Detectors for Synchrotron Radiation

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Factors Limiting Science

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

The pie chart shows the distribution of factors limiting science, with detectors accounting for 54%. Other factors include sample (15%), beam (15%), time (5%), and other factors (11%).
X-rays and their Interaction with Matter

Synchrotron Radiation

Surface Adsorbate

Inelastic Scattering

Defect

Bragg Diffraction

Laue Diffraction

Bulk Crystal

Ions and Neutral Atoms

Photoelectrons

Reflected Photons

Fluorescence

Transmitted Photons

Courtesy SRRC, Taiwan
Scientist’s View of Detector

Input

Detection process

Output

Result
The Truth!

Input

Output

Result
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. CCDs

- **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

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

X-ray photon $\lambda_1$

K fluorescence

X-ray $E \sim E_k$

Photoelectron
Arthur Holly Compton

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

Compton Effect

\[ \Delta \lambda = \frac{h}{m_0 c} (1 - \cos \phi) \]
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 DIFFERENCE

- 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?
An Example Detector

Echidna
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
Operation regions of gas filled detectors

- Pulse amplitude vs. Applied Voltage
  - Ionisation chambers
  - Proportional counters
  - Proportional region
  - Limited proportional region
  - Geiger-Mueller region

Threshold for gas multiplication:
- Typically $10^6$ Vm$^{-1}$
- $10$ kVcm$^{-1}$

$n$ is number of charges
$x$ is distance
$\alpha$ is the first Townsend coefficient

\[
\frac{dn}{n} = \alpha dx
\]

\[
n(x) = n(0)e^{\alpha x}
\]
Field Variation

Cathode

Anode

\[ E(r) \sim \frac{1}{r} \]
Avalanche & Proportional Counter

Increasing electric field

Positive ions

Electrons

X-Ray photon

Initial ionisation

Gain >> 1

Electron avalanche

Gas Volume

Anode

Electrons out
Microstrip Variants

Typical anode width
10 microns

Micro Dot

- surface cathode (20 µm wide)
- anode (20 µm dia.)
- implant
- SiO₂ (5 µm thick)
- buried anode readout bus (metal 1)

readout pitch 200 µm

cell size 225 µm
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

Detector output vs. Time

- Photon
- Signal

Noise = 1
Signal = 0.01
Counting and Integrating

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

Detector output vs Time

Photon
Signal

Noise = 1
Signal = 1
Counting & Integrating

Detector output

Photon
Counting
Integrating

Noise = 0.01
Signal = 1
Counting & Integrating

 Photon
 Counting
 Integrating

Noise = 1
Signal = 1
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
  - ♦ $2 \times 20$ keV phs = $1 \times 40$ 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

Input flux

Output signal
Dark Signals & Fog

Measured signal overtakes background signal

Time

Intensity

Real Signal

Total background

Dark Signal

Fog level / Digitisation Threshold

Time
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 and 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 a certain degree of unsharpness will be introduced into the image in comparison to non-screen film.
CCD Readout

Photons in

Clock rows into 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.
  - 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.
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
TV detector with IIT

Phosphor
Gain >> 1

Optics
Gain < 1

Image
Intensifier
Gain >> 1

Optics
Gain < 1

CCD/SIT
Gain > 1

X-Ray in

Optical Photons

Electrons
Computed Radiography-Image Plate

**Exposure**
- Creation of F centres
  - Gain >> 1

**Scanning**
- Stimulation of PSL
  - Gain < 1
- Collection of PSL
  - Gain < 1
- PMT Amplification
  - Gain > 1

Blue Filter
X-Y Flat bed Scanner

- He Ne Laser
- Galvanometer mirror
- F-theta correcting mirror
- Phosphor Plate
- Fibre optic light guide
- Photomultiplier tube
- Distributed Light Collection
TFT Flat panel Detector
a-Si:H TFT arrays

Indirect Conversion

Direct Conversion

Needle diameter 6 μm
a-Si:H Array dpiX - Flashscan 30

- **Row line**
- **Data Line**
- **Bias Line**
- **TFT Switch**
- **Photodiode**
- **Read Amplifiers**
- **Row Drivers**
- **Bias supply**
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 x 12 = 60 modules
  - Reverse-biased silicon diode array
  - Thickness 320 µm
  - Pixel size 172 x 172 µm²
- 2463 x 2527 = 6,224,001 pixels
- Area 431 x 448 mm²
- 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 x 10⁶ 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).
Spectroscopic Detectors

