X-ray area detectors for synchrotron experiments

Characteristics and Technologies

Cyril Ponchut
ESRF Instrumentation Services and Development Division

Outline

- Introduction
- 2D detector parameters
- 2D detector principles
- 2D detector technologies

Introduction

- The beamline user problem
- X-ray area detector on a SR beamline

The beamline user problem

What is the optimum detector for a given (range of) experiment(s) ?

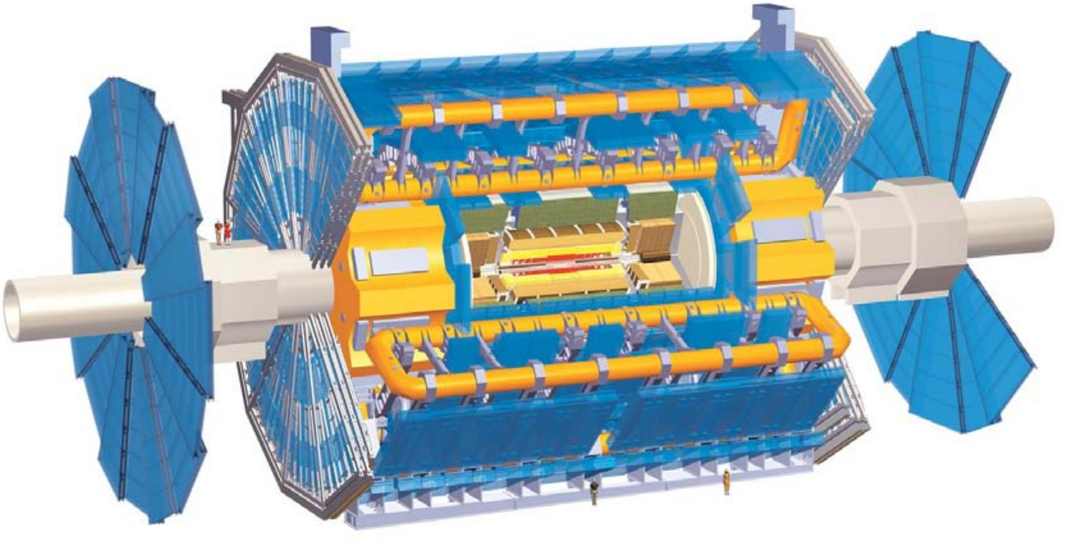
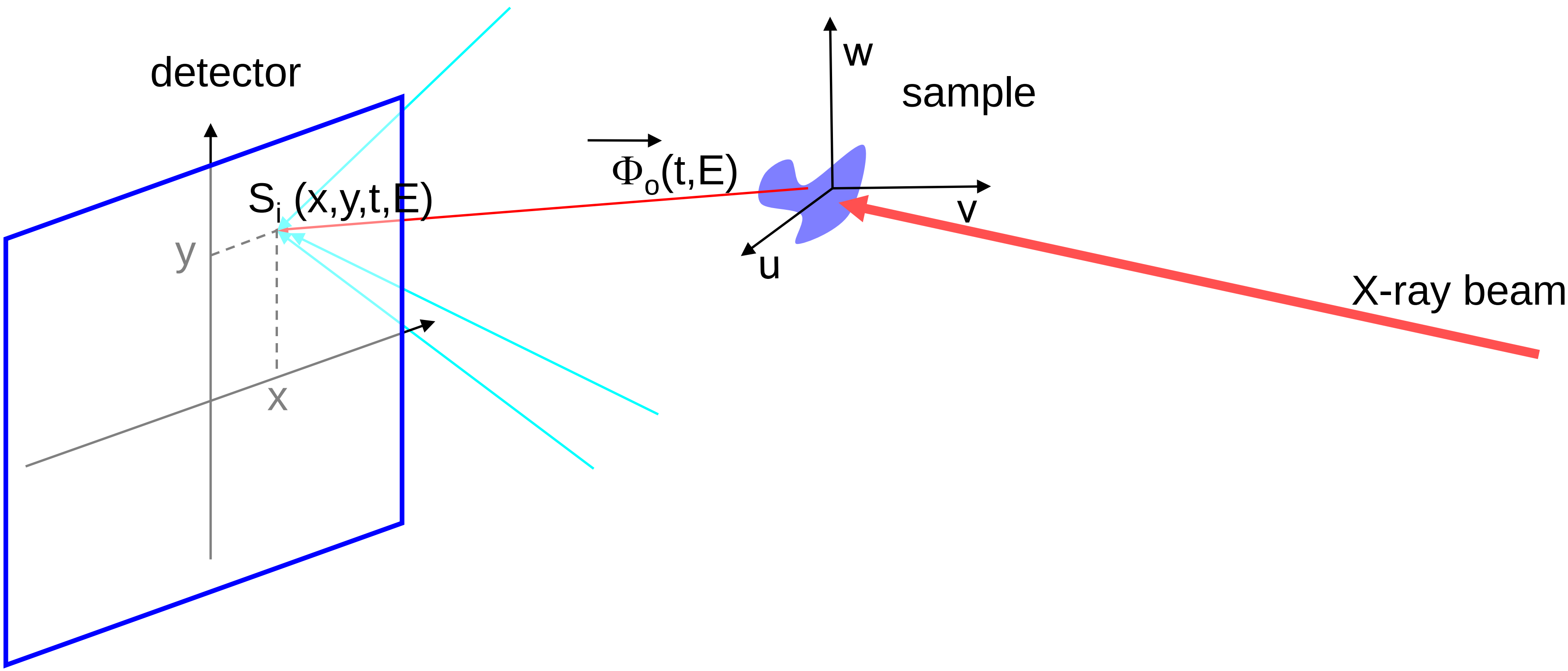


Image : “The ATLAS experiment at CERN”

X-ray area detection on a SR beamline



Detector parameters and characterization

- 2D detector parameters
- 2D detector model
- Gain
- Noise
- Dynamic range

2D detectors parameters

Gain
Noise
Dynamic range
Linearity

X-ray area detector = device that measures the **intensity** of an incident X-ray flux with a certain **efficiency**, as a function of **position**, **time** , **energy**.

MTF
LSF
spatial distortions

Frame rate
Readout dead time
Decay time

Energy resolution
Energy threshold

QE
DQE

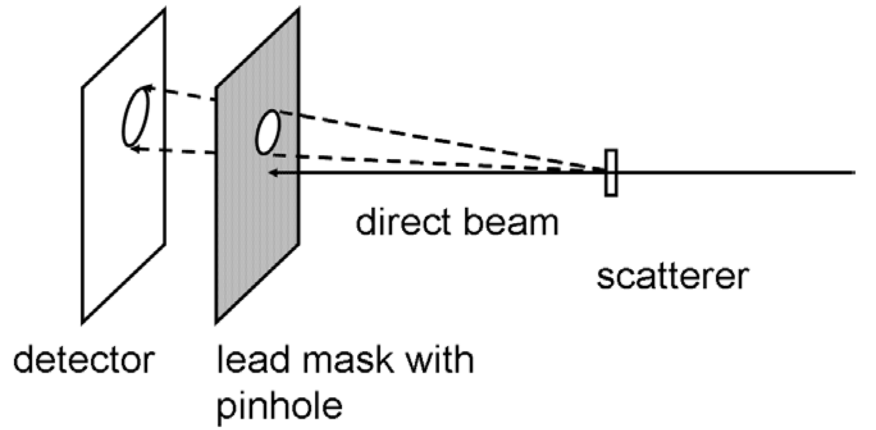
Gain

$$G = \frac{output}{input}$$

G = image level (**ADU**) per incident X-ray

ADU : analog to digital units

Measuring G :



$$G = \frac{\text{integrated pixel signal in the exposed region}}{\text{X-ray counts through pinhole measured with a counter}}$$

G includes X-ray interaction probability => **depends on energy**

Noise

Image noise : $N_o = \sqrt{Var(I(i,j))}$ $\quad (i,j) \in ROI$ $\quad$ ADU/pixel r.m.s.

Noise components :

$$N^2 = N_Q{}^2 + N_R{}^2 + N_P{}^2 + N_D{}^2$$

quantum readout proportional DSNU

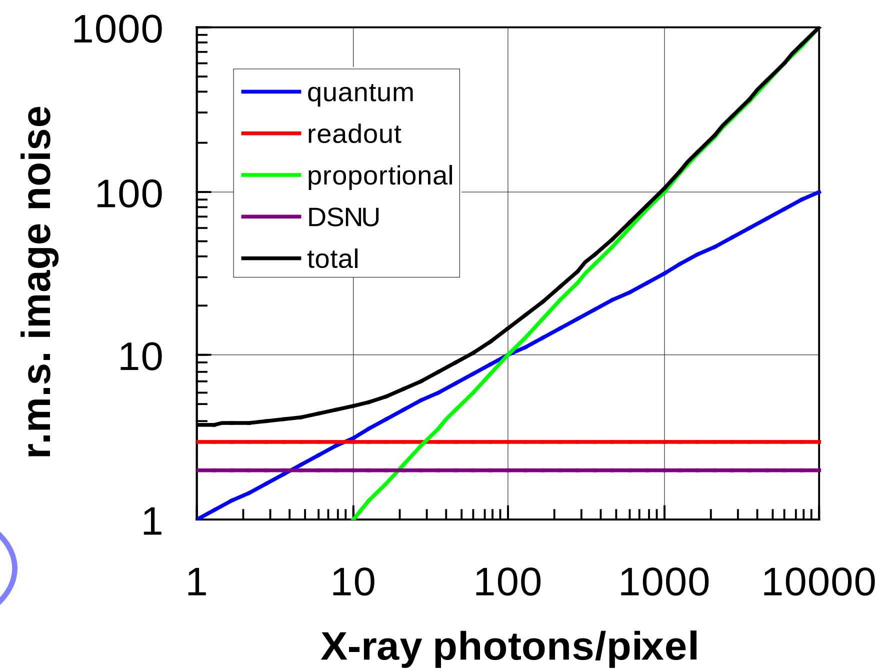
stochastic spatial

incoming photons (Poisson)

electronics

inhomogeneities (fixed pattern noise)

dark pattern



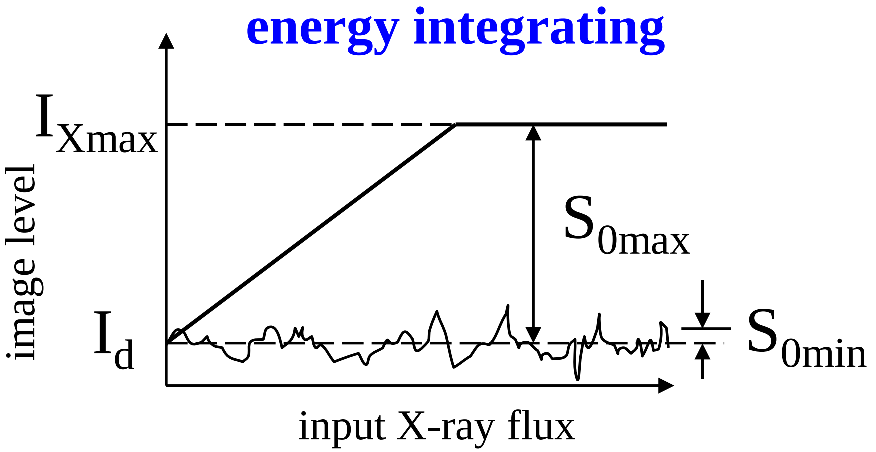
Dynamic range

$$DR = \frac{S_{0\max}}{S_{0\min}}$$

$$DR_{bits} = \log_2 DR$$

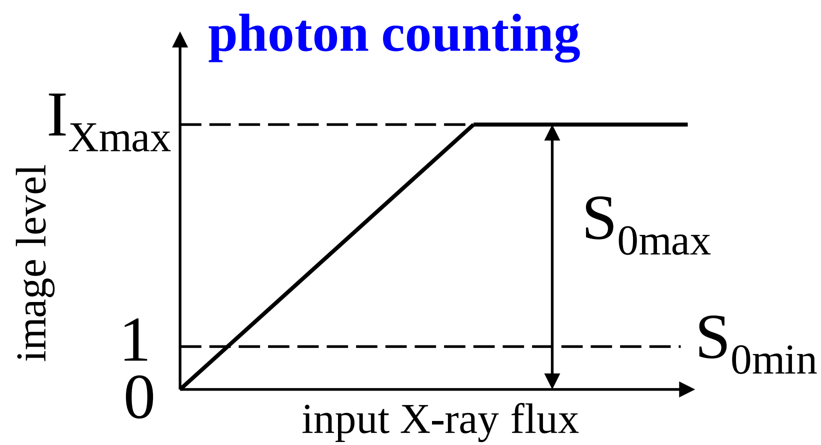
DR = 10000 = 80 dB = 13.2 bits

Not to be confused with ADC range = $\log_2 I_{max}$



$$DR = \frac{I_{X\max} - I_d}{N_0}$$

($S_{0min} \approx N_o$ = readout noise)

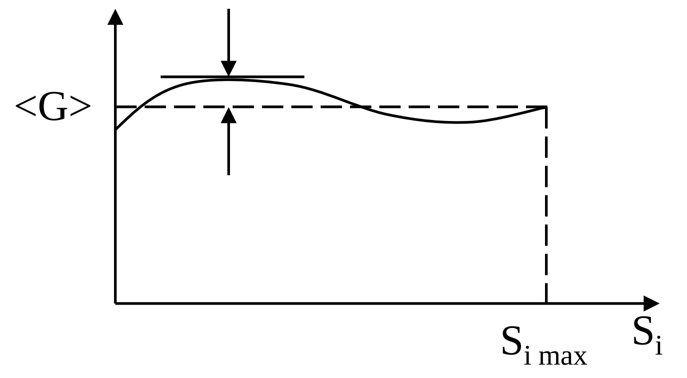


$$DR = I_{X\max}$$

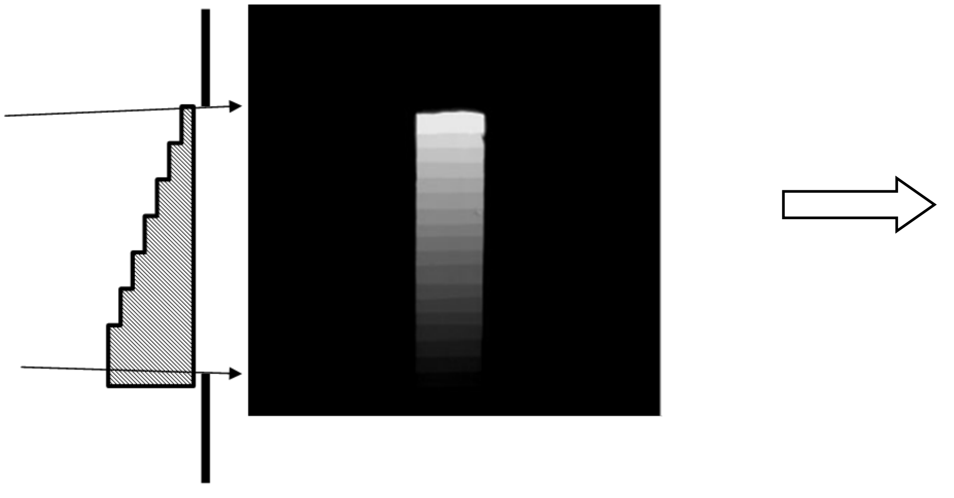
Linearity

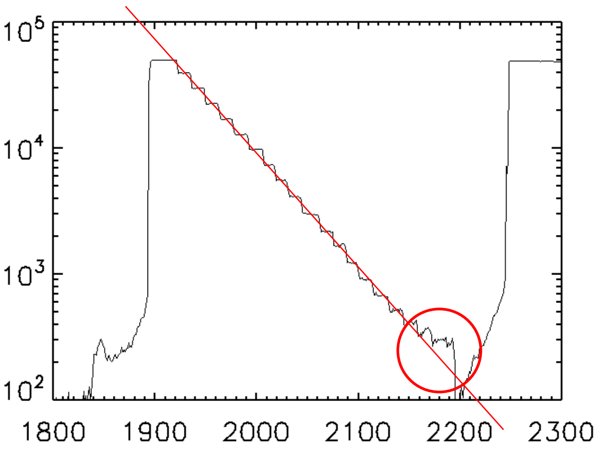
Integral non-linearity

$$INL = \frac{\max(|G(S_i) - \langle G \rangle|)}{\langle G \rangle}$$



Quick non-linearity test





Quantum efficiency

QE = X-ray interaction probability = characteristic of the X-ray conversion medium

