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Detection of 1 - 100 keV x-rays from high intensity, 500 fs laser-produced plasmas using charge-coupled devices

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ABSTRACT

We describe a compact, vacuum compatible, large format, charge-coupled device (CCD) camera for scientific imaging and detection of 1 - 100 keV x-rays in experiments at the Lawrence Livermore National Laboratory JANUS-1ps laser. A standard, front-illuminated, multi-pin phase (MPP) device with 250 k electron full well capacity, low dark current (10 pA/cm² at 20 °C) and low read noise (5 electrons rms.) is cooled to -35 °C to give the camera excellent 15-bit dynamic range and signal-to-noise response. The intensity and x-ray energy linear response have been determined for optical and x-ray (< 65 keV) photons and are found to be in excellent agreement. Departure from linearity has been measured to be less than 0.7%. The inherent linearity and energy dispersive characteristics of CCD cameras are well suited for hard x-ray photon counting techniques in scientific applications. X-rays absorbed within the depletion and field-free regions can be distinguished by studying the pulse height spectrum. Results are presented for the detection of 1 - 100 keV Bremsstrahlung continuum, K-shell and L-shell fluorescence spectra emitted from high intensity (10¹⁸ W cm⁻²), 500 fs laser-produced plasmas.

Keywords: CCD, x-ray detection, K- α fluorescence, photon-counting, laser-produced plasma

1. INTRODUCTION

Charge coupled devices (CCDs) have been used for nearly two decades for direct x-ray detection in the 50 eV - 10 keV energy range for scientific applications¹⁻⁹. The combination of superior spatial resolution (7 - 25 μ m), low inherent noise, excellent linear response and high quantum detection efficiency (QDE) have made CCDs the detectors of choice over x-ray film and other photo-electric detectors for two-dimensional imaging. Various researchers, Janesick *et al*⁹ and Castelli *et al*¹⁰, have shown that cooling to low temperatures in order to lower the electronic system noise and utilizing back-illuminated or thinned front electrode sensors can give further improvements in the low energy x-ray response below 1 keV. The use of deep depletion CCD sensors as described recently by Owens *et al*¹¹ and McCarthy *et al*¹² has also improved the QDE to near unity for 4 keV radiation and also extended the useful x-ray response at 10 keV and beyond. These CCD characteristics, particularly the good spatial resolution, high charge collection efficiency and inherent low noise⁹, demonstrate the potential of single-photon counting techniques with energy resolution as a powerful diagnostic for studying x-ray emission from various laboratory and astrophysical plasmas^{13,14}.

In this paper, results are presented to show that standard, scientific, front-illuminated CCD sensors can be used effectively to measure harder x-rays > 10 keV. These solid state 2-D imaging detectors can be used to characterize the x-ray emission from high Z solid targets irradiated by an intense ultra-short laser

pulse¹⁵. By studying the pulse height spectrum, x-ray events absorbed within the depletion layer or the field-free regions of the epitaxial silicon can be distinguished. X-rays detected in the depletion layer give the best energy resolution as described by Owens *et al*¹¹.

A description of the low noise, miniature, vacuum compatible camera system used for single-photon counting in the experiment is presented together with its specification. An absolute calibration is made at 520 nm and shows excellent detector intensity linearity at optical wavelengths. The detector energy linear response is determined for x-rays up to ~60 keV and is in excellent agreement with the equivalent optical measurements. A laboratory hard x-ray line source is used to measure the absolute CCD responsivity at energies above 8 keV. The quantum detection efficiency at different energies is compared to predicted values based on the nominal detector epitaxial region thickness and is in agreement to better than 20%. Hard x-ray spectra and source imaging are performed for various laser-irradiated target materials.

2. CAMERA DESCRIPTION

The Compact Charge-Coupled Device Camera (C³) head used in the experiment was designed and built at LLNL. A description of the vacuum compatible, miniature CCD camera has been reported recently by Conder *et al*¹⁶. Briefly, the philosophy driving the camera design was to accommodate a large format scientific CCD to give the maximum active detection area possible within the smallest overall volume. The camera had to be vacuum compatible and retain the low noise, high dynamic range characteristics of present CCD devices necessary for state-of-the-art scientific x-ray, ultra-violet and optical imaging in laser-produced plasma experiments. To this end, cooling to cryogenic temperatures was ruled out because of the long cool down times incompatible with the miniature and compact concept. However, with the advent of multi-pin phase devices run in inverted mode to give low dark current of <10 pA/cm² at 20°C MPP, low read noise and reasonable pixel full well capacity, it was decided early on in the project (1992/1993) to utilize these devices.

