The Point-Spread Function of X-ray Image-Intensifiers/CCD-Camera and Imaging-Plate Systems in Crystallography: Assessment and Consequences for the Dynamic Range

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Abstract
The point-spread functions (PSFs) of two X-ray CCD detectors and two imaging-plate (IP) scanners were compared using the monochromatic beam of the Materials Science beamline of the ESRF. The CCD detectors were a commercial medical type X-ray image intensifier (XRII) for energies above 20 keV and a tube with a beryllium window especially designed for the 5–50 keV range, optically coupled to a high-resolution cooled charge-coupled-device (CCD) camera. The IP scanners were the Fuji BAS2000 and the Molecular Dynamics PhosphorImager 400E, with plates from Fuji and Kodak. The PSFs were recorded using a 30 x 30 μm pinhole at energies from 8 to 41 keV under normal and highly saturated conditions. Special care was taken in the study of PSF wings. Dynamic-range capabilities in the presence of PSF bleeding were also measured using a standard X-ray generator. The Fuji and MD IP scanners give very similar PSFs when used with Fuji plates [circa 130 μm full width at half-maximum (FWHM), 1100 μm at 0.1% of peak maximum]. The Kodak plates showed a broader PSF than the Fuji plates, one which also increases with X-ray energy. The standard XRII/CCD gave the coarsest PSF [circa 4000 μm at 0.1% of peak maximum], whereas the finest PSF was recorded with the beryllium XRII/CCD used in magnified mode (900 μm at 0.1%). The best dynamic range was obtained with the XRII/CCDs; the lowest with the Fuji scanner.

Introduction
The new generation of synchrotron-radiation sources like the ESRF offer a spectacular increase in brilliance. High-quality X-ray diffraction patterns of tiny crystals may now be obtained in a very short time, even with large unit cells yielding thousands of Bragg reflections. Detectors must obviously match these new conditions, requiring both a high spatial resolution and a large dynamic range.

Imaging-plate (IP) scanners have been extensively used at synchrotron facilities (Amemiya, 1990; Amemiya et al., 1988; Bilderback et al., 1988) and have proved to be far superior to film in terms of dynamic range, sensitivity and detector quantum efficiency (Hillen, Schiebel & Zaengel, 1987). However, they are limited by a readout time in the 100 s range, resulting in an unfavourable duty cycle, especially when short exposure times are used with on-line scanners.

X-ray imaging systems based on CCD cameras and image intensifiers (II/CCDs) (Naday, Strauss, Sherman, Kramer & Westbrook, 1987) have been developed to overcome this shortcoming and to provide real-time imaging (Arndt & In'T Veld, 1988). However, this has been achieved at the expense of limited field of view, spatial distortion and low dynamic range in the case of sub-second readout times. X-ray image intensifiers (XRIIs) have been used for medical and industrial applications above 30 keV for more than 20 years (Driard, Guyot & Verat, 1971). They consist of a large vacuum vessel with a thin metallic window transparent to X-rays. A scintillating layer covered with a photocathode converts the X-ray image into electrons. Electrodes focus the electron image onto a high-resolution-output phosphor screen. Electronic zooming capability is often implemented. The ESRF detector group decided to adapt XRIIs to synchrotron-radiation applications.

In this paper, we assess and compare the spatial resolution of IP scanners and XRII/CCDs by measuring the point-spread function (PSF) as a function of X-ray energy, position on detector and incidence angle. The PSF is the two-dimensional response to a point excitation (in practice, a beam smaller than one pixel). The PSF is the best figure of merit for the spatial resolution of a detector to be used in X-ray diffraction, since diffraction patterns essentially consist of closely spaced Bragg spots on a weak background, with intensities frequently spanning four or more decades. In order to be able to separate and integrate neighbouring spots, it is essential, when selecting an imaging system, to judge it not only by the FWHM, which is usually given for area detectors, but also by the width at 1% (FW@1%) or even the width at 0.1% (FW@0.1%) of the PSF maximum. The PSF in highly saturated
conditions is also of interest since saturated spots frequently occur in diffraction patterns and because fine details of detector technology can be assessed under these conditions.

