

Previous studies have shown that the Angular Distribution (AD) of CDR is sensitive to RMS bunch length [2]. It is relatively straightforward to calculate the AD, I^{CDR}_{bunch} for a given RMS bunch length. This has been shown to be the AD from a single electron, I^{DR}_{e}, multiplied by longitudinal bunch form factor, S_z, integrated over the applicable spectral band [3]. Explicitly this is:

$$\frac{dI^{CDR}_{bunch}}{d\Omega} \approx N_e^2 \int_{\delta\omega} \frac{d^2 I^{DR}_{e}}{d\omega d\Omega} S_z(\sigma_z, \omega) d\omega, \qquad (1)$$

where $d\Omega$ is the solid angle of observation, N_e is the number of electrons in the bunch, σ_z is the RMS bunch length, and $\omega = 2\pi/\lambda$ is the angular frequency of the CDR for a given wavelength, λ.

The spectral band over which the integration in Equ. (1) is carried out is dictated by a combination of the bunch length in question and the dimensions of the target used to produce the CDR. Indeed in practise these parameters are leveraged to optimise the AD produced. Low frequencies are cut-off by the outer radius of the target, and high frequencies are truncated by both the aperture radius of the target and the fall off of $S_z(\sigma_z, \omega)$, as λ of the emitted radiation becomes small and no longer comparable to σ_z.

CDR SPATIAL IMAGING

The AD of a radiation source is typically collected by placing a detector in the focal plane of a lens. A lens in this configuration is said to be focussed at infinity, i.e. all rays from points in the source plane with similar angles, as well as upstream sources with the same angles, are collected and focussed to the same point in the focal plane of the lens. However this method has previously been shown to provide issues for CDR, and coherent wavelengths in general [4]. When multiple radiation sources are within the coherence length, $L = \gamma^2\lambda/2\pi$, of one another they can destructively interfere and distort the expected AD of a single source. In an ideal AD system, any two sources of coherent radiation would be kept separated by a distance, d, such that $d >> L$. At coherent wavelengths this becomes impossible in practise, as often $L \sim> 10\,\mathrm{m}$. In these cases interference can occur amongst the various upstream sources, and the resulting AD becomes useless for diagnostic methods.

Virtual photon theory states that the properties of radiation produced by the interaction of relativistic particles with other media, follows those of real photons [1]. An example of this is the similarity in properties of DR from an aperture, and the diffraction of real photons from the same aperture. This theory can be applied in the case of CDR, i.e. the SD of CDR should be related via Fourier transform to the AD of CDR. It directly follows that as the CDR AD is dependent upon bunch length, the SD of CDR must also depend upon bunch length. This concept has been explored previously for the case of transition radiation (TR) [5]. As DR and TR are related via Babinet's principle [6], TR based theory should also apply to DR.

EXPERIMENTAL PREPARATIONS

Experimental plans are currently in place to test the hypothesis put forth above, i.e. to show that the SD of CDR can be used to measure RMS bunch length. An experimental

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station at SwissFEL facility at PSI (Zurich, Switzerland) allows access to a 330 MeV electron beam with bunch lengths ~1 ps and an associated charge per bunch of ~200 pC. The station also comes equipped with a specially designed aperture to generate and extract THz radiation, with an inner radius of 1.5 mm and an outer radius of 13 mm. A THz imaging system has been specially designed for use at this station to measure the CDR SD and its dependence on bunch length. A schematic of the imaging system is shown in Fig. 1. The system makes use of TPX lenses, which have the spe-

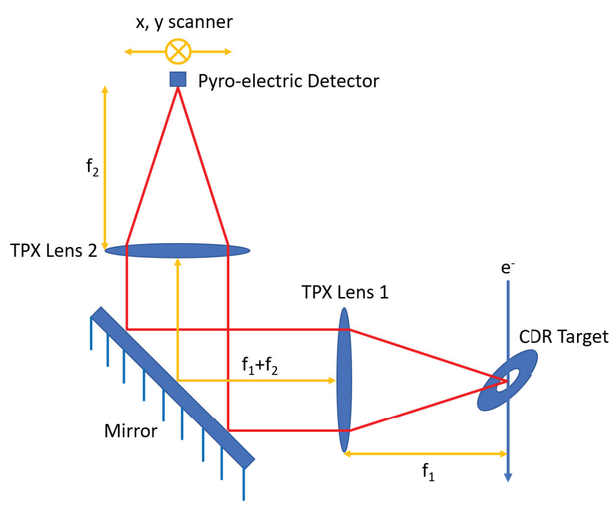

Figure 1: Diagram of the two lens imaging system to be used at the SwissFEL facility at PSI.

cial property of having an index of refraction which is almost completely independent of wavelength. This allows the system to approach the achromatic properties of parabolic mirrors, without the associated alignment problems.

