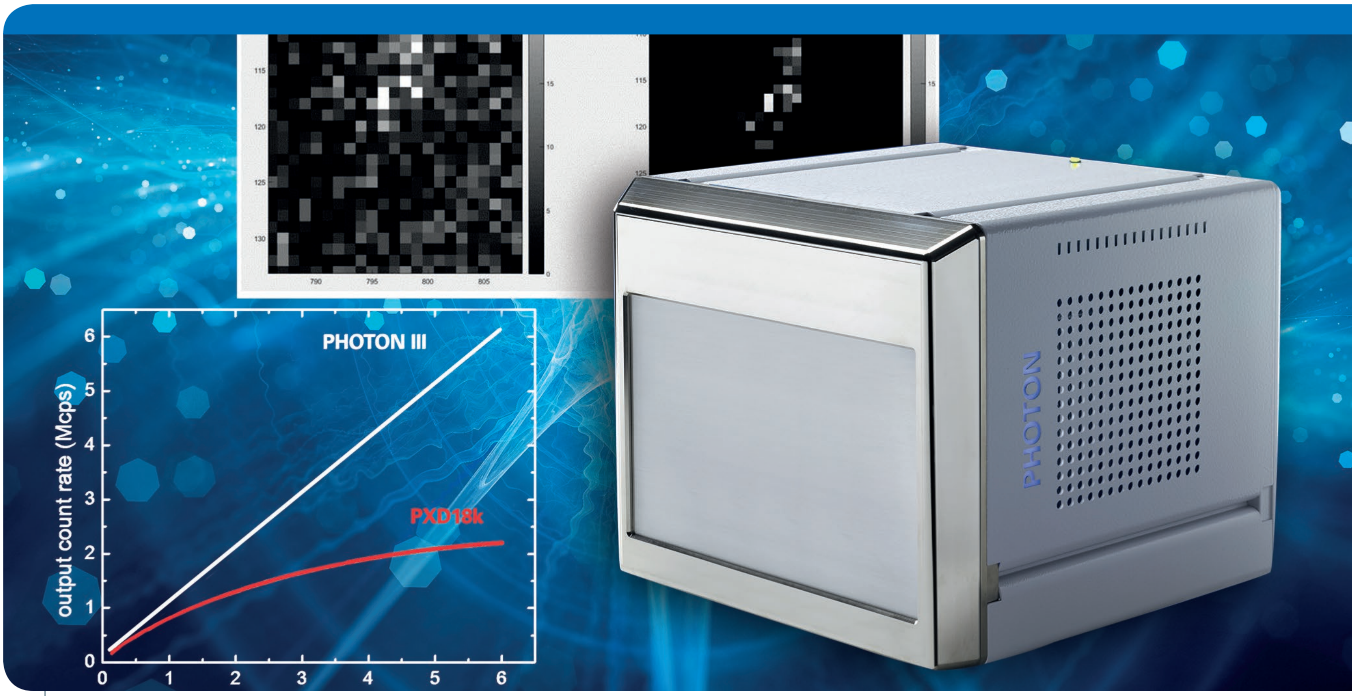

Technical Note SC-XRD 19

Good, Better, Best: Photon Counting, Integration and Mixed-mode Detection

Traditionally there are two basic detector readout schemes: integration and photon counting. Photon counting offers advantages especially for weak signals while integration offers advantages especially for stronger signals. However, more recently a new generation of detectors offers the capability to perform both integration and photon counting simultaneously. Such "mixed mode" detectors have all the advantages of photon-counting detectors for weak signals, but do not suffer from the count rate limitations and charge-sharing noise of conventional photon counters.

Photon-counting detectors

In photon-counting detectors, as the name implies, individual X-rays are counted. In the typical implementation, each X-ray is converted into a pulse of charge which is then compared to a threshold. Those pulses that exceed the threshold are counted while any signals below the threshold are discarded as noise.

The principle advantage of photon counting is that electronic noise that falls below the detection threshold is excluded from the measured signals.

This implies that photon-counting detectors can accurately measure very weak signals with high Detective Quantum Efficiency and they also can take very long exposures without the accumulation of dark current noise.

