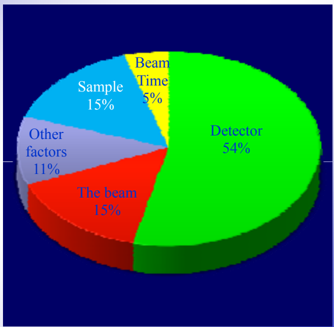
Detectors for Synchrotron Radiation

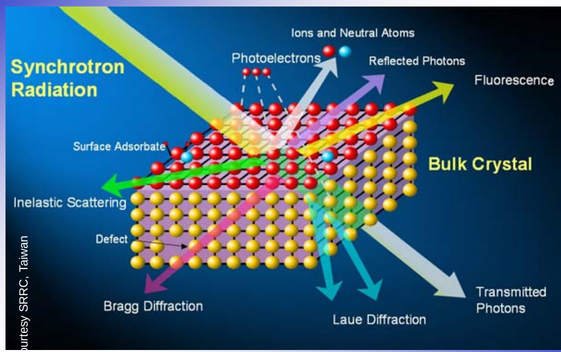
Rob Lewis
Monash University

Factors Limiting Science

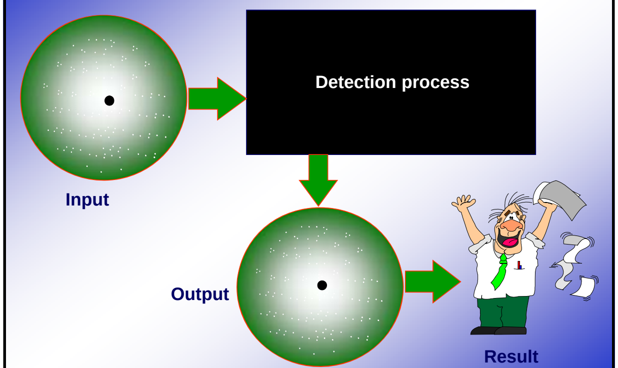
- Detectors are an oft-neglected but crucial part of an experiment
- They often limit the science



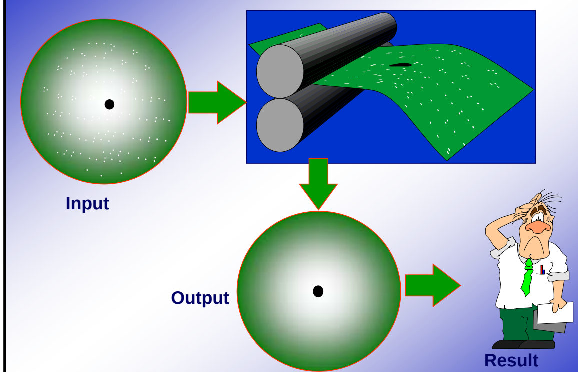
X-rays and their Interaction with Matter



Scientist's View of Detector



The Truth!



Detection Mechanisms

- There are many means of detection. All require the interaction of photons with matter
- Examples include
  - Gas ionisation
    - Photons produce electrons and ions which are then detected
    - E.g. Ion chambers, proportional counters
  - Photoelectric effect
    - Photons eject electrons from a solid creating a current which is measured
    - E.g.. Beam monitors
  - Generation of electron hole pairs
    - Photons produce electrons and holes in a semiconductor which are then detected
    - E.g.. CCDz
  - Fluorescence, scintillation and F centres
    - Photons produce prompt fluorescence or F centres
    - E.g. Image plates and Scintillation counters
  - Chemical effect
    - Photons create a chemical change such as dissociating Ag halide
    - E.g. Film

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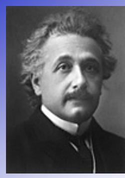
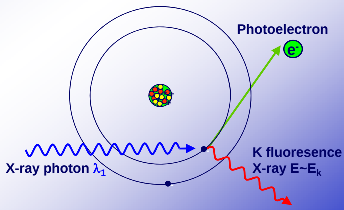
Albert Einstein



Germany and Switzerland
Kaiser-Wilhelm-Institut
(now Max-Planck-Institut)
für Physik
Berlin-Dahlem, Germany
1879 - 1955

Nobel prize in physics 1921
"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"

Photoelectric Effect



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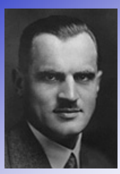
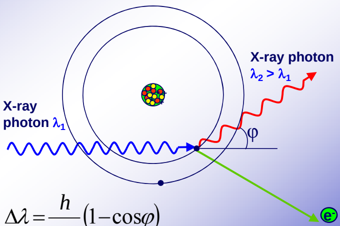
Arthur Holly Compton



University of Chicago
Chicago, IL, USA
1892 - 1962

Nobel prize in physics 1927
"for his discovery of the effect named after him"

Compton Effect



$$\Delta\lambda = \frac{h}{m_0 c}(1-\cos\varphi)$$

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What are we trying to do?

- We are usually trying to determine the effect of the sample on the beam
- i.e. we are looking for a DIFFERNCE
- We therefore need to measure the beam both before and after the sample

- There are many means of detection. All require the interaction of photons with matter
- How can we do that without the detector changing the beam?

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An Example Detector

Echidna

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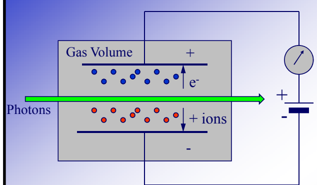
Ionisation Chamber



- Very simple device
- Approximately 1 e⁻ ion pair per 30eV deposited
- Important that recombination low as possible
  - Higher voltages required at higher rates since more carriers
  - Diffusion losses caused by separation of carriers minimised by higher voltages
- Ion chambers are sensitive pressure and temperature

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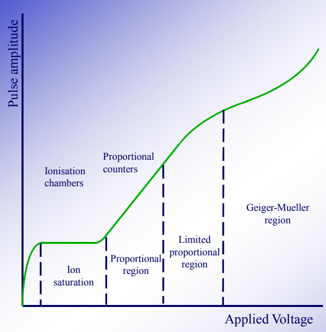
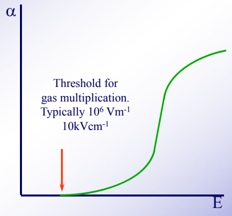
Operation regions of gas filled detectors



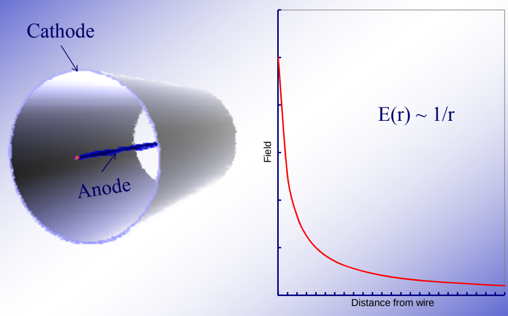


n is number of charges
x is distance
α is the first Townsend coefficient

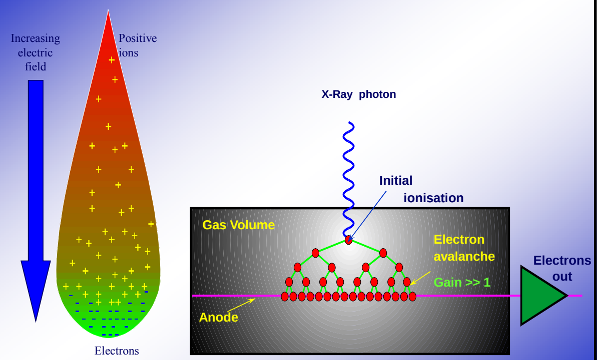
$$\frac{dn}{n} = \alpha\, dx$$

$$n(x) = n(0)e^{\alpha x}$$

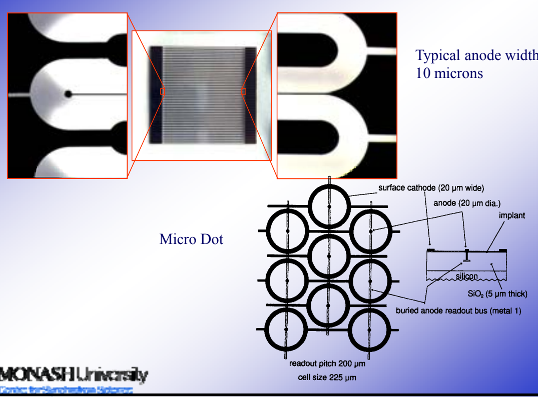
Field Variation



Avalanche & Proportional Counter



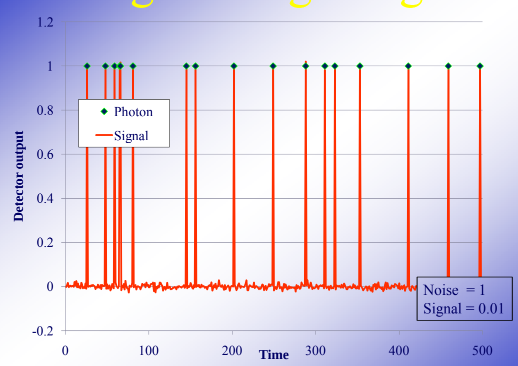
Microstrip Variants



Counting and Integrating

- If there is sufficient signal produced by the interaction of a photon or a particle in the detector then it is possible to operate the detector as a counter

