INITIAL COMMISSIONING EXPERIENCE WITH THE LCLS INJECTOR*

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Abstract

The Linac Coherent Light Source (*LCLS*) is a SASE x-ray Free-Electron Laser (FEL) project presently under construction at SLAC [1]. The injector section, from drive-laser and RF photocathode gun through first bunch compressor chicane, was installed in fall 2006. Initial system commissioning with an electron beam is taking place during the spring and summer of 2007. The second phase of construction, including second bunch compressor and full linac, will begin later, in the fall of 2007. We report here on experience gained during the first phase of machine commissioning, including RF photocathode gun, linac booster section, S-band and X-band RF systems, first bunch compressor, and the various beam diagnostics.

INTRODUCTION

The months of April through August 2007 have been (and will be) spent commissioning the *LCLS* injector. This is the first phase of machine commissioning, with the second phase starting in Dec. 2007 after a 3-month downtime, and the final phase in Nov. 2008, culminating in FEL light in 2009. First electrons from the new photocathode RF gun were observed on April 5 and beam was quickly established to the full (injector) energy of 250 MeV in the main SLAC linac on April 14, 2007 (Figure 1). Over the next two months many systems were commissioned and many machine parameters are now approaching their design values. The typical bunch charge (200 pC) is about 5-times too low, due to a reduced level of quantum efficiency (*QE*) from the copper photocathode. This is not yet an impediment since commissioning is proceeding well, and the FEL should be operable with as low as 200 pC [2]. However, work will continue to improve the cathode *QE*, including laser cleaning, which has not yet been attempted.

Beam has also been transported to the end of the SLAC linac, with acceleration up to 16 GeV. A list of typical measured machine parameters is shown in Table 1, including 'design' (dsgn) values at 1 nC of charge. Many of these measured parameters are quite variable at this early stage, and are only listed here for an estimate.

DRIVE LASER

The drive laser was manufactured by *Thales Laser* and is a frequency-tripled, chirped-pulse amplification system based on Ti:sapphire. It consists of a mode-locked Ti:sapphire oscillator, followed by a pulse stretcher, a Dazzler for shaping, a regenerative amplifier, two multi-pass amplifiers, a compressor, and a frequency tripler.

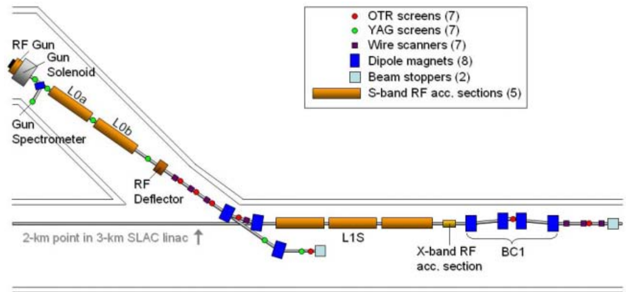

Figure 1: Layout of *LCLS* injector from gun to BC1. The off-axis injector is in a separate enclosure from the linac.

Table 1: Approximate and typical machine parameters.

Parameter	sym	dsgn	meas.	unit
Final injector e^- energy	γmc^2	250	250	MeV
Bunch charge	Q	1000	200	pC
Init. bunch length (fwhm)	Δt_0	10	6.5	ps
Fin. bunch length (fwhm)	Δt_f	2.3	1.5	ps
Initial peak current	I_{pk0}	100	30	A
Projected norm emittance	$\gamma\varepsilon_{x,y}$	1.2	1.5, 1.8	μm
Slice norm. emittance	$\gamma\varepsilon^s_{x,y}$	1.0	1.2, 1.3	μm
Single bunch rep. rate	f	120	10-30	Hz
RF gun field at cathode	E_g	120	110	MV/m
Laser energy on cathode	u_l	250	250	μJ
Laser wavelength	λ_l	255	255	nm
Laser diameter on cath.	$2R$	1.5	2	mm
Cathode material	-	Cu	Cu	
Cathode quantum eff.	QE	2	0.4	10^{-5}
Commissioning duration	-	8	5	mo

The amplifiers are pumped at 120 Hz (30 Hz for commissioning) by two frequency doubled, Q-switched, qcw-diode-pumped Nd:YAG lasers (*Thales Jedi*). The amplifier produces 25 mJ per pulse at 755 nm with a width that is adjustable between 3 and 20 ps. After tripling we typically see 2.0-2.5 mJ per pulse at 250 nm. The laser system was designed to produce a flat-top temporal profile, which has not yet been achieved.

