

DRAFT

Beam Commissioning the LCLS Undulator System

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Contents

1	Introduction	2
2	Goal of Commissioning	2
3	Commissioning Procedure	4
3.1	Pre-commissioning Status	5
3.2	Electron Beam to Dump	5
3.3	Beam-Based Alignment (BBA)	5
3.3.1	BBA Procedure	5
3.3.2	BBA Verification	6
3.4	Commission FEE Diagnostics	6
3.5	FEE Diagnostics Configurations	9
3.6	Commission Undulator Diagnostics - Milton	9
3.7	FEL Commissioning at Long Wavelength	10
3.8	Measurement of FEL Gain Curves	10
3.8.1	Trajectory distortion method	11
3.8.2	using undulator xray diagnostics - Milton	12
3.8.3	Independently removable segments	12
3.8.4	Variable gap undulator	13
4	Radiation Characteristics	13
4.1	Along the Undulator	13
4.2	Downstream of the Undulator	13
4.2.1	FEL	13
4.2.2	Spontaneous	14

5	Diagnostics	14
5.1	Undulator Diagnostic Instruments - Milton	14
5.2	Downstream X-Ray Diagnostics Instruments	14
5.2.1	Diagnostics in the FEE	14
5.2.2	Diagnostics in the Commissioning Diagnostics Tank	16
5.2.3	Total Energy	16
5.2.4	Pulse Length	18
5.2.5	Photon Spectrum	18
5.2.6	Transverse Coherence	18
5.2.7	Spatial Shape and Centroid Location	18
5.2.8	Divergence	18
6	Troubleshooting	20
A	Details: Electron Beam to Dump	21

1 Introduction

In this note we describe the process of the final commissioning of the undulator system and associated xray diagnostics. To establish that these systems are working properly it will be necessary to produce and measure FEL radiation at least in a limited way (low repetition rate, low intensity, and possibly only at low electron beam energy). It may in fact be necessary to employ electron beams with essentially final emittance and current specifications before confidence can be established in the performance at 14.1 GeV, but the procedure described here takes optimal advantage of electron beams with relaxed emittance tolerance. In any case further commissioning, whereby the operational performance parameters of the LCLS xray beam is obtained will still be needed after the undulator and the xray diagnostics are commissioned. Pre-beam checkout of the undulator subsystems, e.g. movers, vacuum system, phase controls, steering coils, etc., is not discussed here and is assumed to have already taken place before beam commissioning begins.

2 Goal of Commissioning

The ultimate goal of the beam commissioning process is to demonstrate that the undulator system and the associated xray diagnostics will reliably and stably generate an ultra-bright coherent x-ray beam when a high current, low emittance electron beam is supplied to it. The demonstration is broken into three phases. In the first phase we rely only on gross properties of the electron beam and don't require FEL lasing in any way. Table 1 lists specific commissioning performance goals for this phase. If we are successful in attaining these parameters simultaneously then we have a real possibility of producing significant amounts of FEL radiation at low energy even with a less than optimal electron beam. The electron beam parameters for this phase are listed in table 2.

		4.54 GeV	14.1 GeV
Orbit straightness	μm [rms]	30?	3?
Orbit stability	$\mu\text{m}/\text{day}$ [rms]	2?	2?
Radiation Levels?	[Gy/day]?	1?	1?
Radiation λ	[nm]	15	1.5
Linewidth	?	?	?
Rep. freq.	[Hz]	10	10

Table 1: Specific performance goals for beam commissioning the undulator and xray diagnostics which don't require very high quality electron beam properties.

Table 2: Minimum electron beam parameters for various stages of commissioning.

parameter	symbol		units
electron energy	E_0	4.54—14.1	GeV
bunch charge	Q	0.2—1.0	nC
transverse norm. emittance	$\gamma\epsilon_{x,y}$	4.0—10	μm

The second phase of the demonstration consists of measurements and analysis of:

- gain curve
- saturation length
- saturation power.

using an electron beam at 4.5 GeV with relaxed tolerances as given in table 3. Measurement of a gain curve showing the development of FEL power as a function of the distance along the undulator is critical to the demonstration of good phase accuracy distributed throughout the undulator magnet. We have several possible approaches to make this type of measurement. One is to use trajectory distortions which can be applied to selectively ‘turn off’ the undulator gain mechanism downstream of the source of the distortion. In this case only the downstream xray diagnostics would be needed. Another is to use xray diagnostics in the undulator to directly measure the FEL radiation at that location. These and other methods are discussed in section 3.8.

