LCLS-II INJECTOR PHYSICS DESIGN AND BEAM TUNING*

F. Zhou†, D. H. Dowell, P. Emma, J. Schmerge, SLAC, Menlo Park, USA
C. Mitchell, F. Sannibale, LBNL, Berkeley, USA

Abstract

LCLS-II CW injector consists of a 186 MHz NC RF gun, two solenoids, two BPMs, 1.3 GHz NC RF buncher and 1.3 GHz SC standard 8-cavity cryomodule to boost the beam energy >95 MeV, and 5 pairs of steering correctors. In this paper, we describe the injector physics design including the beam performance with imperfections. The beam tuning procedure is developed with the correctors, two BPMs, and a beam screen. The beam-based calibrations for the phase/amplitude of the gun/buncher and alignments for the key components with the existing diagnostics are presented.

INTRODUCTION

LCLS-II currently under construction at SLAC National Accelerator Laboratory is a continuous wave (CW) x-ray free electron laser (FEL) user facility driven by a 4 GeV superconducting (SC) linac. To meet with the x-ray FEL requirements, the LCLS-II injector must simultaneously deliver high repetition rate up to 1 MHz and high brightness electron beam with normalized emittance of <0.4 μm at nominal 100 pC/bunch and peak current of 12 A (at ~100 MeV). The major beam requirements for LCLS-II injector are summarized, as presented in Table 1.

Table 1: Major LCLS-II Injector Beam Requirements

Parameter	Nominal
Gun energy (keV)	750
Electron energy (MeV)	~100
Bunch repetition rate (MHz)	0.62
Bunch charge (pC)	100
Peak current (A)	12
Slice emittance (μm)	0.4

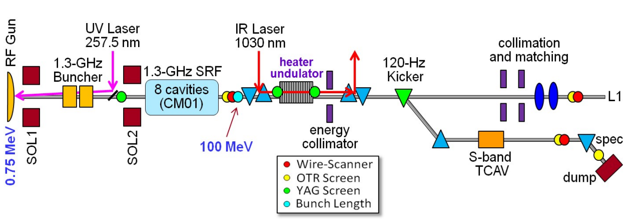

Figure 1: Schematic of the full LCLS-II injector.

Figure 1 shows the schematic layout of the full LCLS-II injector, consisting of a CW RF gun operating at 186 MHz, two solenoids, two BPMs, a YAG screen, a 1.3-GHz 2-cell normal-conducting RF buncher for bunch compression, beam current diagnostic ICT, a standard 1.3-GHz SRF 8-cavity cryomodule (CM) to boost the energy to 100 MeV, laser heater for suppression of micro-bunching instability, beam collimation systems, and a dedicated off-axis diagnostic section. First, this paper discusses the beam dynamics studies with inclusion of various errors. Then the beam tuning including the beam-based RF calibrations and alignments is presented.

BEAM PERFORMANCE WITH ERRORS

The injector front beamline (from cathode to CM entrance) has been extensively optimized since the conceptual design report of the LCLS-II project. A few changes are made including increasing distance between the gun and CM to accommodate essential components, moving the 1st solenoid closer to cathode to reduce emittance and increasing the physical aperture of the beamline to avoid the beam loss. After the significant optimizations, the final projected emittance at 95 MeV is ~0.3 μm, close to the input thermal emittance contribution, 0.23 μm for 100 pC. Following subsections are to discuss the imperfection effects with more practical laser temporal profile, RF coupler effect, possible failure of superconducting cavities, and misalignments. The low level RF requirements for the injector are also defined.

Corrected Emittance with RF couplers

A standard 8-cavity CM is used to increase the electron beam energy to ~100 MeV from <1 MeV. The strong asymmetrical field from RF couplers located at the low energy of <1 MeV significantly increases the emittance for larger-size beams. Figure 2 shows the RF coupler induced emittance growth (green) in comparison to the perfect RF field (blue) for 300 pC. The results indicate ~20% emittance growth due to the RF couplers is expected from the simulations.

The kicks of quadrupole fields induced by the RF couplers can be expressed by coupling term in x and y planes, which causes the notable emittance growth. The kicks of coupled term can be corrected with a skewed quadrupole [1]. With proper skew quadrupole setting, the RF coupler induced quadrupole terms can be cancelled. As shown in Fig. 2 (red) the RF coupler induced emittance growth is completely corrected with a very weak skew quadrupole (integrated strength 3 G and 10° of rotation angle). This method using quadrupole correction allows for adjustable corrections compared to traditional RF coupler correction with absorbers, or cavity coupler cell deformations and/or penetration to cancel quad terms.

