SIMULATIONS FOR THE LCLS INJECTOR

C.Limborg-Deprey*, D.H. Dowell, P.Emma, R.Iverson, J.Frisch, H.Loos, J.Turner, J.Schmerge, J.Welch, J.Wu, Y.Ding, Z.Huang, J.Castro, G.Hays, P.Hering, S.Gilevich, A Miahnahri, W.White
SLAC#, MS 18, SLAC 2575 Sand Hill Road, Menlo Park, CA , U.S.A.

Abstract

The Linac Coherent Light Source (LCLS) Injector has now been commissioned for five months. Measurements made at the end of the Injector beamline show that the beam quality meets the specifications. The transverse projected emittances at 135MeV are in the range of 1.2 mm-mrad for 1nC/100A and the horizontal slice emittances are below 1 mm-mrad. In this paper, we discuss the validity of both emittance and bunch length measurements by comparing them with results from simulations made with a multi-particle tracking code.

INTRODUCTION

The LCLS Injector commissioning started on April 5th 2007 after several years of design, manufacturing and installation. After a few months of commissioning, the beam quality at 135 MeV reached design performances with projected emittances varying from 1 to 1.5 mm-mrad at 1nC and peak current of 100A [1] .

A bunch charge of 1nC charge was obtained after “passive” and “active” laser cleaning were done. “Passive” cleaning is done at nominal laser fluence while operating. In particular, when the laser radius was decreased from 1.0 to 0.7 mm, to minimize the transverse emittances, a factor two increase in quantum efficiency was obtained after one week of operation at that new setting. “Active” cleaning was then performed switching off the RF and forcing the laser fluence to 2.5 times higher levels than nominal while scanning the cathode position. It then allowed us to reach 1nC at 300 μJ on the cathode and 30 degrees laser injection phase.

In this paper, we discuss the validity of transverse emittance numbers deduced from the measurements by comparing them to numbers obtained from simulated data after processing those latter following the same method as that applied to measured data. In the 135 MeV section of the LCLS Injector, the emittance can be obtained by either determining beam sizes at three screens (separated by 60 degree phase advance) or at a single screen while scanning an upstream quadrupole (quad scan). The beam sizes are measured using OTR screens or wire scanners. All combined, this gives at least four types of measurements. The rms beam sizes can be extracted following various algorithms which truncate the tails of the distributions at different levels. Similar truncation levels were applied to the simulated data. The first part of this paper shows that the emittance value rapidly decreases when long tails are truncated. Emittances as low as 1.2 mm-mrad in both planes for 1nC seem realistic for 90-95% of the particles constituting the core of the bunch.

In the second part of this paper, we report on the effort made to benchmark the simulation code IMPACT [2] to the experimental data. Multi-particle tracking codes [3,4] had been used intensively at the design stage of the LCLS injector to specify tolerances of the beamline components and of the drive laser [5]. In this paper, we present results calculated with the 3D algorithm of the IMPACT code. 3D simulations are essential to represent our asymmetric beam. IMPACT can run on parallel processors, making 3D calculations time efficient.

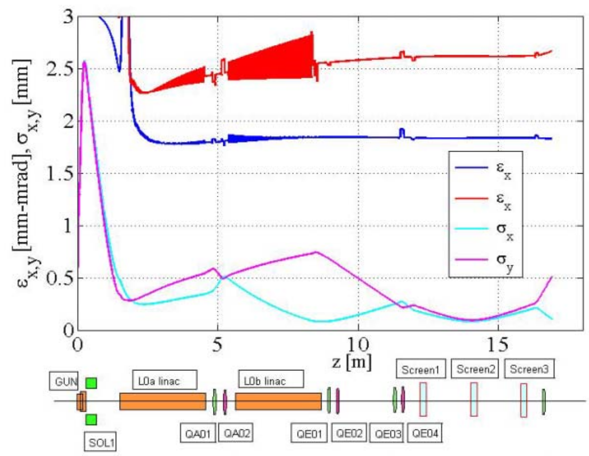

Figure 1: Beam size and 100% projected emittance for optimized beamline – the beam is matched to the 3-screens – the three OTR screen locations are shown

EMITTANCE

Transverse Tails

The initial distribution used in the simulations presented in this chapter uses the virtual cathode drive laser image as a transverse profile. The laser spot on the cathode, and thus the virtual cathode, is the image of an aperture limiting our transversally Gaussian laser profile. Even if the emission profile has hard edges, see figure2-a, the photo-electron beam develops large transverse tails. To evaluate the effect of those tails on the emittance calculations, simulations with 2 levels of meshing were used: 32 x 32 x 32 or 128 x 128 x 64. The first set was run with 200k particles and the second one with 4 million particles. No noticeable difference was seen in the generation of transverse tails and emittance results were within a few percent. In both cases some islands of higher density were preserved down the beamline as shown in the three screen profiles of figure 3. The 4 million particle distribution case shows finer structure in the profile than the 200k distribution. But, the 12μm

* Corresponding author: limborg@slac.stanford.edu
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resolution of the screens sets the limit to the fine structure visible on the experimental data. The long transverse tails seen in the simulations are similar to those observed in the experiment (see figure 3d). The longitudinal profile used in the simulations (see figure 2-b) is directly the laser one measured with the cross-correlator.

