Rigaku

PILATUS 200K

Towards the ideal detector

Rigaku

Towards the ideal detector

Introduction

An ideal detector should detect every X-ray photon that impinges on it and tell you when and where the photon landed. Throughout the history of macromolecular crystallography, a number of different detector types have been used. Common recent detector types for home laboratories and synchrotron facilities include Imaging Plates (IP); Charge Coupled Device (CCD) detectors; phosphor-based, analog Complementary Metal-Oxide Semiconductor (CMOS) detectors; and Hybrid Pixel Array Detectors (HPAD). Some of these more closely approach the conditions for an ideal detector than others. The following document describes some modern detectors used for macromolecular crystallography and the benefits or disadvantages of each. We will provide an example of data collection with an HPAD detector to show that they provide high quality data for even the most challenging samples, and demonstrate how they differ from CMOS detectors, even though they make use of the same technology.

Detect every photon

The most accurate way to measure X-ray diffraction data is to directly detect X-ray photons. Hybrid Pixel Array Detectors (HPADs) are the only commercially available area detectors for X-ray crystallography that perform direct detection of X-ray photons. Examples of HPADs are PILATUS detectors manufactured by DECTRIS® and Dual Mode HPADs, recently introduced by Area Detector Systems Corp (ADSC). Most detectors, however, use indirect methods to detect X-rays, usually by converting X-ray photons to visible light. For example, IP detectors record X-rays in a film-like radiation-sensitive matrix of specifically designed phosphors. Energy from X-ray photons impinging on an IP is stored until scanned with a laser beam during the read operation. The laser directed at the IP converts the stored energy to "light" via "photostimulated luminescence" (PSL), which is then measured and subsequently converted to a digital signal. By comparison, CCD detectors contain a phosphor that emits visible light when exposed to X-rays. The light is transmitted via a fiber optic taper to the CCD chip, where it is converted to an analog signal for readout and digitization.

Similarly, some CMOS detectors make use of a phosphor to convert X-rays to light, using a much shorter fiber optic "stub" to transmit visible light to the CMOS device. The analog signal is read out and digitized. Though CCDs and CMOS detectors are both capable of collecting high quality X-ray diffraction data, these types of detectors are "lossy", in that there is both signal loss and the addition of noise during the conversion of X-rays to light, the conversion of light to electrons, storing and reading the sensor, and digitization.

The architecture of the HPAD is significantly different from these other detector types. In particular, PILATUS HPADs consist of an array of silicon sensor pixels that directly detect X-ray photons. When an X-ray photon impinges on the sensor, which is a 2D array of p-n diodes processed in high resistivity silicon, an electrical charge is produced. This charge is transferred from each individual sensor pixel to a readout channel by way of a single micro-bump bond. Because each pixel is individually bump bonded to its readout channel through an 18 µm indium bump, the point spread function of the detector is 1 pixel. The readout pixel for the HPAD detector is manufactured using CMOS production technology and is comprised of an amplifier, a discriminator and a digital counter. The amplifier boosts the signal generated in the sensor, while the discriminator generates a digital pulse for those incoming charges that are above a minimum energy value. The digital counter then counts the number of digital pulses that reach the appropriate energy threshold. Thus, the readout pixel for the PILATUS detector discriminates to measure only those photons of the desired energy and not those that might arise from fluorescence.