A gain curve measurement will also determine the saturation length and, if absolute calibration can be made, determine the saturation power. Saturation power can also be measured in the Front End Enclosure (FEE) without a gain curve measurement along the length of the undulator.

For gain curve measurements FEL radiation will have to be produced and distinguished from spontaneous radiation. Perhaps a reasonable criteria for

Table 3: 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	4.54	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 $\times 20$	$20L_G$	115	85	m
FEL power at saturation	P_{sat}	0.7	18	GW
orbit straightness (per 10 m)	δx	6	2	μm
segment tuning	$\Delta B/B$	4	1.3	$\times 10^{-4}$ (rms)

establishing that FEL radiation has been produced is if 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 seem adequate to demonstrate this goal.

The third phase of commissioning requires the electron beam emittance and current to be within tolerance. It consists of measuring gain curves at 14.1 GeV and demonstrating the saturation length and power are at or above the design goals per pulse.

These goals are to be distinguished from an ‘End of Construction’ goal, which has yet to be defined, but might be something along the lines of getting an electron beam from the source to the dump with the undulator in place. Undulator commissioning may start before we achieve our end of construction goal.

3 Commissioning Procedure

As explained in section 2, our overall commissioning strategy is to first use conventional electron beam instrumentation to tune up an ultra-straight electron beam through the undulator, thereby demonstrating the absence of substantial dipole errors, extremely good orbit straightness and stability, and freedom from unwanted radiation. Next we will probe for phase errors in the undulator by measuring FEL xray radiation produced at 15 Å. At this long wavelength the tolerances for such a generating an FEL beam are quite relaxed, as shown in

section 3.7, and the generation of significant amounts of FEL radiation is quite likely. We could conclude commissioning when we reach the performance goals stated in section 2, but if a very high quality electron beam can be delivered.

3.1 Pre-commissioning Status

Before commissioning starts we assume that the entire undulator system is installed and the beamline is complete from the source to the electron beam dump. Diagnostics in the FEE are assumed to be installed and operational, PPS systems must be certified for operation, the stopper in front of the undulator is closed. To complete the commissioning we assume that the monochromator in the FEL hutch in the Near Hall is installed and operational. It is not necessary to have the X-Ray Transport Hall and beyond operational, though some provision may be needed to block the x-rays from going downstream of the hutches.

3.2 Electron Beam to Dump

The object of this activity is to get a stable 10 Hz electron beam to the dump without damaging the undulator. Note that commissioning of the LTU (Linac to Undulator Hall) beamline cannot begin while the Undulator Hall (UH) is occupied, unless some new provision for temporary shielding is made. Possibilities for the schedule would be either to wait until the UH installation is complete before the commissioning the LTU, or commissioning the LTU at night and proceed with installation during the day. If the LTU was scheduled to be ready much earlier than the undulator and dump beamline (> 6 months) we could consider putting a temporary shielding block behind the LTU tune-up dump to allow access to the undulator hall during LTU commissioning.

The detailed commissioning steps are given in Appendix A where we go through the process of launching a beam into the LTU, the setup of protection collimators, and launching a beam through the undulator. We also discuss the possible use of a spoiler for reduced charge for commissioning and tune up purposes.

3.3 Beam-Based Alignment (BBA)

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

3.3.1 BBA Procedure

The procedure is... blah-blah-blah... Oh shutup Emma, we're sick of this!

