



Detectors

Things you should be aware of

Rob Lewis

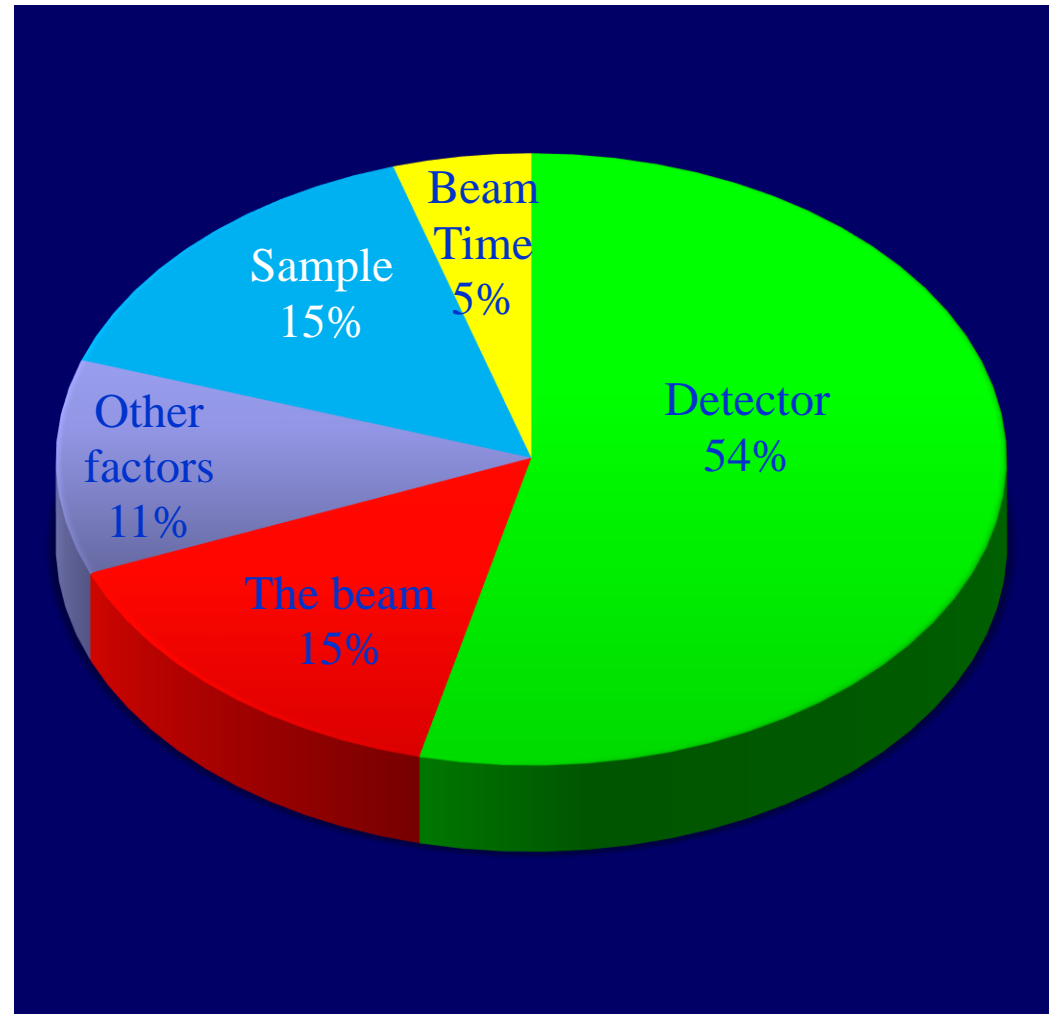
Medical Imaging, University of Saskatchewan

Medical Imaging and Radiation Sciences, Monash University

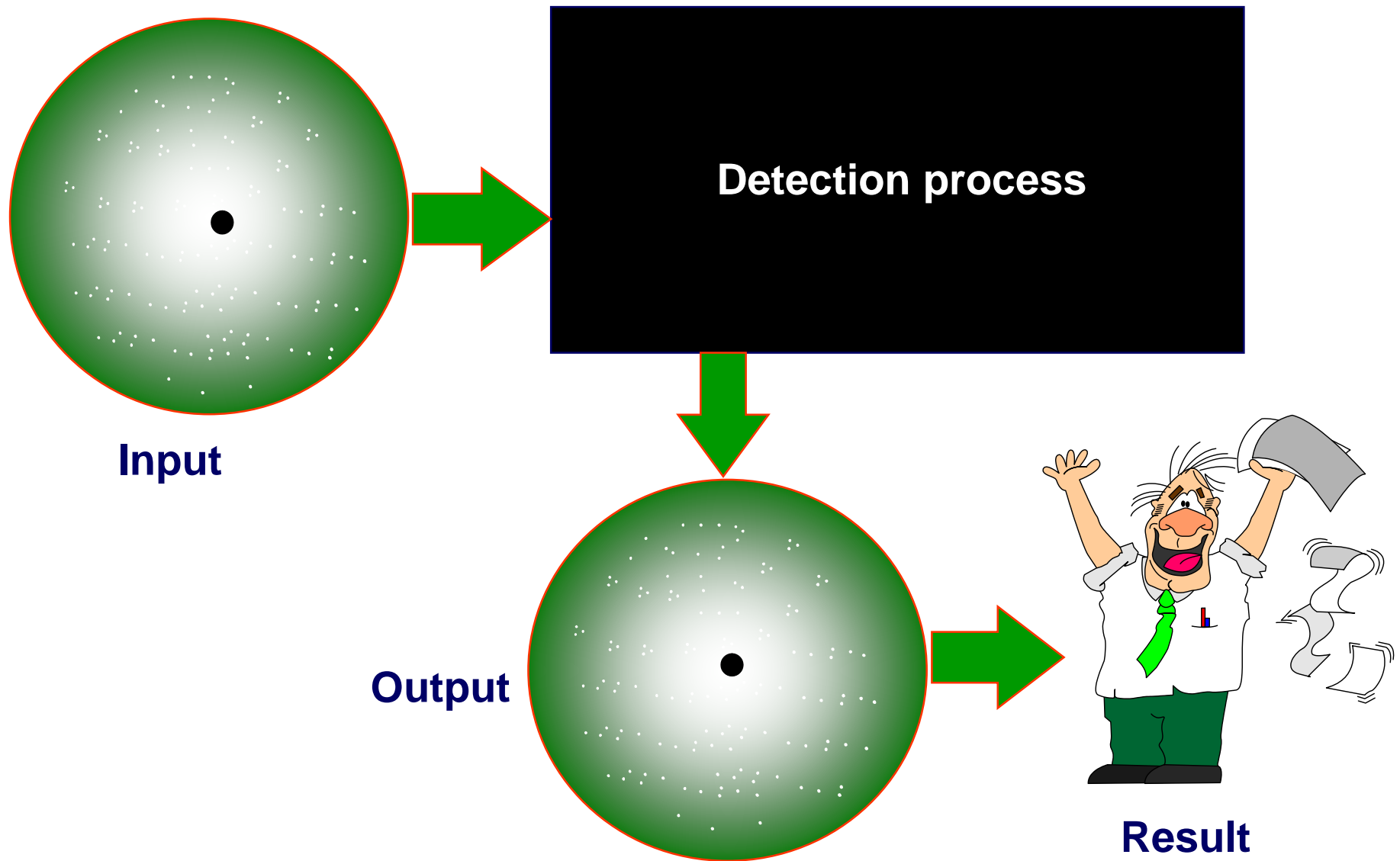
Applied Sorting Technologies, Melbourne

Factors Limiting Science

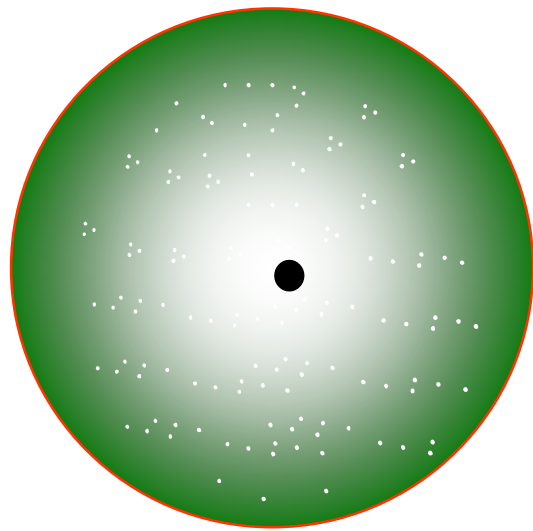
- Detectors are an oft-neglected but crucial part of an experiment
- They often limit the science



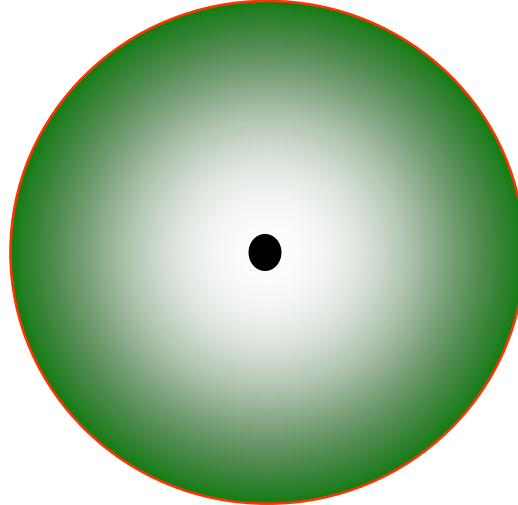
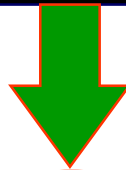
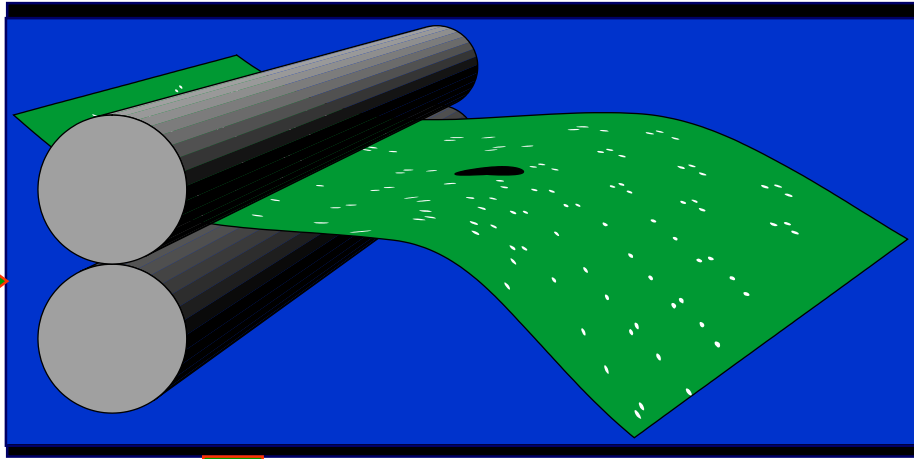
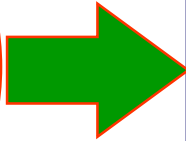
Scientist's View of Detector



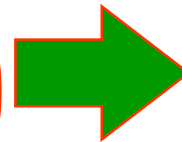
The Truth!



Input

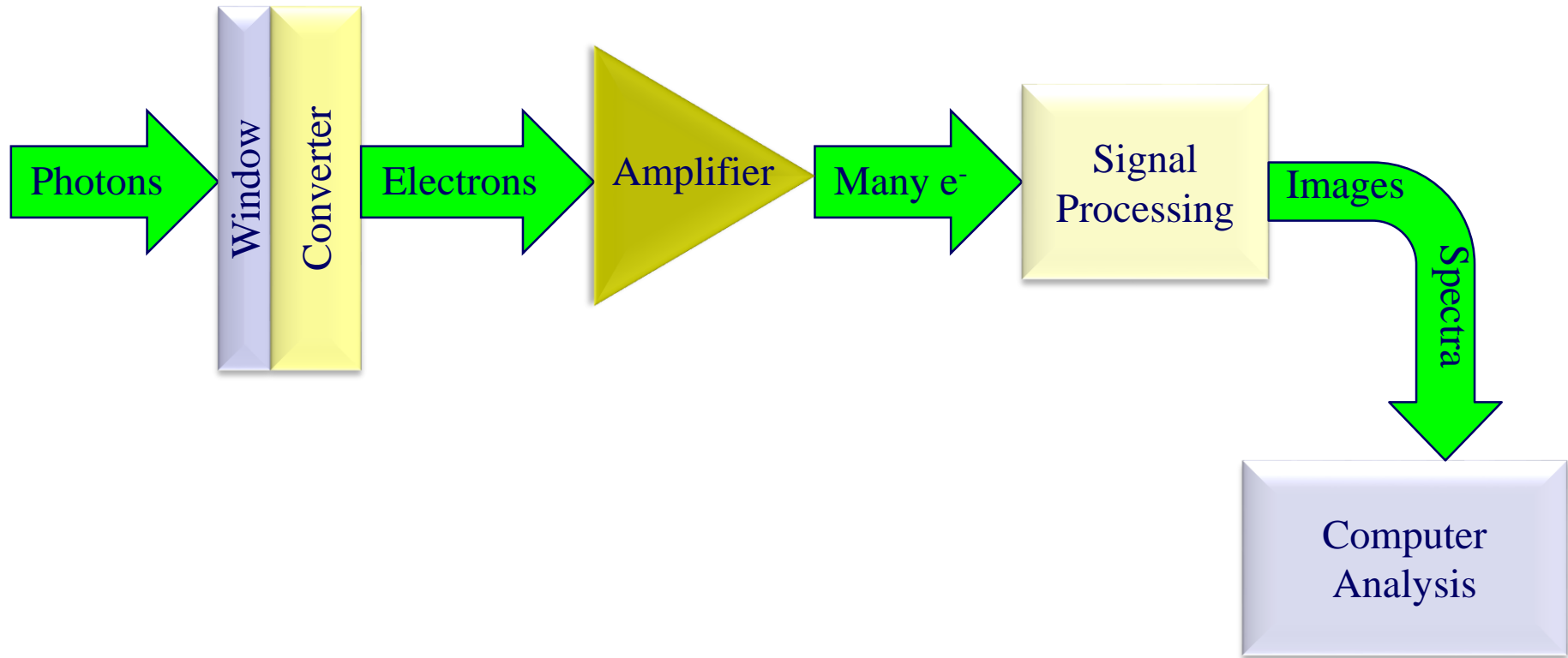


Output



Result

Detector Chain of Events



Detection Mechanisms

- There are many means of detection. All require the interaction of photons/electrons 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.. CCD
 - ◆ 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

Albert Einstein



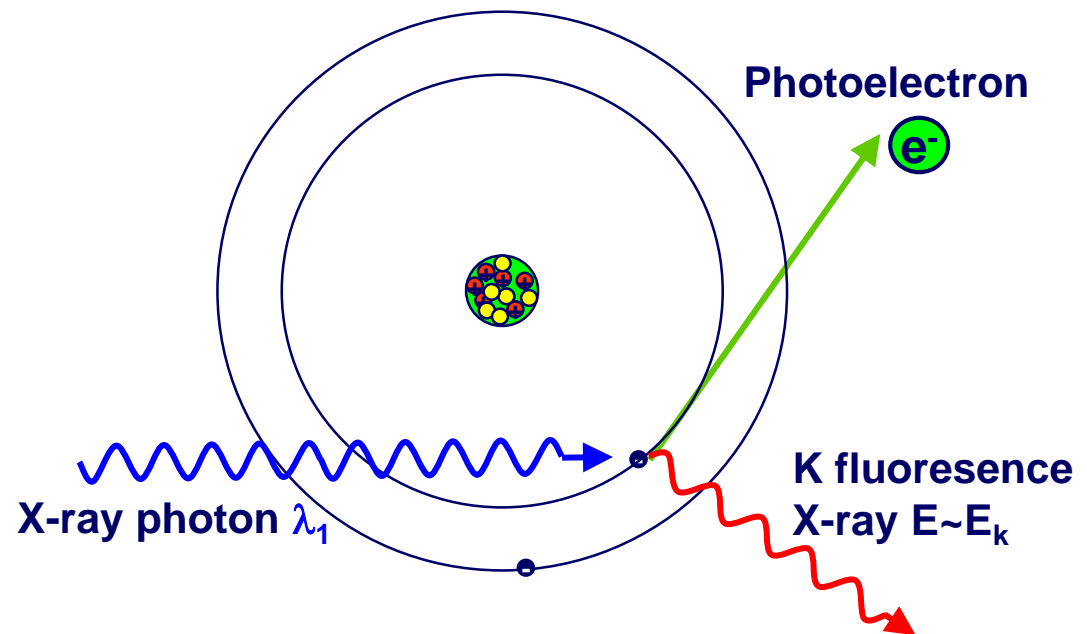
Germany and Switzerland
Kaiser-Wilhelm-Institut
(now Max-Planck-Institut)
für Physik
Berlin-Dahlem, Germany
1879 - 1955



**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



Arthur Holly Compton



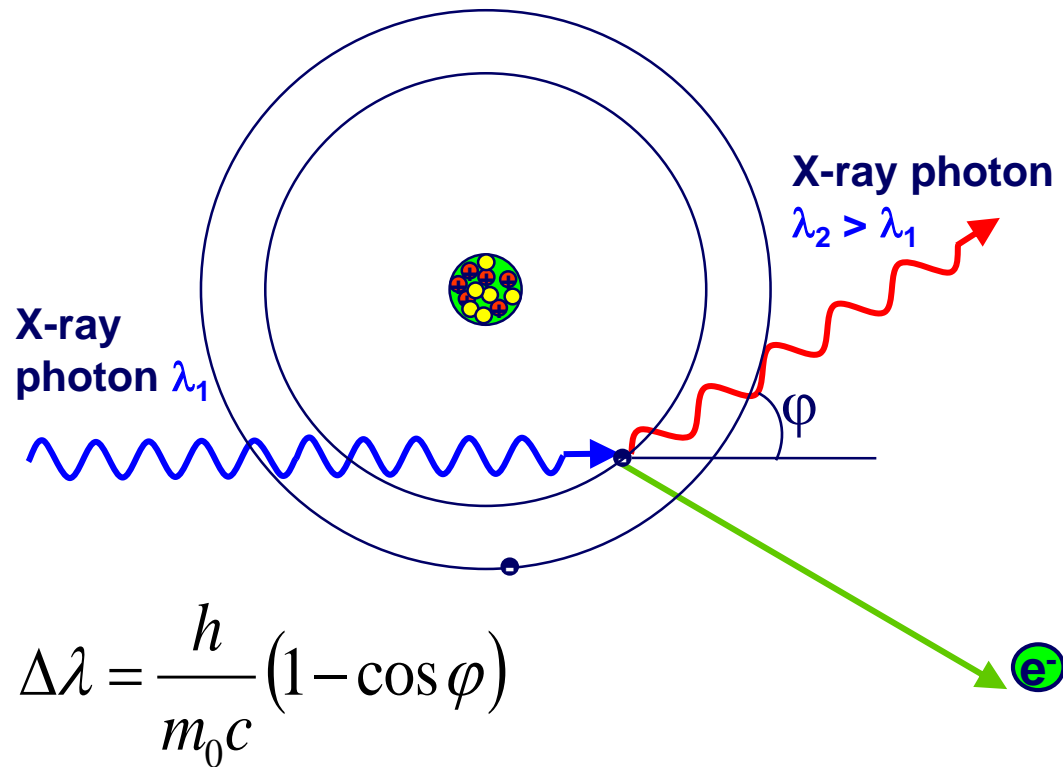
University of Chicago
Chicago, IL, USA
1892 - 1962



**Nobel prize in
physics 1927**

"for his discovery of
the effect named
after him"

Compton Effect

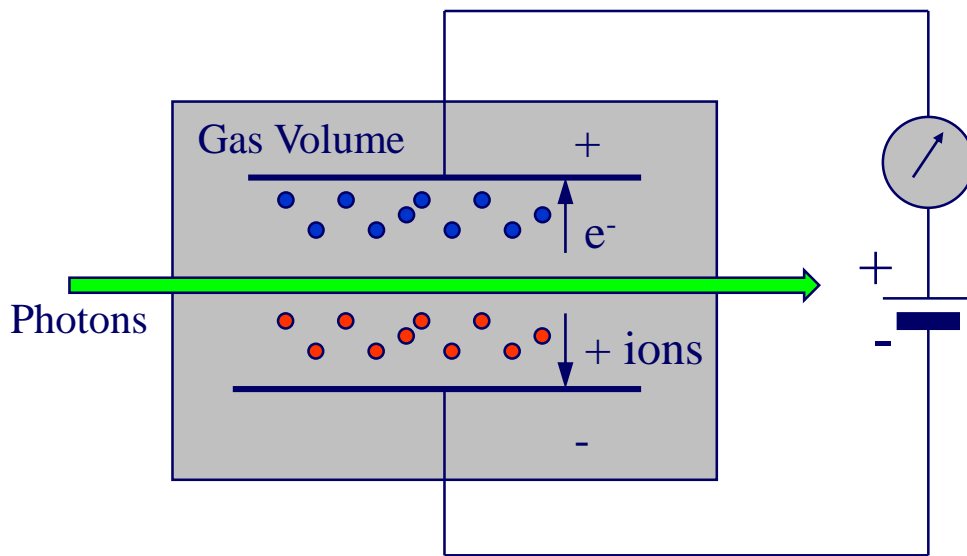


An Example Detector



Echidna

Ionisation Chamber



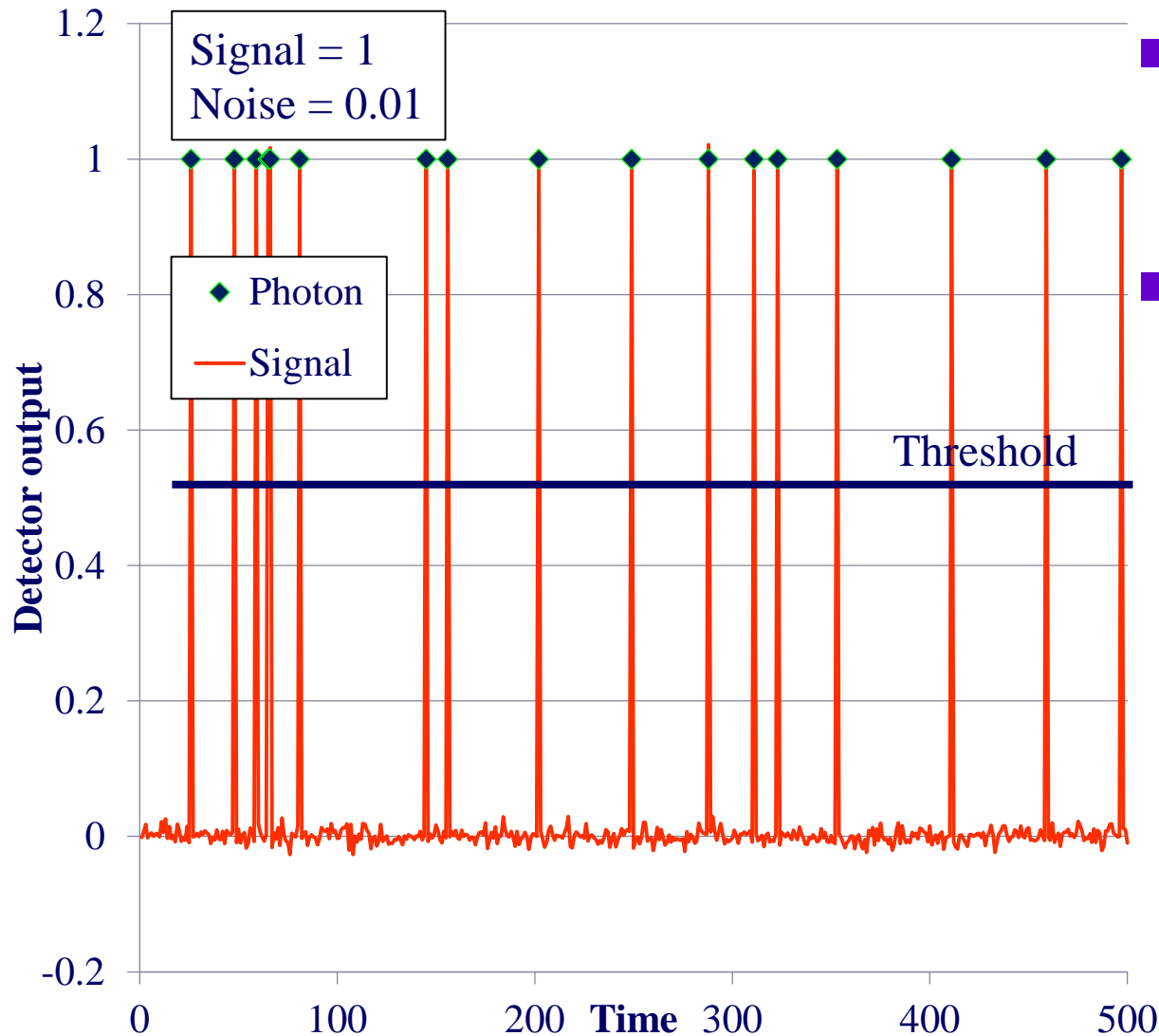
- Approximately 1 e^- ion pair per 30eV deposited (symbol often w)
- IF you know w , and density and composition of gas, it is possible to convert current to flux
- Number can be affected by several factors
 - ◆ **Recombination of e^- and ions**
 - Higher voltages required at higher rates since more carriers
 - ◆ **Diffusion losses**
 - Higher voltages, small gap
 - ◆ **Electron losses**
 - Larger gap
- Pressure, temperature and humidity affect density



Counting and Integrating

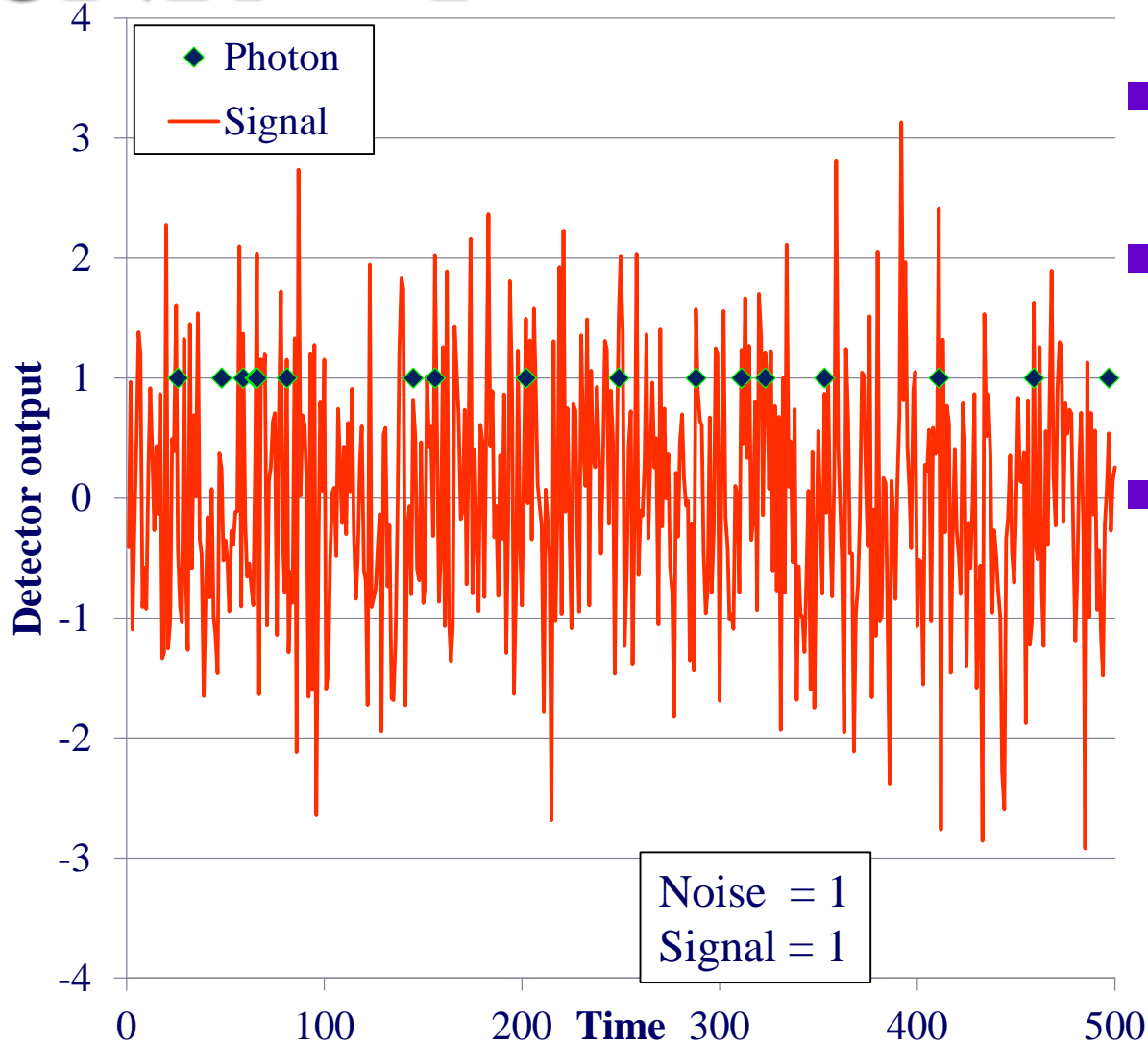
- If there is sufficient signal produced by the interaction of a photon or a particle in the detector then it is possible to operate the detector as a counter
- It's all about signal to noise ratio!

SNR \equiv 100



- In this case 17 photons hit detector but only 16 recorded
- Illustrates a problem with counting
- ◆ Pulse pair resolution

SNR = 1

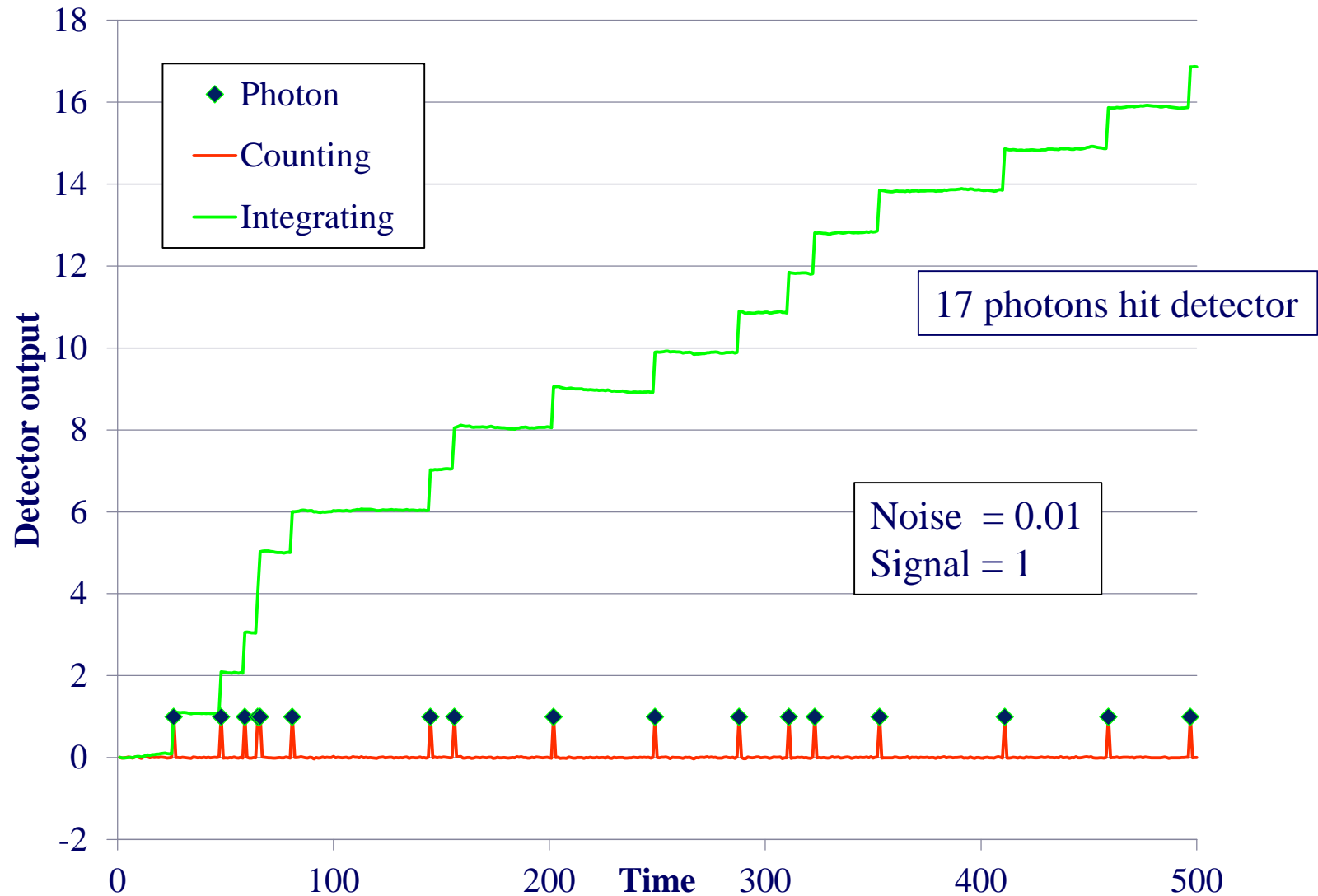


- Black dots show when photons arrive
- Impossible to decide where to set threshold
- Counting detectors require very high SNR

