## LCLS Engineering Specifications Document # 1.5-112

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<th>Specifications Document #</th>
<th>X-Ray Transport and Diagnostics</th>
<th>Revision</th>
<th>0</th>
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## XTOD Direct Imager

- **Richard Bionta**
  - Author, XTOD WBS Manager

- **Peter Stefan**
  - XTOD Physics Liaison

- **John Arthur**
  - Photon Systems Manager

- **Darren Marsh**
  - Quality Assurance Manager

**Signature**

- Richard M. Butz
  - Date: 5/13/08

- Peter M. Stefan
  - Date: 2008/5/12

- [Signature]
  - Date: 5/13/08

- [Signature]
  - Date: 5/13/08

## Summary:

This document analyzes and summarizes the physics behind the operation of the Direct Imager and derives its consequent engineering design.

## Change History Log

<table>
<thead>
<tr>
<th>Rev Number</th>
<th>Revision Date</th>
<th>Sections Affected</th>
<th>Description of Change</th>
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</thead>
<tbody>
<tr>
<td>000</td>
<td>2008/5/5</td>
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Auspices Statements

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1. Executive Summary:

This document provides engineering requirements for the XTOD Direct Imager Systems (DIS). The DIS consists of two electronic imaging systems, in a single tank, viewing a set of 3 YAG:Ce scintillators that can be remotely inserted into the x-ray beam. The 3 scintillators provide optimal viewing of 1) faint soft x-ray FEL radiation in the presence of spontaneous background radiation; 2) faint hard x-ray FEL radiation in the presence of spontaneous background; and 3) faint spontaneous radiation from single undulator segments. One imager has optics providing 117 µm resolution over a wide field-of-view (WFOV). The other has optics providing 20 µm resolution over a narrow field-of-view (NFOV). The WFOV system is optimal for observing the soft x-ray FEL, which has an expected diameter of ~ 1 mm FWHM (Full Width Half Maximum). The NFOV system is optimal for observing the hard x-ray FEL, which has an expected diameter of ~ 200 µm FWHM. The Direct Imager will also be used in conjunction with the $K$-Measurement Monochromator System for locating the center of the spontaneous radiation beam.
2. DIS Overview

Figure 1 is a block diagram for the principle components of the DIS. The NFOV imaging system is in the upper left of the diagram, and the WFOV imaging system is in the lower right of the diagram. The imaging systems are outside of the vacuum and each consists of a vacuum window, a lens, a remotely-controlled wheel of neutral-density filters, a high-speed CCD camera, a camera mount that provides manual control of the tip and tilt of the camera axis, and a remotely-controlled camera focus adjustment mechanism. The optical systems view a set of 3 YAG:Ce scintillator plates, mounted on a frame inside the vacuum enclosure, which can be remotely positioned to intercept the x-ray beam. The movable frame contains a fourth slot with a resolution chart. When placed in the x-ray beam, the scintillator plates stop a portion of the incident x-ray photons. The YAG:Ce material converts a small fraction of the energy deposited by the x-ray photons into visible and near-UV light which is radiated into $4\pi$ steradians. A small amount of this light is captured by the lenses and directed onto the CCD focal plane array. A fraction of the UV/visible photons that strike the focal plane array are converted into photoelectrons that are counted, on a pixel-by-pixel basis, by the CCD readout electronics.

The thin YAG:Ce scintillator plates provide crude x-ray photon energy selection, in that the higher energy photons have a smaller chance of interacting in the thin plates than the lower energy photons. This is important since the photon energy of the desired fundamental of the LCLS beam is lower than the photon energies of the unwanted higher harmonics of the spontaneous. Because the LCLS fundamental photon energy can be tuned from 830 eV to 8300 eV, two thicknesses of YAG:Ce are
provided for FEL studies: 5 µm for viewing soft x-ray fundamental settings, defined to be < 2 keV, and 50 µm for viewing hard x-ray fundamental settings, defined to be > 2 keV. In addition, a 1 mm thick YAG:Ce plate is provided to study the fainter spontaneous radiation from single undulators. The YAG:Ce can, under high levels of x-ray irradiation, emit enough light to saturate the high-sensitivity CCD cameras. Therefore both the WFOV and NFOV systems include neutral density (ND), visible light filters, mounted on a remote-controlled wheel. These filters can be inserted into the optical path in a controlled fashion to attenuate the light hitting the CCD.

