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X-ray Detectors for Synchrotron Radiation Applications

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ESRF | The European Synchrotron

OUTLINE

- **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
  - X-ray imaging
  - Scattering/diffraction detectors

SR BEAMS AT STORAGE RINGS: SOME TYPICAL NUMBERS

Beam at the sample

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

Photon flux (@ $\delta E/E = 10^{-4}$): up to **10^{14} ph/sec** ***(up to 10^{16} with pink beam)***

X-ray beam used as probe

Although X-rays may also be used to modify the samples (chemical reactions, radiotherapy, …)

Extremely variable flux at the detector depending on the application

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

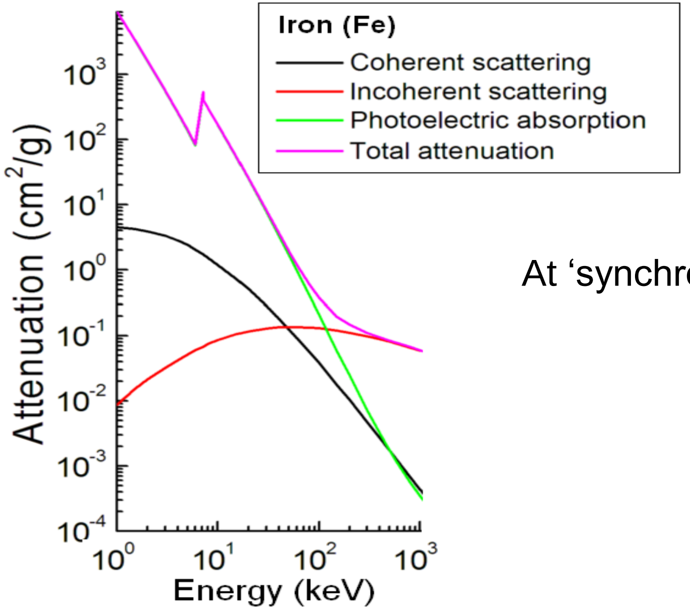
And very high X-ray ionising radiation dose rates are possible

e.g. **10^{12} ph/s** (10 keV) in 100μm×100μm = **3 MGy/s** (in silicon)

X-RAY ENERGY RANGES

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

INTERACTION OF X-RAYS WITH MATTER



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

Beer's law: $I(x) = I_o \exp(-\mu(E).\ x)$

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

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

X-RAY CONVERSION PROCESS/SENSORS

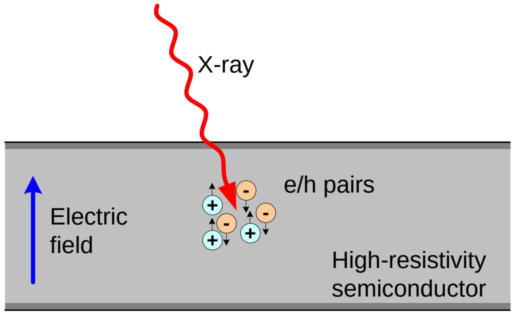
Sensors mostly used in SR X-ray detectors:

- ✓ ***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, MMC)**
- ✓ ***superconductors*** **X-ray → charged quasiparticles (STJ)**
  - Count rates too low for fluorescence measurements at synchrotrons
  - Energy resolution is insufficient for spectroscopy experiments

SEMICONDUCTORS (DIRECT DETECTION)

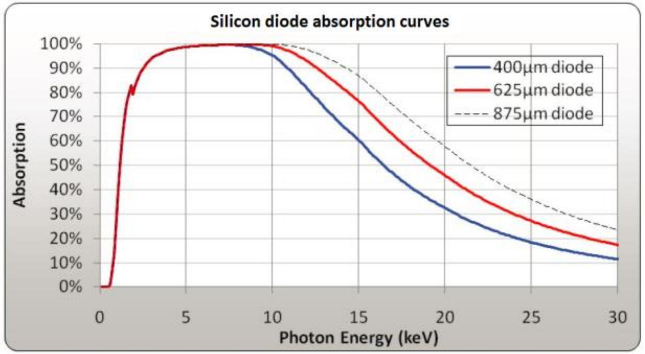


X-rays generate electron-hole pairs (photoelectric absorption)

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

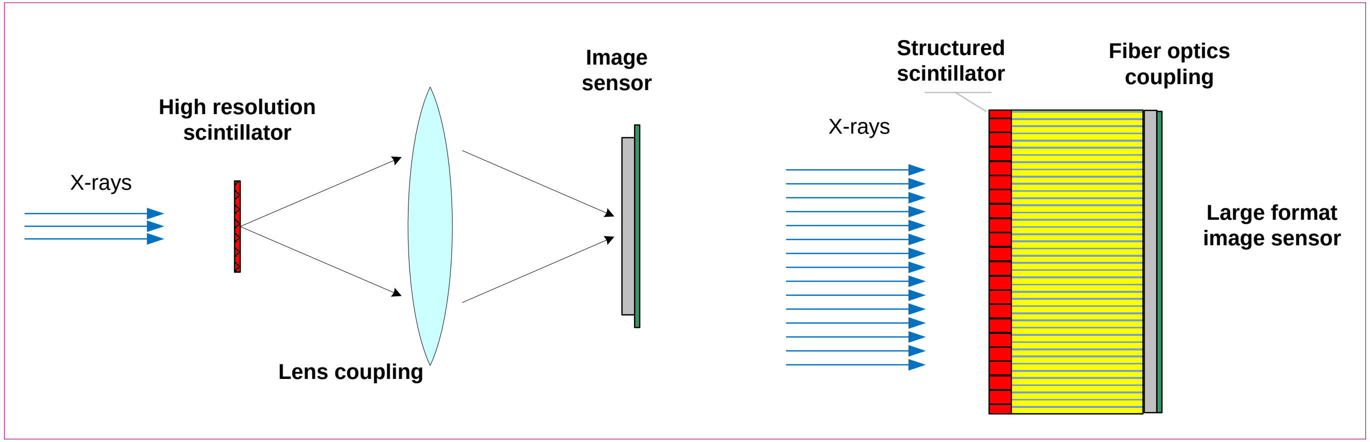
Silicon is the reference material, but:

limited energy range up to 15-20 keV

not too radiation hard devices

That is why other semiconductors are used or investigated (Ge, GaAs, Cd(Zn)Te, …)

