ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB061

SIMULATIONS AND MEASUREMENTS OF COHERENT SYNCHROTRON RADIATION AT THE MAX-IV SHORT PULSE FACILITY

B. S. Kyle*[1], R. B. Appleby[1], University of Manchester, Manchester, United Kingdom
P. H. Williams[1], T. H. Pacey[1], ASTeC, STFC Daresbury Lab, United Kingdom
J. Wolfenden[1], University of Liverpool, Liverpool, United Kingdom
E. Mansten, S. Thorin, M. Brandin, MAX-IV, Lund, Sweden
[1]also at Cockcroft Institute, STFC Daresbury Lab, United Kingdom

Abstract

The Coherent Synchrotron Radiation (CSR) interaction is a source of unwanted correlated energy spread in short-bunch Free-Electron Lasers (FEL), diluting the desired FEL spectrum and reducing the total brightness of the light source. Many accelerator codes make use of 1-dimensional approximations in the calculation of the CSR-wake, which breaks down for bunch dimensions typical within bunch compressor dipoles in FELs. General Particle Tracer [1] simulations of the CSR interaction make use of the 3-dimensional bunch distribution, making it advantageous in modelling the short-bunch, high aspect ratio regimes typical of modern 4$^{\text{th}}$-generation light sources. Measurements of THz CSR emitted from the final bunch compressor dipole of the SP02 beamline at the MAX-IV Short Pulse Facility (SPF) were used, alongside start-to-end GPT and Elegant [2] simulations, to characterize coherent radiation emission across a broad range of bunch lengths.

INTRODUCTION

The brightness of 4$^{\text{th}}$-generation light sources is dependent on high peak current electron beams with low energy-spread [3, 4]. Conventional bunch compression methods making use of chicane or dogleg lattice structures can bring about unwanted correlated energy spread induced by CSR wake. Numerical methods for estimating the energy redistribution often make use of assumptions regarding the bunch dimensions, bunch trajectory and dipole field form, limiting the generality of their application [5–7].

The validity of a CSR calculation making use of the 1-dimensional approximation is characterized by the so-called "Derbenev Criterion" [8, 9],

$$\kappa = \frac{\sigma_x}{\left(\sigma_z^2 \rho\right)^{1/3}} \ll 1, \tag{1}$$

where σ_x and σ_z are the longitudinal and transverse (in-plane) r.m.s beam sizes, and ρ is the bending radius. When this criterion is satisfied, the transverse projection of a portion of the trajectory, corresponding to a slippage length on the order of the electron bunch length, is much larger than the bunch's transverse extent. Outside of this regime, the full 3-dimensional distribution must be taken into account when modelling the coherent interaction and the subsequently emitted radiation [10].

GPT's CSR model, csr1d, simulates the interaction directly from the Liènard-Wiechert (L-W) fields [11], taking into account the transverse bunch distribution, although currently only calculating the resultant longitudinal field. By employing a sub-bunch method for modelling the electron distribution, and a history manager to store coordinates for use in the L-W calculation [12], GPT is able to simulate the interaction with far fewer assumptions than many currently available codes. Transverse effects are captured by source points offset from the centre of each sub-bunch [12], and the because no assumptions are made on the nature of the magnetic field the interaction in the fringe region of a magnet can also be modelled. This could potentially aid towards the design of compression structures in which the CSR interaction becomes partially self-cancelling [13] in terms of energy spread and emittance increase.

While the GPT code does not currently support explicit radiation calculations, such as obtaining spectra or angular distributions, the total instantaneous power can be calculated simply from changes to the centroid energy of the bunch. This total energy loss can then be compared against measurements of emitted radiation power to quantify agreement between simulation and observation, thus benchmarking the CSR algorithm.

EXPERIMENT

Measurements of CSR power were carried out alongside complementary measurements of CTR power. A gold-plated mirror, positioned 1.678 m downstream from a bunch compressor dipole, was used to generate CTR as well as reflect CSR emitted from the dipole edge. In order to isolate the CSR the mirror was partially extracted from the beamline alongside with a trajectory kick to the beam such that no CTR was generated, with part of the CSR signal captured. Beam loss monitor observations were used alongside a downstream screen to confirm that no CTR was generated.