The illuminator system provides visible light in the object plane to aid focusing and alignment. The UV light source excites visible and near-UV photons from the YAG:Ce scintillator, and so provides a check on the spatial uniformity and stability of the light output from the YAG:Ce.

The Direct Imager is a primary diagnostic for the LCLS. This necessitates rapid turn-around for any repairs or modifications. Therefore, the vacuum system is equipped with its own turbopump, roughing pump, and isolation valves, to allow rapid access and fast pump-down after entry, with minimal impact to the surrounding beam line elements. The ion pump maintains vacuum when the turbopump is off.

3. DIS Subsystems

The DIS subsystem requirements are described below, and generally stem from LCLS PRD 1.5-010 "Physics Requirements for the XTOD Direct Imager". A specific mechanical layout, a proposed CCD imager, and proposed lenses are also described, in anticipation of the overall system performance estimates of Section 4.

3.1. Mechanical Layout

3.1.1. Overall requirements

The design should allow rapid replacement of the DIS scintillators in case of damage or changes to the scintillator requirements.

The beam line height for the DIS is ~ 1.4 meters (55.118 inches) above the finished floor.

The coordinate system used below is Cartesian with the X axis horizontal, the Y axis vertical, and the Z axis pointing along the beam direction.

The camera optical axis is rotated with respect to the incident beam axis. Since the spontaneous x-ray beam is significantly narrower in the vertical direction, it is preferred that the camera optical axis and the beam axis lie in a common, vertical plane.

We require the DIS design to meet an overall positional stability requirement of 100 µm long-term (day) and 100 µm short-term (hour), as a combined total in all three translational axes.
3.1.2. Proposed Layout

A proposed mechanical layout for the DIS is shown in Figure 2. The layout is based on a spherical tank with the scintillators riding in a track that slides in the horizontal direction. The stand is based on the stand designed for the Fixed Mask. Table 1 shows the expected movement calculated for the stand of the Fixed Mask, using a finite-element model, with a temperature variation of ±1°C about 20°C. The analysis includes the stainless steel vacuum chamber, the steel support structure, and a large piece of heavy tungsten alloy inside the chamber. Since the vacuum enclosure and support structure for the DIS are based on a similar design, we conclude that no special design considerations or materials will be necessary to meet the stability requirements.

<table>
<thead>
<tr>
<th>Thermal changes</th>
<th>Day/Hour</th>
</tr>
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<tbody>
<tr>
<td>Change in stand height (μm)</td>
<td>±16.4</td>
</tr>
<tr>
<td>Support length change from radiation heating</td>
<td>± 1.2</td>
</tr>
<tr>
<td>Width change from radiation heating</td>
<td>± 0.4</td>
</tr>
<tr>
<td>Width change from room temperature change</td>
<td>± 0.12</td>
</tr>
<tr>
<td>Stability</td>
<td></td>
</tr>
<tr>
<td>Center stability</td>
<td>± 16.4</td>
</tr>
<tr>
<td>Width stability</td>
<td>± 0.5</td>
</tr>
</tbody>
</table>

Figure 2: Mechanical Layout
3.2. Imaging camera

3.2.1. Overall requirements

The DIS must produce moderate resolution images of several different scintillator plates, over a wide range of light levels, at frame rates up to 30 Hz. The requirements on the imager are therefore high sensitivity, large dynamic range, low noise at high frame rates, and sufficient pixel count. The requirement for low noise at high frame rates drives the choice of imaging chips to the recently developed “Electron Multiplying” CCD (EMCCD) technology, in which the photoelectrons undergo impact multiplication before being detected by the readout electronics. The high sensitivity requirement is best achieved using back-thinned EMCCD’s. The chosen pixel size involves a tradeoff between resolution and full-well capacity. The requirement of large dynamic range at moderate resolution favors larger pixel sizes. The requirement of < 32 µm resolution over a 10 mm FOV (PRD 1.5-010, Section 4.2) requires a pixel format > 313 x 313.