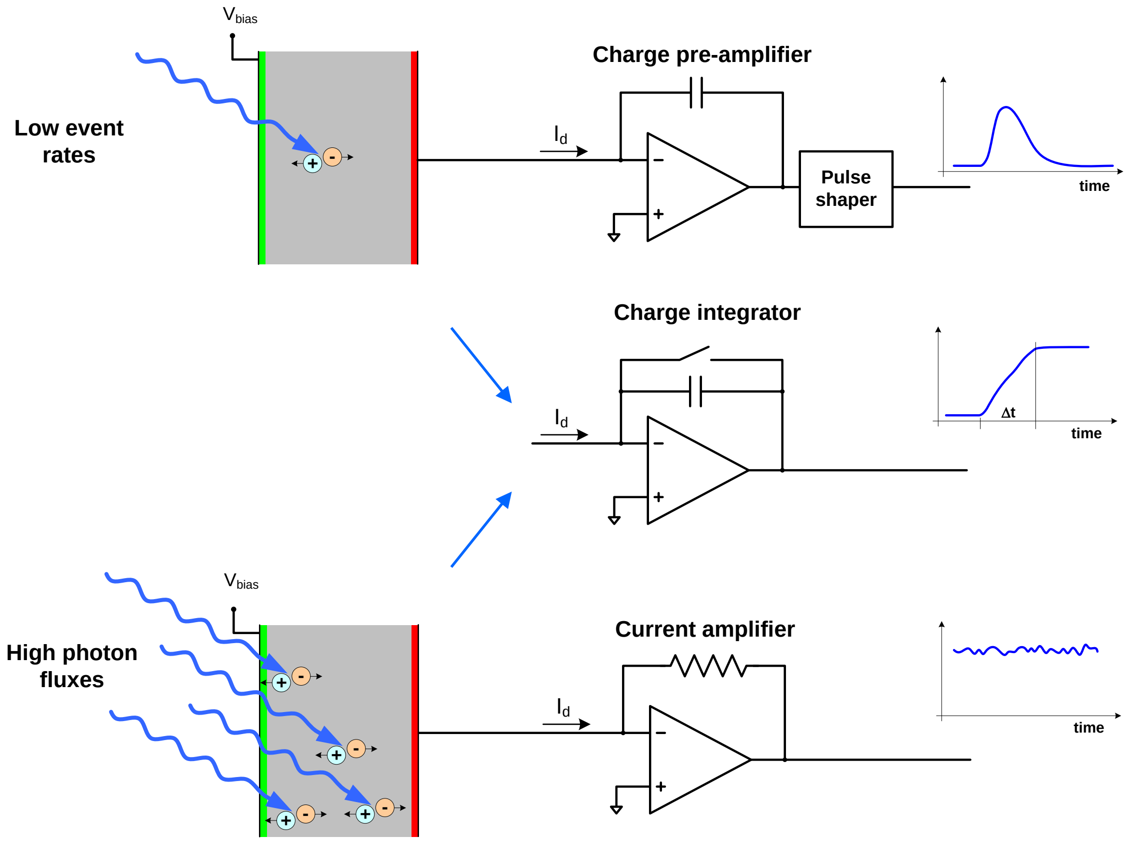
SCINTILLATORS (INDIRECT DETECTION)



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

DETECTOR MEASUREMENTS

Quantities to measure:

intensity:
- *photon flux integrated over a given time interval*

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

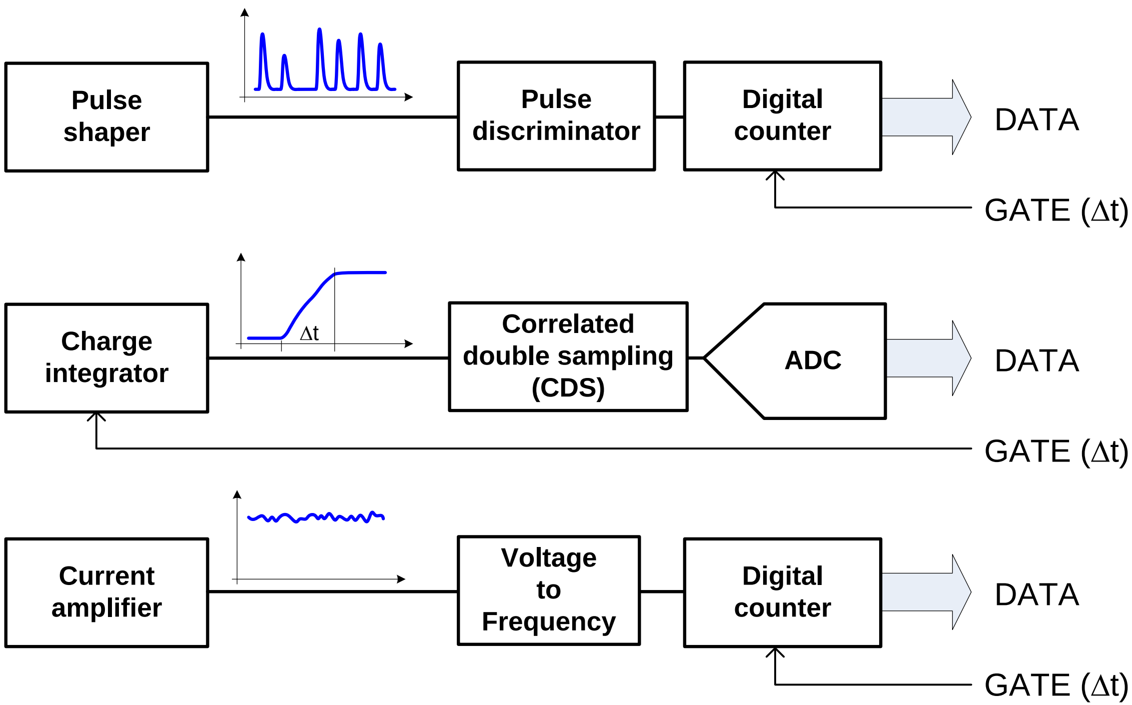
position
- *intrinsic to 1D and 2D detectors*

Others:

