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DESIGN OF A NON-INVASIVE BUNCH LENGTH MONITOR USING COHERENT SYNCHROTRON RADIATION SIMULATIONS

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Abstract

Synchrotron radiation (SR) is a phenomena found in most accelerator facilities. Whilst many look to reduce the amount of SR produced to minimise beam losses, its existence allows for several types of novel non-invasive beam instrumentation. The aim of this study is to use SR in the development of a non-invasive, high resolution, longitudinal bunch length monitor. The monitor will be capable of sub 100 fs bunch measurements, which are becoming more common in novel acceleration and free electron laser facilities. This contribution details the simulation work carried out in Synchrotron Radiation Workshop (SRW), which allows for complex studies into the production and features of coherent synchrotron radiation (CSR). The design of the monitor has also been discussed, alongside simulations of the planned optical setup performed in Zemax OpticStudio (ZOS).

INTRODUCTION

As accelerator upgrades and novel acceleration have lead to multi-GeV beams and fs scale bunch lengths, new diagnostic options are needed to provide the resolution necessary to properly study them. One option under consideration across the beam instrumentation community is the utilisation of coherent synchrotron radiation (CSR). Synchrotron radiation is is produced in any facility where the beam passes through a magnetic field causing it to bend. Whilst SR can prove problematic for some operations, its availability as a possible non-invasive diagnostic can be very useful. Some sections of the radiation emitted are coherent, where the wavelength is equal to or greater than the bunch length ($\lambda \geq \sigma$). CSR is of specific interest for bunch length diagnostic applications, as the spectral content is directly affected by the charge distribution of the bunch.

Minimally invasive diagnostics utilising diffraction (DR) and transition (TR) radiation have been previously designed at the Cockcroft Institute (CI) and tested at the MAX IV Short Pulse Facility (SPF) [1, 2]. However, given these types of radiation are created by interfering directly with the beam, a non-invasive CSR upgrade to the system has been proposed. Initial theory, simulation work, and calculations for this upgrade have been presented previously [3].

For the monitor discussed in this contribution, broadband CSR is being utilised. Equation 1 gives the multi-particle SR image ($S(\omega)$) for a bunch, integrated across a frequency bandwidth $\Delta\omega$. This bandwidth is defined by the longitudinal bunch length, as this affects the emitted radiation frequencies. $S_p(\omega)$ is the single-particle image, which have been simulated as detailed in the following section. $F(\omega)$ is the bunch form factor, given by Eq. (2) in Ref. [4], and N is the number of electrons per bunch.

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

The form factor shows how the longitudinal charge distribution ($s(z)$) affects the resulting CSR broadband image. There is a transverse component to form factor, but at the working frequency range of $\leq$ 30 THz - as dictated by the fs scale bunch lengths produced in many modern facilities - it tends towards unity.

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

Utilising Eq. (1), simulated single-particle images combined with the bunch specific parameters can be used to calculate a multi-particle image for a given bunch length. These resulting theoretical images provide information against which images gained from the planned system can be compared, allowing for bunch length measurements to be gained from the experimental images. This method of analysis leads to opportunities for machine learning integration in future.

SYNCHROTRON RADIATION SIMULATIONS

This study uses Synchrotron Radiation Workshop (SRW) [5,6], a specially designed code which calculates electric and magnetic fields for a series of accelerator optics (dipoles, undulators, drift spaces, etc.), and is then able to propagate a particle beam through these fields and calculate the SR which is created. It is also designed in such a way as to allow for the addition of diagnostic optics (lenses, mirrors, etc.), and propagate the radiation through these via Fourier optics calculations [7]. Whilst some input cases can be solved entirely numerically, others require Monte-Carlo method generation of initial conditions [8]. These simulations are CPU-intensive, and therefore parallelisation support has been implemented.

Several beam and magnet parameters used for these simulations are listed in Table 1. They are taken from literature [9, 10] and simulations carried out downstream of the secondary bunch compressor (BC2) of the MAX IV linac prior to the SPF. Here, electron bunches are compressed to lengths of $\leq$ 100 fs at a bunch charge of 100 pC [11].

Figure 1 shows example results from the simulations carried out. Figure 1a shows the radiation as calculated at the

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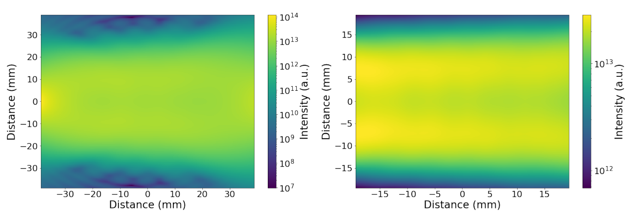
Table 1: MAX IV Beamline and Magnet Parameters

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

position of the previous monitor, 1.678 m downstream of the final BC2 dipole [12] with a frequency of 9 THz, and Fig. 1b shows the same simulation with a radiation frequency of 18 THz. The differences in size, intensity, and distribution of the radiation at different frequencies can be seen when comparing the figures. Currently, simulations have been carried out across a range of frequencies $5 \leq f \leq 30$ THz as would be produced by the compressed ≤ 100 fs bunches.



(a) 9 THz (b) 18 THz

Figure 1: CSR simulated in SRW downstream of MAX IV BC2 final dipole, comparing different radiation frequencies.

