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X-ray detectors

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X-RAY DETECTORS

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1. Introduction

Research with synchrotron radiation has emerged in the last 20 years to be one of the most powerful tools in almost every field of science and technology. The best known research fields extend from diffraction measurements, to spectroscopy and imaging for microscopic description of materials and for industrial and medical use.

Because of this enormous potential for science, medicine and industrial research, the number and the power of synchrotron radiation centres increases continuously, providing photon sources of unparalleled flux and brilliance. These new sources, however, pose the demand for efficient, reliable and precise detector systems. with characteristics at the moment not available. Detector development will be one of the strategic research fields of the near future.

2. Definition of requirements

The choice of a detector implies the definition of a series of proper factors of merit which provide an accurate description of the system with respect to the required characteristics. In particular the following properties must be defined in a quantitative way, allowing for the comparison between different instruments:

1. detector efficiency
2. dynamic range
3. count rate (local and global)
4. linearity of response
5. uniformity of response over the active area
6. spatial resolution
7. spatial distortion
8. energy resolution

In addition, in the case of imaging/time resolved systems the data flow can be extremely high, so that the data handling capabilities become also of great importance, and should be treated as part of the detection system. Other important factors are the size and the weight of the system. Flexibility, i.e. the feasibility to use the instrument over a wide spectrum of applications might also be important. Finally, cost consideration should not be forgotten.

2.1 Detection efficiency

The efficiency of the detection is determined both by the absorption efficiency and by the noise level. Since the incoming photon flux obeys Poisson's statistics, the detection of N photons implies always a fluctuation proportional to $\sqrt{N}$. This is usually known as *shot noise*, and represents the ultimate limit in the photon detection process.
An ideal detector is than an apparatus which has, in experimental conditions, an intrinsic noise level smaller than the *shot noise*, and this consideration is at the origin of the factor of merit known as Detective Quantum Efficiency:

$$\text{DQE} = \frac{(S_o/N_o)^2}{(S_i/N_i)^2} \tag{1}$$

where S is the total integrated signal, N the rms. integrated noise and the subscripts i and o refer to input and output respectively.
Suppose α is the absorption of the detector: if all the absorbed photons contribute effectively to the output signal, and no other source of noise is present, then:

$$\begin{aligned} (S_i/N_i)^2 &= N, \\ (S_o/N_o)^2 &= \alpha N \end{aligned} \tag{2}$$

so that the DQE of an ideal detector is simply equal to its absorption coefficient, over the entire range of input intensities.
Since the DQE takes into account all noise sources, including the characteristics of the signal source, it is a particularly useful tool in evaluating the behaviour of a detector in real operating conditions. Considering for example the ideal detector described by equations (2), suppose to require a measure with an accuracy ρ:

$$\rho = S_o/N_o \tag{3}$$

it is then easy to obtain that for a source with a fixed number n of photons per unit time the time t needed is given by:

$$t = \frac{1}{n \cdot \text{DQE} \cdot \rho^2} = \frac{1}{n\alpha\rho^2} \tag{4}$$

It should be borne in mind that the DQE is in general intensity-dependent. A detector with a good absorption and a poor noise figure will perform better at high incident fluxes, where the *shot noise* is larger than its intrinsic noise, while at low intensities its DQE will drastically decay. This is generally the case for "integrating" systems, in which the signal is accumulated for a certain time before the read-out. On the contrary, counting detectors will generally have a constant DQE from very low input intensities up to the point where saturation reduces the counting capabilities

2.2 Count rate, dynamic range and linearity

All these terms refer substantially to the minimum and maximum number of events – photons – that the instrument is able to measure. The lower end is limited by the intrinsic noise level while the upper limit is fixed by the saturation level.

In the case of a counting device, a single X-ray photon can produce a large pulse compared to other effects, so that the count rate is the relevant factor of merit in this case. The maximum intensity at which the counter can be operated is set by the dead-time introduced by the electronics or by the incident photon to electronic charge conversion stage. Above this value, the detector response becomes non-linear.

The dynamic range is typically defined as the ratio between the largest measurable value and the noise level in absence of input signal. In the case of an integrating device, saturation will occur at a certain value of the input signal, which is an other way of saying that the response becomes highly non-linear.