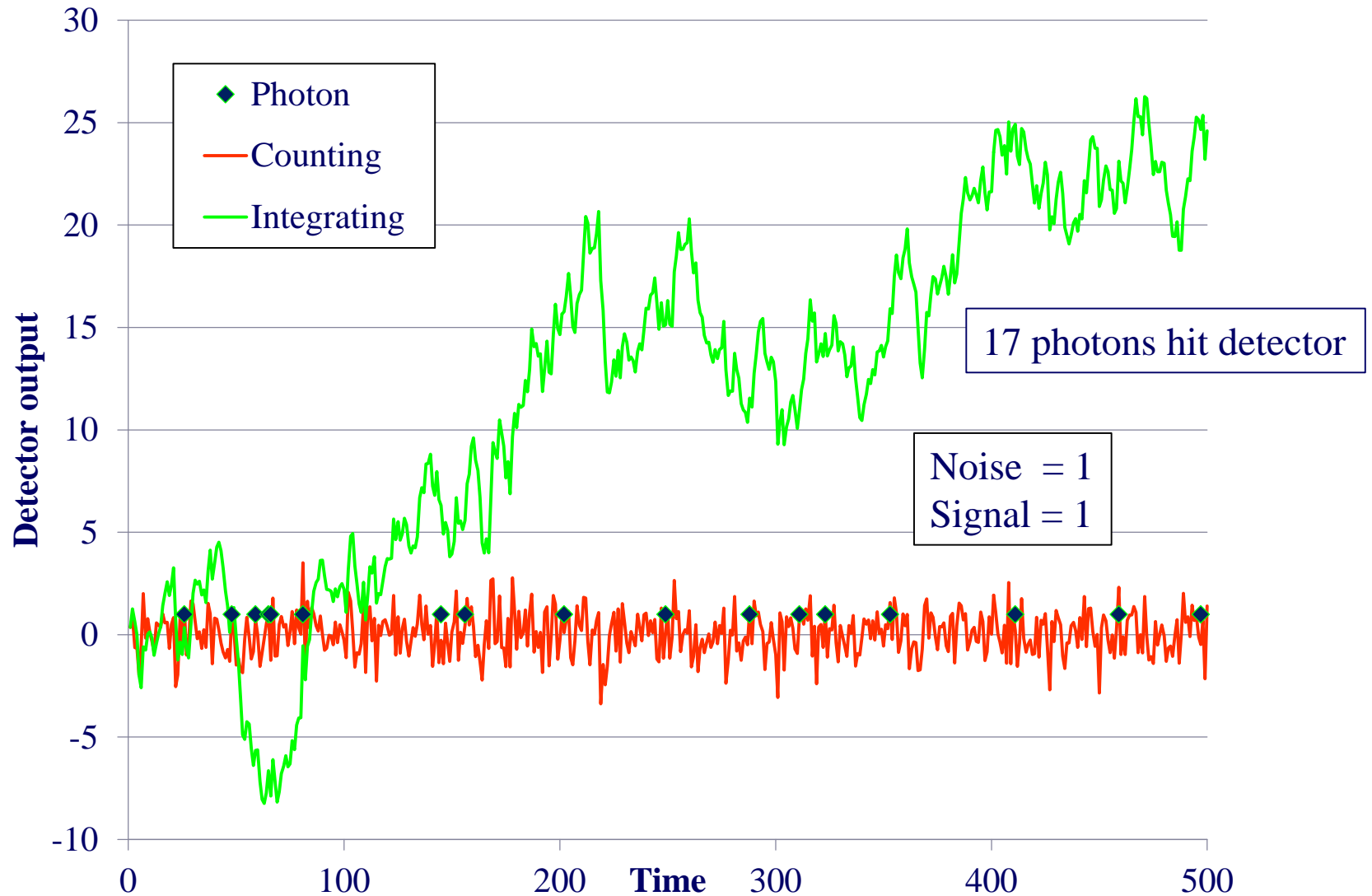
Counting and Integrating

- Usually SNR is insufficient and we have to accumulate many photons/particles before the signal becomes measurable

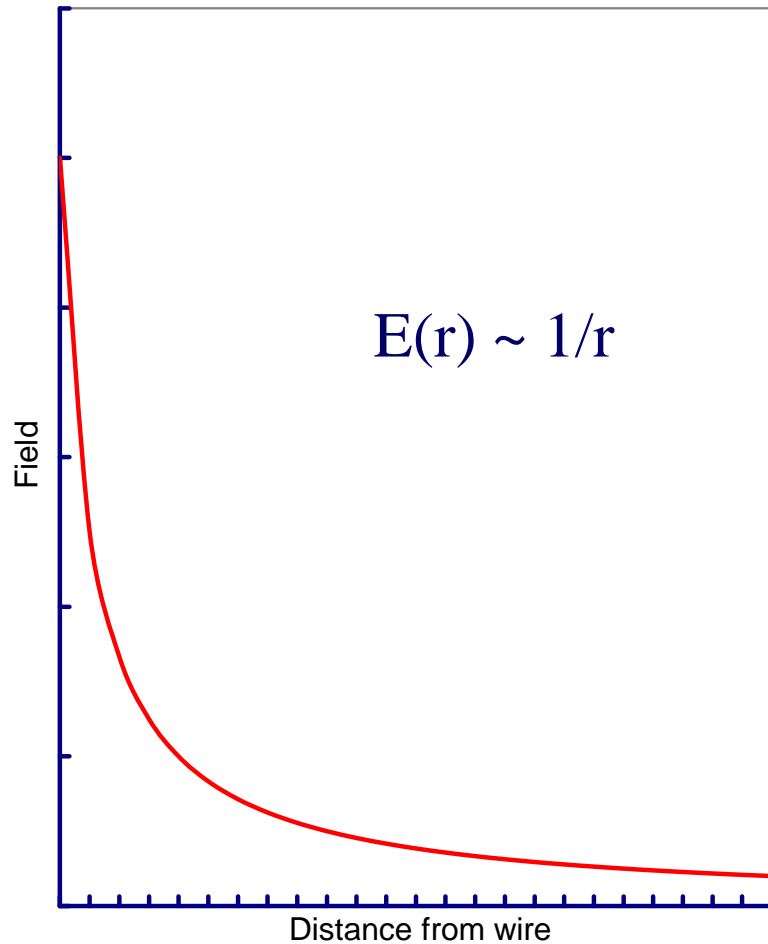
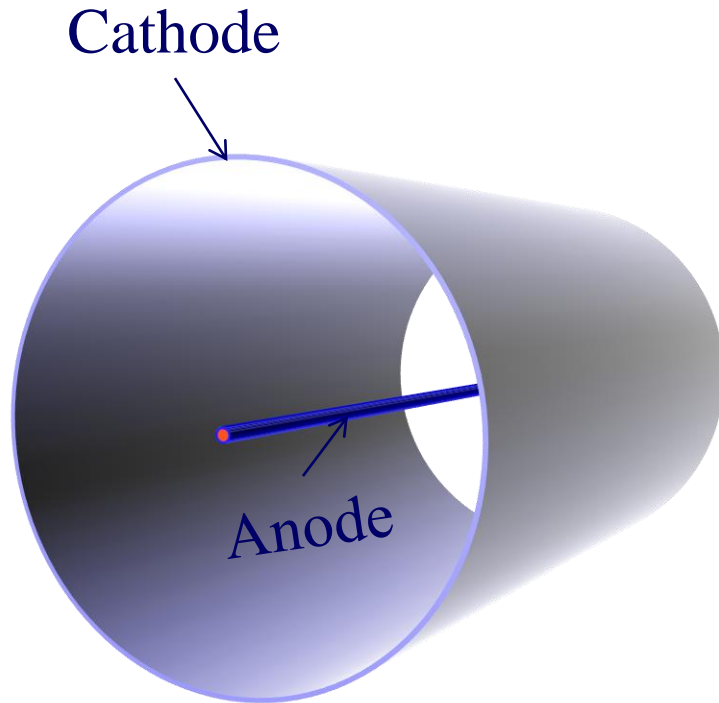
Counting & Integrating SNR $\equiv 100$



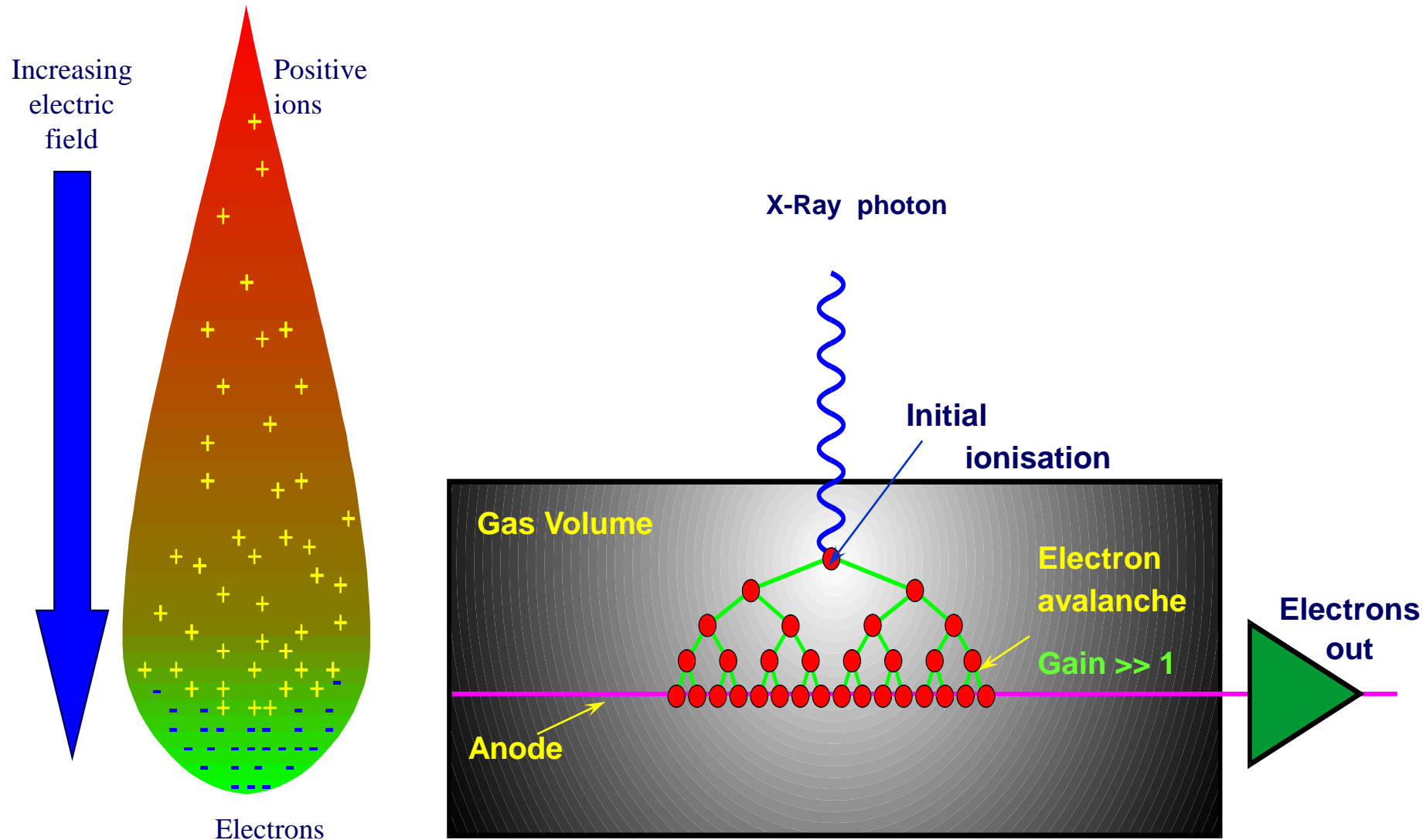
Counting & Integrating SNR $\equiv 1$



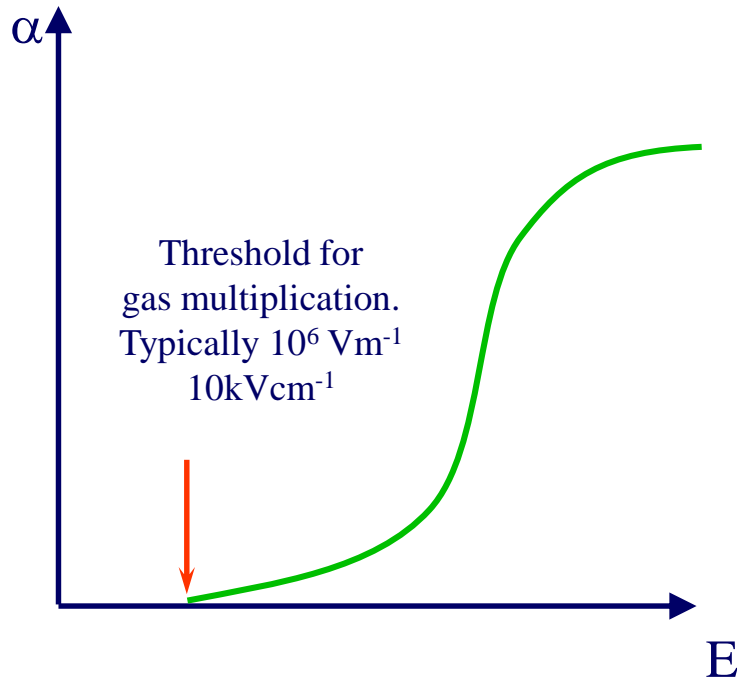
From Analogue to Digital



Avalanche & Proportional Counter



Operation regions of gas filled detectors



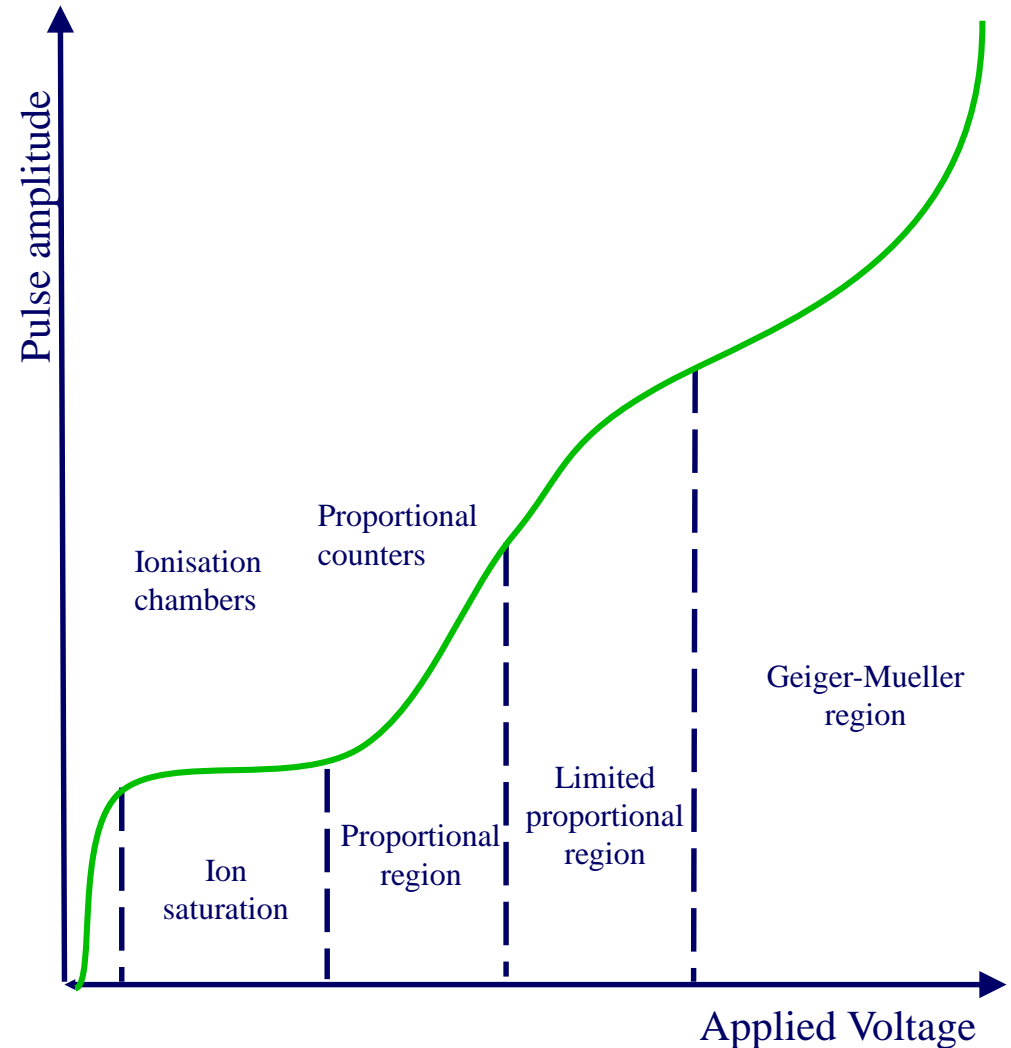
n is number of charges

x is distance

α is the first Townsend coefficient

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

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



Georges Charpak



Nobel prize in physics 1992

"for his invention and development of particle detectors, in particular the multiwire proportional chamber"



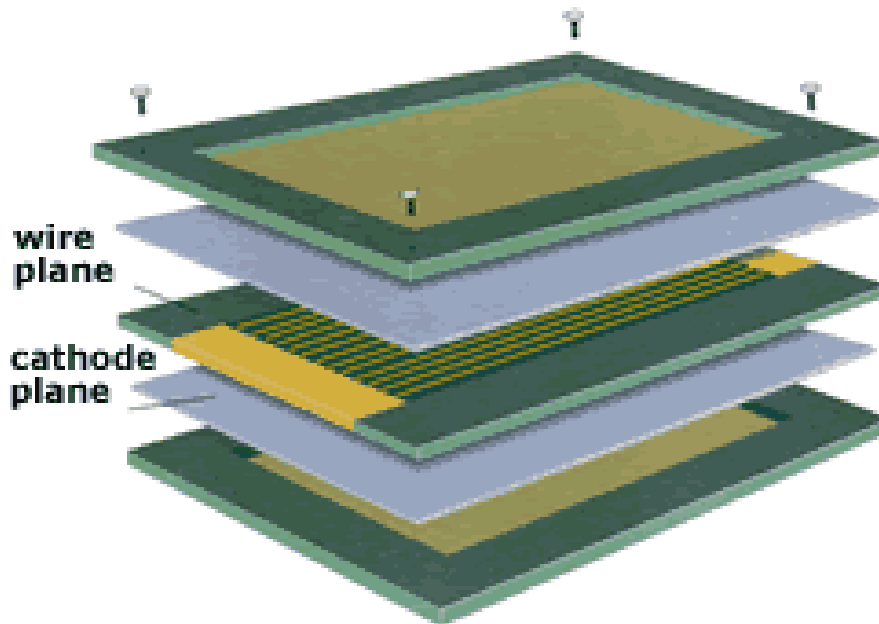
Which he invented in.....

**196824 years
publication to prize!**

France
École Supérieure de
Physique et Chimie
Paris, France; CERN
Geneva, Switzerland

b. 1924
(in Dabrovica, Poland)

Multi-wire Proportional Counter



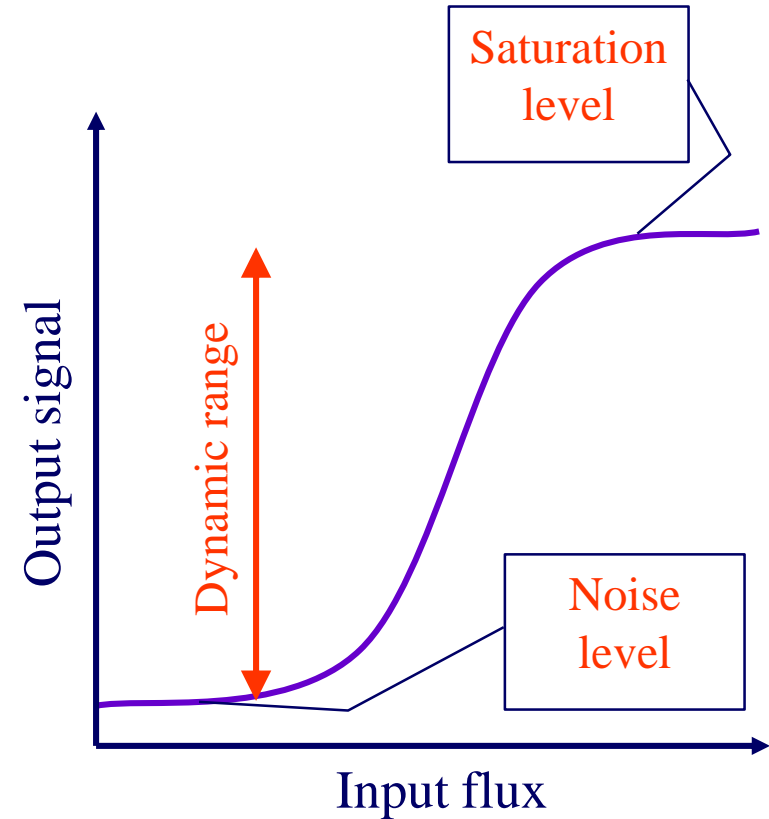
Integrating Detectors

■ 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
- ◆ $2 \times 20 \text{ keV phts} = 1 \times 40 \text{ keV photon}$
i.e. Cannot perform simultaneous spectroscopy and positioning
- ◆ Examples: Image plates, CCDs



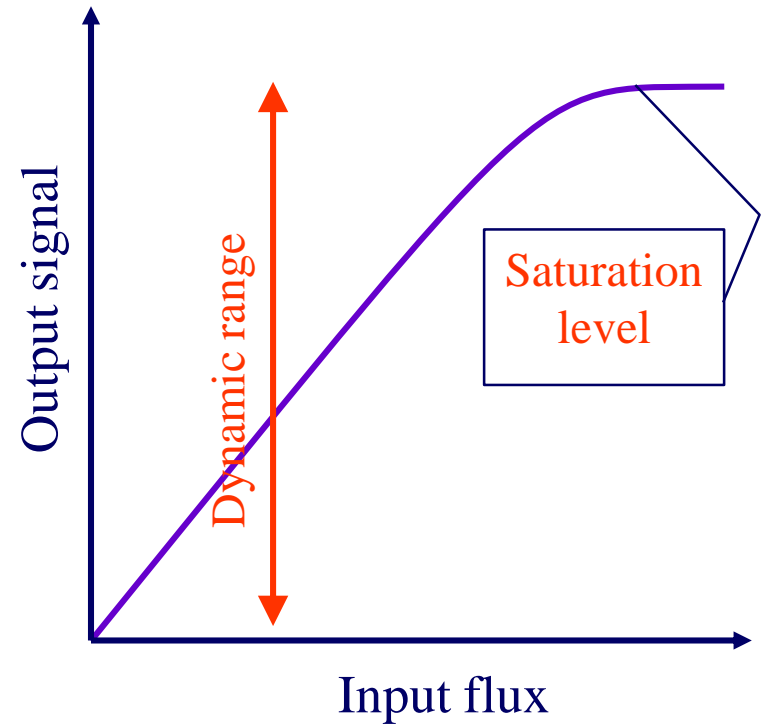
Counting Detectors

■ Mode

- ◆ Detects every particle 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



Willard S. Boyle & George E. Smith



Bell Laboratories
Murray Hill, NJ, USA

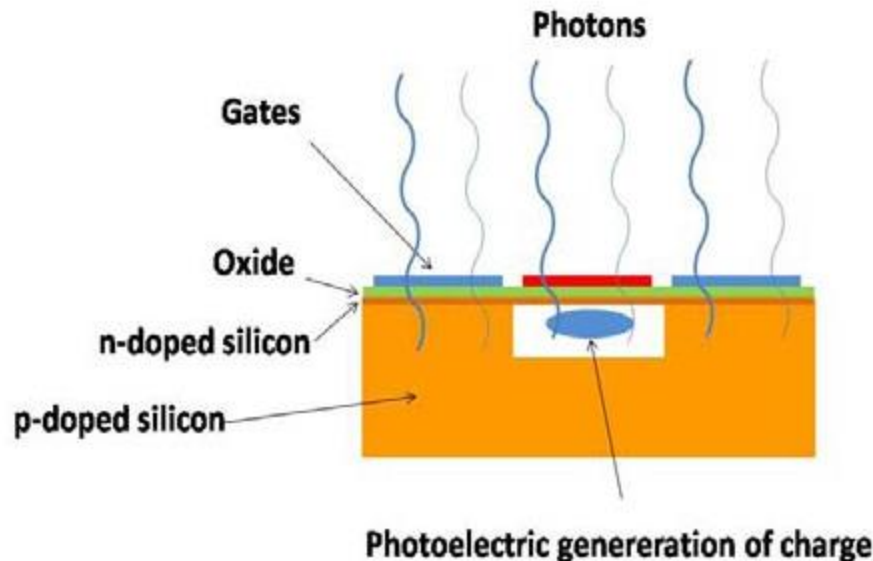
Which they invented
in.....



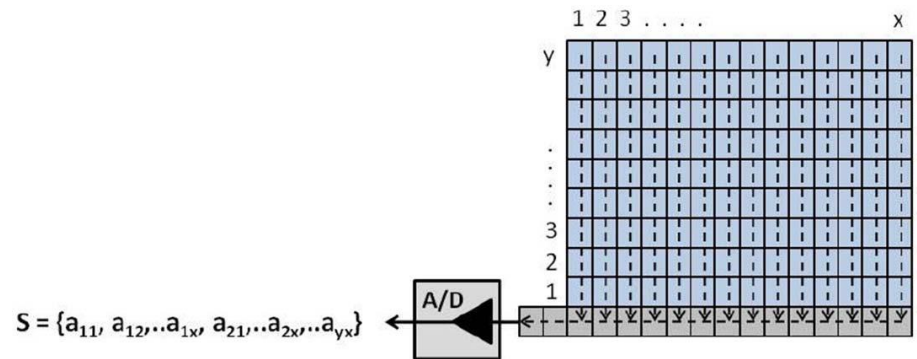
**Nobel prize in
physics 2009**

"for the invention of
an imaging
semiconductor circuit
– the CCD sensor"

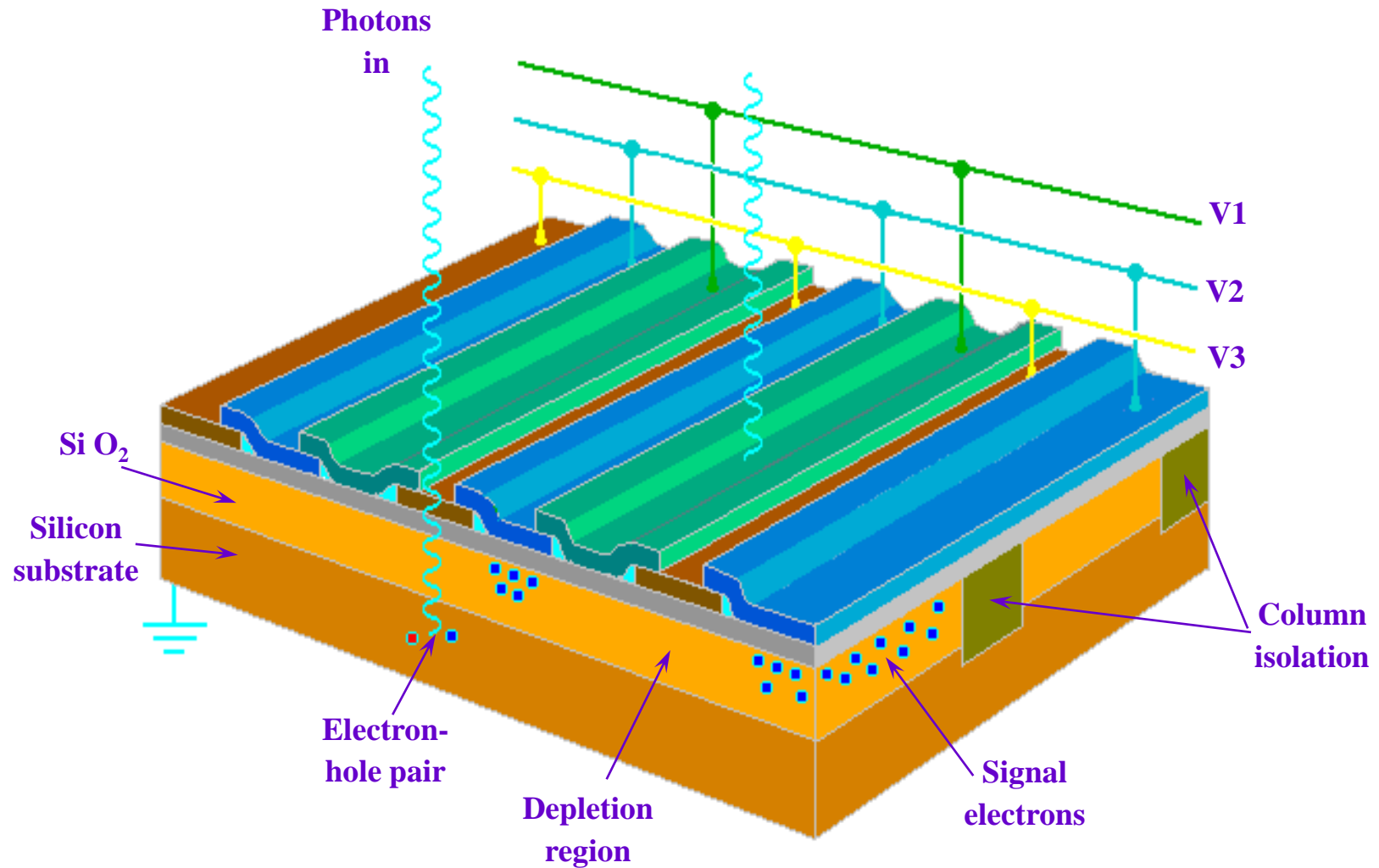
**196940 years
publication to prize!**



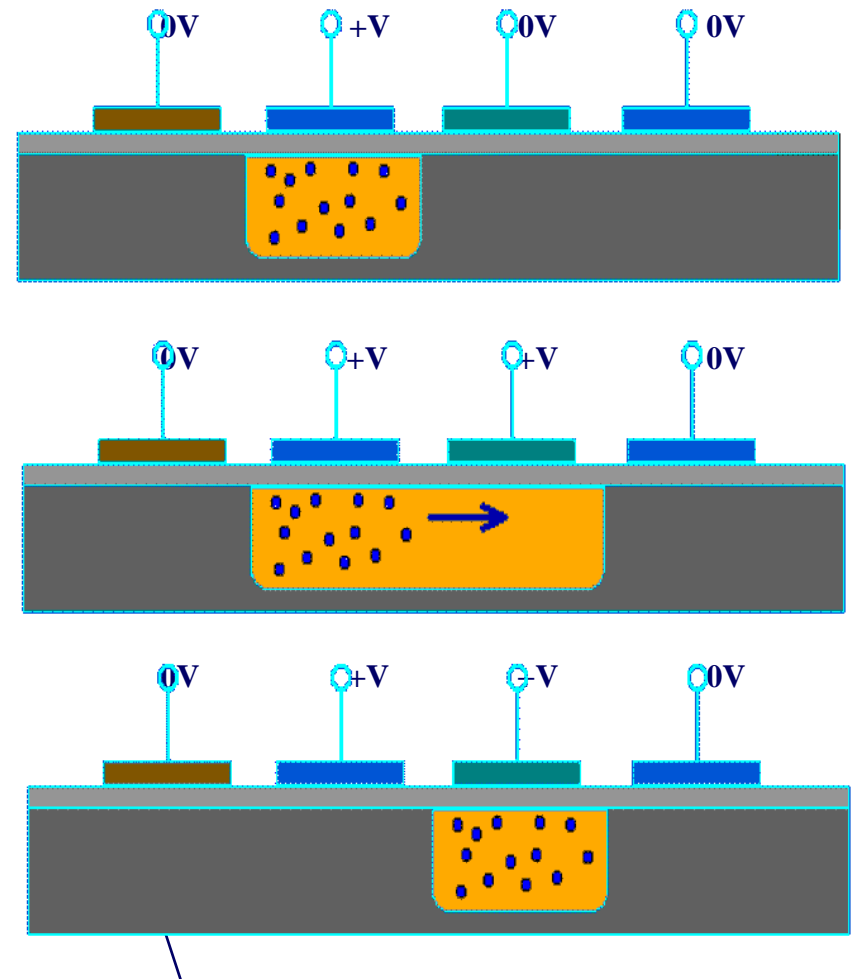
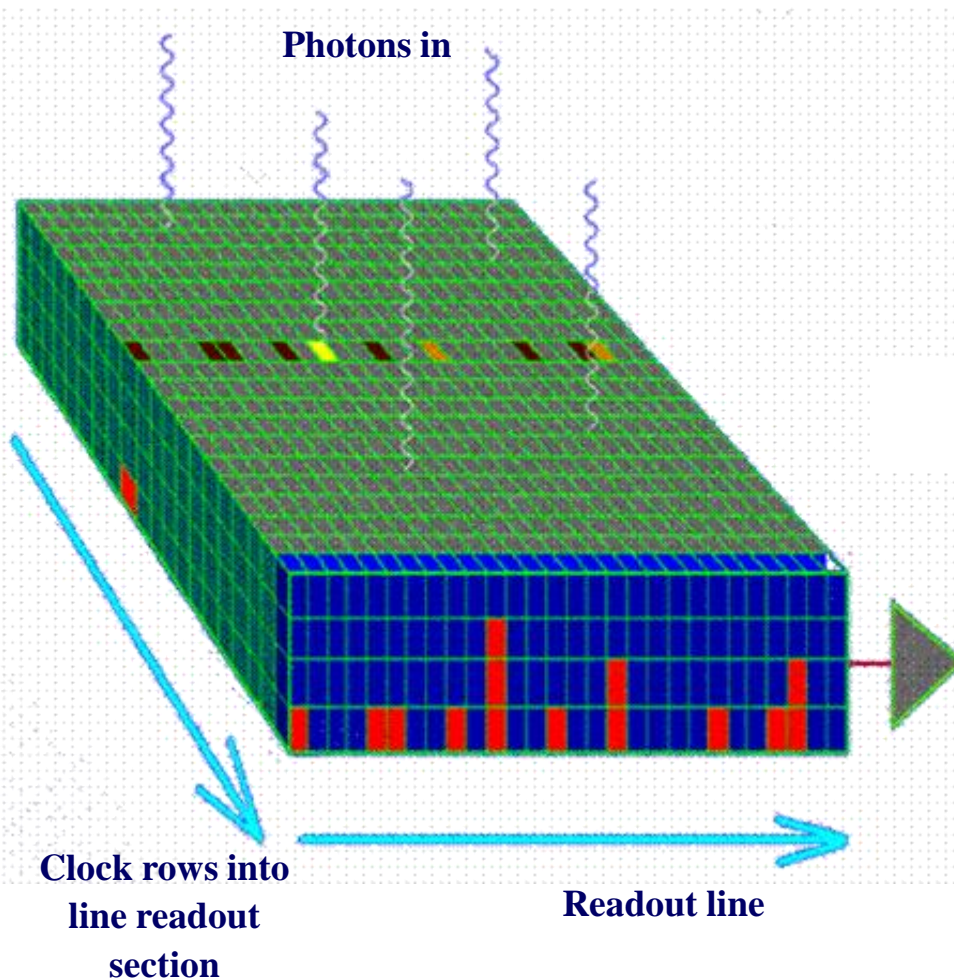
CCD