Commissioning involved installation of the laser and verification of specs, optical transport, and diagnostics and controls. The transport system uses a spatial shaper (aspheric telescope) to change from Gaussian to flat top, but has high energy losses and sensitivity to alignment. As an alternate, a simple imaged aperture is overfilled.

A critical part of commissioning was installing and verifying the virtual cathode. This is in an equivalent plane and allows a monitor on the position and shape of the cathode laser spot. Amplitude control is accomplished

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by rotating a waveplate within the tripler. Other controls involve centroid feedback loops at several points, allowing the system to “lock” the position on the cathode.

RF PHOTOCATHODE GUN

The *LCLS* RF photocathode gun [3,4] was installed March 16, 2007 in the off-axis injector vault (Figure 1 & Figure 2). The gun was processed at 120 Hz with a field of 107 MV/m, and at 60 Hz with 120 MV/m in Oct-Nov, 2006 in the SLAC Klystron Lab [5]. The peak field was limited at 120-Hz operation due to heating of the gun RF probes. This limitation is corrected in Gun-2 and the Gun-1 probes will be replaced at the next opportunity. After RF conditioning the gun remained under UH vacuum (mid-10^{-10} Torr) during final alignment of the solenoid and installation in the injector housing. This required less than two weeks of RF processing after installation, which was mostly limited by the long waveguide vacuum.

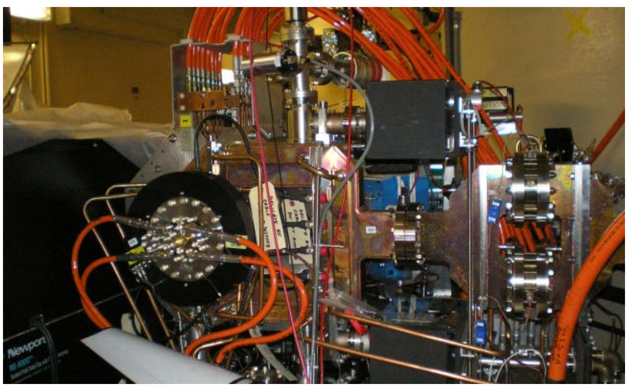

Figure 2: The *LCLS* Gun-1 installed. View is from rear of gun with dual RF feed at right and cathode assembly toward left. The cathode flange has cooling lines and black bucking coil connected. The drive laser launch optics and virtual cathode camera are in black box at left.

In order to maintain the RF resonance frequency, the water system regulates the gun body temperature to 96.25±0.25 deg-F, and the LLRF control system uses signals from the gun probes to keep the field amplitude and phase constant. The gun vacuum pressure rises to approximately 1×10^{-9} Torr during operation, mostly due to the additional vacuum load of the injector beamline. In general, the gun’s operation has been very reliable with the only significant difficulty being the low cathode *QE* (4×10^{-6}). There are plans to perform laser cleaning of the copper cathode and possibly replace it in the near future.

RF SYSTEMS

The *LCLS* Injector RF system consists of 6 stations, 5 of which operate at S-band and use standard SLAC modulators and klystrons, and one which operates at X-band using a modified SLAC modulator and an XL-4 klystron [6]. With exception of the L1S station (Figure 1), a separate klystron is used to drive each structure, with no pulse compression. For L1S, a single station with SLED [7] pulse compression drives 3 structures. The S-band accelerators are standard SLAC structures approximately 3 meters long, with the L0a & L0b structures (Figure 1) modified for a dual feed RF input. The X-band uses a 60-cm structure test accelerator, and the RF deflector is a 0.55-m long transverse structure.

Each station has an RF source controlled by an *I*/*Q* modulator “PAC”, driven by a 100-Ms/s arbitrary waveform generator. This allows controlled power ramps to reduce RF gun reflections, and direct production of the phase flip required for SLED operation. Signals from couplers on the structure inputs and outputs are down mixed in a “PAD” to a 25-MHz IF, then digitized at 100 Ms/s, measuring phase and amplitude during the pulse.

The measured phase and amplitude from the “PAD” is used in feedback to control the *I* and *Q* output of the PAC. The feedback runs on an EPICS aware microcontroller in the PAD at the full machine rate – currently 30 Hz, to be increased to 120 Hz for future runs. The set points for the RF feedback loops are controlled at a lower rate by beam-based measurements, or by other high level applications.