However, at higher count rates photon-counting detectors begin to saturate [1]. This is because it takes a finite time to collect and count the charge produced by an X-ray absorption event in the detector. This detection dead time is typically on the order of a microsecond during which the pixel is blind. Therefore, any X-ray hitting a given pixel within this dead time will be lost. The typical saturation curve of a photon-counting pixel array detector is shown in Figure 1 [2]. Significant nonlinearity occurs above 10^6 counts per pixel per second. It is possible to calibrate this effect and make corrections to the observed signals in software, however, such corrections are only approximate. In practice, because of this count rate saturation effect, photon counting is not useful for count rates above about 10^7 counts per pixel per second, even with sophisticated correction algorithms [3].

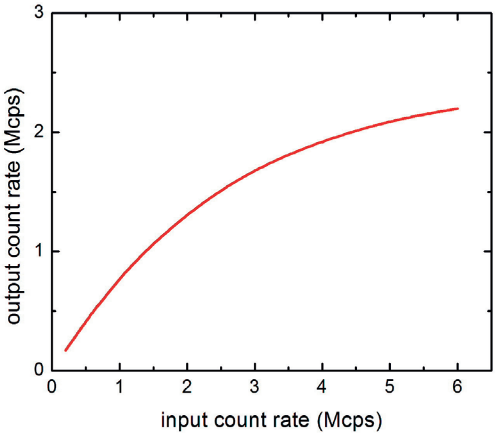

Figure 1. The measured output count rate of a typical photon-counting detector (PXD18k). There is significant nonlinearity starting at about 1 million counts per second (Mcps). At count rates above 4 Mcps more than half the incoming X-rays are lost [1].

Another serious limitation of conventional photon-counting detectors is charge-sharing noise. This occurs when an X-ray hits near the boundary of two or more pixels and the resulting charge is shared between multiple pixels [4]. When the resulting charge is compared to a fixed threshold, counts can be lost. This leads to a loss of signal accuracy, especially for strong reflections [5].

Integrating detectors

In an integrating pixel array detector, the signal from each pixel is stored for an integration period (a “frame time”) and then read out. All the charge in a given pixel is integrated. This means that even if more than one X-ray hits a given pixel within a microsecond, it is still counted. This type of detector thus does not suffer from count rate saturation and can deal with extremely high photon count rates [6].

Another advantage of integrating detectors is that they do not suffer from charge-sharing noise [7]. The charge from an X-ray that hits near the edge of a pixel will indeed be ‚shared‘ in an integrating detector, exactly as they are in a photon-counting detector. However, in the case of an integrating detector, this shared charge is not compared to a threshold and thus it is ***not lost,*** as it is in a photon-counting detector. That is, the charge-shared signal can be recaptured [7].

For both of these reasons, it has been shown that integrating detectors produce significantly superior data quality for stronger signals, that is, an integrating detector has a higher Detective Quantum Efficiency than an equivalent pixel array detector operating in photon-counting mode [8].

However, a conventional integrating detector integrates everything, not just the signal from X-rays but also electronic noise and dark current noise [9]. For this reason, conventional integrating detectors can suffer degraded Detective Quantum Efficiency for very weak signals, especially for very long integrations where significant dark current can accumulate.

So, in short, photon-counting detectors have an advantage for recording weak signals while integrating detectors are inherently better at recording strong signals.

Mixed-mode detection

As noted above, both photon-counting and integrating detectors have inherent advantages: photon-counting being optimal for weak signals and integrating being best for stronger signals. A new generation of pixel array detectors exploits a novel readout mode referred to as “mixed-mode” detection [10]. “Mixed-mode” here means that the detector is capable of both photon-counting and integration simultaneously. That is, photon-counting is performed for weak signals while for stronger signals integration is performed. This type of mixed-mode detector can thus achieve quantum-limited detection over a broad dynamic range [11].

A mixed-mode detector is essentially an integrating detector that is run at high frame rates. If both the frame rate and the single photon sensitivity are sufficiently high, then single photon events can be seen on the individual frames as shown in Figure 2. Single events that span two or more pixels can be identified and the signal on adjacent pixels summed together so that there is no information loss due to charge sharing. These single photon events can then be counted by applying a threshold, exactly like in a conventional photon-counting detector. However, this threshold is applied in software after the frame is read out. Application of this threshold rejects any background noise, exactly as in a conventional photon-counting detector.

Larger signals on the same frame are simply integrated without applying a threshold thus avoiding count rate saturation for stronger signals. Strong reflections are integrated as in a conventional integrating detector while weak signals are counted. This allows a mixed-mode detector to achieve the best of both worlds: the ultimate low-level sensitivity of a photon-counting detector together with the immunity to charge sharing-noise and nonlinearities due to count rate saturation.

