4. Synchrotrons

Beamlines

Front End, Optics & Monochromators

What you will learn about…

- Front End
- Focussing Mirrors
- Monochromators:
- Secondary Optics
- Photon Detectors

ETH PSI

Typical Beamline

Insertion Device

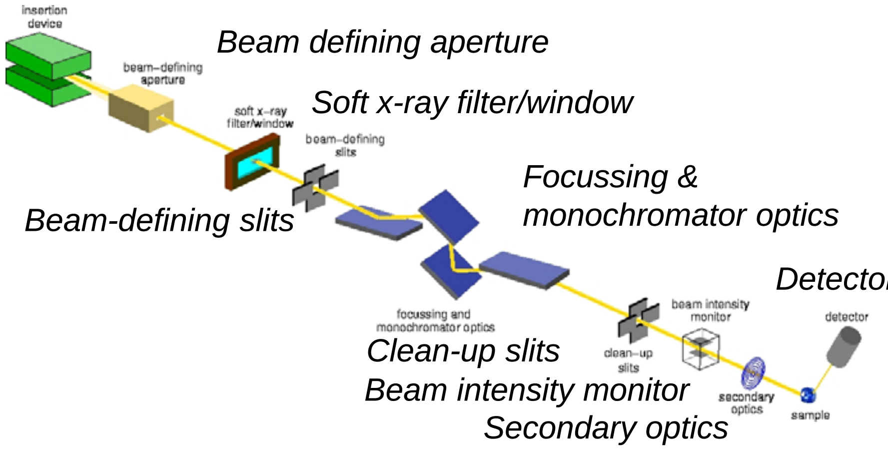
Beam defining aperture

Soft x-ray filter/window

Beam-defining slits

Focussing & monochromator optics

Detector



Clean-up slits

Beam intensity monitor

Secondary optics

Sample

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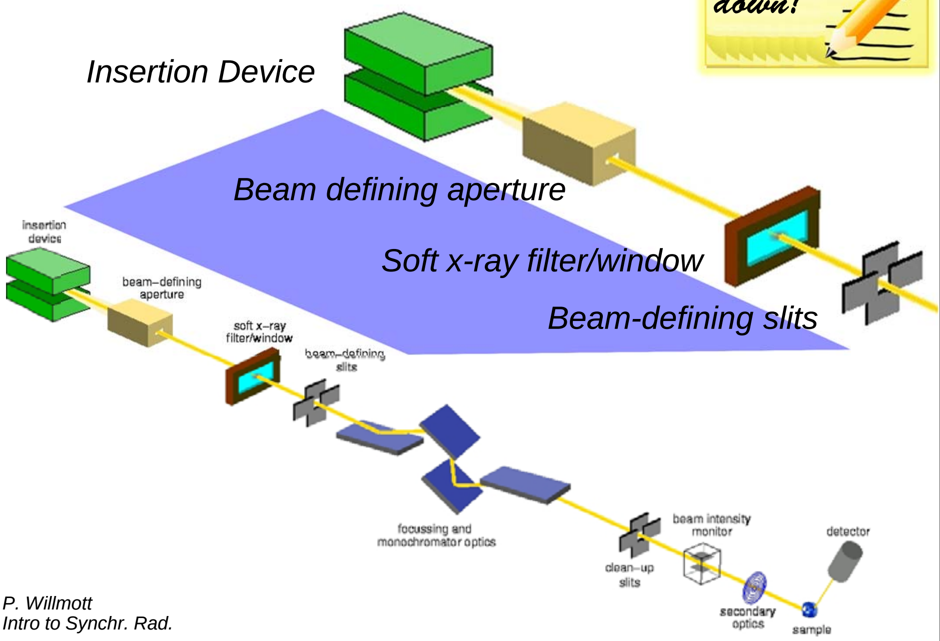
Front End

