## Physics Requirements for the XTOD Direct Imager

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<td>Jacek Krzywinski</td>
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<td>Author, XTOD Manager</td>
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<td>John Arthur</td>
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**Brief Summary:** This document provides general Physics Requirements for the XTOD Direct Imager. The Direct Imager employs scintillators placed directly into the LCLS beam, viewed by digital camera systems through suitable optics, to provide images of the FEL and Spontaneous Radiation patterns on a pulse-by-pulse basis. The Direct Imager will be the primary instrument for viewing the LCLS beam in the Front End Enclosure (FEE) and for locating and identifying the first faint FEL produced by the LCLS. The Direct Imager will be used to image the spontaneous radiation from one or more undulator segments, to optimize the transport of x-rays to the FEE. Its images will be of sufficient quality to provide quantitative information about the beam pulse energy, spatial shape, and centroid location, to allow FEL physicists to bring the LCLS FEL up to full (saturated) power. At > 1% to 10% of FEL saturation, the scintillators will suffer damage unless the FEL is attenuated using the Gas and/or Solid Attenuators.

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1. Introduction

In this Introduction, a general description of the Direct Imager is given, along with a summary of its primary functions. In the following section, results of LCLS beam simulations are presented, to introduce the important parameters and range-of-conditions under which the Direct Imager must operate. From these, the Modes of Operation for the Direct Imager are defined in the next section. The requirements for the system are then listed in the final sections.

The XTOD Direct Imager is located in the Front End Enclosure (FEE) at approximately 738 meters from Station 100 (~91 meters from the end of the Undulator.) The Direct Imager is a collection of one or more x-ray imagers, which share a common tank, and can be moved into or out-of the beam to obtain images of the transverse spatial distribution of Spontaneous and FEL x-ray radiation from single LCLS pulses. The individual imagers in the system will likely consist of screens of x-ray converters viewed by electronic imaging cameras through suitable optics, as illustrated in the top sketch of Figure 1, and/or x-ray-sensitive CCD or photodiode arrays placed directly in the beam (lower two sketches of Figure 1). The latter are less desirable, as they place sensitive electronics in the path of the beam. In either case, at high FEL intensities, these screens and arrays will be damaged, so the Direct Imager can only be used in low-intensity situations or with a highly-attenuated FEL beam.

Figure 1: Possible “Direct Imager” X-Ray Cameras

The Direct Imager is the last element in a string of optics and diagnostics used to condition, commission, and monitor the LCLS beam, as shown in Figure 2. The optics and diagnostics upstream of the Direct Imager include 1) the Fixed Mask, which defines the maximum possible transverse spatial extent of the x-ray beam, 2) an adjustable X-Ray Slit, 3) a Gas Detector, which
can measure FEL pulse intensity non-intrusively, 4) an Attenuator, utilizing both gas and solids, to attenuate the x-ray beam, 5) another Gas Detector, 6) a General-Purpose Spectrometer/K-Spectrometer, and 7) the Total Energy Measurement System, which measures x-ray pulse energy using the temperature rise in a small volume of material.

**Figure 2 : Commissioning Optics and Diagnostics in the Front End Enclosure**

In this location, the Direct Imager will be used to align the upstream instrumentation by providing images that are essentially x-ray radiographs taken with the LCLS spontaneous radiation beam. These images will show the relative positions of each upstream instrument with respect to the beam spatial distribution. In this way the Direct Imager will be used 1) to determine the absolute coordinates of the X-Ray Slit blocks, 2) to determine the positions of the 3 mm apertures in the Gas Detectors and Gas Attenuator subsystem so that they may be collocated to the axis of the FEL beam, and 3) to place the General-Purpose Spectrometer/K-Spectrometer optics and Total Energy Calorimeter into their proper transverse positions when they are in use. Another reason to locate the Direct Imager downstream of these systems is to enable use of the Attenuator and X-Ray Slit to condition the incident beam.

The Direct Imager must also perform commissioning and characterization functions. Its images must be of sufficient quality to determine the LCLS radiation spatial shape, centroid, and intensity/pulse-energy, on a pulse-by-pulse basis. During commissioning, the Direct Imager will monitor the SASE start-up process at low power levels of the FEL beam. Under these conditions, the FEL intensity will be comparable to the fundamental spontaneous emission. Direct Imager measurements will be used to optimize machine settings to achieve FEL saturation. At high FEL fluences, attenuation will be required to avoid saturation of the Direct
Imager scintillator and detector damage. For Direct Imager pulse-energy measurements, the physical processes involved in the conversion of x-ray energy to signals in the detector are complex; they cannot be accurately calculated. Therefore, the Direct Imager measured FEL intensity distribution/pulse-energy will be cross-calibrated with measurements from other energy detectors.