Counting & Integrating



Counting and Integrating

- Usually this is not true and we have to accumulate many photons/particles before the signal becomes measurable

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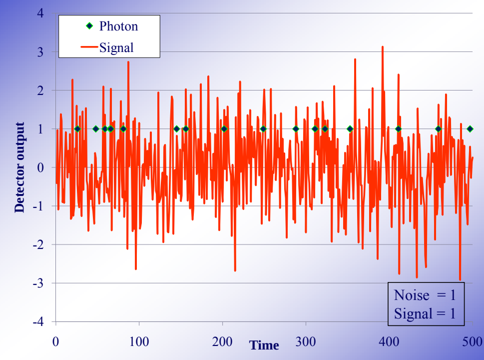
Counting & Integrating



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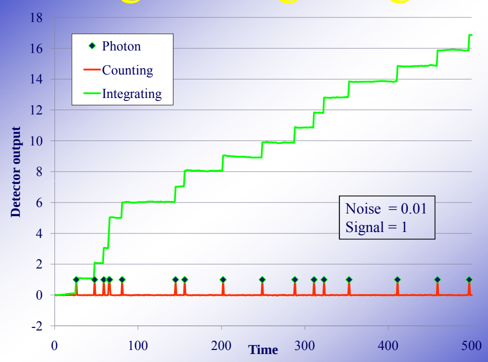
Counting & Integrating



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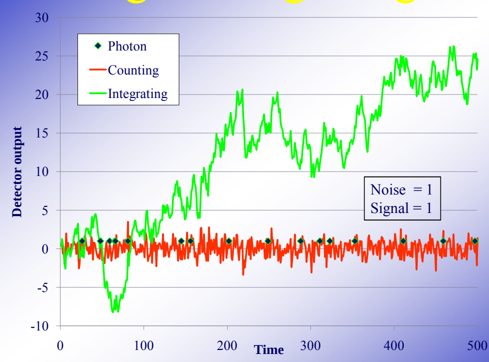
Counting & Integrating



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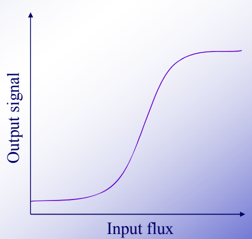
Integrating Detectors

- Mode
  - Measures deposited energy at end of integration period
- Characteristics
  - High input flux capability
  - Read noise dominates at low signal ("fog level")
  - Dead time between frames
  - 2×20 keV phts = 1×40 keV photon i.e. Cannot perform simultaneous spectroscopy and positioning
  - Examples: Image plates, CCDs



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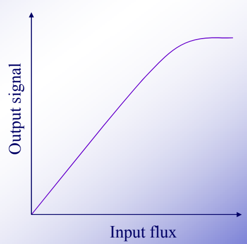
Photon Counting Detectors

- Mode
  - Detects every photon as it arrives. Only active pixels read
- Characteristics
  - Quantum limited, Detector noise often negligible
  - No dead time between frames
  - Can measure position and energy simultaneously
  - Limited input flux capability
  - Examples: Prop counters, Scintillators



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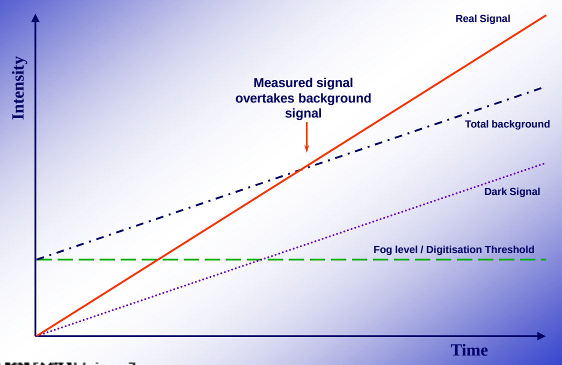
Dark Signals & Fog

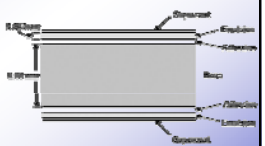


Types of Detectors

Crimson Rosella and King Parrot

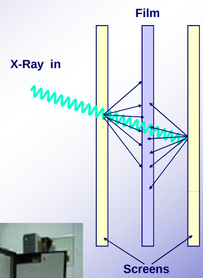
X-ray Film

- Active Ingredient
  - Small crystals of silver halide ~1.0 - 1.5µm
  - Typically 90-99% silver bromide and 1-10% silver iodide.
  - Suspended in the gelatin of the film emulsion.
  - Crystals have a cubic lattice with many point defects and free silver ions
- Exposure
  - A photon liberates an electron from a bromide ion
  - The electron travels until trapped at a defect
  - A free silver ion is attracted to the negative charge and combines (is reduced) to form an atom of metallic silver (which is optically black).
  - The single silver atom acts as an electron trap for another electron which then attracts another atom of silver which is then reduced to metallic silver. This process continues while the exposure to light continues.
- Conventional film is usually coated with emulsion on only one side, radiographic film is usually double coated (on each side of the base) to be used with intensifying screens.

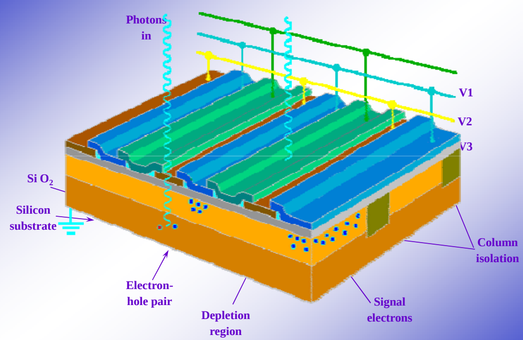


Intensifying Screens

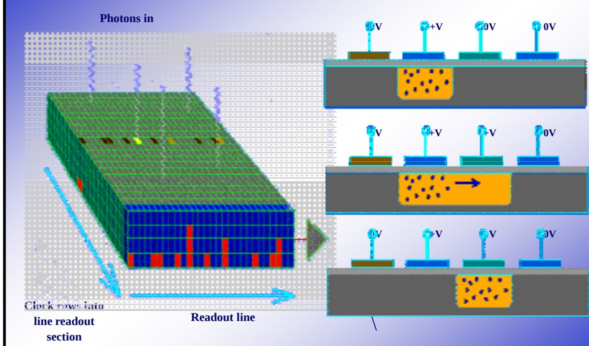
- An intensifying screen converts x-ray energy into light energy
- X-rays are absorbed by the phosphor
- The phosphor becomes excited & fluoresces emitting UV and/or visible light
- For every x-ray photon absorbed, hundreds of light photons are emitted
- The use of intensifying screens inevitably means that certain degree of unsharpness will be introduced into the image in comparison to non-screen film



Charge Coupled Device



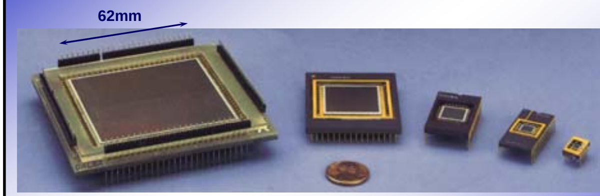
CCD Readout



CCD Readout

- Charge is moved from pixel to pixel by clocking
- Each pixel has a limited capacitance (well depth) typically 10^4-10^5 e^-
- This limits dynamic range for direct detection
  - 10keV photon creates ~ 3000e^- so saturation = ~ 10 photons
- Speed of clocking is restricted by line capacitance and charge transfer efficiency
  - Size of CCD restricted by this
- Noise can be reduced by cooling
- Amplifier usually on chip
  - Heats up that part of chip

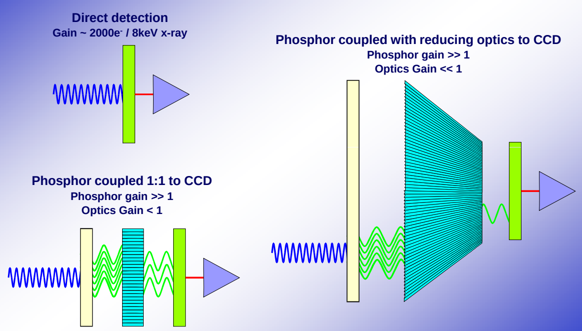
CCDs



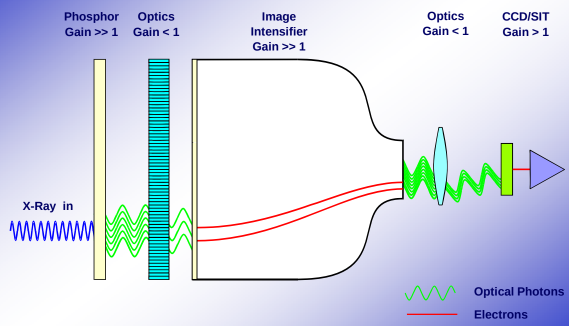
Although sizes > 50mm are available, the read speed is slow to preserve low noise and cte (line capacitance becomes very high)

