ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB220

MULTIBUNCH STUDIES FOR LCLS-II HIGH ENERGY UPGRADE*

R. J. England†, K. L. F. Bane, Z. Li, T. Raubenheimer, M. Woodley
SLAC National Accelerator Laboratory, CA, USA
M. Borland, Argonne National Laboratory, Lemont, IL, USA
A. Lunin, Fermi National Accelerator Laboratory, Batavia, IL, USA

Abstract

The Linac Coherent Light Source (LCLS) X-ray free electron laser at SLAC is being upgraded to LCLS-II with a superconducting linac and 1 MHz bunch repetition rate. The proposed high-energy upgrade (LCLS-II-HE) will increase the beam energy from 4 to 8 GeV, extending the reach of accessible X-ray photon energies. With the increased repetition rate and longer linac of LCLS-II-HE, multi-bunch effects are of greater concern. We use recently introduced capabilities in the beam transport code ELEGANT to study dipole and monopole beam breakup effects for LCLS-II HE beam parameters. The results indicate that resonant dipole kicks have steady-state settle times on the order of 500 bunches or less and appear manageable. We also consider statistical variation of the cavity frequencies and transverse offsets of cavities and quadrupoles. Resonant emittance growth driven by monopole kicks is found to be disrupted by frequency variation between cavities.

INTRODUCTION

With the proposed high-energy upgrade of the LCLS-II free electron laser at SLAC to LCLS-II-HE, the superconducting linac will be extended by an additional 27 cryomodules, for a total of 56 cryomodules and 448 individual cavities, as shown in Fig. 1.

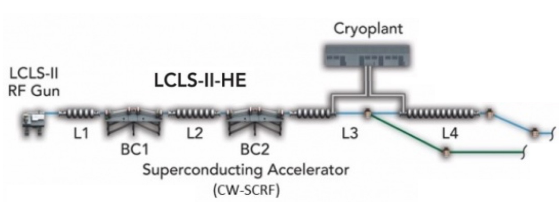

Figure 1: Schematic of the proposed LCLS-II-HE superconducting linac (not to scale).

With the increased length and high repetition rate (1 MHz) of the accelerator, buildup of bunch-to-bunch wake effects, including transient and steady-state bunch displacements and emittance dilution, are a potential concern. In the present investigation, we use a combination of simulated higher-order-modes (HOM) of the superconducting cavities and particle tracking using using the recently introduced multibunch mode in ELEGANT to simulate the transient bunch-to-bunch effects on a train of microbunches under nominal operating conditions with 100 pC bunch charge. The beam lattice (including number and positions of cavities) is based off of the canonical LCLS-II-HE configuration from July 2020 by M. Woodley.

HOM EVALUATION

The higher order modes (HOMs) of the 1.3 GHz LCLS-II superconducting cavity were simulated in ACE3P to yield anticipated values for the mode frequencies and transverse impedances [1, 2]. We include in our calculations a total of 129 modes up to dipole order with frequencies up to 2.7 GHz, just below the beam pipe cutoff of 2.94 GHz. Dipole modes above this frequency are not anticipated to contribute to resonant multibunch effects since they will escape from the cavity on a time scale that is short compared to the 1 µs bunch-to-bunch interval. The eigenmode simulation uses the canonical LCLS-II cavity design (including HOM couplers). Variation was then incorporated by inclusion of statistically distributed offsets of the mode parameters in subsequent particle tracking simulations, as discussed below.

Dipole modes were classified as either x or y modes and their transverse shunt impedances calculated separately. These are shown as separate points (blue and grey respectively) on the plot in Fig. 2. Azimuthally rotated dipole modes are not considered in our analysis, although they can arise due to cavity machining errors and asymmetries in the HOM coupler design. The modes are enumerated by n in order of increasing mode frequency f_n.

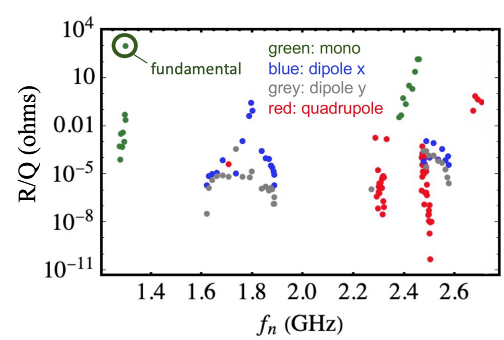

Figure 2: The plot shows simulated transverse R/Q for dipole modes and longitudinal R/Q for monopole modes of the LCLS-II superconducting 1.3 GHz cavity.