Insertion Device

Beam defining aperture

Soft x-ray filter/window

Beam-defining slits



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Primary Optics

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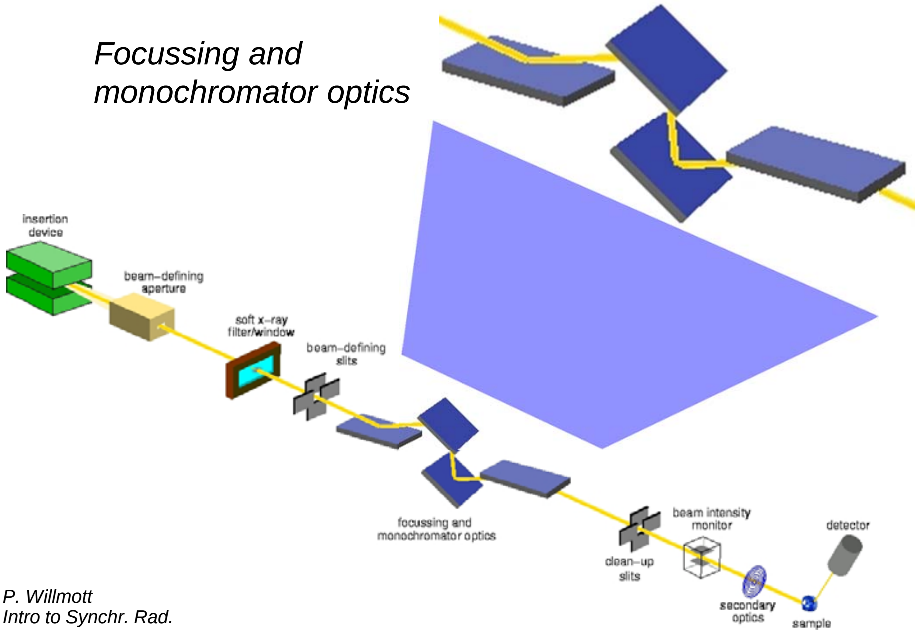
Focussing and monochromator optics



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Primary Optics

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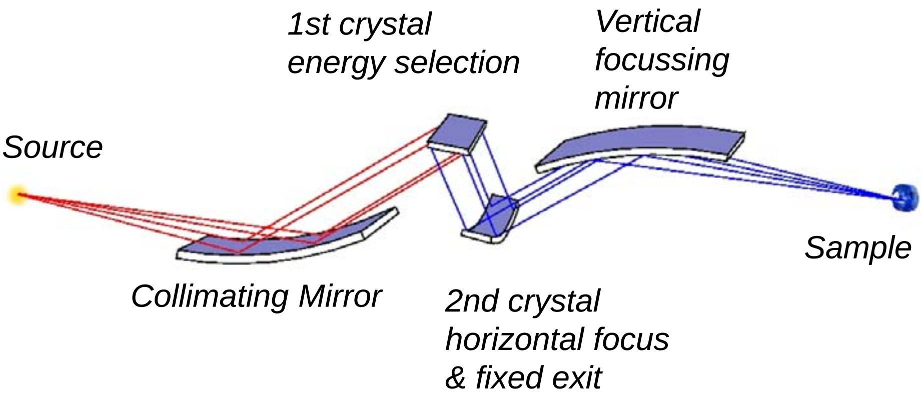

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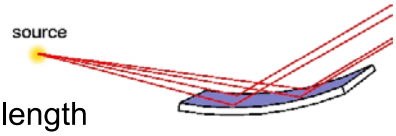
Beamline Optics

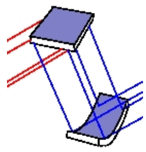
1st mirror (optional)

- Collimates beam vertically
  → parallel beam & single wavelength



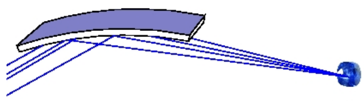
Monochromator

- Selects wavelength (energy)
- Optional: can also focus horizontally (sagittally)

