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LCLS-II INJECTOR BEAMLINE DESIGN AND RF COUPLER CORRECTION*

F. Zhou,** D. H. Dowell, R.K. Li, T. O. Raubenheimer, and J. F. Schmerge,
SLAC National Accelerator Laboratory, Stanford, CA 94309, USA
C. Mitchell, C. Papadopoulos, F. Sannibale, LBNL, Berkeley, CA 94720, USA
A. Vivoli, FNAL, Batavia, IL 60510, USA

Abstract

LCLS-II CW injector beamline consists of a 186 MHz normal conducting (NC) RF gun for beam generation and acceleration to 750 keV, two solenoids for the beam focusing, two BPMs, 1.3 GHz NC RF buncher for bunch compression down to 3-4 ps rms, 1.3 GHz superconducting standard 8-cavity cryomodule to boost beam energy to about 98 MeV. The beamline is being optimized to accommodate all essential components and maximize beam quality. The beamline layouts and beam dynamics are presented and compared. The 3D RF field perturbation due to cavity couplers where the beam energy is very low (<1 MeV) causes significant emittance growth especially for a large-size beam. A theory of rotated fields predicted and simulations verified using a weak skew quadrupole located even a significant distance from the perturbation can completely eliminate the emittance growth. A layout for future upgrade is developed. The results are presented and analysed.

INTRODUCTION

LCLS-II [1] 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 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 12 A [2-3]. The major beam requirements for LCLS-II injector are summarized, as presented in Table 1.

Table 1: Major LCLS-II Injector Beam Requirements

Parameters	Nominal
RF gun energy (keV)	750
Electron energy (MeV)	98
Bunch repetition rate (MHz)	0.62 (0.93 max)
Nominal/max bunch charge (pC)	100/300
Peak current for 100/300 pC (A)	12/30
Nominal average current (mA)	0.062
Slice emittance for 100/300 pC (µm)	0.4/0.6
Bunch length for 100/300 pC (mm)	1/1.4
Slice energy spread 100/300 pC (keV)	1/5
Cathode QE lifetime	0.5%
Dark current (nA)	<400

The proposed full LCLS-II CW injector consists of a CW RF gun operating at 186 MHz (7^{th} sub-harmonic of 1.3 GHz for superconducting linac) for beam generation and acceleration, two solenoids for the beam focusing and emittance compensation, two BPMs for measurements of beam positions and bunch charge, 1.3 GHz 2-cell RF buncher for the bunch compression down to 3-4 ps rms from 10-15 ps rms, beam current diagnostic ICT, a standard 1.3 GHz superconducting 8-cavity cryomodule (CM) to boost beam energy from <1 MeV to 98 MeV, laser heater for suppression of micro-bunching instability, beam collimation systems and a dedicated diagnostic section. Figure 1 shows the schematic layout of the full LCLS-II injector. As the electron beam emittance and bunch length have been frozen at the CM end, the interest of this paper only focuses on the front part of the injector from the cathode to the CM end. This paper only discusses the beam dynamics issues. Technical details of the CW RF gun and cathode/laser performance are described elsewhere [4-5].

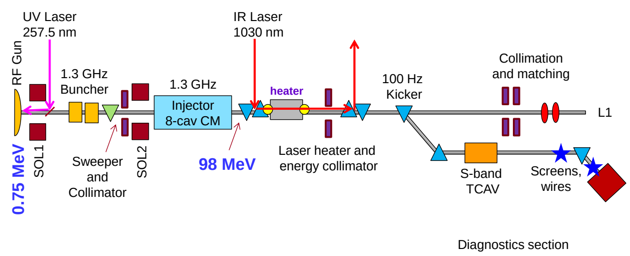

Figure 1: Schematic of the full LCLS-II injector. The front part of the injector discussed in this paper starts from the cathode to the CM end; downstream of the CM includes laser heater system, collimation systems and a dedicated beam diagnostics beamline.

INJECTOR BEAMLINE DEVELOPMENTS

The injector front beamline (called injector for simplification) is being optimized since the conceptual design report (CDR) of the LCLS-II project launched in summer 2013. The LCLS-II injector beamline is required:

- To accommodate essential beam components and diagnostics, and adapt to the standard 8-cavity CM.
- To maximize electron beam performance in 6-d phase spaces.
- To make large half physical aperture for beam pipe, >4 times rms beam size to avoid the CW electron beam loss.

