Technical Note SC-XRD 17

Charge Sharing in Pixel Array Detectors: Origins, Impact on Data Quality and Solutions

Hybrid Photon-Counting (HPC) detectors have a number of advantages, including the ability to detect very weak signals and to collect very long exposures without dark current noise. However, these advantages come at a price: HPC detectors are significantly noisier than other detectors for stronger signals due to the charge sharing effect.

To address this limitation, new detectors have recently been developed which offer the benefits of photon-counting without noise due to charge sharing. These new detectors employ two distinct but related approaches: Charge Summation Mode and Mixed Mode.

Origin of the charge sharing effect

Charge sharing, as the name implies, is the division of the charge cloud produced by an X-ray photon between adjacent pixels. It occurs when an X-ray is absorbed near the boundary between two or four pixels as shown schematically in Figure 1 below. The width of the region where charge sharing occurs depends on the energy of the absorbed X-ray (as the initial charge cloud size is larger for more energetic X-rays) and also for thicker sensors (as more diffusion of the charge carriers occurs in thicker sensors). Typically the outer 20-30 microns of the pixel are affected by charge sharing.

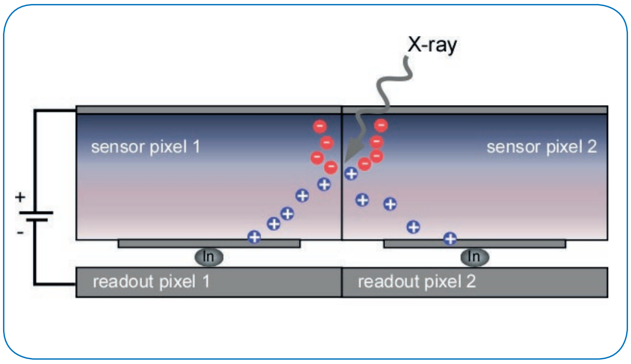

Figure 1. The origin of the charge sharing effect.

Loss of X-ray counts due to charge sharing

In pixel arrays that employ a simple binary threshold charge sharing becomes a noise source. This is because the charge pulses seen in a given pixel are smaller at the edges of a pixel due to charge sharing. Therefore, X-rays can be lost because they fall below the binary threshold as shown schematically in Figure 2.

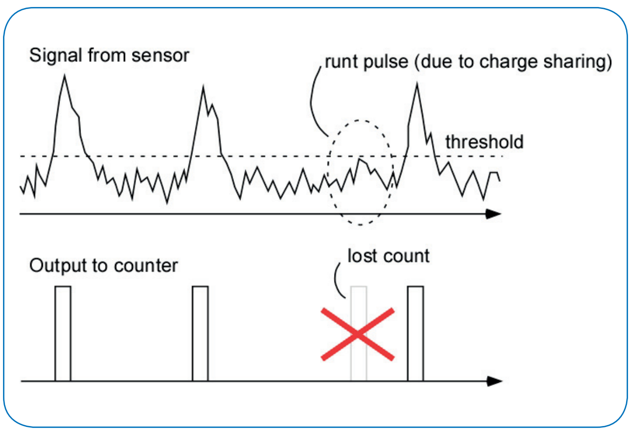

Figure 2. Charge sharing results in lost counts near the pixel boundaries.

The magnitude of the effect depends on the threshold setting, as shown in Figure 3 [1]. For low thresholds (as shown on the far left of Figure 3 for a threshold of 0.25 times the average pulse height), charge sharing results in double counts near the pixel boundaries (as both parts of the divided pulse are then counted). When the threshold for a given pixel is set to exactly half the average pulse height (as shown in the second figure from the left), then the charge sharing effect is minimized (as a divided pulse at the edge of two pixels is then counted in one pixel or the next but not in both). This is thus the typical standard mode of operation for most photon-counting pixel arrays, as this minimizes charge sharing noise. However, it can be seen that counts are still lost at the corners of pixel (where the charge pulses are shared between four adjacent pixels).

If the threshold is set above half the mean pulse height (as is the case when the threshold is used to reject fluorescent background radiation), then X-rays are lost not only in the corners but on the sides (as shown in the two right figures for thresholds of 0.75 and 1.0 times the average pulse height respectively).

