LCLS-II Injector Tuning Procedures

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1. Introduction

Figure 1 shows <1 MeV LCLS-II injector source, consisting of a 750 keV RF gun, two solenoids, one buncher, one YAG screen, two BPMs, one ICT, five pairs of x/y correctors, and one temporary 300-W beam dump with a faraday cup. It will be commissioned in the first 6 months of calendar year 2018.With the existing diagnostics/devices, the phase/amplitude of RF gun and buncher can be calibrated and beam through the cathode/gun, solenoids, and buncher will be aligned. The <1 MeV beam energy can be measured with either one steering corrector or one solenoid. Following sections are to discuss the calibrations for the phase/amplitude of the gun and buncher, beam-based alignments for the components, and beam energy measurements with the existing devices.

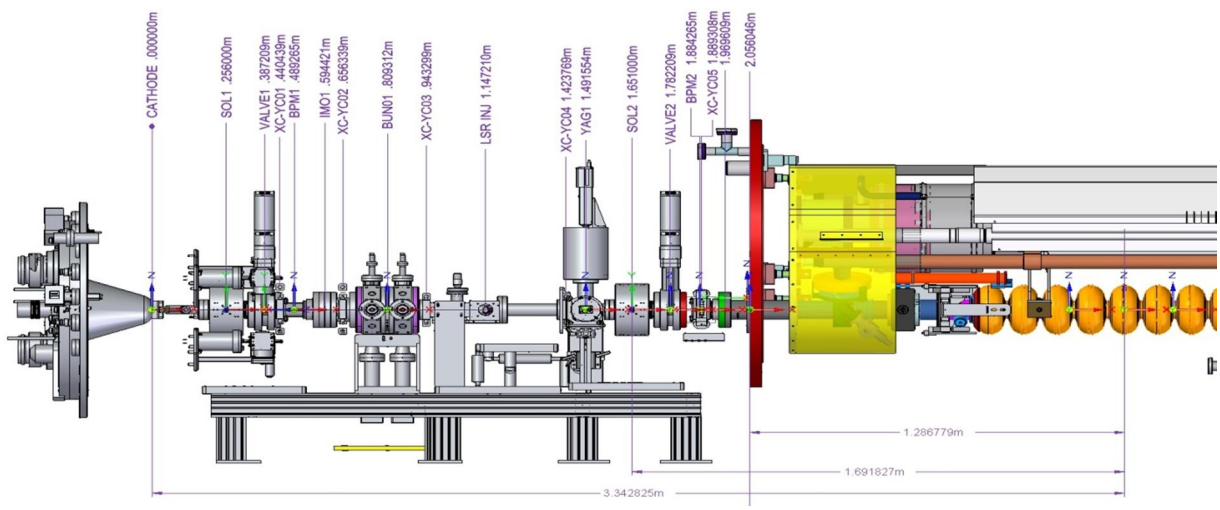

Figure 1: Layout of the LCLS-II injector source (<1MeV). All components and corresponding z-locations are labelled.

2. RF phase calibrations

2.1 Laser launch phase

As LCLS1, the LCLS-II gun phase with respect to (w.r.t.) RF reference is assumed to be fixed, but the laser launch phase w.r.t. RF reference is adjustable. The laser zero-crossing phase w.r.t. RF reference can be determined through measuring the bunch charge vs. laser phase. When the charge production starts to extinguish, the corresponding laser phase is determined to zero-crossing (~-86°) shown in Fig. 2. The desired laser phase can be thus set with an offset to the zero-crossing phase. For nominal operation, the laser phase is near on-crest, i.e., about 86° w.r.t. the zero-crossing phase. The bunch charge is measured at

the ICT or calibrated BPM1/2 located downstream of the first solenoid (SOL1). During the early commissioning, the ICT and the Faraday cup are used for the absolute charge measurement.