<table>
<thead>
<tr>
<th>Table 2: Cascade 512B camera properties</th>
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<tbody>
<tr>
<td><strong>Image Sensor</strong></td>
</tr>
<tr>
<td><strong>Pixel Count</strong></td>
</tr>
<tr>
<td><strong>Pixel Size</strong></td>
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<tr>
<td><strong>Quantum Efficiency</strong></td>
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<tr>
<td><strong>Cooling</strong></td>
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<tr>
<td><strong>Readout rate</strong></td>
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<tr>
<td><strong>Digitization</strong></td>
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<td><strong>Well depth</strong></td>
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<td><strong>Read noise</strong></td>
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<td><strong>Dark current</strong></td>
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<tr>
<td><strong>On chip gain</strong></td>
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</tbody>
</table>
3.2.2. Proposed Camera
The Photometrics model Cascade 512B is a good candidate for the DIS cameras because of its high quantum efficiency (sensitivity), large dynamic range (well depth), and the low readout noise inherent to the EMCCD. Table 2 lists the relevant specifications of the Cascade 512B camera and Figure 3 shows the quantum efficiency of the backed-thinned EMCCD.

![Figure 3: e2v CCD97 quantum efficiency curve](image)

3.3. Camera Focus adjustment
The camera mounting system will need to provide ±1 mm remote-controlled motion along the camera focus axis, since the proposed lens cannot be focused remotely. This allows the camera to be focused within the ± 50 μm depth-of-field of the NFOV lens and also allows for some variation in the position along the optical axis of the individual scintillators. The LLNL Controls Group has requested that Newport Corporation stages not be used to provide this adjustment.

3.4. Camera tip/tilt adjustment
Yaw, pitch, and roll adjustments will be necessary to align the camera focal plane parallel to the scintillator face. It will not be necessary to make these adjustments remotely.

3.5. Optics
3.5.1. Overall requirements
The lenses for the NFOV and WFOV cameras must provide the correct magnification to achieve < 32 μm and < 220 μm resolutions over fields of > 10 mm and > 50 mm, respectively (PRD 1.5-010, Sections 4.1 and 4.2). The lenses must have sufficient working distance that they are well clear of the spontaneous radiation transverse spatial extent. The lenses must have maximal collection efficiency and throughput over the spectral range of the YAG:Ce emission (400 to 600 nm).

3.5.2. Proposed Lenses
The constraints for the NFOV and WFOV cameras, with regard to field, magnification, resolution, and light collection efficiency, drive the choice for imaging optics beyond the capabilities of lenses
typically offered for video. However, the machine vision industry has driven a need for high performance lenses capable of matching ever improving CCD cameras. Both Navitar and Schneider-Kreuznach offer diffraction-limited, large-aperture lenses in this arena, which meet the requirements for the DIS. Table 3 lists the specifications and working parameters for the proposed lenses, which result in camera-pixel-limited resolution for both the WFOV and NFOV imagers.

| Table 3: WFOV and NFOV lens specifications |
|-----------------------------------------|---------|---------|
| **WFOV** | **NFOV** |
| **Imaging lens** | Navitar Platinum-50 | Schneider-Kreuznach Tele-Xenar 2.2/70 |
| **Focal Length (mm)** | 50 | 70 |
| **F-number** | 1 | 2.2 |
| **Field of View (mm)** | 60x60 | 10x10 |
| **Magnification** | 0.1365 | 0.8 |
| **Working distance (mm)** | 334 | 110 |
| **Object NA** | 0.06 | 0.1 |
| **Resolution at Scintillator (um)** | 117 | 20 |
| **Diffraction limit at Object (um)** | 10 | 6 |
| **Depth of Field (um)** | 140 | 50 |

