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MAXIPIX, a fast readout photon-counting X-ray area detector for synchrotron applications


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ABSTRACT: A 2D photon-counting X-ray detector system with 1.4 kHz frame rate and 55 µm spatial resolution has been developed and commissioned on ESRF beamlines. The system called MAXIPIX (Multichip Area X-ray detector based on a photon-counting PIXel array) consists of a detector module implementing up to five MEDIPIX-2 or TIMEPIX photon-counting readout chips, a custom readout interface board and a Linux acquisition workstation. The detector module readout time is 290 microseconds, allowing the system to achieve sustained frame rates of 280 Hz to 1400 Hz depending on the number of connected chips. An effective time resolution of 60 ns was measured using the ESRF pulsed modes and a TIMEPIX module. The system architecture and characteristics are presented, as well as a summary of its applications on ESRF beamlines.

KEYWORDS: X-ray detectors; Pixelated detectors and associated VLSI electronics; Hybrid detectors; X-ray diffraction detectors

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1 Introduction

Currently a majority of 2D detectors used in synchrotron experiments are based on CCD sensors optically coupled to an X-ray converter screen. This detector concept can be implemented in a wide variety of layouts, allowing very diverse requirements in terms of field sizes, spatial and temporal resolutions to be met. However the CCD readout noise and light scattering in the optical coupling [1] both limit the dynamic range so the detector does not meet the needs of techniques like SAXS or GISAXS for instance. Direct-detection CCDs can sometimes be used to overcome these limitations, for instance in X-ray Photon Correlation Spectroscopy (XPCS) [2], but with the major drawbacks of a limited sensor lifetime due to direct X-ray irradiation and a slow readout.

A need therefore existed for detectors with faster readout and higher dynamic range yet providing noise-free detection and high spatial resolution. The MAXIPIX detector, based on the MEDIPIX-2 [3, 4] photon-counting readout chip, was developed with these requirements in mind. In this respect MEDIPIX-2 was found the best suited readout chip owing to its small pixel size as well as fast readout capabilities, in addition to the photon-counting mode which enables noiseless detection and thus a virtually unlimited dynamic range. MAXIPIX therefore complements the range of existing large area photon-counting systems like PILATUS [5] or XPAD [6] by providing higher spatial and time resolutions but smaller detection areas.
Figure 1. MAXIPIX detector head, with input window (version with $5 \times 1$ detector chipboard) on black side and heat extractor (one on each side) on lateral side.

2 System architecture

2.1 Detector head

The detector head (figure 1) includes the detector chipboard, the readout interface board, the main power supply and the high voltage power supply in a metallic housing. The heat produced by internal components is extracted by forced air circulation. In addition the chipboard holder can be connected to a thermostated fluid circulator if readout chip temperature control is critical for stable operation. Various detector modules with different geometries can be mounted in the detector head.

2.2 Readout interface

The readout interface called "PRIAM" (parallel Readout Image Acquisition for Medipix) [7] is designed for simultaneous readout of up to five MEDIPIX-2 chips using the fast 32-bit parallel readout port of MEDIPIX-2. It achieves a readout time of 290 $\mu$s at 100 MHz, equivalent to a front-end data rate of 15.8 Gbit/s. The PRIAM also allows MEDIPIX-2 readout via its serial port, in this case the readout time is 10 ms at 100 MHz clock rate regardless of the number of chips (table 1).

The PRIAM board is also compatible with TIMEPIX [8], a variant of MEDIPIX-2 initially developed by CERN for tracking detectors and providing time over threshold (TOT) mode and time of arrival (TOA) detection modes in addition to the standard photon-counting mode. The time range in TOA mode and the pulse width range in TOT mode are adjusted by proper setting of the chip clock frequency in the exposure phase.

