ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOPA12

PRESERVING BRIGHT ELECTRON BEAMS: DISTORTED CSR KICKS

A. Dixon*[1], University of Liverpool, Liverpool, United Kingdom
S. Thorin, MAX IV Laboratory, Lund, Sweden
P. H. Williams[1,2], ASTeC, Warrington, United Kingdom
T. K. Charles[1], University of Liverpool, Liverpool, United Kingdom
[1] also at Cockcroft Institution, Warrington, United Kingdom
[2] also at STFC Daresbury Laboratory, Warrington, United Kingdom

Abstract

Short pulse, low emittance electron beams are necessary to drive bright FEL X-rays, for this reason it is important to preserve and limit emittance growth. The strong bunch compression required to achieve the short bunches, can lead to coherent synchrotron radiation (CSR)-induced emittance growth, and while there are some methods of CSR cancellation, these methods may be less effective when the CSR kicks are distorted. In an attempt to understand why CSR kicks become distorted, we compare the CSR kicks calculated using the whole beam parameters to the CSR kicks calculated using the longitudinally sliced beam parameters, when propagated to the end of the bunch compressor. We find that CSR kicks can become distorted when calculated with non-uniform slice beam parameters. While slice beam parameters that are uniform along the centre of the bunch, do not result in distorted CSR kicks.

INTRODUCTION

Free-electron lasers are a fourth generation light source which aim to provide bright, coherent light over a wide range of wavelengths [1]. The demand for research using FELs is driving demand for shorter pulse, brighter FEL X-rays. As such it is necessary for high quality electron bunches driving the FELs, which have small emittance and short bunch lengths.

Bunch compressors are used to compress the bunch longitudinally, however this can lead to unwanted collective effects such as coherent synchrotron radiation (CSR) [2–7] and microbunching instability (MBI) [8]. CSR causes kicks in the horizontal coordinates, which increases the projected emittance (as in Fig. 1). This projected emittance growth can be managed using CSR cancellation techniques, however these methods may be less effective if the CSR kicks become distorted [9]. In this paper we explore how CSR kicks could be distorted by considering how the slice Twiss parameters vary.

MAX-IV

MAX-IV facility located in Lund, Sweden, hosts 1.5 GeV and 3 GeV electron storage rings and the short pulse facility (SPF), all driven by the same linear accelerator. The laboratory provides a wide range of spectroscopy techniques for industry and research. In this study we focus on the existing

* sgadixon@liverpool.ac.uk

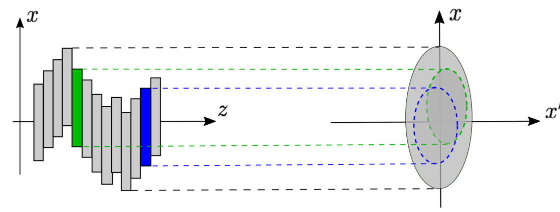

Figure 1: Horizontal slice offset leading to increased projected emittance [10].

short pulse facility (SPF) [11] and soft X-ray laser (SXL) [12], which is in the conceptual design phase [13]. The layout of the MAX-IV linac is shown in Fig. 2.

COHERENT SYNCHROTRON RADIATION

Synchrotron radiation is emitted by relativistic electrons when the bunch goes through a dipole. The electron bunch will radiate coherently when the bunch length is shorter than the radiation emitted and the following inequality is satisfied,

$$\lambda \geq 2\pi\sigma_z, \tag{1}$$

where σ_z is the bunch length and λ is the wavelength of synchrotron radiation.

Coherent synchrotron radiation leads to a redistribution of energy in the bunch due to some electrons reabsorbing emitted radiation. This effect can be approximated by the 1-D CSR wake as, excluding entrance and exit transient effects [14–17]. The 1-D CSR wake is defined as

$$\frac{dE}{cdt} = \frac{-2e^2}{4\pi\epsilon_0(3\rho^2)^{1/3}} \int_{\tilde{z}-s_L}^{\tilde{z}} \frac{df}{dz} \left(\frac{1}{\tilde{z}-z}\right)^{1/3} dz, \tag{2}$$

where ϵ_0 is the permittivity of free space, ρ is the bending radius of the dipole, $\frac{df}{dz}$ is differential of the linear charge density, $\tilde{z}$ is the position within the bunch, and s_L is the slippage length.

