SYNCHROTRON RADIATION SIMULATIONS FOR THE DEVELOPMENT OF A COHERENT SYNCHROTRON RADIATION BUNCH LENGTH MONITOR

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Abstract

High resolution bunch length monitors are an important diagnostic for the optimisation of any accelerator, from typical linacs or storage rings to novel acceleration systems. Given the availability of synchrotron radiation (SR) in these systems, studies have been carried out into how the spatial profile of the radiation changes with bunch length. Understanding these profile variations offers a non-invasive method of studying bunch profile characteristics. This contribution presents coherent SR simulations carried out in Synchrotron Radiation Workshop (SRW) for bunch lengths less than 100 fs, which are of interest to free electron lasers and novel acceleration facilities. These simulations have been carried out for the short pulse facility (SPF) situated in MAX IV. This is the location of a previously developed coherent transition radiation (CTR) monitor, which is currently being utilised as a compression monitor. The results of these simulations will be used to train a machine learning model to predict bunch profile characteristics, following the application of this process with the CTR monitor.

INTRODUCTION

Synchrotron radiation (SR) is produced in almost all accelerator facilities, as it is an effect of the path of charged particles being bent by magnetic fields. Whilst in many cases it is preferred to minimise the SR produced (and therefore the energy lost to it) [1], it can be very useful for diagnostics. Some sections of this emitted radiation are coherent. Coherent synchrotron radiation (CSR) occurs at frequencies where the wavelength is equal to or greater than the bunch length. The spectral content of the CSR image is directly influenced by the charge distribution of the bunch, making CSR a good choice for bunch length diagnostics [2]. Whilst incoherent radiation is also emitted, the spectral images produced are lower in frequency and do not vary with bunch length.

$$S(\omega) \approx N^2 \int_{\Delta\omega} S_p(\omega) F(\omega)\, d\omega \qquad (1)$$

Equation 1 gives the synchrotron radiation spectrum ($S(\omega)$) for a bunch. Here, N is the number of particles per bunch, $\Delta\omega$ is the frequency bandwidth, $S_p(\omega)$ is the spectrum for a single particle, and $F(\omega)$ is the bunch form factor, given by Eq. 2 [3].

$$F(\omega) = \left| \int_{-\infty}^{\infty} s(z) e^{-i\frac{\omega}{c}t} .dz \right|^2 \qquad (2)$$

Equation 2 shows how the form factor relates directly to the longitudinal charge distribution, $s(z)$. Whilst there are both longitudinal and transverse contributions to the form factor, the transverse component is omitted here as at the working frequency range it approaches unity, and therefore can be removed from the equations.

Previous experiments based at the Cockcroft Institute (CI) into using coherent radiation to study bunch length utilised diffraction (CDR) [4] and transition (CTR) [5] radiation. The CTR monitor tested in the SPF at MAX IV provided useful data, and so is still in place and has since been utilised as a bunch compression monitor. However, using CTR involves placing a target within the beamline, and thus disrupting the beam. The benefits of using CSR for measurements is that it is completely non-invasive, as the radiation is produced without any interference to the beam. This allows for continual monitoring without any disturbance to beam downstream of the diagnostic.

CSR SIMULATION

In order to simulate the CSR produced by the beam to be used for imaging, Synchrotron Radiation Workshop (SRW) [6, 7] was used. SRW is a commonly used code within the accelerator community for studying CSR [8]. It is capable of calculating electric and magnetic fields within accelerators for a large range of input parameters, then propagating a particle beam through these fields, drift spaces, optics, and other elements. From these inputs SRW offers a large range of calculable outputs, including on-axis spectra (e.g. Fig. 1), electron trajectories, power densities, spectral image intensities (e.g. Fig. 3), and spectral flux. It has the ability to calculate fields for bending magnets, wigglers, and undulators, allowing for any number of situations to be simulated. The code offers options for both single and multiple electron propagation through the system. The simulations carried out for this study were single electron, to be used in Eq. 1 ($S_p(\omega)$).

Given this monitor is being designed to replace the CTR bunch length monitor in MAX IV's SPF, CSR simulations were carried out for the last dipole of the linac's second bunch compression area (BC2) which precedes it. Table 1 gives beam and magnet parameters within the SPF ([9, 10]).

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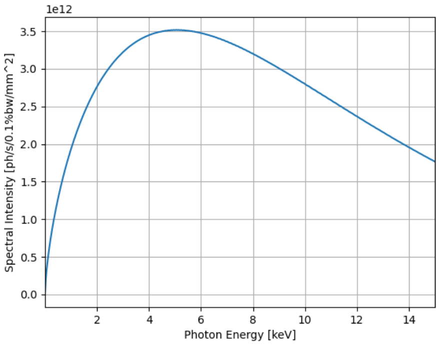

Figure 1: On-axis SR intensity spectrum for photon energies up to 15 keV as output from SRW.

Table 1: MAX IV beamline and magnet parameters

Parameter	**Value**
Energy	3 GeV
Energy spread	0.018%
Magnetic radius	9.85 m
Magnetic field	1.015 T
Magnet length	0.55 m

CSR SIMULATION RESULTS

The first simulations run were to gain the on-axis CSR intensity spectrum which would be created with the beam parameters provided. Figure 1 shows the intensity of CSR created for photon energies in the range of 0 to 15 keV. However, as this study focuses on THz frequencies, the photon energies are low (less than 0.2 keV). The on-axis spectrum across this range is shown in Fig. 2. This plot shows a much more linear response across the energy range than Fig. 1. Also, it shows that the intensity has reduced from 1×10^{12} to 1×10^{9} ph/s/0 1%bw/mm^2. Whilst this is a relatively large difference in maximum intensity, it is still high enough for imaging.

