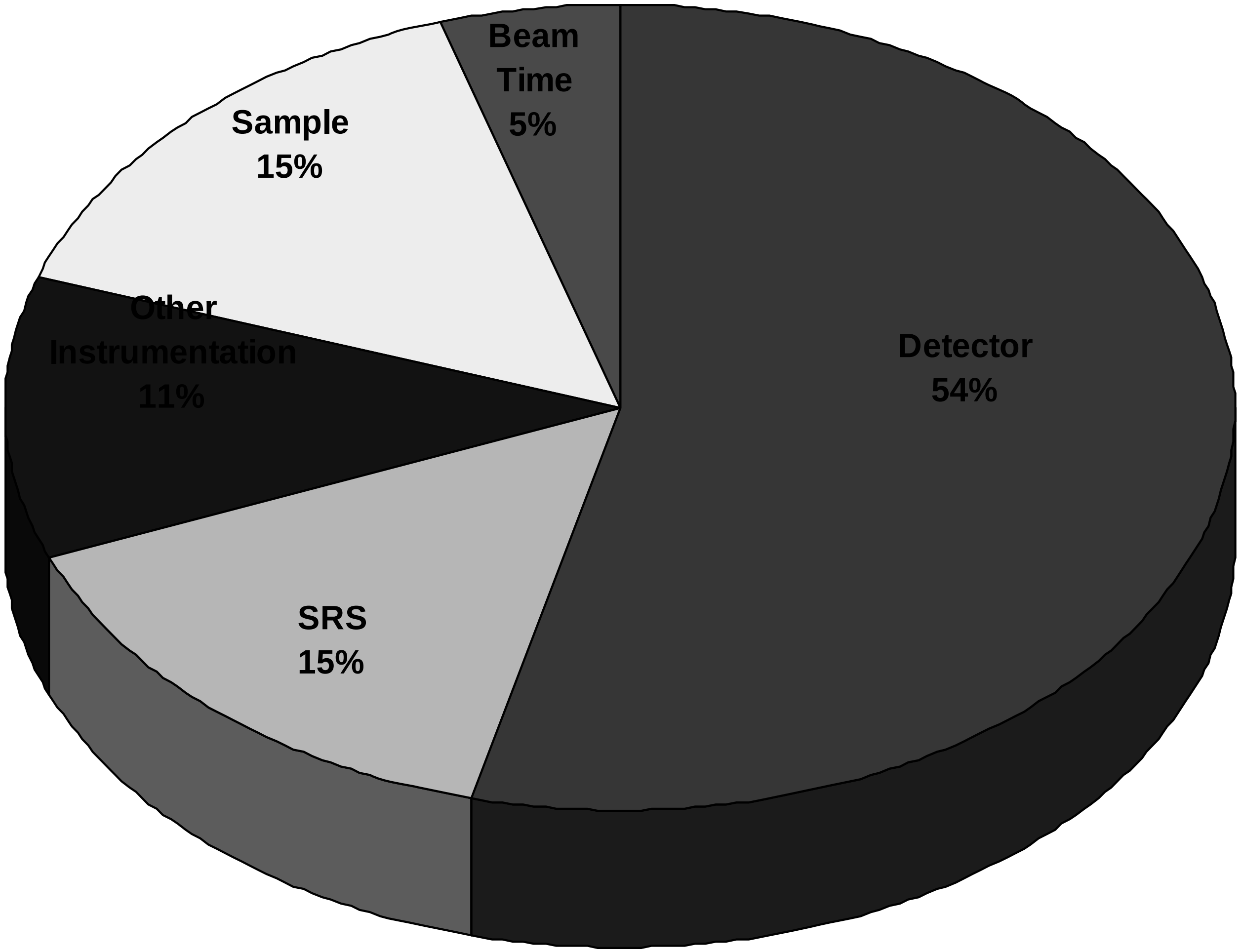
Detectors for Synchrotron Radiation

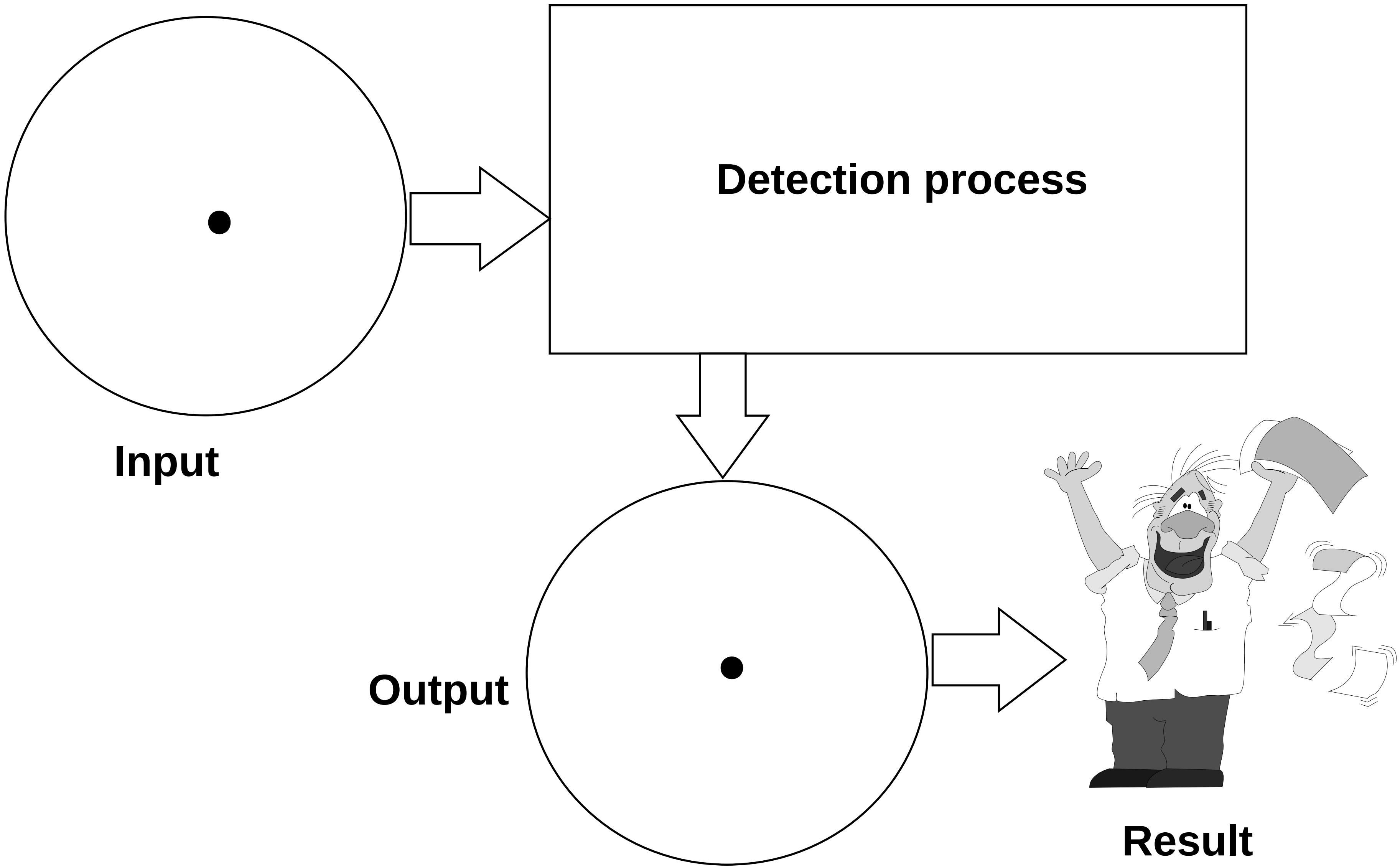
Chris Hall

Monash University

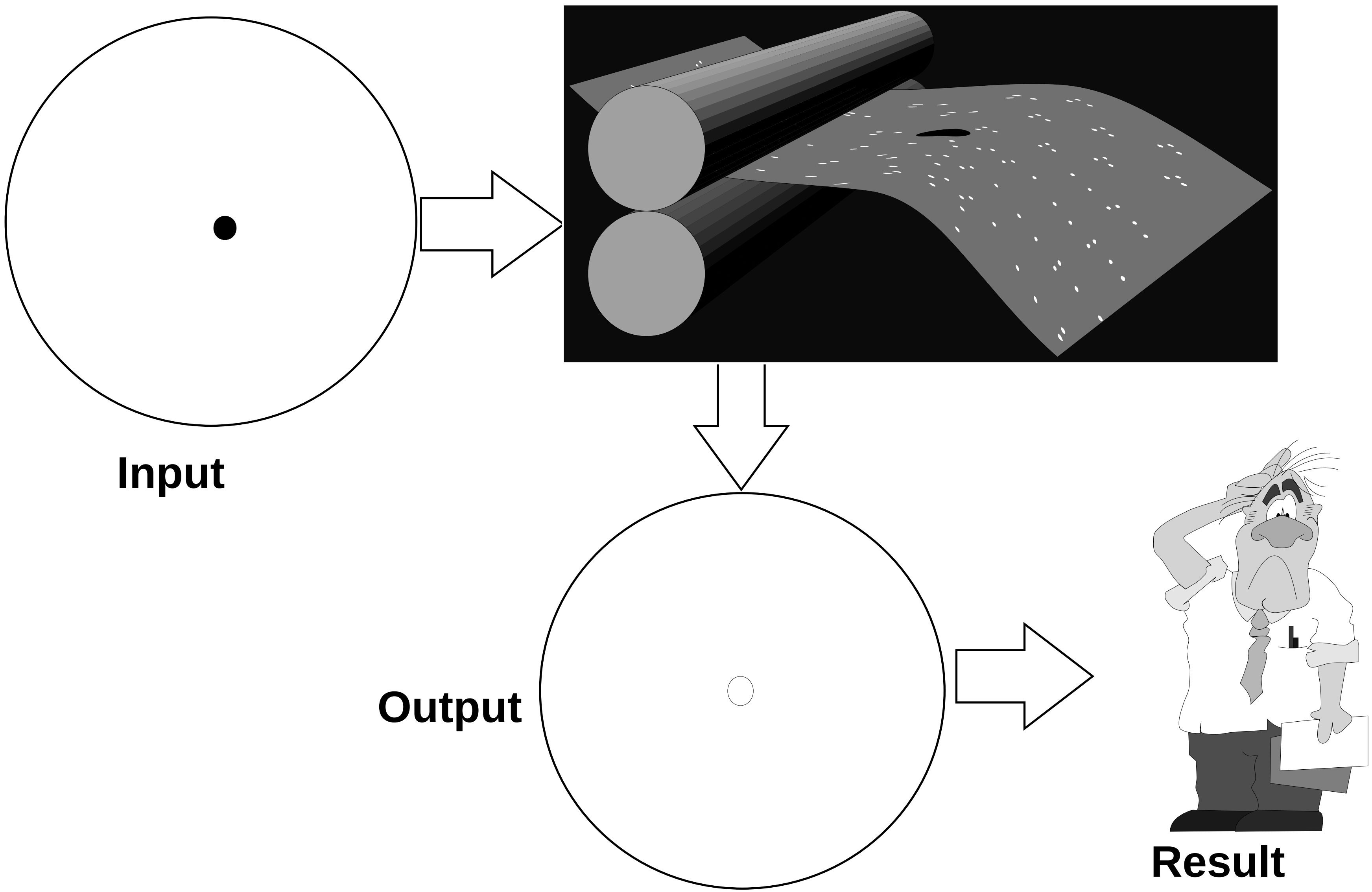
Factors Limiting Science



A Scientist’s View of the Detector



The Truth!



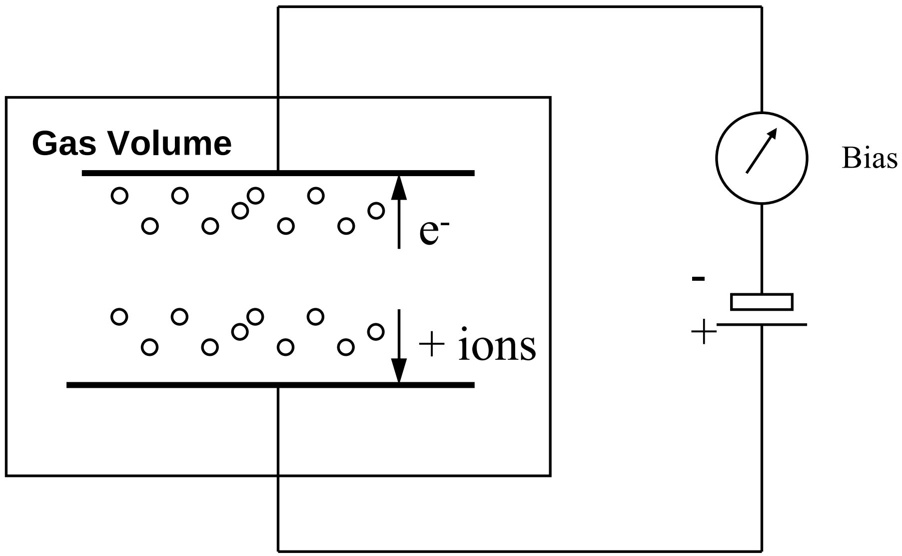
Detection Mechanisms

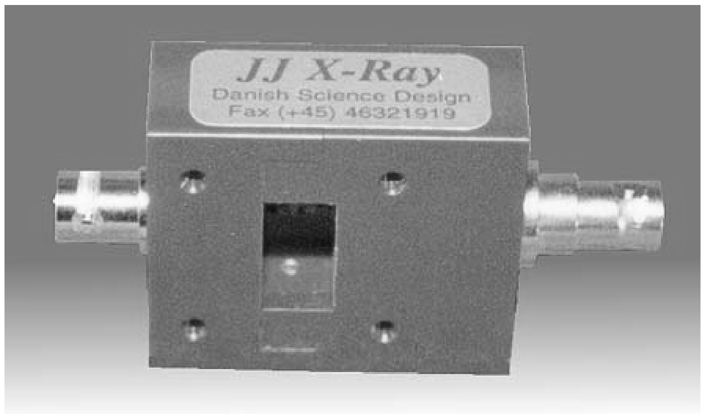
Photons in…

- Gas ionisation
  - Detect the electrons and ions
  - E.g. Ion chambers, proportional counters
- Photoelectric effect
  - Detect the electrons or measure current
  - E.g.. CsI photocathodes in image intensifiers
- Generation of electron hole pairs
  - Detect the electrons and holes
  - E.g.. Semiconductor detectors
- Fluorescence or scintillation including the creation of F centres
  - Measure the light
  - E.g. Image plates, Scintillation counters
- Chemical
  - Measure the absorption of light
  - E.g. Film

…out

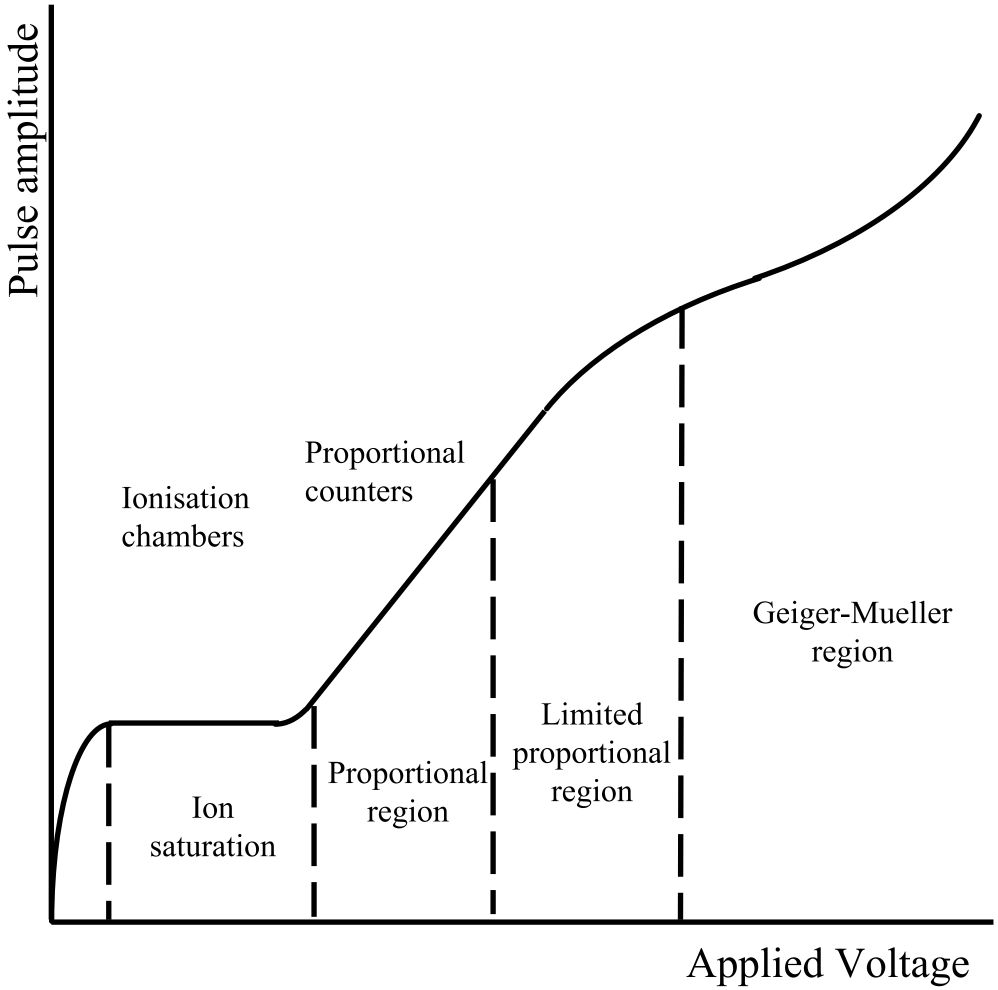
The Ionisation Chamber

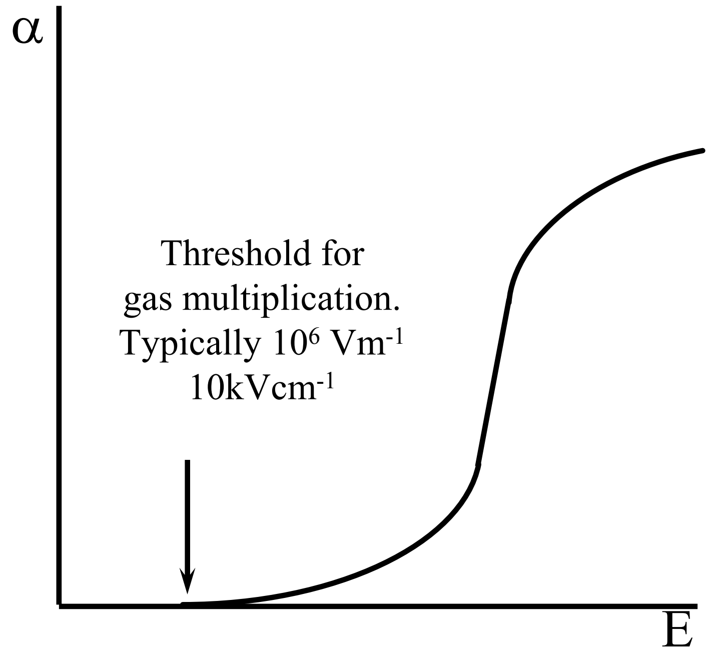




- Very simple device
- 1 e^- ion pair per 30eV of energy deposited
- Important that recombination is low as possible
  - Higher voltages required at higher rates since more carriers
  - Diffusion losses caused by separation of carriers minimised by higher voltages
- Ion chambers are sensitive pressure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

Operation regions of gas filled detectors



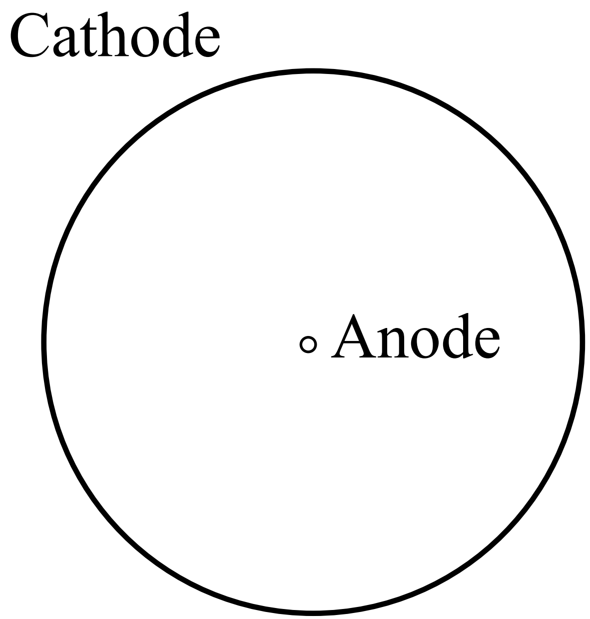


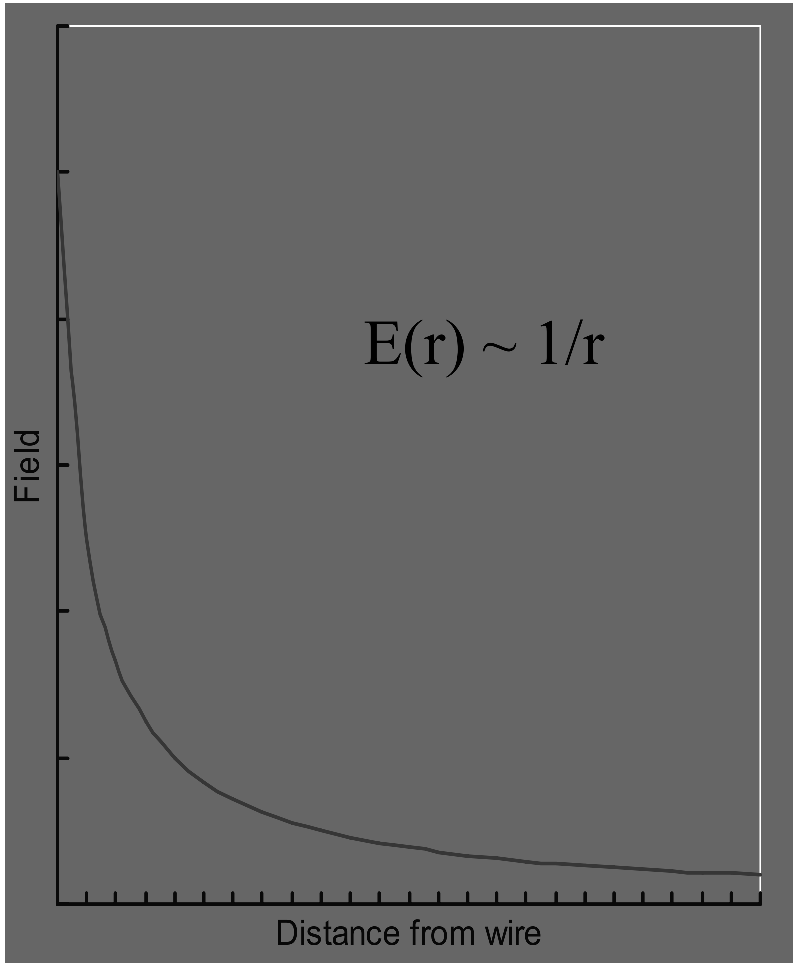
n is number of charges

x is distance

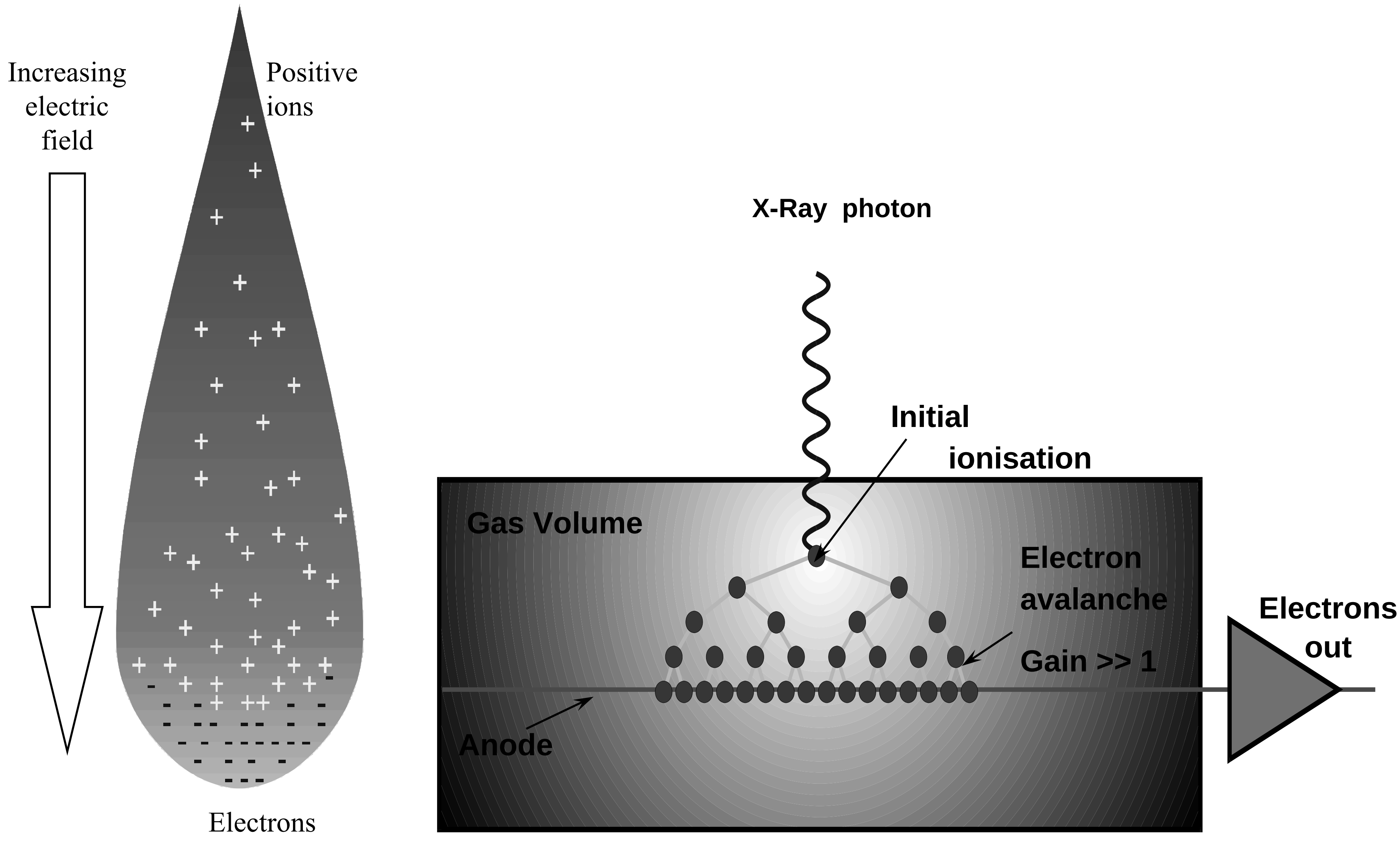
α is the first Townsend coefficient

Field Variation





Avalanche & Proportional Counter



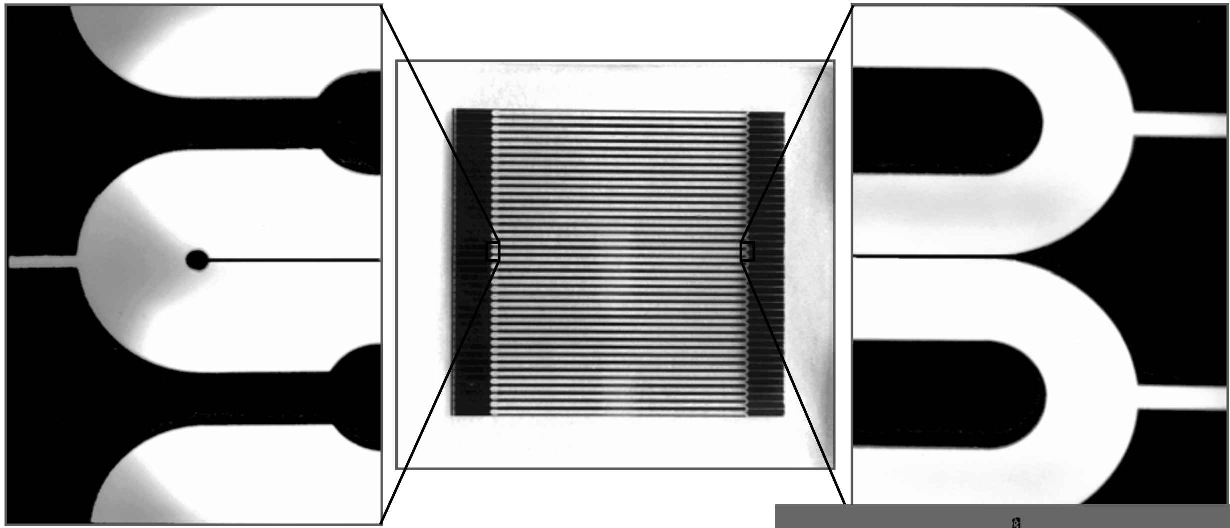
Gas Fillings

- Primary Gas
  - Minimal electron attachment coefficient. (No air).
  - High electron drift velocity

  Argon, Krypton, Xenon
- Quench Gas
  - High UV absorption cross section
  - For SR it should not crack

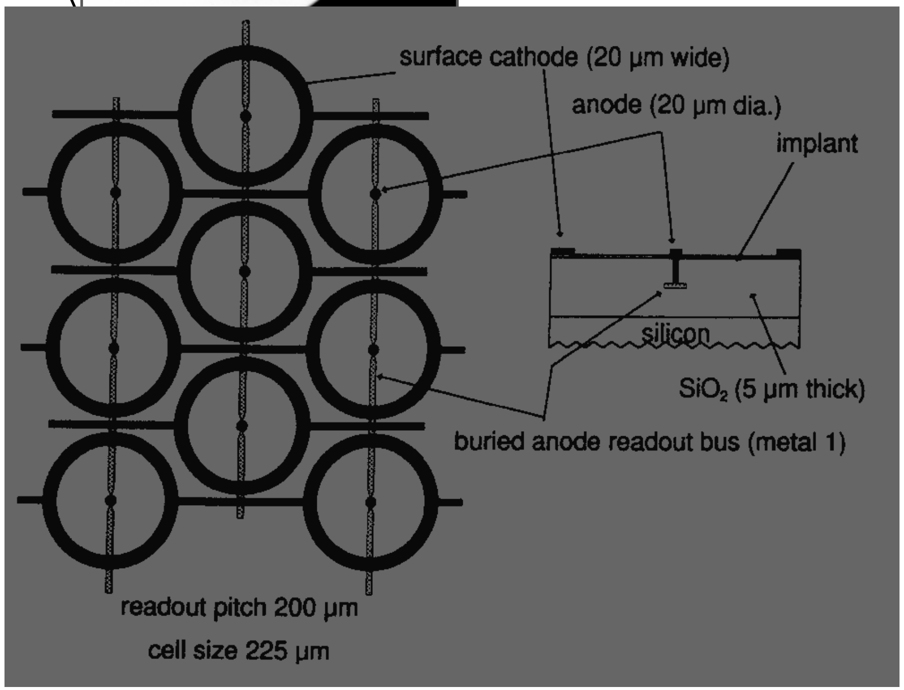
  Polyatomic, organic molecules. CH_4, CO_2