Alternatively, the dynamic range can be defined as the range of input signal intensity for which the DQE exceeds a given value. Actually, this second definition for the dynamic range, taking into account the effects of the input signal, gives a better description of the behaviour of a detector in working condition, which can be affected by e.g. the spatial response of the instrument. Consider for example a 2-D detector with a saturation level at 10^5 photons in each picture element (pixel) and an intrinsic noise level of 10 photons/pixel. The dynamic range is then expected to be 10^4. Suppose now that the same detector is affected by a 1% glare. Then, if a region receives the maximum signal, the rest of the sensitive area will receive 10^3 photons/pixel, therefore limiting the real dynamic range to two decades.

In some cases the dynamic range can be adjusted by varying the gain of the system. For example, the gain can be reduced in order to allow strong signal detection, but this to the detriment of weak signals, which may become unmeasurable.

Moreover, in the case of 2-D detectors, it is sometime necessary to distinguish between local and global count rate. In principle in an ideal pixel detector each pixel behaves like an separate detector, capable of measure independently up to the maximum count rate. But in some other cases, like a Multi-Wire Proportional Chamber with non-parallel read-out, the entire detector undergoes a dead time after each measurement, and this is referred to as the global count rate. In addition, an intense peak in a region of the chamber can saturate the gas ionisation, introducing a limit to the local counting capabilities.

2.3 Spatial properties

Many applications of synchrotron radiation involve 2-D detection. Spatial resolution, i.e. the ability of distinguish two adjacent objects, is obviously a basic requirement for any position-sensitive detector, and as for all imaging systems, the Modulation Transfer Function (MTF) is a suitable factor of merit.

The MTF is given by the ratio between the intensity variation in the image and the intensity variation in the object, as a function of the spatial frequency. The advantage of the MTF in analysing a detector system is that the MTF of a cascade of series elements is simply the product of the MTF of each element. The same information can be obtained also from the Point Spread Function, which is the Fourier transform of the MTF, and is often simpler to use measure. The PSF of a cascade of series elements is given by the convolution of the PSF of each element.

The Full Width at Half Maximum of the PSF is often taken as the value of the spatial resolution. We have already seen, however, that the dynamic range may be affected by the PSF. Correspondingly, the PSF does not take into account directly of the possibility of distinguish between details of different intensity. Therefore the FWHM of the PSF can be a very optimistic estimate of the spatial resolution achievable in real operating conditions. In this case the FW at 1% or 0.1% of the PSF may be a better factor of merit.

The uniformity of response is also an important requisite of an area detector. This is in general not a problem for photographic film but, to a certain extent, all position sensitive electronic detectors show both long and short range variations of response. Low spatial frequency distortions can be easily corrected by using smooth functions. Calibration of high spatial frequency variation (pixel-to-pixel non-uniformity) is instead usually performed by providing a smooth and constant flat field illumination across the whole detector area. Moreover these fluctuations are in general dependent on the energy deposited in the detector, i.e. on the energy of the incoming photons. For use at a synchrotron source, where the photon energy spectrum is wide, the calibration of such a detector becomes consequently a delicate and time-consuming procedure.

2.4 Energy discrimination

Higher energy photons deposit more energy when absorbed in the detector than low energy photons, so that the amplitude of the signal response of the detector is often proportional to the energy of the incident X-ray photon.

The attainable resolution depends basically on the fluctuation in the number of events produced by the absorption, e.g. electron-hole pairs in a solid, ionisation in a gas, visible photons in a scintillator.

The FWHM of the energy distribution is given by:

$$\Delta E_{FWHM} = 2.35\sqrt{F \cdot E_i \cdot E_{event}} \tag{5}$$

where E_i is the energy of the absorbed photon, E_{event} is the average energy required to get an event in the detector (electron-hole pair...), while F is an empirical parameter which gives the deviation of the observed resolution value from the resolution expected for pure Poisson statistics. Typical values for F are 0.1 for semi-conductors and 0.2 for gases. E_{event} is 26 eV in Argon and 3.6 eV for Silicon at room temperature.

Instead of the full spectroscopic information, in some cases the possibilities to distinguish between few definite input energies is the only requisite. This is for example the case of Laue diffraction pattern, where several harmonics are superimposed in the same angular position, and hence reach the same region of a detector. An alternative kind of energy discrimination is then available also for integrating devices, like e.g. the photographic film. In fact, since the absorption efficiency varies with the energy, by placing several films one behind the other, it is possible to resolve the harmonics by comparing the measured spot intensity on successive films.

