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DETECTORS FOR ELECTRON ENERGY SPECTROSCOPY

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ABSTRACT

The efficiency of the detector in an electron energy loss spectrometer is crucial to the performance of the system. The quality of this performance can be quantified in terms of the Detector Quantum Efficiency (DQE), the Modulation Transfer Function (MTF) and the radiation dose resistance (DR). The energy loss spectrum can be obtained either serially, by scanning the energy dispersion across a defining slit in front of a detector, or in parallel, by employing a detector or detectors with spatial resolution. The DQE, MTF and DR of serial detectors varies widely with the design chosen, but the fundamental limit to the DQE imposed by the sequential nature of the data collection process is such that serial detection, although simple, is never competitive with parallel collection. Present parallel detection schemes offer about an order of magnitude improvement in DQE over serial systems, but improvements in dynamic range, radiation resistance and fixed pattern noise are required before the full abilities of these detectors can be exploited.

Keywords: Energy Loss Spectroscopy, Detector Quantum Efficiency, Modulation Transfer Function, Charge Coupled Devices, Scintillators, Radiation Resistance, Self Scanned Diode Array, Semiconductor Detector, Continuous Electron Multiplier, Photographic Emulsion.

INTRODUCTION

The image plane of an electron spectrometer contains electrons dispersed according to their energy. The spectrum can then be recovered in two possible ways. Firstly, as a serial operation, by placing a defining slit followed by a detector in the image plane and scanning the dispersion across the slit. Alternatively the spectrum can be obtained in a parallel operation by putting a detector with spatial resolution in the image plane. The detection sensitivity of the spectrometer system in either case, for a given set of electron-optical parameters, will be determined by the performance of the detector and its associated electronics, and its efficiency is therefore a matter of importance. The purpose of this paper is to review the characteristics of detector systems in current use, and to indicate areas in which improvements are now possible.

BASIC REQUIREMENTS

The signal to be detected is an electron beam with an energy typically in the 80 to 200 keV range and a peak current as high as 100 pico-amps although, since the signal intensity falls rapidly with increasing energy loss, it is also necessary to be able to monitor currents as low as 0.01 pico-amps. The beam itself is of strongly ionizing radiation and can inflict severe damage on detectors sensitive to radiation effects. A suitable detector must therefore combine high sensitivity with low noise, a wide dynamic range, an adequate bandwidth, and an immunity to beam induced deterioration. These quantities can be formalized in a variety of ways, the parameters chosen here follow the scheme by Jones (1959). The efficiency of the detector can be specified in terms of the Detective Quantum Efficiency (DQE) which is defined as the square of the ratio of the experimentally obtained signal to noise ratio to the signal to noise ratio which would have been obtained with a perfect detector.

$$DQE = \frac{(S/N)^2_{exp}}{(S/N)^2_{perfect}} \quad (1)$$

The DQE, which is always less than unity, is a measure of the

LIST OF SYMBOLS

A = Detector area (cm^2)
B = Bandwidth (hz)
e = Electronic charge (coulombs)
E_H = Energy required to create electron-hole pair (eV)
E_O = Incident beam energy (eV)
f = Modulation frequency (hz)
I_B = Beam current (amp)
I_n = Beam noise (amp)
N = Electron flux onto detector
p = Photoelectron yield
R = Penetration depth (cm)
T = Number of channels in spectrum
ϱ = Density (gm/cm^3)
β = Diode efficiency

efficiency with which the detector uses the electrons reaching it. The "perfect" detector would add no noise to the incident beam and use every electron incident upon it. If an average number $\bar{N}$ of electrons strike this perfect detector per unit time, then the actual number reaching the detector in any given interval will follow a Poisson distribution with mean $\bar{N}$ and variance N. The signal to noise ratio from the ideal detector would then be the number of incident quanta N divided by the inherent shot noise of the beam $\sqrt{N}$, thus

$$(S/N) = \frac{\bar{N}}{\sqrt{N}} = \sqrt{N} \tag{2}$$

a result often expressed by the statement that the detector is "shot noise limited". It is sometimes more convenient to consider the detector and its associated electronics as a combination (Everhart et al 1959). If the bandwidth of the complete system is B (hz), then the inherent beam noise I_n for an incident I_B is:

$$I_n = \sqrt{(2 \cdot e \cdot I_B \cdot B)} \tag{3}$$

where e is the electronic charge (coulombs). The signal to noise ratio of the beam as measured by an ideal detector of this bandwidth B is then:

$$(S/N) = \sqrt{\frac{I_B}{2 \cdot e \cdot B}} \tag{4}$$

So an ideal detector with a bandwidth of 10 khz would yield a signal to noise ratio of 17.3 from an incident beam of 1 pico-amp, but only 1.7 when run at 1 Mhz bandwidth. The DQE will control the ultimate sensitivity of a detector. Using the standard statistical analysis (e.g. Goldstein et al 1981), it can be shown that, to a first approximation, the minimum detectable signal will vary inversely with the DQE.