Microstrip Variants

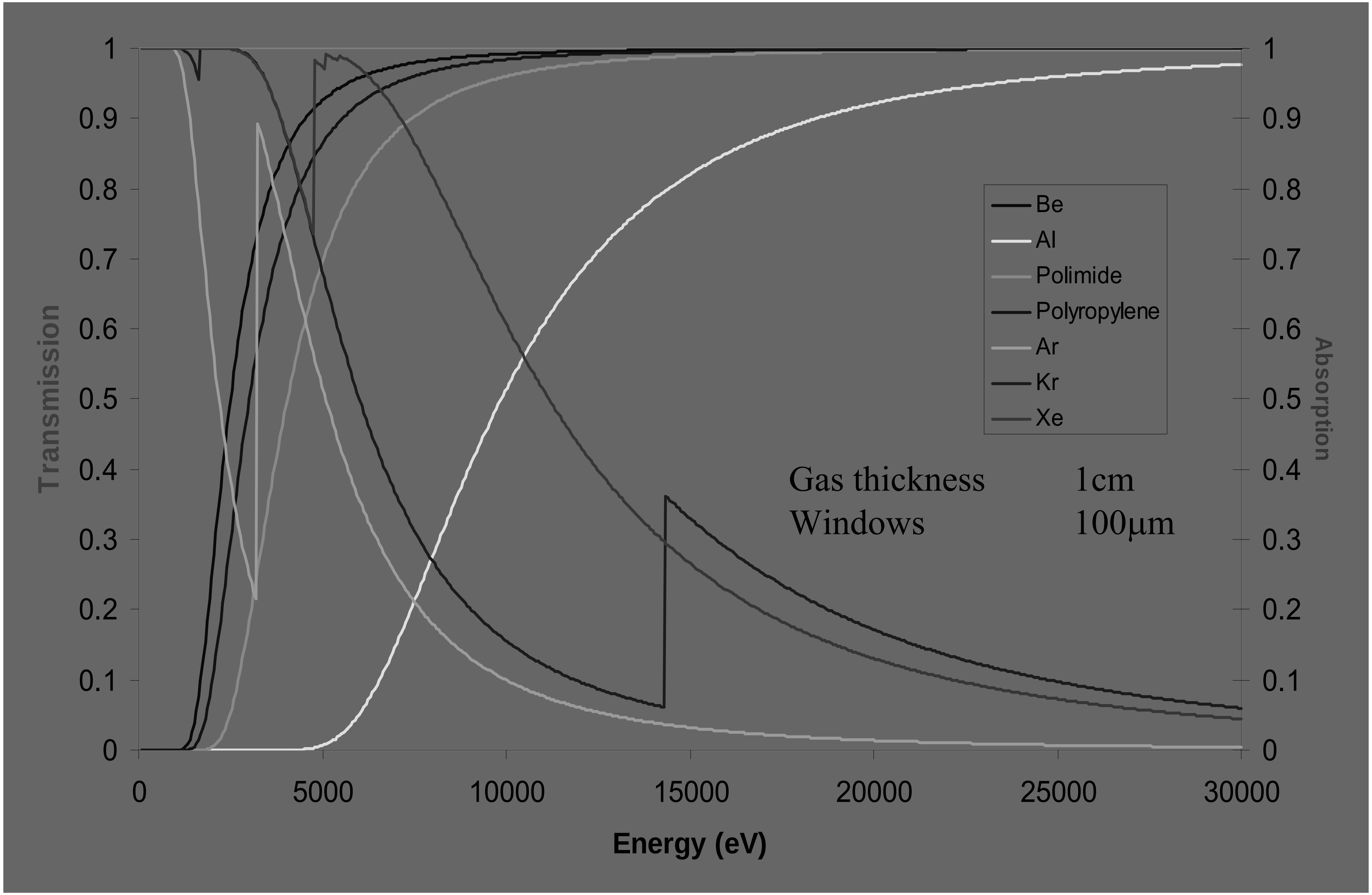


Typical anode width
10 microns

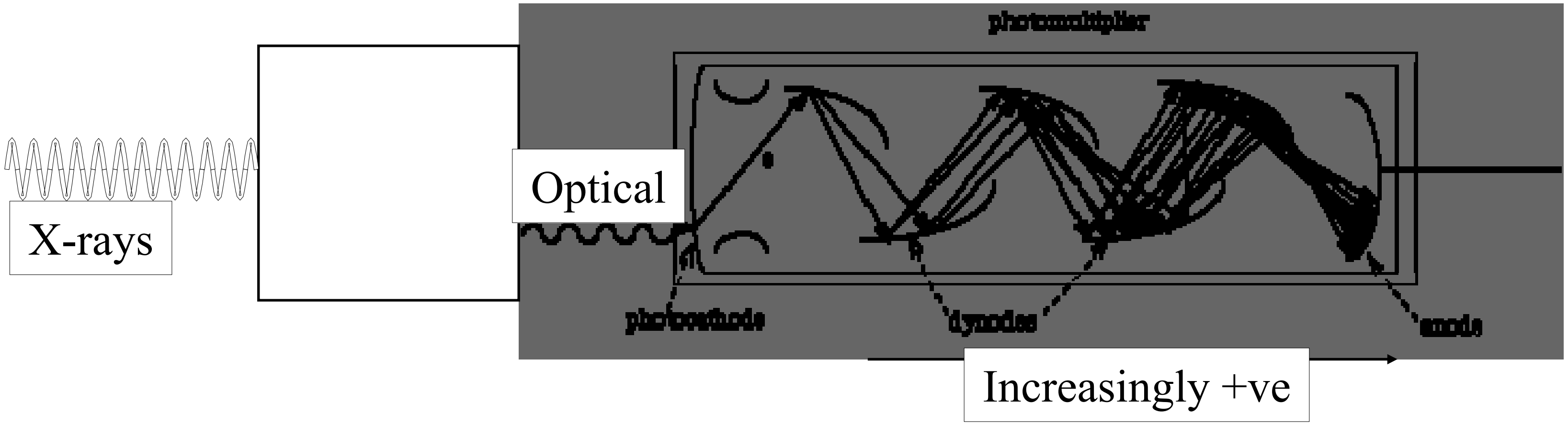
Micro Dot

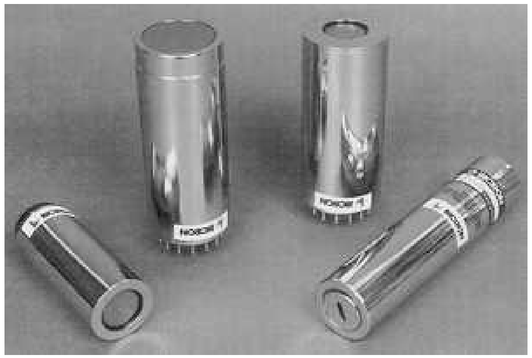


Efficiencies



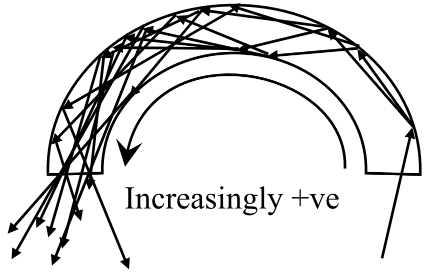
Photomultipliers & Scintillators



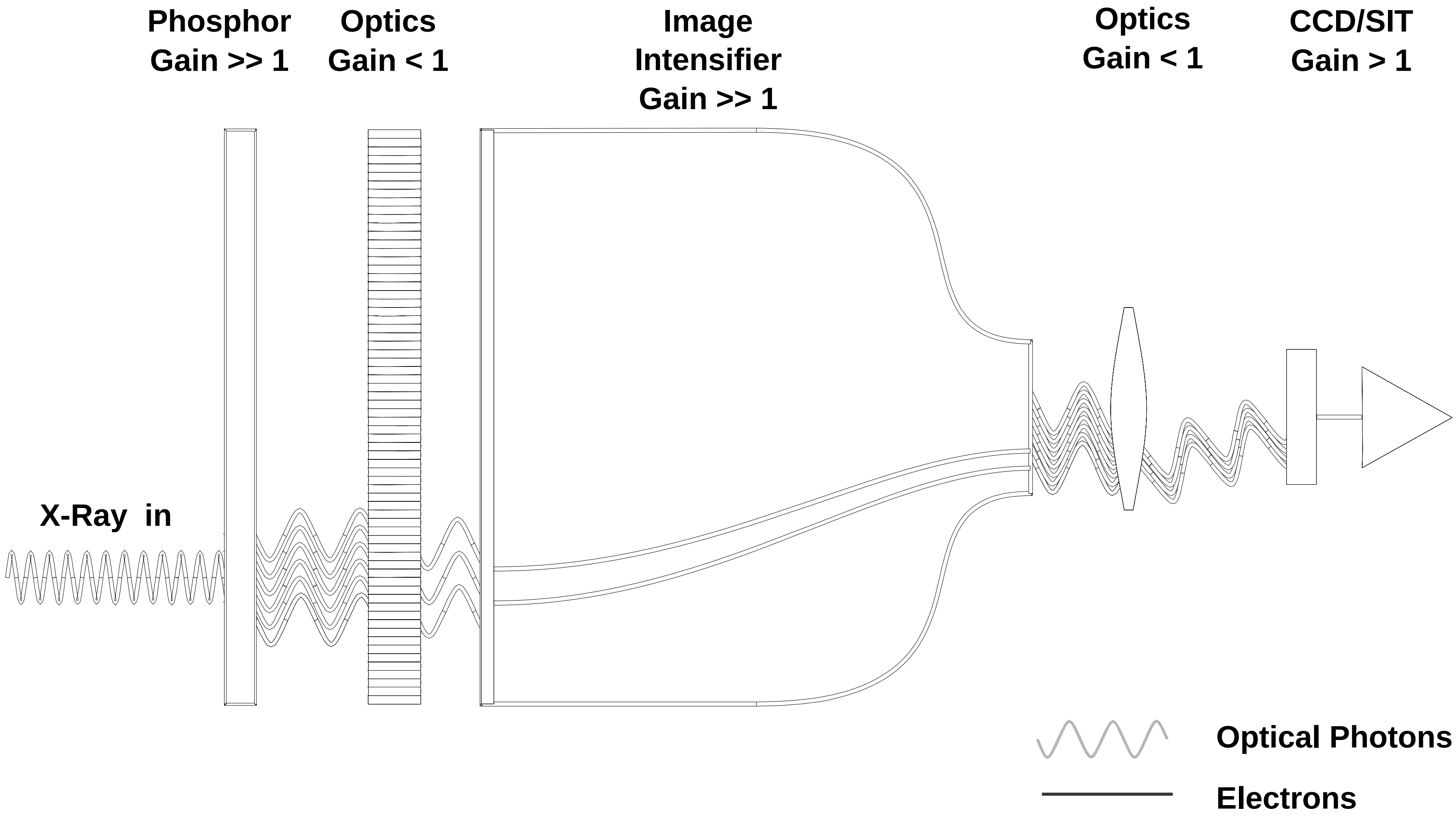


Channeltron is a similar with distributed dynode

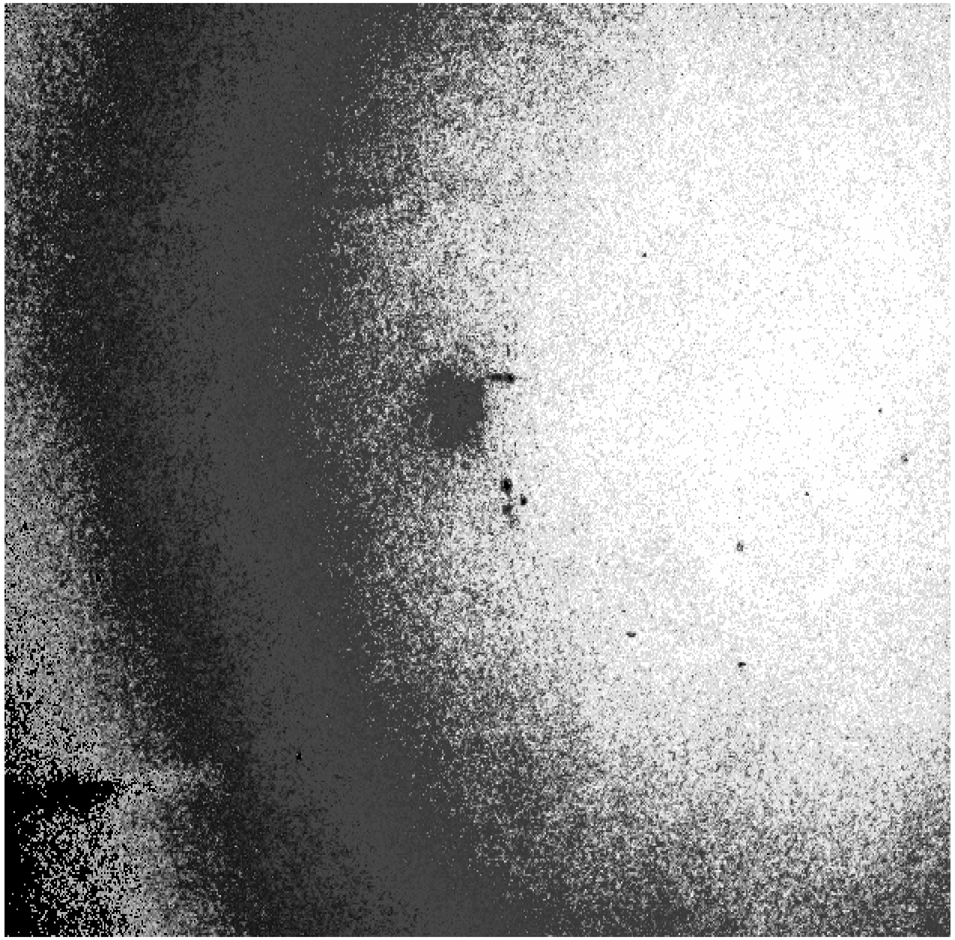
Micro-channel plates are mutlichannel channeltrons with each channel being an electron multiplier.