For these reasons, we have measured and compared the shapes of PSFs down to the noise level for various configurations. The modulation transfer function (MTF), being the Fourier transform of the PSF, potentially carries the same information. However, the inevitable experimental error on the MTF at very low frequencies would result in a very large uncertainty in the wings of the PSF, which are critical for our application. The MTF, although being widely used as a figure of merit of imaging systems, is therefore not adequate in the case of X-ray diffraction.

Measurements and theoretical assessments of the PSFs of X-ray area detectors have been reported by other groups (Amemiya et al., 1988; Templer, Warrender, Sedddon, Davis & Harrison, 1991; Né, Gazeau, Lamard, Lesieur & Zemb, 1993; Whiting, Owen & Rubin, 1988; Lubinski, Owen & Korn, 1986) but they were limited to a single photon energy, or suffered from the poorly defined energy bandwidth of X-ray generators. However, energy-resolved sensitivity measurements have been achieved on IP detectors (Ito & Amemiya, 1991). There are several reasons to believe that the spatial performance of both types of detector varies with X-ray energy. In the case of IP scanners, four main parameters act on the observed width of the PSF: (i) phosphor thickness and grain compactness; (ii) scattering and penetration depth of the laser light; (iii) scattering of photo-stimulated luminescence (PSL) light; (iv) acceptance of the light-collecting system. All these parameters act differently upon variations of X-ray energy, the main variable being the mean photon-penetration depth. For XRIIs, the area of electron emission by the photocathode lying on top of the CsI:Na crystal scintillator results from both the X-ray penetration depth inside the scintillator and the solid angle covered by scattered visible photons. Both factors may be competing and the global effect on the PSF is not clearly predictable.

We have used the very high brilliance of the ESRF to test two off-line imaging plate scanners with two different types of BaFBr:Eu²⁺ plates, as well as two XRII/CCDs. The PSF was measured both under normal (nonsaturated) and highly saturated conditions, for different positions on the detector surface and for different incidence angles. The dynamic range was also measured for all four detectors using a standard X-ray tube with a demanding 'diffraction-like' set-up where tiny peaks are located in the proximity of a 1000 times more intense peak. The consequences of large PSF wings in terms of achievable dynamic range could be assessed in this way.

**PSF requirements for area detectors**

The necessary PSF characteristics for single-crystal diffraction experiments can be analysed in terms of wavelength, unit-cell parameters and sample-to-detector distance. Since one has to obtain accurate integrated intensities for all reflection spots, the following one-dimensional diffraction pattern was simulated to study peak overlap as a function of the detector PSF. Six weak Gaussian diffraction peaks were placed at various distances away from a main peak of intensity three orders of magnitude higher. A Lorentzian PSF was simulated and convoluted with the Gaussian diffraction peaks to yield the pattern of Fig. 1. It is seen that a distance between the main peak and a satellite peak corresponding approximately to the FW@0.1% of the PSF is required to clearly resolve the two peaks.

Numerical calculations can be made to clarify the consequences for the detector PSF. For a monochromatic diffraction experiment out to a resolution limit \( \lambda_s \) at a wavelength \( \lambda \), it can be shown by simple geometrical analysis of the Ewald sphere that the maximum diffraction angle \( 2\theta_{\text{max}} \) and the minimum distance between diffraction maxima \( \Delta S \) are approximately

\[
2\theta_{\text{max}} = 2 \arcsin \left( \frac{\lambda}{2\lambda_s} \right) \quad (1)
\]

\[
\Delta S = L \lambda/a, \quad (2)
\]

where \( L = D/2 \tan (2\theta_{\text{max}}) \). \( D \) and \( a \) are the sample-to-detector distance, linear detector size and largest unit-cell axis of the sample, respectively. Using the

![Fig. 1. One-dimensional six weak diffraction spots located in the vicinity of a 1000 times more intense main spot. The PSF is Lorentzian and all spots are of original Gaussian shape with a FWHM of 10% of the PSF FW@0.1%. The nearest isolated satellite spot is located at a distance of circa 1 FW@0.1% of the PSF from the main spot.](image-url)
THE POINT-SPREAD FUNCTIONS OF X-RAY IMAGING SYSTEMS

above formulas on a potential macromolecular case \((i = 0.5, \ i_r = 1, \ a = 300 \text{ Å} \text{ and } D = 40 \text{ cm})\), one obtains a smallest spot separation \(\Delta S\) of 600 µm. Clearly, even smaller \(\Delta S\) values are to be expected in other cases like Laue crystallography.