Shutter required

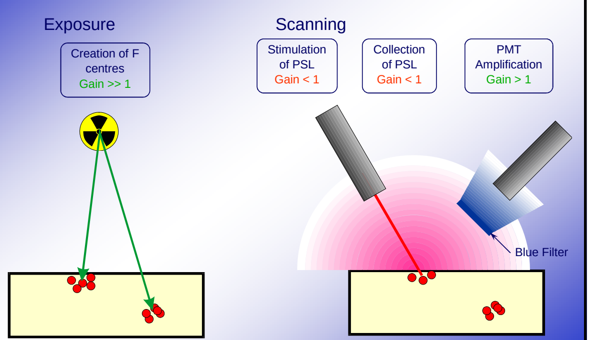
CCD detectors



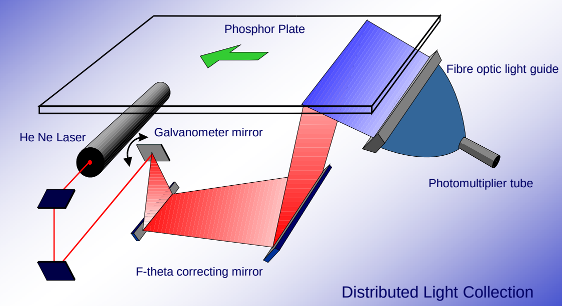
TV detector with IIT



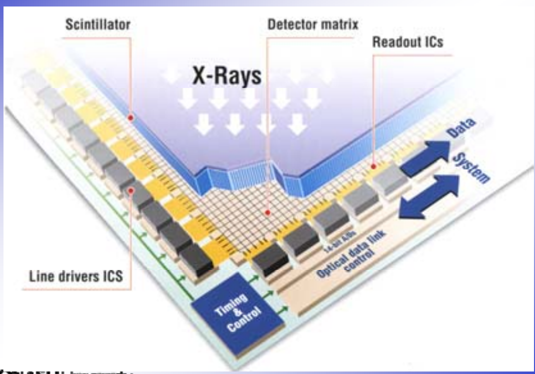
Computed Radiography-Image Plate



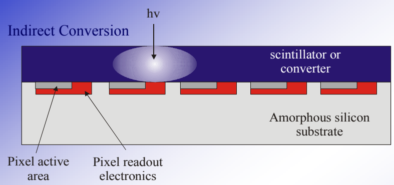
X-Y Flat bed Scanner

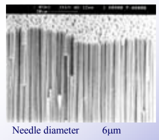


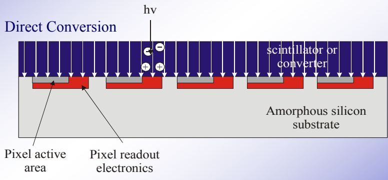
TFT Flat panel Detector



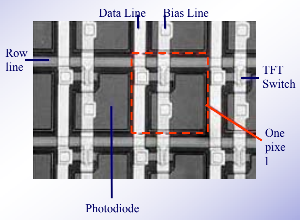
a-Si:H TFT arrays

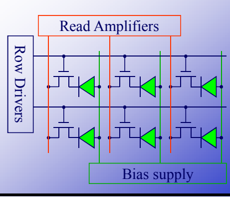






a-Si:H Array dpiX - Flashscan 30

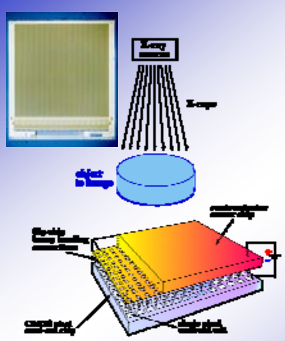




CMOS Imagers

- Based on standard manufacturing technology
  - Electronics integrated onto same chip as image sensor
  - Gd_2O_2S - Kodak Lanex® Fine
- Rad Eye 1 from Radicon
  - 1024x512 48 micron pixels
  - 24.6 x 49.2 mm² active area
  - MTF good to 10 lp/mm
  - Tileable on 3 sides
  - Dark current ~4000e-/s = 10 x CCD room temp
  - 10000:1 dynamic range
  - 4.5 frames/s
- Cheap

Medipix 1



- Square pixels of 170µm side-length
- 64 x 64 pixels per chip
- Sensitive to positive charge
- Leakage current compensation at the input
- Maximum count rate: ~2 MHz
- 1 comparator per pixel with 3 bits fine tuning
- Minimum threshold ~1500e^-(~5.5 keV deposition in a Si sensor)
- 15 bit counter per pixel (32767) single events
- Variable acquisition time
- Read-out time: 384µs @ 10 MHz
- Active area of the chip: ~1.2 cm²

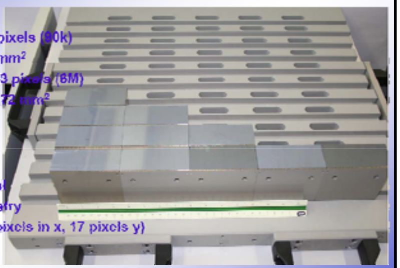
http://medipix.web.cern.ch/MEDIPIX/

Sardine

- Mo X-ray tube + 30 µm Mo filter 25 kV, 10 mAs,
- Detector stepped for one detector width in X and half a detector width in Y
- Aquisition time per image: 500 ms.
- No image correction was used (raw data!).
- The thickness of the fishbones corresponds roughly to the pixel size.

PILATUS 6M Detector

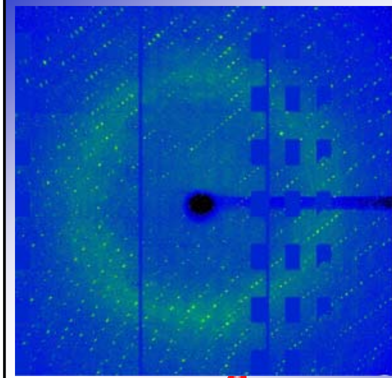
No. of Modules	60
Module size	487 x 195 pixels (90k)
Detector Size	431 x 448 mm²
No of Pixels	2527 x 2463 pixels (6M)
Spatial resolution	0.172 x 0.172 mm²
Dynamic range:	20bits
Readout time	~2ms
Frame rate	5-10 Hz
Rate	1 MHz/pixel
Spatial distortion	Flat geometry
Dead area	~8.4 % (7 pixels in x, 17 pixels y)



Ch. Brönnimann, E. Eikenberry, B.Schmitt, M. Naef, G. Hülsen (SLS); R. Horisberger, S. Streuli (TEM); Ch. Buehler (LOG); F. Glaus (LMN); M. Horisberger (LNS)

Paul Scherrer Institut SLS Detector Group

Lysozyme PILATUS



- 1° rotation
- 2s exposure,
- E=12 keV
- 7 detector positions
- Flatfield corrected

Paul Scherrer Institut SLS Detector Group

Spectroscopic Detectors

Rainbow Lorikeets

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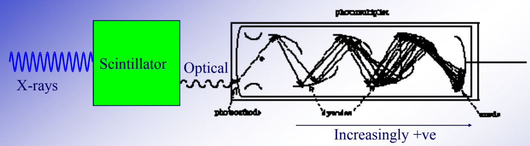
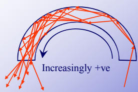
Electron multipliers & Scintillators



Channeltron is a similar with distributed dynode

Micro-channel plates are mutlichannel channeltrons with each channel being an electron multiplier.



