LCLS Start-Up Test Plan

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Brief Summary: This document records the system Start-Up Test Plan for the LCLS X Ray Laser Facility.

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1 Introduction

We present our plan for commissioning the LCLS. The end result of this activity will be the generation of ultra-high power coherent X Ray FEL radiation, delivered to the Near and Far Hall hutches. Commissioning will be technically challenging. To generate X Ray FEL radiation it is necessary to simultaneously achieve extremely high brightness high current electron beams, precisely tuned undulator magnets, and an ultra-straight trajectory of the electron beam through the undulator magnets. Previous SASE FEL demonstrations operated at considerably longer wavelengths where many important tolerances are much relaxed. Besides the challenge of meeting the demanding tolerances, we anticipate grappling with new physical phenomena, such as instabilities due to coherent synchrotron radiation and space charge, in order to achieve our overall performance goals.

Acceptance and operational systems tests are identified in Section 3. In addition three sets of overall performance goals are set in Section 2 corresponding to three phases of commissioning. The goals for the final stage are aligned with project operational performance goals stated in the Global Requirement Document[1].

The schedule for the overall LCLS commissioning plan is described in Section 4. FEL commissioning will require concurrent commissioning of the X Ray Diagnostics and Optics system, primarily in the Front End Enclosure. Other commissioning activites — establishing X Ray beam(s) at the end station user hutches, and reaching full performance specs from the gun and linac — where possible are to be done in parallel with FEL commissioning.

2 Overall Commissioning Goals

The ultimate goal of the LCLS commissioning process is to demonstrate that we are able to consistently produce a stable ultra-bright coherent X Ray beam and reach our CD0 goals. The CD4 milestone of detecting X Rays in the Far Hall will be reached before the LCLS operates at CD0 levels. The demonstration is broken into three phases. For each phase there is a table of specific performance parameters which constitute intermediate goals before we reach the full LCLS design specification. In the first phase we rely only on gross properties of the electron beam. We will concentrate on making the beam-based alignment technique work smoothly, reducing radiation to negligible levels, commissioning X Ray diagnostics, and measuring spontaneous synchrotron radiation. During the second phase of FEL commissioning we will focus efforts on generating and measuring FEL photons. For this to happen electron beam properties will have to be closer to the final specifications. Tuning a low emittance beam through the linac and measuring gain curves with the trajectory bump method will be typical activities during this phase. The third and final phase of commissioning will be to establish full rep rate beams and stable operating conditions over the full energy range. Identifying and fixing sources of instability, and finalizing operational procedures for re-starting beams and changing energy will be the main activites.

2.1 Phase I - Spontaneous Radiation

Spontaneous radiation will be generated as soon as the electron beam passes through the undulator, no matter what the emittance or bunch length is, and can be used to begin commissioning the X Ray diagnostics. Table 1 lists specific performance goals for the first phase of commissioning. To obtain this level of performance will require stable electron beams, a well oiled beam based alignment procedure and fully functional electron beam and radiation detection diagnostics, and undulator segments field accuracy that is at least close to final specifications.

Table 1: Specific performance goals for Phase I LCLS commissioning.

e-beam energy		4.45 GeV	14.1 GeV
Orbit straightness	μm [rms]	30	30
Orbit stability	μm/day [rms]	10	10
Radiation λ	[nm]	15	1.5
Linewidth, (relative)		1/1000	1/1000
Rep Rate	[Hz]	10	10
Emittance $\gamma\epsilon_{x,y}$	[μm]	10	4
peak current	[A]	100	100
charge	[nC]	0.2	1
bunch length	[fs]	500	500

Table 2: Specific performance goals for Phase II LCLS commissioning.

e-beam energy		4.45 GeV	14.1 GeV
Orbit straightness	μm [rms]	9	3
Orbit stability	μm/day [rms]	3	3
Radiation λ	[nm]	15	1.5
Linewidth (relative)		1/2000	1/2000
Rep Rate	[Hz]	10	10
Norm. emittance $\gamma\epsilon_{x,y,slice}$	[μm]	2.5	1.2
peak current	[A]	1900	3400
charge	[nC]	0.5	1
bunch length	[fs]	250	250
saturation length	[m]	30	100
X Ray peak power	[GW]	19	8

2.2 Phase II - FEL Radiation

Once we are successful in attaining phase I performance parameters simultaneously our next goal will be to produce and detect FEL radiation. The final performance goals for this phase of commissioning are listed in Table 2.

The second phase of the commissioning will include measurements and analyses of gain curves and output X Ray intensites. Gain curves show the development of FEL power with distance along the undulator and are sensitive to errors such as undulator phase, K, tapering, and trajectory errors. The method we will use to make these measurements is called the "trajectory distortion method" and is described in Section 3.8. A gain curve measurement will also determine the saturation length and once an absolute calibration is made, determine the saturation power. X Ray beam properties will be measured primarily in the Front End Enclosure (FEE) and near hall hutches by the X Ray Transport, Optics, and Diagnostic System (XTOD).

For gain curve measurements FEL radiation will have to be distinguished from spontaneous radiation. The criteria we will use for establishing that FEL radiation has been produced is that the measurements show power amplification of a factor of ten over spontaneous radiation at the output of the FEL. A pulse frequency of 10 Hz would is adequate to demonstrate this goal.

Table 3: Specific performance goals for the final phase of LCLS commissioning.

e-beam energy		4.45 GeV	14.1 GeV
Und Radiation (max)	[Gy/day]	1	1
Repetition Rate	[Hz]	120	120
Radiation λ	[nm]	15	1.5
Photon energy spread	[%]	0.47	0.13
Peak Power	[GW]	19	8
Average Power	[W]	0.25	0.61
Peak Brightness	[units[a]]	8.5×10^{32}	0.64×10^{32}
FEL rms fund. trans. beam size	μm	31	28
FEL ms fund. trans. beam div.	μrad	3.8	28

[a] $ph/s/mm^2/mr^2$/0.1%bw

2.3 Phase III - Transition to Operation

The third and final phase of commissioning will bring the FEL performance up to full operating performance levels. These are listed in Table 3. Phase II activities establish the basic FEL performance inherently possible. Phase III demonstrates that we can consistently and reliably tap this potential so that the LCLS can be turned over to operations.