Figure 1 (a) shows a photograph of the CCD camera with the front cap removed to display the CCD device more clearly. Figure 1 (b) shows the block diagram of the CCD head electronics and is discussed in detail elsewhere¹⁶. Figure 1 (c) is an exposed view of the compact camera with the main components labeled. The front removeable window (A) can be glass for optical calibration outside of vacuum or 13 μ m beryllium for x-ray detection in vacuum. For the former case, the front chamber of the camera holding the CCD is evacuated in order to prevent water condensation damage on the cooled CCD sensor (B). The sensor is in thermal contact with the cold side of a two-stage thermoelectric (TE) cooler (C) which typically can be operated at temperatures of -30 to -50°C. The hot side of the TE cooler is glued or soldered to a copper block (D); water is continuously circulated through the copper block as a heat exchanger. Room temperature coolant can be run to reach -30°C temperatures while chilled water at 10°C will give lower coldside temperatures and faster cool down times. The on-board CCD electronic boards (E) and aluminum chassis (G) are in thermal contact with the copper block. The CCD and front cap, however, are thermally isolated from the hot side of the TE cooler. The signals for camera control, TE control and analogue video out are addressed through a flexible 25-pin D connector (F). The camera functions are adjusted by a commercial controller¹⁷ which acquires and digitizes the video signal to a Macintosh or PC at a fast 12-bit or slower but higher resolution 16-bit analogue-to-digital converter (ADC). The camera has been operated reliably under vacuum for continuous periods of 12 hours. It can be cooled down to full operating temperature in under 15 minutes and brought back to room temperature in a similar time.

Figure 1 (a) shows a photograph of the compact CCD camera with SITe TK1024 sensor. Camera dimensions are listed in Table 1. Figure 1 (b) is a block diagram of the CCD head electronics. Figure 1 (c) shows the main components and their function in an exposed diagram of the camera.

To date, the camera has been designed to be compatible with large format devices from Scientific Imaging Technologies (SITe)¹⁸ and English Electric Valve Ltd. (EEV)¹⁹. The SITe TK1024 sensor, 1024×1024 pixel array with a $24 \mu\text{m} \times 24 \mu\text{m}$ pixel size giving an active area of $24.6 \times 24.6 \text{ mm}^2$, and the EEV CCD05-30 sensor, 1242×1152 pixel array with a $22.5 \times 22.5 \mu\text{m}^2$ pixel giving an active area of $28.0 \times 25.9 \text{ mm}^2$, have been successfully operated. For the rest of this paper, we will deal specifically with the SITe TK1024 sensor.

We summarize the CCD and camera performance in Table 1. Exceptionally low dark current noise is possible when a low 10 pA/cm^2 MPP SITe TK1024 device is used in the camera. In the high resolution 16-bit mode, the r.m.s noise level which includes all sources of electronic noise is measured to be ~ 2 ADC counts corresponding to 7 - 8 elec. The minimum detectable signal/pixel is defined as giving a signal-to-noise ratio of 1:1. Therefore, the useful dynamic range of the camera system before saturation is a true 15-bit or $3.2 \times 10^4:1$.

Table 1. CCD and C³ Camera System Specification

Parameter	C ³ Detector
Camera dimensions:	60 × 60 × 72 mm ³
Cooling:	Two stage thermoelectric cooler with water cooled Cu heat exchanger, T=-35°C to -50°C
<u>CCD</u>	
CCD Sensor:	SITe TK1024
Active Area:	24.6 × 24.6 mm ²
Number of pixels:	1024 × 1024
Pixel size:	24 × 24 μm ²
Full well capacity:	2.4 × 10 ⁵ elec./pixel for MPP device 4.0 × 10 ⁵ elec./pixel for standard device
CCD dark current:	10 - 35 pA/cm ² (typically) for MPP device at 20°C
Read Noise:	5 - 7 elec. rms @ 50 kHz @ T=-40°C
<u>Camera System</u>	
Dark Current:	<0.52 elec./pixel/s measured @ T=-35°C for TE-cooled MPP device with 10 pA/cm ² dark current at 20°C
System read noise:	7.4 elec. rms @ 100 kHz with 16-bit ADC
Linearity:	deviation <0.7% measured by optical and x-ray techniques
Gain:	3.7 elec./count (16-bit ADC)
Dynamic Range:	15-bit, (3.2 × 10 ⁴ :1) using 16-bit ADC
Full frame readout time:	12 s @ 100kHz with 16-bit ADC 2.5 s @ 500 kHz with 12-bit ADC

