COMMISSIONING OF THE *LCLS* LINAC AND BUNCH COMPRESSORS*

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Abstract

The Linac Coherent Light Source (*LCLS*) is a SASE x-ray Free-Electron Laser (FEL) project under construction at SLAC [1]. The injector section, from drive-laser and RF photocathode gun through the first bunch compressor, was commissioned in the spring and summer of 2007. The second phase of commissioning, including the second bunch compressor and various main linac modifications, was completed in January through August of 2008. We report here on experience gained during this second phase of machine commissioning, including the injector, the first and second bunch compressor stages, the linac up to 14 GeV, and beam stability measurements. The final commissioning phase, including the undulator and the long transport line from the linac, is set to begin in December 2008, with first light expected in July 2009.

INTRODUCTION

The *LCLS* injector (Figure 1) was commissioned in 2007 during March through August. This successful first commissioning phase [2] was followed by a 4-month installation of the second bunch compressor, BC2, and related linac modifications. The second phase of commissioning, with beam accelerated to 14 GeV through the last one third of the SLAC linac and both bunch compressors, began in Dec. 2007 and finished in Aug. 2008 (see Table 1) with beam stopped at the end of the linac while the undulator was being installed.

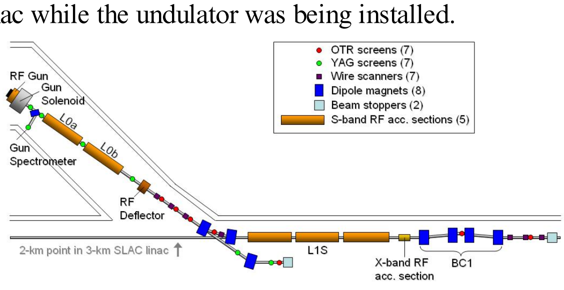

Figure 1: Layout of *LCLS* injector from gun to BC1. The off-axis injector is in a separate enclosure from the linac.

The goals of this second commissioning phase include demonstrating bunch compression in the new BC2 chicane at 4.3 GeV; preserving the injector emittance through the linac up to 14 GeV; commissioning all new beamline components, diagnostics, and feedback systems; and developing precise, automated controls tools to quickly characterize, correct, and stabilize the beam.

To initially minimize the more subtle effects of transverse wakefields in the linac and coherent synchrotron radiation (CSR) in the compressor bends, much of the commissioning was done at a bunch charge of 0.25 nC, although 1 nC was also established at 14 GeV.

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Table 1: Design and typical measured parameters.

Parameter	sym.	dsgn	meas.	unit
Final linac e^- energy	γmc^2	13.6	13.6	MeV
Bunch charge	Q	1	0.25	nC
Init. bunch length (rms)	σ_{z0}	0.9	0.75	mm
Fin. bunch length (rms)	σ_{zf}	20	8-10	μm
Proj. emittance (injector)	$\gamma\varepsilon_{x,y}$	1.2	0.7-1.0	μm
Slice emittance (injector)	$\gamma\varepsilon^{s}_{x,y}$	1.0	0.6	μm
Proj. emittance (linac)	$\gamma\varepsilon^{L}_{x,y}$	1.5	0.7-1.6	μm
Single bunch rep. rate	f	120	30	Hz
RF gun field at cathode	E_g	120	115	MV/m
Laser energy on cathode	u_l	250	20-150	μJ
Laser diameter on cath.	$2R$	1.5	1.2	mm
Cathode quantum eff.	QE	6	0.7-7	10^{-5}

DRIVE LASER AND GUN

Both the spatial and temporal profiles of the drive laser have been improved in 2008, where the spatial shaping is accomplished by over-filling an iris and the temporal shaping is formed using a Dazzler (see Figure 2). The drive laser demonstrated an impressive availability time of 99% during the 8-month run with 20-300 μJ of UV energy on the cathode, depending on the bunch charge and quantum efficiency (*QE*) of the copper cathode.