Rainbow Lorikeets
Electron multipliers & Scintillators

Channeltron is a similar with distributed dynode

Micro-channel plates are mutlichannel channeltrons with each channel being an electron multiplier.
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 $3 \times 10^5$ cts s$^{-1}$ channel$^{-1}$ have been built
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
Spectral Resolution

- Average number of carriers, \( N = \frac{E}{w} \)
  where \( w \) is energy to create electron hole/ion pair
- Poisson statistics \( \sigma = \frac{1}{\sqrt{N}} \)
  \[ = \left(\frac{E}{w}\right)^{-\frac{1}{2}} = \left(\frac{w}{E}\right)^{\frac{1}{2}} \]
- \( \Delta E/E \) fwhm \[ = 2.355\sigma \]
  \[ = 2.355\left(\frac{w}{E}\right)^{\frac{1}{2}} \]

- 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
- Reality is somewhere in between so we introduce Fano factor $F$
- Fano factor is defined as $F = \frac{\sigma^2}{\mu}$ where $\sigma^2$ is the variance and $\mu$ 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
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%
Graded Absorber Comparison

Mar Image Plate  ESRF-Thompson IIT / CCD  Daresbury MWPC
Spatial distortion

ESRF Image intensifier detector
IPlate Single Peak PSF
Parallax Broadening

Input

Output

Position

Detection Volume
Parallax Effect

Image Plate

Gas Proportional Counter
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

MicroGap Curved Detector

Sample

MicroGap Quadrant Detector

RAPID electronics
Geometric Distortion
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

\[
Corrected = \frac{\text{image} - \text{dark}}{\text{flat} - \text{dark}}
\]
Dark Current

Number failing 2 measurements 5-2000s

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>nb. 14300 pixels not common to both</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>44764</td>
<td>40822</td>
<td>48706</td>
<td></td>
</tr>
</tbody>
</table>
Subtraction of dark images
Radiation Damage (Medipix)

- Damage occurred at 40Gy or $1.3 \times 10^{10} \text{pht/mm}^2$ in the readout chip
- At 13 keV photon energy
  - Strong diffraction spots typically $10^5 \text{phts/s or } 10^6 \text{phts/mm}^2/\text{s}$
  - Damage requires $\sim 8$ hours exposure
  - Direct beam ($10^{10}-10^{13} \text{photons/mm}^2/\text{s}$)
    - Damage in less than a second.
Flashscan 30 - Performance

Mar Image Plate $t_{int}=30s$

Flashscan-30 $t_{int}=190s$
Electronics Issues

Koalas

Albino Kookaburra
Amplification

- In almost all cases we require amplification
- Amplifier-detector interaction is critical
- 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
    - White noise
  - Shot Noise
    - Fluctuations in current
    - White noise
    \[ \bar{i}^2 = 2q_e \bar{I}\Delta f \]

- Voltage mode
  - Output \( \alpha \) input voltage
  - Effect of \( R_f \) dominates \( C_f \)

- Current mode
  - Output \( \alpha \) input current
  - Low input impedance

- Charge mode
  - Output \( \alpha \) 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

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

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)
- \( \tau \) = Rise time of amplifier
- \( C_{in} \) = input / stray and feedback capacitance

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

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

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

- Choosing optimum \( \tau \) gives best noise performance but may not be fast enough
- We often have to sacrifice energy resolution for speed
Optimum $\tau$

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

- $R_g$ as large as possible $\sim 10^{10} \Omega$
- $I_D$ (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 $\omega_s/2$, then aliasing will occur at frequencies $\omega_1 \pm n$ where;

- $\omega_1$ = original signal frequency, $\omega_s$ = 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
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!
Dead Time

- Non-paralysable
  - Fraction of time detector is dead = $R_d \tau$
  - Live time is therefore = $1 - R_d \tau$
  - Input rate = $R_i = \frac{R_d}{1 - R_d \tau}$

- Paralysable
  - $R_d$ = Probability of getting no event within $\tau$ 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 $R_d = P(0, \tau) = R_i e^{-R_i \tau}$

---

$R_i$ = input rate, $R_d$ = detected rate, $\tau$ = dead time
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
## Ion Mobility