3. CALIBRATION PROCEDURE

The CCD camera was calibrated and characterized using laboratory optical and x-ray sources at LLNL. The camera responsivity, linearity, gain and full well capacity were primarily determined using a TV Optoliner, made by Optical Instruments Corp., with a 50 μs pulsed xenon flashlamp source filtered to pass 520 nm light. The source output had previously been referenced with an absolutely calibrated photodiode. Neutral density filters were introduced in order to vary the incident light fluence on the CCD. The camera gain of 3.7 elec./count was set in order that the pixel full well capacity from the manufacturer's specification corresponded to the maximum of the 16-bit ADC. Figure 2 shows the CCD response to 520 nm light for nearly 5 orders of magnitude incident light fluence measured at a CCD temperature of -20°C. Excellent linearity, with measured deviation less than 0.7% from fit, is evident from the camera system to within ~10% of the ADC maximum. For higher incident fluence, the CCD response begins to deviate from linearity and saturate as the pixel full well capacity is reached. Ultimately image blooming will be produced. The measured CCD responsivity of 0.109 C/J is determined from the linear slope of Figure 2. This corresponds to QDE of 0.26; both figures are in excellent agreement with the manufacturer's specification at 520 nm for a front-illuminated sensor.

The CCD x-ray response was measured using the LLNL High Energy X-ray (HEX) source which is capable of producing intense hard x-ray lines of high spectral purity in the 8 - 98 keV energy range. The HEX source and calibration philosophy are described by Gaines and Wittmayer²⁰. Briefly, primary x-rays from a radiographic x-ray tube excite characteristic fluorescent K-α radiation from thin foil targets. The radiation is filtered using K-shell absorption edges in order to make the x-ray beam more monoenergetic.

Figure 2 shows the CCD response to incident 520 nm optical light flux. The data points are fitted by a linear equation and exhibit excellent linearity over nearly 5 orders of magnitude.

Figure 3 (a) shows the pulse height spectrum from the CCD detector for a 4 s exposure. The HEX x-ray source is a $25 \mu\text{m}$ Cu fluorescer producing Cu K- α at 8.048 keV filtered by $25 \mu\text{m}$ Ni. Camera is used in single-photon counting mode and x-rays from 1 or 2 pixel events are analyzed. Figure 3(b) shows CCD response for 1 to 1000 s exposures for Cu K- α radiation. Excellent intensity linearity is evident from linear fit to data points.

A calibrated sodium iodide scintillator with photo-multiplier tube is used as the monitor detector to calibrate the absolute x-ray flux incident on the C³ CCD detector. The CCD x-ray response to high spectral purity Cu K- α emission of the HEX source is shown in Figure 3 (a). The camera is used in single-photon counting mode for low incident x-ray fluence from a 4 s exposure. The pulse height spectrum, after the energy scale has been determined as discussed below, for isolated 1 and 2 pixel x-ray events is measured. This represents detected signal from x-rays absorbed within the depletion layer. As expected the spectrum shows an intense well-resolved line feature corresponding to the Cu K- α at 8.048 keV. The peak below 1 keV is due to partial events and residual thermal background. Two weaker peaks labeled at 6.3 keV, 16.1 keV correspond to the Si K- α escape peak and 2 $\times$ Cu K- α multiple events, respectively.

