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1999; Durst *et al.*, 2002; Blanton, 2003; Khazins *et al.*, 2004). X-ray photographic plates and films were the first generation of two-dimensional X-ray detectors. Now, multiwire proportional counters (MWPCs), image plates (IPs), charge-coupled devices (CCDs) and microgap detectors are the most commonly used large area detectors. Recent developments in area detectors include X-ray pixel array detectors (PADs), silicon drift diodes (SDDs) and complementary metal-oxide semiconductor (CMOS) detectors (Ercan *et al.*, 2006; Lutz, 2006; Yagi & Inoue, 2007; He *et al.*, 2011). Each detector type has its advantages over the other types. In order to make the right choice of area detector for a 2D-XRD system and applications, it is necessary to characterize area detectors with consistent and comparable parameters. Chapter 2.1 has more comprehensive coverage on X-ray detectors, including area detectors. This section will cover the characteristics specifically relevant to area detectors.

2.5.3.2.1. *Active area and pixel size*

A 2D detector has a limited detection surface and the detection surface can be spherical, cylindrical or flat. The detection-surface shape is also determined by the detector technology. For example, a CCD detector is made from a large semiconductor wafer, so that only a flat CCD is available, while an image plate is flexible so that it is easily bent to a cylindrical shape. The area of the detection surface, also referred to as the active area, is one of the most important parameters of a 2D detector. The larger the active area of a detector, the larger the solid angle that can be covered at the same sample-to-detector distance. This is especially important when the instrumentation or sample size forbid a short sample-to-detector distance. The active area is also limited by the detector technology. For instance, the active area of a CCD detector is limited by the semiconductor wafer size and fabrication facility. A large active area can be achieved by using a large demagnification optical lens or fibre-optical lens. Stacking several CCD chips side-by-side to build a so-called mosaic CCD detector is another way to achieve a large active area.

In addition to the active area, the overall weight and dimensions are also very important factors in the performance of a 2D detector. The weight of the detector has to be supported by the goniometer, so a heavy detector means high demands on the size and power of the goniometer. In a vertical configuration, a heavy detector also requires a heavy counterweight to balance the driving gear. The overall dimensions of a 2D detector include the height, width and depth. These dimensions determine the manoeuvrability of the detector within a diffractometer, especially when a diffractometer is loaded with many accessories, such as a video microscope and sample-loading mechanism. Another important parameter of a 2D detector that tends to be ignored by most users is the blank margin surrounding the active area of the detector. Fig. 2.5.10 shows the relationship between the maximum measurable 2θ angle and the detector blank margin. For high 2θ angle measurements, the detector swing angle is set so that the incident X-ray optics are set as closely as possible to the detector. The unmeasurable blank angle is the sum of the detector margin m and the dimension from the incident X-ray beam to the outer surface of the optic device h. The maximum measurable angle is given by

$$2\theta_{\max} = \pi - \frac{m+h}{D}. \qquad (2.5.16)$$

It can be seen that either reducing the detector blank margin or optics blank margin can increase the maximum measurable angle.

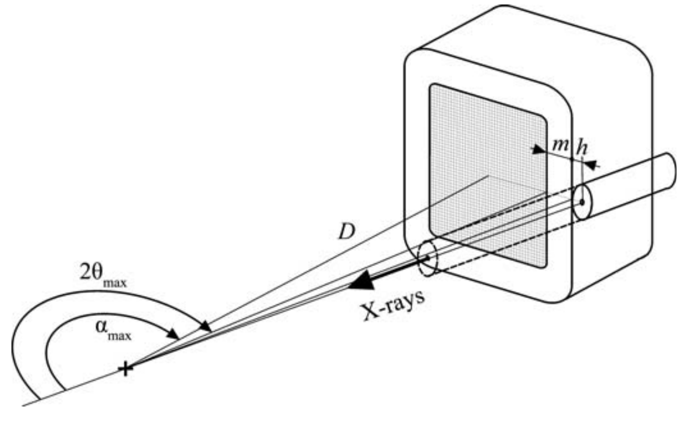

Figure 2.5.10
Detector dimensions and maximum measurable 2θ.

