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AN EMITTANCE-PRESERVATION STUDY OF A FIVE-BEND CHICANE FOR THE LCLS-II-HE BEAMLINE

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Abstract

The Linac Coherent Light Source II (LCLS-II) is an upgrade intended toward advancing on the great success of its predecessor, LCLS, to maintain its position at the forefront of X-ray science. The introduction of a niobium metal superconducting linac for LCLS-II not only increases the repetition rate to the MHz level (from 120 Hz) but also boasts an average brightness many orders higher (~10^4) than that of LCLS. Though, these improvements do not come without a price: the peak brightness suffers by a factor of 10 in part due to the impact of Coherent Synchrotron Radiation (CSR) diminishing the peak current of the beam in the second bunch compressor (BC2) [1]. In this paper, we discuss the impact of implementing a plug-compatible 5-bend chicane for BC2 on the beam's emittance dilution for a high energy, low emittance configuration of LCLS-II (LCLS-II-HE). The results are compared with that of a standard 4-bend chicane under various settings in ELEGANT and CSRTrack [2, 3].

INTRODUCTION

The detrimental effects of CSR in the accelerator environment is one of most challenging problems to study, let alone counter, for current free electron laser (FEL) facilities. The CSR energy chirp induced by the beam onto itself from traveling along arced sections of the beam line has direct consequences on the beam's bend-plane emittance. The issue is exacerbated by the push to produce even shorter and more compact electron bunches for ultra-brilliant FEL radiation in the X-ray regime at facilities such as the European XFEL at DESY, Spring-8 Angstrom Compact Free Electron laser (SACLA), Pohang Accelerator Laboratory X-ray Free Electron Laser (PAL-XFEL) and the LCLS-II, which is currently being construction. The ceiling of producing such radiation is in the painstaking details of the beam transport line, in particular, the latter stage bunch compression systems [4]. Many techniques have been researched and developed but, as the limits are continually pushed, new solutions are needed to adjust with the demand.

LCLS-II HIGH ENERGY (HE)

The LCLS-II high-rate FEL can generate X-ray pulses from 200 eV to 5 keV at MHz repetition rates [5]. The electron beam for the FEL is generated in an RF gun and accelerated in a superconducting RF (SCRF) linac to a beam energy of 4 GeV. While the beam is accelerated, it is compressed to a peak current of 400 to 1000 Amps, depending on the bunch charge. Over much of the photon energy range, the LCLS-II electron beam will generate X-rays with peak powers of roughly 10 GW [6].

While the average brightness of the LCLS-II X-ray laser will be many orders-of-magnitude higher than that of the LCLS operating at 120 Hz, the peak brightness will be a factor of 10 or more lower. For comparison, the LCLS routinely produces X-ray pulses with over 200 GW using a 5 kA electron bunch and beam shaping techniques [7].

There are two reasons for the relatively poor peak performance of the LCLS-II: first, the peak current of the LCLS-II electron bunch is 5 to 10 times lower than that in the LCLS and, second, the beam energy is a factor of 2 to 3 times lower than that in the LCLS. The reduced peak current is largely due to the impact of Coherent Synchrotron Radiation (CSR) and Longitudinal Space Charge (LSC) which are exacerbated by a lower beam energy at the second bunch compressor (BC2) of 1.6 GeV versus roughly 5 GeV. These effects are further amplified in the 2-km long bypass transport line which, at the 4 GeV beam energy, lead to a significant micro-bunching instability [8].

To extend the photon energy range to upwards of 20 keV and improve the X-ray pulse performance, the LCLS-II-HE was proposed with a high energy upgrade from 4 to 8 GeV and a possible lower beam emittance where the gun emittance is reduced from 0.4 to 0.1 µm. The upgrade will increase the beam energy in the 2 km Bypass line from 4 to 8 GeV, significantly reducing the impact of the largest LSC contribution. However, the energy of BC2 will be roughly the same, increasing from 1.6 to 1.9 GeV, leaving the impact of CSR on the beam comparable and diluting the beam emittance significantly. In December 2016, the LCLS-II-HE concept received CD0 from the DOE. Further details on the upgrade can be found in the supporting documentation at https://portal.slac.stanford.edu/sites/conf_public/-lclsiihe2017/Pages/default.aspx.

