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Percival: a Soft X-Ray Imager for Synchrotron Rings and Free Electron Lasers

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Abstract. In this paper, we are presenting the Percival detector, a monolithic CMOS Imager for detection of soft x-rays in Synchrotron Rings and Free Electron Lasers. The imager consists in a 2D array of many (2M) small (27um pitch) pixels, without dead or blind zones in the imaging area. The imager achieves low noise and high dynamic range by means of an adaptive-gain in-pixel circuitry, that has been validated on prototypes. The imager features on-chip Analogue-to-Digital conversion to 12+1 bits, and has a readout speed which is compatible with most of Free Electron Laser Facilities. For direct detection of low-energy x-rays, the imager is back-illuminated and post-processed to achieve 100% fill factor.

INTRODUCTION

Considerable interest has been manifested for the use of high-brilliance X-ray sources (3rd generation Synchrotron Rings and Free-Electron Lasers) for Photon Science applications ([1], [2]).

The use of such sources, however, imposes demanding constraints on detectors, as the high peak brilliance of the generated beam means that many photons might arrive at the same time on the same detector area, thus preventing the use of the classical “photon-counter” detector architecture, and enforcing the use of a charge integration scheme.

At the same time, Photon Science experiments usually require single-photon resolution in the weakly illuminated areas of each picture, thus calling for low-noise signal-processing circuits. The classical circuital approach to overcome this issue (i.e. the introduction of a high-gain stage to amplify the signal between the photodiode and the signal-processing circuitry) cannot be directly applied without further modification, since a high-gain circuit would quickly saturate when a high photon flux arrives on the detector. It is quite often the case in Photon Science

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applications to have images with both highly illuminated areas (requiring high-dynamic-range circuits) and weakly illuminated areas (requiring single-photon resolution), and for the boundaries of these areas to change dynamically from image do image.

The detection problem is compounded by the increasing importance of single-shot experiments at Free-Electron Lasers (FEL), where the high beam brilliance is used to record a diffraction pattern from a biological sample before its destruction. This calls for circuits able to acquire an image, process the signal, stream it out, and be ready for the next image acquisition, in a time comparable to the FEL repetition rate (usually in the range of 10-120 frame/second).

The last, but not the least, problem comes from the use of soft x-rays. Such photons tend to have a very short absorption length: special care must thus be taken in the post-processing of the detector surface that is exposed to the incoming radiation, to minimize the detector entrance window.

Percival is a soft-X-ray detector under development as a collaboration between DESY, STFC, ELETTRA, DLS and PAL to answer those needs [3]. It is a 2D imager with small pixel pitch (27um), aimed at direct x-ray detection with high efficiency in the 250-1000eV (primary energy range), with an extended range down to <100eV and up to >2000eV. The Percival "P2M" system is a 2-million-pixel imager, featuring a large imaging area (~4x4cm^2) without any dead or blind spaces.

THE PERCIVAL X-RAY IMAGER

The core of the Percival system (Fig. 1) is a Monolithic Active Pixel Sensor (MAPS) array (embedding charge collection junctions and signal processing circuitry on the same substrate), manufactured using a commercial 180nm CMOS technology on wafers having a thick, high-resisitivity epitaxial layer. The layout-stitching technique is used to accommodate the sensor dimensions (larger than the typical recticle size) within the CMOS process. The sensor is basically a n-on-p diode, able to collect photo-generated electrons by the use of partially pinned photodiodes as collecting junctions, to minimize capacitance (and thus noise), while not reducing collection area. The in-pixel circuitry is limited to nmos devices only, embedded in a pwell biased to ground, so that the well acts as a potential barrier, funneling the charge generated in the epi layer towards the photodiode (to avoid parasitic collection of charge by the n+ junctions of the devices).

