Detectors for Imaging and Microanalysis

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School on X-ray Imaging Techniques at the ESRF, Grenoble 5-6 Feb 2007

Overview

1. Some fundamental issues: spatial- and energy- resolution, noise, ...

2. Detectors in use, properties and limits:

    i. direct 2D imaging by scintillator-CCD systems

    ii. (raster imaging) microanalysis with spectrometric semiconductor detectors

Spatially resolving, imaging detectors

'Spatial Resolution': some definitions…

For imaging applications, resolution is usually described by the *Modulation Transfer Function* (M), i.e. the system response to a sine-wave spatial-frequency amplitude. Response of a complex system (e.g. scintillator-lens-sensor) can then be evaluated as simple *product of the individual component MTF's*.

In practice, it is easier to measure ***either***

the *Contrast Transfer Function (C)* i.e. the square wave spatial frequency response, related to M by:

$$M\,(N) = \frac{\pi}{4}\left[C(N) + \frac{C(3N)}{3} - \frac{C(5N)}{5} + \frac{C(7N)}{7} - \ldots\right]$$

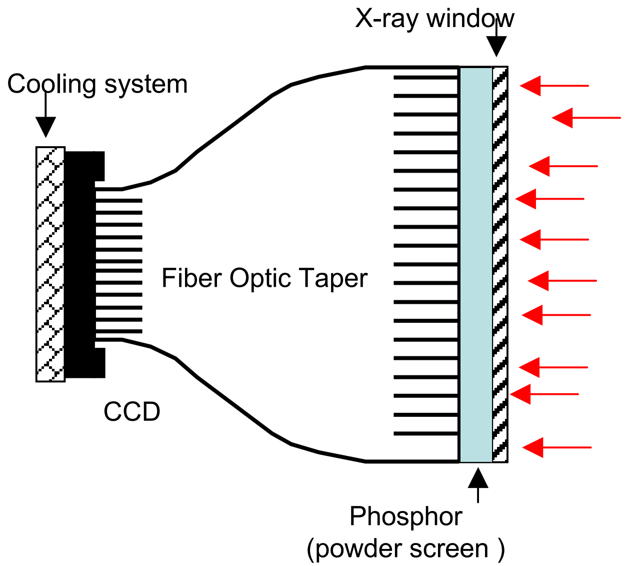
where N is the signal spatial modulation frequency in 'line pairs' per unit distance

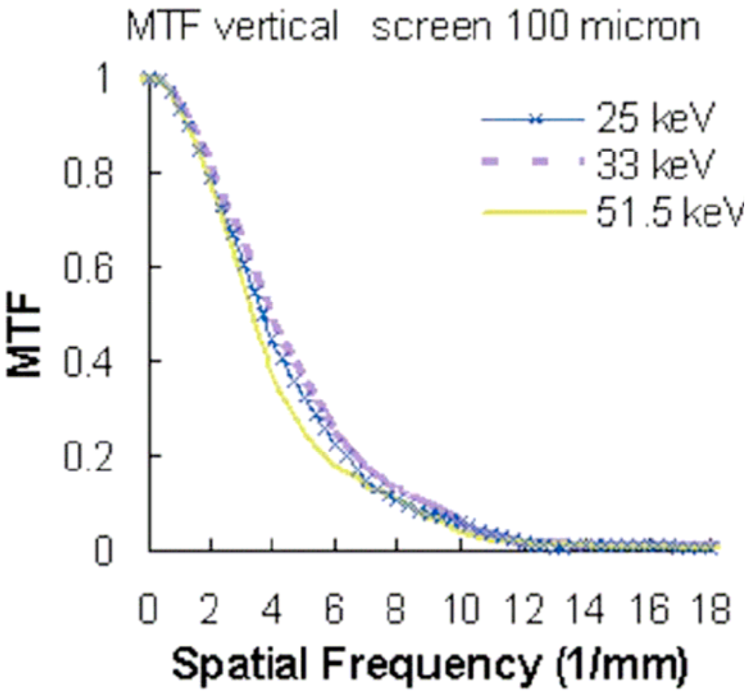
or

measure the *Line Spread Function (LSF)* i.e. the response of the system to illumination by a narrow slit. The LSF is related to M by the 'simple' Fourier transform

$$\mathrm{M}(v) = \frac{\left|\sum_{k=-\infty}^{+\infty} \mathrm{LSF}(k\Delta x)\mathrm{e}^{-\mathrm{j}2\pi v k\Delta x}\right|}{\sum_{k=-\infty}^{+\infty} \mathrm{LSF}(k\Delta x)}$$