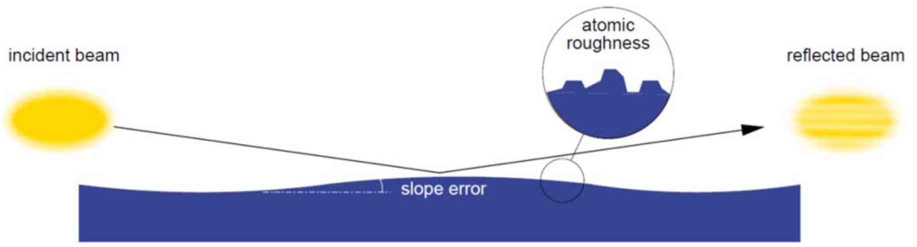


2nd mirror

- Focuses vertically
- Also sometimes horizontally



X-ray Mirrors



$$\delta = \frac{2\pi\rho r_0}{k^2} = \frac{2\pi\lambda^2[\text{Å}^2].0.34\text{Å}^{-3}.2.82\times10^{-5}\text{Å}}{4\pi^2} = \frac{\lambda^2.0.9588\times10^{-5}}{2\pi}$$

$$\alpha_c[degrees] \approx \frac{180}{\pi}\sqrt{2\delta} = \lambda\ [\text{Å}]\ \frac{180}{\pi}\sqrt{\frac{0.9588\times10^{-5}}{\pi}} = \boldsymbol{\lambda\ [\text{Å}]/10}$$

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X-ray Mirrors

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X-ray Mirrors

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Mirror Materials

- Glass (silica) or Silicon, which has better conductivity and thermal management
- Coated with one or more strips: Rh, Pt….
  - Different α_c ($\propto \rho_e^{1/2}$, $\propto$ 1/E)
  - **Harmonic suppression:** x-ray absorption spectra can be distorted or degraded by harmonics. Harmonic contamination can be removed with a *harmonic rejection mirror:* glancing angle mirror coated with a high-Z material as part of beamline optics.

Monochromators

- Well-defined photon energy: selects quasi-monochromatic portion of polychromatic SR
- Can be tuned over wavelength (energy) range
- Important for many synchrotron experiments
- Achieved by diffraction:

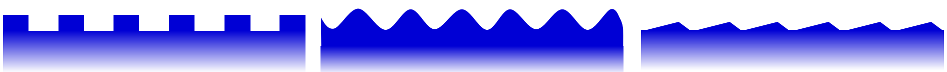
λ > ~ 10 nm → ________________ with grating line separation µm's down to 10's nm's depending on λ

λ < ~ 10 nm → __________________________ making use of 'natural' gratings of crystal planes (Å's)

__________________________ → larger bandwidth ($\Delta\lambda/\lambda$) therefore more flux!

Grating Monochromators

- Surface with parallel grooves
- Mainly reflection (rather than transmission) gratings
- Several profiles:



___________ ___________ ________

- Geometrical surface:
  - Planar
  - Concave (spherical, elliptical or toroidal)
    → combines focussing with spectral dispersion so do not need a focussing mirror
- Blaze grating: ________________________________

Fill in the Gaps!

Line-by-line...

Resolving power of gratings

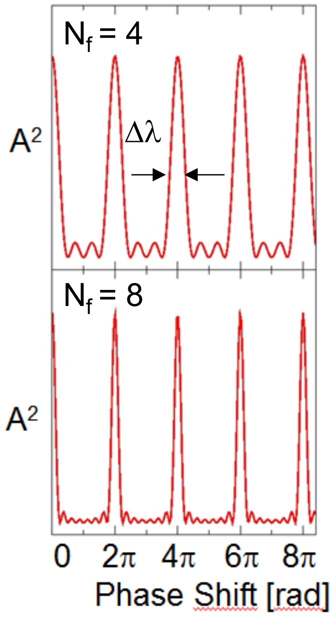
Resolving power given by:

$$\frac{\lambda}{\Delta\lambda} = mN_f\left(\sin\theta_i + \sin\theta_r\right)$$

$\Delta\lambda$: bandwidth of interference maxima

N_f: number of illuminated facets

- N_f ~ several thousand
  → Resolving power of ~ 10^4 possible
- N_f small (lower number of lines per mm): larger bandwidth → more flux, but lower resolution
- N_f large (higher line density): higher resolving power, but fewer photons