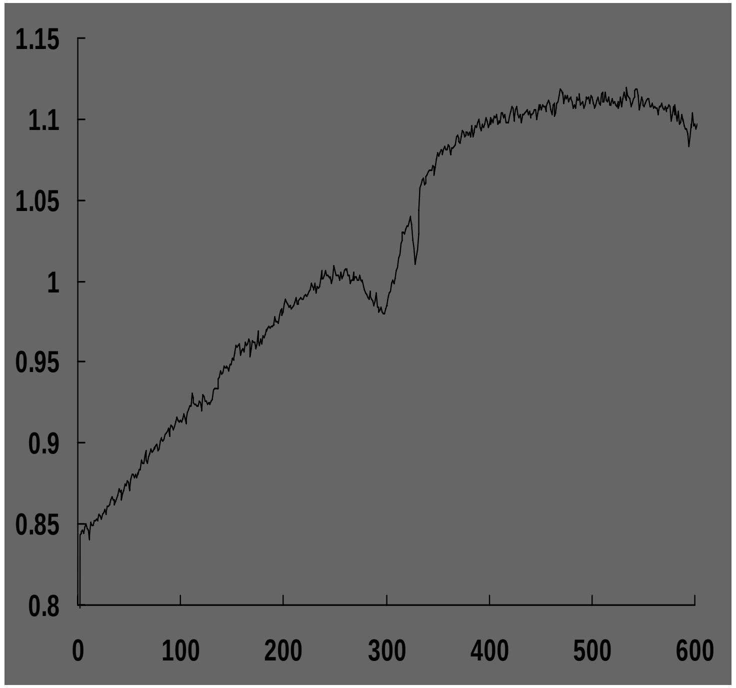
TV detector with IIT



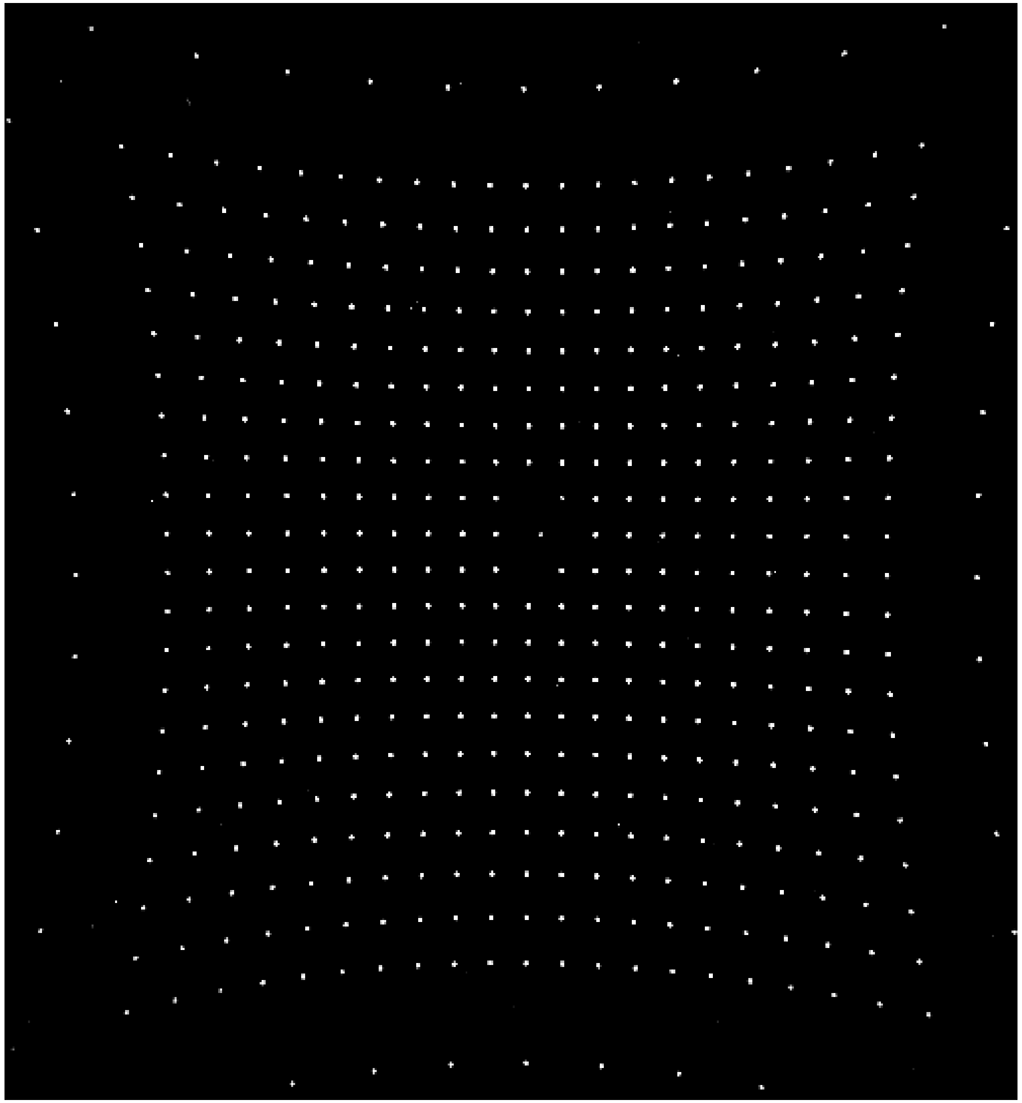
Response to Uniform Illumination



ESRF TV Detector
Thompson IIT & CCD

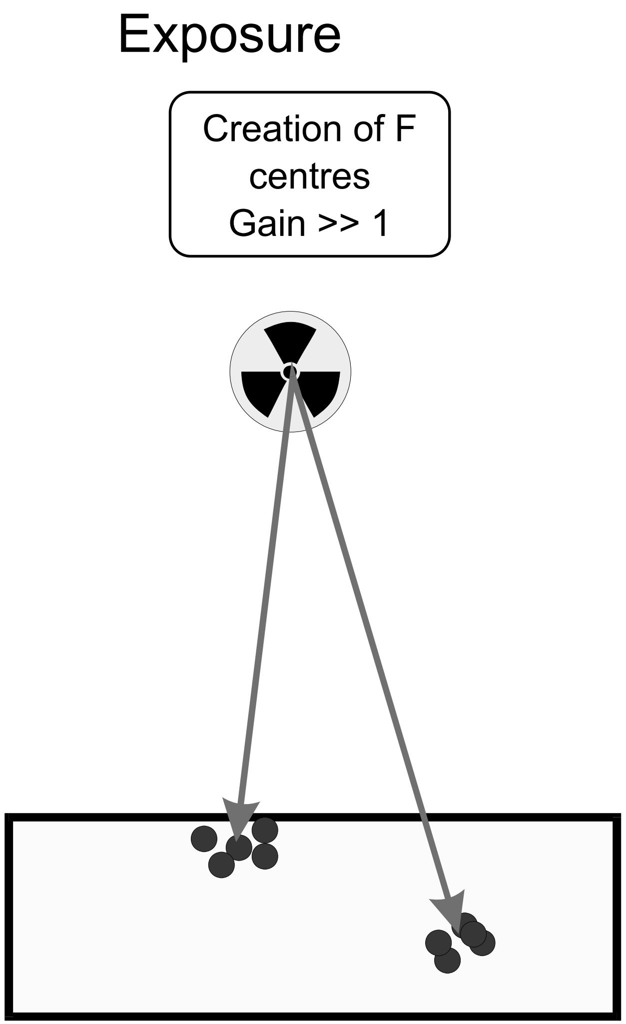


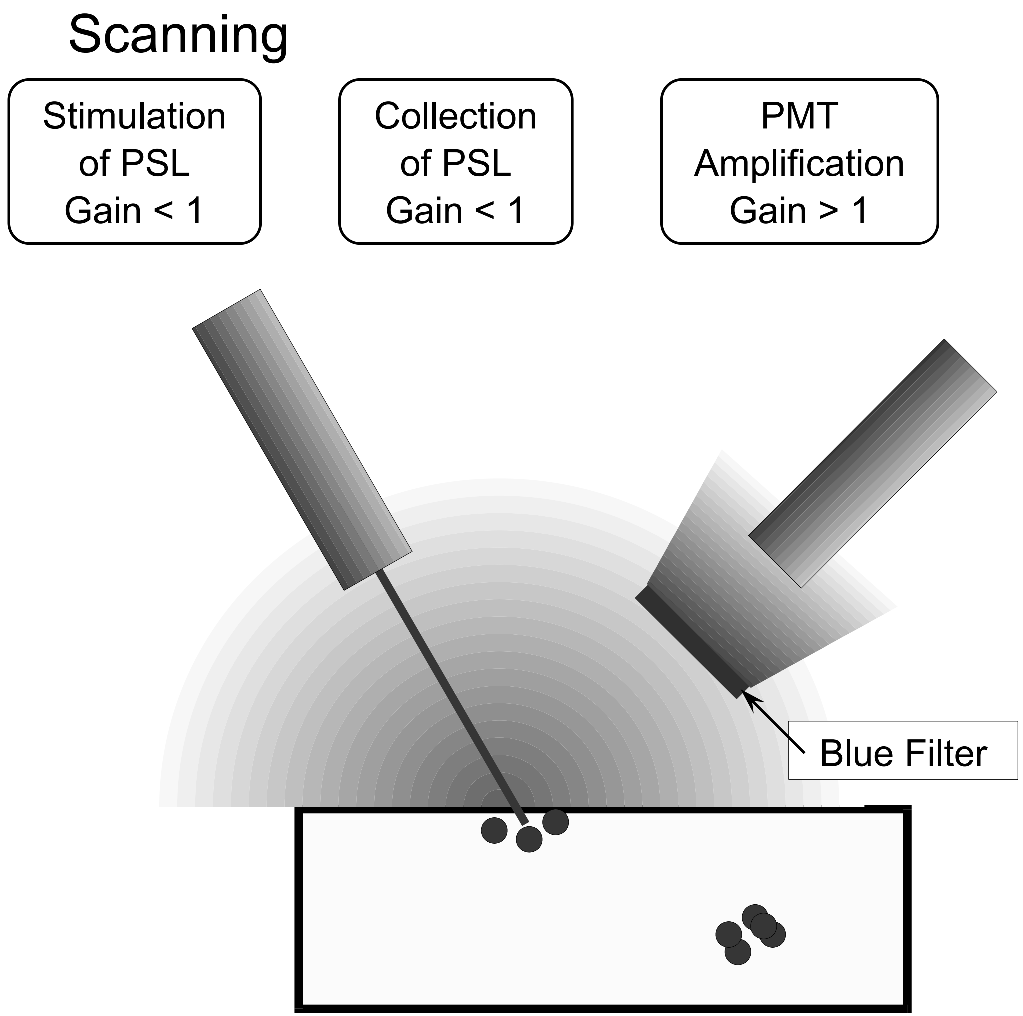
Spatial distortion



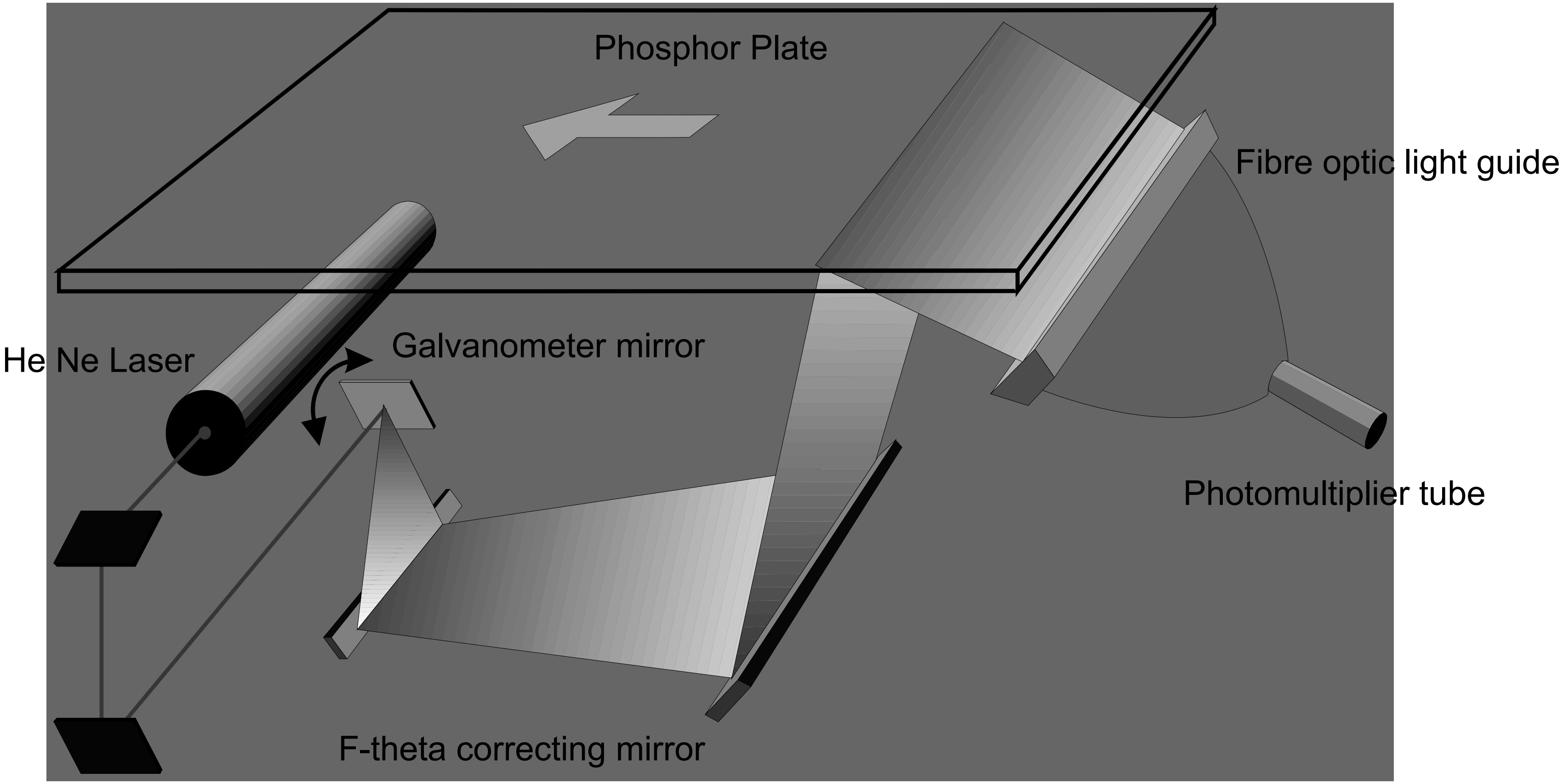
ESRF Image intensifier detector

Computed Radiography-Image Plates



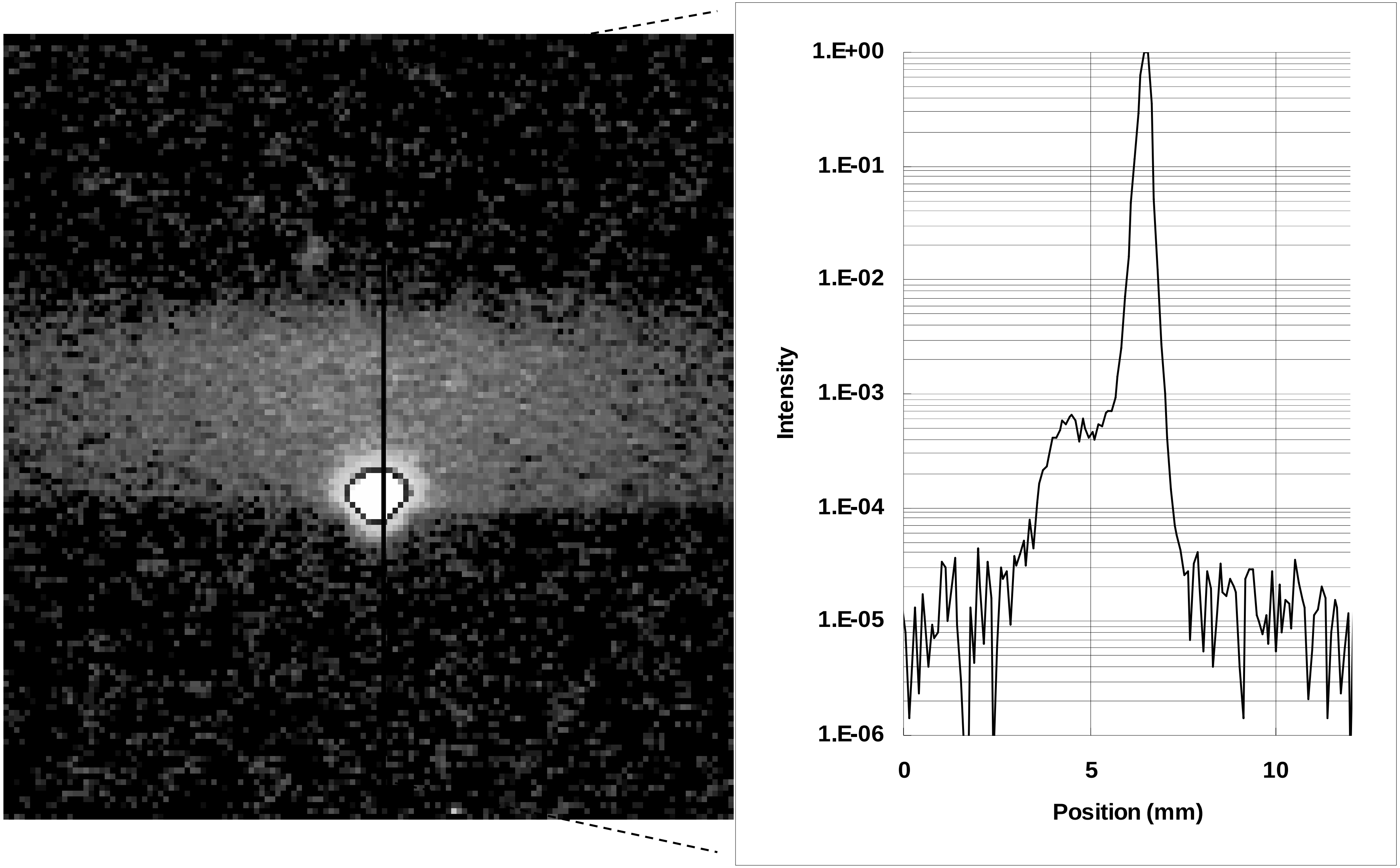


X-Y Flat bed Scanner

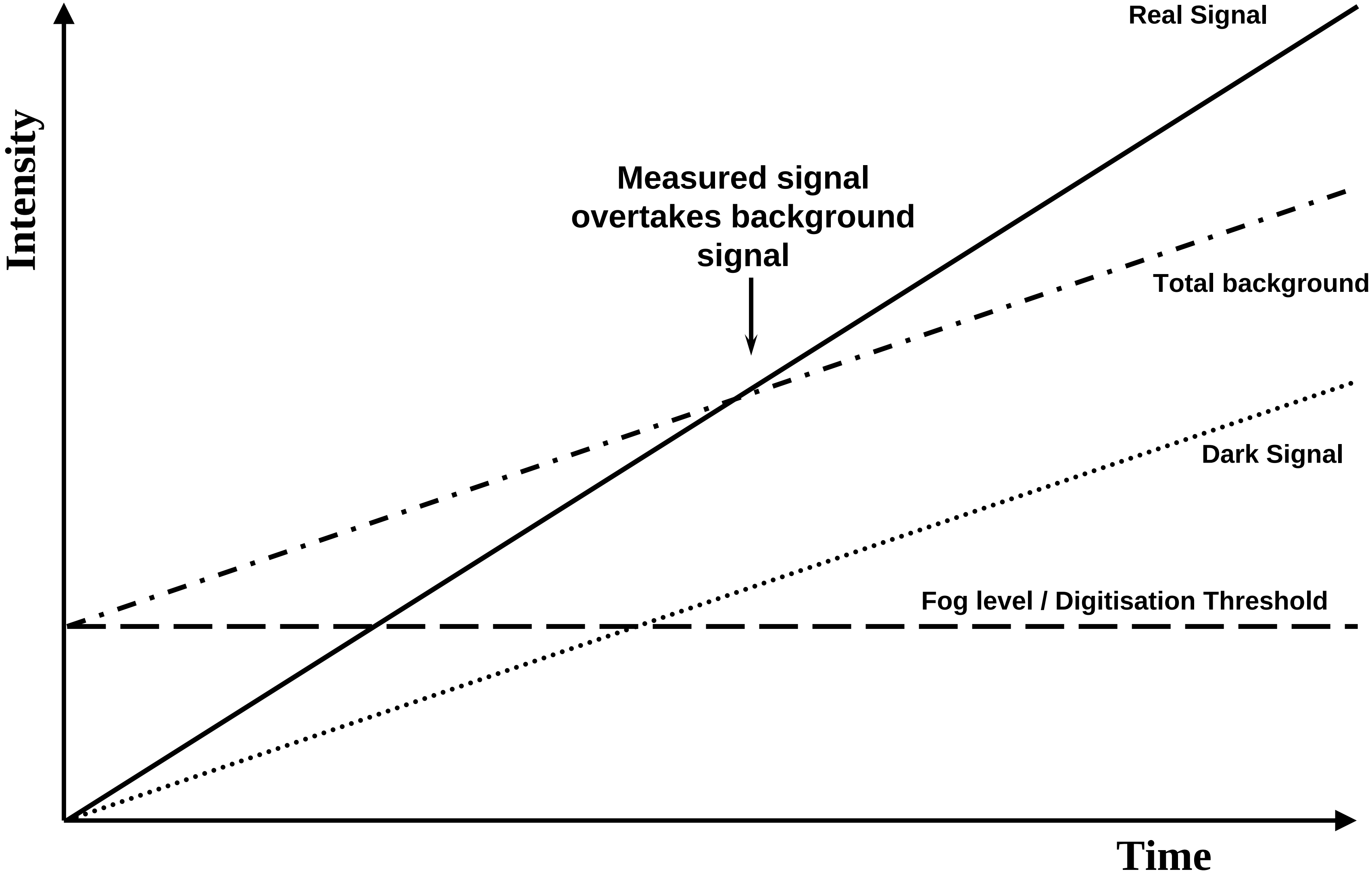


Distributed Light Collection

IPlate Single Peak PSF

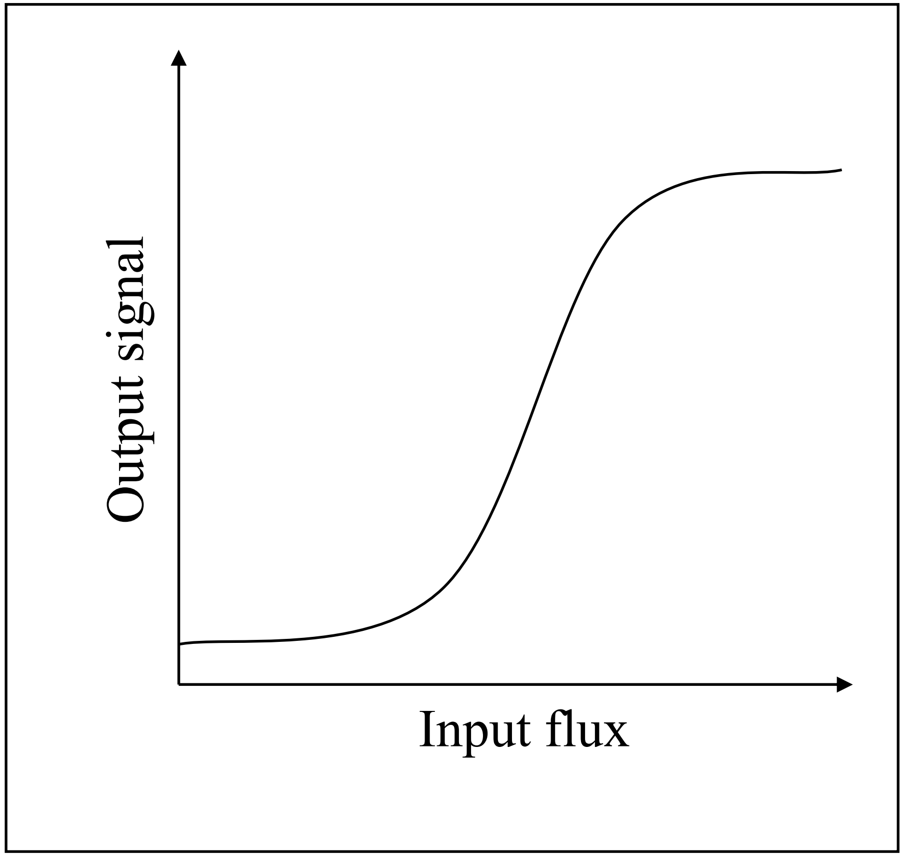


Dark Signals & Fog



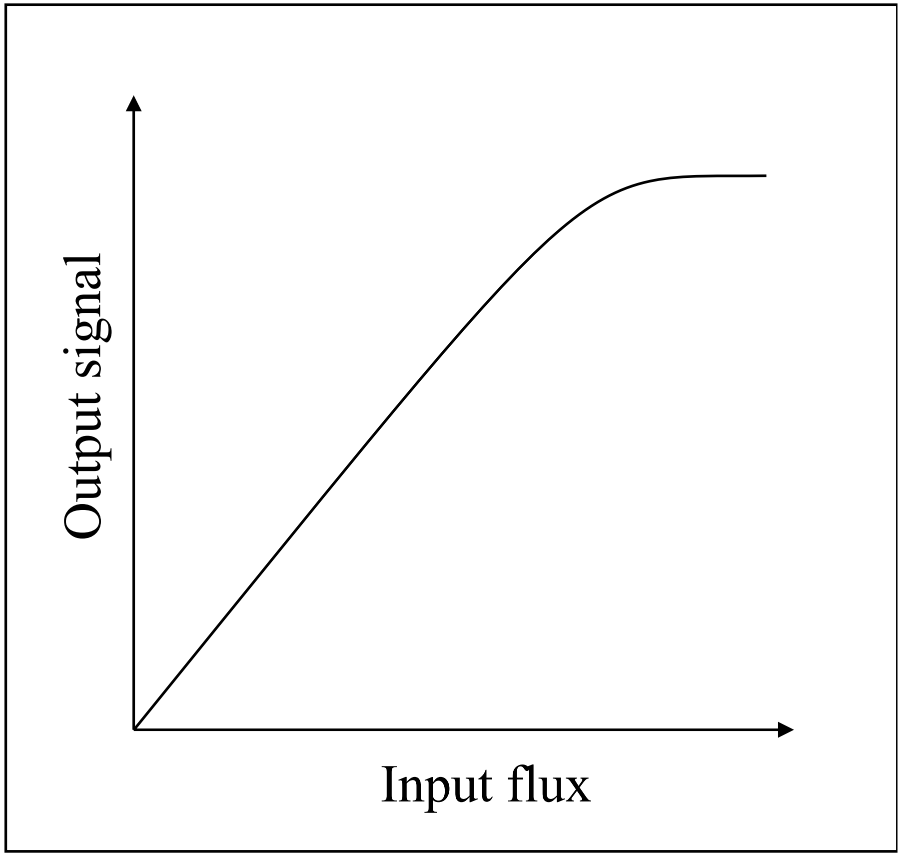
Integrating Detectors

- 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

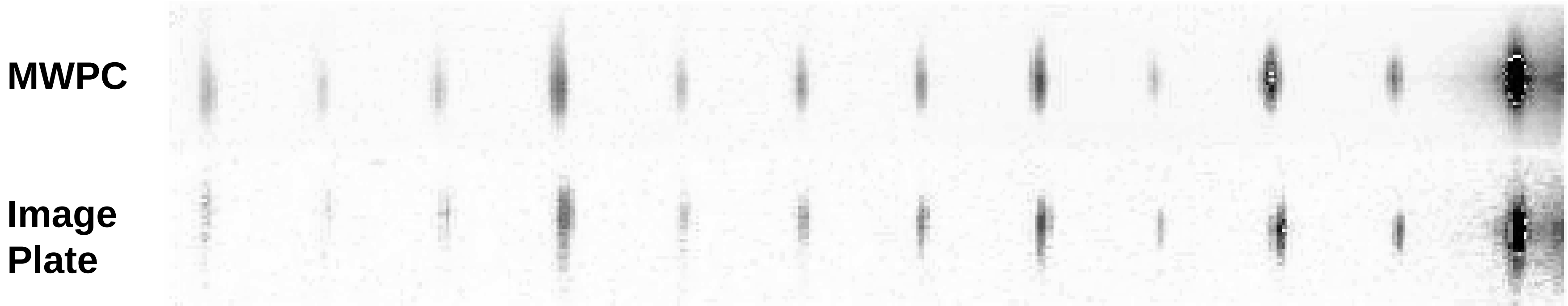


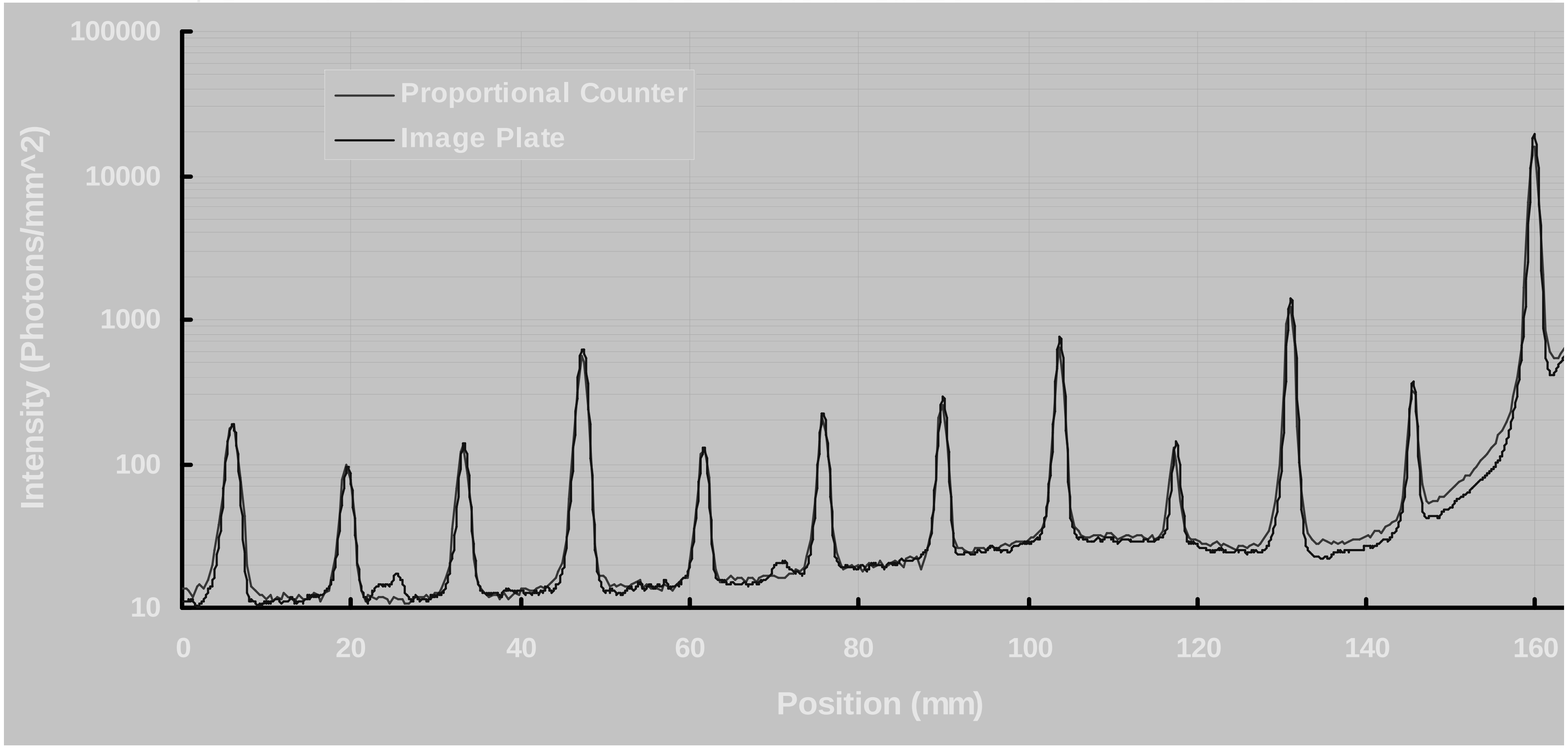
Photon Counting Detectors

- 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

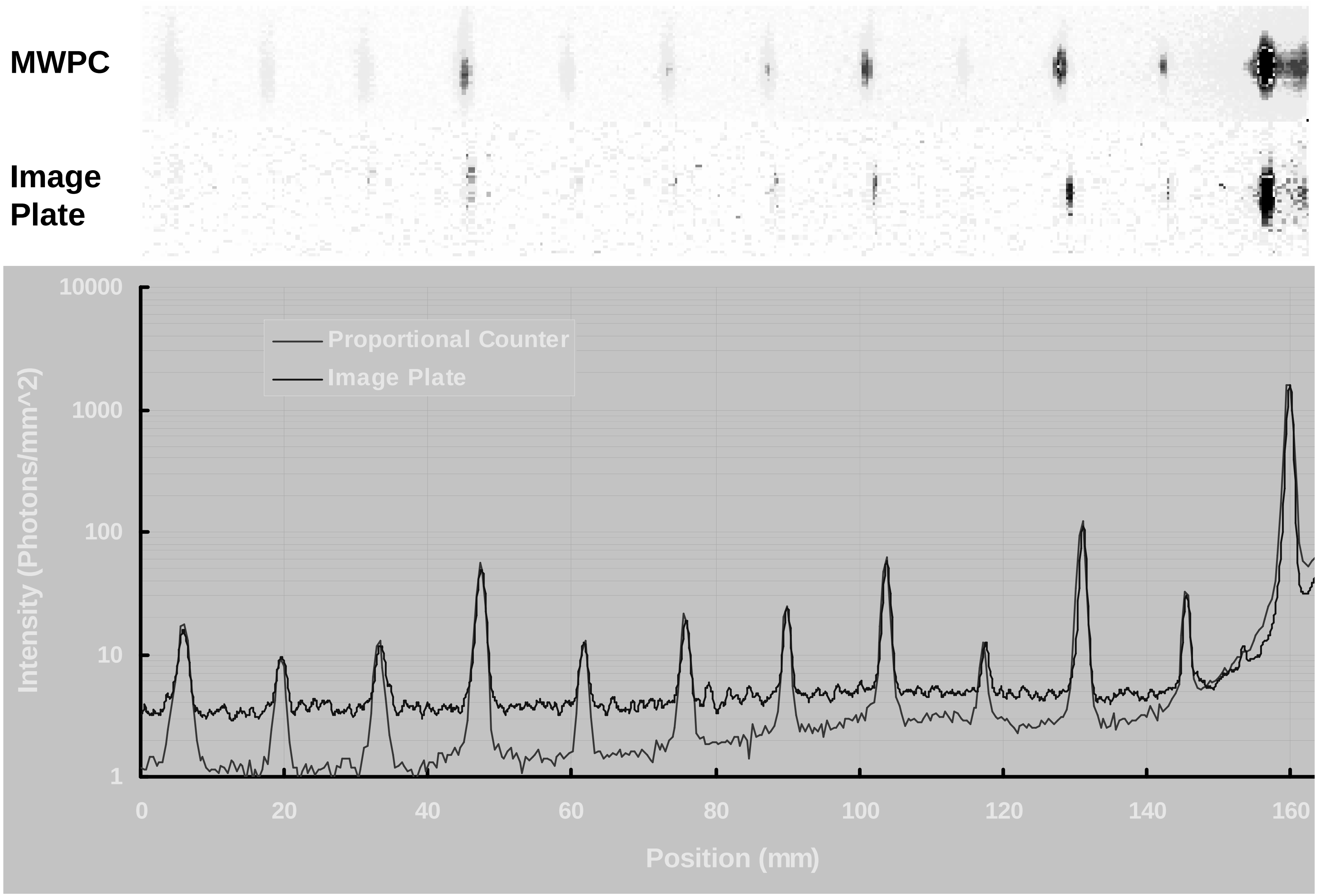


Collagen 100s Exposure

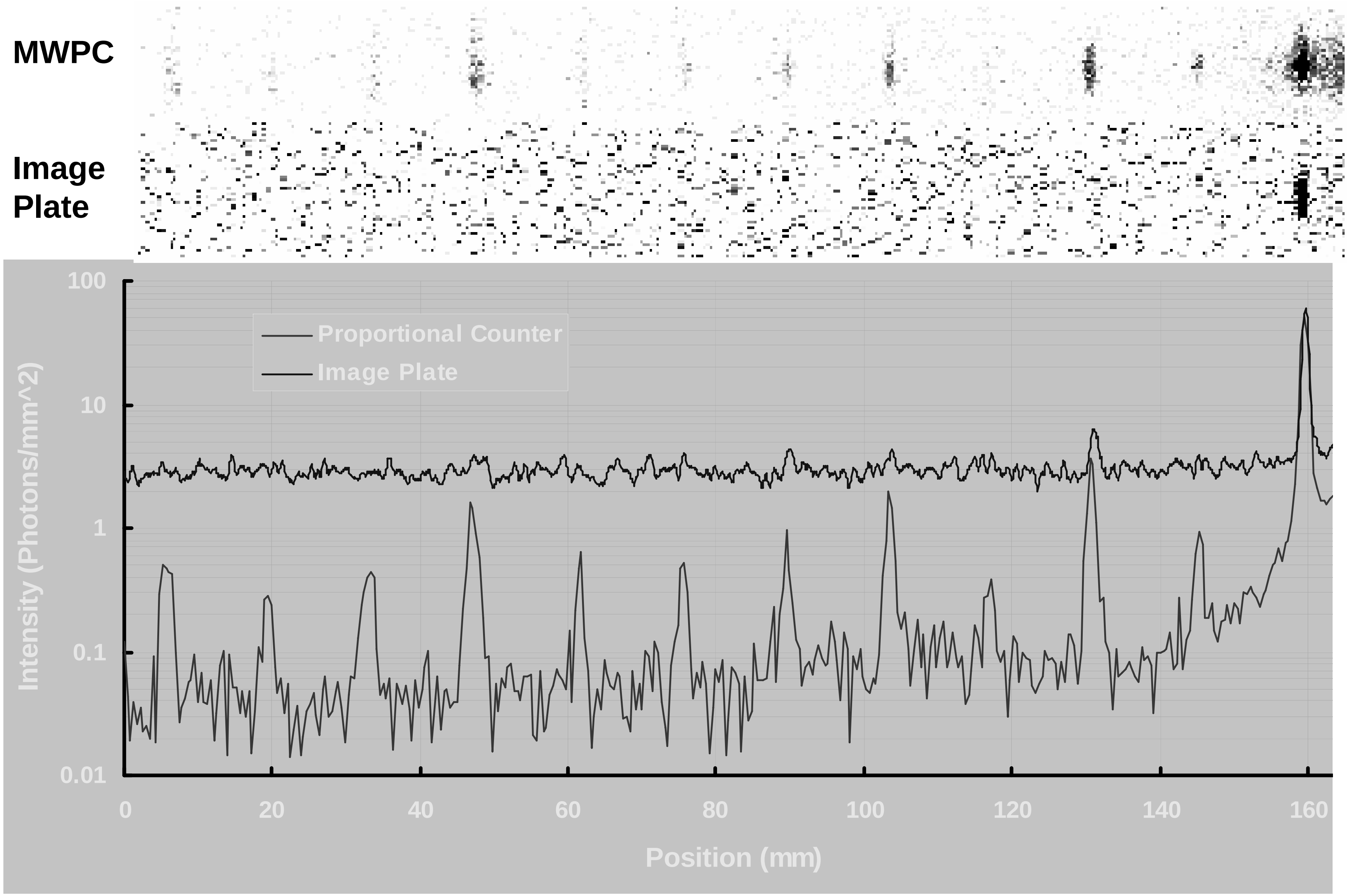




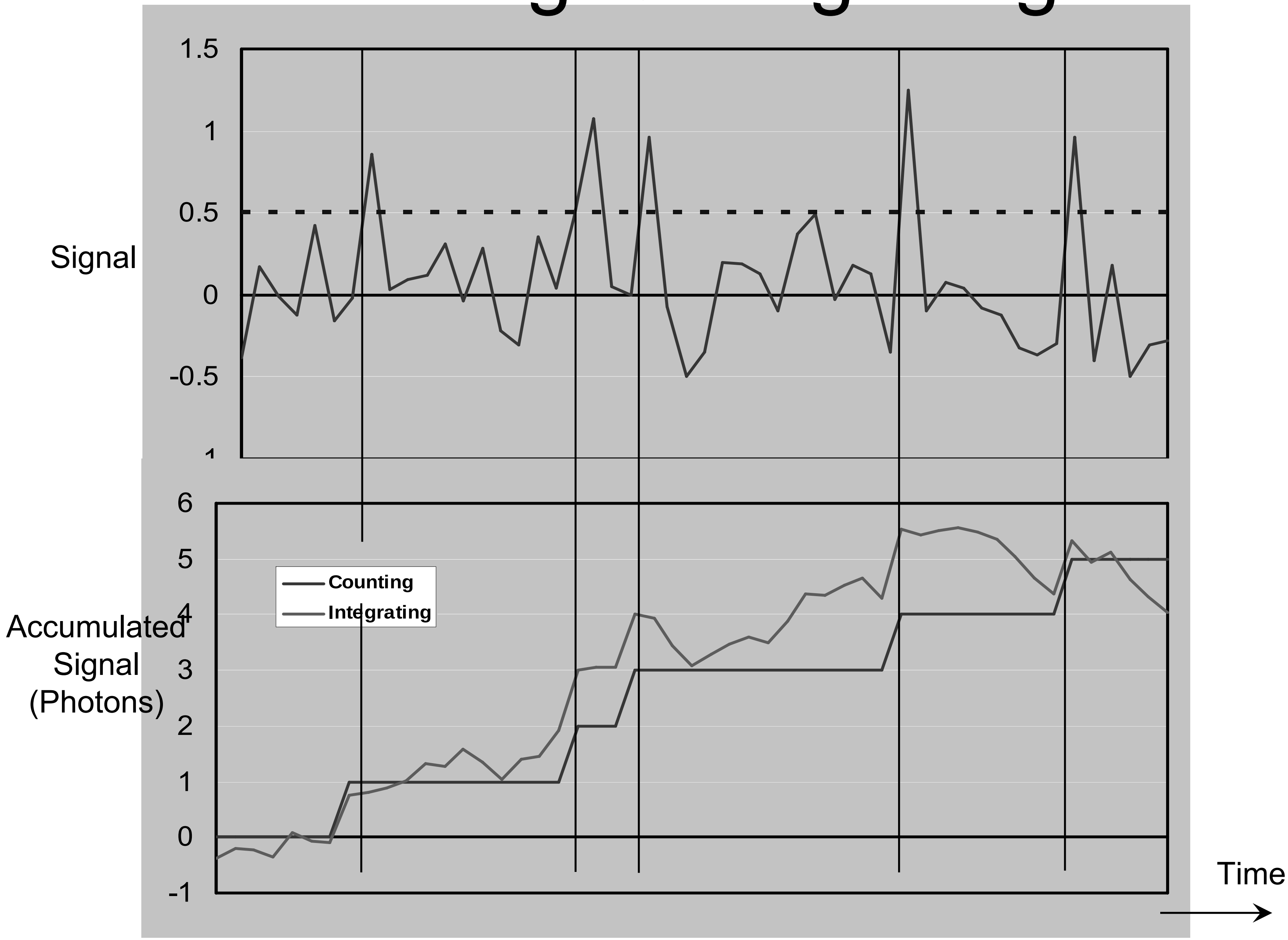
Collagen 10s Exposure



Collagen 0.3s Exposure



Counting & Integrating



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

Spectral Resolution

- Average number of carriers, $N = E/w$

  where w is energy to create electron hole/ion pair
- Poisson statistics: $\sigma = 1/\sqrt{N}$
- $\Delta E/E = 2.355\sigma = 2.355(E/w)^{-1/2} = 2.355(w/E)^{1/2}$

- For Ge, w= 3eV so at 10keV $\Delta E/E$ = 4%
- For Ar, w= 25eV so at 10keV $\Delta E/E$ = 12%

Fano Factor

- If all energy from photon or particle were converted into electrons there would be no variance.
- If a random portion of the photon energy were converted there would be no energy resolution.
- Reality is in between these extremes so introduce fudge factor called the Fano factor F
- Observed relative variance = F x Poisson relative variance.

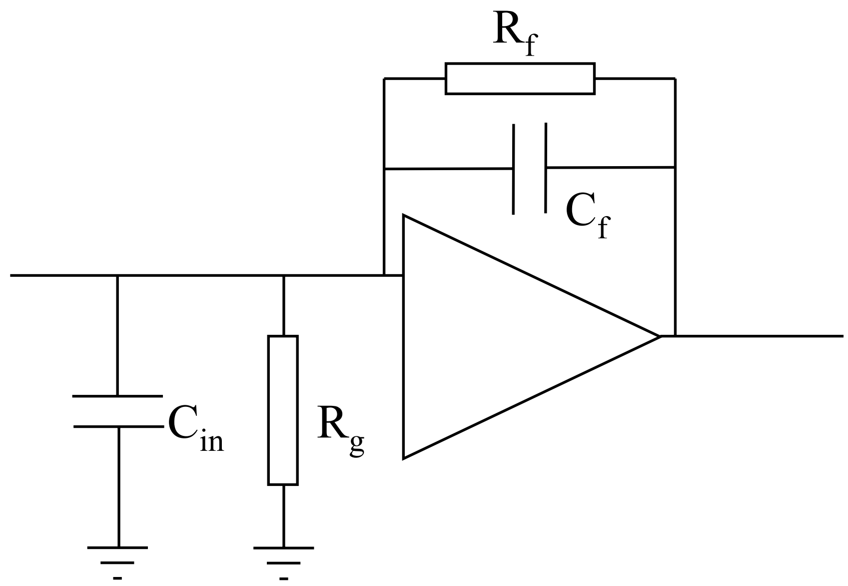
Amplification

- 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

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



- 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

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

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

Noise Dependence

- τ optimum at

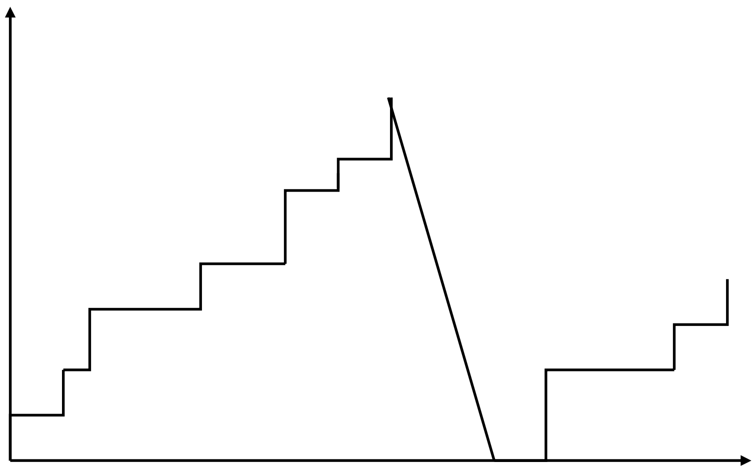
- Choosing optimum τ gives best noise performance but may not be fast enough
- We often have to sacrifice energy resolution for speed

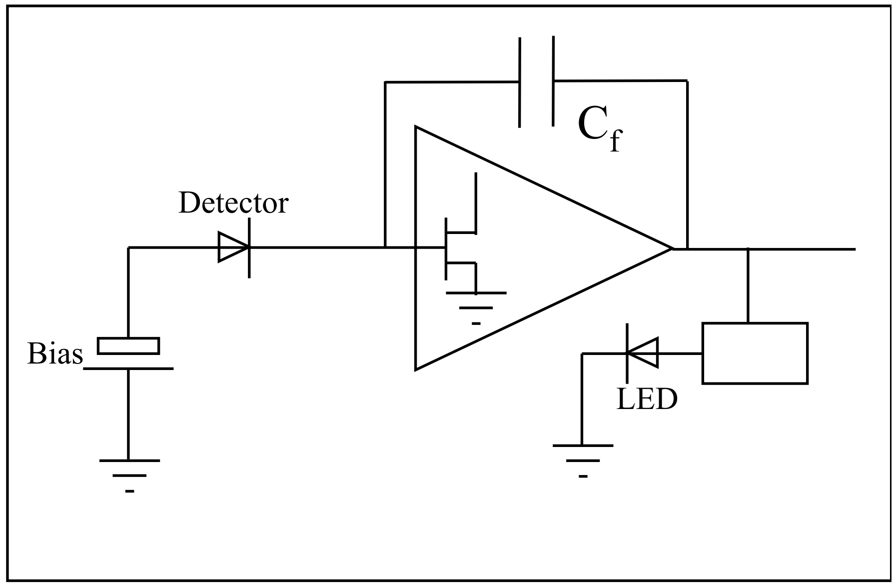
Optimum τ

- 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}

Optimum Spectral Resolution

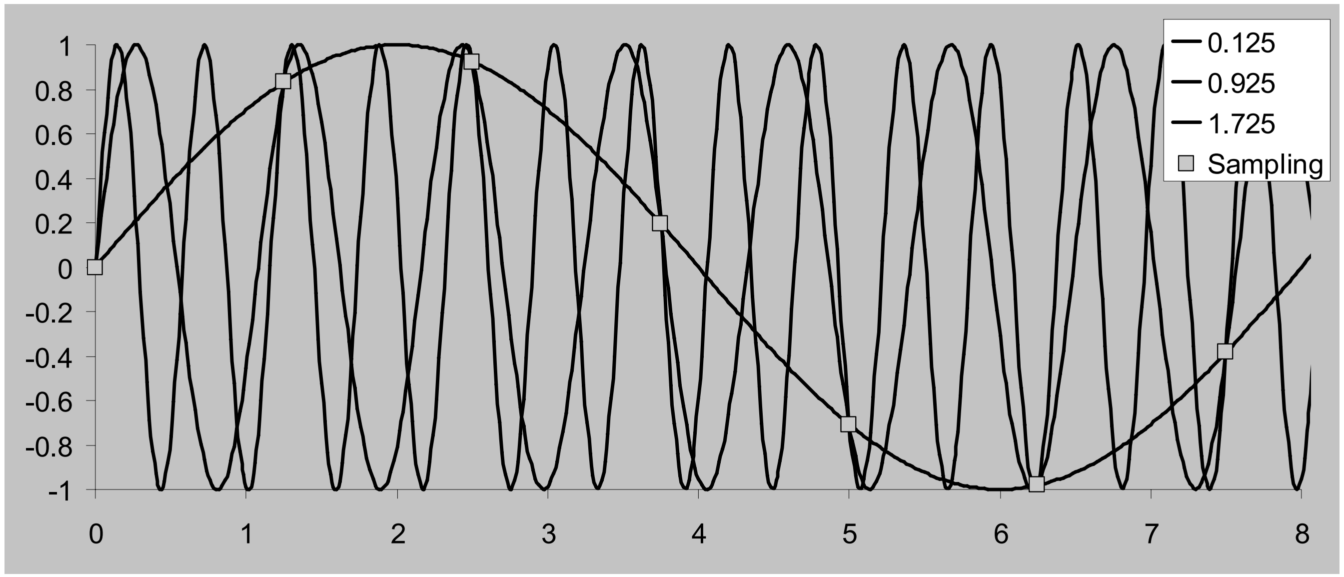
- Low capacitance
  - Small planar < 1pF
- Low leakage currents
- Maximise R_g and/or R_f
  - Remove altogether so $R_f = \infty$
- Use optical reset
- Can improve FWHM by 20%





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

Performance Measure - DQE

Perfect detector

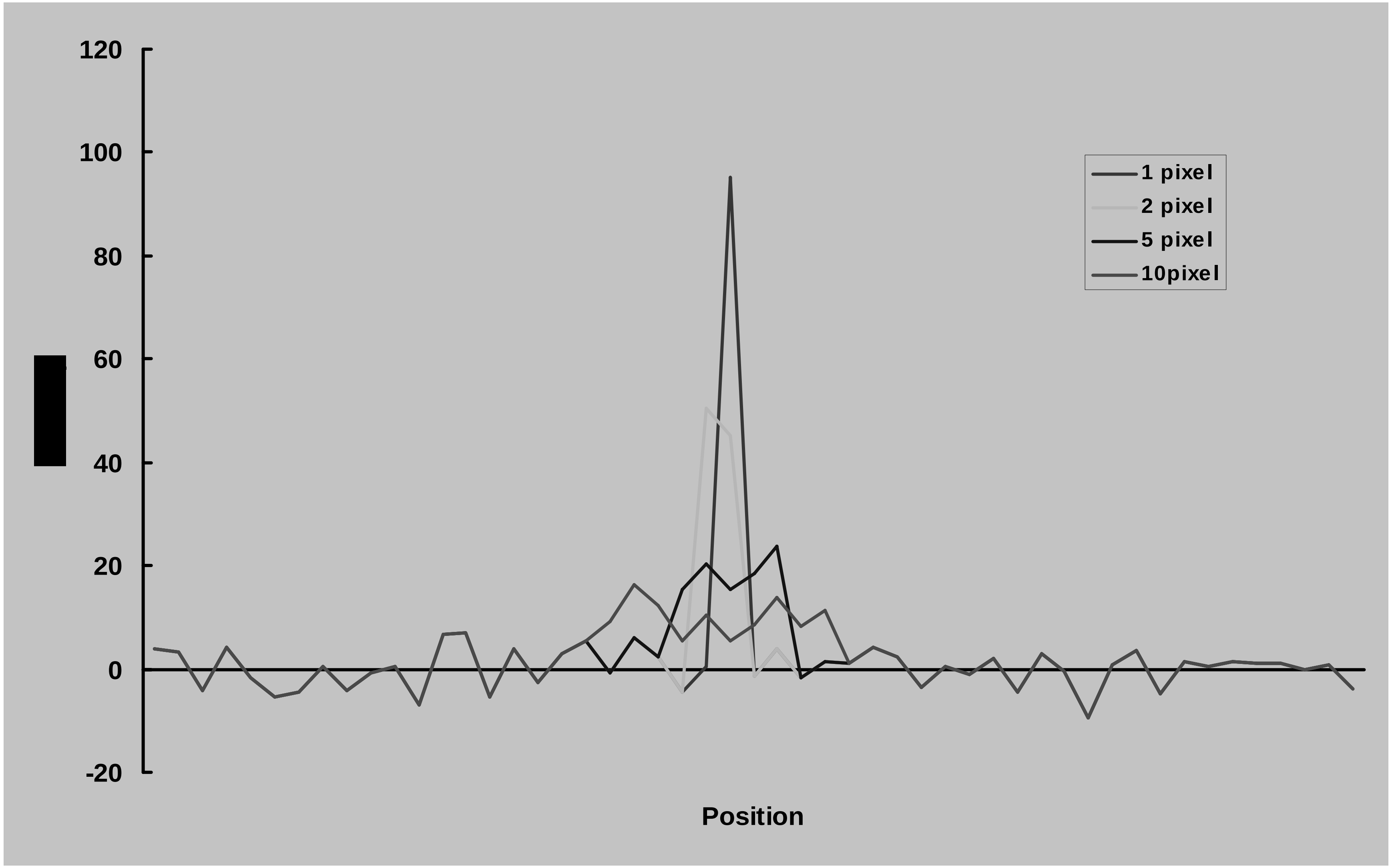
Real detector

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

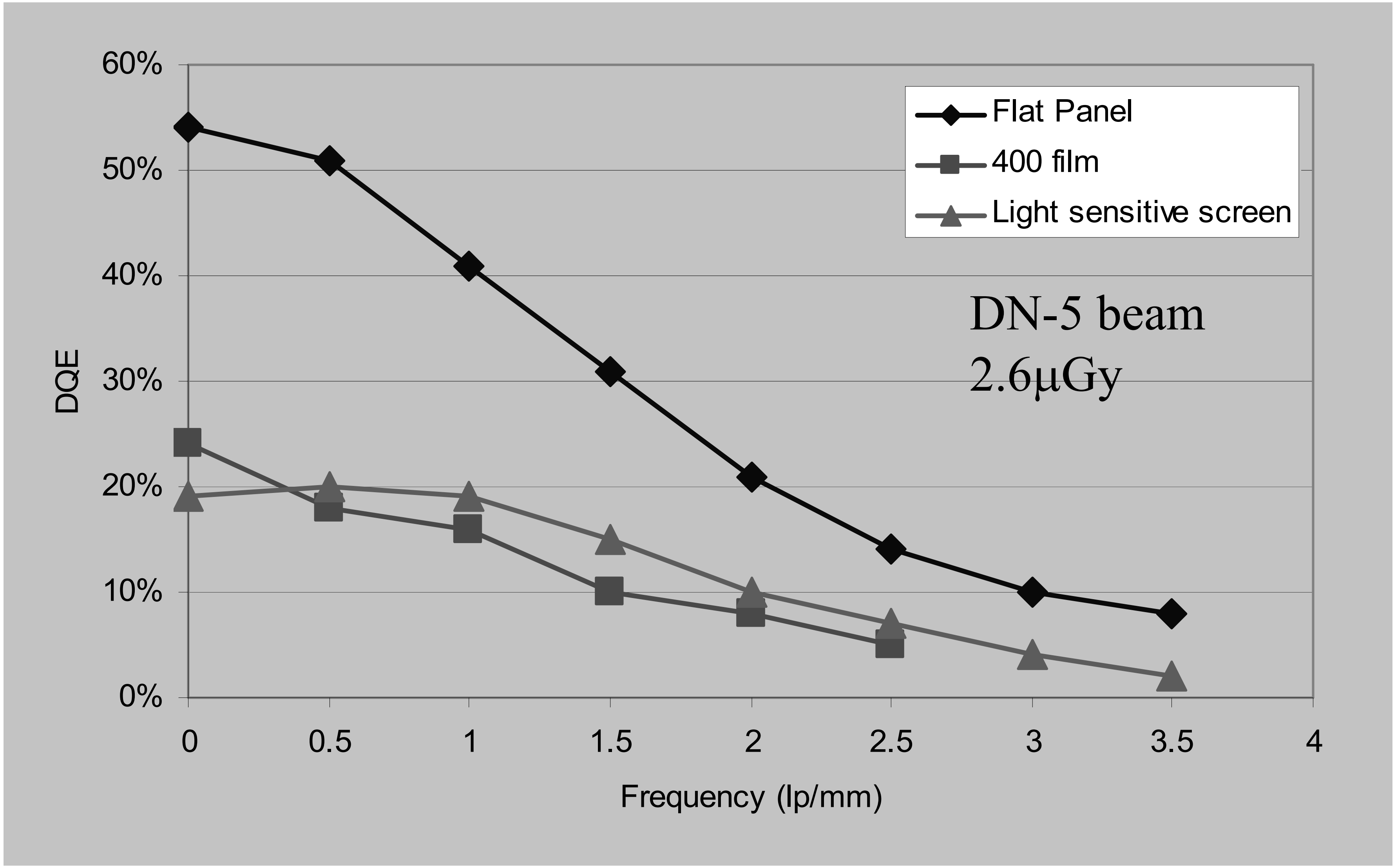
Ratio of this to N_{inc} is a measure of efficiency

Note that DQE is f(spatial and spectral frequencies)

Effect of Peak Width



DQE Comparison



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!

