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CANCELLATION OF COHERENT SYNCHROTRON RADIATION KICKS AT LCLS

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Abstract

In this paper, we look at a phase advance manipulation technique used for the Coherent Synchrotron Radiation (CSR) emittance growth cancellation pioneered by D. Douglas [1]. The idea was then further developed by R. Hajima in the matrix formalism and later extended in the Courant-Snyder formalism by S. Di Mitri [2,3]. With the ever-growing demands of high energy, short wavelength Electron Storage Rings (ESR) and Free Electron Laser (FEL) drivers, the CSR effect has proven to be a detrimental factor in emittance stability. Under linear approximation, it has been shown that the CSR induced dispersive kicks in successive bending magnet systems can, with careful balancing of the linac optics, cancel each other to nullify the bend plane emittance growth. This technique of optics balancing in the constant bunch length regime is the focus of this paper. We will present our findings, analytically and numerically, of the emittance measurements for the current Linac Coherent Light Source (LCLS) dogleg system (DL2).

INTRODUCTION

Bending systems in linear accelerators are essential for beam transport and bunch compression. When electrons travel in curved orbits in the bending magnets of an accelerator they emit synchrotron radiation [4]. For longer bunches, the electrons radiate independently and the radiation is incoherent with a power scaling of N, the number of electrons in the bunch. The situation is vastly different when the bunch length becomes ultra-short and comparable to the radiation's wavelength; the electrons begin to radiate as a unit and the radiation is coherent with a power scaling of N^2. The dramatic increase in radiation power for the coherent case has the ability to induce a sizable energy chirp along the beam which will, consequently, dilute the transverse emittance of the beam as its transported through the linac [5]. Conserving the transverse emittance is essential in delivering high brightness electron beams. The CSR radiation induces a variation of the electron energy that is correlated along the longitudinal bunch coordinate (barring transverse effects). It is in this correlation that we may manipulate and attempt to suppress the CSR driven transverse emittance dilution.

The LCLS at the Stanford Linear Accelerator Center (SLAC) is one of the world's premiere X-ray free-electron laser (XFEL) facilities. It is the source of the brightest coherent radiation in the sub-nanometer wavelength regime and has remarkable capabilities in the biological, chemical, material science and the molecular research fields [6-8]. After injection, the beam transport line consists of a two-stage bunch compression system with three accelerating sections, as shown in Figure 1. The bunch length at the second bunch compressor is short (~10 μm) and the radiation emitted in the dipoles is coherent for the wavelengths comparable to the electron bunch length.

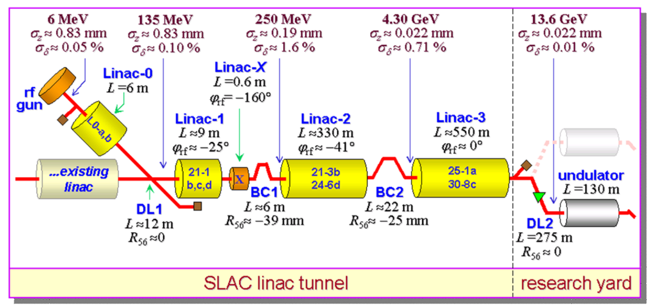

Figure 1: LCLS beamline schematic.

At the end of the 3rd linac section is a dogleg (DL2) bending system implemented to transport the electron bunch to the undulator beamline. It is at this location where we will conduct our studies of CSR emittance growth cancellation via optics balancing. As we will see, with careful balancing of the optics in between the dispersive CSR kicks in BC2 and DL2, we can orient the kicks to cancel each other and preserve transverse emittance along the beam line.

OPTICS BASED BALANCING OF CSR DISPERSIVE KICKS

We first acquaint ourselves with Hajima's first order matrix approach to the analysis of CSR induced transverse emittance growth [3]. To the first order, the bend plane space coordinates can be written as $\mathrm{x(s)} = (\mathrm{x}, \mathrm{x}', \delta_0, \kappa \mathrm{L_B}, \kappa)^\mathrm{T}$ where x is the deviation from the on energy path, x' is derivative of the deviation with respect to the ideal path, δ_0 is the initial relative energy deviation, $\mathrm{L_B}$ is the magnet length, and κ is the normalized CSR wake potential in a bend magnet measured in [eV/m]. In this formalism, the CSR energy deviation is found by $\delta_{CSR} = \kappa \mathrm{L_B}$. When a particle gains or loses energy within a bending system, its transverse coordinates are altered with respect to the on-energy path as $\Delta \mathrm{x} = \mathrm{R_{16}} \delta$ and $\Delta \mathrm{x}' = \mathrm{R_{26}} \delta$, where the matrix terms $\mathrm{R_{16}}$ and $\mathrm{R_{26}}$ are the first order dispersion and its slope. The corresponding bend magnet matrix can then be constructed via the Green's function method to include the effect of CSR [9]:

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$$R_{BEND} = \begin{pmatrix} \cos(\theta) & \rho\sin(\theta) & \rho(1-\cos(\theta)) & \rho(1-\cos(\theta)) & \rho^2(\theta-\sin(\theta)) \\ -\frac{1}{\rho}\sin(\theta) & \cos(\theta) & \sin(\theta) & \sin(\theta) & \rho(1-\cos(\theta)) \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & \rho\theta \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

where ρ is the bending radius and θ is the bending angle of the dipole magnet. This is an extension of the dispersion matrices used in beam transport, but with the addition of a CSR dispersive kick element. Combining the matrices for a simple bend-drift-bend system, as is the case with the LCLS DL2, we can compile a system where the CSR spatial and angular kicks are explicitly written and a cancellation scheme can be quantified.

Alternatively, S.D. Mitri extended this matrix approach to the Courant Snyder (C-S) formalism [10]. For a particle with the reference energy, the invariant, bend-plane deviation and angle are $J = x = x' = 0$. Upon traversing a bending magnet, the particle will receive a CSR energy kick, which will instantaneously alter the particle's invariant and bend plane phase space coordinates with respect to the ideal path:

$$X = \sqrt{2J\beta}\,\cos(\phi) = \eta\delta_{CSR}$$
$$X' = -\sqrt{\frac{2J}{\beta}}\left(\alpha\cos(\phi) + \sin(\phi)\right) = \eta'\delta_{CSR}$$
$$2J = \gamma X^2 + 2\alpha XX' + \beta X'^2, \quad (2)$$

where β and α are the Twiss optics functions, γ is $(1+\alpha^2)/\beta$, and ϕ is the phase advance. Subsequent magnets result in the same addition to the transverse deviation, angle and invariant. The ensemble average of each particle's invariant in the beam is the representative transverse emittance, $< J_i >= \epsilon_X$. The results are equivalent as those derived in the Hajima matrix approach though achieved in a different way. Each method has their strengths and merits depending on the situation in which they are to be implemented.

Both methodologies assume that the bunch length is constant between successive bending magnets and therefore the CSR RMS energy spread induced on the beam is identical for each bend. This assumption greatly simplifies the mathematics of the system. Although, these methods are still valid in systems where the bunch length is evolving, such as bunch compressors, the mathematics is quite rigorous adding an extra variable for each CSR energy spread term of each bend involved in the system.

LCLS DOGLEG2

The LCLS DL2, sketched in Figure 2, is a bending system consisting of 4 dipole magnets which form two double-bend achromats [11]. The parameters of the system are such that the dispersion function is symmetric and its derivative is anti-symmetric across a single achromat. The Twiss parameters are roughly symmetric across the two achromats, and the phase advance between the two magnets in each achromat is roughly π, as shown in Table 1.

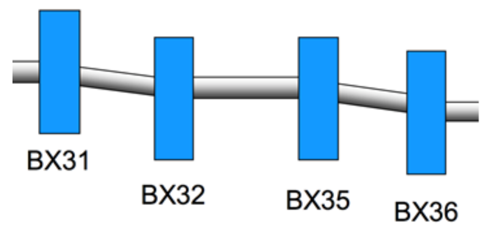

Figure 2: Cartoon of the dipole layout of DL2 of LCLS-I.

In the nominal operation of the LCLS, there are two prominent sources of CSR transverse emittance growth located at BC2 and DL2 as can be seen in Figure 3 of the normalized (dispersion corrected) transverse emittance along the beamline. The CSR energy kick experienced by the beam will be constant in each of the magnets of DL2 due to the fact that the bunch length is not changing and is a prime candidate for the aforementioned CSR emittance growth cancellation via optics balancing techniques. We apply the principles of Douglas, Hajima and Mitri to develop a configuration where the dispersive CSR kicks of BC2 and DL2 cancel each other to minimize the cumulative transverse emittance growth of the beam.

