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Future of ePix Detectors for High Repetition Rate FELs

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Abstract. Free-electron lasers (FELs) made the imaging of atoms and molecules in motion possible, opening new science opportunities with high brilliance, ultra-short x-ray laser pulses at up to 120 Hz. Some new or upgraded FEL facilities will operate at greatly increased pulse rates (kHz to MHz), presenting additional requirements on detection. We will present the ePix platform for x-ray detectors and the current status of the ePix detectors: ePix100 for low noise applications, ePix10k for high dynamic range applications, and ePixS for spectroscopic applications. Then we will introduce the plans to match the ePix detectors with the requirements of currently planned high repetition rate FELs (mainly readout speed and energy range).

INTRODUCTION

Free-electron lasers (FELs) can produce x-ray laser pulses with short duration (on the order of femtoseconds), high brilliance (many orders of magnitude higher than at existing storage rings), and high coherence, making the imaging of atoms and molecules in motion possible. The first hard x-ray free-electron laser, the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory, is using a linear accelerator operating at 120 Hz and started operating in 2009 [1].

Building upon the success of the first FELs, next generation FELs are being constructed. LCLS-II will be built on some of the existing LCLS infrastructure, adding a high repetition rate superconducting linear accelerator operating initially at 100 kHz (with an upgrade path to 1 MHz) [2]. The European X-ray Free-Electron Laser Facility (XFEL.EU) will operate with 27 000 pulses s^{-1} (structured in 10 bunches s^{-1} of 2700 pulses at 4.5 MHz) [3]. Both LCLS-II and the XFEL.EU are expected to use photon energies between ~ 0.2 keV and 25 keV [2, 3].

For FELs, the main requirements for x-ray detection include [3, 4, 5, 6]: low noise (down to single photon sensitivity), high maximum detectable signal range (further called ”range”), speed, large area, energy range, radiation hardness, modular design facilitating repairs [7], energy dissipation, cost. It is essential to detect quasi-instantaneous pulses (femtosecond scale) containing multiple photons; integrating detectors are thus suitable for FELs while typical photon-counting detectors are not [6]. Additionally, if integrating multiple pulses in one acquisition, a linear detector response is essential.

High repetition rates (HRR) require corresponding upgrades of FEL detectors (and other instrumentation), notably high speed readout (kHz to MHz range). For subsets of applications, extended energy ranges towards ~ 0.2 keV and towards 25 keV are required for both LCLS-II [2] and the XFEL.EU [3]. This paper concentrates on readout speed and energy range.

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TABLE 1. CSPAD and ePix detectors, current status and readout speed, with planned increases in speed

	CSPAD[*] high / low gain	**ePix100**	**ePix10k**	**ePixS**
Summary	deployed	low noise	high range	spectroscopic
Mode of Operation	2 gains, fixed	1 gain	2 gains, auto-ranging	1 gain
Range (8 keV photons)	350/2700	100	10 000	10
Pixel size	110 μm × 110 μm	50 μm × 50 μm	100 μm × 100 μm	500 μm × 500 μm
ASIC pixel array size[†]	185 × 194	352 × 384	176 × 192	10 × 10
ASIC noise (e^- r.m.s.)	300 e^- / 1000 e^-	50 e^-	120 e^-	8 e^-
Operating temperature	room	room	room	−40 °C
Frame rate:				
- current version	120 Hz	240 Hz	480 Hz	30 kHz
- phase 1: multiplexing	—	1 kHz–2 kHz	2 kHz–4 kHz	—
- phase 2: fast ADCs	—	5 kHz–10 kHz	10 kHz–20 kHz	—

[*] The CSPAD is not part of the ePix family; it is shown here for reference.
[†] The typical detector module size is 2 × 2 ASICs [4, 9].

TOWARDS HIGH READOUT SPEED EPIX CAMERAS

Current ePix Cameras

The ePix x-ray hybrid pixel detectors are built on the ePix platform [8, 9], which is modular and easy to adapt for particular detection requirements. The current ePix ASICs (ePix100, ePix10k, ePixS) have been initially developed for the LCLS requirements to expand the range of applications covered today by the CSPAD [10, 4, 5], providing better signal to noise ratios, larger range, reduced pixel size, and an upgrade path to high speed detection (see summary in Table 1).

