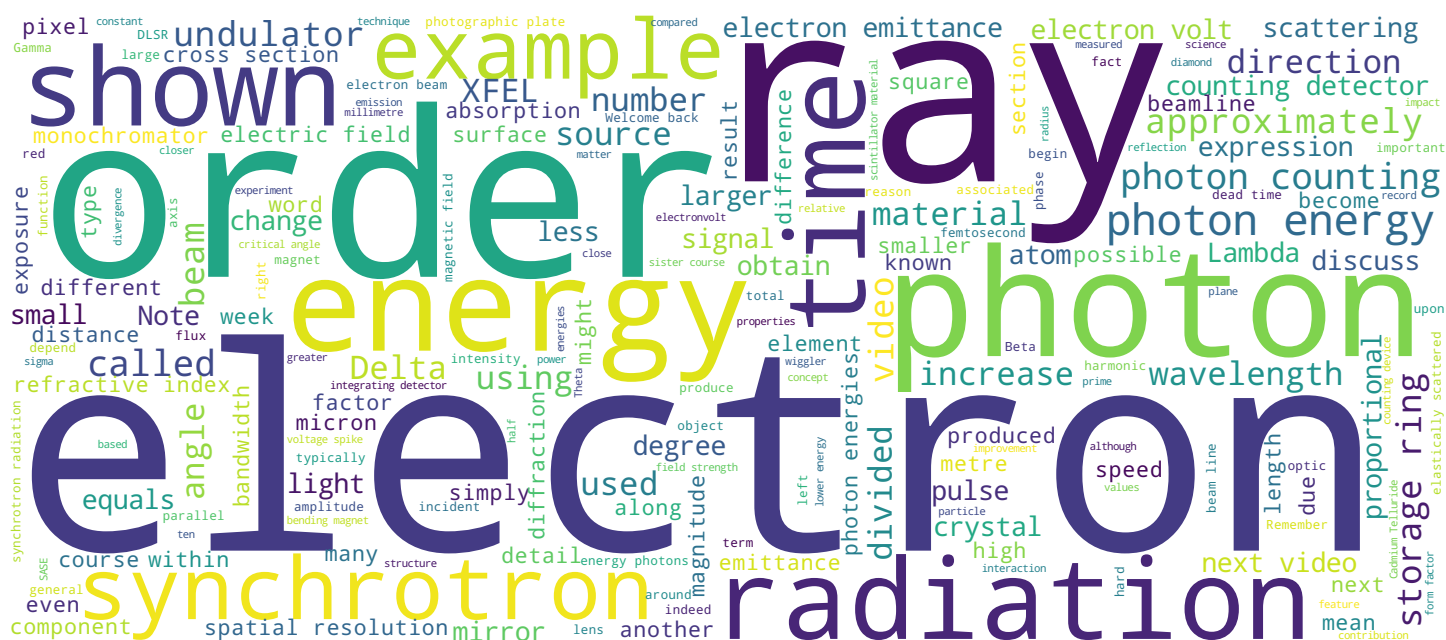


Synchrotrons and x-ray free-electron lasers

Techniques and applications

Prof. Philip Willmott



Search MOOC



Video



Contents and objectives of this video



- Photon detectors
 - Photon-counting v integrating
 - Maximum count rate
 - Hybrid photon-counting detectors

Welcome back. In this video, we look at different photon detector types and distinguish between photon counting detectors, which record in real time, updating each pixel every time it detects a single photon, and integrating detectors, which silently accumulate the information about light intensity during an exposure and only read this out once the exposure is finished. We finish this video by taking a closer look at photon counting detectors, considering the maximum acceptable and correctable count rate, and looking at the basic architecture of an increasingly popular photon counting device, the so called hybrid photon counting detector.

