Commissioning the Linac Coherent Light Source injector

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The Linac Coherent Light Source is a SASE x-ray free-electron laser (FEL) project presently under construction at SLAC [J. Arthur *et al.*, SLAC-R-593, 2002.]. The injector section, from drive laser and rf photocathode gun through first bunch compressor chicane, was installed in the fall of 2006. The initial system commissioning with an electron beam was completed in August of 2007, with the goal of a 1.2-micron emittance in a 1-nC bunch demonstrated. The second phase of commissioning, including second bunch compressor and full linac, is planned for 2008, with FEL commissioning in 2009. We report experimental results and experience gained in the first phase of commissioning, including the photocathode drive laser, rf gun, photocathode, S-band and X-band rf systems, first bunch compressor, and the various beam diagnostics.

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I. INTRODUCTION

The months of April through August 2007 were spent commissioning the Linac Coherent Light Source (LCLS) injector. This is the first phase of machine commissioning, with the second phase starting in December of 2007 after a 3-month downtime, and the final phase in November of 2008, culminating in free-electron laser (FEL) light in 2009. First electrons from the new photocathode rf gun were observed on April 5 and beam was quickly established to the nominal injector energy of 250 MeV in the main SLAC linac on April 14, 2007. Over the next five months all injector systems were commissioned and the beam accelerated to as high as 16 GeV at the end of the SLAC linac. The bunch charge of 1 nC and measured transverse normalized emittance of 1.2 microns (at 135 MeV) meet the design brightness requirements of the LCLS. A list of typical measured machine parameters is shown in Table I, including ''design'' values at 1 nC of bunch charge.

II. DESCRIPTION OF THE INJECTOR

Figure 1 shows the major components of the LCLS injector located at the 2 km point of the 3-kilometer SLAC linac. The below-ground, off-axis housing was built during the original construction of the linac in 1962 [1], anticipating future injectors such as the LCLS.

The LCLS injector begins with a photocathode rf gun followed by two modified SLAC S-band (2.856 GHz) linac sections (L0a and L0b) producing a single electron bunch at a 10 to 30-Hz repetition rate (120 Hz in 2009) with an energy of 135 MeV and up to 1 nC of bunch charge. A low-energy (6 MeV) spectrometer is included just after the rf gun and the cathode drive laser is located above ground in a reconstructed alcove above the injector vault.

The 135-MeV beam is deflected onto the main linac axis by a two-dipole 35-degree achromatic bend. With these magnets switched off, the beam can optionally be transported to a 35-degree spectrometer for refined energy spread measurements. This spectrometer also allows the LCLS injector to operate simultaneously when a high-energy (30 GeV) beam is being accelerated in the 3-km linac. Once on the axis of the main linac, the LCLS electrons are accelerated to 250 MeV in three 3-m long S-band accelerating structures (L1S) before entering the first bunch compressor chicane (BC1). Located between these structures and BC1 is a 60-cm long X-band (11.424 GHz) 4th harmonic rf accelerating structure, which straightens the beam's longitudinal phase space for more linear bunch compression. Beam diagnostics for charge, position, energy, energy spread, beam phase,

TABLE I. Design and typical measured parameters.

Parameter	Symbol	Design	Measure	Unit
Final injector e^- energy	$\gamma_0 mc^2$	135	135	MeV
BC1 e^- energy	$\gamma_1 mc^2$	250	250	MeV
End of linac e^- energy	$\gamma_L mc^2$	14	16	GeV
Bunch charge	Q	1	1	nC
Initial bunch length (FWHM)	Δt_0	9	11	ps
Final bunch length (FWHM)	Δt_f	2.3	0.4–11	ps
Initial peak current	I_{pk0}	100	95	A
Projected normal emittance [a]	$\gamma\varepsilon_{x,y}$	1.2	1.2	μm
Slice normal emittance [a]	$\gamma\varepsilon^s_{x,y}$	1.0	0.9	μm
Slice energy spread (rms)	σ_E	<5	<6	keV
Single bunch repetition rate	f	120	10–30	Hz
rf gun field at cathode	E_g	120	115	MV/m
Laser energy on cathode	u_1	250	300	μJ
Laser wavelength	λ_1	255	253	nm
Laser spot diameter on cathode	$2R$	2.0	1.3	mm
Cathode quantum efficiency	QE	6	3.7	10^{-5}
Commissioning duration	$\cdots$	8	5	month

[a]Transverse emittance values are representative of 95% of the core bunch charge, as described below.