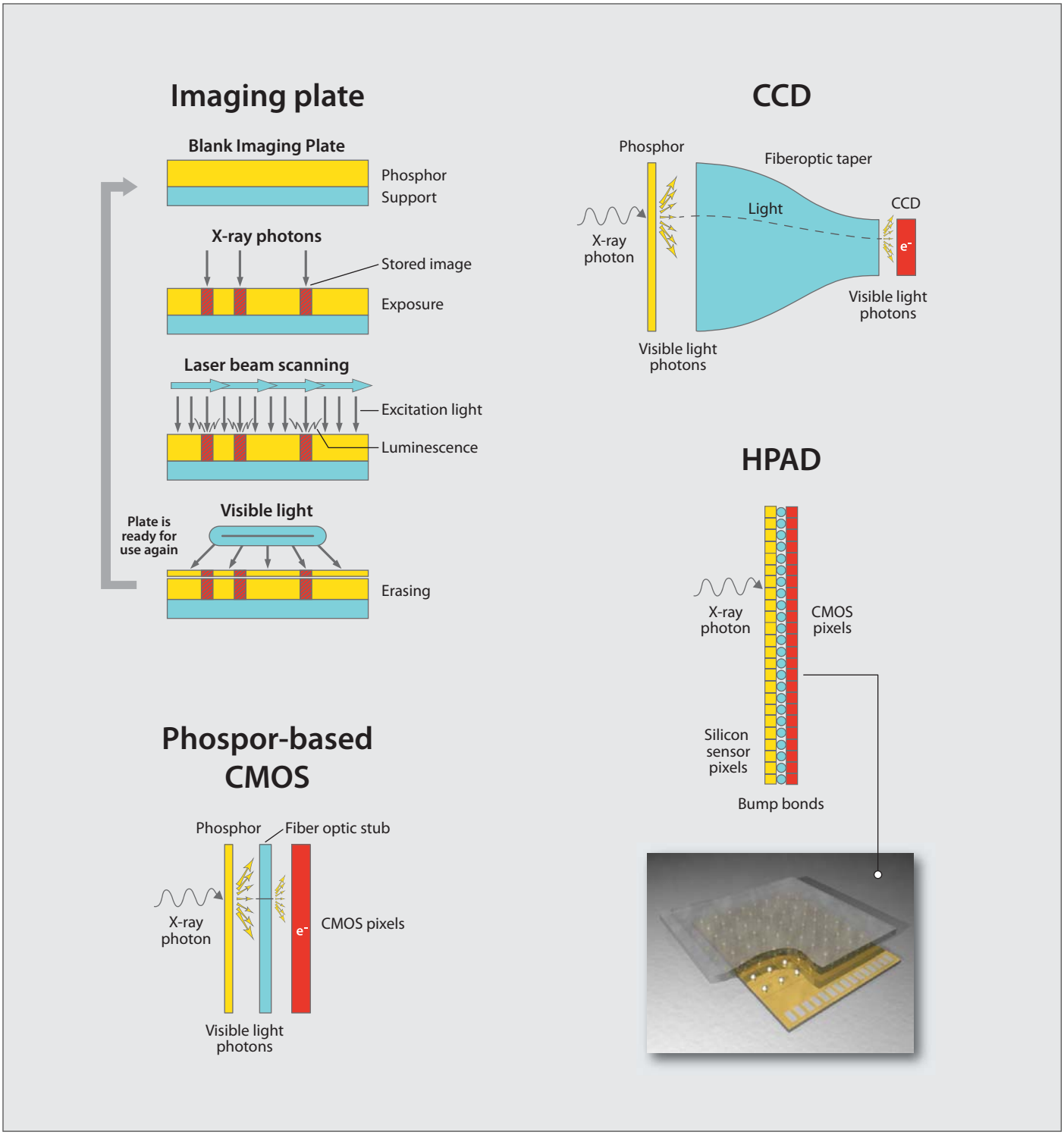

Figure 1. Comparing IPs, CCDs, phosphor-based CMOS detectors and HPADs

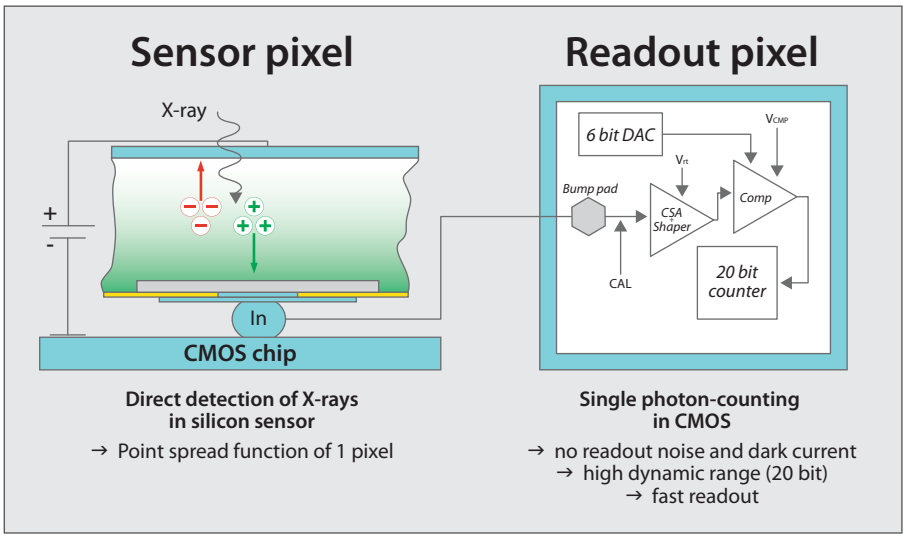

Figure 2. The architecture of the PILATUS detector

HPADs are currently the class of detector that comes closest to achieving the desired characteristics of an ideal detector. Moreover, HPADs such as the PILATUS detectors feature a number of advantages compared to IPs, CCDs and CMOS detectors. Some of these features, outlined in Table 1, include an excellent point spread function of a single pixel and direct detection of X-ray photons. As photon counting detectors, HPADs do not suffer from dark current accumulation as integrating (CCD and phosphor-based CMOS) detectors do.

The consequence of dark current and read noise

The impact of dark current accumulation and read noise is most readily understood by looking at a plot of data collection efficiency (DCE) versus reflection intensity. In the following plot you will see that weak measurements for both CCD and CMOS detectors are degraded due to the inherent error introduced from dark current and read noise. In X-ray crystallography, the ability to accurately measure weak data improves the ability to