**Abstract.** The Timepix detector can be operated in Time-over-Threshold mode to allow for charge integration measurements as required by short (< 50 fs) x-ray pulses of the Linac Coherent Light Source (LCLS). Initial commissioning activities have started at the X-ray Correlation Spectroscopy (XCS) instrument at LCLS, where speckle patterns have been measured.

1. Introduction

The LCLS free electron laser at the SLAC National Accelerator Laboratory (Menlo Park, USA) requires 'integrating' detectors because of the large number of photons arriving all at once (typically over a pulse duration below < 100 fs). Hence, photon counting is not possible but single shot measurements of the number of photons per pixel are required.

The X-ray Correlation Spectroscopy (XCS) instrument came on line in the beginning of 2012 and measures the time evolution of coherent diffraction patterns, also known as speckles. Since the angular size of the speckles is small one needs a detector with a small pixel size located at a large sample-detector distance. The detailed analysis of single-shot speckle patterns can reveal information on the intrinsic dynamics of the system under investigation. The Timepix Quad detector has been used to measure such single shot speckle patterns.

2. The Timepix chip

Timepix [1] is a pixel readout chip of size 14 x 14 mm containing 256 x 256 square pixels of 55 µm, and can be bump-bonded to several types of sensors. The Timepix chip is developed by the Medipix collaboration [2], derived from the Medipix2 chip which operates in photon counting mode. Every pixel in the Timepix chip can be configured in one of three operation modes. These are the Time over Threshold (ToT), Time of Arrival (ToA) and single photon counting modes.

At XCS the Timepix chip is used in ToT mode to be able to image X-ray photons coming from a single LCLS pulse. The collected signal is integrated by a capacitor then slowly discharged via a constant current hence the time a signal is over a predefined threshold is a measure of its magnitude. Each pixel records this ToT value by counting clock pulses in a 14 bit counter which is proportional to the deposited energy in a pixel. The energy discrimination threshold of the Timepix pixel allows noise free detection, so no dark frame subtraction is needed.
Each pixel cell is divided into an analogue and a digital area, where the analogue part contains a preamplifier, discriminator and a 4-bit threshold adjustment. The digital side of the pixel consists of the counting and synchronization logic, and the pixel configuration registers. After the acquisition is completed, the contents of all 65k pixel counters are shifted out serially in about 8 ms. Hence a maximum rate of 125 Hz can be achieved.

Although the preamplifier output voltage is only linear up to 50k electrons, the discriminator output pulse width is linear up to larger input charges because of the constant discharge current in the preamplifier. The discharge slope of the preamplifier signal is controlled by the Krummenacher current \(I_{\text{krum}}\)\(^1\). A higher \(I_{\text{krum}}\) current decreases the ToT pulse width for a given input signal. This means that the resolution of the ToT measurement is determined by the frequency of the counting clock, which can be up to 100 MHz, and the Krummenacher current. Simulations have shown that the ToT dynamic range extends up to about 150k electrons. However, first measurements at LCLS described in section 4 have shown that the dynamic range is about 125k electrons.

To facilitate tiling the chip, the global chip circuitry is placed at one side of the chip, leaving three sides which have less than 50 \(\mu\)m non-sensitive distance between the pixels and the physical edge of the chip. The periphery contains wire-bonding pads and the digital control logic for input and output. The analog part of the periphery has 13 global Digital to Analog Converters (DAC). One of the voltage DACs sets the global threshold (THL) using 14 bits. In addition each individual pixel has a 4-bit threshold equalization DAC \(^1\).

Threshold equalization is used to compensate the pixel to pixel threshold variations due to local transistor mismatches. This procedure determines the threshold distributions using a ‘noise scan’ for the ‘lowest’ and ‘highest’ threshold adjustment values. Then an adjustment value is selected for each pixel to shift its threshold as close as possible to the average of the threshold distributions. Measurements show an electronic noise of 113 electrons (rms) for a bump-bonded pixel and a full matrix threshold variation of 95 electrons (rms) after equalization. This results in a minimum detectable charge of about 880 electrons (2.7 keV).

### 3. The Timepix-Quad detector

The QTPX-262k detector \(^3\) consists of a silicon diode sensor divided into a 512 x 512 array of pixels. The ‘Quad’ sensor is connected via 30 \(\mu\)m In-Sn bump-bond balls to four Timepix chips below the sensor, providing each sensor pixel with its own readout circuitry. The Silicon sensor has a thickness of 300 \(\mu\)m, collecting holes because of the p-type implant in n-bulk (p-on-n). The Aluminum entrance window on the entrance (non-pixel) side of the sensor has a thickness of 1 \(\mu\)m.