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For the CDR, the distance from the 2nd solenoid (SOL2) to the 1st cavity (CAV1) of the 8-cavity CM was about 1 m. Although a good emittance of <0.6 µm for 300 pC was achieved from the simulations with the CDR layout, no space was available to accommodate a few essential components such as a 2nd BPM (BPM2) and gate valve. In 2014, a new layout was developed to add about 50 cm between SOL2 and CAV1 for the missing components with a customized reduced endcap for the CM. The emittance was found to increase ~10-15%, to 0.62 µm for 300 pC with the extra 0.5 m of drift-length. Later it was concluded that the CM would need to be modified for shortening the standard CM endcaps. Extra cost and potential construction delays prevented the modification of the CM for shortening the endcap. Thus it was decided the standard CM including endcaps is adopted for the LCLS-II injector source. For that purpose, another 21 cm was added in the distance between SOL2 and CAV1. Particle simulations using Astra code [6] show the emittance increases to 0.67 µm from 0.62 µm for 300 pC with this extra 21 cm. In addition, two pairs of solenoid/BPMs described in the CDR have small physical aperture, 1.4 cm of half aperture, ~2.6 times the rms beam size. According to the simulations, the beam starts to be lost at the 1st solenoid (SOL1) with only a 1 mm transverse offset of laser beam on the cathode. We determined to re-design the layout to reduce the emittance to < 0.6 µm with both added drifts and increase the solenoid/BPM aperture so the ratio of half aperture to rms beam size > 4.

New Baseline Layout Developments

To shorten the distance between the SOL2 and CAV1 and enlarge physical apertures of the solenoids and BPMs, we seek to redesign the solenoid and modify the BPM with large bores and shorter length [7] without compromising the electron beam performance. Table 2 presents the comparisons of the new solenoid/BPM with CDR design. With the new solenoid/BPM the physical apertures increase >50% and the lengths are shortened by 30%-50%. Combination of the new solenoid with the modified BPM saves about 15 cm in length in comparison to previous SOL/BPM. Figure 2 shows the comparison of the longitudinal solenoid field B_z vs. z for the new design and the CDR design. The new solenoid improves emittance, although its field quality factor is similar to the previous one. It is believed the new solenoid improves the emittance compensation process with space charge. Studies also show that moving SOL1 closer to the cathode can reduce the beam size thereby reducing chromaticity induced emittance. The new solenoid structure is compatible with a z-position shift in the cathode direction. After extensive simulations, with the new layout shown in Fig. 3 the emittance significantly improves. The optimized emittance is 0.25 µm and 0.43 µm for 100pC and 300 pC respectively, compared to 0.42 and 0.67 µm respectively for the CDR layout with added drifts ("CDR+71 cm"). The optimized emittance values are already close to the cathode thermal emittance contribution of 0.2 µm and 0.33 µm for 100 pC and 300 pC respectively. In addition, the ratio of the half physical aperture g to the rms beam size σ_x (i.e., g/σ_x) is >4.5 at all locations for 300 pC, compared to 2.6 for the "CDR + 71 cm" case. Table 3 presents the comparisons of the major beam performances for layouts. With the new layout, the slice emittance and longitudinal bunch distribution and higher order nonlinear energy spread at the end of CM are shown in Fig. 4. The slice emittance for 100 pC is <0.25 µm (100% particles) much smaller than 0.4 µm of required value, and the non-linear energy spread is about 6.3 keV rms comparable to previous layouts. The following changes are made compared with the "CDR + 71 cm" layout:

- moved the SOL1 5 cm closer to the cathode and
- moved SOL2 and 5 cm upstream
- reduced the distance between SOL2 and cavity1 about 15 cm
- increased physical apertures of SOL1, SOL2, BPM1, BPM2, and beam pipe for the laser injection area and ICT.

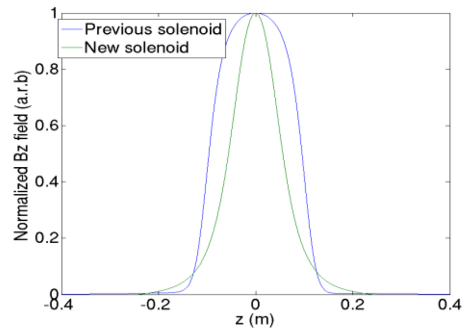

Figure 2: Magnetic field B_z along z for new and CDR solenoids.

