Stanford Linear Accelerator Center

Stanford Synchrotron Radiation Laboratory

LCLS Physics Requirements Document # 1.2-001	Injector	Revision 0

LCLS Injector Physics Requirements

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Brief Summary: This Document, the LCLS Injector Systems Requirements document, specifies the physics requirements for generating and accelerating the electron beam. It specifies performances for the laser system, the emittance compensation system, the laser heater system. It describes tolerances on components for emittance preservation. It also depicts diagnostics, stability and operational flexibility.

Keywords: Injector Laser, RF gun, Emittance, Linac, Diagnostics

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LCLS Injector Requirements

Introduction

In the Injector, the electron beam is generated and accelerated up to 135 MeV with a 120Hz repetition rate; it is then injected into the linac with the appropriate emittance, pulse length and energy spread [1]. The LCLS Injector components are located in the vault of sector 20. They include a laser system, a transport line of the UV pulse to the RF gun, a 1.6 cell S-Band RF gun operated at 120Hz, an emittance compensation solenoid, two accelerating cavities and a laser heater system. A schematic layout with main parameters, is shown in Figure 1 below.

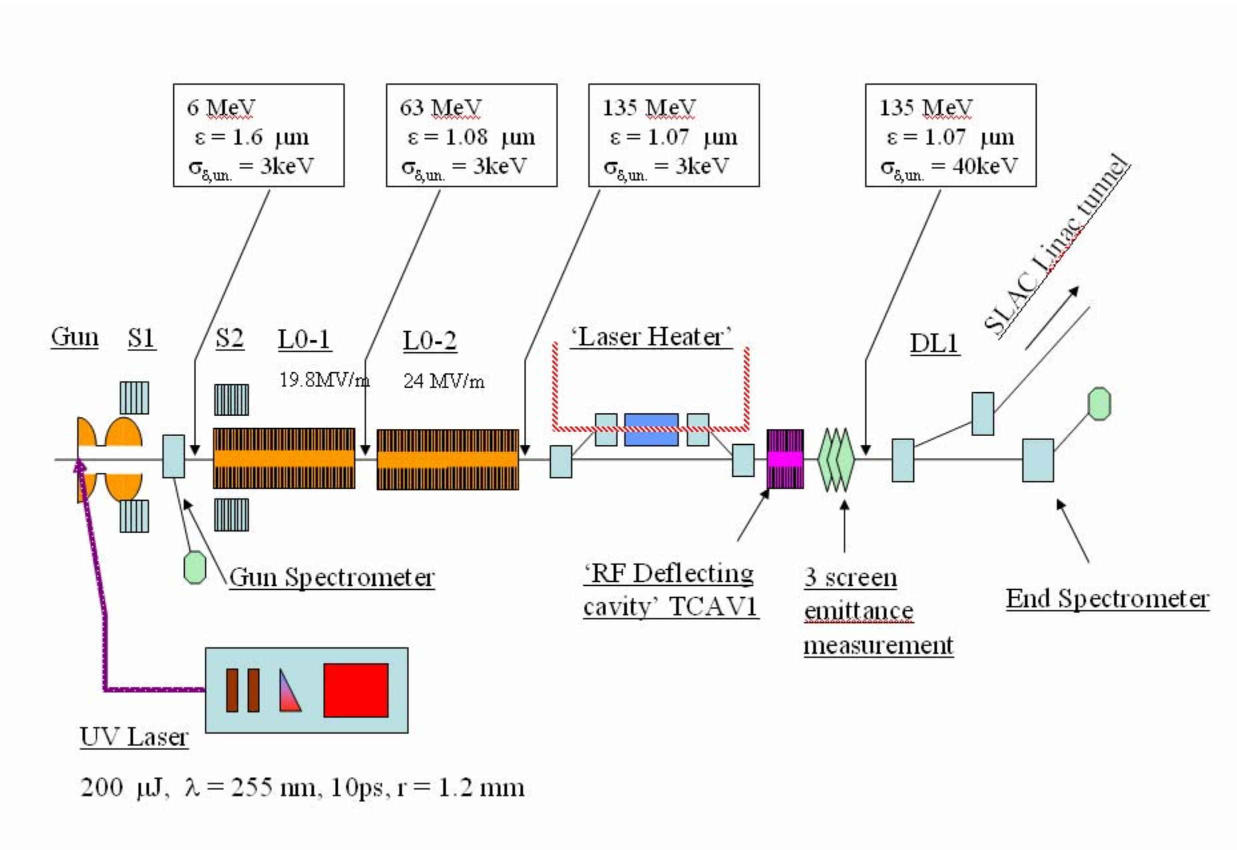

Figure1: LCLS PhotoInjector schematic layout with main parameters listed

Performance Goal

For reaching saturation at 1.5-A in the LCLS FEL, the slice emittance of the electron beam needs to be less 1.2 μm, the peak current more than 3.4 kA, and the slice energy spread smaller than 2.10^{-4} at the entrance of the undulator. To reach those goal parameters, the Injector has to provide a beam with slice emittance smaller than 1 μm and a projected emittance of less than 1.2 μm for a 1nC, 10ps long electron bunch. A slice emittance corresponds to the emittance of particles contained in each 1/100 length along the bunch length. The emittance values targeted for the Injector are obviously more restrictive than those required at the entrance of the Undulator to leave room for emittance growth in the linac and bunch compressors.

Commissioning of the Linac systems is scheduled to begin in September 2008. It requires at least 0.2 pC charge, a pulse length at least of 3 ps and a projected emittance smaller than 2 μm from the injector. Those performance goals are routinely obtained at the Gun Test Facility at SLAC.

Laser system

The laser system needs to provide UV pulses of at least 37 μJ with temporal and spatial structure as described in Table 1. This table also describes the range of tunability of the laser beam characteristics. More details are given in [2].
