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Simulations of charge summing and threshold dispersion effects in Medipix3

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ABSTRACT

A novel feature of the Medipix3 photon-counting pixel readout chip is inter-pixel communication. By summing together the signals from neighbouring pixels at a series of "summing nodes", and assigning each hit to the node with the highest signal, the chip can compensate for charge-sharing effects. However, previous experimental tests have demonstrated that the node-to-node variation in the detector's response is very large. Using computer simulations, it is shown that this variation is due to threshold dispersion, which results in many hits being assigned to whichever summing node in the vicinity has the lowest threshold level. A reduction in threshold variation would attenuate but not solve this issue. A new charge summing and hit assignment process is proposed, where the signals in individual pixels are used to determine the hit location, and then signals from neighbouring pixels are summed to determine whether the total photon energy is above threshold. In simulation, this new mode accurately assigns each hit to the pixel with the highest pulse height without any losses or double counting.

1. Introduction

In a hybrid pixel detector, a pixelated sensor (such as a silicon photodiode) is bonded face-to-face to a readout chip, with each pixel being connected to an individual readout channel on the chip. This makes it possible to achieve superior detector count rate performance by performing signal processing in each pixel. However, pixel-to-pixel variations in these readout channels ("threshold dispersion") can affect the uniformity of the detector's response.

"Medipix" is a family of readout chips developed at CERN for X-ray detection. The Medipix2 readout chip [1] has a 256 by 256 array of 55 μm square pixels, each of which incorporates an amplifier, a pair of comparators and a counter. Whenever a pixel is hit by a photon, the resulting signal pulse from the amplifier has an amplitude which is directly proportional to the charge collected by the pixel, and its length also increases with the collected charge. The signal amplitude is compared to a pair of adjustable thresholds, and if it falls between them the counter is incremented. So, this detector can count individual photon hits within a user-defined energy range, making it possible to achieve virtually noise-free X-ray images while excluding unwanted signals such as lower-energy fluorescence photons.

However, the performance of Medipix2 is degraded by charge-sharing effects. If the charge carriers generated by an incoming photon are shared between two or more pixels, then none of the pixels will measure the full photon energy. Depending on the threshold used, the photon may be counted by more than one pixel or missed altogether. The hit registration will also be affected by threshold dispersion [2], leading to fixed-pattern noise. The Medipix2 chip allows fine adjustment of the threshold levels in each pixel to reduce this.

The most recent member of the family of Medipix chips, Medipix3 [3], retains the same array and pixel size as Medipix2, while implementing new features within each pixel. One particularly novel feature is the use of inter-pixel communication to compensate for the effects of charge sharing.

2. Medipix3 and charge summing

The Medipix3 detector can be operated in a variety of modes. In "single pixel" mode, the pixels count photons independently like in Medipix2. Alternatively, in "charge summing" mode the signal pulses produced by each group of four adjacent pixels are added together at a summing node, as shown schematically in Fig. 1. This means that even if the signal generated by an incoming photon is shared between neighbouring pixels, at least one summing node will detect the full photon energy. The total signal at each summing node is then compared to an adjustable threshold. If two or more neighbouring summing nodes are above

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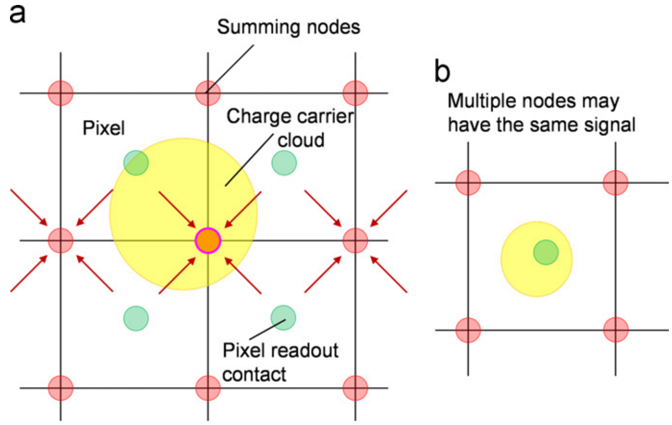

Fig. 1. Illustration of charge summing in Medipix3. (a) The charge carriers collected in each set of four neighbouring pixels are added at a summing node, thus reconstructing the total signal produced by the incoming photon despite charge sharing. (b) If all the carriers are collected within one pixel, the four surrounding nodes will measure the same total signal, creating an ambiguity in the hit assignment.

threshold, then arbitration circuitry is used to ensure that the hit is registered only by the node with the largest signal. The node with the greatest signal pulse will remain above the discriminator threshold for longest, so this arbitration can be done by determining which node's discriminator output remains high for longest [4]. This process will be affected by threshold dispersion; if a particular node has a higher threshold, then the time that the signal remains above the threshold will be reduced.