### 3.6. Vacuum windows

Optical-quality vacuum windows will be provided for both the NFOV and WFOV cameras. The windows must transmit light in the spectral band from 400 nm to 600 nm. The vacuum windows and the camera lenses will need to be operated such that no external light is introduced into the chamber or camera during operation. Therefore, any additional viewing ports will also need to be covered so that no external light is introduced into the system during operation.

### 3.7. Scintillators

#### 3.7.1. Overall requirements

Generally, the scintillator should have high conversion efficiency, defined as the number of photons emitted per incident x-ray energy absorbed. Its emission spectra should be matched to the quantum efficiency of the imager, i.e. should be in the range of 440 nm to 650 nm for detection by a Si CCD. The decay time of the scintillator should be short compared to the minimum dwell time of the CCD at its maximum readout rate (typically hundreds of µsec). The x-ray attenuation length and mechanical properties of the scintillator must allow it to be fabricated in thin sheets that will preferentially absorb low-photon-energy FEL radiation over the high-photon-energy spontaneous background. The sheets should be large enough to cover the required FOV's. In addition, the scintillator material must have a high damage threshold and a demonstrated ability to operate with short (< 250 fsec) x-ray pulses.
3.7.2. YAG:Ce Scintillator

The requirement of a demonstrated ability to operate with short pulses limits the choice of scintillator to YAG:Ce, which is the only scintillator tested at the FLASH facility using its short (< 100 fsec) extreme ultraviolet pulses (see below for more about the FLASH tests).

![Figure 4: YAG::Ce spectral output](image)

Figure 4 shows the emission spectrum of YAG:Ce. The emission below 450 nm is due to defects and contamination and varies from sample to sample. This emission is irrelevant for the DIS since the quantum efficiency of the EMCCD is very small below 400 nm. The main emission feature is from 450 to 600 nm, peaking at 530 nm, and is right in the region where the EMCCD has its maximum quantum efficiency.

The YAG:Ce conversion efficiency is defined as the number of photons emitted by the YAG:Ce between 450 nm and 600 nm divided by the x-ray energy deposited in the YAG:Ce. The conversion efficiency depends on the Ce concentration, which can vary between 0.01% to 0.3% (atomic). YAG:Ce crystals with the lower Ce concentrations have lower conversion efficiency but tend to be clearer, with fewer flaws. The conversion efficiency at the lower concentrations is reported to be $\eta = \frac{8 \cdot \text{photons}}{keV}$ and the light yield for a given energy deposited, $e$, is $\phi = \eta \cdot e$.

The YAG:Ce output has been observed to saturate, i.e. deviate from the linear relation above, when exposed to the short pulses from an FEL. Figure 5 shows measurements of the light output from YAG:Ce when exposed to the focused FEL at FLASH, as a function of FEL pulse energy. The FEL pulse length for these exposures was < 100 fsec. The different curves correspond to different focal spot sizes, hence different energy densities on the YAG:Ce. At the tightest focus (bottom curve), the light output is very non linear and quickly approaches a value that is independent of pulse energy. The other curves, taken at lower energy density, saturate at higher values of FEL pulse energy. It is likely that other scintillator materials also exhibit similar saturation effects but thus far have not been tested with short FEL pulses in this fashion.
This data can be explained by modeling the light output of the YAG:Ce as $\phi = \eta \cdot e$ for $e < e_s$, and $\phi = \eta \cdot e_s$ for $e \geq e_s$, then summing this output over the Gaussian shape of the FEL footprint.