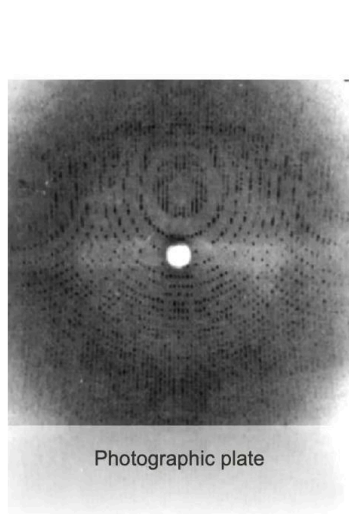
Notes

Summary

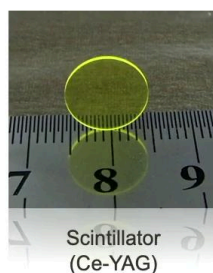
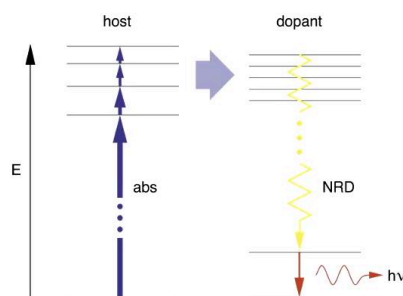


0m 05s

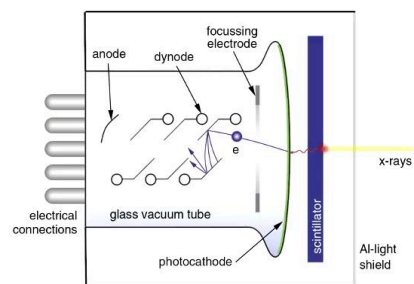
Detector types – historical devices



Photographic plate



Scintillator
(Ce-YAG)



Photomultiplier tube



Si-photodiode

R.L. Owen *et al.*, J. Synchrotron Rad. **16** 143-151 (2009)
<https://doi.org/10.1107/S0909049508040429>

The first approach to detecting X rays was using photographic plates. Even today, they're widely used in hospitals for qualitative purposes. The exact transmission of a tibia need not be known in order to recognise that it is snapped in two. Since photographic plates are generally fairly insensitive to X rays, phosphorescence screens are usually placed in contact with the emulsion of the plate or film. The X rays strike the phosphor screen, which emits visible light, which thus exposes the film. However, for quantitative purposes, photographic plates are very limited, due to difficulties in obtaining quantitative relative intensities to primarily to a non linear response for the change in transparency of the photographic plate with signal intensity and the poor dynamic range, poor spatial resolution, and the very long read out times. Scintillation counters operate by the partial conversion of absorbed X rays into visible or near visible light, which can then be amplified using a photo multiplier tube or PMT, which we briefly explain in a moment. Typical inorganic scintillator materials are salts or metal oxides doped with high-Z materials.

