Beyond single photon counting X-ray detectors

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Abstract

Synchrotron radiation applications require detectors with a high sensitivity and a large dynamic range in order to study both the strong and weak features of the samples. Moreover, a high spatial resolution is necessary for imaging and diffraction studies.
The photon counting technique is currently the best solution to these requirements but it presents some limitations which can only be partially overcome by technological improvements i.e. the count loss at high impinging intensities, due to the readout electronics shaping time, and the restrictions on the minimum pixel size, due to the charge diffusion in the sensor.
In order to overcome both these limitations a new generation of charge integrating hybrid detectors with single photon sensitivity is being developed. These preserve the advantages of counting detectors and at the same time allow a processing of the analogue information in order to enhance the spatial resolution and perform some spectral analysis.
A comparison between purely counting and analogue readout for 50 μm and 25 μm pitch microstrip detectors is presented in terms of spectral reconstruction capability and spatial resolution.

Key words: single photon counting, analogue readout, X-ray imaging detectors

1. Introduction

The Detectors Group of the Swiss Light Source (SLS) is active in the development of X-ray detectors satisfying the strict requirements of Synchrotron Radiation (SR) applications i.e. mainly a high sensitivity, a large dynamic range and a good spatial resolution [1]. Hybrid single photon counting detectors providing the necessary dynamic range and spatial resolution have been developed [2, 3, 4] and are used for a wide range of applications like powder diffraction, protein crystallography, small angle scattering and X-ray imaging. These detectors are often considered the state-of-the-art thanks to the absence of noise in the acquired data and to the capability of suppressing the fluorescent light possibly emitted by the samples under examination.

However, single photon counting detectors present some intrinsic limitations due to the pure binary information they provide [5]. Firstly, the pile up of the analogue signal results in a loss of counts at high rates which distort the intensity measurements in the image at high fluxes.
Moreover, the spatial resolution of single photon counting detectors is limited by the diffusion of the charge produced by the X-ray while drifting towards the sensors pads [6]. This effect can in principle be corrected using pixel-to-pixel communications in case the charge shared between first neighbors but is extremely challenging when the diffusion length is larger than the pixel size and the spread is over many pixels [7].

The advent of X-ray Free-Electron Lasers (XFEL) is triggering the development of a new generation of charge integrating detectors with single photon sensitivity and a dynamic range larger than 10^4 at 12 keV [8].
Their capability of detecting several thousand of photons simultaneously absorbed by the detector is far beyond the needs of SR applications, but can successfully be exploited e.g. in single crystal diffraction experiments which still suffer from the rate saturation effect of counting detectors on the high intensity diffraction peaks.
Moreover the low electronic noise of such detectors, opens the possibility of detecting the charge spread of single photons over more than one channel of the detector with a good Signal-to-Noise-Ratio (SNR) thus improving the spatial resolution of the system. This opens the possibility of building systems with a higher segmentation in order to reach spatial resolutions of a few microns, inaccessible to hybrid counting detectors.

In this work measurements acquired with microstrip detectors with digital and analogue readout are compared and the feasibility of achieving a spatial resolution of a few microns while preserving the single photon sensitivity is proved.

2. The detectors

Microstrip sensors are particularly convenient in order to test the behavior of detectors with different spatial resolution since strip implants of different pitches can be routed to fixed pitch readout pads by using fan-out on the metal layer of the sensor, while for pixel detectors such tests would require a complete redesign of both the sensor and the readout electronics.

The MYTHEN single photon counting and the GOTTHARD charge integrating Application Specific Integrated Circuits (ASIC) have been designed at the Paul Scherrer Institut (PSI) in UMC 0.25 μm technology. Both are based on the same charge preamplifier and are optimized to read out 320 μm thick silicon microstrip detectors with 50 μm pitch and 8 mm strip length.