Charge Coupled Device



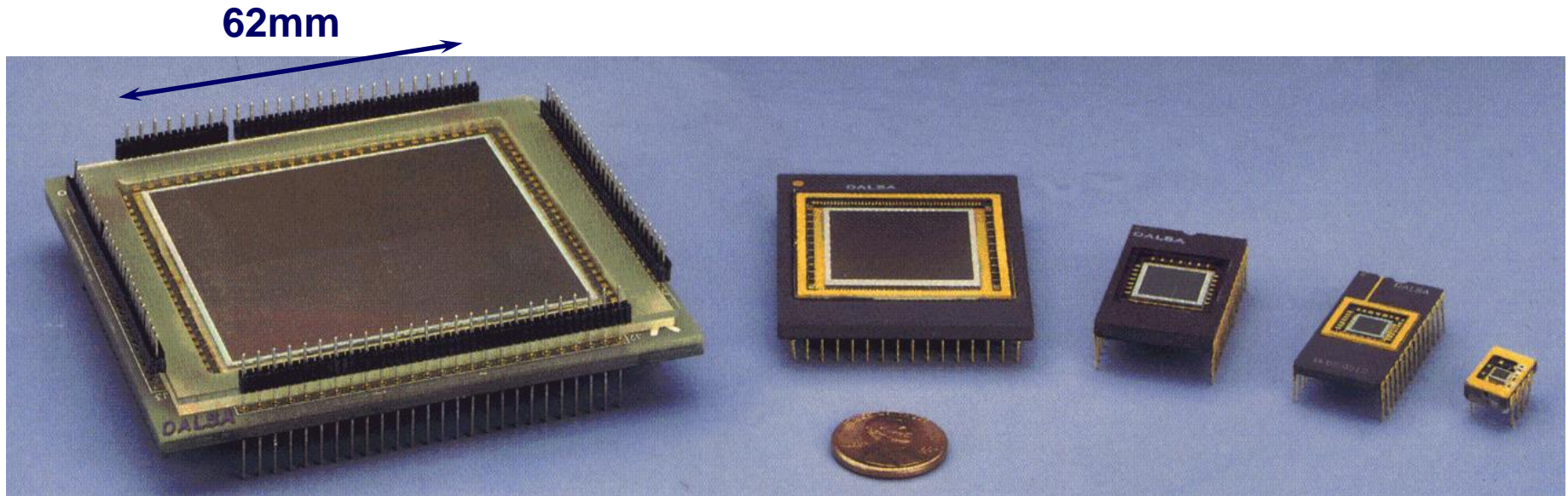
CCD Readout



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 $\sim 3000e^-$ 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

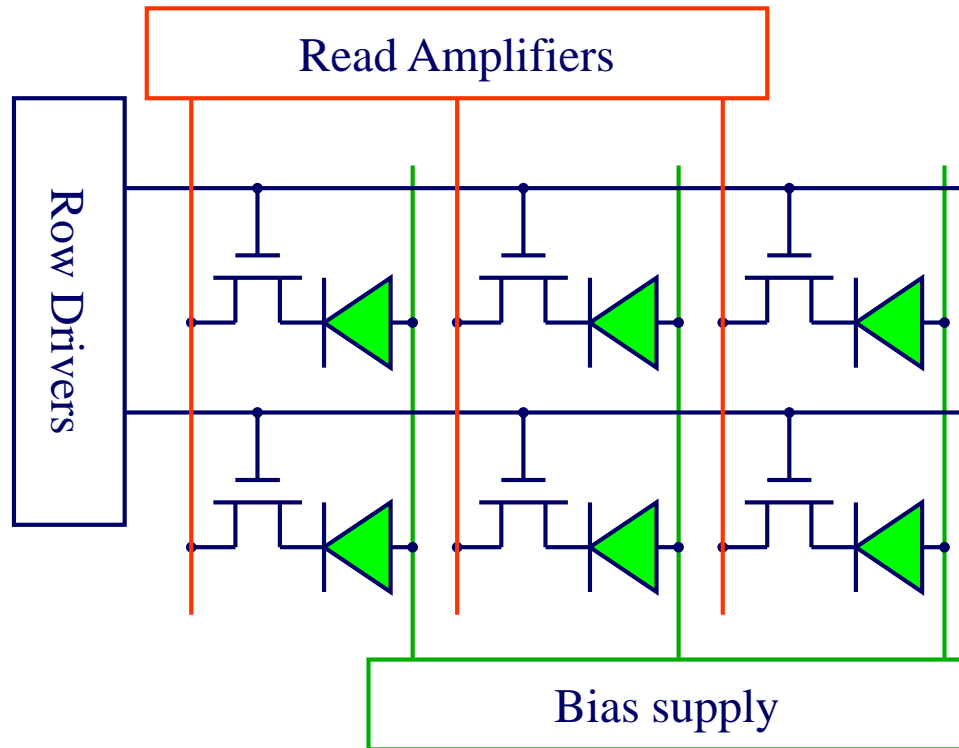
CCDs



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

Shutter required

Complimentary Metal-Oxide Semiconductor (CMOS)

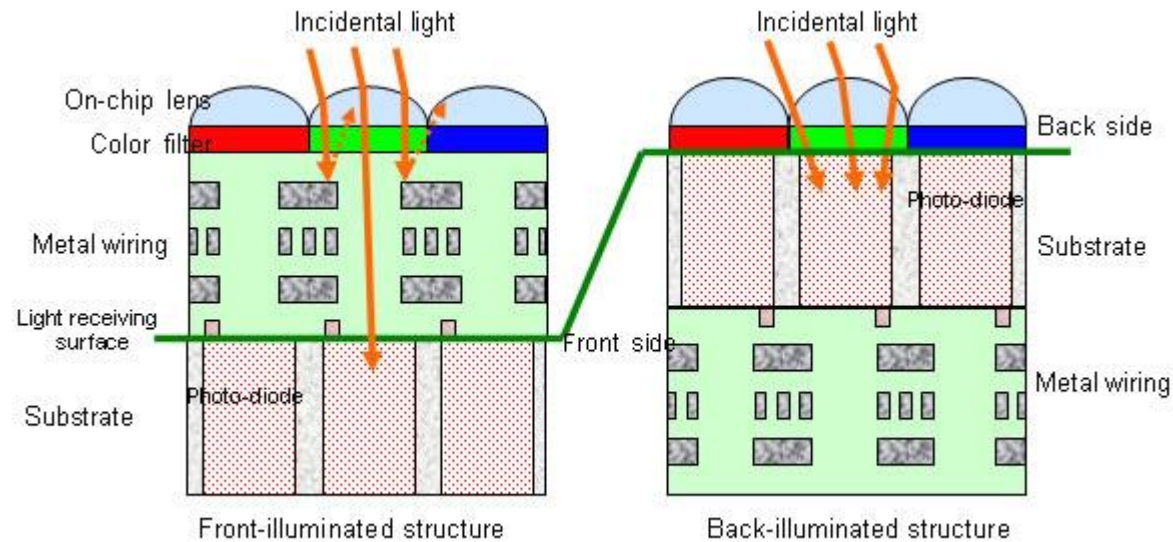


- A readout amplifier transistor on each pixel converts charge to voltage
- Allows random access to pixels, similar to the row-column memory cell access in RAM

CMOS vs CCD

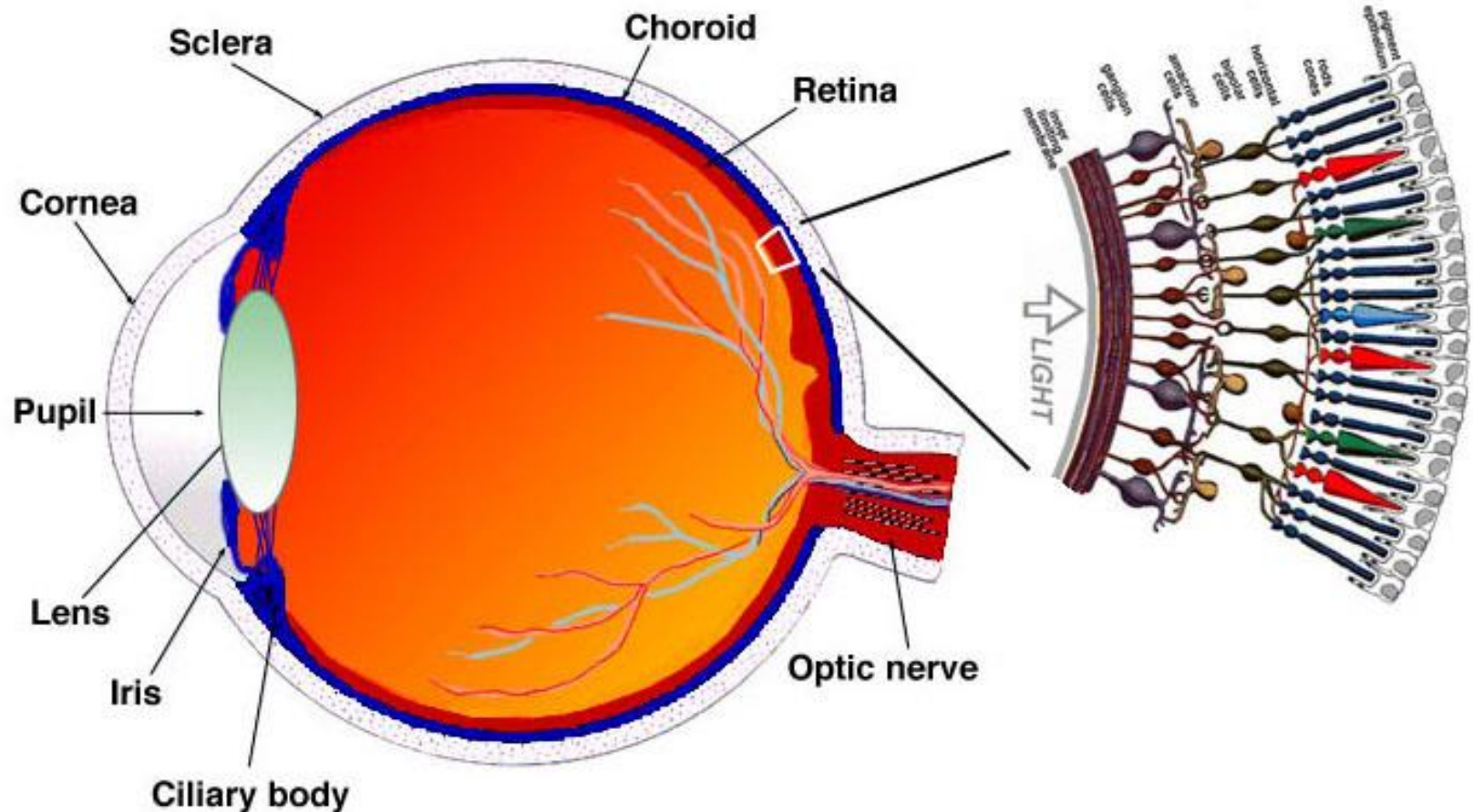
- Traditionally CCD has had higher sensitivity and lower noise
- Modern techniques mean that the differences are small
- CMOS sensors can have much more functionality on-chip than CCDs
 - ◆ On chip image processing, edge detection, noise reduction, and analog to digital conversion
- CMOS lower power → less heat → less noise

Front and Back Illumination



<http://www.sony.net/SonyInfo/News/Press/200806/08-069E/index.html>

Human Eye

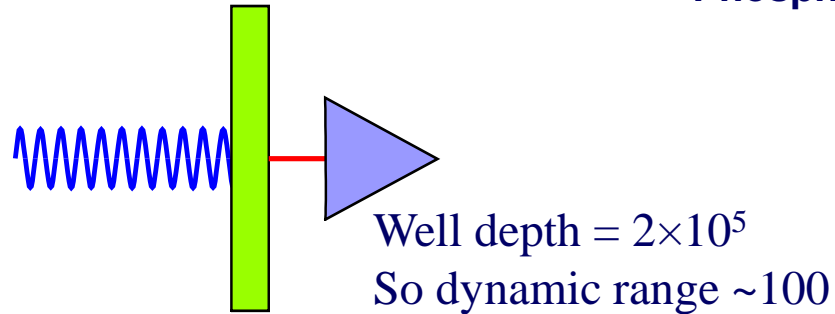


<http://webvision.med.utah.edu/imageswv/Sagschem.jpeg>

Use with X-rays

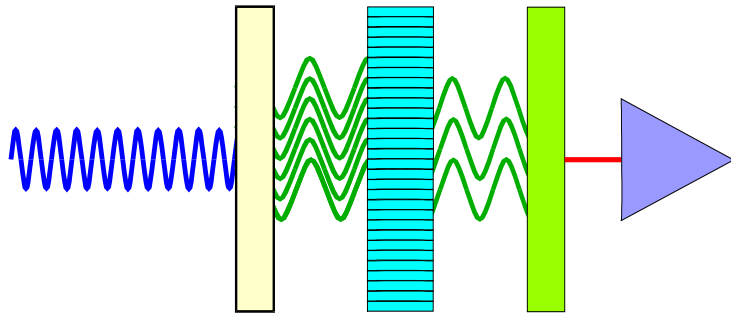
Direct detection

Gain $\sim 2000e^- / 8\text{keV x-ray}$



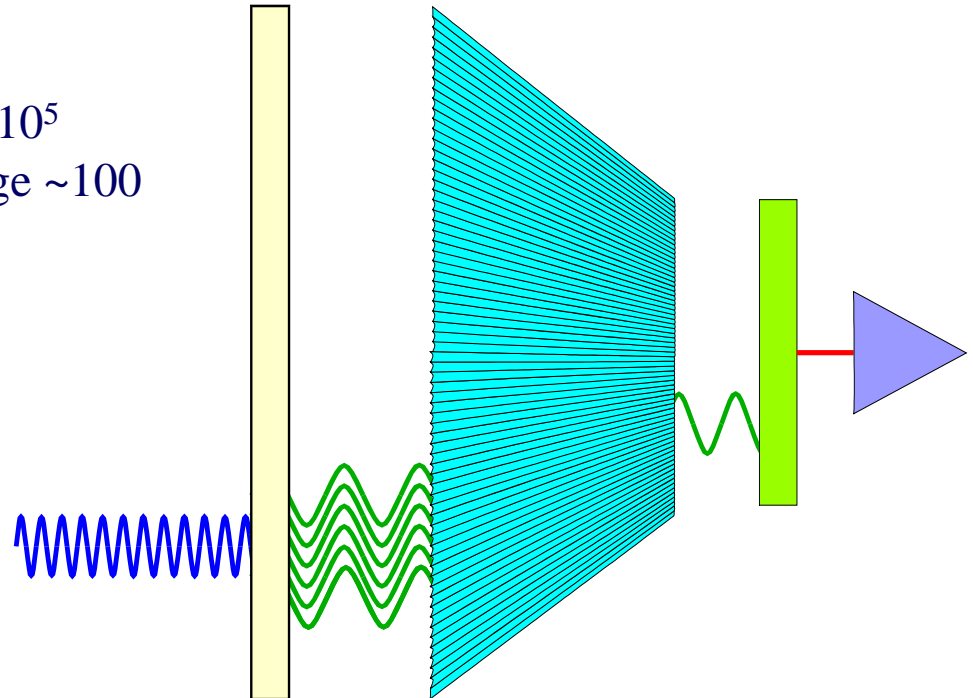
Phosphor coupled 1:1 to sensor

Phosphor gain $\gg 1$
Optics Gain < 1



Phosphor coupled with reducing optics to sensor

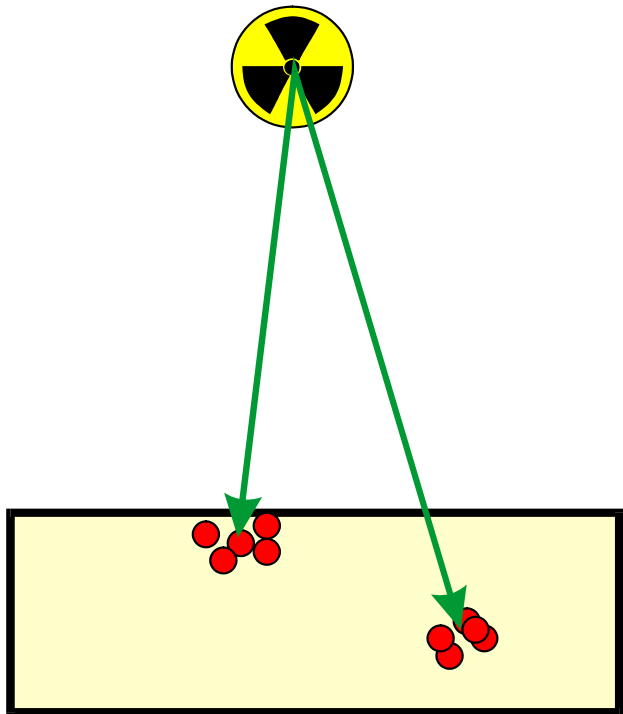
Phosphor gain $\gg 1$
Optics Gain $\ll 1$



Computed Radiography-Image Plate

Exposure

Creation of F
centres
Gain $\gg 1$

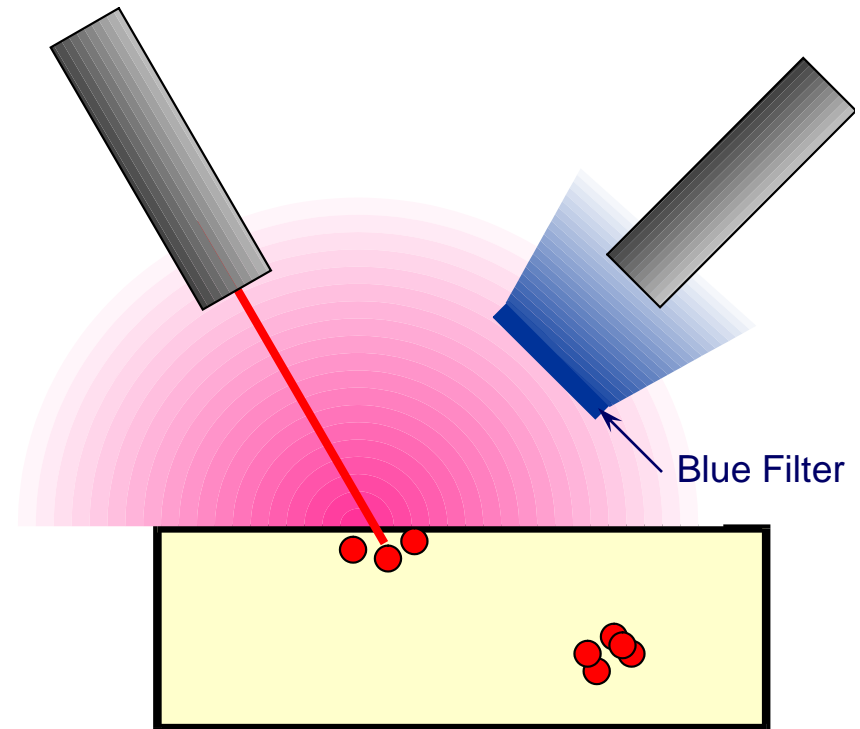


Scanning

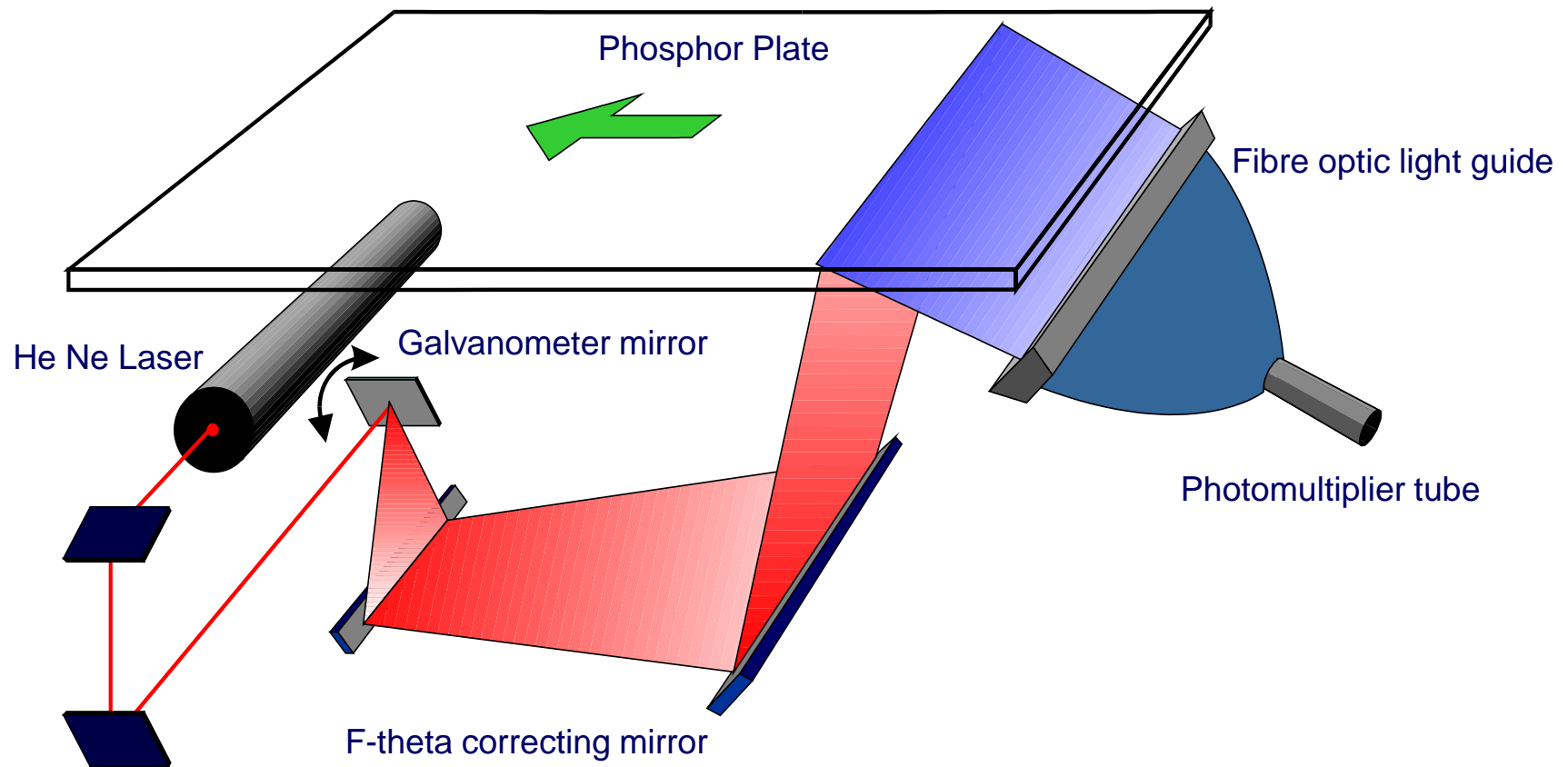
Stimulation
of PSL
Gain < 1

Collection
of PSL
Gain < 1

PMT
Amplification
Gain > 1

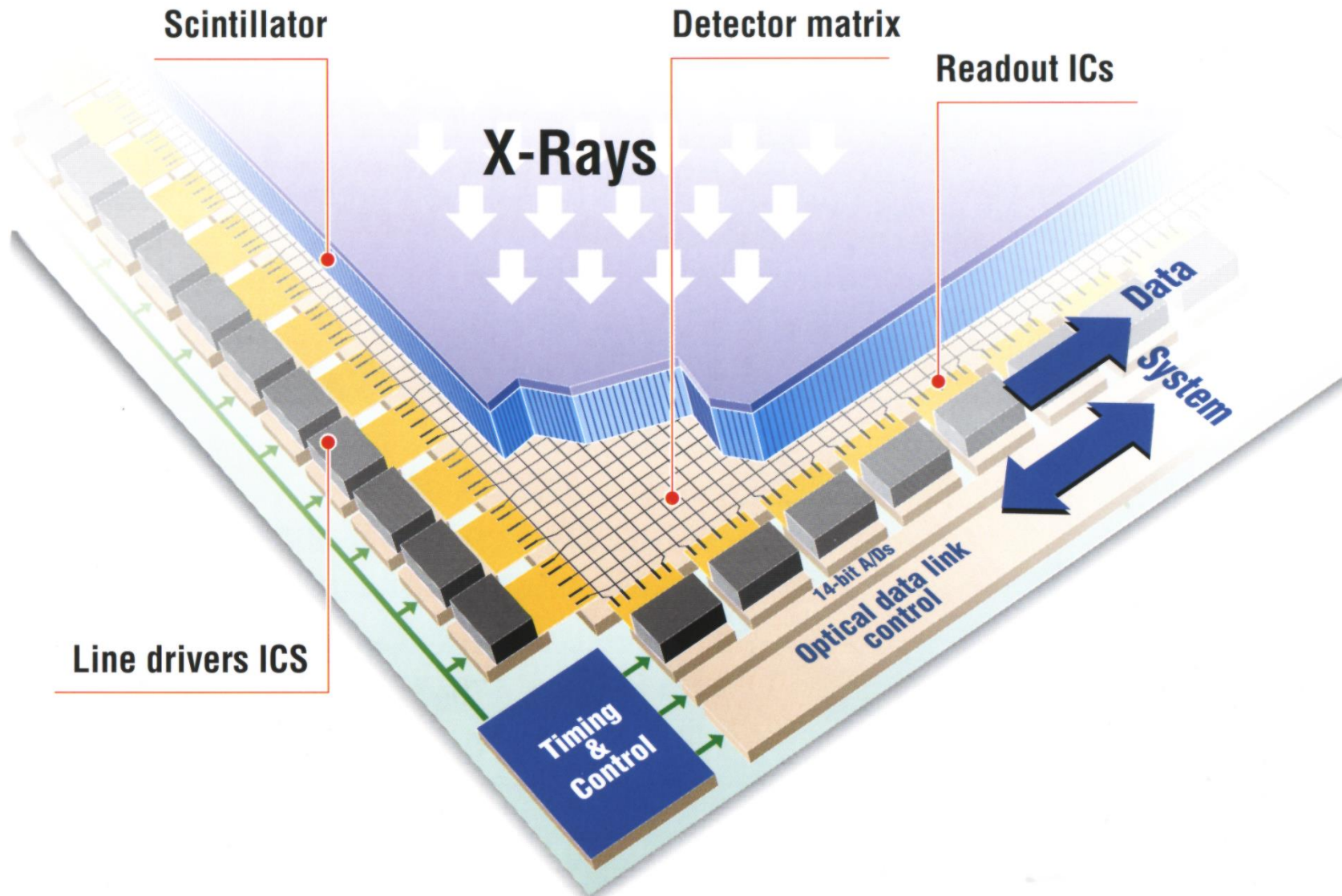


X-Y Flat bed Scanner

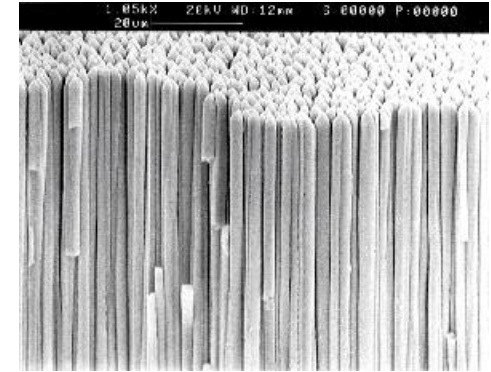
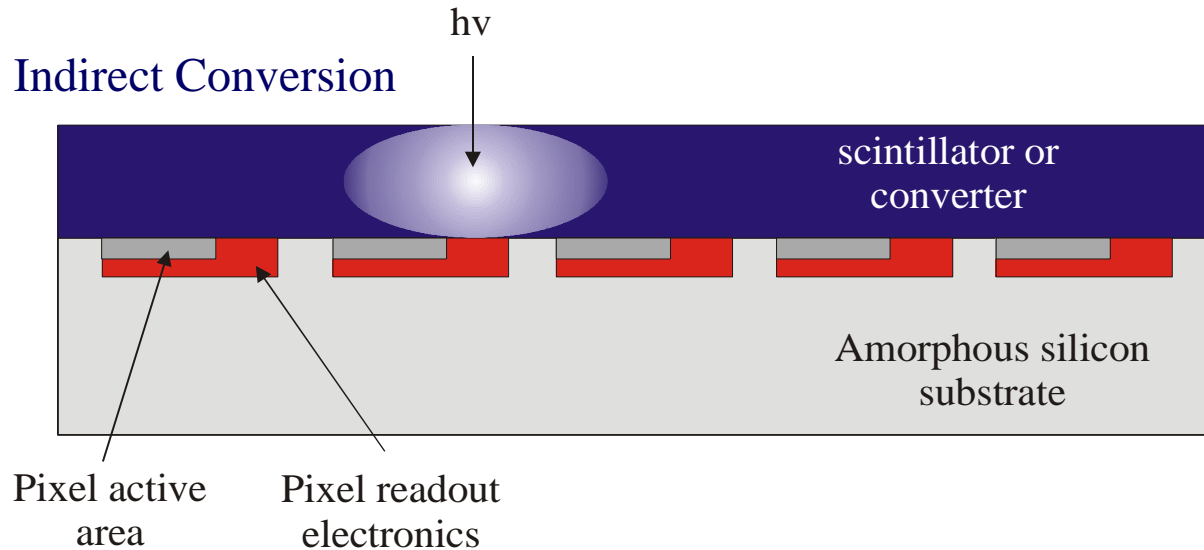


Distributed Light Collection

TFT Flat panel Detector

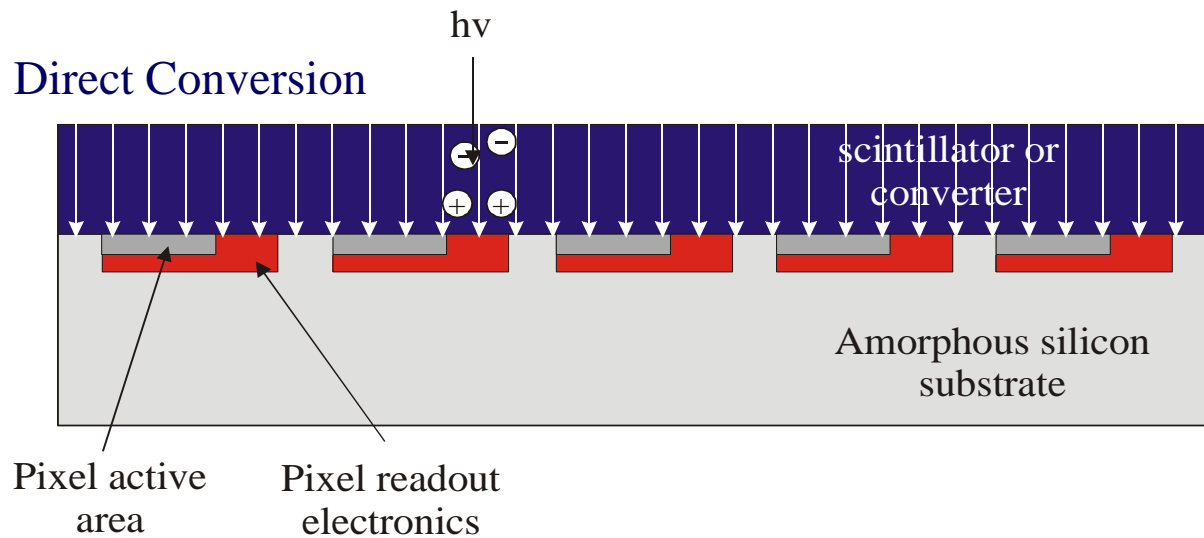


a-Si:H TFT arrays

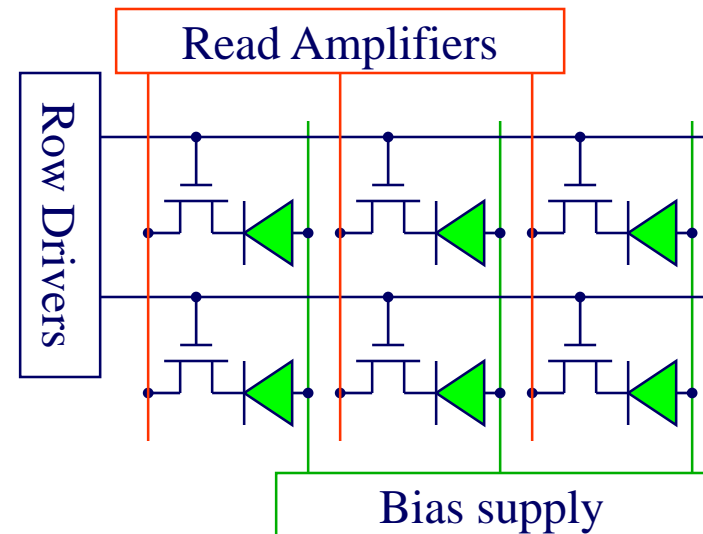
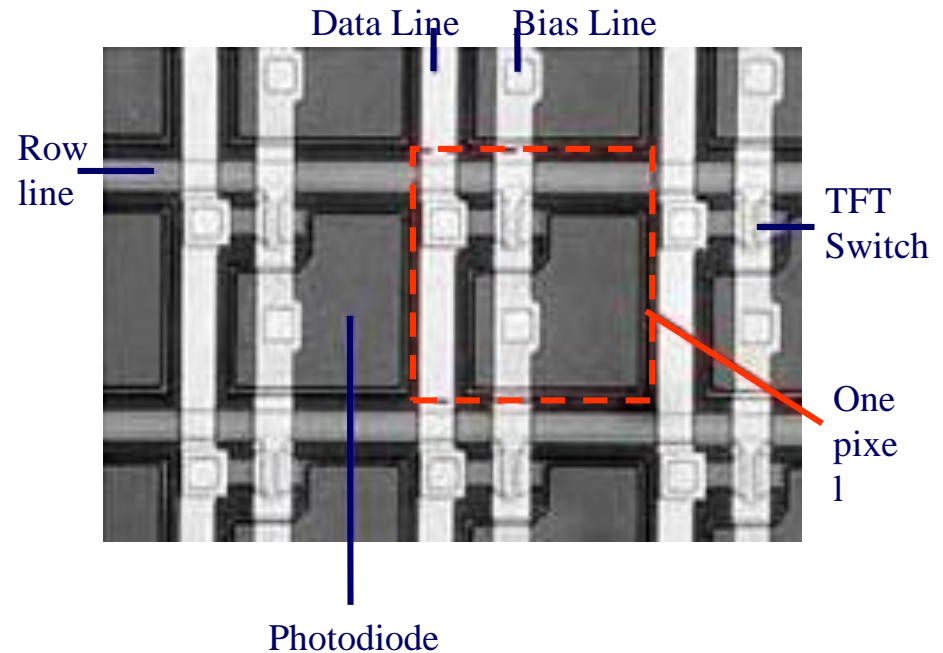