QE can be deduced from knowledge of detection material, but not measurable directly

QE does not take into account signal degradation across the system

$\Rightarrow$ Need for a general and measurable quantity for detection efficiency :

DQE

(Detective Quantum Efficiency)

Detective Quantum Efficiency (DQE)

$DQE = SNR_{out}^2/SNR_{in}^2 = (S_o^2/ N_o^2) / (S_i^2/ N_i^2)$ (Gruner, 1978)

Measuring the DQE :

$S_o/ S_i = G$

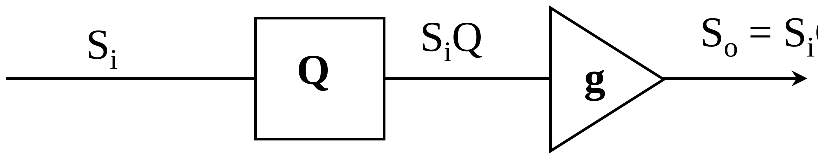
$N_i^2 = S_i$ (Poisson statistics)

$$DQE = \frac{G \cdot S_0}{N_0^{\ 2}}$$

DQE approximated expression

X-rays incident **X-rays detected** **output signal**

signal S_i S_iQ $S_o = S_iQg$



variance S_i (Poisson) S_iQ (Poisson) $S_iQg^2 + n_{e-}^2$

$$DQE \approx \frac{Q}{1 + \dfrac{n_{e-}^{2}}{g^{2}QS_i}}$$

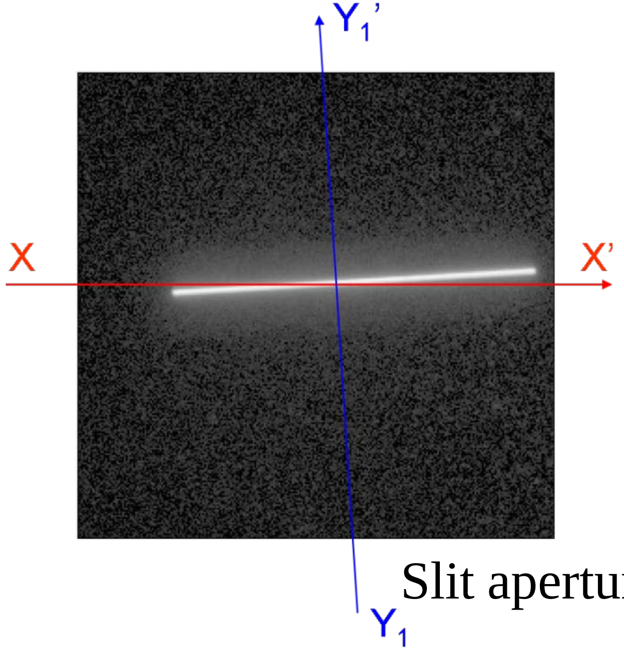
Input-equivalent noise $N_{eq} = n_{e-}/gQ$:

$$DQE \approx \frac{Q}{1 + \dfrac{QN_{eq}^{2}}{S_i}}$$

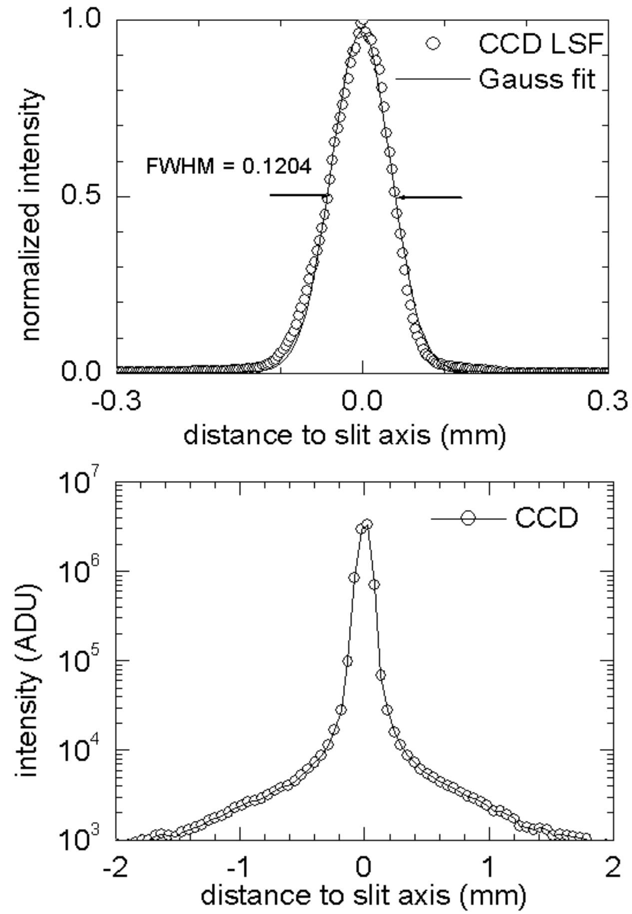
"perfect" detector ($n_{e-} = 0$) => DQE = Q

Line-spread function (LSF)

Measuring the LSF :



Slit aperture << pixel size



Tilted slit (Fujita, 1992) : oversampling 1/sinθ
=> Provides the presampling LSF

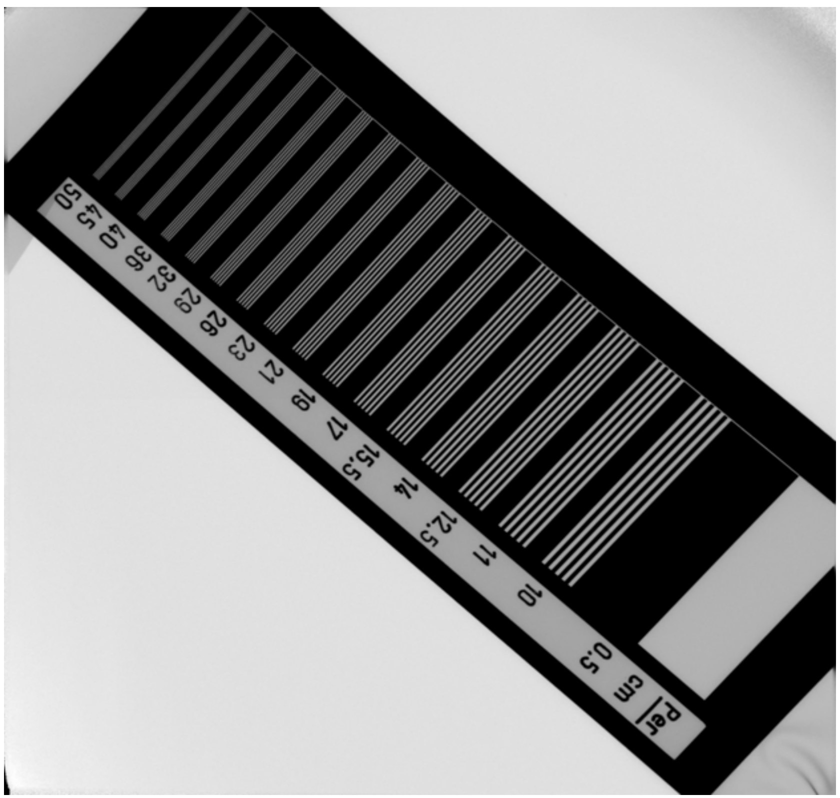
For non-isotropic spatial response : PSF (point-spread function)

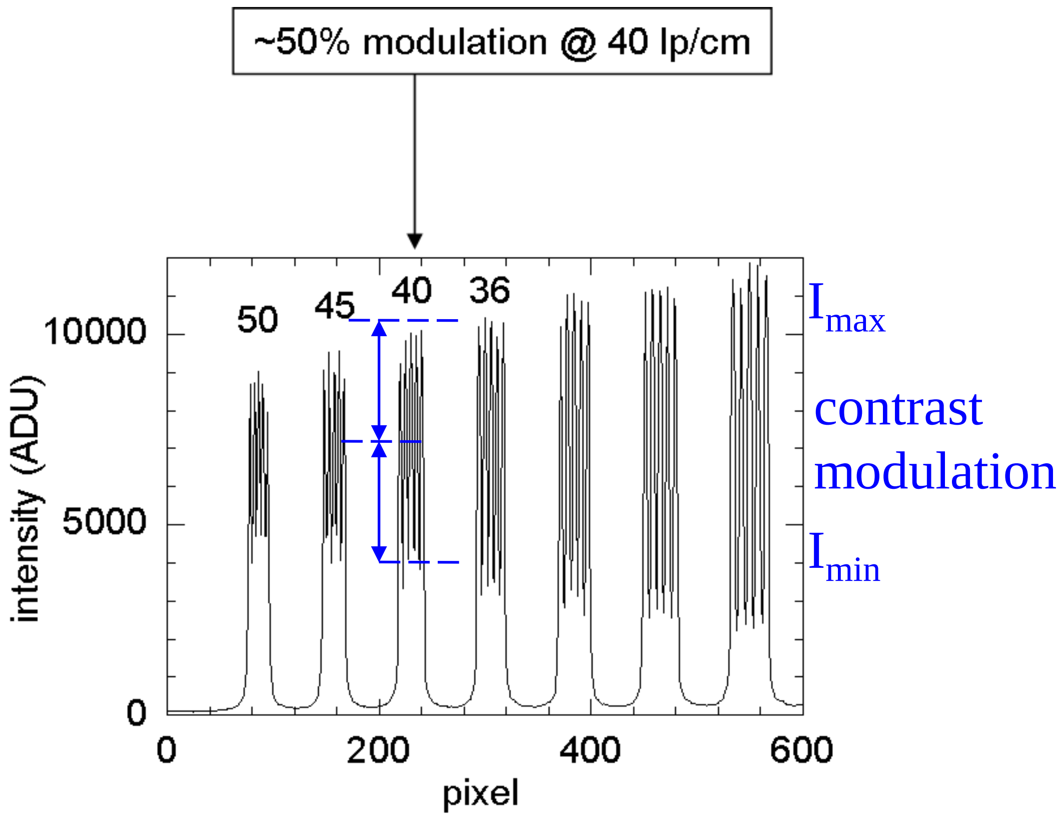
IEEE TNS 52 (2005)

Contrast Transfer Function (CTF)

$$CTF(\nu) = \frac{I_{max}(\nu) - I_{min}(\nu)}{I_{max}(\nu) + I_{min}(\nu)} \qquad \text{(square modulation)}$$

Measuring the CTF :

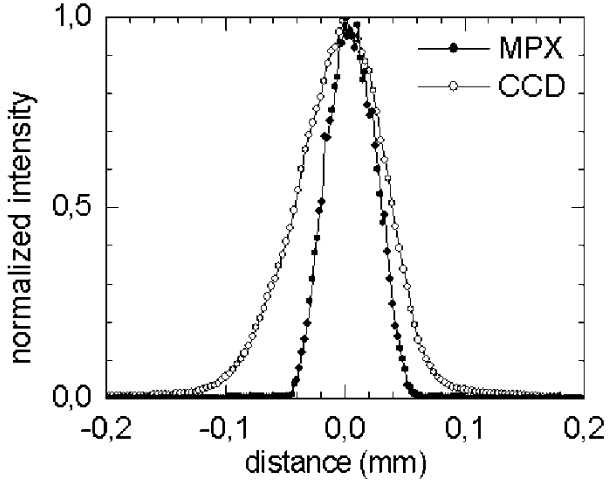




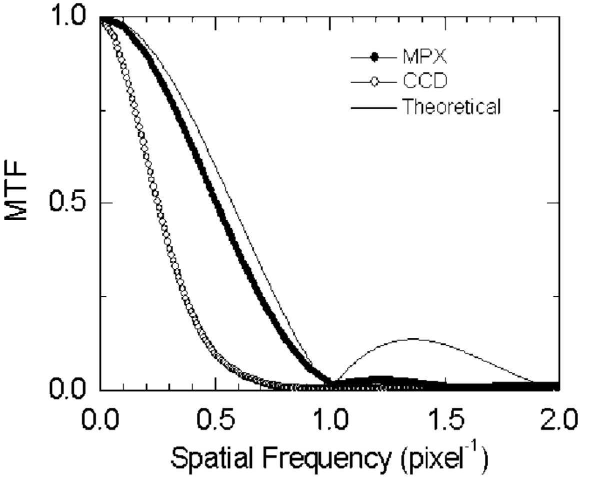
Modulation Transfer Function (MTF)

$$MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$ (sine modulation) Not measurable directly

Indirect measurement from LSF :



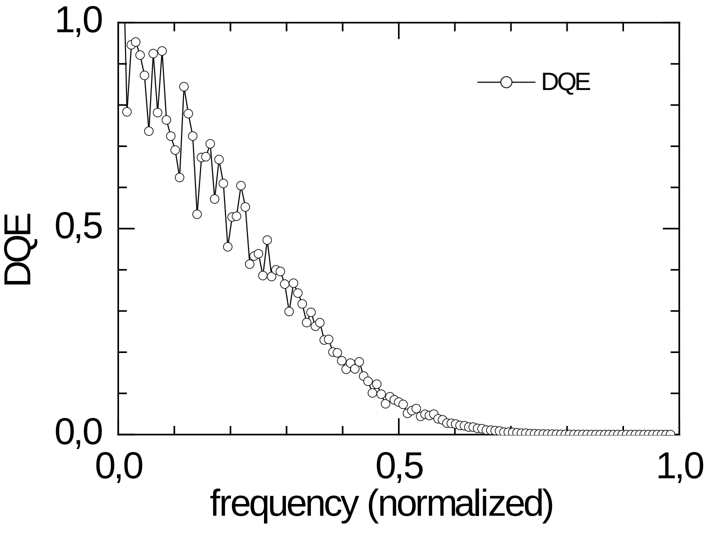
$$MTF(\nu) = \int LSF(x) \exp^{-2j\pi\nu x} dx$$