The detector readout system consists of two printed circuit boards. One board supports the Quad sensor assembly with four Timepix ASICs, and this board is mounted perpendicular to the Relaxd \(^4\) read-out board. This Relaxd board supplies the necessary voltages to the Timepix, and the control signals to and from these chips via a low-power Field Programmable Gate Array (FPGA, Lattice SC series). Communication with the Relaxd board goes through a standard one Gbit/s Ethernet connection (GbE). The T-shaped mechanical topology allows 2D tiling of multiple Quad modules into a larger detector array.

At the core of the Relaxd module is an FPGA. Its firmware, including an embedded microcontroller, controls the various devices on the module, as well as the external interfaces (USB, Gigabit Ethernet and the Timepix devices). On-board non-volatile memory stores the FPGA firmware and configuration data (optional). The Gigabit Ethernet connection is the main communication port for control and data. About 50% of the 1 GbE bandwidth is used to readout a Quad at a frame rate of 120 Hz.

At the boundaries between the Timepix chips, the sensor pixels are 3 times as large (165 x 55 \(\mu\)m\(^2\)) due to a small dead area at the boundary of the chip. These large sensor pixels cover the...
gaps between the chips, showing up in the raw images as a cross centered at the detector, and must be corrected offline in the software. This results in a Quad sensor with an active area of 2.8 x 2.8 cm² without any dead area. The QTPX-262k detector is a compact unit in a housing of 36 x 50 x 96 mm³, requiring only 12V DC external power, and one 1 GbE link to a Data Acquisition host.

4. Commissioning of the QTPX-262k detector at the XCS instrument
A Timepix Quad detector was recently used at the XCS instrument at LCLS. XCS [5], the fifth of the LCLS instruments, came on-line in 2012. XCS allows investigation of atomic and molecular dynamics down to extremely fast time scales. XCS type of experiments rely on the observation of speckle patterns. It requires a 2-dimensional detector to image 8 keV photons (ideally a wider range from 4-25 keV) with a quantum efficiency close to 100%, a dynamic range of 10⁵ photons, very low noise (≪ 1 photon), and small pixels of order 50 x 50 μm². Furthermore, a 120 Hz frame rate is needed to keep up with the maximum LCLS repetition rate. The QTPX-262k specification basically fulfills all these requirements and is currently under commissioning at the XCS instrument.

4.1. Detector operation
The variation in the discharge of the preamp generates a pixel to pixel gain variation in ToT mode. Therefore, each pixel has to be calibrated and fit with an analytical function[7] to get the conversion from ToT value to deposited energy. Calibration of the detector over the full dynamic range required for XCS is in progress. Fluorescence spectra measured so far with an X-ray tube at Nikhef show kα peaks down to 4.5 keV (Titanium). Lower values down to about 3 keV should be possible.

The TPXQ has been integrated into the LCLS DAQ System, a network of detectors and Linux servers synchronized by the LCLS Timing Event System [6]. Readout of the Timepix is done by UDP over a dedicated Ethernet link, and the readout node uses two Xeon CPU cores to sustain a 120 Hz frame rate. First images at XCS have been taken with a highly attenuated LCLS beam. The LCLS beam flux was carefully increased to find the intensity where the pixels start saturating. However, Figure 1 shows that the detector signal drops to zero in the region where you expect it to saturate. Several causes have been considered but a fast discharge of the preamp storage capacitance is the most likely reason. Simulations of the ToT values for input charges up to 400k for both holes and electrons show a drop in ToT for positive inputs above 125k holes. The maximum ToT values we measure with a hole collecting sensor according to Figure 1 correspond to an input charge of about 135k holes (60 8keV photons), and agree with the simulations. The behavior of the larger edge pixels confirms this finding: the signal drop is more pronounced in the edge region (white circle in Figure 1) because these pixels collect more charge.

4.2. Speckle patterns
The XCS instrument measures time-resolved speckle patterns. Speckles originate from the illumination of a disordered system by coherent light and present a typical grainy appearance. These features are related to the exact position of the scatterers in the sample. By monitoring the time evolution of such speckle patterns, one can describe the characteristic time scales of the dynamics in the investigated system. To perform such experiments, a spatially and temporally coherent beam is required, such as the one generated by LCLS. Figure 2 shows a single shot Small Angle X-ray Scattering (SAXS) speckle pattern measured with the TPXQ using a 7.908 keV monochromatic beam. The sample-to-detector distance was 7.7 m, and the detector was running with a 2.5 MHz counting clock. The sample is a colloidal dispersion, which shows some
concentric rings around the incident beam direction, that is partly covered by a beam-stop. One can clearly observe the speckles forming the structural rings.

5. Outlook
Commissioning of the QTPX-262k detector will continue in the coming months. Additional calibrations and characterization measurements will be performed to fully understand the behavior of the detector in XCS type of experiments. Further improvements to the detector are foreseen: an electron collecting sensor, thicker sensors and different sensor materials, and tiling into even larger arrays while minimizing dead area.

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