ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-WEP043

TUNE-UP SIMULATIONS FOR LCLS-II

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Abstract

The planned superconducting LCLS-II linac poses new operational constraints with respect to the existing copper linac currently operated for LCLS. We present the results of exhaustive accelerator simulations, including realistic machine errors and exploring beam tune-up strategies. Specifically, these simulations concentrate on longitudinal and transverse beam matching as well as orbit and dispersion control through the new linac and up to the hard x-ray FEL. Dispersion control is achieved by a novel method presented within this paper. The results confirm that the beam diagnostics in the current scheme are sufficient for tune-up, yet identify the importance of dispersion control leading to minor changes in the lattice to further improve performance.

INTRODUCTION

The planned FEL upgrade LCLS-II includes a variety of new subsystems. The complex interplay of all the systems requires good electron beam diagnostics to guarantee beam quality and thus FEL performance. This proceeding outlines three key aspects to evaluate tune-up performance through simulations:

- Identify redundancy and lack of diagnostics
- Asses tolerances
- Test tune-up algorithms

All simulations were done using Elegant 29.0 [1]. The simulations start off with machine settings as present after preliminary phasing of the cavities and initial steering to establish partial transmission and simulate tune-up using readouts as available from LCLS-II diagnostics (Figure 1) only. Low probability corner cases were covered by repetitions of the simulation using newly generated machine and beam imperfections for each run. Simulated machine imperfections include misalignments of magnets, cavities and beam position monitors (BPMs) as well as strength errors of magnets and cavities. Non-static imperfections like shot-to-shot fluctuations and machine drifts are expected to be small and were neglected. The beam was simulated with a standard setup of 750 A final peak current, 100 pC bunch charge and 4 GeV final beam energy, but initially off momentum and displaced in space for all 3 dimensions, optics and charge. All initial values but the beam optics parameters were randomly drawn from normal distributions with standard deviations as summarized in Table 1. The beam optics error is expressed by the mismatch parameter [2], which was simulated with constant magnitude but random phase drawn independently for both transverse planes. To ensure validity of these studies, the assumed errors are larger than what is expected after initial RF machine phasing and beam based alignment.

The main components of beam misalignment are orbit offsets, dispersion and transverse and longitudinal mismatches. Orbit offsets may arise from various effects. With increasing offset the following effects manifest: Quadrupole magnets will kick the beam and thereby generate dispersion, small apertures (RF cavities, etc) excite transverse wakefields and the beam halo will be lost along the machine. Core beam losses are not assumed for the simulation as the collimation and machine protection system would prevent prolonged operation in this condition [3] and initial phasing and steering is expected to establish transmission.

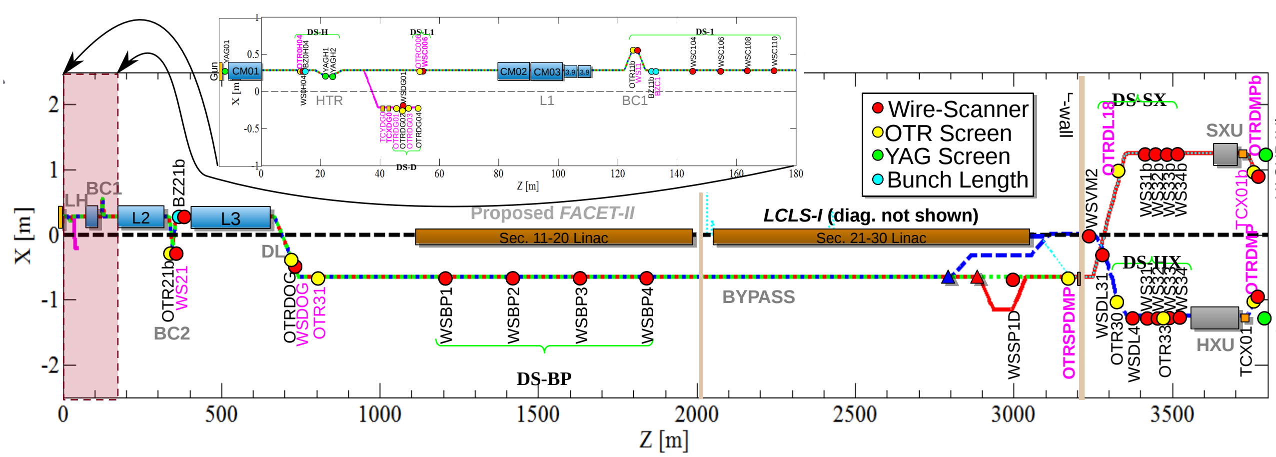

Figure 1: Schematic setup of LCLS-II highlighting locations where the bunch profile can be measured. Not shown on the schme are BPMs and bunch length monitors

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Uncorrected dispersion increases not only the projected emittance but also the discrepancy between slice and projected optics. It leads to a slice mismatch if only the projected optics can be measured, which is the case for LCLS-II baseline design. Therefore, dispersion control is a major issue. Strong sources of dispersion include dipole strength errors and quadrupole strength errors in dispersive sections and off-center BPMs that are included in a orbit steering.