Scintillator screen cameras: spatial resolution





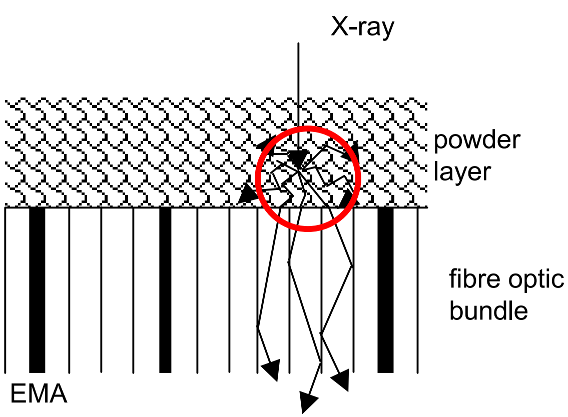
Coan et al., J. Synch Rad, 13 (2006) 260-270

ESRF FReLoN tapered fiber optic camera at ID17: active input surface of 94mm x 94mm, $Gd_2O_2S:Tb$ powder scintillator screen, 3.2:1 demagnification onto 2048^2 x 14 µm pixel CCD effective input pixel size 46 µm

System MTF evaluated from scanning a tungsten blade ('edge spread function' ~ spatial integral of LSF)

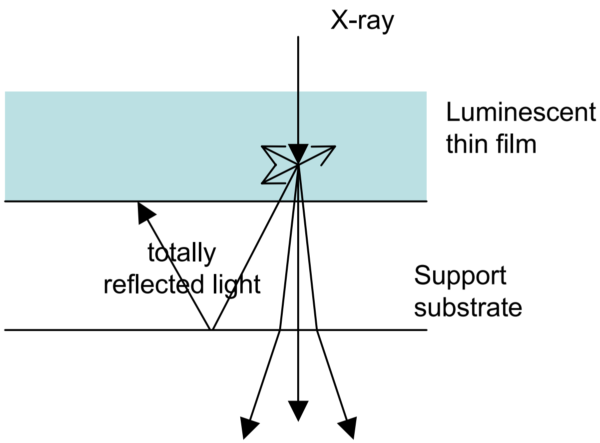
Scintillator cameras: screen types

Powder-granular phosphor screen



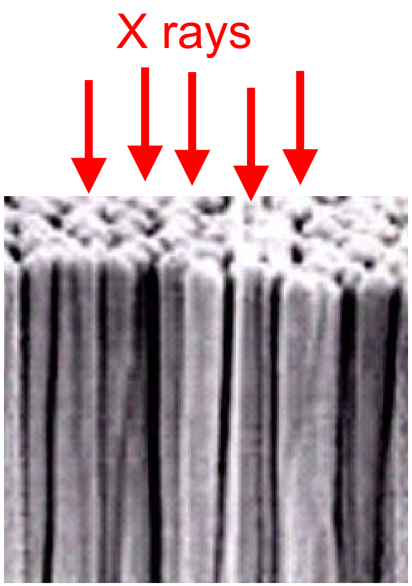
resolution -> few microns fwhm
size -> 50cm