<table>
<thead>
<tr>
<th>Gas</th>
<th>Ions</th>
<th>Mobility (cm² V⁻¹ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>(OCH₃)₂ CH₂⁺</td>
<td>1.51</td>
</tr>
<tr>
<td>Iso C₄ H₁₀</td>
<td>(OCH₃)₂ CH₂⁺</td>
<td>0.55</td>
</tr>
<tr>
<td>(OCH₃)₂ CH₂</td>
<td>(OCH₃)₂ CH₂⁺</td>
<td>0.26</td>
</tr>
<tr>
<td>Ar</td>
<td>Iso C₄ H₁₀⁺</td>
<td>1.56</td>
</tr>
<tr>
<td>Iso C₄ H₁₀</td>
<td>Iso C₄ H₁₀⁺</td>
<td>0.61</td>
</tr>
<tr>
<td>Ar</td>
<td>CH₄⁺</td>
<td>1.87</td>
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<tr>
<td>CH₄</td>
<td>CH₄⁺</td>
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<tr>
<td>Ar</td>
<td>CO₂⁺</td>
<td>1.72</td>
</tr>
<tr>
<td>CO₂</td>
<td>CO₂⁺</td>
<td>1.09</td>
</tr>
<tr>
<td>Ar</td>
<td>electrons</td>
<td>~1000</td>
</tr>
</tbody>
</table>

For 1kV across 1cm. Electrons take 1ms. Ions take ~1ms!
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
A Universal Specification?

Wombat
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 $\sqrt{n}$.
- Fractional error = $(\sqrt{n})/n=1/\sqrt{n}$
- As $n$ increases, uncertainty and noise decrease.
Performance Measure - DQE

Perfect detector

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

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

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

Note that DQE is $f$(spatial and spectral frequencies)
Effect of Peak Width

![Graph showing the effect of peak width with different peak widths: 1 pixel, 2 pixel, 5 pixel, 10 pixel. The graph plots intensity against position, with peaks varying in height and width depending on the peak width.]
DQE Comparison

DN-5 beam
2.6μGy

DQE vs Frequency (lp/mm)

- Flat Panel
- 400 film
- Light sensitive screen

Typical values:
- Flat Panel: 400 film: 2.6μGy

Frequency (lp/mm)

0 0.5 1 1.5 2 2.5 3 3.5 4

DQE

0% 10% 20% 30% 40% 50% 60%
To Count or Not to Count

Tasmanian Devil
Specifications
Collagen 100s Exposure
Collagen 10s Exposure

MWPC

Image Plate

Proportional Counter

Intensity (Photons/mm²)

Position (mm)
Cornell PAD (Integrating)

- **Rapid Framing Imager**
  - 15×13.8mm² active area
  - 150µm square pixel
  - Storage for 8 frames
  - Selectable $T_{\text{int}}$ 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

The Future
A Detector System

Detector → Preamp → HPD → ADC

X-ray

101 010101

E=23
X=145
Y=2371

FPGA GDAQ
Pixel Array Detector

A. Top electrode
B. Pixellated semiconductor
C. Collection electrodes
D. Bump bonds
E. Input electrode
F. Pixellated ASIC
5 bits RAM (1 frame) : 0.35\(\mu\)m
5 bits RAM (1 frame) : 90nm
The Problem of Multiple Scatters

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

Paul Sellin, Surrey
Absorption Efficiency of Semiconductors

Calculated for 500μm thick material

- Si
- GaAs
- CdTe
- HgI₂
- TIBr

Detection Efficiency (%)

Photon energy (keV)

Paul Sellin, Surrey
CdZnTe Spectral Resolution

- 15x15x7.5 mm$^3$
- 3.2% FWHM with Te inclusions
- 2.6% FWHM without Te inclusions

Counts vs. Channel for 662 keV energy.
References

■ Delaney CFG and Finch EC

■ Knoll GE
  ♦ Radiation Detection and Measurement, John Wiley and Sons 1989

■ Proceedings of the 6th International Conference on position sensitive detectors