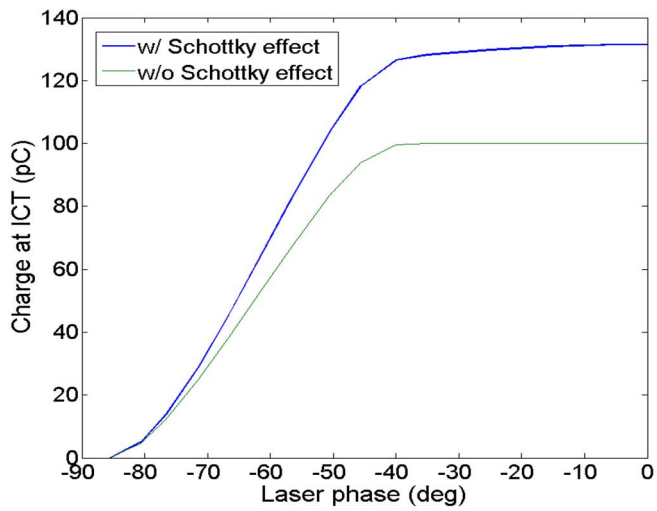

Figure 2: Bunch charge production with (blue) and without (green) Schottky effect vs. laser phase.

2.2 Buncher phase

The net energy gain from the RF buncher is negligible when the buncher phase sits at zero-crossing (nominal buncher phase is near zero-crossing for bunching). 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. For the two zero-crossing phases (90° and -90°) shown in Fig. 3, one phase is for bunching (-90°) while the other for debunching. 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, as shown in Fig. 4. Thus, we can determine the desired zero-crossing phase for the bunching through comparison of the measured beam size at the YAG screen for the two zero-crossing phases. Simulations show that the beam energy at -90° and +90° of the zero-crossing phases shown in Fig. 3 has about +10 keV and -10 keV shift respectively to 755 keV of the kinetic beam energy with the gun only. This energy shift is due to the buncher phase slippage at such low energy. The buncher on-crest phase for maximum energy gain is not at 0°, but at about -3°. As the nominal buncher phase can be chosen near the zero-crossing (-60° – -90°) for bunching the bunch, the ~3° accuracy is not important for beam performance after optimizing the solenoids. The steps for buncher phase determination:

- Measure gun energy only
- Scan the energy with the gun and buncher vs. buncher phase to determine zero-crossing phases
- Determine the zero-crossing phase for bunching through comparison of the beam size at the YAG screen
- For nominal operation, the buncher phase usually sits near zero-crossing phase for bunching (about 0–30° from the zero-crossing for the bunching).

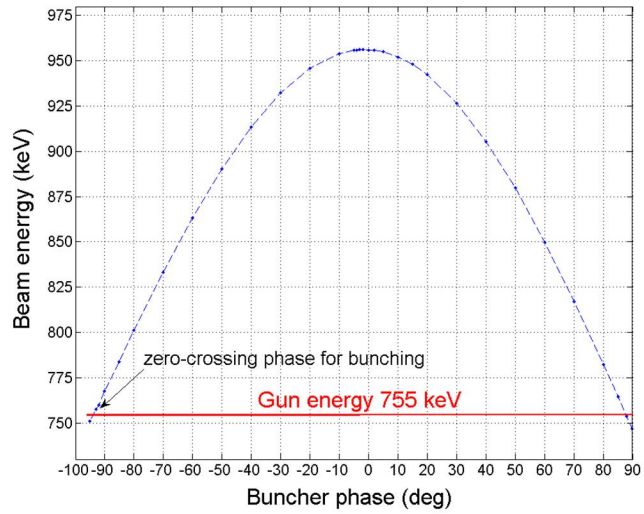

Figure 3: Beam energy (including gun and buncher) with the buncher phase (gun-only energy is 755 keV). The nominal buncher phase can be chosen in between -60° and -90°.