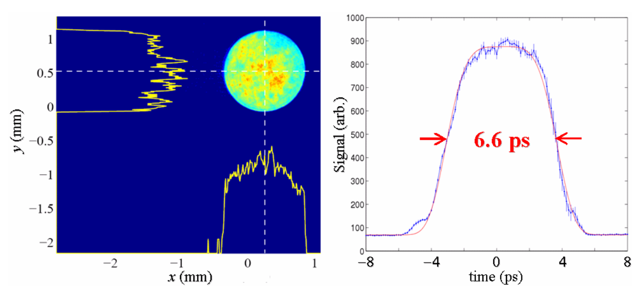

Figure 2: Spatial (left, dia.=1.2 mm) and temporal (right, fwhm=6.6 ps) profiles of the UV drive laser in 2008.

The RF photocathode gun has continued to provide 30-Hz high-brightness electron bunches with normalized rms emittance levels from 0.7 to 1.0 μm at a bunch charge of 0.25 nC (peak current of 30 A), and 1.1 to 1.4 μm at a bunch charge of 1 nC (90 A). The *QE* of the cathode has been variable, from 0.7×10^{-5} to 7×10^{-5}, with UV laser cleaning used when the *QE* dropped below 1×10^{-5}, after one year of operation. A new cathode was installed late in July, showing an initial *QE* of 5×10^{-5} and a *time-sliced* emittance of 0.60 μm at 135 MeV, 250 pC, and a 1.2-mm cathode laser spot diameter. Exploring lower charge levels of 20 pC and a 0.6-mm cathode spot diameter (4-ps fwhm laser pulse), the *slice* x-emittance in the bunch core was measured at 0.14 μm (5 A peak current - Figure 3).

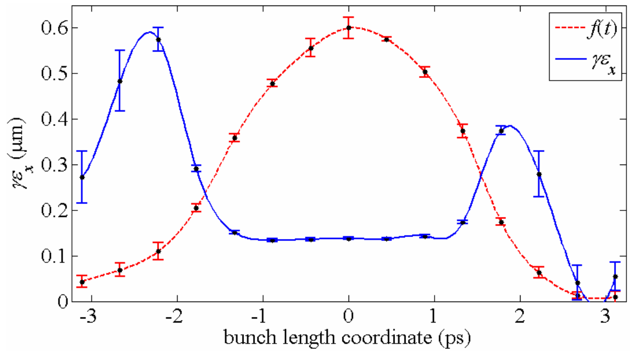

Figure 3: Measured (0.14 μm) *slice* hor. emittance, $\gamma\varepsilon_x$, (blue) at 135 MeV, 20 pC, and 0.6-mm cathode laser spot diameter, with temporal distribution, $f(t)$, (red) in arbitrary units. The rms bunch length is 0.40 mm and $I_{pk} \approx 5$ A.

BUNCH COMPRESSORS

The two bunch compressor (BC1 & BC2) typically compress a 0.25-nC bunch from a length of 0.75 mm rms to 0.1 mm in BC1, and then to 0.01 mm in BC2. The first compressor is located at 250 MeV and the second is at 4.3 GeV (see Table 2). Each compressor is composed of four dipole magnets plus two weak quadrupole magnets used to empirically suppress the dispersion after the last bend.

Table 2: BC1 and BC2 compressor parameters at 0.25 nC.

Parameter	sym.	BC1	BC2	unit
Electron energy	E_0	0.25	4.3	GeV
Energy spread (rms)	σ_E/E	1.4	0.38	%
Momentum compaction	$\|R_{56}\|$	45.5	24.7	mm
Chicane total length	L_T	6.5	23.0	m
Bend angle per dipole	$\|\theta\|$	5.4	2.0	deg
Eff. length of each bend	L_B	0.20	0.54	m
B1 to B2 (= B3 to B4)	ΔL	2.43	9.87	m
Dispersion at center	$\|\eta_x\|$	247	363	mm
Translation range	$\|\Delta x\|$	0-30	0-52	cm

The center two dipoles, a BPM, a pair of horizontal collimator jaws, and an OTR screen are supported on a sliding table with remote motor control to adjust the compression factor (R_{56}) while keeping the beam in the center of the vacuum chamber. This design also allows switching the compressor off (straight) during non-*LCLS* programs to pass a 30-GeV beam from the upstream linac.