measure to a higher resolution limit. Since the higher resolution shells are dominated by weak reflections and PILATUS HPAD detectors have improved the ability to accurately measure all reflections, users can expect improvements for both phasing and refinement.

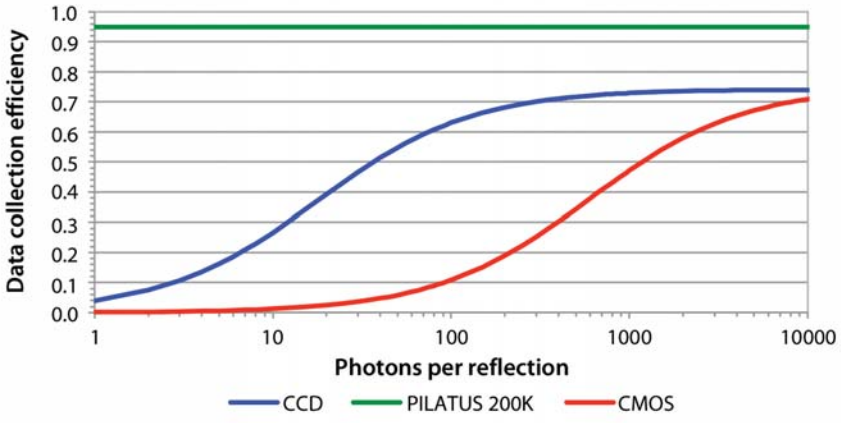

Figure 3. Data collection efficiency of CCD, PILATUS and phosphor-based CMOS detectors for copper radiation

Shutterless data collection with PILATUS detectors

Traditional data collection in the home lab takes place as a series of discrete steps in which the crystal is rotated over a small angular range while being exposed to X-rays. Data images are collected by a sequence that first opens the shutter and starts goniometer movement. The crystal is exposed for a set angular range and time interval. Then the X-ray shutter closes, goniometer rotation stops and the image is read out. This readout time varies depending on the detector technology and model. For CCDs and CMOS detectors, the read time is on the order of a few seconds while for IP detectors the readout time ranges from 30 seconds to minutes. Following readout, the goniometer moves to the start position for the next image and data collection resumes.