CSR leads to projected emittance growth by causing longitudinal slices of the beam to become offset in the horizontal coordinates (see Fig. 1) [2–7]. The projected emittance growth can be mitigated by using CSR cancellation techniques, such as CSR kick matching [5, 18, 19] and optical balance [2, 3, 18–20].

Point-Kick Model

The point-kick model is an analytical method of evaluating the CSR kick from a dipole, by approximating the CSR

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOPA12

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

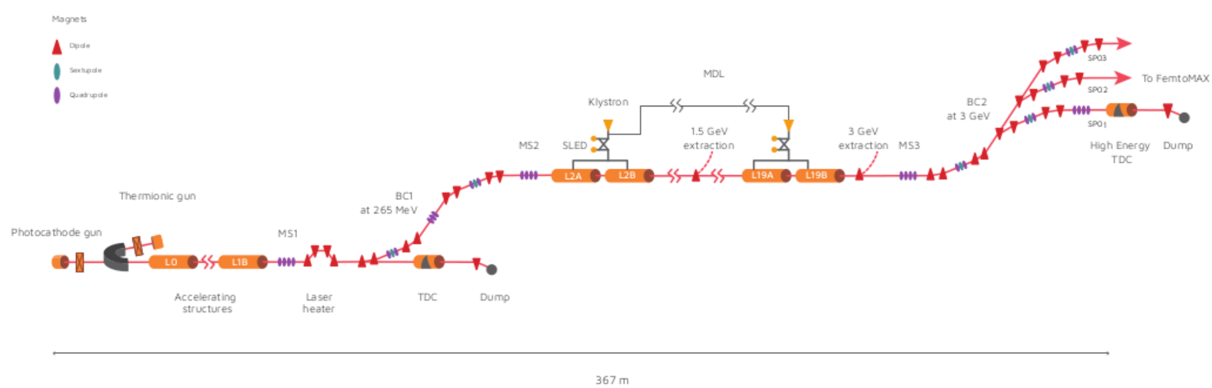

Figure 2: Layout of the MAX-IV linac. Including the beamlines to the short-pulse facility (SP02/FemtoMAX) and the soft X-ray laser (SP03) [13].

kick as single kick which occurs at the centre of the dipole [18]. The point-kick matrix $\boldsymbol{X}_k$ is given as

$$\boldsymbol{X}_k = \begin{pmatrix} x_k \\ x'_k \end{pmatrix} = \begin{pmatrix} \rho^{4/3} k [\theta \cos(\theta/2) - 2\sin(\theta/2)] \\ \sin(\theta/2)[2\delta + \rho^{1/3}\theta k] \end{pmatrix}, \quad (3)$$

where the x_k and x'_k represent the change in horizontal position and momentum due to the CSR kick. θ and ρ are the bend angle and bend radius of the dipole, respectively, δ is the momentum deviation at the centre of the dipole and $k = \frac{dE}{cdt}\frac{\rho^{2/3}}{E_0}$.

This model can be used to approximate the overall CSR kick from multiple dipoles [18], such as in a bunch compressor. This is done by evaluating the CSR kicks (x_k, x'_k) at the centre of a dipole, then these kicks are propagated to the centre of the following dipole using the 2-D horizontal transfer matrix [18, 21, 22]. The kicks are evaluated for the second dipole and the two kicks are summed. The summed kick can then be propagated to the region where you are evaluating the overall CSR kick, such as at the end of a bunch compressor or achromat. In the case of the second bunch compressor (BC2) in SPF and SXL, the overall kick from 8 dipoles was evaluated at the end of the bunch compressor.

The horizontal transfer matrix used to propagate the CSR kicks depends on beam properties such as the Twiss parameters (β_x and α_x) and the phase advance (ψ_x) [21, 22]. However, when a chirped bunch is passed through multipole magnets within a dispersive region, the bunch undergoes focusing dependant on longitudinal position z. As such, the slice beam parameters (slice β_x, slice α_x and slice ψ_x) may become non-uniform along the bunch. When the CSR kicks are propagated with the slice parameters they can also become distorted [9].

DISTORTED COHERENT SYNCHROTRON RADIATION KICKS

In the point-kick model of CSR, the CSR kicks are transported by the 2-D horizontal transfer matrix. When the whole beam Twiss parameters and phase advance are used to calculate the CSR kicks, we will refer to the CSR kicks as 'typical'. However, when the slice Twiss parameters and slice phase advance are used to calculate the CSR kicks, we will be refer to the CSR kicks as 'distorted' or 'atypical'.