photon arrival time
- *event timestamping, ultimate time resolution*

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

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

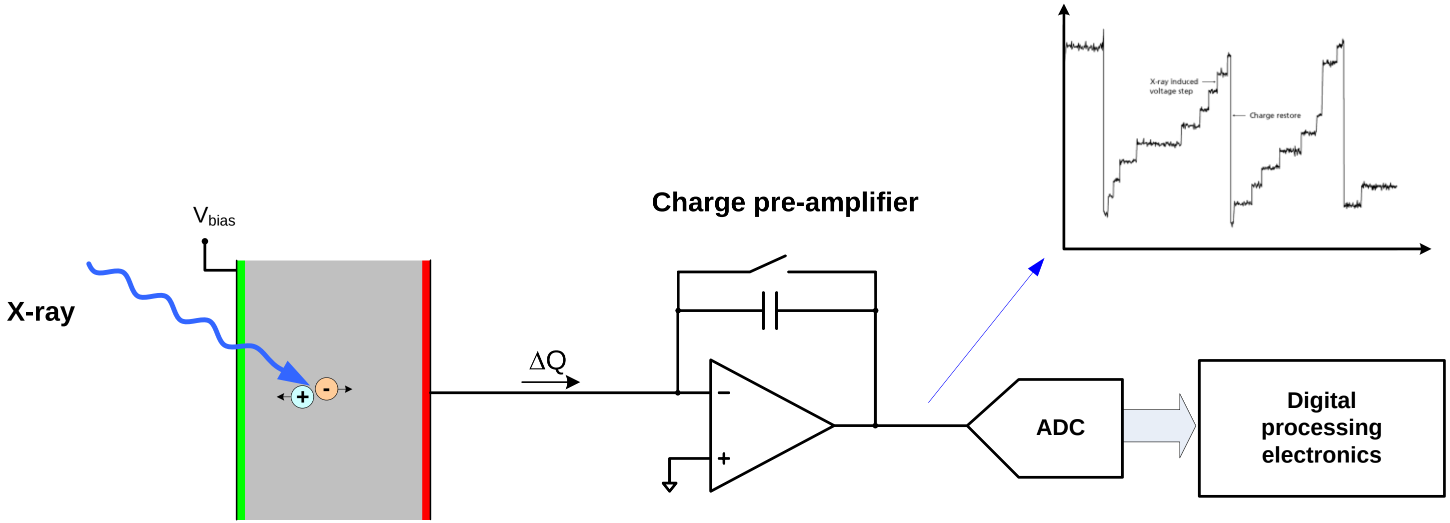


Pulse discriminator: from simple level discrimination to complex pulse-height analysis

CDS is most often built in the charge integration scheme

Also signal sampling (ADC) + digital integration

ENERGY DISPERSIVE X-RAY DETECTORS (EDX)



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

Modern EDX detectors rely on very fast **digital pulse processors** (DPP) implementing rather sophisticated algorithms:

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

UNDESIRED EFFECTS

'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**)*

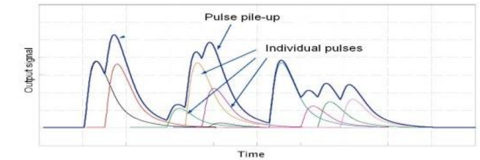
PILE-UP AND DEAD TIME CORRECTIONS

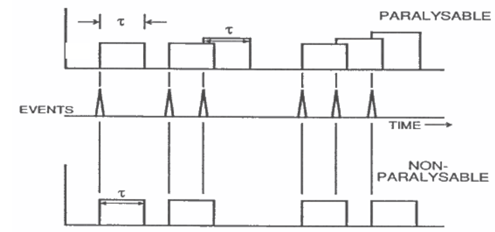
deadtime: the time required by the counting channel after the arrival of a photon to count properly a second one.

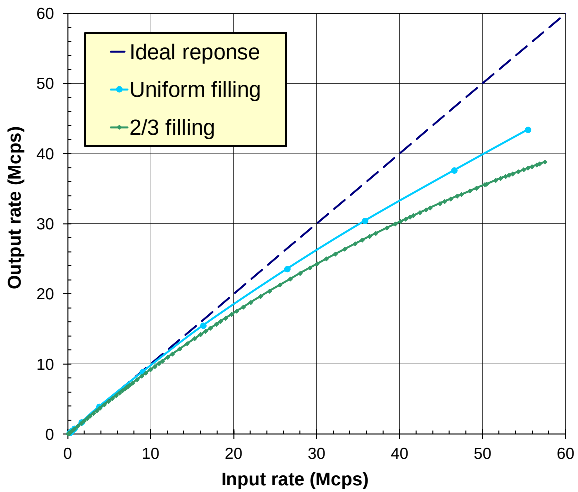
From few ns to few µs

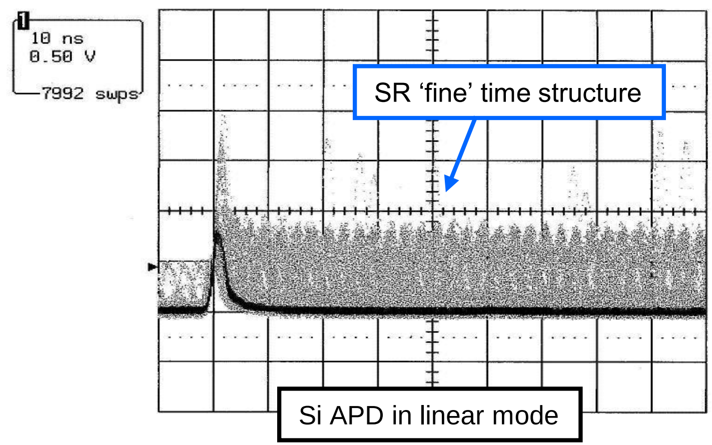
In SR applications count rates are usually high → deadtime corrections are mandatory.

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









DETECTOR NOISE

*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

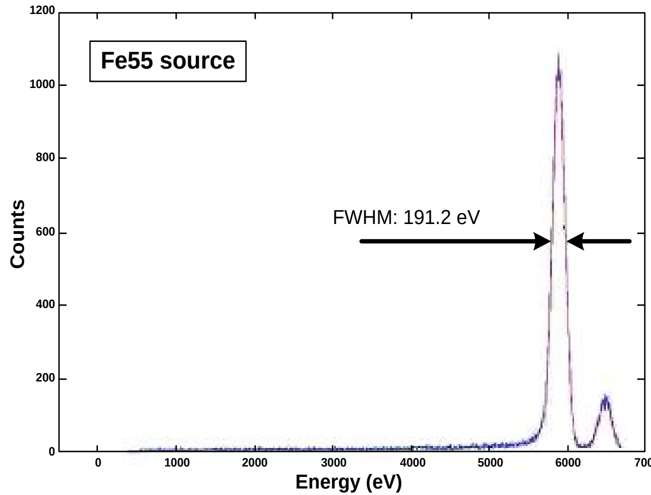
'Effective noise' sources:

- *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 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:

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

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 :

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

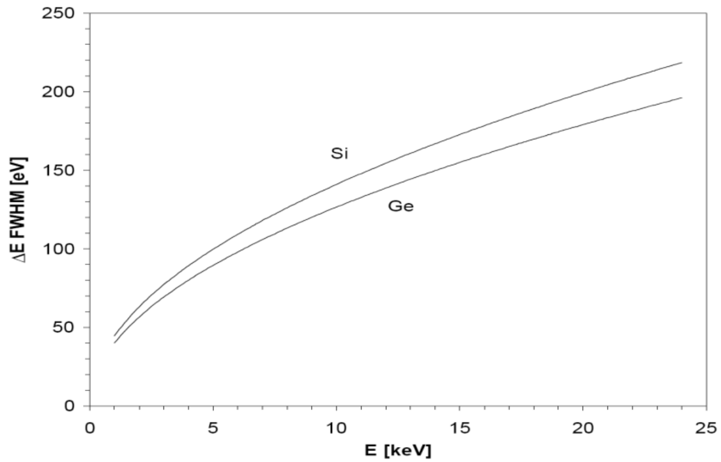
Where the ionisation energy ε_i is the average energy required to produce an elementary charge.