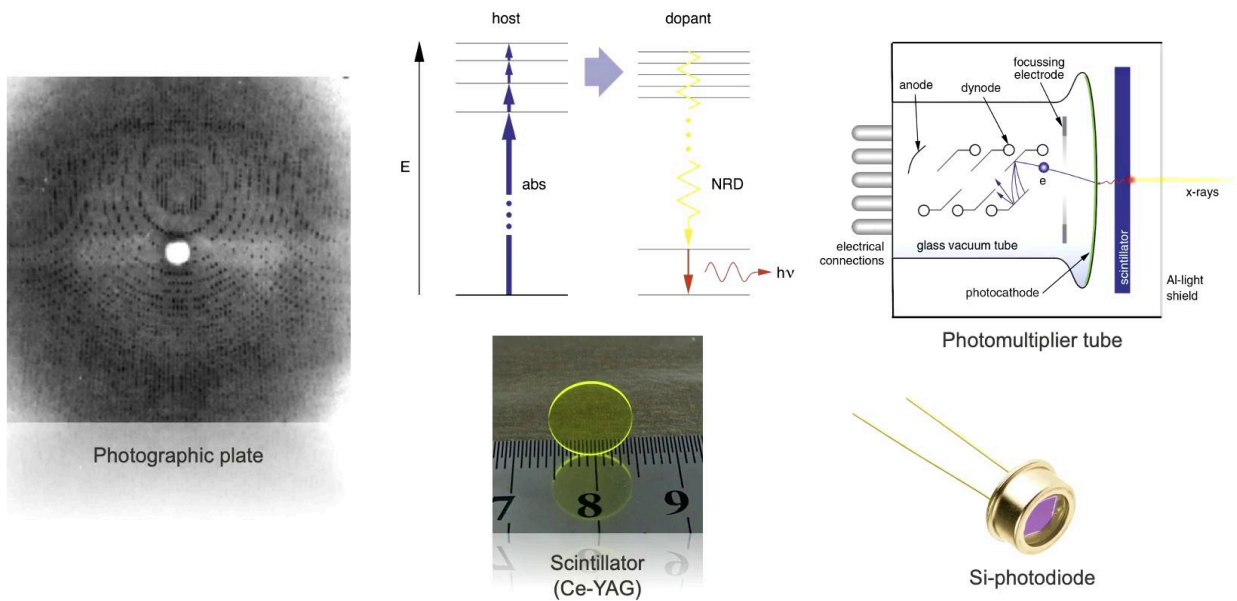
Notes

Summary



0m 54s

Detector types – historical devices



R.L. Owen *et al.*, J. Synchrotron Rad. **16** 143-151 (2009)
<https://doi.org/10.1107/S0909049508040429>

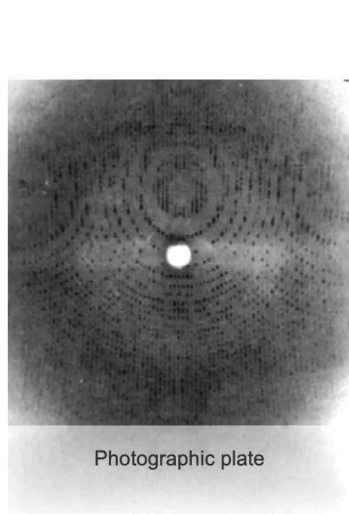
The host material is electronically excited by the absorption of an X ray photon, and this excited state rapidly transfers its energy to energetically nearby states of the dopant ion. These relax efficiently but non radiatively, in other words, without the emission of a photon, to a much lower excited state, only a few electron volts higher in energy than the final relaxed ground state, which is then accessed by the emission of a photon in the visible or soft ultra violet range. There are many types of scintillator material, both organic and inorganic. They have typical dead times of a few nanoseconds to a few hundred nanoseconds. The thicker the scintillator material, the more efficient it is for stopping the X rays, hence stronger the signal. So why not then make the scintillator as thick as possible? Well, the reason why in imaging applications is that the spatial resolution is negatively impacted by the increased point spread function as the lower energy photons propagate out and get reabsorbed in all directions from the original absorption volume. Combining a scintillator with a photo multiplier tube allows the latter to become sensitive to X rays.

Notes

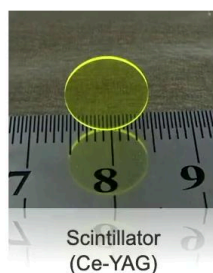
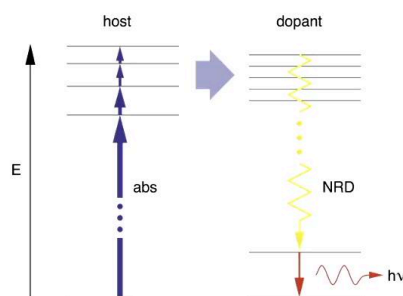
Summary



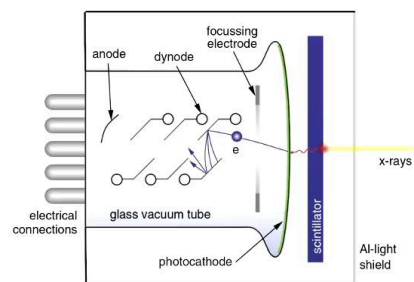
Detector types – historical devices



Photographic plate



Scintillator
(Ce-YAG)