The exposure time was increased from 1 to 1000 s in order to measure the CCD response as a function of time for a constant x-ray source. The results plotted in Figure 3 (b) again show excellent camera stability and linearity in time. The data points are fitted by a linear equation with a regression coefficient of >99.999%. The intensity response of the camera is found to confirm the optical response linearity even though the x-ray energy is more penetrating and being absorbed deeper within the device. Changing the HEX fluorecser to 75 μ m Sn produces harder 25.27 keV K- α x-rays which are readily resolved as shown in Figure 4 (a). The energy linearity of the CCD camera to hard x-rays was determined by exposure to various copper through Hafnium filtered fluorescers²⁰ to produce monoenergetic 8 - 63.2 keV x-rays. The pulse height spectrum was analyzed for depletion layer events. The centroid positions of the detected peaks, in units of ADC counts, were measured and plotted as a function of the incident x-ray energy using the x-ray data of Bearden²¹. For the lower Z fluorescers where the CCD detector resolution was insufficient to resolve the K- α doublet, the single measured peak was given a weighted x-ray energy. The weak lines from the Se and Ag K- β were also included. Figure 4 (b) shows the data points labeled with the corresponding fluorescer. The linear fit to the data points is excellent; the measured deviation is better than 0.4% and is mainly limited by the photon statistics for the higher energy x-ray peaks.

Figure 4 (a) shows the pulse height spectrum from the CCD detector for a 3 s exposure from the HEX. A 75 μ m Sn fluorecser produced Sn K- α x-rays at 25.27 keV filtered by 63 μ m Ag. Figure 4(b) shows CCD energy linear response for x-rays from 8 to 63.2 keV. The x-ray data points are labelled with the corresponding fluorescer. Excellent intensity linearity is evident from linear fit to data points.

The CCD signal output as a function of absolutely determined x-ray flux is measured to find the camera responsivity and quantum detection efficiency (QDE) at a particular x-ray energy. The camera response is typically measured over several orders of magnitude of x-ray fluence as plotted in Figure 5 (a). The family of curves show response to Cu, Mo and Sn K- α at 8.048, 17.47 and 25.27 keV, respectively. As expected, the response is lower to more energetic x-rays due to reduced absorption within the detection region. Hence, at any given incident x-ray fluence a higher CCD response is measured for the Cu K- α in comparison with the Sn K- α x-rays. The linear fit to the camera response at each energy can be used to yield the QDE of the overall epitaxial layer. Detector geometry, filter transmission and scintillator detection efficiency are all included in the measurement.

A simple detection model based on manufacturer's CCD data, tabulated cross-sections from Veigele²² and Henke *et al*²³ is used to calculate the absorption of x-ray photons as a function of incident x-ray energy. No charge diffusion effects are included but all charge produced within the field-free region is assumed to be reflected at the epi/substrate boundary and to diffuse without loss into the collection region. Charge transfer inefficiency is extremely low in present devices. The manufacturer's specification²⁴ for the SITe TK1024 depletion layer and epitaxial thickness is $8 \pm 1 \mu\text{m}$ and $20 \mu\text{m}$, respectively. The QDE is plotted as a function of 1 to 50 keV x-ray energy on Figure 5 (b). The solid line is the predicted QDE based on the model for a $20 \mu\text{m}$ epitaxial layer. Measured data points are shown from 8 to 46 keV. Total uncertainties and statistics from the signal rates, filter transmission, geometry and scintillator detection efficiency give error bars of $\pm 10\%$. Good agreement is found between the measured points and the QDE model to within 20%; there is an indication that the measured data points lie slightly above the predicted curve. Measured QDE varies from 28% at 8 keV to 0.2% at 46 keV. Deep depletion devices on $65 \mu\text{m}$ epitaxial silicon, recently characterized by McCarthy *et al*¹², will give higher detection efficiency for hard x-rays. Nevertheless, laser-produced plasmas are bright x-ray sources and the incident x-ray flux on the CCD has to be adjusted in order to achieve single-photon counting. So in practice the optimal x-ray flux may be achieved by adjusting the detector to source distance to compensate for low detection efficiency.

Figure 5 (a) shows the CCD response to incident x-ray flux for three different K- α energies. Figure 5 (b) shows CCD detection efficiency from 1 to 50 keV. Solid curve is predicted model for $20 \mu\text{m}$ epitaxial region based on manufacturer's nominal data. Measured data points at 8 to 46 keV have $\pm 10\%$ error bars and are in good agreement with predicted model.