For the above example and from the simulation in Fig. 1, we conclude that the \(\text{FW}(a)/0.1\%\) of the detector PSF should not exceed \textit{circa} 600 µm, unless larger detector sizes become commercially available. A larger ratio between the peak intensities would naturally demand an even better performance of the detector. However, it must be kept in mind that, although any profile-fitting software would benefit from a narrow PSF, other peak-broadening factors such as thermal diffuse scattering or mosaic spread may dominate the effect of the PSF.

**Experimental**

*Energy-resolved point-spread function*

Experiments were carried out at the Materials Science beamline at the ESRF. As shown in Fig. 2, the size of the beam emerging from the wiggler was limited to \(30 \times 30 \mu\text{m}\) by four successive pairs of slits and monochromatized using either a double-bounce silicon 311 monochromator or silicon wafers. Exposure times were controlled via a millisecond shutter. The wiggler gap was opened up to 60 mm \((E_r = 7.7 \text{ keV})\) in order to minimize harmonic contamination from high energies and to limit the amount of background radiation due to secondary and Compton scattering. With this gap, the flux at the highest energies was still sufficient. To reduce background radiation, the detector was positioned behind a large lead plate with a 1 mm-wide slit. The location of the spot with respect to the detector surface was remotely controlled through a motorized translation stage (x direction) or optical table (z direction). For each energy, the proper exposure time was chosen in order to bring the spot intensity close to saturation. Opening of the shutter and translation of the detector were automatically alternated to record a set of spots covering approximately one quarter of the detector surface. Preliminary exposures were acquired on high-resolution photographic film to check the actual shape of the incident beam. On the basis of previous work (Templer et al., 1991), the PSF was assumed to be dose independent up to saturation level. Intentionally saturated spots were also recorded to study long-distance bleeding.

*Dynamic-range test*

Measurements were performed with a standard X-ray generator (W, 40 kV, 10 mA). The detector surface was covered with a lead plate through which seven 200 µm pinholes were drilled 1 mm apart in two orthogonal directions. Six of the holes were covered by 0.8 (1) mm of copper, which resulted in an intensity reduction of three decades with respect to the unattenuated main hole. The exposure time was chosen to nearly saturate the main spot.

*System description – XRII/CCD detectors*

**X-ray image intensifiers**

The XRIIs (HX series) were built by Thomson Tubes Electroniques (78148 Velicy, France). We first used a standard triple-field 310 mm (12 in) medical tube TH 9432 HX. This tube has been optimized for the 30–80 keV range for use in medical radiology and uses an aluminium input window that is opaque to X-rays below 20 keV. Since the X-ray-diffraction community is also interested in lower energies, the ESRF developed in collaboration with Thompson a special XR dedicated to low-energy X-rays. The required modifications were essentially (i) a 220 mm (9 in) beryllium input window and scintillator substrate for sensitivity down to 5–6 keV, (ii) a thinner scintillator for increased resolution (as absorption depth is dramatically reduced at lower energies) and (iii) an optional fast-output screen for lag-free imaging at high frame rates (Moy, Koch & Nielsen, 1993). This new tube (TH 49425) is mechanically and optically identical to the standard triple-field 220 mm medical tube TH 9438 HX.

Both tubes have a thick window, a 25 mm P20 output phosphor converter and a built-in electron-optics zoom with 1.4 × and 2 × magnifications.

