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X-ray Detectors for Synchrotron Radiation Applications

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The European Synchrotron

- ⊕ **A few general considerations**
- ⊕ **Detection principles used in SR detectors**
 - ⊕ X-ray sensors and basic detection schemes
- ⊕ **Main families and types of SR X-ray detectors**
 - ⊕ Energy dispersive
 - ⊕ Scattering/diffraction detectors
 - ⊕ X-ray imaging

Beam at the sample

Energy range: **0.1 keV** to **150keV**

Photon flux (@ $\delta E/E = 10^{-4}$): up to **10^{14} ph/sec**

Extremely variable flux at the detector depending on application

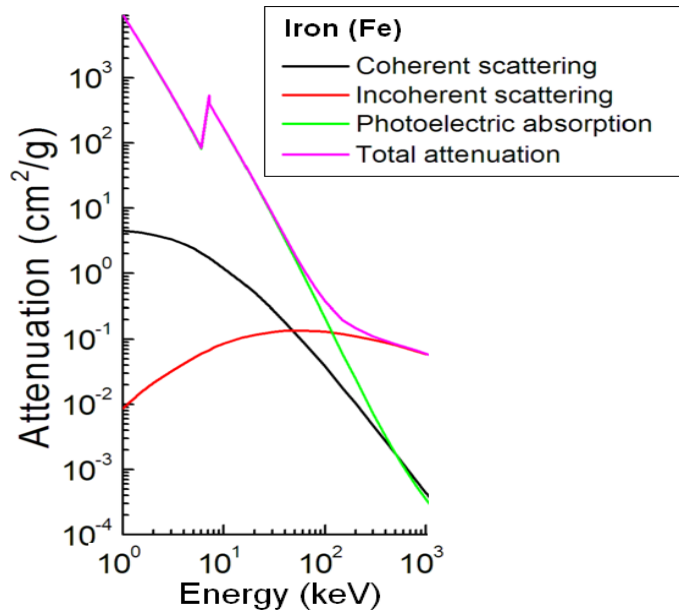
From very low (**~ 1 ph/s**) to full beam (**$\sim 10^{14}$ ph/sec**)

And very high X-ray ionising radiation dose rates are possible

e.g. **10^{12} ph/s** (10 keV) in $100\mu\text{m} \times 100\mu\text{m}$ = **3 MGy/s** (in silicon)

X-RAY TERMINOLOGY AT SYNCHROTRONS: ENERGY RANGES

Photon energy range		Typical detection technologies
Soft X-rays	200 eV – 2 keV	Drain current measurements <i>Si photodiodes</i> <i>MCPs</i> Direct detection CCDs <i>SDDs</i>
	2 – 20 keV Low/medium energy	PMTs, APDs Hybrid pixel detectors Indirect detection: <i>CCDs and CMOS</i> <i>Gas filled detectors</i> Silicon drift diodes (SDDs)
Hard X-rays	20 – 150 keV High energy	a:Si flat panels (CsI, a:Se) CMOS flat panels Indirect detection: <i>CCDs and CMOS</i> <i>Image plates</i> <i>Image intensifiers</i> HPGe



At 'synchrotron' energies, the photoelectric effect is usually the dominant interaction

Beer's law:

$$I(x) = I_0 \exp(-\mu(E) \cdot x)$$

The intensity of a photon beam decreases exponentially with distance into the material, *but the **energy** of photons in the transmitted beam remains the same.*

At very high energies the contribution of incoherent scattering (Compton) may be significant: not desirable for detectors...

- Main efforts in X-ray detector developments for SR applications focus on **hard X-rays**
- Not as many applications requiring soft X-ray detection:
 - Scattering cross-sections are low with soft X-rays, **absorption dominates**
 - **No Bragg diffraction**, main fluorescence lines are not excited
 - X-ray imaging requires **sufficient beam transmission** (~ 30%)
- Many soft X-ray beamlines are devoted to **electron and absorption spectroscopy**
- However some experiments need soft X-ray detectors:
 - Certain **resonant scattering techniques** need X-rays tuned to L or M absorption edges
 - **X-ray microscopy** benefits from soft X-rays (thin samples, full-field optics)
 - It is easier to produce **coherent beams** at longer wavelengths

X-RAY CONVERSION PROCESS/SENSORS

Sensors mostly used in SR X-ray detectors:

- ✓ **semiconductors** X-ray → electron-hole pairs
- ✓ **scintillators** X-ray → visible light → light sensor

Much less used in practice:

- ✓ **gas** X-ray → ions
 - Used primarily for diagnostics (ion chambers)
- ✓ **photocathodes** X-ray → photoelectrons
 - Certain soft X-ray applications or special cases (e.g. streak cameras)
- ✓ **microbolometers** X-ray → phonons → precision thermometer (TES)
- ✓ **superconductors** X-ray → charged quasiparticles
 - Count rates too low for fluorescence measurements at synchrotrons
 - Energy resolution is insufficient for spectroscopy experiments

SEMICONDUCTORS (DIRECT DETECTION)

X-rays generate electron-hole pairs (photoelectric absorption)

Efficient charge collection requires high resistivity *semiconductors*:

Possibility of depleting the active volume
Minimise dark current (may need cooling)

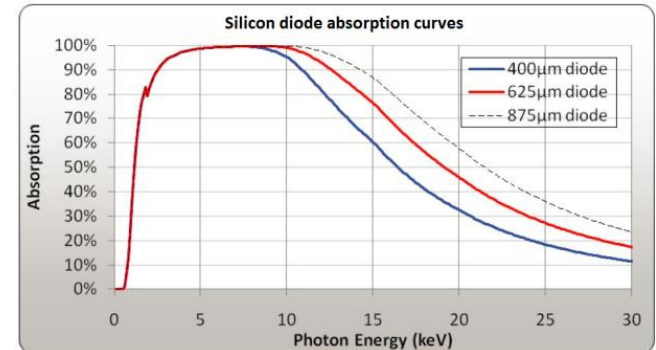
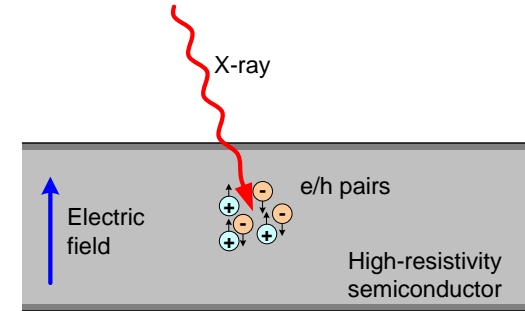
Usable X-ray photon energy range :

lower limit: due 'entrance window' cut-off
higher limit: sensor transmission

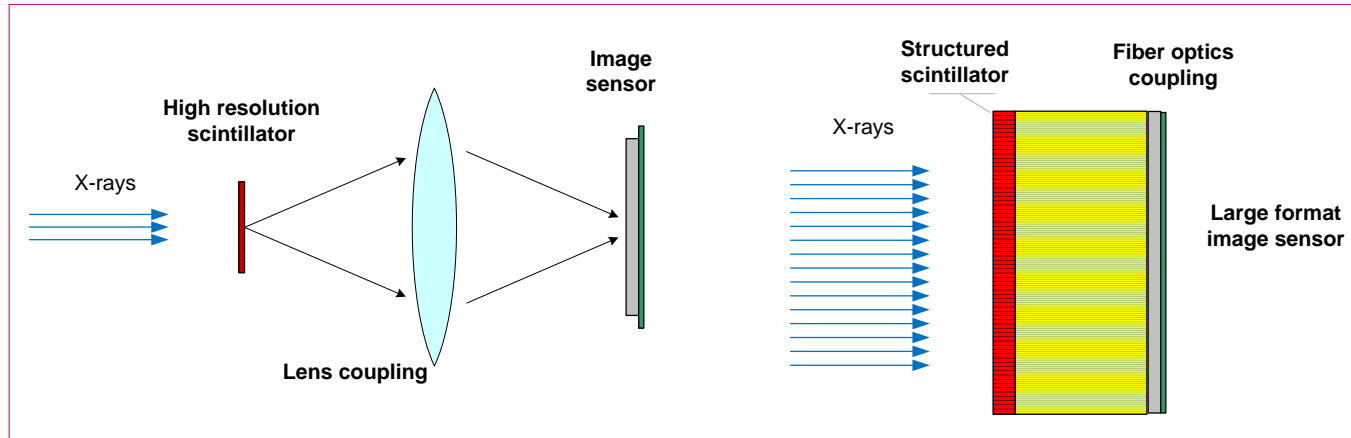
Silicon is the reference material, but:

limited energy range up to 15-20 keV
not too radiation hard devices

That is why other semiconductors are used or investigated (Ge, GaAs, CdTe, ...)