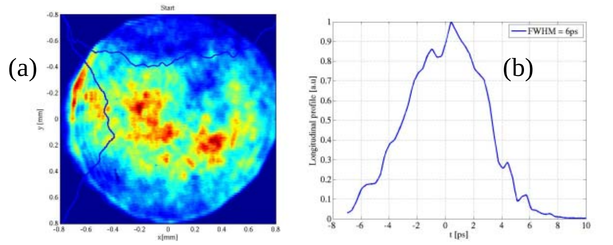

Figure 2: Laser profiles July 13th 2007 (a) virtual cathode (b) Longitudinal profile

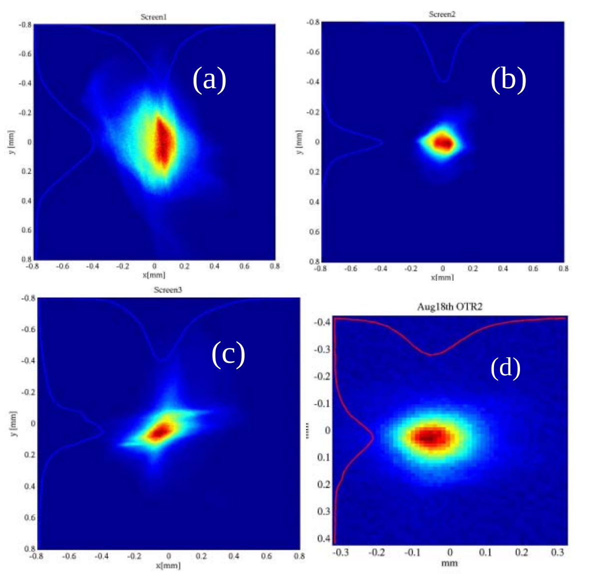

Figure 3: Transverse profiles ; Simulations data (a) OTR1; (b) OTR2 ; (c) OTR3 ; Experimental data (d) OTR2 (scale different to show graininess)

Rms Beam Size Calculation

The rms beam size of the profiles can be computed following various methods, but the “rms area cut” is most commonly used. The rms beam size is typically computed by integrating each measured 1D transverse profile and cutting out 2.5% of the area (charge) on each side. Accordingly, the truncated profile then contains 95% of the charge at the beam core. Other methods are applied less commonly, including Gaussian fits, and full 100% rms calculations, but the 95% core emittance value is less sensitive to baseline profile noise as well as weak beam tails, which will likely not contribute to the FEL gain in any case. Applying the same robust method uniformly in both measurement and simulation allows a fair, reproducible comparison. Accordingly, the intensity profile, after these cuts, should then contain 95% of the charge.

Three Screen Emittance Measurement

The beamline quadrupoles are tuned such that the beam sees a 60 degree betatron phase advance between each successive screen of the three screen emittance station. The transverse phase space is then probed optimally in size and angle. Both experimental and simulations data correspond to a well matched beam as the one presented in figure 1. Slightly different magnet settings were used in the simulations compared to the experimental one in order to compensate for small inaccuracies in the beamline model and beam characteristics. In figure 4, the emittance numbers are computed from the three profiles after appropriate truncation. Figure 4 shows that the horizontal and vertical emittances get respectively close to 1.2 and 1.5 mm-mrad in the horizontal plane for 5% cut area, while the numbers are 1.8 and 2.6 mm-mrad for the distribution containing all the particles.

Quadrupole Scan Emittance Measurement

A simulation of the quadrupole scan using QE04 (see figure 1) was performed. For each of the quadrupole setting, the appropriate truncation levels were applied to the profiles. The numbers obtained are nearly identical to those obtained for the 3-screen emittance calculations and are plotted in figure 4. Once again, the simulations were done starting from a matched configuration. Running 4 million particles instead of 200k did not change the results by more than a few percent.

