Count rate linearity and spectral response of the Medipix3RX chip coupled to a 300$\mu$m silicon sensor under high flux conditions

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ABSTRACT: For clinical X-ray imaging, the detector performance under high flux conditions is very important, with typical flux rates for modern CT systems reaching $10^{9}$ photons s$^{-1}$ mm$^{-2}$ in the direct beam. In addition, for spectral imaging a good energy resolution under these conditions is needed. This poses difficulties, since pulse pileup in the pixel electronics does not only affect the count rate, leading to a deviation from the otherwise linear behavior, but also degrades the spectral response of the detector, making k-edge subtraction and other contrast enhancement techniques less efficient. In this paper, we investigate the count rate capabilities and the energy response of the Medipix3RX chip under high flux conditions using 10 keV monochromatic photons.

KEYWORDS: X-ray detectors; Hybrid detectors

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1 Introduction

Single photon processing detectors offer several advantages over energy integrating detectors such as being free from non photonic noise [1, 2], giving the possibility of energy weighting of photons [3] and k-edge imaging [4]. However, the processing of the pulse from each photon takes a finite time. If another hit occurs during this time, it can either be lost or added to the first pulse which will then lead to an underestimation of the photon flux and a distorted energy response.

2 Medipix3RX

The Medipix3RX chip is a single photon processing hybrid pixel detector, developed in the framework of the Medipix3 collaboration. The pixels matrix consists of 256 × 256 pixels with a pixel size of 55 × 55 µm². There are two analog thresholds and two counters in each pixel. The chip can be used either in single pixel mode (SPM) where each pixel works independently or in charge summing mode (CSM) where the charge from a single interaction is summed over a dynamically allocated 2x2 pixel cluster.

In addition to the intrinsic 55 µm pixel pitch the Medipix3RX can also be used with 110 µm pixel pitch, combining thresholds and counters in four pixels. This gives the possibility to use up to eight thresholds in single pixel mode and four thresholds in charge summing mode.

Details on the chip and different operating modes can be found in R. Ballabriga et al. [5]
2.1 Gain modes

The Medipix3RX [5] chip offers four different gain modes, implemented by selecting the value of the preamplifier’s feedback capacitance, 7 fF for the highest gain, 14 fF, 21 fF and 28 fF for the lowest gain. In this paper, the four gain modes are referred to as super high gain mode (SHGM), high gain mode (HGM), low gain mode (LGM) and super low gain mode (SLGM). All the dead time measurements presented here were done in HGM, but some of the energy resolution measurements were performed in SHGM as well.

2.2 $I_{KRUM}$ current

The Medipix3RX chip uses a preamplifier scheme proposed by Krummenacher [10]. The charge sensitive amplifier is based on a cascoded differential CMOS preamplifier. The preamplifier output return to zero is controlled with a bias current $I_{KRUM}$ which is sent globally to the pixels. The value of this current affects the count rate capabilities, and as a second order effect the gain of the chip.

3 Paralyzable detector model

A number of models are commonly used to describe a detector’s performance under high fluxes. [6–9] In this paper, a simple paralyzable detector model [6], shown in equation (3.1) is used to fit the count rate data ($x$) and extract the dead time ($\mu$).

$$f(x) = xe^{-\mu x}$$

(3.1)

4 Experimental setup

The measurements presented in this study were performed at the TOPO-TOMO beam line at the ANKA synchrotron. Monoenergetic X-rays from 6 keV to 15 keV were used and the sensor was flood illuminated. Two detectors were investigated, one with 55 $\mu$m pixel pitch and one with 110 $\mu$m pixel pitch. Both detectors had a thickness of 300 $\mu$m. The sensor material was silicon, which we chose to provide a clean signal in order to investigate the ASIC rather than effects in the sensor layer. To control and read out the chip a Fitpix USB Readout System [11] was used in combination with a custom software.

The photon flux was varied with a combination of Aluminium filters and in addition because the beam was not homogeneous, multiple points could be extracted from different areas of the sensor using the same measurement. The incoming photon flux was measured for the low flux case, thus in the linear range, using the Medipix3RX chip and then calculated from the change of filtration for higher fluxes.

Before the measurements the detectors were equalized using test pulses to optimize the energy response but no offline alignment of the spectrum or gain correction has been done. Data analysis including the fitting of the dead times was carried out using a combination of Python and ROOT [12].
5 Results

5.1 Low flux energy resolution

Before the dead time measurements the energy response under low flux conditions was measured. This sets a baseline performance to compare against during the high flux measurements. As shown in figure 1, the detectors show similar energy resolution but the charge sharing is, as expected significantly lower for the 110 µm detector. In charge summing mode, charge sharing is fully suppressed for both detectors but the energy resolution is slightly degraded because the chip sums not only the charge from four pixels but also the uncorrelated noise in quadrature. It can also be seen that the Medipix3RX charge summing over an 110 × 110 µm² area is superior to fixed 110 × 110 µm² pixels. This is due to the dynamic allocation of the summing area being more likely to capture the full charge.