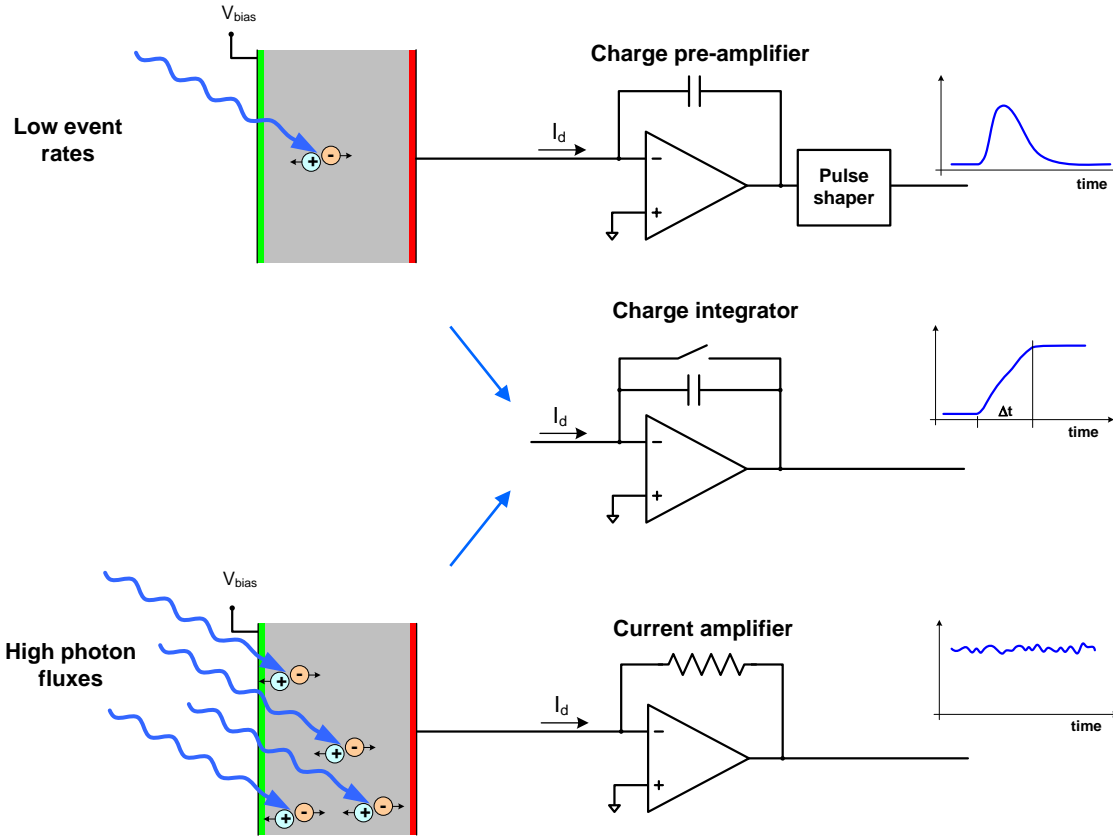
SCINTILLATORS (INDIRECT DETECTION)



Main key points:

- Scintillators can be radiation hard (not always the optics)
Convenient also for practical and cost reasons
- High spatial resolution is possible (optical magnification)
- Efficient for high energy photons.

BASIC READOUT PRINCIPLES



Charge integration can be partially or totally built in the sensor (i.e. CCDs)

Used for very high fluxes: i.e. beam intensity measurements

Quantities to measure:

intensity:

- *photon flux integrated over a given time interval*

photon energy

- *energy dispersive detectors*
- *single photon processing*

position

- *intrinsic to 1D and 2D detectors*

Others:

photon arrival time

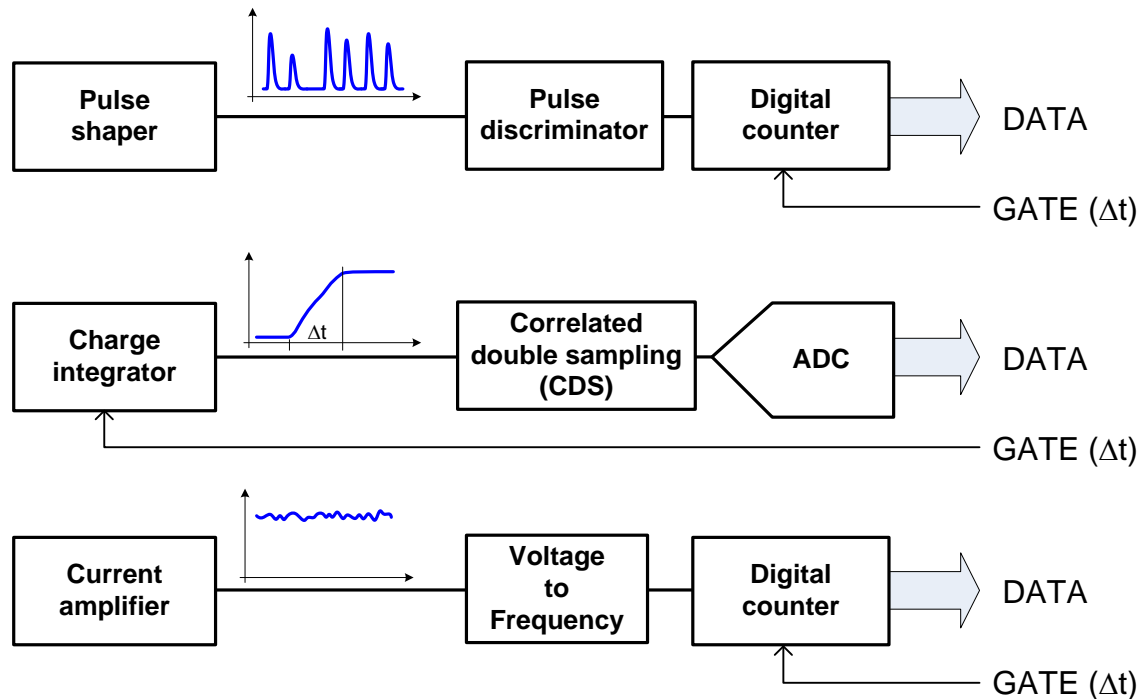
- *event timestamping, ultimate time resolution*

polarisation

- *usually done with X-ray optics (polarization analysers)*

INTENSITY MEASUREMENTS

The X-ray intensity is measured by integrating the signal during an exposure time Δt :



Pulse discriminator: from simple level discrimination to complex pulse-height analysis

CDS is most often built in the charge integration scheme

Also signal sampling (ADC) + digital integration

'Undesired' components of the measurement

- **Noise:** *random and unbiased*
- **Systematic effects**

Correction of systematic errors in intensity measurements:

- **offset** (*dark signals, electronics offsets*)
- **flat field** (*efficiency or gain inhomogeneity*)
- **spatial distortion** (*construction defects, parallax errors, ...*)
- **linearity corrections:**
 - *charge integrating detectors: non-ideal electronics (INL correction)*
 - *photon counting detectors: photon pile-up (**deadtime correction**)*

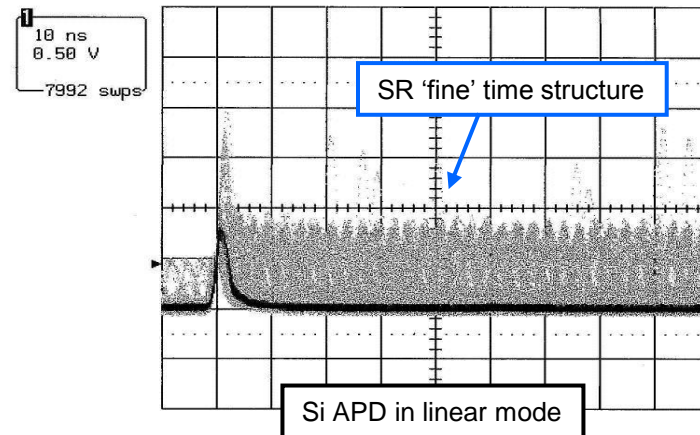
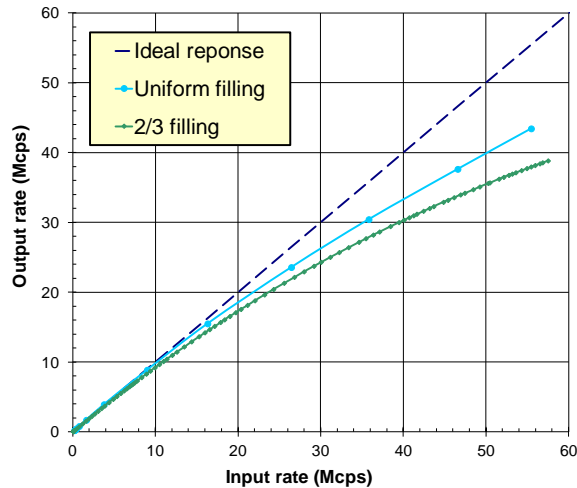
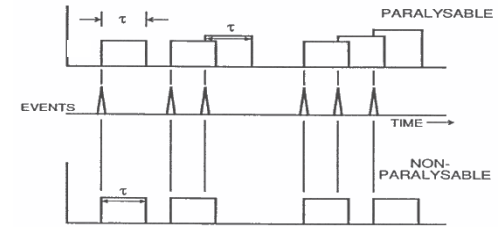
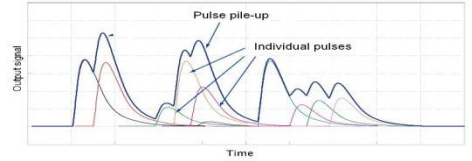
PILE-UP AND DEAD TIME CORRECTIONS

deadtime: the time required by the counting channel after the arrival of a photon to count properly a second one.