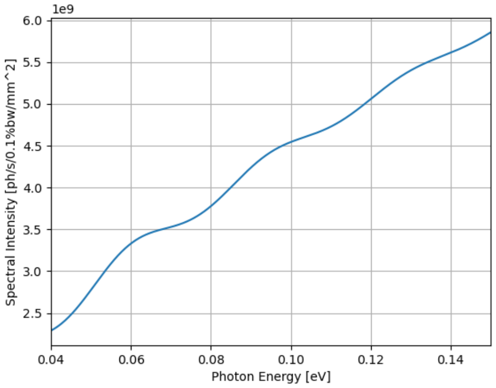

Figure 2: On-axis SR intensity spectrum for photon energies up to 0.15 keV ($\approx$ 30 THz).

The next set of simulations involved placing a simple lens after the magnet, so the CSR could be focused and imaged. Whilst the final imaging system will employ a series of mirrors alongside this, these simulations will be more complex and therefore are not included in this initial paper. Figure 3 shows the CSR after propagation through the lens for a frequency of 30 THz.

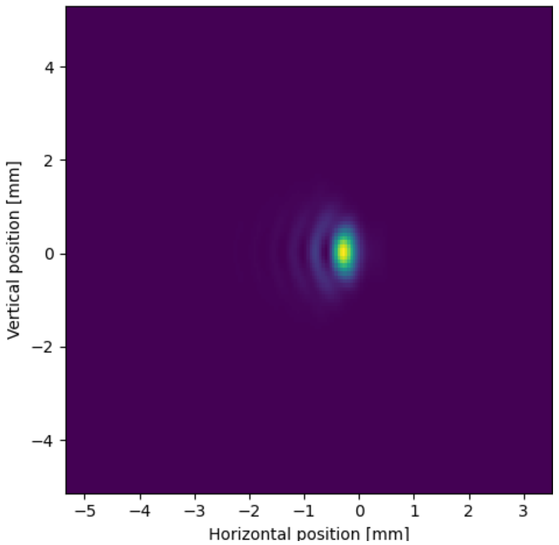

Figure 3: Image of simulated CSR after propagation through a simple lens.

FORM FACTOR CALCULATION

After simulating single electron intensity images for frequencies of 5 – 30 THz, the next stage was calculating form factors (using Eq. 2). Figure 4 shows how the form factor varies for Gaussian bunches with σ spanning 20 – 100 fs across the working frequency range.

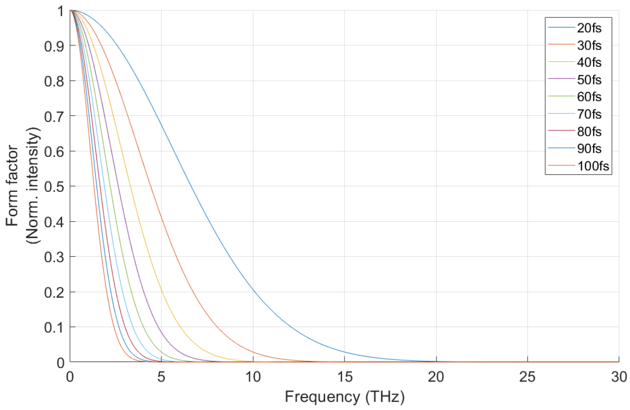

Figure 4: Calculated form factors for sub 100 fs bunches.

The form factor modifies the intensity of the original spectral contribution to the image by a factor ≤ 1. An example of this is shown in Fig. 5. The normalised intensity of the centre of a single electron spectral image simulated at 5 THz is plotted in black. The form factors for bunches 20 – 60 fs (as shown in Fig. 4) are then used to modulate this initial intensity value; this new intensity profile has then been plotted.

This figure shows how the intensity for a single frequency reduces as the bunch length increases. This is due to the form factor being related to the charge distribution within the bunch, as larger bunches have a lower charge density at any given point.

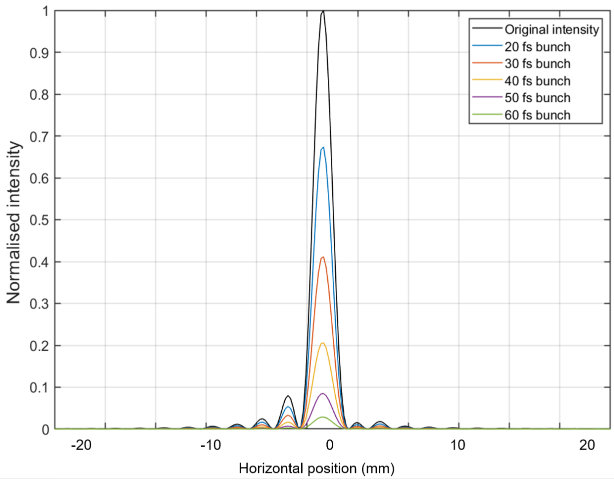

Figure 5: Intensity from single electron intensity at 5 THz, and normalised intensity plots corrected with form factors for bunches of 20 – 60 fs.

Whilst the proposed bunch length monitor will work broadband and not at single frequencies, this figure demonstrates how the spectral image of a single particle is affected by the form factor.

CONCLUSIONS

This contribution discussed the development of a non-invasive longitudinal bunch length monitor utilising CSR. It is being designed as an update to the CTR bunch length monitor previously developed by CI which is in use at MAX IV. Using beam and magnet parameters from the SPF, initial simulations of single electron intensities have been carried out using SRW. Longitudinal bunch form factors have been calculated and used to modulate single frequency spectral images.

The next stage of this project will involve simulating the single electron intensity images through the full imaging system. This will allow studies into the effects of the window, mirrors, and lenses on the resulting intensities. This will allow us to refine the design of the planned setup, which can then be assembled and tested.

ACKNOWLEDGEMENTS

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