Needle diameter

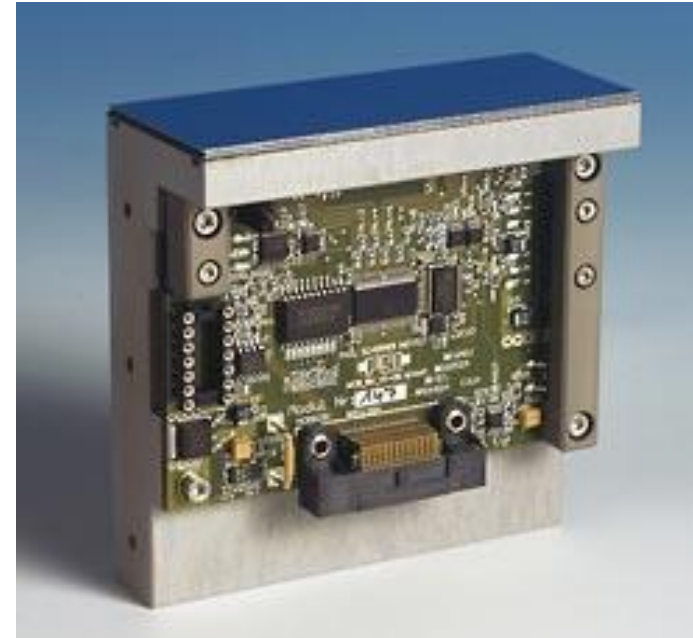
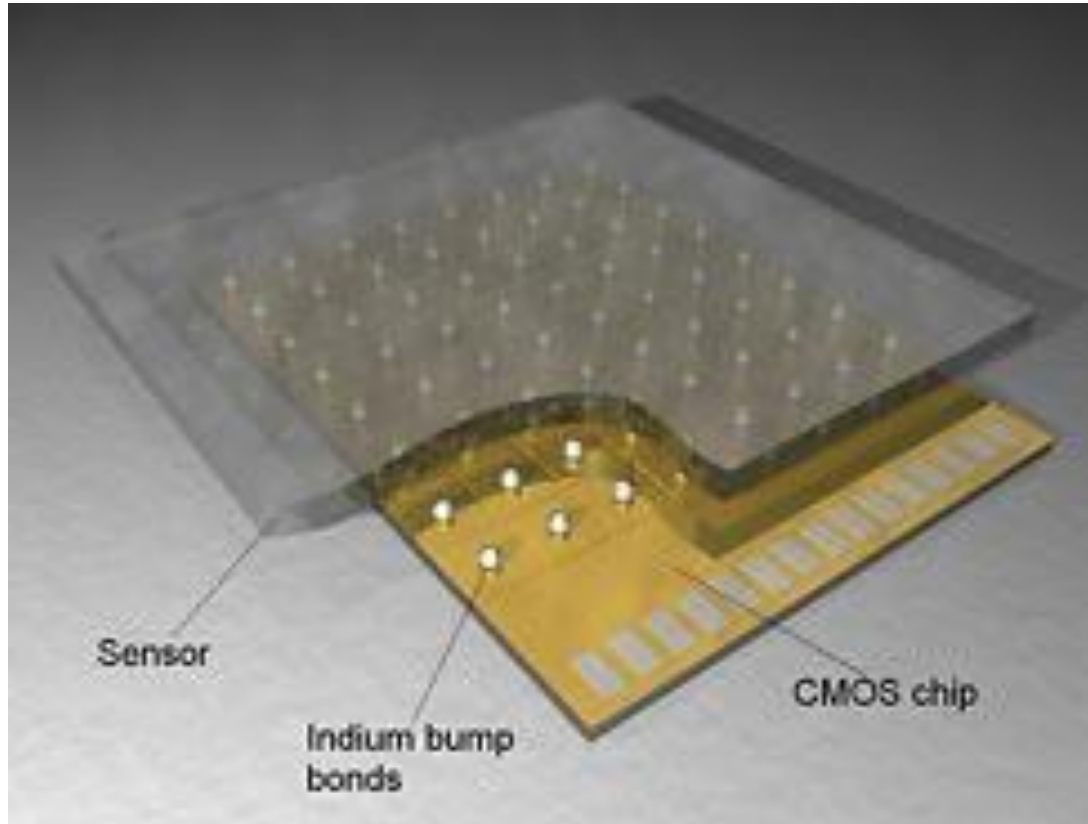
6 μ m



a-Si:H Array dpiX - Flashscan 30



PILATUS 6M Detector



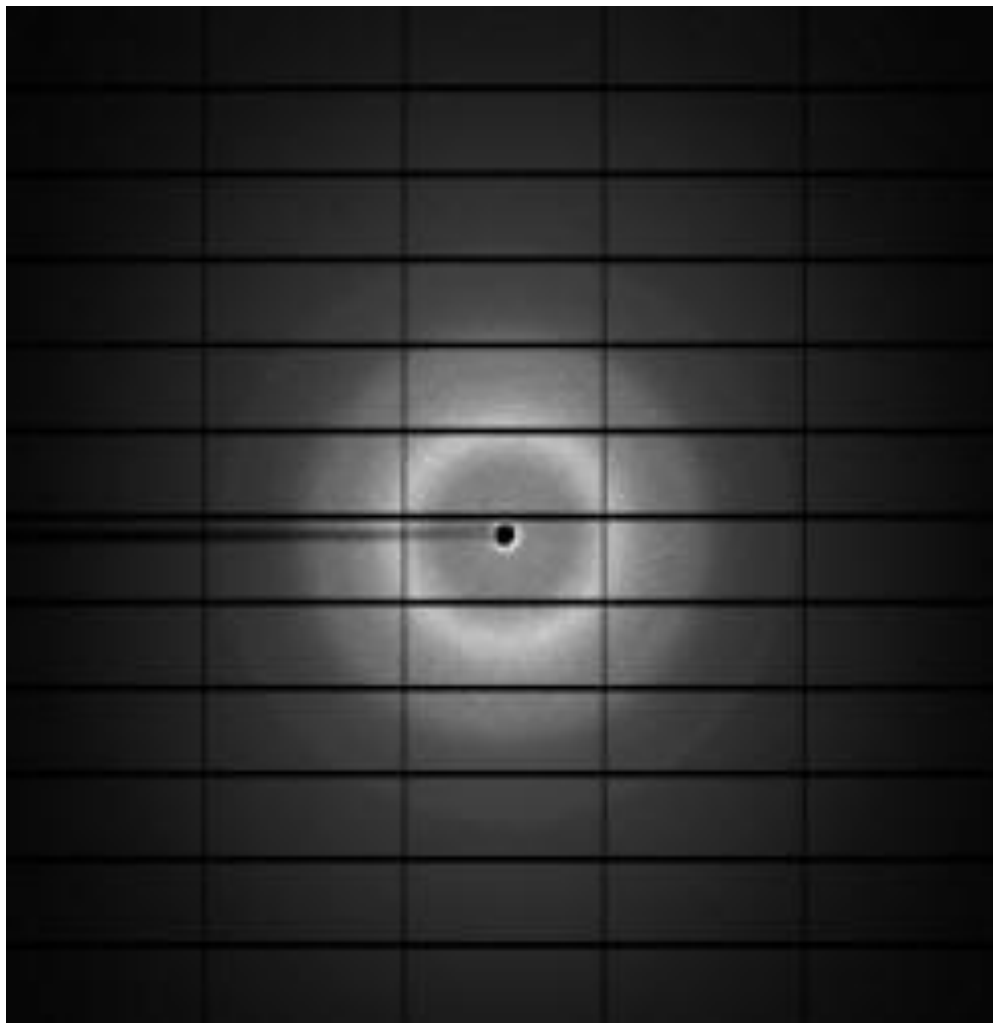
Ch. Brönnimann, E. Eikenberry, B. Schmitt, M. Naef, G. Hülsen (SLS); R. Horisberger, S. Streuli (TEM); Ch. Buehler (LOG); F. Glaus (LMN); M. Horisberger (LNS)

PILATUS 6M Detector

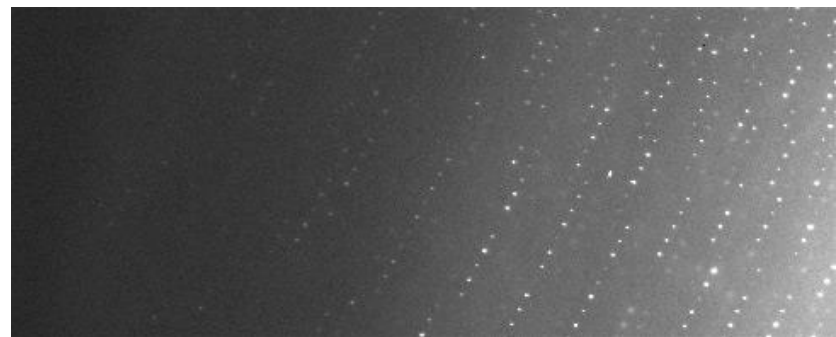


- Sensor $5 \times 12 = 60$ modules
 - ◆ Reverse-biased silicon diode array
 - ◆ Thickness $320 \mu\text{m}$
 - ◆ Pixel size $172 \times 172 \mu\text{m}^2$
- $2463 \times 2527 = 6,224,001$ pixels
- Area $431 \times 448 \text{ mm}^2$
- Intermodule gap x: 7 pixels, y: 17 pixels, 8.4% of total area
- Dynamic range 20 bits (1:1,048,576)
- Counting rate per pixel $> 2 \times 10^6$ X-ray/s
- Energy range 3 – 30 keV
- Quantum efficiency (calculated)
 - ◆ 3 keV: 80%
 - ◆ 8 keV: 99%
 - ◆ 15 keV: 55%
- Energy resolution 500 eV
- Adjustable threshold range 2 – 20 keV
Threshold dispersion 50 eV
- Readout time 3.6 ms
- Framing rate 12 Hz
- Point-spread function 1 pixel

PILATUS 6M Detector



- X-ray diffraction image recorded from a ferritin crystal (energy=16 keV, distance = 204 mm).



Agilent S2 CCD with Smart Sensitivity



- The S2 CCD detectors employ groundbreaking Smart Sensitivity Control, which tunes detector sensitivity to match the strength of the data observed. Similar to ISO settings in digital photography, this selects the widest dynamic range or the highest sensitivity, as needed, to maximize your data quality.

Spectroscopic Detectors

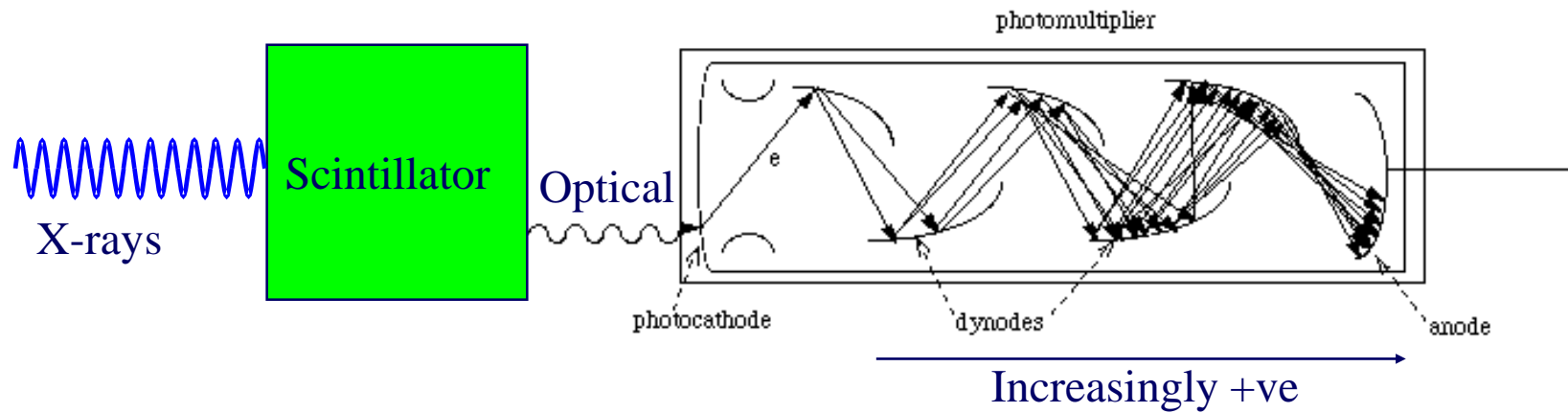


Rainbow Lorikeets

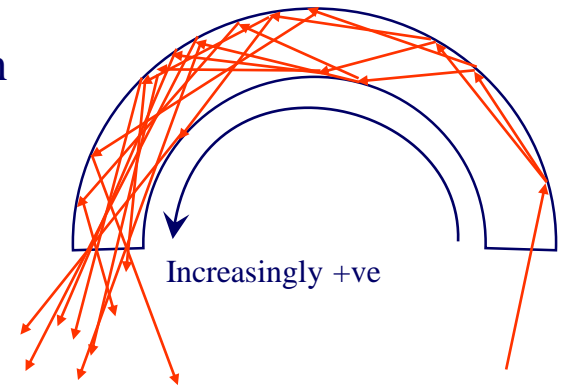
Spectroscopic Detectors

- For quantitative work, most are counting detectors that measure the size of individual energy deposits
- Alternative is the use of filters as in optical colour cameras

Electron multipliers & Scintillators



Channeltron is a similar with distributed dynode



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

Multi Channel Spectroscopic Detectors

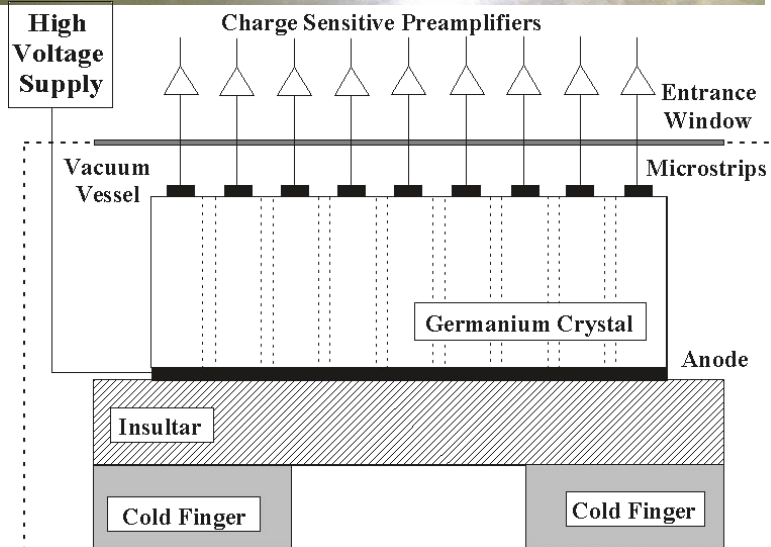


Canberra Ultra-LEGe detector

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

SPring-8 128 channel Ge strip



■ Ge

◆ $55.5 \times 50.5 \times 6 \text{ mm}$

■ Strips

◆ Number 128
◆ Width $300 \mu\text{m}$
◆ Interstrip $50 \mu\text{m}$
◆ Length 5 mm

■ Readout

◆ Single channel 100 ns
◆ 32 channels 3.2 ms

■ Max expected count rate

◆ 14 kcps

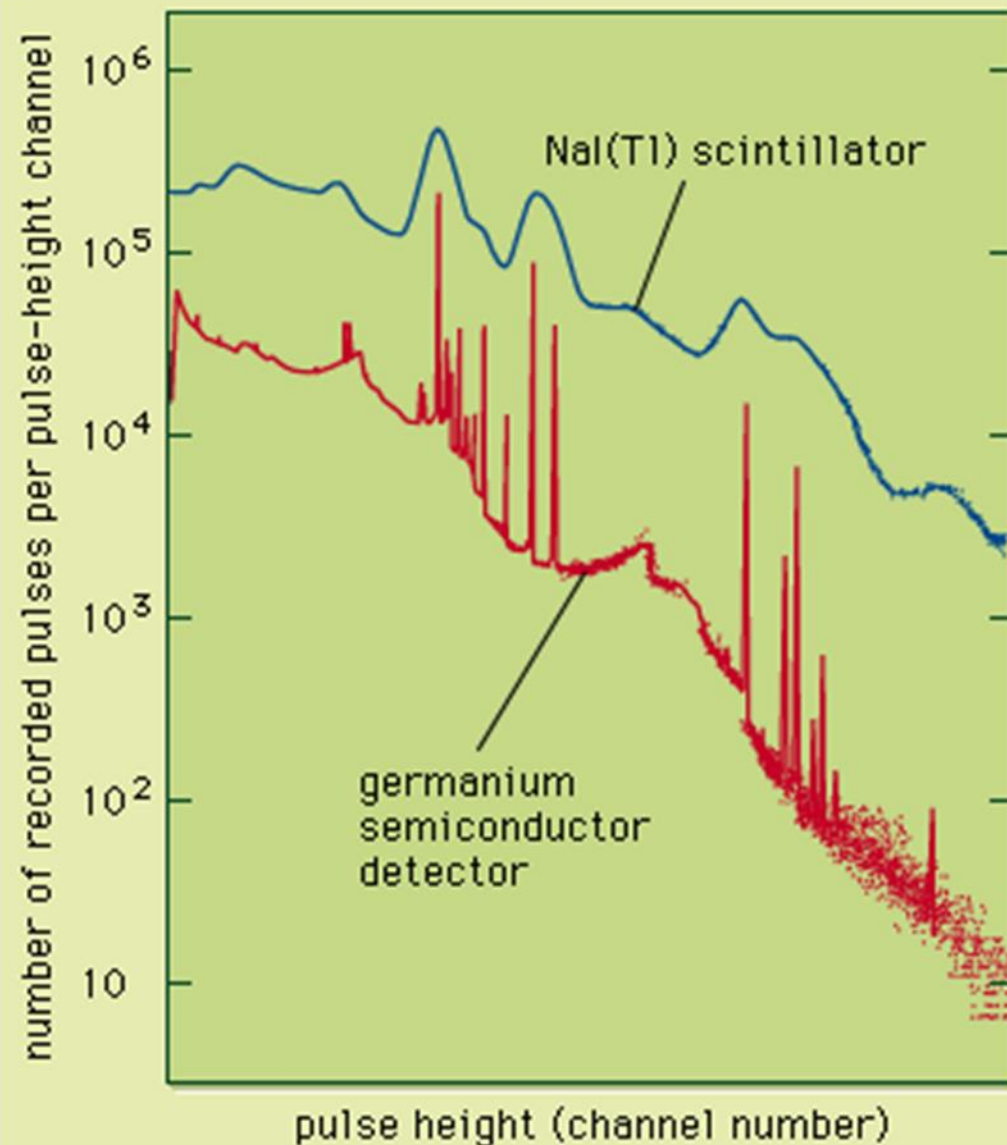
Spectral Resolution

- Average number of carriers, $N = E/w$
where w is energy to create electron hole/ion pair
- Poisson statistics $\sigma = 1/\sqrt{N}$
$$= (E/w)^{-1/2} = (w/E)^{1/2}$$
- $\Delta E/E$ fwhm $= 2.355\sigma$
$$= 2.355(w/E)^{1/2}$$
- For Ge, $w = 3\text{eV}$ so at 10keV $\Delta E/E \sim 4\%$
- For NaI, $w = 30\text{eV}$ so at 10keV $\Delta E/E \sim 13\%$

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. $\sigma = \sqrt{N}$
- Reality is somewhere in between so we introduce Fano factor F
- Fano factor is defined as
$$F = \frac{\sigma^2}{N}$$
where σ^2 is the variance and N 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 = $F \times$ Poisson relative variance

Scintillator vs Germanium



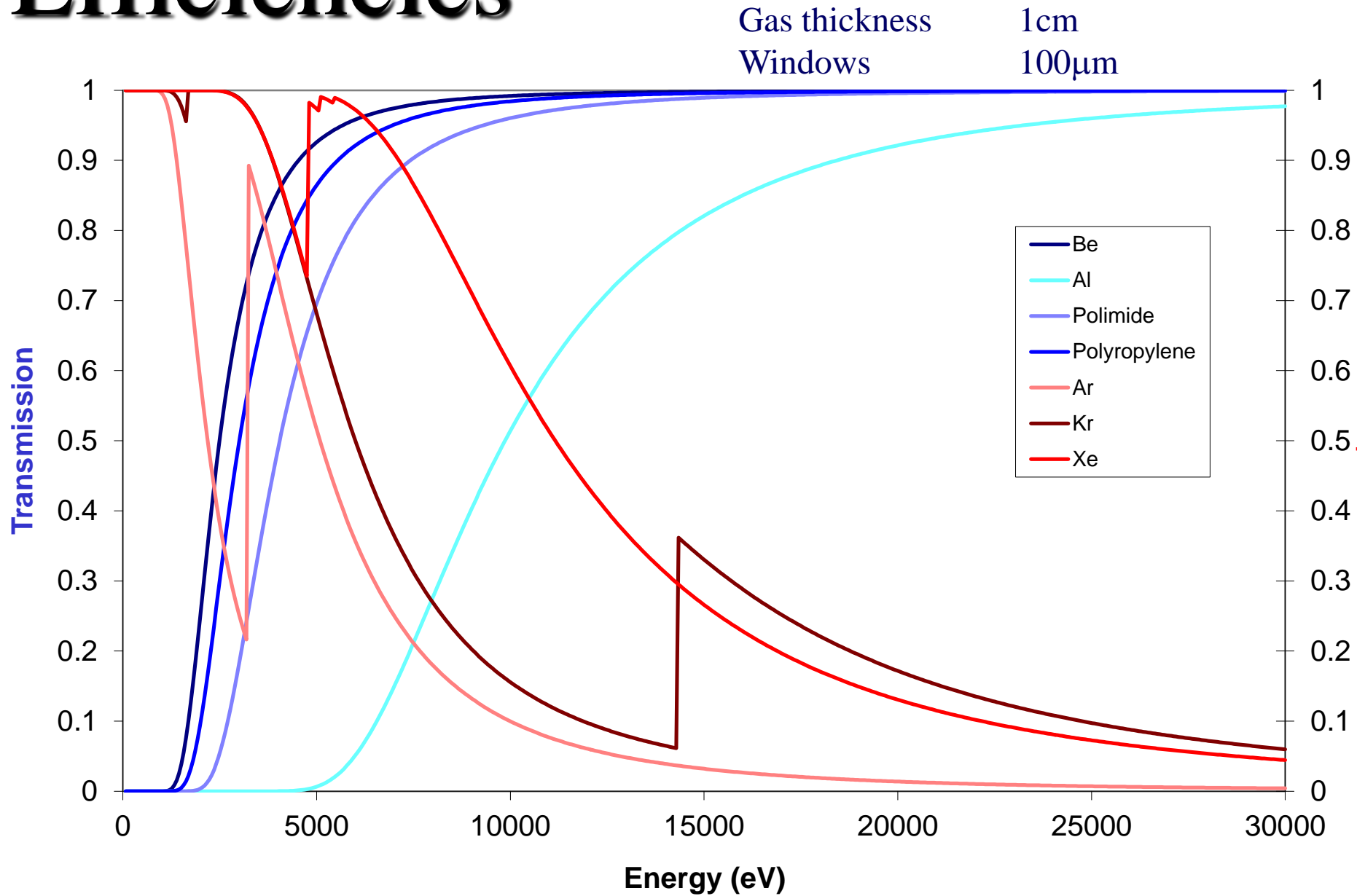
The top spectrum is from a scintillation detector, and the bottom is from a germanium semiconductor detector. The superior energy resolution of the germanium is evident from the much narrower peaks, allowing separation of gamma-ray energies that are unresolved in the scintillator spectrum.