BENCHMARK

Bunch-to-bunch effects were evaluated using multibunch mode in the particle tracking code ELEGANT [3, 4]. To benchmark the tracking method, we first compared the transverse offsets of the bunches against the analytical formulation of Refs. [5, 6] for the simplified case of a single linac section

* Work supported by DOE Contract No. DE-AC02-76SF00515.
† england@slac.stanford.edu

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB220

(L4) consisting of 27 cryomodules (or 216 cavities). The analytical form is derived from the beam breakup (BBU) equation for transverse offset of the beam $\delta X(\sigma, \xi)$ relative to the betatron orbit as a function of relative position ξ within the bunch train and normalized distance along the linac $\sigma = z/\mathscr{L}$ where $\mathscr{L}$ is the total linac length. We employ the (approximate) coasting beam solution for a beam of periodic bunches of equal charge with uniform bunch shape:

$$\delta X(\sigma, \xi) \simeq X_0 \frac{\epsilon\sigma}{2\kappa} \sin(\kappa\sigma) h_1(\xi), \tag{1}$$

where X_0 is the initial offset at the linac entrance, ϵ is a dimensionless wake coupling factor, κ is the betatron focusing, and $h_1(\xi)$ is the lowest order term in a Fourier expansion of the bunch form factor and dipole wake function [6]. The comparison with the tracking code is shown in Fig. 3 for the two dominant dipole modes in x and y respectively. The corresponding mode parameters are shown in Table 1. We find that the particle tracking data (dots) overlap nearly exactly with the analytical curve (solid lines).

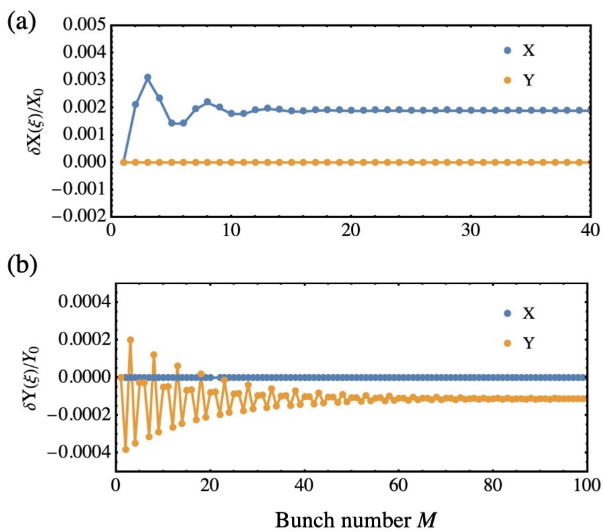

Figure 3: Comparison of ELEGANT tracking results (dots) against analytical solution (solid lines) of the BBU equation for linac section L4 for (a) x and (b) y dipole modes with the largest transverse R/Q. Mode parameters are shown in Table 1.

Table 1: Mode Parameters for Fig. 3

Parameter	Unit	X Value	Y Value
f_n	GHz	2.5772	1.7346
n	-	125	23
$R_\perp$	MΩ	2.36	10.98
ϵ	–	4.17×10^{-6}	4.06×10^{-6}
$\omega\tau$	–	5154.4 π	3469.2 π
κ	–	2.20 π	2.15 π
Q	–	29168	93635
w_0	V/C/m^2	2.32×10^{13}	1.52×10^{13}

The analytical formulation was further used to classify the BBU domains and growth rates for all of the dipole modes represented in Fig. 2. The modes were found to generally lie in Domain B of the classification scheme by Lau [7]. Dipole modes with resonances lying within 0.35% of the mode frequency were examined. The threshold of 0.35% was chosen as an upper limit based on maximum variation observed in measured data of the LCLS-II superconducting cavity mode frequencies. Of this subset of modes, those with the highest growth rates were predicted to reach steady-state within less than 2000 bunches and with fractional bunch displacements of less than one part in 10^6.