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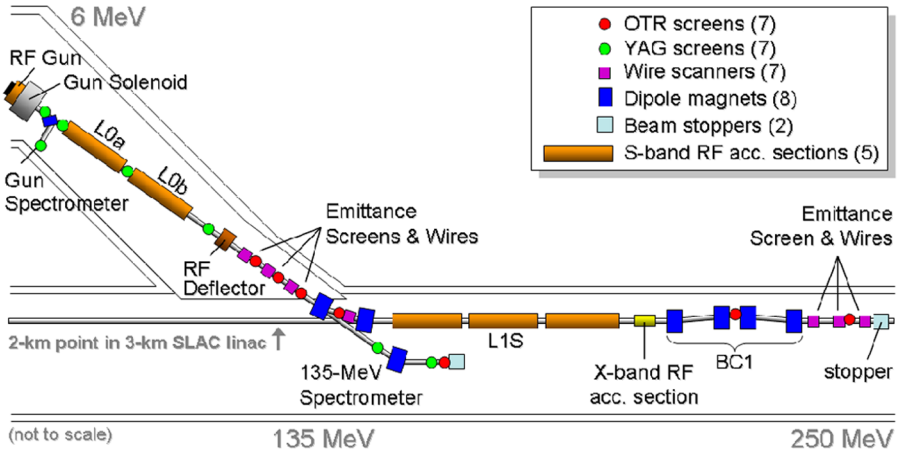

FIG. 1. (Color) The LCLS injector, from gun through first bunch compressor (BC1), with gun located in a separate, off-axis enclosure at the 2/3-point along the SLAC linac.

phase-space matching, bunch length, and emittance are located both upstream and downstream of the BC1, including time-resolved bunch measurements using an S-band transverse rf deflector. An insertable beam stopper is included six meters downstream of BC1 to allow aggressive injector tune-up without sending beam down the main linac.

A "laser-heater" system used to Landau-damp the microbunching instability [2] by increasing the uncorrelated energy spread in the beam will not be installed until the fall of 2008.

III. DRIVE LASER

The gun's copper cathode is illuminated by a UV laser operating at 253 nm delivering up to 500 microjoules per pulse at 30–120 Hz. In addition to the wavelength and energy, the laser must meet stringent stability and reliability requirements as well as strict transverse and longitudinal shaping specifications.

The drive laser was manufactured by *Thales Laser* and is a frequency tripled, chirped-pulse amplification system based on Ti:sapphire [3]. The system consists of a mode-locked Ti:sapphire oscillator, followed by a pulse stretcher, a Dazzler for pulse shape control, a regenerative amplifier, two multipass amplifiers, a compressor, and finally a frequency tripler, as shown in Fig. 2. The amplifiers are pumped at 120 Hz (mostly 30 Hz in commissioning) by two frequency doubled, Q-switched, qcw-diode-pumped Nd:YAG lasers (*Thales Jedi*). The amplifier produces 25 mJ per pulse at 760 nm with adjustable pulse duration between 3 and 20 ps. After tripling, the energy per pulse is typically 1.5–2.5 mJ at 253 nm. The system was designed to produce a flattop temporal profile, which was not fully achieved during initial commissioning. One of the optimal temporal profiles measured during commissioning with the scanning cross correlator (see below) is shown in Fig. 3. Work with the vendor after the first commissioning run, however, has greatly improved the temporal shape (not shown here).