2. LCLS Beam Characteristics at the Direct Imager

2.1. Introduction

The LCLS x-ray beam contains both Spontaneous and FEL radiation. The FEL radiation has wavelength, \( \lambda_1 \), equal to the fundamental wavelength of the electron beam/undulator system. This fundamental wavelength depends on the kinetic energy of the electrons in the undulator through the Lorentz boost factor, \( \gamma_e \), the undulator magnetic period, \( \lambda_w \), and the deflection parameter, \( K \). The fundamental wavelength is given by:

\[
\lambda_1 = \frac{\lambda_w}{2} \cdot \left( 1 + \frac{K^2}{2} \right).
\]

The FEL also contains small contributions from higher harmonics, whose photon energies are odd multiples of the fundamental. The spontaneous radiation spectrum is peaked around the wavelengths of the fundamental and its harmonics. By varying the Linac electron beam kinetic energy, the LCLS fundamental can be set to any wavelength between 1.5 nm (830 eV photon energy) and 0.15 nm (8.3 keV photon energy). We divide this range of possible fundamental photon energies into a "soft x-ray regime" with photon energies between 830 eV and 2.0 keV and a "hard x-ray regime" with photon energies between 2.0 keV and 8.3 keV. In addition, we define the accelerator configurations producing the extreme photon energies as the "soft x-ray FEL setting" (1.5 nm, 830 eV) and the "hard x-ray FEL setting" (0.15 nm, 8.3 keV).

Spontaneous radiation is the normal undulator radiation produced when electrons travel through an alternating magnetic field. When electron beam and undulator conditions are correct, FEL radiation will be seen in addition to the spontaneous radiation. These conditions must be found during LCLS commissioning by changing the electron beam and undulator parameters while looking for faint FEL radiation against a background of spontaneous radiation. The effect of this background is much reduced by the fact that the spontaneous radiation has a much larger angular divergence than the FEL. This causes its signal contribution to be spread over a much larger spatial extent than the FEL at the position of the Direct Imager.

Simulations have been performed for both the spontaneous radiation and FEL radiation at the location of the Direct Imager, for the soft x-ray FEL setting and the hard x-ray FEL setting. These help establish the performance requirements for the Direct Imager. The spatial distribution and absolute intensity of the spontaneous radiation is difficult to predict exactly, due to reflection and absorption off the walls of the Undulator vacuum chamber (sections of 5 mm V x 10 mm H rectangular tubing interspersed with sections of \( \varphi \) 8 mm circular tubing) and passage through other XTOD systems to the location of the Direct Imager. Nevertheless, these factors are included in the results which appear below.
2.2. **LCLS Soft X-Ray Characteristics**

2.2.1. **Soft X-Ray Spontaneous Characteristics**

Figure 3, left, shows a simulation of the fluence spatial distribution for the soft x-ray FEL setting (830 eV fundamental), produced by the full complement of 33 LCLS undulator segments and transported to the position of the Direct Imager over an 80 mm x 80 mm area transverse to the beam axis. The soft x-ray spontaneous has considerable divergence and fills the undulator vacuum chamber. This results in the uniform, 20 mm H x 10 mm V bright region in the center. A large fraction of radiation also spreads beyond the central bright spot, all the way out to the edges of the Fixed Mask aperture, whose shadow is seen at ±25 mm H and ±15 mm V.

**Figure 3: Spontaneous Fluence at Direct Imager:**
**Soft X-Ray FEL Setting, 0.79 nC**

In the soft x-ray setting, the spontaneous photon energy spectrum extends to above 500 keV and has a prominent peak around the 830 eV fundamental.

Figure 3, right, shows the spatial distribution for photons having energies, $E_\gamma$, around the fundamental, between 0.4 keV and 1.0 keV. By using a suitably-thin scintillator, this portion of the photon energy spectrum can be preferentially absorbed and imaged from the full spectrum. The spatial distribution of these photons near the fundamental is somewhat narrower than that of the full energy distribution, but is still clipped by the Fixed Mask in the vertical direction.