Transverse matching along the beam line is important to reduce chromaticity and limit adverse effects from transverse wakefields and CSR [4]. Final matching prior to entering the undulator line is critical for good FEL performance.

Simulated collective effects include Coherent Synchrotron Radiation (CSR), transverse and longitudinal wakefields and resistive wall wakefields. While space charge is a major driver of micro-bunching for LCLS-II, it can be neglected with respect to the evaluation of the electron diagnostics and tune-up effectiveness [5] and was therefore not considered here. The presented figures show results after completed tune-up recorded for a typical simulation run.

Table 1: Assumed RMS Error Used for Tuning Simulation Assuming a Normal Distribution. * While the absolute mismatch was kept constant the mismatch phase was altered randomly. The mismatch was introduced prior to QCM01

Item	rms
BPM transverse offset	300 µm
Dipole strength error	1‰
Quadrupole transverse offset	300 µm
Quadrupole longitudinal offset	3 mm
Quadrupole strength error	1%
RF amplitude error	1%
RF phase error	5°
RF transverse offset	300 µm
Initial mismatch* ($\xi = \frac{\beta\gamma_0+\gamma\beta_0-2\alpha\alpha_0}{2}$)	1.5
Initial centroid offset	1 mm
Initial angular offset	100 µrad
Charge error	5%
Momentum error	5 MeV

RESULTS

We run tune-up algorithms to improve orbit and dispersion control as well as longitudinal and transverse beam matching within the simulations. First, orbit offsets were corrected given their severe effects and the relative ease of correction using a simplex algorithm relying on the available orbit correctors and BPMs. The resulting orbit offset with respect to the machine center was kept well below 1 mm along the machine, indicating that the available BPMs are sparse but sufficient for tuning.

Next, dispersion was reduced. Dispersion can be measured by correlating orbit with energy fluctuation. The electron central momentum is measured within bunch compressors and the final dogleg. Orbit fluctuations are measured by the over 220 BPMs along the beam line. Given the low shot-to-shot energy jitter expected in LCLS-II (0.01% rms) [6] the sensitivity of energy measurements is not sufficient to calculate dispersion with enough resolution for correction, which thus requires a scan of energy. Dispersion is corrected for by either changing the BPMs offsets and steering the orbit to relative zero within the BPMs, or changing the strength of quadrupole magnets within the dispersive sections. The required correction values are calculated by the pseudo inverse of the dispersion response. Iteration redresses non-linearities and measurement errors. Figure 2 shows the response of dispersion as measured with BPMs to changes in perturbation values (BPMs and quadrupoles) in both transverse directions for the beam line past the bypass line. The values in the upper right and lower left quadrants correspond to offsets in the elements within the 60° rotated transfer line, indicating that this rotated linac turns the correction into a true 4D problem. With this method dispersion errors throughout the machine were reduced below cm level from initial meter size levels.

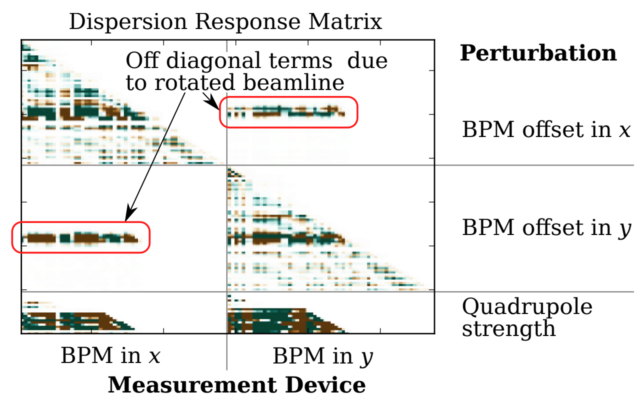

Figure 2: Magnitude of dispersion response to BPM offsets and dispersive quadrupole strengths. Vertical: quadrupoles with altered strengths or BPMs that were offset. Horizontal: BPMs at which dispersion was measured. Each BPM was offset in both transverse directions and dispersion was measured in both directions as well.