4. 500 fs LASER EXPERIMENT RESULTS

The C^3 CCD hard x-ray photon counting camera was used as part of a suite of x-ray diagnostics to characterize the x-ray emission from solid targets irradiated by high intensity 500 fs laser pulses. The other x-ray diagnostics included: (1) a CCD pinhole camera⁸ to image the soft x-ray emission from the laser focal spot; (2) a filtered streak camera with 2 ps time resolution to record the x-ray time history; (3) various soft x-ray crystal spectrometers; (4) scintillator array to measure hard x-ray bremsstrahlung. As described in Dunn *et al*²⁵, a maximum of 700 mJ of 1.053 μm laser light in a 500 fs (FWHM) *sech*² shape was focused to a 12 μm (FWHM) focal spot on a high Z target. This corresponds to a peak irradiance near $10^{18} \text{ W cm}^{-2}$. A significant fraction of the laser energy is absorbed into heating hot electrons which are subsequently further accelerated in the intense field of the laser. These electrons then collisionally excite the high Z solid target to produce characteristic K- α fluorescence often observed in a region or halo surrounding the focal spot. This radiation can be measured to determine the electron distribution.

The CCD hard x-ray camera was set up about 93 cm from the laser focal spot. This was the minimum distance where single-photon counting could still be carried out on account of the bright emission from the source. Various K-edge absorption filters, matched to the target material, were placed in front of the CCD to attenuate the intense continuum and soft x-ray line emission below 10 keV. A front collimator with strong magnets was introduced to divert charged particles from the detector. The CCD camera was triggered to integrate for 1 s during which time the laser was fired on target. This integration time is considerably longer than the hard x-ray emission duration: the streak camera filtered for the K- α emission shows that the x-rays lasts for ~ 3 ps, (3×10^{-12} s). Figure 6 (a) and (b) below show typical spectra

Figure 6 (a) and (b) are typical pulse height spectra measured from the 500 fs laser produced plasma experiment. The data shown has not been corrected for filter response or detector efficiency. Figure 6 (a) shows intense single shot Mo K- α and K- β emission lines at 17.48 and 19.61 keV, respectively from a molybdenum target irradiated with 650 mJ of laser energy. For this spectrum a 50 μm Mo foil was used in front of the CCD sensor to attenuate continuum radiation below 10 keV. Figure 6 (b) shows a 3 shot L-shell line and continuum spectrum from a Au target irradiated with an average of 660 mJ laser per shot. A 50 μm Sn foil is the filter material. Stronger continuum radiation can be observed between 10 and 30 keV and above the Sn K-edge to 45 keV.

recorded from the 500 fs laser produced plasma experiment. Figure 6 (a) shows Mo K- α and K- β line emission at 17.48 and 19.61 keV, respectively for a 25 μm molybdenum foil irradiated with 650 mJ of laser light. A 50 μm Mo foil is used to attenuate the softer x-radiation below 10 keV. The first thing to notice is the hard x-ray line emission is remarkably intense and has similarities to the HEX monoenergetic calibration spectrum shown in Figure 3 (a) or 4 (a). Closer examination shows that there is more continuum in the spectrum of Figure 6 (a) from 10 to 18 keV and this extends beyond 38 keV. The high energy x-rays above 20 keV are detected signal and not noise. Since the emission is measured to last a few picoseconds, these hard x-ray sources are remarkably bright.

Figure 6 (b) is a spectrum recorded from a gold foil integrated over 3 laser shots with an average of 660 mJ/ shot. The characteristic Au L-shell fluorescence is observed with L- α , L- β and L- γ lines measured at 9.71, 11.44. and 13.38keV, respectively. The 50 μm tin filter attenuates the the L- α line intensity more strongly than the higher energy lines and passes the radiation up to the Sn K-edge at 29.2 keV. The spectrum has not been corrected for filter transmission or QDE. It can be seen that the continuum emission extends to higher x-ray energies than Figure 6 (a) and contains higher proportion of the radiated energy. Also, the Au K- $\alpha_{1,2}$ lines which would be expected at 68.8, 67.0 keV are absent. This can either be explained by the plasma suprathermal electron distribution being not high enough to excite the high energy Au K- α emission or the CCD detection efficiency is too low to detect these x-rays.