In silicon : ε_i = 3.6 eV , a 10 keV photon produces 2800 e/h pairs.

The RMS fluctuation (σ_E) associated to the charge generation

$$\left.\begin{aligned} \sigma_{N_Q} &\propto \sqrt{N_Q} \\ \sigma_E &= \varepsilon_i \, \sigma_{N_Q} \end{aligned}\right\} \longrightarrow \boxed{\sigma_E \propto \sqrt{E_{photon}\varepsilon_i}}$$

Intrinsic resolution of Si and Ge detectors (Fano noise)



In semiconductors $\sigma_E = \sqrt{F\,E_{photon}\varepsilon_i}$ usually known as "*Fano noise*"

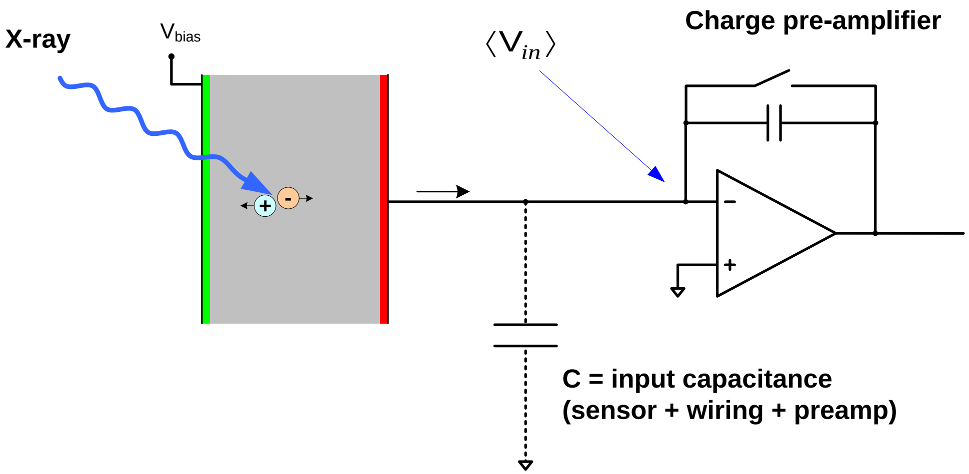
where F is the Fano factor ($F \approx 0.11$ for Si and Ge)

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):

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

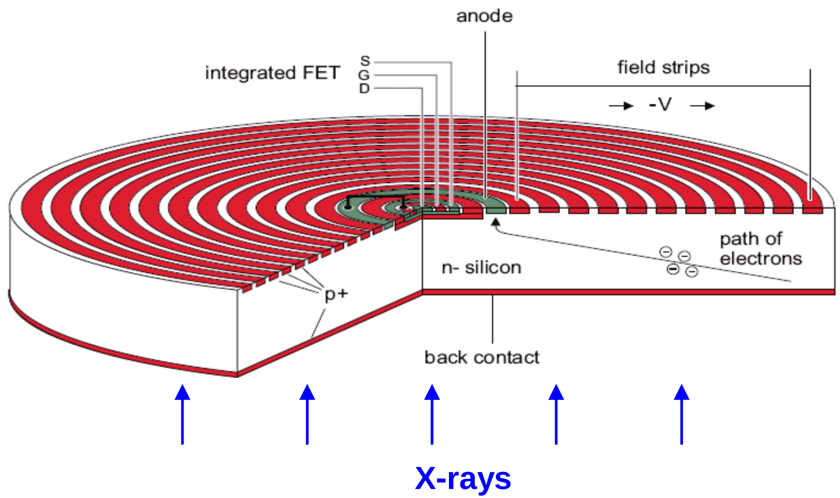
The preamplifier noise in ‘charge-equivalent’ units is **strongly dependent on the input capacitance**

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 ~1Mcps/channel, with nearly 'Fano limited' energy resolution

SDDs is the reference energy dispersive detectors for synchrotron applications.

But relatively thin (< 1mm) detectors and limited to low energies (< 15keV)

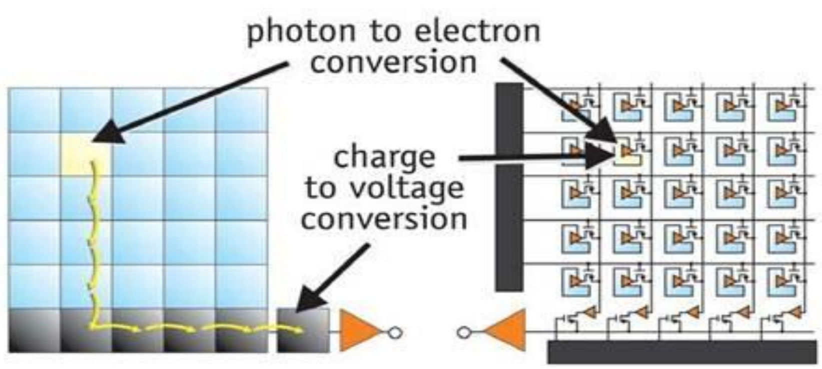
Can operate with moderate cooling (Peltier cooling -10ºC…-50ºC)

DETECTOR CHANNEL CONFIGURATION

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

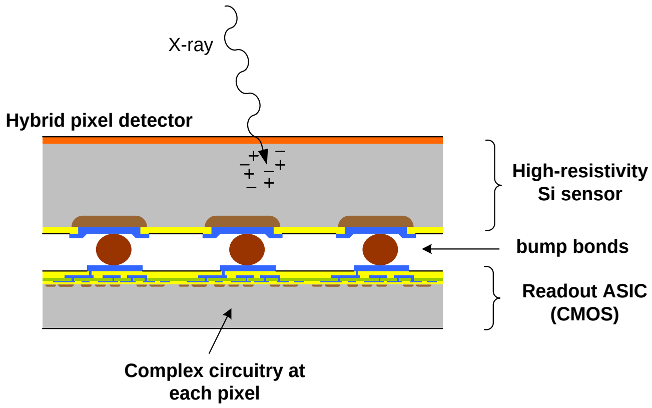
b) ***Multielement**:* *discrete or monolithic sensors*
readout: packaging of single element channels

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



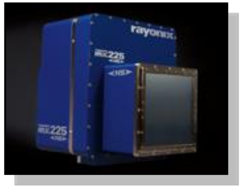
Charge coupled device (CCD)

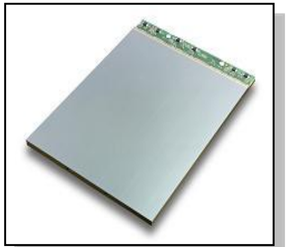
CMOS image sensor (CIS)