From few ns to few μ s

In SR applications count rates are usually high \rightarrow deadtime corrections are mandatory.

Corrections depend on the time structure of the X-ray beam (accelerator filling pattern of the storage ring)



Noise **cannot be corrected** (random nature) → must be minimised (development + usage)

Noise is meaningful as a relative value:

Signal-to-Noise ratio: (S / N)

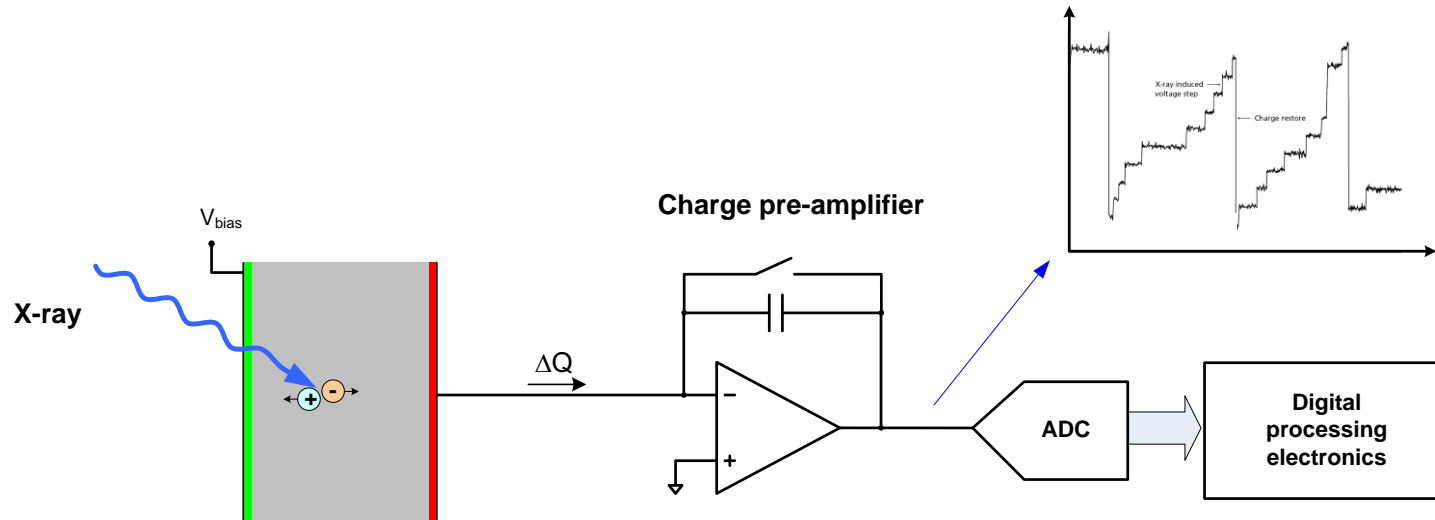
Dynamic Range: $DR = S_{max} / N$

Any effect that degrades the (S/N) ratio can be considered as an effective source of noise

'Effective noise' sources:

- Photon fluctuations (input noise) $\sigma_{N_{ph}} = \sqrt{N_{ph}}$ (Poisson noise)
- Quantum efficiency (QE) of the sensor
- Fluctuations of the conversion process: X-ray → e-
- Dark current fluctuations
- Readout electronics:
 - preamplifier noise (analog)
 - digitisation/quantisation noise (ADC resolution, V-to-F max. frequency, ...)
- Interference/coupled noise (50Hz, pumps, motors, power supplies)

ENERGY DISPERSIVE DETECTORS



Evaluate the **photon energy** by measuring the charge generated in the sensor

Today EDX experiments often make use of very fast **digital pulse processors** (DPP) that implement rather sophisticated algorithms:

- Fast channel to identify photon events (hits)
- Slow channels to evaluate charge/energy content associated to each individual event

ENERGY RESOLUTION

The resolution of the detector at a certain energy is usually defined as the full width at half-maximum (FWHM) of recorded spectra.

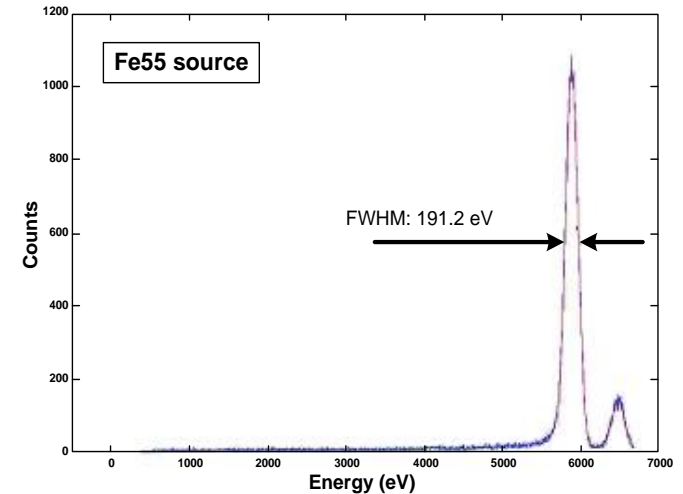
$$\text{FWHM} = 2.35 \sigma_E$$

The *measured* spectral resolution is the quadratic-sum of various noise sources present in the detector:

$$\text{Resolution} = \sqrt{(\text{conversion noise})^2 + (\text{dark current noise})^2 + (\text{preamplifier noise})^2}$$

Dominant terms

Can be reduced by
proper sensor design
and cooling



CHARGE GENERATION FLUCTUATIONS

The number of elementary charges generated by a single X-ray photon, N_Q , can be estimated as :

$$N_Q = \frac{E_{\text{photon}}}{\varepsilon_i}$$

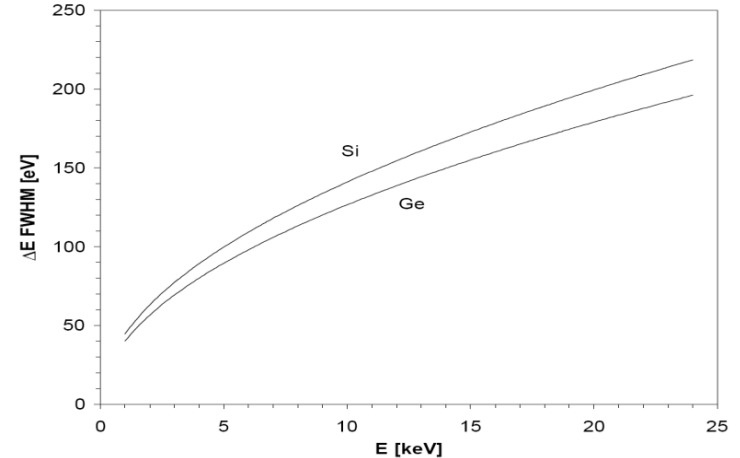
Where the ionisation energy ε_i is the average energy required to produce an elementary charge.

In silicon : $\varepsilon_i = 3.6 \text{ eV}$, a 10 keV photon produces 2800 e/h pairs.