5. HARD X-RAY IMAGER

It was possible to utilize the CCD 2-D spatial resolution to image the target source region in the 500 fs laser-produced plasma generating the hard x-rays above 10 keV. This was achieved by positioning a knife-edge assembly along the axis defined by the laser focal spot and the photon-counting CCD camera shown in Figure 7. This technique has been described recently by Rousse *et al* ^{26,27} for imaging 1 - 6 keV x-rays from 100 fs laser plasmas. The assembly, consisting of a pair of stainless steel knife-edges crossed at right angles, was placed 7 cm from the focal spot giving an imaging magnification of 12.3 $\times$. Since x-ray diffraction at the knife-edge is negligible, the overall imaging spatial resolution was determined by the effective size of the CCD pixel, $\sim 2 \mu\text{m}$. Field-free region events were included to increase detected x-ray signal. This produced some loss of spatial resolution due to charge diffusion into adjacent pixels. The overall spatial resolution was determined to be 4 - 5 μm . Gold foil 25 μm thick was added to each knife-edge in order to reduce the transmission of 10 - 30 keV x-rays through the edge material. This was found to significantly improve the imaging contrast.

Figure 8 (a) shows a typical 750 $\times$ 750 pixel single shot image from a Mo target irradiated with 646 mJ of laser light in a 12 μm (FWHM) spot. The imaging from the right-angled knife-edges can be seen clearly on the left and bottom sides of the image. The curved edge on the top and right sides is produced by the circular filter holder on the nose piece of the CCD camera. The hard x-ray source size is determined in 1-D from this image using the following procedure. A lineout normal to the left side of the image is taken as shown in the top plot of Figure 8 (b). The change in the imaged x-ray signal occurring between pixel position 200 and 300 shows the hard x-rays are mostly emitted from within a 200 μm source region. The curve smoothness is limited by photon noise which can be reduced by averaging over 5 or 10 data points, indicated by open circles. An interpolated fit is then applied to the averaged data to recover the original pixel sampling while retaining the general shape of the curve. The numerical derivative, shown in the lower plot of Figure 8 (b), is then extracted from the interpolated fit. The imaging magnification is used to

convert the scale to dimensions measured at the source. This shows that the target region emitting the hard x-rays has dimensions of $55\text{ }\mu\text{m}$ (FWHM). This is larger than the laser focal spot and is indicative of electron transport phenomena within the plasma. The analysis process can be repeated for the bottom side to obtain the spatial emitting region in the orthogonal direction. With this experimental arrangement hard x-ray single photon counting for spectral resolution and imaging, Figures 6 (a), 8 (a), (b), can be conducted simultaneously on a single laser shot.

Figure 7 shows a schematic of the laser-produced plasma experiment used to simultaneously image and record the hard x-ray spectrum. A right-angled stainless steel knife-edge is placed close to the target in order to image the emission. The knife-edge is covered with $25\text{ }\mu\text{m}$ of Au foil to reduce the transmission of 10 - 30 keV x-rays through the knife-edge material.

Figure 8 (a) shows a hard x-ray 750×750 pixel image from a laser-irradiated molybdenum target in a single shot. 2-D knife-edge imaging is apparent on the left and bottom sides of image. Figure 8 (b) top plot is a lineout normal to the left side of the image of 8 (a). Averaged data points are shown as open circles. Numerical derivative, lower plot, indicates spatially emitting region of hard x-rays has dimensions of $55\text{ }\mu\text{m}$ (FWHM).

6. SUMMARY

We have described a CCD camera system which has been successfully used to detect 8 - 100 keV x-ray emission. This has been achieved with a standard 1024×1024 , scientific front-illuminated MPP device in a compact, vacuum compatible LLNL designed head. The intensity and energy linearity have been measured for 520 nm light and hard x-rays over a wide range of fluences and exposure times: departure from linearity is below the 1% level. The camera responsivity and QDE have also been measured using absolutely calibrated high spectral purity x-ray line sources up to 55 keV energy. The measured QDE is in good agreement with the expected detection efficiency based on absorption within the epitaxial region. We have utilized this camera effectively to measure and image hard x-ray spectra from 500 fs laser-solid experiments where the hard x-ray emission typically lasts for 3 ps. In conclusion, this further demonstrates the versatility of these solid-state imagers for scientific applications.

7. ACKNOWLEDGMENTS

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