Things to Look Out For

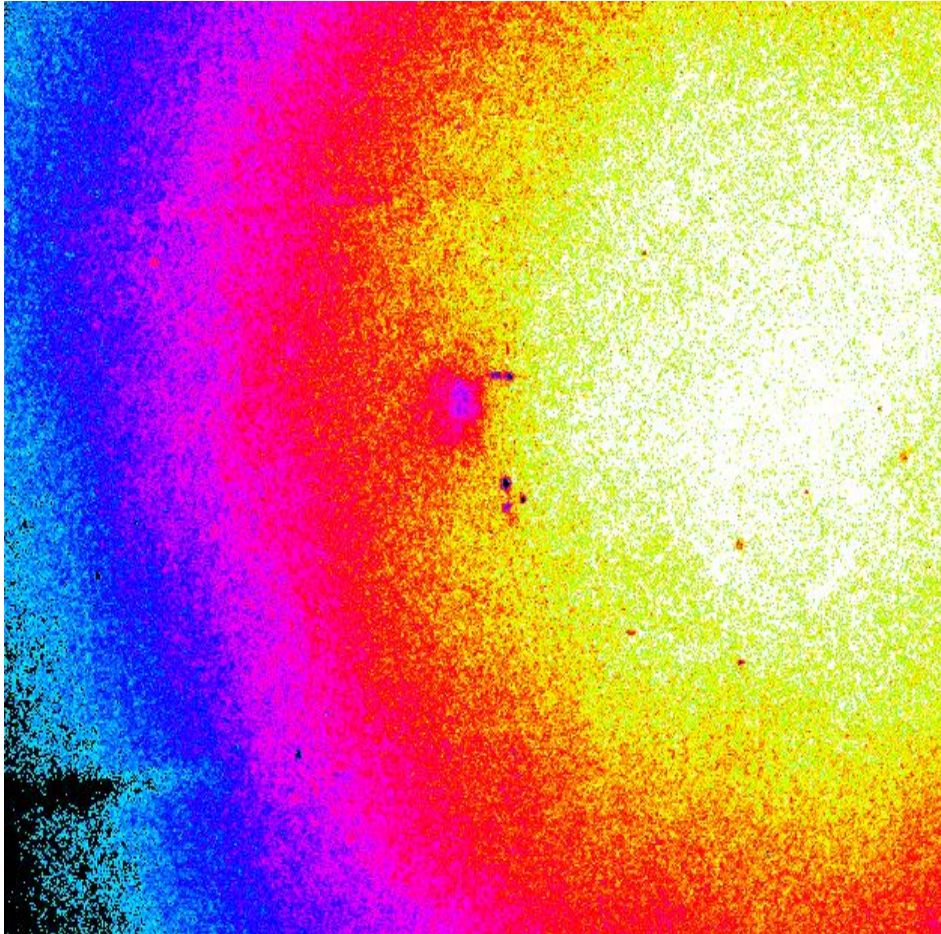


Crocodile

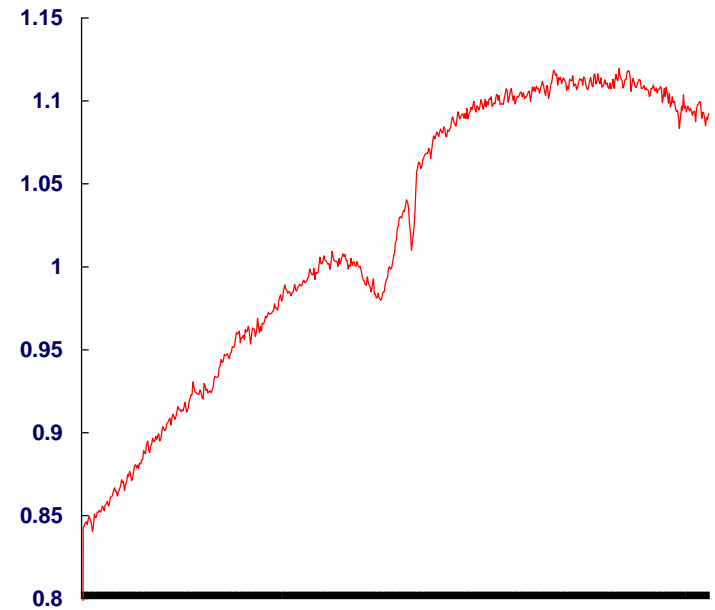
Efficiencies



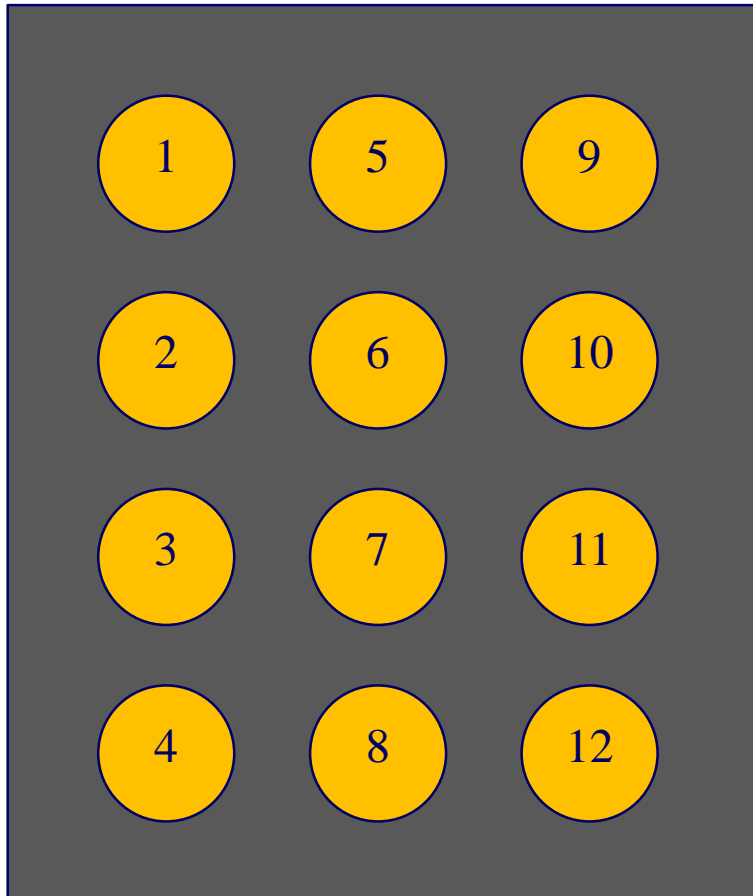
Response to Uniform Illumination



ESRF TV Detector
Thompson IIT & CCD

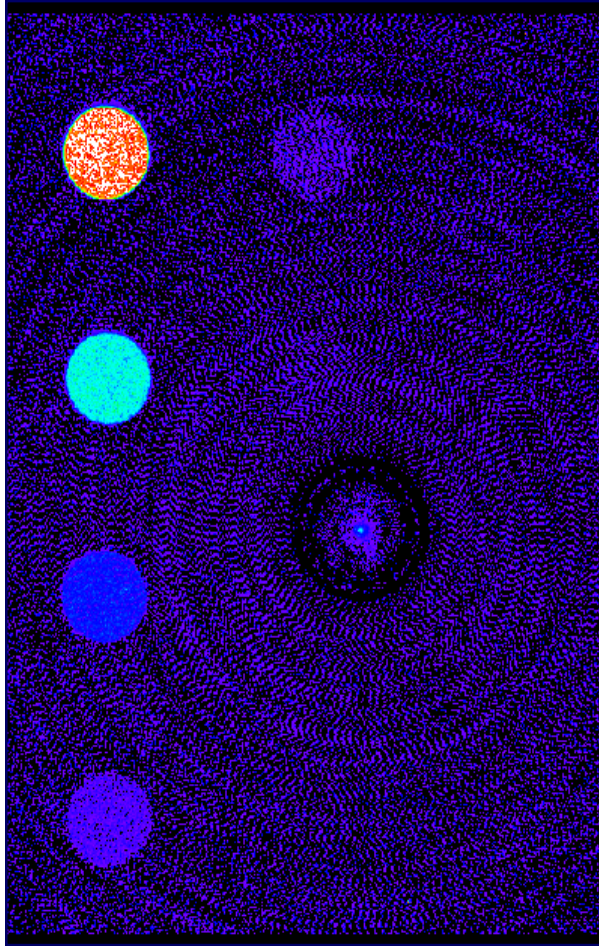


Intensity Test

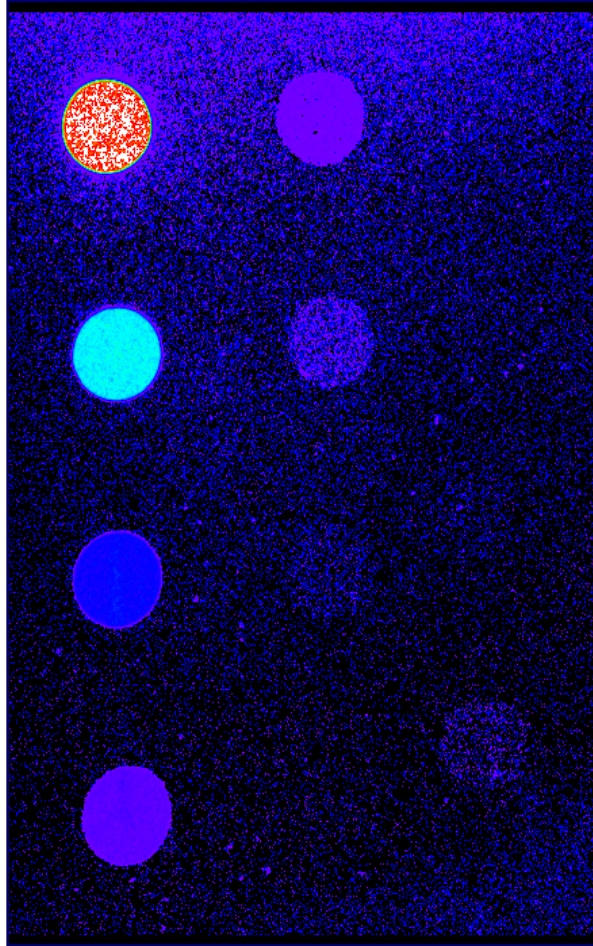


Graded Absorber Comparison

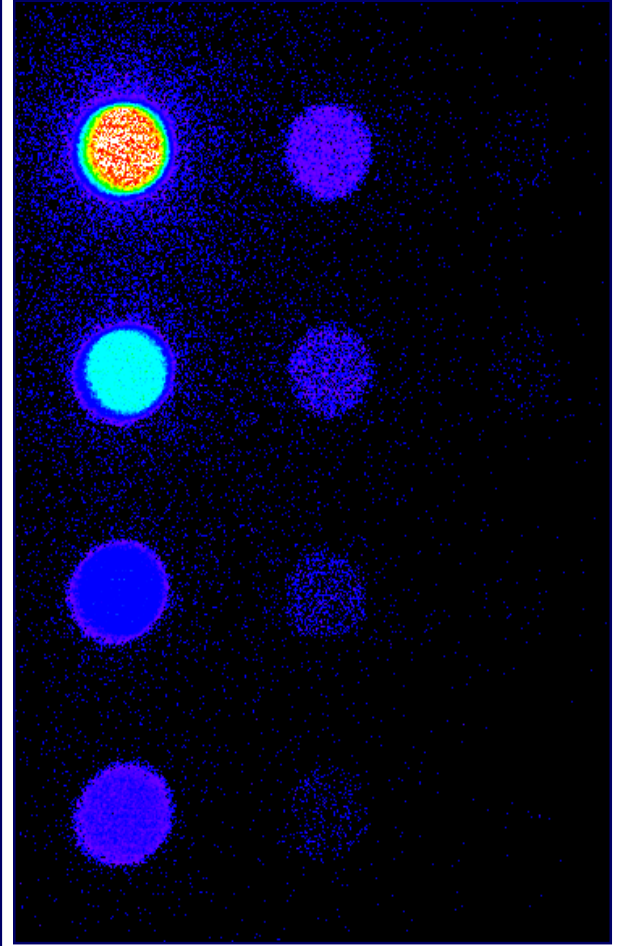
Mar Image Plate



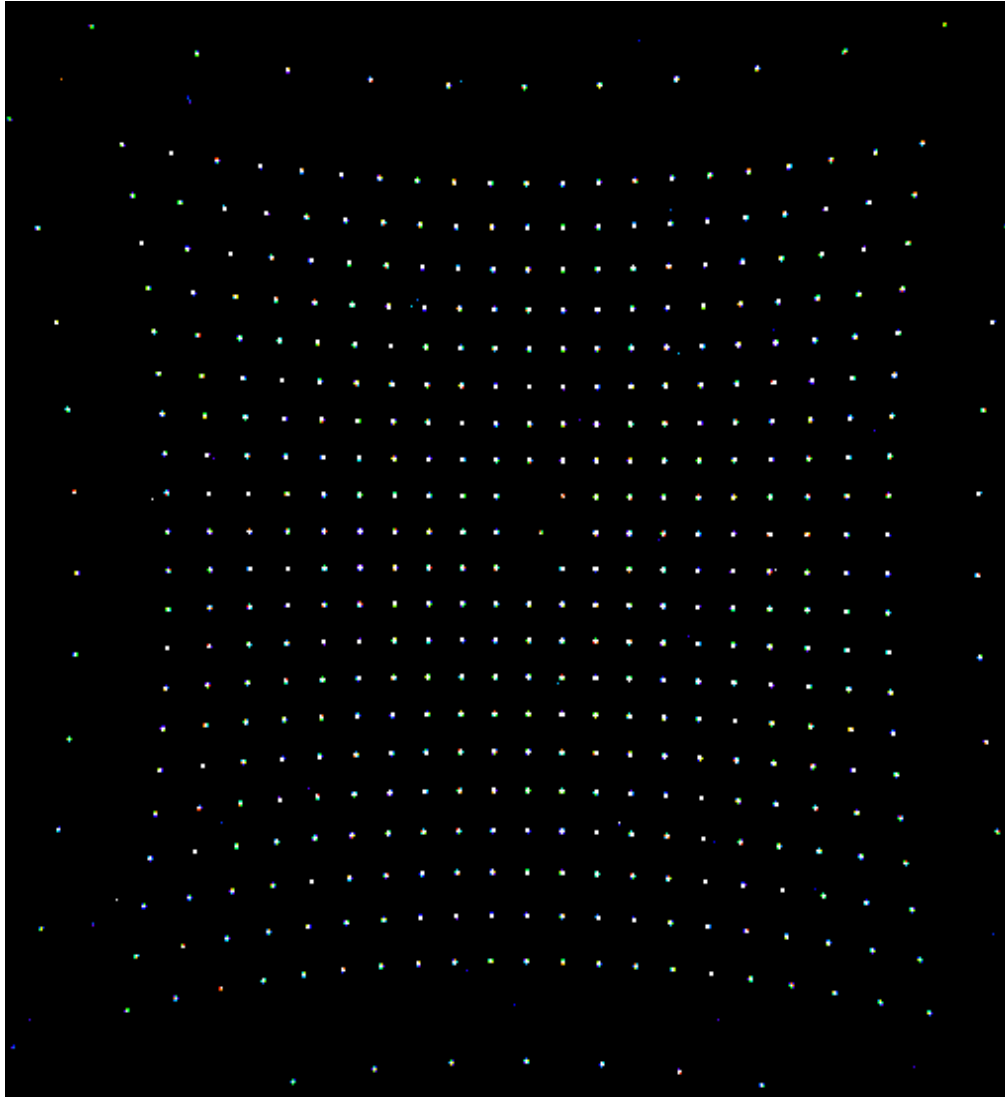
ESRF-Thompson IIT / CCD



Daresbury MWPC

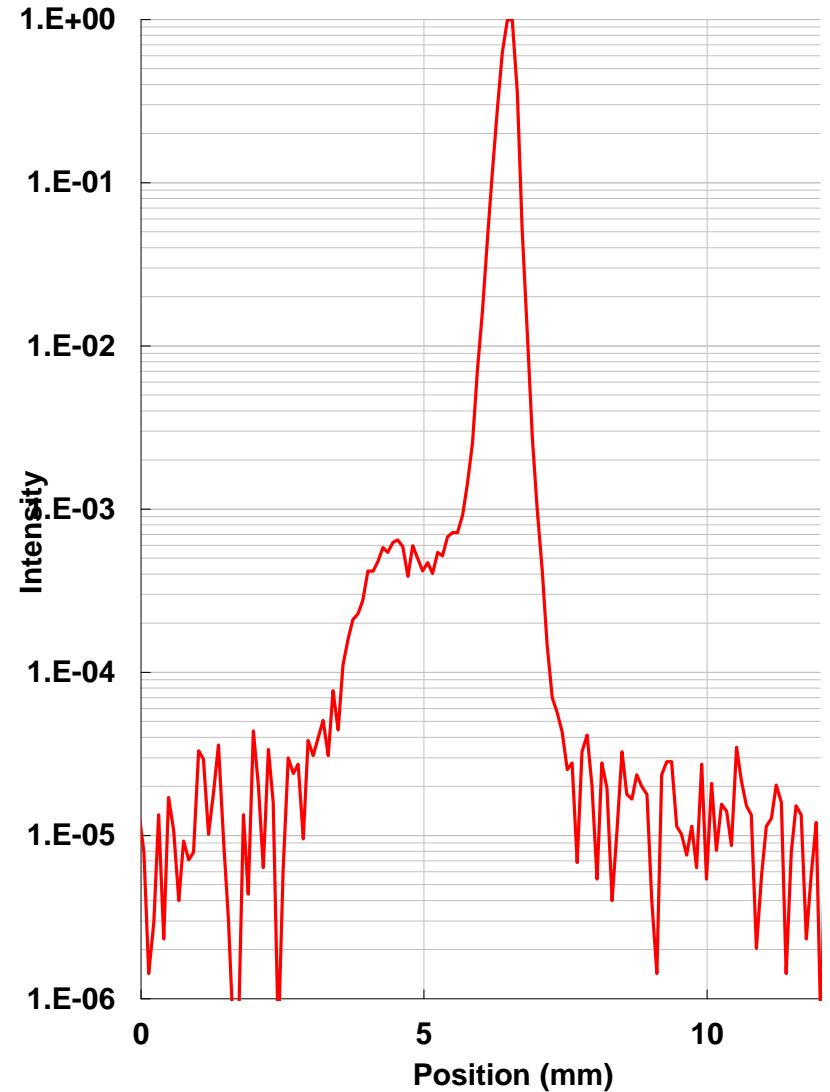
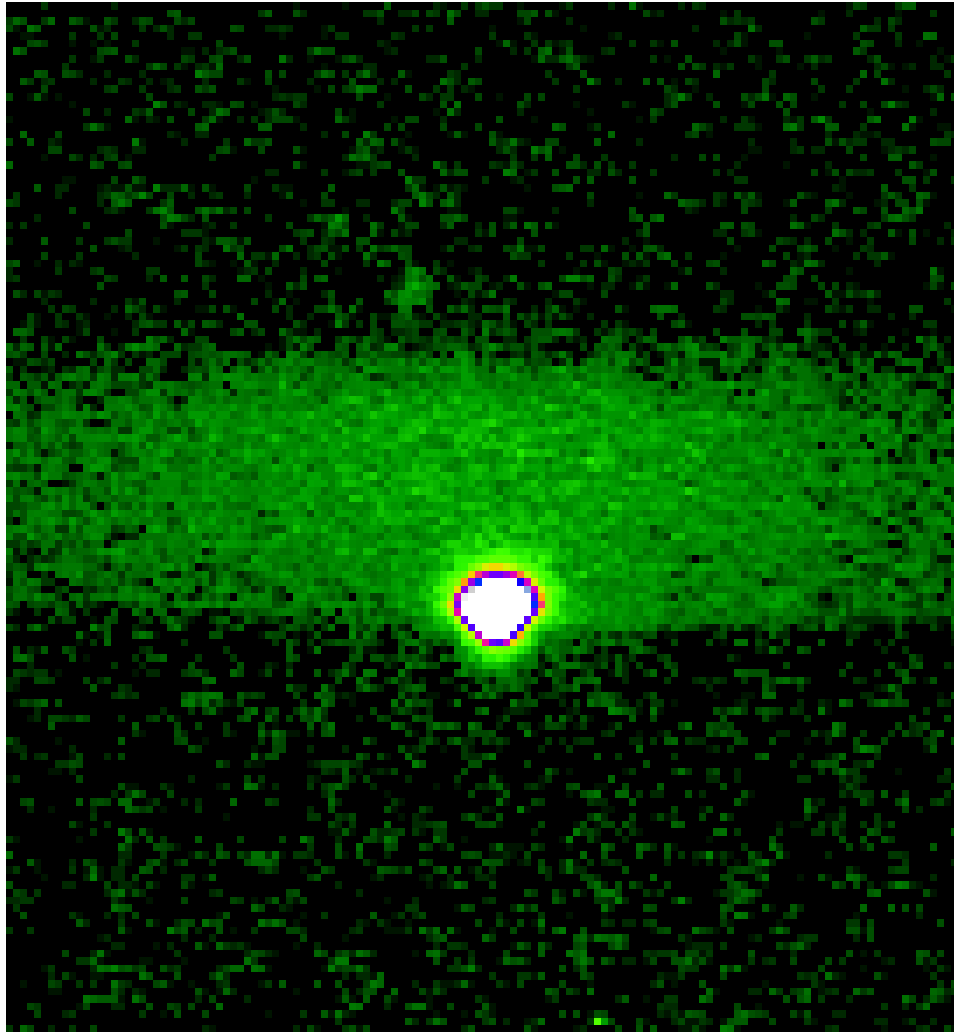


Spatial distortion $x \equiv f(y)$

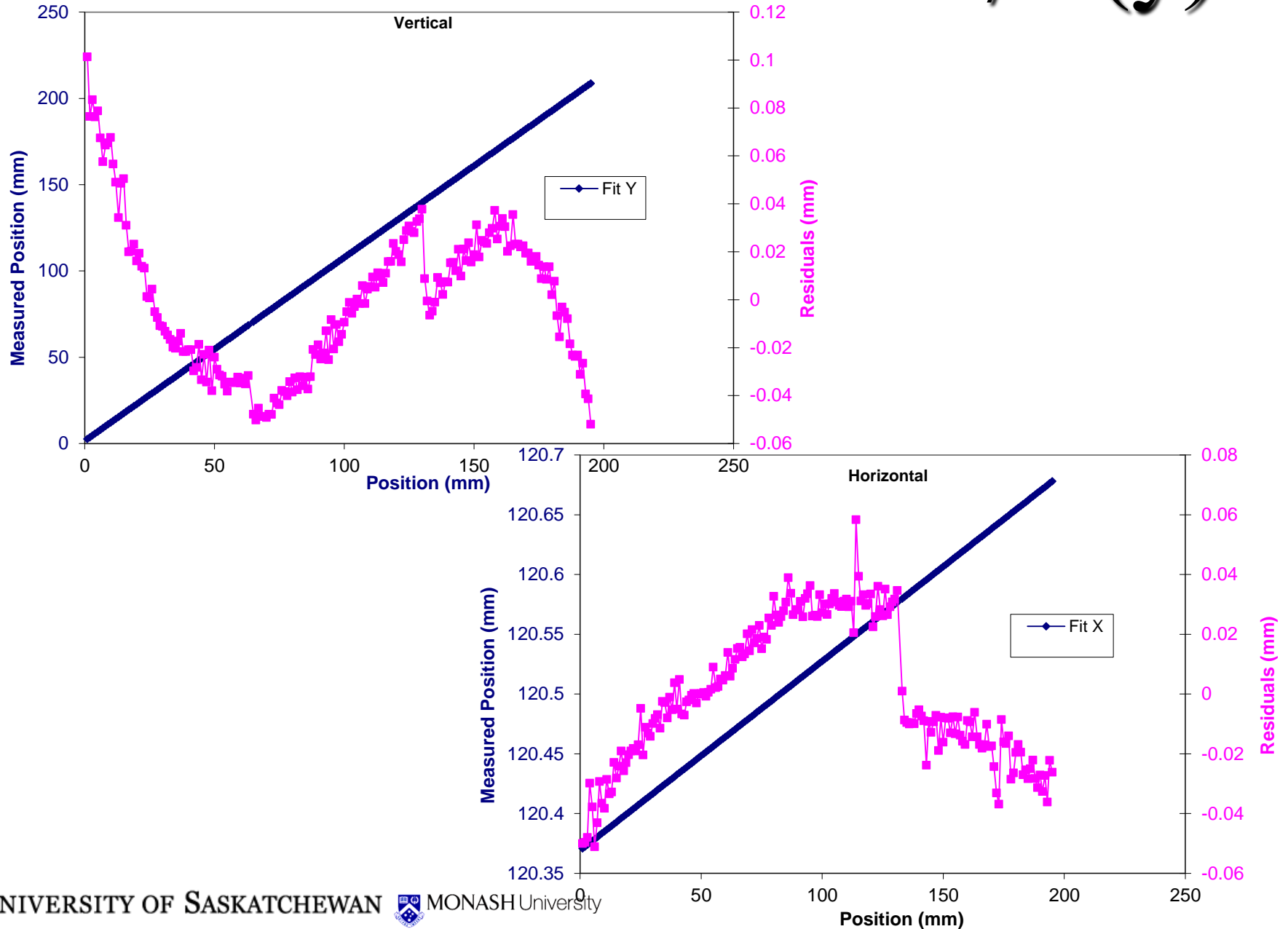


ESRF Image
intensifier
detector

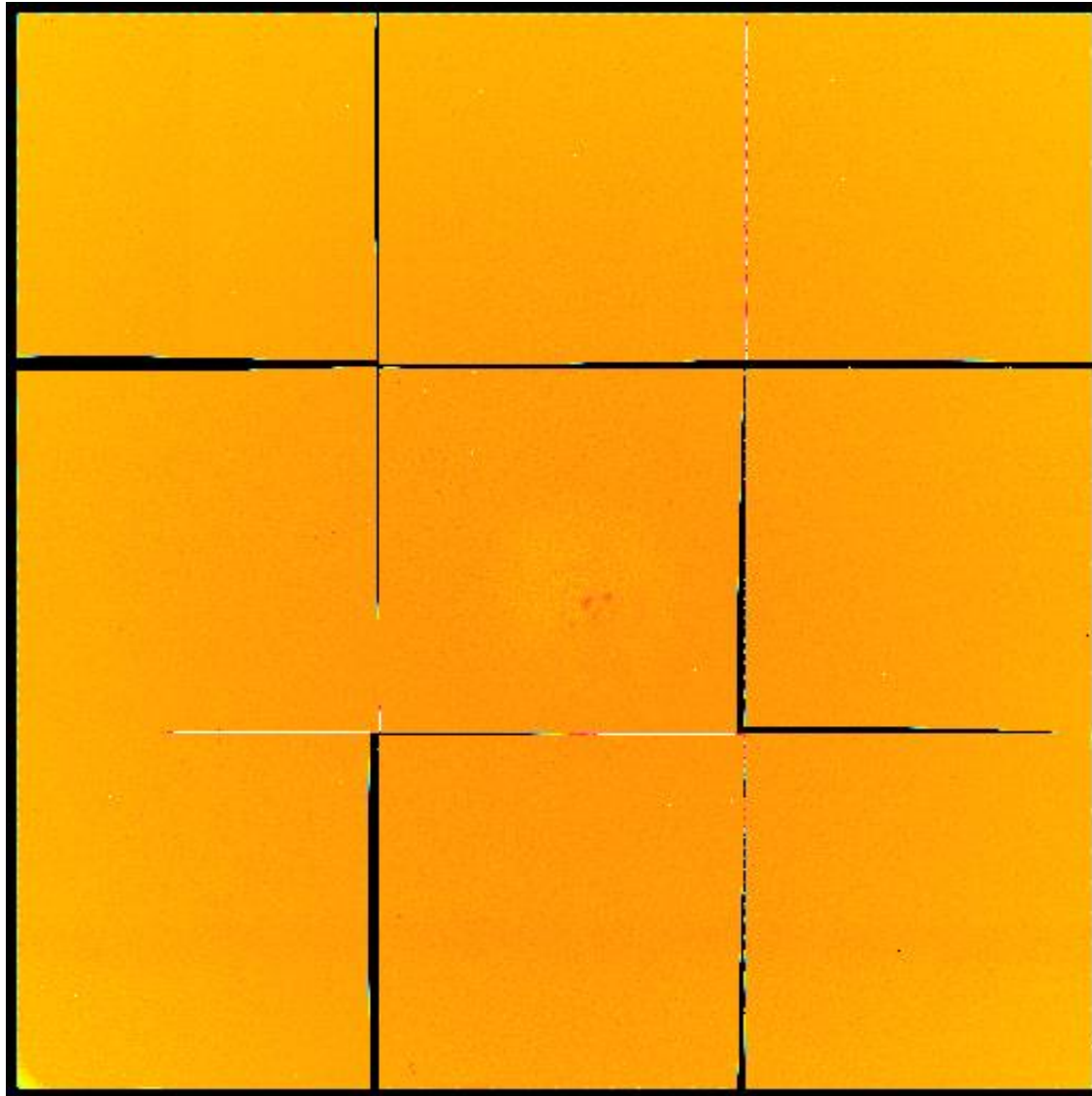
IPlate Single Peak PSF



Geometric Distortion $x \neq f(y)$

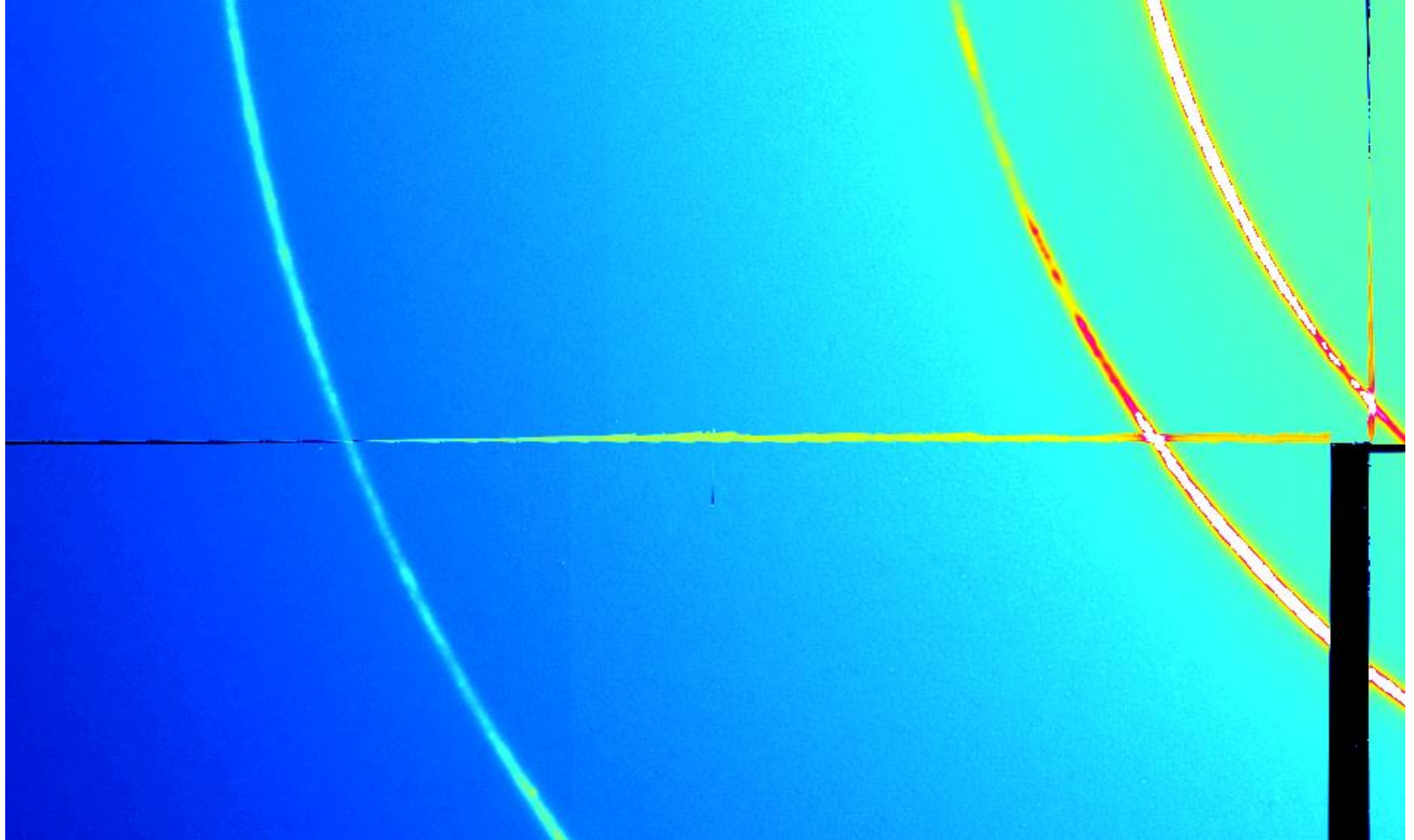


Gaps

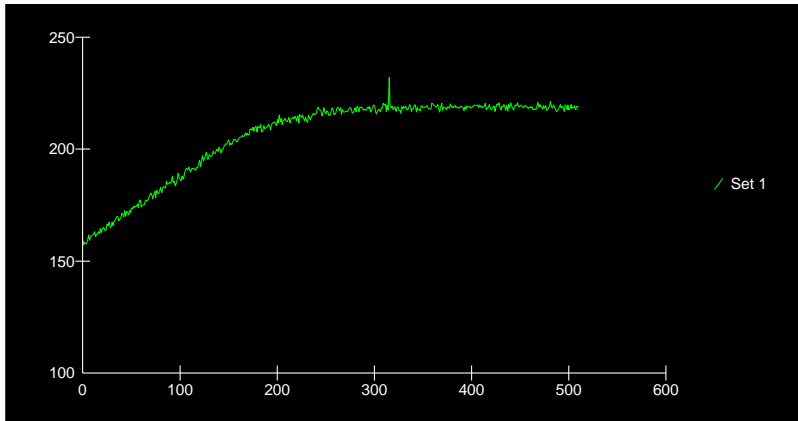
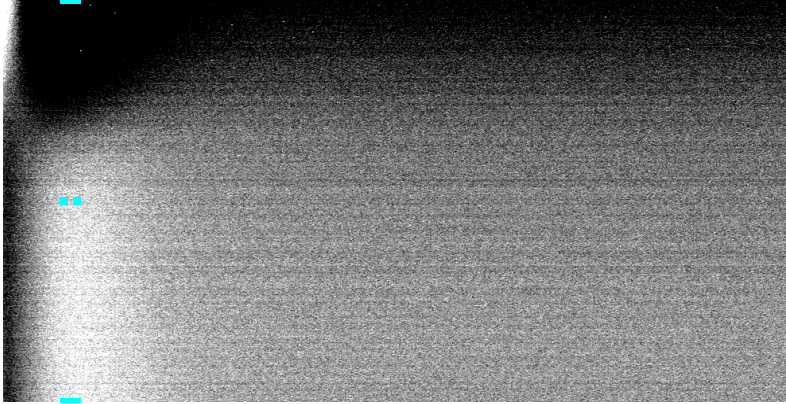


Spec	0.2mm max
Worst gap	2.97mm
Pixels in gaps	513922 5.45%

Overlaps



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)

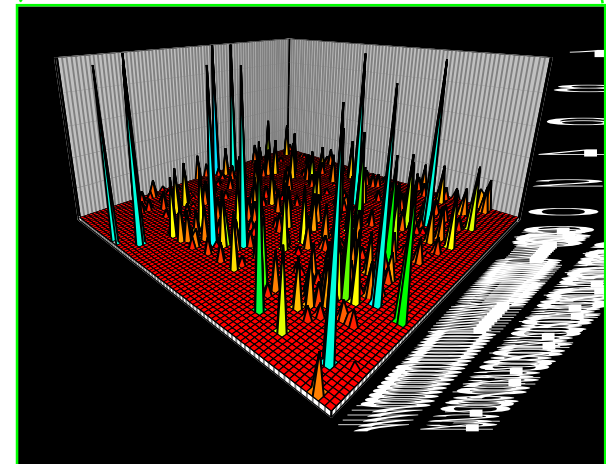
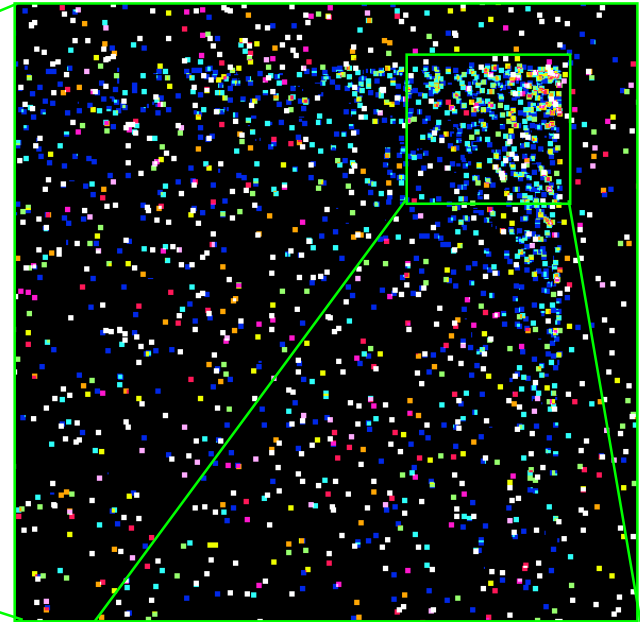
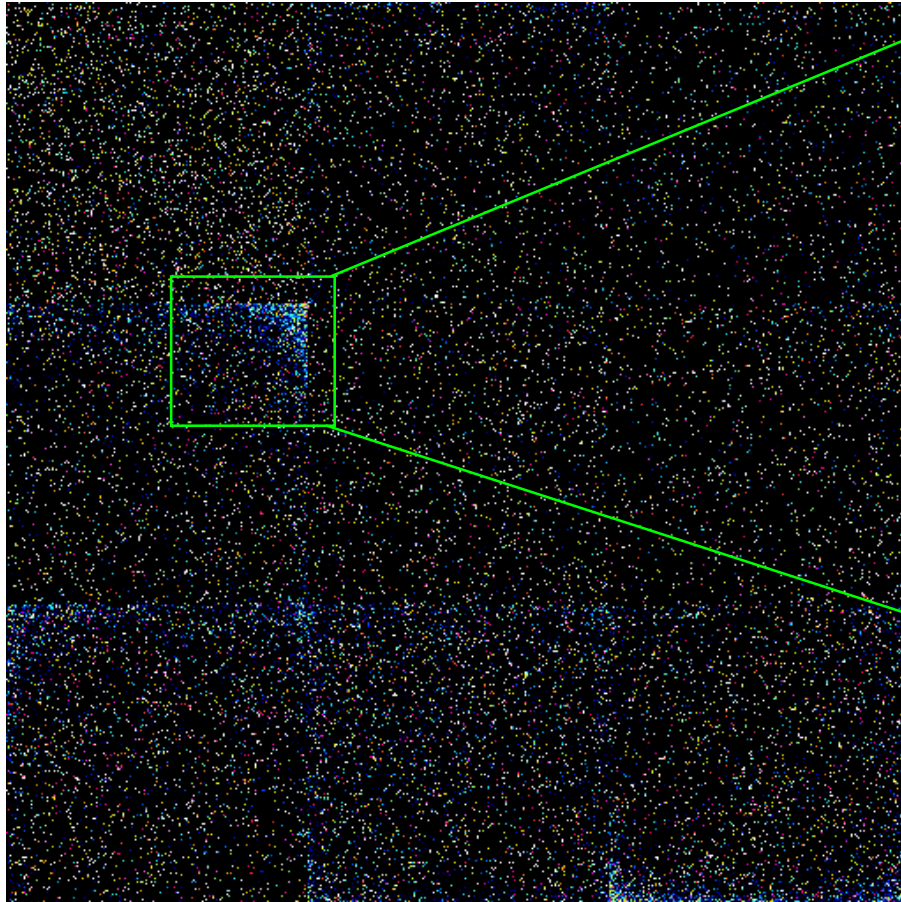
Both must be recorded with the same exposure time as the original image since dark current is a function of exposure time.

Then apply the following correction

$$Corrected = \frac{(image - dark)}{(flat - dark)}$$

Dark Current

Pixels above the 0.2 photons pix^{-1} specification

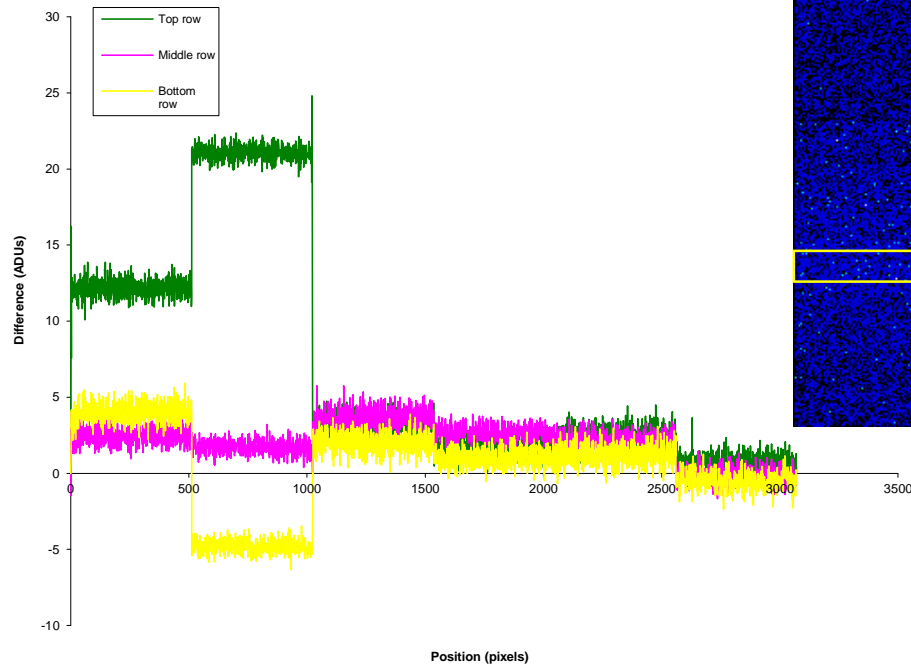
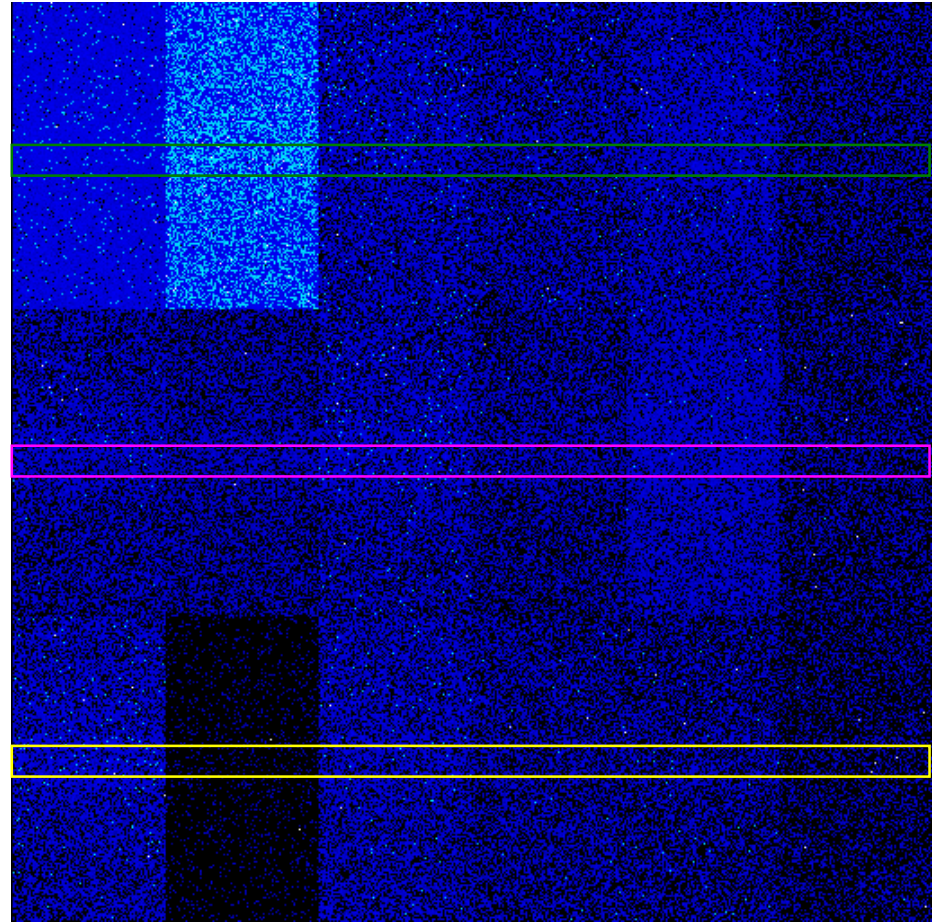


Number failing 2 measurements 5-2000s

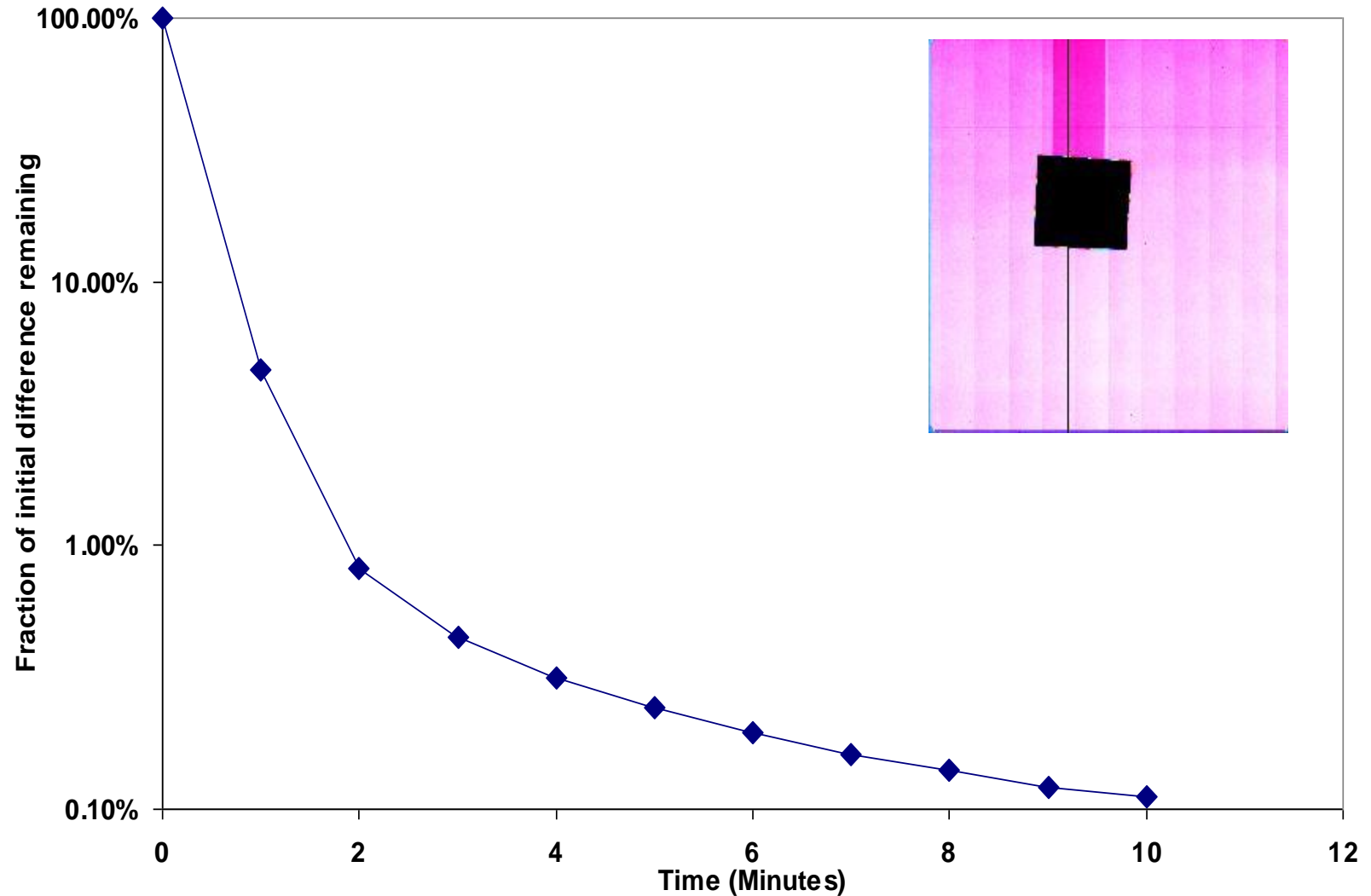
Mean	44764	0.47%
Min	40822	0.43%
Max	48706	0.52%

nb. 14300 pixels not common to both

Subtraction of dark images



Flashscan 30 - Image Lag



Radiation Damage (Medipix)