The numbers below each image give the number of photons per pulse, the total pulse energy, and the energy density on axis. These numbers scale linearly in the Linac bunch charge and have been scaled to represent the levels expected for a
bunch charge of 0.79 nC. The absolute intensity strongly depends on absorption in the undulator vacuum beam tube. Without absorption, the pulse energy for the spontaneous radiation in the soft x-ray setting is 1.8 mJ for a bunch charge of 0.79 nC (not shown). With reasonable assumptions about reflection and absorption, the simulation shows that this pulse energy is reduced by a factor of 4.7 to 0.38 mJ. However, the energy density in the center, $9.1 \times 10^{-5}$ J/cm², is actually a factor of 1.75 higher than the case of no absorption or reflection, indicating that reflected spontaneous photons will cross the beam axis by the position of the Direct Imager. Photons with wavelengths near the fundamental (right-hand image) carry only 0.82% of the total pulse energy and produce 0.86% of the energy density on axis.

2.2.2. Soft X-Ray FEL Characteristics

Figure 4 shows the saturated FEL spatial distribution for the soft x-ray FEL setting at the position of the Direct Imager, calculated under the most optimistic assumptions for the FEL divergence, source position, and FEL pulse energy. The width of the beam spot is 1.1 mm FWHM (Full Width Half Maximum.) The total pulse energy is 2.5 mJ and the energy density in the center of the spot is 0.2 J/cm². More pessimistic assumptions would yield beams with a larger divergence, spot diameters up to 3 times larger, and a central intensity 9 times smaller. As the LCLS FEL is tuned to shorter wavelengths, the FEL energy per pulse remains roughly constant but the divergence becomes smaller. This results in smaller spot sizes with higher energy densities on axis.

Figure 4: Saturated Fluence at Direct Imager:
Soft X-Ray FEL Setting

1.9 x 10¹³ photons, total
2.5 x 10⁻³ J, total
0.2 J/cm², center

1.1 mm, FWHM
2.3. LCLS Hard X-Ray Characteristics

2.3.1. Hard X-Ray Spontaneous Characteristics

Figure 5, left, shows a simulation of the fluence spatial distribution for the hard x-ray FEL setting (8.3 keV fundamental) produced by the full complement of LCLS undulator segments and transported to the position of the Direct Imager over a 50 mm x 50 mm area transverse to the beam axis. In the hard x-ray FEL setting, the spontaneous radiation has a smaller divergence. It just fills the undulator vacuum chamber in the horizontal and vertical directions. This results in a peaked, oval-shaped, 20 mm H x 10 mm V, bright region in the center. Very little radiation is reflected out of the central region and clipped by the Fixed Mask.

**Figure 5: Spontaneous Fluence at Direct Imager:**

**Hard X-Ray FEL Setting, 0.79 nC**

![Fluence distribution graphs](image)

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Photon Energy Spectrum</th>
<th>Photon Counts</th>
<th>Energy Flux</th>
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<td>All photon energies</td>
<td>9.2 x 10^{11} photons, total</td>
<td>9.8 x 10^{10} photons, total</td>
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<tr>
<td>4 keV &lt; E_{\gamma} &lt; 10 keV</td>
<td>1.3 x 10^{-2} J, total</td>
<td>1.1 x 10^{-4} J, total</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.3 x 10^{-3} J/cm^{2}, center</td>
<td>8.3 x 10^{-5} J/cm^{2}, center</td>
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</table>

In the hard x-ray FEL setting, the spontaneous photon energy spectrum extends to above 4 MeV. The spatial distribution of photons around the fundamental, Figure 5, right, is narrower, shows a central peak, and is changed very little by the reflection and scattering process. Its spatial distribution is also slightly clipped by the Fixed Mask in the vertical direction. As in the soft x-ray case, a suitably-thin scintillator can be used to preferentially absorb this portion of the spontaneous photon energy spectrum.

Without absorption, the total spontaneous pulse energy in the hard x-ray FEL setting is 18 mJ, for a bunch charge of 0.79 nC (not shown.) In this setting, the spontaneous radiation has a narrower angular distribution than in the soft x-ray
FEL setting. Therefore, it suffers less from reflection and absorption in the undulator beam tube. The simulation shows that after reflection and absorption, the pulse energy is reduced to 13 mJ. As in the case of the soft x-ray FEL setting, the hard x-ray photons with wavelengths around the fundamental carry ~ 1% of the total pulse energy and contribute ~ 1% of the energy density on axis.