Ion Mobilities

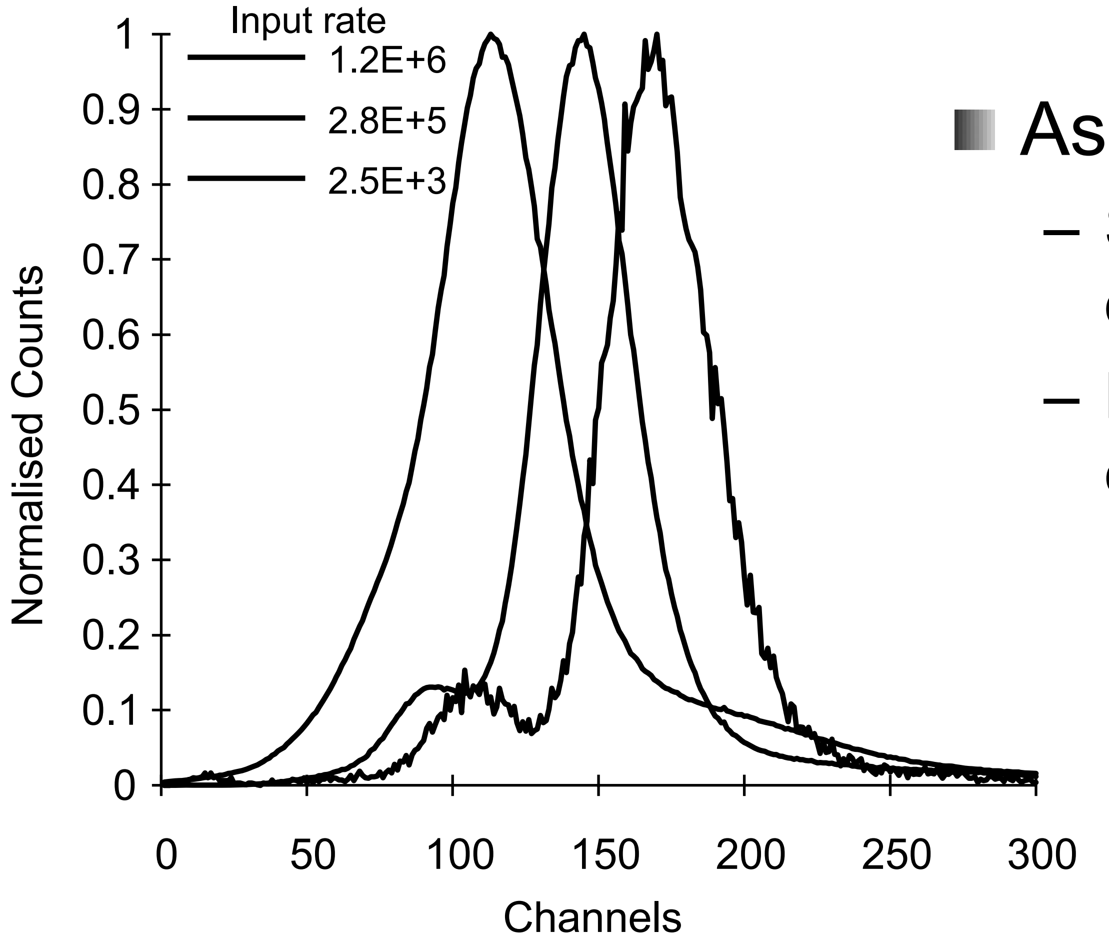
Gas	Ions	Mobility ($cm^2\ V^{-1}\ s^{-1}$)
Ar	$(OCH_3)_2\ CH_2^+$	1.51
Iso $C_4\ H_{10}$	$(OCH_3)_2\ CH_2^+$	0.55
$(OCH_3)_2\ CH_2$	$(OCH_3)_2\ CH_2^+$	0.26
Ar	Iso $C_4\ H_{10}^+$	1.56
Iso $C_4\ H_{10}$	Iso $C_4\ H_{10}^+$	0.61
Ar	CH_4^+	1.87
CH_4	CH_4^+	2.26
Ar	CO_2^+	1.72
CO_2	CO_2^+	1.09
Ar	electrons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

For 1 kV across 1cm.

Electrons take 1μs

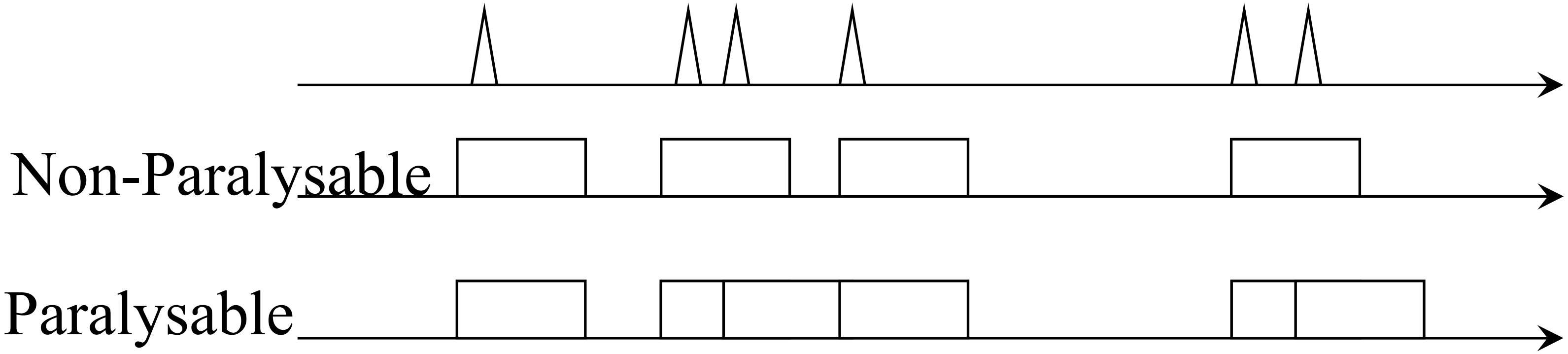
Ions take ~1ms!

Spectral Peak Shift vs Rate



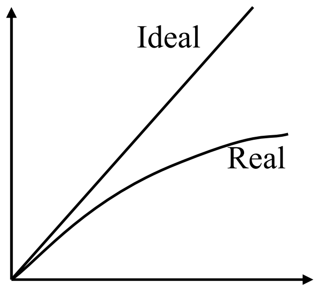
- As rate rises
  - – Spectral resolution deteriorates
  - – Note also the K escape feature

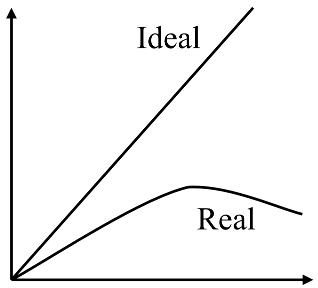
Dead Time



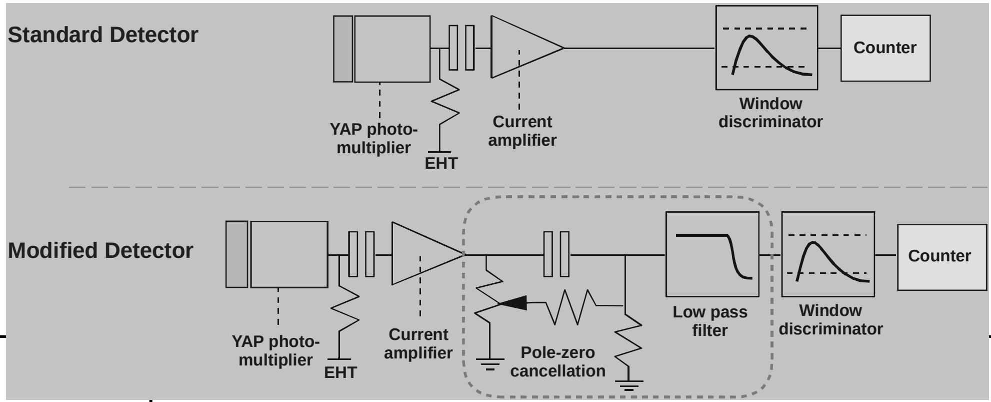
R_i=input rate, R_d=detected rate, τ dead time

- 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

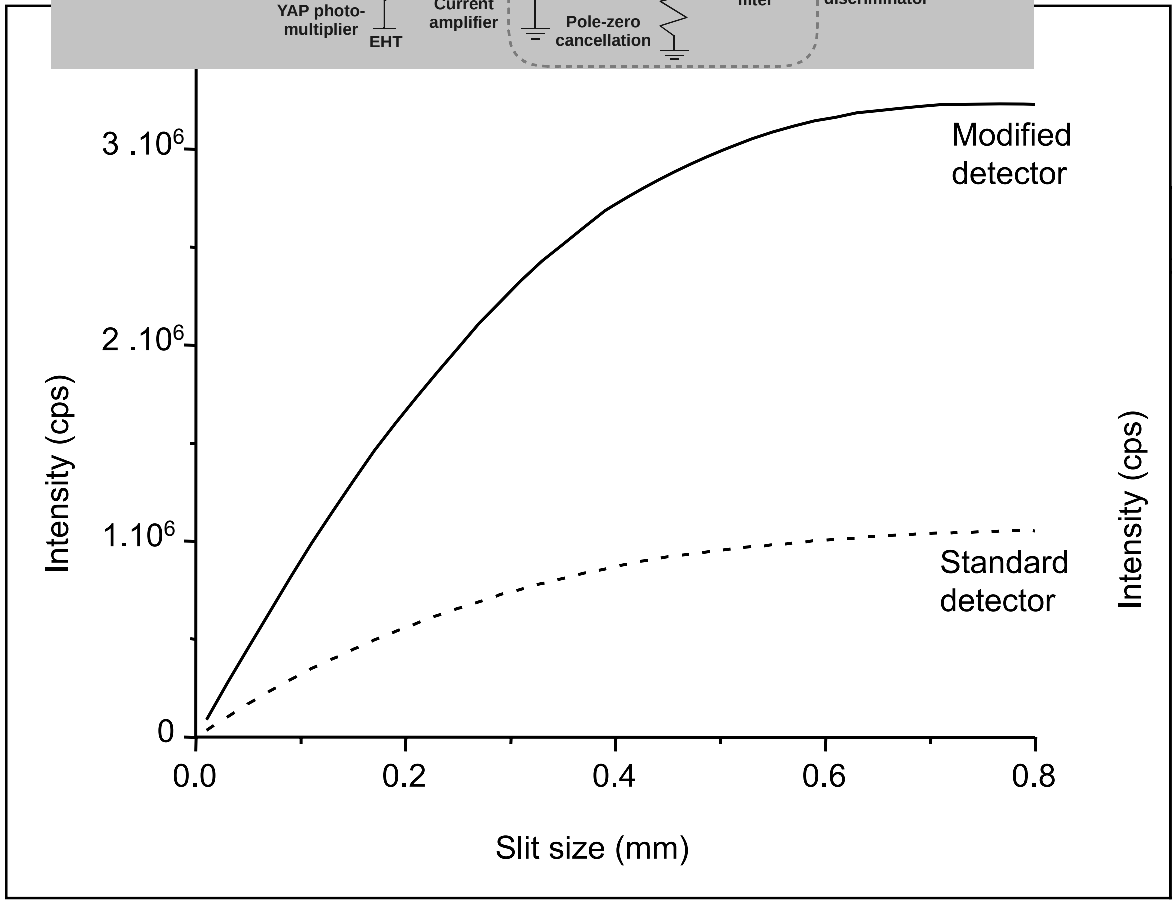


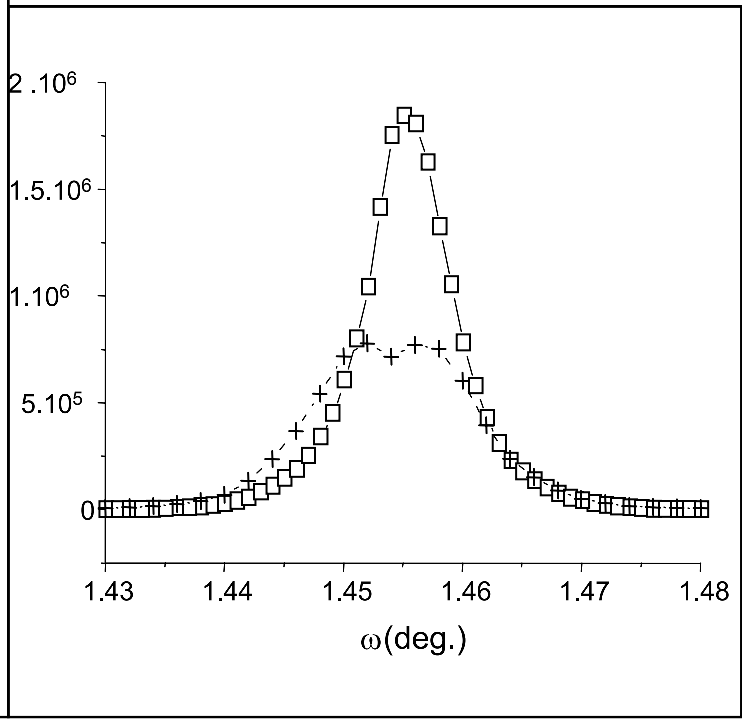
Standard detector

- 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

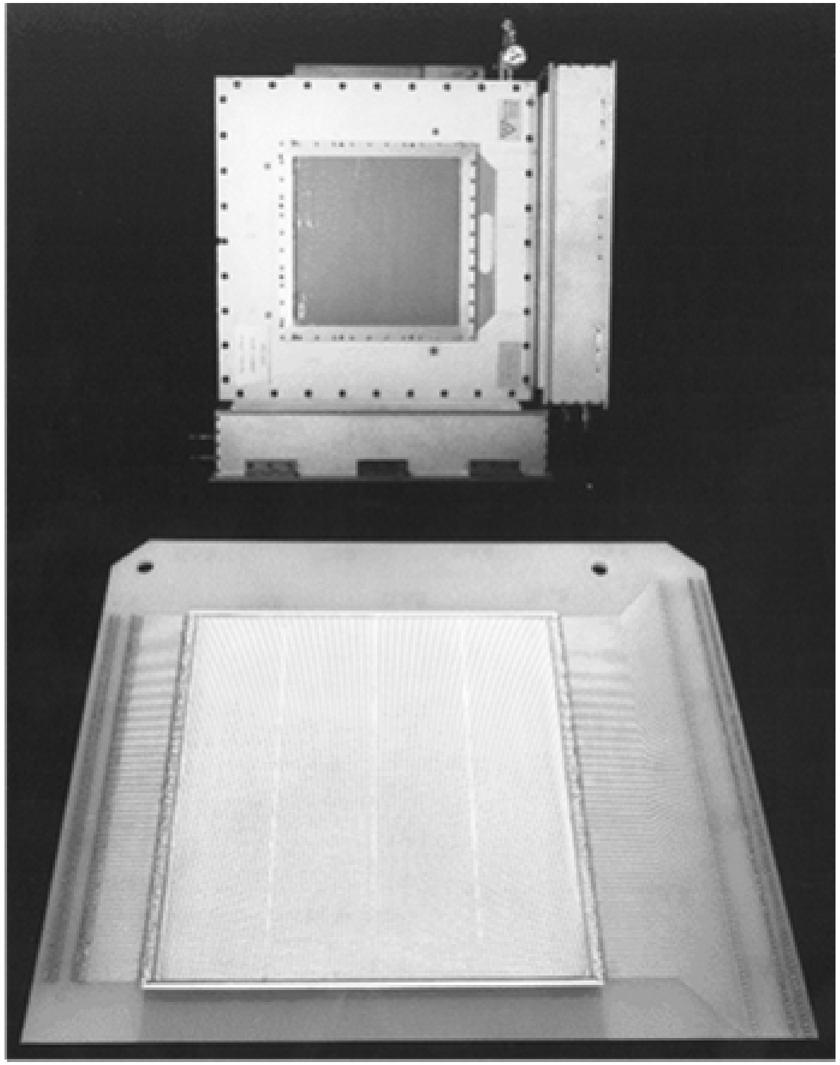


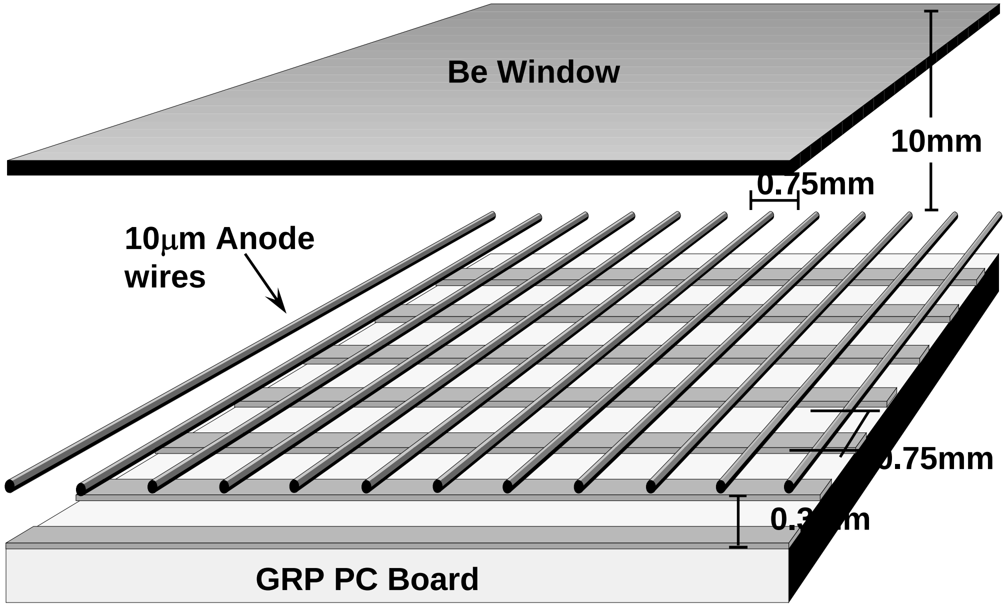


Readout Strategies

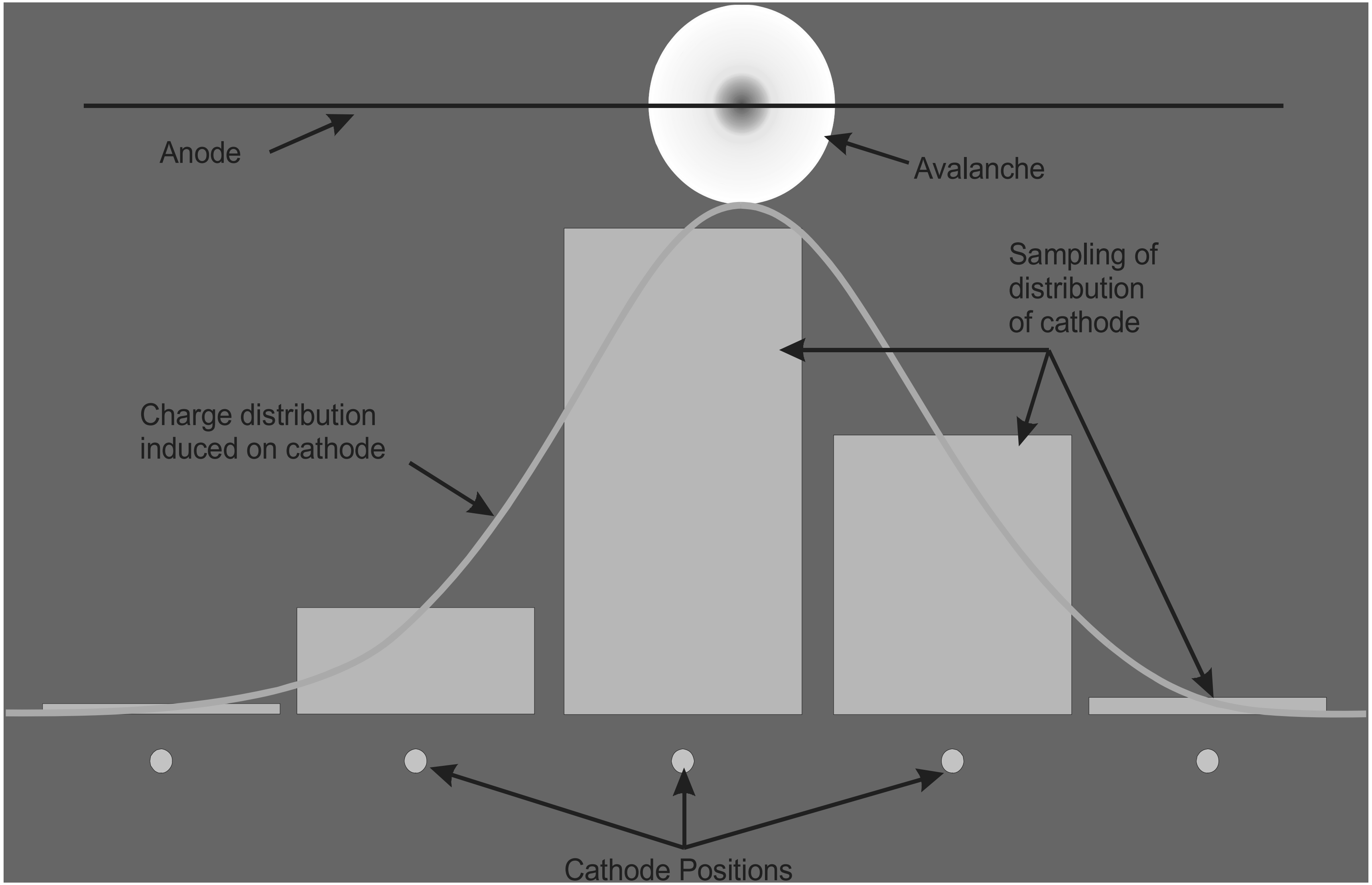
- Imaging
  - Massively parallel
    - Position derived from individual pixel
    - Highly parallel: 2000×2000 pixels = 4 million channels!!!
    - Suitable for counting and integrating systems
    - Pixel array detectors
  - X-Y Interpolating
    - Position derived from measuring signals
    - Moderately 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

RAPID 1 System

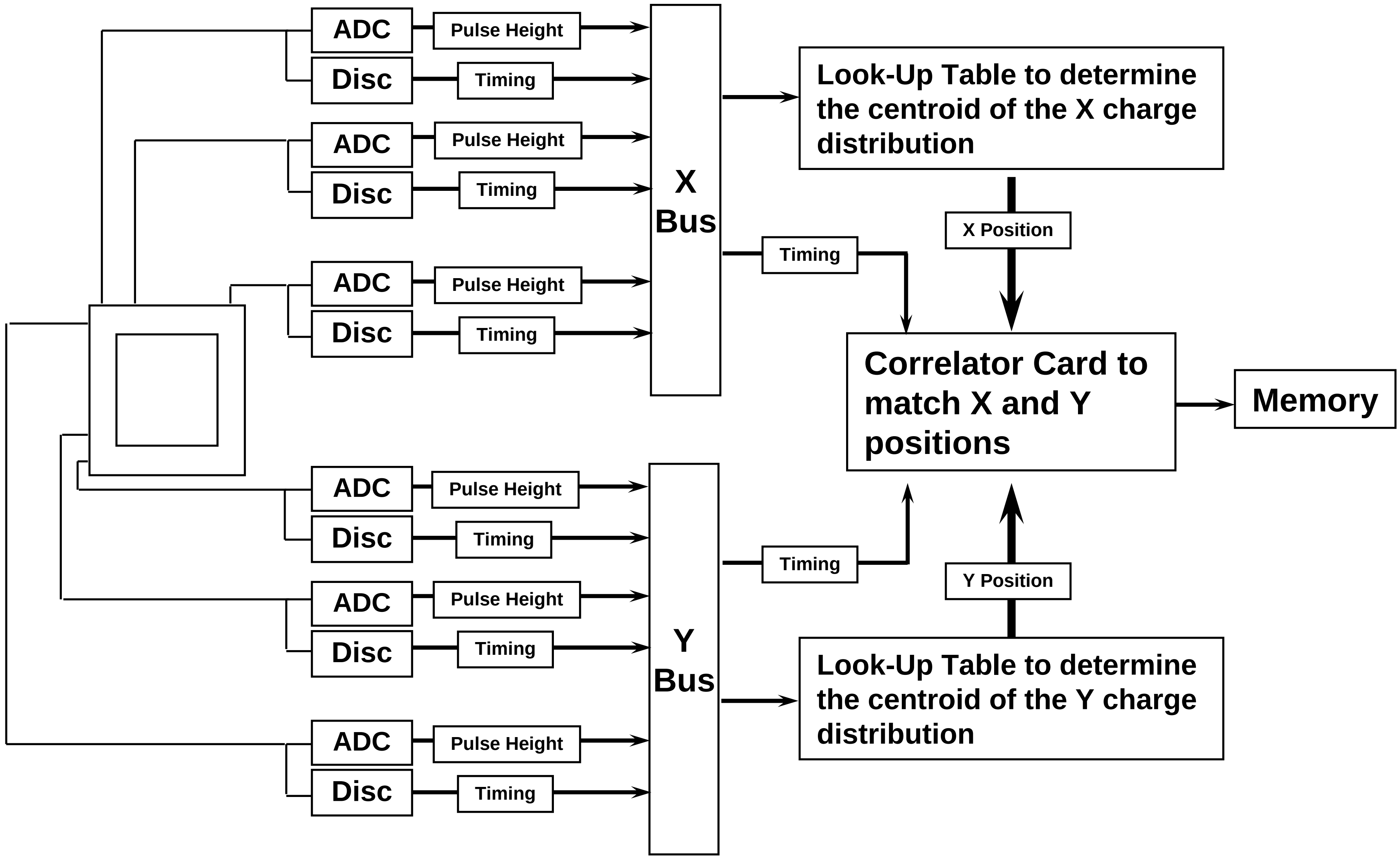




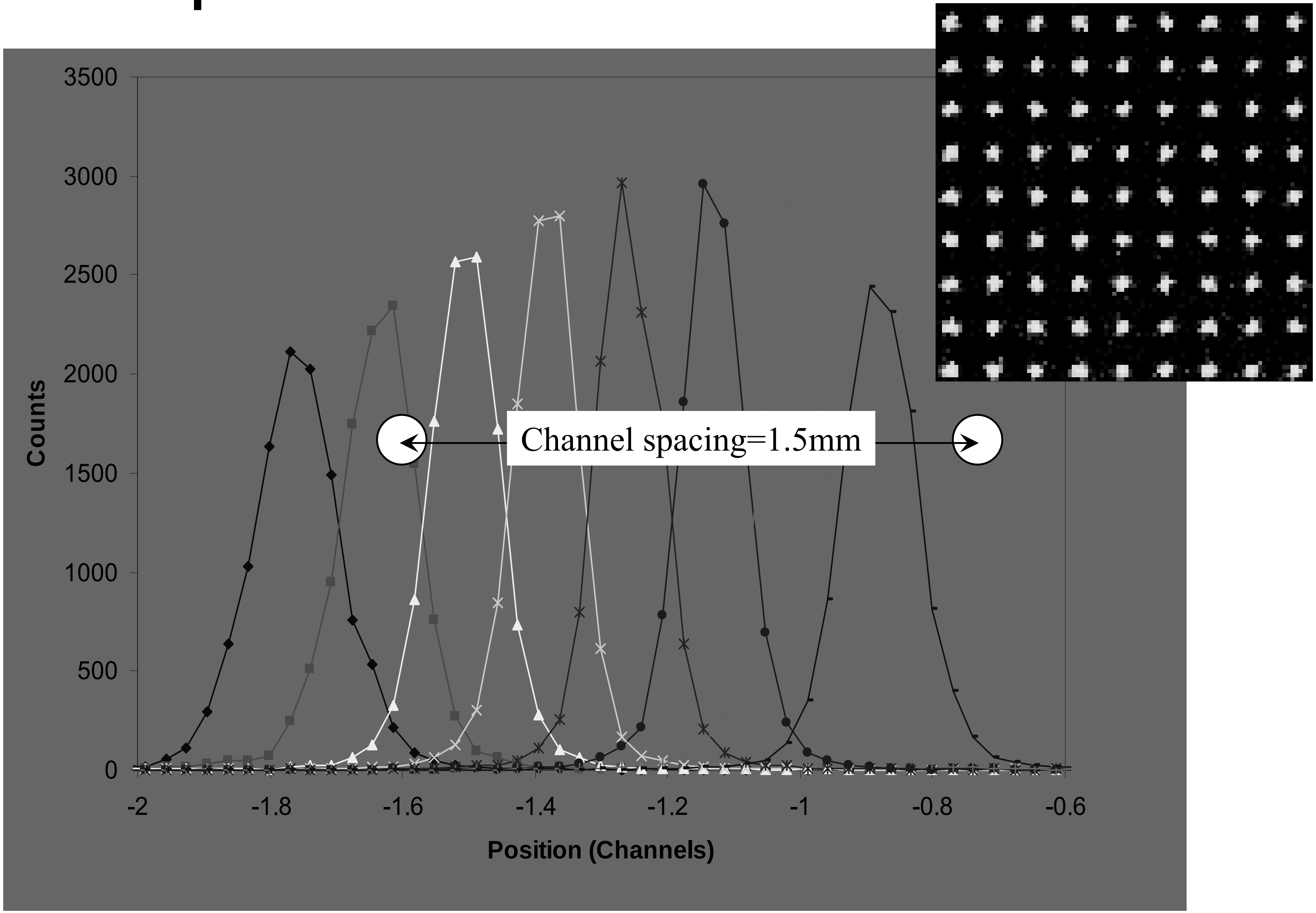
Charge Distribution (Cathodes)