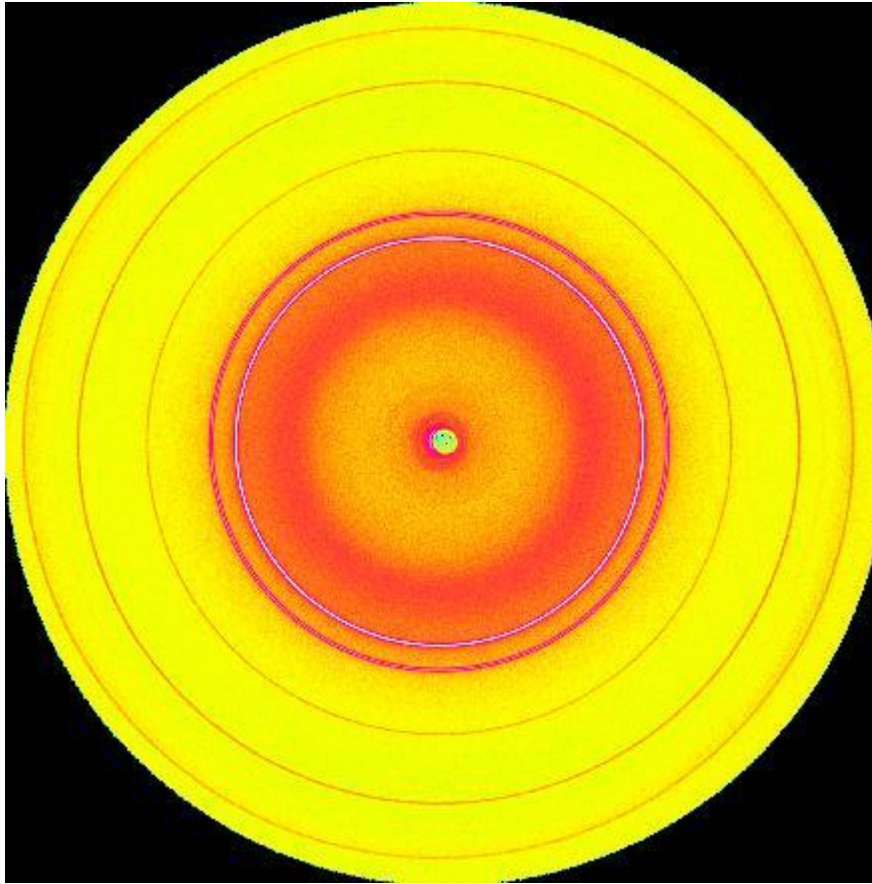
- Damage occurred at 40Gy or 1.3×10^{10} pht/mm² in the readout chip
- At 13 keV photon energy
 - ◆ Strong diffraction spots typically 10^5 phts/s or 10^6 phts/mm²/s
 - Damage requires ~ 8hours exposure
 - ◆ Direct beam (10^{10} – 10^{13} photons/mm²/s)
 - Damage in less than a second.

dpiX Flashscan 30 PaxScan 4030



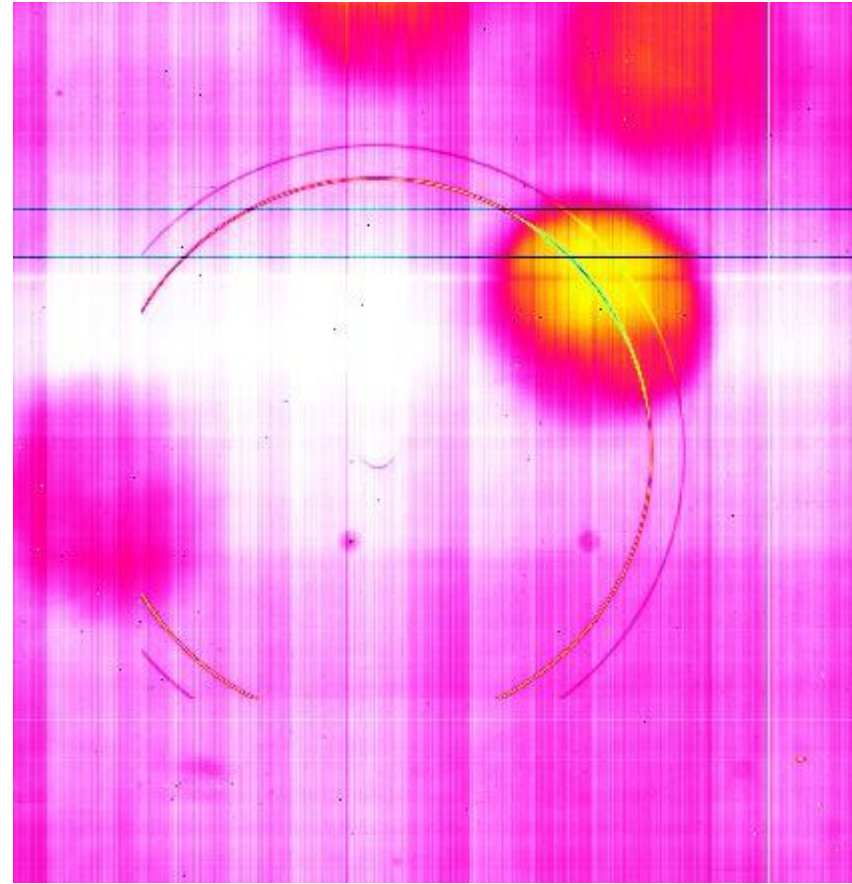
Flashscan 30 - Performance

Mar Image Plate



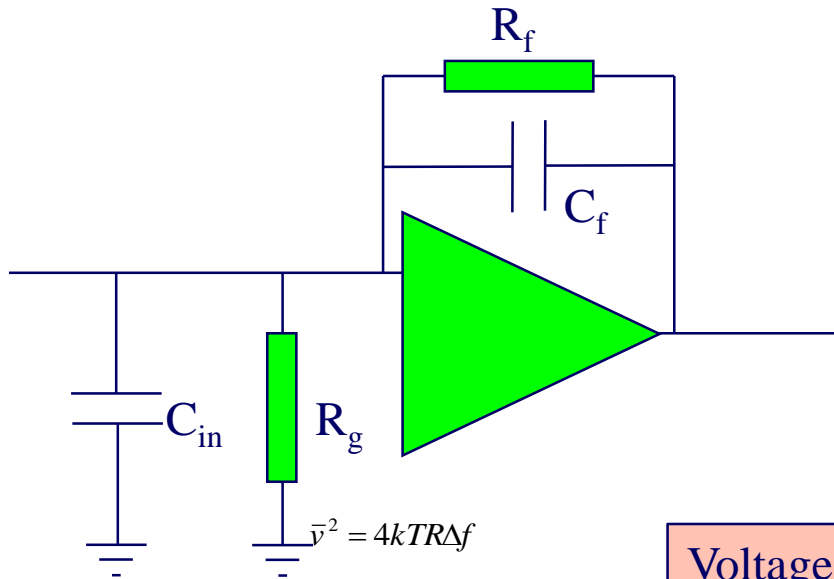
$t_{\text{int}}=30\text{s}$

Flashscan-30



$t_{\text{int}}=190\text{s}$

Amplification



- In almost all cases we require amplification
- Amplifier-detector interaction is critical
- Most important element is the input
- Noise is the major issue

◆ Thermal or Johnson Noise in Resistor

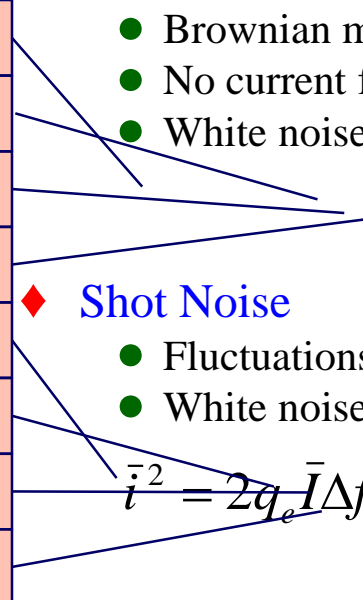
- Brownian motion of electrons
- No current flow or voltage required
- White noise

◆ Shot Noise

- Fluctuations in current
- White noise

$$\bar{i}^2 = 2q_e \bar{I} \Delta f$$

Voltage
Temperature
Resistance
Bandwidth
Current
Charge e^-
DC current
Bandwidth



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

Equivalent Noise Charge

- 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
 - I_D = Drain current
-
- Note that ENC is directly related to energy resolution
 - $FWHM(\text{keV}) = 2.355 \times 10^{-3} \text{ ENC}/ew$ where w is the energy per electron

Noise Dependence

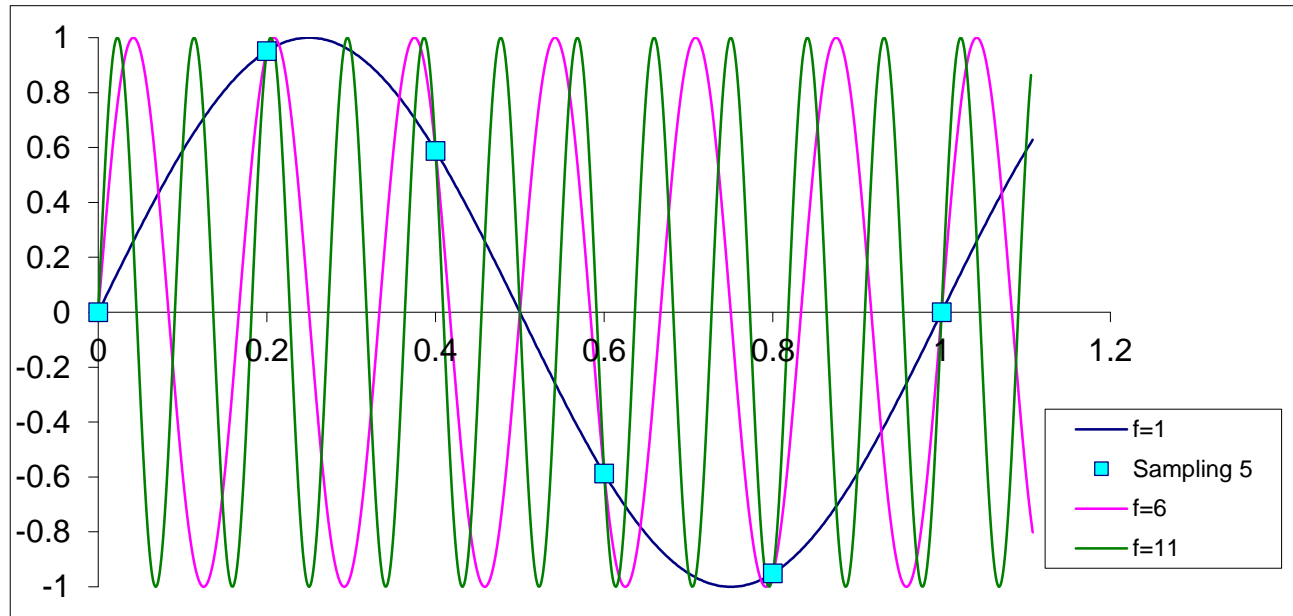
$$ENC^2 = e^2 \left[\frac{kT}{2R_f} \tau + \frac{q_e I_D}{4} \tau + \frac{kT(C_{in})^2}{2g_m \tau} \right]$$

- τ optimum at

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

- Choosing optimum τ gives best noise performance but may not be fast enough
- We often have to sacrifice energy resolution for speed
- TAKE home message
 - ◆ Make electronics only just fast enough

Sampling & Aliasing



- Shannon's Theorem and Nyquist Criterion
 - ◆ The highest frequency that can be 'measured' is twice the sampling frequency
- If the input is not band limited to frequencies less than $f_s/2$, then aliasing will occur at frequencies $f \pm nf_s$
 - ◆ where f = signal frequency, f_s = sampling frequency, n = integer
- If you have $100\mu\text{m}$ pixels, the ideal spatial resolution (PSF) $> 200\mu\text{m}$

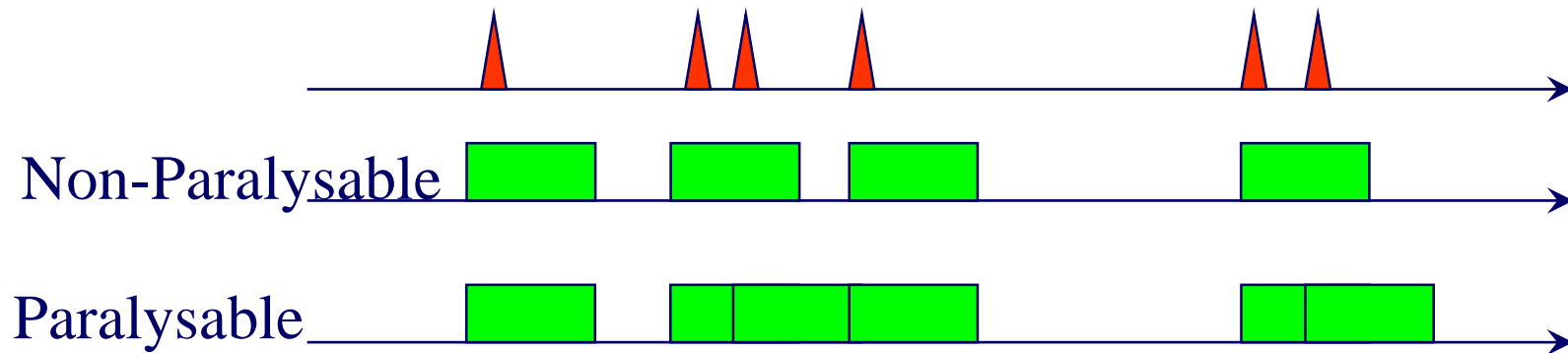
Synchrotron Detectors

- 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 for detectors!

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 for detectors!

Dead Time



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

■ Non-paralysable

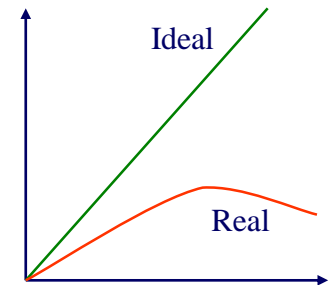
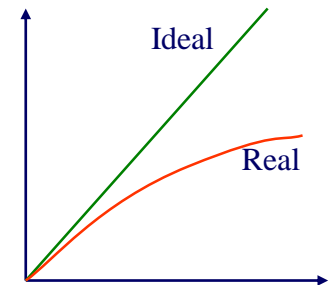
- ◆ Fraction of time detector is dead = $R_d \tau$
- ◆ Live time is therefore = $1 - R_d \tau$
- ◆ Input rate = $R_i = R_d / (1 - R_d \tau)$

■ Paralysable

- ◆ R_d = Probability of getting no event within τ of an event

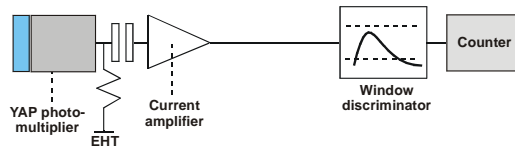
- ◆ Probability of n events in time t is
$$P(n, t) = \frac{e^{-R_i t} (R_i t)^n}{n!}$$

- ◆ Detected rate
$$R_d = P(0, \tau) = R_i e^{-R_i \tau}$$

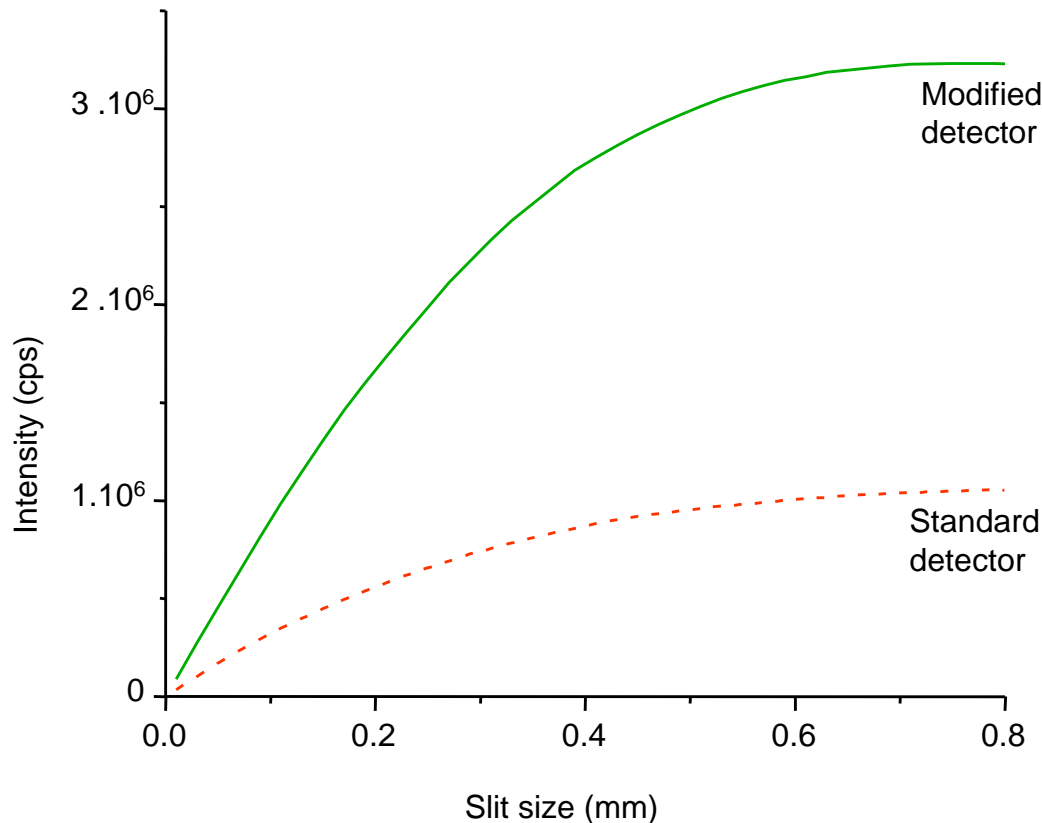
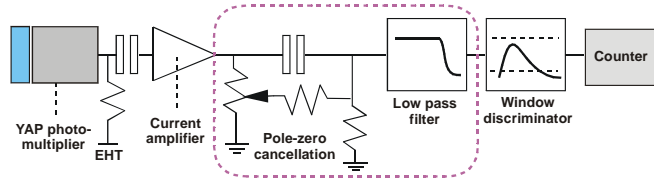


EDR Detector for Powder Diffraction

Standard Detector



Modified Detector

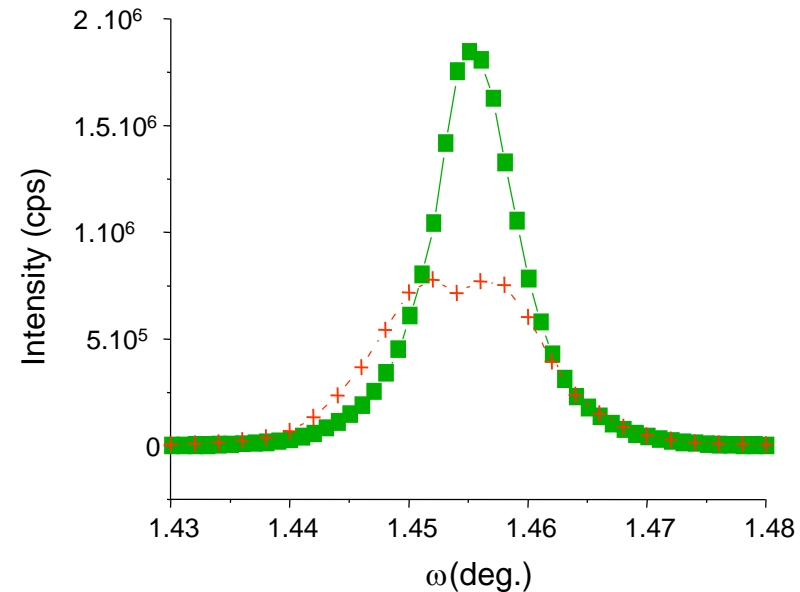


Standard detector

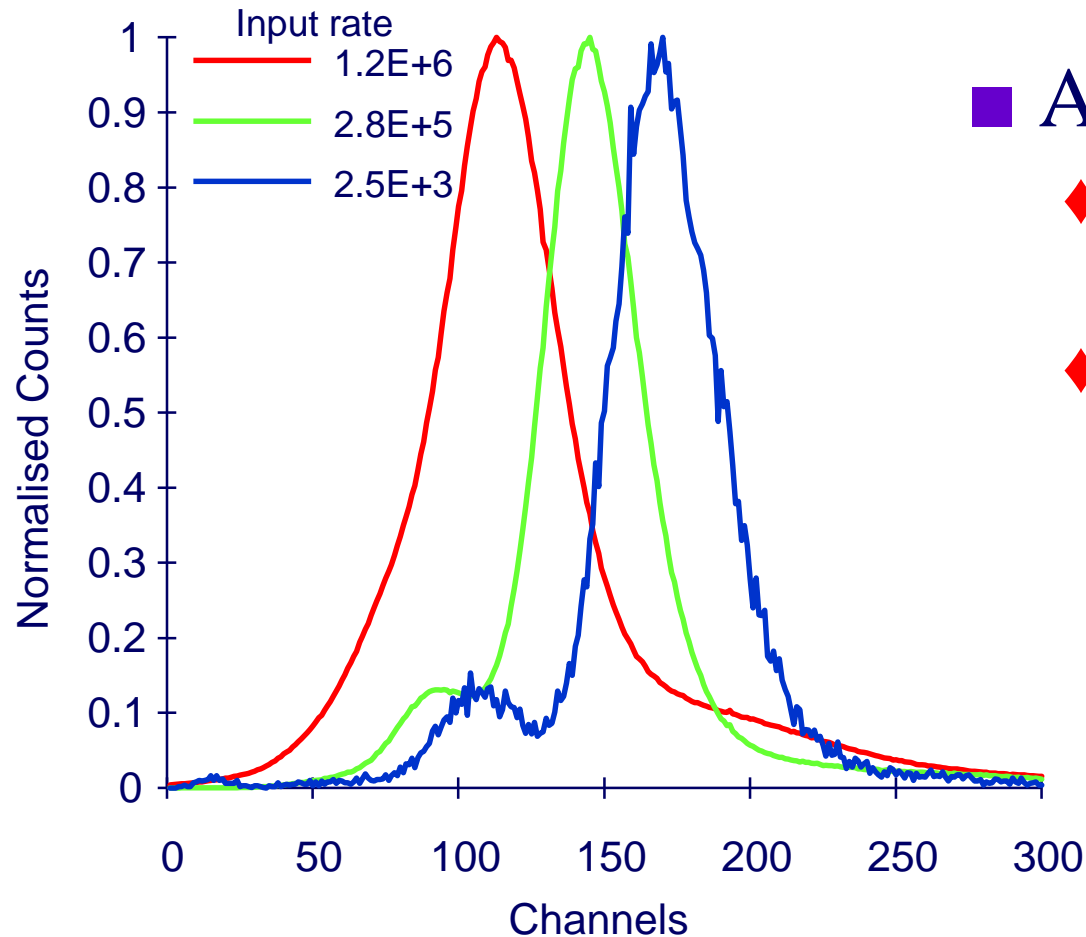
- Saturation count rate: 1 MHz
- Linear region: up to 300 kHz
- Electronic background: 0.2 cps
- Energy range: 4-25 keV

Modified detector

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



Spectral Peak Shift vs Rate



■ As rate rises

◆ Spectral resolution deteriorates

◆ Note also the K escape feature

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

Counting Statistics

- Photons are quantised and hence subject to probabilities
- The Poisson distribution expresses the probability of a number of events, k occurring relative to an expected number, n

$$P(n, k) = \frac{n^k e^{-n}}{k!}$$

- The mean of $P(n, k)$ is n
- The variance of $P(n, k)$ is n
- The standard deviation or error (noise) is \sqrt{n}
- If signal = n , then $\text{SNR} = n/\sqrt{n} = \sqrt{n}$
- As n increases, SNR improves

Performance Measure - DQE

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

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

Can define $N_{photons}$ describes real SNR

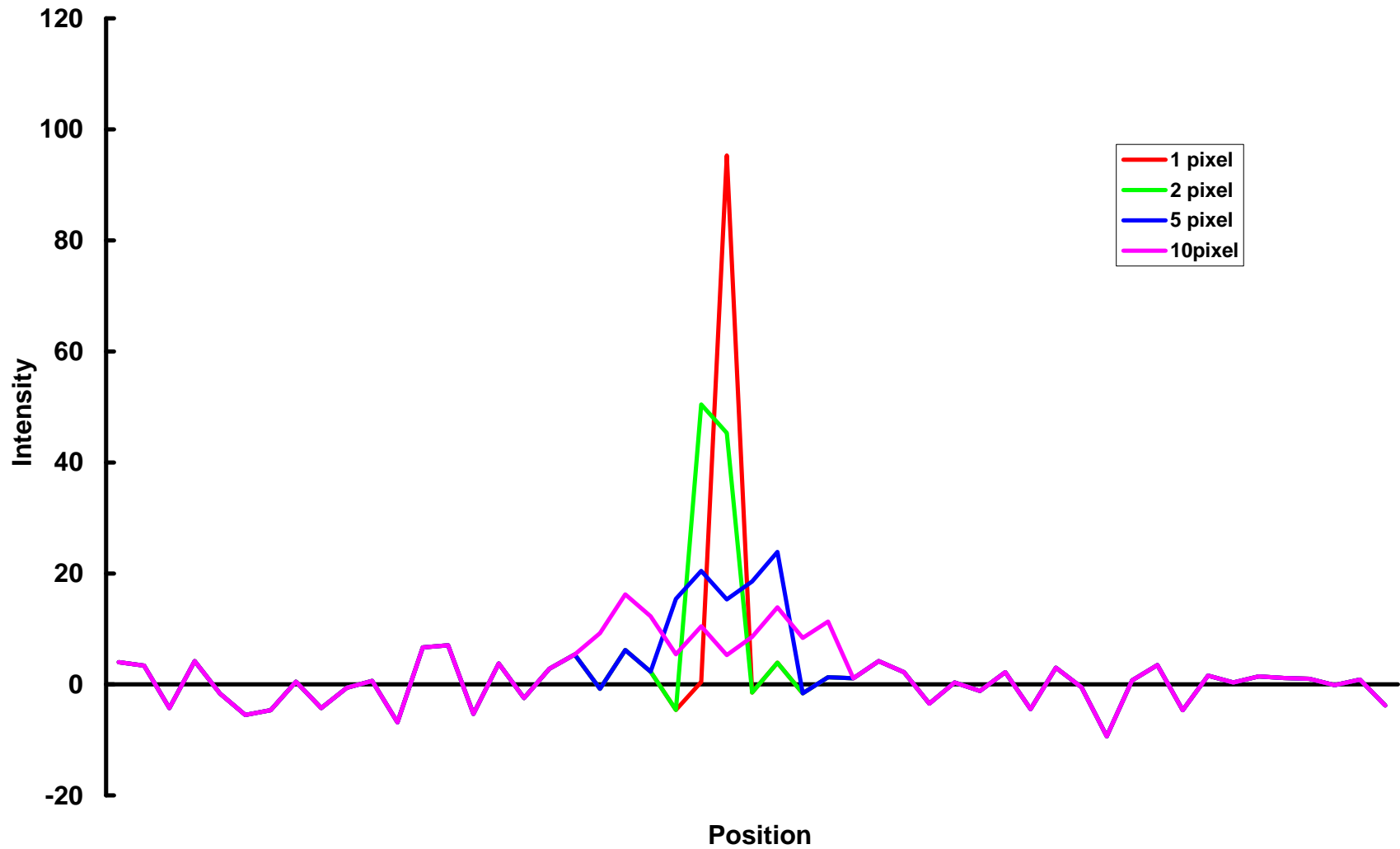
$$NEQ = SNR_{Non-ideal}^2$$

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

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

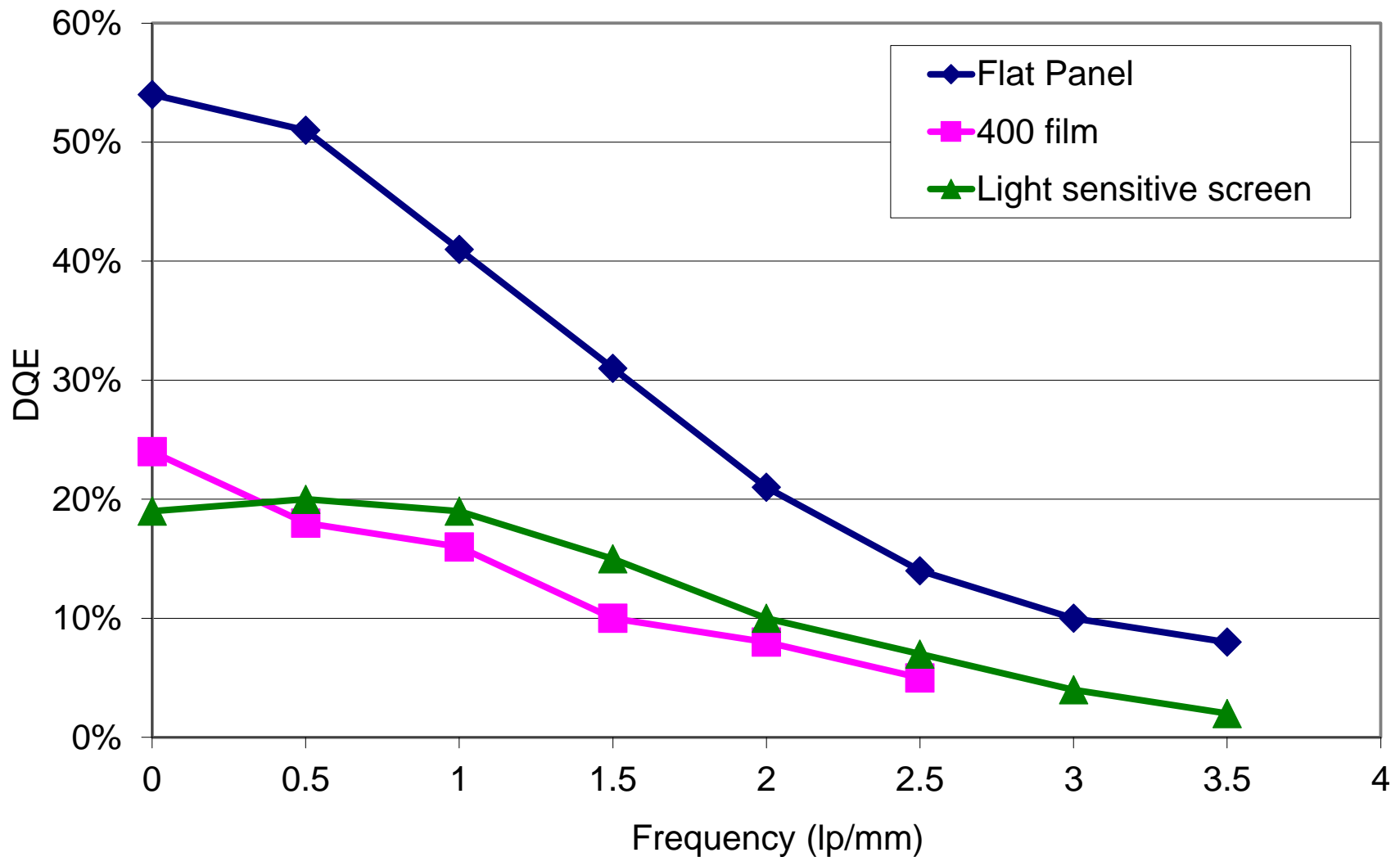
Note that DQE is f(spatial and spectral frequencies)