Crystal screen



resolution -> ~0.5µm fwhm
in 'thin' limit
size ~1cm

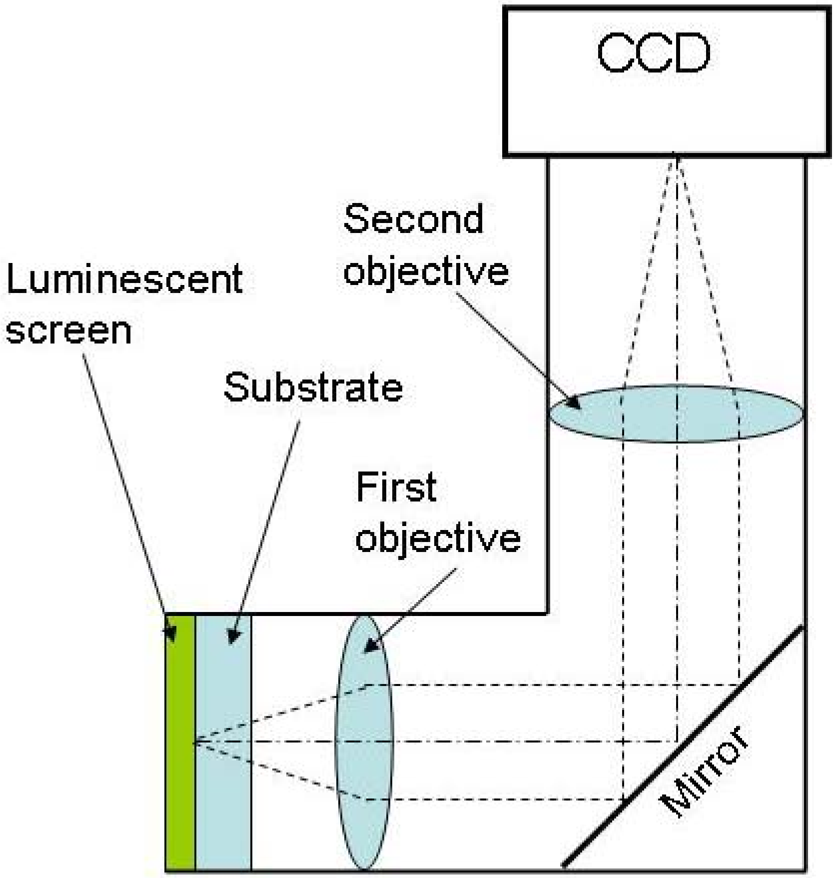
'Structured' scintillator



evaporated CsI:Na

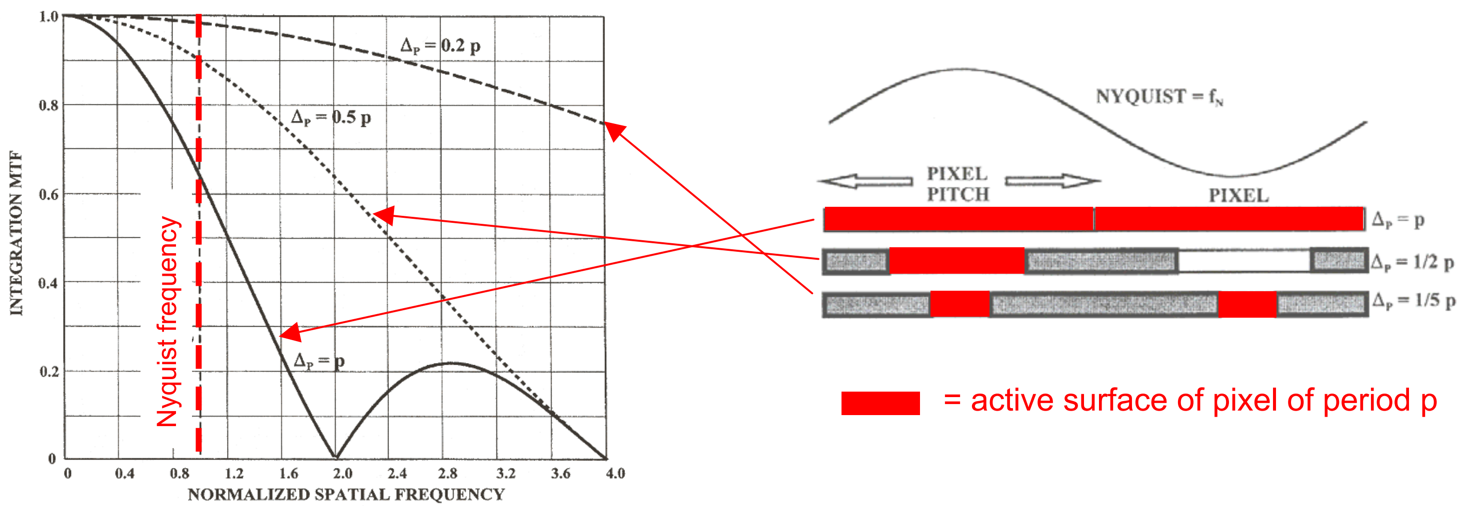
-spatial artifacts ?
-efficiency ?