Setting $e_s = 0.002 \cdot \text{eV/atom}$ results in the solid lines in Figure 5, which clearly fit the data. This model must be used when estimating the light output from the YAG:Ce at the LCLS.

The attenuation length of YAG:Ce is 0.4 µm at 826 eV and 35 µm at 8261 eV. The optimal thickness for detecting a faint FEL in the presence of spontaneous background occurs when the scintillator thickness is of order 1 to a few times the attenuation length. This translates into YAG thicknesses of a few µm for the soft x-ray settings and 30 µm to 100 µm for the hard x-ray settings. YAG:Ce in thicknesses > 500 µm can be obtained in self-supporting plates 60 mm across. Thicknesses of 50 µm can be obtained in self-supporting plates 25 mm across. Very thin, 2 µm to 5 µm, YAG:Ce is produced by forming a few µm layer of YAG:Ce on a thick YAG substrate, also 25 mm across. The thin plates will be assembled into a mosaic to cover the 60 mm FOV.

### 3.8. Frame

The vacuum flight path must be sized to exclude the possibility of its being struck by the FEL x-ray beam. All components that are exposed to the x-ray beam inside the DIS are to be fabricated of Al. The frame is to be designed to support up to four, 60 mm x 60 mm scintillators. The frame must cover the outer edges of each scintillator plate, which emit significant amounts of visible light through light-guiding internal reflections. The surface normal to the plane containing the scintillators and resolution test chart lies in the y-z plane, and makes a 45° angle to both the positive y axis and negative z axis. This orientation will allow the NFOV camera (low depth-of-field) to view the upstream side of the scintillator (greatest number of photons produced) and the WFOV camera (greater depth-of-field) to view the downstream side of the scintillator.
Figure 6 shows a possible frame layout. The frame provides support for the full 60 mm x 60 mm scintillators, as well as for mosaics of smaller-area scintillators.

3.9. Scintillator/Frame Motion

The design of the insertion assembly is to provide enough motion to completely remove the scintillators, and any support hardware, from the projected FOV defined by the Fixed Mask. The system must accurately position the scintillators and focusing chart along the x axis within ±0.13mm and be repeatable to ±0.13mm. Limit switches and an absolute positioning encoder will be required. Figure 7 shows the layout of a possible scintillator insertion assembly based on a rack-and-pinion drive.
3.10. ND filter sets
An analysis of the YAG light output (see Section 4.3 below) shows that the CCD will saturate before the YAG:Ce scintillator, and attenuation levels of at least 100 will be required for the brightest signals. For this reason, an array of visible light attenuators will be provided using a filter wheel placed between the scintillator and the CCD.

3.10.1. Drive and housing
Figure 8 shows the model CFW1-5 filter wheel from Fingerlakes Instrumentation, a manufacturer of precision components, primarily for astronomy. This wheel accommodates five, 50mm diameter filters that can be selected under remote control. It has been integrated into the DIS layout.

3.10.2. Filter values
The range between YAG:Ce scintillator saturation and the CCD full-well, described in Section 4.3, indicates an attenuation of one half to one order of magnitude (5 to 10 dB, or OD0.5 to OD1.0) will be required. To accommodate different scintillators, we extend the attenuation range to ~ OD2.0, and implement this range in OD0.5 steps. These are listed in Table 4.

<table>
<thead>
<tr>
<th>Filter Slot</th>
<th>Optical Density</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>0 (clear)</td>
</tr>
<tr>
<td>B</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1.5</td>
</tr>
<tr>
<td>E</td>
<td>2.2</td>
</tr>
</tbody>
</table>
### 3.11. Illuminator

A remote-controlled lamp will need to be provided to allow visual inspection and alignment of the scintillators. In addition, a UV source, operating in the spectral range < 400 nm, will be needed to provide independent excitation of the YAG scintillators, to monitor the spatial uniformity and stability of the light output from the YAG:Ce.