Several trigger modes are implemented for real-time control of X-ray shutters and other beamline equipment in time-resolved experiments. The trigger signal input can be configured either to start a sequence of frames, or to start each frame one by one in a sequence, or to control the exposure start and stop of each frame, with a precision of 10 ns. In addition the readout interface provides a gating input that allows inhibition or enabling of the MEDIPIX-2 pixel counters during
the exposure phase. In this way it is possible dynamically to define exposure windows with 10 ns time resolution.

2.3 Detector modules

Three different modules have been developed in order to adapt to different experimental requirements: a single chip module, a 5-chip module in linear $5 \times 1$ arrangement (figure 2), and a 4-chip module in $2 \times 2$ arrangement. Modules dimensions are summarized in table 1. The module chipboards are made of a 9-layer PCB with one flex connection per readout chip to the PRIAM interface. The $5 \times 1$ version consists of five MEDIPIX-2 or TIMEPIX chips bump-bonded onto a monolithic
high-resistivity n-type 500 µm thick silicon sensor. Connection of the five readout chips to the chipboard is made by 495 wirebonds distributed in two staggered rows along the chipboard width. The PCB has a slightly smaller width than the sensor in order to allow butting several modules on the 3 sides. The pixel size is $55 \times 55 \mu m^2$ for inner pixels and $165 \times 55 \mu m^2$ for pixels at the edge of neighboring chips in order to fill the small gap between the chips. For the same reason the corner pixels at the centre of the $4 \times 4$ assembly have a size of $165 \times 165 \mu m^2$.

2.4 Acquisition workstation

The acquisition system is a computer with quad-core 2.33 GHz Xeon processor and Linux Redhat 2.6 operating system, with 8 GBytes of RAM and a 4-disk RAID system with a capacity of 584 GBytes. The MAXIPIX readout interface is connected to the PC via a 2 Gbit/s fiberoptic connection to a PCI 64 bits interface board. The acquisition software starts transferring data from memory to the hard disks as soon as an acquisition begins. Data transfer from memory to the RAID disk system is fast enough to avoid memory overflow during the acquisition of long image sequences at maximum frame rate. The image geometrical reconstruction and the optional post-processing steps are performed on-line without reducing the frame rate.

On ESRF beamlines MAXIPIX is operated using SPEC (Certified Scientific Software, Cambridge, Massachusetts, USA) as the user interface. A TANGO device server [9] provides the connection between the SPEC client and the acquisition system.

3 Detector calibration and characterization

3.1 Threshold calibration

In a first step the individual thresholds of each pixel in a chip are equalized by adjusting the 3 threshold adjust bits of each pixel [10], using the noise centroid as the threshold reference. In a second step an offset correction is applied to the global threshold of each chip in order to obtain a uniform response of all chips of the detector module. After this calibration a raw flatfield image taken at 8 keV shows no difference in the average response of each chip.

3.2 Energy calibration

Energy calibration consists in determining the relation between the discriminator threshold digital-to-analog converter (DAC) setting and the corresponding X-ray energy. A copper anode tube with 50 µm Cu filtration is used as the X-ray source. The average image level is measured as a function of the threshold DAC leading to an S-curve (figure 3). The Cu Kα emission line (8.04 keV) is associated with the first S-curve inflexion point and the zero energy reference is associated with the noise peak midrange. The energy characteristic of MEDIPIX-2/TIMEPIX being linear [11] these two points are sufficient for a basic energy calibration. On the tested TIMEPIX module we obtain an energy scaling of 90 eV/DAC unit. The same calibration with MEDIPIX-2 gives typically 150 eV/DAC unit. This energy calibration enables the user to enter the discriminator threshold directly in keV units at the command line prompt.

Using this calibration to rescale threshold scan data into X-ray energy units we measure noise thresholds of typically 3.5–4 keV with TIMEPIX and 4.5–5 keV with MEDIPIX-2. Noise threshold
3. Energy calibration with a copper anode X-ray source (TIMEPIX module). The plot represents the total counts recorded in an image as a function of the threshold setting. Due to the negative threshold DAC characteristic, the energy threshold increases from right to left on the horizontal axis.

is defined as the threshold setting giving less than typically ten isolated noisy pixels per chip for 1 second dark exposure, after excluding defective pixels.