2.3.2. Hard X-Ray FEL Characteristics
Figure 6 shows the saturated FEL spatial distribution at the position of the Direct Imager, calculated under the most optimistic assumptions for the FEL divergence, source position, and FEL pulse energy. The width of the beam spot is 160 µm FWHM. The pulse energy is 2.4 mJ and the energy density in the center of the spot is 3.4 J/cm². Again, more pessimistic assumptions yield beams with larger divergence and result in spot diameters up to 3 times larger and a central intensity 9 times smaller.

**Figure 6: Saturated Fluence at Direct Imager: Hard X-Ray FEL Setting**

![Fluence (J/cm²)](image)

- 1.8 x 10^{12} photons, total
- 2.4 x 10^{-3} J, total
- 3.4 J/cm², center

160 µm, FWHM

2.4. LCLS Single Undulator Segment Spontaneous Characteristics
During commissioning, it will be necessary to observe spontaneous radiation from a single undulator segment or pairs of undulator segments. This will occur during the K-measurement process, when instrumentation in the Direct Imager will be used both to align the K-Spectrometer and to measure the resulting transmitted signal.

Because of its large distance from the diagnostics and the fact that its radiation must traverse the full length of the undulator vacuum chamber, the 1st undulator segment (most-upstream segment) will produce the smallest spontaneous signal. Figure 7 shows a simulation of the fluence spatial distribution for the spontaneous radiation in the soft
x-ray FEL setting (left) and the hard x-ray FEL setting (right) produced by the 1st undulator segment and transported to the position of the Direct Imager over a 50 mm x 50 mm area transverse to the beam axis. The simulation shows that this light suffers significantly from reflection and absorption as it traverses the undulator vacuum chamber. As a result, no discernible structure is visible in the central rectangular area in either image of Figure 7. The total pulse energy, for a bunch charge of 0.79 nC, is 2.5 μJ for the soft x-ray FEL setting and 160 μJ for the hard x-ray FEL setting.

**Figure 7: Spontaneous Fluence at Direct Imager: 1st Undulator Segment, 0.79 nC**

![Soft x-ray spontaneous (826 eV fundamental)](image1.png) ![Hard x-ray spontaneous (8261 eV fundamental)](image2.png)

1.3 x 10⁵ photons, total  
2.5 x 10⁻⁵ J, total  
9.3 x 10⁻⁷ J/cm², center

9.8 x 10⁹ photons, total  
1.6 x 10⁴ J, total  
9.6 x 10⁻⁵ J/cm², center

The K-Spectrometer will produce a spectrally-sliced image of the spontaneous radiation at the position of the Direct Imager. To perform the K-measurement alignment procedure, the intensity in this sliced image must be carefully measured. To estimate the on-axis photon flux density available at the Direct Imager under these conditions, the table in Figure 8 gives expected x-ray intensities, over a 1 mm² central area, for a 3 eV and a 50 eV band pass, centered on the fundamental at 8.3 keV with a bunch charge of 0.79 nC. As the table shows for a 3 eV bandwidth, the number of photons in the 1 mm² area centered on axis is ~ 3 x 10⁵.

The photon spatial distribution output from the K-Spectrometer will display significant and useful structure, unlike the full-spectrum images displayed in Figure 7. The distributions will be essentially axially-symmetric in all cases, but will range between "normal", center-peaked distributions to hollow-centered "doughnuts", depending upon the precise Linac electron beam energy for any given pulse. It should be possible to determine a beam centroid for every pulse.
3. Modes of Operation
The Direct Imager will have several distinct modes of operation with differing requirements. These modes are listed here:

3.1. **Soft X-Ray FEL Search and Measure**
This mode of operation is optimized to search for a faint FEL at the soft x-ray FEL setting. To overcome the background from spontaneous radiation, the x-ray absorber/scintillator must preferentially absorb FEL radiation, rather than the spontaneous radiation at higher photon energies. One can estimate the required minimum FEL pulse-energy sensitivity by estimating the absorbed spontaneous pulse energy in the proposed scintillator over an area equal to the diffraction-limited FEL beam. If the FEL pulse energy is ~equal to this energy, the FEL should be distinguishable from the spontaneous background. Using Figure 3 to estimate the spontaneous pulse energy absorbed in the scintillator, Figure 4 to estimate the relevant area associated with a diffraction-limited FEL beam, and some factor of conservatism (~3X), one obtains a required minimum FEL pulse-energy sensitivity of 30 nJ for diffraction-limited FEL beams. The field-of-view must be large enough to detect the FEL anywhere within the footprint of spontaneous radiation that lies within a ± 50% bandwidth about the FEL fundamental photon energy (Figure 3, right image). The spatial resolution must be better than 1/5 the FWHM of a diffraction-limited FEL beam at the soft x-ray FEL setting, illustrated in Figure 4.