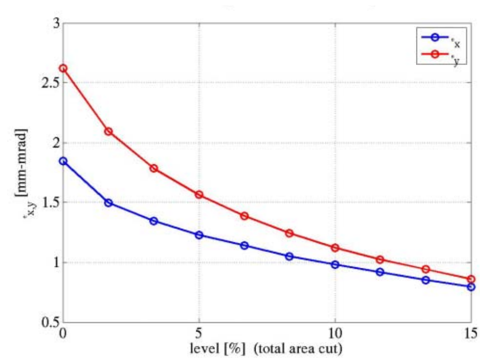

Figure 4: Emittance calculated from simulations for different levels of area cut on the transverse profile; the curves are identical for both quadrupole scan simulated data (using 7 profiles) and the three screen simulated data

SIMULATIONS VS EXPERIMENT

Initial Distribution

The initial particle distribution needs to be as close as possible to the emitted photo-electron distribution.

In the transverse plane, the intensity of the emission profile can differ dramatically from that of the virtual cathode image due to variation in quantum efficiency across the cathode. To measure the emission profile, a point-to-point imaging of the cathode is performed at extremely low charges. Such images show that our cathode presents some high density emission spots. It is not clear that those emission spots were generated by high intensity spots in the drive laser beam or by some RF arcing in the gun at the early stage of commissioning. Since we operate in the space charge limit regime, it is not certain that the intensity emission profile is the same at high charge and at low charge [6]. However, in the simulations presented below, we used the intensity profile measured at low charge on the first imaging screen and transported back to the cathode.

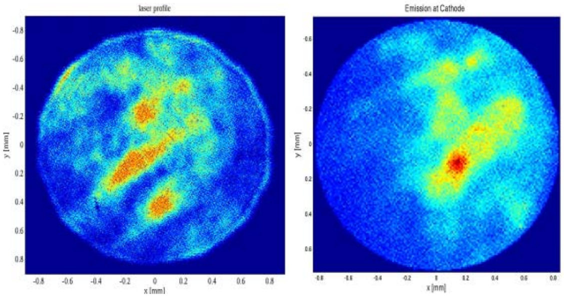

Figure 5: (a) virtual cathode; (b) emission scaled and rotated from point-to-point image at first screen

In the longitudinal plane, we used directly the laser longitudinal profile measured with the cross-correlator (mixing the UV and the IR of the Ti:Sa laser), see figure 6. This profile should in theory be corrected for Schottky effect, see figure 7, but the intensity variation is small over the 6 ps, i.e. the 6 degrees of the bunch extent.

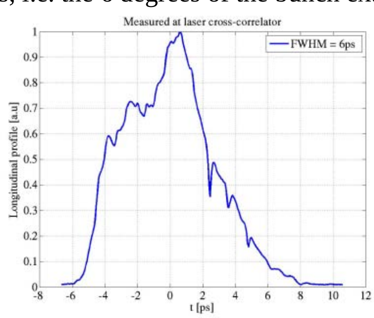

Figure 6: Longitudinal profile measured at the cross-correlator

The distributions of the transverse momenta are Gaussian with rms values giving a thermal emittance of 0.6 mm-mrad per mm of cathode radius. Thermal emittance measurements were done early in the run confirming this level.

A six-dimensional distribution is then generated numerically using a quiet start algorithm based on Halton sequences [7].

Beamline Model

The beamline components have been described in [5] and are briefly summarized at the bottom of figure 1. Other magnetic fields present in the gun region have been ignored as of now, but will be included in a second round of simulations. The beam is assumed to be on axis and not perturbed by wakefields. The beam is usually steered into the linac section to prevent wakefield-based emittance growth.

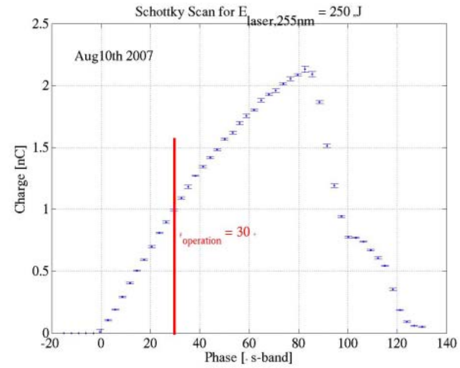

Figure 7: Schottky scan; charge vs laser injection phase

Operating Parameters

The nominal parameters are

- Laser pulse (6ps FWHM, 1.66 mm diameter)
- Charge from 200pC to 1nC
- 30 degrees injection phase
- Gun gradient 110MV/m (more recently 115 MV/m)
- Linac sections 20 MV/m , 24 MV/m

Machine Tuning

The standard procedure for tuning the LCLS Injector follows these steps:

(1) verify laser injection phase to 30 degrees by performing a Schottky scan (charge vs laser injection phase)
(2) realign the laser on the solenoid axis (the solenoid was aligned to the gun very accurately before installation)
(3) matching to emittance station
(4) perform emittance minimization by scanning solenoid, steering into the linac section

Solenoid Scan Emittance Measurement

Solenoid scans are done on a regular basis for operating the LCLS Injector. The optimum solenoid value changes mostly when gun RF parameters and slightly with charge.