First any remaining deficiencies in FEL per pulse performance will be addressed. This might include cleaning up the FEL spot size, shape or linewidth. Then we will establish full rep rate beams and stable operating conditions over the full energy range. This is the time to really attack the stability beam problems such as power fluctuations or spatial instabilities by identifying the sources and coming up with remedies. Finally operational procedures need to be finalized for restarting the beams after a short downtime and for changing energies. These procedures will evolved from the informal set that are developed in the course of earlier commissioning. In commissioning during Phase III, control system programs need to be written and tested to perform these functions smoothly.

3 Detailed Start-Up Plan

Our overall strategy is to start commissioning with a modest quality electron beam and then turn to commissioning the FEL X Ray beam as the electron beam quality improves. In this manner we attempt to take maximum advantage of the availability of whatever quality beam can be delivered at any time. We have identified an intermediate set of “relaxed tolerance” parameters (section 3.7) which are adequate to observe FEL saturation at 4.45 GeV and should be relatively easy to meet. Thus with a low energy beam we can start to operate all hardware systems and study FEL physics behavior well before the final beam quality is achieved. Final X Ray power at 1.5 Å and coherence can only be developed after the beam emittance and undulator tuning parameters are both near the specified values. After full power has been attained at 15 Å and 1.5 Å we will increase the repetition rate and work on stability and transition to operations problems.

This Start-Up Plan begins with a discussion of systems that must be operational before electron beam can be launched from the injector. Next are sections covering the commissioning of the Injector, Linac, Undulator and Beam Based Alignment systems with an electron beam. The next three sections deal with the commissioning the X Ray beam: measuring its properties under different conditions and gain curve measurements showing the development of the X Ray power along the

Table 4: Critical design parameters for the LCLS Injector output beam.

Beam Parameter	**Symbol**	**Goal value**	**Tolerance**	**Unit**
Projected transverse emittance	$\gamma\epsilon_{x,y} \leq 1$ μm	< 1.2	0.05	μm
Time-sliced transverse emittances	$\gamma\epsilon_{x,y} \leq 1$ μm	< 1.0	0.05	μm
Time-sliced rms relative energy spread	σ_E/E_0	2.0	0.4	10^{-4}
Bunch length (FWHM)	Δ_t	10	0.25	ps
Bunch charge	Q	1.0	0.05	nC
Final electron energy	E_0	135	0.5	MeV
Trajectory stability	$\langle x\rangle/\sigma_x$	< 30		%
Energy stability	$\langle E\rangle/E_0$	< 0.5		%

undulator using the X Ray Transport, Optics, and Diagnostics System. The final section covers the commissioning of the X Ray endstations.

3.1 Safety Systems

Before any beam commissioning can begin modifications to three SLAC safety systems must be installed and commissioned. The Personnel Protection System (PPS) insures that no person can be in a potentially high radiation area when the beam is energized. The Machine Protection System (MPS) assures that there is no risk to equipment from undesirably steered electron beams. And the Beam Containment System (BCS) assures that it is virtually impossible for the beam to burn through the shielding under any credible scenario.

3.2 Pre-commissioning Status

For the purpose of this Plan, we assume LCLS start-up begins after the entire beamline is complete from the source to the electron beam dump, and the entire undulator system is installed. Diagnostics in the FEE are assumed to be installed and operational, beam related safety systems must be operational, the beam stopper in front of the undulator is closed. It is not necessary at start-up to have the X Ray Transport Hall and beyond operational, though beam stoppers in the Near Hall will need to be operational to block the X Rays from going downstream of the Near Hall hutches.

3.3 Injector

The Injector is where the electron beam is born and so it is the first system to start commissioning with beam. It is designed to transport a single 1-nC electron bunch at 120 Hz to the Linac entrance with an output energy of 135 MeV, a projected emittance of $\gamma\epsilon_{x,y} \leq 1.2$ μm, and a time-sliced emittance of $\gamma\epsilon_{x,y,slice} \leq 1$ μm, and a pulse length of less than 10 ps. The beam is then injected in the main linac for further acceleration and compression.

When the Injector laser has produced its design parameters, in energy (200 μJ per pulse at 255 nm) and shape (10 ps flat top, transversally uniform of radius 1.2 mm), a 1 nC, 10 ps electron bunch will be accelerated in the gun. A series of measurements will be performed to tune the injector and produce a beam with the required performances at the end of the injector. The required design parameters performances are listed in Table 4.

Provisions have been included in the injector design to support these measurements. Each parameter test is briefly described in the itemized list below.

Projected transverse emittance The projected transverse emittance will be measured using the beam size at three beam size monitors to do a "three screen' emittance measurement. The screen locations were chosen to maximize the resolution by setting the phase advance to 60 degrees between them. the beam size monitors will be OTE screens (OTR1, OTR2, OTR3). Another type of emittance measurement will also be available: the standard "quadrupole scan". By varying the quadrupole strength of QE03 and observing the variation in beam size at the OTR2 screen, the emittance will be deduced. This measurement is very critical, so the redundancy which comes for free will be very useful.

Time-sliced transverse emittance In the horizontal plane, the time-sliced transverse emittance will be measured by using the transverse deflecting cavity (vertical deflection), which introduces a time/position correlation, in conjunction with the three screen emittance diagnostic. From the variation of beam size for individual slices, we will deduce the time-sliced horizontal emittance. A similar measurement will be made in the vertical plane. 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 introduce beam size variation in the vertical plane at the OTR2 location, the vertical slice beam sizes will be measured at OTRS1. A similar measurement can be performed using the OTR monitor OTR4 of the dogleg DL1.

Time-sliced rms energy spread Similar to the emittance measurements described above, the time-sliced (relative) energy spread is measured on a dedicated OTR screen (OTR4), again using the transverse RF deflector by observing the horizontal beam size at the spectrometer screen (OTRS1). Simulations indicate that this measurement can be made at the resolution necessary to meet the Table 4 specifications.

Final rms bunch length The electron bunch length prior to injection into the linac is measured at the same time as the time-sliced energy spread, using OTR2 and with the transverse RF deflector switched on. In this case, the vertical beam size directly reflects the final absolute rms bunch length. Simulations indicate that this measurement can be made at the resolution necessary to meet the Table 4 specifications. Three electro-optic (EO) instruments will also be available along the beamline (BL01-3). The bunch length at the entrance of the linac will be available on the EO monitor BL03.