MONITOR DESIGN

The monitor design is similar to that presented in [1, 2], utilising a series of mirrors and lenses to retrieve radiation from the beam pipe and focus it onto a camera for imaging. Figure 2 shows the planned design. A gold plated mirror is currently in place in the beamline as a target for CTR, and for the new system will be moved out of the beam path using the linear actuator to direct SR out of a window to the diagnostic area. Given size constraints of the diagnostic area, a mirror is then used to change the propagation path of the radiation and direct it towards an imaging lens. High resistivity float zone silicone (HRFZ Si) will be used for the lens due to its performance in the THz region. HRFZ Si offers consistently high transmission and low dispersion at long wavelengths, improving the imaging quality over traditional lens materials.

A Pyrocam [13] will be used for imaging, featuring an array of pyroelectric crystals which offer high resolution and high broadband sensitivity. Unlike many pyroelectric arrays available it features a 2D array, allowing for imaging in both x and y planes simultaneously. The Pyrocam offers an active imaging area of 12.8×12.8 mm with at a pixel pitch of 80 µm.

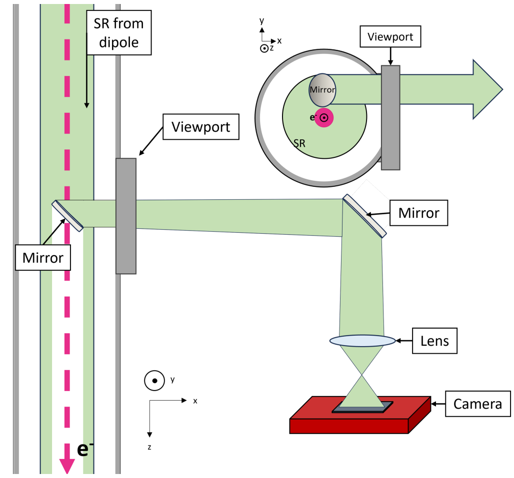


Figure 2: Diagram of the planned setup of the CSR bunch length monitor.

OPTICS SIMULATION

Whilst SRW allows for simulation of CSR passing through the optical elements which make up this planned diagnostic, it does not offer complex simulation options such as the inclusion of optical component materials and coatings. Therefore, Zemax OpticStudio (ZOS) [14] was used for a full optics simulation. ZOS allows the user to recreate full optical systems and then enables physical optics propagation (POP) analysis throughout the system. The process of POP involves propagating a wavefront through a given system, surface by surface via diffraction calculations. The size, thickness, and material of each component can be customised for full recreation of a physical system.

In order to perform POP analysis, electric fields were calculated in SRW, propagated downstream of BC2 to the position of the monitor, and then introduced to ZOS. Figure 3 shows both the real and imaginary components of the electric field for $f = 5$ THz.

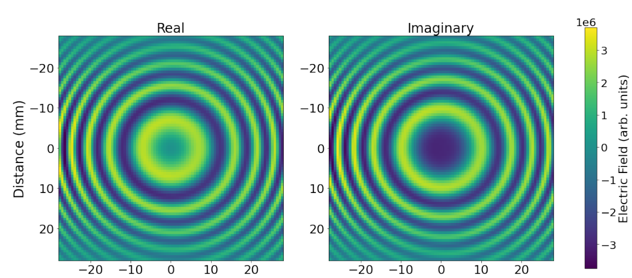


Figure 3: Simulated electric fields from SRW to be converted into SR output for 5 THz radiation.

The electric fields in the $5 - 30$ THz range were passed into a simulated version of the monitor shown in Fig. 2. In this simulation, mirrors have been assumed to have perfect reflectivity and cause no aberration, the window is 5 mm thick HRFZ Si, and the lens is 50.8 mm in diameter with a

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focal length of 100 mm. The resulting image from the 5 THz fields shown in Fig. 3 is shown in Fig. 4.

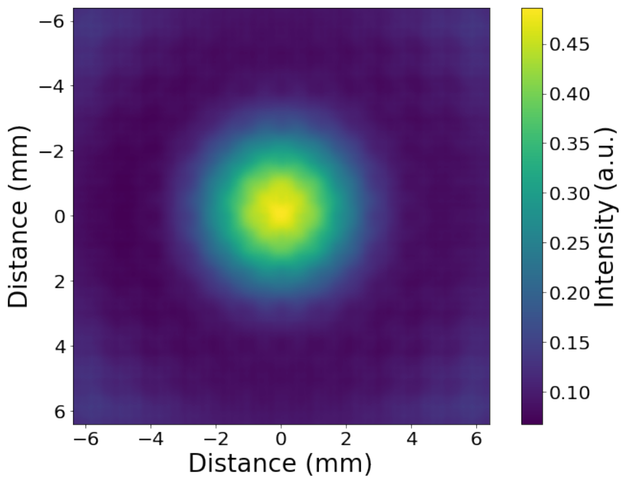

Figure 4: Simulated 5 THz SR after being propagated through the monitor design shown in Fig. 2 using ZOS.

The next step is to combine the simulated images across the frequency bandwidth of a chosen bunch length to find the resulting images which should be gained by the system. The effects of different optical components will be investigated, as will the inclusion of polarisation.

CONCLUSIONS

This contribution discussed the ongoing development of a non-invasive, high-resolution longitudinal bunch length monitor designed to replace prior versions in place at MAX IV. Simulations of the CSR created at the exit of bunch compressor 2 prior to the SPF have been carried out in SRW, and the results have been forwarded into simulations of the planned monitor optical design in ZOS. This initial monitor design is being assessed for suitability regarding imaging component selections, image quality, and space constraints.

The next stage of this project is to recreate the simulated monitor setup for testing at CI. After this, benchmarking against the previous CTR system currently in use as a bunch compressor will take place.

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