The measured energy resolution for the different operating points used in the experiment is summarized in table 1. The best energy resolution, a full width at half maximum, (FWHM) of 0.96 keV was measured at 12 keV, in single pixel mode using the highest gain setting, (SHGM). This is achieved directly off the chip without any offline alignment of the data.

5.2 Dead time measurements

The count rate linearity was measured for I_KRUM DAC settings of 5, 25 and 100, using 10 keV photons and an energy threshold set to 7 keV. The slightly high threshold of 7keV was chosen so that the same threshold could be maintained through the different I_KRUM settings since we did not achieve noiseless operation at I_KRUM 100 and a 5 keV threshold at high flux. Figure 2 shows the measurement points and the fitted dead times for the 55 µm detector and in table 2 the fitted dead times are presented. When compared to the 110 µm detector, we see no difference in the count rate capability per pixel but due to the larger pixels it means that the 110 µm detector can handle four times less photons per unit area. In figure 3 the response in counts pixel⁻¹ s⁻¹ is presented. As expected, for all operating modes increasing I_KRUM values lead to a better count rate linearity.
Table 1. Measured energy resolutions for the various modes of operation.

| Configuration | FWHM (keV) |
|---------------|------------|
|               | 6 keV      | 10 keV | 12 keV | 15 keV |
| 55µm HGM SPM  | 1.30       | 1.37   | 1.36   | 1.37   |
| 55µm HGM CSM  | 1.85       | 2.03   | 1.95   | 2.2    |
| 55µm HGM SPM+PZC | 1.72   | 1.65   | 1.45   | 1.72   |
| 55µm HGM CSM+PZC | 2.26   | 2.52   | 2.46   | 2.66   |
| 55µm SHGM SPM  | 1.12       | -      | 0.96   | -      |
| 55µm SHGM CSM  | 1.54       | -      | 1.3    | -      |
| 110µm HGM SPM  | 0.69 µs    | 5.05 · 10⁷ | 1.26 · 10⁷ |
| 110µm HGM CSM  | 25 · 0.57 µs | 6.11 · 10⁷ | 1.53 · 10⁷ |
| 110µm HGM SPM  | 25 · 1.62 µs | 8.17 · 10⁷ | 2.18 · 10⁷ |
| 110µm HGM CSM  | 25 · 2.66 µs | 9.95 · 10⁶ | 2.49 · 10⁶ |
| 110µm HGM SPM  | 100 · 2.49 µs | 1.21 · 10⁷ | 3.02 · 10⁶ |
| 110µm HGM CSM  | 100 · 4.02 µs | 1.72 · 10⁷ | 4.31 · 10⁶ |

Table 2. Measured dead times for the different operating modes along with the point at which a dead time loss of 10% occurs.

| Mode       | IKRUM | Dead Time | 55 µm Pixels | 110 µm Pixels |
|------------|-------|-----------|---------------|---------------|
| SPM        | 5     | 0.69 µs   | 5.05 · 10⁷    | 1.26 · 10⁷    |
| SPM        | 25    | 0.57 µs   | 6.11 · 10⁷    | 1.53 · 10⁷    |
| SPM        | 100   | 0.40 µs   | 8.17 · 10⁷    | 2.18 · 10⁷    |
| CSM        | 5     | 3.50 µs   | 9.95 · 10⁶    | 2.49 · 10⁶    |
| CSM        | 25    | 2.88 µs   | 1.21 · 10⁷    | 3.02 · 10⁶    |
| CSM        | 100   | 2.02 µs   | 1.72 · 10⁷    | 4.31 · 10⁶    |

5.3 Spectral response at high flux

The count rate deviation can be modeled and corrected for, but the spectral response is also affected, an effect, which in general cannot be compensated for. [13] As shown in figures 4, 5, 6 and 7, the single pixel mode is, as expected, much less affected by high count rates than the charge summing mode. This is because in charge summing mode, when a hit is assigned to a pixel its neighbors are inhibited during the process. In figure 8 the energy response of the 55 µ and 110 µm detector is compared at approximately the same flux. Due to larger pixels there is more pileup in the 110 µm detector but on the other hand there is less charge sharing. The charge summing mode in the 55 µm detector shows less charge sharing than the single pixel mode in the 110 µm but there is slightly more pileup.
6 Conclusions

Both the count rate linearity and the energy response of the Medipix3RX chip were measured for several operating points. The charge summing mode fully suppresses charge sharing in the investigated energy range but the count rate capabilities are about 4-5 times less than for the single pixel mode, as expected. The measurements for count rate linearity agrees with similar measurements done by T. Koenig et al. [14] using a Medipix3RX chip with a CdTe sensor. We could not find a notable difference in the count rate capabilities between the 55\(\mu\)m pixel sensor and the 110\(\mu\)m sensor that would go beyond the factor of four due to the larger pixel areas.
Figure 4. Energy response for various X-ray fluxes for the 55 µm detector in SPM.

Figure 5. Energy response for various X-ray fluxes for the 55 µm detector in CSM

Figure 6. Energy response for various X-ray fluxes for the 110 µm detector in SPM
Figure 7. Energy response for various X-ray fluxes for the 110 µm detector in CSM

Figure 8. Comparison of 55µm pixels in CSM and 110µm pixels in SPM

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