Hybrid pixel detector

EXAMPLES OF 2D DETECTORS

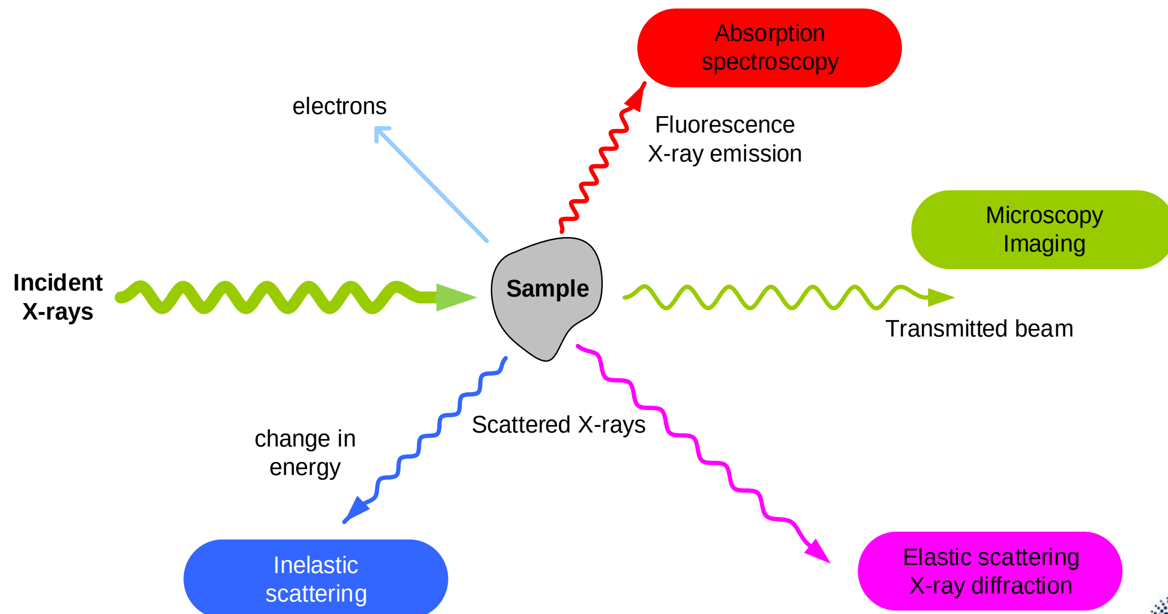




3 MAIN “FAMILIES” OF X-RAY DETECTORS FOR SR EXPERIMENTS

Simplified classification based on application (type of interaction):

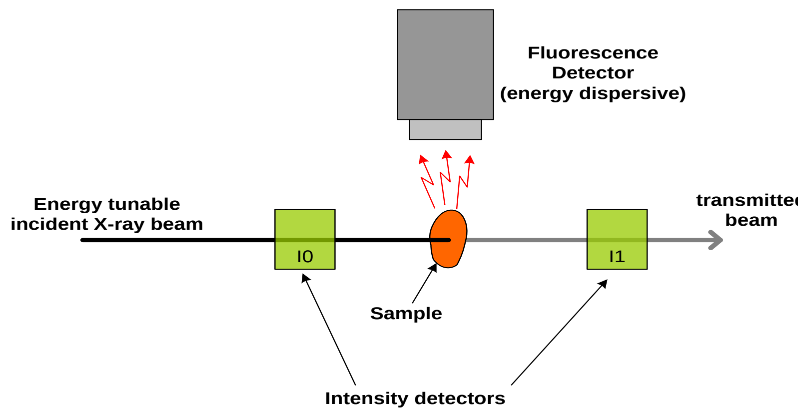
- **Energy dispersive** detectors (fluorescence)
- **X-ray imaging** (transmitted beam)
- **Diffraction / scattering** detectors (elastic/inelastic)



FLUORESCENCE DETECTION (ENERGY DISPERSIVE)

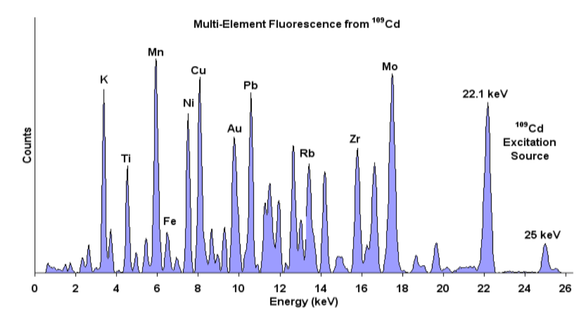
Absorption spectroscopy:

- Sample absorption (as a function of energy)
- Polarization dependence (dichroism)
- Measure either:
  - Transmitted intensity (I1/I0)
  - or
  - Fluorescence yield
- Detectors:
  - Intensity: ion chambers, photodiodes
  - Fluorescence: semiconductor detectors



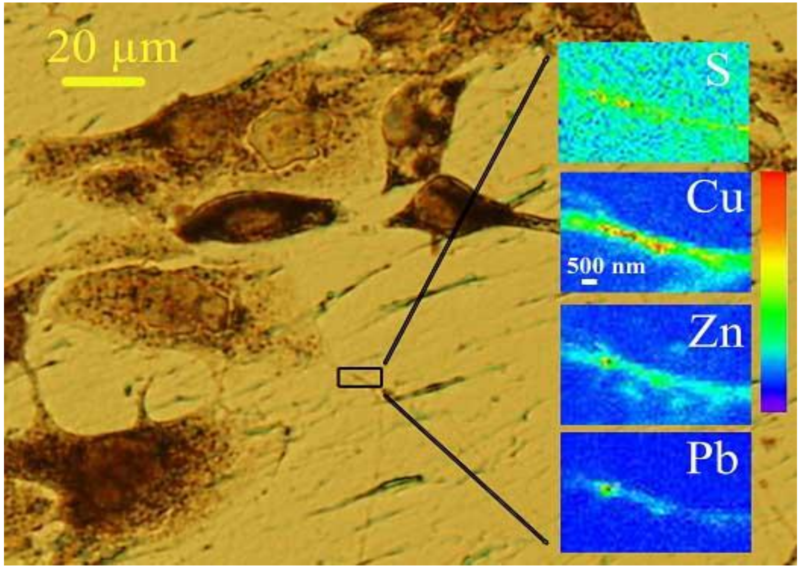
Fluorescence analysis:

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



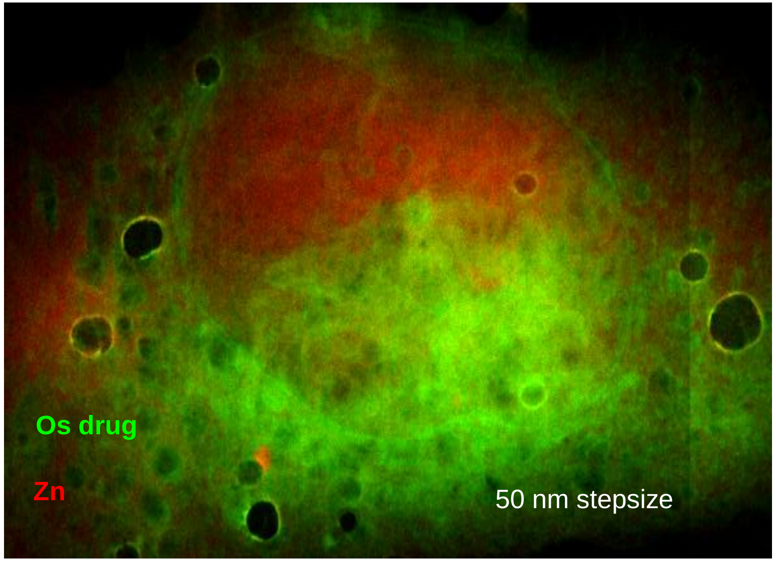
FLUORESCENCE 2D ENERGY RESOLVED 'IMAGING' OF SAMPLES

Neurite process



A Carmona et al. JAAS (2008)

Deciphering intracellular targets of new Anticancer Drugs in breast cancer cells



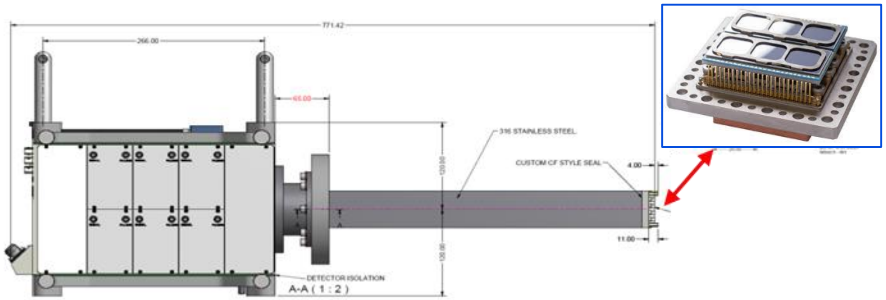
S. Bohic et al., Inserm U836, ESRF, Grenoble

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)

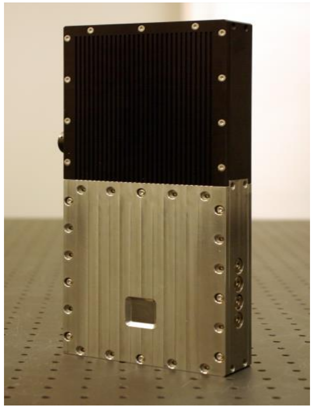
Customised instruments (multielement and special devices):

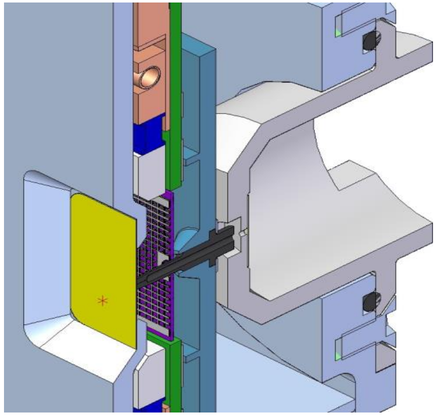


ESRF/ID16A

- SDD 6 element arrays = 2 x 540mm^2
- Energy range ~2…20keV
- Global *throughput* count rate to ~6Mcps
- 1kHz readout by XIA-XMAP pulse processors

Sensors from PNdetectors integrated by SGX Sensortech

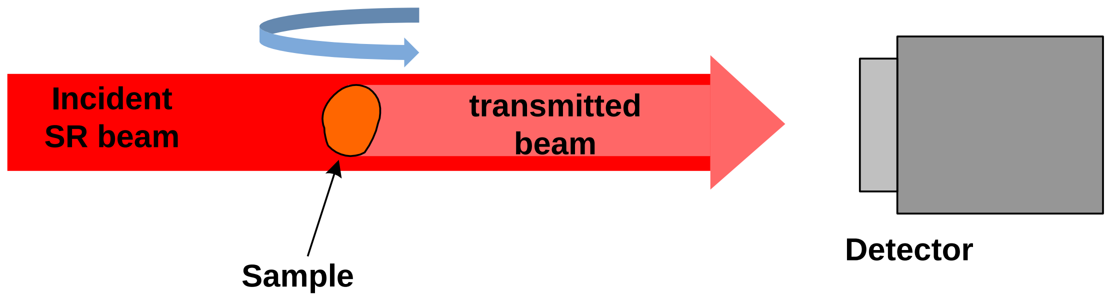




Maia *(CSIRO and BNL/NSLS)*

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

X-RAY IMAGING



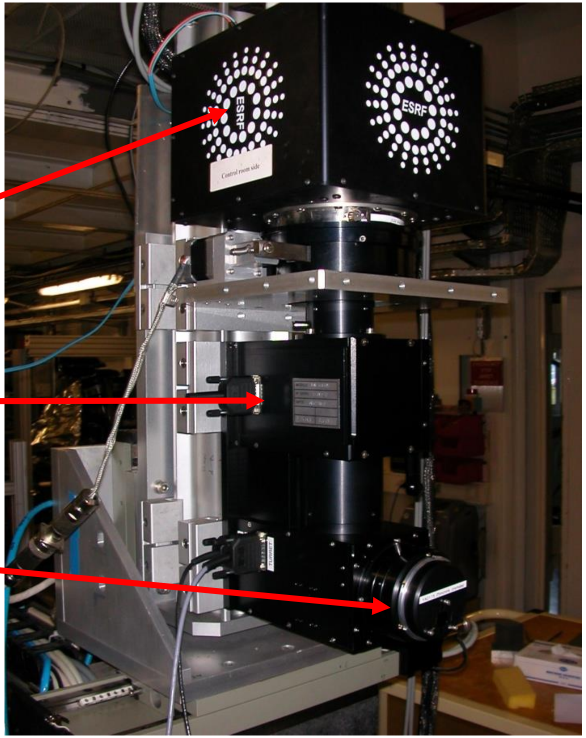
- The detector sees a projection image of the sample
  absorption or phase contrast (beam is partially coherent)
- Very high flux on the detector (close to the full incident beam)
- Small pixels (0.5 to 50 µm)
- Indirect detection schemes are required
- 3D imaging is made by tomographic reconstruction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