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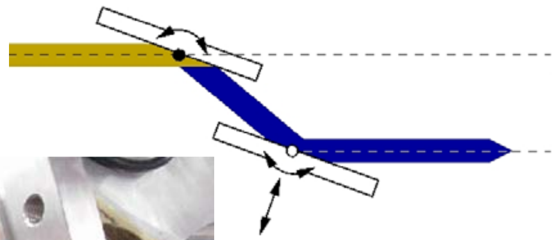
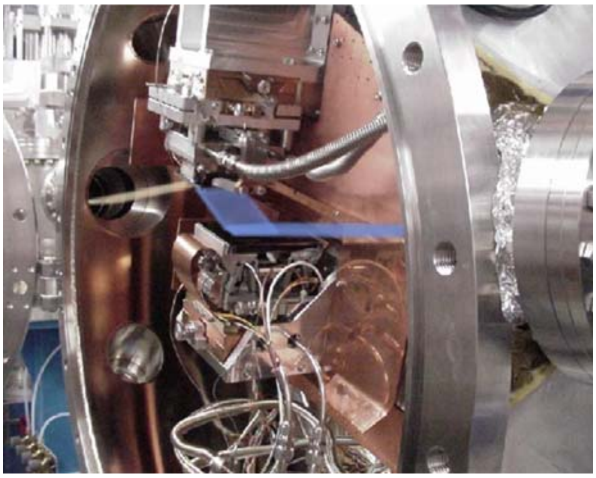
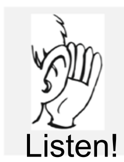
Crystal Monochromators







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Crystal Monochromators

Separation of scatterers ≈ to wavelengths being diffracted

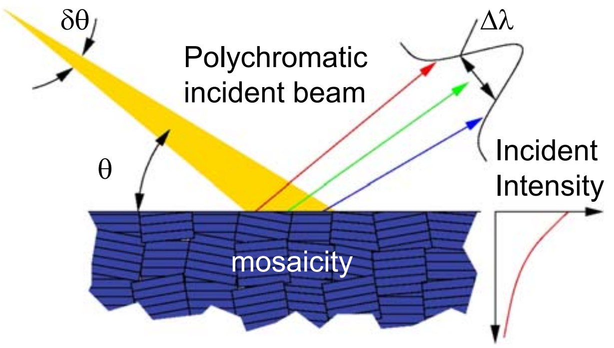
Therefore, for wavelengths of 0.01-1 nm use crystals as a "diffraction grating". Bragg's Law: $n\lambda = 2dsin\theta$

- Often use 2 crystals: beam in || beam out
- **1st crystal** monochromatizes → high heat load: absorbs radiation that does not satisfy Bragg condition ~ 99.9% flux, so cooled using water or liq. N_2.
- **2nd crystal** (usually not cooled)

  Redirects diffracted beam parallel to incoming beam

  Can perform horizontal (sagittal) focussing

Crystal Monochromators



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Crystal Monochromators

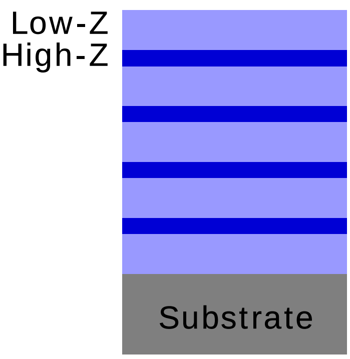
Only “quasi-”monochromatic, $\Delta\lambda$

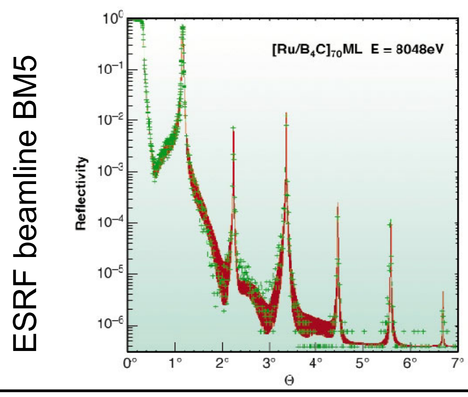
- Residual beam divergence $\delta\theta$
- Mosaicity: Imperfect crystal with misaligned crystallites
- Finite extinction depth: attenuation due to elastic scattering although small when Bragg condition met
- Finite absorption depth: $1/\mu$