3.3 Linearity

In order to measure the dead-time characteristic of the pixel counters the image level is recorded as a function of the incident X-ray intensity at 8 keV (copper anode X-ray tube) and with 5 keV energy threshold. The X-ray intensity is varied by changing the distance $D$ of the detector to the tube focus as well as the generator anodic current $I_a$. The incident X-ray rate per pixel therefore varies as $N_i = k I_a / D^2$. With MEDIPIX-2 modules, fitting the measured counts/pixel $N_d$ with the non-paralyzable dead-time model [12] of eq. (3.1)

$$N_d = N_i \frac{1}{1 + N_i \cdot \tau}$$

yields a characteristic dead-time $\tau = 1.2 \mu s$ and a count-rate of $2.1 \times 10^5$ incident counts/pixel/s at 20% dead time error, equivalent to $\sim 7 \times 10^7$ incident counts/pixel/mm$^2$/s (figure 4). These figures are obtained with standard DACs settings of the readout chip and may differ with different settings. With TIMEPIX the measured dead time is typically 2$\mu$s. This calibration of the characteristic dead-time allows us to perform an on-line correction of the pixel values in order to restore a linear characteristic at high count rate.

3.4 Spatial resolution and uniformity

With multichip modules an online image reconstruction process splits the larger sensor pixels in the interstitial areas between chips into the appropriate number of geometrical pixels, thereby resulting in a geometrically correct image with physically relevant pixel values in interstitial areas.

Image uniformity and spatial resolution are assessed by taking an image of a lead bar pattern (figure 5): the image modulation is higher than 50% at Nyquist frequency (9 lp/mm), and after flatfield correction the residual non-uniformity along an averaged horizontal cross-section in the
Figure 4. Linearity at high count rate (MEDIPIX-2).

Figure 5. Top: flatfield corrected image of a lead bar pattern, image levels in log scale. Bottom left: cross-section in modulated region, bottom right: cross-section in free region.

free area is less than 0.5% r.m.s. In the reconstructed image the larger sensor pixels in interstitial areas reduce the spatial resolution but do not introduce geometrical distortions nor image level discontinuities.

3.5 Accumulation mode

The capacity of each MEDIPIX2/TIMEPIX pixel counter is 11810 counts, corresponding to a dynamic range of 13.5 bits. In order to achieve a higher dynamic range the software implements an
online accumulation mode which replaces a single exposure by a sequence of short exposures and directly outputs the sum of the recorded frames. By setting the exposure time of single frames to 50 ms, pixel counter saturation is avoided even at the highest practical count rate of $2.10^5$ counts/pixel/second and the X-ray counts loss during the readout time of 0.29 ms is only 0.58% of the total counts. Frame accumulation is therefore transparent for the user and provides the equivalent of a pixel counter with unlimited depth. Since noise is thresholded out in each frame there is no noise buildup and the dynamic range increases linearly with the total exposure time.

