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Characterization of the eLine ASICs in prototype detector systems for LCLS

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***Abstract*– “eLine”, a class of multichannel time-variant integrating front-end Application Specific Integrated Circuits (ASICs), has been completed at SLAC National Accelerator Laboratory for applications at the Linac Coherent Light Source (LCLS). The class, designed for pixelated sensors with column-parallel readout, is composed of two front-end ASICs: one designed for high-dynamic range applications (eLine10k) and one designed for ultra-low noise applications (eLine100). The first allows large input full-scale signals, on the order of 10^4 8keV photons, with a resolution of half a photon FWHM; while the second provides low noise charge integration, up to a full-scale signal of 100 8keV photons, with an equivalent noise charge (ENC) of 55e- r.m.s. Three different prototype systems utilizing the ASICs are described. The first is a 32k-pixel X-ray Active Matrix Pixel Sensor (XAMPS) detector developed at Brookhaven National Laboratory (BNL) for the X-ray Pump Probe instrument (XPP) at LCLS. The XAMPS are monolithic detectors with fast-frame readout and large full-scale signal. In particular, they provide a full well capacity on the order of 10^4 8keV photons per pixel and a resolution of half a photon FWHM. The second prototype, developed around eLine10k, is a beam finder with high dynamic range. The third prototype is developed around eLine100 to be used as detector in a spectrometer. Applications, test results and performance are discussed.**

I. INTRODUCTION

A new “eLine” class of multichannel time-variant integrating front-end Application Specific Integrated Circuits (ASICs) has been completed at SLAC National Accelerator Laboratory for applications at the Linac Coherent Light Source (LCLS). The unique characteristics of fourth generation light sources, namely their pulsed nature and extremely high peak brilliance, demand a dedicated detector development effort. Some common features, such as the fast readout, are intrinsically dictated by the source structure. Noise requirements and full-scale signal capability vary with the experiment. The two ASICs in the eLine class, eLine10k [1, 2] and eLine100 [3], cover applications with very different requirements as demanded by LCLS experiments. The first allows large input full-scale signals, on the order of 10^4 8keV photons, with a resolution of half a photon FWHM; the second provides low noise charge integration, up to a full-scale signal of 100 8keV photons, with an Equivalent Noise Charge (ENC) of 55e$^-$ r.m.s. The ASICs are fabricated in TSMC CMOS 0.25μm technology with 64 and 96 channels respectively. A charge pump scheme implementing a zero-balance measurement method [1 - 3] used in both ASICs is their characteristic feature. It provides on-chip coarse analog to digital conversion of the signals and a measurement of the residues with the required resolution. The residues are converted with external 14-bit ADCs.

eLine is the first example of a class of ASICs for LCLS sharing a common back-end section and interface to the rest of the system. During the first years of operation at LCLS, the need for several new large area detectors arranged in different form factors and shapes, and supporting a wide spectrum of experiments has been apparent. Modular, scalable designs are a must. To simplify integration and reduce development time, detectors have been designed around common platforms so that dedicated sensing heads could be incorporated in a common detector system. Detectors based on this platform are then firmware compatible and easy to integrate in the LCLS DAQ system.

TABLE I
ELINE10K PERFORMANCE

Technology	TSMC 0.25μm
Die Area	6 mm x 3.5 mm
Number of Channels	64
Optimum Input Load	15pF
Programmable Gain	5mV/fC or 2.5mV/fC
ENC	480e$^-$ r.m.s. @ 15pF
Maximum Signal	26Me$^-$ (12k photons @ 8keV)
Dynamic Range	95 dB
Power Consumption	3mW/channel
Speed	500k pixel/s/channel

TABLE II
ELINE100 PERFORMANCE

Technology	TSMC 0.25μm
Die Area	6.8 mm x 5 mm
Number of Channels	96
Optimum Input Load	3pF
Gain	58mV/fC
ENC	55e$^-$ + 8e$^-$ /pF r.m.s
Maximum Signal	260ke$^-$ (120 photons @ 8keV)
Dynamic Range	74 dB
Power Consumption	3.5mW/channel
Speed	250k pixel/s/channel

In this paper, the performance of the ASICs, summarized in Table I and Table II, are experimentally demonstrated. Three different prototypes have been developed and characterized.

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Results are reported and discussed in the following paragraphs.