The electron bunch length characterizes the relevant frequency range for coherent radiation. With final bunch lengths in the range of ~ 0.4-0.02 ps (Table 1), the expected coherent cutoff frequency is between 2.5 and 50 THz. In order to measure sub-THz, THz and IR wavelengths, a pyroelectric detector (PED) array was used because of it's broad

* billy.kyle@postgrad.manchester.ac.uk

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB061

Table 1: Key Machine Parameters for the MAX-IV SP02 Beamline

Parameter	Value
Repitition Rate, ν_0	2 Hz
Dipole Bending Radius, ρ	9.84771 m
Beam Energy Centroid, $\langle U \rangle$	3 GeV
Bunch Charge, Q	85–100 pC
R.M.S Bunch Length, σ_t (Elegant)	0.02-0.4 ps
Normalized Horizontal R.M.S Emittance, $\epsilon_{n,x}$ (Elegant)	3-34 mm mrad
Normalized Vertical R.M.S Emittance, $\epsilon_{n,y}$ (Elegant)	2-9 mm mrad

spectral range. The array consisted of 256 pixels, each with a width of 50 µm and a pyroelectric crystal thickness of 5 µm. Such thin layers of pyroelectric crystal are sensitive to damage from visible wavelengths, requiring a HFZ-Si window be fitted over the detector head. A Z-cut quartz window is installed at the mirror location to permit transmission of THz radiation. The combined spectral transmissions of these two window materials resulted in a detectable spectral range of up to 7 THz; considerably smaller than that of the expected radiation spectrum.

The PED array was mounted on a 2-axis translation stage, with one axis controlling the detector position along the optical axis, and the other controlling the horizontal position of the array. The linear detector array was oriented vertically to enable 2-dimensional scanning of the radiation distribution (Fig. 1). A 200 mm focal length TPX lens was used to focus the radiation onto the detector head, with all wavelengths focused equally owing to the TPX's near-constant refractive index across the relevant spectral range. The PED array enabled the acquisition of shot-to-shot measurements, although signals were averaged over multiple shots to allow for better confidence in each measurement by mitigating the effect of machine jitter.

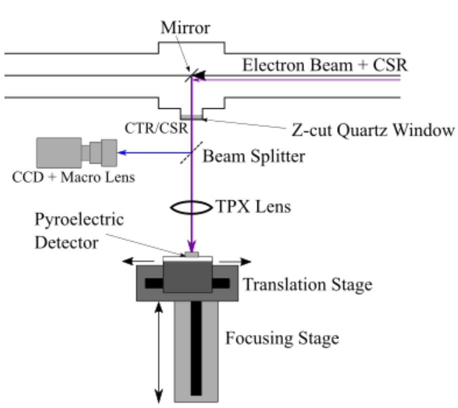

Figure 1: Schematic of experimental setup. Optical radiation is isolated through the use of a 3 µm thick beam-splitter, and measured using a CCD camera. Optical measurements were used for alignment of the beam and mirror only.

Short electron pulses in SP02 are achieved through two bunch compressors, BC1 and BC2. BC1 lies just after the first accelerating structure on the MAX-IV linac, K01, which accelerates electrons from ~100 MeV to ~250 MeV, as well as controlling the compression in BC1 via a longitudinal energy chirp imparted by the off-crest phase in K01. When operating close to the maximal compression phase of K01, BC1 compresses electron bunches from lengths of approximately 1.8 ps down to approximately 300 fs. From there, electron bunches are accelerated to 3 GeV in the main linac over a distance of 232 m before entering BC2 were it is further compressed down to around 50 fs.

The off-crest phase of K01 ($\delta\phi_{K01}$) was scanned for three different values of K02 offset ($\delta\phi_{K02}$), to enable a broad characterization of the longitudinal machine parameter space. The scans featured in this report focus on the measurement technique as a concept, with transverse sizes kept small enough to be within the bounds of validity for a 1-dimensional CSR approach (Equation 1). While the presented measurements and simulations do not serve to benchmark the 3-dimensional capabilities of GPT's CSR model, they are a test of the model's efficacy in modelling CSR emitted from a dipole edge.