The overall typical and distorted CSR kicks have been calculated for bunch compressor 2 in the SPF and SXL lines in the MAX-IV linac, as in Fig. 2. `Elegant` [23] simulations of the bunch compressors were performed using 2, 000, 000 macro-particles. The simulations allowed us to calculate the whole beam and slice Twiss parameters, and whole beam and slice phase advance to be used in the calculation of the CSR kicks.

Short Pulse Facility

The short pulse facility uses a 100 pC electron beam for FemtoMAX. At the entrance of BC2 the electron beam has an energy of 3 GeV. The horizontal and vertical β-functions, and horizontal dispersion through BC2 are shown in Fig. 3. The first-, second- and third-order longitudinal dispersion of R_{56} = 26 mm, T_{566} = 42 mm and U_{5666} = 49 mm, respectively.

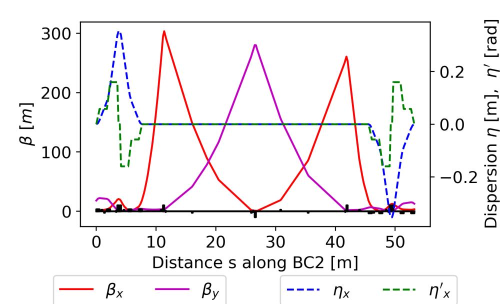

Figure 3: β-functions (solid lines) and horizontal dispersion (dashed lines) through SPF bunch compressor 2.

The slice beam parameters for dipole 5 and 6 in BC2 of SPF are shown in Fig. 4. This figure shows the slice parameters at the centre of dipoles 5 and 6 that are non-uniform along the centre of the bunch. Similar behaviour is seen in the other dipoles (not shown in this paper).

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOPA12

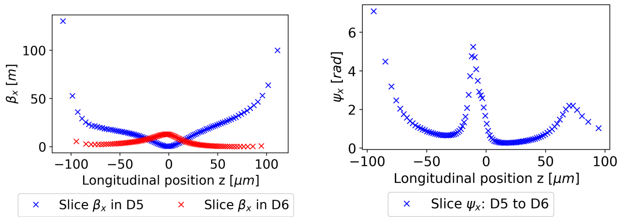

Figure 4: Slice beam parameters for BC2 of SPF. Slice β_x in dipole 5 and dipole 6 (left), and slice phase advance between dipole 5 and 6 (right).

The overall typical and distorted CSR kicks for BC2 of SPF are shown in Fig. 5.

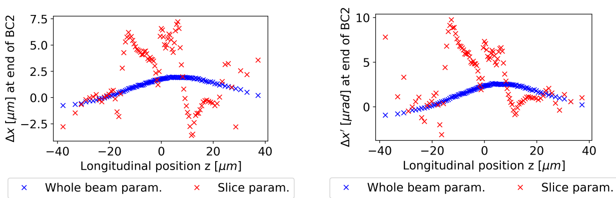

Figure 5: The overall typical (blue) and distorted (red) CSR kick in x (left) and x' (right) as a function of longitudinal position z, at the end of SPF BC2.

From Fig. 5 we see that the CSR kicks calculated with the slice parameters are distorted in shape and size compared to those calculated with the whole beam parameters. The root mean square (RMS) of the typical CSR kick is Δx_{RMS} = 1.40 µm and $\Delta x'_{RMS}$ = 1.82 µrad at $\bar{z}$ = −0.07 pm. The RMS of the distorted CSR kick is Δx_{RMS} = 3.63 µm and $\Delta x'_{RMS}$ = 4.51 µrad at $\bar{z}$ = −0.07 pm.

Soft X-ray Laser

The soft X-ray laser will use a 10 pC electron beam to drive MAX-IV's proposed FEL. At the entrance of BC2 the electron beam has an energy of 3 GeV. The horizontal and vertical β-functions, and horizontal dispersion through BC2 are shown in Fig. 6. The first-, second- and third-order longitudinal dispersion of R_{56} = 26 mm, T_{566} = −86 mm and U_{5666} = 87 cm, respectively.