DQE in the Fourier domain

Frequency-dependent DQE

$$DQE(\nu) = \frac{G \cdot S_o \cdot MTF^2(\nu)}{N.NPS_o(\nu)}$$

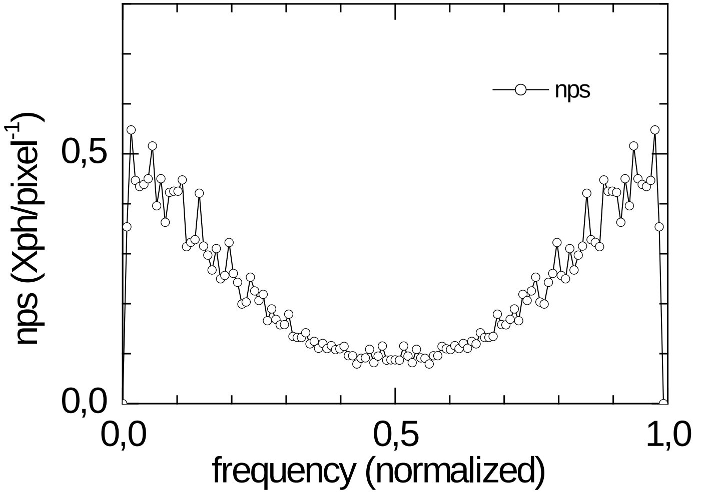


Noise power spectrum

$$NPS(k,l) = \| FFT(I(i,j)) \|^2$$

angular averaging

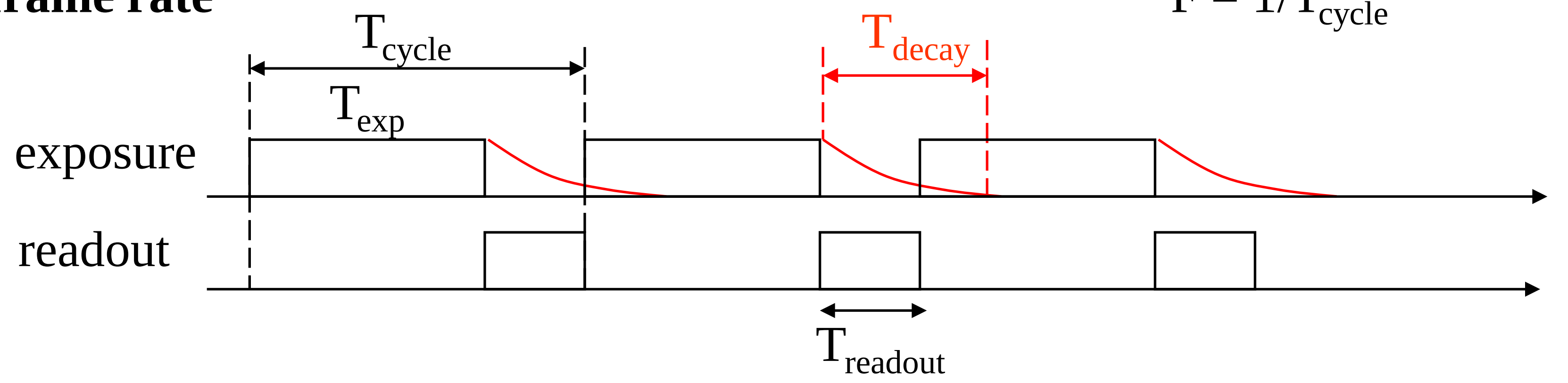
$$NPS(\nu) = \int_0^{2\pi} NPS(\nu,\theta) d\theta$$



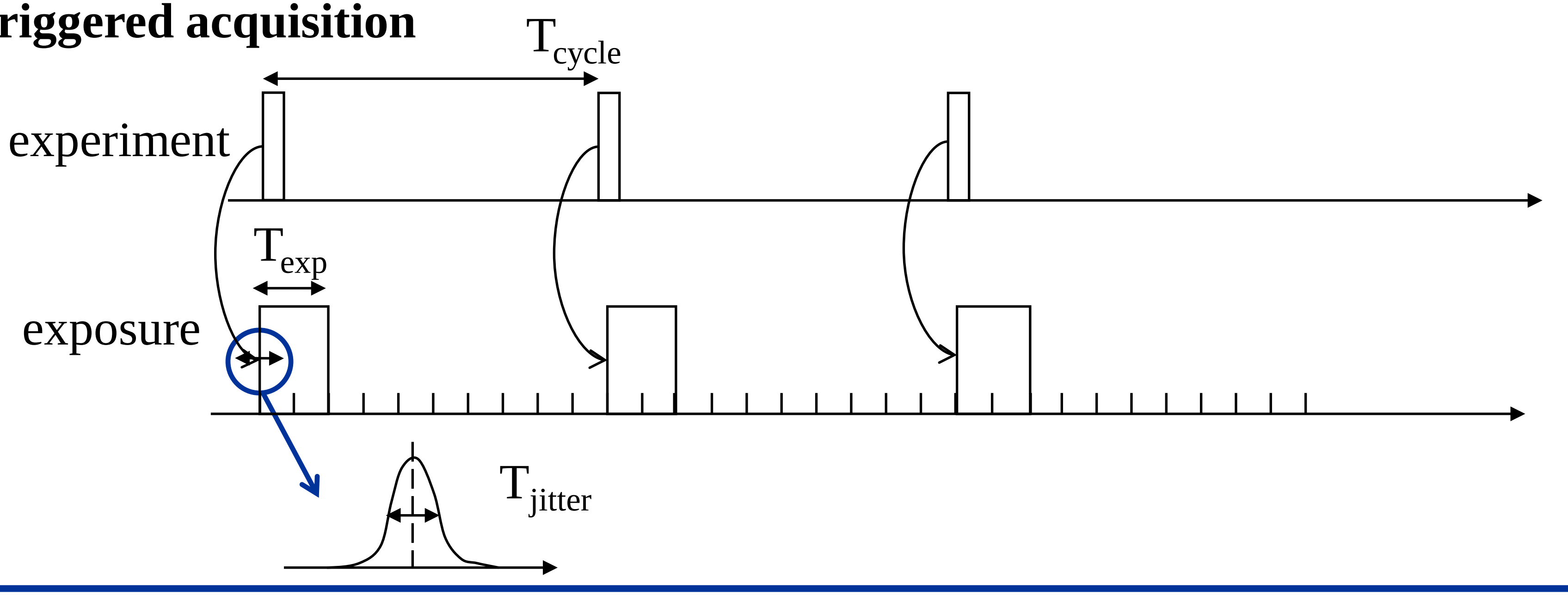
Time resolution

frame rate

$F = 1/T_{cycle}$



triggered acquisition



Summary : basic area detector specification list

- Detection field, pixel size, LSF
- Gain, noise, dynamic range
- Linearity
- DQE at a given energy
- Frame rate, readout dead time, minimum exposure time
- Energy range

2D X-ray detection principles

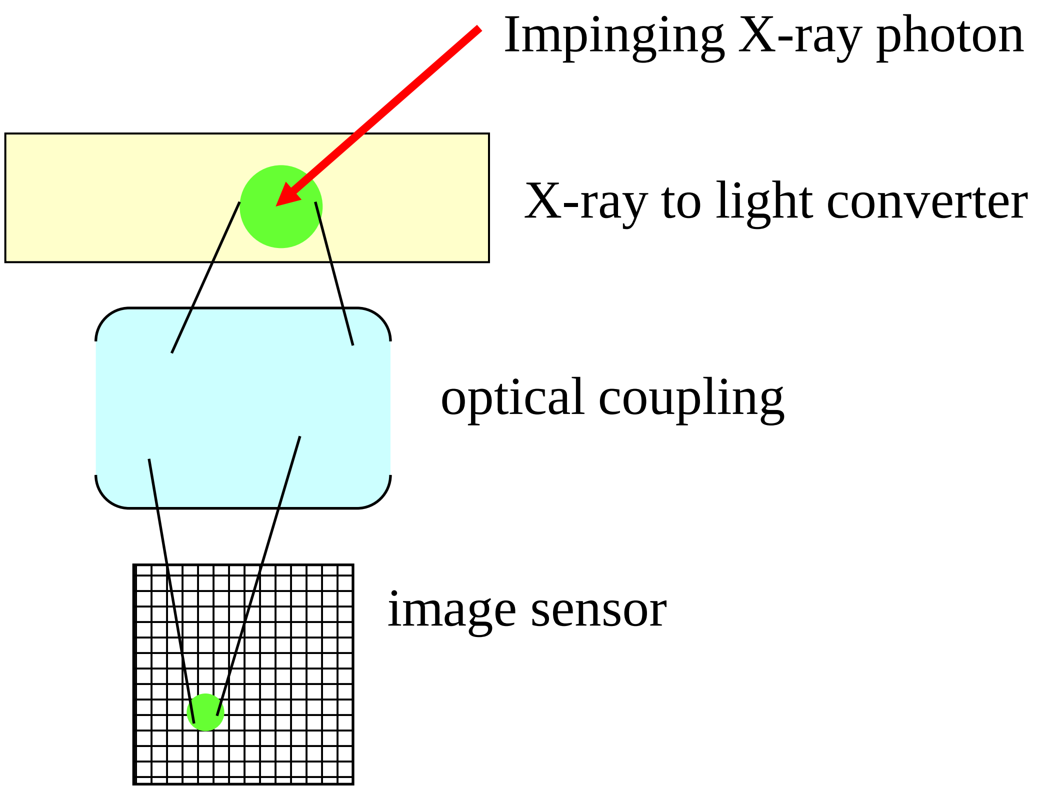
- Indirect conversion

  X-ray converters

  Optical coupling

- Direct conversion

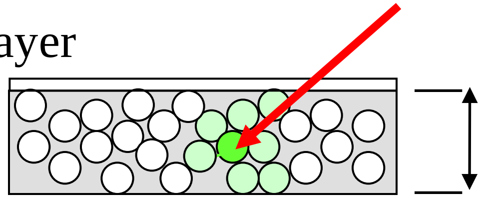
Indirect conversion



X-ray to light converters

reflective layer

phosphor powder + binder

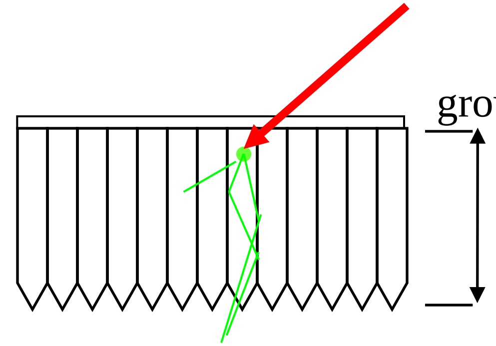


e=5…100 µm

Gd_2O_2S:Tb (P43), YAG:Ce (P46),…

spatial resolution ≈ e

growth substrate



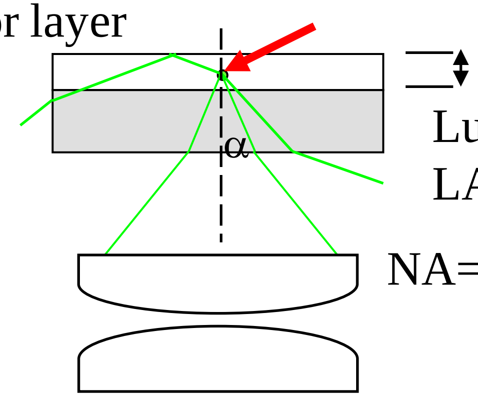
columnar CsI

e = 100…500 µm

spatial resolution < e

scintillator layer

transparent substrate



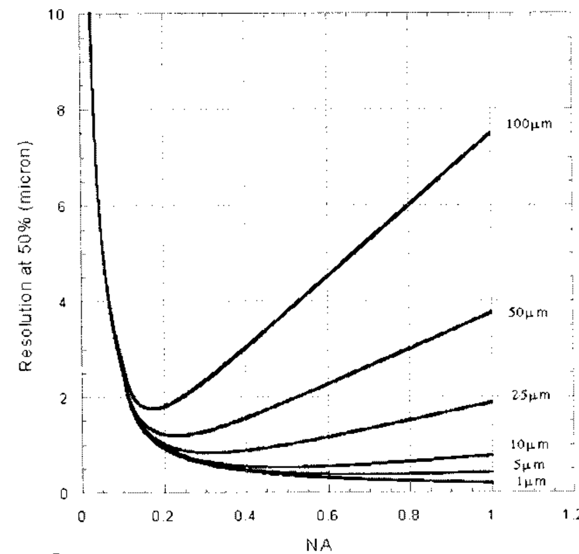
e=1…25 µm

LuAG, YAG:Ce, LAG:Ce,…

NA=n.sin α

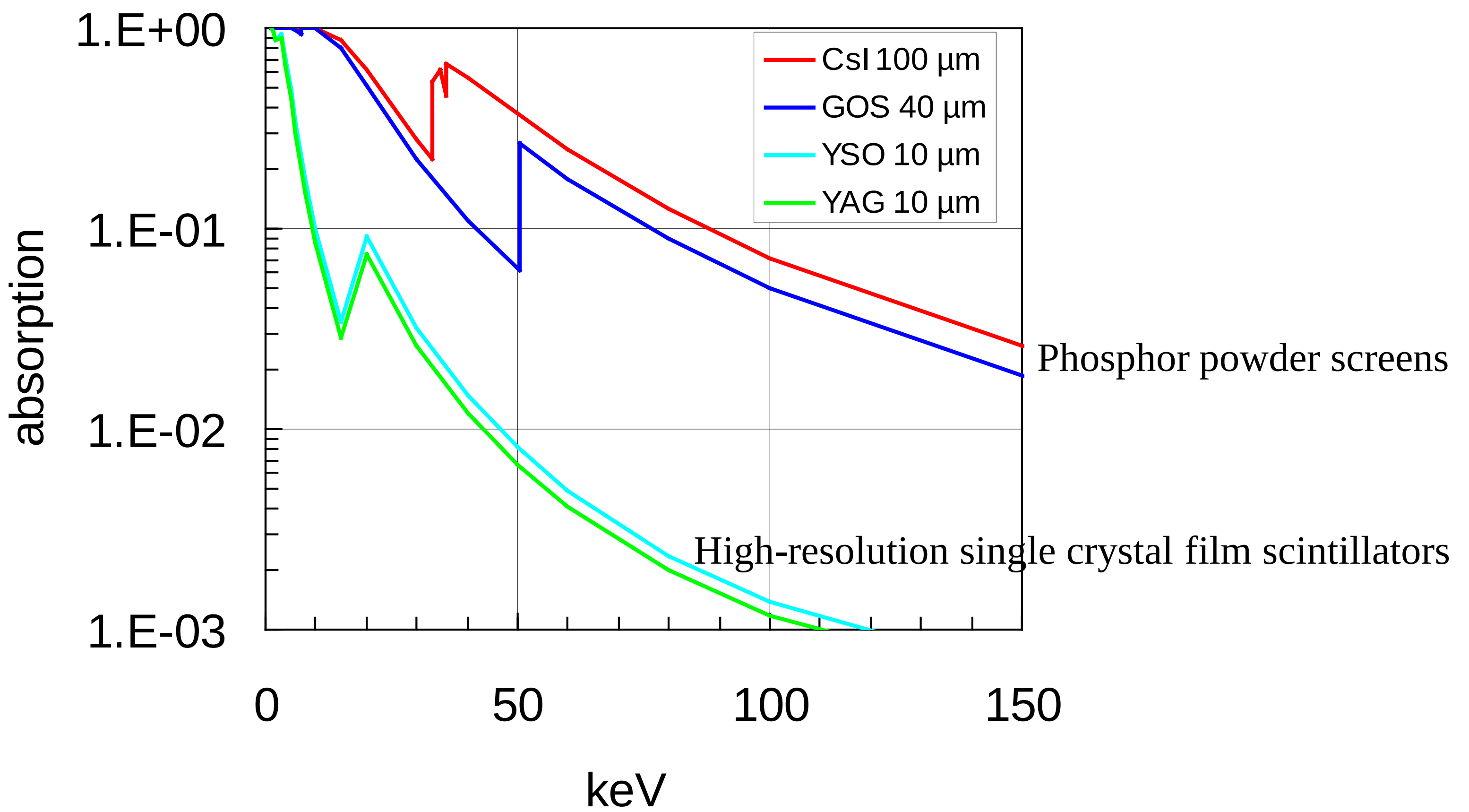
microscope objective

spatial resolution = 0.5…5 µm



Martin, Koch, JSR (2006)