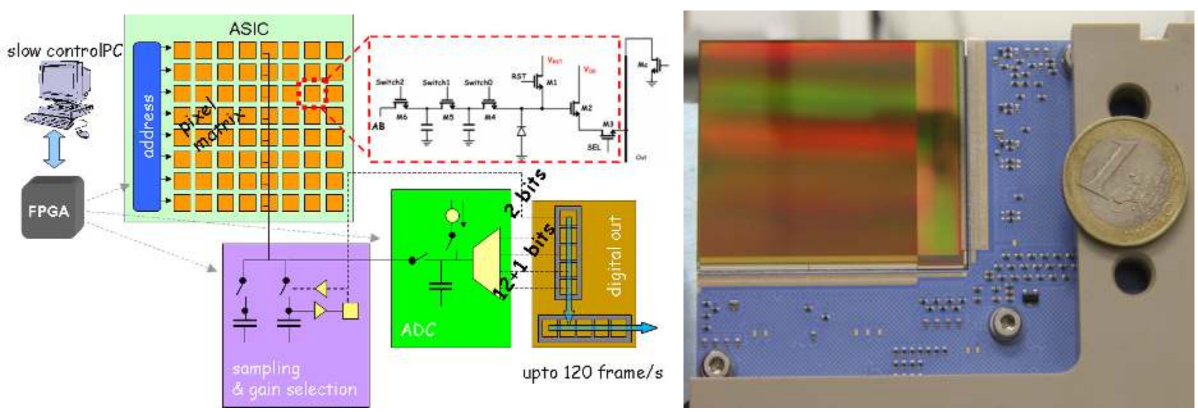

FIGURE 1. Conceptual sketch (left) and photo (right) of the core of the P2M system

In its soft-x-ray version, the MAPS is coupled to a handling wafer, backthinned and back-side illuminated (for for 100% fill factor). The backside is doped with a shallow junction, to minimize the entrance window.

In-pixel circuitry is used to extend the dynamic range by modulating the pixel gain according to the impinging photon flux (lateral overflow) [4]. A system of switches and capacitors is embedded in each pixel, able to change the charge-to-voltage transfer function of a pixel exposed to a high photon flux, thus avoiding its saturation and effectively increasing its dynamic range. This adaptive gain modulation happens independently for each pixel, and in real time, allowing the detector to have at the same time a high gain (and thus a fine level of charge discrimination) for pixels exposed to a low photon flux, and a coarser level of charge discrimination (thus an increased dynamic range) for pixels in exposed to a high photon flux.

Further on-chip data processing capabilities include: digital Correlated Double (or Multiple) Sampling (to eliminate reset noise and fixed pattern noise), analogue-to-digital conversion to 12(+1) bits, and fast digital streamout up to 300 frame/s. A circuit in the periphery keeps track of the lateral-overflow "Gain" modulation level (independently for each pixel and for each frame), and embeds it in an appropriate bit configuration that is streamed out along with the digitized signal amplitude of each pixel.

The MAPS itself is wire-bonded on two sides only to a Low-Temperature Co-fired Ceramic board, so that four detectors could be arranged in a cloverleaf configuration around a central hole. The sensor is generally kept in vacuum, to avoid absorption of low-energy photons by atmosphere, and cooled to -40°C for optimal performance. Analogue biasing and auxiliary system monitoring is provided by an ad-hoc developed board; addressing is reconfigurable and is controlled by an external FPGA, which the user can interact with by means of a Graphical User Interface.

To cope with the considerable data rate (~20Gbit/sec), the digitized sensor outputs are passed to a fast data-concentrator board, streamed out through parallel 10Gb ethernet links [5], and then addressed in a round-robin fashion to multiple receiving nodes through a buffer switch [6]. A HDF5 Virtual Dataset [7] architecture has been decided for the data storage, to allow the user to access the recorded images as a single data archive.

The Full 2M-pixel system in its Front-Side-Illuminated version (Figure 2,3) has been manufactured and assembled, and is at the present moment under preliminary tests at room temperature. A suitable vacuum vessel has been designed and built for sub-zero operation and low-energy-photon detection.

Reduced-sized prototypes have also been used to validate circuital and technological solutions (both in the lab and in several Synchrotron Ring and FEL beamlines).