1. **CSPAD** [10] is the principal detector currently used for LCLS hard X-ray experiments [5]. It is built around the CSPAD 1.5 ASIC, with 185 × 194 pixels (110 μm × 110 μm), and 2 ASICs flip-chip bonded to one sensor. These sensor assemblies are used in 140 kpixel, 560 kpixel and 2.3 Mpixel cameras [5].
2. **ePix100** [11, 12, 13] is a low noise detector (50 e^- r.m.s.) with a range of 100 8 keV photons per pixel per pulse and 352 × 384 pixels of 50 μm × 50 μm. Applications include photon correlation spectroscopy (PCS) and wavelength-dispersive spectrometers
3. **ePix10k** [14, 15] is a high range x-ray detector (10 000 8 keV photons) with 2 gains, auto-switching, and 176 × 192 pixels of 100 μm × 100 μm. Applications include x-ray diffraction and pump-probe experiments
4. **ePixS** [16] is a spectroscopic x-ray detector with a low noise (8 e^- r.m.s.) comparable to silicon drift detectors (SDDs), featuring 10 × 10 pixels of 500 μm × 500 μm. Applications include energy-dispersive spectroscopy and limited photon counting (up to 10 8 keV photons). This detector already operates at 30 kHz.

Increasing the ePix Readout Speed

Existing ePix detectors have been developed for LCLS and operate at up to a few hundred Hz. Current camera versions read out ASICs with several off-chip analog-to-digital converters (ADCs). The readout speed is limited by the analog multiplexing of rows and columns. Speed improvements will come in several phases:

1. **first phase: digital domain multiplexing**: the readout will become much faster by adding on-chip ADCs in each column and multiplexing columns in the digital domain (see Fig. 1a). This will be achieved with minimal risk by changing only the ASIC balcony. The speed is expected to increase to 1 kHz–4 kHz (see Table 1).
2. **second phase: faster ADCs and buses**: the row settling time is currently 500 ns, equivalent to a speed limit of 3.5 kHz for the ePix100 (352 rows). To match this throughout the system, a new design will use high performance ADCs, which probably will require a deeper technology than the current 0.25 μm. A redesign in a deeper technology will also allow improving the bus speed, implementing fast I/O, low power techniques, etc. With these changes, a new ePix100 version is expected to reach 5 kHz–20 kHz (see Table 1).

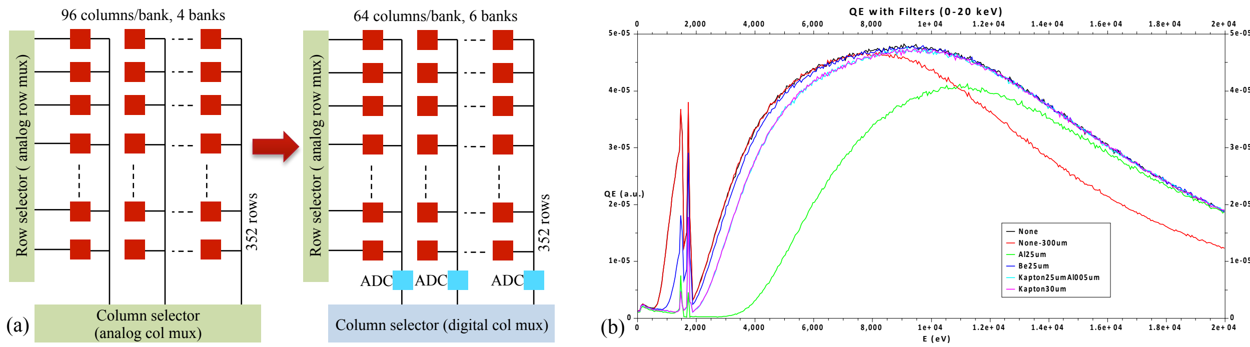

FIGURE 1. (a) Moving from analog to digital column multiplexing and one ADC per column greatly speeds up the readout to kHz rates; (b) quantum efficiency of Silicon sensors (300 µm and 500 µm with different filters), showing good QE at 3 keV–18 keV and 1.2 keV–1.5 keV (just under the aluminum absorption edge). Horizontal scale: 0 keV–20 keV; vertical scale: 0–1 QE. Legend: typical 500 µm Si sensors (black), 300 µm Si sensors (red), 500 µm Si sensors with typically used filters: 25 µm Al (green), 25 µm Be (blue), 25 µm polyimide + 5 µm Al (cyan), 30 µm polyimide (magenta).

3. **beyond**: to reach speeds beyond 5 kHz–20 kHz, more ”exotic” approaches are needed. Each approach has its own advantages and disadvantages (see Table 2). Some applications might greatly benefit from the implementation of particular selections of these techniques.

TABLE 2. Other improvements for speeds beyond 5 kHz–20 kHz and their corresponding trade-offs

Approach	**Advantages**	**Trade-offs**
Sparsification*	improved readout speed for low photon occupancy	increased pixel complexity, size
Reduced ASIC size	readout speed proportional to (number of rows)$^{-1}$	smaller active areas, same gap
Reduced settling time	higher readout speed	increased noise
Pipelining	simultaneous acquisition and readout	increased noise, crosstalk
In-pixel memory cells†	beyond speed gains shown above	multiple‡

* Demonstrated by, e.g, VIPIC1 [17].
† Demonstrated by KPiX [18] and subsequently by Keck-PAD [19], DSSC [20], AGIPD [21], and LPD [22].
‡ Trade-offs could include: much larger pixels, design complexity, yield and cost.