Due to this similarities, the two ASICs are optimal candidates to compare the features of binary and analogue readout.
MYTHEN and GOTTHARD have both been wirebonded to a 320 μm thick multi-pitch silicon microstrip sensor. It consists of groups of 2 mm long strips with different pitches (10, 15, 20, 25, 30, 35, 40, 45, 50 μm) routed to the 50 μm pitch readout pads. The readout ASICs were not optimized for the input capacitance of this sensors which are only used as test structures to characterize the behavior of the frontend with different strip pitches.

2.1. The photon counting ASIC

The MYTHEN (Microstrip sYstem for Time rEsolved experimeNts) detector has been developed for SR powder diffraction experiments. The frontend ASIC consists of 128 channels operating in parallel in single photon counting mode [9].
Each channel mainly consists of a charge sensitive preamplifier AC-coupled to two shaping gain stages and followed by a comparator. The analogue chain can be tuned in order to achieve the noise and speed specifications required by the applications. Equivalent Noise Charge (ENC) ranging between 195 e^- and 260 e^- corresponding to a shaping time of 650–90 ns are normally used.
The comparator threshold can be trimmed on a channel by channel basis by means of an internal 6 bits Digital to Analog Converter (DAC) which adds to the global externally adjustable threshold. Each comparator output is fed into a 24 bits gateable counter.
In addition the chip contains the digital logic for configuring the internal DACs, resetting and reading out the counters serially over 4 parallel data output lines. The counters are readout using a 16 MHz clock and the dynamic range of the counter can be reduced in order to decrease the readout time. Frame rates ranging between 4 kHz (24 bits) and 14 kHz (1 bit) are achievable.

Modules with 1280 independent channels have been assembled and are used for detector characterization and scientific measurements.

2.2. The charge integrating ASIC

GOTTHARD (Gain Optimizing microsTrip sysTem witH Analog ReaDout) is a prototype charge integrating ASIC for silicon strip sensors compatible with XFEL requirements. Each of the 100 channels of the ASIC consists of a low noise Charge Sensitive Amplifier (CSA) with dynamic gain switching as described in [10], two sample and hold capacitors and an analogue output buffer.
In this paper only measurements using the highest gain settings, which allow the single photon sensitivity, are presented. The two sample and hold capacitors are normally operated in order to perform correlated double sampling measurements i.e. subtract the reset and low frequency noise from the integrated charge value.
In addition the chip contains the digital logic necessary in order to configure the gain settings, reset and serially read out the voltage from the sample and hold capacitors. The analogue output of the channels is read out using a 10 MHz clock and is digitized by two 14 bit 80 MHz Analogue to Digital Converters (ADC).

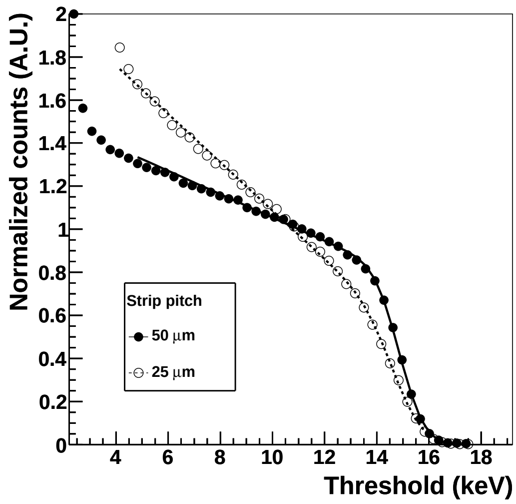

Figure 1: Threshold scan measurement acquired at 15 keV using the MYTHEN detector for 25 μm and 50 μm pitch microstrip sensors.

Modules with up to 400 channels have been assembled and tested in order to characterize the ASIC. A Peltier system is used to cool down the detector to about 12^o C in order to reduce the leakage current of the silicon sensor, to which integrating systems are particularly sensitive. A pedestal subtraction, correcting for the integrated leakage current, is also applied to the data.