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Multi Channel Spectoscopic Detectors

Canberra Ultra-LEGe detector

WRULEAD (Windowless, Retractable, Ultra Low Energy Array Detector) works down to 300eV

Multichannel devices up to 30 channels at 3×10^5 cts s^{-1} $channel^{-1}$ have been built

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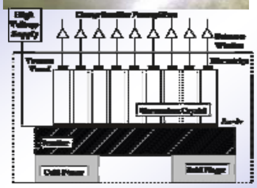
SPring-8 128 channel Ge strip



- Ge
  - 55.5×50.5×6mm
- Strips
  - Number 128
  - Width 300μm
  - Interstrip 50μm
  - Length 5mm
- Readout
  - Single channel 100ns
  - 32 channels 3.2ms
- Max expected count rate
  - 14kcps

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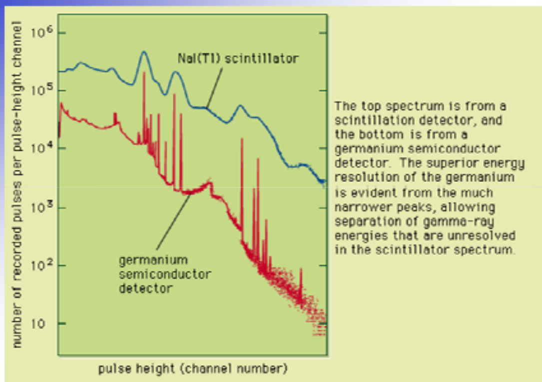
Scintillator vs Germanium



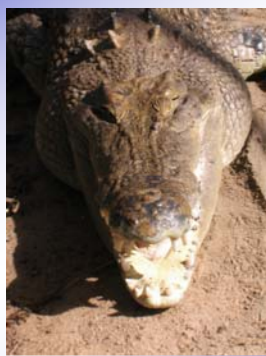
Spectral Resolution

- Average number of carriers, N = E/w
  where w is energy to create electron hole/ion pair
- Poisson statistics $\sigma = 1/\sqrt{N}$
  $= (E/w)^{-½} = (w/E)^{½}$
- $\Delta E/E$ fwhm $= 2.355\sigma$
  $= 2.355(w/E)^{½}$
- For Ge, w= 3eV so at 10keV $\Delta E/E$ ~ 4%
- For NaI, w= 30eV so at 10keV $\Delta E/E$ ~ 13%

Fano Factor

- If all energy from photon or particle were converted into carriers there would be no variance
- Poisson statistics assume only a small fraction of energy goes into charge creation
- Reality is somewhere in between so we introduce Fano factor F
- Fano factor is defined as $F = \frac{\sigma^2}{\mu}$
  where σ^2 is the variance and μ is the mean number of carriers
- For a Poisson process, the variance equals the mean, so $F = 1$
- Examples
  - Si: 0.115
    Ge: 0.13
    GaAs: 0.10
    Diamond: 0.08
- Observed relative variance = F x Poisson relative variance

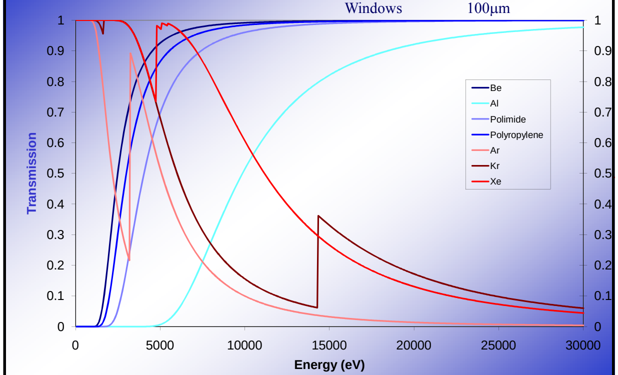
Things to Look Out For



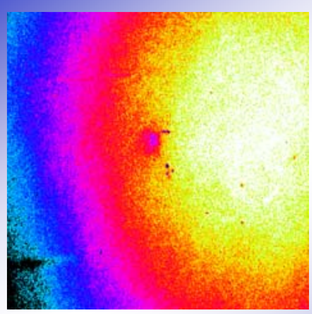
Crocodile

Efficiencies

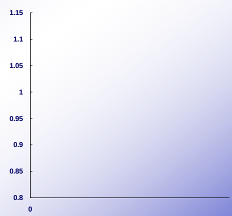
Gas thickness 1cm
Windows 100µm

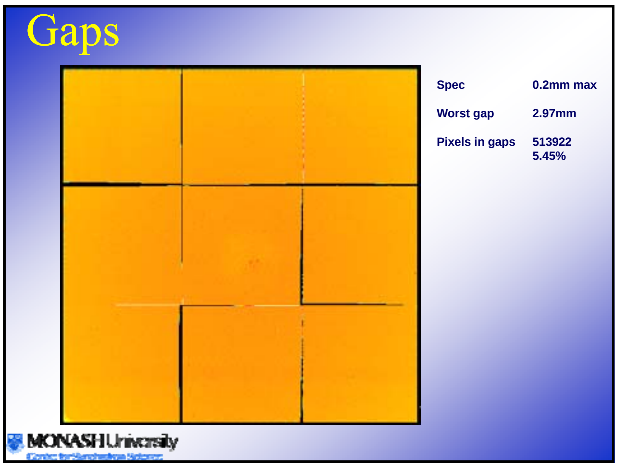


Response to Uniform Illumination



ESRF TV Detector
Thompson IIT & CCD




Gaps
Spec 0.2mm max
Worst gap 2.97mm
Pixels in gaps 513922
5.45%
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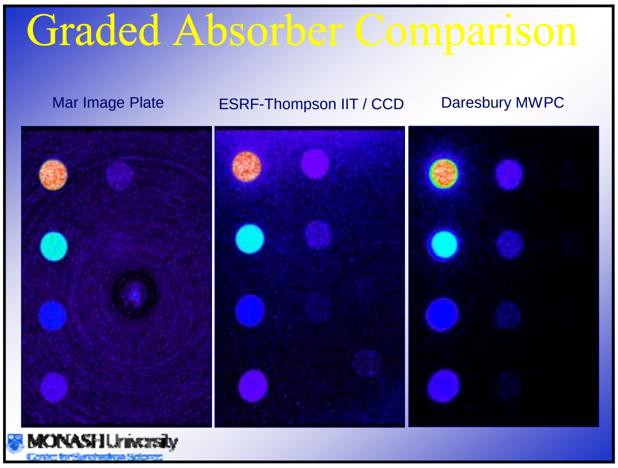
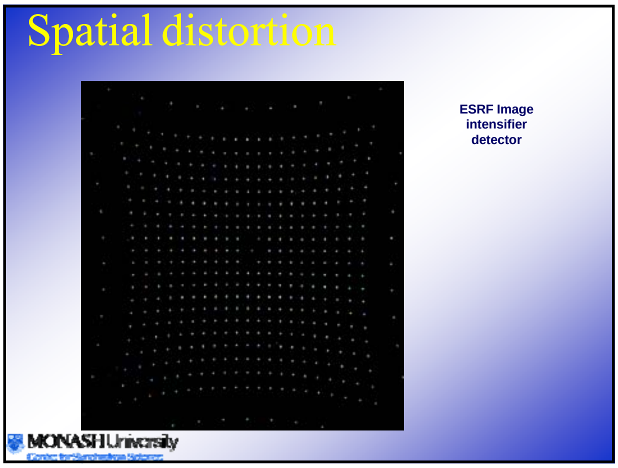
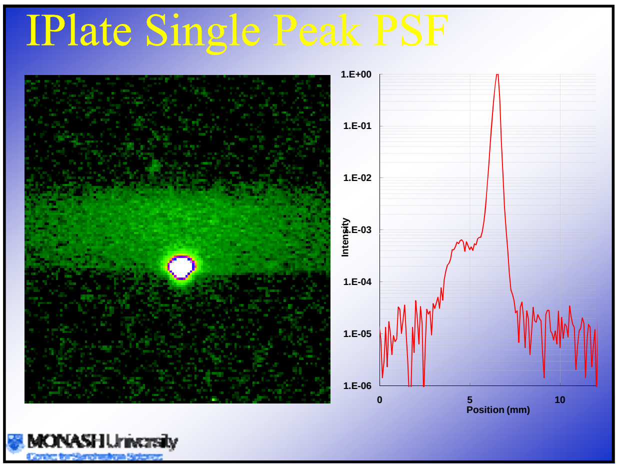
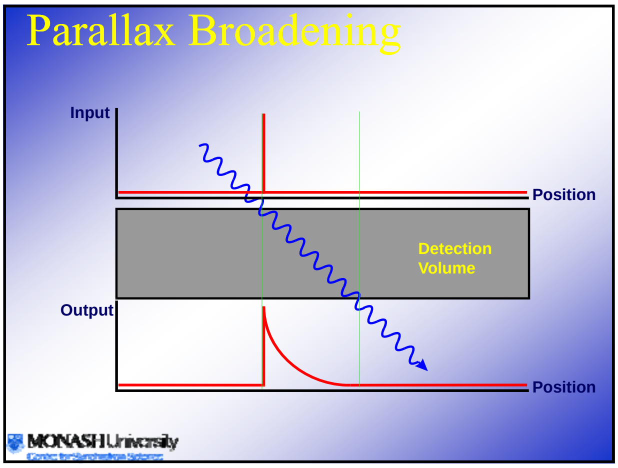
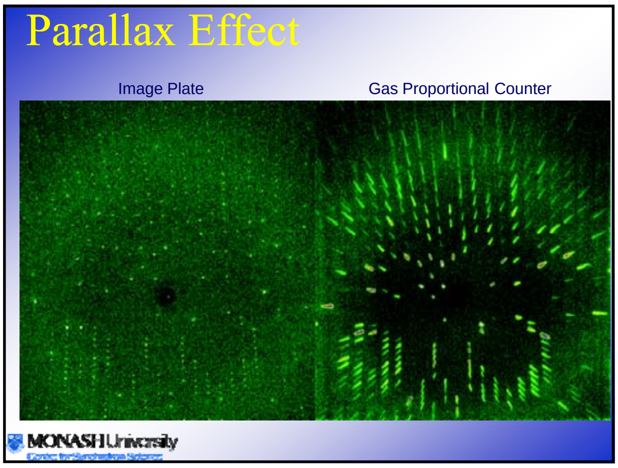
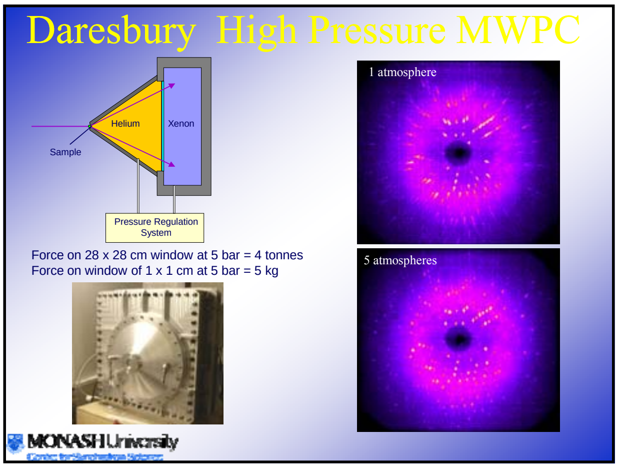