2.5 Data handling

When area detector are concerned, data analysis and storage are as important factors as the acquisition itself, and should be considered as one of the main features of the instrument. To give an idea of the dimension of the problem, it is enough to consider that a 1000x1000 pixel image with a dynamic range of 16 bit gives already 2 Mbytes/frame. The problem may extend then also to data transfer if time resolution requires fast framing.

3. Detector systems

3.1 Latent image detectors

These have been the historically the first X-ray detectors, and are still the most widely used in a broad spectra of applications. The energy deposited by the impinging photon is stored in the sensitive element and read successively off-line. These are all integrator devices.

3.1.1 Photographic film

Photographic film was in the past the commonest area detector both for imaging applications and for X-ray crystallography. Especially in the latter case it has been now largely supplanted by electronic devices, but it is still much used for preliminary investigations of specimens. Moreover, due to its excellent spatial resolution, its use for very dense diffraction patterns from viruses of Laue patterns is likely to continue.
The image is formed by the reduction of AgBr into metallic Ag grains during the chemical development. The blackening, expressed in optical density units D, is then read with a microdensitometer measuring the ratio between the light transmitted and incident onto the film:

$$D = -\log_{10}\left(I_{transmitted}/I_{incident}\right) \tag{6}$$

The values of D are limited to the interval 0.1-2.5, with the lower limit fixed by the chemical fog effect and the upper limit given by saturation. The observed intensity values are in general digitalized between 0 and 255. In the case of the measure of integrated diffraction intensities, which are angularly separated, the limited dynamic range can be increased by exposing a stack of films. In this way the weaker spots may be measured on the first film, while the strongest, due to the limited absorption of X-rays in a single film, pass through multiple layers until the attenuation in sufficient to avoid saturation.

The main advantages of the photographic film are:
- big dimensions;
- excellent spatial resolution;
- low cost;

while the disadvantages are:
- off-line read-out system, which needs the user's intervention to change and develop the films;
- low DQE value,
- limited dynamic range.

3.1.2 Imaging Plate

This Imaging Plate detector (IP) retains all the main advantages of the photographic film, while drastically reducing the disadvantages, and is probably at the moment the most widely used position sensitive detector at synchrotron sites.

The general detector scheme is similar to that of the photographic film, with a screen which temporarily stores the X-ray image and an image reader or scanner which converts the latent X-ray image into a digital signal. The sensible element consist in this case of a film containing fine phosphor crystals of BaFBr:Eu, a heavy material which is capable to store the electrons resulting from the absorption of an X-ray photon in F-centres. The stored image decays with time with a half-life of approximately 8 hours at room temperature.

After exposure, the F-centres can be optically stimulated with a laser for read-out, and the light emission is in the range of energies where the efficiency of photomultipliers is high. The information is then stored with a 16-18 bit depth, corresponding a dynamic range of 5 decades.

After laser illumination the sensible element retains part of the information as a residual image, which must be properly erased before the next exposure to X-rays takes place. This is done by exposing the plate to an intense source of visible light. The full measurement cycle of an IP is sketched in Fig. 1.

With respect to the photographic film the IP offers a lower level of the intrinsic noise and a higher absorption efficiency, which together account for a better DQE value. Spatial response can be assumed uniform and distorsionless. Also the possibility to re-use the plate and the wider dynamic range make the IP a big improvement over the photographic film.

The characteristics are summarised below:

- large lateral dimensions (up to 400 × 400 mm);
- high efficiency in the 8-17 keV energy range;
- PSF between 100 e 200 μm;
- wide dynamic range (limited by the read-out system to 10^4-10^5);

The disadvantages are those connected with the fact that the IP is, like the photographic film, a latent image system, needing user's plate handling and/or poor duty cycle at the read-out, while exposure times at synchrotron sites can be now as short as few seconds.

3.2 Gas detectors

In all gas-filled counters the initial event is the absorption of the incoming X-ray photons in the gas molecules and the consequent creation of ion-electron pairs. The detection efficiency depends on the fraction of absorbed photons. Ionisation energy is e.g. about 30 eV for noble gases, which means about 250 ion-electron pairs created per one 8 keV photon. The ion-electron pairs are then accelerated in an electric field aiming at a large multiplication factor prior to detection. Figure 2 shows the four regimes observed when an ion-electron pair is created in the presence of an electric field. Of these, the second and the third are of interest for synchrotron radiation applications.

