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EMITTANCE PRESERVATION FOR LCLS-II-HE PROJECT *

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Abstract

A small transverse slice emittance at the undulator entrance is essential for high performance of the free electron laser. To achieve this, preservation of the phase space density of the electron bunch during acceleration and compression is absolutely necessary. The LCLS-II-HE is designed to transport a 100 pC bunch with an emittance of ~0.3 mm-mrad with minimal emittance dilution. In this paper, encouraged by the fact that a normalized emittance on the order of 0.1 mm-mrad can be potentially obtained from the LCLS-II-HE injector, we show that such an ultra-small emittance can be preserved largely along the LCLS-II-HE accelerator and bunch compression system. In achieving this, the sources of emittance growth, the mechanism, and the solutions are investigated carefully, in particular, around the laser-heater, the two bunch compressors. Studies are carried out with IMPACT simulation code.

INTRODUCTION

The LCLS-II is a CW X-ray FEL covering a photon spectral range from 200 to 5,000 eV. It is based on a 4 GeV SRF linac installed in the 1st km of the SLAC linac tunnel [1]. The LCLS-II-HE is a high energy upgrade, which will increase the beam energy to 8 GeV and the photon spectral range to 12.8 keV; this range may be extended through 20 keV with improvements of the electron injector and beam transport [2]. Hence, large efforts have been invested to explore such possible improvements. While the optimization on the injector performance is out of our scope for this paper; here we conduct our study based on the feasibility that the electron injector can generate a normalized transverse emittance of ~ 0.1 mm-mrad. We show how such ultra-low emittance can be largely preserved in the electron bunch acceleration, compression and transport system till the entrance of undulator.

CHALLENGES AND CONSIDERATIONS

The schematics of the LCLS-II-HE layout is shown in Figure 1 with the major accelerator and bunch compression system components. For LCLS-II optics design [3] and transport optimization [4] studies, different electron bunch charges: 20 pC, 100 pC, and 300 pC were studied. In this paper, we focus on the nominal 100 pC case to discuss the challenges in transporting an electron bunch with an ultra-low normalized transverse emittance on the order of 0.1 mm-mrad out of the injector.

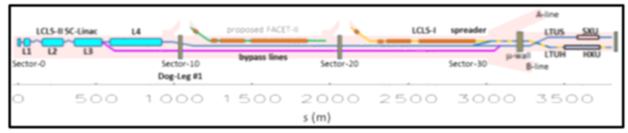

Figure 1: Schematics of LCLS-II-HE layout.

In nominal LCLS-II studies, for 100 pC, the initial normalized transverse emittance out of the injector is about 0.3 mm-mrad. Most of the emittance growth, both the projected and the slice, happens in the first 500 meter where the electron bunch out of the injector is sent through a Laser Heater chicane, two bunch compressors and the accelerator cavities including the harmonic cavity for linearizing the electron bunch longitudinal phase space [4]. Hence, in this paper, we will mostly report studies for the first 500 meters; even though the final results are given at the undulator entrance.

Initial e-bunch Properties Out of the Injector

The initial properties of the electron bunch out of the injector are illustrated in Figure 2, where the x-p_x, y-p_y, z-x, and z-p_x phase space plots are shown as well as the normalized transverse slice emittance and the mismatch factor along the electron bunch.

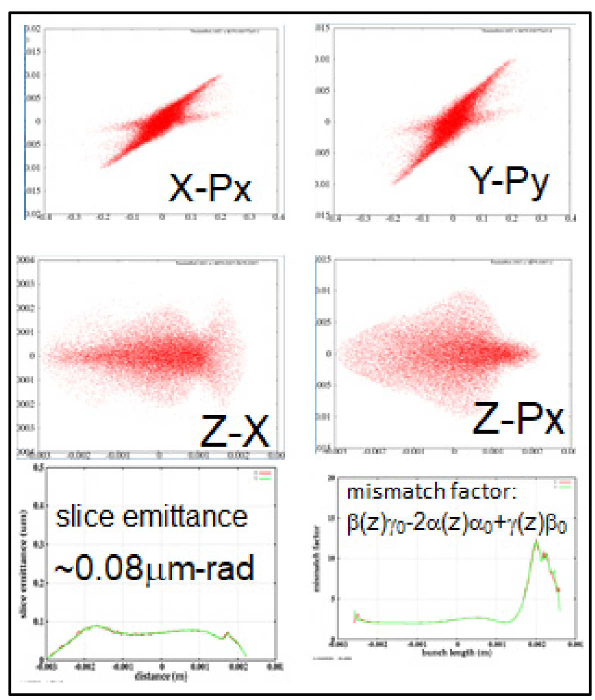

Figure 2: Initial *e*-bunch properties out of the injector.