II. XAMPS DETECTOR TESTS AT SSRL AND LCLS

The eLine10k ASICs (also referred to as FEXAMPS) was originally conceived as readout electronics for X-ray Active Matrix Pixel Sensors (XAMPS) [4, 5]. The XAMPS, developed at Brookhaven National Laboratory (BNL), are monolithic detectors with fast readout and large full-scale signal. In particular, they provide a full well capacity on the order of 10^4 photons of 8keV per pixel and a resolution of half a photon FWHM. Each pixel of the matrix is 90 x 90µm^2 and contains a JFET switch to control charge integration and readout, which is performed in parallel row by row through the eLine10k ASICs. The rows are addressed by another switcher ASIC, which effectively implements the operation of a rolling shutter.

The devices are fabricated in high resistivity n-type silicon substrates with a thickness greater than 400µm, and fully depleted through a junction on the photon entrance window. The charges generated by an impinging photon drift to the exit side of the device where they are collected by an implant, constituting the floating electrode of the pixel or the source of the JFET. This region together with the isolated metal layer on its top forms the capacitor in which the charge is stored. To allow 3.5pC of full well capacity, this region occupies most of the pixel area.

This version of XAMPS was designed for the X-ray Pump Probe (XPP) instrument at LCLS, for which a 1M-pixel camera is currently being produced. Given the 120Hz LCLS repetition rate, a frame has to be read out in ~8ms, which, due to the XAMPS parallel row readout, turns into a readout time of ~8µs per row.

4k- and 32k-pixel prototypes were fabricated and tested at BNL, satisfying the requirements of large full-scale signal, noise and fast readout [5, 6]. Here we report the results of measurements performed at the Stanford Synchrotron Radiation Lightsource (SSRL), BL2-2, and at the LCLS XPP instrument with the 32k-pixel prototype camera.

The prototype camera comprises two 128 x 128 sensors tiled and wire-bonded in an aluminum frame. In the ASIC-sensor bonding scheme, five chips were used to read out the 256 columns: this was required to compensate for the space between the sensors, and resulted in 32 non-connected channels at the end of each sensor. In addition to the analog board on which sensors and front-end electronics are mounted, two other boards complete the system: a digital board with a Virtex5 Field Programmable Gate Array (FPGA) and a high voltage daughter board. The FPGA controls the settings of front-end and switcher ASICs in the analog board, and communicates data at 2.5Gbs through a SLAC protocol (PGP) implemented in a PCIe-compliant board. A liquid-cooled copper plate is mounted between analog and digital boards to keep the temperature at ~20ºC. The overall system, which can accommodate the full 1M-pixel sensor area, is very compact and can be mounted and precisely aligned in a robotic arm at the XPP instrument (Fig. 1).

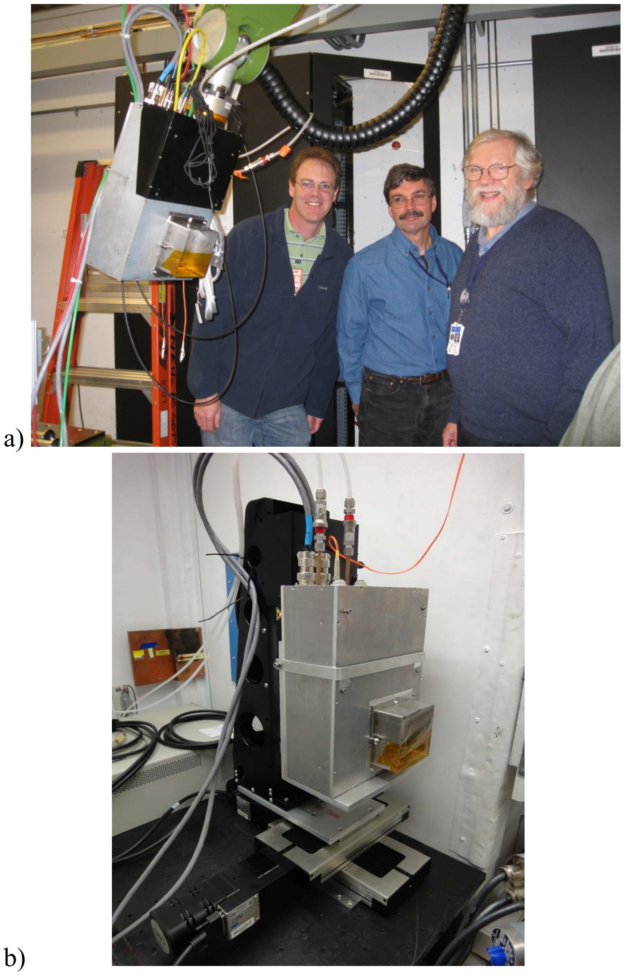

Fig. 1. a) XAMPS system at LCLS XPP; b) XAMPS system at SSRL BL 2-2.