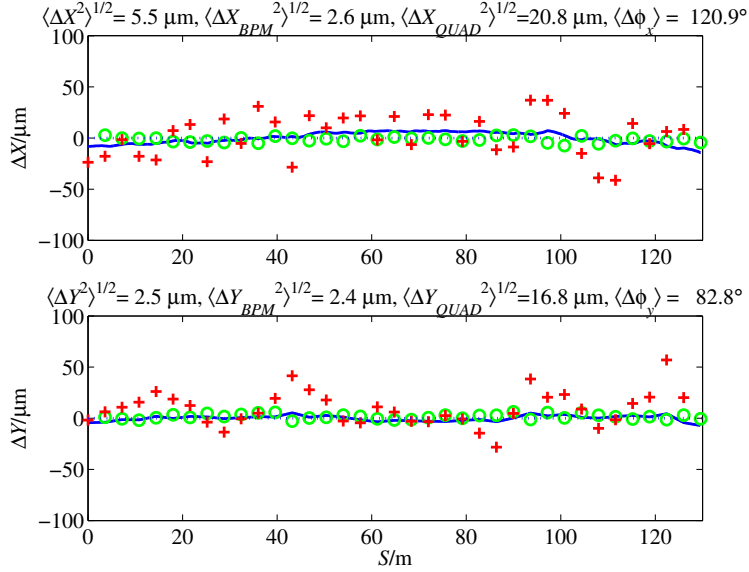


Figure 1: Trajectory (solid lines: X top, Y bottom) through undulator at 14 GeV after 3 passes of the BBA procedure. The crosses represent the quadrupole center positions while the circles are the BPM readbacks.

3.3.2 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 ($50 \mu\text{m}$ rms assumed here), the trajectory will change by the order of $500 \mu\text{m}$ 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 $< 50 \mu\text{m}$ (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 by carefully steering the BPM readings back to zero, allowing FEL commissioning at long wavelength.

3.4 Commission FEE Diagnostics

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

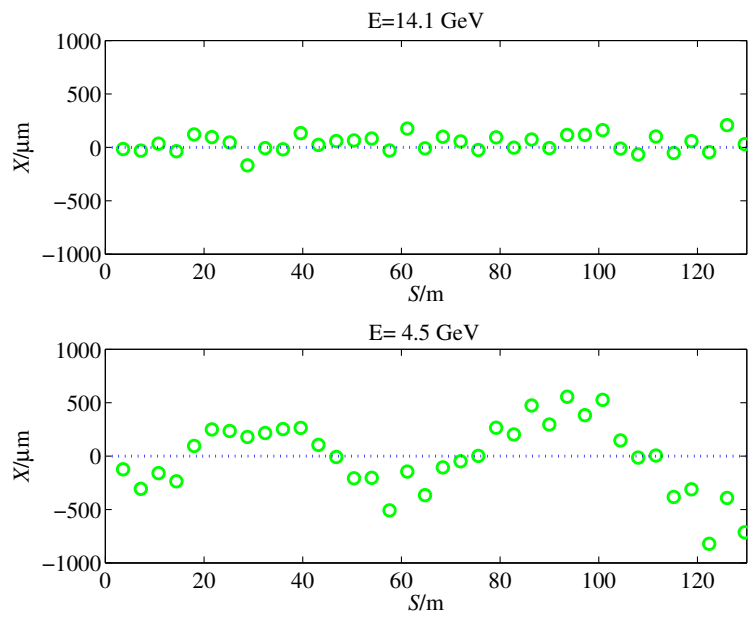


Figure 2: BPM readbacks of trajectory through undulator at 14 GeV (top) and 4.5 GeV (bottom) after rough steering, but before the BBA procedure, where trajectory changes with energy are expected at the 500- μm level.

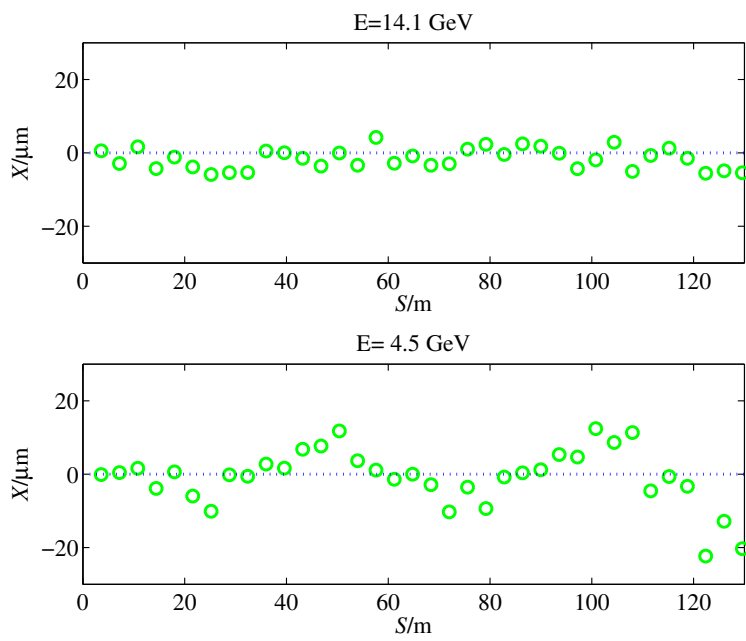


Figure 3: BPM readbacks of trajectory through undulator (note scale change) at 14 GeV (top) and 4.5 GeV (bottom) after three rounds of the BBA procedure, where trajectory changes with energy are expected at the 20- μm level.