Finally, transverse and longitudinal matching along the beam line was accomplished. Initial difficulties in transverse matching were over-come by the dispersion correction. The beam is matched in the following locations:

- Prior to the laser heater (1 Wire scanner)
- After the second Bunch compressor (1 Wire scanner)
- After the dogleg (4 Wire scanner)
- Within the LTU (4 Wire scanner)

Each matching station is equipped with 4, or more, matching quadrupole magnets. Beam sizes are measured by wire scanners. The matching quadrupole magnets at the bunch compressor are located prior to the chicane ensuring a good match in the critical forth bending magnet. Correction to mismatch values of $\xi < 1.01$ were achieved for all cases. For longitudinal matching, peak current and energy were tuned using RF phase and amplitude at both bunch compressors and the dogleg (for energy only). The simplex algorithm

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readily converged for all cases resulting in final longitudinal beam parameters which are only limited by detector resolution.

The performed simulations showed good tune-up capabilities. Figure 3 shows the projected emittance along the lattice after orbit correction only (top) and a fully tuned run (bottom). In the first case the main contributer to emittance is unclosed dispersion. The simulations showed good preservation of the projected emittance after complete tune-up. The residual emittance increase after the bunch compressors originates from Coherent Synchrotron Radiation (CSR) resulting in transverse offsets along the longitudinal slices. Baseline correction capabilities allow to correction scheme this beamtilt [7].

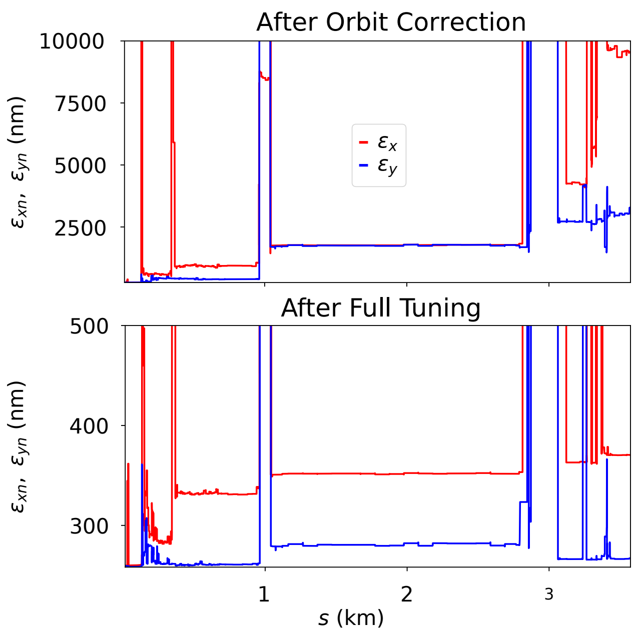

Figure 3: Projected emittance along the beam line for a typical simulation run. Top: Emittance after orbit correction only. Bottom: Emittance after complete tuning.

Figure 4 shows that the slice parameters at the undulator entrance are preserved after complete tune-up. This indicates that there are no major transverse problems, safe for centroid slice offsets due to CSR. However, the simulations did not include space charge after the first cryo module. These effects [8] would decrease the resolution of the beam towards the measured sensitivities but increase the values of the slice parameters as compared to the presented results. Impact simulations specifically taking into account space charge were done elsewhere [8].

DISCUSSION

This study shows that both longitudinal and transverse correction and diagnostic as present in LCLS-II are sufficient to match the beam even for tolerances looser than expected in the real machine. Both the projected and slice final beam parameters are more than sufficient for good lasing [9]. The applied correction algorithms performed well and converged

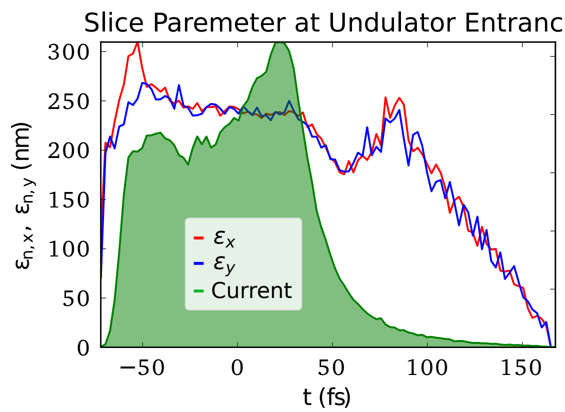

Figure 4: Slice emittance at the undulator entrance of the hard X-ray line.

for all 10 simulated cases. Furthermore, this study highlights the importance of dispersion correction despite the low energy jitter as present in LCLS-II. In consequence, to further empower the presented method for dispersion control, the power supply layout has been updated to allow individual tuning of the quadrupole magnets within the dogleg area enabling better dispersion control.

The authors thank Micheal Borland, Jim Welch, Mark Woodley and Feng Zhou for fruitful discussions. This work has been supported by DOE contract #DE-AC02-76SF00515.

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