Scintillator cameras: crystal screen, high resolution



Resolution: imager pixel frequency and fill factor

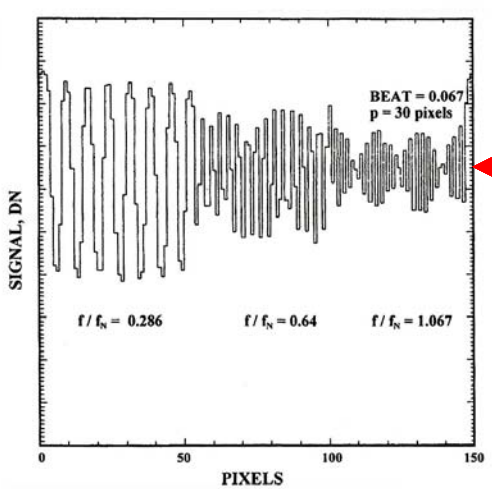
$$MTF_I = \frac{\sin\left(\frac{\pi f \Delta_p}{2 f_N p}\right)}{\frac{\pi f \Delta_p}{2 f_N p}}$$

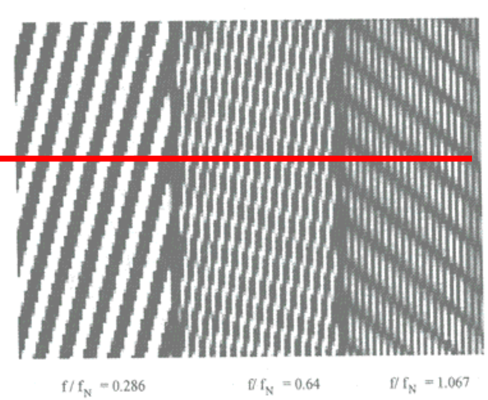


Beating may be observed as *Nyquist sampling limit* is approached.

Nyquist limit: to preserve information, f_{samp} (= 1/p) must be >2x highest spatial frequencies in image

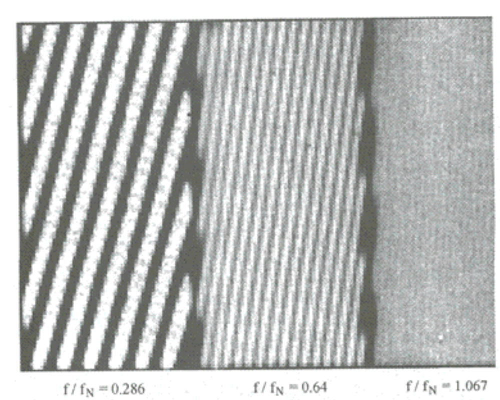
Frequencies > f_N are aliased to *false* lower frequencies in the image…