An Infrared laser system will provide the beam which will serve as the input for the ultraviolet (UV) conversion (third harmonic generation) unit to be used for photoemission at the cathode.
The UV pulse requirements mandate that the infrared pulse should have energy exceeding 25mJ, a 765nm wavelength, and 10nm bandwidth. A titanium-sapphire (TiS) oscillator will provide the performance when combined with a chirped pulse amplification (CPA) system. The 10nm bandwidth is small enough to limit the amplitude of the ripple on the plateau of the temporal profile but large enough to obtain rise/fall times of less than 1ps.
The generation of UV is accomplished using two stages of conversion based on non-linear crystals, and has an assumed conversion efficiency of 10%. Beam shaping and polarization tuning optics can be used before and after the first crystal to optimize the third harmonic conversion.
Spatial profile flattening will be accomplished with the aspheric optical system. The circular aperture and relay optics, which will image the UV beam to the photocathode with the appropriate magnification, will help to achieve the spatial profile and beam spot size requirements.

Laser beam transport and stability

The optical transport system includes a final UV beam steering stabilization apparatus, to position stability on the photocathode with an accuracy as good as 0.06 mm.
The losses in the transport line should not exceed 40% total. UV transport diagnostics will be located at the gun site in the tunnel to monitor UV pulse energy (incident and reflected from the photocathode) and the transverse spatial profile of the beam at the photocathode.
The UV beam prior to illuminating the photocathode, will go through the conditioning system, which will alter the beam properties (spatial anamorphism and time slew of the wave front) to meet the specifications.

	Parameter	**Symbol**	**Nominal Spec**	**Tolerance**	**Range**
Energetic	Wavelength	λ_{UV}	255nm	+5nm – 0nm	[255, 265]nm
	Pulse Energy	E_{UV}	>0.2mJ	<2% rms *	[0,0.2] mJ
Spatial	Fluence Profile	-	Uniform	<20% (ptp**)	-
	Spot Radius	R_{spot}	1.2mm	<4% (ptp**)	[0.3, 1.5] mm
	Centroid Offset	$\Delta_{r,y}$	< 0.12mm		[0.03,0.15]mm
Temporal	Repetition Rate	f_{rep}	120Hz		[1, 120] Hz
	Temporal Profile	-	Uniform	< 5 % rms	-
	Profile FWHM	τ_{fwhm}	10 psec	< 2 % rms	[2, 20] ps
	Rise/Fall time		1.0ps (10%-90%)	0.25 ps	[0.5, 2] ps
	Timing Jitter	$\Delta\tau$	< 0.5 psec rms		-

Table 1. Tolerance on UV laser beam properties at the cathode. Range of tunability.
* variation over multiple shots
** peak-to-peak