Bunch 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. Charge measurements at the 5% level, consistent with the Table 4 specifications, are possible using these toroids.

Final electron energy The final electron energy is measured at both the spectrometer monitor OTRS1 and at OTR4 of DL1. The dipole field strengths will be known to better than 1%, allowing for a final energy measurement which meets the Table 4 specifications.

Energy stability Several BPMs will also be located at dispersion locations where the beam position is highly sensitive to electron energy variations. Relative measurements from shot-to-shot will be available at the level of 1 MeV, again easily meeting the Table 4 specifications.

Intermediate measurements in Gun-to-Linac section In the early stage of commissioning, measurements will be performed at the exit of the gun. Both the energy and energy spread will be measured at the gun spectrometer. Simulations have shown that a 10 keV resolution should be achieved for the energy spread. The spectrometer magnet field will be know to better than

Table 5: Critical design parameters for the LCLS Linac output.

Beam Parameter	**Symbol**	**Goal value**	**Tolerance**	**Unit**
Time-sliced transverse emittances	$\gamma\epsilon_{x,y} \le 1$ μm,	1.2	0.3	μm
Time-sliced rms relative energy spread	σ_E/E_0	1.0	0.3	10^{-4}
Final rms bunch length	σ_z	22	3	μm
Bunch charge	Q	1.0	0.05	nC
Final electron energy	E_0	14.1	0.3	GeV
Trajectory stability	$\langle x\rangle/\sigma_x$	< 30		%
Energy stability	$\langle E\rangle/E_0$	< 0.2		%

1% giving a 1% resolution on the energy at the gun exit. A thermal emittance measurement will be done at very low bunch current (5pC) by varying the solenoid current and observing beam size variations at the first screen YAG01

3.4 Linac

The LCLS linac is designed to transport a single 1-nC electron bunch at 120 Hz to the FEL undulator with adequate energy, emittance, charge, energy spread, and stability to operate the FEL at its shortest radiation wavelength of 1.5 Å.

When the LCLS injector has produced its design parameters, especially with respect to the time-sliced transverse emittance goal of $\gamma\epsilon_{x,y} \le 1$ μm, the linac output beam can then be passed through a series of measurement tests to confirm the linac output design parameters have been achieved. These critical design parameters are listed in Table 5.

Provisions have been included in the linac design to support these measurements. Each parameter test is briefly described in the itemized list below.

- **Time-sliced transverse emittance** A well placed OTR screen (OTR33) has been designed into the pre-undulator transport line which, when used in conjunction with the transverse RF deflector in sector-25, and a specific quadrupole strength variation (QEM3), will support this measurement in the x-plane. The same measurement in the y-plane is accomplished on a separate OTR screen (OTR21) in the BC2 chicane, without the use of the RF deflector. Simulations indicate that this measurement can be made at the resolution necessary to meet the Table 5 specifications.

- **Time-sliced rms energy spread** Similar to the emittance measurements described above, the time-sliced (relative) energy spread is measured on a dedicated OTR screen (OTR30), again using the transverse RF deflector in sector-25, by observing the horizontal beam size. Simulations indicate that this measurement can be made at the resolution necessary to meet the Table 5 specifications.

- **Final rms bunch length** The electron bunch length prior to the FEL undulator is measured at the same time as the time-sliced energy spread, using OTR30 and with the transverse RF deflector in sector-25 switched on. In this case, the vertical beam size directly reflects the final absolute rms bunch length. Simulations indicate that this measurement can be made at the resolution necessary to meet the Table 5 specifications.

- **Bunch charge** : The electron bunch charge is initially measured in the injector, and should, in all probability, be constant over the linac. Final charge verification is made using toroid charge monitors designed into the pre-undulator beamline. Charge measurements at the 5% level, consistent with the Table 5 specifications, are possible using these toroids.

- **Final electron energy** The final electron energy is easily verified when the bunch has passed the final pre-undulator beamline dipole magnets. The dipole field strengths will be known to better than 1%, allowing for a final energy measurement which meets the Table 5 specifications.
- **Trajectory stability** The x and y beam position and angle will be monitored by non-intercepting Beam Position Monitors (BPMs) incorporated into the beamline design, which will be used to measure shot-to-shot (120 Hz) trajectory variations. These BPMs will have resolution at the 1-5 μm level and therefore will easily meet the Table 5 specifications.
- **Energy stability** Several BPMs will also be located at dispersion locations where the beam position is highly sensitive to electron energy variations. Relative measurements from shot-to-shot will be available at the level of 1 MeV, again easily meeting the Table 5 specifications.

3.5 Undulator

There are two main Undulator system start-up tests: One is a test that the Beam-Based Alignment system works properly (Section 3.6). The other is a demonstration that the magnetic field quality and alignment of the installed undulator segments meet design specifications by measuring properties of the FEL X Ray output and the properties of the input electron beam, and comparing with theoretical calculations. This latter demonstration is described in Section 3.7 and includes measurements of FEL radiation at long wavelength and a set of gain curve measurements.

3.6 Beam-Based Alignment (BBA)

Once a stable 10 Hz beam to the dump has been obtained we can procede testing the BBA system. We will start with a 14.1 GeV beam which should have the minimum orbit excursions, and work down to lower energy beams.

BBA Verification After the BBA procedure has been initially applied 2-3 times, it will be very useful to verify its convergence. This verification can be done during the procedure itself. As the procedure is iterated, the trajectory sensitivity to large energy changes should be reduced with each application. Initially, depending on the initial quadrupole misalignment levels (50 μm rms assumed here), the trajectory will change by the order of 500 μm as the energy changes from 14 GeV down to 4.5 GeV (see Fig. 2). After 3 passes of BBA, this sensitivity should be reduced to < 50 μm (see Fig. 3). Note that since the BPM offsets will also be known to a high degree of precision (2-3 μm rms), the 4.5-GeV trajectory can be straightened simply be carefully steering the BPM readings back to zero, allowing FEL commissioning at long wavelength.