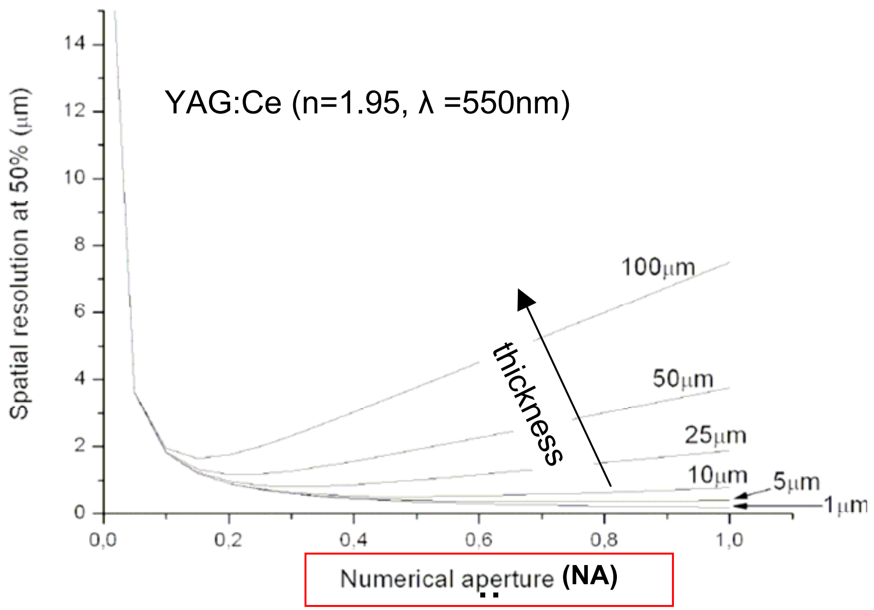


Low pass filter

e.g. by optics; scint' screen



Scintillator cameras: resolution of crystal screen & lens-optic



after Th. Martin/A Koch

from *simple'* optical model, limits to resolution for a crystal screen:

- focus defect $\sim \delta z \cdot NA$
- Diffraction $\sim \lambda / NA$
- Spherical aberration $\sim t \cdot NA^3$

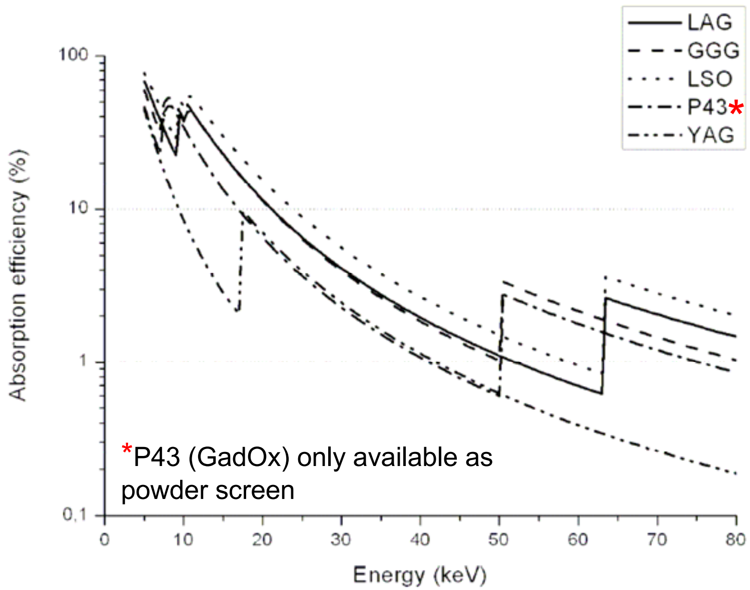
nb. simple analysis ignores*:*

*photoelectron thermalization range, and **Compton scatter**…*

⇨ *valid only at 'low' X-ray energies*

⇨ *problem of **residual scintillation of substrate** (e.g. YAG:Ce epitaxial film on 'pure' YAG crystal) long range 'tails' to PSF*

Scintillator X-ray Absorption and Light Collection Efficiency, η



*P43 (GadOx) only available as powder screen

Crystal screen + microscope lens:

Optic	Scintillator	Absorption	DQE FReLoN	DQE Dalsa	Spatial resolution (μm)
10x NA=0.3	YAG:Ce	0.07	0.021	0.013	2
	LAG:Eu	0.11	0.031	0.017	
	GGG:Eu	0.11	0.037	0.021	
20x NA=0.7	YAG:Ce	0.07	0.049	0.038	1.04
	LAG:Eu	0.11	0.076	0.056	
	GGG:Eu	0.11	0.082	0.063	

after Th. Martin

calculated for 20keV, and 25µm thickness scintillator

Scintillator 'quality' factors:

- Z, ρ (…refractive index!)
- conversion efficiency' (light photons / absorbed X-ray energy)
- decay time and *afterglow*
- radiation hardness, environmental stability
- K edge energy (application dependent)
- fabrication feasibility of *thin films of optical quality*

Light Collection Efficiency, lens vs. fibre optic bundle

Crystal screen + lens:

$$\eta = \left| \frac{T_L \cdot M^2}{16 \cdot n^2 \cdot f^2 (1+M)^2} \right|$$

Powder screen* + lens:

$$\eta = \left| \frac{T_L \cdot M^2}{M^2 + 4 \cdot f^2 \cdot (1+M)^2} \right|$$

*assumes ‘Lambertian’ emission, I (Θ)~ I(cosΘ)

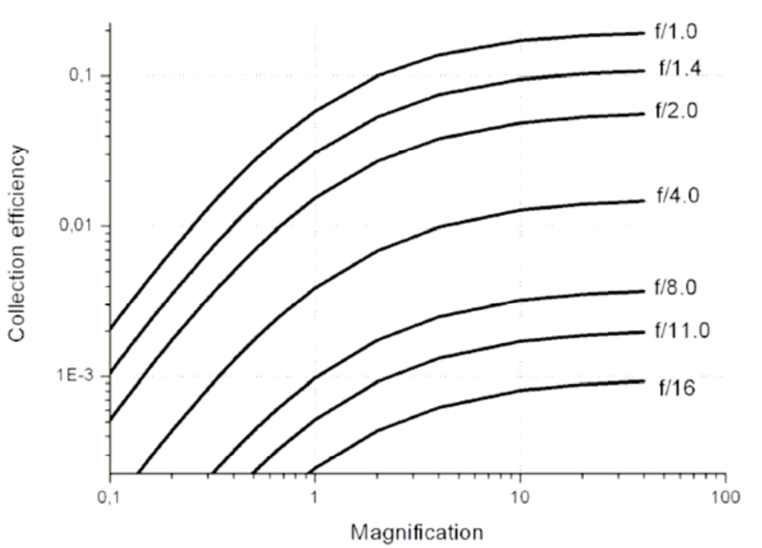
M = image/object size; f= Ø lens / focal length

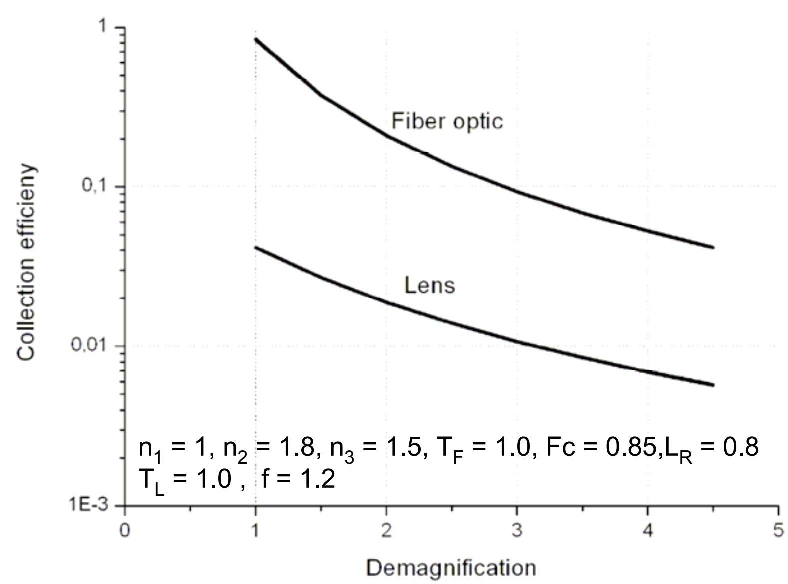
Powder screen* + fibre optic:

$$\eta = \left(\frac{1}{m}\right)^2 \cdot \left(\frac{(n_2^2 - n_3^2)^{1/2}}{n_1}\right)^2 \cdot T_F \cdot (1 - L_R) \cdot F_c$$

