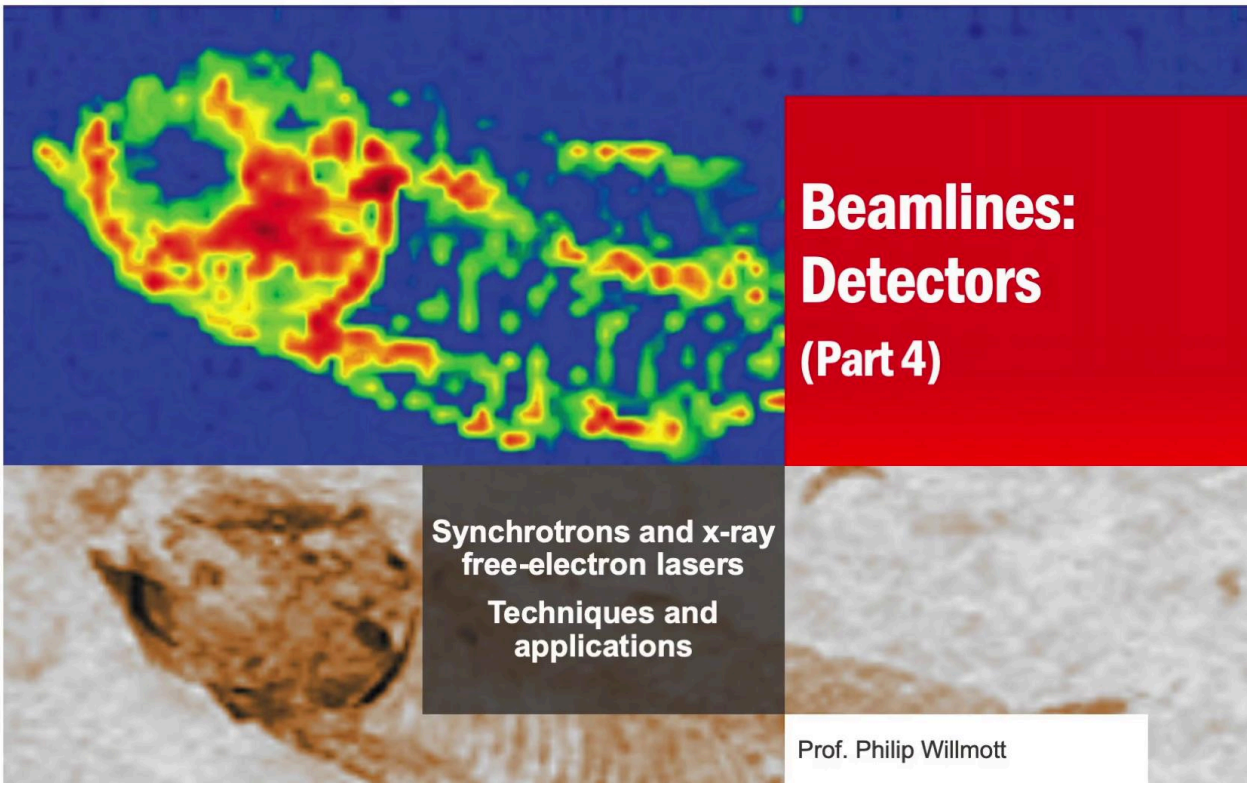
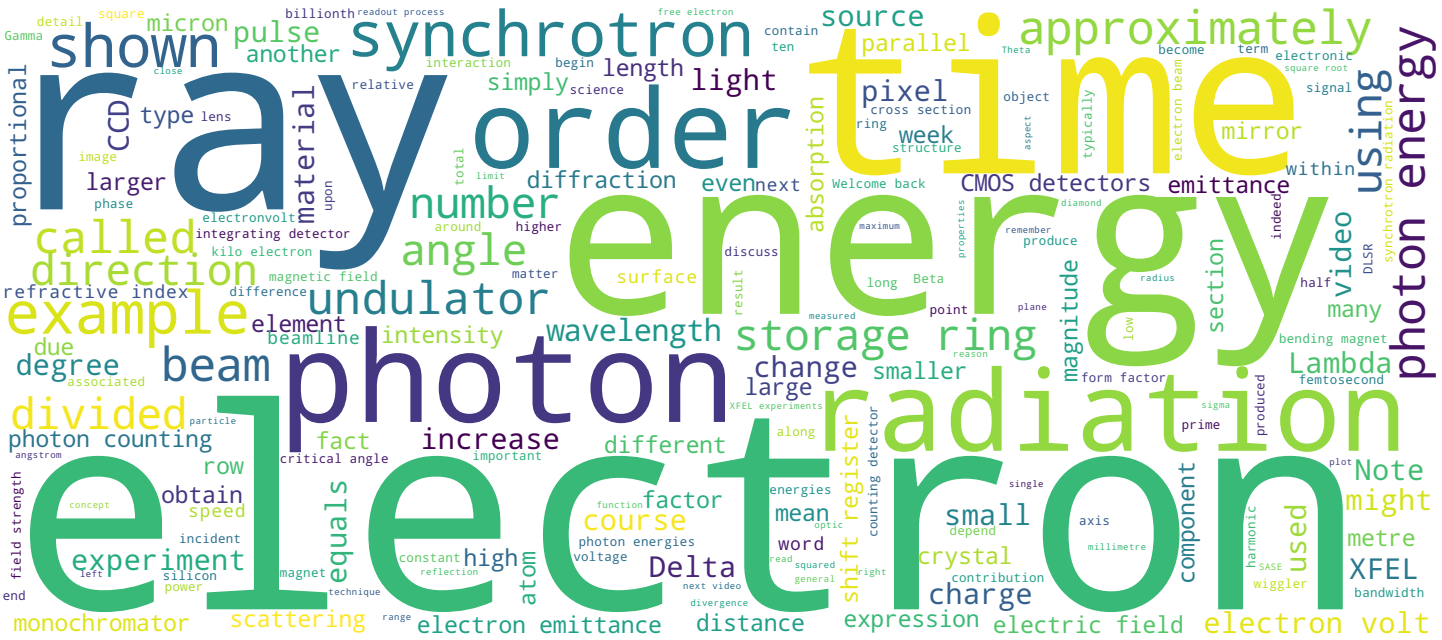