### 3.12. Vacuum

The Vacuum System Requirements are as follows:

#### 3.12.1.

The DIS system will be designed to Ultra High Vacuum (UHV) specifications but is expected to operate at a high-vacuum level.

#### 3.12.2.

The DIS is a primary diagnostic for the LCLS, which necessitates rapid turn-around for any repairs or modifications. Therefore the vacuum system is to be equipped with its own turbomolecular pump, dry scroll pump, and isolation valves to allow rapid access and fast pump-down after entry, with minimal impact to the surrounding beam line elements.

#### 3.12.3.

The average pressure inside the DIS vessel will be < 10^{-5} Torr.

#### 3.12.4.

The pressure at the ion pumps will be low enough to ensure long pump life (>10 years).

#### 3.12.5.

The pump-down time will be 8 hours or less.

#### 3.12.6.

Vacuum components that are highly susceptible to radiation damage, such as elastomer o-rings, will be excluded from the design.

#### 3.12.7.

Standard procedures for cleaning and handling of UHV components, detailed in ESD 1.5-118 "LCLS XTOD UHV Specifications", will be followed.

#### 3.12.8.

The following SLAC documents, as well as other relevant documents, apply to the design of the vacuum system:

1. **ESD 1.5-118, LCLS XTOD UHV Specifications**
2. **PRD 1.5-001, X-Ray Transport and Diagnostics**
3. **PRD 1.5-002, XTOD Mechanical-Vacuum Systems**
4. **ESD 1.1-302, LCLS Mechanical Vacuum Specification**
5. **SLAC-I-007-12004-001 R1, Guidelines for Vacuum Systems**
3.13 Controls

Figure 9 is a block diagram of the principle components of the Control System. The NFOV and WFOV imaging systems are identical, each consisting of a CCD camera connected through a PCI frame-buffer in a shared industrial PC (not shown) running Linux with EPICS. Both imaging systems also have a remotely-controlled filter wheel (with a serial-line interface), and a remotely-controlled camera focus adjustment mechanism (using a stepper motor and a standard LCLS VME-based stepper indexer/driver). The scintillator insertion assembly uses the same interface, but is fitted with an absolute rotary encoder. Like all LCLS VME systems, EPICS is installed on the RTEMS operating system (referred to as an IOC—not shown). Vacuum pumps, valves, and gauges are identical to those used throughout LCLS, with an Allen-Bradley PLC directly connected to this hardware; an IOC (not shown; shared with other vacuum areas) connects EPICS to the PLC and to additional controller functions using a serial interface.

4. DIS Expected Performance

The DIS is required to support 3 modes of operation. One of the first modes to be used is to search for the soft x-ray FEL as the FEL physicists tune the LCLS, and to measure its properties when it appears. Likewise, another mode is to search for the hard x-ray FEL and to measure its properties. A third mode is to characterize the spontaneous radiation from one or more undulator segments.

The FEL transverse spatial distribution at the position of the DIS is calculated assuming that all of the FEL energy is contained in the zeroth order Gaussian-Hermite mode. The spatial/energy distribution of the spontaneous radiation at the position of the DIS is calculated as follows: First, a transverse x-ray spatial spectral flux density (number of x-ray photons vs. photon energy and position) from the oscillating stream of electrons in the undulator was calculated using Liénard-Wiechert potentials and fields for a line charge. These distributions were used in a Monte-Carlo code to generate photons in the undulator whose angular and energy distributions matched the Liénard-Wiechert calculations at the position of the DIS. These photons are propagated down...
the beam line and allowed to interact with the walls of the undulator vacuum chamber where they can be absorbed, reflected, or Compton scattered. The resulting photons are propagated to the position of the YAG:Ce scintillators where they interact photoelectrically and via the Compton effect. The Monte-Carlo records the spatial distribution of the energy deposition in the YAG:Ce. The deposited x-ray energy is converted to visible photons using a conversion factor of 13 visible photons (300 nm to 600 nm) per keV of energy deposited. Taking into account the Fresnel reflectivity of the YAG/vacuum interface, the numerical aperture of the lens, and the power of the lens, the number of photons striking each pixel is calculated. This number is converted into photoelectrons using the integral of the YAG:Ce emission spectra over the quantum efficiency of the CCD.