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.

3.5 FEE Diagnostics Configurations

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.

3.6 Commission Undulator Diagnostics - Milton

This section should describe how we commission the diagnostics in the undulator line: what energy to run, what to look at. Presumably this can be done with a low quality electron beam.

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, including a significantly larger transverse emittance, a reduced bunch charge and peak current, and less than ideal undulator trajectory. Therefore it will be preferable to do the initial FEL commissioning (i.e., first attempts at establishing FEL gain) at the longer wavelength of 15 Å, where electron brightness requirements are much less demanding. 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 ($\sqrt{\lambda_r/1.5}$ 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 3, 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 preferred over a one-step commissioning process at 1.5 Å, where no FEL power may be available initially.

3.8 Measurement of FEL Gain Curves

Measurement and interpretation of gain curves can help diagnose errors 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

Table 4: Parameters for FEL saturation at 15 Å with 0.5 nC of bunch charge. Also listed is the nominal design at 1.5 Å with 1 nC. In both cases: $K = 3.64$ and $\lambda_u = 3$ cm.

parameter	symbol	15.0 Å	1.5 Å	units
electron energy	E_0	4.54	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
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FEL power at saturation	P_{sat}	0.7	18	GW
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The sensitivity of gain curve measurements to these errors has yet to be calculated for the full range of commissioning conditions and constitutes one of the most important technical problems yet to be solved before the commissioning plan can finalized. Ideally the sensitivity would be evaluated for the 15 Å relaxed parameter case, shown in Table 3, as well as as other expected commissioning conditions, and for segments distributed all along the length of the undulator.

There are at least four methods of measuring the gain curve under consideration which are explained below. **These methods need to be developed so a decision can be made on which one to design to.**

3.8.1 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 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 $\sqrt{1 + K^2/2}/\gamma \approx 100 \mu\text{rad}$. Alternatively, data taken with a large acceptance angle can be analyzed to identify the “hot spot” of the FEL mode. Thus, in the following GENESIS simulation runs, we will examine

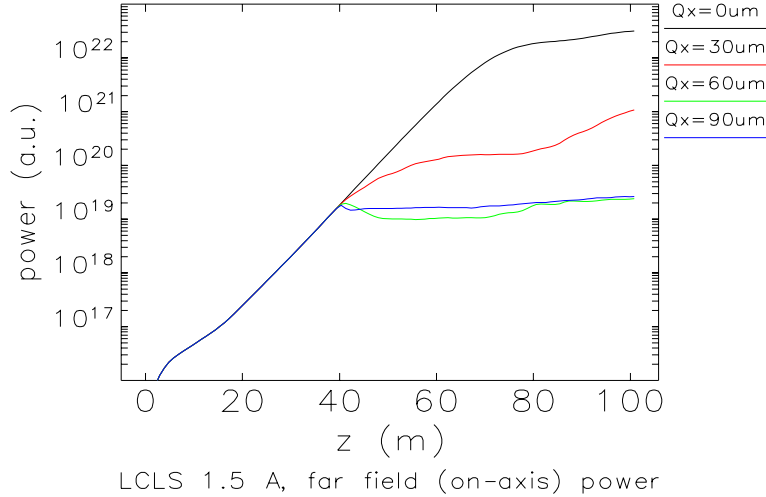


Figure 4: GENESIS simulation of the far-field power for a quad offset at $z = 40$ m undulator.

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

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

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 $Q_x = 60 \mu\text{m}$ 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 $60\text{-}\mu\text{m}$ quad offset at $z = 20$ m and $z = 60$ m.

3.8.2 using undulator xray diagnostics - Milton

Diagnostic stations every third undulator are used to sample the radiation along the undulator.