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This electron bunch with transverse normalized emittance around 0.08 mm-mrad (both x- and y-plane) as shown in Figure 2 is tracked through the LCLS-II baseline lattice. While that baseline lattice was optimized for a 100 pC electron bunch with initial ~ 0.3 mm-mrad normalized transverse emittance; larger emittance growth is observed in the Laser Heater chicane region and the two bunch compressors regions for this ultra-low emittance electron bunch at ~ 0.1 mm-mrad. All simulations presented in this study are carried out using a 3D parallel beam dynamics simulation framework IMPACT [5,6].

Space Charge Effect and Chromaticity

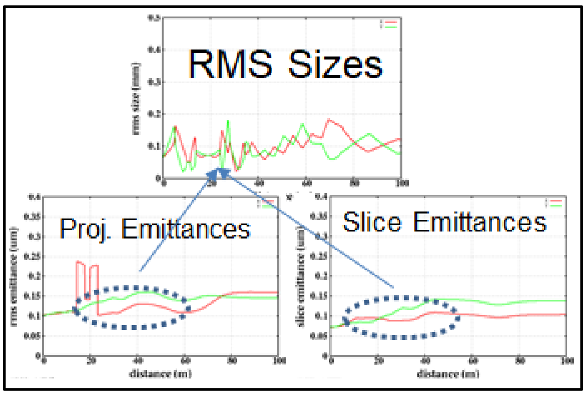

Figure 3: Emittance growth around the Laser Heater.

In the simulation, the electron bunch from the injector is first re-matched to the lattice considering the space charge effects. Significant emittance growth (> 50%) at the beginning and after the Laser Heater is observed as shown in Figure 3. Due to the strong space charge effect, there is a variation of the mismatch factor from slice to slice of the electron bunch. Hence a onetime re-matching for the overall electron bunch is not sufficient to fully resolve this space charge induced slice mismatch problem.

To avoid a relatively large emittance growth in the first bunch compressor (BC1), the BC1 only provides a factor of ~ 3 compression. With this gentle compression, there is negligible x-emittance growth in BC1 and during the lattice transition; yet the y-emittance growth is not small (> 30%). To achieve a total of ~ 100 compression factor, a factor of ~ 30 compression is designed for BC2, the second bunch compressor. Due to strong CSR (Coherent Synchrotron Radiation) effects and fold-in contribution, there are large (> 50%) x-project emittance growth after BC2 and large (> 30%) y-slice emittance growth. Tracking through the entire acceleration and bunch compression system, the projected emittance growth in the core is about 40 – 80%; while for the entire beam, it is greater than 100%. The averaged slice emittance growth in the core is about ~100%.

To understand the reasons behind this large emittance growth, the β–function in the front part of the accelerator system is plotted in Figure 4. There, we find violent betatron oscillation with a very small minimum β-function. For a quickly divergent or convergent electron bunch, there can be strong space charge effect [7]. Integrating along the front part of the accelerator system as in Figure 4, the longitudinal space charge force with such a violent variation of the β–function, causes non-negligible energy spread (~ keV) on the electron bunch. Such non-negligible energy spread and the very low value of minimum β–function leads to large chromatic effects [8] with the W-function as defined in Ref. [8] plotted in Figure 5. In explicit, $W = \frac{1}{2}\sqrt{A^2+B^2}$ with $A = \lim_{\delta\to 0}\left[\frac{1}{\delta}\frac{\alpha(\delta)\beta(0)-\alpha(0)\beta(\delta)}{\sqrt{\beta(\delta)\beta(0)}}\right]$ and $B = \lim_{\delta\to 0}\left[\frac{1}{\delta}\frac{\beta(\delta)-\beta(0)}{\sqrt{\beta(\delta)\beta(0)}}\right]$ where $\delta = \Delta p/p$ is the momentum deviation and α, β are Twiss parameters as function of δ. The large W-function indicates a strong chromatic effect.