Drive laser commissioning involved verification of the specifications and characterization of the optical transport system, diagnostics, and controls. The first part of the transport system is the spatial shaping. Initially an aspheric telescope was used to change the spatial profile from Gaussian to flattop. During commissioning this system produced a high-energy loss and was very sensitive to alignment. As a result, the design was changed to a simple imaged, overfilled aperture (laser iris). This provided a similar shape with higher energy and much less sensitivity to alignment.

The most critical part of transport system commissioning was installation and verification of the virtual cathode. The virtual cathode camera sits in an equivalent plane and provides a monitor of the position and shape of the drive

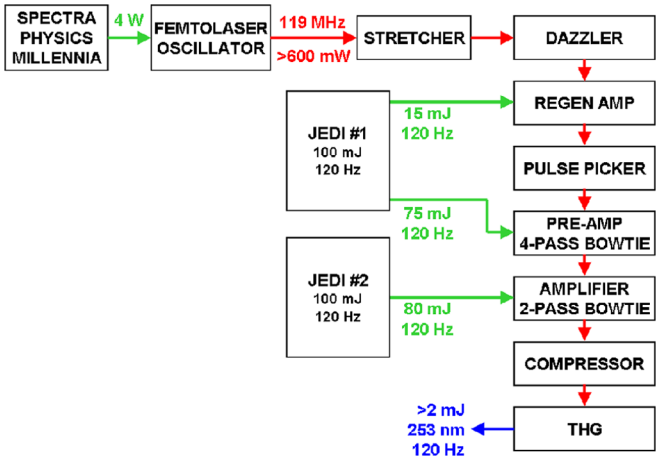

FIG. 2. (Color) Block diagram of the gun drive laser designed and built by *Thales Lasers*.

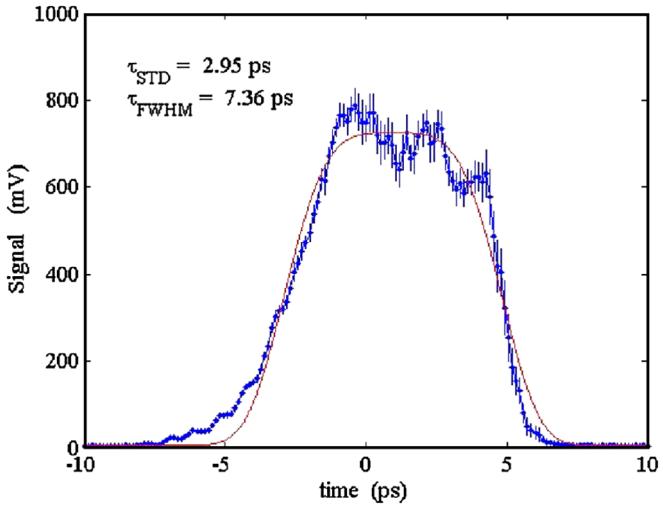

FIG. 3. (Color) Laser temporal profile, with 7.4-ps FWHM pulse length, measured (blue) on the scanning cross correlator, fit with an nth-order super-Gaussian curve (red): $f(t) = A \cdot \exp\{-|(t - t_0)/(2^{1/2}\sigma)|^6\}$.

laser spot on the cathode. A typical image of the virtual cathode taken during commissioning is shown in Fig. 4. Again, work with the vendor later, in the fall of 2007, has greatly improved the spatial shape (not shown here).

The UV light illuminates the cathode using near normal incidence with a symmetric pair of in-vacuum metal mirrors 50 cm downstream of the cathode and just 6.9 mm horizontally off axis. Only one mirror is actually used but the symmetric pair avoids transverse wakefields.