Neet to consider crystal quality, dissipation of thermal load, resistance to radiation damage: $\rightarrow$ Si (& also Ge) cf. semiconductor industry cooled by liq. N_2

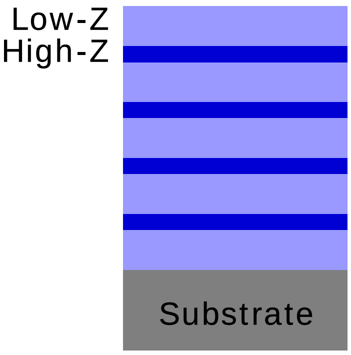
Also Diamond: expensive, but of interest for XFELs…..

Multilayer Monochromators





Multilayer Monochromators



FWHM of multilayer peak:

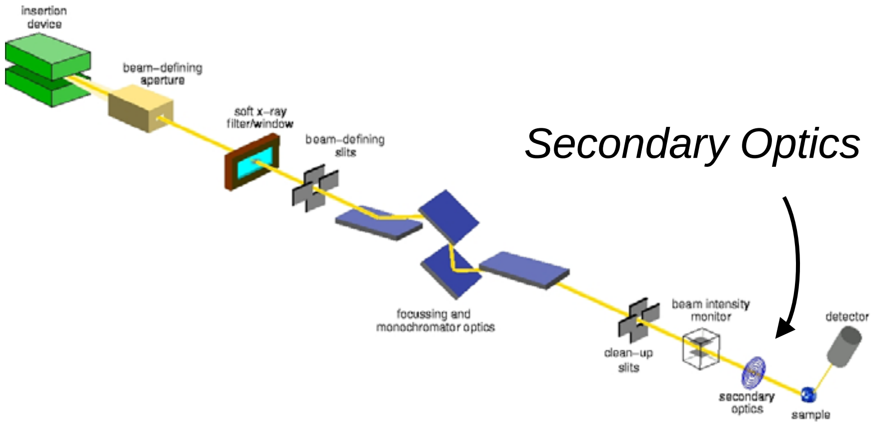
$$\Delta\theta = \frac{\lambda}{m\Lambda}$$

λ x-ray wavelength
m number of periods in multilayer
Λ multilayer period

$\Delta\theta = 0.02°$ for multilayer

Much larger than natural (Darwin) bandwidth of Si(111) ~ 10^{-3} degrees

Secondary Optics



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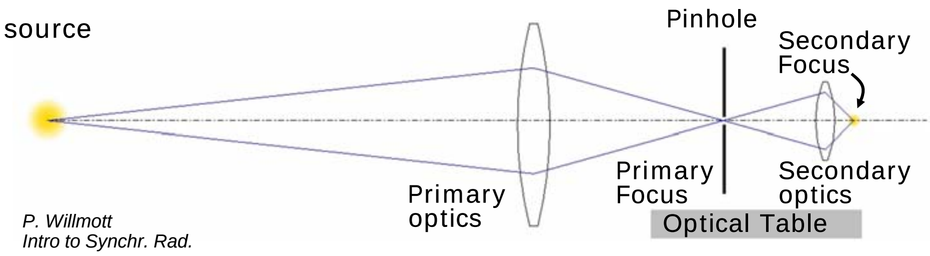
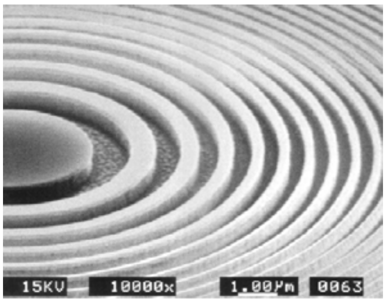
Microfocusing and Nanofocusing



Typical undulator source size: 200 μm x 20 μm

- Max. demagnification using primary optics ~ 0.1
- Demagnification to micron or submicron sizes needs secondary optics
- Focus spot at pinhole, which has a diameter much smaller than the primary focal spot → secondary source
- Vibrations must be significantly smaller than desired focal size → pinhole, secondary optics & sample on optical table