Beamlines:
Detectors
(Part 4)
Synchrotrons and x-ray
free-electron lasers
Techniques and
applications
Prof. Philip Willmott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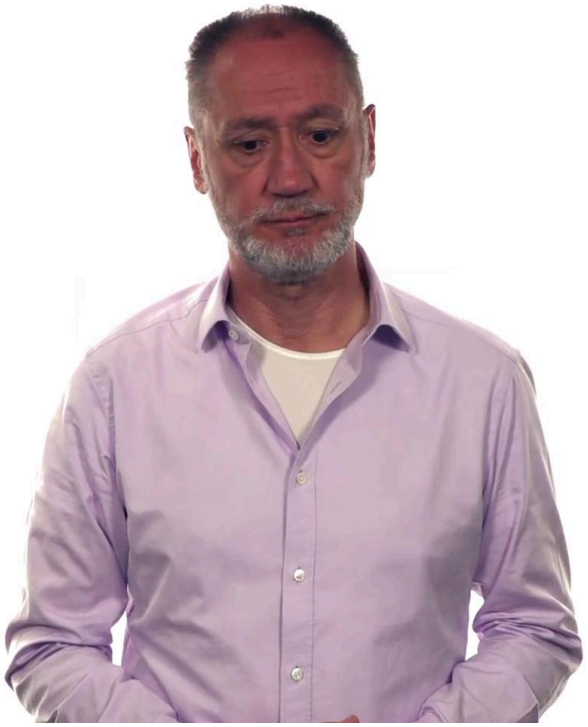
Video

Contents and objectives of this video



- Photon detectors
  - Charge-coupled devices
  - CMOS devices
  - Blooming and smearing
  - Detectors for XFEL experiments

Welcome back. In this penultimate video of this course, we look at two types of integrating detectors, namely CCDs and CMOS detectors. We will see that one must use integrating detectors with XFEL radiation, and we will make a comparative summary of photon counting CCD and CMOS detectors.

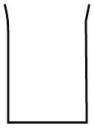
Notes

Summary

0m 05s

Charge-coupled devices

- Array of linked (‘coupled’) capacitors in an integrated circuit
- Each capacitor can transfer its charge to its neighbour
- During exposure to light, photons converted to electric charge in capacitor
  - Integrating device
  - Amount of charge ∝ photon energy
- After exposure, charges readout out sequentially
  - “Shift register”
- Converted to digital signal using an analog-to-digital converter (ADC)



Charge-coupled devices consists of lines of connected pixels, each pixel being a charge storing capacitor.

