

# ALTERNATE TUNINGS FOR THE LINAC COHERENT LIGHT SOURCE PHOTOINJECTOR \*

C.Limborg-Deprey, P.Emma

MS 18, SLAC 2575 Sand Hill Road, Menlo Park CA, U.S.A.

## Abstract

The Linac Coherent Light Source (LCLS) is an x-ray free-electron laser (FEL) project based on the SLAC linac. The LCLS Photoinjector beamline has been designed to deliver 10-ps long electron bunches of 1 nC with a normalized projected transverse emittance smaller than 1.2 mm-mrad at 135 MeV. Tolerances and regulation requirements are tight for this tuning. Half of the total emittance at the end of the injector comes from the “cathode emittance” which is 0.7 mm-mrad for our nominal 1nC tuning. As the “cathode emittance” scales linearly with laser spot radius, the emittance will be dramatically reduced for smaller radius, but this is only possible at lower charge. In particular, for a 0.2 nC charge, we believe we can achieve an emittance closer to 0.4 mm-mrad. This working point will be easier to tune and the beam quality should be much easier to maintain than for the 1 nC case.

In the second half of this paper, we discuss optimum laser pulse shapes. We demonstrate that the benefits of the ellipsoidal shapes seem to be important enough so that serious investigations should be carried out in the production of such pulses.

## INTRODUCTION

The commissioning of the LCLS PhotoInjector beamline will start in January 2007. The LCLS will be constructed to operate nominally with a 1 nC charge and to produce 100 A with projected and slice emittances of less than 1.2 and 1.0 mm-mrad. Simulations have proven that many challenges of the operation at high charge will be relaxed at lower charge. A 0.2 nC case was then studied from start-to-end in the LCLS [1].

## LOW CHARGE

With a reduction of the charge by a factor of 5 from 1 nC to 0.2 nC, one can decrease the volume of the laser pulse to keep about the same charge density at emission.

### Standard Scaling

According to [2], one can scale each of the three real space dimensions  $\sigma_i$  following  $\sigma_i \propto Q^{1/3}$  and the emittance should then scale like  $Q^{2/3}$ . Table 1 shows how our parameters would scale from our nominal 1nC case. This scaling leads to a beam brightness which follows  $1/Q^{2/3}$ .

Table 1: Standard scaling based on [2]

	fwhm	R <sub>hard-edge</sub>	$\epsilon$
1 nC	10 ps	1.2 mm	1 mm-mrad
0.2 nC	5.8 ps	0.7 mm	0.34 mm-mrad

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#limborg@slac.stanford.edu

### Addendum to Standard Scaling

One component omitted in the description of [2] is the scaling of the cathode emittance. The cathode emittance has been measured to be larger than the theoretical thermal emittance [3]. For copper cathode, it was measured to be of 0.6 mm-mrad per mm against 0.3 mm-mrad per mm for the theoretical value. In the following, we assume that the total emittance is the quadratic sum of the cathode emittance and of the irreversible emittance. The irreversible emittance corresponds to the emittance which cannot be cancelled with perfect emittance compensation [4,5,6]. It principally includes RF effects and non-linear space charge effects. The cathode emittance scales linearly with radius and accordingly like  $Q^{1/3}$ . The irreversible emittance scales like  $Q^{2/3}$ .

Table 2: Emittance Scaling including cathode emittance

$\epsilon$ in mm-mrad	$\epsilon_{\text{cathode}}$	$\epsilon_{\text{irreversible}}$	$\epsilon_{\text{total}}$
1 nC	0.72	0.70	1.0
0.2 nC	0.42	0.24	0.48

### Optimization

In [7] we described the optimization of the 0.2-nC tuning for a 10-ps long pulse. We reported minimum projected emittance of 0.45mm-mrad. Figure 4 of [7] showed that the 80%-emittance, i.e. the projected emittance for the 80 core slices out of 100 constituting the beam, was 0.39 mm-mrad and the average of the slice emittance for those 80 slices was 0.25 mm-mrad for the nominal radius of 0.3 mm. However, this tuning was not satisfactory as the peak current of ~20A was too low and the mismatch between slices too large.

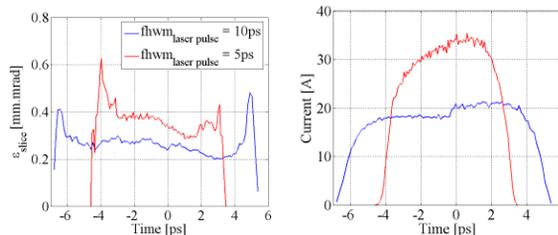


Figure 1: Slice emittance and peak current for 0.2nC Two cases correspond to fwhm laser pulse of 5 and 10ps.