3.6 Time-resolved capabilities with TIMEPIX modules

In the TIMEPIX time of arrival (TOA) mode the information stored in the pixel counter is the number of clock cycles counted from the detection of an X-ray signal to the end of exposure. In this mode the timing resolution is 20 ns with 50 MHz clock frequency. In order to demonstrate possible applications of this feature for time-resolved SR experiments we acquire TOA data in the 16-bunch and 4-bunch pulsed modes of the ESRF storage ring, consisting of equally distant pulses of about 100 ps duration with 176 ns and 704 ns periods respectively. A Ge-doped amorphous glass sample is placed in the beam to produce a large fluorescence emission at 9.886 keV (Ge Kα) covering the entire detector area. The detector is placed 90° aside of the main beam axis. A trigger signal generated by an avalanche photodiode also placed in the sample emission is used to trigger each frame of a sequence with constant phase with respect to the X-ray bunches. With this setup, for an exposure time of 10 µs we detect typically 3000 time-stamped X-ray events uniformly scattered in each frame. Taking into account the 290 µs readout dead time the corresponding incident flux is 4500 counts/pixel/s and the effective detector live time is 3.5%. By comparison, achieving the same time sampling in standard counting mode would require acquisition of individual frames with 20 ns exposure windows, resulting in an effective live time of 0.07%. As expected the X-ray beam time structure is clearly resolved in the image histograms (figure 6).
The measured bunch profile width is about 60 ns FWHM and represents the temporal pulse response of the system. This is more than expected from the 20 ns quantization time and from the APD trigger signal jitter estimated less than 10 ns. This is partly attributed to the charge sharing effect, since the charge signals created by a single X-ray event and split into neighboring pixels have a different time-walk (meaning that low energy hits will be registered later in time) [8] depending on their amplitude. By processing the images so that only the pixel with the shortest time-walk is kept in each X-ray spot, the pulses profiles can be sharpened (figure 6) and thus the time resolution improved without losing X-ray counts, i.e. without reducing the detector DQE.

This test shows that association of TIMEPIX time mode and of MAXIPIX short readout dead time allows time-resolved experiments in the 50–100 ns resolution range with an increased detection efficiency. This might open new possibilities for instance in time-resolved XPCS experiments.

4 Application examples at ESRF

MAXIPIX is used on ID10A for XPCS [13] as a replacement of direct-detection CCD cameras [14], which allowed the time resolution to be extended from a few seconds down to the millisecond range. For this application the 55 µm pixel size of MEDIPIX-2 is still acceptable, although close to the upper limit.

On ID16 beamline a single chip MAXIPIX module is mounted at the focus of a high energy resolution X-ray spectrometer. The detector is used in replacement of a 0D photon-counter. Photon-counting is necessary for detection of the very low X-ray flux produced by the spectrometer. Since the setup is energy-dispersive in the vertical axis, the small pixel size allowed a significant increase in energy resolution [15].

On BM05 beamline the detector was used for characterization of multilayer mirrors in grazing incidence. The short readout time allowed reduction of the duration of surface mapping measurements as well as the carrying out of real-time in-situ surface state monitoring during etching or layer growth operations.

On ID03 beamline the detector is used in place of a 0D counting scintillator on a diffractometer arm to collect surface diffraction data thereby avoiding time-consuming scanning sequences in the reciprocal space. The small pixel size allows the diffractometer dimensions to be minimized and the high frame rate opens possibilities in the study of dynamic surface or interface processes.

On ID13 beamline the detector is used for micro-SAXS experiments requiring accurate frame triggering, noiseless detection and small pixel size.

5 Further developments

With 4500 µm Si sensors the energy range is limited by the sensor absorption efficiency (40% absorption at 20 keV). CdTe and GaAs pixelated sensors are being developed in order to increase efficiency in the 20–50 keV range and also to access energies above 50 keV in order to enable new applications particularly in materials science and in medical imaging. A higher absorption will also improve the radiation hardness at all energies. The 50000 e- linear range of MEDIPIX2 pixel preamplifiers [4], corresponding to 180 keV X-ray energy with Si sensors and about 220 keV with CdTe sensors, provides a sufficient energy margin for high-energy synchrotron experiments.
6 Conclusions

A photon-counting system with high frame rate and high spatial resolution has been built for SR experiments. The small pixel size is well suited for XPCS and for inelastic scattering experiments. The detector compactness facilitates the mounting on diffractometers setups. The fast frame rate extends the capabilities of the beamlines in time-resolved experiments. Pump-probe experiments with time resolutions in the 100 ns range can be considered with Timepix-based systems. The versatility of the readout board and the modular system design allows a large range of requirements to be covered with minimum further investments. Further improvements will mainly consist in implementing high-Z pixel sensors for high energy applications.

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