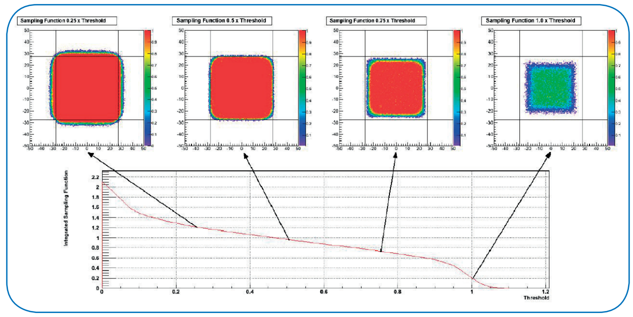

Figure 3. (© SISSA Medialab Srl. Reproduced by permission of IOP Publishing. All rights reserved doi:10.1088/1748-0221/8/10/P10008). The effect of threshold setting on the magnitude of charge sharing. The magnitude of charge sharing is minimized when the counting threshold is set to half the mean pulse height. However, even in this best case counts are lost in the pixel corners. If the threshold is increased to reject fluorescence, then the charge sharing effect becomes significantly more severe [1] .

Noise due to charge sharing

Charge sharing results essentially in a stochastic loss of information. That is, if we imagine a series of symmetry equivalent reflections which are recorded using a pixel array detector, ideally the measured intensity of each such reflection should be identical (within photon-counting statistics). In reality, due to the charge sharing effect, those reflections that impinge on a pixel boundary or pixel corner will be recorded with a weaker intensity than those that impinge on the center of a pixel.

Thus, the symmetry equivalents will not, in general, be recorded with identical intensities. This loss of information is therefore a type of noise, a new type of noise not seen in previous generations of detectors.

How much noise is introduced by the charge sharing effect?

Charge sharing noise can be characterized using the Detective Quantum Efficiency (DQE) [2]. DQE is defined as the ratio of the signal-to-noise in a real detector normalized by the signal-to-noise of an ideal detector in question.

So, a detector with a DQE of 1.0 is a perfect, quantum-limited detector (that is, the only source of noise being photon-counting statistics). A detector with a DQE of 0.5 is two times noisier than an ideal detector. This means in practice that such a detector needs to integrate two times longer than an ideal detector in order to achieve comparable measurement confidence.

A careful experiment to compare the DQE of an HPC pixel array detector and an integrating detector (CCD) was carried out by Ponchut et al at the ESRF [3]. The HPC detector has the advantage of no electronic noise. However, despite this it was found that *the HPC detector was significantly more noisy than the CCD detector,* as shown in Figure 4 [3].

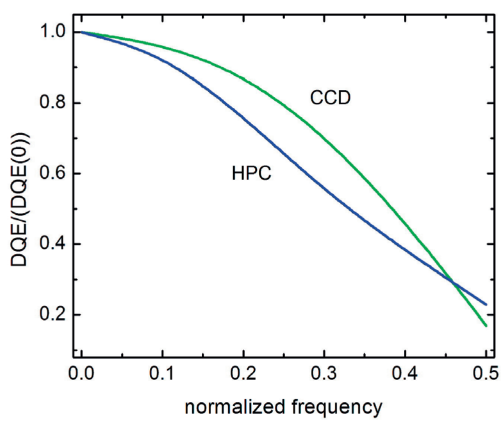

Figure 4. The measured DQE versus spatial frequency for a CCD and an HPC measured under identical conditions at ESRF [3]. The HPC has a significantly lower DQE (that is, it is considerably noisier than the CCD detector).

How can a photon-counting detector with no read noise and no dark current noise be noisier than an integrating detector (CCD) that suffers from both? This remarkable result was explained theoretically by Acciavatti and Maidment [4]. They computed the theoretical DQE of a pixel array detector operated in both integrating and photon-counting modes. They showed that for typical pixel arrays (typical in pixel size, electronic noise and charge sharing effect) the DQE of the array is always better in integrating mode than in photon-counting mode as shown in Figure 5. *That is, because of the charge sharing effect the noise of the photon-counting detector is higher than the same detector running in integrating mode.* Simply put, charge sharing causes more noise than the integrated electronic noise in the typical pixel array detector.