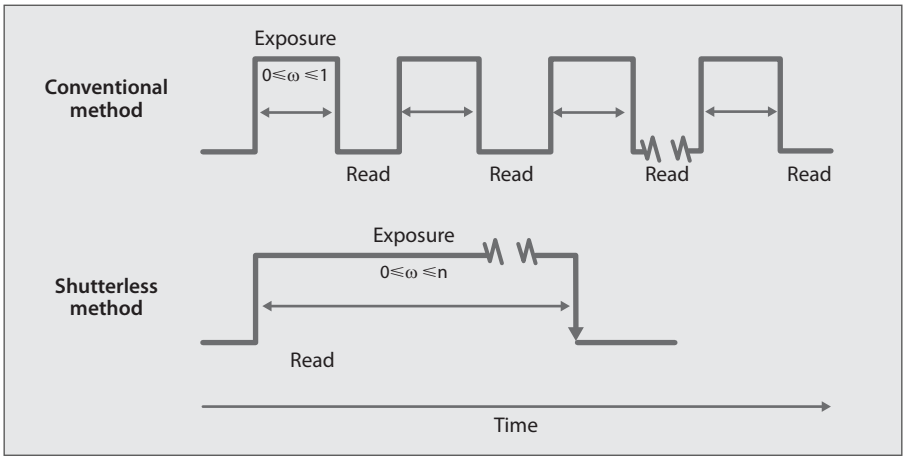

Figure 4. Comparison of conventional versus shutterless data collection versus time

In contrast, the nearly instantaneous readout time of the PILATUS detectors means that the readout step can be eliminated altogether, making shutterless data collection possible. During shutterless data collection, the shutter opens once and the goniometer starts rotating at the start of data collections. During collection the PILATUS detector outputs images throughout data collection until the goniometer reaches the end angle for the full scan of data. Thus, shutterless data collection can save valuable instrument time by allowing fast data collection and can provide better data quality because of reduced error due to goniometer stops/starts and shutter opening/closing.

Table 1. Comparison of detector characteristics

	Imaging plate detector	CCD detector	Phosphor-based CMOS detector	Pixel array detector
Direct detection of X-rays	NO	NO	NO	YES
Free from dark current errors	YES	NO	NO	YES
Point spread function = 1 pixel	NO	NO	NO	YES
Fluorescence suppression	NO	NO	NO	YES
Dynamic range > 1,000,000	YES	NO	NO	YES
Readout < 10 ms	NO	NO	NO	YES
Radiation tolerant	YES	YES	YES	YES
Shutterless data collection	NO	NO	MAYBE	YES

PILATUS detector for challenging samples

No matter how long the list of features purported by a detector manufacturer, the true test of any detector is the ability to accurately measure high quality data. There are many examples in the literature of high quality diffraction data and structures resulting from data collected on PILATUS detectors. Additionally, we routinely collect data for samples in the Rigaku applications lab that is readily solvable using S-SAD phasing methods with as little as 4-fold redundancy. The example below describes the versatility of PILATUS detector on very challenging samples. Specifically, data were collected using an exposure time of 60 seconds/ 0.1° for mouse angiotensinogen on a Rigaku FR-X rotating anode generator configured with a VariMax HF Arc)Sec confocal optic, AFC-Kappa goniometer and PILATUS 300K detector. This sample is challenging due to the presence of a long unit cell axis ($P6_122$, a=b=65, c=462 Å). The long axis was easily resolved for this sample at a crystal-to-detector distance of 260 mm, as shown below. Scaling statistics for these data are provided in Table 2.