EPIX AT HIGH REPETITION RATE FELs

LCLS-II

CSPAD [10] is the principal detector currently used for LCLS hard X-ray experiments [5]. ePix is extending the CSPAD performance with high range and low noise detection at LCLS, with an upgrade path to high speeds for LCLS-II.

Current ePix detectors can already be used in high-energy density (HED) type experiments (e.g., at MEC) because high power lasers have low repetition rates. Also the ePixS is already fast (30 kHz); a 2×2 ASIC assembly with interleaved readout can reach 120 kHz, thus providing spectra on a shot-by-shot basis in LCLS-II at 100 kHz.

In some types of experiments the detectors limit the acquisition rate, thus readout speed is an important requirement. However, a successful pulse acquisition occurs when all required conditions are met (which could include successful pumping, probing, sample delivery, beam parameters, intensity, depending on application), relaxing somewhat the speed requirements. The LCLS-II HRR applications typically fall under one of these two scenarios [2]:

1. integrating multiple pulses in one frame and then reading out, requiring low noise and high range;
2. individual pulses at HRR, triggered and read out individually, requiring low noise and high readout speed.

The ePix cameras feature a global reset, enabling per-pulse decisions whether to reset the camera or read it out (unlike CCDs which require shifting charge out, resulting in a slower reset). This can be used (1) in the selection of individual pulses to be read out or dumped, and (2) to decide whether to continue integrating multiple pulses or dump the already integrated pulses if an undesirable condition occurs (and be ready to integrate from the following pulse).

For LCLS-II, ePix cameras have a number of advantages compared to XFEL.EU-specific developments (see next subsection): (1) small pixels, (2) relatively radiation tolerant, and (3) low energy consumption which results in a greatly reduced size, with lower demands on vacuum chamber, mechanical and thermal design, camera maintenance etc.

In many applications, the expectation is to use detectors operating around 5 keV–10 keV (see applications and their individual requirements in [2]).

XFEL.EU

While the XFEL.EU will have a repetition rate of 27 000 pulses s^{-1}, they are grouped in 10 bunches. Within each bunch, pulses will come every 220 ns, leading to an effective pulse rate of 4.5 MHz. This is significantly more difficult to detect than a sustained 27 kHz operation. The current XFEL plan is to acquire 3000–6000 frames per second [3].

A number of detector developments target specifically the XFEL.EU bunch structure: AGIPD [21], DSSC [20], and LPD [22]; for a review see [6]. These use either analog or digital frame storage with read-out between bunches. The XFEL.EU bunch structure is in general not a good match to current ePix detectors (until multiple in-pixel memory cells will be implemented, see Table 2).

However, current ePix cameras are already adequate in applications (1) on high-energy density science (HED) [23], due to the low repetition rate of the high power optical lasers, and (2) integrating multiple pulses. The advantages mentioned for the ePix detectors in the LCLS-II subsection above also apply here.

Sensors and Energy Range

The ePix cameras are hybrid pixel detectors, meaning that the ASICs are bump-bonded to the sensors. This approach facilitates the decoupling of ASIC development from sensor development. Different sensors can be developed to cover different parts of the energy range.

Si sensors 50 µm–1000 µm thick are being studied. Typical 300 µm–500 µm Si sensors are already adequate between 3 keV–18 keV (see Fig. 1b). For better hard x-ray performance, CdTe, GaAs, and Ge sensors are under investigation. For better soft x-ray performance, thin entrance windows are under investigation.

CONCLUSIONS

Current ePix detectors meet the requirements for relatively low repetition rate FELs (currently ePix100 and ePix10k operate at 240 Hz–480 Hz). To approach the HRR FEL requirements, their readout speed will be increased in 2 phases: first to 1 kHz–4 kHz by changing from analog to digital multiplexing, and then to 5 kHz–20 kHz with more drastic upgrades (probably in a deeper technology than the current 0.25 µm). ePixS already operates at 30 kHz, allowing a 2×2 array with interleaved readout to collect spectra at 120 kHz (on every LCLS-II pulse at the planned 100 kHz at first light).

At LCLS-II, when taking into account: probabilities of successful shots, the speeds of other instrumentation, fast pulse-by-pulse feedback to either trigger readout on successful shots or reset on unsuccessful shots, the fast ePix cameras are expected to capture a high fraction of successful shots.

At the XFEL.EU, the bunch structure is complex (bursts of 4.5 MHz pulse rate), requiring specialized detectors with some trade-offs. However, low repetition rate experiments (e.g., HED) can use existing ePix detectors.

An additional challenge is represented by extending the energy range towards 0.2 keV–25 keV. For high energies we are investigating high-Z sensors (CdTe, GaAs, Ge) and thick Si sensors (up to 1000 µm). For low energies we are investigating thin entrance window sensors and thin Si sensors (down to 50 µm).

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