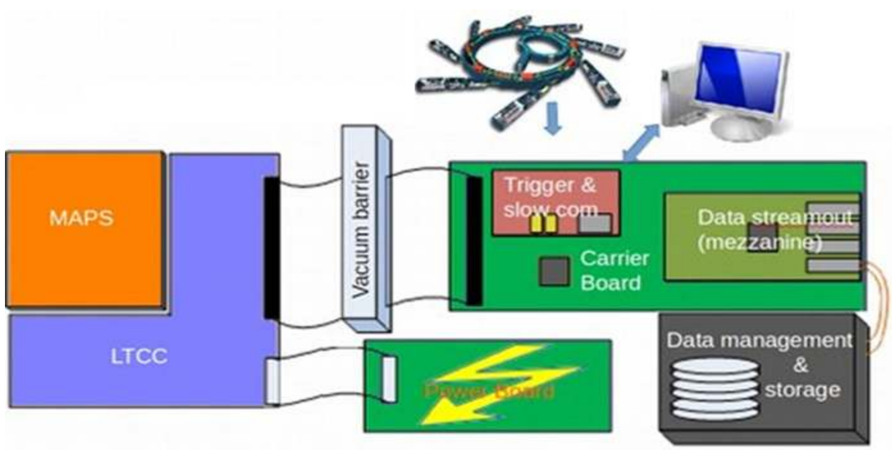

FIGURE 2. Conceptual sketch of the Percival system

FIGURE 3. Picture of the "naked" P2M system, used for in-air lab tests (left) and of the vacuum vessel (right) developed for sub-zero operation and low-energy-photon detection

PROTOTYPE CHARACTERIZATION AND PRELIMINARY P2M TESTS

The adaptive gain modulation induced by the lateral overflow mechanism has been verified on reduced-sized prototypes, measuring the system response to a increasingly large charge integration. Results (Fig. 4) show that the system is able to span through several orders of magnitudes while remaining linear.

It is to be observed that, because of the lateral overflow mechanism, the sensor response to an increasing integrated charge deviates from the classical shape (a straight line), and is instead divided in three lines having increasingly gentler slopes, each one characteristic of one of the detector “Gain” stages. A 3-level signal (encoded in 2 bits) is provided by each pixel to identify its “Gain” stage in that image (and thus to be able to reconstruct the collected charge).

The pixel response was measured to saturate at an integrated-charge-level exceeding 3.5 million electrons, corresponding to 50000 x-ray photons at an energy of 250eV. The bits encoding the lateral-overflow information were also verified to correctly report the pixel “Gain” stage.

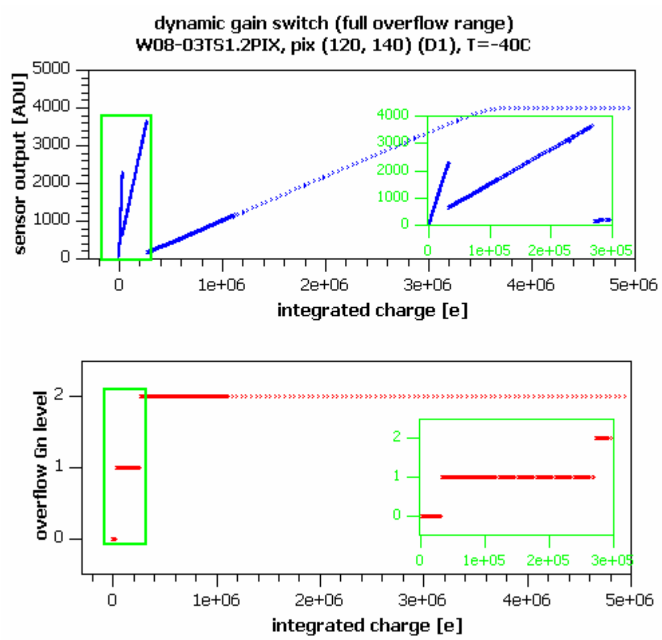

FIGURE 4. Dynamic range characterization of the Percival system, spanning several order of magnitudes. The green inset shows a magnification of the system response to low flux

The response of the reduced-sized prototypes has been measured in dark condition, and the r.m.s. of the output signal (reported to an equivalent input charge) has been used as a measure of its noise. The low value (~15e) measured on cooled (-40°C) system confirms that the detector is suitable for single-photon discrimination in the 250-1000eV energy range. The system performance has been confirmed on a wide range of readout speeds, from 10 frame/s up to 120 frame/s (Fig. 5), thus confirming the compatibility of Percival with most of the Free Electron laser facilities (built or under construction).

