Detectors for Synchrotron Radiation

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Factors Limiting Science

- Detector: 54%
- SRS: 15%
- Sample: 15%
- Beam Time: 5%
- Other Instrumentation: 11%
- Other: 15%
A Scientist’s View of the Detector

Detection process

Input

Output

Result
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 to pressure and temperature
Operation regions of gas filled detectors

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

Threshold for gas multiplication. Typically $10^6 \text{ Vm}^{-1}$ $10\text{kVcm}^{-1}$

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

\[ E(r) \sim \frac{1}{r} \]

Cathode

○ Anode

Distance from wire

Field
Electrons
Positive ions
Increasing electric field
Avalanche & Proportional Counter

X-Ray photon
Initial ionisation
Electron avalanche
Gain >> 1
Gas Volume
Anode
Electrons out

Electrons out
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

- surface cathode (20 μm wide)
- anode (20 μm dia.)
- implant
- SiO$_2$ (5 μm thick)
- buried anode readout bus (metal 1)
- readout pitch 200 μm
- cell size 225 μm
Photomultipliers & Scintillators

Channeltron is a similar with distributed dynode.

Micro-channel plates are multichannel channeltrons with each channel being an electron multiplier.
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
Response to Uniform Illumination
Spatial distortion
Computed Radiography-Image Plates

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

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

Blue Filter
IPlate Single Peak PSF

Intensity

Position (mm)
Dark Signals & Fog

- Measured signal overtakes background signal
- Real Signal
- Total background
- Dark Signal
- Fog level / Digitisation Threshold
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
  - $2 \times 20 \text{ keV photons} = 1 \times 40 \text{ keV photon}$ 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

![Graph showing the relationship between input flux and output signal.](image-url)
Collagen 100s Exposure

MWPC

Image Plate

Proportional Counter

Image Plate

Intensity (Photons/mm²)

Position (mm)

Proportional Counter

Image Plate

100000

10000

1000

100

10

0 20 40 60 80 100 120 140 160
Collagen 10s Exposure

MWPC

Image Plate

Proportional Counter

Image Plate
Collagen 0.3s Exposure

MWPC

Image Plate

Proportional Counter
Image Plate

Position (mm)

Intensity (Photons/mm²)

0 20 40 60 80 100 120 140 160

0.01 0.1 1 10 100
Counting & Integrating

Signal

Accumulated Signal (Photons)

Time
## Signal Levels

<table>
<thead>
<tr>
<th></th>
<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>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argon</td>
<td>24.4</td>
<td>410e⁻</td>
<td>1</td>
<td>410</td>
<td>$10^5$</td>
<td>$4 \times 10^7$</td>
</tr>
<tr>
<td>Xenon</td>
<td>20.8</td>
<td>481e⁻</td>
<td>1</td>
<td>481</td>
<td>$5 \times 10^4$</td>
<td>$2.4 \times 10^7$</td>
</tr>
<tr>
<td><strong>Solid State</strong></td>
<td></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>
<td>$2.8 \times 10^3$</td>
</tr>
<tr>
<td>Germanium</td>
<td>2.96</td>
<td>3380e⁻</td>
<td>1</td>
<td>3380</td>
<td>1</td>
<td>$3.4 \times 10^3$</td>
</tr>
<tr>
<td><strong>Fluorescence or scintillation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaI(Tl) + PMT</td>
<td></td>
<td>266 photons</td>
<td>0.1</td>
<td>30</td>
<td>$10^5$</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>Gd₂O₂S + IIT</td>
<td></td>
<td>500 photons</td>
<td>0.04</td>
<td>20</td>
<td>$10^4$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>BaFBr:Eu²⁺</td>
<td></td>
<td>75 F centres</td>
<td>0.07</td>
<td>5</td>
<td>$10^5$</td>
<td>$5 \times 10^5$</td>
</tr>
</tbody>
</table>
Spectral Resolution

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

- For Ge, $w= 3\text{eV}$ so at 10keV $\frac{\Delta E}{E} = 4\%$
- For Ar, $w= 25\text{eV}$ so at 10keV $\frac{\Delta E}{E} = 12\%$
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 $= F \times \text{Poisson relative variance}$.
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 \( \propto \) 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

- 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)
- \( \tau \) = 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

- $\tau$ optimum at

- Choosing optimum $\tau$ gives best noise performance but may not be fast enough

- We often have to sacrifice energy resolution for speed
Optimum $\tau$

- $R_g$ 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;
- $\omega_1 = \text{original signal frequency}$, $\omega_s = \text{sampling frequency}$, $n = \text{an integer}$