3.8.3 Independently removable segments

In this method some fraction of the undulator segments are temporarily moved off the beamline, leaving the vacuum chamber, quadrupoles and bpms intact. No spontaneous or FEL radiation will be produced by the moved segments. By systematically removing (replacing) one segment at a time starting at the downstream end, the radiation measured on the downstream xray diagnostic

stations will trace out a form of the gain curve, if proper account is taken of the distances and effects of the vacuum chamber.

3.8.4 Variable gap undulator

This method is essentially the same as having independently movable segments except the field is turned off by opening the gap to reduce the magnetic field. If the gap is opened a lot the spontaneous radiation is drastically reduced from the opened segments. If the gap is opened only a little then the FEL action will be turned off but spontaneous radiation will be produced. Variable gap capability solves several other problems: setting the segment K to high precision, correcting phase between segments, and provides programmable tapering of the fields for enhanced gain.

4 Radiation Characteristics

A description of the realistic development of the SR and FEL radiation along the undulator and through the diagnostic stations after the undulator. Beam sizes, intensities and distributions should be noted. The effect of losses to the vacuum chamber is discussed.

4.1 Along the Undulator

The best description of the development of the FEL along the undulator is given in the design study report.

4.2 Downstream of the Undulator

4.2.1 FEL

We have been using an optical Gaussian waveform emanating one Rayleigh length from the end of the undulator, as a model of the FEL downstream of the undulator. In this model the FWHM of the FEL is about 100 microns in the front end closure (FEE) near the undulator exit, and the high-energy beam broadens to 0.5 mm and the low-energy beam broadens to 3 to 4 mm in the far experimental hall (FEH). The saturated power levels are predicted to be around 10 G Watts over the full energy range.

Comparisons with Ginger simulations, show that the Gaussian model tends to underestimate the FWHM, especially at low energies when the laser is taken beyond saturation. In these instances the power levels are three times saturation.

The Gaussian waveform model has been integrated into the x-ray photon ray tracing system used to develop the diagnostics.

4.2.2 Spontaneous

Roman Tatchen has done several calculations of the spontaneous radiation patterns in the far field. These results appear in the design study report. Calculating the radiation patterns in the near field is more difficult and has not been completed.

The $\gamma\theta = 1$ diameter of the spontaneous is expected to grow from the size of the vacuum pipe (8 mm) to 10 to 20 mm at the entrance to the near hall, and unobstructed, to be from 100 to 150 mm in the far hall. The integrated power in the spontaneous beam will be of the same order as the integrated power in the FEL spot, but the spectral content of the two beams will be quite different with the spontaneous having significant flux at very high photon energies.

Work is in progress to integrate Romans spontaneous into the detector simulations.

5 Diagnostics

This section provides a basic description of the basic diagnostic tools at our disposal.

5.1 Undulator Diagnostic Instruments - Milton

A brief description of the undulator diagnostics, both xray and electron beam, we are planning to use.

5.2 Downstream X-Ray Diagnostics Instruments

5.2.1 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 where 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.

5.2.2 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.
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.

5.2.3 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

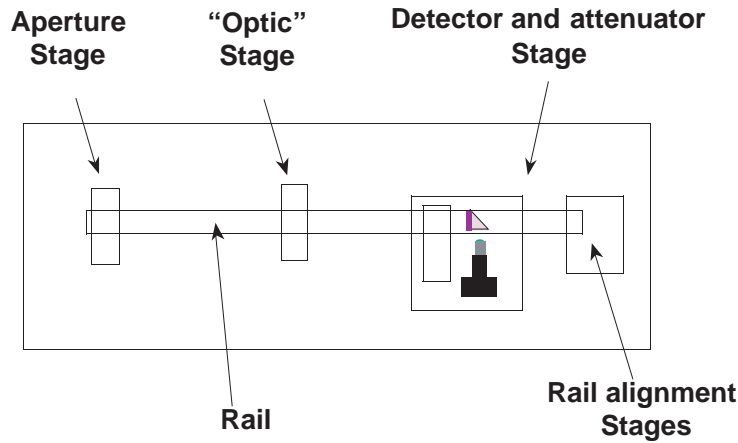


Figure 5: Commissioning diagnostic tank

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 ~ 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

5.2.4 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.

5.2.5 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 either case the optic is curved so as to focus onto the x-ray sensitive region of a fast readout linear array.