The ability of the system to handle signals varying in the time domain is a function of the bandwidth B and is described by the modulation transfer function (MTF). The MTF at some frequency f is the ratio of the amplitude A(f) of the modulation at that frequency in the incident signal to the corresponding amplitude in the output signal:

$$MTF(f) = \frac{A(f)_{out}}{A(f)_{in}} \tag{5}$$

The MTF is usually close to unity for low frequencies, falling smoothly to zero at higher frequencies. Although the spatial frequencies encountered in recording a spectrum are relatively low, the MTF is significant when the spectrometer is used for energy filtered imaging purposes. The DQE of the detector system will be influenced by the MTF (Nudelman et al 1976) so that the DQE at the frequency f is related to the DQE for zero frequency by the expression:

$$DQE(f) = DQE(0) \cdot MTF(f) \tag{6}$$

The radiation dose received by a detector is measured in Rad, where a dose of one Rad deposits 100 ergs of energy per gram of absorber. Therefore with an incident beam of energy E_O (keV), and current I_B (amp), striking a detector surface of area A (cm^2), density ϱ (gm/cm^3) and penetrating to a depth R (cm) before adsorption the dose rate DR is given as:

$$DR = \frac{I_B \cdot E_O}{A \cdot \varrho \cdot R} \text{ (Rad/sec)} \tag{7}$$

For example an electron beam of 100 keV energy, containing 1 pico-amp, impinging on a detector of 1 cm^2 and unit density and penetrating to a depth of twenty microns deposits 5 Rads/second. This would be a typical dose rate for ELS operation in most instruments.

SERIAL DETECTIONS

Serial detection of the ELS spectrum is accomplished by scanning the energy dispersed electrons across the defining slit, either by ramping the spectrometer or through the use of a separate set of scan coils. The detector output can then be digitised for storage in the multichannel analyzer (MCA) in several ways. Firstly the detector can be run in a "pulse counting" mode, with a suitable amplifier and discriminator being used to shape the pulse for acceptance by the MCA. Alternatively the detector can be used as an analog device and its output digitized by the use of a voltage to frequency converter (Joy and Maher 1980) or through an analog to digital converter (Egerton and Kenway 1979). In principle the pulse counting approach is superior because the result is essentially independent of the gain of the detector, and contains no component due to dark current signals from the detector (assuming, in both cases, that the discriminator is properly set up). However as discussed below the dynamic range for counting operation is often rather limited. Direct digitisation of the analog output of a detector is straightforward, but A/D converters with greater than 16 bit precision are expensive and there is thus a limit to both the accuracy (2 parts in 10^4) and the dynamic range of the result that can be obtained in this way. Voltage to frequency converters are relatively cheap and current commercial 10 Mhz units, when carefully set up, offer a precision equivalent to a 19 bit A/D converter together with a dynamic range in excess of 10^5. However such units generate a substantial dark current

count which must be stripped from the spectrum before analysis. In either case the accuracy of the result obtained will depend on the gain stability of the detector and its associated electronics, and there can be significant errors due to, even transient, overloading of any part of the signal chain.

Before considering the performance of specific detectors it must be realized that the DQE for any form of serial detection is limited since, of the spectrum of T channels, only one is being sampled at any time. If the intensity/channel were constant then the signal/noise ratio of the entire spectrum would be reduced by a factor $(1/\sqrt{T})$ (from equation 2), so the DQE for a perfect serial detector compared to that for a perfect parallel detector must satisfy the inequality.

$$DQE(SERIAL) \leq 1/(T).\ DQE(PARALLEL) \qquad (8)$$

The serial mode of detection is thus at a considerable disadvantage compared to any form of parallel collection.