The highest frequency that can be measured is twice the sampling frequency

- If you have 100$\mu$m pixels, ideal PSF > 200$\mu$m
Performance Measure - DQE

Perfect detector

Real detector

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

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

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

DN-5 beam
2.6μGy

Flat Panel
400 film
Light sensitive screen

DQE
Frequency (lp/mm)
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

<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>
</tr>
<tr>
<td>CH₄</td>
<td>CH₄⁺</td>
<td>2.26</td>
</tr>
<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 1 kV across 1cm. Electrons take 1µs
Ions take ~1ms!
As rate rises
- Spectral resolution deteriorates
- Note also the K escape feature
Dead Time

Non-Paralysable

Paralysable

$R_i =$ input rate, $R_d =$ detected rate, $\tau =$ 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 $P(n,t) = \frac{e^{-R_i \tau} (R_i \tau)^n}{n!}$
  - 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

Graphs showing
- Intensity (cps) vs. Slit size (mm)
- Intensity (cps) vs. ω (deg.)
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

Be Window

10μm Anode wires

0.75mm

10mm

0.75mm

0.3mm

GRP PC Board
Charge Distribution (Cathodes)

Anode

Avalanche

Sampling of distribution of cathode

Charge distribution induced on cathode

Cathode Positions
RAPID Data Acquisition System

Look-Up Table to determine the centroid of the X charge distribution

Correlator Card to match X and Y positions

Look-Up Table to determine the centroid of the Y charge distribution
Spatial Resolution Cathodes

Channel spacing = 1.5 mm
Probabilities of Event Overlap  $\Delta t=7.7\text{ns}$
2 Axis X-Y Detector
Deadtime Correction

Low Rate Image     3 MHz Raw Image     Corrected 3MHz Image
Time Framing

**Weight falling into trough of water.** 10ms time frames. Data rate=$14.33\times10^6$ cts s$^{-1}$

0ms  20ms  60ms  230ms  400ms

**Xenon filled balloon bursting.** 3ms time frames. Data rate=$12.15\times10^6$ cts s$^{-1}$

0ms  33ms  36ms  15ms  56ms
Collagen 1s exposure 16.1

Image Plate
No attenuation

Delay Line
8.7 x attenuation

RAPID
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

![Graph showing data and background removal](image)
Parallax Broadening

Input

Position

Detection Volume

Output

Position

Volume
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

line readout section

Readout line

Clock rows into Readout line

of substrate

of substrate
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.
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
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

Vertical

Measured Position (mm)

Position (mm)

Fit Y
Residual Y

Horizontal

Measured Position (mm)

Position (mm)

Fit X
Residual X
Overlaps
Graded Absorber Comparison

Mar Image Plate  
ESRF-Thompson IIT / CCD  
Daresbury MWPC
Detector noise level comparison

![Graph showing comparison of MWPC, Image Plate, and Intensified CCD in terms of intensity (photons/mm²) vs. position (arb. units).]
a-Si:H Array dpiX - Flashscan 30
a-Si:H TFT arrays

Indirect Conversion

Direct Conversion

Needle diameter 6μm
Flashscan 30 - Performance

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

Flashscan-30  
$t_{\text{int}}=190\text{s}$
Flashscan 30 - Image Lag

![Graph showing the fraction of initial difference remaining over time. A line graph with time in minutes on the x-axis and fraction of initial difference remaining on the y-axis.]
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 $3 \times 10^5$ 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

PIN diode array on high resistivity silicon

Pixel readout array on low resistivity silicon

Bump bonds
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.
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 mm²
- 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 $1.3 \times 10^{10}$ pht/mm$^2$ in the readout chip
- At 13 keV photon energy
  - Strong diffraction spots typically $10^5$ phts/s or $10^6$ phts/mm$^2$/s
    - Damage requires ~ 8 hours 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
  - 15×13.8mm² 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 SF₆
  - $10^8$-$10^9$ 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 $5 \times 10^4$ images

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**
  - $55.5 \times 50.5 \times 6$ mm

- **Strips**
  - Number: 128
  - Width: 300$\mu$m
  - Interstrip: 50$\mu$m
  - Length: 5 mm

- **Readout**
  - Single channel: 100 ns
  - 32 channels: 3.2 ms

- **Max expected count rate**
  - 14 kcps
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
References

- Delaney CFG and Finch EC

- Knoll GE

- Proceedings of the 7th International Conference on position sensitive detectors

- IEEE Nuclear Science Symposia