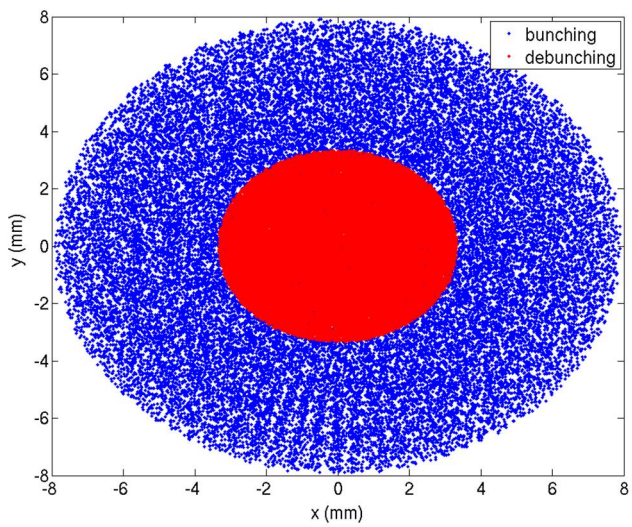

Figure 4: Beam size at the YAG screen with the buncher's phase at zero-crossing for bunching (blue) and debunching (red).

3. RF amplitude calibrations

3.1 Beam energy measurement method

Gun and buncher RF amplitudes can be calibrated with the measured electron beam energy. There are two methods to measure electron beam energy with one existing corrector or solenoid. In this note, only the corrector method is discussed for beam energy measurements.

First, steer beam with a corrector and measure the resulting beam displacement at downstream screen or BPM, then, the slope of the beam displacement in x-plane at the screen or BPM to the corrector strength is measured. The kinetic beam energy can be extracted from the measured slope x/BL:

$$E_k = 0.511 \cdot \left(\sqrt{\left(\frac{d}{33.356 \cdot 0.511 \cdot 10^{-3}} \cdot \frac{1}{\frac{x}{BL(kG.m)}} \right)^2 + 1} - 1 \right) \qquad (1)$$

where d is the distance between the corrector and the screen, BL is the integrated strength of the corrector, x is the beam displacement at the screen, and E_k is the kinetic beam energy in MeV.

3.2 Gun amplitude calibration

First, turn off the buncher and focus the beam at the YAG screen with adjustment for the SOL1; then measure the beam displacement in the x-plane at the YAG screen vs. XC01 strength (i.e., slope). Figure 5 (left) and (right) shows the slope for 750 keV and 760 keV, and difference of the transverse beam displacement between the two energies, respectively. With the measured slope the kinetic beam energy can be extracted using the Eq. 1. Figure 5 (right) shows that the corrector method may resolve ~10 keV energy difference, according to the YAG screen resolution. The gun amplitude calibration procedure is:

- Turn off buncher and adjust SOL1 to focus the beam at the downstream YAG screen (or BPM)
- Scan the beam displacement in the x-plane at the YAG screen (BPM) vs. XC01 strength (slope)
- Use Eq. 1 to extract gun energy with the measured slope
- Calibrate the gun RF amplitude according to the gun energy measurement

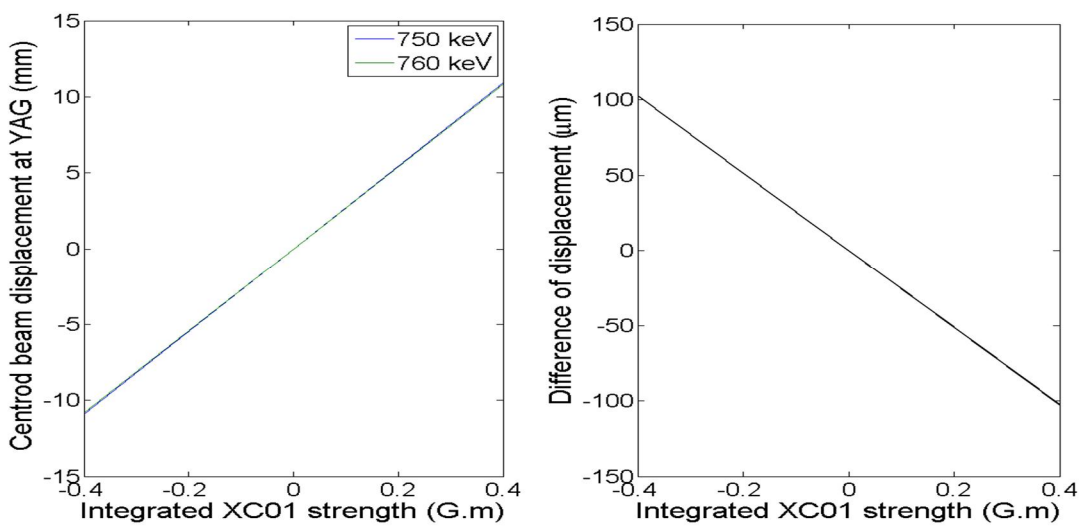

Figure 5: beam displacement at the YAG screen for 750 keV and 760 keV gun energy (left), and difference of the displacement for the two energies (right) to demonstrate the possible resolution.