Photomultiplier tube



Si-photodiode

R.L. Owen *et al.*, J. Synchrotron Rad. **16** 143-151 (2009)
<https://doi.org/10.1107/S0909049508040429>

Little or no spatial resolution is provided, however, and such systems are fairly bulky. Lastly, Silicon photodiodes are still used as diagnostic tools at beam lines to tune up optics and reposition mirrors, etc. It's relatively easy from the generated current to calculate the flux of photons on the detector if the diode thickness and dimensions and materials of its housing are known. A summary of the physics and mathematical approach to calibrate such diodes is given in the reference provided here.

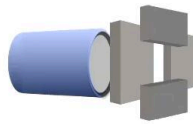
Notes

Summary



3m 49s

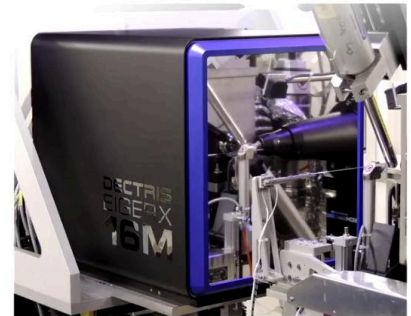
Detector dimensions



Point detector
0D



Microstrip detector
1D



Area detector
2D

Point detectors are those, while not necessarily being points like in size, have no aspirations to spatial resolution. Any improvement on the spatial resolution beyond the physical size of their sensitive area must be obtained by the use of slits. One dimensional detectors, such as the MYTHEN Microstrip detector allow one to perform scans over large angular ranges in parallel, which accelerates data acquisition by three or more orders of magnitude compared to the use of zero dimensional point detectors, allowing experiments to be performed, which until their advent in the first decade of this century, would have been completely unthinkable. We will discuss the impact of such detectors on material science and the dynamic processes in the sister course when covering scattering and diffraction experiments. Area, or 2D detectors are now widespread in both scattering and direct imaging experiments, and are becoming increasingly used also in dispersive spectroscopic setups. These can include CCD rays, CMOS arrays, and so called hybrid pixel array detectors. In the past, image plates exploiting phosphor screens and scanning laser readouts were used, but these are essentially extinct today due to their extremely long read out times.

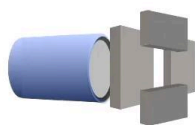
Notes

Summary



4m 27s

Detector dimensions



Point detector
0D



Microstrip detector
1D



Area detector
2D

Some custom made detectors can be extremely sophisticated, such as the cylindrical 12M PILATUS detector used at the low energy PX station, at the I23 beam line at the diamond light source. The low photon energies and associated large wavelengths used mean, according to Bragg's law, that for a given Bragg peak, the corresponding Bragg angle is larger. The cylindrical form was adopted to more easily access these.