The RMS fluctuation (σ_E) associated to the charge generation

$$\left. \begin{array}{l} \sigma_{N_Q} \propto \sqrt{N_Q} \\ \sigma_E = \varepsilon_i \sigma_{N_Q} \end{array} \right\} \longrightarrow \sigma_E \propto \sqrt{E_{\text{photon}} \varepsilon_i}$$

Intrinsic resolution of Si and Ge detectors (Fano noise)



In semiconductors $\sigma_E = \sqrt{F E_{\text{photon}} \varepsilon_i}$ usually known as “Fano noise”

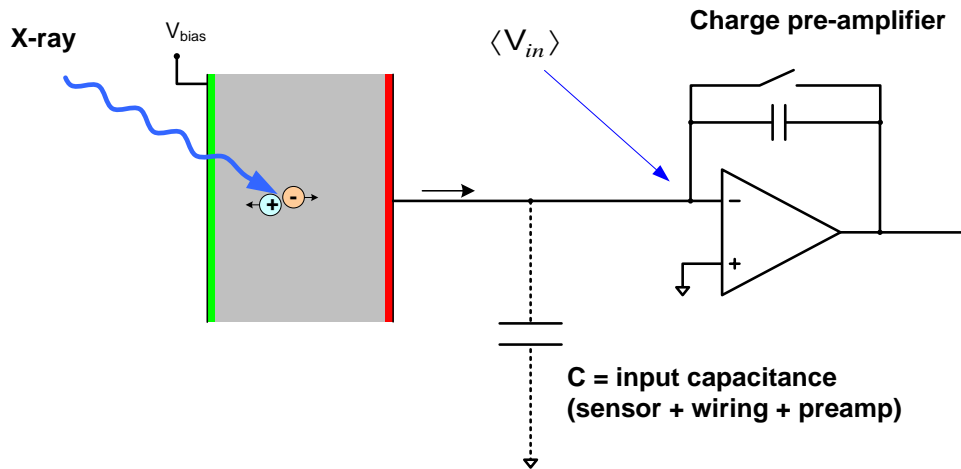
where F is the Fano factor ($F \approx 0.11$ for Si and Ge)

U. Fano, Phys. Rev. **72** (1947) 26

PREAMPLIFIER NOISE

Careful electronics design may reduce the noise contributions to the charge preamplifier noise as the main component.

The electrical capacitance seen at the input node plays a fundamental role through the “equivalent input voltage noise” $\langle V_{in} \rangle$ of the amplifier:



Contribution to charge noise (ENC):

$$\langle Q_{noise} \rangle = C \times \langle V_{in} \rangle$$

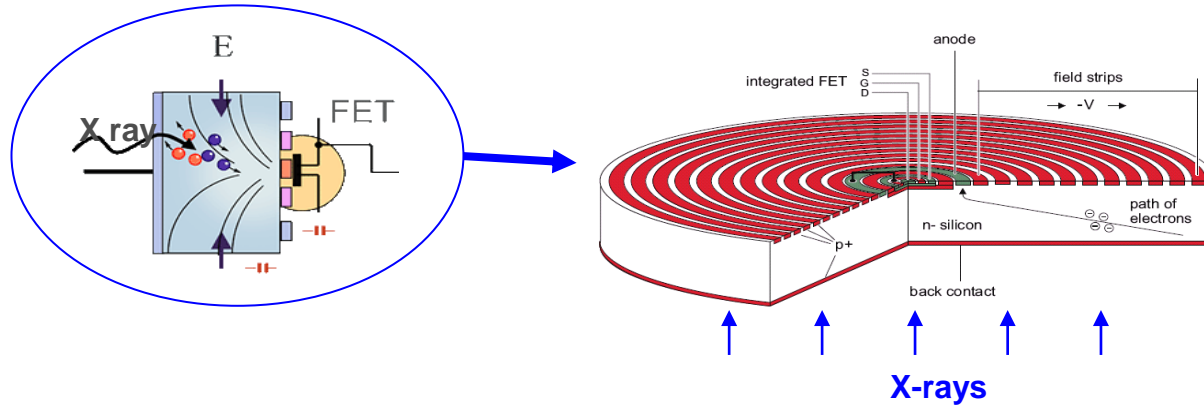
The preamplifier noise in ‘charge’ units is critically dependent on the input capacitance

SILICON DRIFT DIODE (SDD)

The **SDD** is an excellent example of '**capacitance reduction**' techniques:

Multielectrodes create a *transverse drift field* that drives the charge towards a small anode

Charge is collected over large surface area (up to 1cm^2) without increasing the anode capacitance



High rate capability $\sim 1\text{Mcps/channel}$, with nearly 'Fano limited' energy resolution

SDDs is the reference energy dispersive detectors for synchrotron applications.

But relatively thin ($< 1\text{mm}$) detectors and limited to low energies ($< 15\text{keV}$)

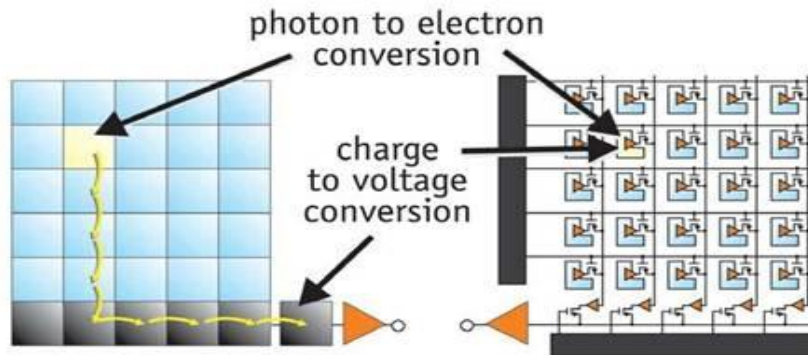
Can operate with moderate cooling (Peltier cooling $-10^\circ\text{C}\dots-50^\circ\text{C}$)

DETECTOR CHANNEL CONFIGURATION

a) **Single element** (0D)

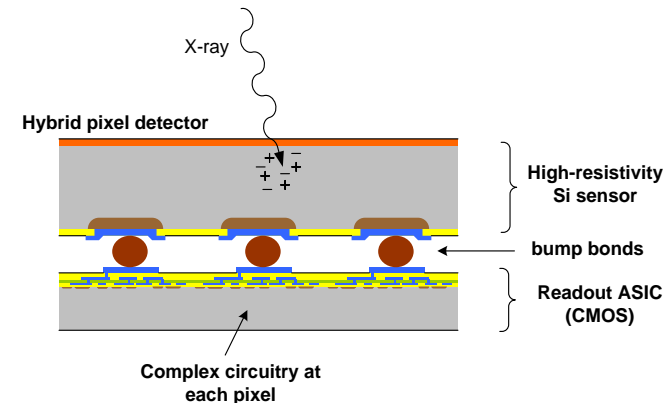
b) **Multielement**: discrete or monolithic sensors
readout: packaging of single element channels

c) **Position sensitive** (large 1D or 2D detector arrays)
from thousand to millions of channels (strips or pixels)
various technologies and readout mechanisms:



Charge coupled device
(CCD)