SEMICONDUCTOR DETECTORS

Semiconductor detectors have been used by several workers (e.g. Trebbia et al 1977) because they are both compact and efficient. A single 100 kev electron will produce in excess of 10^4 electron hole pairs and, in a diode with an optimally chosen depletion depth for this accelerating voltage, a large fraction of these carrier can be collected by the action of the internal bias field giving the device a considerable gain. Even higher collection efficiency can be obtained by biasing the diode, but this also increases the dark current and substantially multiplies the effective shunt capacitance represented by the detector. The DQE of such a detector is

$$DQE \cong \frac{1}{\sqrt{1+(E_H/E_O)}}$$

where E_H is the energy to create an electron-hole pair, and E_o is the incident beam energy. At beam energies in the keV range the DQE is thus very close to unity. The combination of the relatively high impedance and capacitance represented by the detector can be handled effectively by analog amplifiers to give adequate performance under most microanalytical conditions, although the MTF typically goes to zero for frequencies in excess of a few tens of khz restricting imaging operation to slow scan rates. But the pulse counting performance is strictly limited since the internal capacitance broadens the pulses and substantial shaping times are required to ensure accurate discrimination and counting. A typical maximum count rate is only of the order of 10 khz (Egerton 1980) so that in any reasonably efficient spectrometer counting operation will only be feasible at high energy losses. The radiation sensitivity of solid state detectors is also a problem in many cases. Reversible damage, manifested by a loss of gain and an increase in dark current, is often observed for DR in the 5 MRad/hr range and higher DR can result in a permanent loss of performance.

SCINTILLATOR DETECTORS

Scintillator/photomultipliers are the most widely used serial detectors because they combine cheapness, speed and efficiency. The DQE is a function of both the photomultiplier and the scintillator. If, on average, each electron incident on the scintillator produces p photoelectrons from the photocathode then p has a Poisson distribution and the DQE of the combination is:

$$DQE(PM) = \frac{1}{\sqrt{(1+(1/p))}} \qquad (9)$$

The efficiency of the scintillator, its coupling to the photo multiplier tube (PMT), and the quantum efficiency of the photocathode are thus all significant. A single 100 keV electron could generate thirty thousand 3.3eV "blue" photons from, for example, the popular NE102 plastic phosphor. However the actual conversion efficiency is only about two percent (Pawley 1974) so only about 600 are produced and of these only about a quarter are travelling in the right direction to reach the photocathode. Since this has a typical efficiency of about twenty percent the final yield is about 30 photoelectrons, to give a DQE of 0.98. Experimentally (Wiggins 1978) as 0.1 have been reported (Comins et al 1978). When pulse values of 7 to 9 have been measured for p, for a DQE of around 0.94 at 100kV. At lower voltages however the p value and the resultant DQE can be much worse and values as low counting it must be remembered that the statistical fluctuations in p will mean that for a specific discriminator setting some "real" events will be eliminated leading to a fall in the DQE. Thus for a discriminator setting equal to half the average pulse height (Engel et al 1977) about seven percent of true events will be missed, reducing the DQE by 0.96. If the efficiency of the scintillator falls then the scatter around p will increase and the discriminator must be set higher. For a setting close to the average pulse height the DQE has fallen by 0.7. In general experimentally measured DQE values do not approach the theoretical estimates, and it has been surmised (Comins et al 1978) that this is due to the production of a broad amplitude distribution. The measured output is then dominated by the fractional content of high amplitude pulses, leading to diminished DQE values.

The choice of a scintillator involves a trade-off between the conflicting requirements of speed, radiation sensitivity and efficiency. For analog systems, where only the radiation sensitivity and efficiency are important, the most popular choices have been plastics (e.g. NE102), or glasses, such as CaF_2 doped with Europium. Plastic scintillators are a factor of two or three times more efficient than glass scintillators, but they show a rapid loss in efficiency with radiation dose, losing an order of magnitude in efficiency for doses of the order of 100 k.Rads, although it has been claimed (Oldham et al 1971) that some of this damage is reversible in the presence of oxygen. The glass scintillators, by contrast, display a high level of radiation resistance, with little fall off in efficiency of doses exceeding a thousand M Rad (Wiggins 1978), and the damage (which is mostly due to color center generation) is reversible on heating in air. Such materials are thus an ideal choice for analog operation, the only problem being the MTF which falls to one half at about 100 khz.