SIMULATIONS AND RESULTS

Elegant simulations were used to match and track the electron beam through the majority of the accelerator. In order to re-create the conditions during the experiment, simulated transverse beam optics were matched to recreate measured beam profiles at 3 YAG screen locations (Fig. 2). The Elegant beam distribution 0.05 m upstream from the final BC2

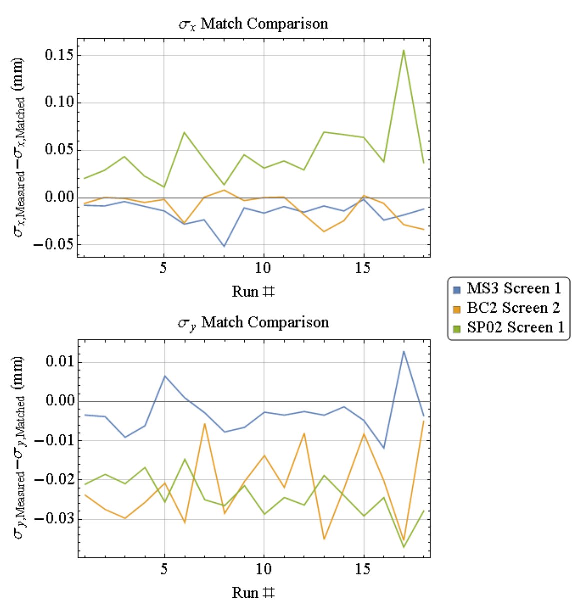

Figure 2: Matching of simulated transverse statistical beam quantities to screen measurements at the entrance (MS3 Screen 1), middle (BC2 Screen 2), and exit (SP02 Screen 1) of the second bunch compressor on the MAX-IV linac beamline.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB061

dipole is then passed to GPT and SPECTRA [14] for CSR simulations. The total radiated energy-per-pulse is inferred from the total energy loss of the bunch close to the dipole exit and within the fringe field zone. SPECTRA is used to calculate an approximate angular distribution of the radiation emitted from the dipole exit, which is normalized and then scaled by the total emitted energy calculated in GPT.

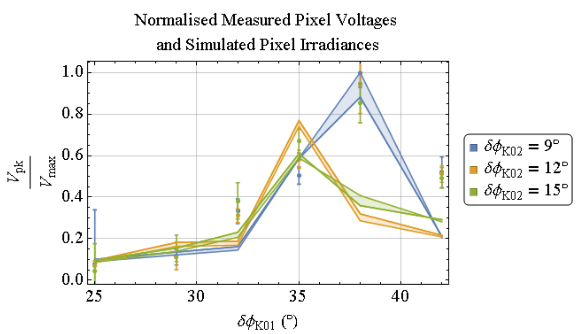

Figure 3: Normalized peak PED voltage and normalized simulated detector irradiance (filled lines). The filled region encapsulates the variation of the peak irradiance with respect to an offset of the detector equivalent to half the pixel spacing.

This distribution is then propagated to the mirror location, with beam centroid offsets and the mirror raised position taken into consideration. The incident radiation fraction is then propagated further to the TPX lens plane, where the surviving angular distribution is mapped to spatial points in the focal plane. The focal plane distribution is integrated over the individual pixel areas to produce an expected irradiance of the detector. As this irradiance does not accurately take into account transport losses and the detector's spectral response is not precisely defined, the distribution is normalized to the peak value over the entire scan (18 machine setups). This is compared to the peak pixel voltages, which have been normalized in a similar fashion as the simulated detector irradiances (Fig. 3).

DISCUSSION

Coherent radiation emitted from the exit of a bunch compressor dipole has been successfully measured using a pyroelectric detection method. The phase of maximum compression are in agreement between simulation and experiment, showing that a similar method may be employed for relative compression monitoring. The radiation pattern captured is only a fraction of the total radiation distribution, meaning that the radiation distribution must be carefully propagated to the detector plane. The particle-tracking tools used to estimate the strength of the CSR interaction do not provide the information necessary to precisely model this distribution, so approximations must be made for this calculation. Improvements to this method of radiation propagation are expected to significantly improve the agreement between simulation and measurement.