Graded Absorber Comparison
Mar Image Plate
ESRF-Thompson IIT / CCD
Daresbury MWPC
MONASH University


Spatial distortion
ESRF Image intensifier detector
MONASH University

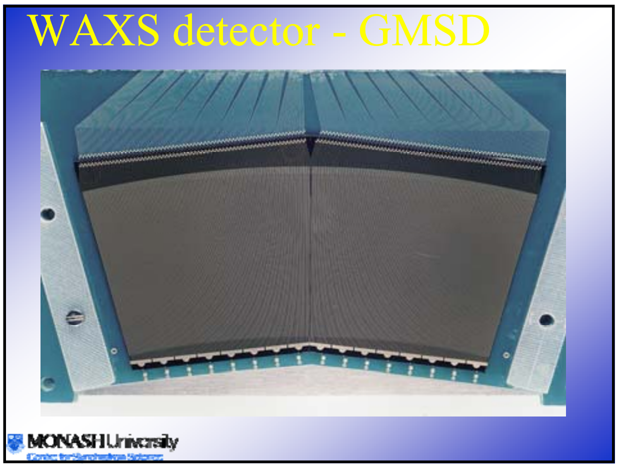

IPlate Single Peak PSF
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
Intensity
0
5
10
Position (mm)
MONASH University

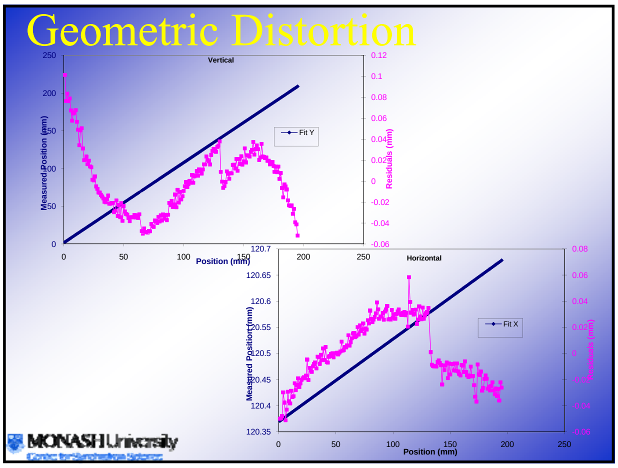

Parallax Broadening
Input
Position
Detection Volume
Output
Position
MONASH University

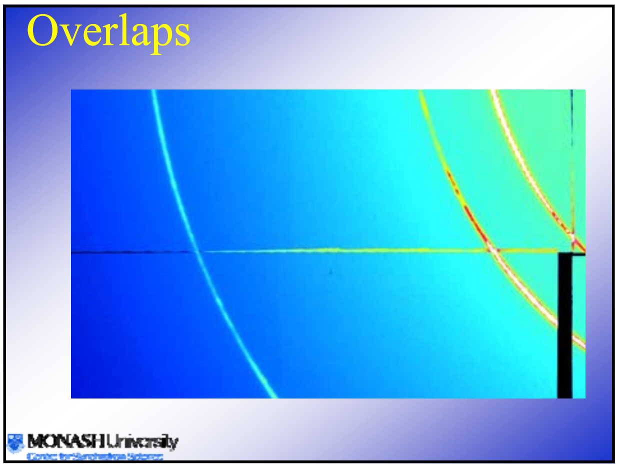

Parallax Effect
Image Plate
Gas Proportional Counter
MONASH University


Daresbury High Pressure MWPC
Helium
Xenon
Sample
Pressure Regulation System
Force on 28 x 28 cm window at 5 bar = 4 tonnes
Force on window of 1 x 1 cm at 5 bar = 5 kg
1 atmosphere
5 atmospheres
MONASH University


RAPID2 SAX WAX
MicroGap Quadrant Detector
MicroGap Curved Detector
Sample
RAPID electronics
MONASH University


WAXS detector - GMSD
MONASH University


Geometric Distortion
Vertical
Measured Position (mm)
Residuals (mm)
Position (mm)
Fit Y
Horizontal
Fit X
MONASH University