Effect of Peak Width



DQE Comparison

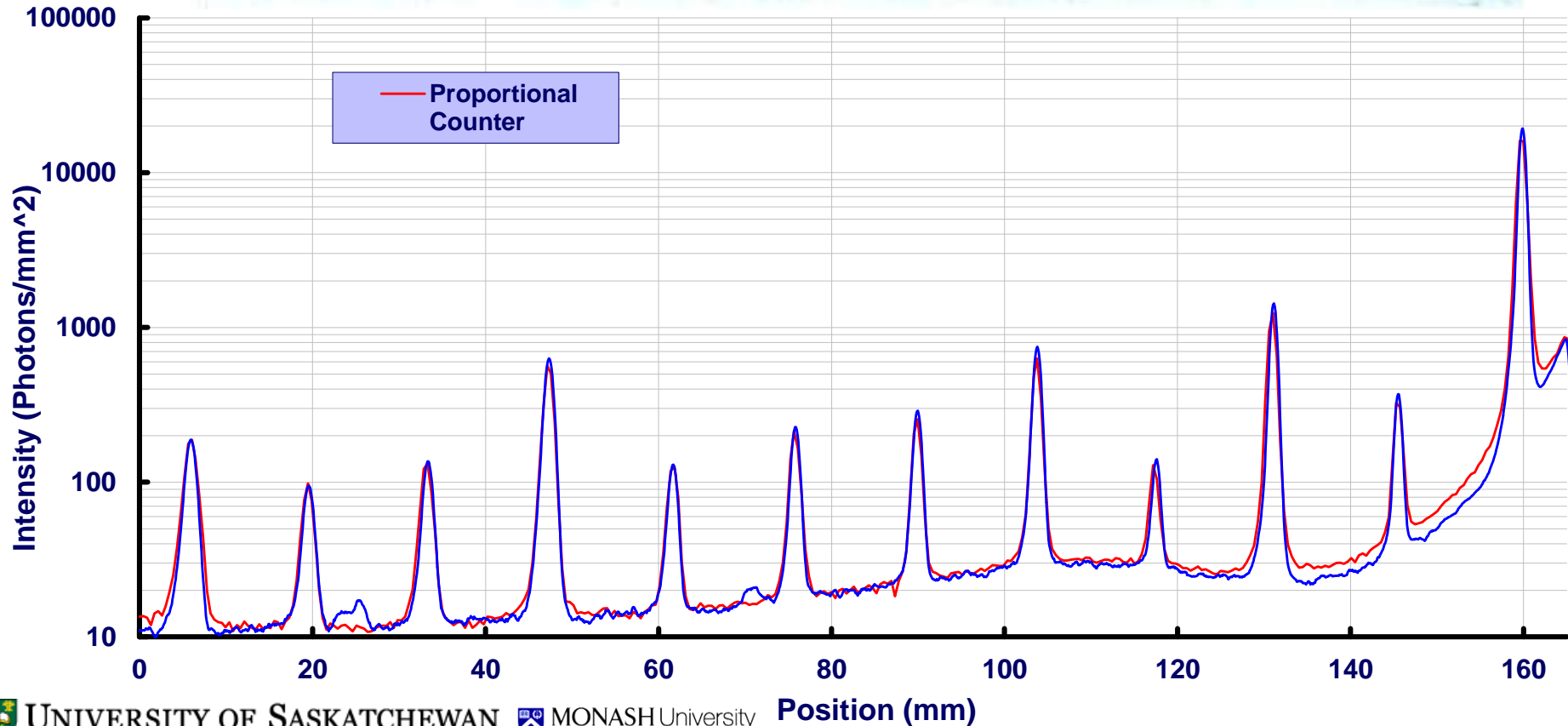
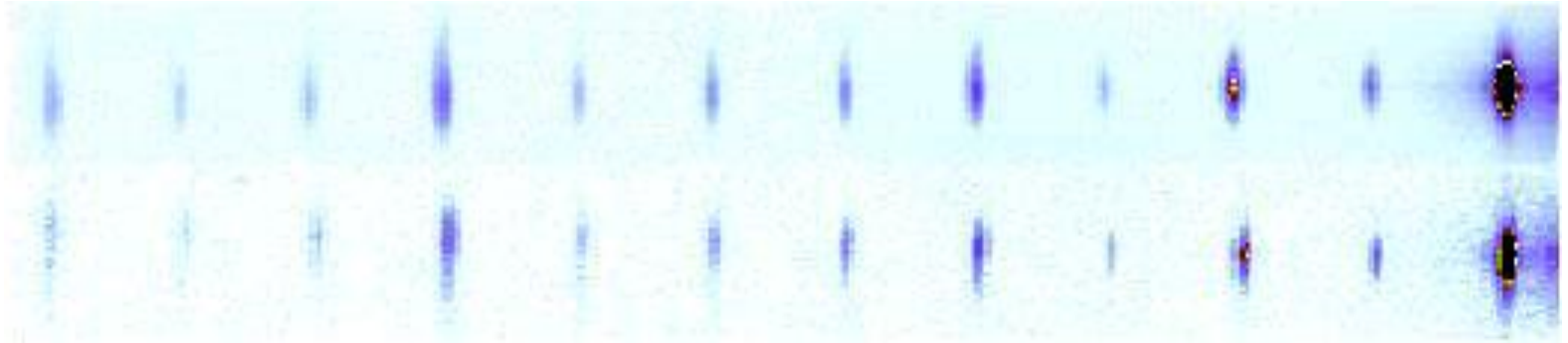
DN-5 beam
2.6 μ Gy



Collagen 100s Exposure

MWPC

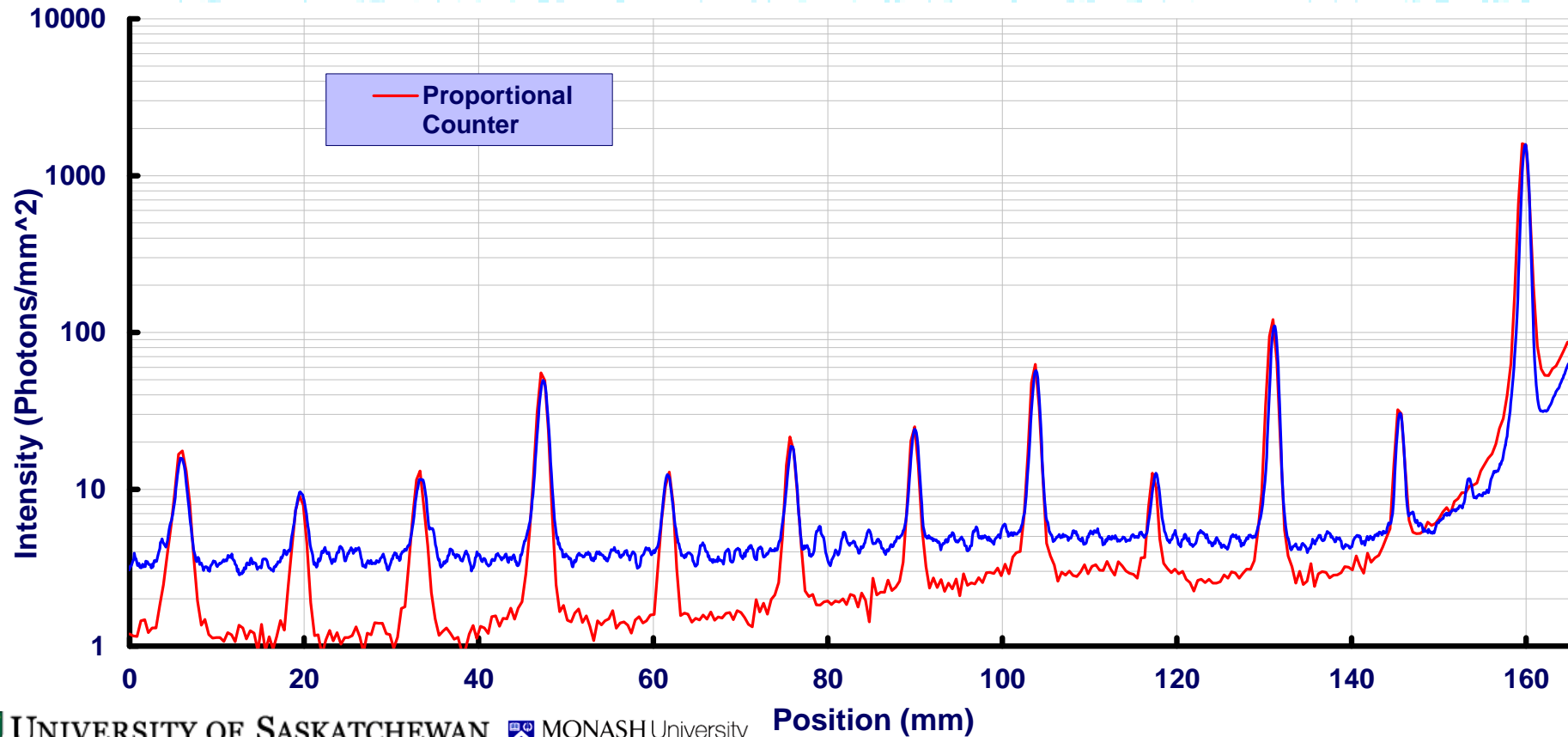
Image
Plate



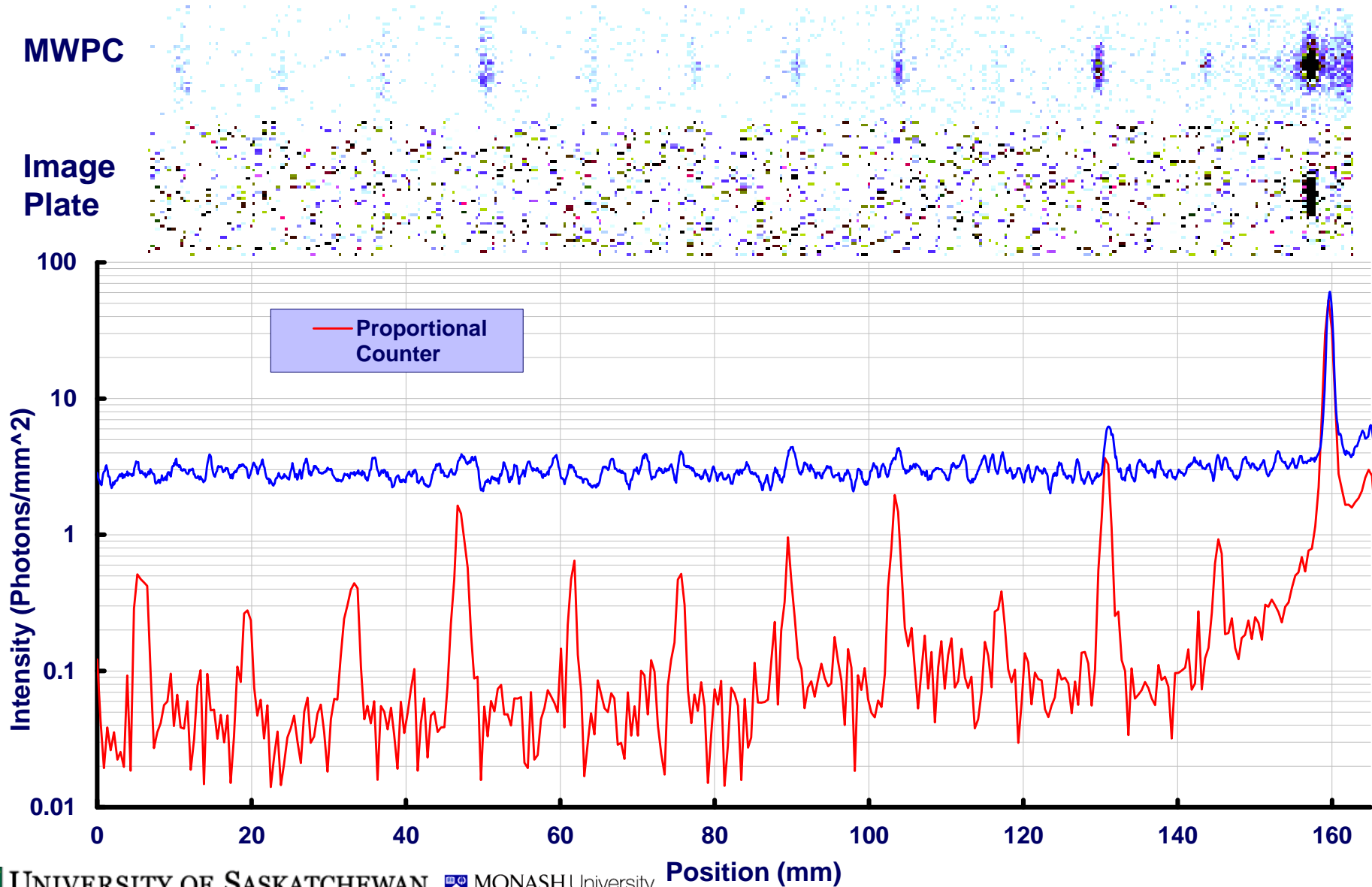
Collagen 10s Exposure

MWPC

Image
Plate



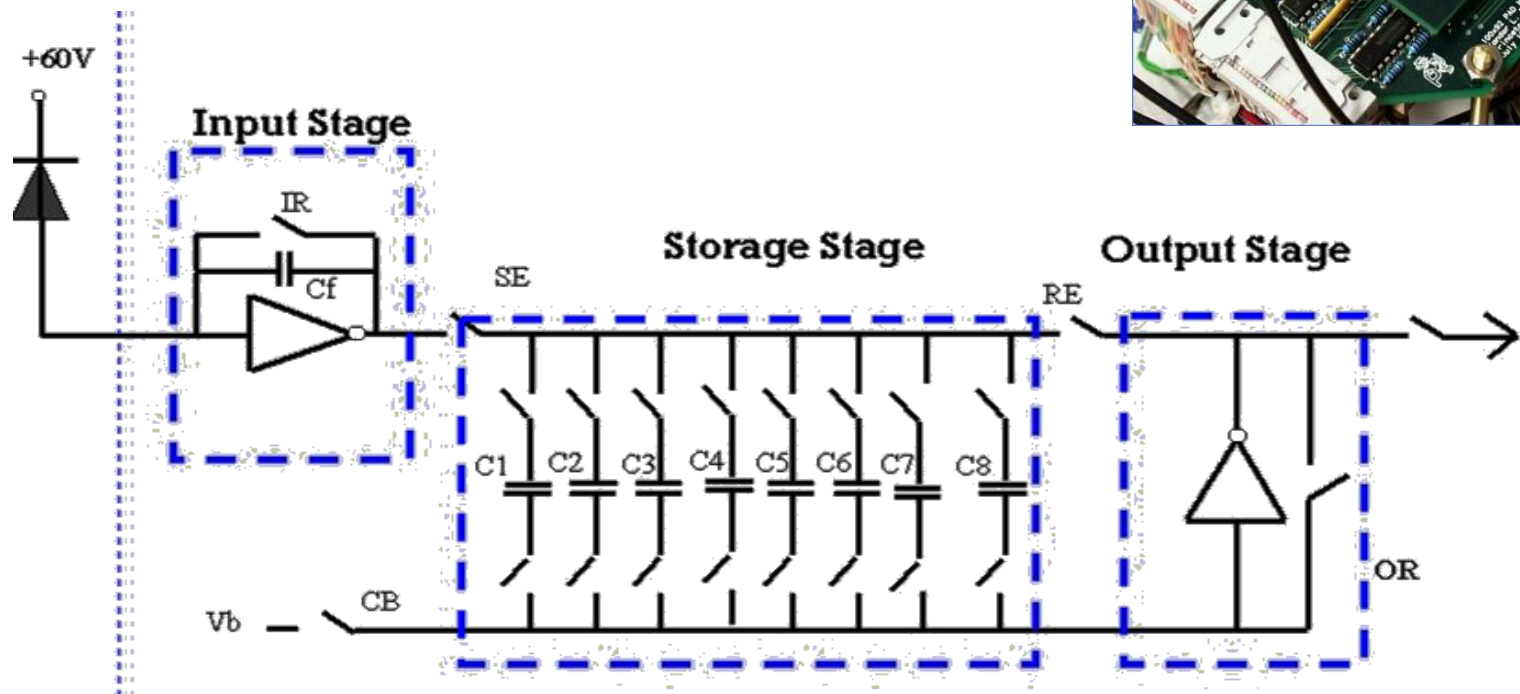
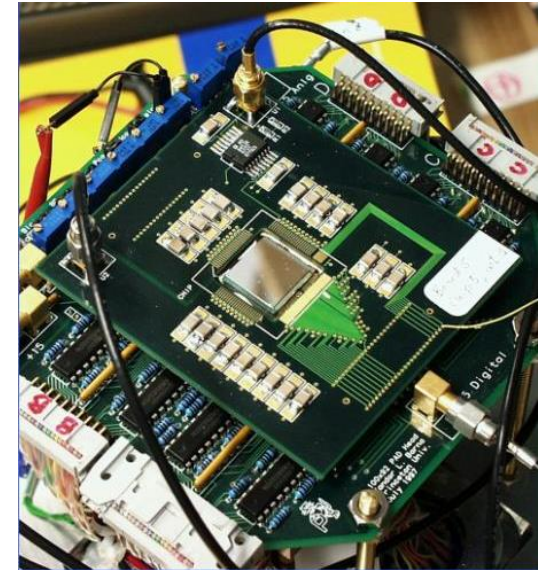
Collagen 0.3s Exposure



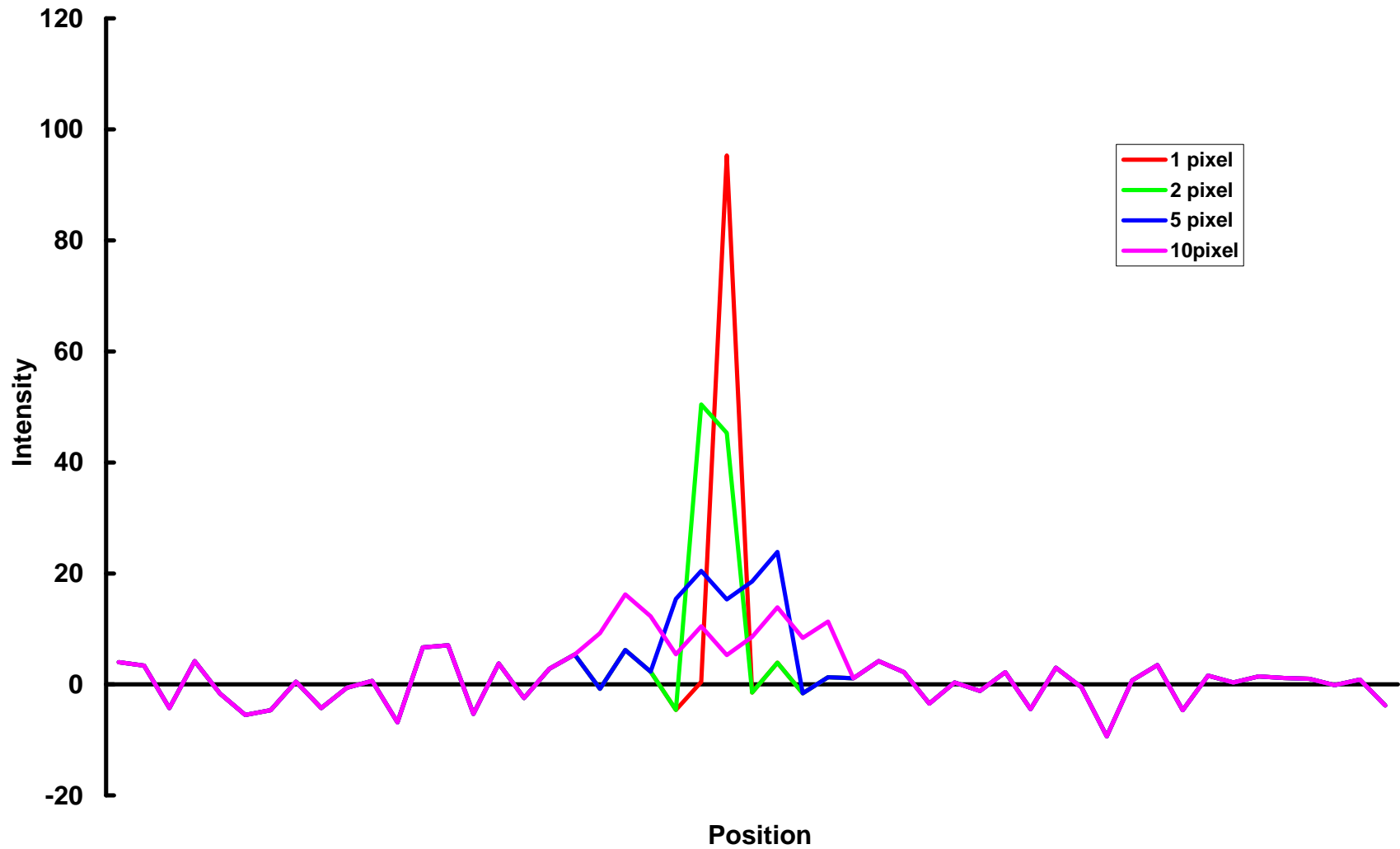
Cornell PAD (Integrating)

■ Rapid Framing Imager

- ◆ $15 \times 13.8 \text{ mm}^2$ active area
- ◆ $150 \mu\text{m}$ square pixel
- ◆ Storage for 8 frames
- ◆ Selectable T_{int} down to $1 \mu\text{s}$
- ◆ Deadtime $< 1 \mu\text{s}$

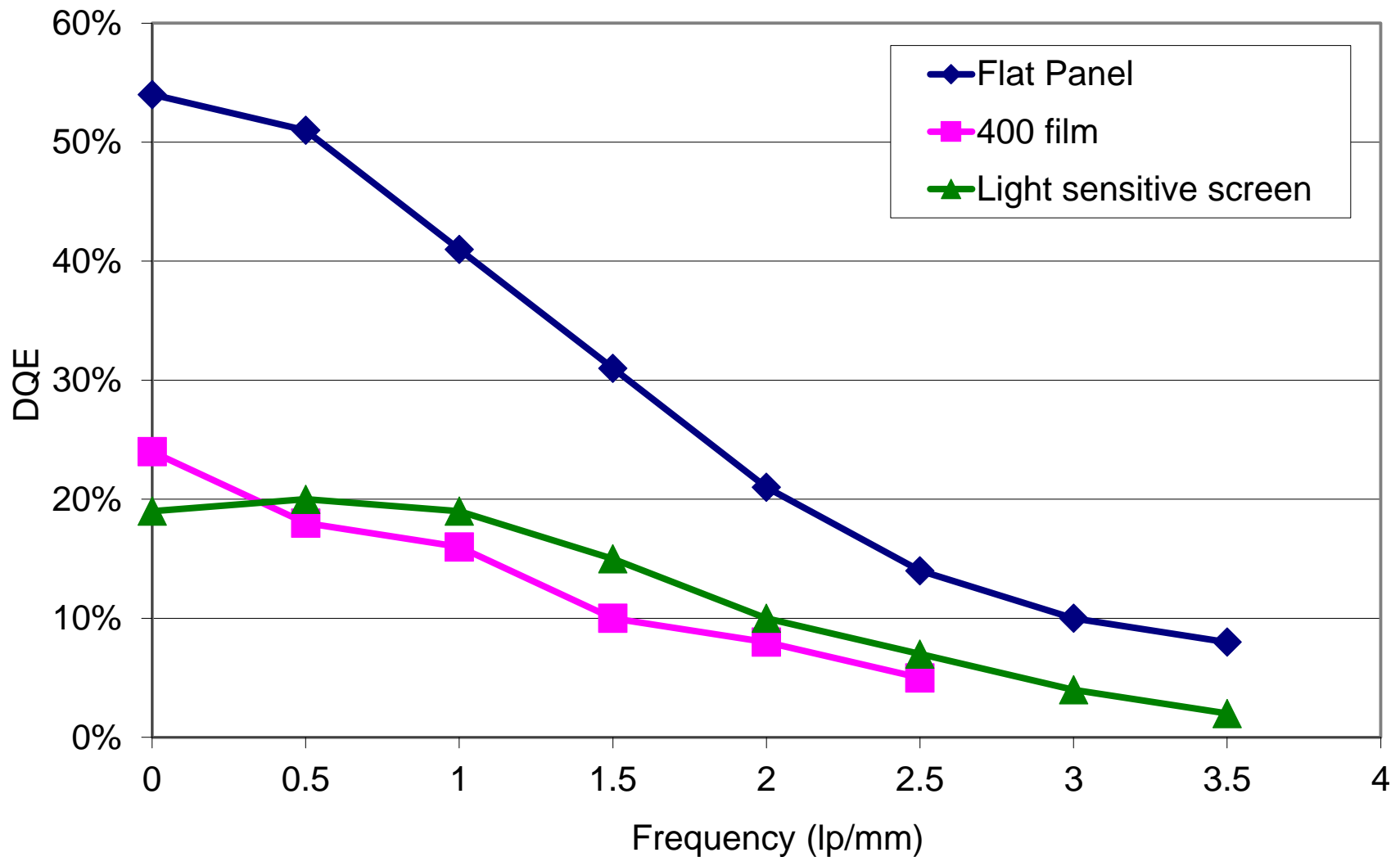


Effect of Peak Width



DQE Comparison

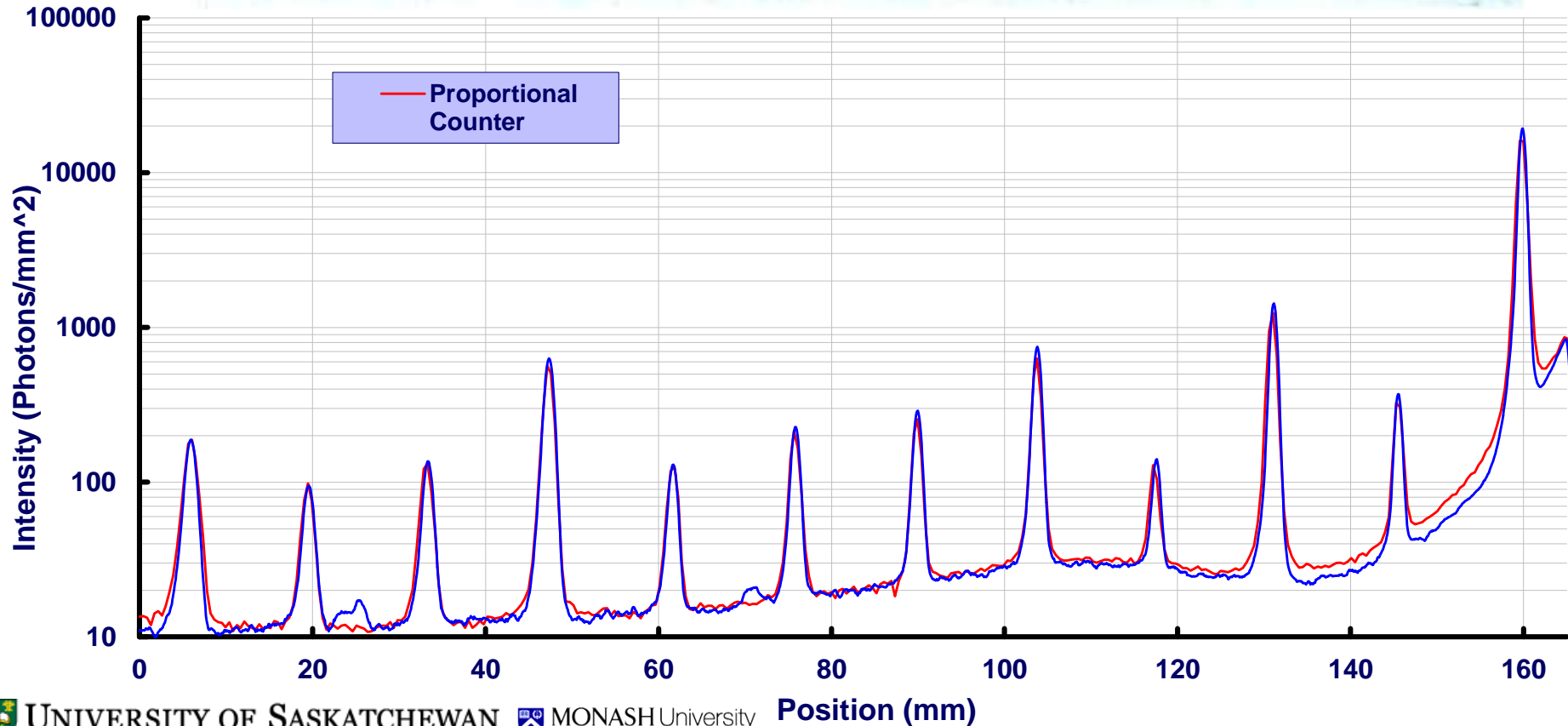
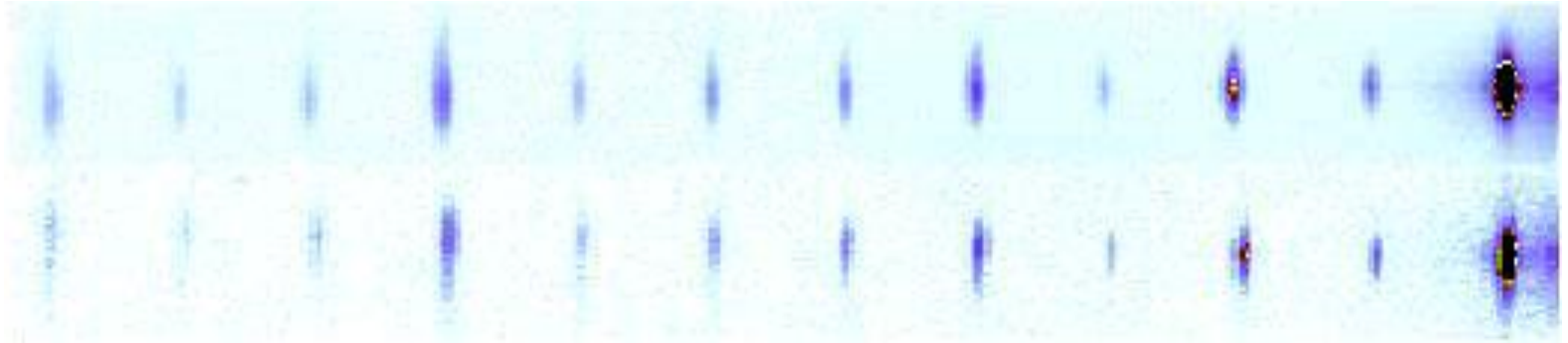
DN-5 beam
2.6 μ Gy