IMAGING DETECTORS

visible-light camera

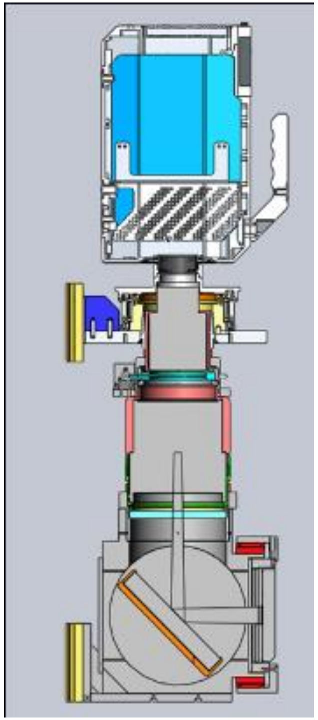
lens/mirror coupling

scintillating screen

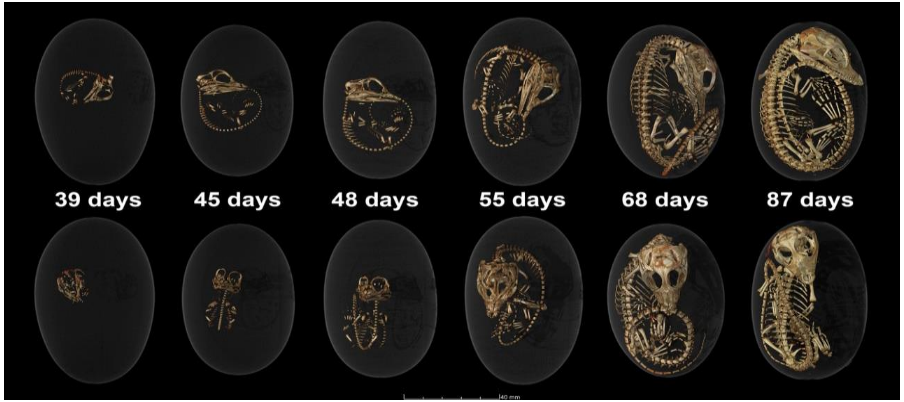


Courtesy: P. Tafforeau, C. Soriano

EXAMPLE: LARGE FIELD-OF-VIEW IMAGING DETECTOR



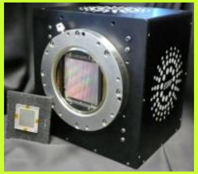
Pixel size	49 µm
FOV	100×20 mm^2
QE @ 100 keV	**> 99%**



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

ID16A-NI: 16 MPIXELS IMAGING DETECTOR (4K X 4K)

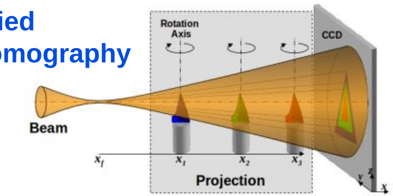
High sensitivity/resolution 16Mpixel camera



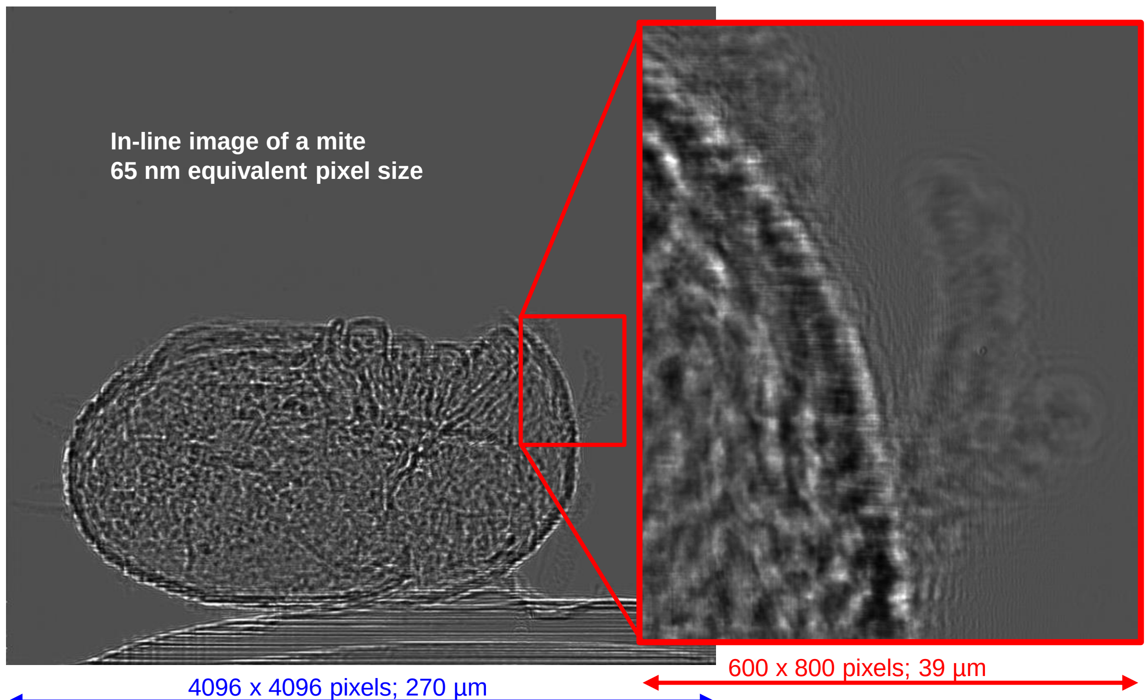
Backilluminated CCD e2v 230-84

4096×4096 pixels (15µm×15µm)

Magnified HoloTomography

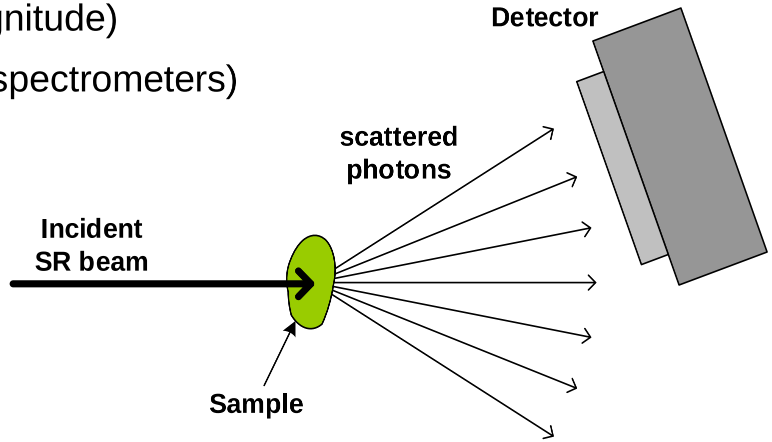


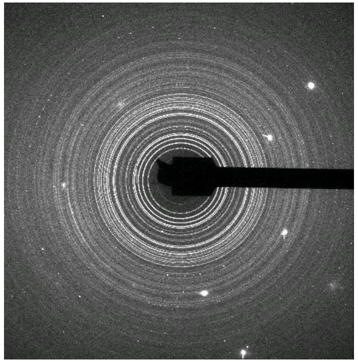
(P. Cloetens, ESRF ID16A)