CMOS image sensor

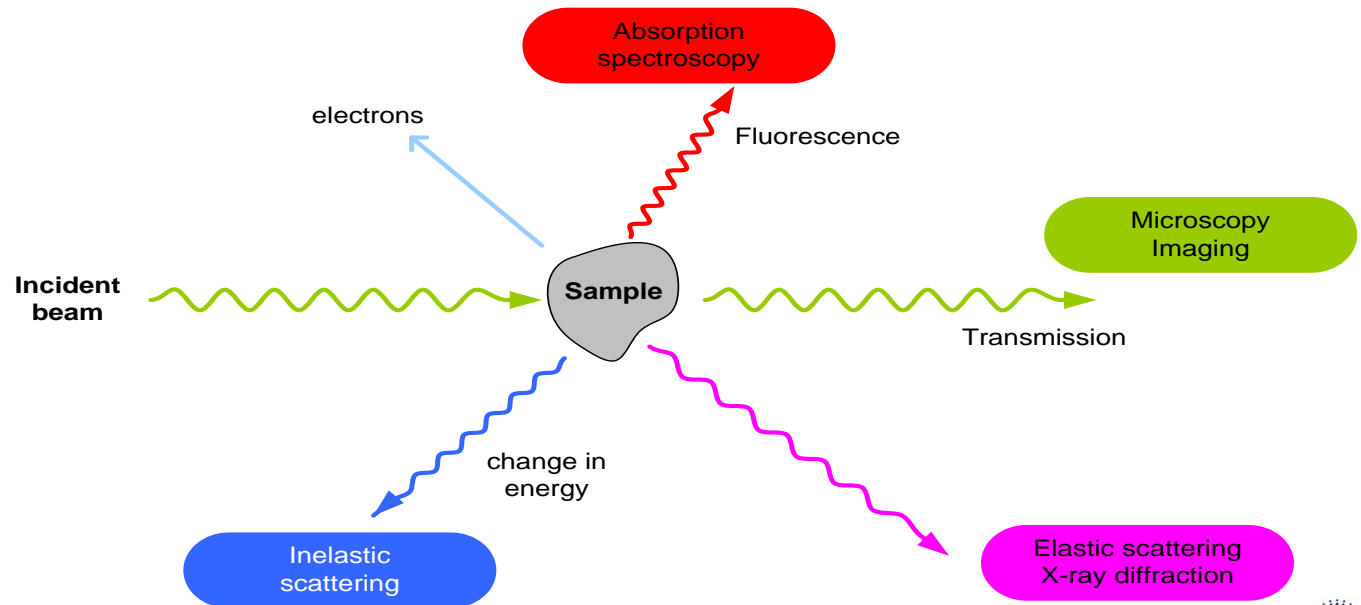


Hybrid pixel detector

3 MAIN “FAMILIES” OF X-RAY DETECTORS FOR SR EXPERIMENTS

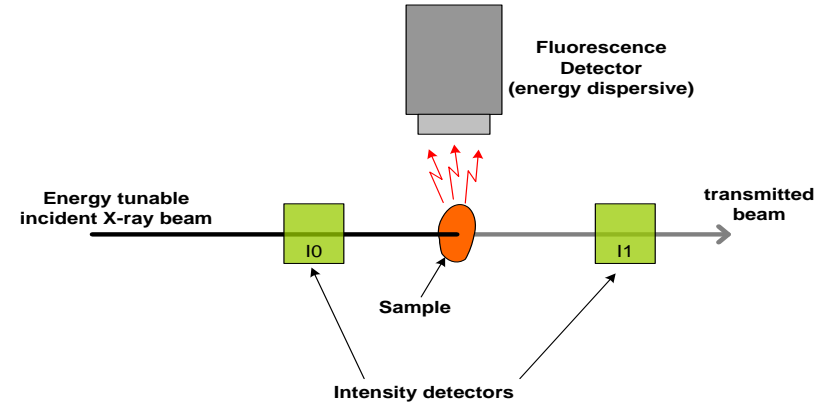
Simplified classification based on application (type of interaction):

- **Energy dispersive** detectors (fluorescence)
- **Diffraction / scattering** detectors (elastic/inelastic scattering)
- **X-ray imaging** (transmitted beam)



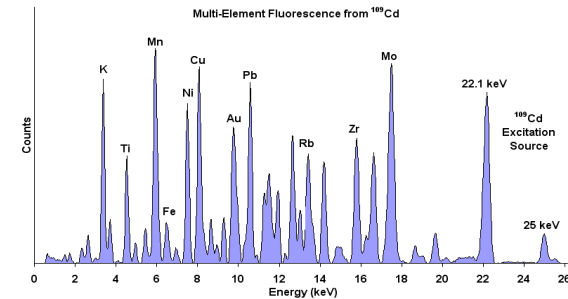
Absorption spectroscopy:

- Sample absorption (as a function of energy)
- Polarization dependence (dichroism)
- Measure either:
 - Transmitted intensity (I_1/I_0)
 - or
 - Fluorescence yield
- Detectors:
 - Intensity: ion chambers, photodiodes
 - Fluorescence: semiconductor detectors

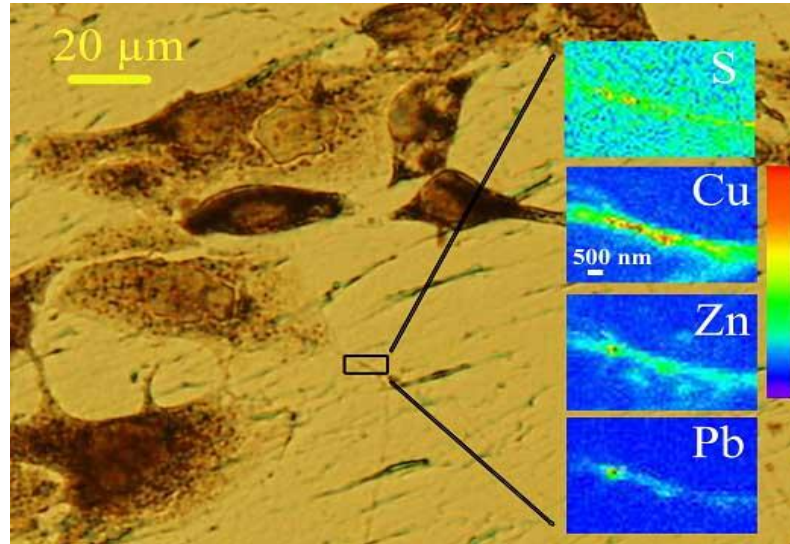


Fluorescence analysis:

- Measurement of fluorescence lines
chemical analysis, mapping, ultra-dilute samples
- Detection: semiconductor detectors



FLUORESCENCE 2D ENERGY RESOLVED 'IMAGING' OF SAMPLES



ESRF ID22-NI

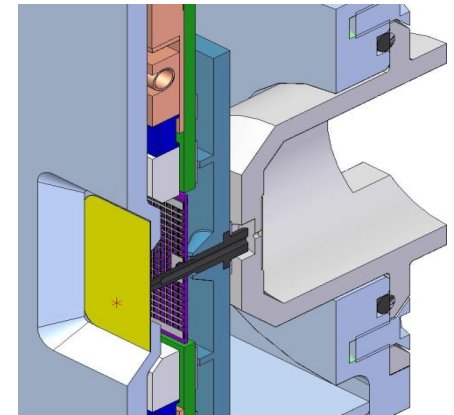
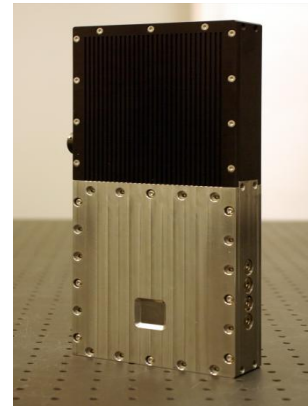
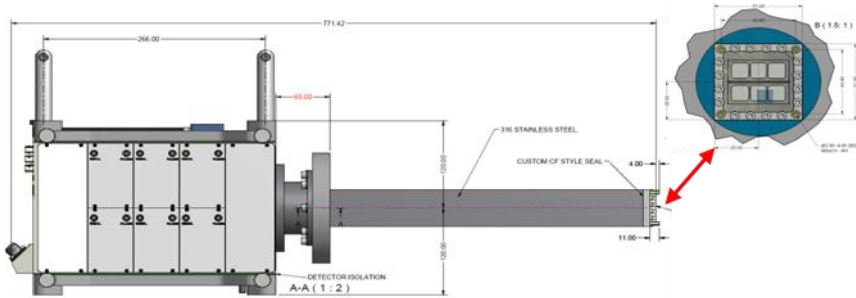
Neurite process
A Carmona et al.
JAAS (2008)

ENERGY DISPERSIVE DETECTORS IN SR EXPERIMENTS

Off-the-shelf detectors (most used in practice in SR experiments):

- Silicon drift diodes (SDDs)
- High purity germanium detectors (HPGe)

Customised instruments (multielement and special devices):



ESRF/ID16A

- SDD 6 element arrays = $2 \times 540\text{mm}^2$
- Energy range $\sim 2\text{...}20\text{keV}$
- Global *throughput* count rate to $\sim 6\text{Mcps}$
- 1kHz readout by XIA-XMAP pulse processors

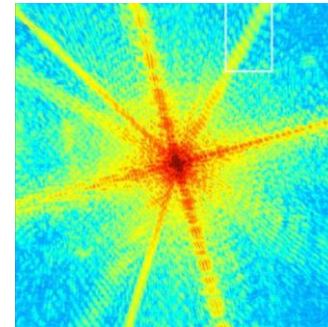
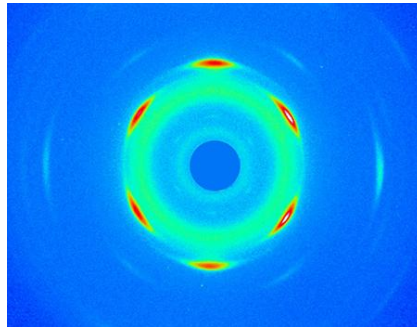
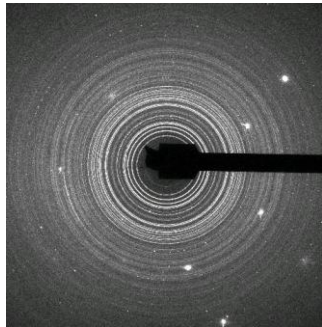
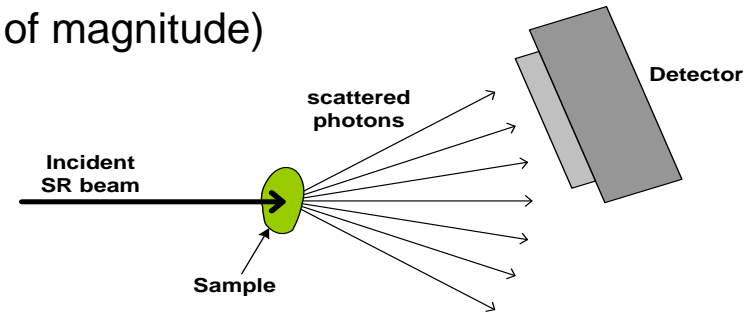
Sensors from PNdetectors integrated by SGX Sensortech