3.7 FEL Commissioning at Long Wavelength

At the time of initial FEL commissioning it is possible that the electron beam will not have achieved its final goals for brightness. It may have a significantly larger transverse emittance, a reduced bunch charge and peak current, and less than ideal undulator trajectory. On the other hand we have a real possibility of producing significant amounts of FEL radiation at 4.5 GeV with substantially less than optimal electron beam and undulator system performance, though such a beam won't produce FEL radiation at 14.1 GeV. A set of relaxed tolerances has been identified through simulations which

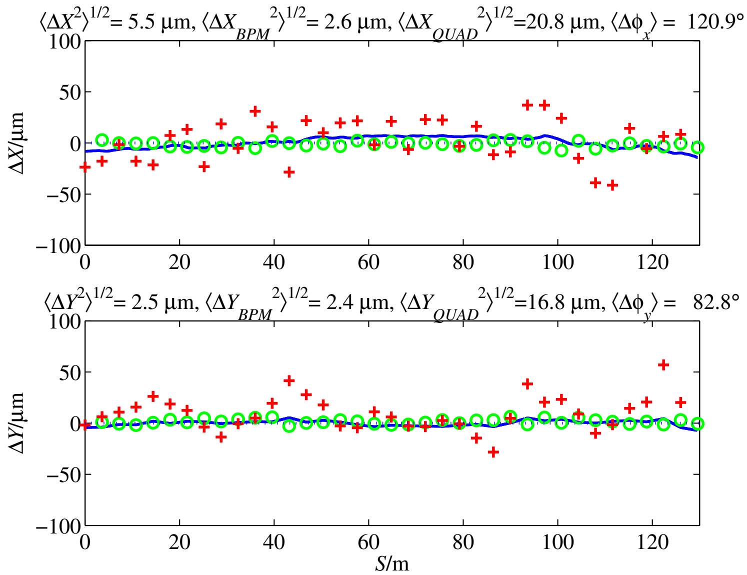

Figure 1: Trajectory (solid lines: X top, Y bottom) through undulator at 14 GeV after 3 passes of the BBA procedure. The crosses represent the quadrupole center positions while the circles are the BPM readbacks.

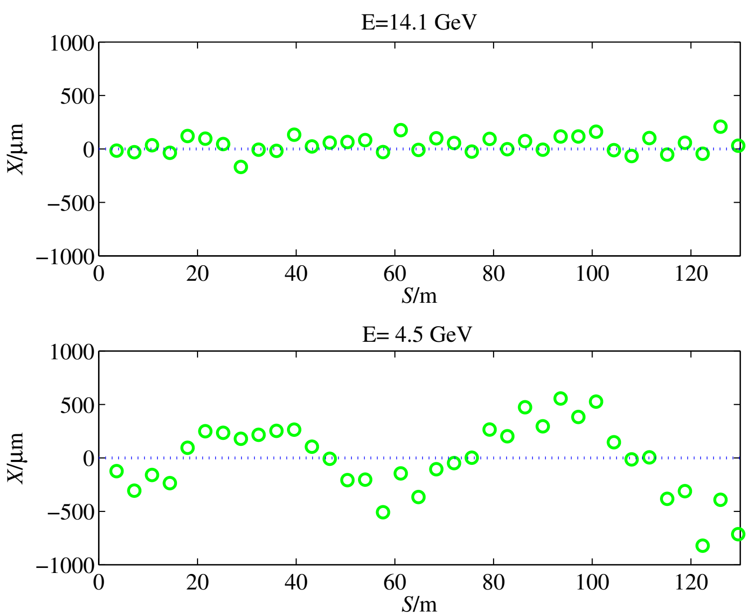

Figure 2: BPM readbacks of trajectory through undulator at 14 GeV (top) and 4.5 GeV (bottom) after rough steering, but before the BBA procedure, where trajectory changes with energy are exepected at the 500-μm level.

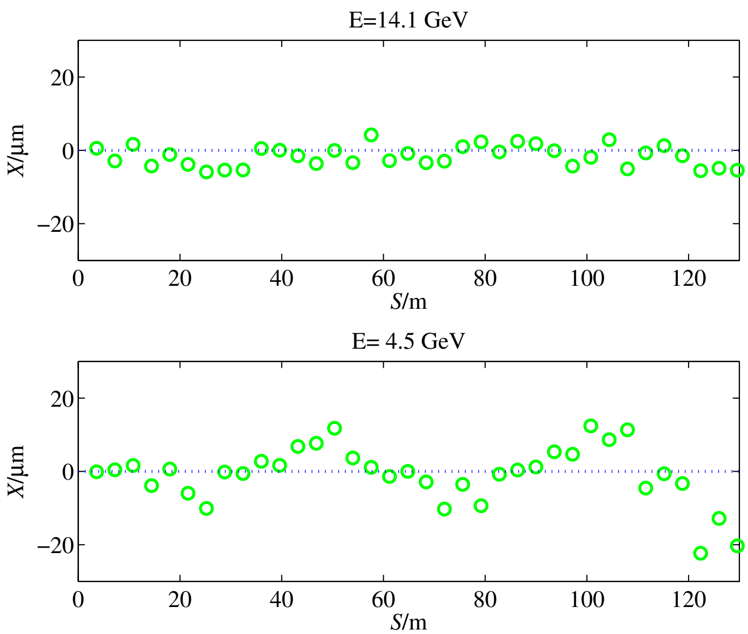

Figure 3: BPM readbacks of trajectory through undulator (note scale change) at 14 GeV (top) and 4.5 GeV (bottom) after three rounds of the BBA procedure, where trajectory changes with energy are exepected at the 20-μm level.

should allow us to just reach full saturation at 4.5 GeV. These are shown in Table 6. Depending on the state of the electron beam we may elect to start measurements at 4.5 GeV, for which FEL generation is likely, or start at 14.1 GeV for which the diagnostics performance is better.

The 15 Å wavelength can easily be established by switching off the L3-linac RF, re-scaling the magnets, and re-matching the beam size into the permanent-magnet undulator FODO-array. Undulator beam-based alignment can then be performed with reduced expectations for these initial commissioning exercises. At $\lambda_r \approx 15$ Å, the undulator BPM resolution is less demanding by a factor of about three ($\sqrt{\lambda_r/1.5\ \text{Å}}$). Simulations have shown that a BPM resolution of 2 μm is adequate to do beam-based alignment at 1.5 Å therefore a relaxed BPM resolution of 6 μm (or less) is acceptable at 15 Å.