For pulse counting all the parameters of the scintillator must be considered. At 100 keV any undamaged scintillator is capable of producing pulses sufficiently large to ensure a

DQE, after discrimination, which should theoretically be close to unity. The problem is then to find the ideal combination of decay speed and radiation resistance. One satisfactory solution is the use of high efficiency YAG phosphors doped with rare earths (Blasse and Brill 1967). A commercial example is P-46 (cerium doped YAG) which is available as a powder. This has a decay time of 20 nano-seconds allowing a peak count rate of about 20 Mhz and an efficiency which is about twice that for NE-102. In its powdered form the radiation resistance is good, a dose of some tens of M Rads being required to cause a fifty percent fall in efficiency, but the powder is not stable on repeated exposure to air.

A recent, important development has been the production of large single crystal scintillators obtained by liquid phase doping of YAG substrates with cerium, or mixed rare-earths, to produce an active region ten to twenty microns deep. The efficiency of such scintillators is very high, absolute photon yields being close to fifty percent of the theoretical value. In addition they have been found to be exceptionally radiation resistant, with negligible losses in efficiency measured for doses in excess of 10^5 M Rads. Their decay time is such as to permit counting at 5 to 10 Mhz. Further development of such materials is in progress and offers hope of enhanced performance, but they are not as yet commercially available and will probably be costly when produced.

In summary the photomultiplier scintillators combination offers good all round performance for serial detection. The MTF and dynamic range are both excellent in the analog mode, although long term gain instability due to slow decay of the scintillator after passing through the zero-loss peak is a problem on high brightness instruments (Joy and Maher 1980). In pulse counting applications the upper limit of 30 Mhz to the counting speed of the photomultiplier tube, set by transit time, interelectrode capacitance, and statistical scatter at the photocathode is acceptable, although still not adequate to allow counting through the zero-loss peak. Two parallel detection chains must then be employed unless the signal is deliberately reduced.

CONTINUOUS ELECTRON MULTIPLIERS

Channel plates and channeltron electron multipliers have been widely used as image intensifiers in transmission electron microscopy (TEM) operation. Because of the geometrical design of these devices their DQE should be higher than that of a comparable scintillator/photomultiplier system, although there is no experimental data to verify this, and their compactness would seem to make them an ideal candidate for applications in an energy analyzer. Unfortunately even the best designs have fundamental limitations in performance which make them quite unsuitable. The MTF of these units is very low, typically falling to one half at only a few cycles, consequently slow scan rates must be employed even to avoid spectral distortion. Secondly the DQE of the device is not constant with gain. As the bias across the channeltron is varied the field seen by the photoelectron leaving the cathode surface also varies and consequently the efficiency at the crucial first multiplication stage changes with applied voltage. In a photomultiplier the first dynode voltage is constant so the DQE remains unchanged at all gain levels. Finally the dynamic range of these devices is restricted by the need to keep the output current (input current times gain) below a specified fraction of the bias current. In practice this limits these units to input currents below one pico-ampere. If the limit is exceeded the devices become markedly non-linear and eventually saturate, require a reduction in gain and consequently a fall in DQE. Channel multipliers are therefore not a competitive alternative to the other systems so far described for serial detection although they might be used in some image intensifier systems and could thus be important for parallel detection.

ELECTRON MULTIPLIERS

A promising new detector is the Focussed Mesh Electron Multiplier produced by Johnson Laboratories (Cockeysville, MD) and a development of the electron multipliers that preceeded efficient photomultipliers. It consists of an aligned stack of dynode plates. Each plate has hundreds of raised electron emissive surfaces, and holes for electron passage, and the assembly is stacked so that the raised surfaces of one dynode are aligned with the holes in the dynode above ensuring efficient transmission of the electrons from one layer to the next. These multipliers offer very high gain, in the range of 10^6 to 10^8 and a specified spurious noise count rate on only count/minute at a gain of 10^7. Because of the compact design transit time dispersion is less than 10 nano-seconds with an output rise time of three nano-seconds, and reliable counting has been reported at rates up to 100 Mhz. The measured DQE, for electrons with energies of a few hundred volts, is better than 0.9. This value falls at higher voltages, but an intermediate converter could be used to maintain performance. Although the photocathode surfaces are exposed to the chamber ambient they are not degraded by dry air, and the gain is stable for repeated cyclings from vacuum. If degradation does occur then reactivation is guaranteed by the manufacturers. These units appear to be ideally suited for electron spectrometry applications, although the only data so far available have been from rocket launched particle spectrometers.