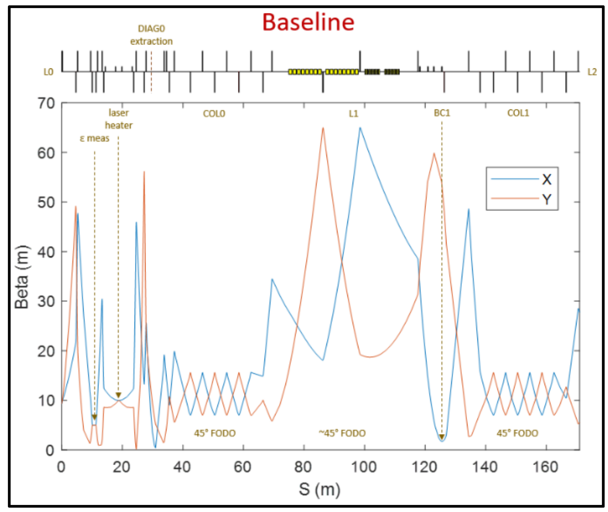

Figure 4: β–function in the front part of the accelerator.

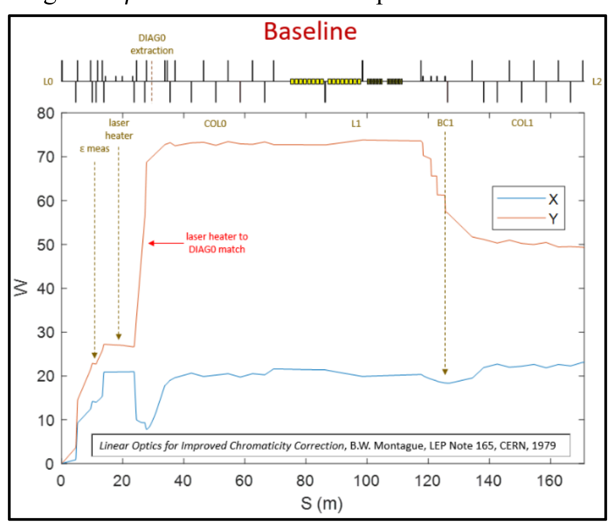

Figure 5: W-function in the front part of the accelerator.

Smooth Lattice and Emittance Preservation

To reduce this chromatic effect, a smoothed lattice is designed where the betatron variation is smoothed with the front part of the accelerator system shown in Figure 6. The chromatic effect as indicated by the W-function is reduced with this smoothed lattice as shown in Figure 7.

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With this smoothed lattice and also increasing the β–function at the Laser Heater to be $\beta_{x,y} = 20$ m, the electron bunch from the injector is again re-matched including the space charge effects. Then the re-matched electron bunch is tracked through the Laser Heater chicane, the two bunch compressors and the accelerator system.

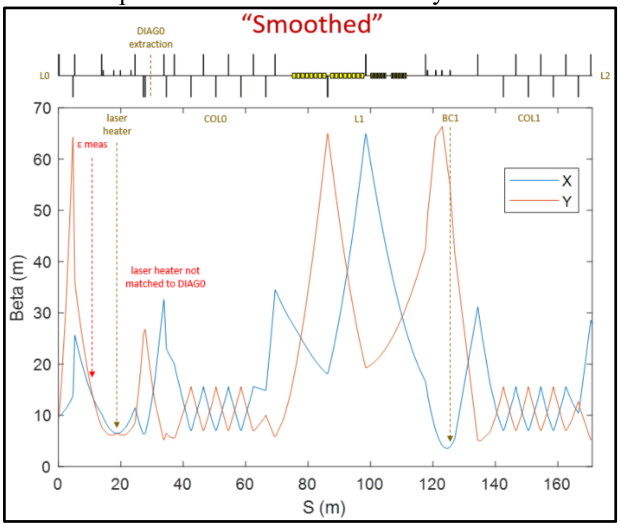

Figure 6: β–function with the smoothed lattice.