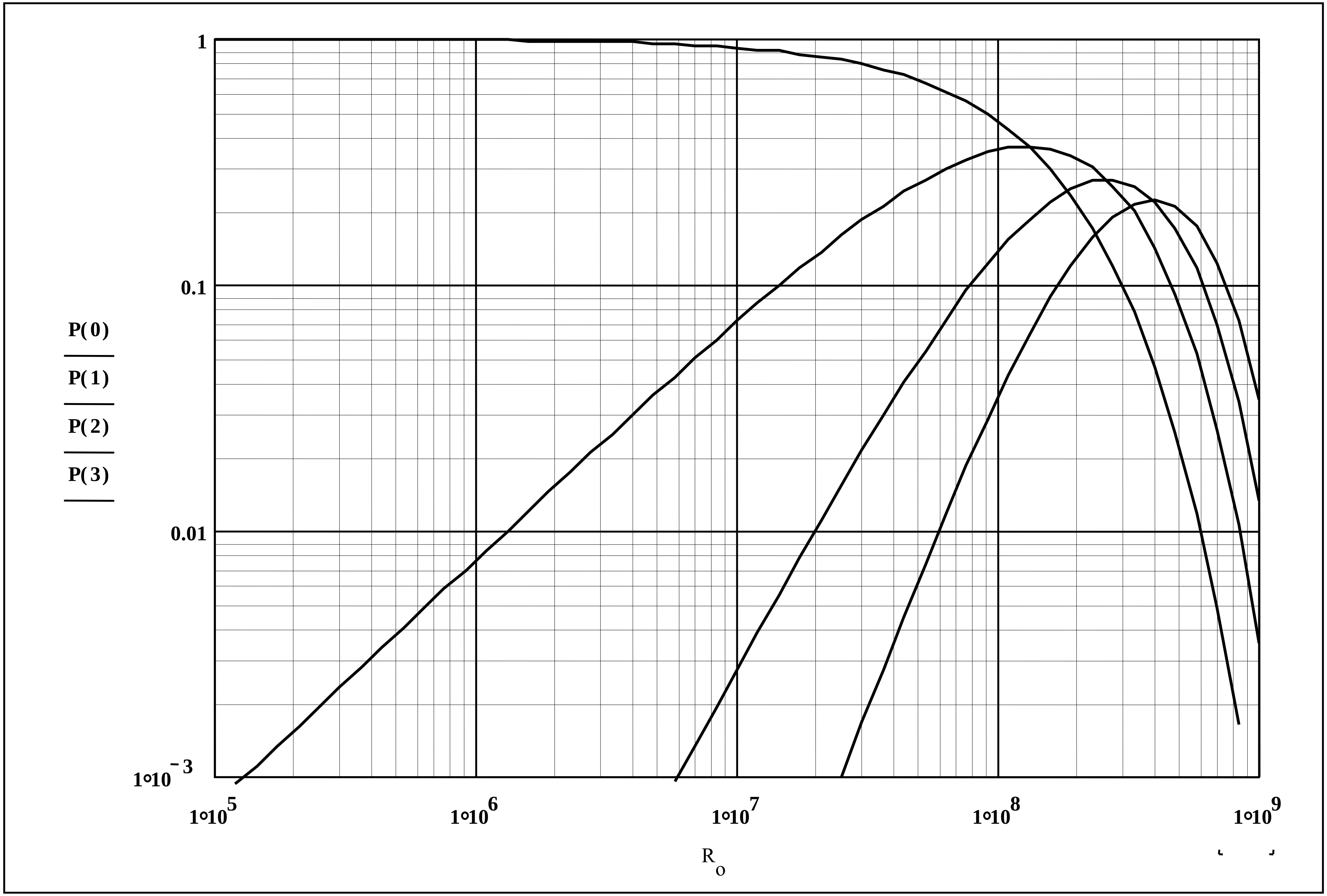
RAPID Data Acquisition System



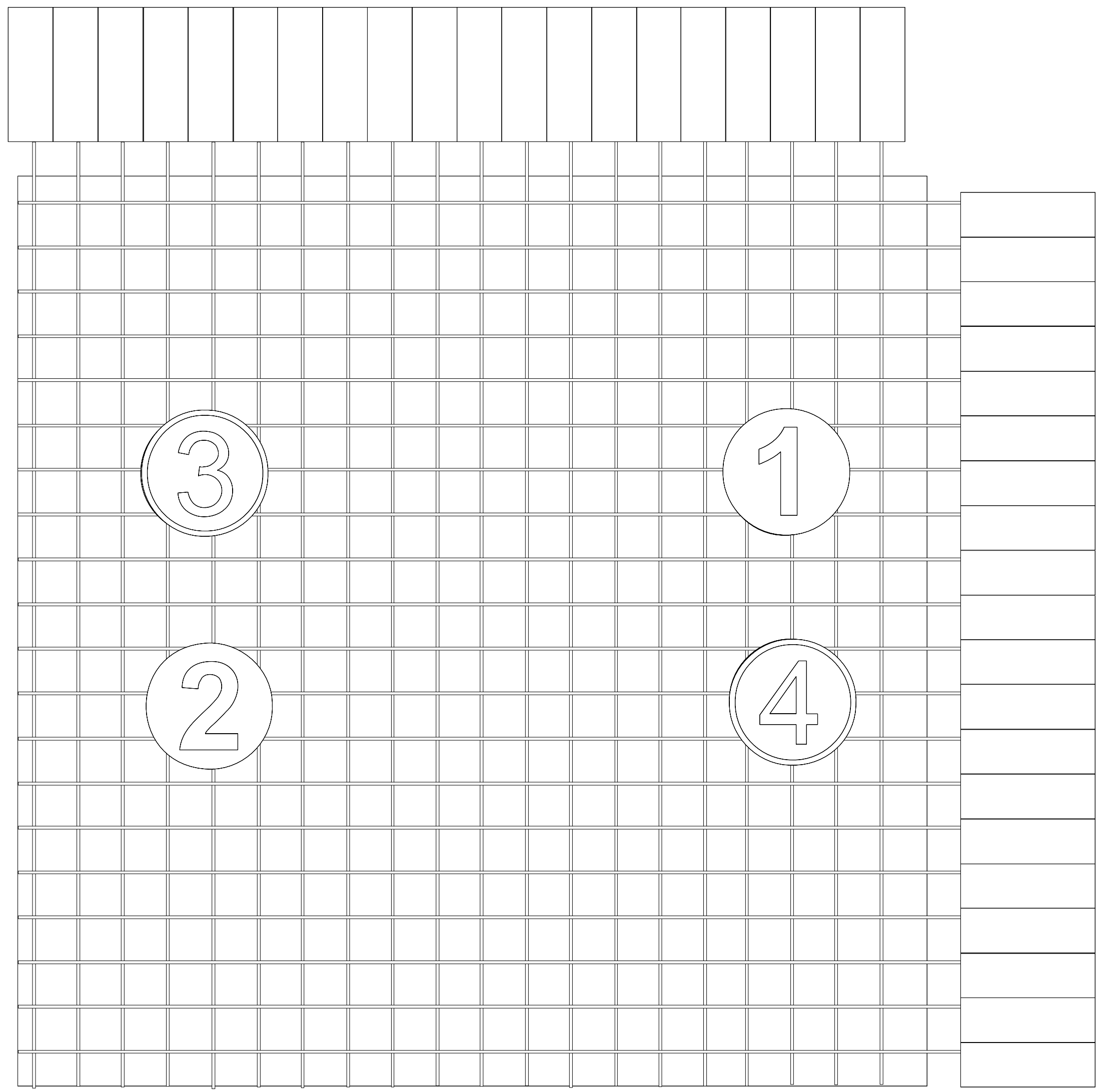
Spatial Resolution Cathodes



Probabilities of Event Overlap Δt=7.7ns

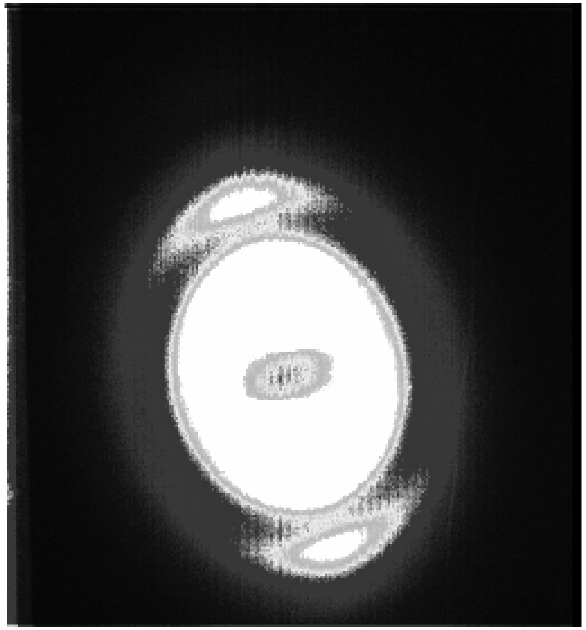


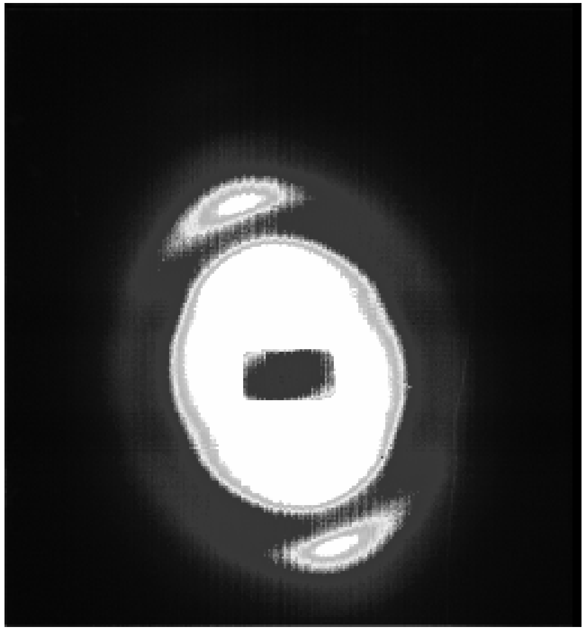
2 Axis X-Y Detector

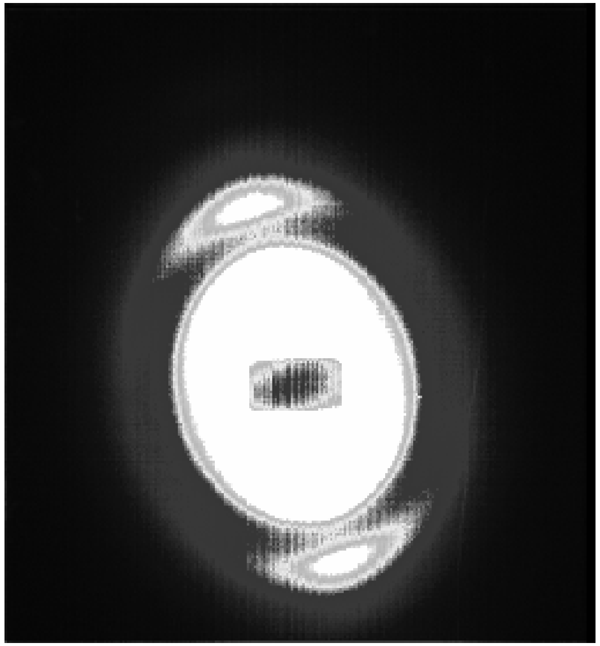


Deadtime Correction

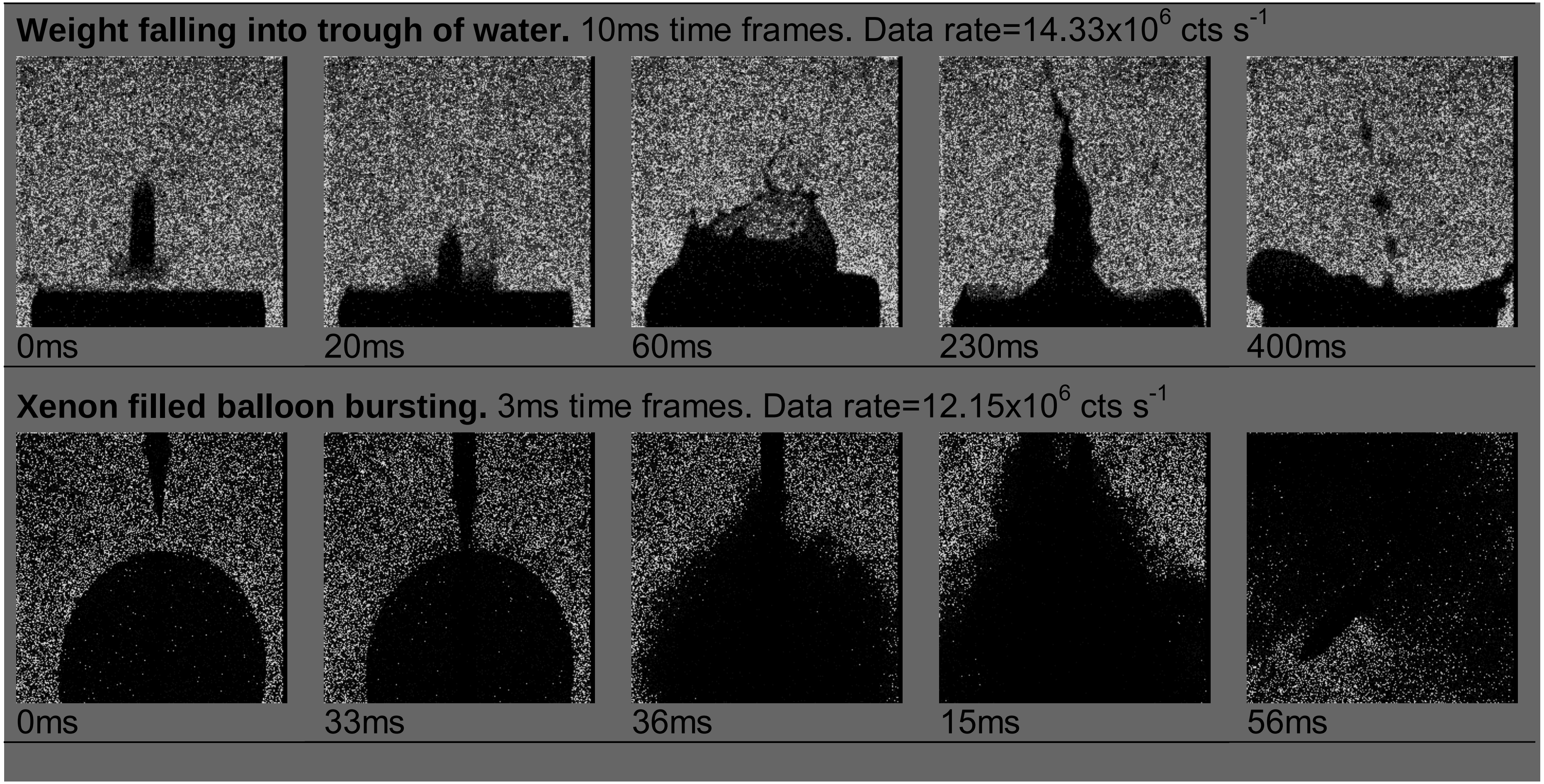
Low Rate Image | 3 MHz Raw Image | Corrected 3MHz Image





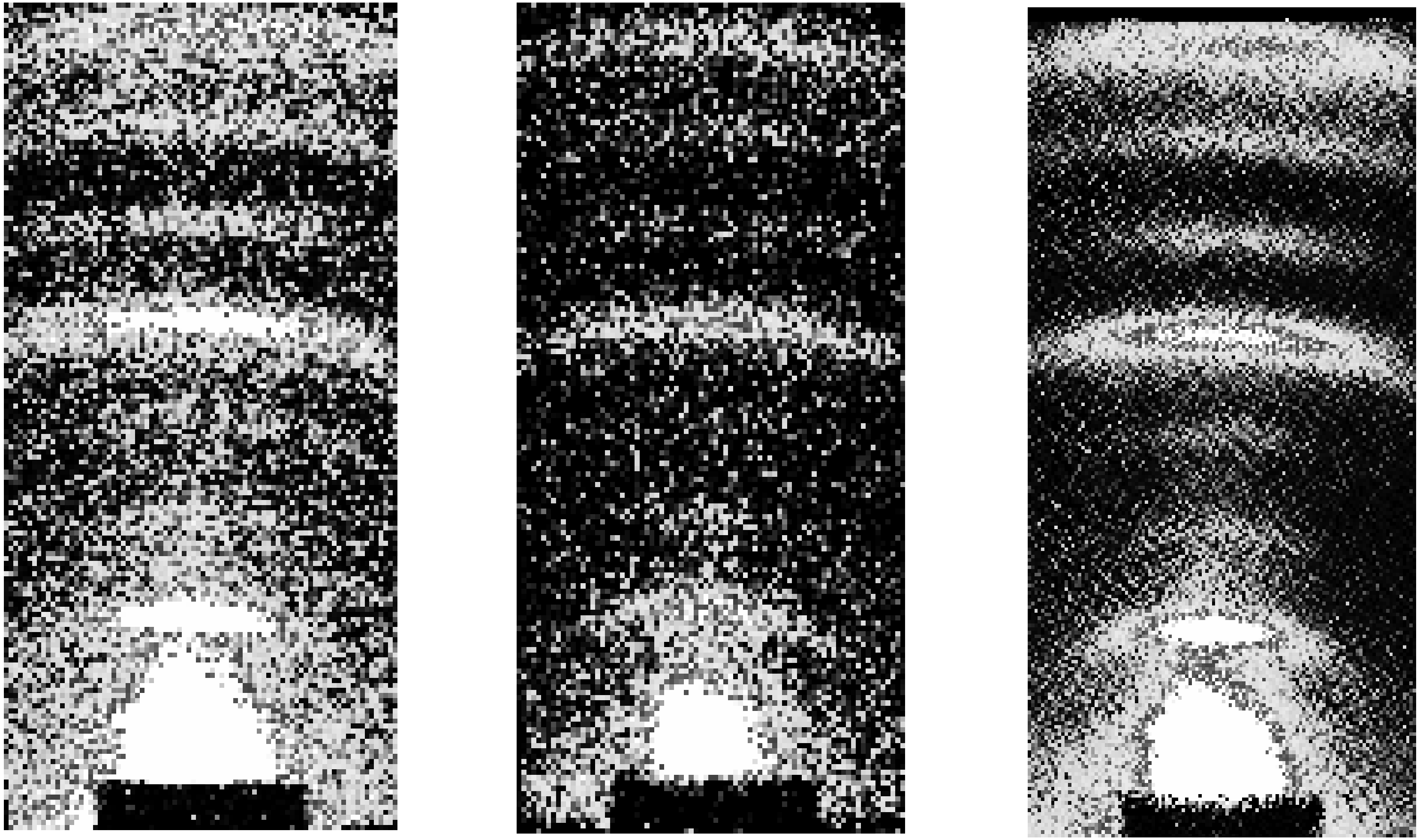


Time Framing



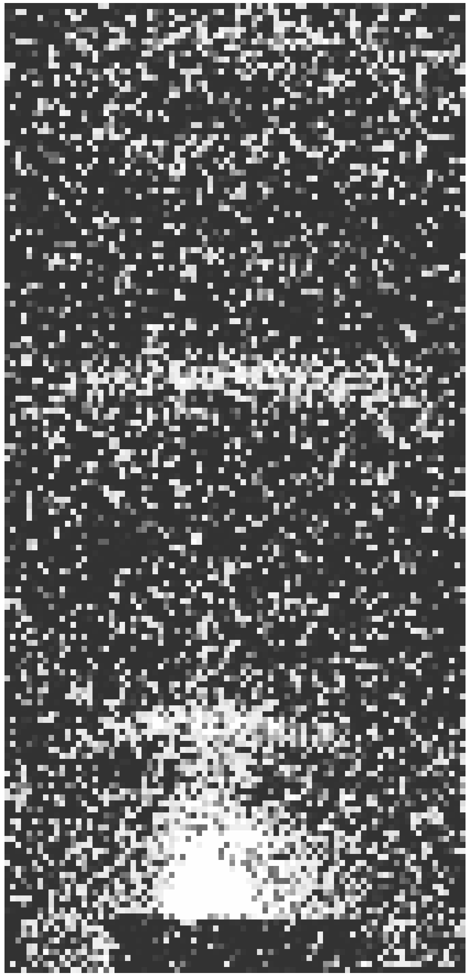
Collagen 1s exposure 16.1

Image Plate	Delay Line	RAPID
No attenuation	8.7 x attenuation	No attenuation

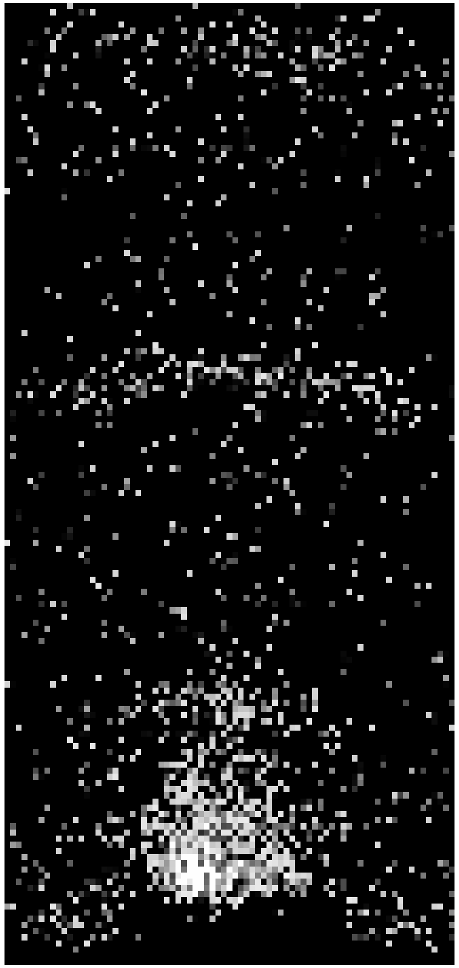


Collagen 100ms exposure 16.1

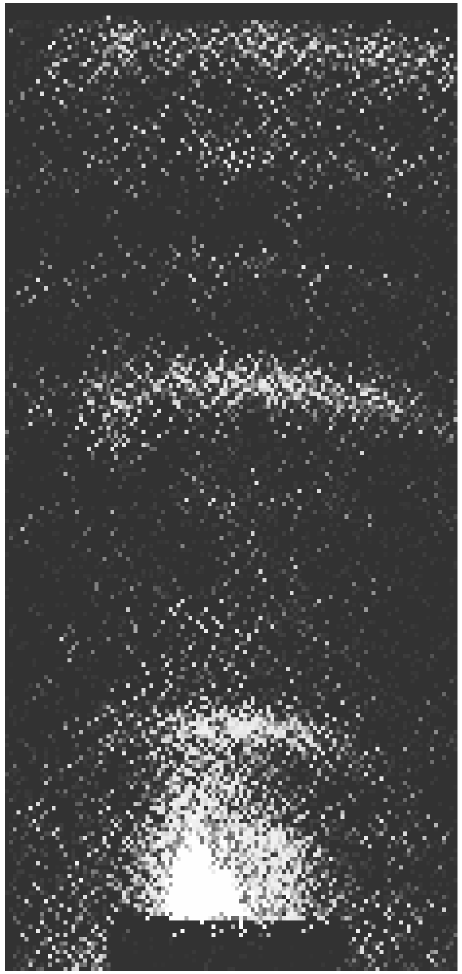
Image Plate
No attenuation



Delay Line
8.7 x attenuation

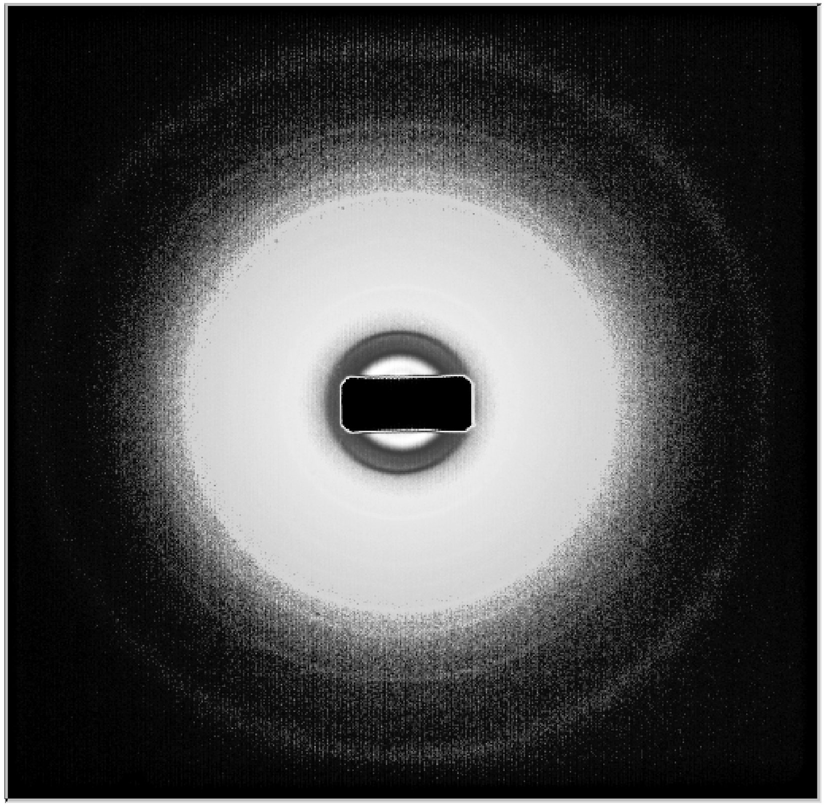


RAPID
No attenuation

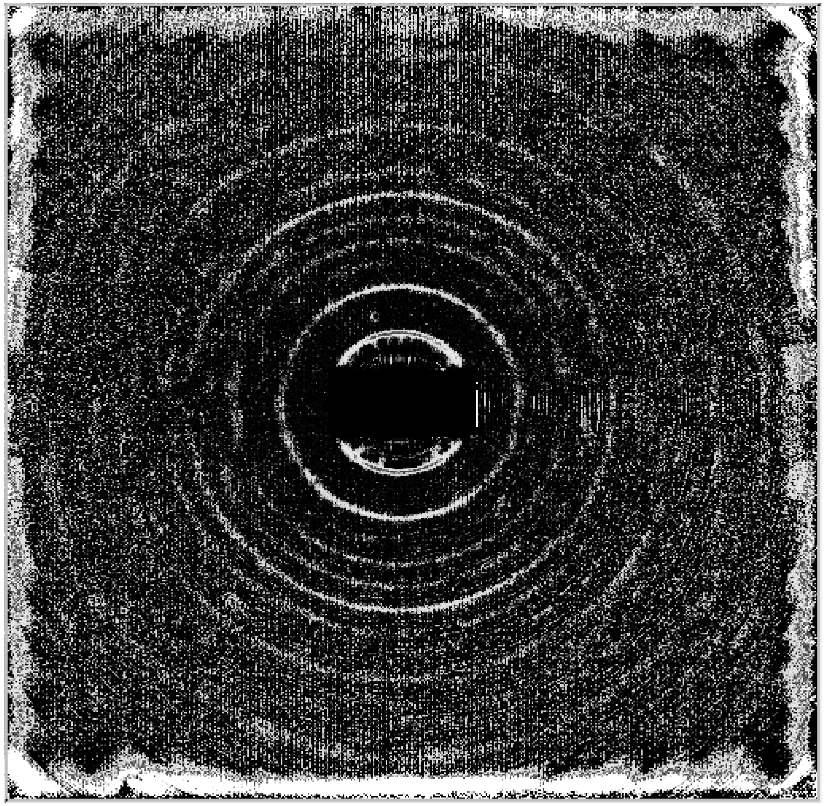


Background Removal

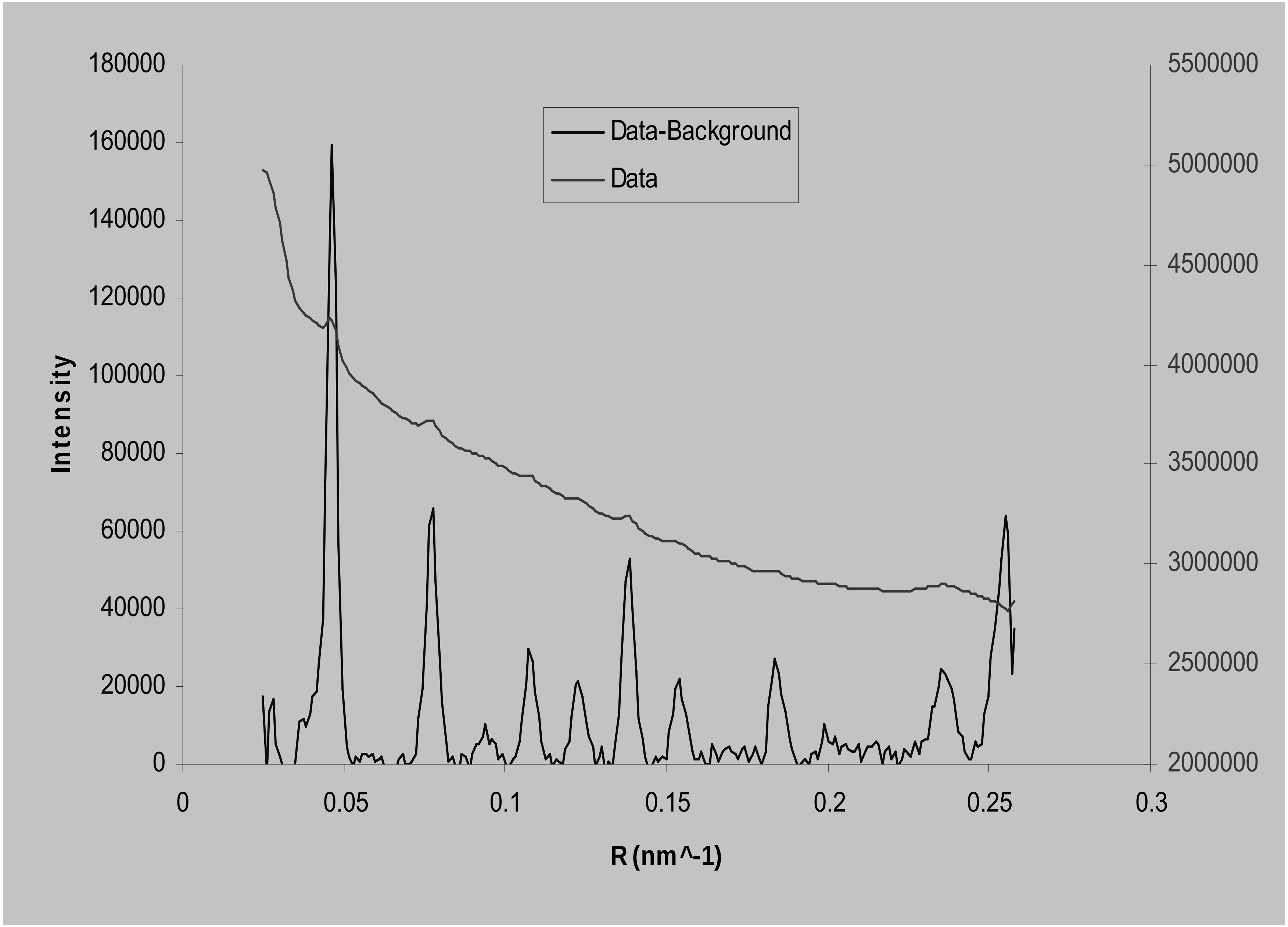
Before



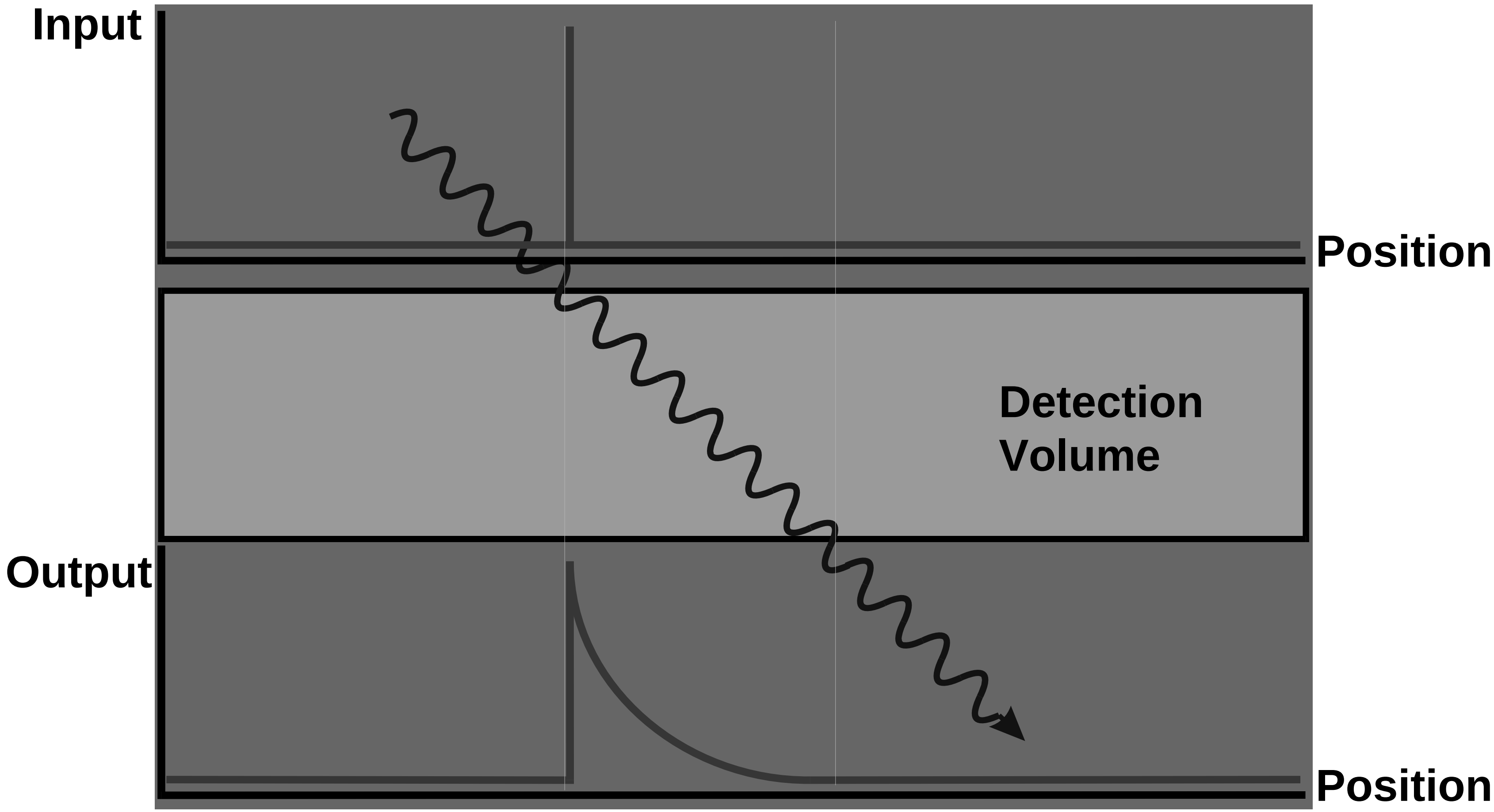
After



Background Removal

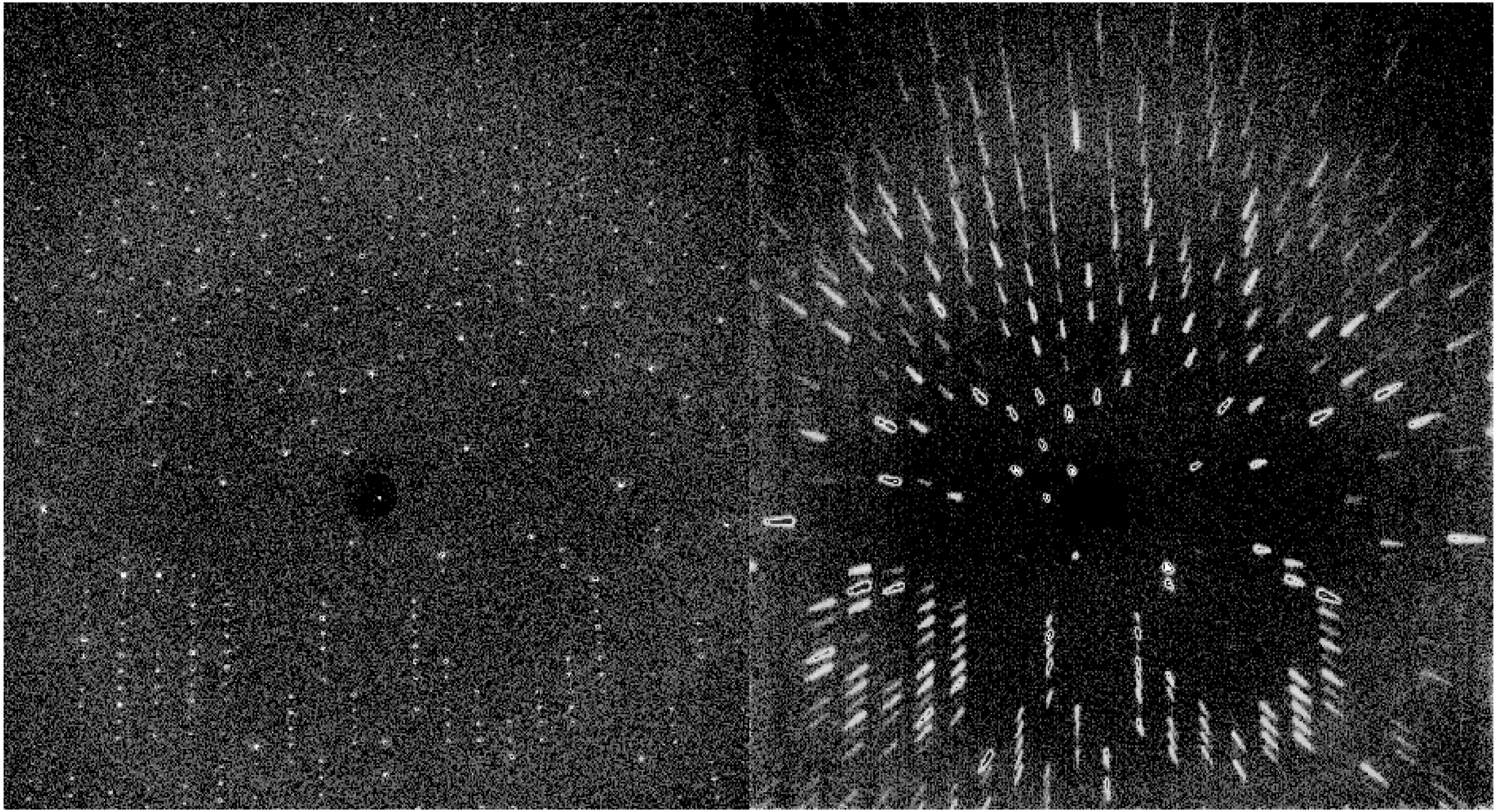


Parallax Broadening



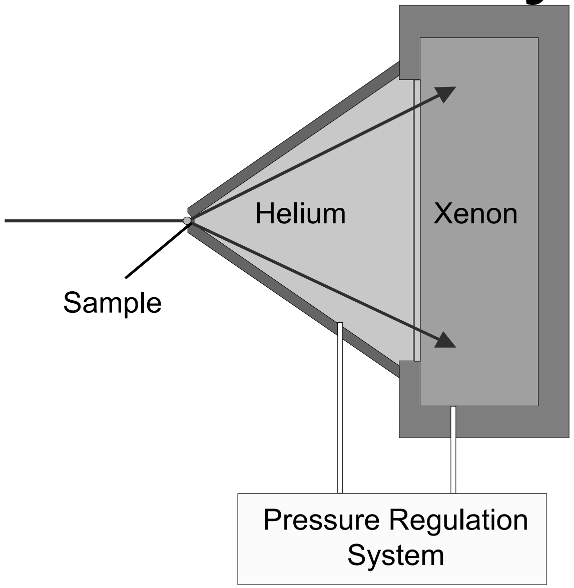
Parallax Effect

Image Plate
Gas Proportional Counter

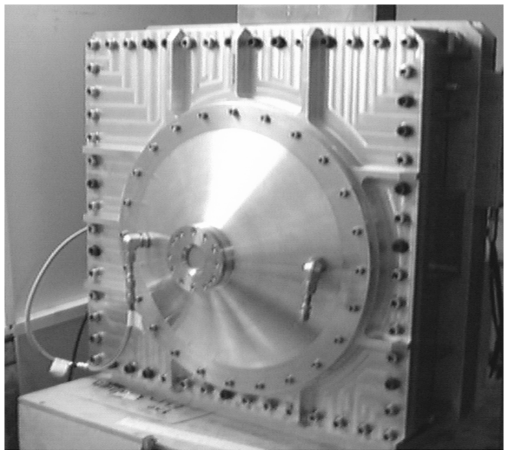


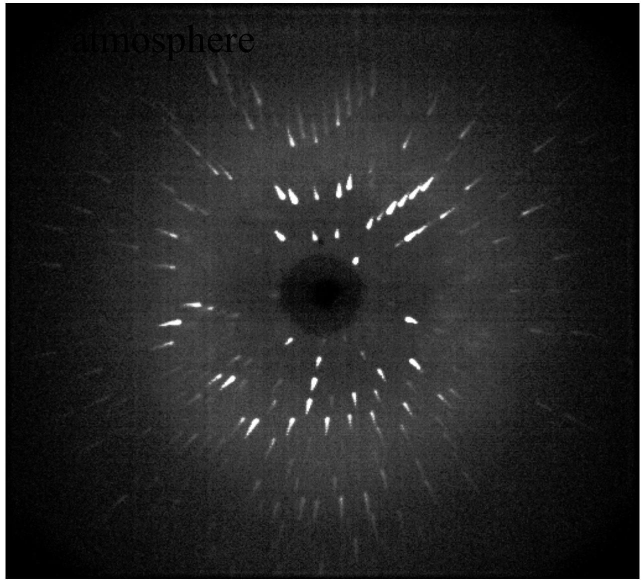
Lysosyme pattern on two detectors

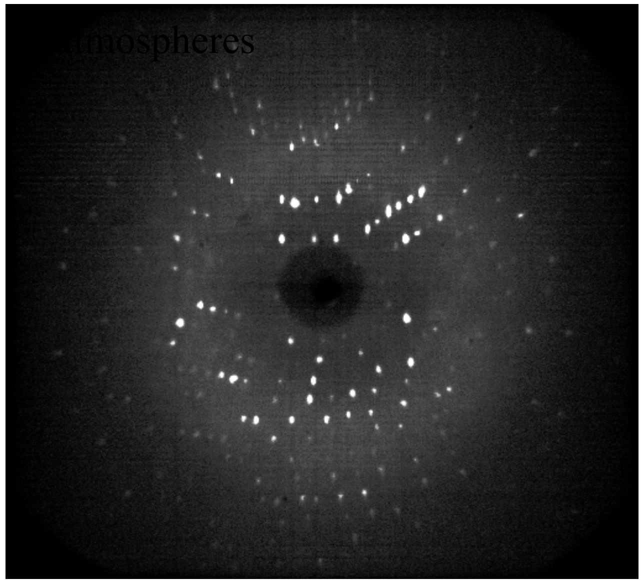
Daresbury High Pressure MWPC



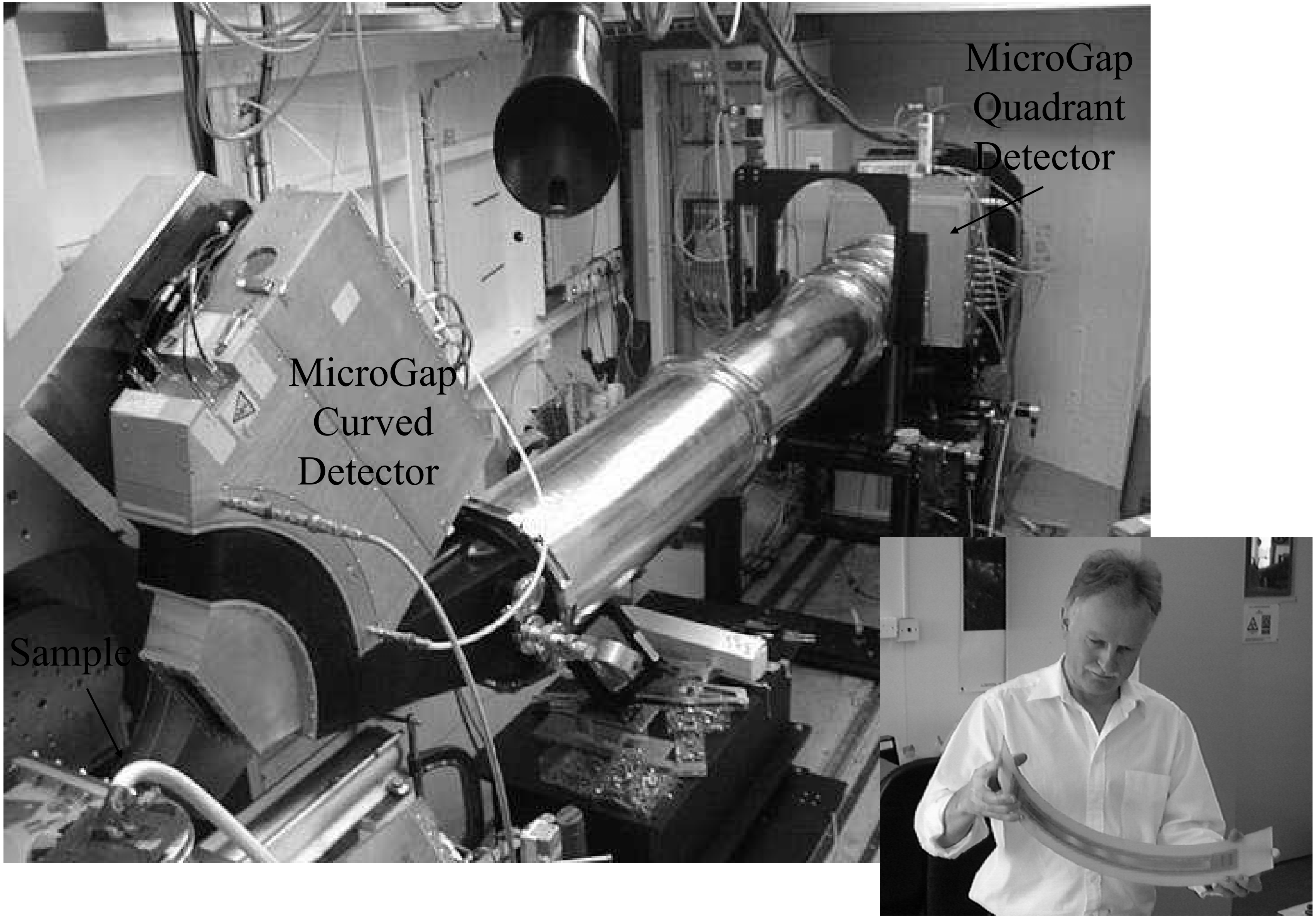
Force on 28 x 28 cm window at 5 bar = 4 tonnes
Force on window of 1 x 1 cm at 5 bar = 5 kg