An x-ray absorption image of a *Sequoia sempervirens* is shown in Fig. 2. The detector was flood irradiated with the Cu K-alpha fluorescence emitted by a Cu-foil illuminated with the white beam at SSRL BL2-2. In this image, background subtraction and gain equalization are applied; cosmetic defects are compensated by interpolation. It should be noted that the sensors used to assemble this system don't have a passivation layer and were severely damaged during handling.

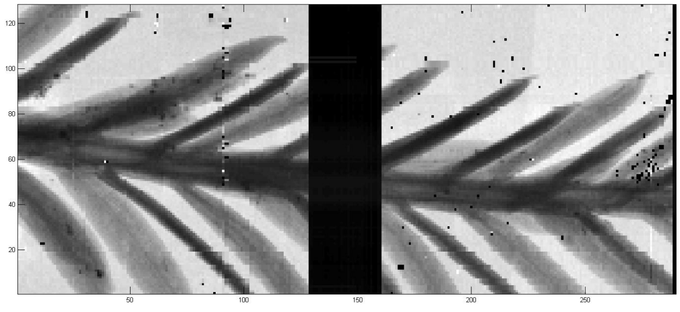

Fig. 2. X-ray absorption image of *Sequoia sempervirens*: the detector was flood irradiated with the Cu K-alpha fluorescence emitted by a foil illuminated with white beam. Gain equalization was applied and cosmetic defects compensated by interpolation.

The features of a California native plant can be appreciated in great detail in Fig. 3. The image was acquired in the same manner: the detector was flood irradiated with the Cu K-alpha fluorescence emitted by a Cu-foil illuminated with the white beam. This 32k-pixel system was also tested at the LCLS XPP instrument. Fig. 4 shows an image and a correspondent histogram of the LCLS beam.

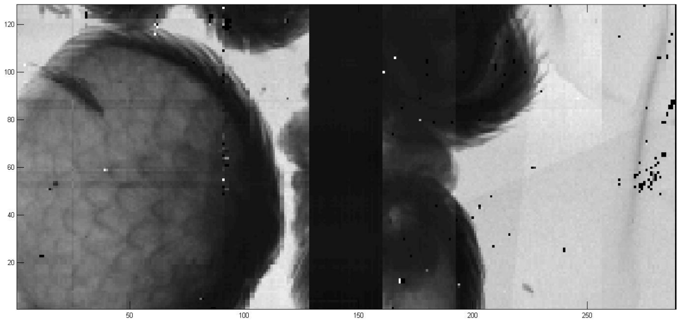

Fig. 3. X-ray absorption image of a California native plant: the detector was flood irradiated with the Cu K-alpha fluorescence emitted by a foil illuminated with white beam. Gain equalization was applied and cosmetic defects compensated by interpolation.

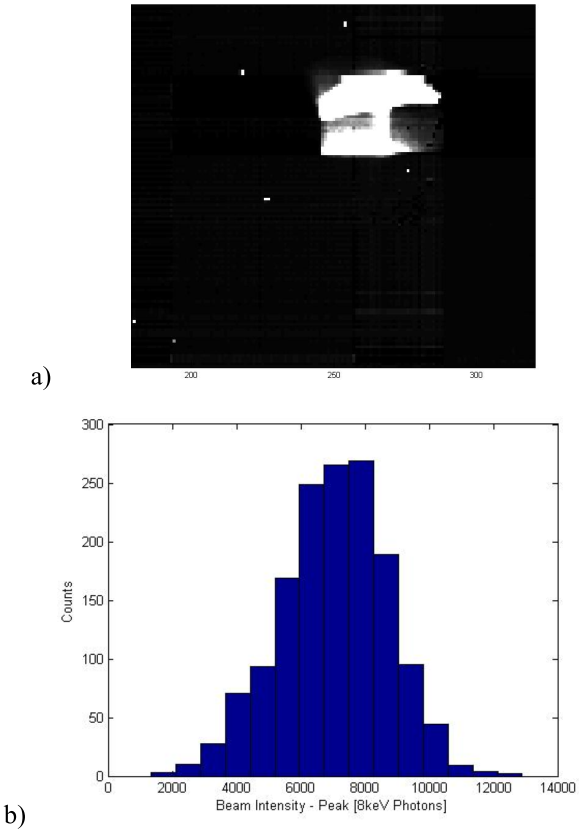

Fig. 4. a) Image of the LCLS beam at XPP: gain equalization was applied and cosmetic defects compensated by interpolation; b) Beam peak intensity average versus number of 8keV photons.

