Experience with the CSPAD during dedicated detector runs at LCLS

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Abstract. In-house developed cameras and other commercial detectors are typically tested with x-ray tubes and at synchrotron beamlines before being deployed and used for science experiments. In a prototyping phase, this is needed to understand and characterize the behavior of the detector. In a more advanced development phase, measurements with x-rays are required to characterize and calibrate the camera. Tests at synchrotron beamlines in actual experimental conditions are indeed a valuable source for detector developers. However, when all photons arrive at once, as for FELs, the response of the detector can be very different from that obtained with a synchrotron beam which behaves more like a CW (continuous) source. This behavior was already observed during users runs at LCLS and recently investigated during dedicated detector beamtime. The linearity of the response of the Cornell-SLAC Pixel Array Detector (CSPAD) was investigated. Results are presented and discussed.

1. Introduction
With the advent of x-ray Free Electron Lasers (FELs), it was clear that a dedicated class of detectors had to be developed to fully exploit the source characteristics. The pulsed nature of these sources requires the use of purely integrating x-ray detectors. Depending on the experiment, a suite of detectors with imaging capability has to cover applications characterized by low signal or very high maximum signal, typically with a good spatial resolution. Detecting intense signals in short times poses new challenges for the silicon diodes, the frontend electronics and the overall camera concept. The response of the detector under these operating conditions can be simulated; although due also to the novelty of the source, comprehensive predictions are difficult. The consequences of operating at these conditions need to be understood and validated by experimental investigation with x-rays so that new generation of detectors can by optimally designed. For this reason tests of cameras developed for FELs with x-ray laboratory sources and at synchrotron beamlines are not sufficient for a complete characterization of these detectors; and the final validation of the detector concept is often achieved during the experiments [1-3]. At the Linac Coherent Light Source (LCLS) the great majority of hard x-ray experiments employs a variant of the Cornell-SLAC Pixel Array Detector (CSPAD) [4-9]. The characteristics of this camera (currently available in three sizes: 2.3 Mpixel, 560 kpixel and 140 kpixel) are summarized in Table 1. Figure 1 shows the schematic of a pixel.
In order to analyse and characterize the behaviour of the CSPAD, a series of measurements were carried out at the Stanford Synchrotron Radiation Lightsource (SSRL) and at LCLS with particular
attention to the case of high photon fluences where differences can be expected. Details of the experimental setups and test results are presented and discussed in the following paragraphs.

### Table 1. CSPAD properties

| Property          | Value                                      |
|-------------------|--------------------------------------------|
| Pixel size        | 110 µm x 110 µm                            |
| Area              | 326 cm² (2.3 Mpixel)                       |
| Maximum signal    | 2700 8 keV photons/pixel (low gain)        |
|                   | 350 8 keV photons/pixel (high gain)        |
| Frame rate        | 120 Hz                                     |
| Noise             | ~ 3.5 keV (low gain), ~ 1 keV (high gain)  |

### 2. Experimental evaluation with x-rays

#### 2.1. Stanford Synchrotron Light Source

A series of tests were performed on CSPADs at SSRL beamlines BL 2-2 and 7-2. Typical working conditions at synchrotrons offer a relatively stable beam, whose intensity is easily measured with ion chambers. Detectors quantum efficiency at different energies can be evaluated with fast scans by simply rotating a monochromator crystal. Figure 2 shows the normalized response of the CSPAD-140k v1.5 (a version of the CSPAD with upgraded electronics, ASIC and firmware) at energies ranging from 7 to 15 keV. The measurements were performed at room temperature. The figure shows histograms of all pixels with pedestal and common mode correction without any per-pixel correction. It can be noted that although the detector is not designed to tackle spectroscopy applications all energy lines are well resolved. To study the linearity of the response of CSPADs scans sweeping the integration time were performed. These measurements allowed improving a previous version of this detector, which had shown non-linearity at low intensities. Results from scans in high and low gain of a CSPAD-140k v1.2 (a version of the CSPAD with upgraded electronics and firmware) are shown in figure 3. They both present saturation at 14000 ADU. Thanks to the short integration time, the attenuated direct beam was used for all the measurements. Harmonic contamination in the beam was negligible.

![Figure 1. Schematic of a CSPAD pixel.](image1)

![Figure 2. CSPAD 140k v1.5: energy scans.](image2)

#### 2.2. Diagnostics at FELs

Working conditions at LCLS are very different: (i) intensity fluctuations downstream a monochromator are significant and present very peculiar intensity distributions as depicted in Figure 4 (in strong contrast to the pink beam intensity distribution); (ii) precise intensity measurements are more difficult to implement. The first step to prepare for detector tests was to improve the electronics of the systems used for diagnostics at the experimental station. Figure 5 shows a correlation plot of the
beam intensity measured with the CSPAD-140k v1.5 versus the beam intensity measured with a new version of the in-house developed beam position and intensity monitor system [10]. These measurements were performed at the X-ray Pump Probe (XPP) instrument with 9 keV monochromatic radiation delivered by a silicon(111) monochromator.

2.3. Linac Coherent Light Source

To investigate how many photons arriving all at once would affect the response of the CSPAD in low gain mode, a series of measurements were taken by using small angle x-ray scattering patterns or the attenuated direct beam at 9 keV. In figure 6 are shown plots correlating the response of the CSPAD to the impinging beam power. Figure 6a shows the response of the detector with “standard” setting. Strong non-linearity can be observed at relatively low fluence. A second set of measurements aimed to extend the limit exhibited with the previous setting by changing the reference voltage of the preamplifier (figure 6b). This obviously allows extending the dynamic range but not up to the expected maximum signal of 14000 as observed previously and presented in Sec 2.1. A third study investigated the effect of the sensor bias voltage and is presented in figure 6c. We observe that for very low bias voltage the response of the detector is very similar to the one measured at SSRL (cf. figure 3).

3. Discussion

The observed behavior can be explained by taking into account the actual response of the pMOS reset and injection transistors. At high intensities and short charge collection times, the voltage builds up at the preamplifier input, due to the limited bandwidth and slew rate of the preamplifier, thus increasing the effective gate-source voltage of the reset pMOS transistor. This effectively elongates the reset time and results in some charges leaking through the still partially closed reset. To avoid this effect the
signal arrival needs to be synchronized with an additional delay from the removal of the reset with respect to the value required for low intensity operation. At very short collection times the charge at the input can also forward-bias the bulk diodes of reset and injection transistors (going through the substrate in the wells and to the supply). These dynamic signal losses can be observed also in the simulations of the linearity response of the preamplifier (figure 7). The voltage on the gate of the reset pMOS transistor is assumed to switch with a 4 $\mu$s time constant equivalent to a reset release time in low signal conditions of about 3 $\mu$s. Three different collection times, 10, 100 and 200 ns, are considered (figure 7). In each case the charge arrival is supposed to happen with three possible delays: 3, 6 and 20 $\mu$s. The simulations confirm that this effect, as demonstrated by the measurements at very low biasing voltage (figure 6c), is strongly dependent on the charge collection time.

Figure 6. Linearity response of the CSPAD in low gain. a) Standard setting. b) Different reference voltages at the preamplifier. The flat-top of the response is generated by the ADCs. c) Different sensor bias voltages.

Figure 7. Simulation of the response of the CSPAD to increasing charge at the input. a) 10 ns charge collection time; b) 100 ns charge collection time; 200 ns charge collection time.

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