**Optics and CCD camera**

The tubes were optically coupled to the CCD camera using a Rodenstock 1:1.9 95 mm collimating lens matched to the 220 mm tube and an Optec 1:1.4 95 mm lens matched to the 310 mm tube. The camera lens was a Kinoptik apochromat 1:2.5 150 mm. The output pupils were superimposed to

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**Fig. 2.** Experimental set-up used for the energy-resolved PSF measurements: (1) white beam; (2) primary slits (0.5 × 0.5 mm); (3) secondary slits (0.2 × 0.2 mm); (4) monochromator; (5) monochromatic beam; (6) slits (0.1 × 0.1 mm); (7) millisecond shutter; (8) fine slits (30 × 30 µm); (9) lead plate with 1 mm slit; (10) detector surface.
minimize vignetting. The MTF of this optical relay system is excellent: at the Nyquist spatial frequency of the CCD (220 line pairs cm⁻¹, corresponding to an input resolution of 3.7 and 2.6 line pairs cm⁻¹, respectively, for the 220 mm ∅ and 310 mm ∅ XR11), for which the CCD MTF is 0.63, the full aperture MTF is 0.65 in the centre and 0.45 at the edges. A significant improvement is obtained when it is used at lower apertures.

The camera, model ST 130 from Princeton Instruments, uses a 1152 × 1242 CCD chip from EEV (Chelmsford, Essex, England), cooled by a thermoelectric module down to 213 K. The pixel size is 22.5 × 22.5 µm. With a readout speed of 2 × 10⁵ pixels s⁻¹, the dark-current noise amounts to circa 10 electrons. The signal is coded on 16 bits with a gain of five electrons per analogue-to-digital unit, giving an expected dynamic range of about 30000.

**Overall performance**

The XR11/CCDs performance has been described elsewhere (Morse & Moy, 1993). The most important features are: (i) a field of view of 22 × 24 cm for the standard aluminium XR11/CCD and of 15 × 17 cm for the beryllium XR11/CCD (in the nonmagnified mode); (ii) detector quantum efficiency > 50% between 33 and 70 keV for the aluminium XR11/CCD and between 6 and 25 keV for the beryllium XR11/CCD, with apertures reduced to give a conversion factor of circa 3–5 electrons in the CCD per X-ray; (iii) total XR11/CCD dark noise equivalent to less than 1 X-ray photon per pixel (lenses fully open) for exposures up to tens of seconds, except for a few pixels that receive cosmic rays and natural radioactivity.

**System description – imaging-plate detectors**

**Imaging plates**

Standard high-resolution Fuji™ plates, 20 × 25 cm, made of a 150 µm-thick BaFBr:Eu²⁺ phosphor layer coated with a 10 µm-thick protective layer, were used on both IP scanners. Kodak™ SO230 plates of the same size were tested on the Molecular Dynamics (MD) scanner. The phosphor layer thickness was 287 µm coated with 7.6 µm of cellulose acetate.

**IP scanners**

The Molecular Dynamics PhosphorImager 400E scanner was used in its high-resolution mode (88 × 88 µm pixels). The readout time was circa 12 min for a 20 × 25 cm plate with analogue-to-digital (AD) conversion over 16 bits but the scanning time could be reduced by selecting a limited region of interest. The photomultiplier voltage was set to 765 V and the power of the He–Ne laser beam was 10 mW. The specified dynamic range was five orders of magnitude.

The Fuji BAS2000 scanner was used in its high-resolution mode (100 × 100 µm pixels). It required 2.5 min to read out a full plate with 10 bits AD conversion but there was no possibility of selecting a limited region of interest. Four different preset ranges of sensitivity were available to the user. The power of the He–Ne laser was 15 mW and the specified dynamic range was four orders of magnitude.

In both cases, AD conversion was performed after logarithmic amplification.

**Data processing**

All data were processed on a Sun SPARC10 workstation with the code IDL (Research Systems Inc.). For the PSF, after background subtraction, each spot was interpolated with a zero-filling procedure based on Fourier interpolation (Bartholdi & Ernst, 1973). Peak contours at 50 and 0.1% were extracted and a semi-automatic search procedure was used to find the longest and shortest axis at the considered level. In the case of the XR11s, the radial and tangential axes were analysed instead. In some cases, the accuracy of the results was slightly affected by residual X-ray scattering originating from the micro slits. However, the search procedure was designed to filter out the spurious signals.