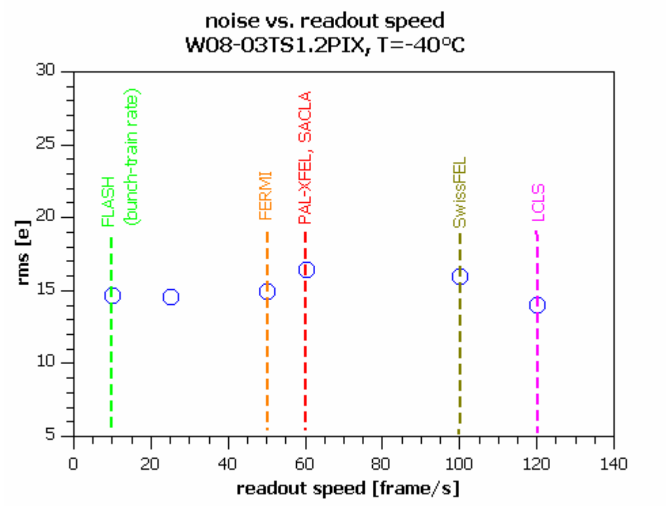

FIGURE 5. Noise measurements performed in dark conditions, using frame rates compatible with several Free Electron Laser Facilities.

When the in-pixel lateral overflow circuit changes the pixel gain (because the pixel is exposed to a high photon flux), the additional capacitors introduced in the circuit increase the system noise. The noise introduced, however, has been measured to remain far below the Poisson limit (i.e. the intrinsic uncertainty of the photo-generation process). This means that the system noise remains shot-noise limited, also in high-flux conditions (Fig. 6). In addition to this, some degree of configurability has been embedded in the system, by means of a Programmable Gain Amplifier in the circuit chain, that can be tuned in advance to find the best trade-off between the noise level and the overflow-"Gain" switching points.

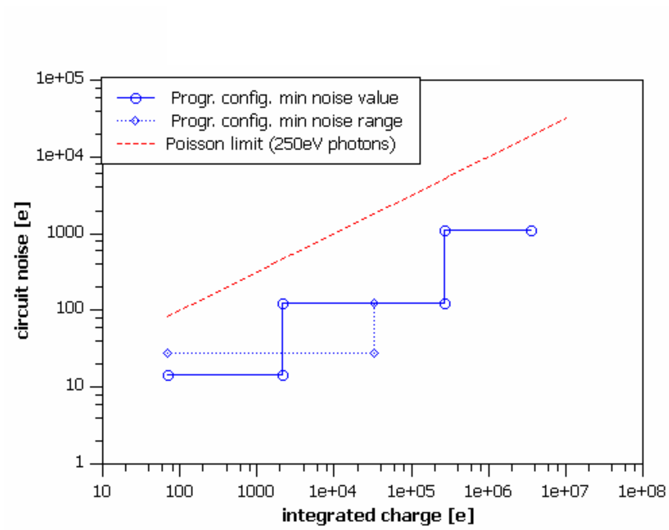

FIGURE 6. Noise measurements performed in high-flux conditions. The circuit contribution to the system noise (blue line) is always below the poissonian uncertainty (red line). The charge values where the noise switches between different levels are defined by the lateral overflow "Gain" switching points; they can be configured by means of a Programmable Gain Amplifier.

Tests were performed on prototypes at several FEL and Sychrotron Rings to verify that the back-side post-processing produces a surface compatible with low-energy-photon detection. As an example, tests were performed at the BL2 beamline of the FLASH FEL ([8],[9]) illuminating the detector with 13.5nm (nominal energy 91.84eV) photons, to verify that the detector response was compatible with the signal expected from such photons, rather than being dominated by the higher harmonics components of the beam (which would be more likely to pass through an eventual entrance window of inert material).