3.3 Buncher amplitude calibration

First, turn on the buncher and set its phase to on-crest (about 200 keV energy gain) with nominally required RF power (assume RF power has been calibrated offline); then focus the beam at the YAG with adjustment for SOL1 strength. The beam energy with the gun and buncher can be obtained from the measured beam displacement at the YAG vs. the XC03 strength (slope), as shown in Fig. 6. Subtracting 750 keV of the gun energy from the measured gun+buncher energy, the net energy gain from the buncher can be obtained, which can be used for the buncher amplitude calibration. The steps for the buncher amplitude calibration include:

- Measure gun-only energy (see section 3.2)
- Turn on the buncher, set its phase to on-crest with nominal RF power, and focus the beam at the YAG screen with adjustment of the SOL1strength
- Measure beam displacement in x-plane at the YAG screen vs. the XC03 integrated strength (slope), and obtain the beam energy for the gun together with buncher
- Obtain the net energy gain from the buncher-only by subtracting the gun energy from the total
- Calibrate buncher RF amplitude by adjusting the appropriate controls PV

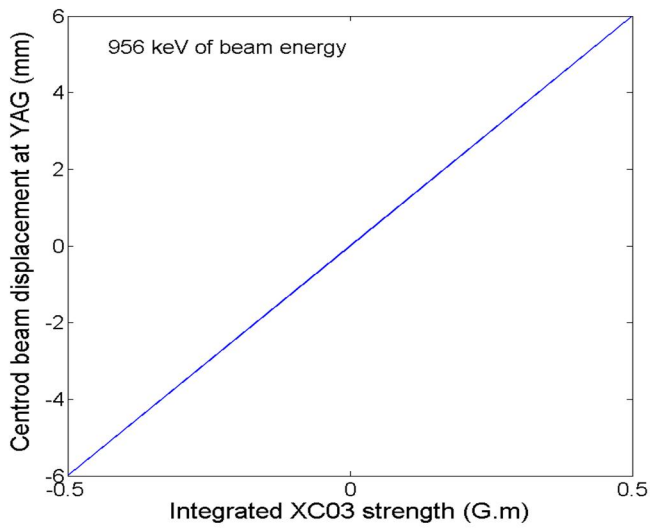

Figure 6: Transverse beam displacement vs. XC03 strength (slope).

4. Beam-based alignments for injector source components

Alignment for the cathode, solenoids, and buncher is essential for the subsequent emittance tuning. The following sub-sections are to describe the beam-based alignments for these crucial components.

4.1 Cathode center

According to the APEX operations, the central 5 mm-diameter area of the cathode is doped with Cs for bunch charge production. The laser steering mirror setting for the QE boundary of the central charge

production area in x- and y-plane can be then determined with subsequent QE mapping. Once the mirror setting for the QE boundary in both planes is measured, the mirror setting for cathode center can be therefore determined. The steps for cathode alignment are:

- Assume cathode plug is well aligned with the gun center within few 10's μm level and Cs is doped on the center 5-mm diameter area
- Map QE through scanning the laser mirror (outside of the laser injection box) in the x-plane, and then record the laser mirror setting for x-plane when the QE starts dropping to zero on both sides of the central area, x_1, x_2
- Set laser mirror in x-plane = $(x_1+x_2)/2$, and map QE through scanning laser mirror in y-plane, and then record the laser mirror in y-plane when the QE starts dropping to zero on both sides of the center area, y_1, y_2
- Laser mirror setting for cathode center $[(x_1+x_2)/2, (y_1+y_2)/2]$

4.2 Solenoids

There are two solenoids in the LCLS-II injector source: SOL1 and SOL2 (see Fig.1). Here, we only describe the alignment for SOL1. The same method can be applied for the alignment of SOL2: i.e., replacing SOL1 and BPM1 with SOL2 and BPM2 respectively.