The solid angle covered by a pixel in a flat detector is dependent on the sample-to-detector distance and the location of the pixel in the detector. Fig. 2.5.11 illustrates the relationship between the solid angle covered by a pixel and its location in a flat area detector. The symbol S may represent a sample or a calibration source at the instrument centre. The distance between the sample S and the detector is D. The distance between any arbitrary pixel $P(x, y)$ and the detector centre pixel $P(0, 0)$ is r. The pixel size is Δx and Δy (assuming $\Delta x = \Delta y$). The distance between the sample S and the pixel is R. The angular ranges covered by this pixel are $\Delta\alpha$ and $\Delta\beta$ in the x and y directions, respectively. The solid angle covered by this pixel, $\Delta\Omega$, is then given as

$$\Delta\Omega = \Delta\alpha\Delta\beta = \frac{D}{R^3}\Delta y\Delta x = \frac{D}{R^3}\Delta A, \qquad (2.5.17)$$

where $\Delta A = \Delta x\Delta y$ is the area of the pixel and R is given by

$$R = (D^2 + x^2 + y^2)^{1/2} = (D^2 + r^2)^{1/2}. \qquad (2.5.18)$$

When a homogeneous calibration source is used, the flux to a pixel at $P(x, y)$ is given as

$$F(x, y) = \Delta\Omega B = \frac{\Delta ADB}{R^3} = \frac{\Delta ADB}{(D^2 + x^2 + y^2)^{3/2}}, \qquad (2.5.19)$$

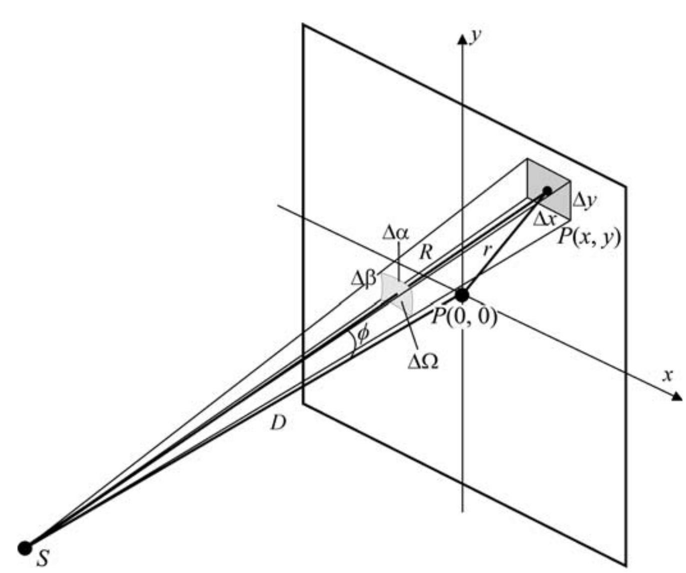

Figure 2.5.11
Solid angle covered by each pixel and its location on the detector.

where $F(x, y)$ is the flux (in photons s^{-1}) intercepted by the pixel and B is the brightness of the source (in photons s^{-1} $mrad^{-2}$) or scattering from the sample. The ratio of the flux in pixel $P(x, y)$ to that in the centre pixel $P(0, 0)$ is then given as

$$\frac{F(x,y)}{F(0,0)} = \frac{D^3}{R^3} = \frac{D^3}{(D^2+x^2+y^2)^{3/2}} = \cos^3\phi, \qquad (2.5.20)$$

where ϕ is the angle between the X-rays to the pixel $P(x, y)$ and the line from S to the detector in perpendicular direction. It can be seen that the greater the sample-to-detector distance, the smaller the difference between the centre pixel and the edge pixel in terms of the flux from the homogeneous source. This is the main reason why a data frame collected at a short sample-to-detector distance has a higher contrast between the edge and centre than one collected at a long sample-to-detector distance.

2.5.3.2.2. *Spatial resolution of area detectors*

In a 2D diffraction frame, each pixel contains the X-ray intensity collected by the detector corresponding to the pixel element. The pixel size of a 2D detector can be determined by or related to the actual feature sizes of the detector structure, or artificially determined by the readout electronics or data-acquisition software. Many detector techniques allow multiple settings for variable pixel size, for instance a frame of 2048 × 2048 pixels or 512 × 512 pixels. Then the pixel size in 512 mode is 16 (4 × 4) times that of a pixel in 2048 mode. The pixel size of a 2D detector determines the space between two adjacent pixels and also the minimum angular steps in the diffraction data, therefore the pixel size is also referred to as pixel resolution.