3. Spectral reconstruction

Measurements concerning the spectral capabilities of MYTHEN and GOTTHARD have been carried out. Due to their relatively large noise, these detectors are not intended to be used in spectroscopy applications, but the possibility of correctly reconstructing the energy of the radiation is important in order to evaluate the functioning of the system. Moreover the possibility of suppressing the fluorescent light possibly emitted by the samples is an important feature for SR detectors.

3.1. Photon counting threshold scans

Single photon counting detectors return only a binary information without indication on the signal amplitude. Therefore, in order to reconstruct the signal spectrum, threshold scans have been acquired i.e. measurements scanning the comparator threshold on the energy range. Figure 1 shows the S-curve acquired with MYTHEN using 15 keV monochromatic X-rays for 25 μm and 50 μm pitches and represent the integral of the spectrum of the signal above the value of the comparator threshold. The S-curves deviate from the ideal step function around the X-ray energy because of the electronics noise, which smooths the step, and because of the charge sharing between the strips, that adds a decreasing slope on the plateau.

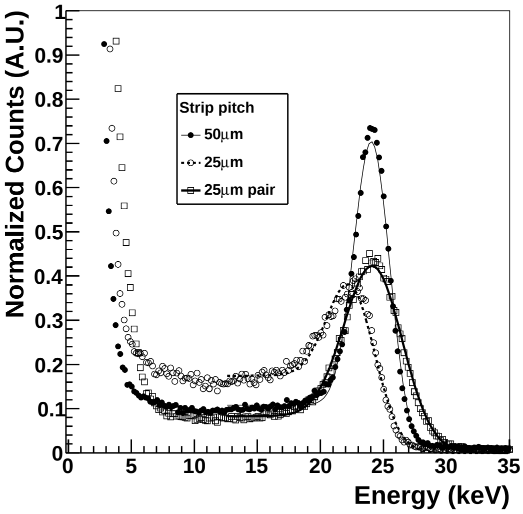

Figure 2: Spectrum acquired at 25 keV using the GOTTHARD detector for 25 μm and 50 μm pitch microstrip sensors. The "pair" curve corresponds to the spectrum reconstructed by summing the charge collected by first neighbors.

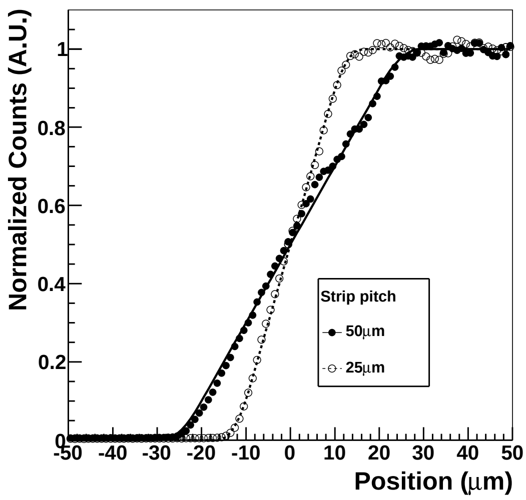

Figure 3: Edge Spread Function measured using the MYTHEN detector using 25 μm and 50 μm pitch microstrip sensors for 15 keV monochromatic X-rays.

From the plots it is evident that not only the smaller strip pitch causes a higher noise (ENC(RMS)=191 ± 5 e^- at 50 μm; ENC(RMS)=205 ± 18 e^- at 25 μm) because of the higher inter-strip capacitance, but also the charge sharing is proportionally higher for the smaller strip pitch since the region among which the charge is shared d remains approximately constant for all strip pitches. This region has been estimated to be about 17 μm for 300 μm and places thus a limit on the minimum strip pitch at which the comparator threshold can be unambiguously set at half of the photon energy [11].
For strip pitches smaller than d in fact the charge is always shared between at least three strips with a consequent lower SNR and the impossibility of counting all photons only once.
However, because of the steep slope of the S-curve on the plateau, also at 25 μm pitch it is evident that the unavoidable uncertainties in the calibration of the threshold introduce large fluctuations in the number of counts and the threshold dispersion results in large nonuniformities between channels.