Only the area of the detector illuminated by the beam is shown in Fig. 4a. Here again, background subtraction and gain equalization are applied and cosmetic defects compensated by interpolation. In Fig. 4b, the histogram of the average beam intensity at its peak position, covering nine pixels, is shown as a function of the number of 8keV photons. The figure, displaying beam variation, shows the large full-scale signal capability of the system, greater than 10^4 8keV photons/pixel/frame. This is currently the highest value measured with a monolithic silicon pixel detector at LCLS.

III. High Dynamic Range Beam Finder at XCS

A prototype system for monitoring direct beam or single scatter peaks has been developed and tested at the LCLS X-ray Correlation Spectroscopy (XCS) instrument. The system is built on the eLine10k test board, a simplified version of the XAMPS system analog board. It mounts one 5mm x 5mm and three 2.1mm x 1.1mm silicon diodes. The setup is completed by a pair of slits, centered on the large diode and mounted on the detector enclosure (Fig. 5).

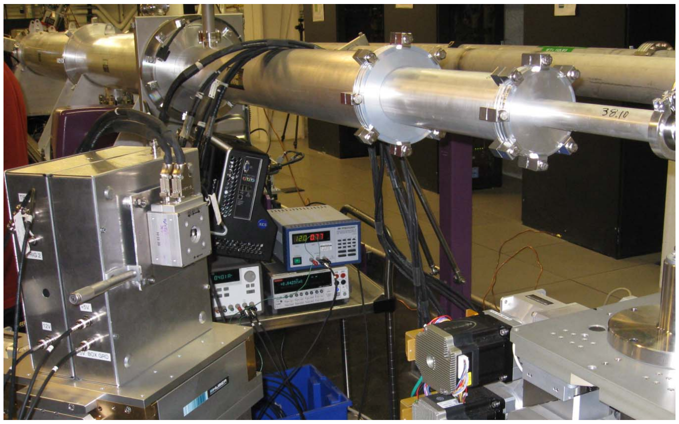

Fig. 5. eLine10k beam finder prototype setup at the XCS instrument.

The slits can be used to raster scan the diode and precisely locate the beam. During this first feasibility study, the detector was illuminated with flood field Cu-K photons.

Fig. 6 shows a single photon measurement from the LCLS beam at the XCS instrument. Although the resolution was limited by the sensor leakage current, single photon peaks are clearly distinguishable.

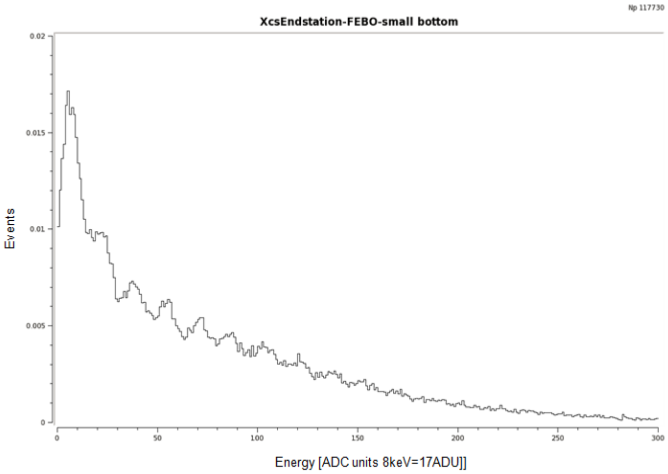

Fig. 6. Single photon measurements: Cu K-alpha fluorescence measured at the XCS instrument at LCLS.

IV. SPECTROMETER

1D and 2D detectors with low noise capabilities are required in a spectrometer configuration in many experiments at LCLS. Detectors for this application should be able to detect very low signal. Therefore, a system developed around the low noise ASIC of the eLine class could provide the required performance. A prototype system consisting of a silicon strip sensor with active edges mounted on the eLine100 test board (a modified version of the XAMPS system analog board) was developed and tested (Fig. 7). The sensor chip measures 3.4mm x 2.4mm. It is divided into sixteen strip elements and enclosed by a plasma-diced doped edge [6]. A Peltier-based cooling system was installed on the test board.