The BC1 dipole fields in 2007 did not meet specifications for uniformity over the horizontal span, but were installed anyway to begin commissioning. Beam measurements in 2007 indicated a large horizontal emittance growth due to linear and 2nd-order dispersion errors after the compressor [2]. The center two dipole magnets were removed in fall 2007, their poles milled off, and new wider poles bolted on [3]. Shims were also added to flatten the measured fields (see Figure 4).

Emittance measurements after BC1 in 2008 (Figure 5) clearly demonstrate the dipole field quality is now adequate, with <0.8 μm normalized emittance routinely measured in both planes immediately after the compressor, even with nominal compression and a large chirped energy spread (1.4% rms). The BC2 dipole fields are adequate and generate no significant dispersion errors.

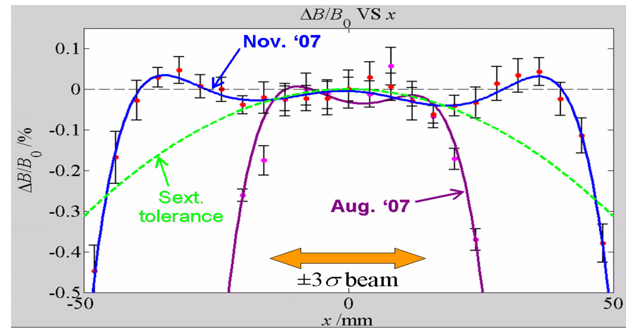

Figure 4: BC1 dipole field profiles before Aug. 2007, and after Nov. 2007 when new poles and shims were added.

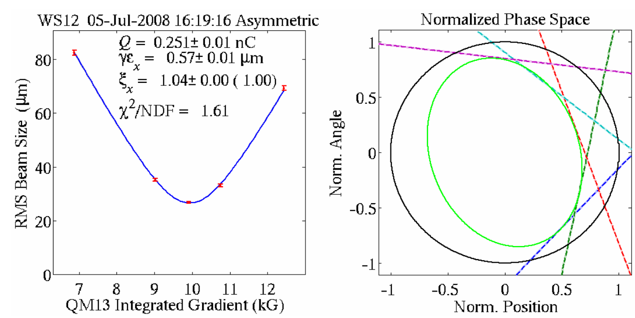

Figure 5: Horizontal emittance ($\gamma\varepsilon_x = 0.57$ μm) measured after BC1, with nominal compression, using a wire-scanner and quadrupole scan with asymmetric Gaussian fits to beam profiles. The horizontal emittance is often below 0.7 μm at 0.25 nC, with 0.7-0.8 μm in the vertical.

Bunch compression has been demonstrated in both chicanes. This is accomplished in BC1 by switching off BC2 and using a transverse RF deflector at 5 GeV (see TCAV3 in Figure 6) to measure the absolute bunch length by streaking the beam vertically on a downstream screen [4] at the end of the linac. The screen calibration is done empirically by varying the RF phase of the deflector around its zero-crossing and fitting the linear beam position response on the screen. In this way, no RF voltage or screen calibration, or beam optics knowledge is required to measure the absolute bunch length.

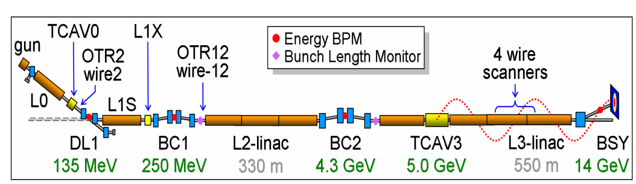

Figure 6: *LCLS* accelerator layout showing transverse RF cavity (TCAV3) and screen at end of linac. The undulator and transport lines beyond 'BSY' are under construction.

The BC1 bunch length is varied using the phase and amplitude of the 'L1S' S-band RF section (see Figure 1 & Figure 6, where the 'L1X' X-band 4th harmonic RF linearizing section in these figures is powered but not varied here). Finally, the initial bunch length is precisely determined by using the low-energy transverse RF deflector at 135 MeV, upstream of BC1 (see Figure 1).