Today, pixel array detectors for next-generation X-ray sources, such as X-ray free electron lasers and diffraction-limited synchrotron beamlines, now support this mixed-mode readout, including the Jungfrau and Mönch detectors developed at the Paul Scherrer Institute [12], the AGIPD developed at DESY [13] and the ePIX developed at the LCLS [14].

PHOTON III: Mixed-mode detection for the home laboratory

The PHOTON III pixel array detector is the first X-ray detector available in the home laboratory that employs mixed-mode detection. The PHOTON III is the only available home laboratory detector that is able to achieve Poisson-limited performance over its entire dynamic range. This means that the weakest signals are recorded with near-perfect fidelity while strong signals are highly linear with no count rate saturation and no charge-sharing noise.

Figure 2 shows an example where mixed photon counting-integration mode is applied to a very weak, high angle reflection of only 30 X-rays. In pure integrating mode significant background noise is seen due to the accumulation of dark current. However, in mixed mode this background noise is completely rejected.

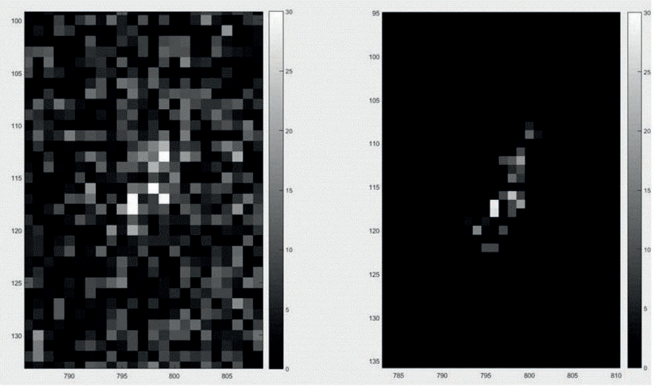

Figure 2. A very weak, high resolution Bragg reflection (30 X-rays) in integrating mode (left) and with photon-counting mode (right). In integrating mode there is significant noise due to dark current integration during the very long (5 minutes) exposure while in mixed photon-counting mode this background is rejected. The reflection is radially elongated due to $K\alpha_1$-$K\alpha_2$ splitting.

Figure 3 shows the linearity of the mixed-mode PHOTON III compared to a typical photon-counting X-ray detector [1]. It can be seen that at high count rates, where conventional photon counting detectors begin to saturate, the PHOTON III remains highly linear.

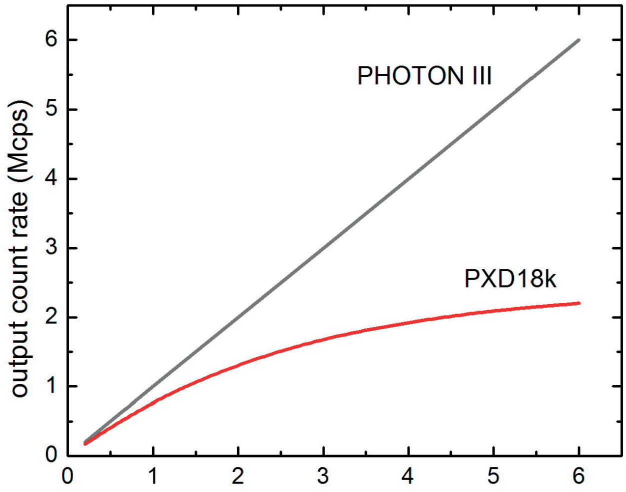

Figure 3. Comparison of linearity of a mixed-mode detector (PHOTON III) and the same photon-counting detector shown above in Figure 1 (PXD18k). Note that the measured count rate linearity of the PHOTON III is nearly perfect up to count rate of 6 Mcps and beyond.

Summary

Mixed-mode detectors offer the best of both photon counting and integration: the near-perfect detection of weak signals via photon counting and also near-perfect detection of strong signals without nonlinearities due to count rate saturation, and without charge-sharing losses. For this reason next-generation pixel array detectors such as the Jungfrau and AGIPD exploit this mixed-mode modality.

The PHOTON III is the first detector offered in the home laboratory with advanced mixed-mode detection. The PHOTON III is thus unique in offering Poisson-limited data quality over its entire dynamic range.

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