Collagen 100s Exposure

MWPC

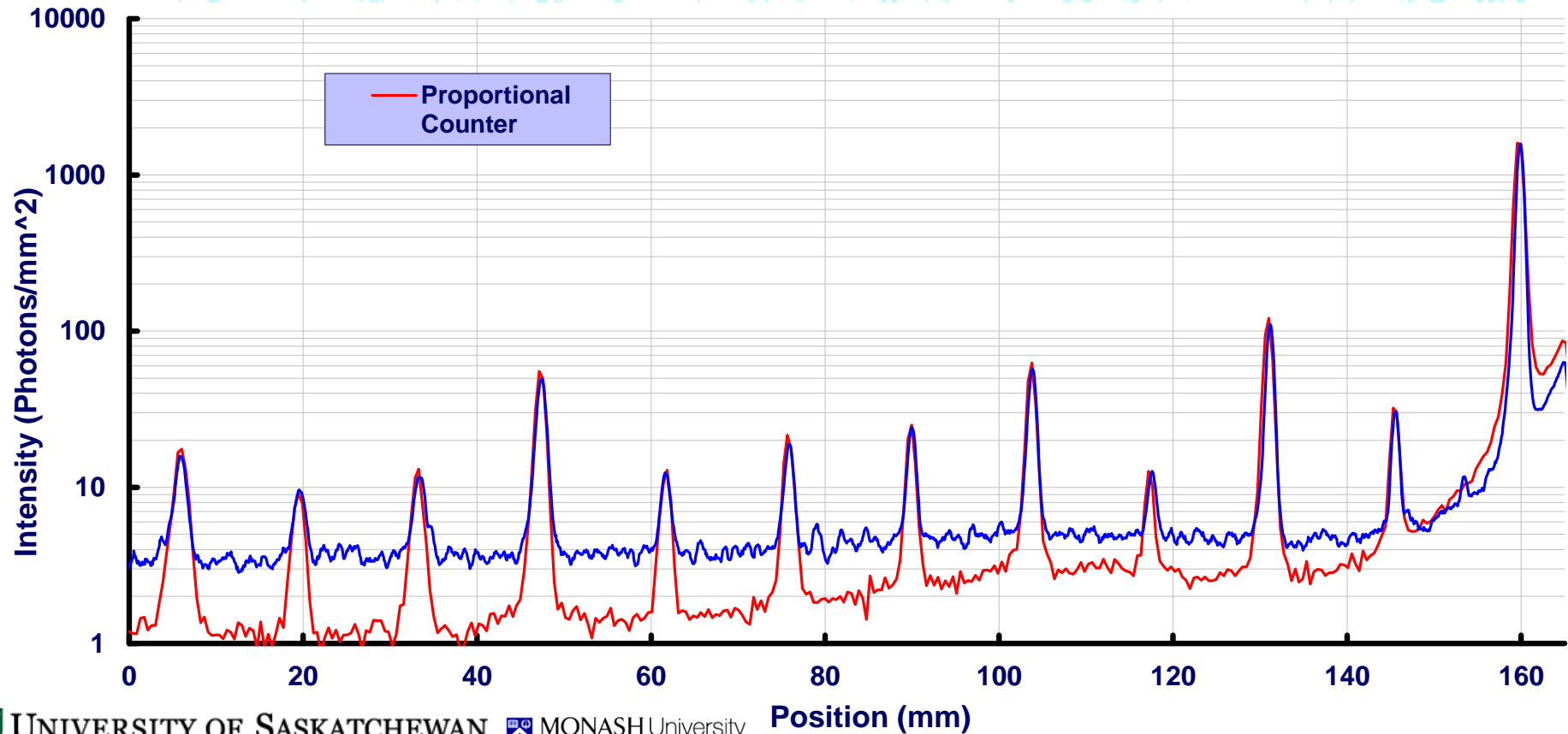
Image
Plate



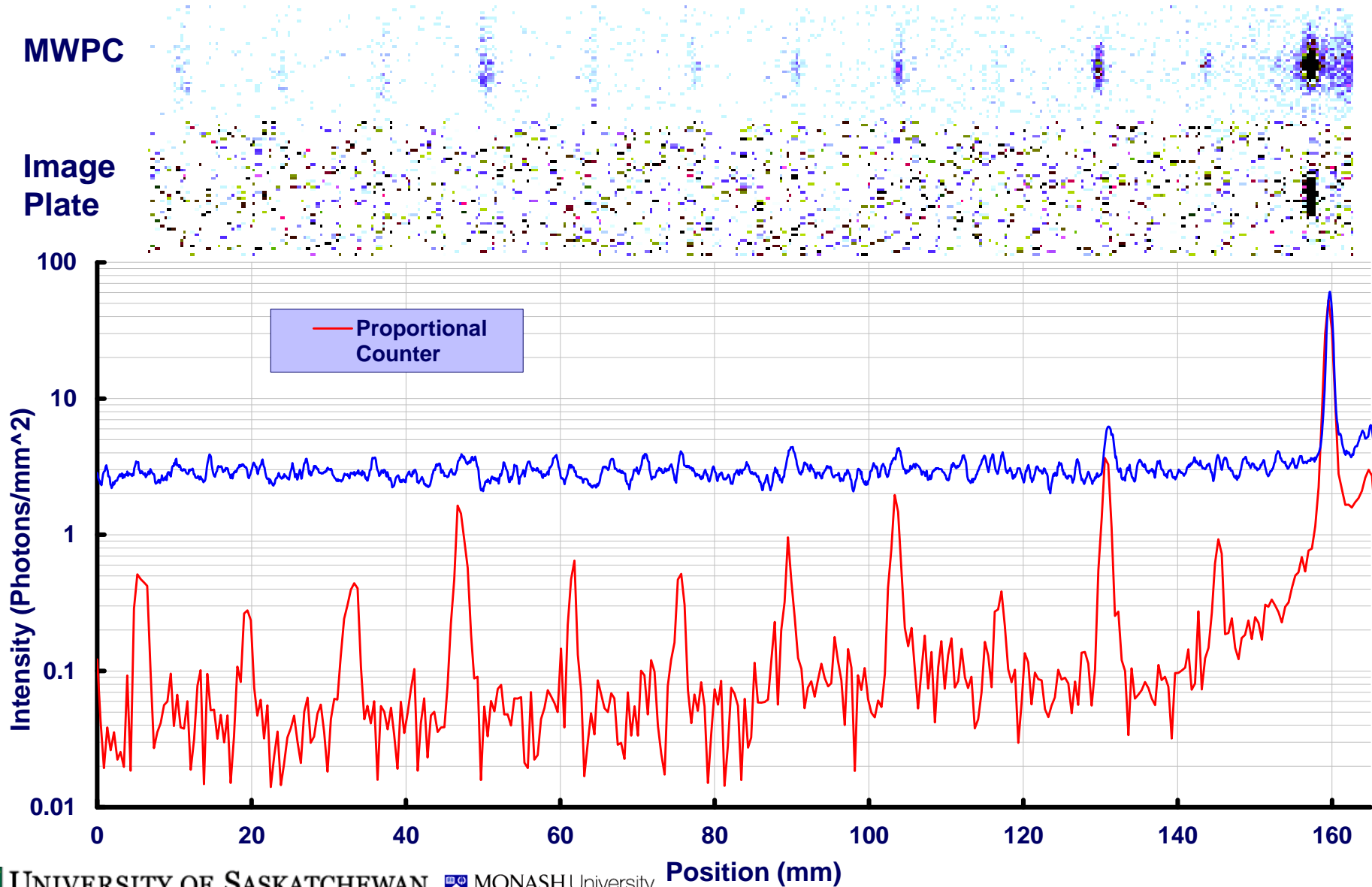
Collagen 10s Exposure

MWPC

Image
Plate



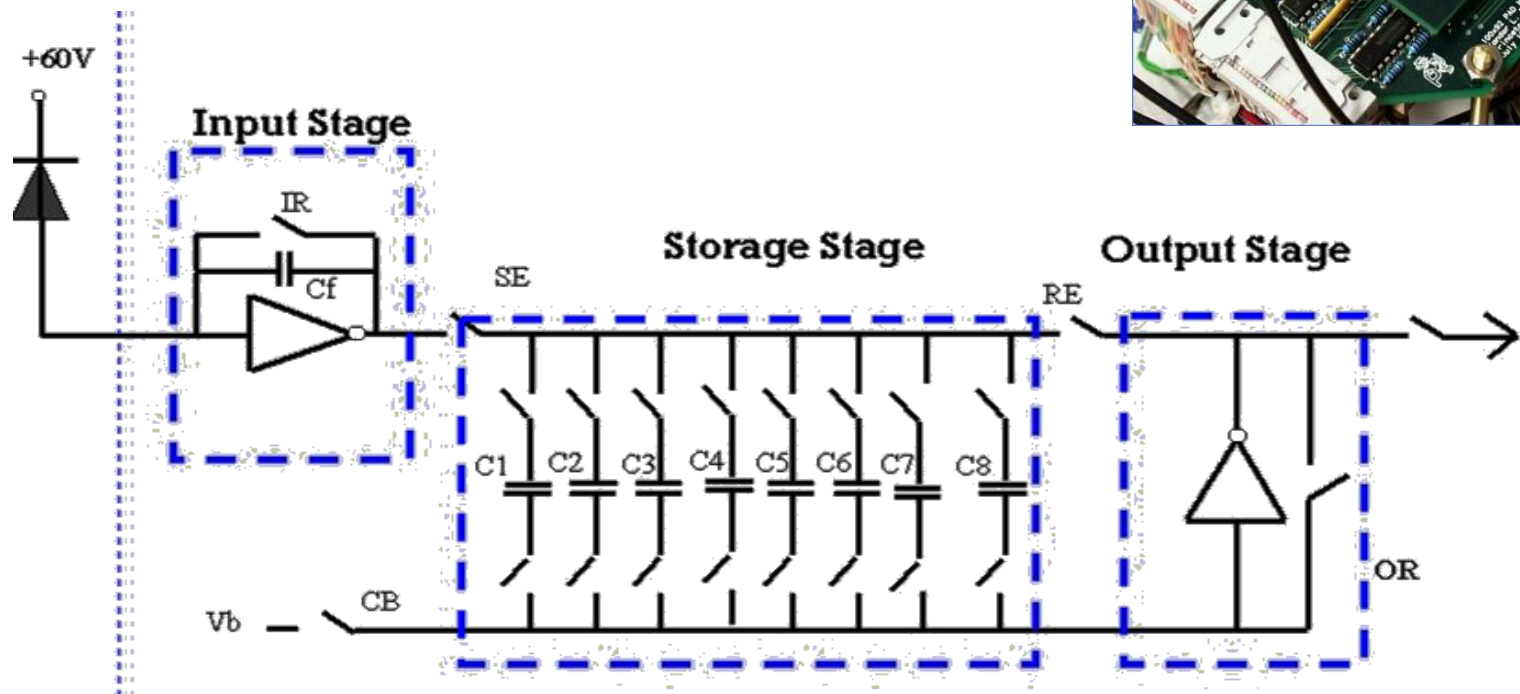
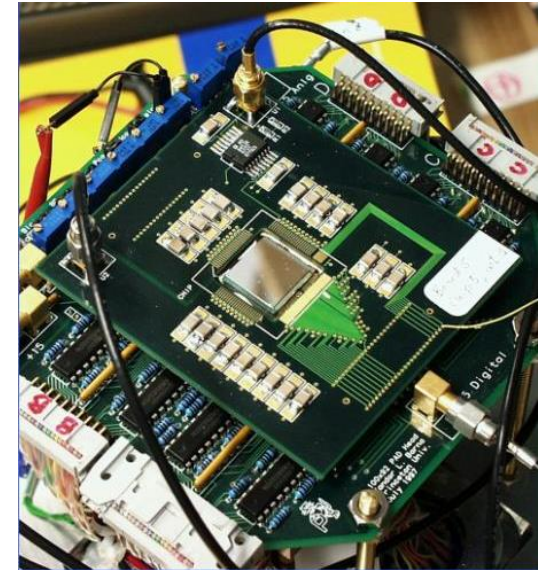
Collagen 0.3s Exposure



Cornell PAD (Integrating)

■ Rapid Framing Imager

- ◆ $15 \times 13.8 \text{ mm}^2$ active area
- ◆ $150 \mu\text{m}$ square pixel
- ◆ Storage for 8 frames
- ◆ Selectable T_{int} down to $1 \mu\text{s}$
- ◆ Deadtime $< 1 \mu\text{s}$



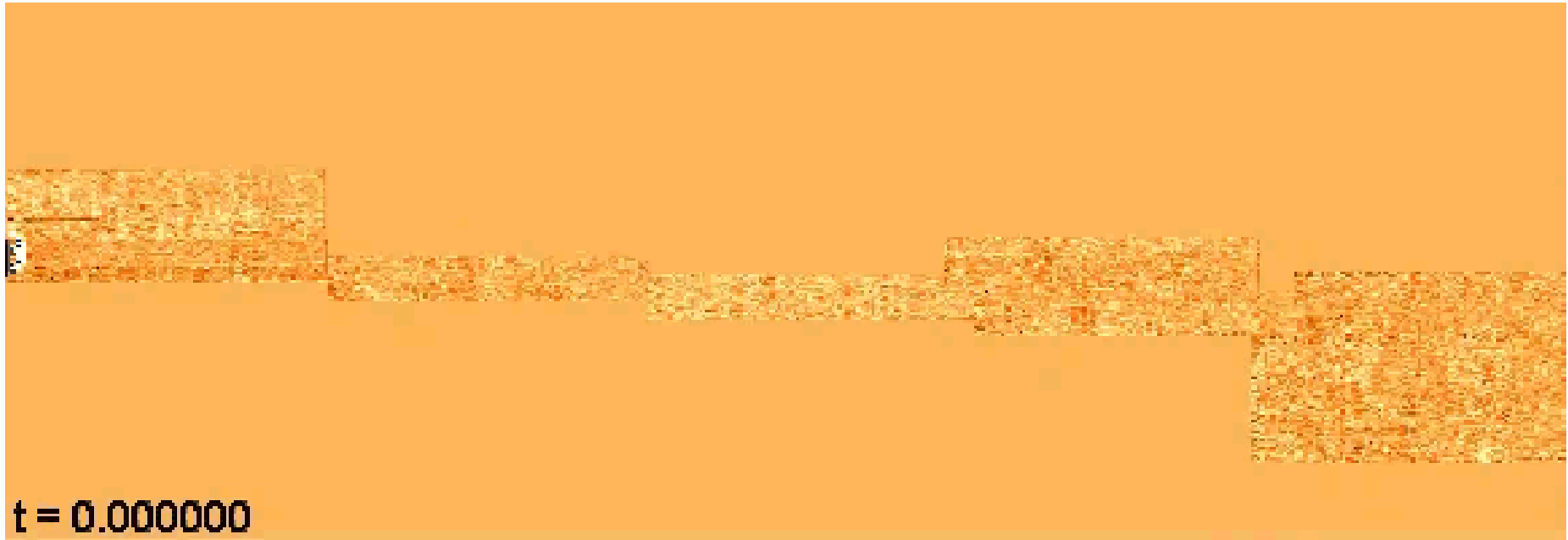
Diesel Fuel Injection Movie

■ Injection

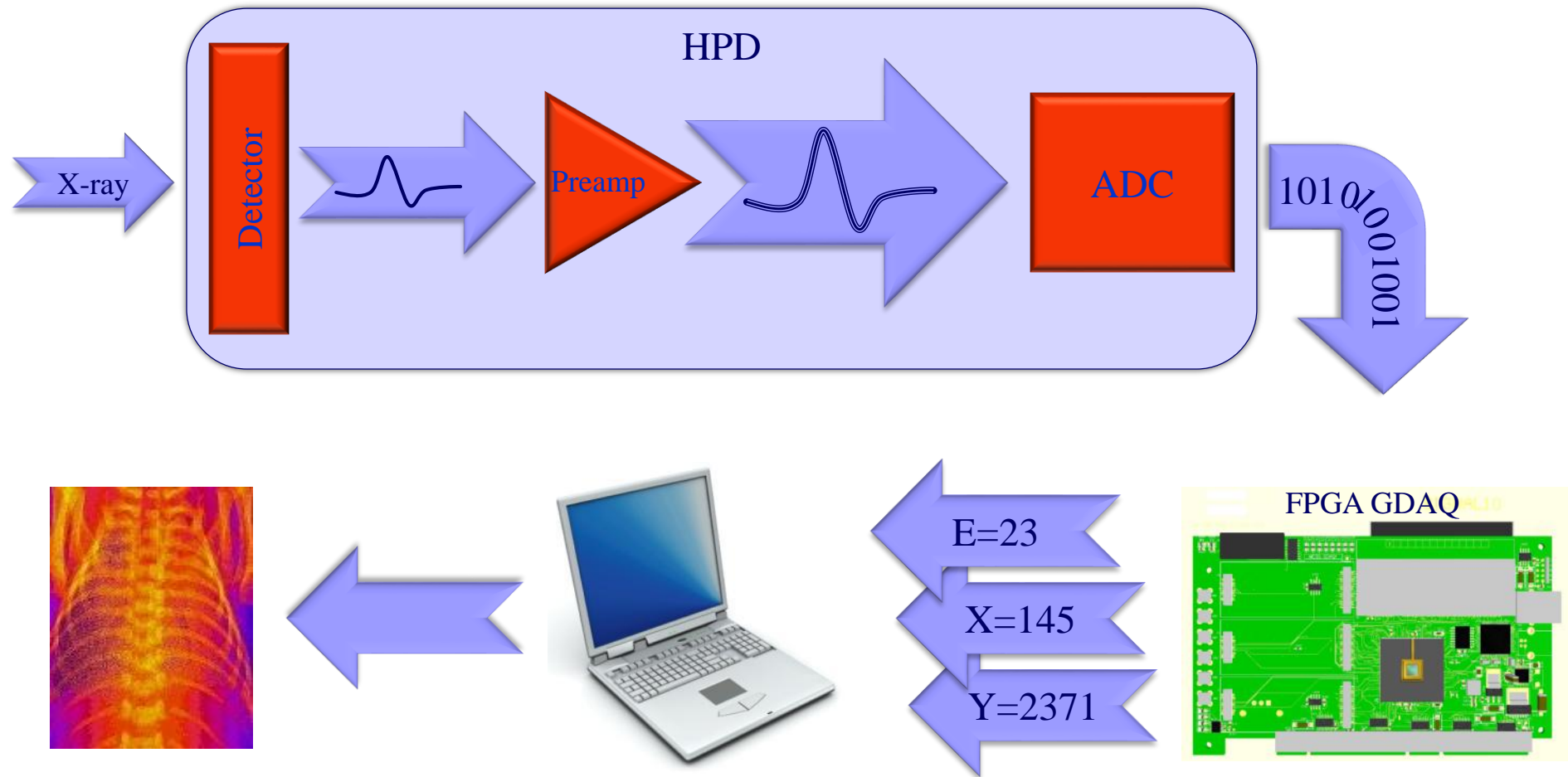
- ◆ Supersonic injection 1350psi Cerium added
- ◆ Chamber 1atm SF₆
- ◆ 10⁸-10⁹ X-rays/s/pix (6keV)
- ◆ 1.1ms Pulse

■ 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

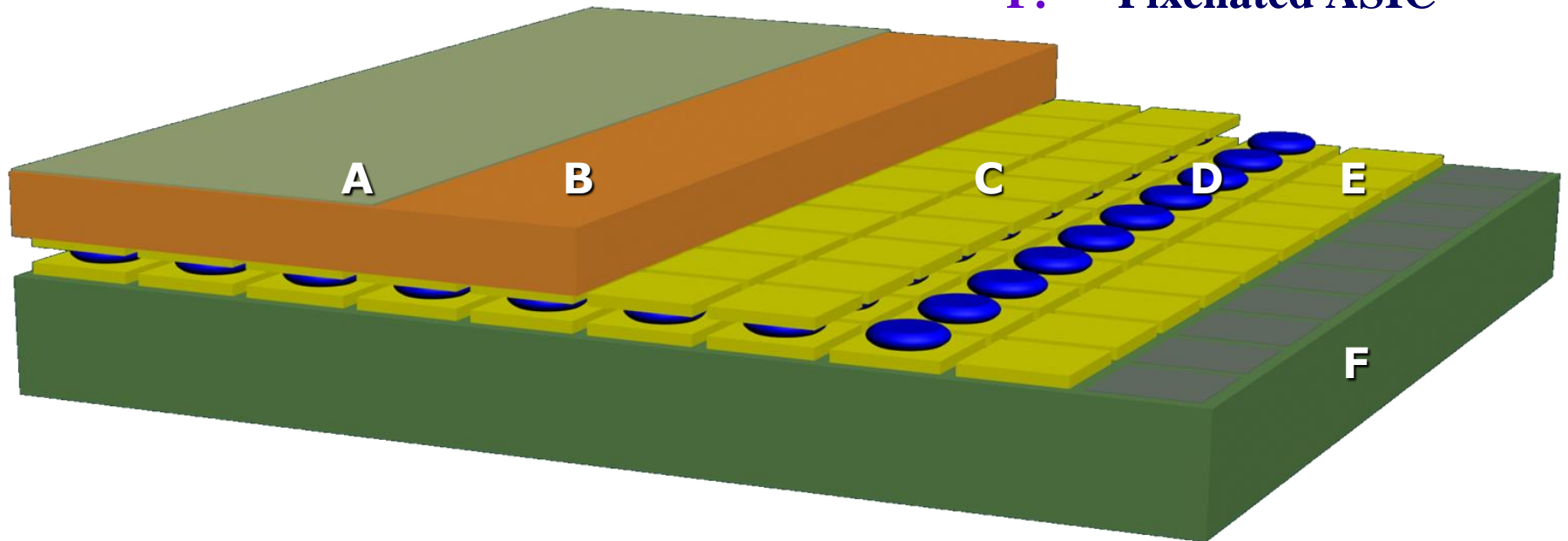


Combine Imaging and Spectroscopy



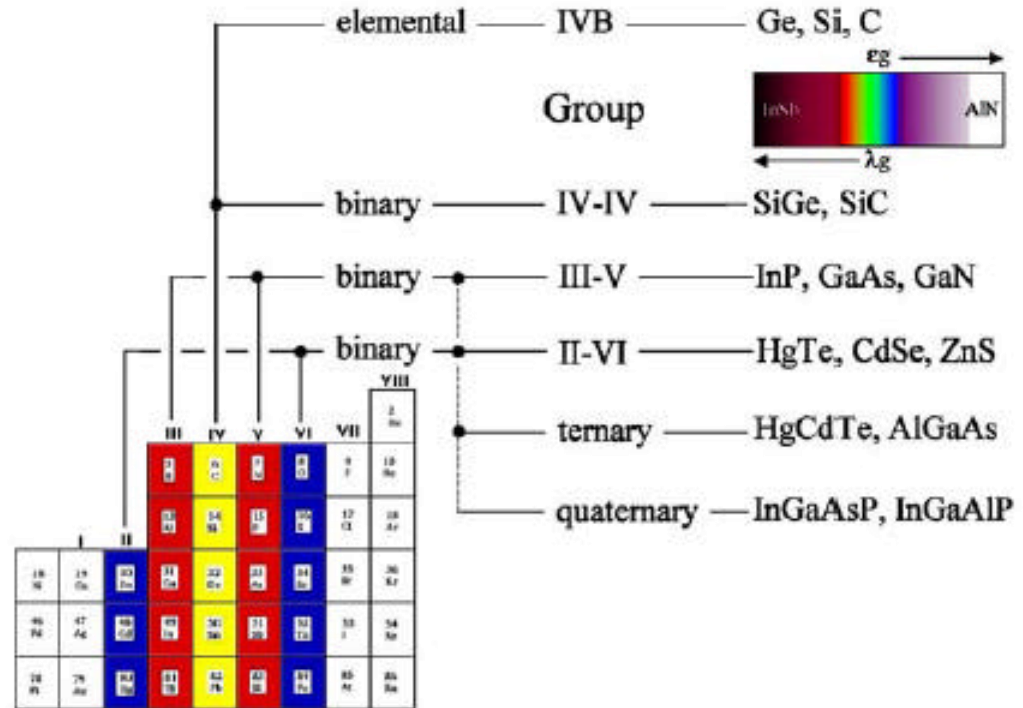
Pixel Array Detector

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

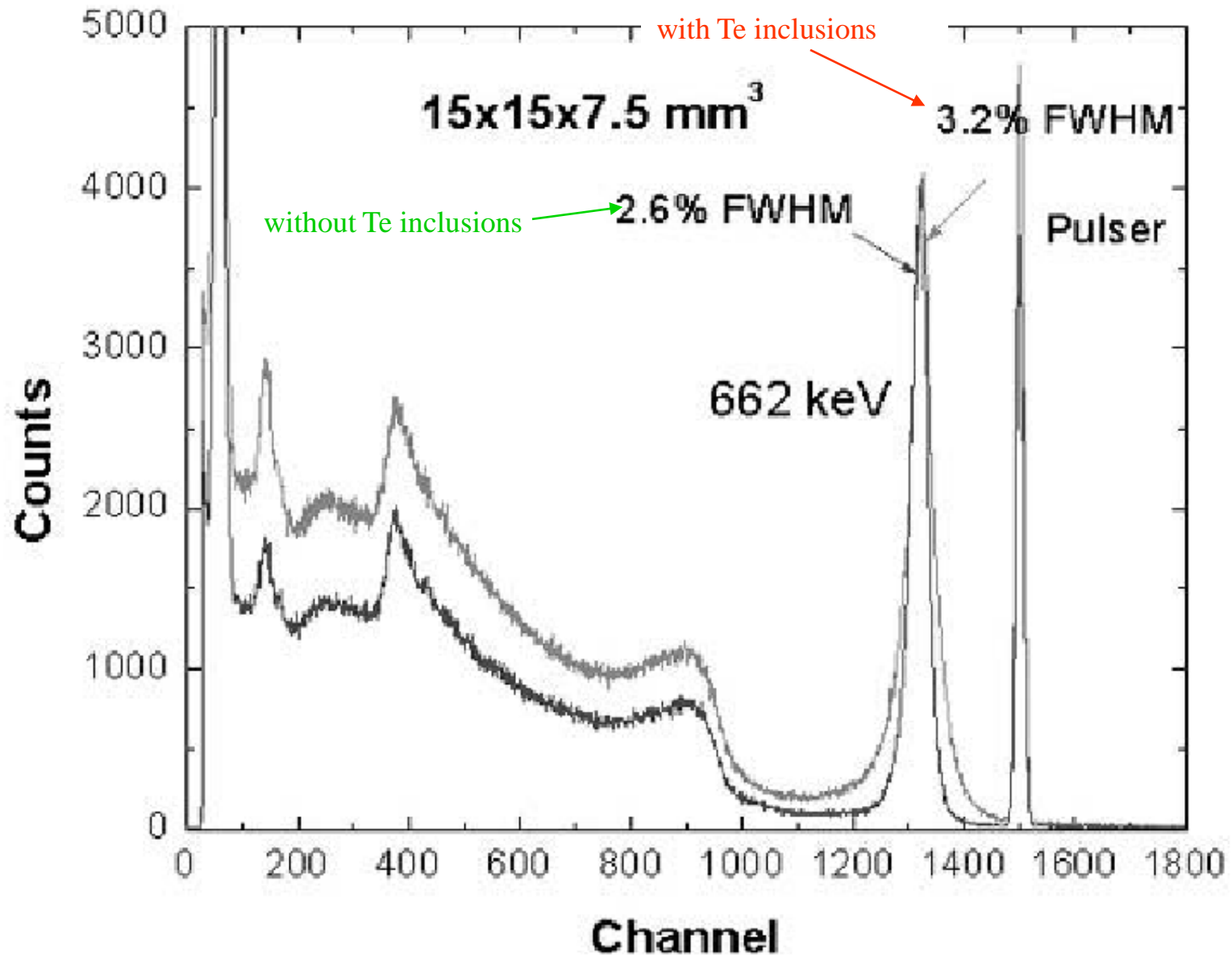


Available Compound Semiconductors

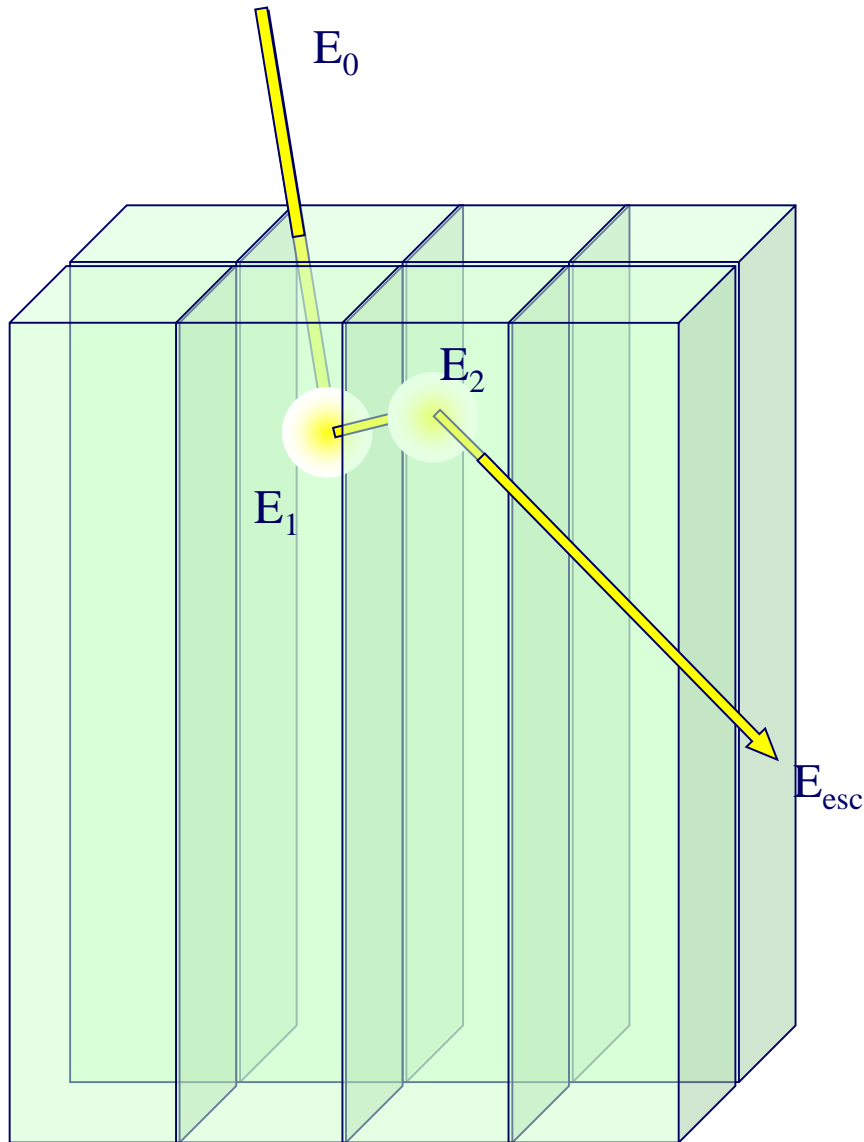
- Predominately CdZnTe, CdTe and GaAs.
- II-VI materials CdTe and CdZnTe cover a suitable range of band gaps:
 - ◆ 1.44 eV (CdTe), 1.57 eV (CdZnTe, 10% Zn), 1.64 eV (CdZnTe, 20% Zn)
- Resistivity of CdZnTe is higher than CdTe, hence lower dark current, higher spectroscopic resolution
- Poor hole transport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



CdZnTe Spectral Resolution



The Problem of Multiple Scatters

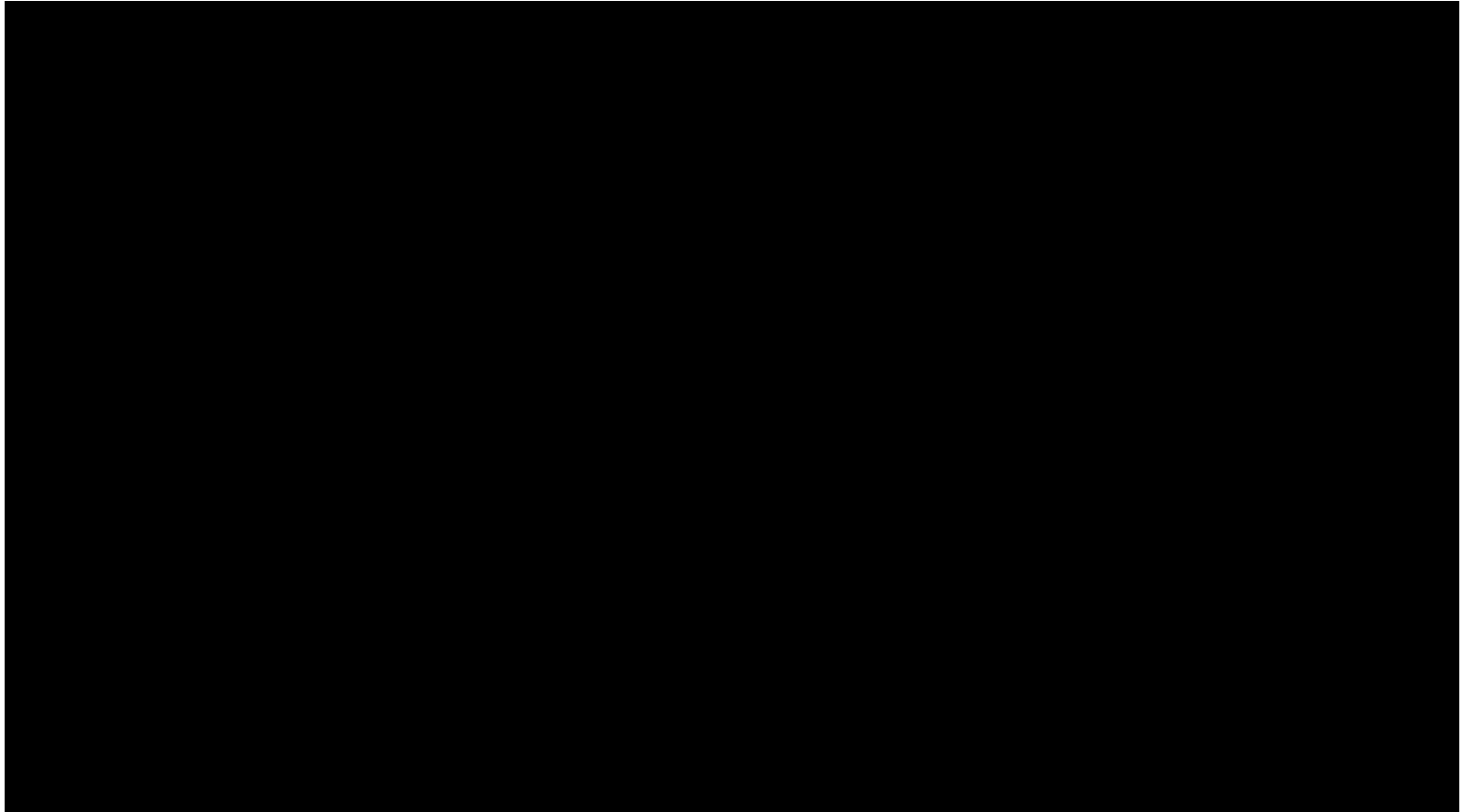


- Need to measure E_0
- $E_0 = E_1 + E_2 + E_{\text{esc}}$
- Must be able to detect multiple deposits as single event
- Must minimise E_{esc}

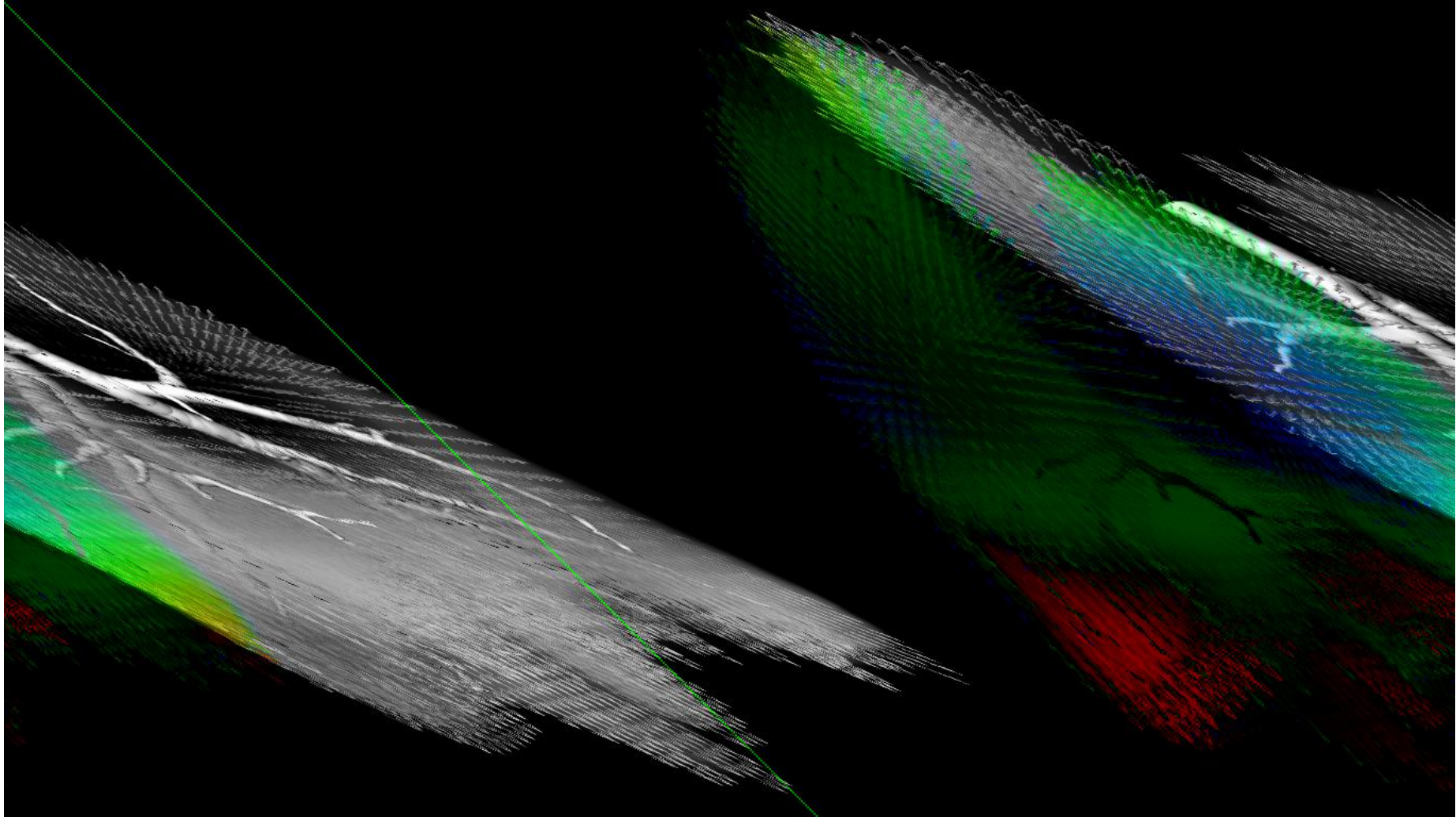
Other Issues

- In addition to detector performance metrics such as
 - ◆ Spatial resolution, Spectral resolution, etc.
- Often we need to measure **function** not form
- Requires that...
 - ◆ The detector respond to triggers
 - ◆ Be able to synchronise with other systems measuring multiple parameters
 - ◆ Do things like phase contrast

Whole Breath Lung Morphology



4D PIV



References

■ Delaney CFG and Finch EC

- ◆ Radiation detectors. Physical Principles and Applications, Clarendon Press, Oxford 1992, ISBN 0 19 853923 1

■ Knoll GE

- ◆ Radiation Detection and Measurement, John Wiley and Sons 2000

■ Proceedings of the International Conferences on position sensitive detectors

- ◆ 9th: *Journal of Instrumentation* **7** (2012) [Open access]
<http://iopscience.iop.org/1748-0221/focus/extra.proc16>
- ◆ 8th: Nuclear Instruments and Methods in Physics Research Section A, Volume 604, Issue 1-2
- ◆ 7th: Nuclear Instruments and Methods in Physics Research Section A, Volume 573, Issues 1-2

■ IEEE Nuclear Science Symposia