To verify this, a pinhole of known diameter was inserted between the beam and the detector (at a known distance), and the detector was used to record diffraction patterns. The diffraction pattern through a circular aperture is known to generate a characteristic image made of concentric circular rings, having a distribution of minima and maxima depending on the wavelength of incoming photons [10]. Fig. 7 shows the comparison between experimental data along a cutline (blue circles) and the analytic prediction of the diffracted image shape (green line): the good agreement confirms that, due to the thin entrance window, the detector response is dominated by the beam main harmonic (~92eV), and that the contribution of higher harmonics is negligible.

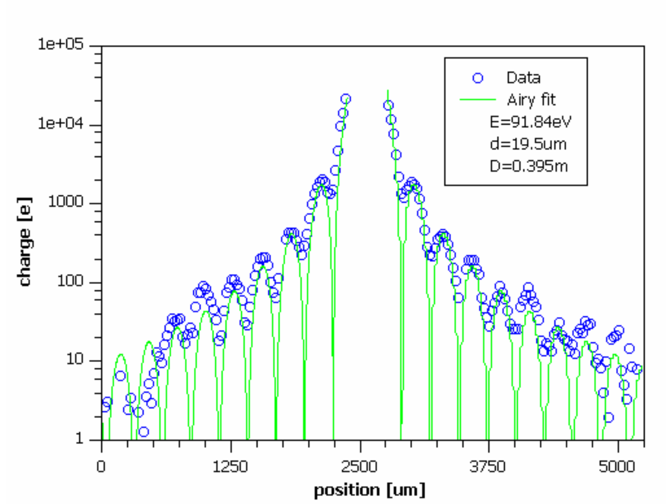

FIGURE 7. Diffraction through a 20um-pinhole: comparison between data (blue circles) and analytical prediction (green line).

Single-shot operation capability has also been verified: Figure 8 shows the comparison between a single-pulse image (taken at the same FEL beamline) and an integrated multi-pulses average. The images show the diffraction rings used for the former evaluation.

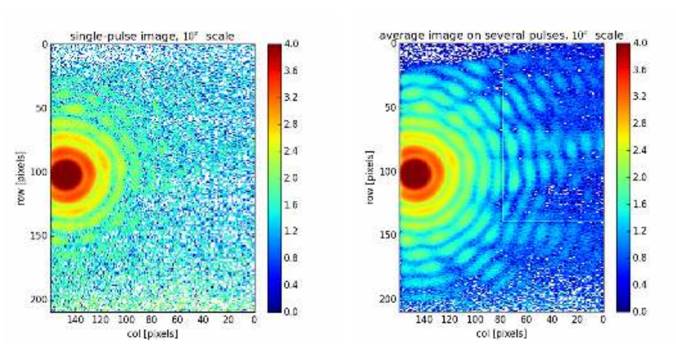

FIGURE 8. Comparison between a single-pulse image (left) and an integrated multi-pulses average (right)

The Full 2M-pixel system in its Front-Side-Illuminated version has been manufactured and assembled, and is at the present moment under test (in air, at room temperature): preliminary electrical and optical tests show the expected behaviour, and the first images to demonstrate the pixel-array functionality (using visible light and a shadow mask between the detector and the light source) have been taken at several frame rates (up to now, from 10 to 100 frame/s).

Fig. 9 shows for example a comparison of images taken at different frame rates: when a longer integration time is used, the signal amplitude progressively increases, and, if high enough, the lateral-overflow mechanism is triggered (which lowers the signal amplitude, and reduces the charge-to-voltage transfer function), thus expanding the dynamic range of the pixels that would otherwise saturate. Such pixels can be recognized by their lateral-overflow "Gain" stage being higher than the baseline.