The bunch length after BC1 vs. L1S RF phase (but with constant energy) is shown in Figure 7 at 0.25 nC where an *Elegant* [5] calculation is overlaid in a solid red curve.

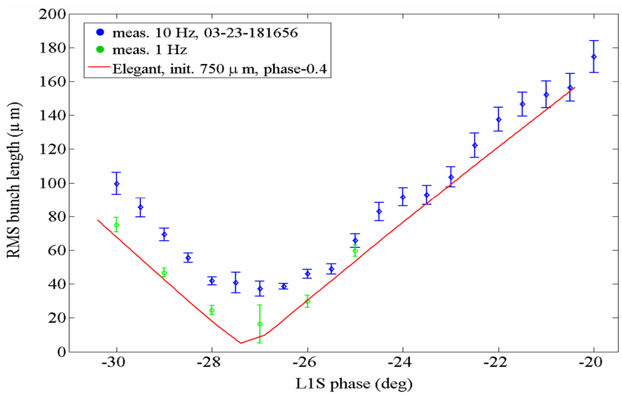

Figure 7: Measured rms bunch length after BC1 vs. L1S RF phase with BC2 OFF and using the RF deflector (TCAV3) of Figure 6. Green points are data taken at 1 Hz to defeat the screen persistence for a more accurate result.

A similar arrangement is made to measure the BC2 bunch length, in this case with the BC2 strength (R_{56}) varied to sweep the bunch length. A set of BC2 bunch length measurements is shown in Figure 9, which is described in the section on "CSR Measurements".

LINAC

The *LCLS* electron bunch is routinely accelerated in the last kilometer of the SLAC linac through both bunch compressors to 13.6 GeV at a repetition rate of 30 Hz. At a bunch charge of 0.25 nC, the RF phasing is adjusted with the L0 section (see Figure 6) on crest, L1S off crest by –22°, L1X (20 MV of 4th harmonic RF) set 20° off decelerating crest (*i.e.*, –160°), the L2-linac off crest by –35°, and the L3-linac on crest. This produces a peak current of about 2.5 kA with an 8-μm rms final bunch length, as shown in Figure 9 at BC2 R_{56} = –24.7 mm.

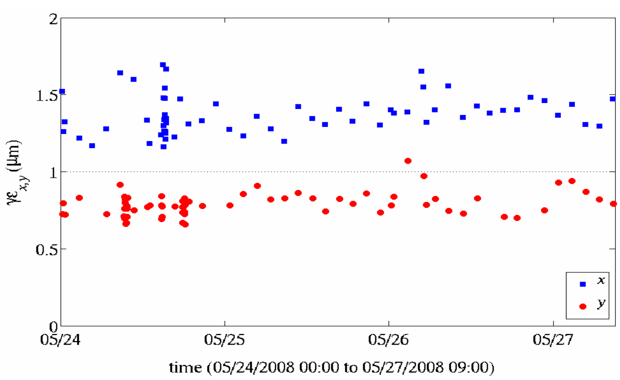

Figure 8: *Projected* emittance (*x* & *y*) measured at 0.25 nC and 2.5 kA near the end of the linac (~10 GeV) over 3.3 days with no tuning. Mean values are $\gamma\varepsilon_x$ = 1.38 μm, and $\gamma\varepsilon_y$ = 0.79 μm, with a geometric mean of 1.04 μm.

Emittance measurements are made near the end of the linac using four wire-scanners (shown in Figure 6). Measurements made every two hours over 3.3 days with no invasive tuning are shown in Figure 8, with nominal bunch compression. Some significant linac trajectory tuning is required to get the horizontal emittance below 2 μm, especially at higher charge, while a small vertical emittance (<1 μm) is usually more easily attained.