BUNCH COMPRESSOR CHICANE

The injector includes a 4-dipole magnetic chicane, BC1 at 250 MeV, as the first bunch compressor. (The second compressor, BC2, will be located 350 m downstream at 4.3 GeV and installed in fall 2007.) Nominally, the bunch is compressed by a factor of 4-5 in BC1, but in the extreme, with X-band 4th harmonic RF switched on, the bunch can be compressed down to a few microns [8].

The absolute bunch length after BC1 will be measured using a 2.4-m long transverse RF deflecting cavity 900 m downstream, which acts as a streak camera [9]. This cavity will be relocated closer to the BC2 in fall ‘07, but is presently near linac end (4-11 GeV). A shorter transverse cavity is also located upstream of BC1 and is used to measure the initial bunch length and longitudinal distribution (Figure 3). In addition, there are coherent radiation monitors for relative bunch length, BPMs, and emittance diagnostics (3 wire scanners and an OTR screen) beyond BC1 (Figure 1). The chicane includes an OTR screen, collimator, and BPM at center [8].

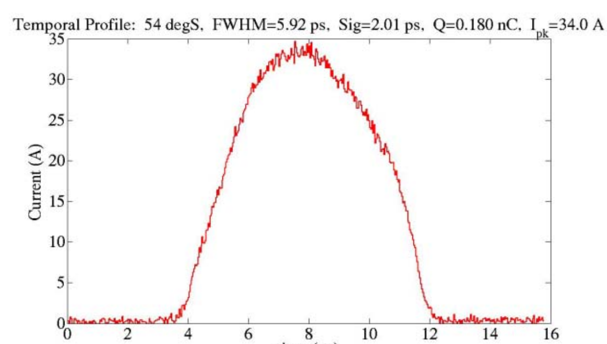

Figure 3: Temporal dist. of 34-A e^- beam measured with the transverse RF deflector upstream of BC1 ($\sigma_t \approx 2.0$ ps).

The BC1 dipole fields are of poor quality, including a significant field gradient which generates large horizontal dispersion beyond BC1. This has been corrected using two small quadrupoles placed in BC1 for this purpose, but the effect is much larger than had been anticipated. The dipoles will need field shimming.

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BEAM DIAGNOSTICS

Many of the beam diagnostic locations are shown in Figure 1. Transverse beam profiles are measured using seven 1-μm thick aluminum OTR (optical transition radiation) screens; seven 100-μm thick Ce-doped YAG (Yttrium Aluminum Garnet) screens for use at low energy where OTR provides limited light. The light from both YAG and OTR screens is detected with a common enclosed optical assembly consisting of a calibration reticle, a set of two insertable neutral density filters, a telecentric lens, and a 12-bit resolution megapixel CCD with digital output. There are also seven wire-scanners (x & y), which require multiple beam shots, but are non-invasive. These are 20-μm thick tungsten wires to accommodate ≥40-μm rms beam sizes and are monitored with LVDTs to 2-μm accuracy. The raw profiles from a scan can be corrected for charge and beam position jitter by simultaneously acquiring data from BPMs. In addition, there are 22 stripline beam position monitors (BPMs) with 5-μm resolution; six beam current toroids; and two Faraday cups (one not functional). Non-intercepting diagnostics downstream of the bunch compressor uses microwave radiation from a ceramic gap in the beam line which is detected with two waveguide-coupled diodes at 90 and 300 GHz to measure the bunch form factor.

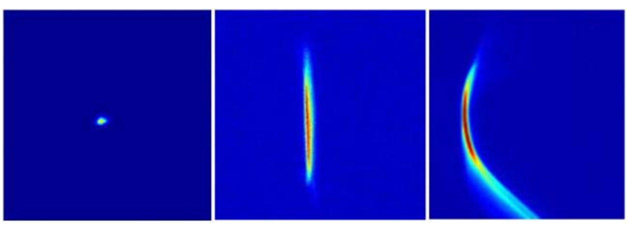

Figure 4: Screen-1 image with RF deflector *OFF* (left) and *ON* (middle), for measuring sliced emittance. Screen-2, after a bend (right), shows longitudinal phase space.