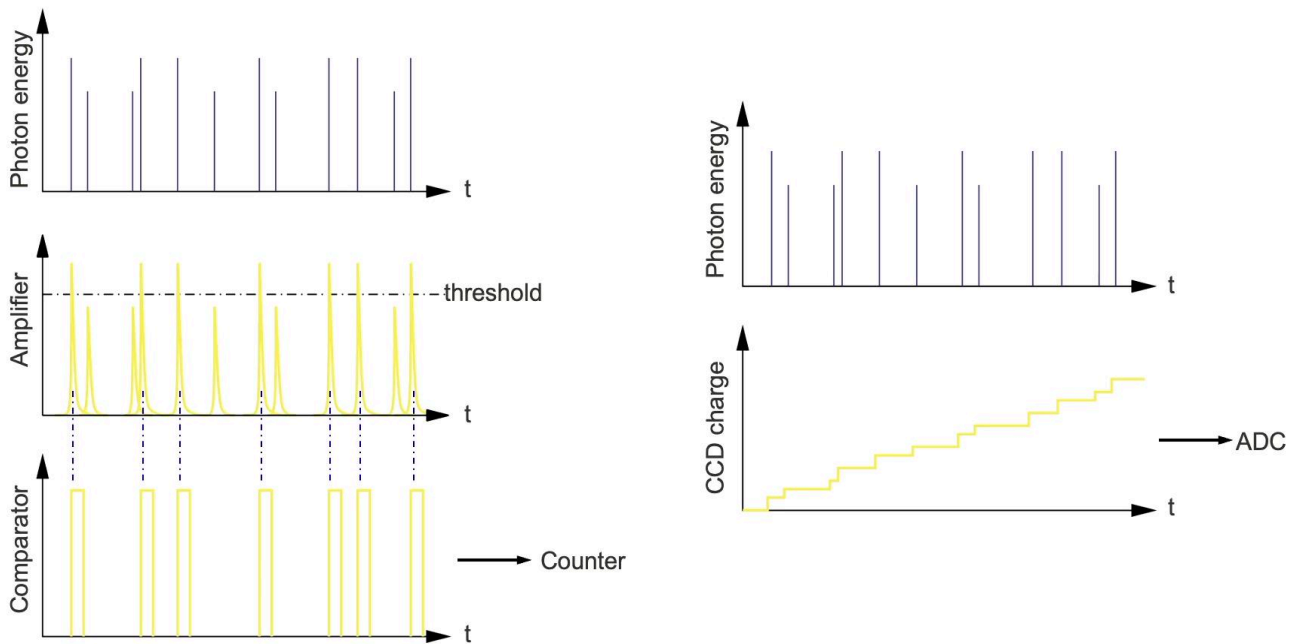
Notes

Summary



6m 02s

Photon-counting v integrating devices



We now discuss the differences and features of photon counting and integrating detectors, then, look in more detail at photon counting devices in the remainder of this video and the integrating devices in the next video. The principle behind photon counting devices is illustrated here on the left. In this simple example, photons having two distinct energies arrive at the detector in a stochastic manner. This might occur in a diffraction experiment, whereby both elastically scattered diffracted photons and lower energy photons, which are produced by photo absorption and subsequent fluorescence, are present. The arrival of a photon at the detector, or a pixel on an area detector produces a voltage spike in the detector electronics that has an amplitude that is proportional to the photon energy. Each voltage spike can then be compared to a certain threshold voltage, which can be set in the detector to be above the voltage spike produced by fluorescence photons, but below that for the elastically scattered photons. As a result, this high pass filter means that the comparator only registers a photon or a digital one for the elastically scattered radiation, thereby effectively suppressing the fluorescence.