LCLS-II Bunch Compressor 2 (BC2)

The LCLS-II second stage bunch compressor, BC2, is a standard 4-bend chicane with its main features listed in Table 1. It is responsible for the final compression of the beam before its transported to the undulators. It is here that the peak current reaches its maximum value thus making BC2 a salient area for CSR driven emittance growth.

Current methods for mitigating BC2's CSR emittance growth are centered on linac optics optimization. First method of which, balances the RF chirp, $h = (1/E_0)\,(dE/dz)$, and the compression factor amongst the bunch compressors to find a minimization of the CSR induced emittance growth. Generally, allocating the linac's R_{56}, so that much of the compression work can be done

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earlier in BC1, allows BC2 to have smaller bending angles and consequently less contribution from CSR due to its $\theta^{2/3}$ dependence [9]. The second method focuses the beam to a waist ($\alpha_x = 0$, $\beta_x = \beta_{\min}$) toward the final bend of a chicane, where the bunch length is the shortest and the CSR is the greatest, to suppress the CSR induced emittance growth via the $\mathscr{H}$-function minimization [10]. These two methods are among many that have been shown to be successful in partially suppressing the CSR induced emittance dilution for a 4-bend chicane bunch compressor.

Table 1: Various Design Parameters of BC2 in LCLS-II

Parameter	Symbol	BC2	Unit
Electron Energy	E_0	1.6	GeV
Momentum Compaction	$\lvert R_{56}\rvert$	39.5	mm
Chicane Total Length	L_T	23.7	m
Bend Angle Per Dipole	$\lvert\theta\rvert$	0.04	Rad
Eff. Length of Each Bend	L_B	0.55	m
Dispersion at Center	$\lvert\eta_x\rvert$	458	mm

THE FIVE-BEND CHICANE BUNCH COMPRESSOR

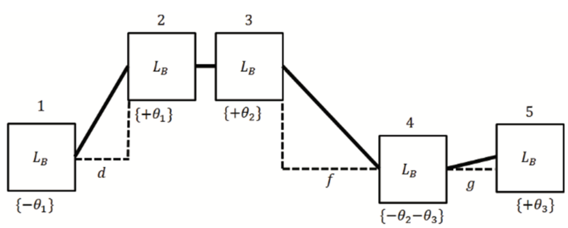

Figure 1: Diagram of a five-bend chicane. Not to scale.

The 5-Bend chicane (Fig. 1) is a dual-polarity dispersive bunch compressor intended for the final-stage bunch compression where an electron bunch reaches it shortest length and where CSR is most detrimental [11]. The 5-bend chicane would be largely plug-compatible with the present LCLS-II 4-bend BC2 design. It would be situated in the same space that will be occupied by the 4-bend chicane and it would reuse much of the LCLS-II BC2 hardware. One additional bending magnet would be added, the supports would be relocated, and the vacuum system would be modified for the different bending magnet spacing. The 5-bend chicane's various features are listed in Table 2.

The plug-compatibility of the 5-bend chicane relies on the fact that it can maximally preserve the beam emittance while minimally reconfiguring the existing BC2 hardware (and engineering cost). To do this, we solved for a 5-bend chicane configuration which can be accommodated in the existing 4-bend chicane space. The design will require only a longitudinal shift of the apparatus housing magnets 2 and 3 and a permanent placement of the additional magnet in between bends 3 and 4 (both, with respect to the 4-bend chicane configuration). In addition, the 5-bend chicane design would have to be able to be turned off i.e. allow a direct line of motion for the beam to travel through. This sets a requirement on the permanent placement of the 4th additional magnet (it cannot be displaced too far from the chicane's axis), and therefore sets a strict requirement on the absolute dispersion value in the 4th bend. Under these engineering guidelines, the robust performance of the 5-bend proves to be a low-cost and simple upgrade to the standard 4-bend chicane.