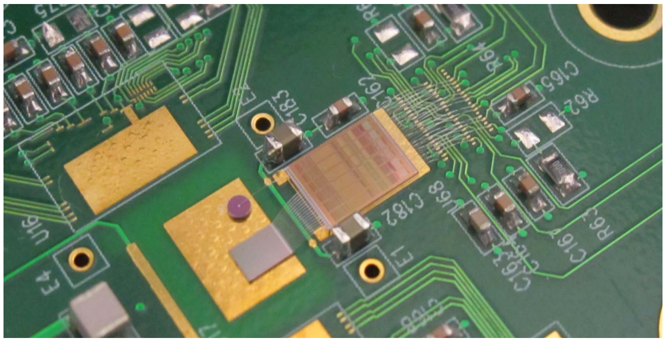

Fig. 7. eLine100 spectrometer: detail of the sensor-ASIC assembly.

A study of the spectroscopic performance of this system was performed and results are reported in Fig. 8. The figure shows ^{55}Fe and ^{109}Cd emission spectra and single 8keV photons from the fluorescence of a copper target acquired at a sensor temperature of 6°C and with an integration time of 32μs. The ENC, measured on bonded channels, is as low as 66e$^-$ r.m.s., which corresponds to a resolution of 560eV. The spectra are cumulative of the 16 strips and do not implement any split events correction.

V. CONCLUSIONS

A new class of ASICs, eLine, for the readout of column-parallel readout sensors has been designed to satisfy the demanding experiments at LCLS. The class is composed of two front-end ASICs and a dedicated controller. eLine10k is the front-end ASIC tailored for high dynamic range applications, optimized for XAMPS detectors and the requirements of the XPP experiment at LCLS. eLine100 is the front-end ASIC tailored for ultra-low noise applications, optimized for XCPS detectors and the requirements of the XCS experiment at LCLS. Prototype systems developed around these two ASICs have been tested at SSRL and LCLS showing the full spectrum of performance and potential applications.

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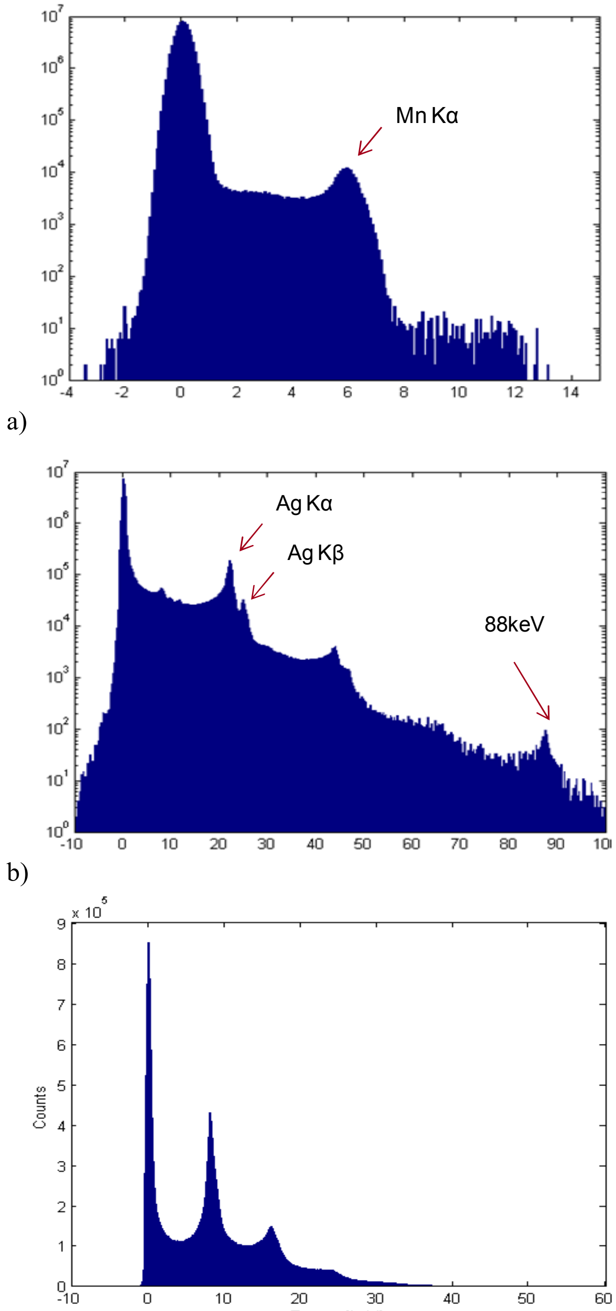

Fig. 8. ^{55}Fe (a) and ^{109}Cd (b) emission spectra acquired at a sensor temperature of 6°C and with an integration time of 32μs. Mn Kα and Ag Kα, Ag Kβ as well as the 88keV gamma ray can clearly be observed in (a) and (b) respectively. (c) Single 8keV photons from the fluorescence of a copper target.

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