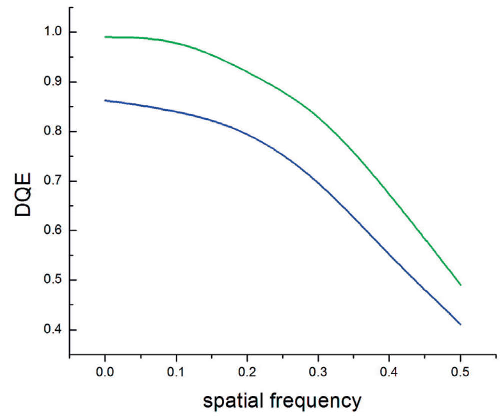

Figure 5. Calculated DQE versus spatial frequency for a hybrid pixel array operated in photon-counting mode (blue curve) and integrating mode (green curve). For normal incidence, charge sharing width 0.075 times pixel size. Charge sharing in photon-counting mode typically introduces more noise than the electronic noise in integrating mode [4].

Photon-counting without charge sharing noise.
Of course, detector designers are well aware of the deleterious effects of charge sharing noise and there has been significant effort in developing approaches to alleviate this problem.

There are two basic approaches to a photon-counting detector without charge sharing noise: a) arrays with charge summation and b) mixed-mode charge-integrating/photon-counting detectors.

In the first approach, when a hit is registered in a given pixel, the charge in the neighboring pixels which is time-coincident is added. This approach is implemented in the Medipix3RX where it is known as "Charge Summation Mode" (CSM) [5].

Figure 6 below shows the experimental response of a 3x3 block of pixels to a very small beam (7×8 μm²) in normal photon-counting mode and in CSM [6]. It can be seen that in normal photon-counting mode, there is a significant loss of signal at the pixel corners due to charge sharing. However, with CSM turned on, the losses in the corners are essentially eliminated.

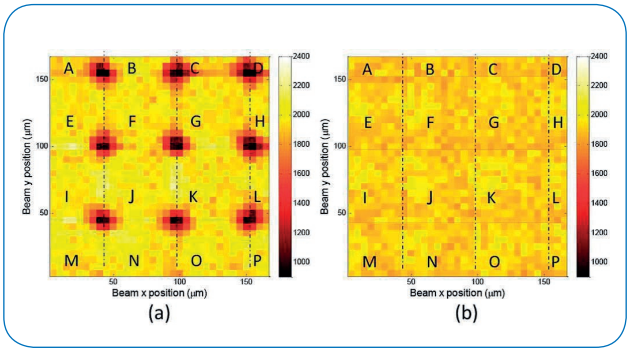

Figure 6. The response of a 3x3 block of pixels to a narrow pencil beam in normal photon-counting mode (5a) and in Charge Summation Mode (CSM) (5b). CSM eliminates the loss of X-rays at the pixel boundaries [5].

The CSM approach used in the Medipix3RX is extremely promising. However, it requires significantly more complex pixel circuitry than a standard pixel array and is not yet available in a commercial detector for crystallography.

The other approach to eliminating charge sharing noise is the so called "mixed-mode" operation. In mixed mode, the detector is operated in integrating mode, but at a high frame rate so that most pixels will have only one or a few X-ray hits. In this case, single photons can be counted in the integrated frames. Charge sharing noise is then eliminated in the same way as in Charge Summation Mode, that is, the charge in a 3×3 array of adjacent pixels can be summed before applying a threshold.

This combines the advantages of photon-counting (namely, the ability to integrate very weak signals and also to acquire very long exposures without adding dark current noise) with the advantages of an integrating detector (namely, no charge sharing noise and also no local count rate limit). This mixed-mode approach is implemented in the latest charge-integrating pixel array detectors for 4th generation beamlines, for example, the Jungfrau and Mönch detectors and the AGIPD detector [6].

PHOTON III: Mixed-mode in the home lab

The new PHOTON III detector is the first home laboratory detector that offers mixed-mode-photon-counting operation.

The PHOTON III offers all the benefits of photon-counting detectors including the ability to measure extremely weak signals without read noise and the ability to take extremely long exposures without dark current noise. However, because the PHOTON III uses an integrating mixed-mode approach, charge sharing noise is completely eliminated. In addition, because the PHOTON III can integrate stronger signals, there is no count rate saturation at high count rates.

The PHOTON III thus captures all of the advantages of photon counting without any of the drawbacks.

References

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