# 7.2. CCD detectors

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## 7.2.1. Overview

After more than 20 years of refinement, CCD (charge-coupled device) detectors have emerged as the most useable and accurate large-area detectors available for the X-ray energies of interest to crystallographers. CCDs are familiar as the imagers in television and digital cameras, but the scientific grade devices used in detectors are larger and have more pixels and a lower noise amplifier. CCD detectors are an assembly of several components: an energy converter (*e.g.* phosphor), an optical relay with or without gain (fibre optics, lenses and/or intensifier) and the imaging CCD.

Although many configurations have been used in the past, improvements in the size and quality of fibre-optic tapers have led to the possibility of direct coupling – eliminating intensifiers and lenses – so long as other components are carefully optimized at the same time (Eikenberry *et al.*, 1991). Optimizations include the phosphor, the CCD and electronics, and the elimination of unneeded optical interfaces. Current commercial designs employ just three elements: phosphor, taper and CCD (Fig. 7.2.1.1). This concept enabled the use of large tapers, machined square at the front, that can be stacked together to form mosaic arrays. Consequently, there is now no inherent limit to the size of a CCD detector.

## 7.2.2. CCD detector assembly

Any practical detector requires compromises in the choice of components to optimize those aspects most important to the diffraction problem at hand. The optimization of one detector characteristic often adversely affects other characteristics, so that it is often difficult to identify the 'best' component. Considerations are given below to aid in making judicious choices.

Most fundamentally, a viable X-ray detector must have good quantum efficiency (see Section 7.1.1 in Chapter 7.1). Necessary, but not sufficient, are a high stopping power for X-rays and a large average signal per X-ray recorded in the CCD. The input signal passes through a sequence of stages and is transformed several times in the process. The statistics of this process are governed by the quantized nature of the signal, whether it be the initial X-ray photon, the visible photons produced in the phosphor, intermediate photoelectrons in intensifiers or the integrated charge in the CCD. To maintain a high detective quantum efficiency (DQE), the associated number of quanta per X-ray must be kept well above unity at each stage in the 'quantum chain'. There are several approaches that meet this criterion.

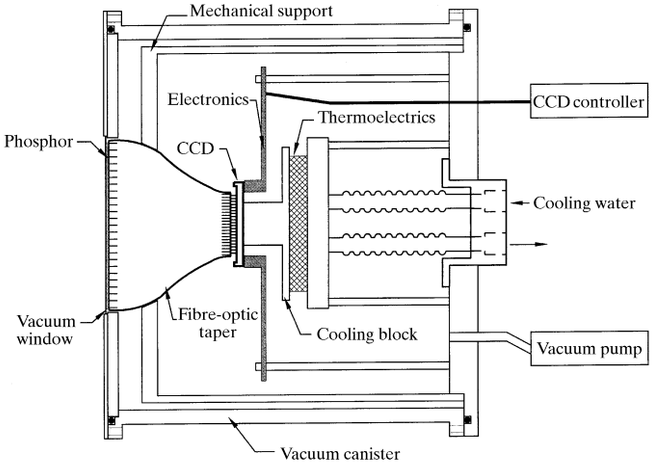


Fig. 7.2.1.1. Schematic of a single-module CCD detector. The thin phosphor screen is behind a light- and vacuum-tight vacuum window and is coupled to a fibre-optic taper, which is, in turn, coupled to a CCD. The CCD is thermoelectrically cooled to 213 K and housed in a vacuum cryostat. Reproduced with permission from Tate *et al.* (1995). Copyright (1995) International Union of Crystallography.

Crystallography applications generally benefit from large detective areas, whereas typical scientific CCDs are quite modest in size (*circa* 25 × 25 mm). The usual solution is to use fibre-optic tapers (which are more efficient demagnifiers than lenses; see Deckman & Gruner, 1986) to optically reduce a diffraction image excited in a larger phosphor screen. However, since optical image reduction is inherently inefficient, the reduction ratio is usually limited to about 4:1 before the number of visible photons per X-ray transmitted to the CCD becomes unacceptably low. Higher reduction ratios require image intensification *before* reduction (Moy, 1994; Naday *et al.*, 1995; Tate *et al.*, 1997) or there will be an unacceptable loss in DQE. Intensification *after* reduction can result in the same average recorded signal per X-ray. However, there is a significant probability that no quanta at all make it through the chain for many of the incident X-rays, thereby lowering the number of X-rays actually 'counted'.

Properties of the individual components affect other important detector characteristics as well. Below is a summary of important parameters for each of the components. Performance variations of CCD detectors from different vendors can most often be traced to the quality of the phosphor screen and the calibrations that are applied to the detector.

*Phosphors.* Although there are a bewildering variety of phosphor types, only a few are typically used with X-ray detectors (Shepherd *et al.*, 1995). A dense, high atomic number material is necessary to make the thin screens required for good spatial resolution while maintaining high X-ray stopping power. $Gd_2O_2S$:Eu offers high light output (>200 visible photons per 8 keV X-ray) and an emission spectrum matched to the typical CCD's spectral sensitivity peak in the red. Although there is a fairly prompt emission of most of the light (< 1 ms to 10%), there is a long-term persistence which decays according to a power law: bright spots glow for seconds after an exposure has ended. This severely limits the dynamic range during fast framing, such as might be encountered in a synchrotron environment.

Other dopants for $Gd_2O_2S$, such as Tb and Pr, have much shorter persistence and are better suited to higher frame rates. These phosphors yield somewhat lower CCD signals because they emit fewer visible photons per X-ray and because their blue–green emission is less well matched to the CCD spectral sensitivity. Interestingly, $Gd_2O_2S$:Tb has one of the slowest 'prompt' emission (exponential decay) time constants, but is one of the fastest phosphors to decay to $10^{-4}$ (< 10 ms), resulting in low persistence.

Thicker phosphors are needed at higher X-ray energies (>15 keV) to maintain high stopping power. This generally reduces spatial resolution. However, structured phosphors offer a way to increase thickness while limiting the lateral spread of the light. For example, CsI:Tl can be grown as an array of columnar crystals, resulting in a screen with enhanced resolution (Stevels & Schrama-de Pauw, 1974*a*,*b*; Moy, 1998). The spectral mismatch of this green-emitting phosphor is offset by the increased signal per X-ray expected at these higher X-ray energies. Recently, a (Zn,Cd)Se phosphor has been described that has excellent characteristics for X-ray energies above 12 keV; the stopping power at lower energies is compromised by absorption edges (Bruker AXS Inc.).





references