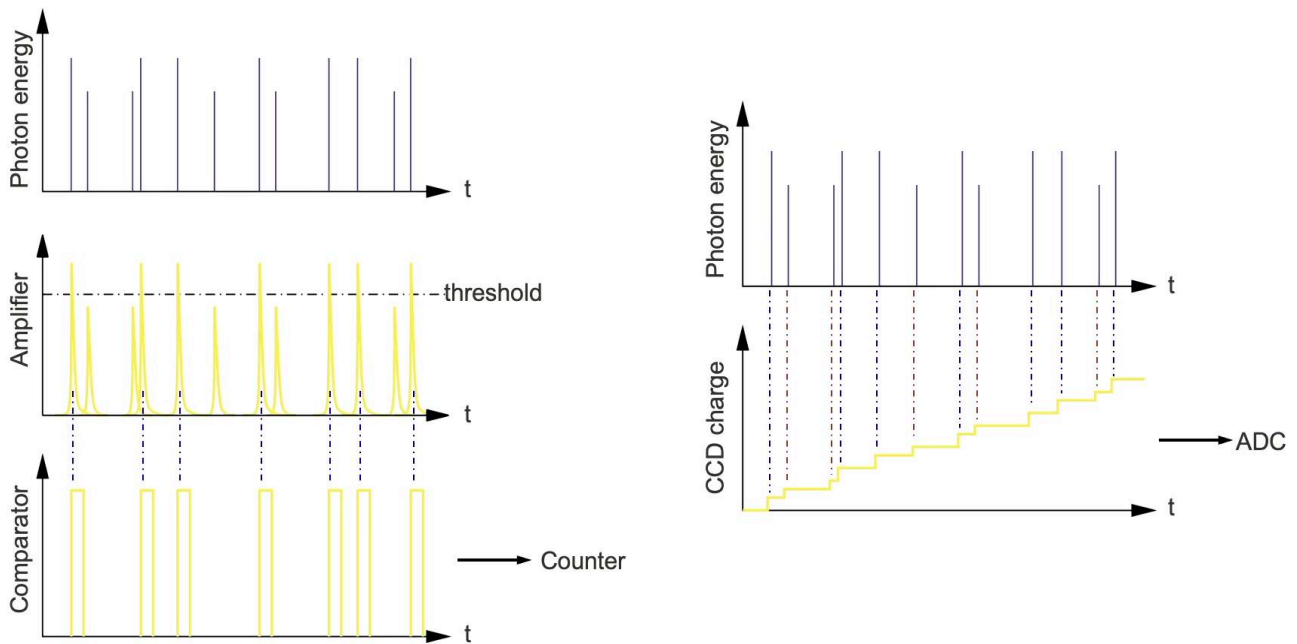
Notes

Summary

6m 36s



Photon-counting v integrating devices



Each detected elastically scattered photon increases a counter by one, so photon counting detectors keep you, the experimenter, updated during a recording. Integrating detectors keep their findings a mystery until after an exposure. In general, they accumulate and store charge produced each time they capture a photon, shown here on the right. The amount of charge generated being proportional to the photon energy. Only once the exposure is over, is the accumulated or integrated charge, then converted into a voltage and then to a digital signal. The signal from a row of pixels in a charge coupled device or CCD, is read out sequentially as the charge is passed along the row, from pixel to pixel. This is the origin of the term charge coupled. We will take a closer look at CCDs and CMOS devices in the next video.

Notes

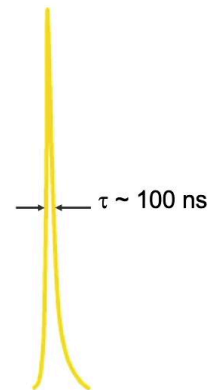
Summary



8m 07s

Maximum count rate in photon-counting detectors

- Synchrotron pulses
 - ~ 50 ps duration
 - Contain $\sim 2 \times 10^4$ photons/pulse (after mono)
 - Average temporal separation between photons within an x-ray pulse $\Delta t_{hv} \sim$ fs!
- Photon-counting detector
 - Recovery (dead) time $\tau \sim 100$ ns
 - Only one photon can be detected per event
 - Need to attenuate direct beam using filter!
 - Assume direct beam all on one pixel
 - Filter transmission $\sim \Delta t_{hv} / \tau \sim 10^{-8}$



Because photon counting detectors count photons, they have a dead time after the arrival of a photon on a pixel before the electronics have recovered again to be ready to record the next photon. This dead time is of the order of 100 nanoseconds, meaning that arrival rate of the order of 10 MHz or greater will lose counts due to so called pile up. Remember that although the average arrival rate of photons at a beam line after monochromatisation, is of the order of 10 to the 13, the instantaneous rate is maybe 100 times higher still, due to the pulse nature of the electron beam in the synchrotron storage ring. Consequently, the average temporal separation of the photons within any one pulse is of the order of a femtosecond, which is some 100 million times shorter than the recovery time of photon counting detectors. So if one focuses the synchrotron beam to a cross section smaller than the detector pixel size, something that is done regularly, one must attenuate the beam by a factor of 10 to the eight or more, in order to obtain reliable measurements.