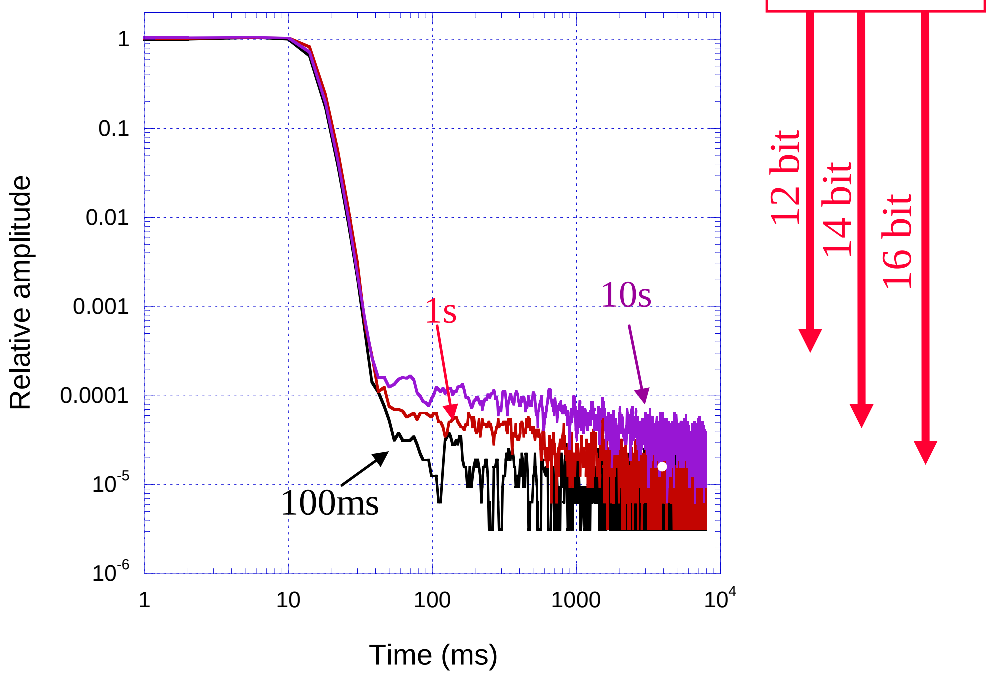
Absorption efficiencies



Absorption efficiency / spatial resolution trade–off

Decay times

Afterglow depend on exposure time
GGG: Eu 14 bit dynamic @ 80ms
16-17 bit are resolved

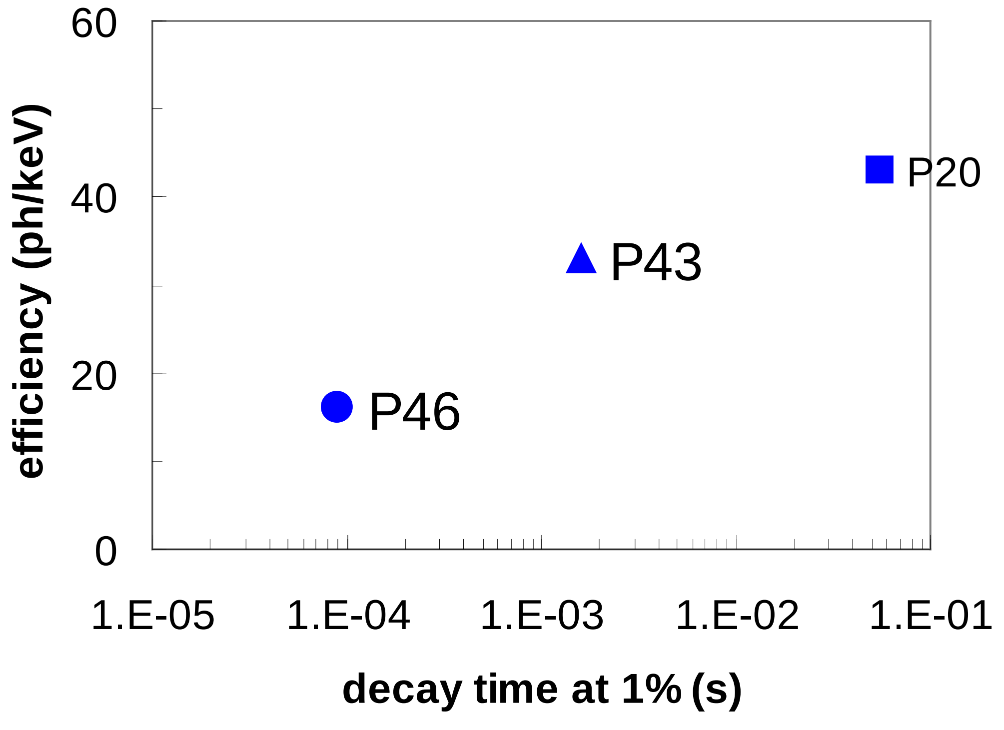


Data from Thierry Martin (ESRF)

speed / dynamic range trade–off

Decay times

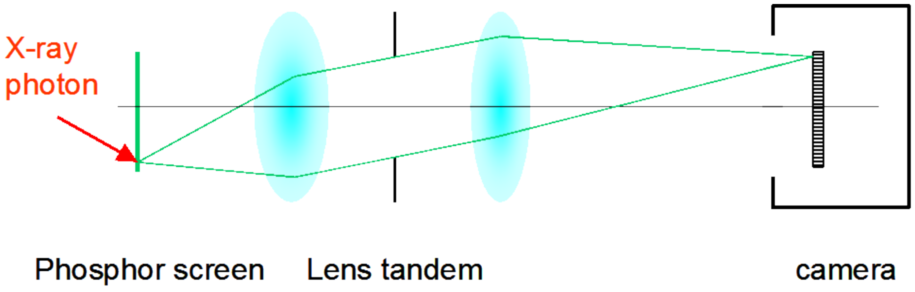
Phosphors with peak emission in the 530-550 nm range :



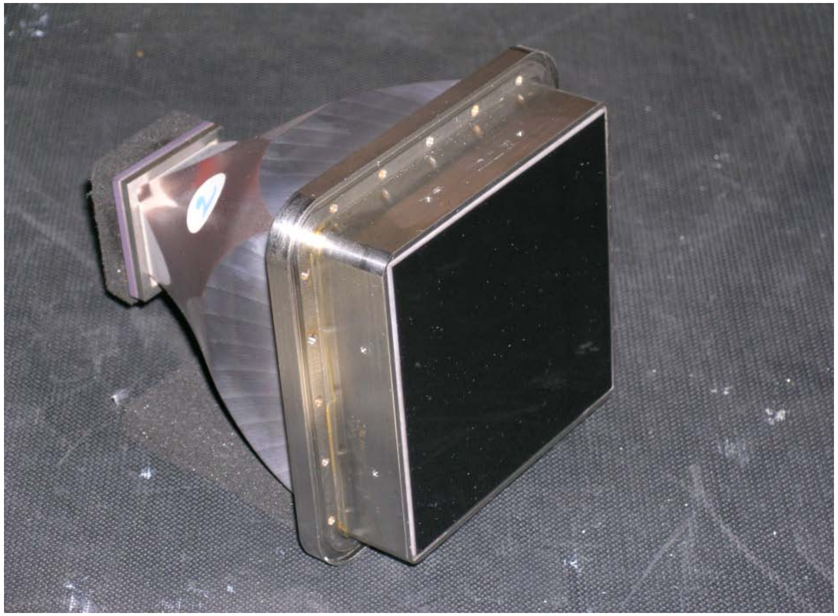
speed / sensitivity trade–off

Optical coupling

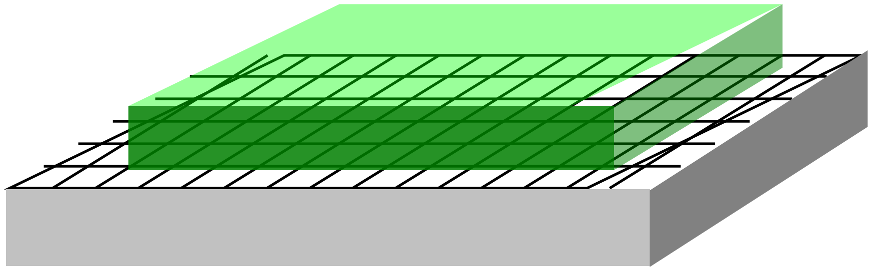
Lens



Fiberoptic taper

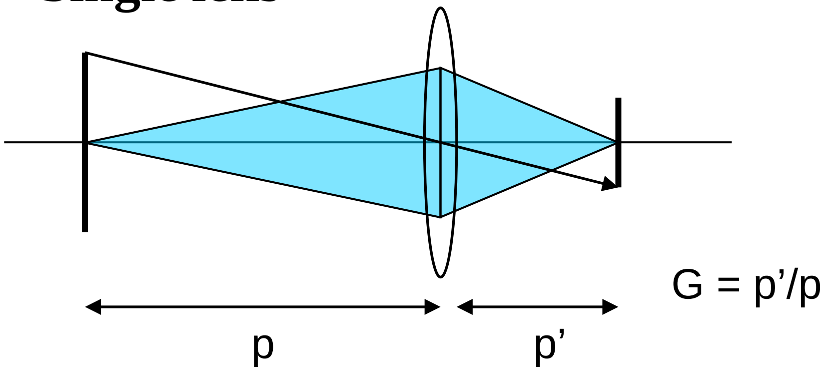


Direct coupling



Optical coupling efficiency

Single lens

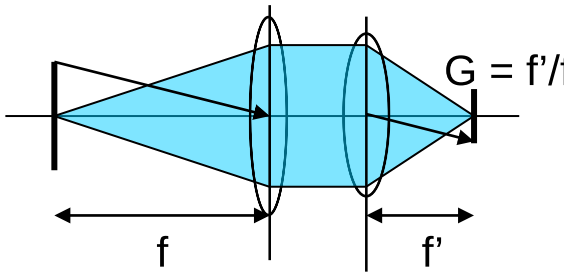


$$\eta_{opt} = T \cdot NA^2 = \frac{T}{1 + 4N^2(1 + 1/G)^2}$$

$$N = \frac{f}{D}$$

G = 1:1 and N = F/2 : η_{opt} **= 0.015**

Improvable using tandem lenses :

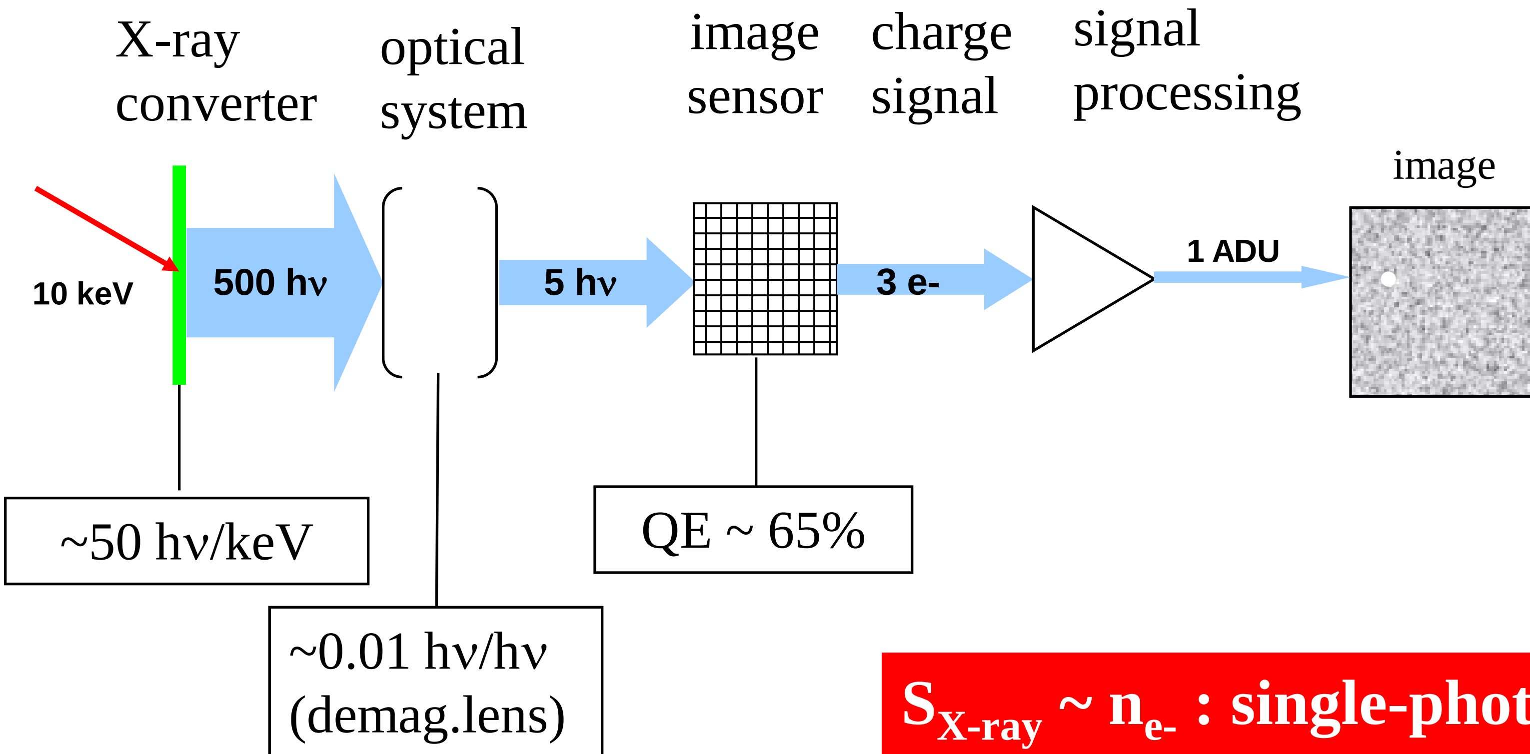


Magnification (G > 1) => coupling efficiency ~NA^2 ~$1/N^2$

Demagnification (G < 1) => coupling efficiency ~$1/N^2G^2$

Field width / sensitivity trade-off

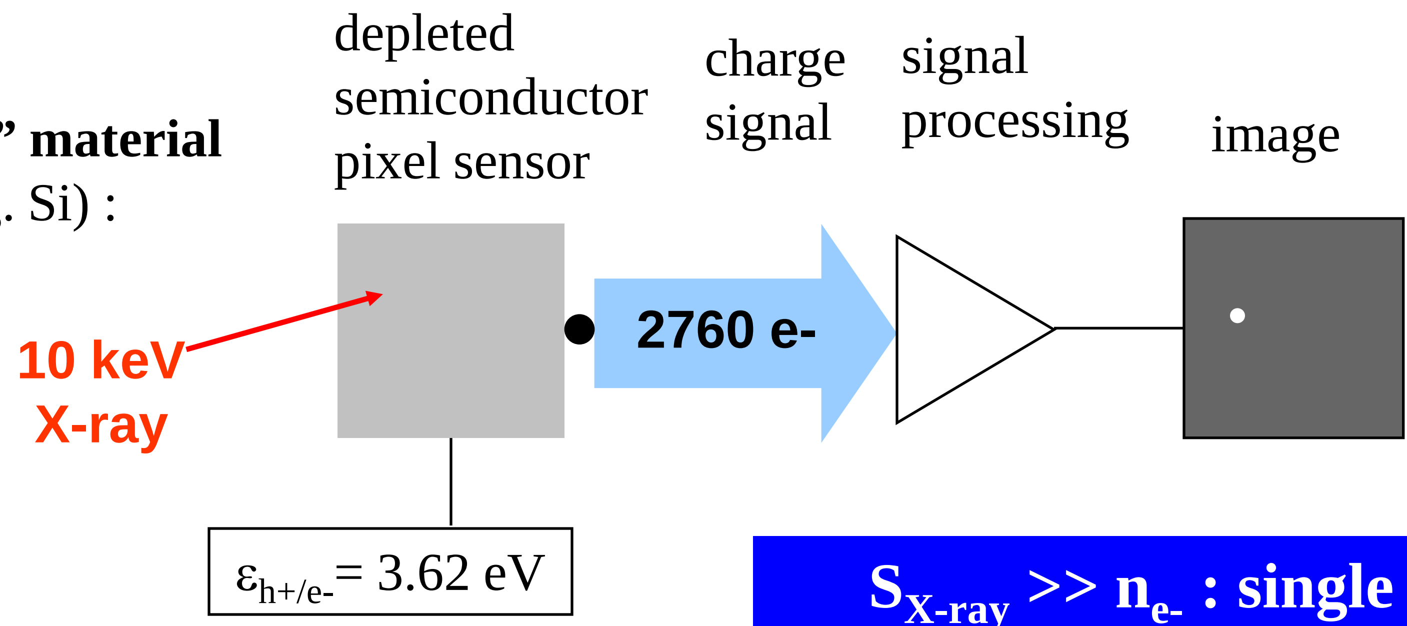
Signal propagation in indirect detection