Fresnel Zone Plates



- Concentric rings, alternating opaque and transparent
  - Called “Fresnel zones”
- Made by electron beam lithography & reactive ion etching
- Advantages & Disadvantages:
  - Easy to align ☺
  - Focus proportional to photon energy 😐
  - Transmission only a few percent ☹

Fresnel Zone Plates

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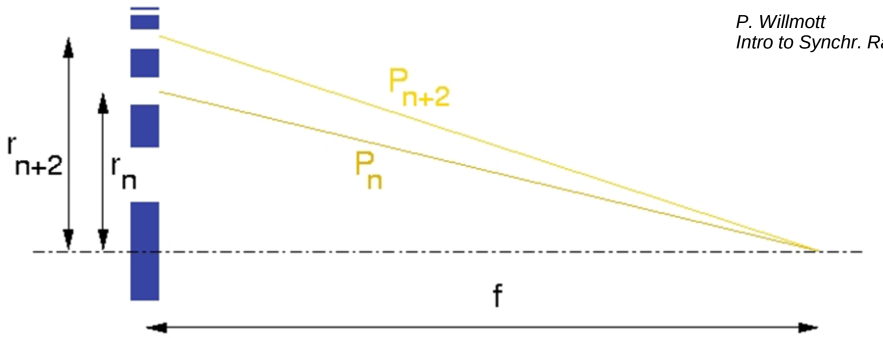
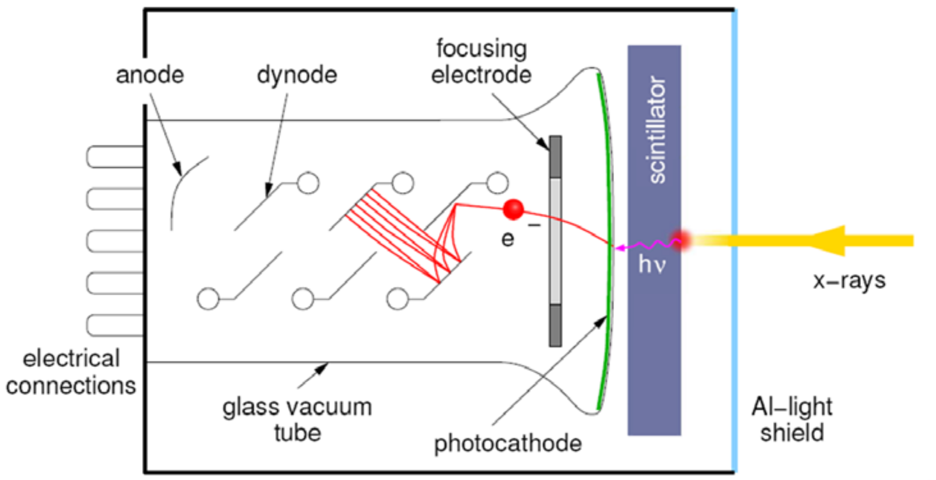


Interference between x-rays emerging from transmission rings. Constructive interference (focussing) when OPD = λ

Ultimate resolution (Rayleigh Criteria)
$\rightarrow 1.22\Delta r_N$ the outer zone width

Scintillator Detectors



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Point Spread Function

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Scintillator plate plus e.g. 2D array of photosensitive elements such as a CCD array can be used to record x-ray images.

The thicker the scintillator layer

- the ____ efficient the stopping power
- but the __________ the resolution: a point “spreads” as the signal travels across the material

CCDs and ‘blooming’

CCDs and 'blooming'

- Pixel is like a bucket filling up with charge
- When bucket overflows, spillover into adjacent buckets

  → Point spread function!