The pixel size does not necessarily represent the true spatial resolution or the angular resolution of the detector. The resolving power of a 2D detector is also limited by its point-spread function (PSF) (Bourgeois *et al.*, 1994). The PSF is the two-dimensional response of a 2D detector to a parallel point beam smaller than one pixel. When the sharp parallel point beam strikes the detector, not only does the pixel directly hit by the beam record counts, but the surrounding pixels may also record some counts. The phenomenon is observed as if the point beam has spread over a certain region adjacent to the pixel. In other words, the PSF gives a mapping of the probability density that an X-ray photon is recorded by a pixel in the vicinity of the point where the X-ray beam hits the detector. Therefore, the PSF is also referred to as the spatial redistribution function. Fig. 2.5.12(*a*) shows the PSF produced from a parallel point beam. A plane at half the maximum intensity defines a cross-sectional region within the PSF. The FWHM can be measured at any direction crossing the centroid of the cross section. Generally, the PSF is isotropic, so the FWHMs measured in any direction should be the same.

Measuring the PSF directly by using a small parallel point beam is difficult because the small PSF spot covers a few pixels and it is hard to establish the distribution profile. Instead, the line-spread function (LSF) can be measured with a sharp line beam from a narrow slit (Ponchut, 2006). Fig. 2.5.12(*b*) is the intensity profile of the image from a sharp line beam. The LSF can be obtained by integrating the image from the line beam along the direction of the line. The FWHM of the integrated profile can be used to describe the LSF. Theoretically, LSF and PSF profiles are not equivalent, but in practice they are not distinguished and may be referenced by the detector specification interchangeably. For accurate LSF measurement, the line beam is intentionally positioned with a tilt angle from the orthogonal direction of the pixel array so that the LSF can have smaller steps in the integrated profile (Fujita *et al.*, 1992).

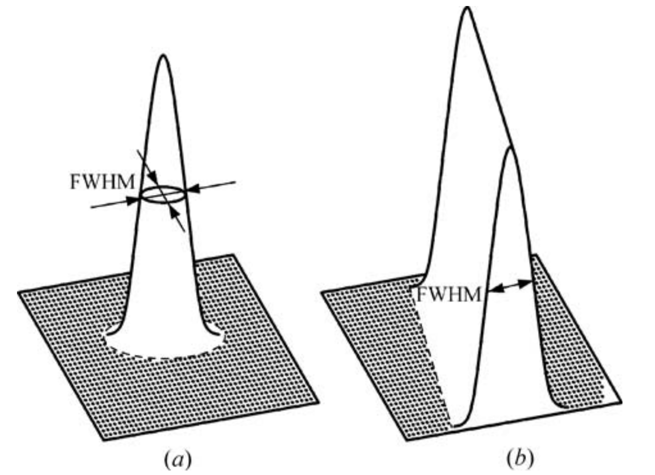

Figure 2.5.12
(*a*) Point-spread function (PSF) from a parallel point beam; (*b*) line-spread function (LSF) from a sharp line beam.

The RMS (root-mean-square) of the distribution of counts is another parameter often used to describe the PSF. The normal distribution, also called the Gaussian distribution, is the most common shape of a PSF. The RMS of a Gaussian distribution is its standard deviation, σ. Therefore, the FWHM and RMS have the following relation, assuming that the PSF has a Gaussian distribution:

$$\text{FWHM} = 2[-2\ln(1/2)]^{1/2}\text{RMS} = 2.3548 \times \text{RMS}. \qquad (2.5.21)$$

The values of the FWHM and RMS are significantly different, so it is important to be precise about which parameter is used when the value is given for a PSF.

For most area detectors, the pixel size is smaller than the FWHM of the PSF. The pixel size should be small enough that at least a 50% drop in counts from the centre of the PSF can be observed by the pixel adjacent to the centre pixel. In practice, an FWHM of 3 to 6 times the pixel size is a reasonable choice if use of a smaller pixel does not have other detrimental effects. A further reduction in pixel size does not necessarily improve the resolution. Some 2D detectors, such as pixel-array detectors, can achieve a single-pixel PSF. In this case, the spatial resolution is determined by the pixel size.

2.5.3.2.3. *Detective quantum efficiency and energy range*

The detective quantum efficiency (DQE), also referred to as the detector quantum efficiency or quantum counting efficiency, is measured by the percentage of incident photons that are converted by the detector into electrons that constitute a measurable signal. For an ideal detector, in which every X-ray photon is converted to a detectable signal without additional noise added, the DQE is 100%. The DQE of a real detector is less than 100% because not every incident X-ray photon is detected, and because there is always some detector noise. The DQE is a parameter defined as the square of the ratio of the output and input signal-to-noise ratios (SNRs) (Stanton *et al.*, 1992):

$$\text{DQE} = \left(\frac{(S/N)_{\text{out}}}{(S/N)_{\text{in}}}\right)^2. \qquad (2.5.22)$$

The DQE of a detector is affected by many variables, for example the X-ray photon energy and the counting rate. The dependence of the DQE on the X-ray photon energy defines the