**Results**

Fig. 3 shows plots of the PSF FWHM and FW(α.0.1%) as a function of energy for both types of detector and averaged over the measurement points in the investigated detector quadrant. The long axis (IP) or the radial axis (XR11) is shown. For IP scanners, the asymmetry between the long and short axes above the 0.1% level was smaller than 10%, the long axis generally corresponding to the laser scanning direction. With the Fuji scanner, after checks that the PSF was not dependent on the chosen sensitivity range, measurements were performed with the lowest gain mode ('400' mode). With Kodak IPs, the PSF significantly broadens as the X-ray energy increases (with a drop in the 36 keV region) whereas it is more nearly constant with Fuji plates. When the latter are used, the two IP scanners have very similar performances and give an average of 130 µm FWHM and 1100 µm FW(α.0.1%).

The FWHM for XR11s varies slightly as energy increases, but statistical analysis shows that, unlike for Kodak plates, these variations are not significant. The FWHM is on average twice as broad for the XR11s as for the IP scanners. The FW(α.0.1%) of the aluminium tube is considerably worse in normal mode...
(4500 μm) than in zoom mode (1600 μm), whereas the beryllium tube reaches very similar performances to the IPs, even being superior to them when used in zoom mode.

Fig. 4 presents the shape of the low-intensity tails of saturated spots for all detectors. The spots were acquired at approximately 20 keV. The degree of saturation was chosen according to the expected dynamic range capability of the detector, so that the contour at 0.005% of the peak maximum was still above noise level. A comparable degree of saturation (10 times) was chosen for the XRIIs/CCD and the MD scanner (used with Fuji plates), and a higher degree (17 times) was recorded with the Fuji scanner (an even higher value would have been more appropriate). For both IP scanners, a clear asymmetry appears in the plate scanning direction. With the image intensifiers coupled to the Princeton Instruments camera, a significant bleeding is observed in one direction, owing to blooming in the saturated CCD. Unlike for the IP scanners, this bleeding is present from the very top of the (observable) peak.

Fig. 5 shows the energy-averaged spatial variations of the PSF for the XRIIs, as a function of the distance between spot and detector centre. No significant variations are seen with IP detectors. Clearly, the aluminium tube when used in normal mode shows a strong astigmatism of the PSF as the radius increases. Experiments were also performed with the surface of the detectors tilted by 15° to simulate parallax effects, but no significant effect could be observed (not shown).

Fig. 6 shows the dynamic-range capabilities of the detectors. With the BAS2000 scanner, all peaks could be observed by choosing a medium sensitivity (‘4000’ mode), whereas the satellite peaks remained under the lowest digitization level when the lowest range (‘400’ mode) was chosen. With the highest sensitivity (‘10000’ mode), the main peak was very quickly saturated, or the small peaks were ruined by exceedingly large counting-statistics errors (in that case, the working conditions were close to single photon counting). Fig. 6 clearly shows the effect of PSF tails on achievable dynamic range: with the MD
scanner used with Kodak plates, the accuracy of the spots located closer to the main peak is reduced owing to leaking, especially on one side of the main peak. Significant improvement was obtained by using Fuji plates instead. With the beryllium XRII used in zoom mode, the situation is very satisfactory. With the aluminium XRII in normal mode, the closest satellite spots are completely missing. With the aluminium XRII in zoom mode or the beryllium tube in normal mode, the small peaks are clearly, but not completely, separated (not shown).

Discussion

**IP scanners**

The overall performance of an IP system depends on both the plate characteristics and the scanner design. Therefore, the two scanners were compared with identical plates and two different plates were tested in the same scanner. From Fig. 3, it appears that the Fuji and MD scanners have very similar PSFs. Only a careful analysis of the baseline of highly saturated spots shows slight differences (Fig. 4).