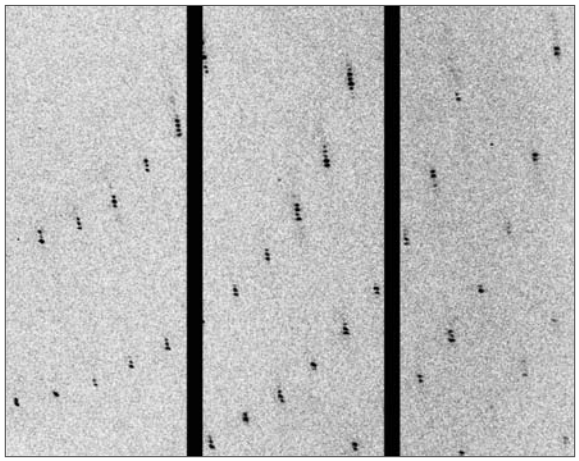

Figure 5. Diffraction pattern for mouse angiotensinogen, showing spot separation along the longest unit cell axis at a crystal-to-detector distance of 260 mm

Table 2. Crystal parameters and scaling statistics for mouse angiotensinogen

Space Group	$P6_122$
Unit cell lengths (Å) angles (°)	65.06, 65.06, 461.90 90, 90, 120
Resolution (Å) (last shell)	50.00 – 3.00 (3.05 – 3.00)
Mosaicity range (°)	0.24 – 0.40
Total # reflections	91688
Unique # reflections	12830
Rejected # reflections /%	92 / 0.10
Completeness (%) (last shell)	87.9 (82.6)
Redundancy (last shell)	8.1 (4.6)
$<I>/<\sigma(I)>$ (last shell)	34.0 (7.1)
R_{merge} (%) (last shell)	4.5 (14.7)
χ^2 (last shell)	0.9 (0.7)

PILATUS detectors for the home lab

The literature contains many examples of high quality data sets and macromolecular structures collected from HPADs such as the PILATUS detectors. PILATUS detectors have revolutionized crystallographic data collection at synchrotrons and are poised to do the same for home labs. Rigaku is proud to offer the PILATUS 200K detector as the standard detector for all of its home laboratory systems, as a replacement for the venerable Saturn 944 HG CCD detectors. Moreover, Rigaku offers larger format PILATUS detectors, such as the P300K and P1M for home lab systems. The benefits provided by this HPAD detector, summarized in Table 3, include faster and more accurate data collection for your samples compared to IPs, CCDs and phosphor-based CMOS detectors.

Table 3. PILATUS benefits

Feature	Benefits to User
Direct detection of X-rays	Photon counting so better signal-to-noise for X-ray diffraction data
Point spread function = 1 pixel (Top Hat)	Better spatial resolution for reflections
No read noise	Better signal-to-noise for both strong and weak reflections
No dark current	Long exposures are possible with little increase in noise
Threshold discrimination	Reduction of noise from inelastic scattering i.e. fluorescence
Dynamic range > 1,000,000	No overloaded reflections or need for rescans means faster, more accurate measurement of reflections
Readout < 8 ms	Shutterless data collection is a reality and data quality is improved because of elimination of start/stops of the goniometer and opening/closing of the shutter
Radiation tolerant	Durable design with reliable performance
Air cooling	Less maintenance compared to other detector systems

Figure 6. Compact HomeLab™ including PILATUS 200K HPAD

Our Passion

The determination of the first protein structure (myoglobin) in 1957 served as a watershed event for structural biology. From that point forward, X-ray crystallography has been among the most powerful techniques used to understand biological systems at a molecular level. Crystallographic methods continue to lead advances in medical science and provide detailed insight to scientists involved in disease control and prevention, with structural information driving creation and optimization of target molecules to treat complex diseases. Additionally, crystallographic structures improve our understanding of biological and metabolic pathways for many species. Rigaku is the leading developer of a wide range of instrumentation encompassing all aspects of macromolecular crystallography. The Life Sciences group of Rigaku is proud to play an integral part in developing and providing the tools that help advance the science of structural biology.

www.Rigaku.com

Rigaku Corporation and its Global Subsidiaries
website: www.Rigaku.com | email: info@Rigaku.com

PILATUS 200K

Towards the ideal detector

DET_WP_PILATUS 06_2013