Notes

Summary

0m 27s

Charge-coupled devices

- Array of linked (‘coupled’) capacitors in an integrated circuit
- Each capacitor can transfer its charge to its neighbour
- During exposure to light, photons converted to electric charge in capacitor
  - Integrating device
  - Amount of charge ∝ photon energy
- After exposure, charges readout out sequentially
  - “Shift register”
- Converted to digital signal using an analog-to-digital converter (ADC)

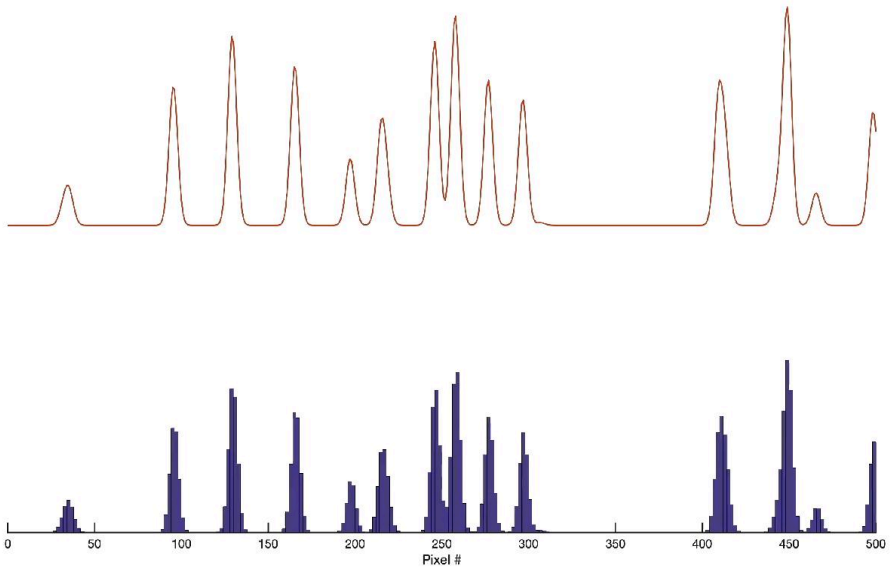
The capacitors collect charge when exposed to radiation, the amount of charge per photon being proportional to the photon's energy. Each capacitor can transfer its charge to its neighbour in the row during the readout process. The rows are called shift registers. At the end of the row, the readout charge is converted to a voltage and then a digital signal.

Notes

Summary

0m 39s

Charge-coupled devices and shift registers



≲ 50 MHz bit rate

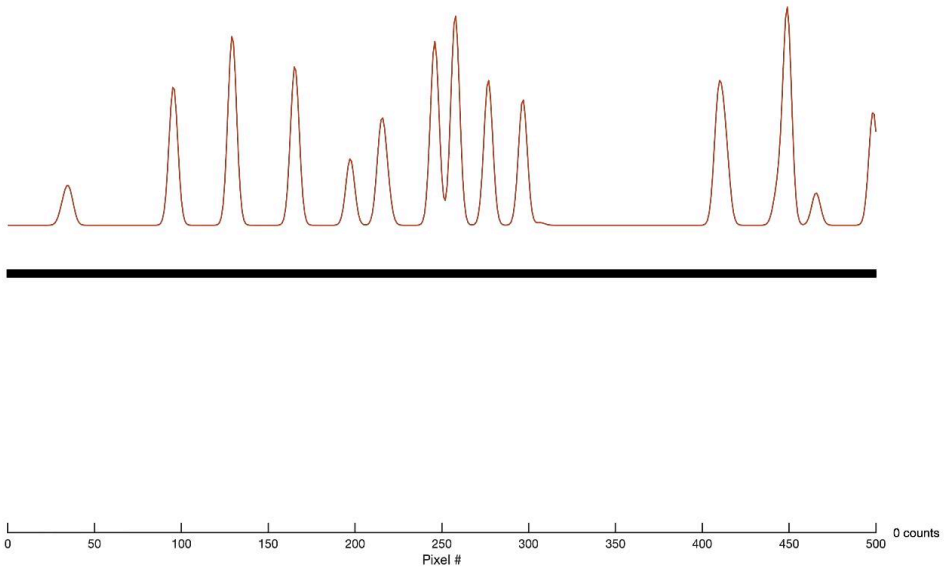
Let's look at a schematic cartoon of a shift register. Imagine a signal consisting of a collection of peaks shown by the red curve.