The plate itself is the key element that controls the PSF: at a given laser-beam spot size, the dominant cause of PSF broadening is apparently the scattering of the laser light inside the plate. Moreover, owing to the large solid angle (particularly the entire plate width) over which the light-collection guides gather the PSL from each pixel, the PSF is expected to be largely independent of the scattering of the PSL. The differences between the tested IPs are: (i) the Fuji plates have a thinner sensitive layer than the Kodak ones, resulting in a narrower PSF; (ii) the finer grain size of the Kodak plate increases laser-light scattering, which may add a significant contribution to the PSF broadening. This may account for the fact that the PSF of the Fuji plates is almost insensitive to the X-ray energy, whereas the PSF of the Kodak plates slightly increases with energy. Harder X rays release
Fig. 6. Dynamic-range performance of (a) a MD IP scanner with Kodak plates, a MD IP scanner (b) with Fuji plates, (c) a Fuji scanner, (d) an aluminium XRII/CCD in normal mode and (e) a beryllium XRII/CCD in magnified mode. Contours are drawn at 0.05 to 0.2% of the main peak maxima. The intensity ratio of the main to the satellite peaks is circa 1000.
electrons deeper in the phosphor layer. The stimulating light therefore has to reach deeper regions, where the effect of laser scattering is more pronounced with the Kodak plates (Fig. 7). The penetration of laser light is more even in the Fuji plates, so that all F centres are equally stimulated regardless of their depth in the layer. This may be due to a better index of refraction matching between the binding agent and the BaFBr powder. Above the K edge of barium (37.4 keV), one could expect a decrease in the PSF width of Kodak plates, as the absorption strongly increases, but no significant change could be observed (the observed drop at 36 keV cannot be attributed to the Ba K edge). This is due to the Ba fluorescence photons, which have ~400 µm absorption length in the phosphor layer: the fraction of fluorescence emitted in the plane of the phosphor layer may account for the continuous increase in PSF width above the Ba edge.

Inspection of Fig. 4 shows that both systems exhibit a strong asymmetry at the foot of a spot. This is easily explained: the scattered light from the laser beam stimulates luminescence from the excited spot when the beam comes into its vicinity. Before the spot has been read, the number of F centres to be stimulated is much larger than after readout. The foot of the PSF is therefore more intense on one side of the raster scan. With the Fuji scanner, the shape of the PSF is half-circular on both sides, as anticipated; the MD system has an elongated response, presumably related to the light-collection system, which gathers the PSL by the PSF wings for the MD scanner, especially when used with Kodak plates. With the BAS2000 in the lowest-sensitivity mode, the satellite peaks in Fig. 6 are simply not digitized (not shown). As previously explained, this is due to the presence of a cutoff threshold, which in this case limits the practical dynamic range to less than four orders of magnitude. The best results with this scanner were obtained with the intermediate sensitivity range: however, they are not reliable, owing to significant counting-statistics errors and unexplained noise. With the MD scanner, the four more distant satellite peaks are clearly observed owing to the absence of a threshold. With Kodak plates, the FW(a:0.1% of the PSF is clearly responsible for the overlapping on the two closest small peaks, whereas its asymmetric shadow accounts for the degradation on one side of the image. As expected, the situation is significantly improved by using Fuji plates, bringing the dynamic range to a level suitable for our applications. Re-scanning of the image plate can be used to improve the dynamic range (Shaw, Herron & Gur, 1992) and was successfully tested on a Fuji BAS 1000 scanner (Shimura & Harada, 1993). However, fine calibrations must be performed to assess consequences for linearity and signal-to-noise ratio.

**XRII/CCD**

The spatial resolution of the XRII/CCD systems results from the combined properties of the XRII itself, the optics and the CCD. The XRII performance is dependent on the input CsI:Na screen properties, the electron optics, the internal light scattering and the output phosphor screen.

In the present systems, the 220 mm Φ beryllium-windowed XRII has an intrinsic PSF narrower at half-maximum than that of the optics and CCD, but similar at 0.1% of maximum. Moreover, the optical design is aimed at a very uniform coverage of the sensitive area. Hence, the PSF FWHM of the whole system is little dependent on the energy or position of the impinging X rays, as shown in Figs. 3 and 5. Zooming the electron optics brings a proportional improvement in FWHM, as the output screen, optics and CCD remain unchanged. The FW(a:0.1%) does not improve linearly with zooming because of the more important contribution from the scattered light in the input screen, which is also multiplied by the zooming factor.