3.2. Analogue readout spectra

The possibility of reading out the analogue value of the charge integrated on the CSA adds further information to the data, although it is affected by the electronic noise. Figure 2 shows the spectrum of the signal acquired with GOTTHARD using 25 keV monochromatic X-rays for 25 μm and 50 μm pitches. The signal is fitted by a gaussian function summed to a pedestal which takes into account the charge sharing between neighboring strips. The estimated noise ENC (RMS) is 390 ± 5 e^- at 50 μm and 520 ± 10 e^- at 25 μm.
The signal collected by the 25 μm pitch strips is smaller because of the capacitive coupling and charge sharing with the neighboring strips. However it is still possible to reconstruct the complete charge by summing up the signal from a cluster. The curve given by the sum of the signal on two neighboring 25 μm pitch strips is plotted and results very close to the one for a 50 μm pitch strip although the noise obviously increases compared to the signal from a single strip (ENC(RMS)=640 ± 10 e^-). However the SNR is still large enough in order to apply a a threshold to the data and operate the detector in counting mode.

If operated with a high frame rate the system has the same advantages of single photon counting systems, but allows also the simultaneous detection of multiple monochromatic photons by using energy binning techniques. The number of photons can be determined in case of less than tens of photons per frame per channel, since for larger fluxes the charge sharing smooths out the energy spectrum and prevents a correct binning of the data. The frame rate represents then the main limitation for operating a charge integrating detector in photon counting mode.
However the standard integrating readout still has the capability of integrating several tens (or up to 10^4 with dynamic gain switching) of photons detected simultaneously.
Moreover thanks to the possibility of summing the signal collected by a cluster of strips, the only limitation to the segmentation of charge integrating detectors is given by the SNR required to maintain the single photon sensitivity.

4. Spatial resolution

The charge sharing between neighboring strips also affects the spatial resolution of the detector. The spatial resolution of the microstrip detectors has been evaluated by measuring their Edge Spread Function (ESF), which represents the integral of the Point Spread Function (PSF). This has been obtained by scanning an edge in front of the detector and averaging the response of the channels as a function of the relative position of the edge from the center of a strip [12].

4.1. Photon counting Edge Spread Function

Ideally the PSF of a single photon counting detector consists in a box function of width given by the pixel size p, but it is

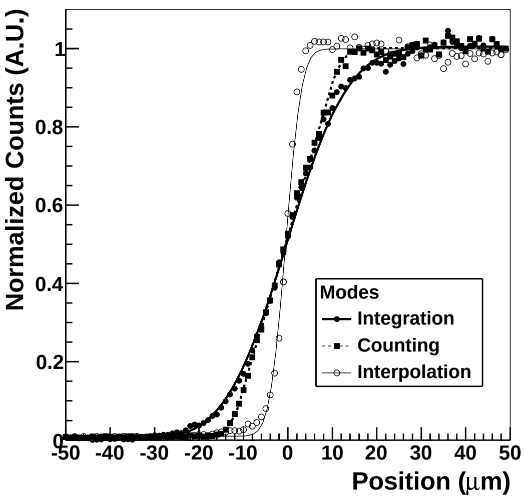

Figure 4: Edge Spread Function measured using the GOTTHARD detector using25 μm pitch strip sensors and different data analysis modes for 25 keV monochromatic X-rays.

deformed in an isosceles trapezoid due to the presence of the charge sharing and of the electronic noise. The half of the difference between the two parallel sides of the trapezoid is indicated as Δ.

Figure 3 shows the ESF measured at 15 keV for 25 μm and 50 μm pitch using the MYTHEN detector. The experimental points have been fitted with the model described in [11] with a resulting $\Delta = 8 \pm 1$ μm for p=50 μm and $\Delta = 7 \pm 1$ μm for p=25 μm.