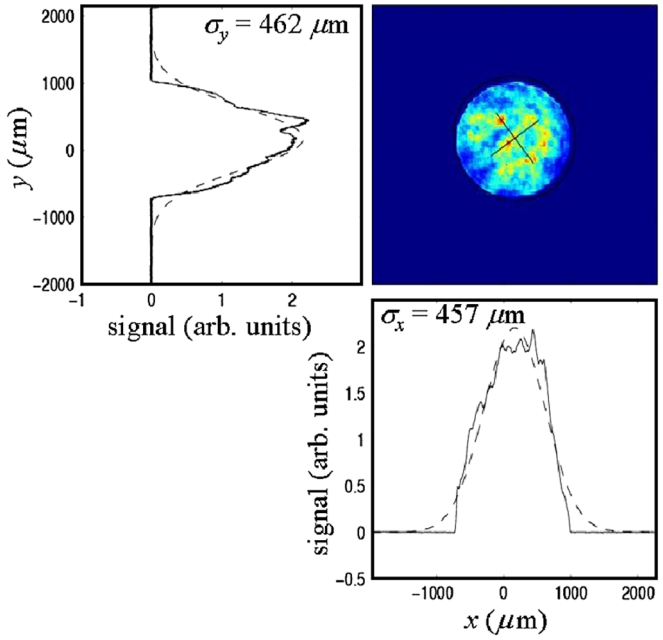

FIG. 4. (Color) The drive laser spot on the virtual cathode with horizontal (x) and vertical (y) projections over the full image. Gaussian (dashed) curves with the same rms are simply overlaid for comparison.

The laser is run at a constant energy and rate with a constant thermal load. Control of repetition rate is accomplished by using a pulse slicer to gate the system, allowing pulses to reach the cathode on demand, including 10-Hz, 1-Hz, or single-shot rate control. Amplitude control is accomplished by rotating a wave plate within the tripler. This changes the pulse energy while maintaining a constant thermal load on the amplifier system. Other controls involve pointing and centering feedback loops at several points throughout the transport system, allowing the control system to "lock" the position on the cathode to a specified location. Finally, calibrated energy meters record the pulse energy at various points throughout the transport system, most importantly at a point representing the cathode.

Temporal characterization is accomplished by use of two independent diagnostics. A *Hamamatsu Fesca 200* with 1-ps temporal resolution in the UV is used to directly measure the temporal profile. Both scanning and single-shot cross correlators were built, which allow the temporal profile to be measured by mixing the UV pulse with a <30-fs IR pulse from the seed oscillator in a beta barium borate crystal (see Fig. 3). The cross correlators have proven to be very robust and reliable and are fully integrated into the controls system.

Drive laser parameters are listed in Table II. With stable UV energy on the cathode, the relative electron charge stability was measured at 1.1% rms at 1 nC over 1 min at a 10-Hz electron repetition rate. This was measured using the sum signal from a stripline beam position monitor (BPM) just after the gun, recording each of 600 sequential beam pulses. The long-term variation is controlled using a feedback loop which varies the laser energy with an adjustable wave plate inside the IR-to-UV frequency tripler. Similarly, the centroid position variation of the laser spot was recorded late in the run, after many improvements, at 11 μm rms in both x and y at 10 Hz over about 1 min. With respect to a round laser rms spot size of $\sigma_R \approx 0.45$ mm (0.7 mm hard-edged radius), the relative rms position jitter

TABLE II. Typical drive laser parameters.

Parameter	Symbol	Value	Unit
UV wavelength on cathode	λ_1	253	nm
Spot diameter on cathode (edge)	$2R$	1.3	mm
Relative energy stability (rms)	σ_E/E	1.2	%
Pulse duration (FWHM)	Δt_{fw}	6	ps
Timing jitter with respect to rf (rms)	σ_t	0.16	ps
x and y centroid jitter (rms)	$\langle x, y\rangle/\sigma_R$	2.5	%
UV energy before transport	E_{UVb}	1.5	mJ
UV energy on cathode	E_{UVc}	0.3	mJ
Repetition rate	f	30–120	Hz
Unscheduled downtime/(6 months)	$\Delta\tau/\tau_0$	2	%