Notes

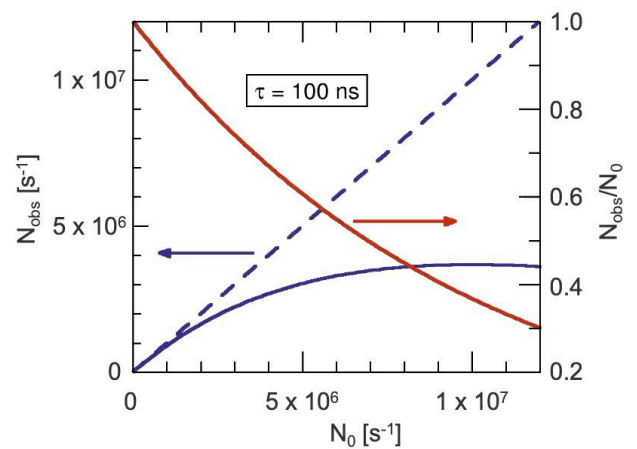
Summary



Maximum count rate in photon-counting detectors

- Photon-counting detector
 - Recovery (dead) time $\tau \sim 100$ ns
 - Only one photon can be detected per event
 - Max. count rate without "pile-up" = $1/\tau \sim 10^7$ ph/s
 - Actually lower, as arrival rate is stochastic $\sim 1/2\tau$
 - Software correction for stochastic pile-up below $N_0 = 1/2\tau$:

$$N_{\text{obs}} = N_0 \exp(-N_0 \tau)$$



Software corrections are, however, possible if the counting rate approaches the inverse of the dead time, τ . If one observes N OBS counts per second, one can use the simple expression that N OBS is equal to N_0 multiplied by the exponent of $-N_0 \tau$. A graph of the observed counting rate as a function of the true rate is shown here, along with the correction factor shown in red, with which one must divide the observed rate to obtain the true rate.

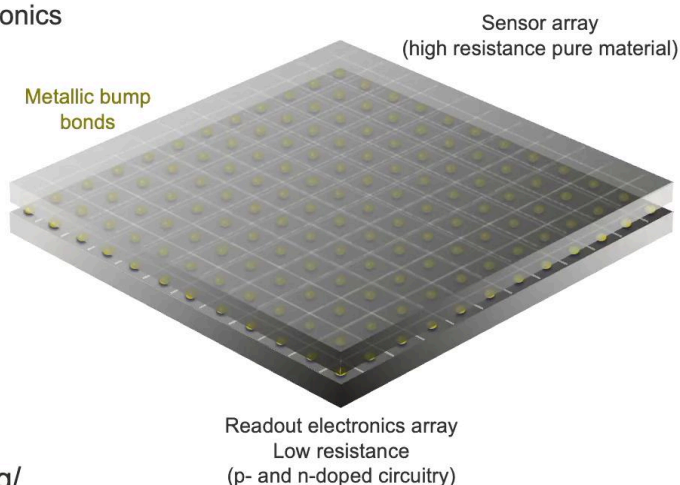
Notes

Summary



Hybrid photon-counting detectors

- “Hybrid”: combination of different material types
 - Low-resistance doped Si readout electronics
 - High-resistance sensor material
 - Si, GaAs, CdTe, ...
- Direct photon detection
- Very high dynamic range up to 10^7
- Perfect linearity for arrival rates $\lesssim 1/\tau$
- Frame rates even beyond 10^5 Hz
- Zero dark noise
- Zero readout noise
- Pixel size $\gtrsim 20 \mu\text{m}$
- HPC detectors now dominate scattering/crystallography experiments at synchrotrons



See also review by Förster *et al.*, Phil. Trans. R. Soc. A. **377** 20180241 (2019)

Hybrid photon counting detectors have become for many synchrotron applications, such as macromolecular crystallography, the gold standard. Due to their unsurpassed performance, including a very high dynamic range, perfect linearity, once an extremely accurate pilot correction term is applied, frame rates that can extend beyond 100,000 per second, and perhaps most importantly, zero dark and readout noise. The reason they are referred to as hybrid is that they are fabricated from two types of semiconductor. The readout electronics are based on low resistance doped Silicon. These are electrically connected, via metallic bump bonds to a high purity high resistance sensor material, which can be made from completely different materials, such as the compound semiconductor Gallium Arsenide or, for example, Cadmium Telluride. It is difficult to make the pixel size much less than approximately 20 microns in linear dimensions, on account of this physical bonding process.