MULTIBUNCH TRACKING RESULTS

The calculations of the prior section were conducted over a single linac section (L4 of Fig. 1) with 100 pC of charge per bunch. Since L4 accounts for approximately half of the active length of the LCLS-II-HE linac, these results should provide some reasonable indication of the HOM behavior. To evaluate the dynamics over the full linac, we utilized ELEGANT in multibunch mode with the dipole and monopole long-range kicks delivered at the center of each cavity within the cryomodules. Misalignments were included by adding transverse offsets to each cryomodule (CM) based on available metrology data for existing LCLS-II (CMs 4-33) and then replicating these statistics with a normal distribution over the remaining (CMs 34-56) with standard deviation of 52 µm in x and 65 µm in y. For the canonical beam orbit, this produces of order 0.5 mm net offset of all bunches in x and 0.2 mm offset in y across the entire linac (up to exit of L4), as shown in Fig. 4(a). The transient contribution to the bunch offsets due to the dipole modes as a function of bunch number, shown in Fig. 4(b) indicates some oscillation in x, which dies down to steady state offset of less than 1 µm within 200 bunches and 0.2 µm in y. Additional inclusion of the laser heater (LH) and short-range (SR) wakes in the simulation shown in Fig. 4(c) shows only minor additional perturbation.

Frequency errors were included by statistically varying the HOM frequencies between cavities with a standard deviation of 0.35% consistent with the maximum frequency variation from measured LCLS-II cavity data. For the dipole modes, the frequency variation was found to produce less than 1% variation in transverse offsets and emittance in both coordinates. Monopole modes were found to couple strongly to the cryomodule misalignments, resulting in a runaway emittance growth (of order 0.1 mm-mrad over 500 bunches) that did not appear to saturate with additional bunches, as seen in Fig. 5(a). This emittance growth was found to be dominated by coupling of the fundamental (1.3 GHz) monopole energy kicks to the transverse CM offsets. However, the resonant coupling is disrupted by addition of random frequency errors between cavities, as shown in Fig. 5(b), reducing it to a random fluctuation of less than 1 nm-rad variation. Note that the emittance changes $\Delta\epsilon_{x,y}$ shown in Fig. 5 are expressed

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB220

relative to the single-bunch emittances in the absence of HOMs.

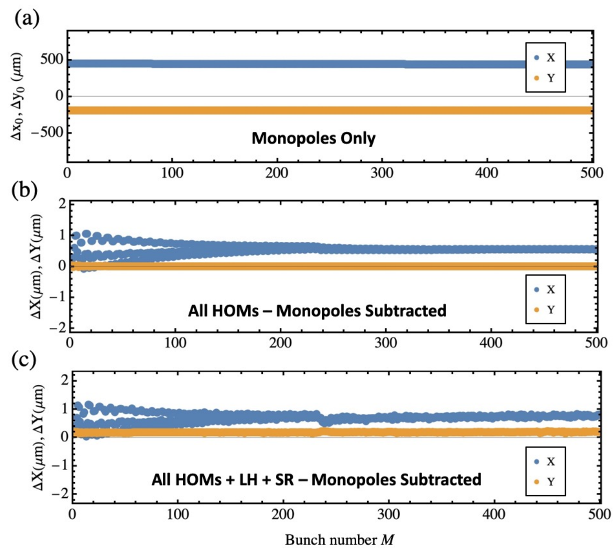

Figure 4: Particle tracking simulation of transverse displacements vs. bunch number M with cavity alignment errors, showing effects of (a) monopole modes only, (b) dipoles only, and (c) dipoles with laser heater (LH) and short-range (SR) wakes included .

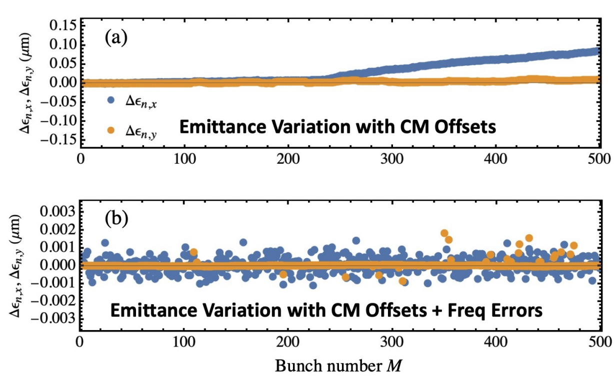

Figure 5: Particle tracking simulation of emittance growth vs. bunch number M with (a) cryomodule (CM) misalignments and (b) both CM offets and cavity frequency errors included.