→ **2D pixel array detector developed in first decade of 21st Century with Single photon counting mode:**

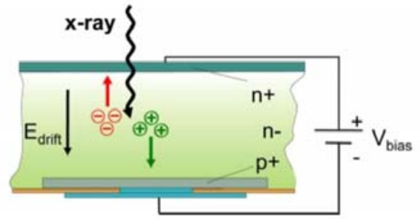
Count registers increase by one increment each time a photon above a set energy is detected

Hybrid Pixel Detectors

CCD: charge accumulated and converted using analogue-to-digital converter

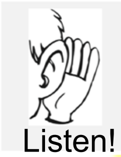
Single photon-counting technology:

- Charge generated by each photon is amplified and converted into voltage pulse
- Height of pulse ∝ photon energy
  - Comparator + threshold
  - Allows discrimination for low-energy photons e.g. elimination of fluorescence in diffraction experiments



Direct detection sensor technology
X-ray photons are directly converted into electric charge in the solid-state sensor

https://www.dectris.com/



Listen!

And then…

Hybrid Pixel Detectors

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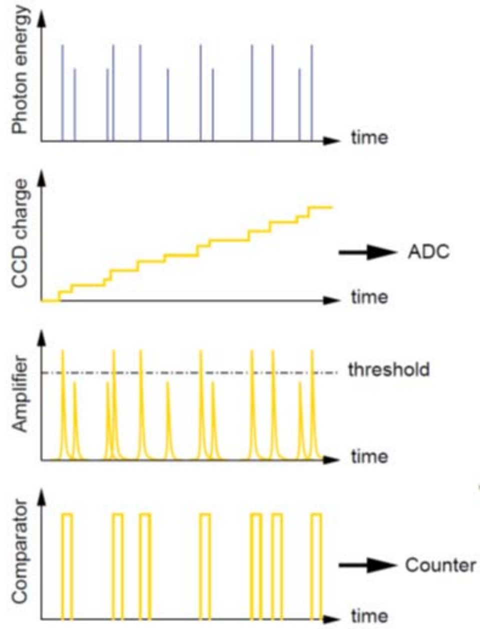

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Hybrid Pixel Detectors

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CCD: charge accumulated and converted using analogue-to-digital converter

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Pilatus Detector

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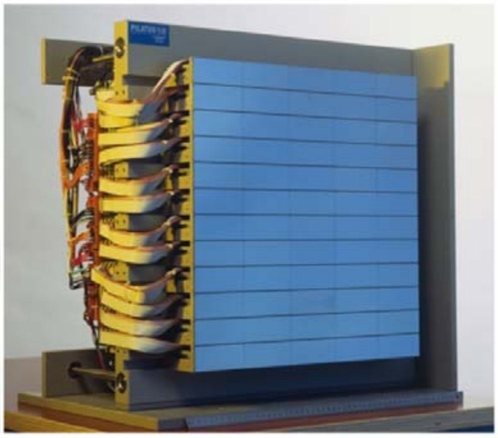
- Each sensor is a continuous 487 x 195 array of 94,965 pixels and covers an active area of 83.8 mm x 33.5 mm.
- Multiple detector modules are assembled to form large-area PILATUS detectors.

Pilatus Detector Module



https://www.dectris.com/

State-of-the-Art Detectors - Dectris

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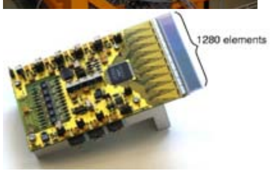
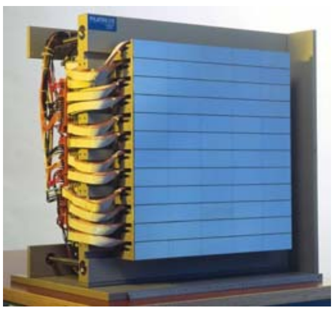
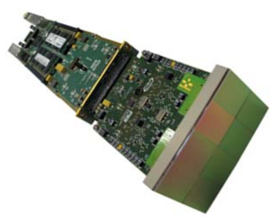
MYTHEN
1k to 30k 50µm strips for powder diffraction, small angle scattering, medical imaging…



Single Mythen module

EIGER
500k to 9M 75µm pixels, for small angle scattering, CDI, XPCS, protein crystallography, imaging ....





PILATUS
100k to 6M 172µm pixels for protein crystallography, small angle scattering, imaging …

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