To reach a higher peak current, the optimization of the beamline was done for shorter laser pulses. We retained the 5 ps fwhm laser pulse case which gives a 6.5 ps fwhm electron pulse length at the end of the beamline, corresponding to peak current of 30 A for most slices, as shown in figure 1. For the 5 ps fwhm laser pulse case, the projected emittance is 0.42 mm-mrad and the 80%-emittance is 0.37 mm-mrad slightly smaller what the modified scaling gives. The optimum radius was found to

be 0.42 mm and not 0.7 mm. This tuning was used in the start-to-end simulations presented in [1]. However, to be on the very conservative side, the slice emittance was artificially raised to 0.80 mm-mrad in [1].

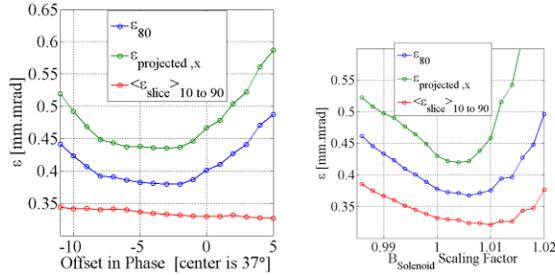


Figure 2: Sensitivity to Injection Phase (a) and to Solenoid field variation (b) (solenoid reference is 2.7kG).

The improved sensitivity of the 0.2 nC case with respect to the 1 nC case is summarized in Table 3 for three key tuning parameters. It shows that the best working point will be more easily reached for the 0.2 nC case than for the 1 nC case. The stability will be easy to maintain. The evolution of emittance as a function of solenoid field and injection phase are given in figure 2.

Table 3: Deviation in parameters leading to a 5% increase in the 80%-emittance given in Column 1

	$\epsilon_{80}$	$\Phi_{\text{rf}}^\circ$	Solenoid	$V_{\text{rf gun}}$
1 nC	0.9	$\pm 2.5^\circ$	$\pm 0.3\%$	$\pm 0.7\%$
0.2 nC	0.37	$\pm 6^\circ$	$\pm 0.8\%$	$\pm 1.0\%$

### 3D-ELLIPSOIDAL PULSES

The emittance for our high charge 1nC case would be greatly improved if appropriate pulse shaping were available. The “Beer Can” shape is not the optimal pulse shape for photoinjectors. The ideal distribution is uniform and contained in a 3D ellipsoid as stated in the literature many years ago [5,6]. The idea of ellipsoidal shape was recently revived [8] for charges in the low range of 0.1 nC using very flat beams, a few tens of fs long. In the next few paragraphs, we demonstrate why the direct production of 3D-ellipsoidal laser pulses should be seriously investigated for high charge cases. Preliminary ideas on the feasibility of producing such pulses are discussed in [9].

The laser pulse shapes used in the next paragraphs is a uniform density distribution contained in a 3D ellipsoid whose hard edges are governed by equation (1), with R the transverse radius and 2L the total bunch length.

$$\frac{x^2}{R^2} + \frac{y^2}{R^2} + \frac{z^2}{L^2} = 1 \quad (1)$$

#### No Space Charge Induced Emittance

For a uniform distribution contained in a 3D-ellipsoid, the space charge force is linear. Consequently, space charge forces can exactly be compensated with linear optics elements. All longitudinal slices are perfectly

aligned in transverse phase space. Accordingly, at the end of the beamline, the emittance growth generated by the space charge forces is exactly cancelled. There is no generation of irreversible emittance compared to the beer can shape. This is illustrated in figure 3. Figure 3-a shows the irreversible emittance generated between the cathode and the end of the beamline. Figure 3-b shows, for the ellipsoidal shape, that the emittance at the end of the beamline exactly matches the initial cathode emittance.

It is not exactly correct to say that the final emittance matches exactly the cathode emittance since there is some RF emittance generated. However, the RF emittance is small  $\sim 0.2$  mm-mrad compared to the cathode emittance. This number is obtained by switching off the cathode emittance. This perfect emittance compensation principally comes from the fact that the longitudinal phase space becomes very linear as shown in figure 4-d. More details are given in [9].

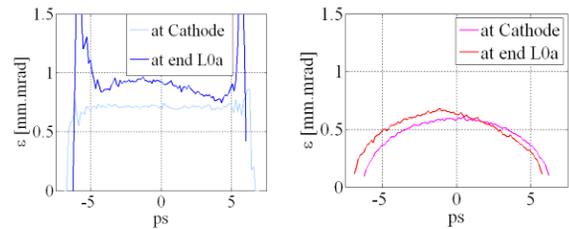


Figure 3: (a) Standard “Beer Can” – (b) 3D-ellipsoid.

#### Optimization

The emittance optimization based on “Beer Can” shape optimization was obtained while meeting the 100A at the end of LCLS PhotoInjector beamline. To make a fair comparison between the Beer-Can and the 3D-ellipsoid, we maintained the constraint of 100A. The optimum laser spot size was found to be 1.2mm for the beer can laser shape while 100A was required. For the “3D-ellipsoid”, we could explore even smaller radius as the space charge force stays linear even if the charge density was increased.