PARALLEL DETECTION

The beam of electrons transmitted through the analyzer is spatially dispersed in the image plane. Parallel readout of the spectrum is therefore possible if an array of detectors, or a single detector with spatial resolution, is placed in this plane. Because of the fundamentally poor DQE of a serial readout of the spectrum there has been considerable interest over the past few years in the development of parallel readouts either collecting the spectrum directly, or through some form of optical conversion. Each of the major approaches to this topic is outlined below, and it can be seen that much has been achieved. However in many cases the use of parallel rather than serial readout has replaced one set of problems and limitations by another.

PHOTOGRAPHIC EMULSIONS

The most obvious way to record the electron dispersion is

through the use of a photographic emulsion, and this was the earliest method described (Hillier and Baker 1944, Curtis and Silcox 1971). For 100 keV electrons the DQE for suitable emulsions is very close to unity (Farnell and Flint 1975) and the film (or plate) is nearly an ideal shot noise limited detector. Different film emulsions show a wide variation however in both their sensitivity and their MTF when exposed at low intensity levels (Downing 1979), and a considerable change can be effected by the details of the film development. In general a high MTF is incompatible with the highest sensitivity, so the emulsion and its processing must be selected to optimise one or the other. To be useful any parallel readout system must be capable of recording both the low loss and the core loss regions of the spectrum, and this is virtually impossible with emulsions because of the limited dynamic range (typically only 100 to 1). Photographic techniques also suffer from the fact the subsequent processing is required before the data can be examined, and because this processing can itself greatly affect the linearity of the information transfer.

ELECTRONIC READOUT SYSTEMS

Semiconductor devices have been examined by many laboratories for their application to electron spectrometry. Such devices could either be used directly to detect electrons, or an intermediate electron to photon conversion can be employed. Since the spectrum is a line dispersion a linear array detector can be used, but if equivalent performance can be obtained there are good reasons to use a two-dimensional (imaging) array since this will permit direct inspection of the aberration figure of the spectrometer and, with the addition of a post-spectrometer lens, allow the observation of energy filtered images and diffraction patterns (Egerton, private communication; Shuman and Somlyo 1981). Two main types of devices have been employed, charge coupled devices and self-scanned photodiode arrays. Although both rely on the generation of electron-hole pairs by the incoming electron or photon they differ in the way that this information is read out from the detector.

In the Charge Coupled Device (CCD) the incoming photon passes through a surface polysilicon electrode and an SiO_2 barrier layer into a p-type silicon substrate, where an electron-hole pair is generated. With a positive potential on the electrodes the minority carriers are swept towards the insulator interface and trapped there. Since each photon generates one electron the stored charge is proportional to the photon intensity incident on the cell. To readout the device the charge is clocked through a chain of "vertical" transport cells, each acting like a storage capacitor, until it eventually reaches the main horizontal transport register where it is measured by a charge integrator. The Self Scanned Diode array (SSD) is similar in basic operation but each storage photodiode is connected to MOS switches which are repetitively scanned in sequence to load the output onto the video bus. In addition SSD cells are often larger in area because of less restrictive device constraints. If instead of photons, high energy electrons are incident on then although the general principle is similar there are important differences. Each electron will now generate several thousand electron-hole pairs, and these will extend for a considerable depth below the surface. The charge signals are therefore considerably greater, and problems can be experienced with the cell "saturating" if the cell is not emptied at sufficient frequent intervals. A lower limit on the incident current will be set by the dark current of the diodes themselves, although this can be suppressed by cooling the array well below room temperature.

CCD or SSD arrays designed for direct exposure can be put in the spectrometer in place of the normal slit assembly (e.g. Jones et al 1977, Chapman et al 1980, Jenkins et al 1980) provided that provision is made to cool the assembly and protect the diode readout electronics from bombardment. In this mode the maximum allowable integration time t will be determined by the incident density I_B from the expression:

$$t = 3{\cdot}6{\cdot}q{\cdot}(V{\cdot}I_B{\cdot}A{\cdot}\beta)^{-1} \qquad (10)$$