Each pixel incorporates two discriminators (each of which can be finely adjusted to reduce dispersion), two sets of charge summing circuitry, and two counters. This makes it possible to reliably count photons at two different energy thresholds, providing a basic energy measurement that can be used to improve image quality with a polychromatic source. Alternatively, it is possible to achieve deadtime-free measurement by reading out one counter while the other counts photons. It is also possible to operate Medipix3 in a spectroscopic mode, where the Medipix3 chip is bonded to a sensor with 110 μm pixels. The Medipix3 is then reconfigured to provide each pixel with eight counters and up to eight different threshold levels, making it possible to obtain more spectral information about the incoming X-rays.

Tests on the first production run of Medipix3 chips have shown various problems, including an unexpectedly high level of threshold dispersion. The general behaviour of the single pixel mode and the spectral response of the charge summing mode are reasonable considering the high level of dispersion. However, the hit assignment in charge summing mode is very poor [5]. When the detector is uniformly exposed to a monochromatic source, some summing nodes register very few hits, while a smaller number register a large number of hits. It is important to understand why these problems occur, and determine whether the problems will persist if the threshold dispersion in Medipix3 is improved.

3. Simulation methods

The behaviour of Medipix3 detectors was simulated using the HORUS detector simulation code in IDL [6]. This code was originally developed to simulate the behaviour of an integrating X-ray detector; the code was therefore modified to perform single photon counting. The program is designed to take an input image representing the distribution of photons produced in some experiment, simulate the interaction of each individual photon with the detector, and return the output image produced by the detector.

The program first compares the input image to the detector structure, to determine which photons are incident in each pixel, and whether any parts of the input image are lost due to limited detector size or dead areas. After this, the simulation consists of a large loop over all the photons incident on the detector. The simulation randomly determines the distance the photon travels through the sensor before photoelectric absorption, using the appropriate absorption cross-section for the particular material and photon energy. (The photon may of course travel through the full sensor thickness and be lost.) If needed, fluorescence effects are also simulated, but the simulation does not include Compton scattering or elastic scattering, which will have very little effect at the photon energies considered here. Following photon absorption, the resulting number of charge carriers collected in each pixel is calculated, using a relatively simple drift and diffusion model described in Ref. [6]. Then, the hit assignment process within each pixel is simulated. This hit assignment process includes the effects of electronic noise and threshold dispersion, which will alter the apparent signal size relative to the comparator threshold level.

The main limitation of the simulation is that, because each photon is simulated independently, it will not model the pile-up effects that occur when a second photon strikes a pixel before the signal pulse from the previous photon hit has returned to zero. The signal pulse in Medipix3 will return to zero within 1 μs of a 12 keV photon hit [3], meaning that these pile-up events will typically affect the performance at hit rates above about 10^5 photons/s/pixel, i.e. about 3×10^7 photons/s/mm^2.

4. Simulation of charge summing

Chips from the first production run of Medipix3 have been tested by Diamond Light Source [5]. In these experiments, the Medipix3 detector was first uniformly illuminated with monochromatic photons, to determine the uniformity of the detector response. A smaller region of the detector was then scanned with a focused beam, to measure the spatial response of individual pixels. These experiments were done both in single pixel mode and in charge summing mode.

A series of simulations were run using the same conditions, in order to test the accuracy of the simulation model and to gain a better understanding of the experimental results.

4.1. Simulation conditions

To match the experiments, a single Medipix3 detector was simulated, using a 300 μm-thick silicon sensor. A photon energy of 15 keV was used; under these conditions, the sensor will have a quantum efficiency of 50%. These simulations did not take into account any variations in the sensor itself; for example, inhomogeneities in the wafer doping may alter the electric field, which will affect the charge collected by each pixel [7].

When simulating the readout chip behaviour, the equivalent charge due to electronic noise in each pixel was taken to be the bare-chip value of 72 e^- rms reported in Ref. [3]; in the charge summing mode, the noise signals from four pixels will be added in quadrature, doubling the effective noise level. The first batch of Medipix3 chips tested experimentally showed pixel-to-pixel threshold dispersion approximately four times higher than in the prototype test chip. To match the high dispersion of these chips, the simulation used a threshold variation of 220 e^- rms in single pixel mode, and 440 e^- rms in charge summing mode. The threshold distribution was assumed to be Gaussian. Finally, a gain