The imaging system is a confocal two lens system that is designed to maximise the collection and transmission efficiency of CDR from the source to the image plane. The first and second lenses have focal lengths of 150 mm and 200 mm respectively. The mirror between the lenses, and the focal length of the lenses have been chosen to allow the system to fit upon a 450 mm×450 mm optical breadboard. The first lens is set at its focal length from the target aperture, collimating radiation it intercepts from the target. The second lens creates an image from this collimated radiation at its respective focal length. Due to the relatively low energy used (~330 MeV) the resulting peak image intensity is expected to be low (~30 nJ). Therefore a single pixel (2 mm×2 mm) pyro-electric detector (Gentec Model THZ2I-BL-BNC) will be used. This provides the required level of sensitivity and will be scanned over the image plane to produce the image. Both the optics, shown in Fig. 2, and the imaging modality have been tested using a combination of a 632.8 nm HeNe laser and a 183 GHz source. Further laboratory measurements prior to the installation at the SwissFEL are planned to benchmark the performance of the single pixel detector scan against that of a multi-pixel detector. Simulations have been carried out in order to understand the potential RMS

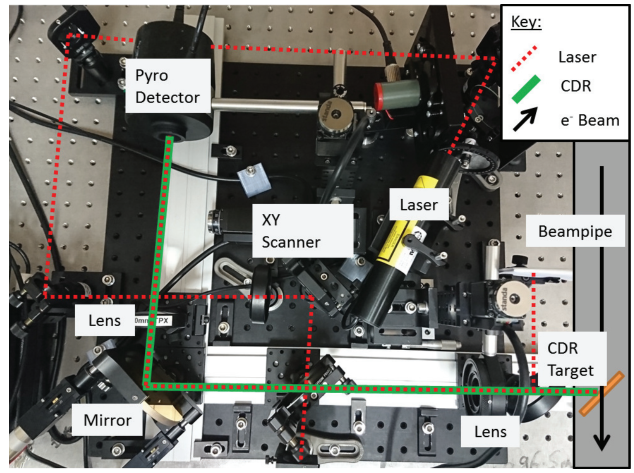

Figure 2: Experimental set-up of the two lens imaging system to be used at the SwissFEL facility at PSI, and it's position relative to the beam path. Both the alignment laser path and the CDR path are shown.

bunch length resolution attainable with this set-up. The results presented in Fig. 3 show the different normalised image distributions expected for three different Gaussian bunch profile lengths. The clear difference between the different bunch lengths is the peak-to-peak distance. This means that the potential RMS bunch length resolution of this monitor is directly dependent upon the image resolution of the imaging system. For this particular system, the limiting factor is the scan time of the detector. For a higher energy beam, a single-shot method could be used, where the only limiting factor would be the resolution of the imaging system.

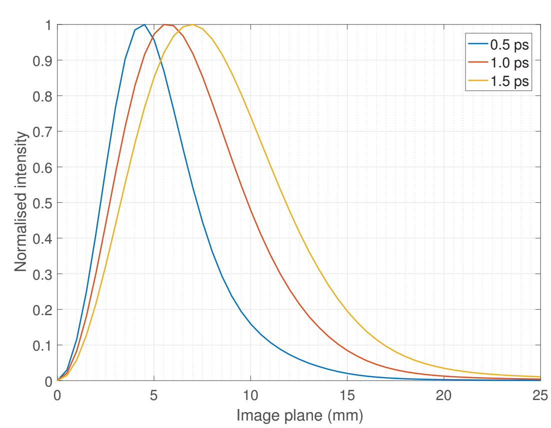

Figure 3: Simulation comparison of the image distribution from three different bunch lengths using the beam parameters found at the SwissFEL facility. The distributions have been normalised in order to better compare the relative widths.

Another potential source of information from this monitor will be the relative intensity of the image distribution. Presented in Fig. 4, is the same information as in Fig. 3 but with the relative intensities still intact. The obvious result here is that the smaller the bunch length, the larger the peak

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intensity of the image distribution. This relationship will also be monitored during measurements as an additional verification of the RMS bunch length.

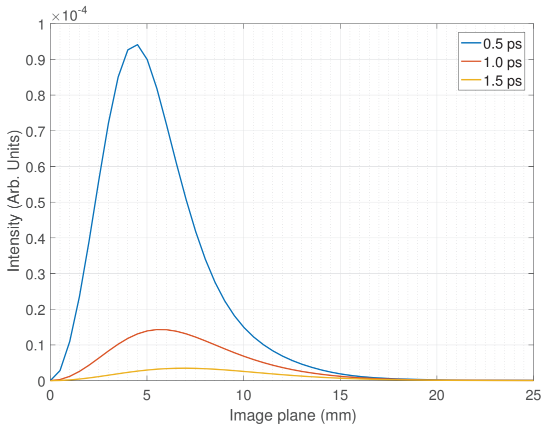

Figure 4: Simulation comparison of the image distribution from three different bunch lengths using the beam parameters found at the SwissFEL facility. The relative intensities of the distributions show an additional dependence on bunch length.

DISCUSSION AND FUTURE PLANS

The ability to monitor the bunch properties of a particle beam without any disturbance to the beam is the ultimate goal for any particle accelerator diagnostic. Described here is a non-invasive RMS bunch length monitor which would achieve that goal. The theoretical background shows that established procedures for ADs can be adapted to that of SDs. This has been further proven with simulations of a planned experimental system, showing the bunch length dependence predicted from theory. The final step is to show this dependence experimentally later this year at SwissFEL.

Following this, plans are in place to test a similar system at MAX IV (Lund, Sweden). These measurements will use a much larger energy (3 GeV), much shorter bunch lengths (~100 fs), and comparable charge per bunch (~200 pC), providing a opportunity to demonstrate a single-shot version of this technique.

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