Table 2: Characteristic Parameters of the Five-Bend Chicane for BC2

Parameter	Symbol	5-Bend Chicane	Unit
Electron Energy	E_0	1.6	GeV
Momentum Compaction	$\lvert R_{56}\rvert$	39.5	mm
Chicane Total Length	L_T	23.7	m
First Chicane Drift Length	L_D	7.3	m
Second Chicane Drift Length	L_F	11.1	m
Third Chicane Drift Length	L_G	0.8	m
Angle 1	$\lvert\theta_1\rvert$	0.052	Rad
Angle 2	$\lvert\theta_2\rvert$	0.037	Rad
Angle 3	$\lvert\theta_3\rvert$	0.018	Rad
Eff. Length of Each Bend	L_B	0.54	m
Dispersion After Magnet 2	$\lvert\eta_x\rvert$	410	mm
Dispersion After Magnet 4	$\lvert\eta_x\rvert$	19	mm

The 5-bend chicane has several distinct features that distinguishes itself from the standard 4-bend chicane with regards to CSR induced emittance growth suppression. Firstly, the additional bend allows the ability to allocate the R_{56} amongst the five bends (the R_{56} of a 4-bend is predominantly constrained into the two middle magnets). This additional flexibility is likened to an optics-like tuning of the CSR energy kicks in each of the bending magnets. Additionally, the dual-polarity dispersion of the chicane opens the possibility of locally cancelling path/angle excursions caused by the CSR energy kicks [12]. To the first order, a CSR energy kick translates to a final spatial/angular devi-

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ation of

$$\Delta x_{\text{exit}} = \eta_{\text{bend}} \delta_{\text{CSR}} \quad (1)$$

$$\Delta x'_{\text{exit}} = \eta'_{\text{bend}} \delta_{\text{CSR}} \,, \quad (2)$$

where Δx_{exit} and $\Delta x'_{\text{exit}}$ are the spatial and angular deviations at the exit of the chicane (where the dispersion closes), η_{bend} and η'_{bend} are the dispersion and its slope at the location of the CSR energy kick and δ_{CSR} is the CSR energy kick normalized to the beam energy. So, for a 5-bend chicane, the dual-polarity of the dispersion opens the opportunity to have the path/angle excursions at the end sum to zero; a feature not present in the 4-bend chicane.

SIMULATION STUDIES

Preliminary simulation studies have been conducted for the present LCLS-II-HE 4-bend BC2 design and the proposed 5-bend BC2 chicane design. The transverse emittance has been studied for moderate and high peak currents (0.8 and 1.5 kA, respectively) in the LCLS-II-HE at 100-pC bunch charge and low-emittance configurations (0.27 µm and 0.10 µm, respectively). The emittance comparison studies between the 4 and 5-bend chicanes were conducted using ELEGANT and CSRTrack.

ELEGANT Simulation Results

ELEGANT was used as the lead simulation software in optimizing the 5-bend chicane and comparing its results with that of a 4-bend chicane.

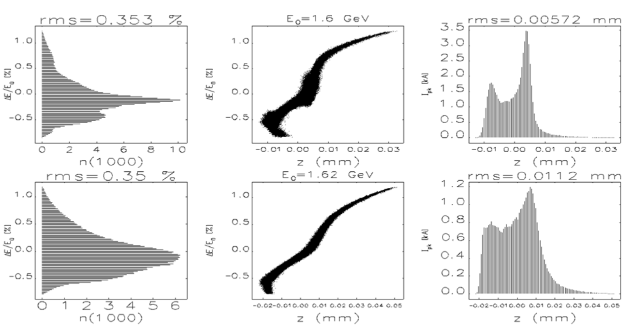

Figure 2: Top: The longitudinal phase space plots, from left to right, respectively, of the energy spread distribution, the $z - \delta_E$ phase space, and current profile for an electron bunch compressed to ~0.8 kA. Bottom: The longitudinal phase space plots for an electron bunch compressed to ~1.5 kA. Both plots are for the 4-bend chicane (the 5-bend's plots are identical) and the 0.27 µm low-emittance case (again, the low-emittance, 0.10 µm case produces visually similar results).