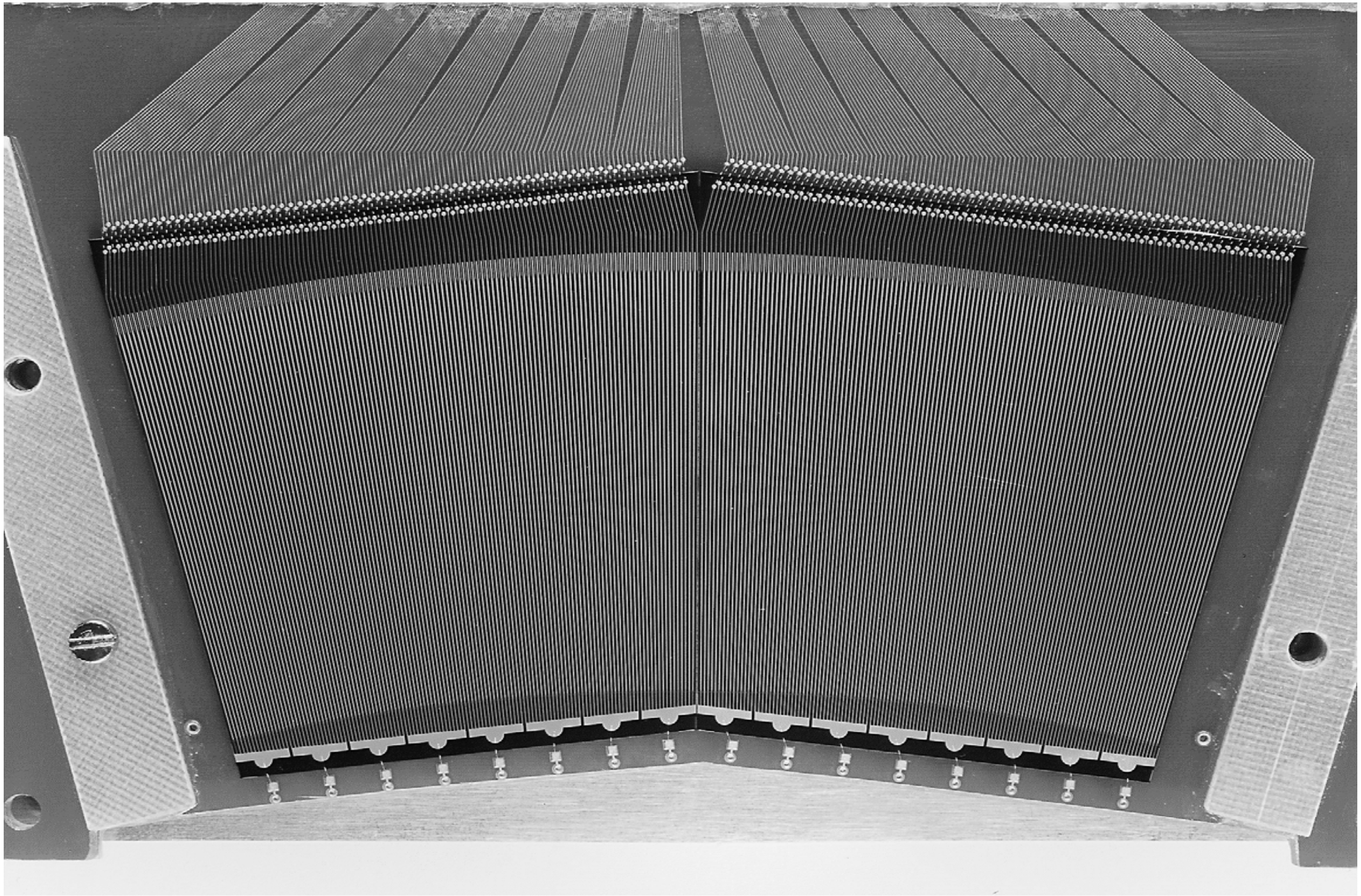




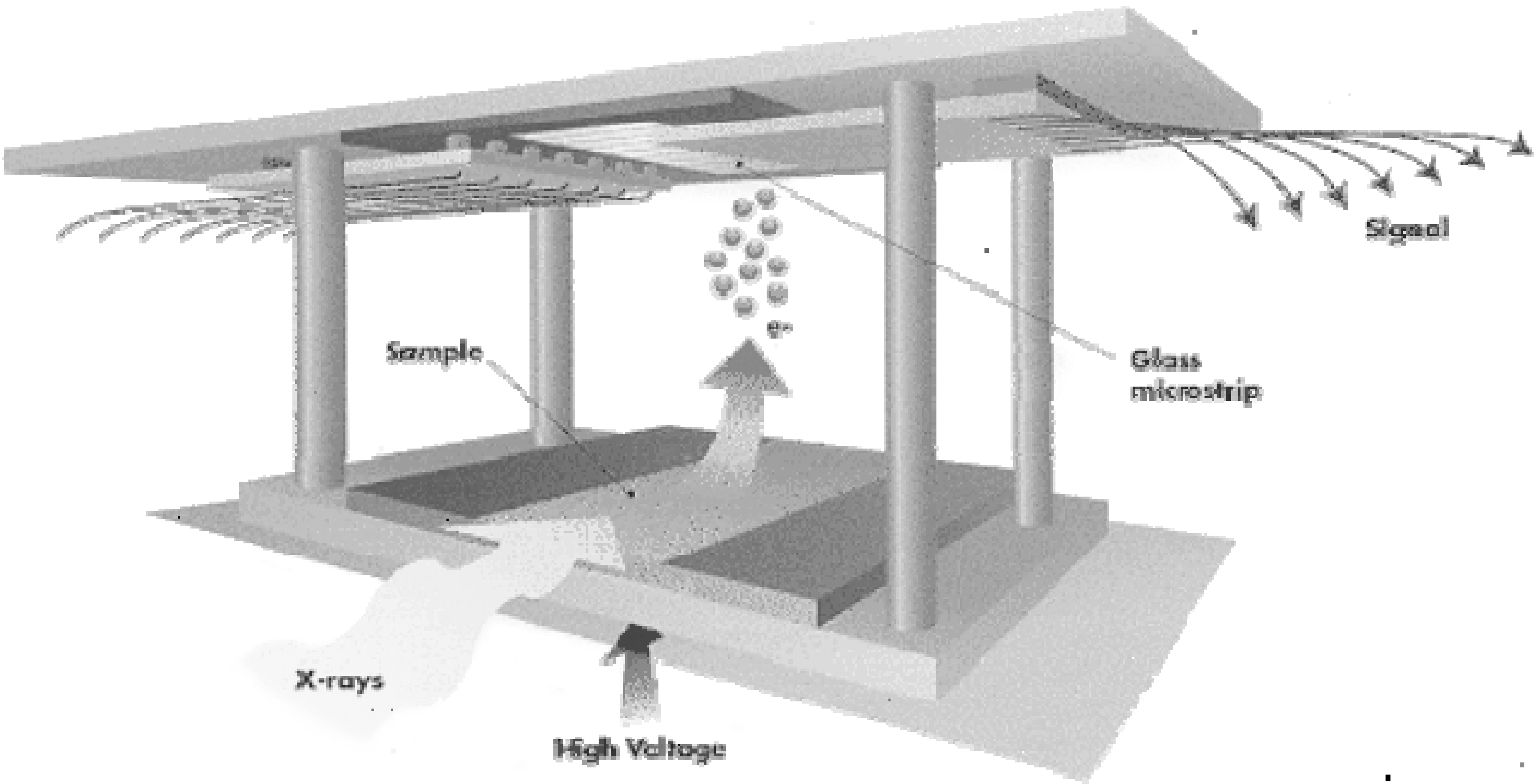
RAPID2 SAX WAX



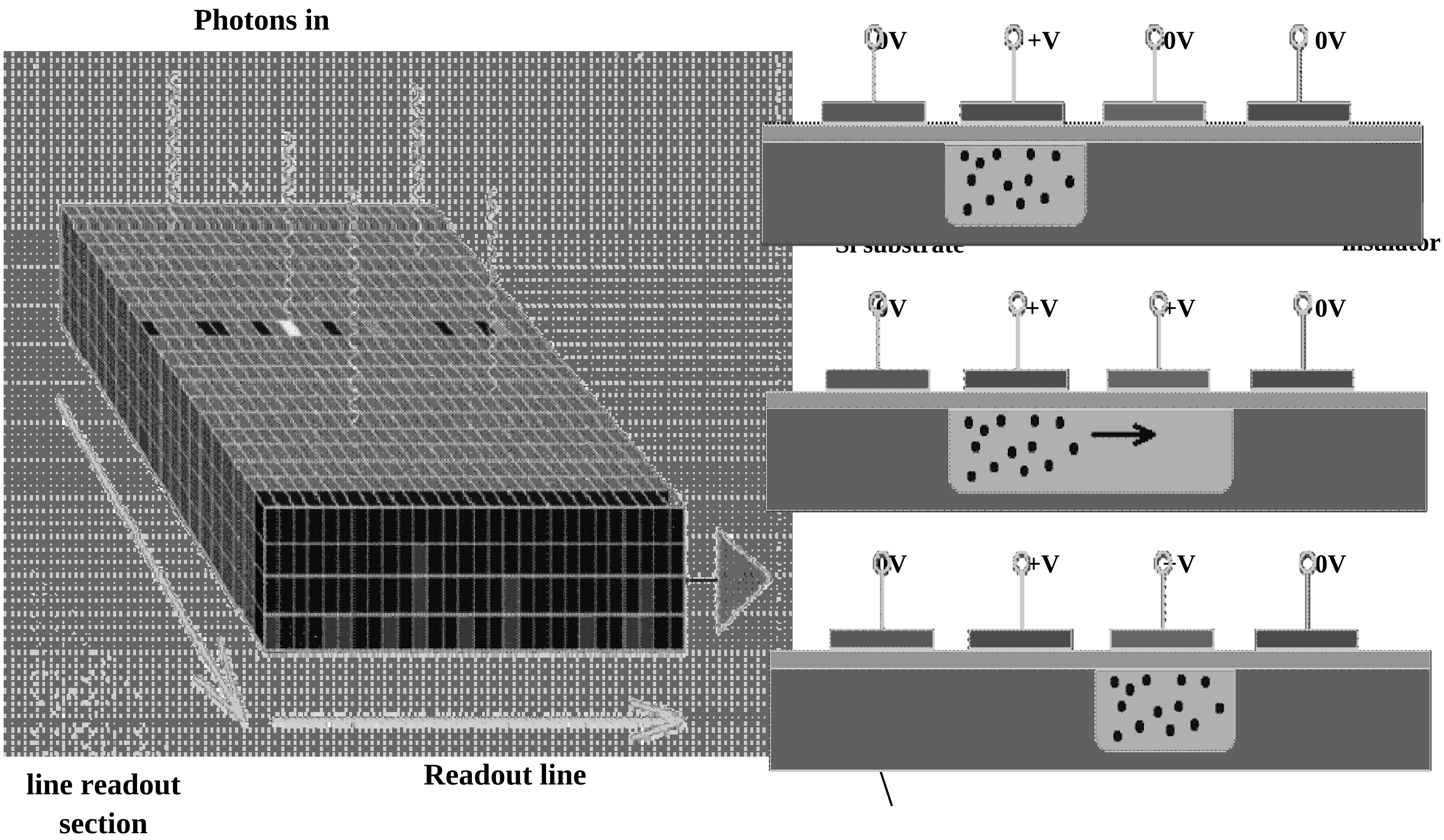
WAXS detector - GMSD



GMSD for electron yield



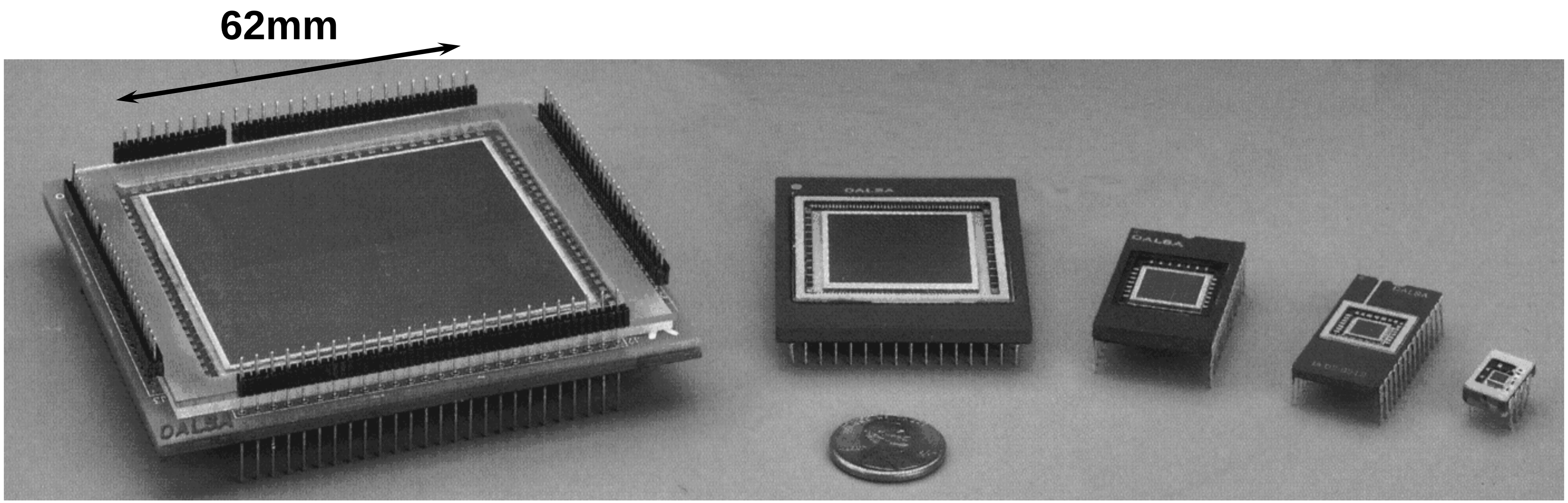
CCD Readout


Photons in
0V
+V
0V
0V
0V
+V
+V
0V
0V
+V
+V
0V
line readout section
Readout line

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
- 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

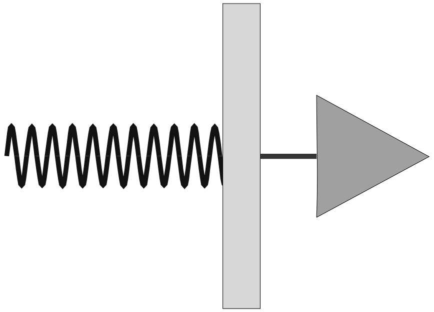


Although sizes > 50mm are available, the read speed is slow to preserve low noise and cte (line capacitance becomes very high)

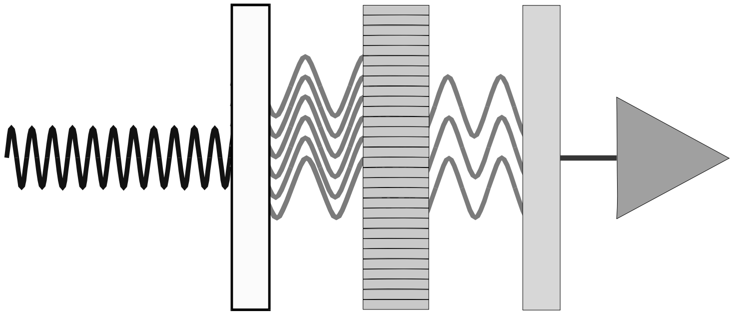
Shutter required

CCD detectors

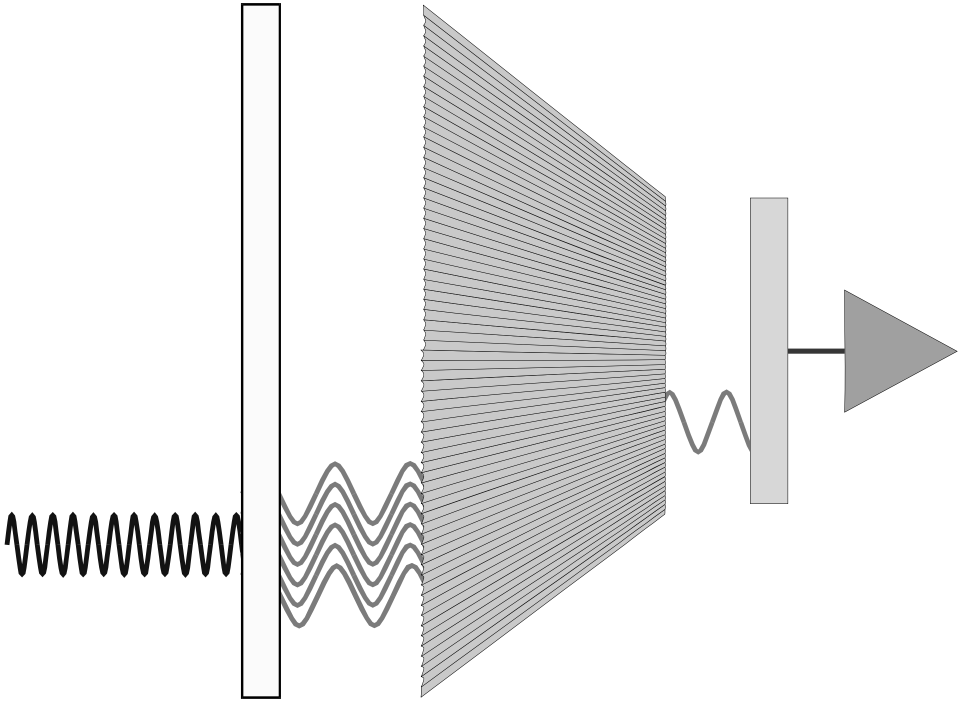
Direct detection
Gain ~ 2000e^- / 8keV x-ray



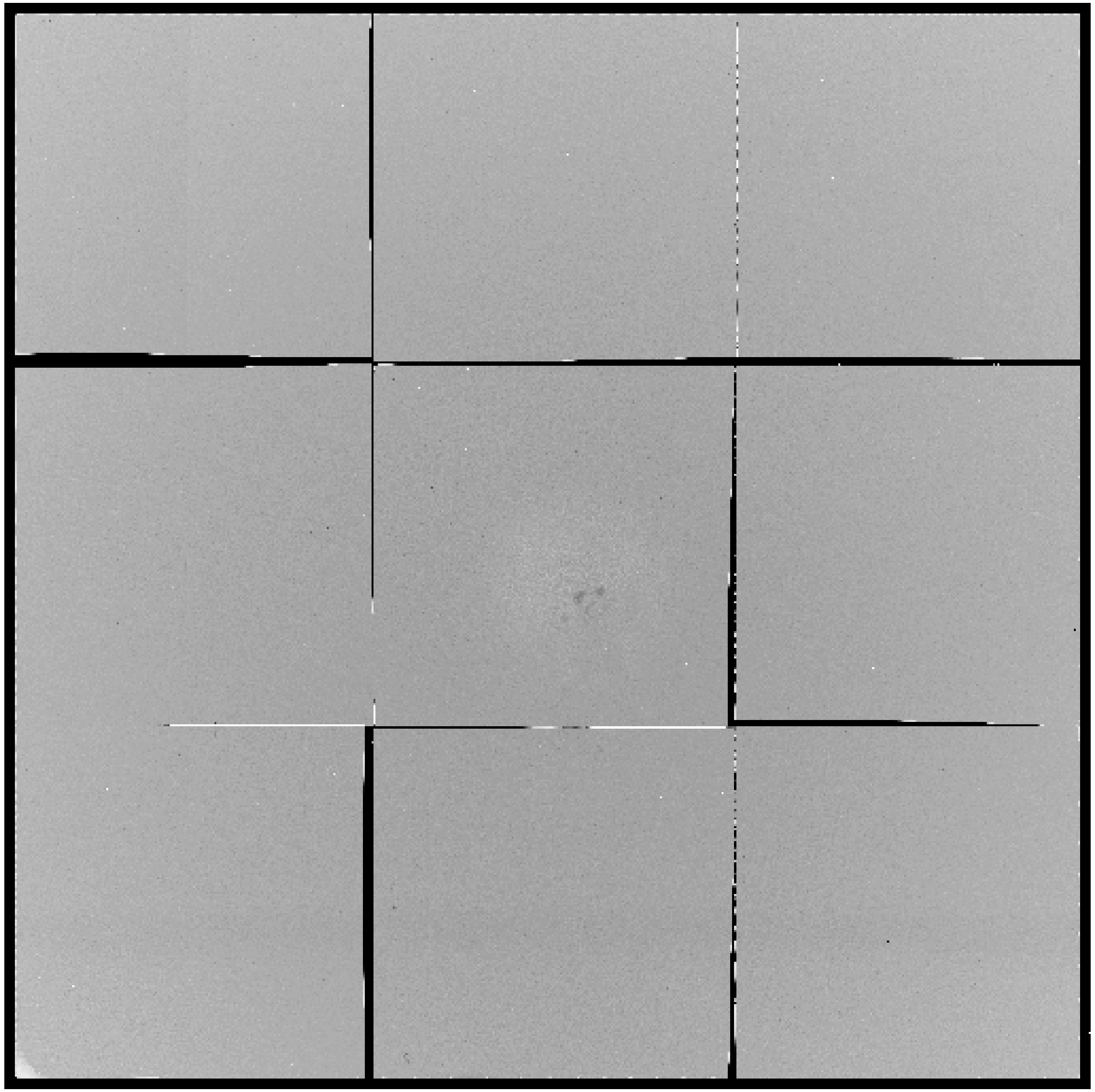
Phosphor coupled 1:1 to CCD
Phosphor gain >> 1
Optics Gain < 1



Phosphor coupled with reducing optics to CCD
Phosphor gain >> 1
Optics Gain << 1

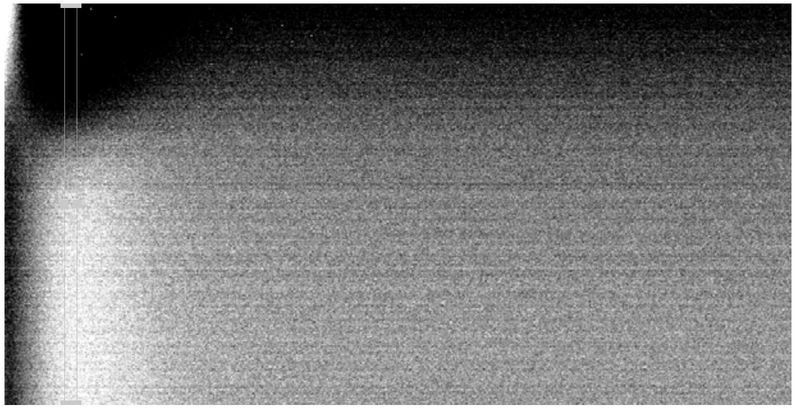


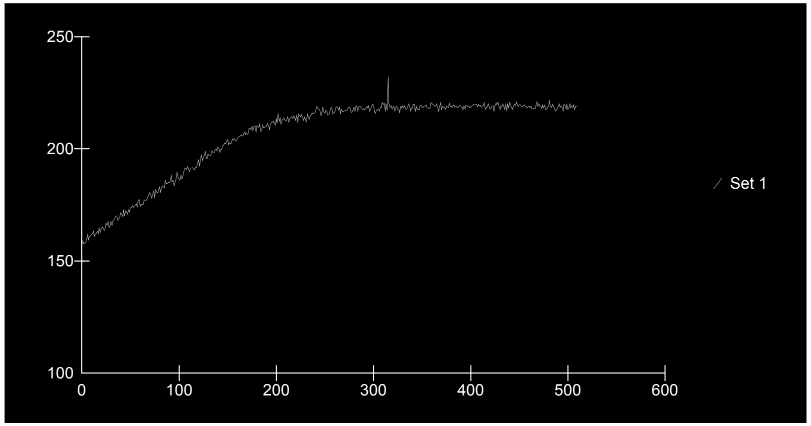
Gaps



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

Dark Currents





Flat and Dark Correction

For each image, two correction images must be recorded.

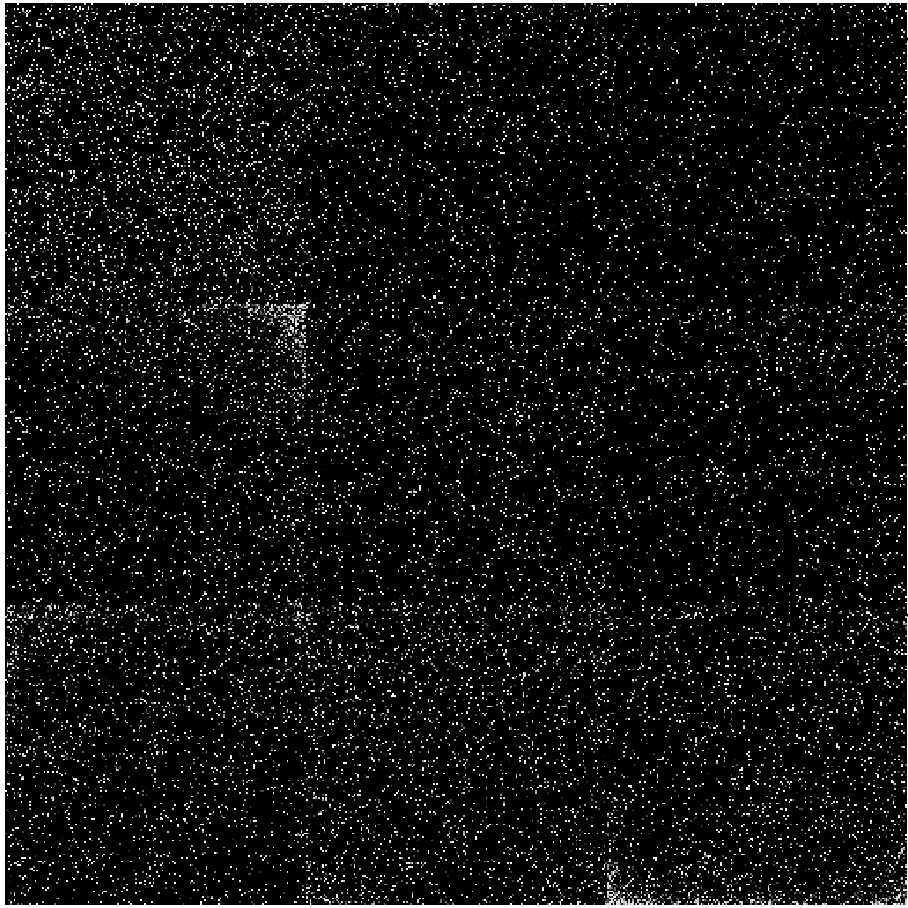
1. A flat field (uniform illumination of the detector)

2. A dark image (no irradiation of detector)

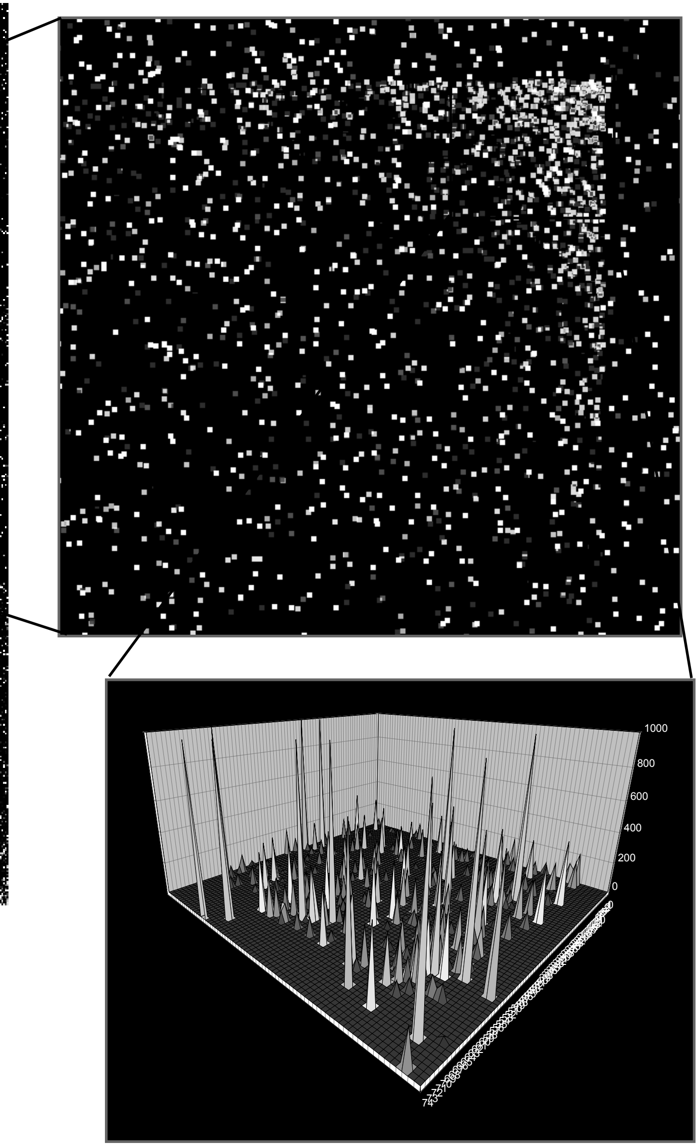
Both must be recorded with the same exposure time as the original image since dark current is a function of exposure time.