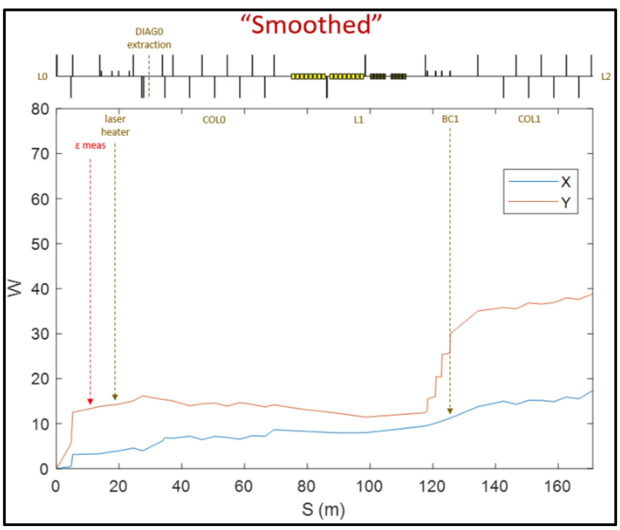

Figure 7: W-function with the smoothed lattice.

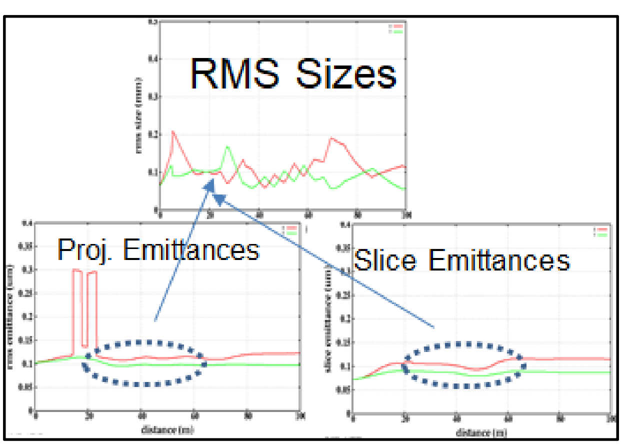

Figure 8: Reduced emittance growth around Laser Heater.

At the Laser Heater region, the minimum value of the β–function is increased as shown in Figure 6. The tracking results show that the emittance growth is indeed reduced (<30%) as shown Figure 8. Further downstream of the accelerator system, there is small projected x-emittance growth after BC1 during the lattice transition. Due to strong CSR effect and particle fold-in from head and tail, there is still strong emittance growth after BC2, which is subject to further improvement of the overall accelerator system design and optimization. With all the known collective effects: CSR, space charge and wakefields, etc. included in the IMPACT [5,6] simulation, the final normalized emittance, both the projected and the slice, is shown in Figure 9 at the undulator entrance.

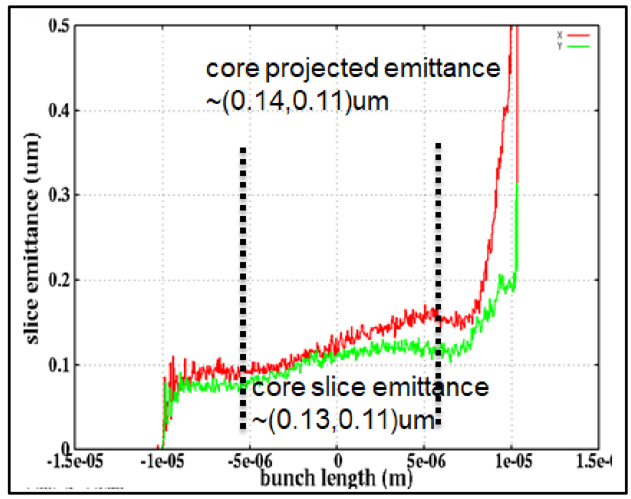

Figure 9: Final emittance at the undulator entrance.

CONCLUSION

In this paper, after identifying the chromaticity issue for a lattice with violent variation of the β–function and a very small minimum β–function, a smoothed lattice is designed for LCLS-II-HE. As shown in Figure 9, with appropriate choice of lattice parameters and space charge re-matching in such a smoothed lattice, it is possible to keep the final emittance growth below 50% for the major core part of the beam with an initial ultra-low transverse normalized emittance (0.1 mm-mrad).

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