4.1 Soft X-Ray FEL Search and Measure Mode

The soft x-ray FEL search mode uses a 5 µm thick YAG:Ce scintillator imaged by the WFOV camera. The pixel size and FOV on the scintillator are 117 µm x 117 µm and 60 mm x 60 mm. Because the scintillator is tilted 45 degrees about the x-axis, the effective pixel size in y is 82 µm and the effective FOV in the y direction is 42 mm.

Figure 10 shows a simulation of the photoelectron levels induced in each pixel by the emission of light from the scintillator under illumination by one pulse of soft x-ray spontaneous radiation. The x-ray pulse was generated assuming 0.79 nC of charge through all of the undulator segments. The rectangle of highest intensity in the center of the image corresponds to the cross section of the undulator vacuum chamber, which is filled with x-rays due to scattering off its walls. At the exit of the undulator, the scattered radiation spreads out, eventually to be cut off by the Fixed Mask, whose boundary defines the outermost extent of the x-rays seen by the camera. The number of photoelectrons per pixel in the center is around 10,000 to 15,000, about 5% to 10% of the full-well capacity of the pixels.

The pixel-to-pixel scatter in the photoelectron levels is due to the limited statistics of the Monte Carlo calculation. The actual image will be much smoother, limited by the statistics of the number of photoelectrons in each pixel. With 10,000 to 15,000 photoelectrons per pixel, the pulse-to-pulse fluctuations in the photoelectrons will be ~ 100 or ≤ 1%.
Figure 11 shows a simulation of the photoelectron levels from a saturated, diffraction limited, soft x-ray FEL pulse of 2.3 mJ, assuming no damage, and full linearity, with no saturation in either the scintillator or CCD. The peak photoelectron level, $3.7 \times 10^8$, can be used to estimate the photoelectron level at other FEL intensities. In particular, an upward fluctuation of 100 photoelectrons in the spontaneous background would look like the peak signal from a 0.6 nJ FEL.

Figure 12 shows a blow-up magnification of the image of the FEL, and shows that the WFOV camera has sufficiently-small pixels to resolve the soft x-ray FEL.
4.2 Hard X-Ray FEL Search and Measure Mode

The hard x-ray FEL search mode uses a 50 µm thick YAG:Ce scintillator imaged by the NFOV camera. The pixel size and FOV on the scintillator are 20 µm x 20 µm and 10.2 mm x 10.2 mm. Because the scintillator is tilted 45 degrees about the x-axis, the effective pixel size in y is 14 µm and the effective FOV in the y direction is 7.21 mm.

Figure 13 shows a simulation of the photoelectron levels induced in each pixel by the emission of light from the scintillator under illumination by one pulse of hard x-ray spontaneous radiation. The x-ray pulse was generated assuming 0.79 nC of charge through all of the undulator segments. The footprint of the hard x-ray spontaneous is larger than the FOV of the NFOV camera and results in a nearly uniform distribution of light. Close inspection of the center of the image reveals a slight increase in intensity due to the relatively higher sensitivity of the thin scintillator to photons from the fundamental. Parts of the off-axis lobes of the second harmonic are also visible on the right and left edges of the image. The number of photoelectrons per pixel in the center is around 20,000 to 30,000, about 10% to 15% of the full-well capacity of the pixels.

Again the pixel-to-pixel scatter in the photoelectron levels is due to the limited statistics of the Monte Carlo calculation. The actual image will be much smoother, limited by the statistics of the number of photoelectrons in each pixel. With 20,000 to 30,000 photoelectrons per pixel, the pulse-to-pulse fluctuations in the photoelectrons will be ~ 150 or ≤ 1%.