Then apply the following correction

Dark Current



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

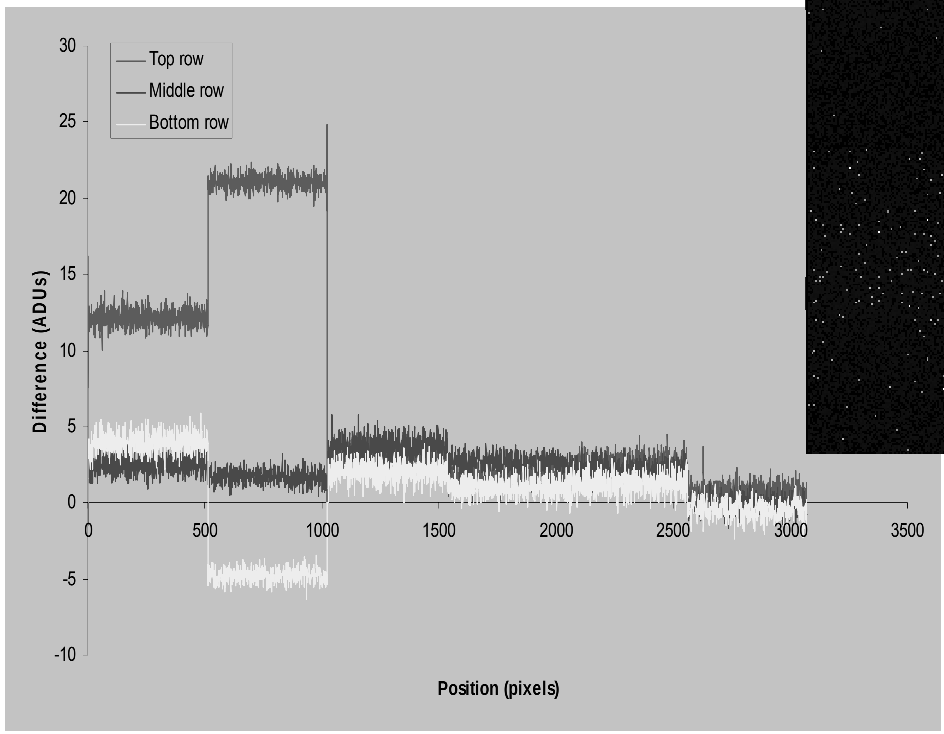


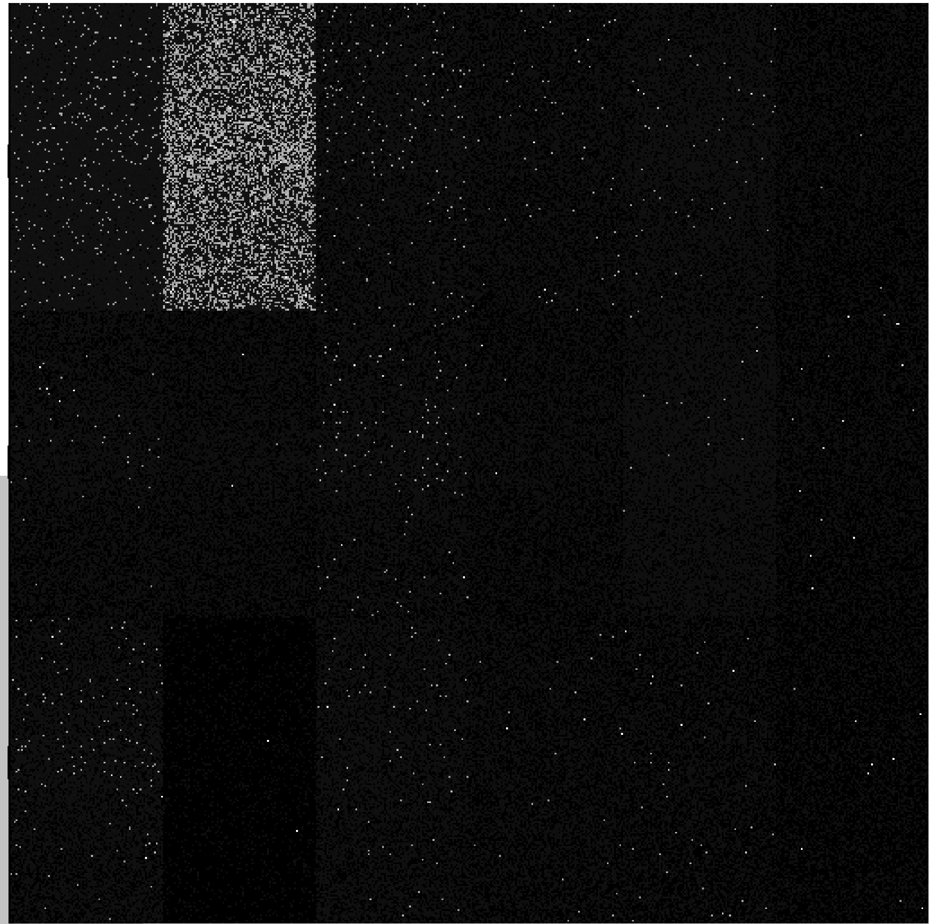
Number failing 2 measurements 5-2000s

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

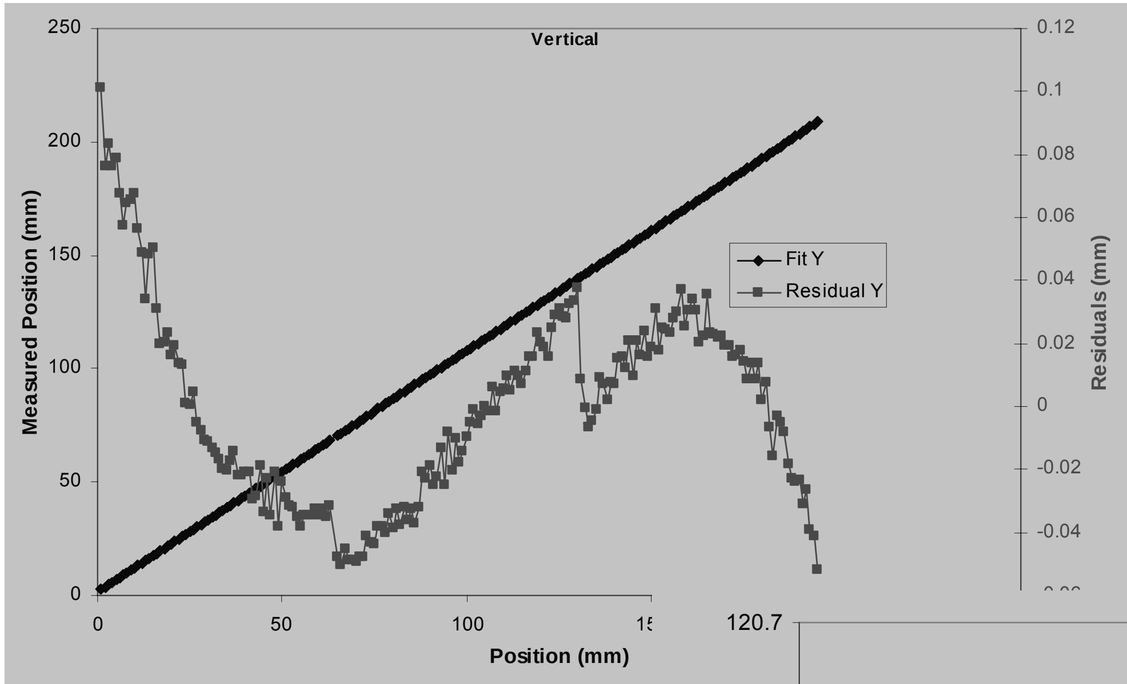
nb. 14300 pixels not common to both

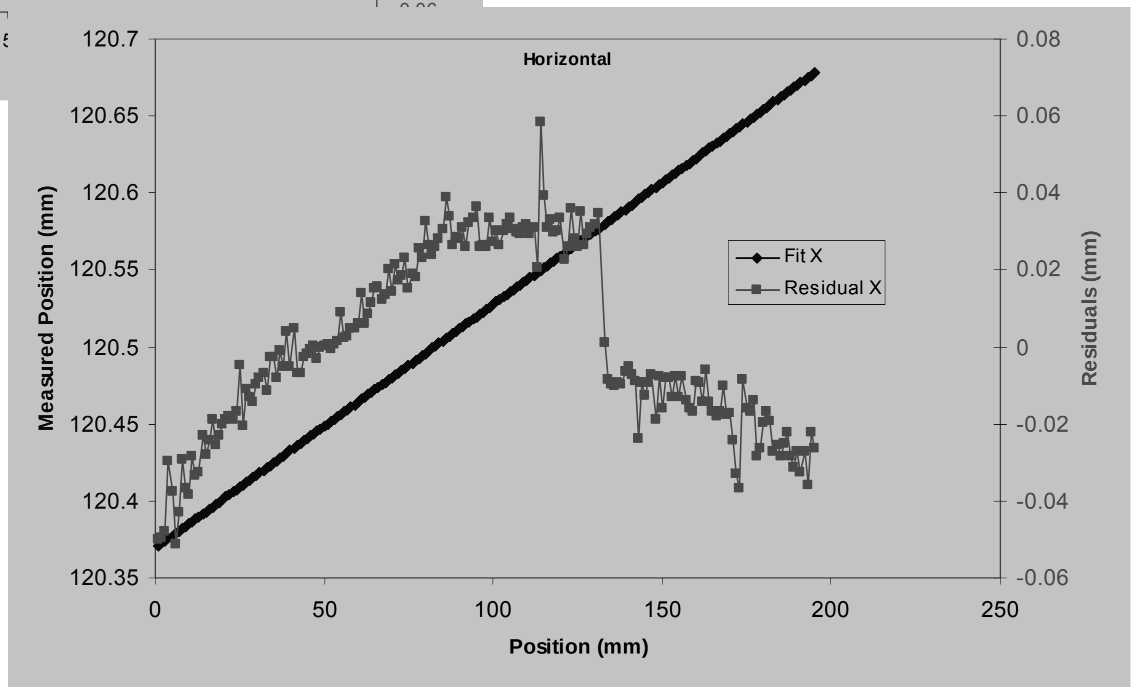
Subtraction of dark images



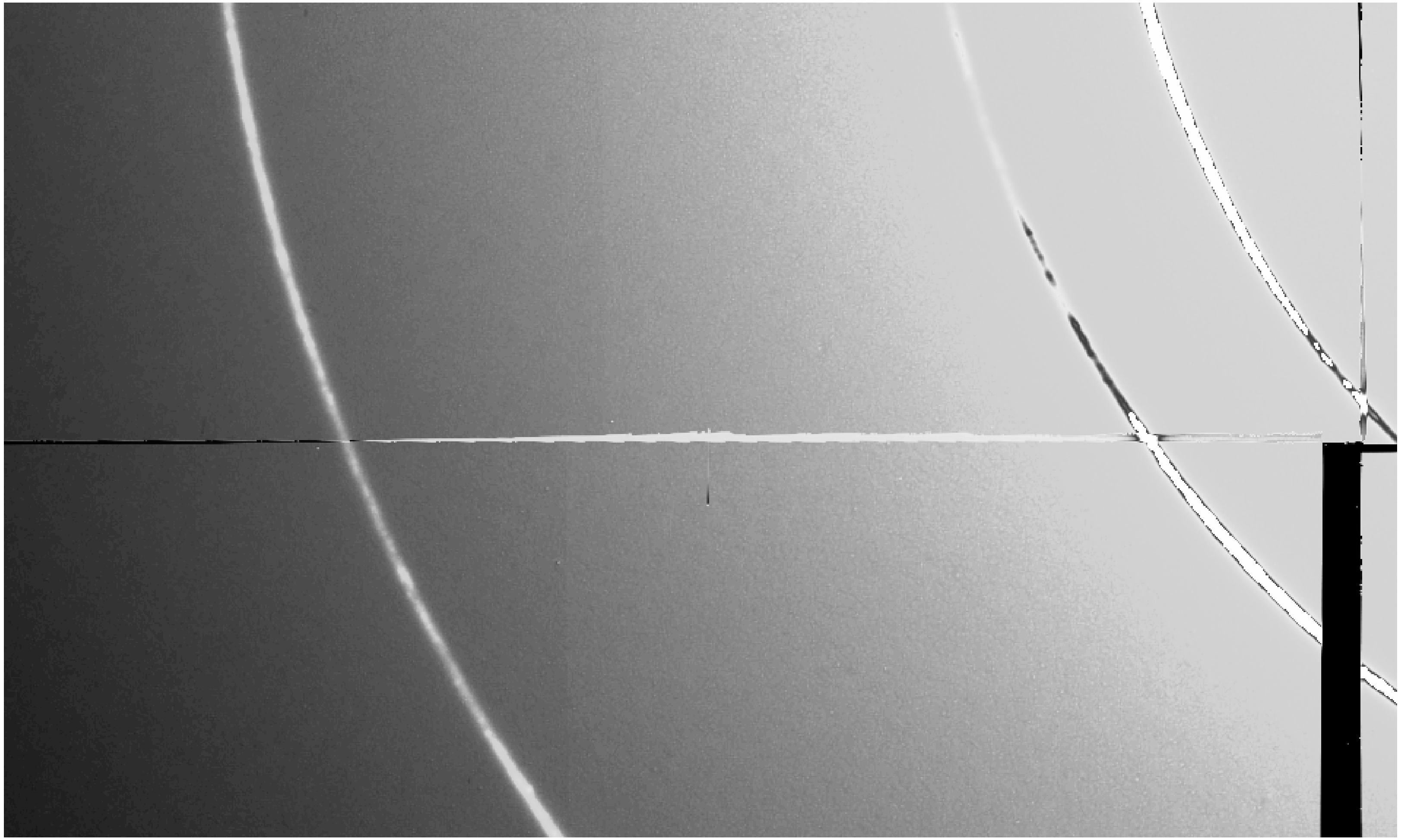


Geometric Distortion



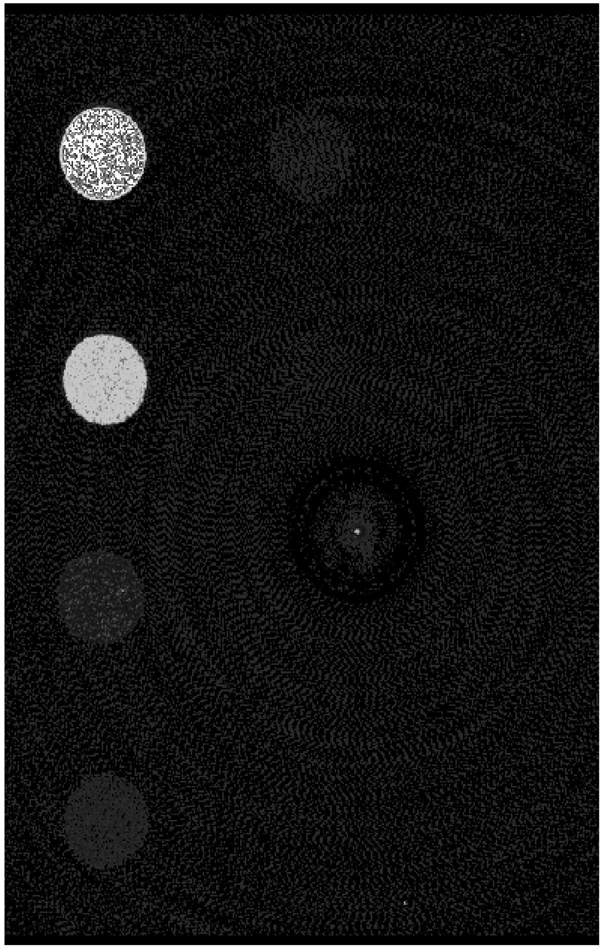


Overlaps

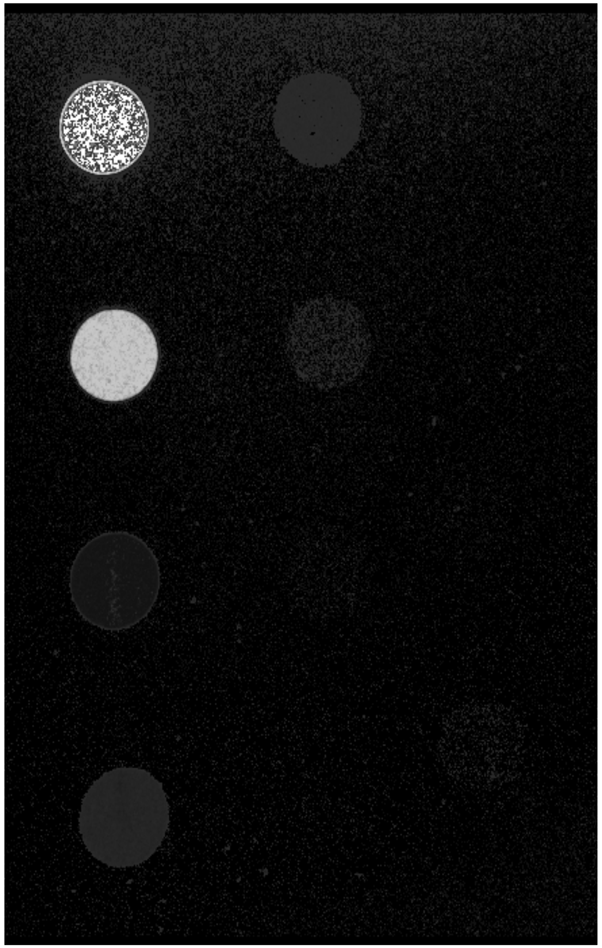


Graded Absorber Comparison

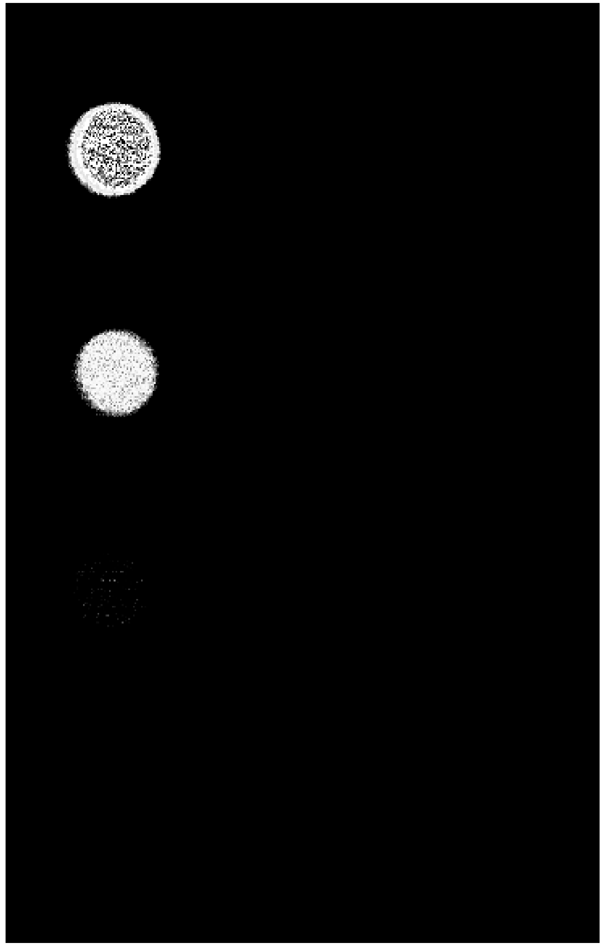
Mar Image Plate



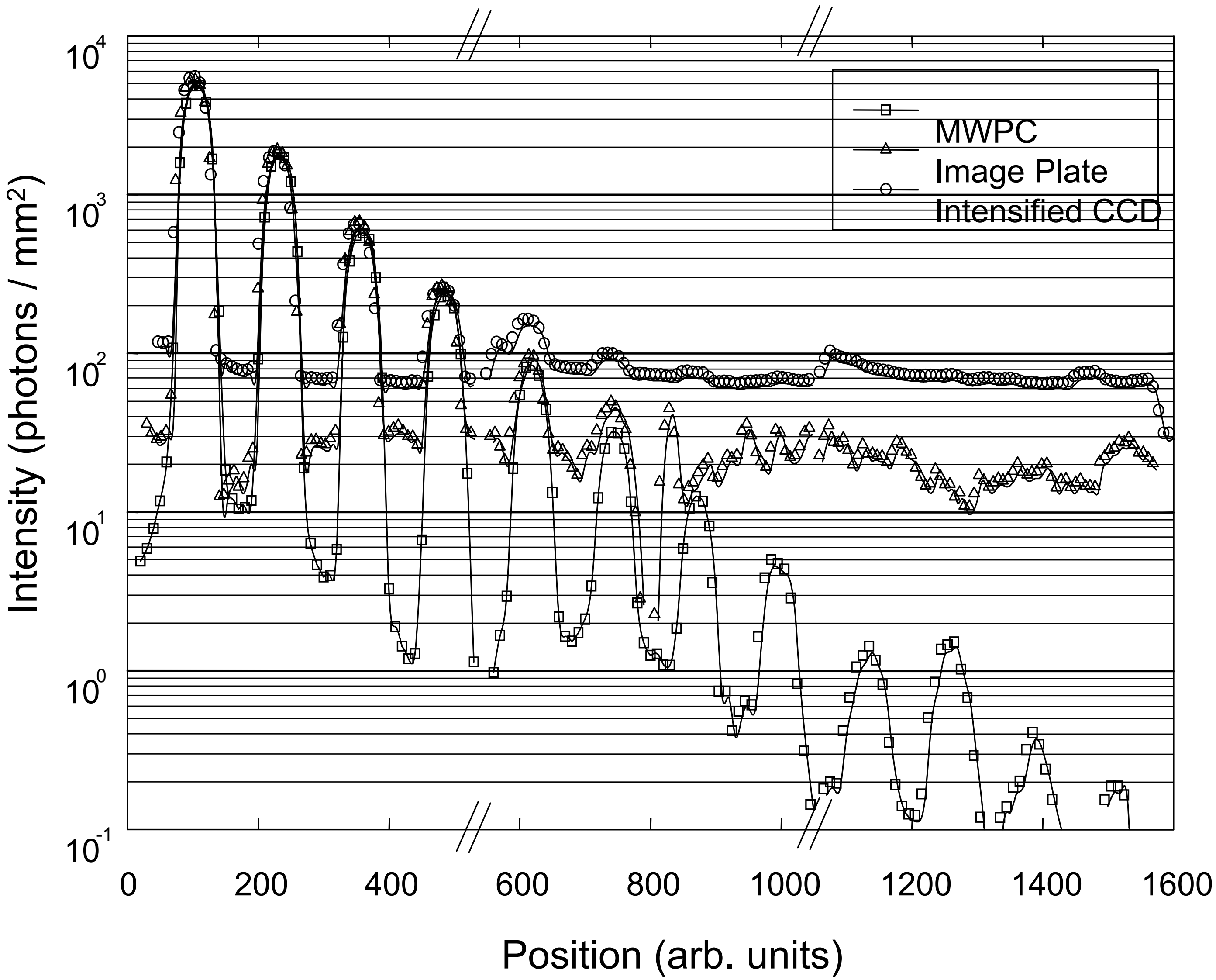
ESRF-Thompson IIT / CCD



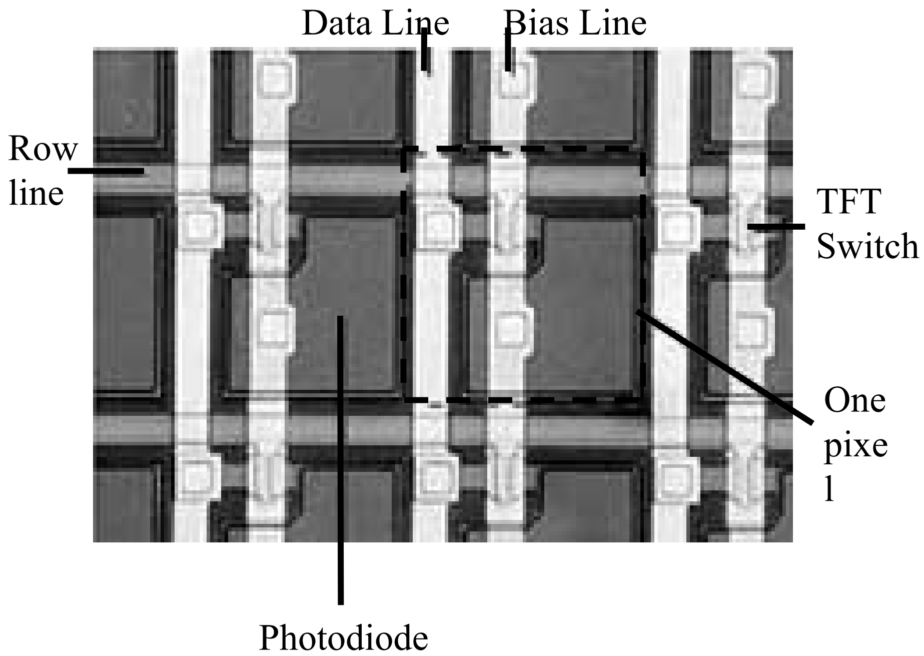
Daresbury MWPC

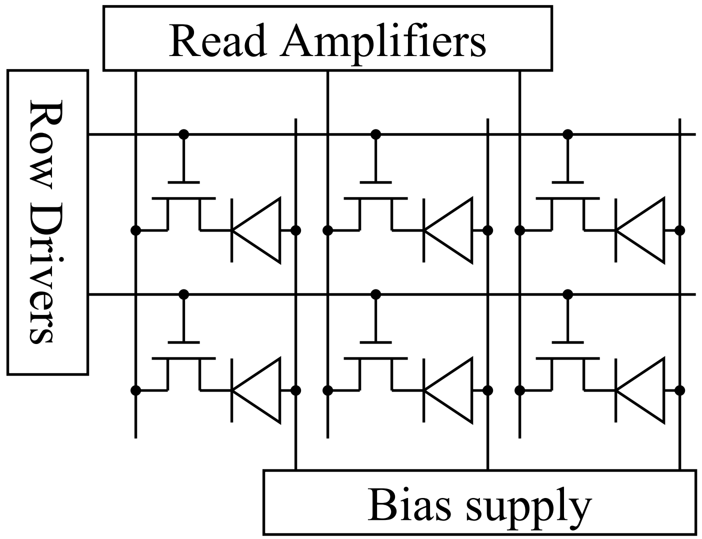


Detector noise level comparison

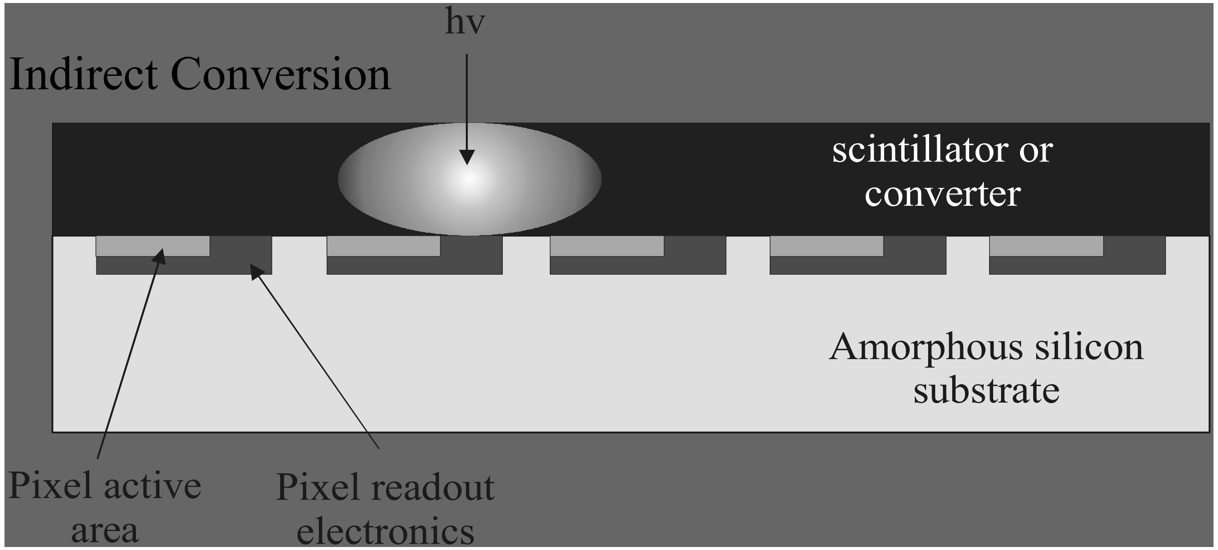


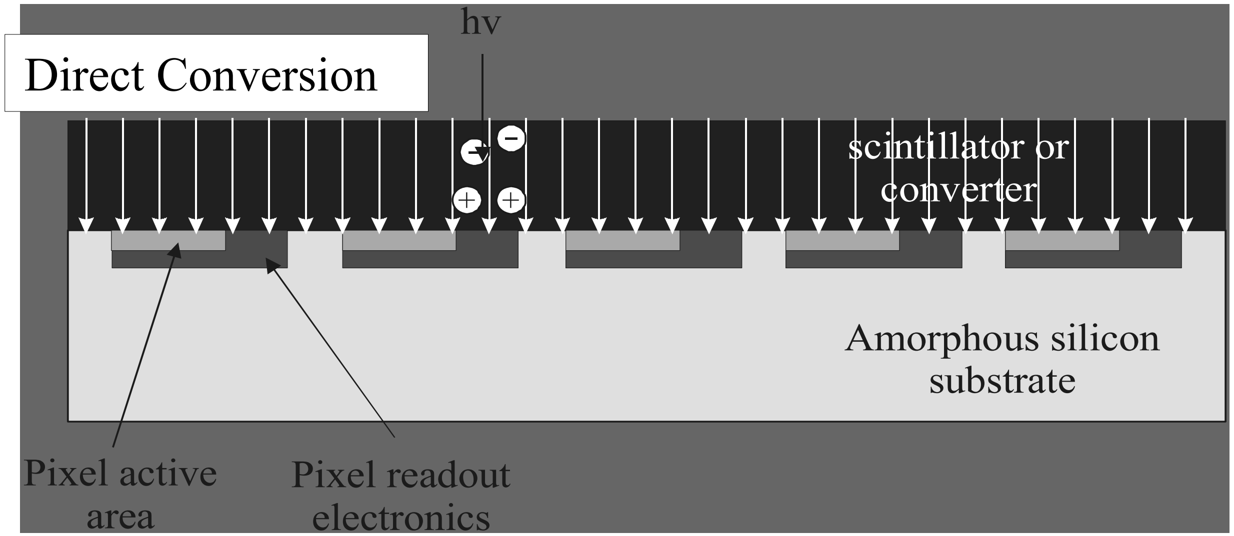
a-Si:H Array dpiX - Flashscan 30

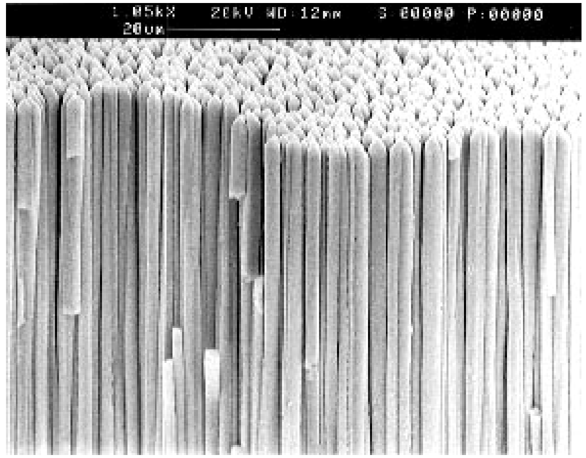




a-Si:H TFT arrays







Needle diameter 6μm

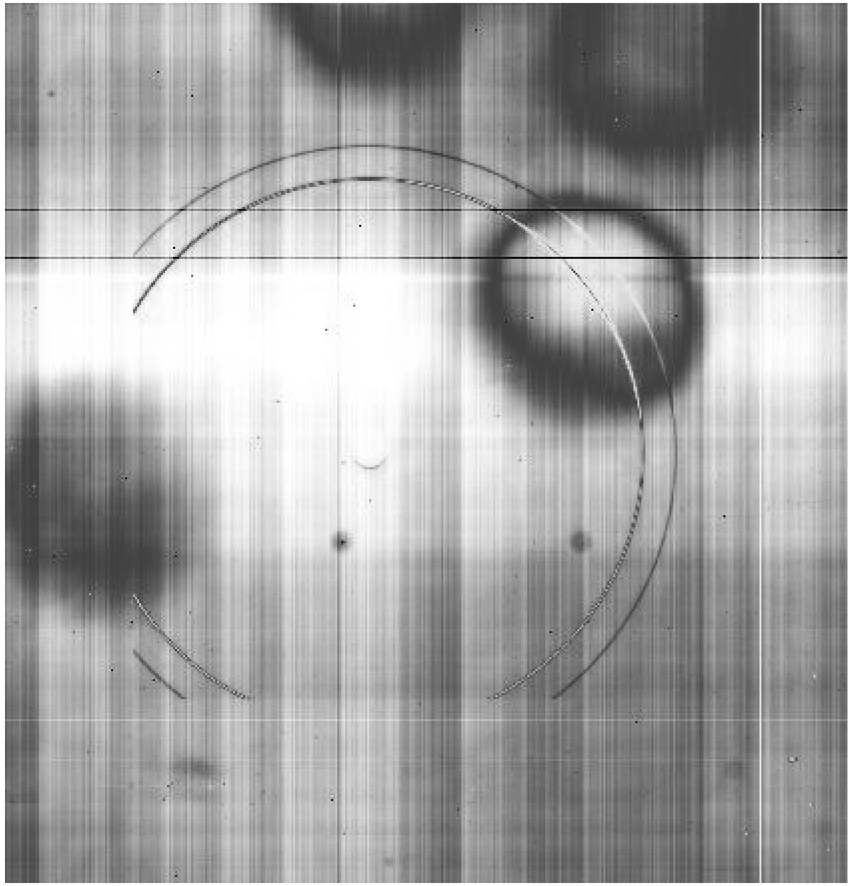
dpiX Flashscan 30 PaxScan 4030

Flashscan 30 - Performance

Mar Image Plate

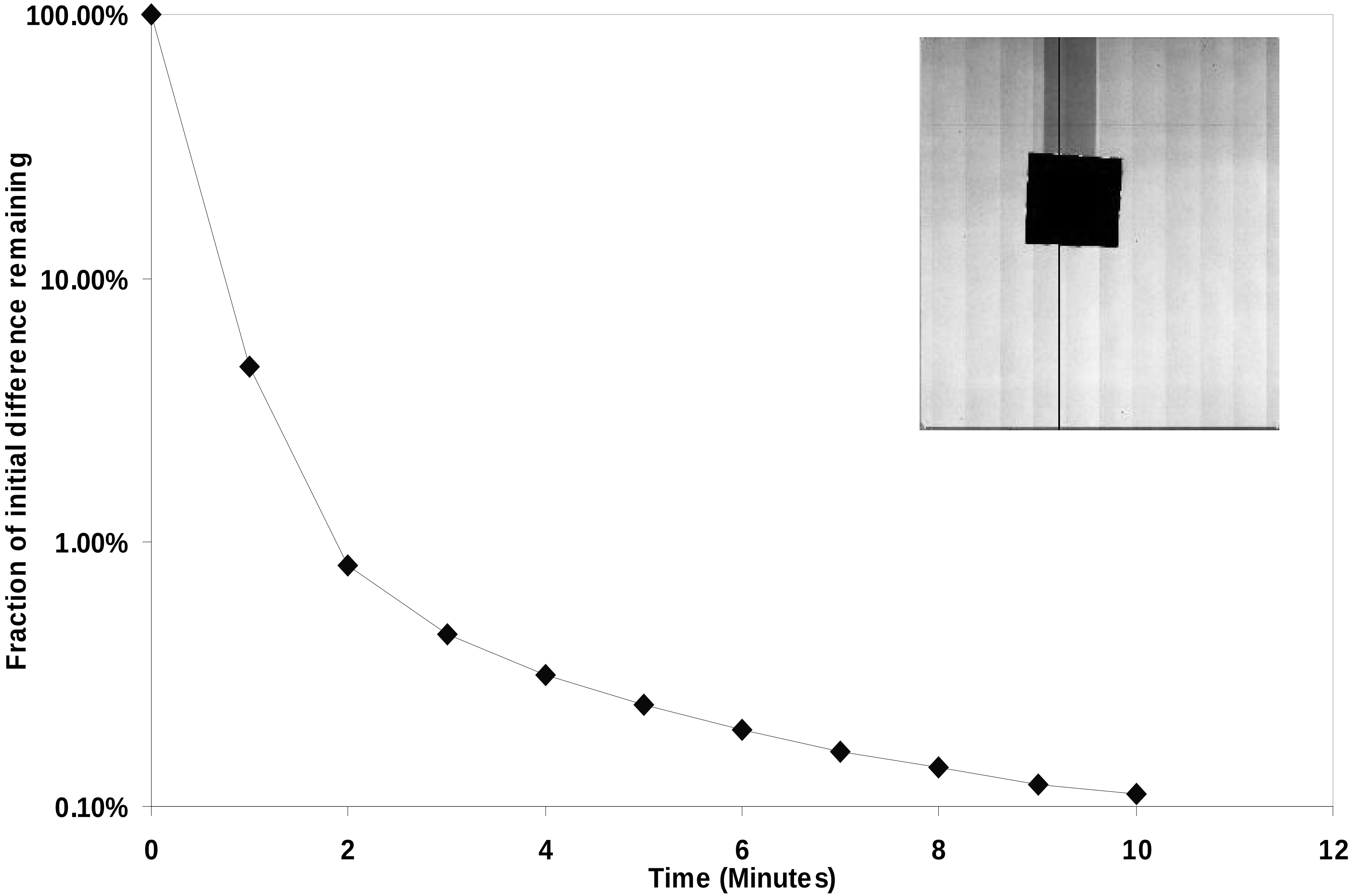
t_{int}=30s

Flashscan-30



t_{int}=190s

Flashscan 30 - Image Lag



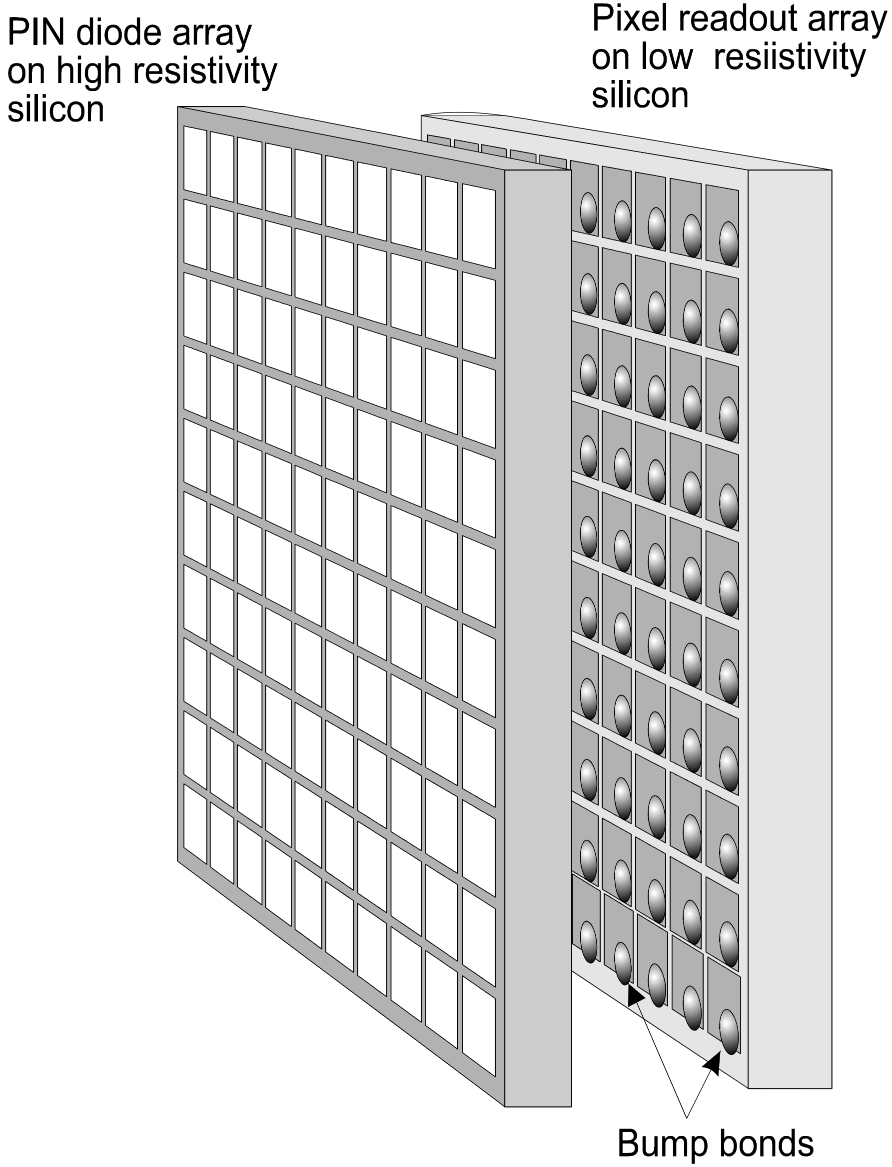
Multi Channel Spectoscopic Detectors

Canberra Ultra-LEGe detector

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

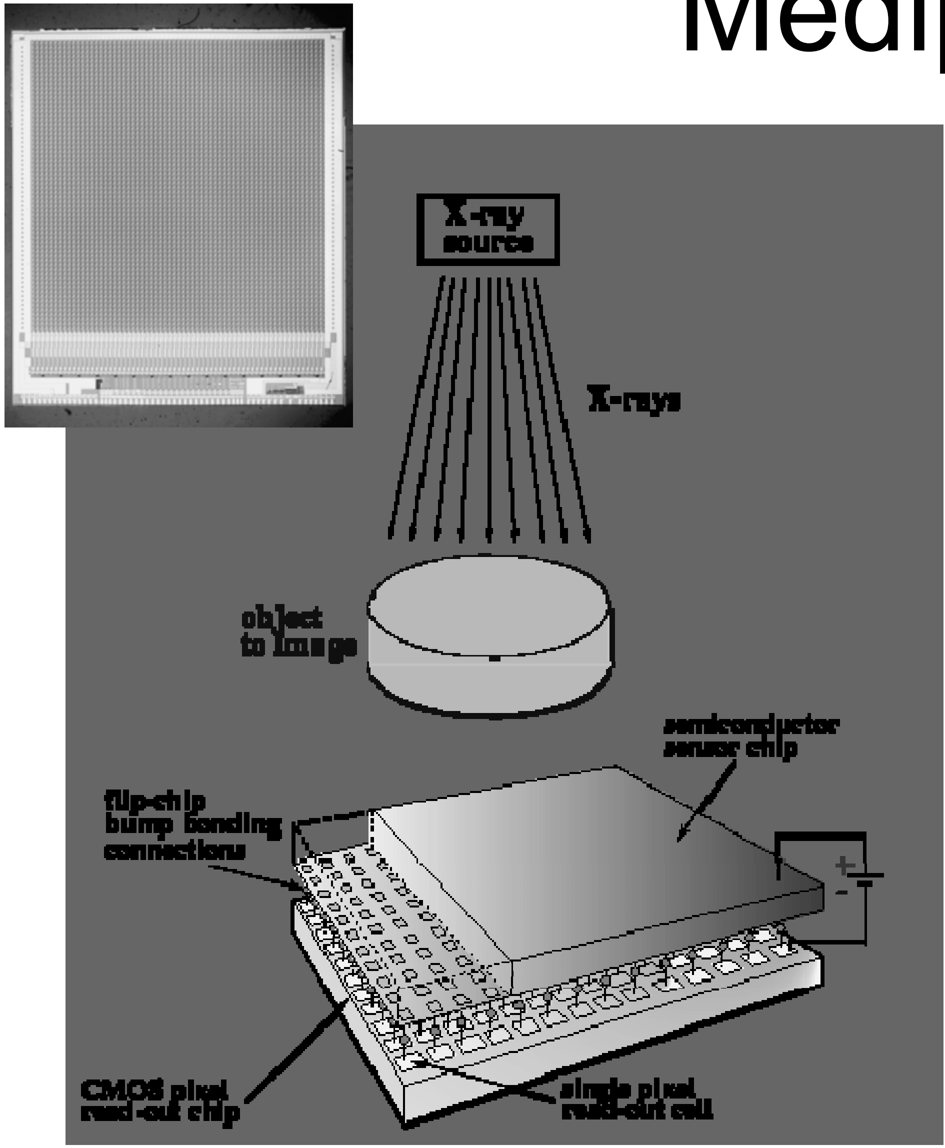
Multichannel devices up to 30 channels at 3×10^{5} cts s^{-1} channel^{-}1 have been built

Pixel Detector



- Photon counting at GHz rates
- Simultaneous imaging and spectroscopy
- Single-pixel PSF
- Low noise
- Large area coverage
- Customised to each experiment

Medipix 1



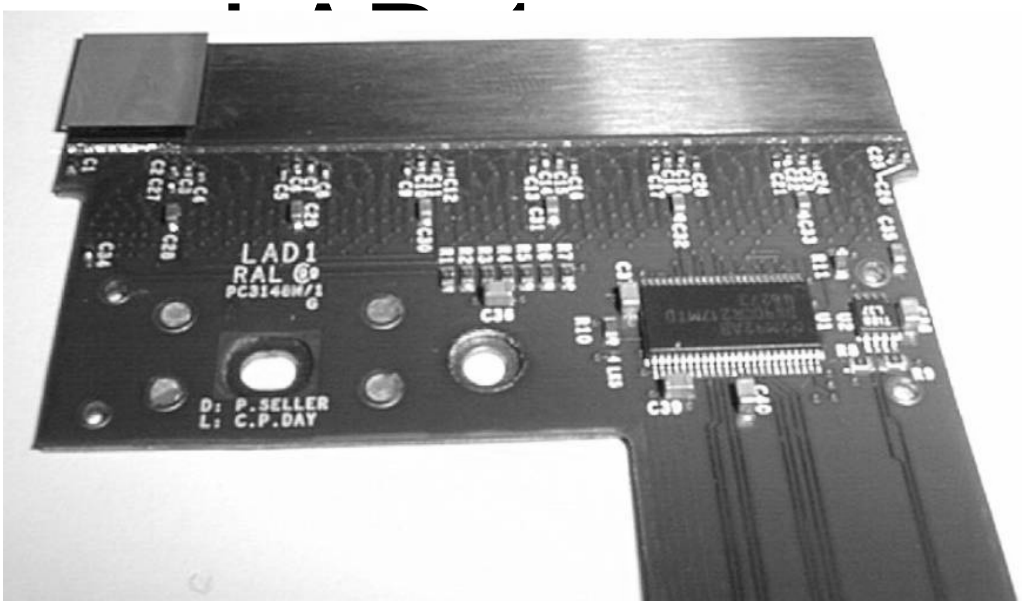
- Square pixels of 170µm side-length
- 64 x 64 pixels per chip
- Sensitive to positive charge
- Leakage current compensation at the input
- Maximum count rate: ~2 MHz
- 1 comparator per pixel with 3 bits fine tuning
- Minimum threshold ~1500e^-(~5.5 keV deposition in a Si sensor)
- 15 bit counter per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

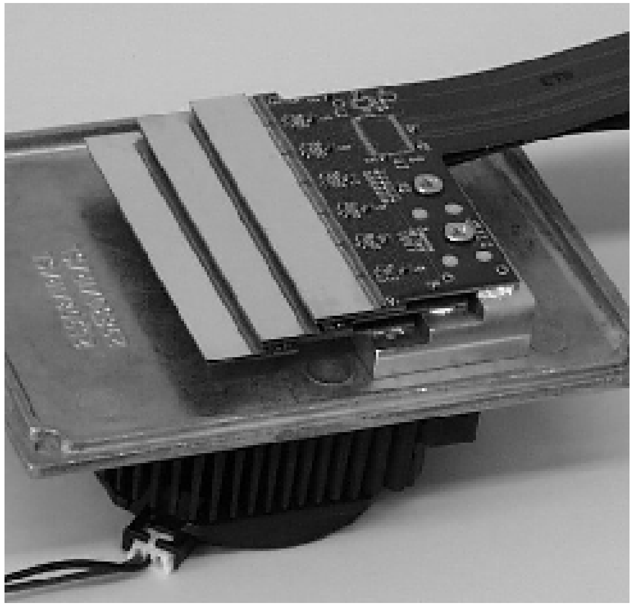
http://medipix.web.cern.ch/MEDIPIX/

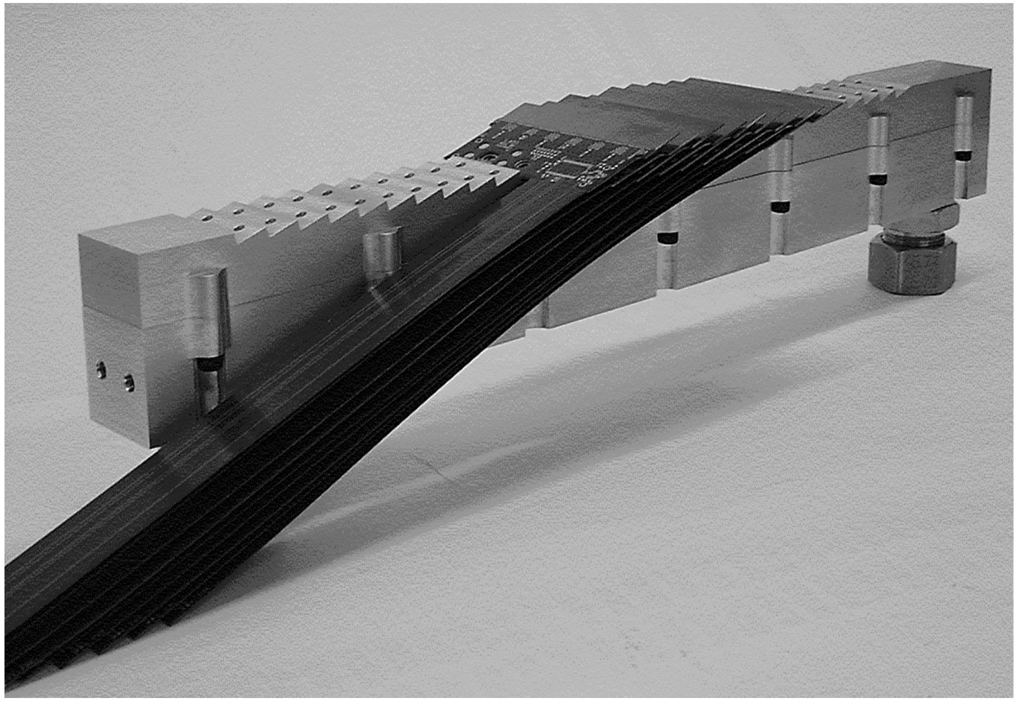
Sardine

- 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
- Acquisition time per image: 500 ms.
- No image correction was used (raw data!).
- The thickness of the fish bones corresponds roughly to the pixel size.

LAD 1

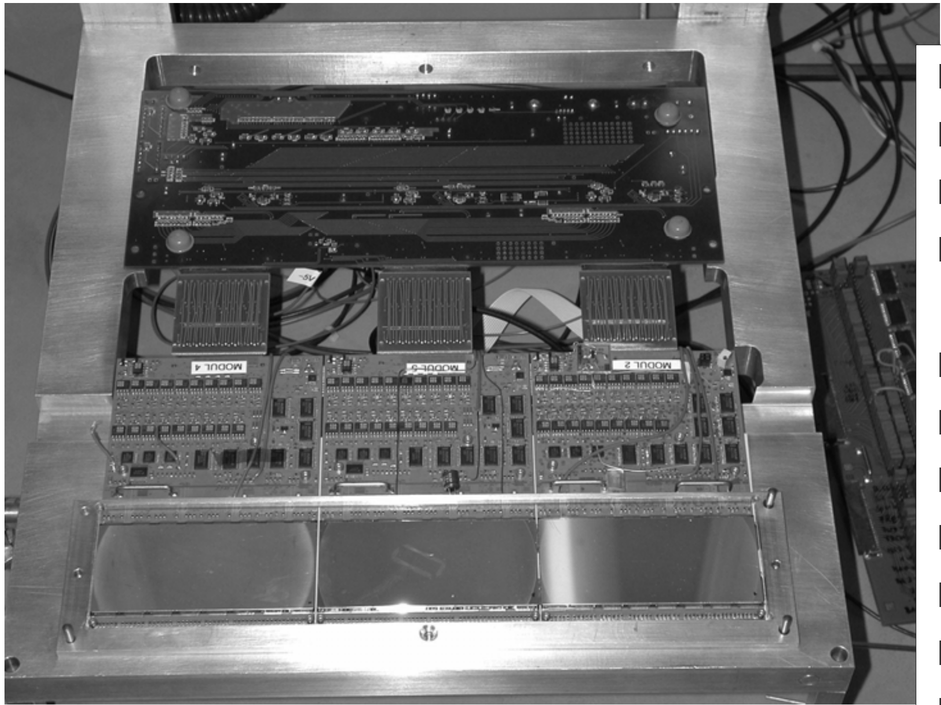






P. Seller RAL

PILATUS Detector with 3 Modules

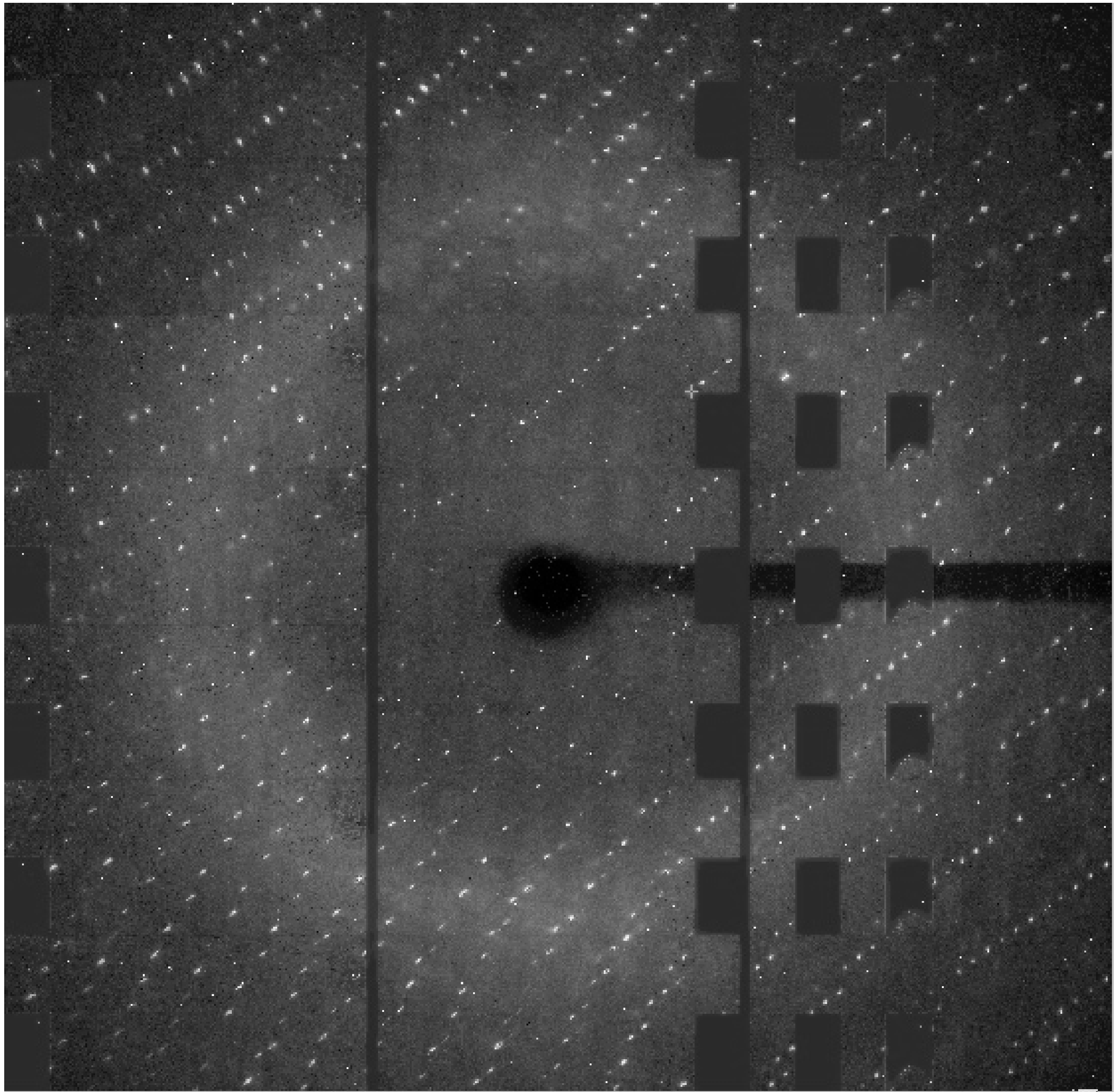


- Pixel size: <200×200µm2
- Dead area ~6%
- High frame rate: >10Hz
- High duty cycle: <3% (Tro<3ms)

- **3 Module Prototype**
- Area: 238.7 x 35.3 mm^2
- 157×1098 = 172386 pixels
- 48 chips (radiation hard)
- 2.38mm gap between modules
- Readout-time: 5 ms
- Energy Range: E.g. >4 keV
- XY-addressing of each pixel
- Threshold adjust of each pixel
- Analog signal of each pixel