5.2.6 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.

5.2.7 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.

5.2.8 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.

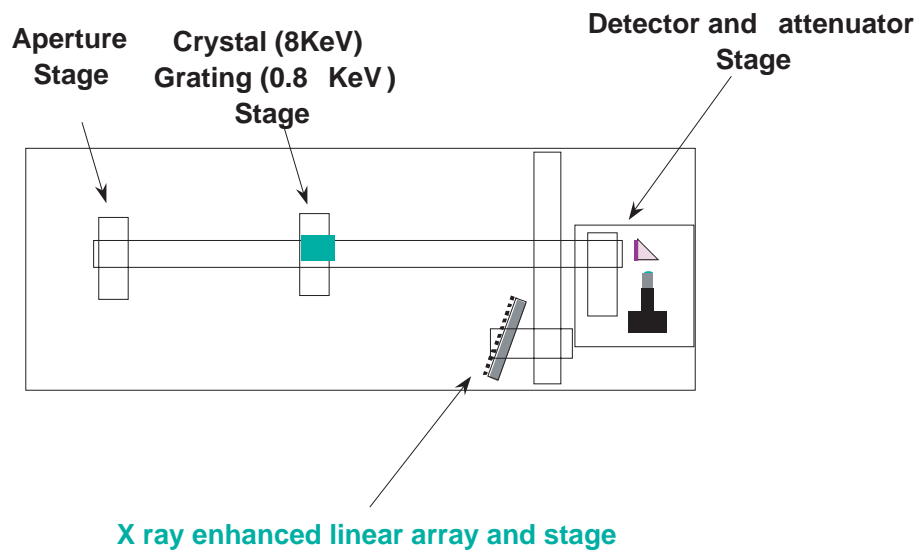


Figure 6: Photo spectrum diagnostics schematic

6 Troubleshooting

If the components of the undulator system and the associated diagnostics are in fact working within their design tolerance and there is no significant conceptual errors, the undulator system will produce the desired FEL radiation when a suitable high quality electron beam is sent through it. In this section we will work through one scenario to see how well we might isolate the cause of the problem. The nightmare scenario is that we measure good emittance and charge upstream of the undulator, a good straight orbit through the undulator, but see little or no characteristic FEL radiation coming out. Ideally, in the FEE or FEL hutch in the Near Hall we should see a bright central FEL spot of about $100\ \mu\text{m}$ in diameter (FWHM) with the advertized power/energy. If we don't see the FEL spot, we should still expect to see a signal from the SR assuring us that there are no gross problems in the xray beamline or downstream xray diagnostics. In this case the lack of FEL signal could be attributed to one or more of the following:

- bpm's are lying, so that we think the orbit is straight but it is in fact crooked
- bad phase accuracy in the undulator
- bad diagnostics or gross misalignment of diagnostics
- emittance measurement is wrong

BPM's will presumably appear to be behaving normally since we would have already run them through beam based alignment and cleaned up most problems with them. However it is conceivable that the BPM's might fool us. For example they might indicate some small energy dependence that we think is ignorable but because of a scale error is in reality quite large. Another round of BBA might turn up such problems with them, but it might not. We could check the BPM response against moving a quadrupole in the undulator, but a systematic error in quadrupole motion might be the source of the scale error. One test that might help is to send an orbit oscillation starting in the linac, where BPM readouts are confirmed, and see if it follows the theoretical trajectory through the undulator.

If the undulator field quality is bad and in particular has lots of phase error (we would see dipole errors in the orbit and recognize their source) this could inhibit the FEL gain process. How could we diagnose this condition? Measurement of the gain curve would show power growing linearly or less (due to losses to the vacuum chamber) and due mostly to the SR. That would be a pretty clear indication of such a problem if we can in fact make such measurements. Otherwise we could try tuning the phase of individual undulators. How much signal could we expect? If the phase is bad everywhere in the undulator (say there is systematic problem in magnetic measurements) there will be no FEL action anywhere so tuning individual segments will not give a signal.

The xray diagnostics should be able to detect the SR, even if there is no FEL radiation present. If they do not, this is a clear indication of a problem with them. Some kind of calibration is necessary as well as a reasonable good prediction of the SR that should be expected.

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A Details: Electron Beam to Dump

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 μm (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.