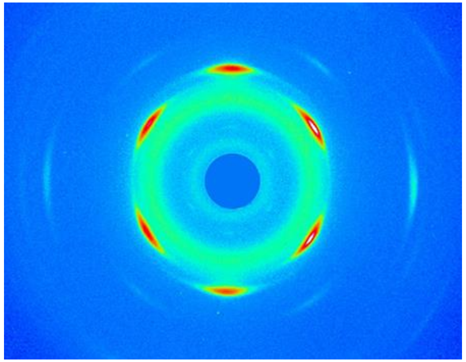


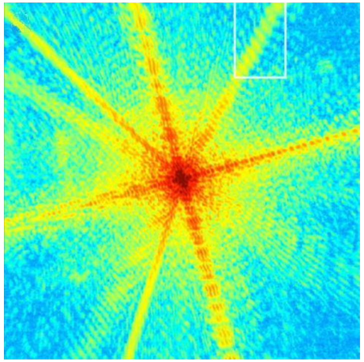
X-RAY SCATTERING (DIFFRACTION, SAXS, INELASTIC, …)

- 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 uses wavelength dispersive setups (spectrometers)







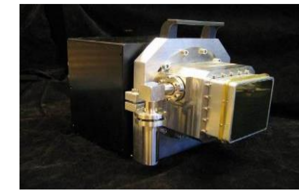


Main technologies for 2D detectors

- **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**

  Photon counting operation

  Modular devices

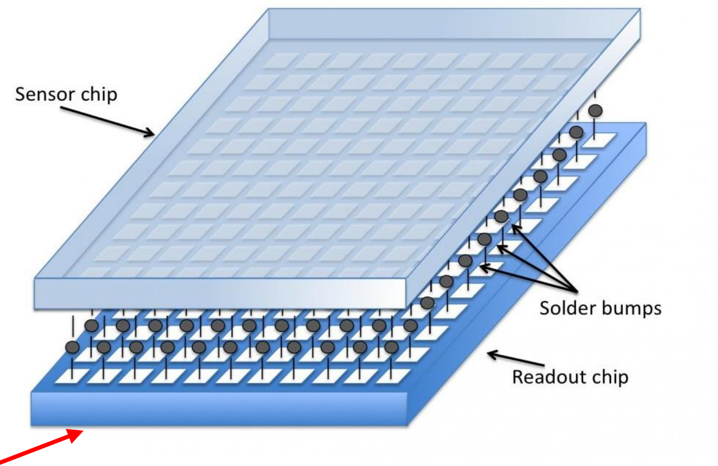
HYBRID PIXEL DETECTORS

1. **Detection Layer**

   Depleted, high resistivity semiconductor:

   Si, GaAs, CdTe…

   Individual 'pixels' formed lithographically



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

   Solder or indium lithographically deposited

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

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

   pixel parallel signal processing: analogue preamp, shaper, thresholds, counter

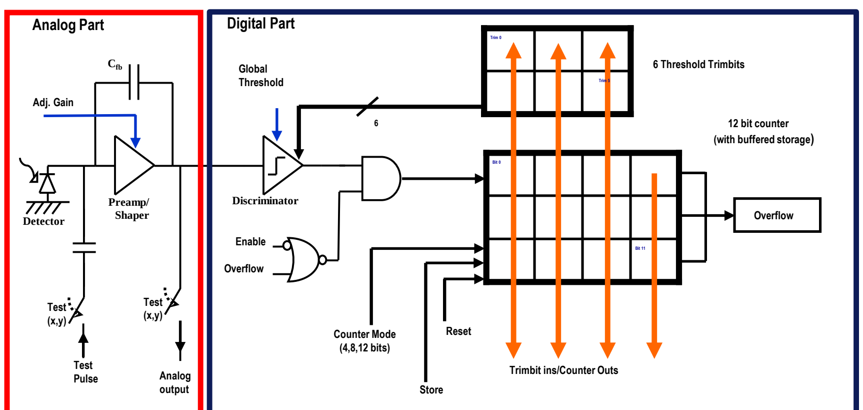
   readout interface (serial-parallel)

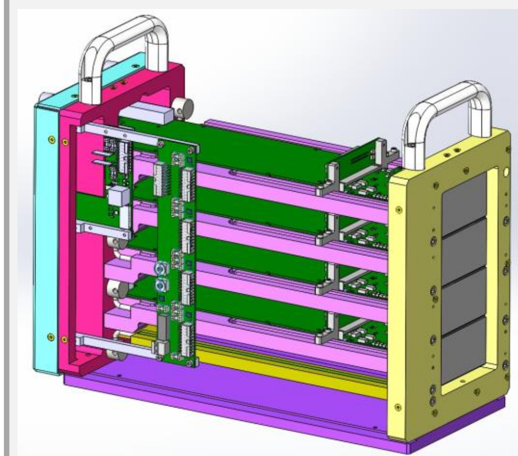
   wide range of possibilities for analogue input stage and digital readout architectures

ID01: PSI/EIGER DETECTOR FOR SAXS AND COHERENT SCATTERING

2M PSI/Eiger detector

- *4 PSI Eiger modules (photon counting)*
- *Active area*: 80 × 160 mm^2
- *Pixel size*: 75µm × 75µm
- *Count rate*: > 10^6 photons/sec/pixel
- *Max. frame rate*: 12000 frames/sec
  (23000 frames/sec @ 4 bits)
- *On-board RAM:* 32 GBytes (16000 frames)
- *Sustained rate*: > 2000 frames/sec (expected)
  (8 GByte/s through eight 10 GbE links)





Vaccum compatible assembly (< 10^{-5} mbar)

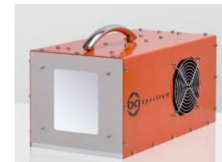
Examples of detector systems in operation

Photon counting

- Few megapixel devices
- 50-200 µm pixel pitch
- Frame rates up to 1-10 kfps

  but
- Count rate (pile up) limitations

EXCALIBUR (*STFC/Diamond*)

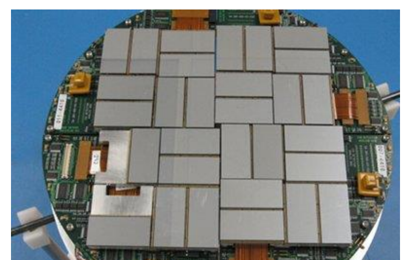


LAMBDA (*DESY*)

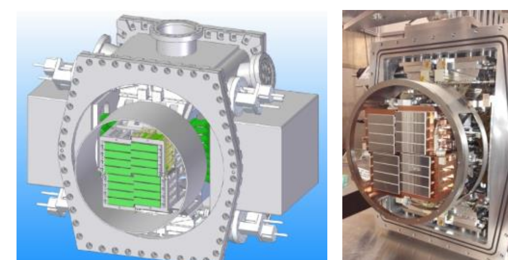
EIGER Family (*DECTRIS*)

Charge integrating

CSPAD (*LCLS*)



AGIPD (*European XFEL*)



- Less mature devices
- Designed for X-ray free-electron lasers
- Can cope with very intense pulses

  but
- Not suitable for high duty-cycle operation or high photon energy (required for storage rings)

SUMMARY

- ✓ 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 X-rays (from few 0.5 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 …