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)

Lysozyme PILATUS



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

Radiation Damage (Medipix)

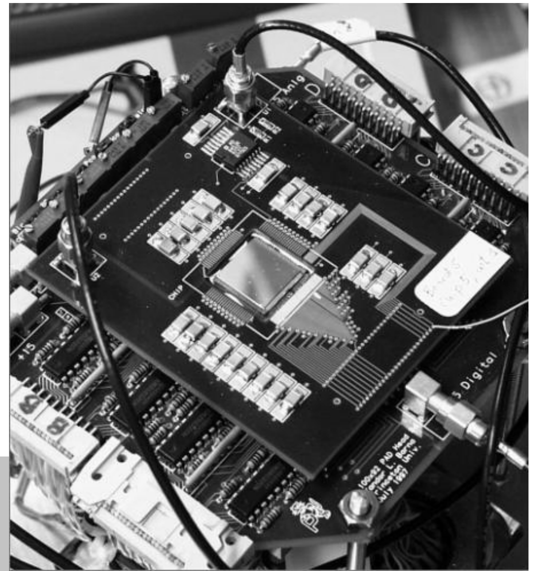
- Damage occurred at 40Gy or 1.3×10^{10}pht/mm^2 in the readout chip
- At 13 keV photon energy
  - Strong diffraction spots typically 10^5 phts/s or 10^6 phts/mm2/s
    - Damage requires ~ 8hours exposure
  - Direct beam (10^{10}–10^{13} photons/mm^2/s)
    - Damage in less than a second.

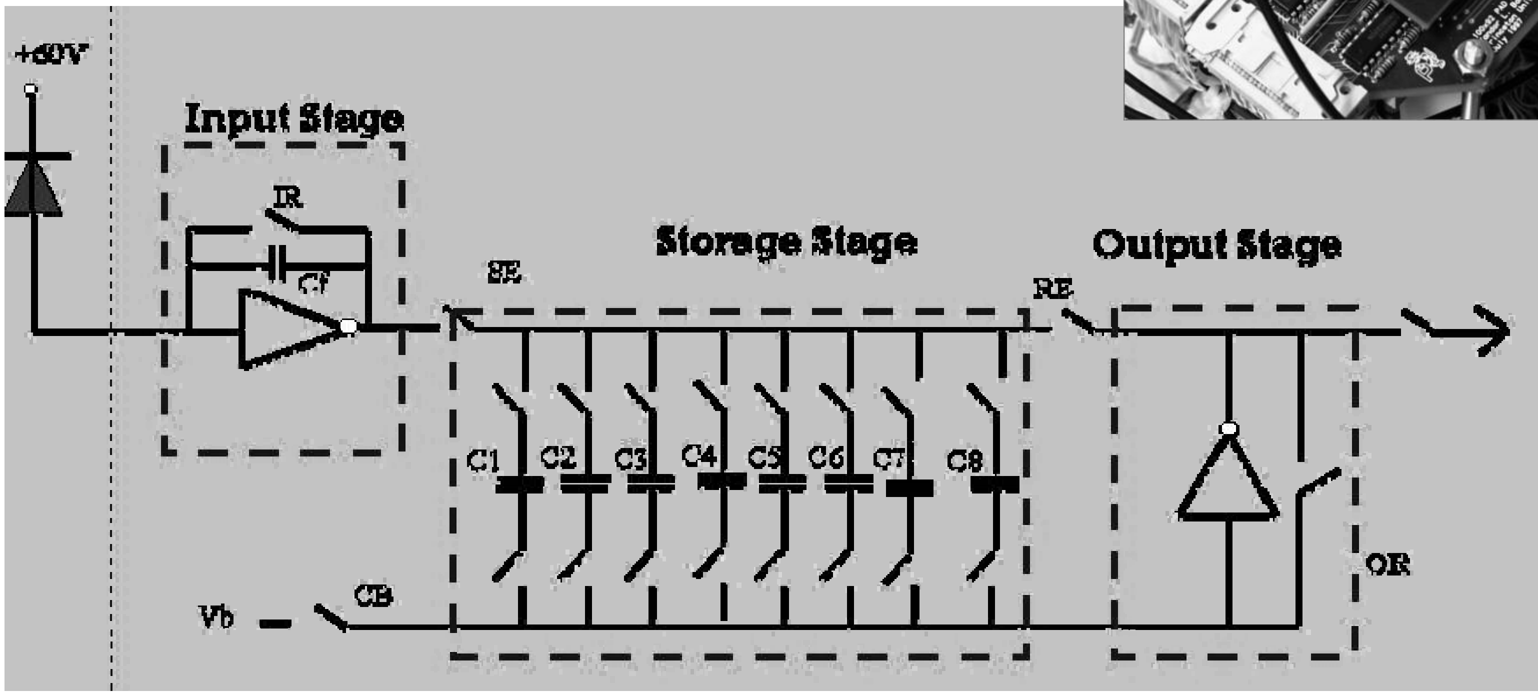
Counting Pixel Detector Problems

- 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

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

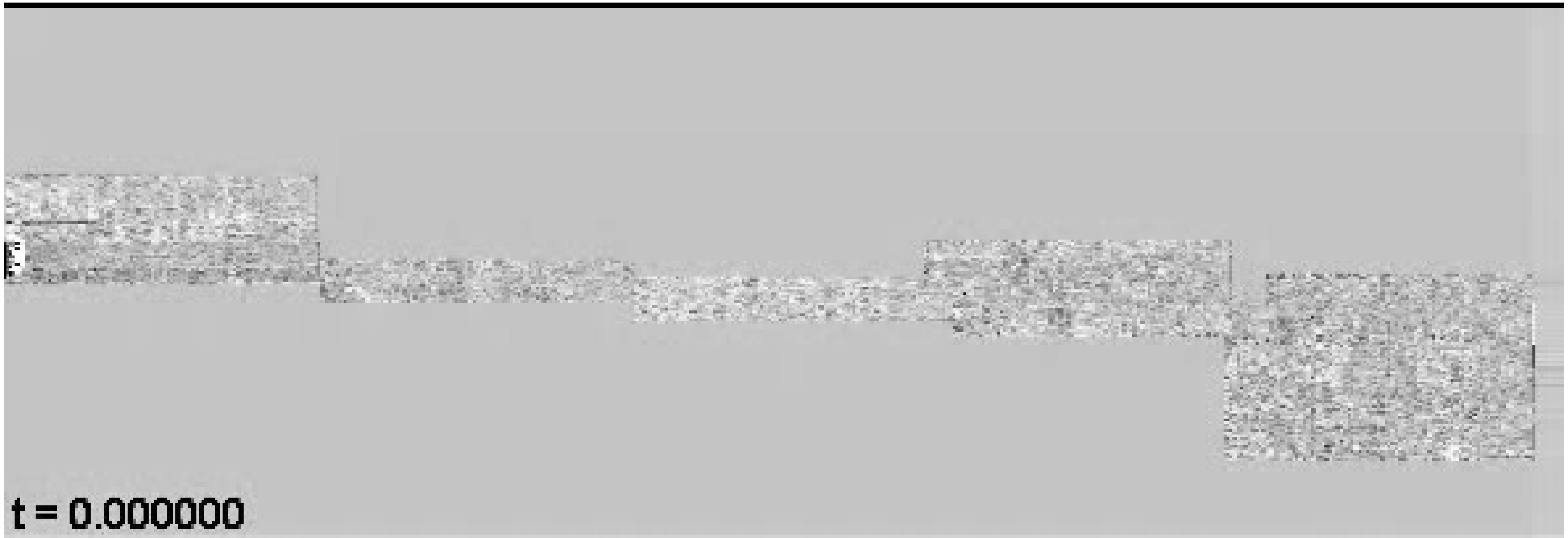




Sol Gruner, Cornell

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 5×10^4 images

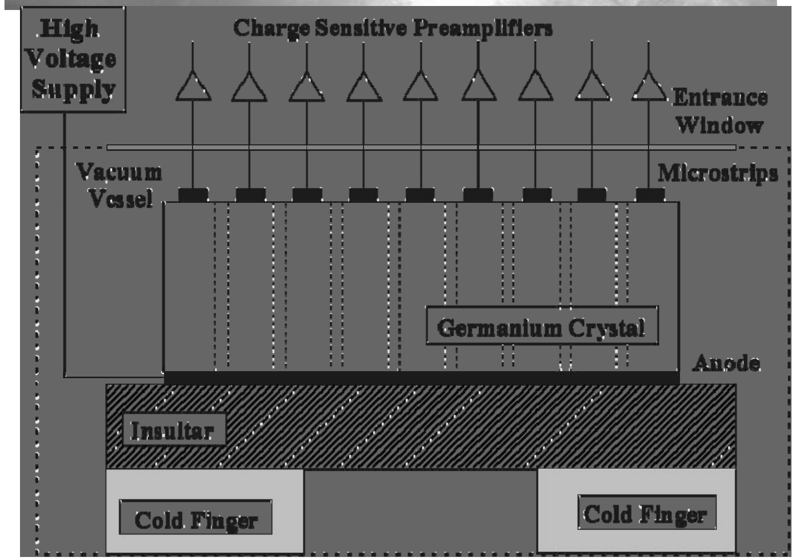


A. MacPhee et al, Science (2002) 295, 1761-1763

Pixel Detectors: The Problems

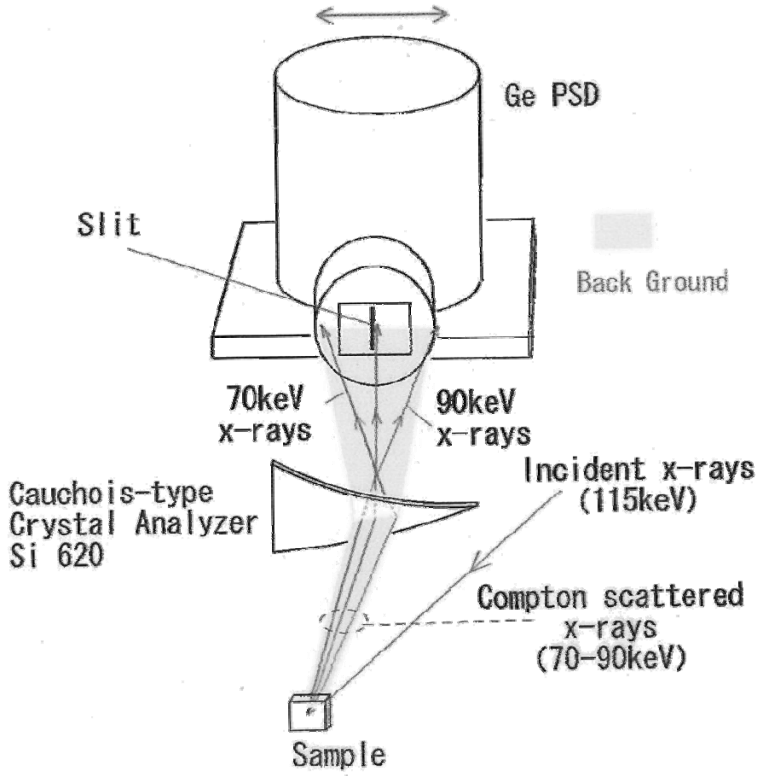
- Large silicon fab requirements
- A lot of infrastructure required
- Radiation damage
- Long iteration times
- Poor stopping power of silicon
- Counting and fast framing not yet possible
- Expensive NRE

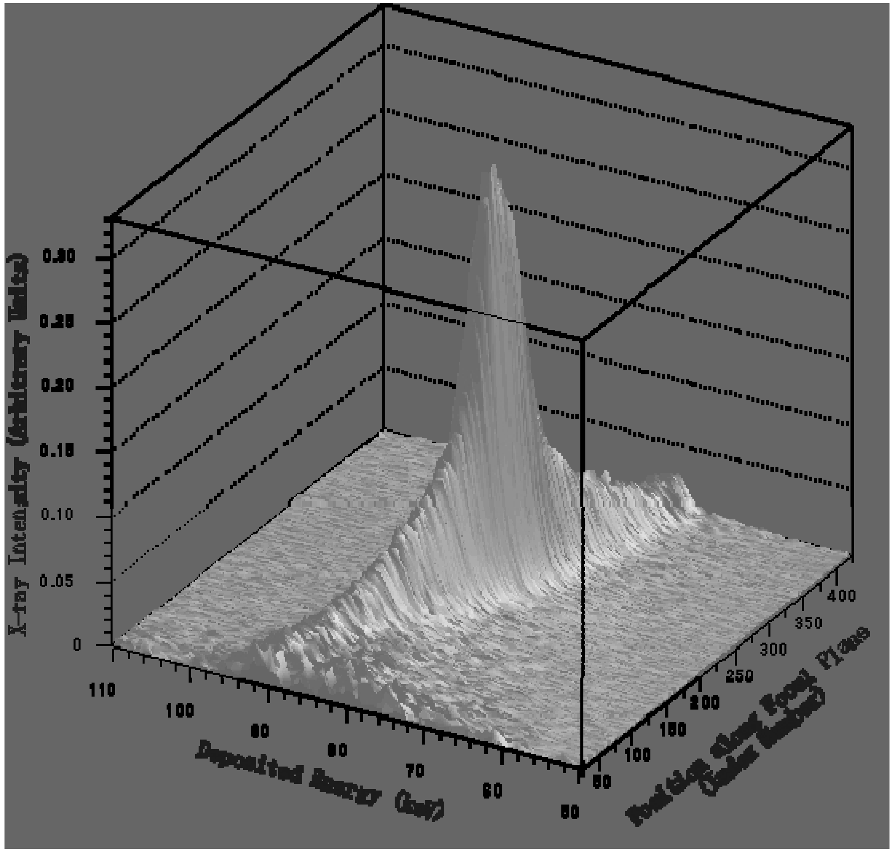
SPring-8 128 channel Ge strip



- 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

SPring-8 Ge strip detector





Compton Spectrum of Nb

Detector Considerations

- Detection Efficiency
- Intensity Measurement
  - Dynamic Range
  - Linearity of Response
  - Uniformity 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

Defining Characteristic?

- Is there a defining characteristic of X-ray detectors for synchrotron radiation?
- Astronomy
  - Sensitivity
- High Energy Physics
  - 3D tracking, multi-technique and huge
- Medical Imaging
  - Large area, low cost

Defining Characteristic

- Defining characteristic
  - Flux capability (count rate)
- Sensitivity (neglected)
- Gulf between modern SR fluxes and detector capabilities is huge
- Repeatedly stated
  - SRI 1991, plenary address Mike Hart
    - The division of funding between source, optics and detectors seems to be seriously out of balance. Neither optics nor detectors can fully meet the experimental requirements of even second generation bending magnet sources
  - Fluxes from 3rd generation insertion devices are 1000 times higher!!
- Defining characteristic
  - Lack of resources

Funding Comparison

- Chandra X-ray Telescope
  - Total budget US$2.8b
  - Detector work began **15 years** before launch!!
  - 2 detectors, each budget ~US$50M
- Linear colliders
  - Budget US$Vast/huge/enormous
  - Detector work began **12 years** before operation!!
  - One small part of detector budget CCDs US$10M
- DIAMOND synchrotron
  - Total budget £350M
  - Detector work not started, planned 1.5 years before ops. In 2005/6/7
  - 20 detectors, each budget £200k

Tortoise and Hare?

- Accelerators currently 10^{13}-10^{14} photons to sample
- New machines e.g. LCLS, 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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