![Fig. 7. Sketch of the effect of laser-light scattering inside image plates. The illuminated region (white area) extends over a larger width in Kodak plates owing to greater thickness of and more pronounced scattering from the medium.](image-url)
The situation is completely different with the standard medical 310 mm \( \varnothing \) aluminium-windowed XRII: (i) because the output (screen, optics and CCD) is identical to that of the beryllium tube, one can expect at best a 1.5 larger input PSF for purely geometric reasons; (ii) because the electronic demagnification is 1.5 times larger, the electron-optics design is much more difficult and more astigmatism is expected, since it grows with the square of the off-axis angles; (iii) because the CsI:Na input screen is expected, since it grows with the square of the range, it is twice as thick as that of the beryllium tube and contributes significantly to the PSF. As a result, the input PSF of this system in normal mode (full field) is two to three times worse than that of the system used based on the beryllium tube. When zoomed down to 160 mm \( \varnothing \), as expected, the spatial characteristics become very similar to that of the 220 mm \( \varnothing \) beryllium-windowed system in normal mode.

The CsI:Na layers are very different from the phosphor layers in IPs. Vapour growth of microcrystals results in a fibre-like structure, so that fluorescent light is channelled to the photocathode with less scattering than in a powder layer. Furthermore, X-rays penetrate the scintillator through the aluminium or beryllium reflecting substrate opposite the photocathode. Therefore, it is not surprising that the absorption depth of X-rays does not strongly influence the PSF.

When X-rays hit the sensitive layer at an angle \( \alpha \), the effective spot size in the phosphor layer increases as \( p \sin \alpha \), where \( p \) is the mean penetration depth. Whenever \( p \sin \alpha \) remains smaller than the PSF, this effect is negligible, as observed with IP systems.

Unlike the IP, which has a flat sensitive area, the XRII has a convex input surface, so that the incidence \( \alpha \) on the scintillating layer increases much faster than the diffraction angle. However, if \( \alpha \) is smaller than 45° (which is always true if the diffraction angle is kept below \( \pm 15^\circ \), only minor degradation of the PSF is expected. This was confirmed by measurements.

Several papers on image converters coupled to CCD sensors used in electron microscopy have recently been published (Daberkow, Herrmann, Liu & Rau, 1991; Krivanek & Mooney, 1993; Fan & Ellisman, 1993; Ishizuka, 1993) showing results similar to ours. However, there are important differences in these approaches, since the image converters described do not include the XRII itself and use a YAG phosphor screen and a fibre-optical plate. Therefore, PSFs are expected to be broader in the X-ray case. This was confirmed by our results, showing PSF FWHMs on average two to three times broader than in the electron-microscopy case.

The dynamic range of both XRII/CCD systems is essentially that of the CCD camera. The beryllium XRII easily separates two peaks 1 mm apart despite a 1000:1 ratio in intensity, in both normal and zoom mode. Consistently, with the measurements of the PSF, the standard aluminium XRII does not resolve unambiguously the closest peaks in normal mode but does so very clearly when zoomed. When saturation is exceeded, the charges created in the CCD are spilled into the neighbouring pixels in the same column. This is the well known blooming effect, which of course does not occur with IP systems.

**Concluding remarks**

The results presented show the clear limitations of the tested detector systems in terms of spatial resolution, when they are to be used in the demanding conditions of crystallography.

The IP system is capable of recording many more diffraction spots than the XRII/CCD because of its better 'size-to-PSF ratio'. However, the XRII/CCD has a larger dynamic range. As a result of the present work, a 16-bit AD conversion over five decades is required to benefit from the potential performance of both systems.

The ultimate choice also depends on criteria of importance of X-ray area detectors not discussed in this article, such as spatial distortions (Hammersley, Svensson & Thompson, 1994), or detector quantum efficiency, linearity or response and flat-field response.

For synchrotron applications, the overall duty cycle is critical for a cost-effective use of beam time and for short-lived radiation-sensitive samples such as biological specimens. The XRII/CCD described here provides the user with data 10 s after the end of the exposure, which is an order of magnitude quicker than any IP system.

As mentioned above, using stacked IPs makes it possible to improve spatial resolution while providing a coarse energy resolution.

Replacing the slow-scan cooled CCD with the faster 1024 \(^2\) camera being developed in the ESRF detector group will result in similar spatial properties, with a readout time of \( \sim 100 \) ms but slightly reduced dynamic range. The fast-output screen of the XRII will eventually allow frame rates of up to 500 images s\(^{-1}\) using smaller multi-output CCDs.

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