CSR MEASUREMENTS

The measured horizontal emittance near the end of the linac is typically larger than the vertical, as seen in Figure 8. Much of this increase is attributed to the effects of coherent synchrotron radiation (CSR) in BC2. This effect has been measured in both BC1 and BC2 [6]. Some of the BC2 measurements are shown in Figure 9, where the final bunch length at 13.6 GeV is measured using the TCAV3 transverse RF deflector (Figure 6) while varying the strength of the BC2 compressor (*i.e.*, R_{56}). The bunch length measurements extend down to 2 μm rms in this 0.25-nC case. During this scan, the horizontal emittance is also measured using the wire-scanners near the end of the linac. Particle tracking calculations using the 1D computer code *Elegant* [5] and the 2D code *CSRTrack* [7], both of which model CSR, are included in Figure 9. The calculated *slice* emittance from *Elegant* and *CSRTrack* are also shown, suggesting that the emittance within an FEL slippage length is significantly smaller than the *projected* emittance and showing good agreement between measurement and results from both codes.

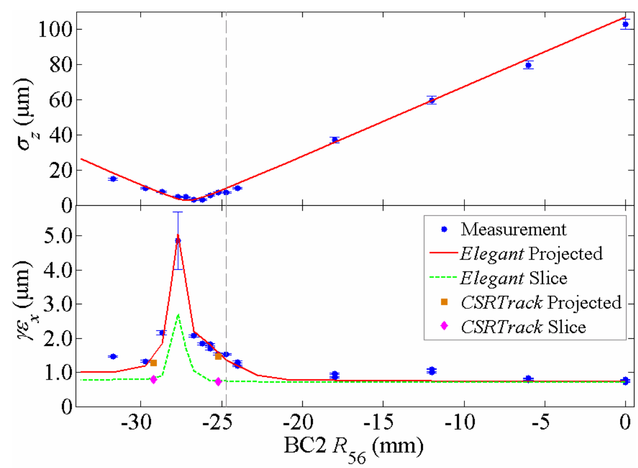

Figure 9: Measured rms bunch length (top) and measured horizontal emittance (bottom) after BC2 at 0.25 nC taken while varying the BC2 R_{56}. The calculated emittances from *Elegant* [5] and *CSRTrack* [7] are also shown (see legend). The nominal R_{56} value at 0.25 nC is –24.7 mm (vertical dashed lines).

BEAM STABILITY

The stability of various beam parameters has been measured continuously over the commissioning period, and slow improvements were seen as systems developed [8]. A sample of rms beam stability measurements is summarized in Table 3, taken over about one minute at 30 Hz. These represent typical beam stability near the end of the run and are consistent with 0.04° and 0.04% rms S-band linac RF phase and amplitude stability, respectively. The final peak current jitter is measured by reading the CSR pyroelectric detector after the last BC2 dipole.

Table 3: RMS beam stability measurements over ~1 min.

Beam parameter	symbol	rms	unit
Relative rel. bunch charge	$\Delta Q/Q_0$	1.5	%
Final rel. energy (at 14 GeV)	$\Delta E/E_0$	0.03	%
Final timing jitter wrt RF	Δt	50	fs
Final rel. peak current jitter	$\Delta I_{pk}/I_{pk}$	9	%
x/y at 250 MeV wrt beam size	$\Delta x/\sigma_x$	4	%
x/y at 14 GeV wrt beam size	$\Delta x/\sigma_x$	15	%

The bunch timing jitter after BC2, with respect to the RF, is measured with a BPM after the transverse RF deflector (TCAV3 in Figure 6). This BPM y-position jitter is measured with the deflector set at a zero-crossing phase. A calibration is made scanning the deflector phase and recording the BPM y-position, showing a very linear response: 2.34-mm/deg (970 fs/deg). So the 0.11-mm rms y-jitter in Figure 10 represents the bunch timing jitter of 46 fs rms, measured with a resolution of 4 fs (0.009 mm).