Notes

Summary

1m 08s

Charge-coupled devices and shift registers



$\lesssim$ 50 MHz bit rate

We open a shutter and the charge begins to accumulate in the row of pixels. After the exposure is over, the charges from each pixel are shifted to their neighbour in the direction of the readout. The last in the row has its charge converted to a voltage and then a digital output. This process continues until the entire length of the shift register is read out. Area CCD detectors consist of parallel arrays of such shift registers. The readout process is the limiting step in CCDs, given by a bit rate of approximately 50 MHz or less.

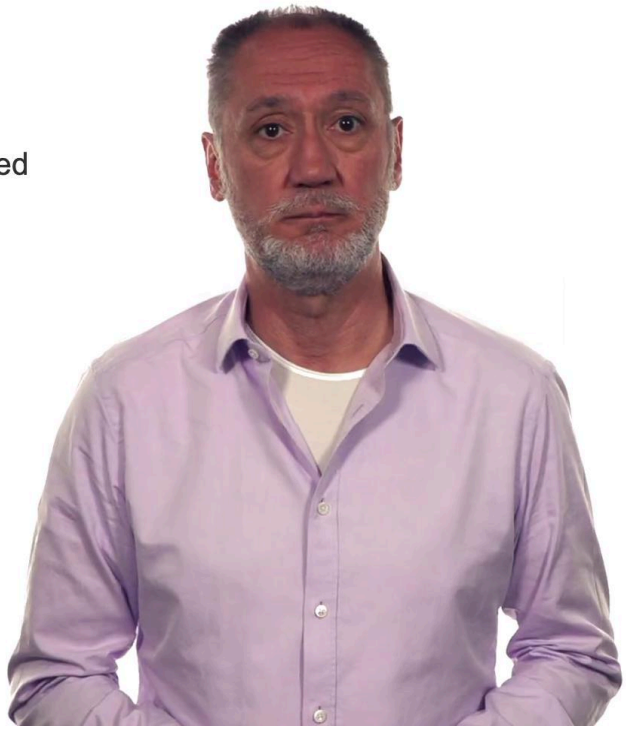
Notes

Summary

1m 20s

Charge-coupled devices summarized

- Strips of pixels read out sequentially via “shift register”
  - Transfer is through a very limited number of output nodes (often just one)
    ⇒ data-transfer bottleneck
  - Readout noise potential issue
  - Slows readout process
    ⇒ slower frame rates
- Whole of pixel available for detecting light
  - High efficiency
- Pixels have uniform response
  - Less need for flat-field corrections (c.f. CMOS)



Summarising CCDs, they consist of strips of pixels in lines called shift registers that are read out sequentially. This process means that the readout from CCDs has its bottleneck in data transfer due to this process, plus the fact that the readout process introduces noise in the signal. On a more positive note, the entire area of the pixel is sensitive to the instant radiation, making CCDs highly efficient. Moreover, they have a good uniformity, making the need for flat-field corrections less critical. Both the uniformity and efficiency are aspects in which CCDs perform better than CMOS detectors. CMOS detectors have other advantages, and we now look at these briefly before discussing artefacts in CCDs that also limit their usability.

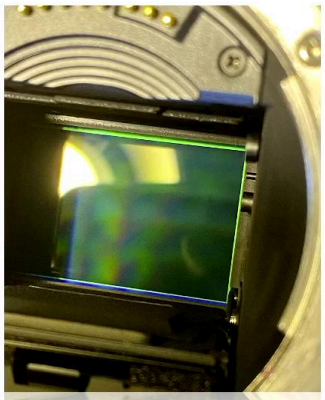
Notes

Summary

2m 02s

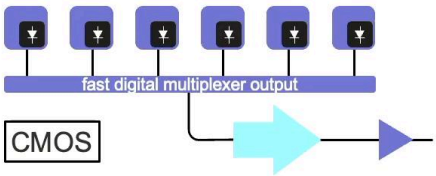
Complementary metal-oxide semiconductor devices

- Integrating (normally) device
- Each pixel
  - Converts photons to electrons
  - Rapid conversion of charge to voltage
    - "on-pixel" electronics ("active pixel sensor, APS)
    - Reduced light-capturing efficiency
    - More challenging to get homogeneous response from all pixels
- Massive parallel readout
  - Very low readout noise
  - Very high frame rates possible



Canon 1DX mk iii CMOS sensor

CCD



CMOS

CMOS detectors are ubiquitous in modern cameras, including those in smartphones. They normally operate, like CCDs, in an integrating mode. Importantly, the conversion from light to a digital signal happens individually on each and every pixel. CMOS sensors are thus called active pixel sensors, or APSs. This technology allows much faster readouts than for CCDs through digital multiplexing, though at the cost of reduced light capturing efficiency per unit area and a less homogeneous response from pixel to pixel.