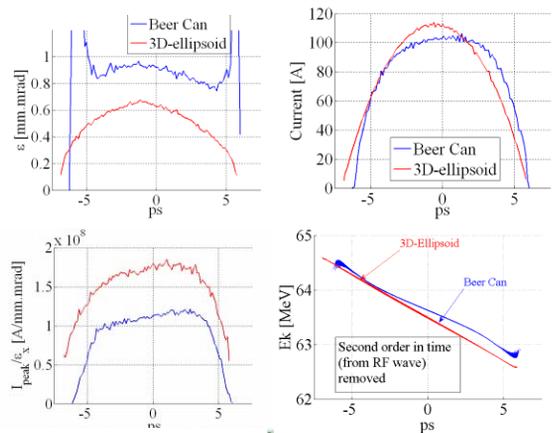


Figure 4: Blue and Red are for “Beer Can” (nominal LCLS tuning) and “3D-Ellipsoid” (LCLS case) (a) Slice emittance at end beamline – (b) Peak current – (c) Ratio of peak current over emittance – (d) Longitudinal Phase Space after removal of 2<sup>nd</sup> order term in polynomial fit.

The reduction in radius is, however, limited by the “image charge” limit stated in equation (2), in which  $E_a$  is the accelerating field,  $Q$  the charge and  $r$  laser spot radius. It corresponds to Gauss law applied on the cathode plane during extraction.

$$E_a > \frac{Q}{\epsilon_0 \pi r^2} \quad (2)$$

This criteria, which would limit our radius to 0.77 mm is in fact slightly relaxed given the long emission time. However as shown in figure 5 (a), the longitudinal bunch profile gets distorted when we approach this “image charge” limit regime.

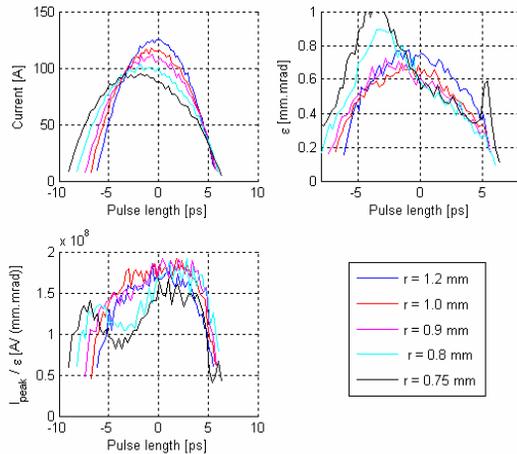


Figure 5: Beam characteristics at the end of the beamline as a function of the  $r$  parameter of equation (1)- (a) Peak Current- (b) Slice Emittance - (c) Ratio Peak Current over Emittance.

Figure 5 shows that the optimum radius is around 0.9-1.0 mm. An initial laser pulse length ( $2L$ ) of 10 ps was chosen. Many combinations of parameters with the radius  $r$  ranging from 0.85 to 1.1mm, with  $2L$  ranging from 9 to 12 ps, the injection phases ranging from 28 to 32 were nearly equivalent. Our best solution was chosen as the one maximizing the ratio of the peak current over the slice emittance. This ratio is the key quantity in the FEL parameter known as the Pierce factor. This ratio is 80% larger than that obtained for the standard beer-can leading to an improvement of 20% of the gain length if this improvement is carried along the accelerator. Complete start-to-end simulations remain to be run for this case.

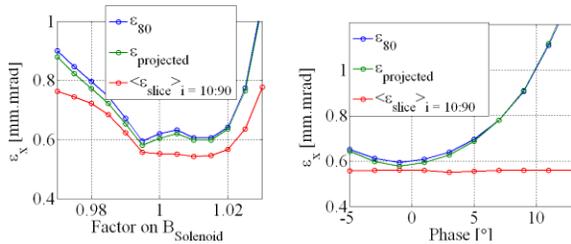


Figure 6: Emittance as a function of Solenoid field (a) with the field normalized to 2.7kG (a) and of Injection Phase (b) the reference phase is 27°.

### Sensitivity

The sensitivity of the emittance as a function of solenoid field and injection phase is given in figure 6. The reference corresponds to an injection phase of 29°, a bunch length  $2L$  of 10 ps and a radius  $R$  of 1 mm. It is not a surprise that the 80% emittance is slightly larger than the total projected emittance as the core slices have a much smaller emittance. The sensitivity with respect to solenoid strength is reduced by more than a factor of 4, for the ellipsoid case, compared to the beer can case.

### Conclusion

3D-ellipsoidal laser pulses would ameliorate dramatically beam characteristics, in terms of emittance, sensitivity to components and linearity of phase spaces, in any Photo-Injector beamline whose beam emittance is space charge dominated. The magnitude of those improvements makes it worth for laser physicists to investigate the production of these challenging pulse shapes. Some preliminary solutions are discussed in [9]. Accelerator physicists now need to compute the optimal pulse shape which would eliminate the deleterious spiky structure at the head and tail of the current profile produced after the compressors as shown for the LCLS case in figure 5 of [1]. In the meantime, the 0.2 nC charge tuning seems to offer some margin to produce saturation of SASE at 1 Angstrom.

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