Emission

The emitting surface of the LCLS RF gun will be a copper photocathode. This photcathode will have a QE of 12×10^{-5} for our nominal injection parameters (120 MV/m, 30 degrees, r=1.2 mm, launching angle of 72 degrees to normal incidence, λ_{UV} = 255nm). Only 40 μJ of UV pulse out of the 200 μJ available will then be required to produce 1 nC [3]. The laser has been specified for providing 0.2mJ to offer a large flexibility of tuning including the lower injection phases, longer pulses and different radius spot sizes (see flexible operation section).
The "intrinsic emittance" (emittance at zero current) of the copper photocathode, when subject to standard preparation, has been measured to be of 0.6 μm per mm radiuis on existing 1.6 cell S-Band RF guns. In theory for a perfectly clean and flat surface, the "intrinsic emittance" is 0.3 μm per mm radius. All computations for the LCLS Injector have been done using the pessimistic value of 0.6 μm per mm.

Emittance Compensation

To provide slice emittance less than 1 μm and a projected emittance of less than 1.2 μm for a 1nC, 10ps long electron bunch, emittance compensation is performed at the early stage of acceleration. By accelerating appropriately the electron beam when its slices have been well focused to be aligned in phase space, the deleterious effects of strong space charge forces at low energy are compensated [4]. This compensation only corrects for the linear part of the space charge forces and the slice emittance does not reach the "intrinsic emittance"of 0.6 μm. The settings and location of the RF gun, the compensation solenoid and the first accelerating structure (L0-1) have been optimized to minimize the slice emittance.
For a perfect machine, the nominal tuning gives slice emittances of 0.9 μm for the core 80 slices out of the 100 slices constituting the bunch. Those slice emittances should remain smaller than 1 μm when fields are regulated to the values specified in the stability column of Table2, with a laser beam meeting specifications shown in Table 1 and with the adequate steering as described below, see also [5].

Parameter	Symbol	Nominal Value	Range	Unit	Stability
Gun RF Voltage	V_{RF}	120	+20 / - 10	MV/m	± 0.5
Gun Phase	$\varphi_{injection}$	27.25	+10/ -10	°S-Band	±0.1°
Gun Balance	E_{cell2}/E_{cell1}	1	±0.2	-	2.5%
Solenoid 1	B_{sol1}	2.723	[0, 3.5]	kG	± 0.02%
Solenoid 2	B_{sol2}	0.748	[0 , 2.2]	kG	±1%
Charge	Q	1	[0.2 , 1.05]	nC	±2% rms
Field L0-1	E_{L0-1}	19.8	[0 , 30]	MV/m	±0.5
Field L0-2	E_{L0-2}	24	[0 , 30]	MV/m	±0.5
Phase L0-1	φ_{L0-1}	2	-	° S-Band	±0.1 rms
Phase L0-2	φ_{L0-2}	10	-	° S-Band	±0.1 rms

Table2 – Specifications and operating range of Injector components

Electron beam Stability

Longitudinal:

Requirements on peak current and energy stability impose the tolerances on RF, bunch charge, laser beam energy, and gun timing. The RF phase variations will be stabilized to 0.1 ps rms. The laser energy will be stabilized to 2% rms. In addition to this pulse-to-pulse stability, long term stability will be provided by running longitudinal feedback systems on the bending magnets of DL1.

Transverse:

Good steering in angle and position at the entrance of the linac sections, most particularly L0-1, will be required to maintain a projected emittance smaller than 1.2 mm.mrad. Adequate BPMs and steerers have to be included in the Gun-To-Linac drift to achieve a steering to less than 150 μm in position and 120 μrad in angle. For achieving this, BPM resolution will be of 25 μm.

Laser Heater

The electron beam needs to be cold enough to undergo the FEL instability but warm enough not to suffer from instabilities. The LCLS injector system will incorporate an inverse free electron laser ('laser heater'), in order to introduce a large enough uncorrelated energy spread on the electron beam, to prevent a microbunching instability to develop in the bunch compressors.