Notes

Summary

3m 01s

Blooming and smearing in CCD and CMOS devices

- Each pixel has a maximum charge it can store
- If charge exceeds this, it will flow into adjacent pixels – “blooming”
- Preferred overflow spill in readout direction
- Results in “smearing” of saturated signal
- Problematic for weak signal close to strong signal

One last issue needs to be addressed regarding CCD and CMOS technology. The first, blooming, affects both types of sensor. Blooming is a spinning out of a bright signal in a certain region of the sensor to the neighbouring pixels due to the fact that each pixel can only store a finite amount of charge before it spills over into neighbouring pixels. In the case of CCDs, this problem is compounded by the shift register readout mechanism which smears the signal out in the readout direction. This is the reason above all, that all modern digital cameras and smartphones use CMOS detectors rather than CCDs, though cost, size of off sensor electronics and the need of more than one DC voltage supply also play a role. CCDs are preferable when the light intensity is low and detector sensitivity is thus at a premium.

Notes

Summary

3m 44s

Photon detectors – a comparative summary

Property	Photon counter	CCD	CMOS
Dead time τ	~ 100 ns	0	0
Fastest photon rate/pixel	~ 10^7/s	Unlimited	Unlimited
Dynamic range	~ 10^7	~ 10^5	~ 10^6
Max frame rate [s^{-1}]	~ 10^5	< 250	~ 10^4
Dark noise	No	Yes	Yes
Readout noise	No	Yes	No
Fluorescence suppression	Yes	No	No
Pixel size	~ 50 μm	~ 5 μm	~ 5 μm
Point-spread function	Pixel size	Depends on oversaturation	Pixel size
Blooming/smearing	No	Yes/yes	Yes/no

Before we move on to the use of integrating detectors or XFELs, it's worth summarising the relative merits of each detector type discussed in this and the previous of video. If photon arrival rates and ultimate pixel size are not an issue, photon counting detectors clearly win. However, if arrival rates of the photons significantly exceed the inverse of the dead time of photon counting devices, one has no choice other than to use CCDs or CMOS devices. This is clearly the case for XFEL experiments.

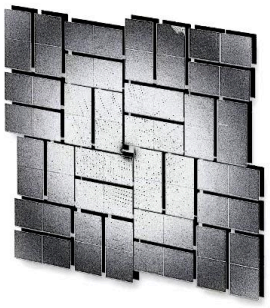
Notes

Summary

4m 49s

Photon detectors for XFEL experiments

- XFEL pulse duration ~ 30 fs
- # photons/pulse ~ 3 x 10^{12}
- Arrival rate of photons during pulse ~ 10^{26}/s
- ⇒ Photon-counting detectors unusable!
- ⇒ Must use integrating detectors
- Require
  - High sensitivity
  - Large dynamic range



S. Boutet *et al.*, Science **337** 362 (2012)
H. N. Chapman *et al.*, Phil. Trans. R. Soc. B **369** 20130313 (2014)

You might remember that a typical hard XFEL pulse has a duration of maybe 30 fs and an energy of five millijoules. If we convert this energy into the number of 10 kilo electron volt X-ray photons, we obtain a number of approximately three times 10 to the 12 photons, meaning that the average separation between photons within any one FEL pulse is 10 billionth of a billionth of a billionth of a second. Consider a diffraction peak produced by scattering of this pulse. It might only contain a billion photons per pulse. Even so, this number far exceeds anything that could be detected using a photon counting detector. Instead, we need to use integrating detectors, ones with high sensitivity and a large dynamic spectral range.