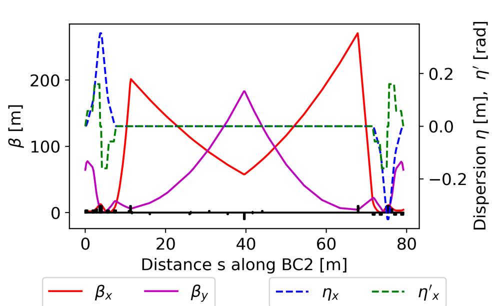

Figure 6: β-functions (solid lines) and horizontal dispersion (dashed lines) through SXL bunch compressor 2.

The slice beam parameters for dipole 5 and 6 in BC2 of SXL are shown in Fig. 7. This figure shows the slice parameters at the centre of dipoles 5 and 6 that are close to uniform along the centre of the bunch, and similar behaviour is seen in the other dipoles (not shown in this paper).

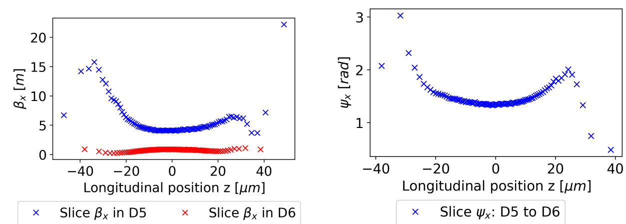

Figure 7: Slice beam parameters for BC2 of SXL. Slice β_x in dipole 5 and dipole 6 (left), and slice phase advance between dipole 5 and 6 (right).

The overall typical and distorted CSR kicks for BC2 of SXL are shown in Fig. 8.

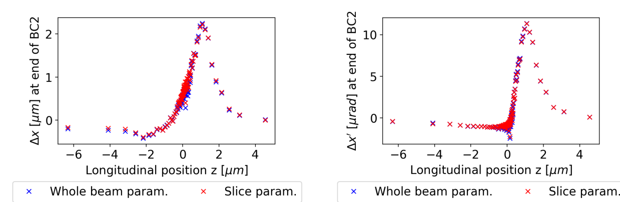

Figure 8: The overall typical (blue) and distorted (red) CSR kick in x (left) and x' (right) as a function of longitudinal position z, at the end of SXL BC2.

From Fig. 8 we see that the CSR kicks calculated with the slice parameters are not distorted in shape or size compared to those calculated with the whole beam parameters. This is because the slice beam parameters are close to uniform along the centre of the bunch. The typical RMS kick is Δx_{RMS} = 0.82 µm and $\Delta x'_{RMS}$ = 3.24 µrad at $\bar{z}$ = −0.01 pm. The distorted RMS kick is Δx_{RMS} = 0.86 µm and $\Delta x'_{RMS}$ = 3.20 µrad at $\bar{z}$ = −0.01 pm.

CONCLUSION

Using the point-kick model of CSR, we find that CSR kicks become distorted in shape and size for SPF BC2 when the kicks are calculated with the slice parameters as opposed to the whole beam parameters. This indicates that CSR cancellation techniques could be less effective at limiting projected emittance growth. Further work is necessary to determine the degree to which distorted CSR kicks limit CSR cancellation techniques. The distortion seen in the CSR kicks for BC2 of SPF is a result of the slice beam parameters being non-uniform along the centre of the bunch, whereas the slice beam parameters for BC2 of SXL are close to uniform along the centre of the bunch leading to CSR kicks which were not distorted.

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOPA12

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2021). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

REFERENCES

[1] H. Winick, "Fourth generation light sources," in *Proceedings of the 1997 Particle Accelerator Conference (Cat. No.97CH36167)*, vol. 1, 1998, pp. 37–41. doi:10.1109/PAC.1997.749539

[2] P. Emma and R. Brinkmann, "Emittance dilution through coherent energy spread generation in bending systems," in *Proceedings of the 1997 Particle Accelerator Conference (Cat. No.97CH36167)*, vol. 2, 1998, pp. 1679–1681. doi:10.1109/PAC.1997.750799

[3] S. Di Mitri, M. Cornacchia, and S. Spampinati, "Cancellation of Coherent Synchrotron Radiation Kicks with Optics Balance," *Physical Review Letters*, vol. 110, no. 1, p. 014 801, 2013. doi:10.1103/PhysRevLett.110.014801

[4] S. Di Mitri and M. Cornacchia, "Electron beam brightness in linac drivers for free-electron-lasers," *Physics Reports*, vol. 539, no. 1, pp. 1–48, 2014. doi:10.1016/j.physrep.2014.01.005

[5] R. Hajima, "Emittance compensation in a return arc of an energy-recovery linac," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 528, no. 1-2, pp. 335–339, 2004. doi:10.1016/j.nima.2004.04.063

[6] R. A. Jameson and R. S. Mills, "On Emittance Growth in Linear Accelerators," *Proceedings of 1979 Linear Accelerator Conference*, pp. 1–8, 1979.