Maia (CSIRO and BNL/NSLS)

- Large solid-angle (1.2 sr)
- High-rate capability (384 Si PIN diodes)

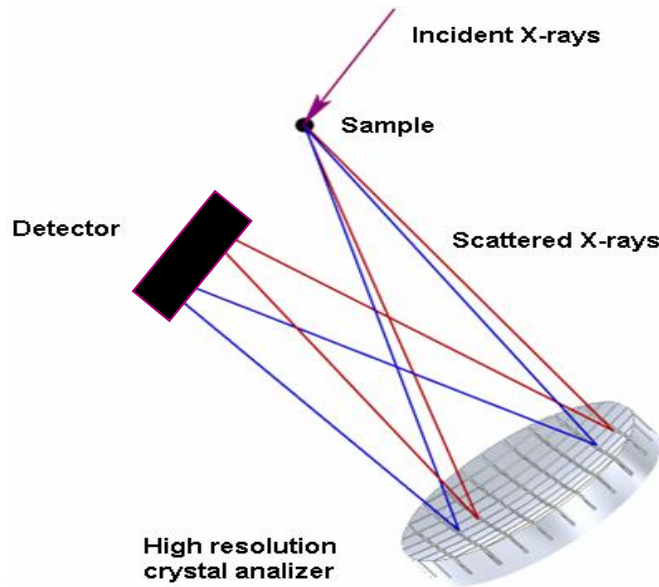
ELASTIC SCATTERING (DIFFRACTION, SAXS, ...)

- Scattered photons conserve the energy of incident ones
- Solid angle collection (0D (scanning), 1D or 2D)
- Spatial resolution depends on detector-sample distance
- Large dynamic range requirements (many orders of magnitude)



INELASTIC SCATTERING

- Measurement of the recoil energy transferred to the sample by the X-rays.
- Very high energy resolution is required: 1 meV – 1 eV (for hard X-rays)
- Use of wavelength dispersive detection setups:
High resolution crystal analyzers + photon detector

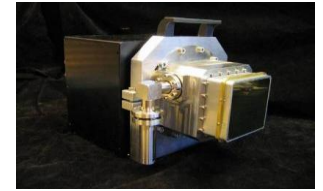


- Needs highly monochromatic radiation
- Very low photon fluxes (counting)
- Position sensitivity detection helps to improve energy resolution

Main technologies for 2D detectors

❑ CCD based

Indirect (hard X-rays) or direct (soft X-rays) detection schemes
Mature technology (little room for improvement)



❑ Flat panels (medical imaging)

a:Si (TFT technology)
CMOS flat panels (tiling or CMOS image sensors)



❑ Hybrid pixel detectors

Today only photon counting devices



1. Detection Layer

Depleted, high resistivity semiconductor:
silicon, GaAs, CdTe...

Individual 'pixels' formed lithographically

2. 'sandwich' construction **connecting bumps**

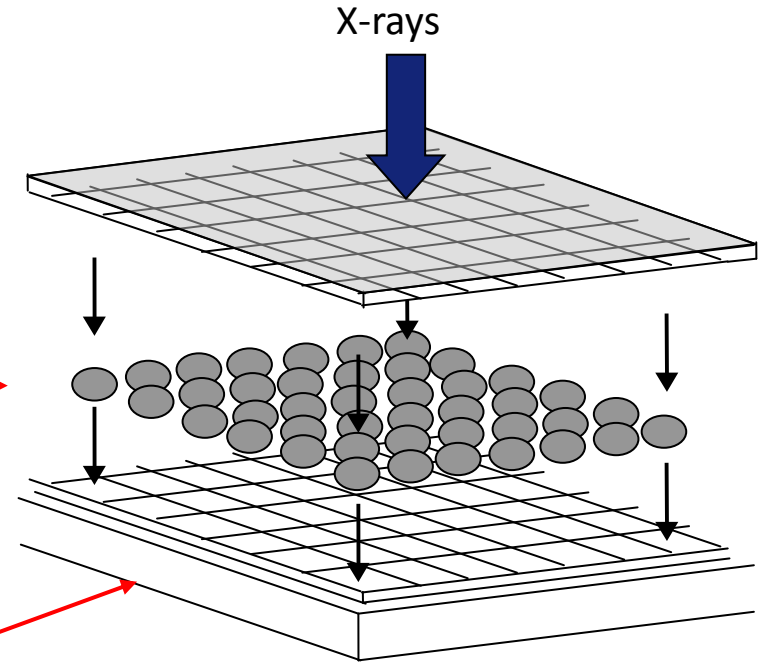
Solder or indium lithographically deposited

$\sim 10^{4...5}$ pixels are individually connected

3. **Mixed analogue-digital ASIC readout** CMOS 'chip'

pixel parallel signal processing: analogue preamp, shaper, thresholds, counter
readout interface (serial-parallel)

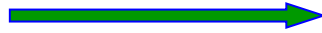
wide range of possibilities for analogue input stage and digital readout architectures



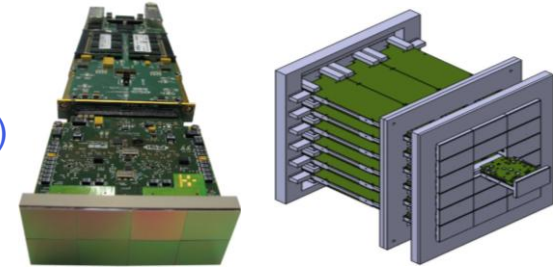
PHOTON COUNTING HYBRID PIXEL DETECTORS

Upcoming generation of detectors push the frame rate by more than one order of magnitude

PILATUS
(PSI/SLS)



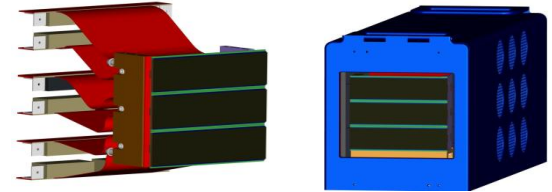
EIGER (PSI)



XPAD3
(CNRS/Soleil)



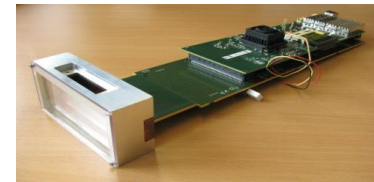
EXCALIBUR (STFC/Diamond)



MAXIPIX
(ESRF)

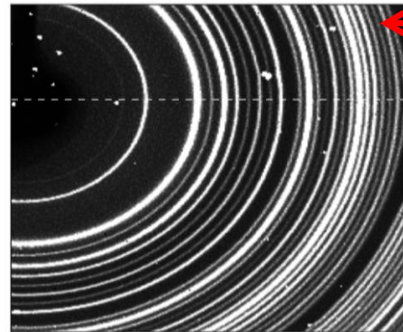
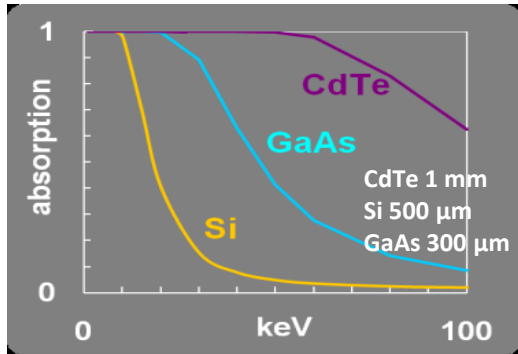


LAMBDA (DESY)



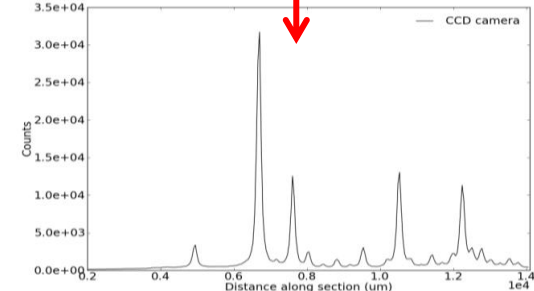
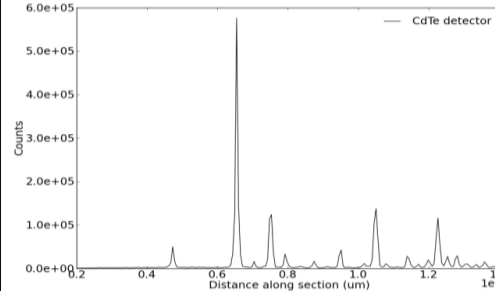
Pixel detector (Maxipix) vs. CCD detector (Frelon)

Quantum efficiency



Yb₂O₃ nano-powder diffraction rings at 50 keV.