A 20 ps long pulse, 2.4 mJ, 765 nm IR pulse from the main drive laser is transported to a four magnet chicane in the injector vault. It is superimposed upon the 10 psec e-beam in a 10 period undulator to increase the electron beam energy spread to 40keV rms. This superposition is made possible by the use of a 4 bend chicane which has very standard specifications (see PRD 'LCLS Laser heater Requirements' [6]).

Diagnostic Integration

Electron beam diagnostics are incorporated in the design of the Injector beamline. Names of monitors, screens and BPMs are given in [7].

The gun to Linac diagnostics will be used during commissioning for optimizing the emittance compensation. The emittance measurements (slice and projected) will then be performed at the end of the second accelerating section, at high energy to eliminate space charge effects.

Transverse

A thermal emittance measurement will be available at YAG1 screen, which provides information on the quality of the copper photocathode. An energy spectrometer at the exit of the gun will allow determination of the gun exit energy and the gun balance and to measure the slice energy spread and slice thermal emittance. The spectrometer magnet will be calibrated to determine the energy to 0.1 keV resolution. Two correctors (one in Solenoid 1 and the other in Quadrupole 1) will provide steering to the entrance of the linac within 150 μm in position and 120 μrad in angle with respect to the linac axis. This can be achieved with a BPM resolution of 25μm.

Three OTR screens (OTR1-3) at the exit of L0-2 will be used for emittance measurement. Their location was chosen to introduce 60 degree phase advance between, and thus to provide maximum resolution.

Both horizontal and vertical slice emittance measurement are made using either of the two techniques:

1- a vertically deflecting RF cavity [8], located downstream of the laser heater, will generate a time/position correlation. Horizontal slice emittance are then be deduced by using the three screen emittance measurement station on that time-projected beam.
2- the straight ahead spectrometer introduces a time/position correlation in the horizontal plane and images the beam at source point OTR2 onto the spectrometer screen OTRS1. Varying the quadrupole strength of QEO3 to measure beam size dimensions going through a waist in the vertical plane at the OTR2 location, the vertical beam sizes of slices will be measured at OTRS1, and vertical slice emittance deduced.

All the emittance measurements will be done to a precision of 10%.

Longitudinal

Bunch length measurements will be done using a streak camera on the Cerenkov Light emitted at a radiator located at YAG02 at the exit of the gun. Longitudinal temporal unformity will be observed at the gun spectrometer screen. An Electro-Optic (EO) device close to the entrance of dogleg 1 , will measure bunch length at 135 MeV before injection in the main linac. Those measurements should have a resolution of 0.5 ps, feasible with streak camera and easy to achieve on an EO measurement.

A direct longitudinal phase space measurement of the electron beam at the end of the Injector will be available on the OTRS monitor of the straight ahead spectrometer. A time-y correlation is introduced at the V-cavity and an energy-x correlation is produced at the bending magnet of the straight ahead spectrometer. From this time-energy projection, we will measure

- the uncorrelated energy spread with a resolution as small as 3keV.
- possible microstructure along the bunch
- distortion introduced by longitudinal wakefields along the beamline

The straight ahead spectrometer will also be used to measure the absolute energy at the "treaty point". This measurement relies on the calibration of the spectrometer magnet. A redundant measurement will be available at the BPM13 of dogleg 1 (DL1).

Charge

The electron bunch charge is initially measured in the Gun-To-Linac (GTL) section with toroid IM01, and should, in all probability, be constant over the injector. Final charge verification is made using toroid charge monitors IM03.

Flexible Operation

Low charge

It has been shown that present commissioning of the linac and lasing of the FEL can be supported with the demonstrated Gun Test Facility beam quality at 0.2 pC. For that reason, all diagnostics will operate for charges ranging from 0.2 nC to 1 nC. Other tunings for low charge and long bunch (10ps to 20ps) will be tested as simulations show that they provide much smaller slice emittances.

Long pulse operation for 1nC charge

The use of long pulses allows the reduction of the spot size on the cathode. The "intrinsic emittance" decreases linearly with the spot size radius and consequently the slice emittance, after emittance compensation, gets smaller than the nominal 0.9 μm obtained with 10 ps long pulse. With

20ps long pulse, and 1nC, slice emittances as low as 0.7 μm at the end of the Injector are expected. The laser system will accommodate such long pulses. Additional pulse shaping will also be necessary to compensate for the variation of emission due to the phase dependent Shottky effect which is RF phase dependent

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