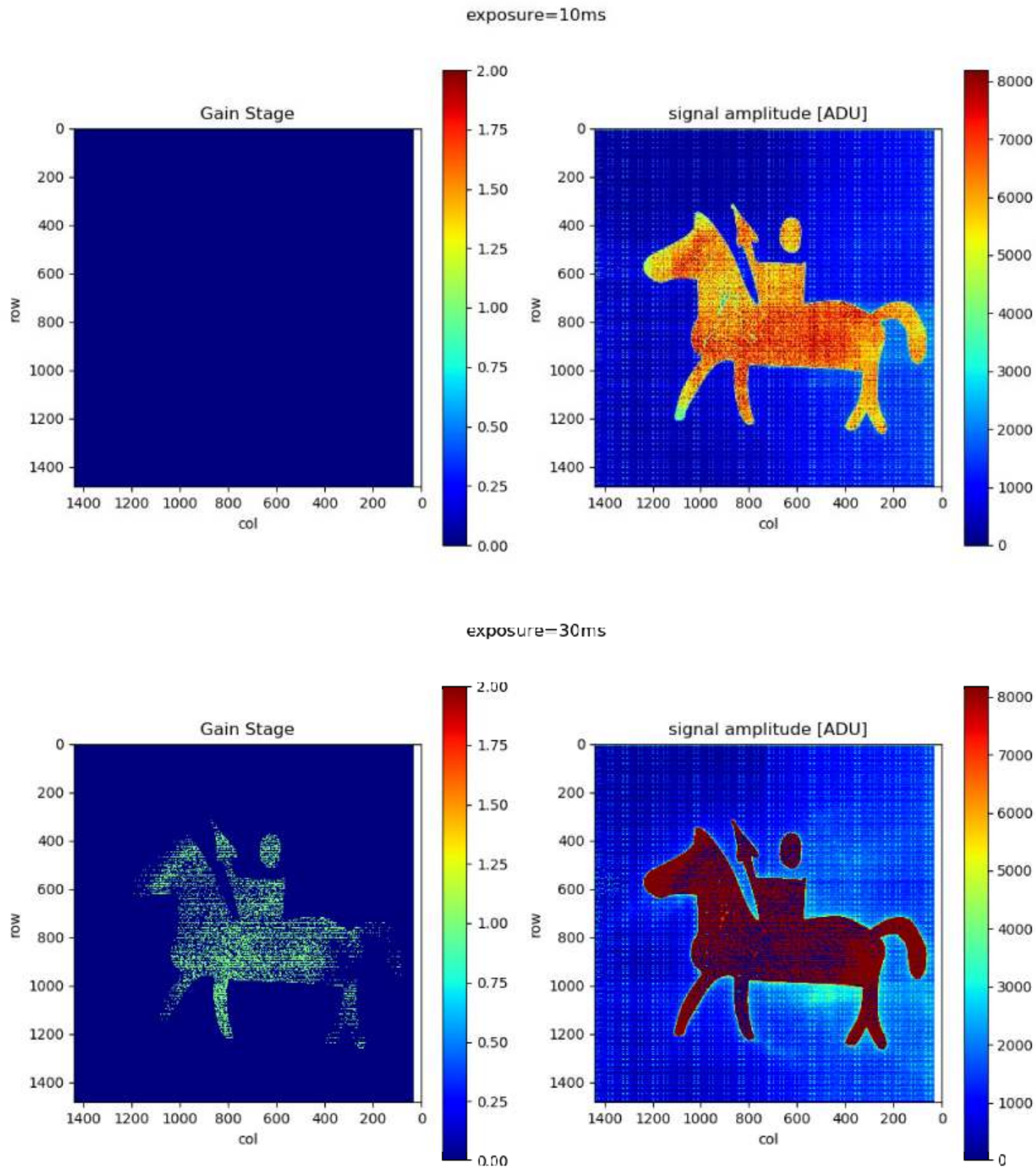

FIGURE 9. Comparison on the P2M system response to visible light, for different integration times. For the higher (30ms) integration time, some pixels extend their dynamic range by means of the lateral overflow mechanism. No correction nor proper calibration was applied to the images

At the same time, Preliminary tests on a Front-Side-Illuminated are used to test appropriate calibration and data-analysis procedures (on the basis of the algorithms that were developed for use in the prototypes).

The Full 2M-pixel system in its Back-Side-Illuminated version is at the moment in its post-processing phase, and is estimated to be ready for test during this summer.

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