3.2.1 Ionisation chamber

In its simplest design an ionisation chamber consists of two planar polar expansion connected to a high voltage supplier and placed in air along the beam path. The multiplication factor is small, so that only few hundred electrons are collected per incident photon. Detection of single photon events is therefore impossible, and these detectors are widely used as non-invasive monitors of the beam, by simply measuring the current with an amperometer.

3.2.2 Proportional counters

Increasing the value of the potential applied between the electrodes, and providing a suitable mixture of gases, photoelectric absorption is followed by secondary ionisation avalanche, providing a charge gain up to 10^6. The total charge collected from each photoelectric absorption event is proportional to the number of initial ion-electron pairs, and thus to the energy of the impinging photon.

Proportional counters are available in various sizes and gas fillings. The detector system consist of the detector itself, a high-voltage power supply, a single-channel pulse-height analyser, and scaling circuit. A typical detector is a metal cylindrical vessel, 2 cm in diameter and 10 cm long, with a central anode wire and Beryllium side windows for the X-ray beam. Due to its high photoelectric cross-section, Xe is widely used as absorbing gas. In these conditions single photons are detected with a good signal-to-noise ratio.

The Multi-Wire Proportional Chambers (MWPC) are the position-sensitive version of this kind of detector The anode is a planar grid of wires, and two other plane grids of wires, parallel respectively to the x and y direction, form the cathode (Fig. 3). The charge amplification takes place in the strong electric field between the anodes and the cathodes, and the electron multiplication avalanche is driven towards the anode. Capacitive coupling induces simultaneously positive pulses on the nearest neighbouring cathode wires. Careful

analysis of the induced pulses centroid lead to the reconstruction of the x-y position of the avalanche, which can reach the 200 μm resolution range.
The global count rate is essentially determined by the dead time required to store the position of each event, and is of the order of 10^5-10^6 photons/sec.

3.3 Scintillation detectors

In suitable materials the electron-hole pairs created by the absorption of an X-ray photon recombine with emission of visible light. The intensity of the light pulse is proportional to the energy deposited by the absorbed photon.
The ideal fluorescent material is a compound with the following properties:

- high value of Z and high density for efficient X-ray absorption;
- good energy conversion efficiency;
- emission wavelength matched to the light detector spectral range;
- fast fluorescence decay, in order to minimise dead-time and increase count rate.

The most frequently used device which exploits the collection of fluorescence light to detect X-ray photons is the scintillator counter. It consist of two elements, a scintillating crystal and a photomultiplier tube, followed by an electronic chain comprising a single-channel pulse-height analyser and a scaling circuit, as for the case of the gas proportional counter. A cleaved single crystal plate of NaI:Tl, whose emission line has an average wavelength of 4100 Å, is often used as scintillator element. The size and shape of the crystal can be selected, and is in general a disk of about 2 cm in diameter. This is hermetically sealed in a cylindrical holder with a thin Beryllium entrance window and glass back for light transmission. Coupled to the photomultiplier tube this makes possible to detect and measure the energy of X-rays from a few keV up to MeV with excellent DQE. Energy resolution is poor – around 50% at 6 keV – and the time response of NaI:Tl limits the count rate to less then 10^5 photons/sec.

Phosphor screens convert an X-ray image into a visible image which can then be captured by any imaging system. In this way a wide class of 2D X-ray detectors have been developed. In medical applications for example, phosphor screens are routinely coupled to photographic films for radiography; and combined with TV cameras, phosphor screens permit real time viewing and digital recording of X-ray images. For all this systems, the detection chain is given by this simplified picture:

$$\begin{matrix}\text{X - ray}\\ \text{photon}\end{matrix} \Rightarrow \begin{matrix}\text{10 to 50}\\ \text{visible photons/keV}\end{matrix} \Rightarrow \begin{matrix}\text{light collected}\\ \text{on sensor}\end{matrix} \Rightarrow \text{electrons} \Rightarrow \text{signal}$$

It is clear that in order to obtain a good DQE value, both the X-ray photon-visible photon conversion and the light collection efficiency must be optimised. The first requisite can be fulfilled by a proper choice of the phosphor material, but the second might be a difficult one. In particular the laws of optics limit the possibilities of coupling large screens with small sensors, since the collection solid angle decreases with the square of the optical demagnification factor, thus reducing the electrons/photons ratio. Therefore most of the large area system use a gain stage between the phosphor element and the demagnification stage. Spatial distortions and extreme sensitivity to magnetic fields are among the drawbacks of these systems.