In these initial FEL commissioning tests it is most important that some significant FEL power be available to boot-strap the various systems, such as the undulator precision, the X Ray diagnostics, and the electron beam characterization. A list of electron beam and undulator parameters needed to provide significant FEL power at 15 Å is shown in Table 6, where the 1.5-Å baseline parameters are also shown for comparison. With safety margins of greater than a factor of 3 on the emittance and peak current, a factor of 2 on the bunch charge, and a factor of 3 on the BPM resolution, the possibility of significant FEL power available early in the commissioning stages becomes quite good. With FEL power available, the gain curve can be measured and used to diagnose and localize potential undulator errors. In addition, the electron beam can then be characterized and compared with beam diagnostic measurements. As the systems are commissioned, allowing a basic understanding of the undulator, diagnostics, and electron beam, the FEL wavelength can be reduced in stages toward more challenging levels, from perhaps 15 Å to 10, to 5, and eventually to 1.5 Å. This is highly

Table 6: Electron beam properties and relaxed tolerances consistent with reaching saturation at 4.5 GeV

parameter	**symbol**	**15.0 Å**	**1.5 Å**	**units**
electron energy	E_0	4.45	14.1	GeV
bunch charge	Q	0.5	1.0	nC
transverse norm. emittance	$\gamma\epsilon_{x,y}$	4.0	1.2	μm
final peak current	I_{pk}	1.0	3.4	kA
final rms bunch length	σ_z	44	25	μm
final rms energy spread	σ_E/E_0	1.8	1.0	10^{-4}
rms e^- beam size	$\sigma_{x,y}$	67	33	μm
FEL parameter	ρ	5.7	4.5	10^{-4}
est. und. BPM resolution	σ_{BPM}	6	2	μm
3D gain-length × 20	$20L_G$	115	85	m
FEL power at saturation	P_{sat}	0.7	18	GW
orbit straightness (per 10 m)	δx	6	2	μ m
segment tuning	$\Delta B/B$	4	1.3	$\times 10^{-4}$ (rms)

preferred over a one-step commissioning process at 1.5 Å, where no FEL power may be available initially.

3.8 Gain Curve Measurement

Measurement and interpretation of X Ray energy gain curves is the principle test of the FEL process of converting electron beam energy into coherent X Rays. It can help diagnose deficiences in:

- segment tuning 'K' or alignment
- segment phase slip
- segment to segment spacing
- unexpected behavior in the FEL process
- degradation of the electron beam phase space
- trajectory errors
- energy spread or chirp

Our method of measuring the gain curve is called the "trajectory distortion method" . The FEL gain curve can be measured with sufficient trajectory distortions that stop the FEL interaction near points of these distortions. The method has been demonstrated to be effective in the TTF1 FEL saturation study. For the LCLS, we can apply this method with a single X Ray diagnostic station installed at the end of the undulator beam line. Since the FEL fundamental mode at 1.5Å, has an rms divergent angle less than 1 μrad, a collimator can be used to separate the FEL power and the large spontaneous power emitted in the entire undulator with an opening angle $\sqrt{1+K^2/2}/\gamma \approx$ 100 μrad. Alternatively, data taken with a large acceptance angle can be analyzed to identify the "hot spot" of the FEL mode. Thus, in GENESIS simulation runs, we have examined the effect of

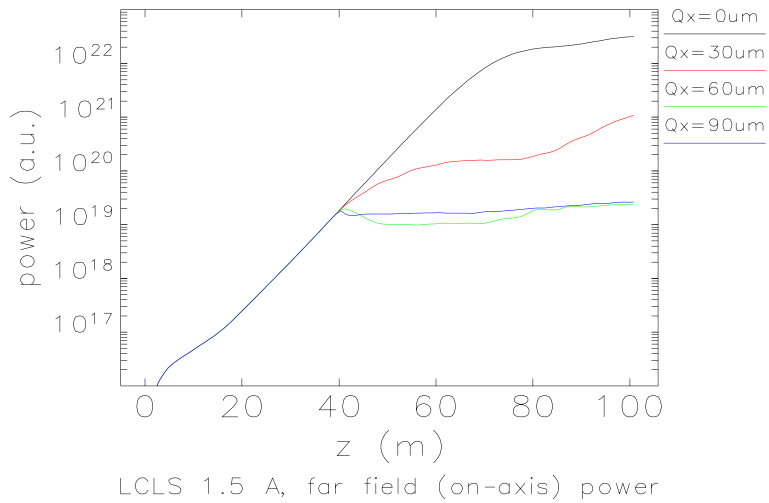

Figure 4: GENESIS simulation of the far-field power for a quad offset at $z = 40$ m undulator.

orbit bumps to the on-axis radiation intensity only. Suppose a quad is offset horizontally relative to the undulator axis by a distance Q_x, creating a betatron motion from that point with the maximum amplitude given by

$$\beta_x(z)\frac{Q_x}{F} \approx 2Q_x, \tag{1}$$

where $\beta_x(z)$ is the horizontal beta function at the location of the quad offset, and F is the focal length of the thin quad. Figure. 4 shows that $Q_x = 60$ μm can stop the FEL interaction after $z = 40$ m (a vertical offset has the similar effect), yielding an approximately constant on-axis radiation intensity which can be detected by the X Ray diagnostics at the end of the undulator. Similar conclusions hold for a 60-μm quad offset at $z = 20$ m and $z = 60$ m.

Other methods for measuring gain curves were investigated as part of the Diagnostics and Commissioning Workshop held at UCLA, Jan 19-20, 2004[2].

3.9 X Ray Transport, Optics, and Diagnostics System

Here we face the problem of trying to bring up and understand a new source while simultaneously trying to bring up and understand a new set of diagnostic detectors. Typically one first brings the source up to a level that saturates the detectors, then keeping the source constant, measures the linearity of the detectors by inserting known attenuators in front of the detector. Once having"commissioned" the detector, one can begin the investigation of the source by varying parameters that affect source power while always inserting appropriate attenuators in front of the detector to keep it in the linear regime established in the previous step. The LCLS case has the additional complication that the attenuators may be suspect at high fluences.

Prior to installing the camera/scintillator and ion chamber packages at the LCLS, we should try to verify their sensitivities and linear regimes at SPEAR or SPPS. We certainly will have to measure the angular dependence of the reflectivity of the indirect imager's Be mirrors at SPEAR prior to their installation at the LCLS.

Presumably, after installation at the LCLS, a stable beam of spontaneous radiation can be produced with enough (low) power to saturate the direct imager and produced signals on the indirect imagers and ion Chambers. Here we would start out with the highest energy photon beam, as we're not trying to make FEL radiation. Then using solid attenuators we would go through and verify the alignment and sensitivities/linearity of each of the detectors. This process would be repeated for different Linac energy settings down to the lowest.