3.2. **Hard X-Ray FEL Search and Measure**
This mode of operation is optimized to search for a faint FEL at the hard x-ray FEL setting. To overcome the background from spontaneous radiation, the x-ray absorber/scintillator must preferentially absorb FEL radiation, rather than the spontaneous radiation at higher photon energies. Using the same procedure described in Section 3.1 above, based on the simulation results from Figures 5 and 6, the required minimum FEL pulse energy sensitivity should be 100 nJ for diffraction-limited FEL beams. The field-of-view must be large enough to detect the FEL anywhere within the footprint of spontaneous radiation that lies within a ± 50% bandwidth about the FEL fundamental photon energy (Figure 5, right image). The spatial resolution must be better than 1/5 the FWHM of a diffraction-limited FEL beam at the hard x-ray FEL setting, illustrated in Figure 6.

3.3. **Spontaneous Characterization**
This mode of operation is optimized to study and measure spontaneous radiation from one or more undulator segments. As such, it must be more sensitive to the higher-

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**Table:**

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<thead>
<tr>
<th>Parameter</th>
<th>Soft X-Ray</th>
<th>Hard X-Ray</th>
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<tbody>
<tr>
<td>Bandwidth, eV</td>
<td>±1.5</td>
<td>±50</td>
</tr>
<tr>
<td>Photons / mm²</td>
<td>$3.1 \times 10^5$</td>
<td>$6.8 \times 10^6$</td>
</tr>
<tr>
<td>Fluence, J/ mm²</td>
<td>$4.7 \times 10^{-10}$</td>
<td>$9.1 \times 10^{-9}$</td>
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photon-energy content of the spontaneous radiation than the previous two modes. It must be sensitive enough to make quantitative measurements of spontaneous radiation from the 1st undulator segment. The field-of-view must be wide enough to cover the entire footprint allowed by the Fixed Mask aperture. The spatial resolution of this mode should permit determination of the spontaneous distribution centroid within ±100 µm.

3.4. **K-Measurement**

This mode of operation is optimized to measure the photon output of the K-Spectrometer optics. It must be able to quantitatively measure the low-level photon pulse expected from the K-Spectrometer Bragg diffraction optics, as estimated in Figure 7 above. For this purpose, either an imaging or non-imaging detector would be acceptable. Detailed requirements stem from PRD 1.5-016, XTOD/XES K-Spectrometer, for the field-of-view, detector noise, gain drift/stability, dynamic range, and output readout rate. In addition, this mode must have sufficient imaging capabilities to locate the centroid of the output beams from the K-Spectrometer. It would be desirable, although not necessary, for centroid-finding to be possible on a pulse-by-pulse basis.

4. **Fundamental Requirements**

4.1. **Soft X-Ray FEL Search and Measure Mode**

4.1.1. Range of Detectable FEL Pulse Energies: From Section 3.1 above, FEL pulse energies exceeding 30 nJ must be detectable for diffraction-limited FEL beams. With the addition of appropriate attenuation, images of FEL pulses with energies up to 10 mJ should be possible.

4.1.2. Instantaneous Dynamic Range: The dynamic range for any given image shall exceed 256.

4.1.3. Spatial resolution: From Section 3.1 above, a spatial resolution better than 220 µm is required.

4.1.4. Field-of-View: From Section 3.1 above, a field-of-view > 50 mm horizontally and > 30 mm vertically is required.

4.1.5. Repeatability: Individual measurements must be repeatable to within 1% for 200 µJ FEL pulses.

4.1.6. Output Readout Rate: Images for every pulse, at pulse rates up to and including 30 Hz are required.

4.2. **Hard X-Ray FEL Search and Measure Mode**

4.2.1. Range of Detectable FEL Pulse Energies: From Section 3.2 above, FEL pulse energies exceeding 100 nJ must be detectable for diffraction-limited FEL beams. With the addition of appropriate attenuation, images of FEL pulses with energies up to 10 mJ should be possible.

4.2.2. Instantaneous Dynamic Range: The dynamic range for any given image shall exceed 256.

4.2.3. Spatial resolution: From Section 3.2 above, a spatial resolution better than 32 µm is required.

4.2.4. Field of View: From Section 3.2 above, a field-of-view > 10 mm horizontally and > 10 mm vertically is required.

4.2.5. Repeatability: Individual measurements must be repeatable to within 1% for 200 µJ FEL pulses.
4.2.6. **Output Readout Rate**: Images for every pulse, at pulse rates up to and including 30 Hz are required.