The spatial resolution of microstrip detectors is highly non uniform but depends on the position of the absorbed photon with respect to the strip center. Therefore the FWHM of the PSF is often not sufficient to evaluate the spatial resolution.

In the case of trapezoidal PSF, the FWHM corresponds to the strip pitch p like in the ideal case of the box PSF, but the full width of the PSF, i.e. the maximum residue, is $(p + \Delta)$ resulting in 58 μm for p=50 μm and 32 μm for p=25 μm.

Therefore not only the pitch of the detector cannot be reduced to less than d=17 μm in order to preserve the integrity of the signal, but also the improvements in the spatial resolution of the detector are not following the efforts needed for reducing the sensor pitch e.g. in terms of SNR.

4.2. Analogue readout Edge Spread Function

Figure 4 shows the ESFs acquired using the GOTTHARD detector with 25 μm pitch sensors. All three curves correspond to the same measurement, but the data have been analyzed using different methods.

The curve acquired in integration mode represents the ESF calculated by summing the ADC signal values for each step of the acquisition. The PSF results a gaussian with standard deviation 15.3 $\pm$ 0.1 μm, suffering mostly from the capacitive coupling between neighboring strip.

The curve in counting mode has been obtained by incrementing a counter for each detector channel in case the ADC value was higher than half of the ADC value for 25 keV photons i.e. simulating the ideal behavior of a photon counting ASIC. The fit with the trapezoidal PSF model as discussed in the previous section returns an estimate $\Delta = 7 \pm 1$ μm, i.e. identical to the one acquired with MYTHEN.

The wider information offered by the analogue readout when the detector is operated in single photon mode gives the possibility to obtain a sub-channels spatial resolution [13]. Position interpolation methods are well known in high energy physics, but had not been fully exploited in X-ray imaging because of the difficulties in achieving either the single photon sensitivity or the high segmentation.

The results obtained using the η-algorithm described in [14] correspond to a Gaussian PSF with standard deviation 4.1 $\pm$ 0.1 μm. Although this result is mainly limited by the relatively high electronic noise due to the interstrip capacitance, it shows the feasibility of developing hybrid X-ray detectors with single photon sensitivity and micron resolution for imaging applications.

5. Conclusions and perspectives

Single photon counting detectors cover the need of many SR applications, however since they are not able to support the simultaneous detection of up to 10^4 photons they must be replaced by integrating detectors for XFEL experiments. Moreover a purely binary readout places a limit on the maximum segmentation and thus on the achievable spatial resolution.

It has been shown that charge integrating systems with single photon counting sensitivity can overcome this limitations.

For X-ray diffraction, photon counting systems still satisfy the experimental requirements, are easy to operate and are superior to integrating systems for the capability of suppressing the fluorescence light emitted by the sample and for their limited sensitivity to the sensor leakage current.

On the other hand, imaging experiments still rely mostly on phosphor-coupled CCD detectors because of their high spatial resolution, but suffer from the often limited dynamic range, SNR and speed. Thanks to the possibility of interpolating between channels, the preliminary measurements acquired using the GOTTHARD ASIC with small strip pitches show the possibility of achieving a spatial resolution of a few microns without compromising the single photon sensitivity and the dynamic range.

Simulations taking into account both the spatial distribution of the energy deposition and the charge transport in silicon are being carried out in order to optimize the design parameters for charge integrating detectors with single photon sensitivity (both strips and pixels) and improved SNR and spatial resolution.

Further prototypes of GOTTHARD and a new 2D-detector with a small pixel size are being designed at PSI in 0.13 μm technology in order to fully exploit the capabilities of charge integrating detectors with single photon sensitivity. Particular effort is put in the maximization of the SNR and in the improvement of the frame rate in order to comply with the high X-ray fluxes typical of SR sources.

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