Table 2: Comparisons of New and CDR Solenoid/BPM Dimensions for 300 pC

Parameters	CDR layout	New layout
SOL length	28.8 cm	17 cm
SOL: half aperture	1.44 cm	2.35 cm
BPM length	20 cm	15 cm
BPM: half aperture	1.44 cm	2.5 cm

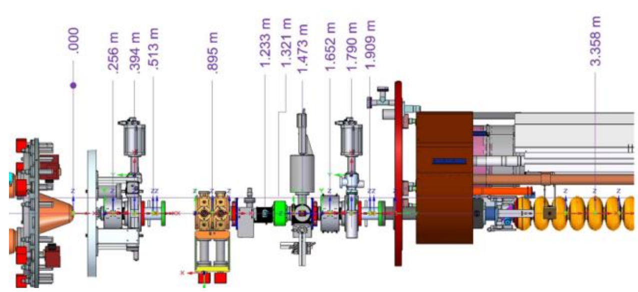

Figure 3: Schematic of new baseline layout from the cathode to CM. Major components are 186 MHz RF gun, two pairs of solenoid/BPM, 1.3 GHz NC RF buncher, ion pump, laser injection box, current diagnostic ICT, YAG screen, two valves, and standard 8-cavity CM.

Table 3: Electron beam performance comparisons (g/σx is the ratio of the half aperture to rms beam size for 300 pC).

Parameters	"CDR + 71 cm"	New layout
g/σx at SOL1	2.6	4.6
g/σx at buncher	6.0	6.6
g/σx at SOL2	4.2	6
Proj. emittance (rms, 100%, μm)	0.67 (for 300 pC)	0.24/0.42 (100/300pC)
Higher order >3 δE (rms, keV)	14 (for 300 pC)	6.3/13.5 (100/300pC)
Peak Current (A)	30 (for 300 pC)	13/30 (100/300pC)

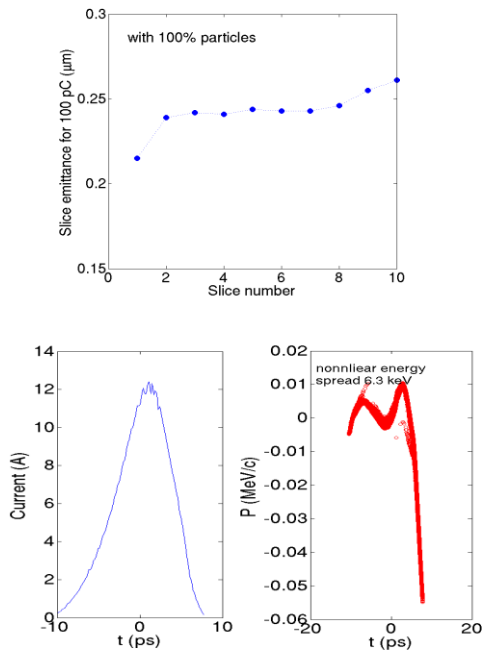

Figure 4: Slice emittance (top); longitudinal beam distribution (bottom left) and higher order energy spectrum (bottom right) at 98 MeV.

The significant emittance improvements with this new layout are mostly contributed by: 1) moving SOL1 closer to the cathode; 2) reduced distance between SOL2 and CAV1; and 3) new solenoid field map. The emittance can be further improved using a spatially truncated Gaussian distribution instead of a current spatially uniform distribution. Note that all beam dynamics simulations presented in this paper are performed using Astra code with 1 μm/mm of thermal emittance, transverse spatially uniform initial distribution and temporal flattop with 2 ps rise/fall time.

Novel Method for RF Coupler Correction

A standard 8-cavity CM is used to boost the electron beam energy to ~98 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 5 shows the RF coupler induced emittance growth (green) in comparison to the perfect RF field (blue) for 300 pC. The results indicate ~40% emittance growth due to the RF couplers is expected from the simulations. The kicks of quadrupole terms induced by RF couplers can be expressed by:

$$\begin{pmatrix} x' \\ y' \end{pmatrix}_{coupler} = \begin{pmatrix} v_{xx}x + v_{xy}y \\ v_{yx}x + v_{yy}y \end{pmatrix}$$

where v_{xx} and v_{xy} are linear terms, and v_{xy} and v_{yx} are coupled terms. The emittance growth is mostly caused by the coupled terms. The kicks of linear and coupled term can be corrected with skew quadrupole [8], which is modeled as:

$$\begin{pmatrix} x' \\ y' \end{pmatrix}_{quad} = \begin{pmatrix} \frac{\cos 2\theta_q}{f_q}x - \frac{\sin 2\theta_q}{f_q}y \\ \frac{\sin 2\theta_q}{f_q}x + \frac{\cos 2\theta_q}{f_q}y \end{pmatrix}$$

where θ_q is the quadrupole rotation angle, f_q is the quadrupole focal length. With proper quadrupole parameters (rotation angle and strength), the RF coupler induced quadrupole terms can be completely cancelled. As shown in Fig. 5 (red) the RF coupler induced emittance growth is completely corrected with a very weak skew quadrupole (integrated strength 3 Gs 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.