3.4 Solid state detectors

The most common form of solid-state detector consist of a lithium-drifted silicon crystal Si(Li). Intrinsic Germanium detectors, which offer higher absorption efficiency, are also commercially available. These are the solid-state analogue of gas detectors: charge carriers of opposite sign (electron-hole pairs) are produced by the absorption of the X-ray photon. They drift in the applied electric field and are collected at the electrodes. The energy required for creating an electron-hole pair is 3.9 eV in Si and 3.0 eV in Germanium, and at 8 keV the typical attainable energy resolution is around 150-200 eV.

The detector has to be operated at liquid-nitrogen temperature in order to reduce thermal noise. Consequently, due to the massive dewar needed, this kind of detector is general used in a fixed position with respect to the sample.

3.5 CCD

The strong investments of consumer's electronics in the last years made available a large number of CCD models, at reasonable prices. Originally designed for visible light imaging applications, these are offered in a variety of lateral dimensions, up to several centimetres, and with pixel sizes spanning between 10 and 30 μm. This wide offer has stimulated the research in order to use these devices also for X-ray imaging. The broad spectra of solutions devised (see fig. 4) and the increasing number of commercial available X-ray detection system makes this device to deserve a separate paragraph.

3.5.1 Direct illumination CCD

The charge carriers generated by the absorption of an X-ray photon are stored in the sensible elements (pixels), which are successively read-out with the same serial procedure used for visible light. The gain is very high, of the order of 275 electron/keV, and the noise level of the output amplifier is in general low, of the order of few electrons. By proper

cooling of the device, also the intrinsic thermal noise can be kept at a very low level. The device can therefore work as counter with a good DQE at low input flux, and in these conditions energy resolution similar to that of other solid state devices it attainable.
At high input fluxes, where read-out dead time forces to use the CCD as an integrating device, the high gain turns to be a severe limit. In fact, since the storage capability of each pixel does not exceed 10^6 electrons, the dynamic range is constrained to not more than two to three decades. Moreover the limited lateral dimensions of the sensible area make the direct illumination CCD not suitable for many applications.

3.5.2. X-ray photon – visible light conversion CCD systems

The use of a conversion stage from X-ray photons to visible light allows a substantial reduction of the gain, and consequently the use of the CCD in high input flux applications. A possible solution is to coat directly the exposed surface of the CCD with a scintillating material. As an example, a 30 μm CsI(Tl) coating gives a gain of about 30 electrons for an 8 keV photon. This solution does not solve however the problems connected with the limited lateral dimensions, which are obviously the same of the direct illuminated CCD.
In systems aiming at a large sensitive area, demagnification from a large phosphor screen to the CCD is needed. Two possible solutions have been implemented to perform the optical coupling: lens systems or tapered optical fibres. The main purpose is then to maximise the transmission efficiency. And since, at least for not extreme demagnification, tapered fibre optic is more efficient, this is the most used collection stage. This solution is however not free of problems. The distortions introduced by the non perfect alignment of the optical fibres with respect to each other is non negligible, and must be corrected for every single detector system. Moreover the field depth is extremely small. As a consequence the tolerance at the fibre optics – CCD interface is very tight, and this may generate interference fringes in the light signal, which deteriorate the image in a non predictable way, which is not possible to correct.
Attainable demagnification values span from 2:1 to 3:1, and considering the typical lateral dimensions of a CCD of 20 × 20 mm^2, the dimension of the sensible area is in any case not larger than few centimetres. Higher demagnification factors require the insertion of a light intensification stage, which in turn introduces other noise sources. A better, but more expensive solution, is to tile more detectors in, say, 2 × 2 or 3 × 3 stacks in order to cover a larger area.