$S_{X\text{-}ray} \sim n_{e-}$: single-photon discrimination (generally) not possible

Signal propagation in direct detection

“perfect” material
(e.g. Si) :



$S_{X\text{-}ray} >> n_{e-}$: single photon detection possible

Imperfect material (≠ Si)

incomplete depletion	→ reduced DQE
incomplete charge collection	→ reduced sensitivity
polarization	→ image afterglow

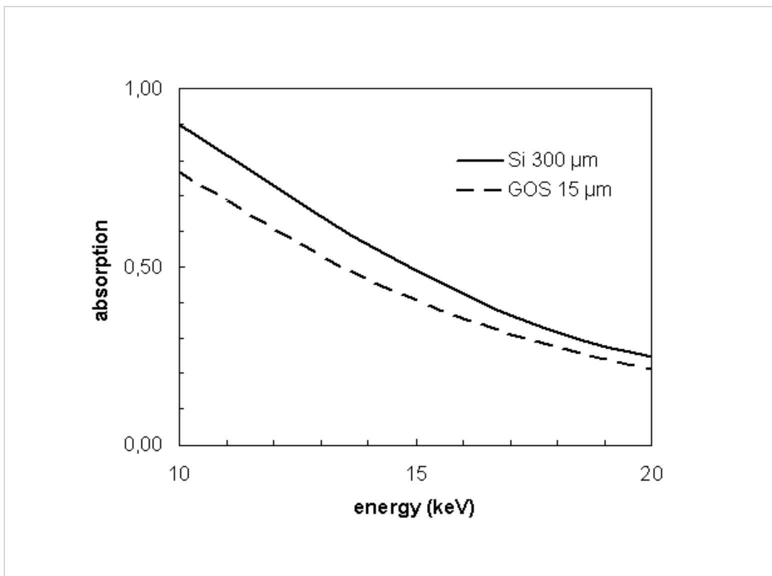
GaAs, HgI_2, CdTe, PbI_2, CdZnTe, a-Se

LSF : indirect vs direct detection

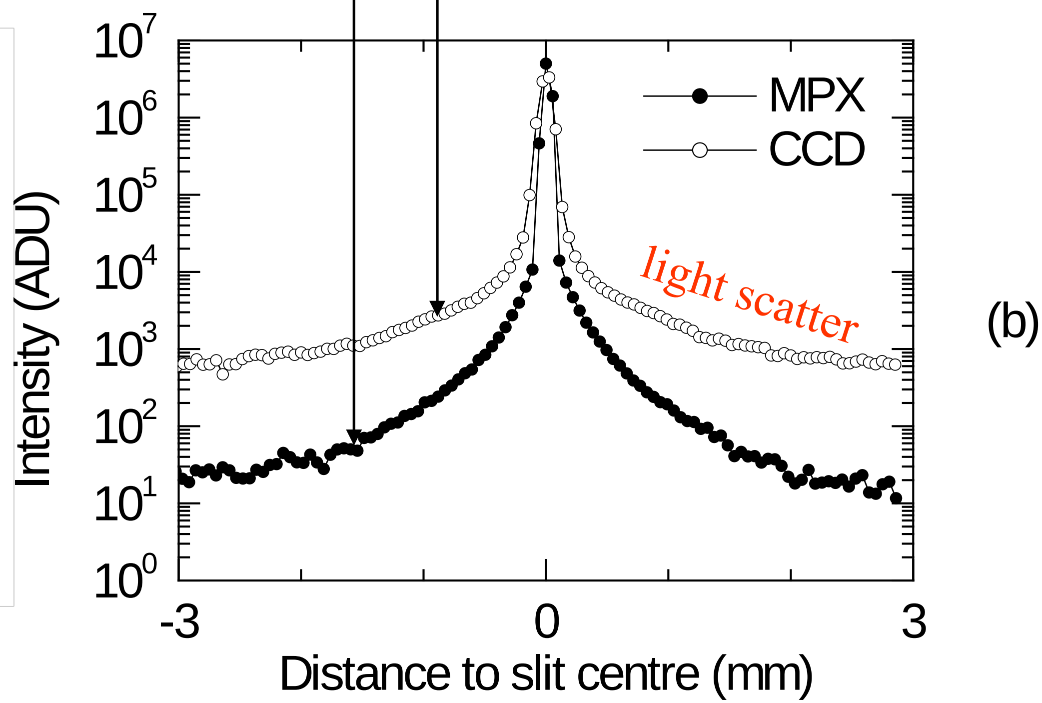
2 different detectors with identical pixel sizes and X-ray absorptions :

Lens-coupled CCD

Direct detection in Si



IEEE TNS 52 (2005)



Summary : indirect vs. direct detection

indirect

wide range of spatial resolutions

versatile

low gain at large input fields

dynamic range limitations

direct

sharp LSF

high gain (=> photon counting)

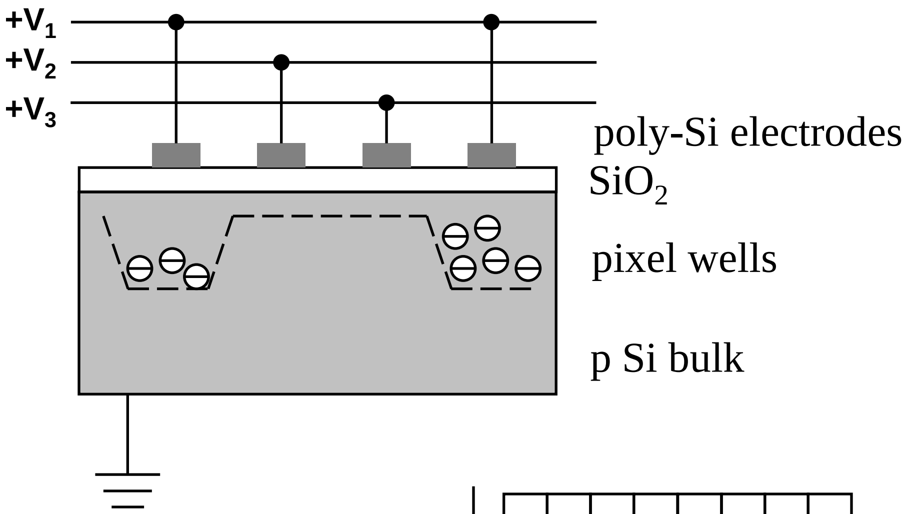
fixed spatial resolution

2D X-ray detector technologies

- Image sensors : CCD, CMOS
- Optically-coupled CCD detectors
- Photon-counting ASICS and detectors
- Flatpanels
- Image plates
- Gas filled multiwire proportional chambers

CCD image sensors

MOS gate structure, 3-phase CCD



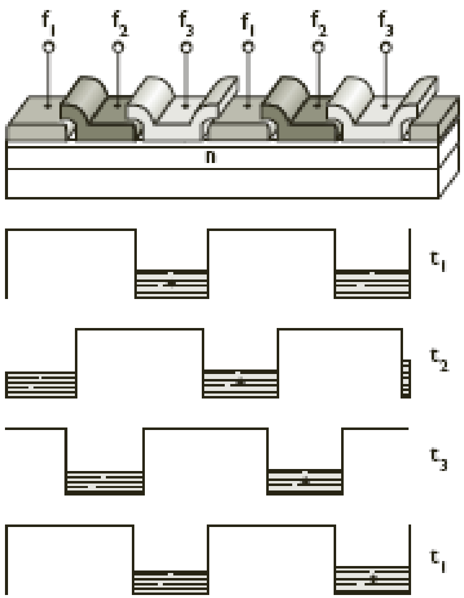
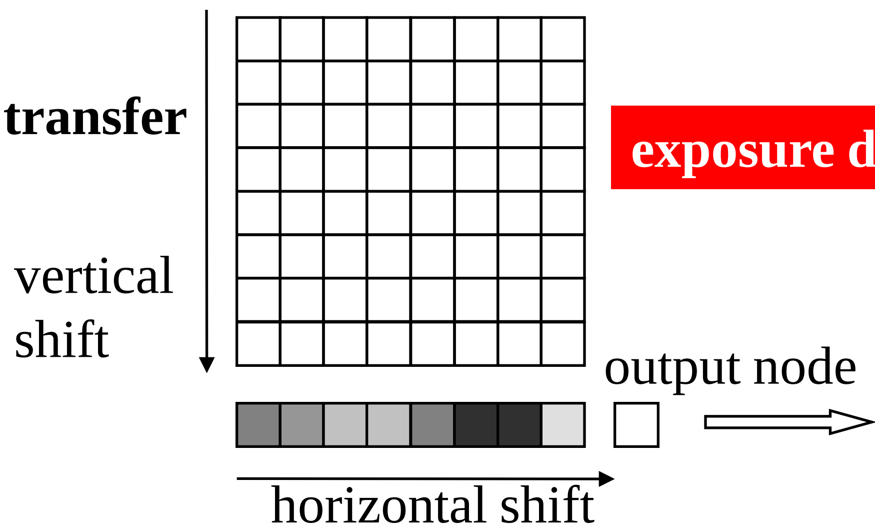
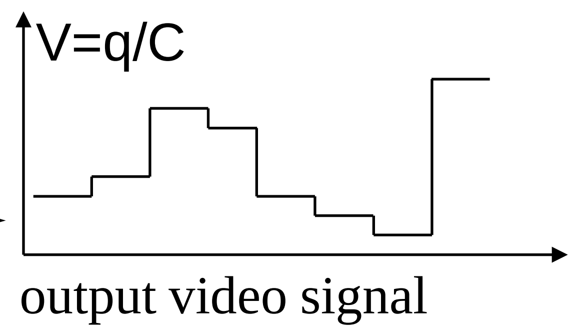


Image credit : DALSA

Full frame transfer



exposure during readout => SMEARING



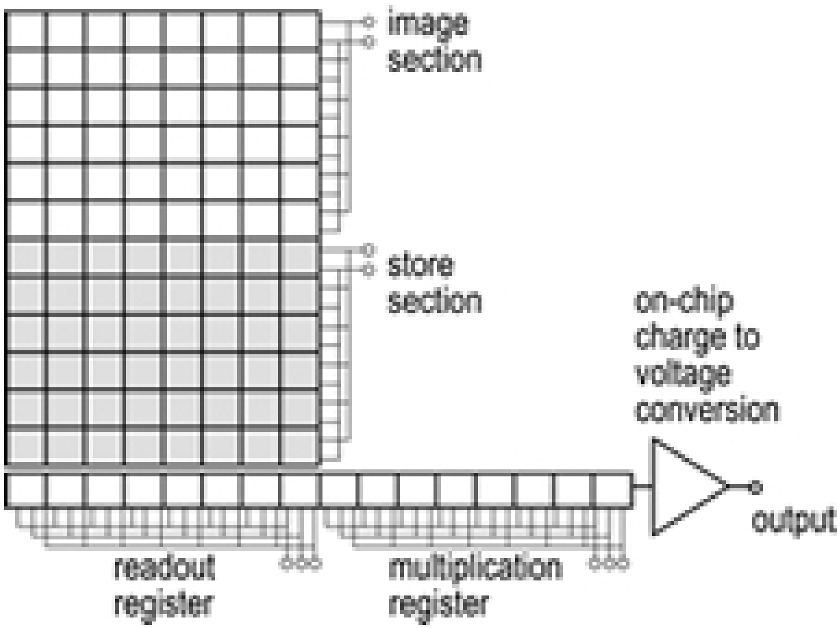
Electron-multiplication CCD

Self-amplification in horizontal shift register

High gain

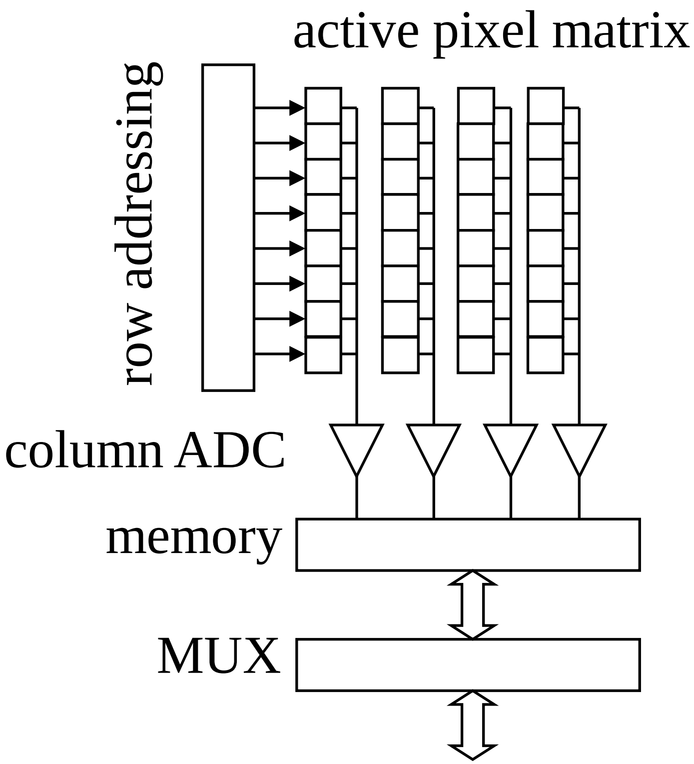
Excess noise at high gain

Dark noise amplification



CMOS image sensor

Example layout



Example characteristics (MICRON):