For two of the three scans of $\delta_{\phi_{K01}}$ there is an offset of around 3 ° between the observed and simulated peak CSR signal. This could be due to one of several reasons: the longitudinal dynamics of the bunch are not being correctly simulated in Elegant, either within the bunch compressors or within the linac, resulting in the LPS not being accurately recreated; the crest phase was not correctly measured at the time of data collection, causing a direct systematic shift of the observed crest phase; the angular distribution is being incorrectly modelled in SPECTRA, and as such the derived detector irradiance deviates significantly.

An issue with the simulation of experimental conditions during the experimental period at MAX-IV lies with the reconstruction of transverse distributions at screen locations. Although transverse statistical parameters of the bunch were matched successfully, the transverse distributions themselves are significantly different in most cases. The significance of this deviation is mitigated by the low value of the Derbenev parameter across all bunches in these scans. Finally, the distribution propagated from the mirror does not incorporate diffractive effects about the sharp edge of the mirror, which would be expected to broaden the CSR distribution incident upon the detector and may serve towards altering the convolution of the propagated signal over pixel areas. The effect of this is expected to be of a similar magnitude to the effect caused by the overall detector vertical offset (Fig. 3).

ACKNOWLEDGEMENTS

Many thanks to the entire control room staff at MAX-IV for enabling these measurements to be taken, and for their patience with our regular requests of searching the SPF hall.

REFERENCES

[1] S. B. van der Geer, and M. J. de Loos, "General Particle Tracer: A 3D code for accelerator and beamline design", in *Proceedings of EPAC98* (Stockholm, Sweden), pp. 1245–1247, August 1998.

[2] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation", in *Proceedings of ICAP2000* (Darmstadt, Germany), p. LS-287, September 2000.

[3] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Self-amplified spontaneous emission FEL with energy-chirped electron beam and its application for generation of attosecond x-ray pulses", *Phys. Rev. ST Accel. Beams*, vol. 9 p. 050702, May 2006.

[4] S. Antipov, *et al.*, "Experimental Demonstration of Energy-Chirp Compensation by a Tunable Dielectric-Based Structure", *Phys. Rev. Lett.*, vol. 112 p. 114801, Mar 2014.

[5] G. Bassi, *et al.*, "Overview of CSR codes", *Nucl. Inst. Methods Phys. Res. A*, vol. 557 pp. 189–204, Feb 2006.

[6] M. Borland, "Simple method for particle tracking with coherent synchrotron radiation", *Phys. Rev. ST Accel. Beams*, vol. 4 p. 070701, Jul 2001.

[7] D. Schulte, *et al.*, "The Tracking Code PLACET", Version 1.00, 2018.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB061

[8] Y. S. Derbenev, J. Rossbach, E. L. Saldin, and V. D. Shiltsev, "Microbunch Radiative Tail-Head Interaction", Tech. Rep. TESLA-FEL 95-05, DESY, Hamburg, Sep 1995.

[9] C. C. Hall, *et al.*, "Measurement and simulation of the impact of coherent synchrotron radiation on the Jefferson Laboratory energy recovery linac electron beam", *Phys. Rev. ST Accel. Beams*, vol. 18 p. 030706, Mar 2015.

[10] O. Grimm, H. Delsim-Hashemi, J. Rossbach, V. Balandin, and N. Golubeva, "Transverse Electron Beam Size Effect on the Bunch Profile Determination with Coherent Radiation Diagnostics", in *Proceedings of EPAC08* (Genoa, Italy), pp. 1113–1115, Jun 2008.

[11] J. D. Jackson, *Classical Electrodynamics*, New York, NY: Wiley, 1962, pp. 464–468.

[12] S. B. van der Geer, M. J. de Loos, I. D. Setija, P. W. Smorenburg, and P. H. Williams, "GPT-CSR: A New Simulation Code for CSR Effects", in *Proceedings of FLS2018* (Shanghai, China), pp. 157–159, Mar 2018.

[13] A. D. Brynes, *et al.*, "Beyond the limits of 1D coherent synchrotron radiation", *New J. Phys.*, vol. 20 p. 073035, Jul 2018.

[14] T. Tanaka, and H. Kitamura, "SPECTRA: a synchrotron radiation calculation code", *J. Synchrotron. Rad.*, vol. 8 pp. 1221–1228, Nov 2001.