Comparison with CCD Detector (50 μm pixel pitch): No significant background, sharper peaks, more low intensity rings

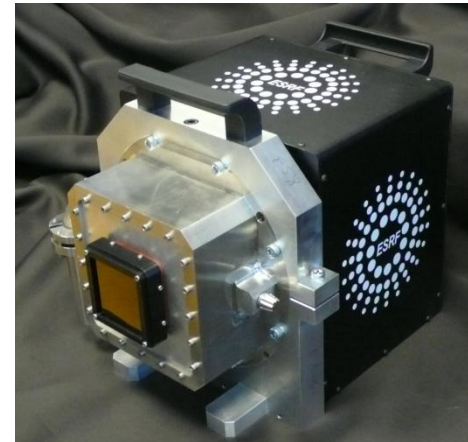
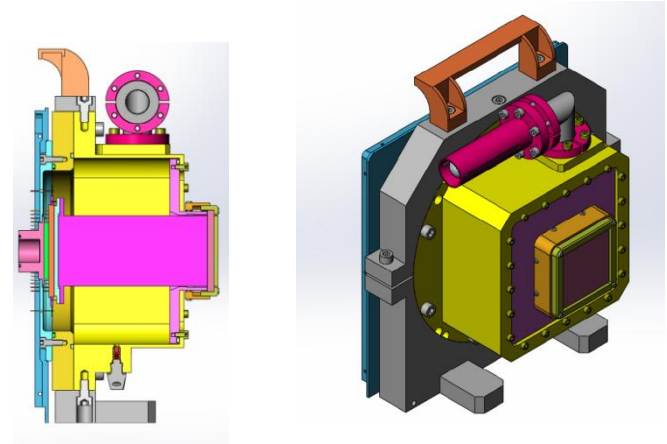


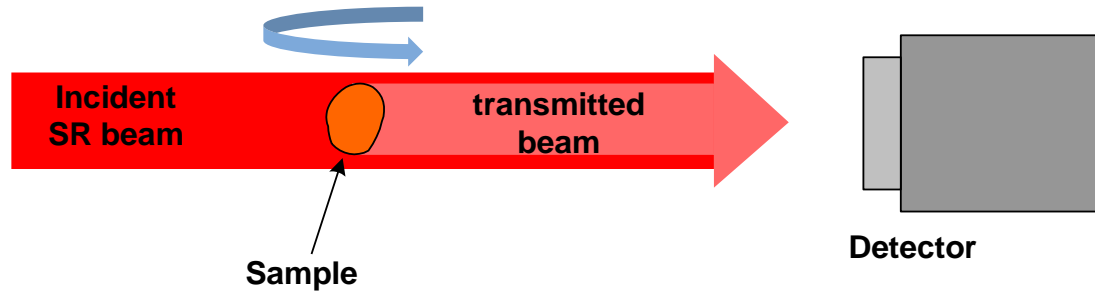
M. Ruat and C. Ponchut, *IEEE Trans. Nucl. Sci.*, Vol. 59, n° 5, pp. 2392-2401, August 2012

M. Ruat, E. Gros d'Aillon and C. Ponchut, *Proceedings of the 2012 IEEE NSS/MIC/RTSD conference*

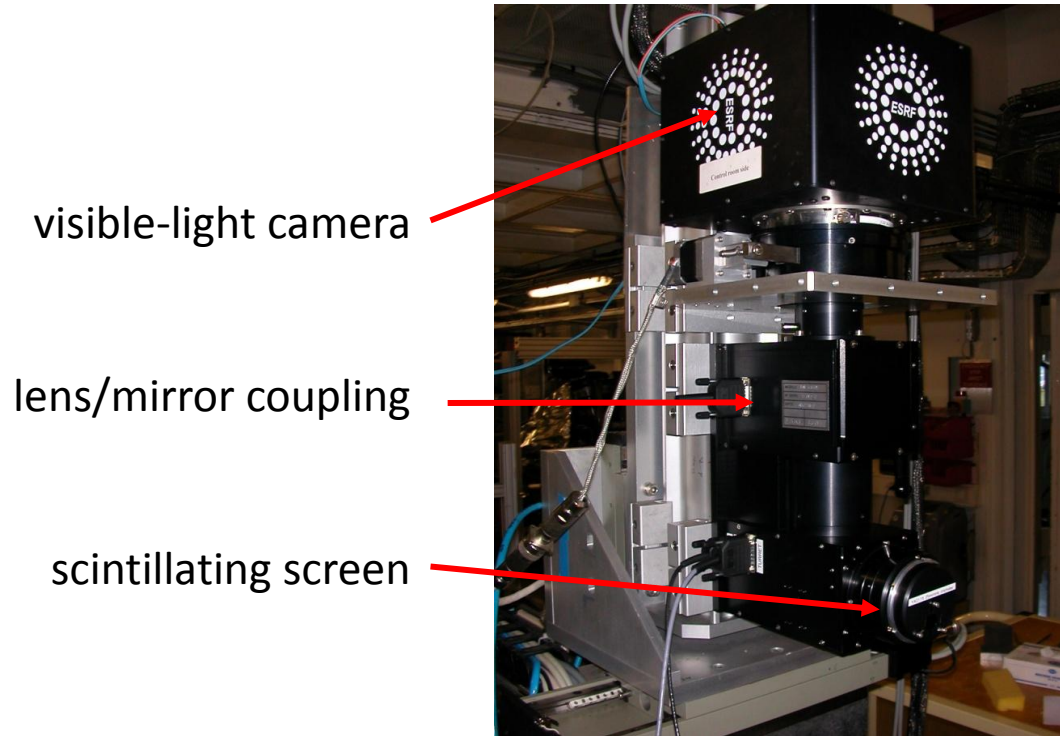
Ultra-Small Angle Scattering (USAXS)

- **FReLoN based detector with fiber optics faceplate**
 - *CCD:* Kodak KAF4320
 - *Number of pixels:* 2048 × 2048
 - *Pixel size:* 24μm × 24μm
 - *Active area:* 50 × 50 mm²
 - *Max. frame rate:* 5 frames/sec
- *Measurements @ 8 keV and 2 frames/sec:*
 - Spatial resolution (LSF): 50 μm FWHM
 - RMS Noise: 1.8 keV
 - Dynamic range: 4×10⁴

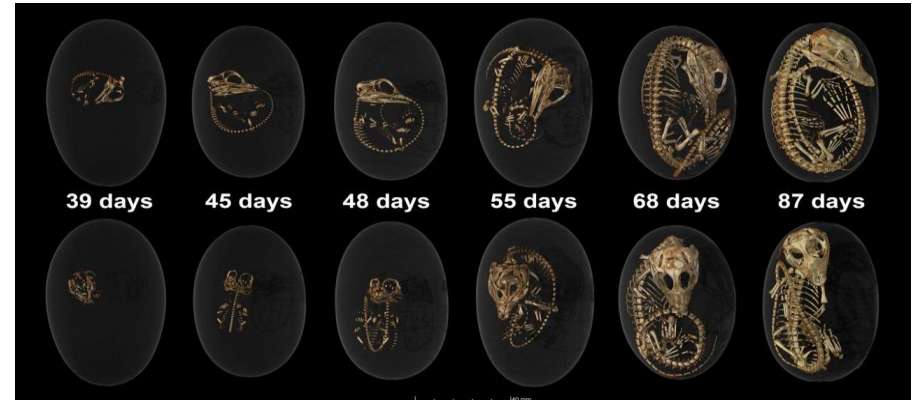
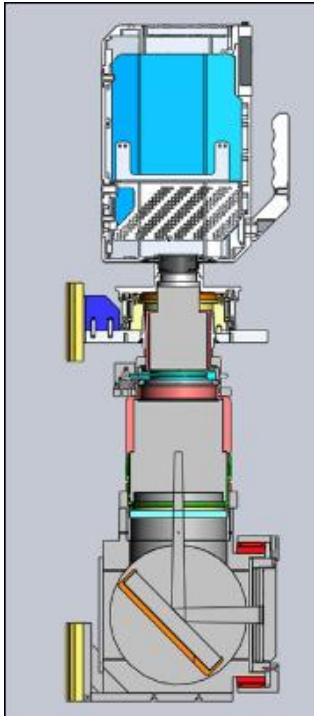




- The detector sees a projection image of the sample absorption or phase contrast (beam is partially coherent)
- Very high flux on the detector (close to the full incident beam)
- Small pixels (0.5 to 50 μm)
- Indirect detection schemes are required
- 3D imaging is made by tomographic reconstruction from sets of 2D images acquired during sample rotation