*The work is supported by DOE under grant No. DE-AC02-76SF00515.
+ zhoufeng@slac.stanford.edu

ISBN 978-3-95450-182-3

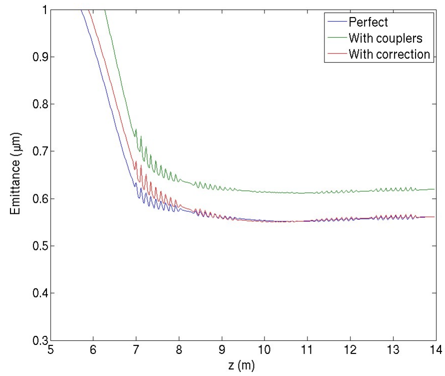

Figure 2: LCLS-II injector emittance with perfect RF field, with RF couplers field and correction using a quadrupole for 300 pC [1].

Beam Performance with Cavity Failure

For the nominal settings, the first cavity (Cav1) in the CM has to be turned on with half nominal gradient, 8 MV/m for beam matching from the <1 MeV to high energy; the second and third cavity (Cav2 and Cav3) are to be turned off for emittance compensation while all other 5 cavities operate at the nominal gradient (16 MV/m).

The beam performance is simulated with one cavity failure (e.g., Cav1, or Cav4, or Cav5) for nominal 100 pC, as given in Table 2. For the worst case with the Cav1 failure, the emittance at 100 pC is increased by a factor of 2 with a lower peak current, in comparison to the nominal case. For such case, the beam performance may still be useful for soft x-ray FEL operation. For the case of cav4 or cav5 failure, the emittance is still good enough for FEL operation.

Table 2: Beam Performance with Cavity Failure

	Nominal	**Cav1 failure**	**Cav4 failure**	**Cav5 failure**
Cav1	7.9/-4°	0	7.9/-4°	7.9/-4°
Cav2	0	7.1/-8°	0	0
Cav3	0	0	16/0°	16/0°
Cav4	14/0°	15/-4°	0	15/0°
Cav5	16/0°	16/0°	16/0°	0
Cav6	16/0°	16/0°	16/0°	16/0°
Cav7	16/1°	16/0°	16/1°	16/1°
Cav8	16/6°	16/13°	16/6°	16/6°
ε (μm)	0.29	0.54	0.4	0.39
I (A)	12	7.5	12	12
E (MeV)	94	94	96	95

Beam Performance with Modulated Laser

Ultra-small emittance requires photocathode drive laser about 30 ps flattop with <2 ps of rise/fall time. Initial ~1 ps (i.e., ~1 ps modulation period) laser pulses have to be stacked to get ~30 ps in total with sharp rise/fall time. Simulation shows the injector emittance growth is negligible with ±10% of laser intensity modulation on the flattop. But, we found the temporal modulation severely impacts longitudinal beam performance through the whole machine. Figure 3 [2] shows the density modulation at the hard x-ray undulator entrance as function of the initial period of the laser modulation on the cathode with the fixed modulation amplitude of ±5%. As a measure of microbunching, the relative rms current fluctuation over the beam core, defined as [-10, 10] μm, is estimated after removing the correlations, $\sigma_{\Delta I}/<I_{fit}>$, where $\Delta I = I - I_{fit}$, I_{fit} is the current profile of the unmodulated beam. The data shows with >4 ps of the modulation period, the strong microbunching at the undulator has been observed from the simulation. The initial laser modulation period on the cathode has to be controlled <2 ps with ±5% of modulation amplitude for the suppression of the microbunching.

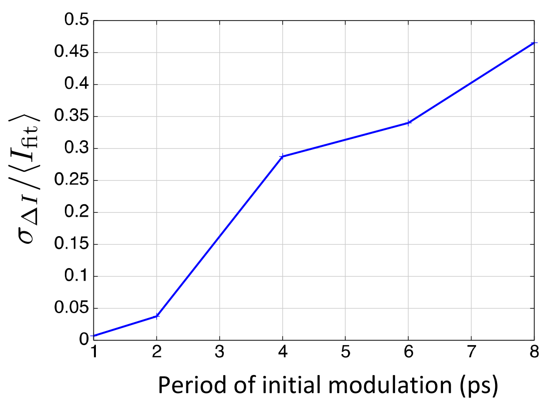

Figure 3: density modulation at the undulator entrance vs. photocathode laser modulation period with fixed ±5% of amplitude change [2].

Misalignment Requirements

At such low energy, notable misalignment can cause emittance growth. Also the misalignments of the components can cause beam steering for emittance optimization with scanning solenoid strength. It is required to align the components to a reasonable value. Table 3 shows the simulated beam effects with the misalignment.

Table 3: Misalignment Requirements

	Misalignment	**ε-growth**
Cathode	100 μm	<2%
Solenoids	0.5 mm or 2 mrad	<2.5%
Buncher	1mm or 2 mrad	<3%
CM01	0.5 mm or 0.5 mrad	<1%

LLRF Requirements

The Injector RF jitter requirement is simulated with ASTRA code, as given in Table 4. Note individual arrival time change is calculated at the 95 MeV injector exit with perturbation of one RF component assuming all other RF components are perfect. For example, with 80 fs of laser timing change, the resulting arrival time changes about 48 fs at 95 MeV, given all other components are perfect. Assume individual jitter contribution is not correlated, the total arrival time change is the square root of the sum of quadrature of the individual jitter contribution. With these RF jitters for the components, total beam arrival time at 95 MeV injector varies by about 90 fs, which is compressed down to <1 fs after ~100 times of bunch compression at 4 GeV.