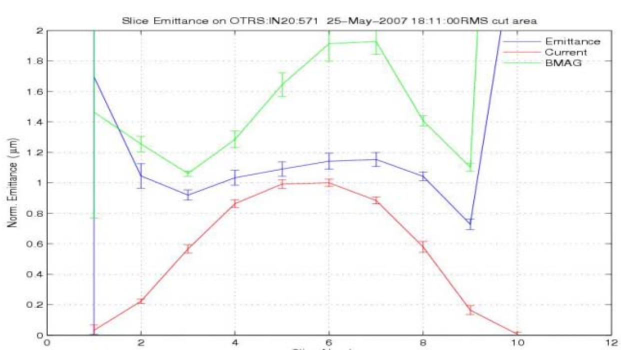

Figure 5: Time-sliced horizontal emittance measurement on OTR screen using quad-scan at 0.2 nC and 1.5-mm cathode spot radius. Each time-slice is about 1 ps wide.

Finally, a transverse RF deflector is included to allow time-resolved measurements such as sliced emittance, sliced energy spread, and absolute bunch length. The RF deflector 'streaks' the bunch vertically across a nearby OTR screen so that the vertical axis becomes the time axis (Figure 4, left two). The time scale is accurately calibrated in degrees S-band (f = 2856 MHz) by scanning the RF deflector phase and recording the vertical beam centroid motion on the screen. Longitudinal phase space is also monitored by using the deflector with a screen after a bend (Figure 4, right). A time-sliced horizontal emittance measurement is shown in Figure 5 at 0.20 nC of charge and a 1.5-mm cathode spot radius using an OTR screen and a quad-scan, where the sliced emittance reaches 1.0 μm. The "BMAG" curve shows the beta mismatch amplitude with respect to the design (BMAG ≥ 1).

The emittance can be measured at 135 MeV using three screens, three wires, or a quad-scan on the center screen or wire. If the transverse cavity is switched on, the quad-scan on the screen produces the time-sliced horizontal emittance with sub-picosecond temporal resolution.

Beyond BC1 there is a second emittance diagnostic station at 250 MeV with three wire scanners and an OTR screen for scanning a quad. In addition, the time-sliced vertical emittance can be measured at the center of the chicane, where the time resolution is provided by the large energy chirp and dispersion. Figure 6 shows the horizontal projected emittance at 135 MeV using a quad-scan measured 80 times over almost 8 hours, averaging $\gamma\varepsilon_x$ = 1.38 μm ($\gamma\varepsilon_y$ = 1.47 μm). The charge (~0.2 nC) dropped after 4 hours causing the optimized emittance to increase a bit. The variations in emittance are larger over longer time scales and depend on the bunch charge and laser phase, which are not stable yet.

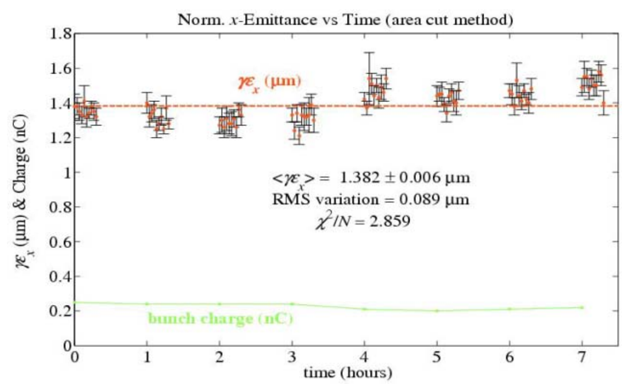

Figure 6: Hor. projected emittance measured over 8 hours.

SUMMARY

Commissioning is proceeding well, but cathode *QE* is quite low with poor uniformity. Laser shaping requires improvement, especially temporal; and machine stability, such as RF and laser phase variations, will need attention.

REFERENCES

[1] J. Arthur *et al.* SLAC-R-593, April 2002.
[2] P. Emma *et al.*, PAC'05, Knoxville, TN, May 2005.
[3] C. Limborg-Deprey *et al.*, Feb. 2005.
[4] L. Xiao *et al.*, "Dual Feed RF Gun Design for the *LCLS*", PAC'05, Knoxville, TN, May 2005.
[5] D.H. Dowell *et al.*, "Results of the SLAC LCLS Gun High-Power RF Tests", these PAC'07 proceedings.
[6] E. Jongewaard *et al.*, SLAC-PUB-7146, 1996.
[7] Z. D. Farkas *et al.*, SLAC-PUB-1561, 1975.
[8] P. Emma *et al.*, these PAC'07 proceedings.
[9] R. Akre *et al.*, PAC'01, Chicago, IL, June 2001.