4.3. **Spontaneous Characterization Mode**

4.3.1. **Lower Limit of Detectable Spontaneous Radiation Levels**: Structured images from the 1st undulator segment alone, with a linac bunch charge of $\geq 0.2$ nC, at both the soft x-ray FEL setting and the hard x-ray FEL setting must be possible.

4.3.2. **Instantaneous Dynamic Range**: The dynamic range for any given image shall exceed 256.

4.3.3. **Spatial resolution**: The spatial resolution shall be no worse than twice (2X) the value of the spatial resolution for the corresponding FEL Search and Measure Mode.

4.3.4. **Field-of-View**: From Section 3.3, a field of view $> 50$ mm horizontally and $> 30$ mm vertically is required.

4.3.5. **Repeatability**: Individual measurements must be repeatable to within 1% for the full undulator complement and within 25% for one undulator segment when running with a linac bunch charge $\geq 0.2$ nC.

4.3.6. **Output Readout Rate**: Images for every pulse, at pulse rates up to and including 30 Hz are required.

4.4. **K-Measurement Mode**

4.4.1. **Incident Photon Energy and Band Pass**: In this mode, the incident photons will have a photon energy of approximately 8.3 keV, in a band pass of approximately 1 eV.

4.4.2. **Range of Quantified Photon Pulse Amplitudes**: Pulse amplitudes must be quantifiable between $2 \times 10^6$ photons and 15,000 photons per pulse.

4.4.3. **Instantaneous Dynamic Range**: The dynamic range for any pulse-amplitude measurement shall exceed 700, for a photon amplitude range between zero and $10^5$.

4.4.4. **Detector System Equivalent Noise**: The equivalent noise for the detector and its processing electronics shall not exceed 100 photons for any photon pulse amplitude measurement.

4.4.4.1. **Detector Spatial Uniformity**: Since the spatial distribution of the incident photon pulse will change dramatically in size and distribution from pulse to pulse, this factor, and any detector spatial non-uniformity, must be specifically evaluated as a contribution to the system noise.

4.4.5. **Field of View**: A field-of-view 10 mm H by 10 mm V is required, in order to conservatively intercept the entire maximum-anticipated distribution of 8.5 mm V x 9.0 mm H.

4.4.5.1. **Detector Translation**: Means to center the detector on the incident photon beam must be provided, if anticipated mis-steering would prevent acceptance of the entire maximum-anticipated photon spatial distribution on the detector.

4.4.6. **Gain Drift/Stability**: Repeatable measurements must be possible to better than 1% over a period of $> 40$ minutes.

4.4.7. **Output Readout Rate**: Pulse amplitude measurements for every pulse, at pulse rates up to and including 10 Hz, are required.
4.4.8. Imaging Capabilities:
   4.4.8.2. Centroid-Finding: Required, but rates < 10 Hz would be acceptable.
     4.4.8.2.1. Spatial Resolution: Centroid determination to within ±100 µm is desirable.

4.5. Global System Requirements
   4.5.1. Stay-Clear Area: The Direct Imager system must be designed such that, when not in operation, all components of the system can be remotely commanded into a configuration that does not obstruct radiation within the stay-clear zone defined by the XTOD Fixed-Mask clear aperture.
   4.5.2. Field-of-Regard: Depending upon the size of available scintillators and upon the field-of-view of the camera optics, some means may be required to re-center the Direct Imager system to the FEL beam axis.
   4.5.3. Periodic In Situ Recalibration: Periodic examination and recalibration of Direct Imager subsystem spatial response and sensitivity may be essential. An in situ procedure shall be developed to accomplish this.

5. Other Requirements
   5.1. The Direct Imager is located downstream of the Attenuator, whose use is required to avoid scintillator saturation and/or detector damage when the FEL operates at high pulse-energy levels. The Direct Imager is also located downstream of the K-Spectrometer, since it serves as the detector for the K-measurement optics.
   5.2. The Direct Imager design shall adhere to all elements of PRD 1.5-002, XTOD Mechanical-Vacuum Systems.

6. Controls
   6.1. The Control System for the Direct Imager shall be EPICS. Gain settings, detector modes, and clear-aperture configuration shall be remotely controllable. Images from the Direct Imager shall be available as a beam-synchronous EPICS process variable for archival and display purposes.