Table 1: Various Twiss parameters for DL2

Magnet	β_x	α_x	η_x	η'_x
BX31	33.5 m	2.3	0.01 m	0.0087
BX32	48.1 m	-3.3	0.01 m	-0.0087
BX35	38.0 m	2.6	-0.01 m	-0.0087
BX36	54.5 m	-3.75	-0.01 m	0.0087

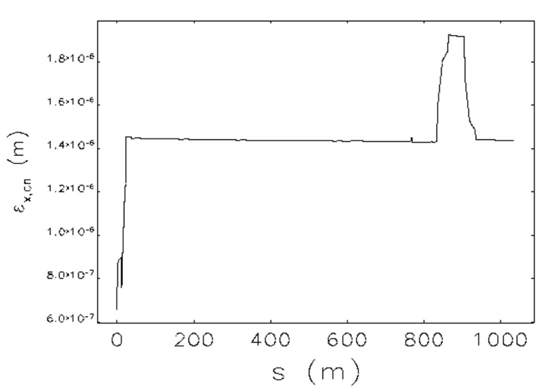

Figure 3: Map of the dispersion-corrected transverse emittance along the LCLS (to shortly past DL2) under nominal settings.

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For this, we follow Mitri's routine in modelling the CSR kicks under the C-S formalism. As a particle exits BC2 (S_0), it leaves with some transverse invariant growth, ΔJ, resulting from the CSR effect from the four bending magnets of the chicane. The CSR induced invariant growth from BC2, J_0, will have some associated transverse phase space coordinates:

$$X_{BC2}(S_0) = \sqrt{2J_0\beta(S_0)}Cos(\phi(S_0)),$$

$$X'_{BC2}(S_0) = -\sqrt{\frac{2J_0}{\beta(S_0)}}\Big(\alpha(S_0)Cos\big(\phi(S_0)\big) + Sin\big(\phi(S_0)\big)\Big). \quad (3)$$

The particle continues along the beamline, while undergoing betatron oscillations, until it encounters the first magnet of DL2 (BX31), in which another CSR dispersive kick is added to its transverse phase space coordinates. The new coordinates are as follows:

$$X_{BX31} = X_{BC2}(\phi(S_1)) + \eta_{BX31}\delta_{DL2}$$

$$X'_{BX31} = X'_{BC2}(\phi(S_1)) + \eta'_{BX31}\delta_{DL2}, \quad (4)$$

where $\phi(S_1)$, η_{BX31}, η_{BX31}, δ_{DL2} is the phase advance (relative to BC2), dispersion and its slope, and normalized CSR energy kick at the location of BX31, S_1, respectively. After the CSR kick, the particle's invariant is changed to $2J = \gamma X_{BX31}^2 + 2\alpha X_{BX31}X'_{BX31} + \beta X'^2_{BX31}$. Again, at BX32 the particle receives another CSR dispersive kick for each bending magnet and the process reiterates for the calculation of the transverse phase space coordinates and invariant as the particle travels through the entire system.

The goal now is to find the phase advance in the L3 linac section and the drift space separating the two achromats of DL2 (from BX32 to BX35) that will achieve optimal cancellation of the CSR kicks. Since we do not know the parameters and details of the CSR kick from BC2 (it is a superposition of the CSR kicks from each of the 4 bending magnets of the chicane, though with different strengths at each bend due to evolving bunch length in the system) we must employ numerical techniques to achieve this optimization.

SIMULATION STUDIES

We can compare our analytical findings with that of simulation studies of the system using the particle tracking code ELEGANT [12]. For this we have developed a phase advance shifter (postscript deriving the phase advance matrix for given Twiss parameters) in L3 and the drift space between the two achromats in DL2, which can be used to scan the phase advance in each section to see its effect on the transverse emittance growth at the exit of DL2. The phase advance shifter is implemented in ELEGANT as a theoretical, zero-length matrix element that shifts only the phase advance at that particular location while preserving all other parameters. For completeness, we scanned the phase advance at each location from 0 to 360 degrees in increments of 10 degrees. The results of the phase advance scans are shown in Figure 4 and demonstrate significant transverse emittance preservation with an additive phase advance of 170 and 190 degrees in L3 and the middle drift section in DL2, respectively.