Overlaps
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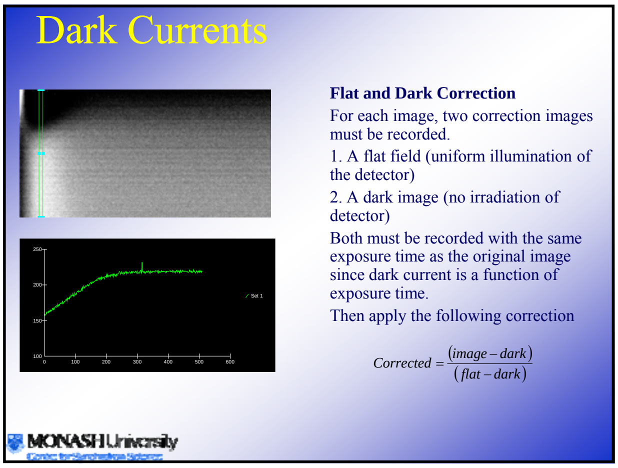
Dark Currents
Flat and Dark Correction
For each image, two correction images must be recorded.
1. A flat field (uniform illumination of the detector)
2. A dark image (no irradiation of detector)
Both must be recorded with the same exposure time as the original image since dark current is a function of exposure time.
Then apply the following correction
Corrected = (image – dark) / (flat – dark)
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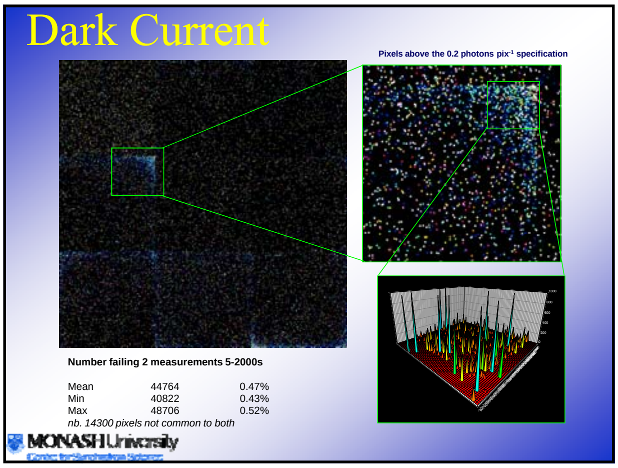
Dark Current
Pixels above the 0.2 photons pix⁻¹ specification
Number failing 2 measurements 5-2000s
Mean 44764 0.47%
Min 40822 0.43%
Max 48706 0.52%
nb. 14300 pixels not common to both
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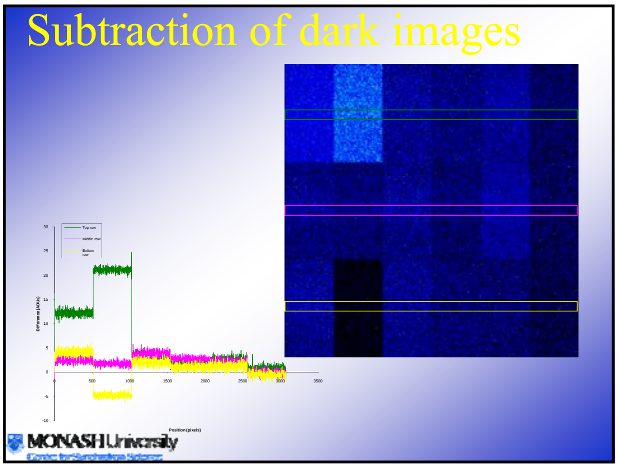
Subtraction of dark images
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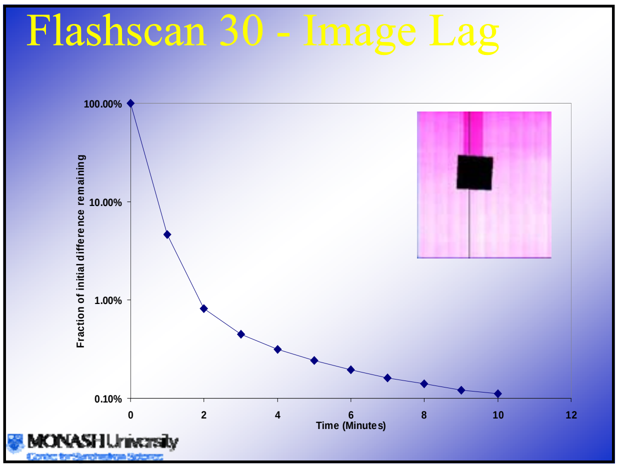
Flashscan 30 - Image Lag
Fraction of initial difference remaining
100.00%
10.00%
1.00%
0.10%
0
2
4
6
8
10
12
Time (Minutes)
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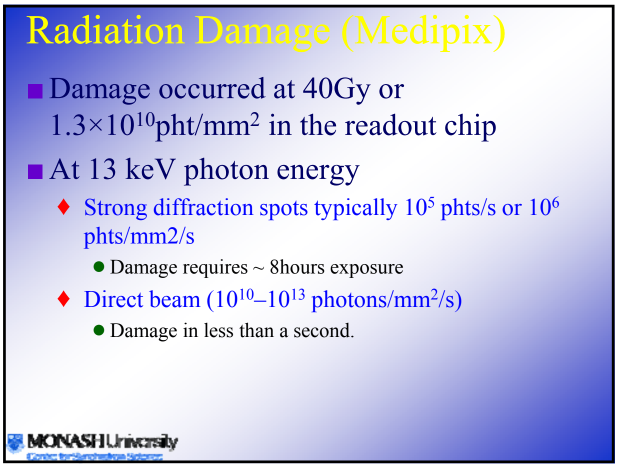
Radiation Damage (Medipix)
Damage occurred at 40Gy or 1.3×10¹⁰pht/mm² in the readout chip
At 13 keV photon energy
Strong diffraction spots typically 10⁵ phts/s or 10⁶ phts/mm2/s
Damage requires ~ 8hours exposure
Direct beam (10¹⁰–10¹³ photons/mm²/s)
Damage in less than a second.
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dpiX Flashscan 30 PaxScan 4030
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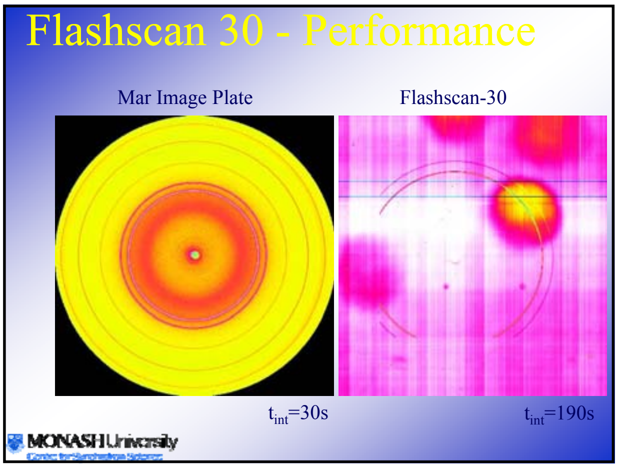
Flashscan 30 - Performance
Mar Image Plate
Flashscan-30
t_int=30s
t_int=190s
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Electronics Issues

Koalas

Albino Kookaburra

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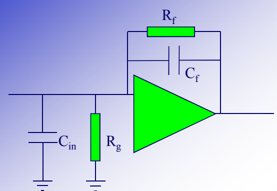
Amplification



- Voltage mode
  - Output α input voltage
  - Effect of R_f dominates C_f
- Current mode
  - Output α input current
  - Low input impedance
- Charge mode
  - Output α input charge
  - C_f dominates R_f

- In almost all cases we require some form of amplification
- Interaction of pre amplifier with detector is critical for performance of system
- Most important element is the input, often a FET
- Noise is the major issue
  - Thermal or Johnson Noise
    - Brownian motion of electrons
    - No current flow required

$$\bar{v}^2 = 4kTRdf$$

  - Shot Noise
    - Fluctuations in current

$$\bar{i}^2 = 2q_e\bar{I}df$$

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Equivalent Noise Charge

- Low noise is no use if signal is low
- Introduce ENC which is that signal charge that will produce the same output as the RMS noise

$$ENC^2 = \exp(2)\left[\frac{kT}{2R_g}\tau + \frac{eI_D}{4}\tau + \frac{kT(C_{in})^2}{2g_m\tau}\right]$$

Where
- k = Boltzman's constant
- T = temperature
- e = the electronic charge
- R_g = Load resistance and/or feedback resistance
- g_m = transconductance of input FET. (Links current in to voltage out)
- τ = Rise time of amplifier
- C_{in} = input / stray and feedback capacitance

- Note that ENC is directly related to energy resolution
- FWHM(keV) = 2.355×10^{-3} ENC/ew where w is the energy per electron

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Noise Dependence

$$ENC^2 = e^2\left[\frac{kT}{2R_f}\tau + \frac{q_eI_D}{4}\tau + \frac{kT(C_{in})^2}{2g_m\tau}\right]$$

- τ optimum at

$$\tau_{opt} = \left[\frac{kT/2g_m}{(kT/2R_f)+(q_eI_D/4)}\right]^2 C_{in}$$

- Choosing optimum τ gives best noise performance but may not be fast enough
- We often have to sacrifice energy resolution for speed

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Optimum τ

$$ENC_{min}{}^2 = 2\exp(2)\left[\left(\frac{kT}{2R_g}\right)+\left(\frac{eI_D}{4}\right)\left(\frac{kTC_{in}{}^2}{2g_m}\right)\right]^2$$

- R_g as large as possible ~ $10^{10}\Omega$
- I_D (leakage) as small as possible
  - For Ge cooling is vital
- Low T is good
- C_{in} as small as possible (note that this includes C_f)
- g_m as large as possible but this affects C_{in}

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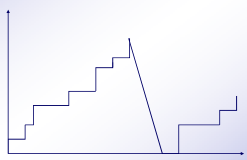
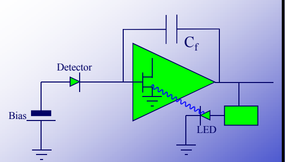
Optimum Spectral Resolution

- Low capacitance
  - Small planar < 1pF
- Low leakage currents
- Maximise R_g and/or R_f
  - Remove altogether so $R_f = \infty$
- Use optical reset
- Can improve FWHM by 20%





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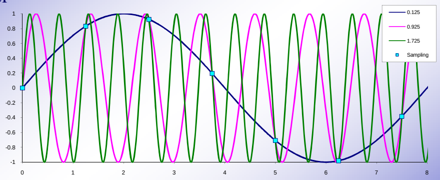
Shannon's Theorem or Nyquist Criterion

- If the input is not band limited to frequencies less than ωs/2, then aliasing will occurs at frequencies ω1±n where;
- ω1 = original signal frequency, ωs = sampling frequency, n = an integer



- The highest frequency that can be measured is twice the sampling frequency
- If you have 100µm pixels, ideal PSF > 200µm

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Synchrotron Detectors

- A synchrotron source is used primarily when sensitivity is an issue
  - Signal too weak
  - Time resolution too poor
  - Sample too small
- More intensity can help this but…
- It places a major strain on detectors and

Flux is a major issue!