Active Array	1,280H x 1,024V
Imaging Area	15.36mm(H) x 12.29mm(V)
Pixel Size	12.0µm
Dynamic Range	59dB
Responsivity	1600 LSB/lux-sec
Frame Rate	0-500+ fps
Shutter type	TrueSNAP
Data Rate	660 Mp/s
Master Clock	66 MHz
Data Format	10-bit digital

CCD vs. CMOS in brief

CCD

High dynamic range

Low readout noise

readout time

smearing (full frame)

CMOS

High frame rate

Short exposures

Readout noise

Fixed pattern noise

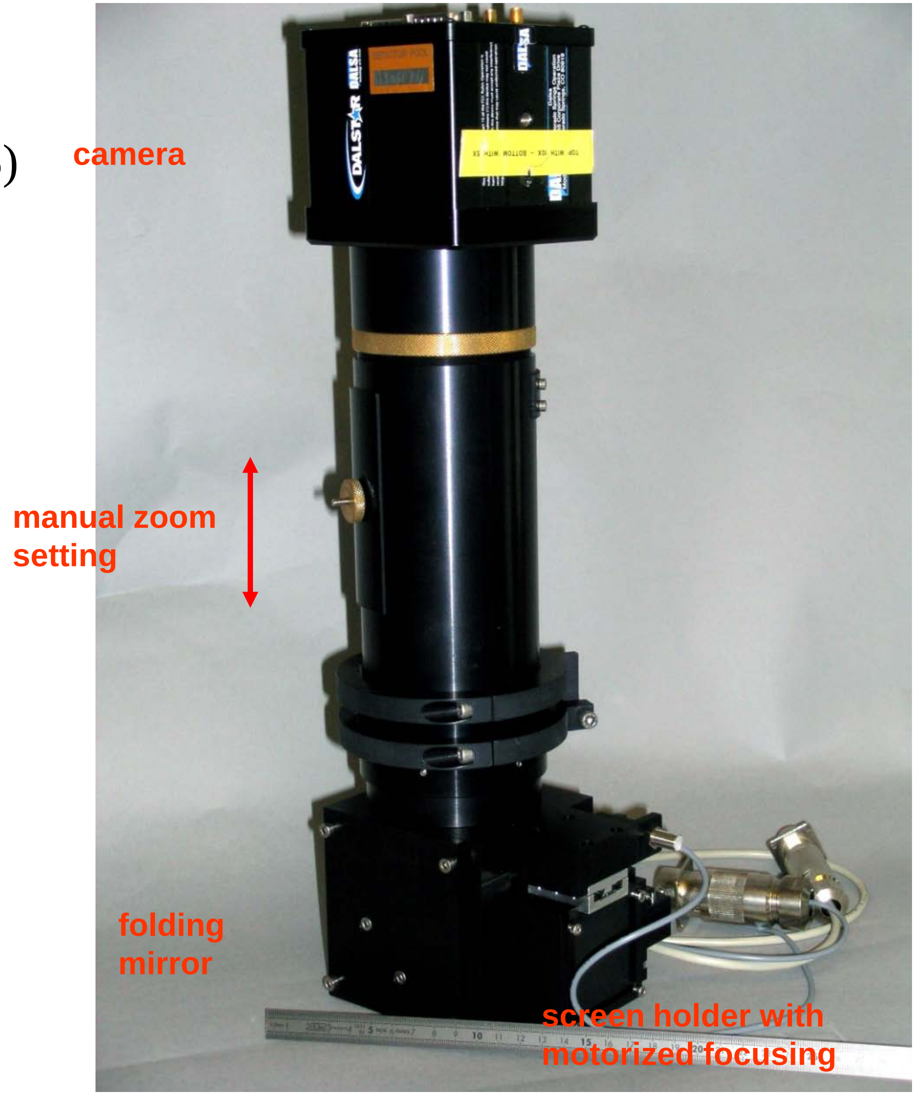
Variable field CCD detector

Application : high-energy imaging (ESRF ID15)

Adjustable field size with zoom lens

Field size	7-19 mm
Pixel size	3.8-9.4 µm
Converter	YAG 280 µm
Gain	2.4 ADU/keV
LSF FWHM	13-25 µm
Frame rate	~10 Hz

Design : ESRF

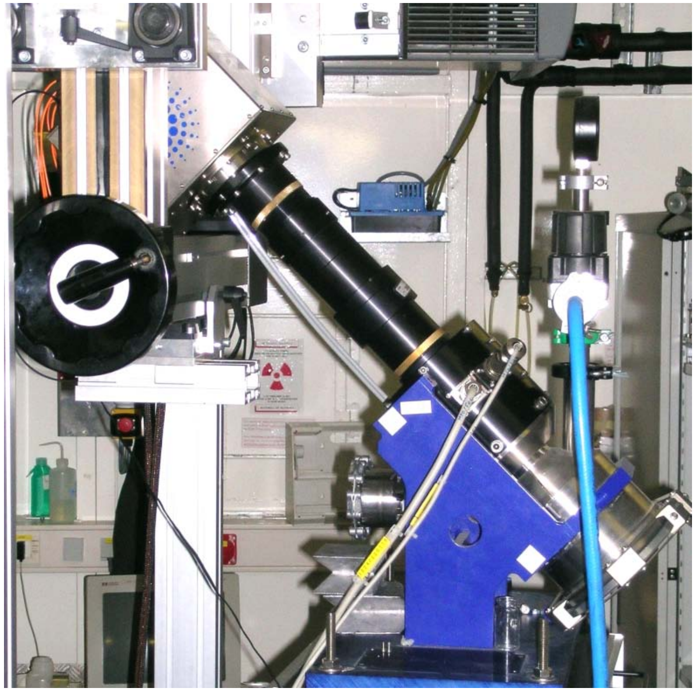


CCD detector for EDXAS

Field size	50x3 mm^2
Pixel size	25 µm
Noise	4 ADU/pixel rms
Dynamic range	14 bits
Frame rate	1 k Hz (kinetics mode)

Based on ESRF FReLoN CCD camera

RSI 78 (2007)



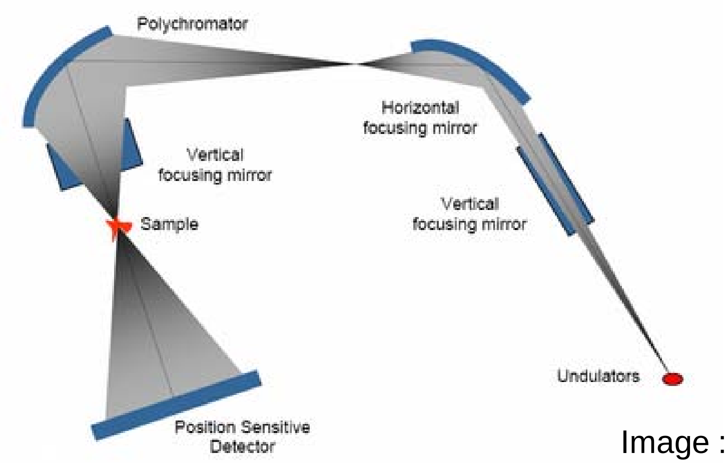
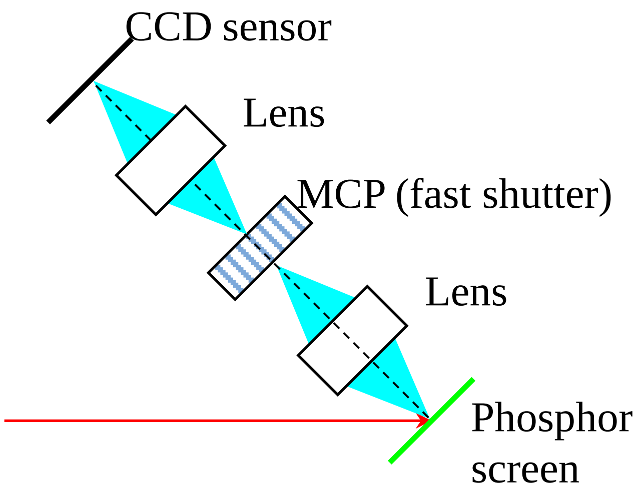
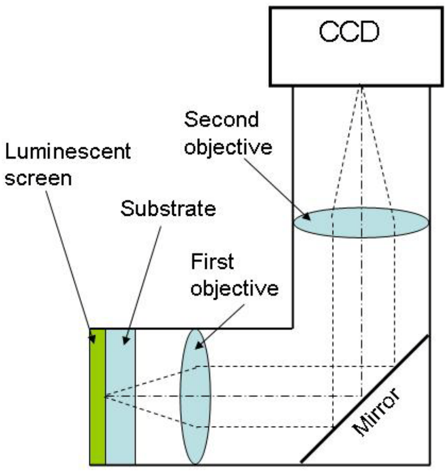


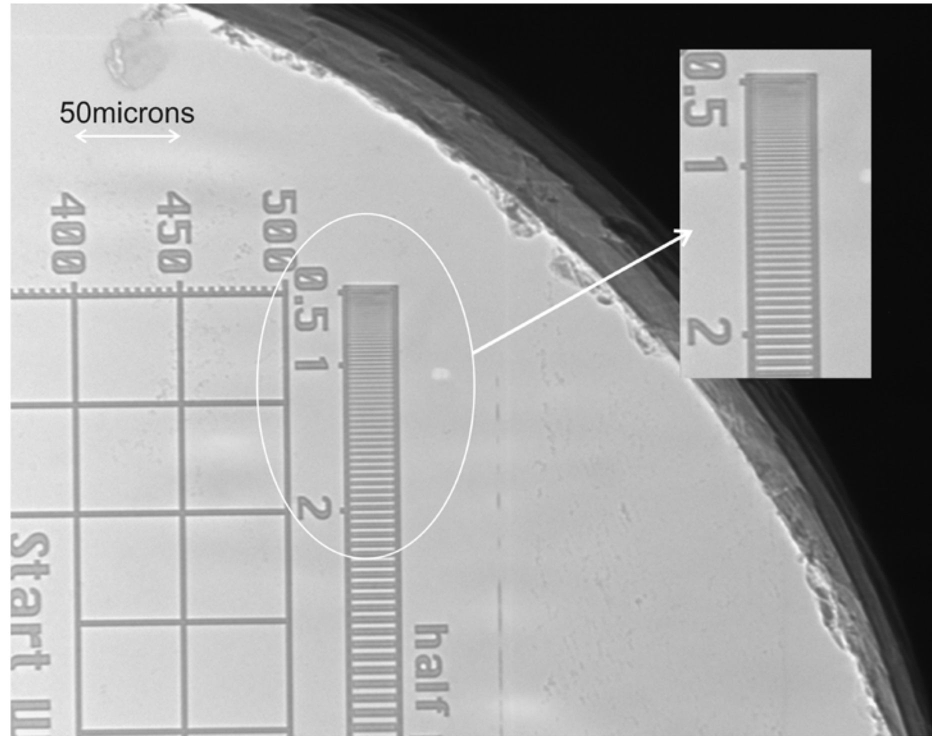
Image : ESRF ID24

http://www.esrf.fr/UsersAndScience/Experiments/XASMS/ID24/



High-resolution CCD detector





Sensitive layer
1-25μm

Substrate 170μm

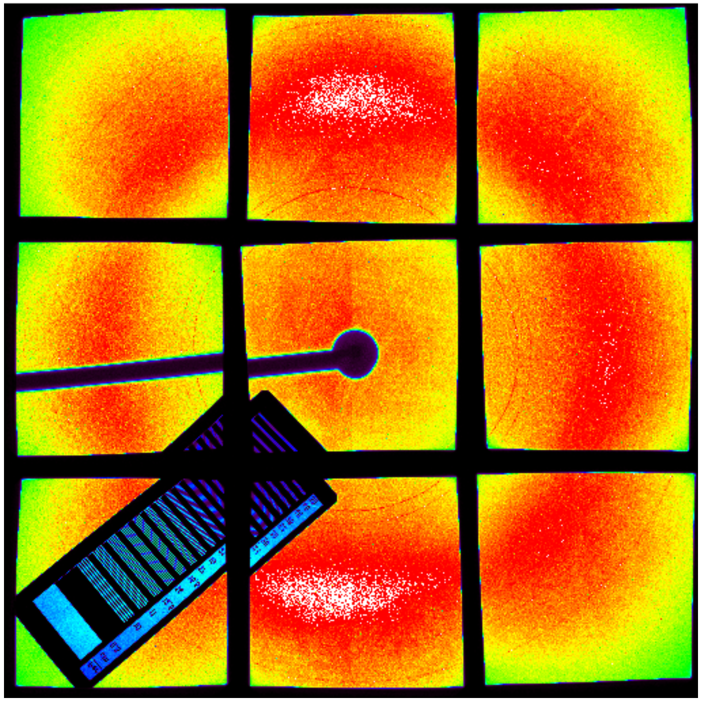
Submicron spatial resolution

Design : ESRF (Thierry Martin)

Large mosaic CCD

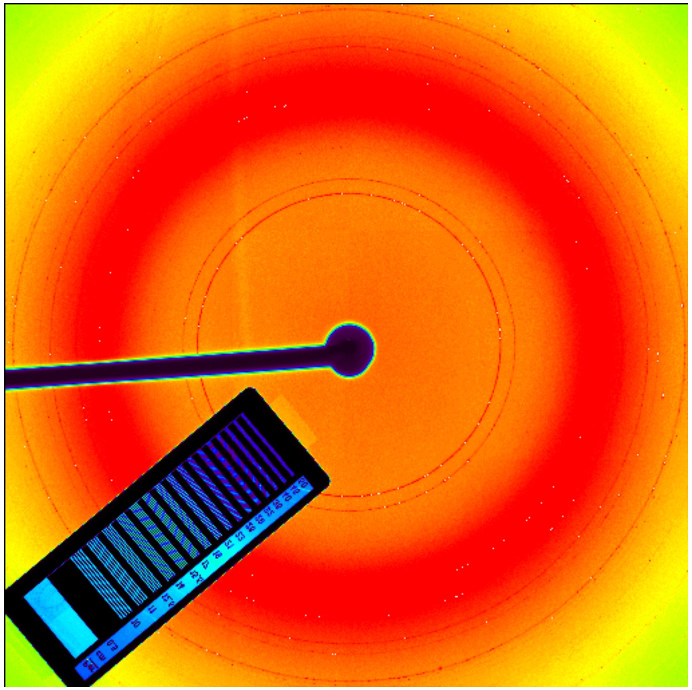
Field size	312 x 312 mm^2
Pixel size	52 µm
ADC range	16 bits
Noise	4 ADU/pixel r.m.s
Gain	2.1 ADU/10 keV X-ray
DQE	0.6 @ 10 keV
LSF FWHM	124 µm
Frame rate	0.26 Hz (1 s exposure)