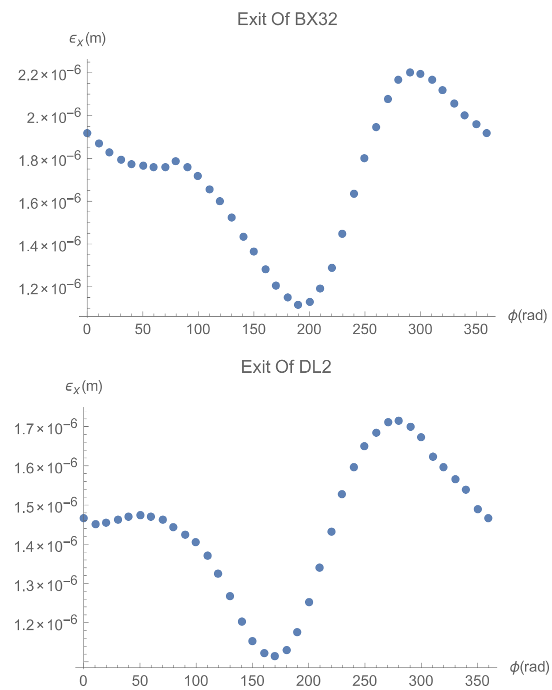

Figure 4: Phase advance scan using theoretical phase advance matrix element in ELEGANT. Top: Transverse emittance plotted at the exit of BX32 for phase advance scans of L3. A minimum is found at 190 degrees. Bottom: Phase advance scan of middle drift in DL2 with a transverse emittance minimum found at 170 degrees.

To actually vary the phase advance in the LCLS machine for demonstration, we would need to configure the quadrupole settings in the linac sections. We can emulate this procedure in ELEGANT by solving for the correct quadrupole configuration in L3 and the drift section of DL2 to achieve the appropriate phase advance conditions. The transverse emittance along the accelerator with the new quadrupole configuration for the optimal phase advance solution is shown in Figure 5. The emittance preservation is considerable when comparing it to the nominal settings in Figure 3.

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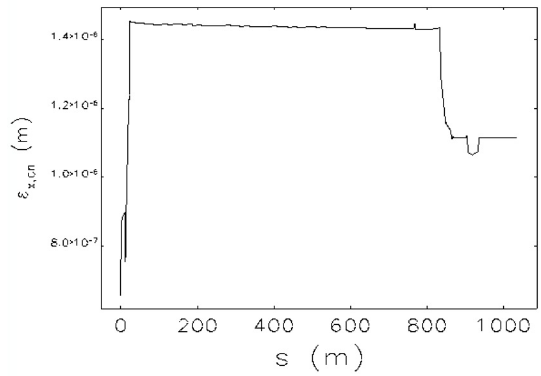

Figure 5: Transverse emittance plot of the LCLS beamline up to the undulator with the altered quad settings.

A POSSIBLE EXPERIMENTAL PROPOSAL AT LCLS

In the previous section, we have shown that there exists a configuration based simply on the optical functions of a multi-bend system that can successfully suppress the CSR emittance growth. To experimentally verify such a phenomenon with the actual LCLS machine we are required to manipulate the phase advance in L3 and the drift space in DL2 by altering the strength of the quadrupoles. The challenge in this task comes from adjusting the quads to meet our specific phase advance requirement while ensuring that matching of the optic functions is preserved so as not to generate emittance dilution due to optics mismatch [13-15]. For this, we will be creating a “tuning knob” for the phase advance that could be programmed into the main controls of the LCLS accelerator to vary the quadrupole strengths with the ability to scan a full 2π phase advance to study the optics-balance effect on the transverse emittance.

CONCLUSION

In this paper, we have demonstrated an application of the Twiss optics balance technique for mitigation of the CSR induced emittance growth between bending systems. The technique relies on de-constructively aligning the CSR spatial and angular kicks in phase space between successive bending magnets. This is achieved by properly tuning the Twiss parameters and phase advance between the sources of CSR. In the case of the LCLS, it was numerically shown that with the proper phase advance condition between BC2 and DL2 the cumulative CSR emittance growth can be suppressed. This technique promotes a simple method of beam optimization that may be used in today’s operating linacs and FELs.

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