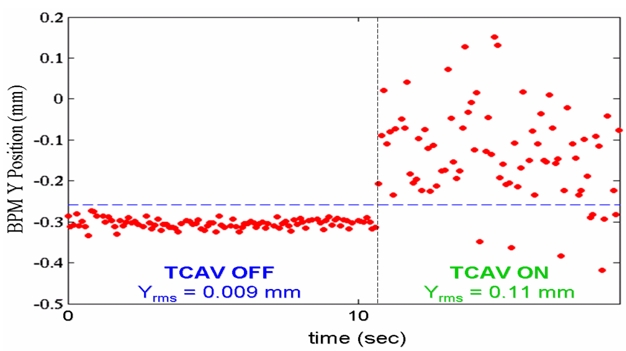

Figure 10: BPM y-position jitter measured with TCAV3 OFF (left side) and ON (right side). The increased y-jitter represents the bunch timing jitter of 46 fs rms wrt RF.

Many RF and beam-based feedback loops have been established to stabilize the electron beam over longer time periods. The injector RF (drive-laser, gun, L0, L1S, TCAV, and L1X) employs RF-based phase and amplitude feedback to maintain these critical parameters [9]. In addition, there are presently seven electron beam-based loops, plus two drive-laser loops. Five of the electron loops maintain beam trajectory by reading BPMs and adjusting steering coils at five locations: These loops maintain: gun launch angle, injector trajectory, position at L1X, trajectory after BC1, and trajectory after BC2. A sixth loop holds the bunch charge constant by reading a BPM sum-signal and adjusting a drive-laser waveplate angle. A special seventh loop [10] maintains six critical longitudinal parameters: 1) DL1 energy (see Figure 6), 2) BC1 energy, 3) BC1 bunch length, 4) BC2 energy, 5) BC2 bunch length, and 6) BSY energy.

The energy measurements are derived from BPM position readings at locations with horizontal dispersion and these signals are used to control various RF phase and amplitude settings. The bunch length measurements for the feedback loops are taken from pyroelectric detectors which sense coherent synchrotron and edge radiation from the last dipole magnets of the BC1 and BC2 compressors. Since the coherent power is (over a small range) inversely proportional to the electron bunch length, the system is able to stabilize and maintain the bunch length after both BC1 and BC2 and the electron energy at four locations.

SUMMARY

Phase-II of *LCLS* commissioning was completed in August 2008 with beam stopped at the end of the SLAC linac while the undulator was being installed in a separate, shielded enclosure. Undulator and FEL commissioning will begin in early 2009 with first light expected in July. The electron beam at 13.6 GeV already appears bright enough for SASE saturation at the shortest wavelength (1.5 Å) based on the measured end-of-linac emittance values and peak current (see Figure 11). Undulator tuning and beam-based alignment remains as the next challenge for phase-III [11]. The addition of a 'laser heater' [12] in late 2008 should improve the accuracy of the OTR diagnostics, most of which are compromised by a strong coherent component of OTR [13]. The heater may also bring an improvement in beam brightness by smoothing high-frequency spikes in the temporal distribution.

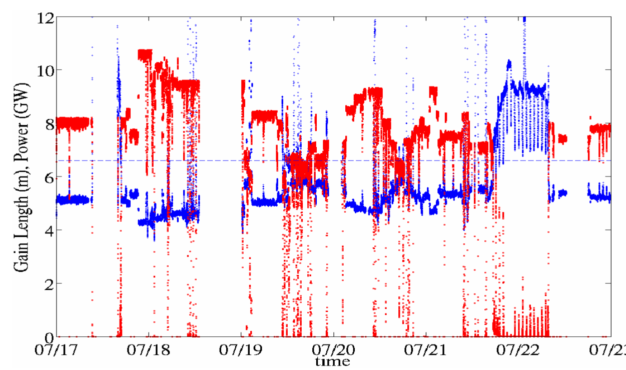

Figure 11: Calculated [14] FEL power at 1.5 Å (red) and 3D gain length (blue) over 6 days based on measured end-of-linac *projected* emittance values, measured BC2 peak current, and the design undulator parameters. The FEL should saturate when the gain length is less than 6.6 m, as in most of this plot. The calculation includes longitudinal wakefield estimates in the undulator and assumes ≤0.01% rms *slice* energy spread, which is not yet measurable. Days with low power were devoted to controls and RF.

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