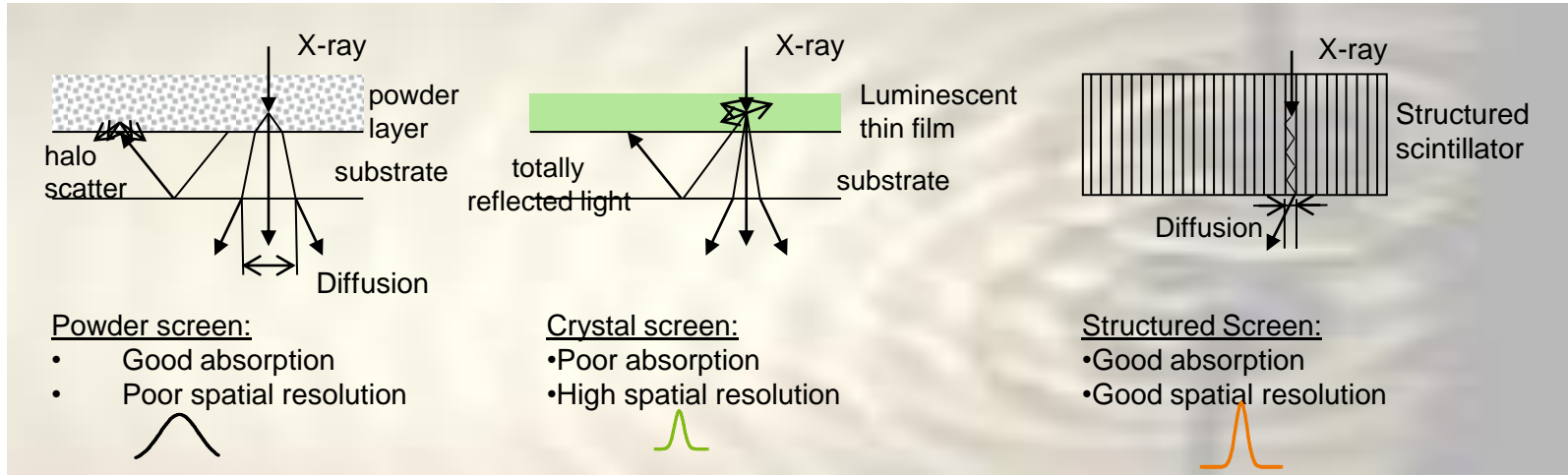
EXAMPLE: LARGE FIELD-OF-VIEW IMAGING DETECTOR



Development of an in-vivo crocodile
(Courtesy of P. Tafforeau, ID19)


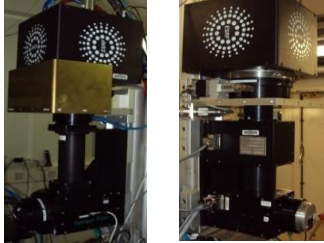
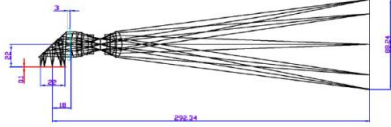

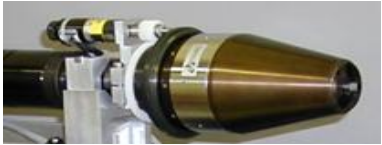
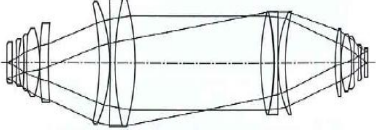
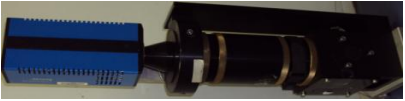
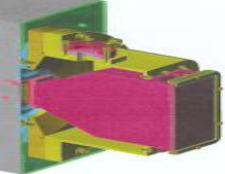
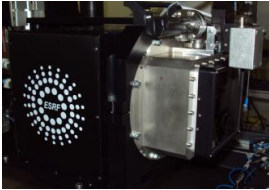
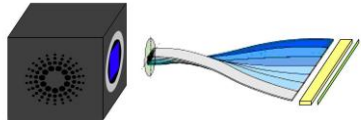
Pixel size	49 μm
FOV	100x20 mm ²
QE @ 100 keV	> 99%

TYPES OF SCINTILLATORS



Applications	Large field of view (cm)	High resolution (μm)	High Energy (>30keV)
2000	Mammography screens	Bulk crystal (YAG) Single Crystal Film (LuAG)	Mammography screen
2015	Custom Gadox screens	Bulk crystal (LuAG) Single Crystal Film (LSO)	Semistructured CsI(Tl)
Future	New deposition process Higher density, smaller grain Faster phosphors	Bulk Crystal (Ceramic) SCF (LuAlO_3 , $\text{Lu}_4\text{Hf}_3\text{O}_{12}$, HfO_2)	Structured new materials filled with CsI(Tl) or nano powders

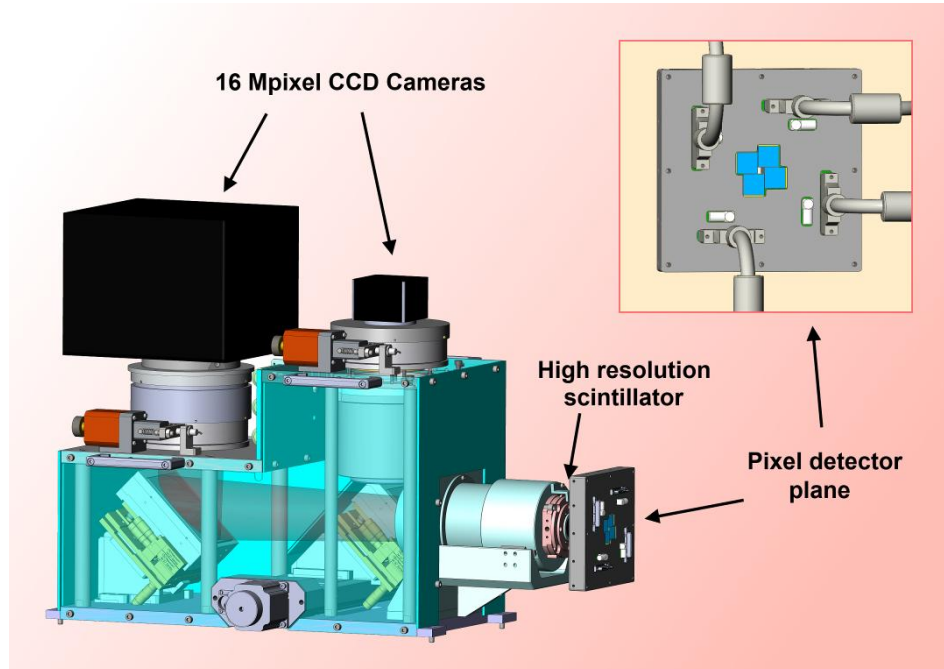
OPTICS FOR IMAGING DETECTORS

Resolution	Past	Recent	On going
<p>High</p> <p><i>Refractive optics</i></p> <p>200 – 500nm</p>			
<p>High</p> <p><i>Reflective optics</i></p> <p>1 – 3 μm</p>			<p>Custom optics for enhancement of imaging contrast and speed in UV-blue band</p>
<p>Medium</p> <p><i>Tandem lens</i></p> <p>5 – 30μm</p>			<p>Custom optics for larger fields of view</p>
<p>Low</p> <p><i>Fibre optics</i></p> <p>20 – 50μm</p>			

EXAMPLE OF COMPOSITE DETECTOR

High resolution X-ray imaging and ptychography

- **Pixel detector plane for cSAXS**
 - 4 Maxipix detector single-chip modules
 - Edgeless sensors
 - Central hole $\sim 5 \times 5 \text{ mm}$
- **Two high resolution 16 Mpixel detectors**
 - 10x, 5x custom design optics
 - $1.5 \mu\text{m}$ pixel size
 - High resolution scintillators
 - Cameras: FReLoN e2v and SVS HR16070



*Detector in operation
at ID16A/ESRF*

- ✓ X-ray detectors are key components of experimental stations that use synchrotron radiation beams to probe a diversity of samples. Detector requirements are strongly dependent on the experimental technique and on the specific application setup.
- ✓ We have presented some of the basic principles and major detector types used at synchrotron sources and given a basic summary of their operation, but there are other detector types in use, not described here.
- ✓ SR detectors have to deal most often with hard X-rays (from few keV to >100keV). Compatibility with very high photon fluxes and radiation doses is a relatively frequent requirement.
- ✓ The majority of current SR detectors rely either on direct detection in semiconductor devices or on the use of phosphor screens (X-ray to light converters).
- ✓ Silicon drift diodes (SDDs) are the reference energy dispersive detectors in SR experiments as well as hybrid pixel detectors are progressively replacing other types of 2D detectors used for scattering and diffraction applications. Indirect detection technologies are however essential for high energy and high spatial resolution X-ray imaging.

... Thank you ...