Figure 14 shows the simulation of the photoelectron levels from a saturated, diffraction-limited, hard x-ray FEL pulse of 2.3 mJ, assuming no damage, and full linearity, with no saturation in either the scintillator or CCD. The peak photoelectron level is 6.3 x 10^8. An upward fluctuation of 150 photoelectrons in the spontaneous background would look like the peak signal from a 0.5 nJ FEL. The blow-up of the image in Figure 14 shows that the camera has sufficient spatial resolution to resolve the hard x-ray FEL.
4.3 FEL Search and Measure Summary

The expectations for the DIS in the two FEL Search and Measure modes are summarized graphically in Figure 15 for the soft x-ray settings on the left and the hard x-ray settings on the right. The vertical axis of the plots is in units of nJ of total FEL pulse energy. The first 6 bars give 1) the FEL pulse energy required to melt the YAG in one shot, 2) the pulse energy of a saturated FEL, 3) the pulse energy of a 200 µJ FEL, 4) the FEL pulse energy, which upon repeated application, may cause fatigue damage in the YAG, 5) the FEL pulse energy that saturates the YAG:Ce visible light output, and 6) the FEL pulse energy which saturates the CCD. The seventh bar gives the FEL pulse energy that would produce, in its highest pixel, the same signal level as the spontaneous background. The eighth bar gives the equivalent FEL pulse energy that would produce a signal equal to a $1\sigma$ statistical fluctuation in the spontaneous signal. A weak FEL pulse would not be recognized until it is several times this level. Finally the ninth bar shows the FEL equivalent pulse energy corresponding to fluctuations from the readout noise of the CCD.

These plots show the scales of the relevant signals and backgrounds. It is seen that the CCD readout noise is far below any signals of interest. The fluctuations in the spontaneous background will limit the minimum detectable (diffraction-limited) FEL to pulses of several nJ. The plots also show that the YAG:Ce saturation level is expected to be 10 to 50 times higher than the CCD full-well, and therefore requires addition of neutral density filters to attenuate the YAG emission so that it produces a signal whose level is under the full-well capacity of the CCD. The plots also show that a saturated FEL will have to be attenuated by factors of 50 to 200 in order not to saturate the light output of the YAG:Ce.
4.4 Spontaneous Characterization Mode

The Spontaneous Characterization mode uses the 1 mm thick YAG:Ce and the WFOV camera to attempt to capture most of the spontaneous radiation. Figure 16 and 17 shows the expected signal for the hard and soft x-ray spontaneous from all 33 undulator segments running with 0.79 nC of charge. The hard x-ray spontaneous, at $2.3 \times 10^6$ photoelectrons, will saturate the YAG:Ce and must be attenuated. The soft x-ray spontaneous from all of the undulators produces a signal of ~14,000 photoelectrons.
It will be of more interest to look at the signals from single undulator segments, which will be less intense. Figures 18 and 19 show the expected signals from the first undulator segment, which is the farthest from the DIS, with a charge of 0.79 nC. The patterns of reflections in the undulator vacuum chamber are much clearer when the source is a single undulator segment. The signal level for the hard x-ray setting is a healthy 25,000 photoelectrons, while the signal for the soft x-ray setting is a much smaller, yet still detectible, 1500 photoelectrons.

5. Safety

5.1. LLNL will meet or exceed SLAC/LCLS safety requirements. All work will be done in accordance with LLNL’s Environment, Safety and Health (ES&H) manual located at:

5.2. All work performed by LLNL employees at SLAC will be in accordance with SLAC’s Environment, Safety and Health manual located at:
http://www-group.slac.stanford.edu/esh/eshmanual/

5.3. All LLNL safety documentation for LCLS will be written to meet or exceed SLAC documentation requirements.

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i LCLS-TN-00-3

ii LCLS-TN-06-16
S. Reiche, "Analysis of the LCLS Spontaneous Radiation." (September 2006)