■ IEEE Nuclear Science Symposia
## Semiconductors

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (Ω cm)</th>
<th>$\varepsilon_r$</th>
<th>$\tau_R$ (ms)</th>
<th>$(\mu\tau)_e$ (cm²/V)</th>
<th>$(\mu\tau)_h$ (cm²/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>$&lt; 10^4$</td>
<td>11.7</td>
<td>$1.0 \times 10^{-8}$</td>
<td>$&gt; 1$</td>
<td>$&gt; 1$</td>
</tr>
<tr>
<td>Ge</td>
<td>50</td>
<td>16</td>
<td>$7.1 \times 10^{-11}$</td>
<td>$&gt; 1$</td>
<td>$\approx 1$</td>
</tr>
<tr>
<td>GaAs</td>
<td>$1.0 \times 10^7$</td>
<td>11.0</td>
<td>$1.1 \times 10^{-5}$</td>
<td>$8.0^{-5}$</td>
<td>$4.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>CZT</td>
<td>$3 - 5 \times 10^{10}$</td>
<td>10.9</td>
<td>$2.9 - 4.9 \times 10^{-2}$</td>
<td>$3 - 5 \times 10^{-3}$</td>
<td>$5 - 8 \times 10^{-5}$</td>
</tr>
<tr>
<td>CdTe</td>
<td>$1.0 \times 10^9$</td>
<td>11.0</td>
<td>$9.7 \times 10^{-4}$</td>
<td>$3.3 \times 10^{-3}$</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>HgI₂</td>
<td>$1.0 \times 10^{13}$</td>
<td>8.8</td>
<td>7.8</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$4.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>PbI₂</td>
<td>$1.0 \times 10^{12}$</td>
<td>$\approx 10$</td>
<td>0.89</td>
<td>$8.0 \times 10^{-6}$</td>
<td>$6.0 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
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
## Signal Levels

<table>
<thead>
<tr>
<th>Energy per electron hole pair, ( w ) (eV)</th>
<th>Stage 1 signal @ 10keV</th>
<th>Stage 2 Transfer to electron gain</th>
<th>Minimum N @ 10keV</th>
<th>Stage n 0 noise gain</th>
<th>Signal (e(^-))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas Ionisation</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Argon</td>
<td>24.4</td>
<td>410e(^-)</td>
<td>1</td>
<td>410</td>
<td>10(^5)</td>
</tr>
<tr>
<td>Xenon</td>
<td>20.8</td>
<td>481e(^-)</td>
<td>1</td>
<td>481</td>
<td>5\times10(^4)</td>
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<tr>
<td><strong>Solid State</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>3.62</td>
<td>2760e(^-)</td>
<td>1</td>
<td>2760</td>
<td>1</td>
</tr>
<tr>
<td>Germanium</td>
<td>2.96</td>
<td>3380e(^-)</td>
<td>1</td>
<td>3380</td>
<td>1</td>
</tr>
<tr>
<td><strong>Fluorescence or scintillation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaI(Tl) + PMT</td>
<td>266 photons</td>
<td>0.1</td>
<td>30</td>
<td>10(^5)</td>
<td>3\times10(^6)</td>
</tr>
<tr>
<td>Gd(_2)O(_2)S + IIT</td>
<td>500 photons</td>
<td>0.04</td>
<td>20</td>
<td>10(^4)</td>
<td>2\times10(^5)</td>
</tr>
<tr>
<td>BaFBr:Eu(^{2+})</td>
<td>75 F centres</td>
<td>0.07</td>
<td>5</td>
<td>10(^5)</td>
<td>5\times10(^5)</td>
</tr>
</tbody>
</table>
### Scintillators - Basic Properties

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>38</td>
<td>250</td>
<td>415</td>
<td>3.7</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>54</td>
<td>1000</td>
<td>550</td>
<td>4.5</td>
</tr>
<tr>
<td>BaF₂</td>
<td>10</td>
<td>0.7/630 fast/slow</td>
<td>220/310 fast/slow</td>
<td>4.9</td>
</tr>
<tr>
<td>LaCl₃(Ce)</td>
<td>49</td>
<td>28</td>
<td>350</td>
<td>3.8</td>
</tr>
<tr>
<td>LaBr₃(Ce)</td>
<td>66</td>
<td>16</td>
<td>380</td>
<td>5.1</td>
</tr>
</tbody>
</table>

FWHM energy resolution at @ 662 keV:

- NaI(Tl) $\Delta E/E \sim 6\%$
- LaCl₃ $\Delta E/E \sim 4\%$
- LaBr₃ $\Delta E/E \sim 3\%$
- CdZnTe $\Delta E/E \sim 2\%$ (after correction for carrier recombination)
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
Probability of Single Events

\[ Q(I_0, 10^{-6}, 0) \quad \text{red line} \]
\[ Q(I_0, 5 \cdot 10^{-7}, 0) \quad \text{blue line} \]
\[ Q(I_0, 10^{-5}, 0) \quad \text{purple line} \]

Input rate (cps/pixel)
Resolving time required

\[ t_{\text{RES}}(0.01, I_0) \]
\[ t_{\text{RES}}(0.1, I_0) \]
\[ t_{\text{RES}}(0.5, I_0) \]

Input Rate (cps/pixel)