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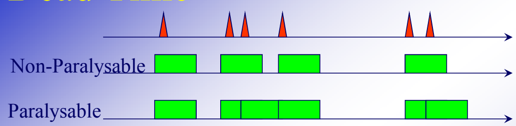
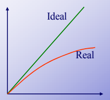
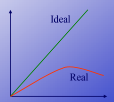
Dead Time



R_i=input rate, R_d=detected rate, τ dead time

- Non-paralysable
  - Fraction of time detector is dead = $R_d\tau$
  - Live time is therefore = $1 - R_d\tau$
  - Input rate = $R_i = R_d/(1-R_d\tau)$
- Paralysable
  - R_d = Probability of getting no event within τ of an event
  - Probability of n events in time t is $P(n,t) = \frac{e^{-R_i t}(R_i t)^n}{n!}$
  - Detected rate $R_d = P(0,\tau) = R_i e^{-R_i\tau}$





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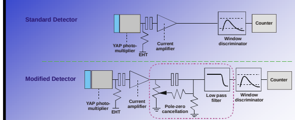
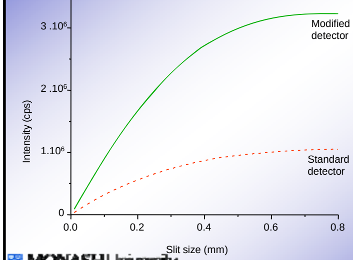
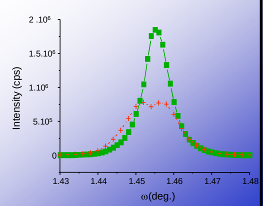
EDR Detector for Powder Diffraction



Standard detector
- Saturation count rate: 1 MHz
- Linear region: up to 300 kHz
- Electronic background: 0.2 cps
- Energy range: 4-25 keV

Modified detector
- Saturation count rate: 3 MHz
- Linear region: up to 2 MHz
- Electronic background: 0.7 cps
- Energy range: 4-25 keV





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Ion Mobility

Gas	Ions	Mobility ($cm^2 V^{-1} s^{-1}$)
Ar	$(OCH_3)_2 CH_2^+$	1.51
Iso $C_4 H_{10}$	$(OCH_3)_2 CH_2^+$	0.55
$(OCH_3)_2 CH_2$	$(OCH_3)_2 CH_2^+$	0.26
Ar	Iso $C_4 H_{10}^+$	1.56
Iso $C_4 H_{10}$	Iso $C_4 H_{10}^+$	0.61
Ar	CH_4^+	1.87
CH_4	CH_4^+	2.26
Ar	CO_2^+	1.72
CO_2	CO_2^+	1.09
Ar	electrons	~1000

For 1kV across 1cm. Electrons take 1ms

Ions take ~1ms!

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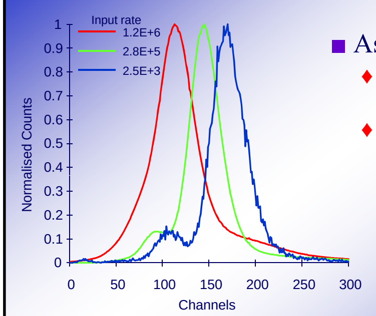
Spectral Peak Shift vs Rate



- As rate rises
  - Spectral resolution deteriorates
  - Note also the K escape feature

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Detector Considerations

- Intensity Measurement
  - Uniformity across device
  - Ageing, radiation damage
  - Dynamic Range
  - Linearity of Response
  - Stability
- Spatial Measurement
  - Spatial Resolution
  - Spatial Distortion
  - Parallax
- Energy Measurement
  - Spectral Resolution
  - Linearity of Response
  - Uniformity of Response
  - Stability
- Time Measurement
  - Frame Rate
  - Photon Time Resolution
- Others
  - Size and weight
  - Cost

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A Universal Specification?

Wombat

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Counting Statistics

- Photons are quantised and hence subject to probabilities
- The Poisson distribution expresses the probability of a number of events occurring in a time period
- If the expected number is n then $P(n,k) = \frac{n^k e^{-n}}{k!}$
- The mean of P(n,k) is n
- The variance of P(n,k) is n
- The standard deviation is √n
- Fractional error = (√n)/n=1/√n
- As n increases, uncertainty and noise decrease

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Performance Measure - DQE

Perfect detector $SNR_{inc} = \sqrt{N_{inc}}$ $\therefore N_{inc} = SNR^2{}_{inc}$

Real detector $SNR_{Non-ideal} < \sqrt{N_{inc}}$

Can define $N_{photons}$ that describes real SNR

$$NEQ = SNR^2{}_{Non-ideal}$$

Ratio of this to N_{inc} is a measure of efficiency

$$DQE = \frac{NEQ}{N_{inc}} = \frac{SNR^2{}_{Non-ideal}}{SNR_{inc}{}^2}$$

Note that DQE is f(spatial and spectral frequencies)

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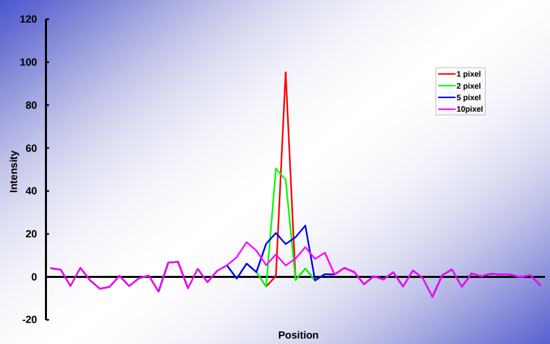
Effect of Peak Width



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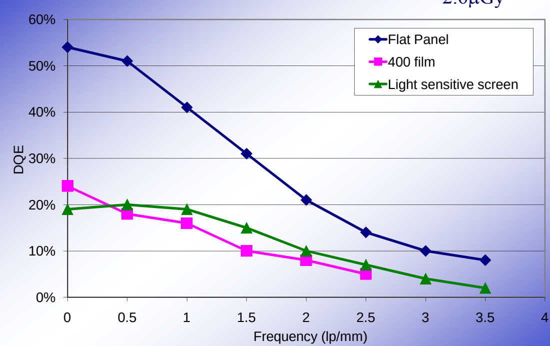
DQE Comparison

DN-5 beam
2.6µGy



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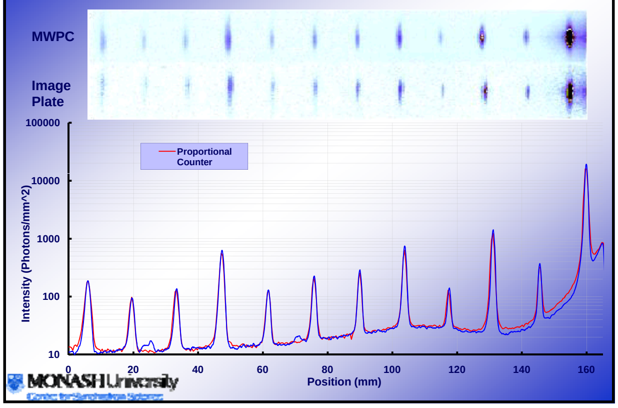
To Count or Not to Count

Tasmanian Devil

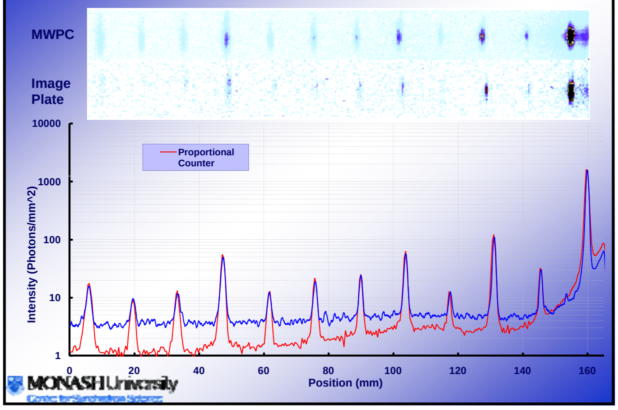
Specifications

Wombat

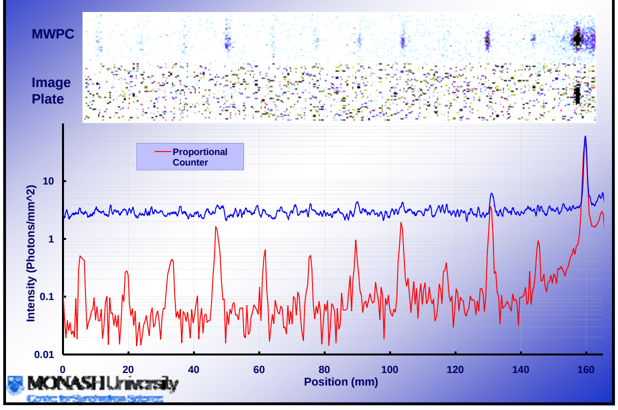
Collagen 100s Exposure



Collagen 10s Exposure

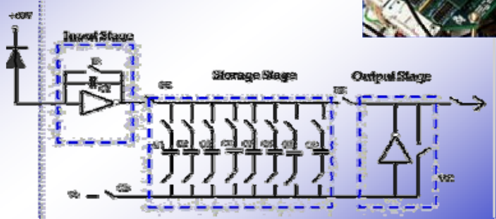


Collagen 0.3s Exposure



Cornell PAD (Integrating)