Figure 8 and Figure 9 show the same measurement of emittance as a function of solenoid value but for two types of analysis. Figure 8 shows the result using the 100% rms, i.e for no truncation of the tails of the profiles. The shape of the curve of measured horizontal emittance is very similar to that obtained with the simulations and computed with 0% truncation level. But the mimimum value differs by 25%. A better agreement on the minimum emittance value is obtained if a 2.5% level cut is applied on the simulated data, in particular for the vertical plane. Figure 9 shows the results from the measurements when the standard 5% rms cut area is used on the profile. Simulations results based on the 5% level give slightly higher emittance numbers. However, if a truncation at 7.5 % level is applied on the simulated data, the agreement with the measurements becomes quite good.

The solenoid currents used in the simulations were scaled by a factor 0.986 to make the solenoid values giving the minimum emittance coincide in both cases. Such an error of 1.4% is within the tolerance of the gun energy measurement done at the gun exit.

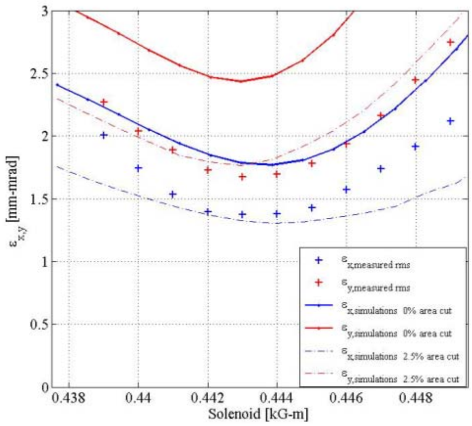

Figure 8: Emittance vs solenoid- Comparison between experimental and simulated data for rms values calculated with no cut on the tails- simulations results at 2.5 % cut level have also been superimposed

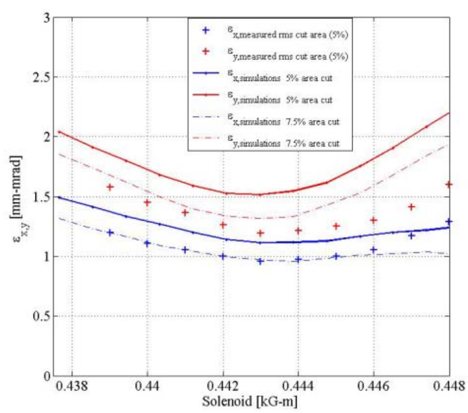

Figure 9: Emittance vs solenoid- Comparison between from experimental data and simulations based on the 5% rms cut area - simulations results at 7.5 % cut have also been superimposed

Bunch Length vs Charge

Bunch lengths are measured using a transverse deflecting cavity. A careful calibration is regularly performed to accommodate the effects of the variation in klystron power. The experimental data presented in figure 10 were taken within less than an hour. Simulations were based on the optimization of the beamline for 200 pC as was the case the day of that measurement. The agreement between the measurement and the simulations is quite satisfactory. The measured longitudinal laser profile used in the simulation was that measured with the cross-correlator and had a 5ps FWHM, i.e. it was slightly smaller than the nominal 6ps long laser pulse used for most of our 2007 run.

At 1nC, when the laser pulse is 6ps long, the rms bunch length of the electron beam at 135 MeV is 1.05mm. It is larger than the design value of 0.84 mm. The space charge induced bunch lengthening is stronger when starting with both a shorter laser pulse and a smaller radius than those calculated at the design stage. The design laser pulse for 1nC was 10ps FWHM and 1mm radius.

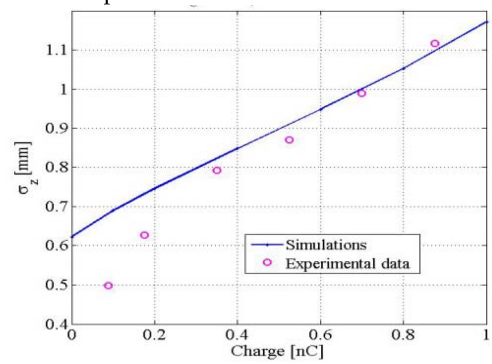

Figure 10: rms bunch length measured compared to results from simulations

CONCLUSION

This first series of simulations seem to validate the acceptable emittance numbers measured at 1nC during the first LCLS Injector run. A fairly good agreement is obtained between measurement and simulations. More experimental data are required to characterize the physics of the emission in the space charge limited regime in which we are running. The related physics might explain the 25% higher emittance numbers obtained in the simulations. A second series of simulations remains to be done including the complete set of known magnetic fields. Further comparisons will include longitudinal phase space characterization and data for low charges.

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