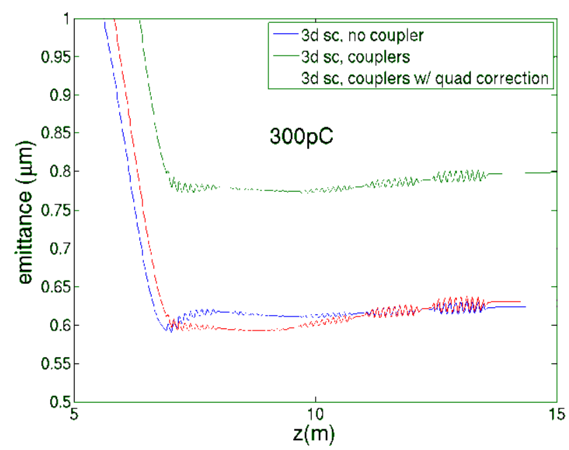

Figure 5: Emittance evolution with perfect RF field (blue), with RF couplers field (green) and correction using a weak skew quadrupole (red) for 300 pC.

Alternate Beamline Development

In the baseline layout we used single standard 8-cavity CM but the 2nd and 3rd cavities are powered off (i.e., ~4.2 m between the first two-powered cavities) for better emittance. It is believed that the drift distance between the CAV1 and next powered cavity improves the emittance compensation process. Further simulations showed that the emittance improves with longer separation between the CAV1 and next powered cavity for 300 pC, as shown in Fig. 6. The optimum emittance is obtained with about 5.5-6 m of the distance between CAV1 and next powered cavity center. In an alternate configuration, we can replace the single standard 8-cavity CM in the baseline layout with two CMs. The first CM (CM1) has only one 9-cell cavity to gain about 10-MeV energy and the second CM is a standard 8-cavity (CM2). As shown in Fig. 7, excluding the space for CM endcaps, about 3.2 m of drift space is available for essential diagnostics including emittance station and energy spectrometer for ~10-MeV 6-d beam phase spaces measurements. The components from the cathode to the CM1 are identical to the new layout (not shown in Fig. 7). The alternate layout may not be adopted for the LCLS-II project due to cost. However, it can be used for future upgrade as it has significant advantages over the baseline layout:

- Emittance is independent of the cavity gradient on the cavities on the CM2. So all cavities of the CM2 can be powered on with at least one cavity as spare.
- The drift between the two injector CMs allows addition of essential diagnostics such as emittance station and energy spectrometer for measurement of 10-MeV beam and cavity alignments.
- Emittance is improved by 5-10% in comparison to the baseline layout.

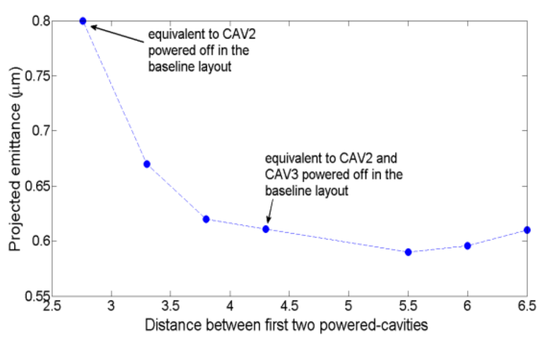

Figure 6: Emittance vs. distance between first two powered-cavities for 300 pC.

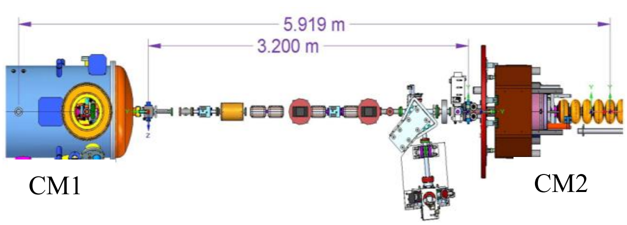

Figure 7: Schematic of the alternate layout (components from cathode to CM1 are identical to Fig. 3). Diagnostics installed in between CM1 and CM2 include the emittance station using slits, collimators, and energy spectrometer.

SUMMARY

LCLS-II injector layout was optimized with significant improvements of emittance and physical apertures. A simple model using a weak skew quadrupole is developed [8] and simulations show the RF couplers effect can be completely cancelled with the skew quadrupole. An alternate layout is also developed with improved emittance and addition of essential diagnostics such as emittance station and energy spectrometer at ~10 MeV.

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** zhoufeng@slac.stanford.edu

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