- Rapid Framing Imager
  - 15×13.8mm^2 active area
  - 150µm square pixel
  - Storage for 8 frames
  - Selectable T_{int} down to 1µs
  - Deadtime < 1µs



Sol Gruner, Cornell

Diesel Fuel Injection Movie

- Injection
  - Supersonic injection 1350psi Cerium added
  - Chamber 1atm SF_6
  - 10^8-10^9 X-rays/s/pix (6keV)
  - 1.1ms Pulse
- Movie
  - Length 1.3ms
  - Frame length 5.13μs
  - Dead time 2.56μs / frame
  - 168 frames (21 groups of 8)
  - Average 20× to improve S/N
  - Sequence 5×10⁴ images

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A. MacPhee et al, Science (2002) 295, 1761-1763

The Furture

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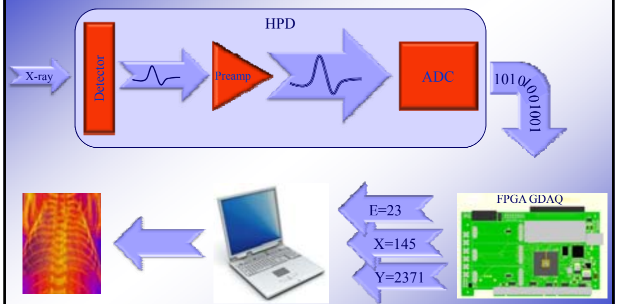
A Detector System



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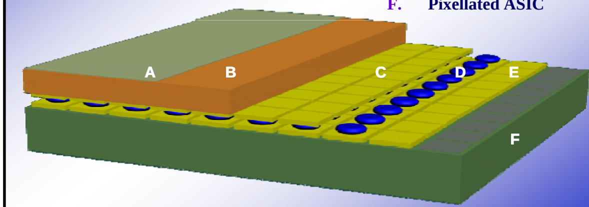
Pixel Array Detector

- A. Top electrode
- B. Pixellated semiconductor
- C. Collection electrodes
- D. Bump bonds
- E. Input electrode
- F. Pixellated ASIC



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Counting Pixel Detector Problems

- High power consumption
  - Cooling
- Number of connections
  - Multiplexing
  - Read out time significant
- Limited number of bits in counter
  - Dynamic range issues for diffraction
  - 15bits @ 1Mcps input rate = 30ms frame
  - Read time can be significant
    - Fast read > high power
- Technology not yet good enough for microsecond framing

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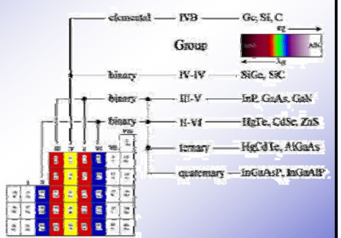
Available Compound Semiconductors

- Predominately CdZnTe, CdTe and GaAs.
- II-VI materials CdTe and CdZnTe cover a suitable range of band gaps:
  - 1.44 eV (CdTe), 1.57 eV (CdZnTe, 10% Zn), 1.64 eV (CdZnTe, 20% Zn)
- Resistivity of CdZnTe is higher than CdTe, hence lower dark current, higher spectroscopic resolution
- Poor hole transport requires electron-sensitive detectors



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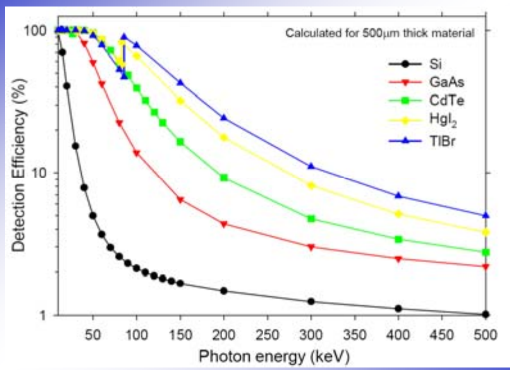
Paul Sellin, Surrey

Absorption Efficiency of Semiconductors



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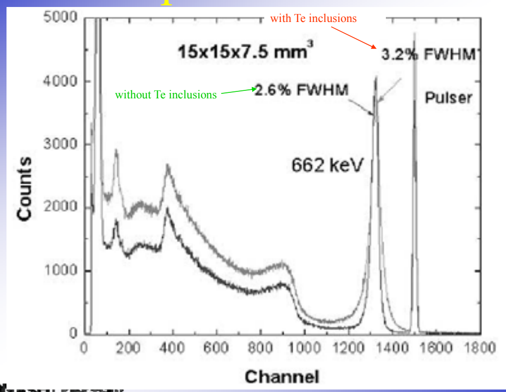
Paul Sellin, Surrey

CdZnTe Spectral Resolution



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References

- Delaney CFG and Finch EC
  - Radiation detectors. Physical Prnciples and Applications, Clarendon Press, Oxford 1992, ISBN 0 19 853923 1
- Knoll GE
  - Radiation Detection and Measurement, John Wiley and Sons 1989
- Proceedings of the 6th International Conference on position sensitive detectors
  - Nuclear Instruments and Methods in Physics Research A513 (2003)
- IEEE Nuclear Science Symposia

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Semiconductors

Material	ρ (Ω cm)	ϵ_r	τ_R (ms)	$(\mu\tau)_e$ (cm^2/V)	$(\mu\tau)_h$ (cm^2/V)
Si	$< 10^4$	11.7	1.0×10^{-8}	> 1	> 1
Ge	50	16	7.1×10^{-11}	> 1	$\simeq 1$
GaAs	1.0×10^7	11.0	1.1×10^{-5}	8.0^{-5}	4.0×10^{-6}
CZT	$3 - 5 \times 10^{10}$	10.9	$2.9 - 4.9 \times 10^{-2}$	$3 - 5 \times 10^{-3}$	$5 - 8 \times 10^{-5}$
CdTe	1.0×10^9	11.0	9.7×10^{-4}	3.3×10^{-3}	2.0×10^{-4}
HgI_2	1.0×10^{13}	8.8	7.8	1.0×10^{-4}	$4.0 \times 10{-}5$
PbI_2	1.0×10^{12}	$\simeq 10$	0.89	8.0×10^{-6}	6.0×10^{-7}

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Readout Strategies

- Imaging
  - Massively parallel
    - Position derived from individual pixel
    - Highly parallel: 2000×2000 pixels = 4 million channels!!!
    - Suitable for counting and integrating systems
    - Pixel array detectors
  - X-Y Interpolating
    - Position derived from measuring signals
    - Moderately parallel: 2000×2000 pixels from few hundred channels
    - Only suitable for counting systems
    - MWPCs e.g. RAPID
  - Sequential
    - Position derived from point in sequence
    - Not really parallel
    - Only really suitable for integrating systems
    - CCDs, Image plates
- Spectroscopic
  - Can only add more channels for speed

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Signal Levels

	Energy per electron hole pair, w (eV)	Stage 1 signal @ 10keV	Stage 2 Transfer to electron gain	Minimum N @ 10keV	Stage n 0 noise gain	Signal (e^-)
Gas Ionisation						
Argon	24.4	$410e^-$	1	410	10^5	4×10^7
Xenon	20.8	$481e^-$	1	481	5×10^4	2.4×10^7
Solid State						
Silicon	3.62	$2760e^-$	1	2760	1	2.8×10^3
Germanium	2.96	$3380e^-$	1	3380	1	3.4×10^3
Fluorescence or scintillation						
NaI(Tl) + PMT		266 photons	0.1	30	10^5	3×10^6
Gd_2O_2S + IIT		500 photons	0.04	20	10^4	2×10^5
$BaFBr:Eu^{2+}$		75 F centres	0.07	5	10^5	5×10^5

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Scintillators - Basic Properties

	Light O/P [photons/keV]	Decay Time [ns]	Emis. Wavelength [nm]	Density [g/cm^3]
NaI(Tl)	38	250	415	3.7
CsI(Tl)	54	1000	550	4.5
BaF_2	10	0.7/630 fast/slow	220/310 fast/slow	4.9
$LaCl_3$(Ce)	49	28	350	3.8
$LaBr_3$(Ce)	66	16	380	5.1

FWHM energy resolution at @ 662 keV

NaI(Tl) $\Delta E/E \sim 6\%$
$LaCl_3$ $\Delta E/E \sim 4\%$
$LaBr_3$ $\Delta E/E \sim 3\%$
CdZnTe $\Delta E/E \sim 2\%$ *(after correction for carrier recombination)*

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Tortoise and Hare?

- Accelerators currently 10^{13}-10^{14} photons to sample
- New machines e.g. XFEL, TESLA
  - 10^{25} photons to sample!!!
- Detectors
  - Currently 10^7-10^8
  - In 10 years............
- Hare shows no sign of slowing down
- Tortoise is not catching up

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