Notes

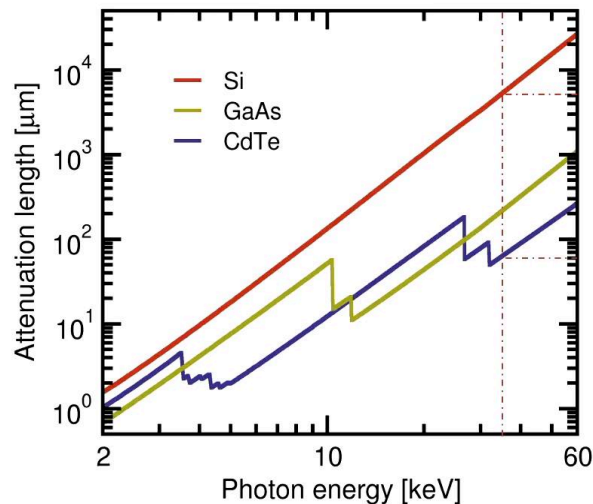
Summary

11m 15s



Hybrid photon-counting detectors

- “Hybrid”: combination of different material types
 - Low-resistance doped Si readout electronics
 - High-resistance sensor material
 - Si, GaAs, CdTe, ...
- Direct photon detection
- Very high dynamic range up to 10^7
- Perfect linearity for arrival rates $\lesssim 1/\tau$
- Frame rates up to 10^5 Hz
- Zero dark noise
- Zero readout noise
- Pixel size $\gtrsim 20 \mu\text{m}$
- HPC detectors now dominate scattering/crystallography experiments at synchrotrons



See also review by Förster *et al.*, Phil. Trans. R. Soc. A. **377** 20180241 (2019)

The use of higher density materials such as Gallium Arsenide and Cadmium Telluride for the sensor is driven by the fact that they are more efficient at absorbing high energy photons. As you can see from the graph here, a Silicon detector would need to be five millimetres thick in order to have the same quantum yield or efficiency as that of a 50 Micron thick Cadmium Telluride detector.

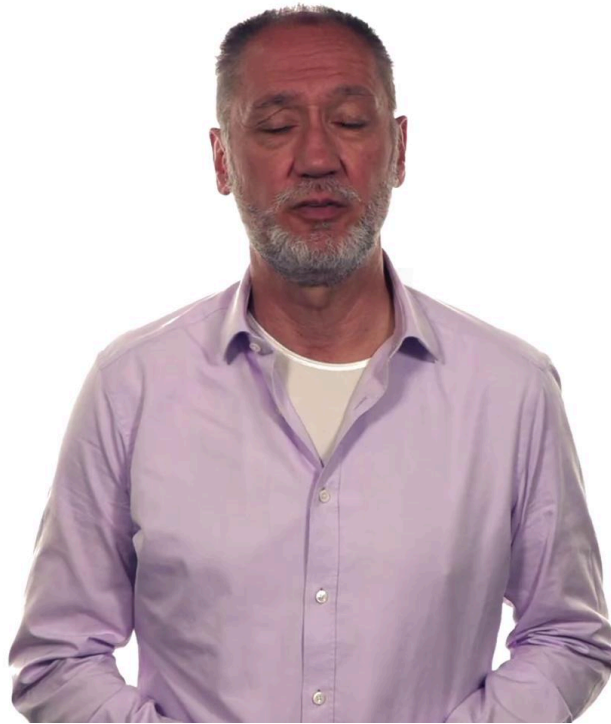
Notes

Summary



12m 27s

In the next video...



In the next video, we look at the integrating charge couple devices and so called complementary metal oxide semiconductor, or CMOS detectors. We will also discuss why these integrating devices are necessary in XFEL experiments.

Notes

Summary

12m 55s