Large mosaic CCD : image corrections

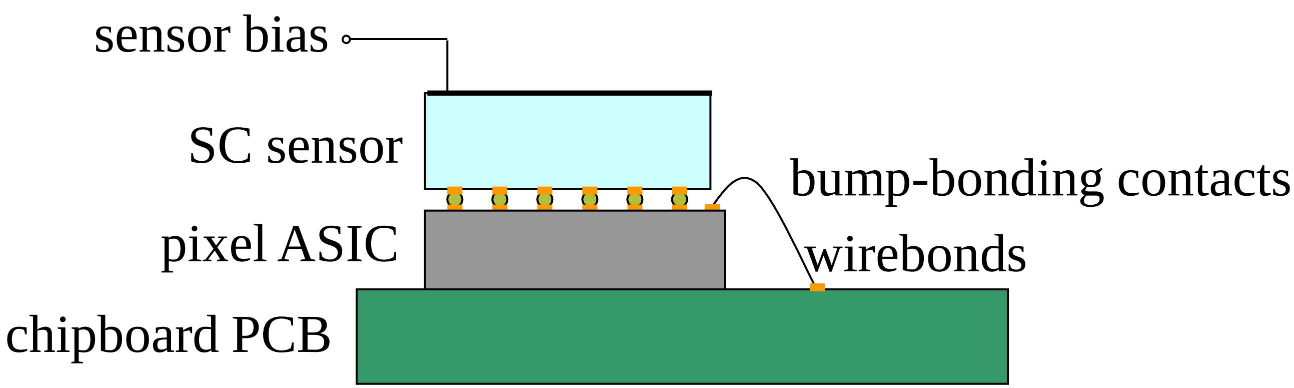


raw image

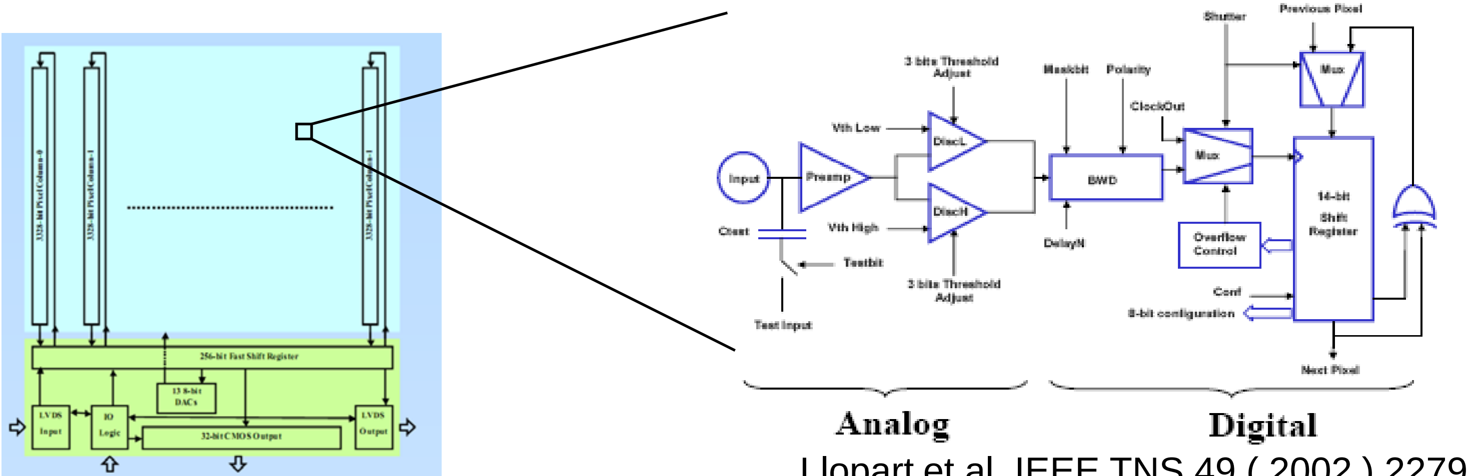
Correction
- Spatial distortion
- flatfield



Hybrid photon-counting pixel detectors



Example : Medipix2

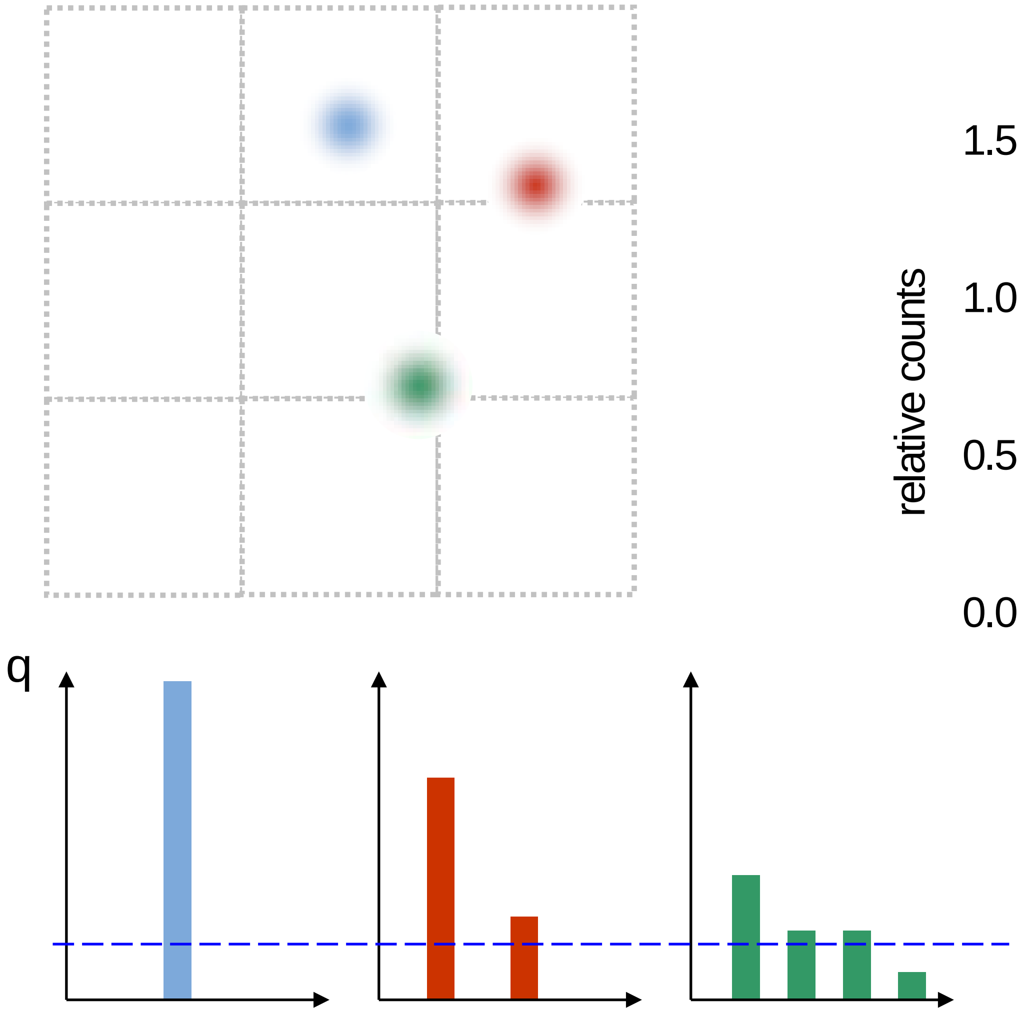


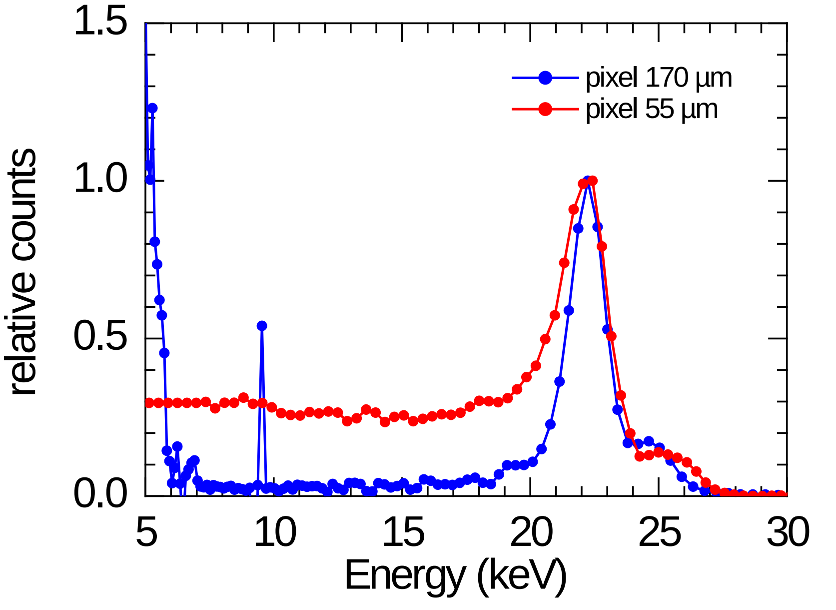
Llopart et al. IEEE TNS 49 (2002) 2279

CERN, the Medipix Collaboration
http://medipix.web.cern.ch/MEDIPIX/

Each pixel is a photon counter

2D photon-counting : charge sharing



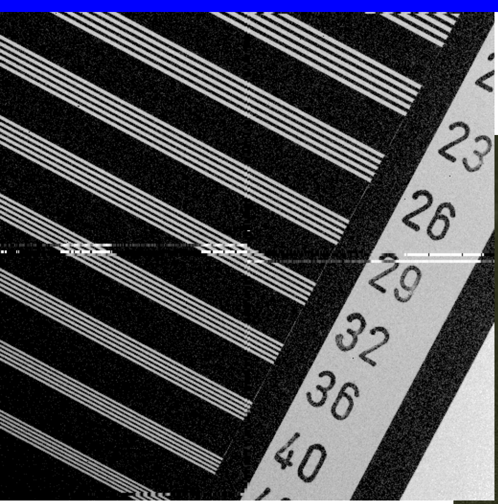


MAXIPIX

Detection areas	256x256 512x512 $pixel^2$ 1280x256
Pixel size	55 μm^2
X-ray converter	Si 500 µm
Counter depth	13.5 bits
Frame rate	280-1400 Hz
Readout dead time	0.29 ms

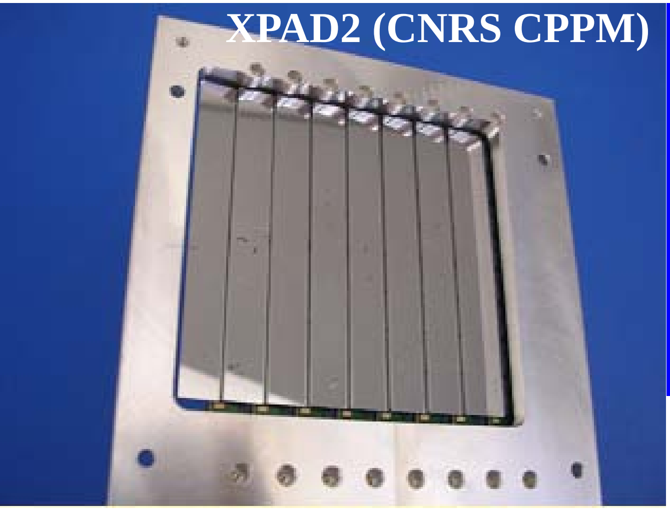
Fast readout photon-counting detector

ESRF development
Based on **MEDIPIX2** chip
http://medipix.web.cern.ch/MEDIPIX/



Other photon-counting pixel detectors

Detection areas	487x195 to 2463x2527 pixel^2
Pixel size	172 µm^2
X-ray converter	Si 300 µm
Counter depth	20 bits
Frame rate	12-200 Hz
Readout dead time	2.7-3.6 ms



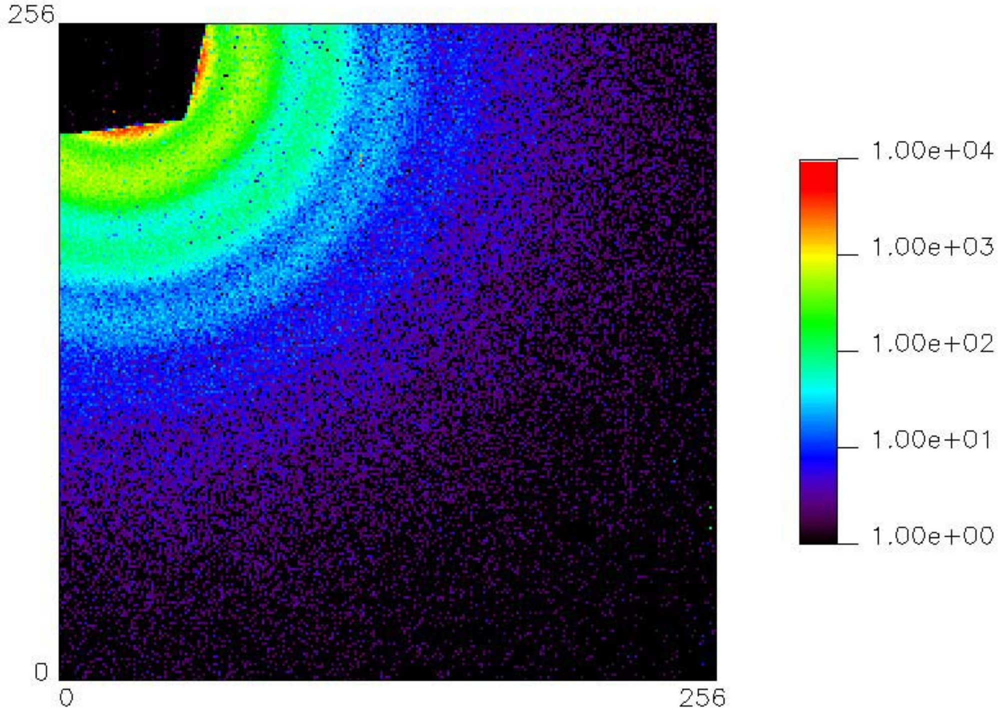
Detection areas	120x75 mm^2
Pixel size	330 µm^2
X-ray converter	Si 500 µm
Counter depth	15 bits
Readout dead time	2 ms

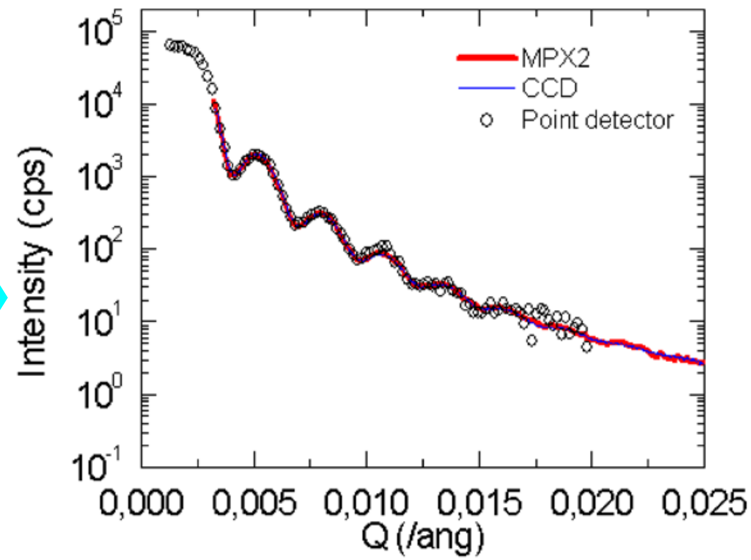
Delpierre et al. NIMA 572 (2007) 250

Example application : SAXS

Photon-counting detector (Medipix2)
Colloidal PMMA, 40% concentration, 8.33 keV

data : F. Zontone (ESRF)





Reduced exposure time
Arbitrarily high dynamic range
No profile distortion at low signal