[7] B. E. Carlsten and T. O. Raubenheimer, "Emittance growth of bunched beams in bends," *Physical Review E*, vol. 51, no. 2, pp. 1453–1470, 1995. doi:10.1103/PhysRevE.51.1453

[8] E. Saldin, E. Schneidmiller, and M. Yurkov, "An analytical description of longitudinal phase space distortions in magnetic bunch compressors," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 483, no. 1-2, pp. 516–520, 2002. doi:10.1016/S0168-9002(02)00372-8

[9] T. Charles, M. Boland, K. Oide, and F. Zimmerman, "Bunch Compression and Turnaround Loops in the FCC-ee Injector Complex," *Journal of Physics: Conference Series*, vol. 1067, p. 062 023, 2018. doi:10.1088/1742-6596/1067/6/062023

[10] T. Charles, *Bunch Compression and CSR Mitigation*, 2018.

[11] S. Thorin *et al.*, "Beam Commissioning and Initial Measurements on the MAX IV 3 GeV Linac," *Proceedings of FEL2015*, pp. 375–378, 2015. doi:10.18429/jacow-FEL2015-TUP14

[12] W. Qin *et al.*, "The FEL in the SXL project at MAX IV," *Journal of Synchrotron Radiation*, vol. 28, no. 3, pp. 707–717, 2021. doi:10.1107/S1600577521003465

[13] "The Soft X-ray Laser @ MAX-IV: Conceptual Design Report," 2021. https://www.maxiv.lu.se/soft-x-ray-laser/

[14] M. Borland, "Simple method for particle tracking with coherent synchrotron radiation," *Physical Review Special Topics - Accelerators and Beams*, vol. 4, no. 7, p. 070 701, 2001. doi:10.1103/PhysRevSTAB.4.070701

[15] D. Dowell and P. O'Shea, "Coherent synchrotron radiation induced emittance growth in a chicane buncher," in *Proceedings of the 1997 Particle Accelerator Conference (Cat. No.97CH36167)*, vol. 2, 1998, pp. 1891–1893. doi:10.1109/PAC.1997.751051

[16] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Analytical treatment of the radiative interaction of electrons in a bunch passing a bending magnet," *Nuclear Instruments and Methods in Physics Research A*, pp. 112–115, 1998.

[17] A. D. Brynes *et al.*, "Beyond the limits of 1D coherent synchrotron radiation," *New Journal of Physics*, vol. 20, no. 7, p. 073 035, 2018. doi:10.1088/1367-2630/aad21d

[18] Y. Jiao, X. Cui, X. Huang, and G. Xu, "Generic conditions for suppressing the coherent synchrotron radiation induced emittance growth in a two-dipole achromat," *Physical Review Special Topics - Accelerators and Beams*, vol. 17, no. 6, p. 060 701, 2014. doi:10.1103/PhysRevSTAB.17.060701

[19] R. Hajima, "A First-Order Matrix Approach to the Analysis of Electron Beam Emittance Growth Caused by Coherent Synchrotron Radiation," *Japanese Journal of Applied Physics*, vol. 42, no. Part 2, No. 8A, pp. L974–L976, 2003. doi:10.1143/JJAP.42.L974

[20] D. Douglas, "Suppression and Enhancement of CSR-Driven Emittance Degradation in the IR-FEL Driver," Tech. Rep. JLAB-TN-98-012, 1998, p. 15.

[21] A. Wolski, *Beam Dynamics in High Energy Particle Accelerators*. Imperial College Press ; Distributed by World Scientific, 2014.

[22] *Particle Accelerator Physics*. Springer Berlin Heidelberg, 2015.

[23] M. Borland, "User's Manual for elegant," *Advanced Photon Source*, pp. 1–567,