At the lowest photon energies, still with a stable spontaneous beam, we would test the gas attenuator for linearity using the upstream and downstream cameras. At this point the detector and attenuation systems should be understood well enough to bring power levels up and look for lasing.

We have a choice in the detector/attenuator configurations that we can use when we first bring up the FEL. The simplest scenario would be to start in the upstream diagnostic tank, which has the least obstructed view of the spontaneous. We will use the direct imager placed directly in the beam and use thin Be foils to keep the signal in the linear regime as we bring up the power. Assuming that our first attempts are at the lower Linac energies, an array of Be foils of thicknesses down to five or 10 microns would be needed. At the lowest Linac energies, at this position, the FEL would appear as a bright spot with an FWHM of 350 microns.

At some point as the FEL achieved full power at the lowest energies, the FEL will begin to damage the Be foils. We could then switch to the indirect imagers, or retreat behind the gas attenuator.

The main uncertainty is the performance of the attenuators and the backgrounds they induce. As we work our way up in FEL power we must constantly check the linearity of our attenuators.

Diagnostics in the FEE The FEE is a 40 meter section of tunnel between the end of the undulator and the near hall where the electron beam is separated and dumped and were initial diagnostic and beam conditioning equipment will be located. It is expected that the diagnostics in the FEE will be operational shortly after the completion of the Undulator installation and therefore will be available for the first light.

The FEE beam line has the following components: 1) a fast close valve, 2) a pair of horizontal and vertical slits, 3) a Diagnostics Tank containing imaging Diagnostics, 4) a gas attenuator system 5) a solid attenuator, 6) another Diagnostics Tank, and 7) a final set of horizontal and vertical slits.

The two sets of slits are to allow beam to be delivered to the experimental hall's stripped of much of the spontaneous. The solid attenuator is a block of low Z material that can be inserted into the beam to attenuate the FEL. The gas attenuator is used at lower photon energies that would damage the solid attenuator. The diagnostics before and after the attenuator are, in the long-term, to monitor the attenuator and slits, and, in the short term, to measure the beam intensity and footprint in the very early commissioning stages of the LCLS.

To mitigate some of the technical risk, and to span the full range of FEL photon energies, the imaging diagnostics in the Diagnostics Tanks come in three varieties with partially overlapping operating regimes. Each diagnostic tank contains the following systems:

- **Direct Scintillation Imager** An insertable, high-resolution scintillator viewed through a microscope objective by a CCD camera for measuring spatial distributions and for alignment and focusing of optical elements. The scintillator is a 100 micron thick Ce doped YAG or LSO crystal. The camera can be configured to have a FOV of 2 to 10 mm with a spatial resolution of 2 to 20 microns

  Placed directly in the beam, the direct scintillation imager will saturate even in response to one pulse from the spontaneous at modest power levels. A set of low-Z foils in front of the camera will attenuate the beam enough to allow unsaturated imaging of the spontaneous radiation pattern at full power.

Direct exposure to the FEL beam will damage the crystal in one pulse. At FEL photon energies above 4000 eV thicker blocks of B4C and Be can be used to attenuate the FEL beam by a factor of 10^{-4}, enough to image it with the Direct Scintillation Imager. In this case the high spatial resolution of the camera will allow the FEL to be spatially separated from the spontaneous. At lower photon energies the solid attenuators will suffer damage and the gas attenuator must be used to lower the intensity of the beam.

The chief technical risk is in our understanding of the photon attenuation and transport through the solid attenuators and their damage thresholds at the FEL fluence levels. Although relatively simple, the Direct Imager will totally block the beam, limiting its usefulness.

- **Indirect Imager** The Indirect Imager utilizes a thin foil of a low Z Be to act as a beam splitter to partially reflect a portion of the beam onto the crystal of a (Direct) imaging camera which remains out of the beam. The reflected intensity can be adjusted by changing the angle of incidence. A reflectivity of 10^{-4} can be obtained with an incident angle of 1° at 8 keV and an incident angle of $> 2^\circ$ at 0.8 keV.

  At the higher energies the Beryllium foil will be transparent and a significant fraction of the beam will be transmitted downstream. This will allow pairs of these detectors to monitor the radiation going into and out of another instrument.

  If indeed the reflector has a higher damage threshold than a normal incidence optic, the indirect imager will work at all FEL photon energies although it will only be transparent at the highest energies. Another foreseeable problem with this concept is the background X Ray radiation impinging on the crystal due to Compton scattering of the FEL beam by the Be foil, and any fluorescence from an oxide layer on the foil surface.

- **Micro-Strip Ion Chamber** The third detector measures the ionization produced by the FEL as it traverses a small amount of gas. The gas is trapped between two differentially pumped sections so there can be no windows or other solids in the beam. By segmenting the anodes and cathodes into strips parallel to the beam direction, we hope to obtain limited spatial information on the profile of the beam sufficient to separate the FEL from the spontaneous.

  The microstrip ion chamber will provide spatially resolved profile data at all FEL photon energies. The utility of this device depends on the performance of the microstrip anode and cathodes arrays. Quantitative interpretation of the data also depends on our understanding of the physics of the gas interactions at FEL fluence levels.

Diagnostics in the Commissioning Diagnostics Tank The "Commissioning Diagnostics" tank will be located in the third hutch of the NEH, approximately 65 meters from the end of the Undulator. Because of its location at the end of the near hall these diagnostics will probably not be in place for several months after the first light, and in any case will require a slightly more stable and controlled FEL operation. Most measurements will have to be done with an attenuated FEL beam to prevent damage to the instrumentation.