where an energy E_H of 3.6 eV is assumed to be required for each electron hole pair generated, and where q is the saturation charge on the diode (of the order of 30 pico-coulombs), V is the accelerating voltage, A is the diode area and β is the collection efficiency of the diode. The charge collection efficiency is significantly less than 1 (because of the depth beneath the oxide layer at which most of the carriers are produced) and varies with the incident energy. Typically an SSD cell can store a few thousand electrons, a CCD cell one hundred or so before saturation. Thus for current densities in the range 10^{-12} A/cm^2, typical of core-loss values, integration times of between 1 and 10 seconds are possible assuming that the array temperature is sufficiently low (<100K) that its own dark current is negligible. No experimental values of DQE have been published, but estimations from the apparent signal to noise ratio of published spectra in the papers cited above suggest that typically the DQE is between 0.03 and 0.05. A perfect detector (DQE = 1) used in the serial mode and scanned through 256 channels would, from equation 8, have a DQE of (1/256) = 0.004 so an order of magnitude has been gained even at this preliminary stage. The estimated DQE may also be pessimistic because it includes a contribution from the "fixed pattern noise" (diode-diode gain variation) which has not been corrected for.

The major drawback of this approach is the problem of radiation sensitivity. Although figures quoted vary widely from essentially "no damage observed" (Jenkins et al 1980) to a projected lifedose of only a few hundred Rad (Chapman et al 1980) it is clear that not only the diode array, but also the associated readout circuitry, is at risk. The extent to which this risk can be minimized by design factors and care in use is still debatable, and it is likely that the use of direct reading arrays will remain restricted. From the electron-optical point of view the situation is relatively straightforward (Egerton 1981, a,b) provided that the dispersion plane of the spectrometer is flat, and that the dispersion is sufficiently high to ensure that the resolution limit determined by the MTF of the array (i.e. the diode-diode spacing/dispersion) is acceptable. Since the DQE of these devices will generally show a maximum for some incident energy less than 100 keV, the optimum application would seem to be in field retarding spectrometers where the energy is low and the dispersion high.

Indirectly exposed devices, where an intermediate electron to photon conversion is followed by optical coupling to the array, are free from problems of radiation damage. Furthermore, the coupling optics can be used to provide both greater

dispersion, and accommodate spectrometers with curved dispersion planes. These advantages are however obtained at the loss of some efficiency because of the inevitable losses at each interface in the system, and because each photon incident on the array only produces a single electron event. In a typical system (Johnson et al 1981 a,b) the electron photon conversion is done in a transparent phosphor, and the resultant image magnified and focussed on to the array by a large f-stop number lens. In this type of arrangement there is some conflict between the requirements for optimising MTF and DQE since an efficient phosphor (i.e. one that absorbs and converts all the electrons) will produce a broadened image point which will reduce the MTF obtained. The use of a fiber-optic coupling, although this is more convenient in some geometrical arrangements, will also be detrimental to the MTF unless the fiber size is below the beam interaction volume in the phosphor. No DQE figures for systems of this type have been published, but estimates of the signal to noise ratio visible on published spectra suggest that the DQE is somewhat worse than that for directly exposed arrays, being in the 0.02 to 0.03 range for 100 keV operation.

This figure can be improved by using an image intensifier either integral with the target (Shuman 1981) or closely coupled to it (Egerton 1981 b, Johnson et al 1981a). Such devices improve the DQE by increasing the efficiency of light transfer, and by multiplying the photon flux reaching the array. Since optical gains of the order of 10,000 are possible (Egerton 1981 b) a gain of an order of magnitude may be possible in the DQE. An estimate from the spectra shown by Egerton suggests that the DQE may be of the order of 0.1, although in this as in other cases the fixed pattern noise due to diode to diode gain variations may be a contributing factor in the result. Shuman et al (1981) have suggested that the effect of such an improvement in DQE is to reduce the minimum detectable mass by a factor of five.

In summary it is clear that parallel detection schemes already offer a significant, though not yet overwhelming, benefit. Some improvement can be expected in the performance of CCD and SSD arrays with respect to both peak storage density and dark current, but the best hope for major gain would appear to be in the design of arrays with hard radiation resistance to fully exploit the benefits of direct coupling. In the meantime indirectly coupled arrays with image intensification represent the current state of the art.

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WRITTEN DISCUSSION

R.D. Leapman: Is it straightforward to relate the output signal from a parallel detection system to the actual number of incoming fast electrons?

Author: No, because of the considerable number of physical parameters involved. Since a knowledge of this quantity is required for any proper statistical analysis careful calibration of the system will be necessary.