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 BPM1 are calculated by the following equations through manipulation of the transfer matrix for a solenoid and a drift:

$$\begin{aligned} x - x_{ref} &= \left(c^2 - d\cdot K\cdot s\cdot c\right)x_0 + \left(s\cdot c\cdot 1/K + d\cdot c^2\right)x_0' + \left(s\cdot c - d\cdot K\cdot s^2\right)y_0 + \left(s^2\cdot 1/K + d\cdot s\cdot c\right)y_0' \\ y - y_{ref} &= \left(-s\cdot c + d\cdot K\cdot s^2\right)x_0 + \left(-s^2/K - d\cdot s\cdot c\right)x_0' + \left(c^2 - d\cdot K\cdot s\cdot c\right)y_0 + \left(s\cdot c/K + d\cdot c^2\right)y_0' \end{aligned} \qquad (2)$$

where c=cos(KL), s=sin(KL), KL=BL/(2Bρ) and K=B/(2Bρ) for solenoid, and *d* is the distance between SOL1 exit and BPM1. Considering the practical measurements, each measured beam position x/y has an offset to the reference x_{ref} and y_{ref} in both planes. According to the Eq.2, 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. The steps for SOL1 alignment:

- Record the beam position x/y at the BPM1 for >3 different solenoid strengths
- Solve the solenoid misalignment according to Eq.2
- According to the above step, correct the misalignment through moving the solenoid actuators, and
- check the alignment again with different solenoid strengths and beam position at the BPM1 should not be changed after the corrections with different SOL1 strength

4.3 Buncher

First, set the buncher to debunching zero-crossing phase for beam focusing and elimination of the stray field effect. Then, turn on the SOL1 and adjust its strength to focus the beam at the YAG screen. Record the beam position at YAG screen, x_{on}. Turn off the buncher, and record the beam position at YAG screen again, x_{off}. Figure 9 shows the difference between x_{on} and x_{off} at the YAG screen vs. buncher offset. It shows the difference between x_{on} and x_{off} is about 40 μm for a 150 μm of the buncher offset. For the alignment, XC01/XC02 correctors are used to correct buncher offset in the buncher until the difference (absolute value) between x_{on} and x_{off} is <40 μm. The steps to align buncher include:

- Turn on the buncher and set its phase to debunching zero-crossing
- Turn on SOL1 and adjust its strength to focus the beam at the YAG screen, and record the beam position at the screen, x_{on}
- Turn off the buncher and record the beam position at the YAG screen, x_{off}
- Calculate the difference between x_{on} and x_{off}, and use the XC01/XC02 to correct the buncher offset until the difference is <40 μm.
- Same method is used for y-offset correction

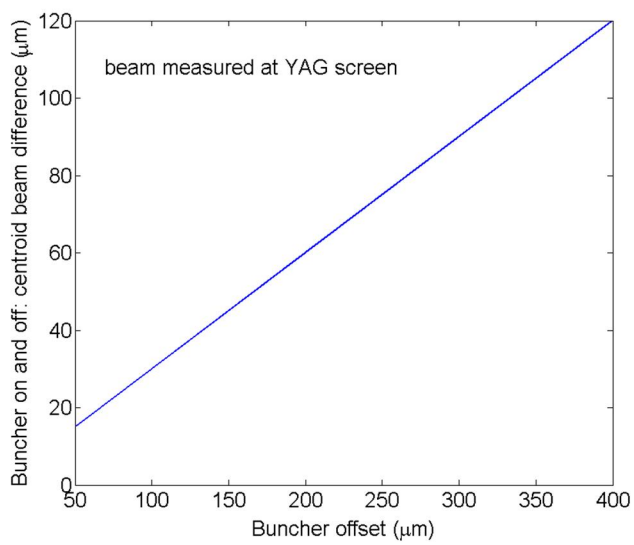

Figure 9: Transverse beam displacement difference between buncher on/off vs. buncher offset.