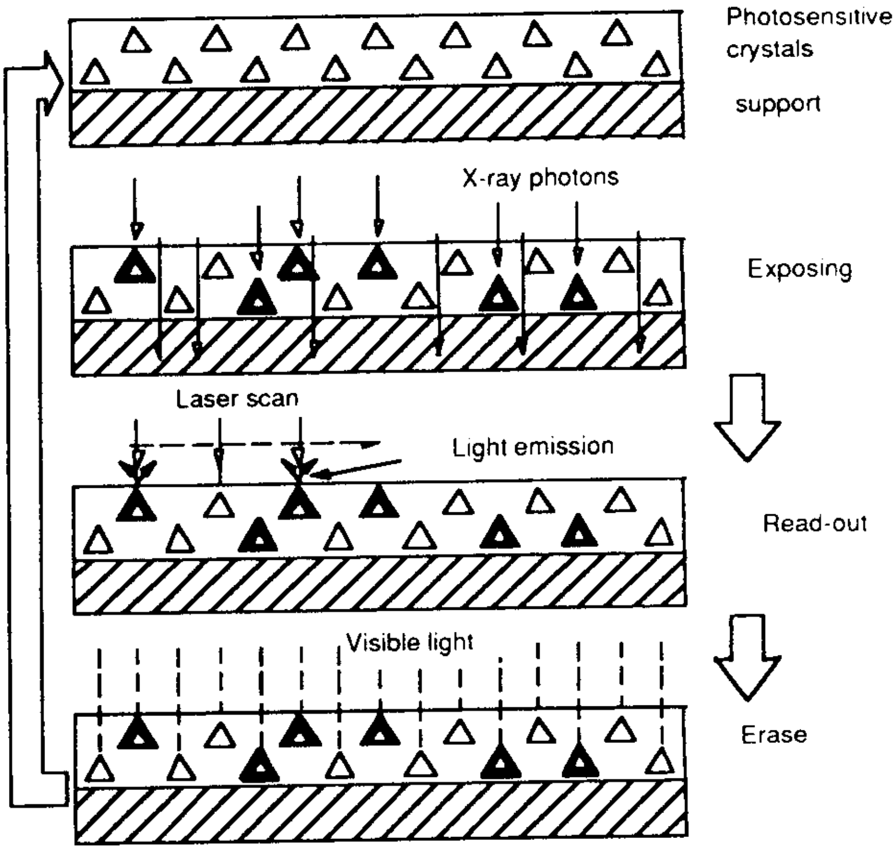

Fig. 1
Measure cycle of an Image Plate system.