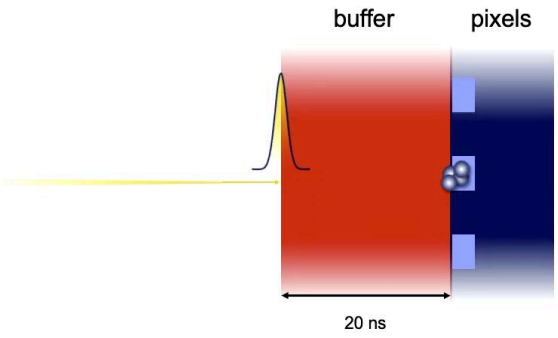
Notes

Summary

5m 27s

Photon detectors for XFEL experiments

- Pixel detector (Eiger) technology with integrating mode
- Automatic variation of sensitivity
  - Small signal: most sensitive
  - Large signal: less sensitive
- How can this work?
  - No electronics that control sensitivity can respond within 30 fs XFEL pulse duration!!!
  - Answer:
    - “buffer” layer slows response
    - Electronics can respond within 20 ns arrival time of charge across buffer layer



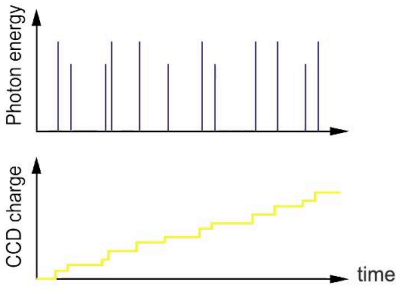
In general, standard CCDs cannot provide anywhere near the same dynamic range as photon counting detectors. However, if the detector can change its sensitivity according to the intensity of the signal, increased sensitivity for weak signals, less sensitivity for strong signals, then they might be ideal for XFEL experiments. But how on Earth could this work? No pixel can predict the intensity of an incoming signal a priori, or use electronics that adjust according to the signal strength within the few tens of femtoseconds of the signal duration or the signal arrival. The solution is to produce photo electrons in the surface region of a buffer layer, which are then allowed to drift across this layer towards the pixel array over approximately 20 nanoseconds. This is plenty enough time for fast electronics to respond to the increase in charge, if necessary.

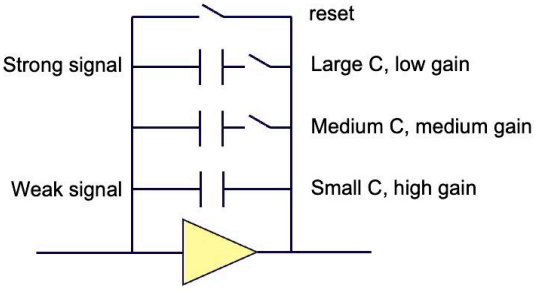
Notes

Summary

6m 26s

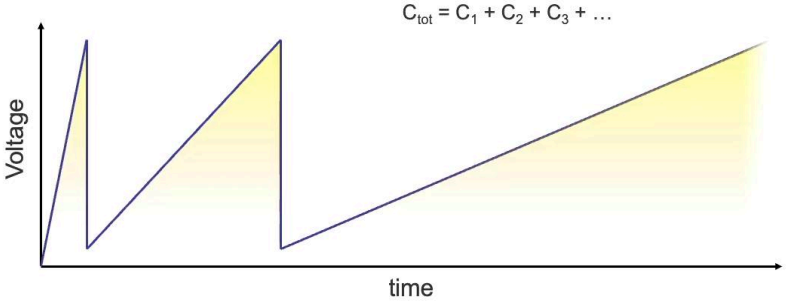
Jungfrau – adjusting the sensitivity on the fly





Capacitors in parallel:
$C_{tot} = C_1 + C_2 + C_3 + \ldots$

$$V = \frac{Q}{C}$$



https://www.psi.ch/en/detectors/jungfrau

In the case of the Jungfrau detector developed at the Paul Scherrer Institute explicitly for XFEL experiments, the relationship between voltage and charge is exploited in a capacitor. This is inversely proportional to the capacitance associated with each pixel. If the voltage increases beyond a certain threshold, a second capacitor circuit is closed in parallel to the first. The total capacitance of capacitors in parallel is simply the sum of the individual capacitor values. Indeed, a third capacitor is included in parallel to increase the dynamic range still further. See also the link provided in the bottom left here.

Notes

Summary

7m 27s

In the next video...

In the next and final video of this course, we complete our discussion of detectors by looking at dispersive photon detectors and concentric hemispherical electron energy analyzers, before giving you, the student, a taste of the second course and how it interfaces with the contents of this course.

Notes

Summary

8m 14s