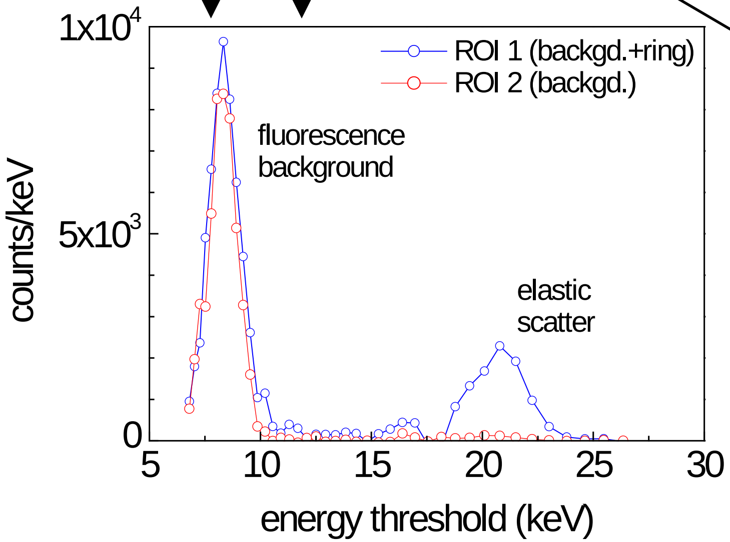
MPX2 : 1 s
CCD : 100 x 1 s
point detector scan : 5s/point

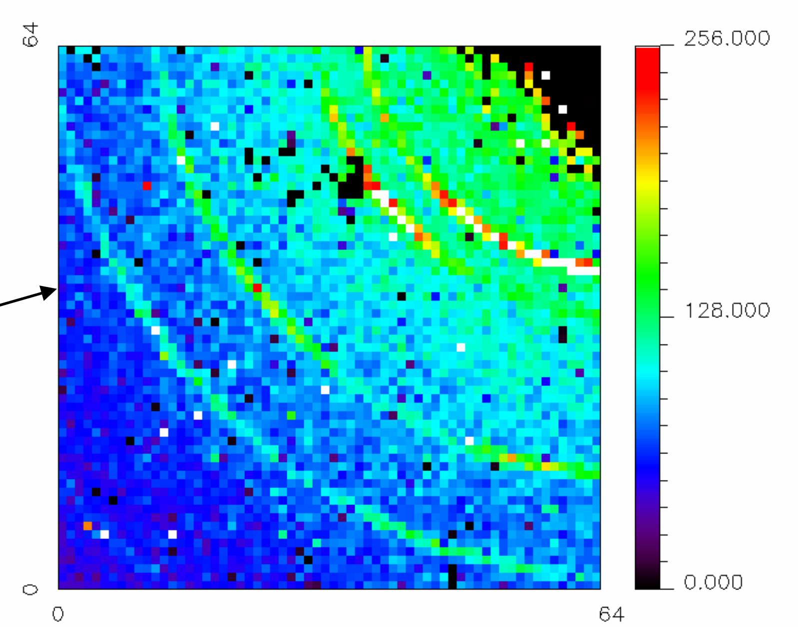
IEEE TNS 52(5) (2005) 1760

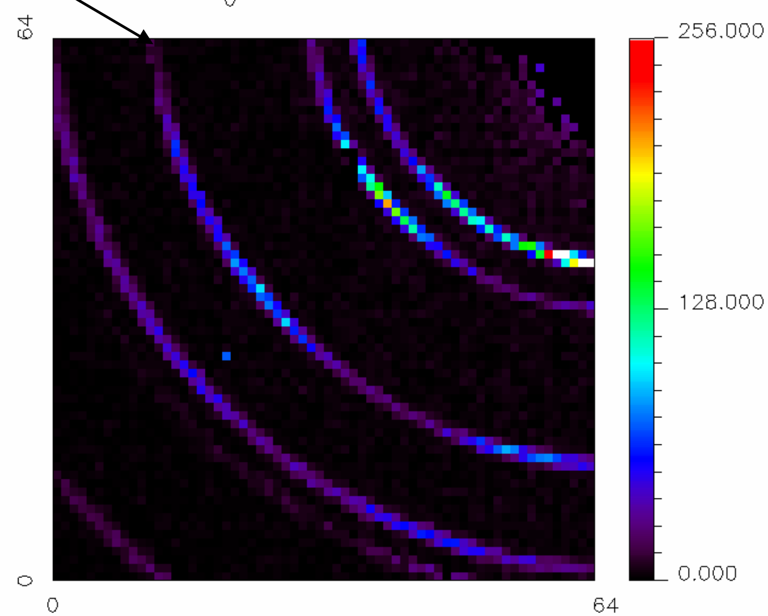
Fluorescence rejection

Photon-counting detector (Medipix1)
Cu foil sample, 20 keV beam

threshold settings





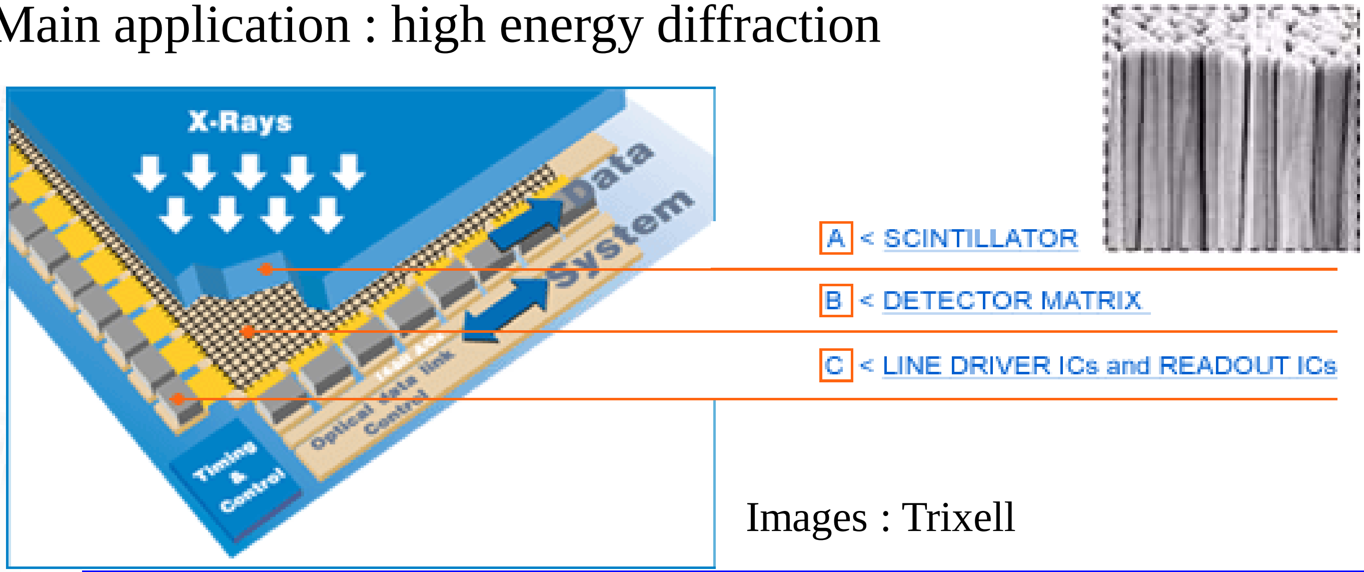


NIMA 510 (2003) 29

Flatpanel + scintillator

Main application : high energy diffraction

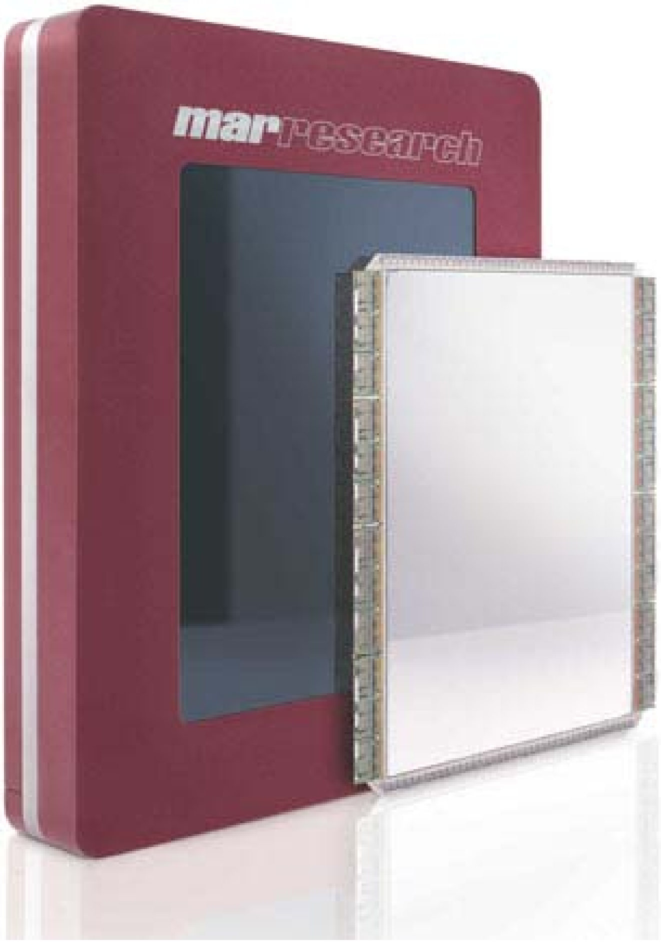
PIXIUM (Thales)



Images : Trixell

Field size	407 x 296 mm^2
Pixel size	154 µm
Noise	0.2-2.6 ADU/pixel r.m.s
Gain	0.2-1 ADU/X-ray @ 37 keV
DQE	0.85 @ 37 keV
LSF FWHM	210 µm
Frame rate	7.5-30 Hz
Energy range	30 - 100 keV

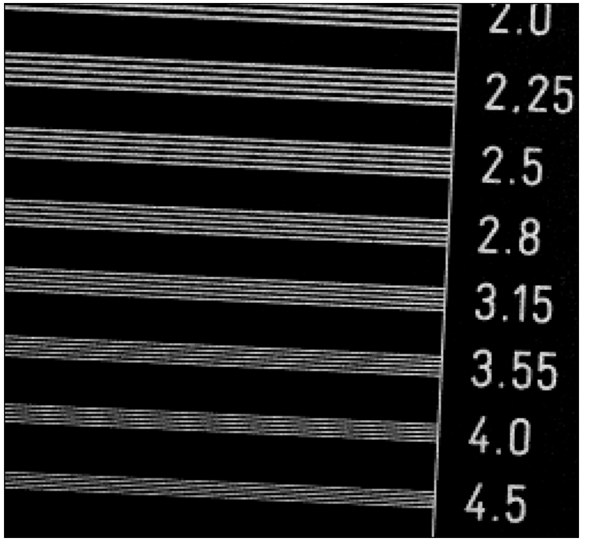
Flatpanel + semiconductor



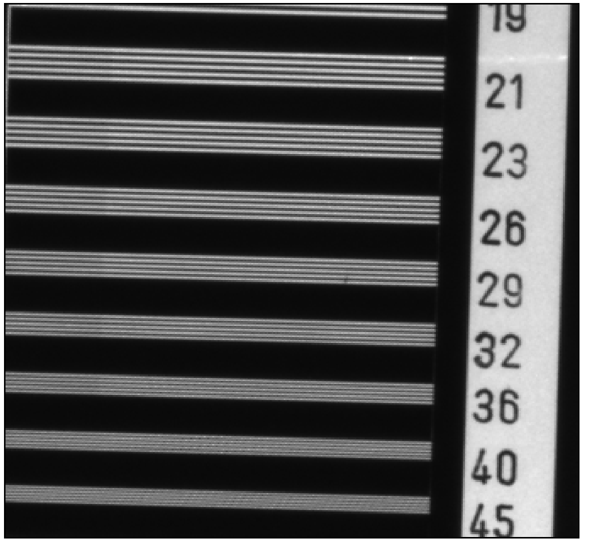
Main application : diffraction

Field size	358 x 430 mm^2
Pixel size	139 μm^2
X-ray converter	a-Se
ADC range	16 (20) bits
Noise	2.8 ADU/pixel r.m.s
Gain	0.6 ADU/17.4 keV
DQE	0.6 @ 17.4 keV
LSF FWHM	~130 μm
Frame rate	0.3 Hz (1 s exposure)

Flatpanel + semiconductor



a-Se flatpanel
pixel size 139 µm



CCD fiberoptic
pixel size 100 µm

- Pixel-limited spatial resolution
- Large uniform detection area
- Image afterglow

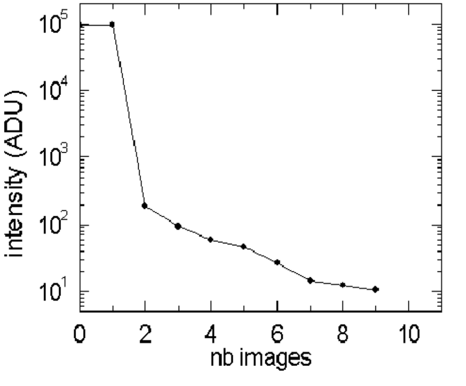


Image plate scanner

Photostimulable luminescent screen

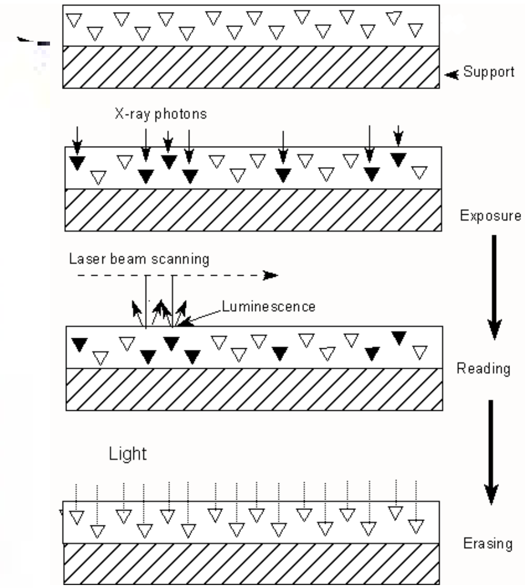
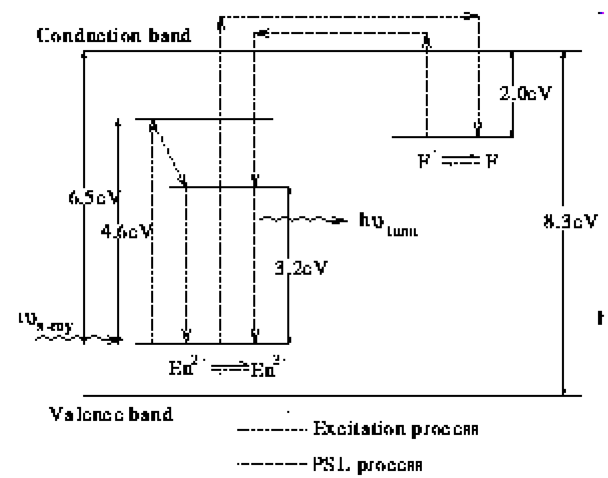


Image : NONIUS



Von Seggern et al., J. Appl. Phys. 64(3) (1988) 1405

Field size	345 mm diametre
Pixel size	100 µm
X-ray converter	BaFBr:Eu^{2+}
ADC range	17 bits
Noise	1 ADU/pixel r.m.s
Gain	1 ADU/8 keV X-ray
Readout time	108 s

Conclusion

This lecture only pretends to be :

An obviously incomplete overview of 2D X-ray detectors for synchrotrons experiments

A guide to help asking oneself the right questions when having to choose or design a 2D X-ray detector

A incentive to learn more about modern 2D X-ray detection technologies

Thank you for your attention