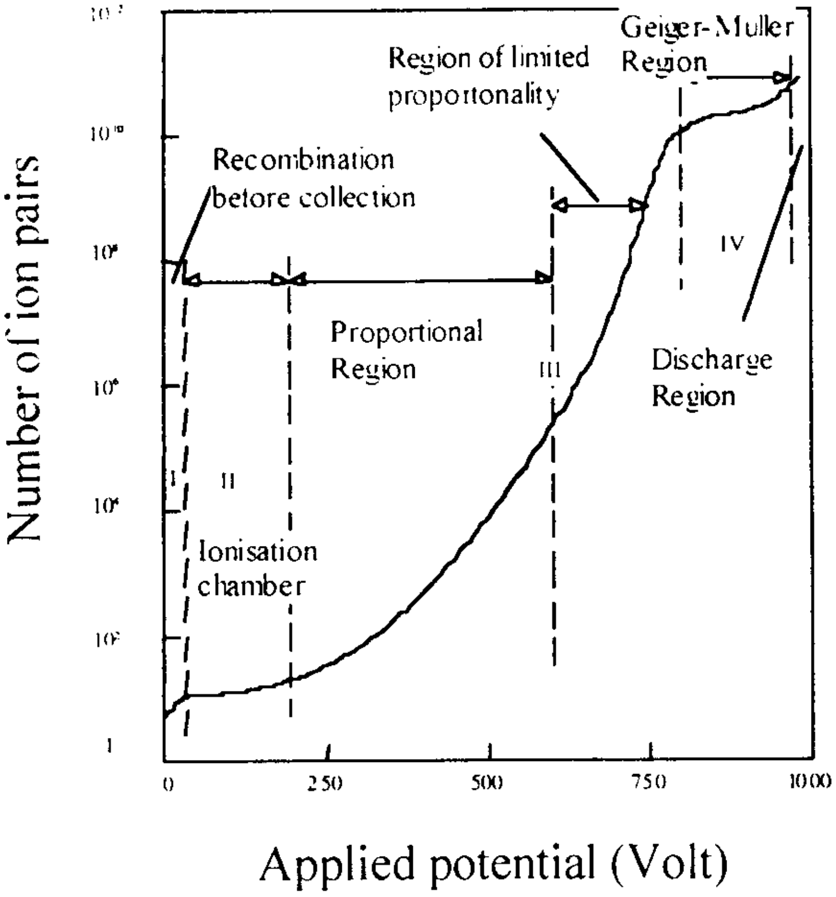

Fig. 2
The different regimes observed when an ion pair is created in a gas in the presence of an electric field.

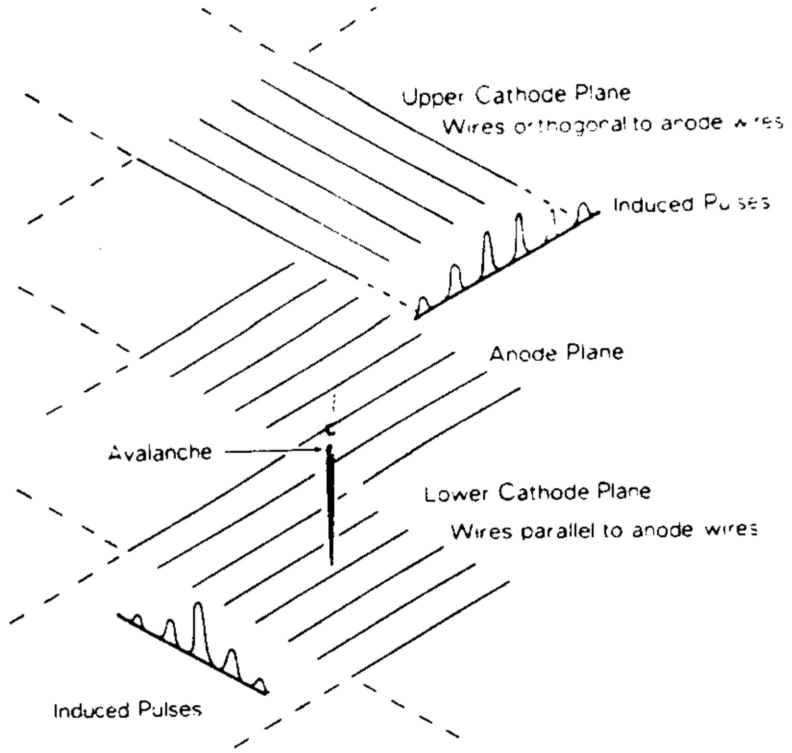

Fig. 3
Three-plane MWPC. The cathode wires may either be connected to a delay line or to individual amplifiers

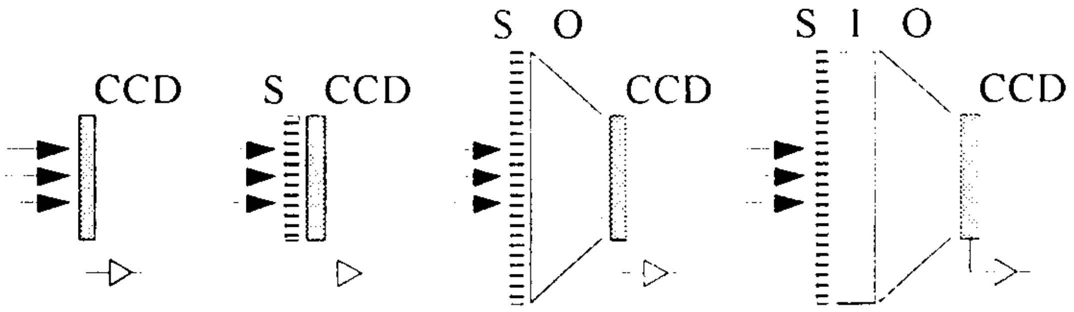

Fig. 4
The four types of CCD-based detector systems: (i) direct illumination; (ii) with scintillator or phosphor (S) in direct contact with the CCD; (iii) with a large screen optically coupled (O) to the CCD; (iv) with an image intansifier (I) inserted between the phosphor screen and the optical coupling