Table 3: LCLS-II-HE X-plane Emittance Measurements

Configuration	4-Bend ($\gamma\epsilon_{xf}, \Delta\gamma\epsilon_x, \Delta\gamma\epsilon_x/\gamma\epsilon_{xi}$)	5-Bend ($\gamma\epsilon_{xf}, \Delta\gamma\epsilon_x, \Delta\gamma\epsilon_x/\gamma\epsilon_{xi}$)
0.8 kA, 0.27 µm	(0.33µm, 0.06µm, 22%)	(0.30µm, 0.03µm, 11%)
1.5 kA, 0.27 µm	(0.62µm, 0.35µm, 130%)	(0.33µm, 0.06µm, 22%)
0.8 kA, 0.10 µm	(0.16µm, 0.06µm, 60%)	(0.12µm, 0.01µm, 12%)
1.5 kA, 0.10 µm	(0.41µm, 0.31µm, 310%)	(0.16µm, 0.06µm, 60%)

CSRTrack Simulation Results

CSRTrack was used as a post verification check of the results obtained in ELEGANT for thoroughness of our study. CSRTrack employs a 2.5-D modelling of the electromagnetic forces an electron beam would experience in an accelerator bending system (though we suspect no transverse coherence of overtaking fields as $R^{1/3}\sigma_s^{2/3} > \sigma_x$).

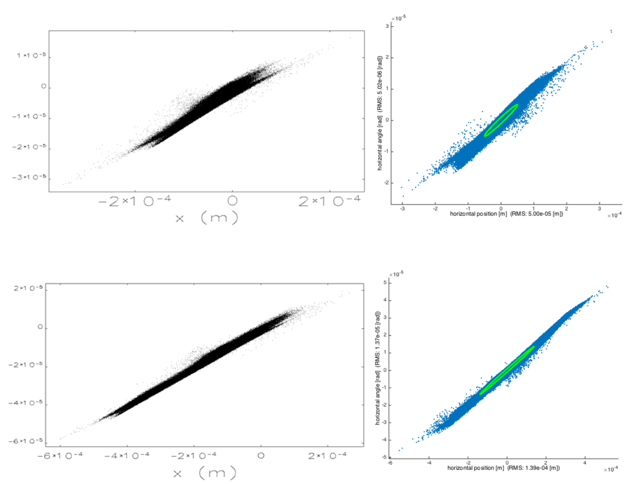

Figure 3: The bend-plane projected emittance at the exit of the nominal 4-bend chicane in ELEGANT (left) and CSRtrack (right) for the low-emittance 0.10-µm beam. The top row of plots is compression to ~0.8 kA and the bottom to ~1.5 kA.

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Table 4: LCLS-II-HE X-plane Emittance Measurements

Configuration	4-Bend ($\gamma\epsilon_{xf}$, $\Delta\gamma\epsilon_x$, $\Delta\gamma\epsilon_x/\gamma\epsilon_{xi}$)	5-Bend ($\gamma\epsilon_{xf}$, $\Delta\gamma\epsilon_x$, $\Delta\gamma\epsilon_x/\gamma\epsilon_{xi}$)
0.8kA, 0.27µm	(0.32µm, 0.05µm, 19%)	(0.29µm, 0.02µm, 7%)
1.5kA, 0.27µm	(0.64µm, 0.37µm, 137%)	(0.34µm, 0.07µm, 26%)
0.8kA, 0.10µm	(0.16µm, 0.06µm, 60%)	(0.13µm, 0.03µm, 30%)
1.5kA, 0.10µm	(0.42µm, 0.32µm, 320%)	(0.15µm, 0.05µm, 50%)

The 5-bend chicane shows strong CSR emittance growth suppression in all cases, more notably when the peak current is increased as in the 1.5kA cases.

CONCLUSION

The expectation is that the 5-bend modification of BC2 would be a cost-effective approach to maximize the capability of the LCLS-II-HE. It would allow operation with low emittance beams as might be required to generate ~20 keV X-rays and/or operate with higher peak beam currents and thereby increase the peak brightness and peak power of the LCLS-II-HE FEL.

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