The "commission" diagnostics are intended to measure the basic FEL performance parameters during commission and are allowed to be "intrusive". The goals of the commissioning diagnostics are to measure

1. Total pulse energy.

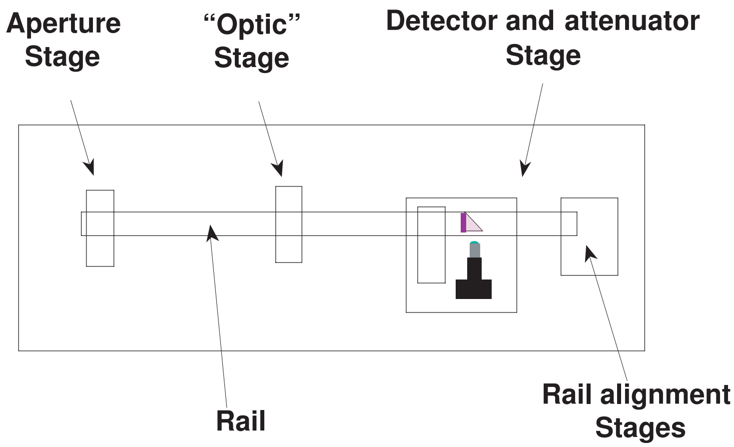

Figure 5: Commissioning diagnostic tank

2. Pulse Length
3. Photon Energy Spectrum
4. Transverse coherence
5. Spatial Shape and Centroid location
6. Divergence

The commissioning diagnostic tank has a central optical rail and stages for apertures, optics, a Direct Scintillation Imager, and other hardware common to these measurements. The specific equipment needed to perform specific measurements such as the calorimeter, will be set up, and taken down as needed.

Total Energy It is desirable to measure the FEL pulse energy utilizing calorimetric techniques to avoid any reliance on the theory of photon-atom interactions at LCLS intensities.

The calorimeter has a small volume X Ray absorber which absorbs all of the X Ray energy resulting in a rapid temperature rise. The heat capacity and mass of the absorber determine the temperature rise. For a 1% measurement, the thickness of the absorber must be at least 5 mean free path lengths in order to capture better than 99% of the X Ray energy. The sensor measures the temperature rise of the absorber. The thermal mass of the sensor is be small compared to the absorber. The heat in the absorber is conducted through the thermal semiconductor to the heat sink. The purpose of the thermal semiconductor is to delay the heat transfer from the absorber to the heat sink long enough to measure the temperature rise in the absorber. The heat sink is held at a constant temperature. The energy deposited by the X Ray is conducted into the heat sink before the next X Ray pulse. The thermal conductivity of the absorber, the thermal conductivity of the thermal semiconductor, the geometry of the absorber, and the geometry of the thermal semiconductor control the rate at which the heat in the absorber is conducted to the heat sink.

For 8 keV operation the absorber will be a Si cylinder 0.5 mm in diameter and 0.5 mm thick. The 0.5 mm thickness is $>$ 5 attenuation lengths and the 0.5 mm diameter nicely accommodates the $\sim$ 340 microns FWHM diameter of the 8 keV FEL at the position of the commissioning diagnostics tank. The dose at 8 keV to Si in this position is 0.12 eV/atom, which is acceptable for a simple absorber.

For 0.8 keV operation the absorber will be a Be disk 3 mm in diameter and > 25 microns thick since the dose to Si at this wavelength is too high. The 3 mm diameter is necessary to contain the 0.88 keV beam whose diameter at this position is 1.9 mm FWHM.

The calorimeter will be positioned on the optics stage in the commissioning tank allowing it to be aligned utilizing the rear imaging detector

Pulse Length Measuring the 233 fs pulse length is perhaps the most challenging measurement at the LCLS. Several concepts have been proposed, all involving a medium which modulates an external laser beam when exposed to the X Ray FEL. The method we have chosen to baseline is illustrated. The beam from a 1500 nm CW laser is split and made to pass through the two arms of an interferometer patterned in GaAs on a substrate. X Rays impinging on one of the arms changes its index of refraction causing a modulation in the CW beam after it is recombined. The modulation of the CW beam is in principle of the same duration as the X Ray pulse and can be measured with a streak camera to > 100 fs. To achieve better temporal resolution, the modulated CW beam is sent through a time microscope which stretches the pulse by a factor of 2 to 100. The stretched pulse length is then measured with the streak camera.

The device can also be used to synchronize an external laser pulse with the X Ray beam. This is accomplished by feeding the external pulse through the time microscope alongside of the X Ray modulated CW pulse and measuring both on the same streak camera.

Photon Spectrum The commissioning diagnostic tank is converted into a spectrometer by adding a crystal at 8 keV or a grating at 0.8 keV. In eather case the optic is curved so as to focus onto the X Ray sensitive region of a fast readout linear array.

Transverse Coherence We will measure the transverse coherence in the commissioning diagnostics tank using the setup shown in the figure that employs an array of double slits with constant slit width but different slit spacings. The slits sample the beam in two places and the resulting diffracted beams interfere with each other at the position of the detector.

At 0.8 keV the slits will be assembled from polished sticks of low Z material such as B4C or Si held apart by spacers. The higher resolution slits for 8 keV will be manufactured by the sputter-sliced method or from an array of fibers.

Spatial Shape and Centroid Location The spatial shape and centroid location of the FEL beam will be measured on a pulse-by-pulse basis by the Scattering Foil Detectors located in the facility diagnostics tanks distributed along the beam lines.

Divergence This measurement is performed at 8 keV using the Scattering Foil Detectors located along the beam line. The measurement is performed at 0.8 keV using the LCLS Segmented Ion Chambers located along the beam line.

4 Schedule

Key milestones in the Start-Up are presented in Table 7. The first milestone denotes the point when electrons are first produced at the photocathode. The Injector laser and gun must be assembled and operational to the point where laser induced photoelectrons can be accelerated to the first diagnostic

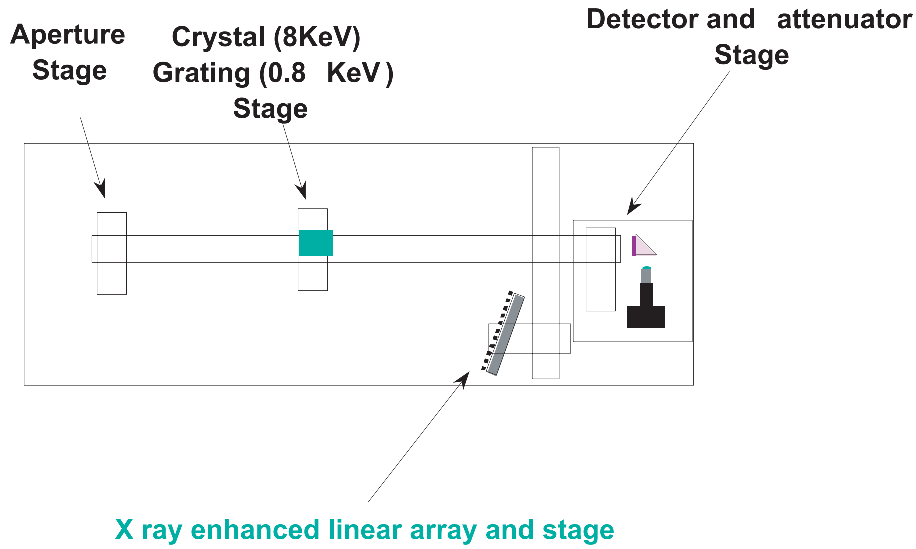

Figure 6: Photo spectrum diagnostics schematic

station. The electron beam will eventually be allowed to go through the injector linac where it picks up additional energy and is measured by a new suite of diagnostics.