Table 4: LLRF Stability Requirements

	RF jitter	Arrival time change (fs)
Laser timing	80 fs	48
Gun phase	0.04°	32
Gun amplitude	0.01%	45
Buncher phase	0.015°	43
Buncher amplitude	0.03%	12
Cav1 phase	0.05°	20
Cav1 amplitude	0.03%	17
Total arrival time change at 100 MeV	-	90

BEAM TUNING SIMULATION

Laser Phase Calibration

The LCLS-II gun phase with respect to (w.r.t) RF reference is fixed, but the laser launch phase w.r.t. rf reference is adjustable. The laser zero-crossing phase w.r.t. RF reference is determined via measuring the bunch charge vs. laser phase. When the charge production starts to extinguish, the corresponding laser phase is determined to zero-crossing. The desired laser phase can be set with an offset to the zero-crossing phase.

Buncher Phase Calibration

The net energy gain from the RF buncher is negligible when the buncher phase sits at zero-crossing. The measured beam energy with gun only is thus ideally the same as the one with gun combined with buncher sitting at zero-crossing phases. The zero-crossing phases can be therefore determined. Further simulations show that the transverse beam size with the buncher at the zero-crossing phase for bunching is about twice the one for debunching. The desired zero-crossing phase for the bunching is thus determined.

Gun & Bunch Amplitude Calibration

Gun and buncher RF amplitudes can be calibrated with the measured electron beam energy. The beam energy is measured via measuring the beam displacement vs. one corrector strength. Thus the RF amplitude for gun and buncher can be respectively calibrated.

Cathode Alignment

As only central portion of cathode plug is photo emissive for charge production, the cathode centre can be determined with the QE mapping. The laser mirror settings, for the QE boundary of the central area in both x- and y-plane, are then determined with the QE mapping. The mirror setting for cathode centre can be therefore determined.

Solenoid Alignment

Given the initial offsets x_0, y_0, x_0', and y_0' between the solenoid and the beam, the transverse beam displacements in x- and y-plane at the downstream BPM are calculated by the following equations through manipulation of the transfer matrix for a solenoid and a drift:

$$\begin{aligned} x - x_{ref} &= \left(c^2 - dksc\right)x_0 + \left(sc/k + dc^2\right)x_0' \\ &\quad + \left(sc - dks^2\right)y_0 + \left(s^2/k + dsc\right)y_0' \\ y - y_{ref} &= \left(-sc + dks^2\right)x_0 + \left(-s^2/k - dsc\right)x_0' \\ &\quad + \left(c^2 - dksc\right)y_0 + \left(sc/k + dc^2\right)y_0' \end{aligned}$$

where $c=\cos(kL)$, $s=\sin(kL)$, $kL=BL/(2B\rho)$ and $k=B/(2B\rho)$ for solenoid, and d is the distance between SOL1 exit and BPM, $B\rho$ the beam rigidity. We can directly solve the solenoid misalignments x_0, y_0, x_0', and y_0' given we have >3 measurements for x/y with different solenoid strength settings.

Buncher Alignment

First, turn on the buncher and record the beam position at YAG screen, x_{on}. Then, turn off the buncher, and record the beam position again at YAG screen x_{off}. Figure 4 shows the difference between x_{on} and x_{off} at the YAG screen vs. buncher offset. According to the YAG screen resolution, alignment within 40 µm for the buncher can be achieved.

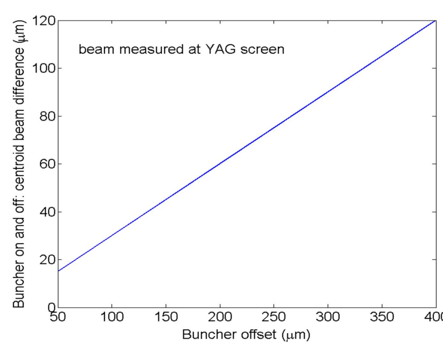

Figure 4: Transverse beam displacement difference between buncher on/off vs. buncher offset.

SUMMARY

LCLS-II injector physics design with imperfections (rf coupler effect, practical laser profile, cavity failure, misalignment and rf jitter) and beam tuning (beam-based rf calibrations and alignments) are presented.

ISBN 978-3-95450-182-3

REFERENCES

[1] F. Zhou *et al*., "LCLS-II Injector Beamline Optimizations and RF Coupler Correction", 2015 Int. FEL Conference. http://accelconf.web.cern.ch/AccelConf/FEL2015/papers/mop021.pdf

[2] C. Mitchell *et al*., "sensitivity of the microbunching instability to irregularities in cathode current in the LCLS-II beam delivery system", in proceedings NA-PAC2016, Oct 9-14, Chicago, IL (2016).