We additionally considered the single-bunch tolerances for quadrupole misalignment on the LCLS-II-HE beamline. To assess this, an ensemble of beam orbits was considered with random variation of the quadrupole transverse offsets (x, y, and skew). Offsets between these three coordinates were randomized for a given quadrupole but with equal RMS for all three (in units of µm for x, y and µrad for skew). The predicted emittance growth is shown in Fig. 6. The error bars at each value represent the RMS variation of the ensemble at each tolerance level on the horizontal axis. The shaded region is bounded by quadratic fits to the upper and lower error bars. The results suggest that quadrupole alignment tolerances should be kept within $\pm 50\,\mu$m to prevent emittance growth of more than 0.1 mm-mrad.

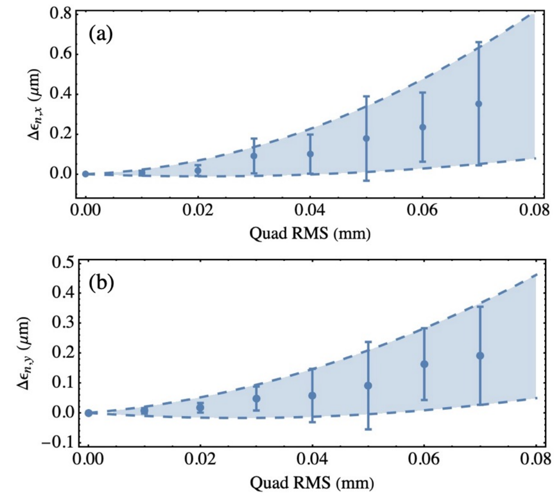

Figure 6: Normalized transverse emittances (a) in x and (b) in y with variation of quadrupole alignment errors.

CONCLUSION

We have utilized the particle tracking code ELEGANT combined with analytical calculations to evaluate multi-bunch effects from HOM modes of the 1.3 GHz cavities in the LCLS-II-HE beamline. The results indicate minimal beam disruption, with small transverse bunch displacements and short (less than 500 bunch) transient times. Resonant monopole kicks appear to produce a runaway emittance growth when coupled with cavity misalignments. However, addition of realistic cavity frequency errors appears to disrupt and mitigate the resonant coupling.

ACKNOWLEDGEMENTS

This work was supported by U.S. Dept. of Energy Contract No. DE-AC02-76SF00515.

REFERENCES

[1] K. L. F. Bane, C. Adolphsen, A. Chao, and Z. Li, "A Study of Resonant Excitation of Longitudinal HOMs in the Cryomodules of LCLS-II", in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper THPB007, pp. 1073–1077.

[2] A. Sukhanov *et al.*, "Resonant excitation of high order modes in superconducting RF cavities of LCLS II linac", SLAC, Menlo Park, CA, USA, Rep. LCLS-II-TN-15-06, Feb. 2015.

[3] M. Borland, "ELEGANT: A flexible SDDS-compliant code for accelerator simulation", Argonne National Lab., Lemont, IL, USA, Rep. LS-287, Aug. 2000.

[4] M. Borland, R. R. Lindberg, and A. Xiao, "Improvements in Modeling of Collective Effects in ELEGANT", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 549–552. doi:10.18429/JACoW-IPAC2015-MOPMA009

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB220

[5] J. R. Delayen, "Cumulative beam breakup in linear accelerators with time-dependent parameters", *Phys. Rev. ST Accel. Beams*, vol. 8, p. 024402, 2005. doi:10.1103/PhysRevSTAB.8.024402

[6] J. R. Delayen, "Cumulative beam breakup in linear accelerators with arbitrary beam current profile", *Phys. Rev. ST Accel. Beams*, vol. 6, p. 084402, 2003. doi:10.1103/PhysRevSTAB.6.084402

[7] Y. Y. Lau, "Classification of beam breakup instabilities in linear accelerators", *Phys. Rev. Lett.*, vol. 63, no. 11, p. 1141, 1989. doi:10.1103/PhysRevLett.63.1141