The next milestone is when the electron beam is allowed to proceed into the main linac. It occurs roughly 7 months after the first electrons are produced at the gun, thus there is substantial time allowed for tuning up the laser while measuring the electron beam properties. In the linac the beam will be further accelerated and sent through two Bunch Compressors to produce very short high current bunches. The beam will be terminated in the Beam Switchyard, which will not be affected by the LCLS construction.

Before beam can be sent further, we must wait for various LCLS construction and installation activities to finish. Hence 10 months go by during which further improvements to the beam qualities can be made before sending the beam to the end of the LTU. At the end of the LTU there a suite of diagnostics that can completely characterize the beam qualities at the full energy. The LTU also contains a collimation system designed to protect the Undulator magnets which will be commissioned before the beam is allowed to go to the Undulator.

Three months are allowed for running the beam from the gun to the tune-up dump at the end of the LTU before the first beam pulse is allowed to go through the Undulator to the Dump. First beam through the Undulator is coincident with Start of Undulator Commissioning and essentially coincides with Start of XTOD Commissioning as the first pulse will produce X Rays that will reach the diagnostics downstream of the Undulator.

The final milestone is getting X Rays to the Far Hall. This is scheduled to occur no later than two months after the first beam through the Undulator. For X Rays to reach the Far Hall all of the X Ray beamlines must be in place thorughout the hutches in the Near Hall and in the X Ray

Table 7: Key milestones during LCLS start-up.

Milestone	Date	Type
Drive Laser: UV Beam to Cathode	11/30/06	Early Finish
First Beam on Linac Axis	6/29/07	Early Start
Start LTU Commissioning	5/1/08	Early Start
Start Undulator Commissioning	7/31/08	Early Start
Start XTOD Commissioning	8/1/08	Early Start
LCLS Start of Operation (X-Ray to Far Hall)	10/1/8	Early Finish

Transport tunnel. Safety system in the downstream areas will also need to be operational. This brings the schedule to the point of Start of Operations.

A Draft Electron Beam to Dump Procedure

Starting point: beam to the end of the linac at 10 Hz (save electricity, dont need 120 Hz for a while) nominally 14.8 GeV, charge in the range 0.2 — 1 nC establish the energy initially in the SLC beamline by switching on the BSY magnet 50B1 and taking the beam to stopper PR55. at this point energy can be measured with an existing BPM (needs > 0.5 nC charge) using energy feedback, FB31 linac emittance will have been measured on sector 28 wires bunch lengths will have been measured with the RF deflecting cavities, although short bunches are not mandatory at this stage.

We need a paragraph here of so about the possibility of using a spoiler to commission with reduced charge.

1. Starting at 1 Hz steer beam through BSY portion of LTU as far as 1st stopper after muon shield. At present this stopper is called ST61. It is before the first dog-leg bend in the LTU and serves to establish the launch into the LTU from the linac.

2. Having established energy on PR55 and launch on ST61, 1 Hz beam can then be steered through the dog-leg to the tune-up dump at the end of the LTU. Once the beam makes it to the LTU tune-up dump the beam rate may be raised to 10 Hz. All LTU collimators are open at this point.

3. Re-establish energy feedback, this time using LTU dog-leg BPMs

4. Commission energy collimators and activate MPS based on beam loss at energy collimators. This MPS will rate limit the linac.

5. Commission orbit feedback through the LTU matching section.

6. Commission single bunch beam dumper (SBBD) in the LTU.

7. Commission transverse collimators in the LTU matching section.

8. Establish MPS based on beam loss at the transverse collimators with the SBBD as the active device which will rate limit the beam at the end of the LTU

9. Commission wire scanners in the matching section.

10. Commission the 6 new cavity BPMS and verify that they read the same orbit as the stripline BPMs.

11. Optics tuning of the LTU: correct residual dispersion from the dog-leg. Beta match to the end of the LTU based on wire scans.

12. Commissioning of bunch-length monitors can begin at this point, but they are not required for the next steps.

13. Beam will be declared ready for the undulator beam line when:

    - Energy is established by feedback
    - MPS is ready
    - Orbit feedback is holding the launch stable
    - Wire scans show emittance less than 10 um (generous enough?)
    - Beta match shows beam is matched at the undulator entrance stopper (how do we spec a tolerance for good enough here?)

14. First beam past the undulator stopper:

    - 14.8 GeV (max energy)
    - 0.2 nC charge
    - launch and energy feedbacks green
    - beam stopped at SBBD
    - open stopper at end of LTU
    - single shot beam into undulator

15. Look for signal on first undulator cavity BPMs Analyze undulator BPM readings for consistency with launch BPMs. E.g. is there an apparent angle at the entrance to the undulator.

16. . If beam only makes it past a few BPMs then calculate change in launch angle required, put in stopper and re-establish beam with launch feedbacks so that their feedback setpoints can be changed accordingly. Stop beam at SBBD, open stopper at end of LTU, single shot beam into undulator and see if beam is transported further. Iterate until beam makes it to the end of the undulator beam line. When converge, can now switch from single pulse mode to continuous 1 Hz.

17. Steer beam through dump line.

18. Commission dumpline energy, energy spread diagnostics.

19. Commission undulator MPS based on distributed loss monitor in undulator hall and the average current monitors.

20. Can now increase rate to 10 Hz, and we are ready for the next step which is beam based alignment in the undulator. Note that charge has remained at 0.2 nC up to now.

References

[1] GRD 1.1-1, (Global Requirements Document), J. Galayda, *Linac Coherent Light Source Project Requirements*

[2] SLAC-R-715