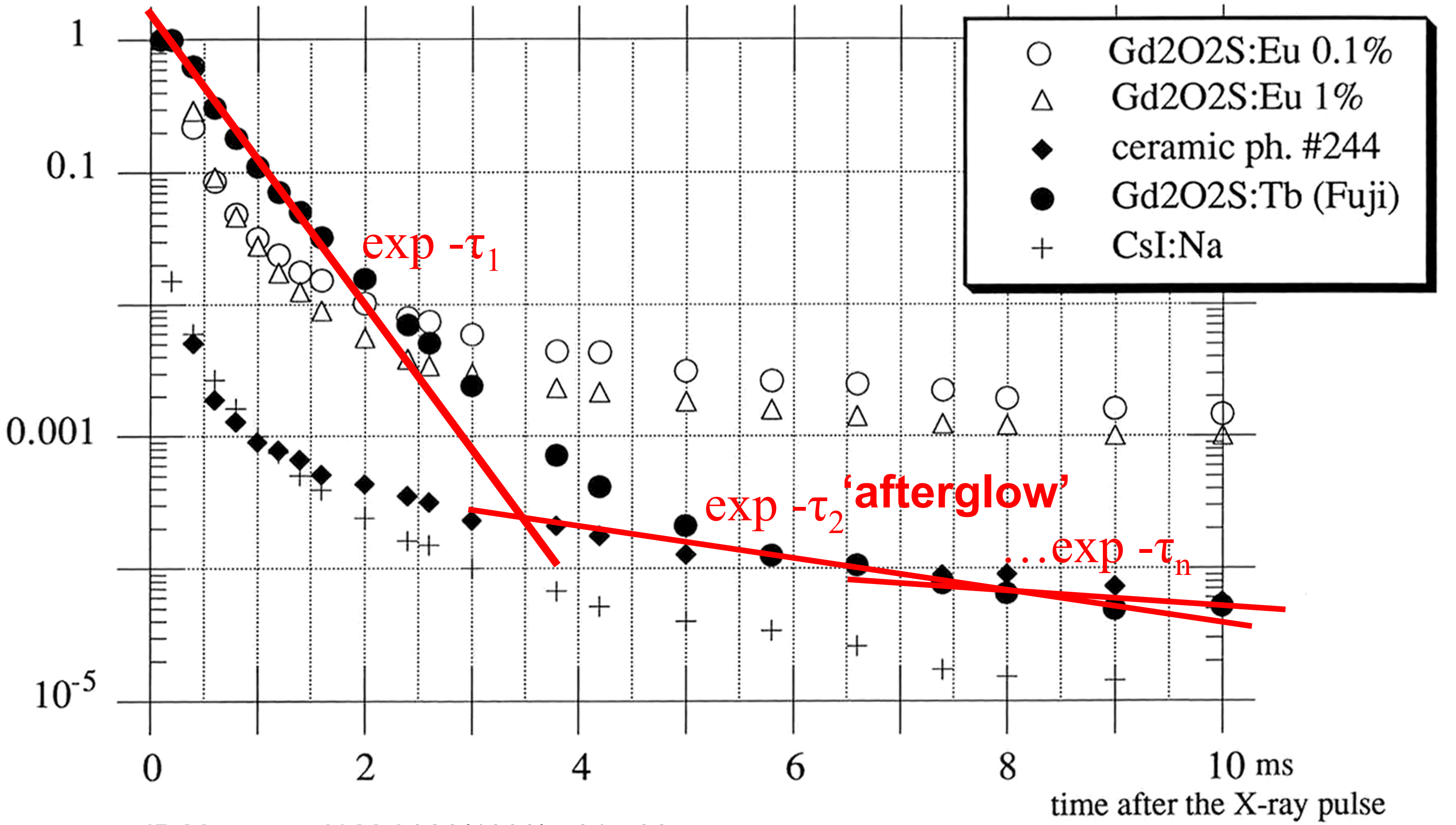
Magnification	Lens %	Fiber optic %
20x	18	-
10x	17	-
4x	13.7	-
1x	4.1	84
0.5	1.9	21
0.25	0.7	6

after Th. Martin



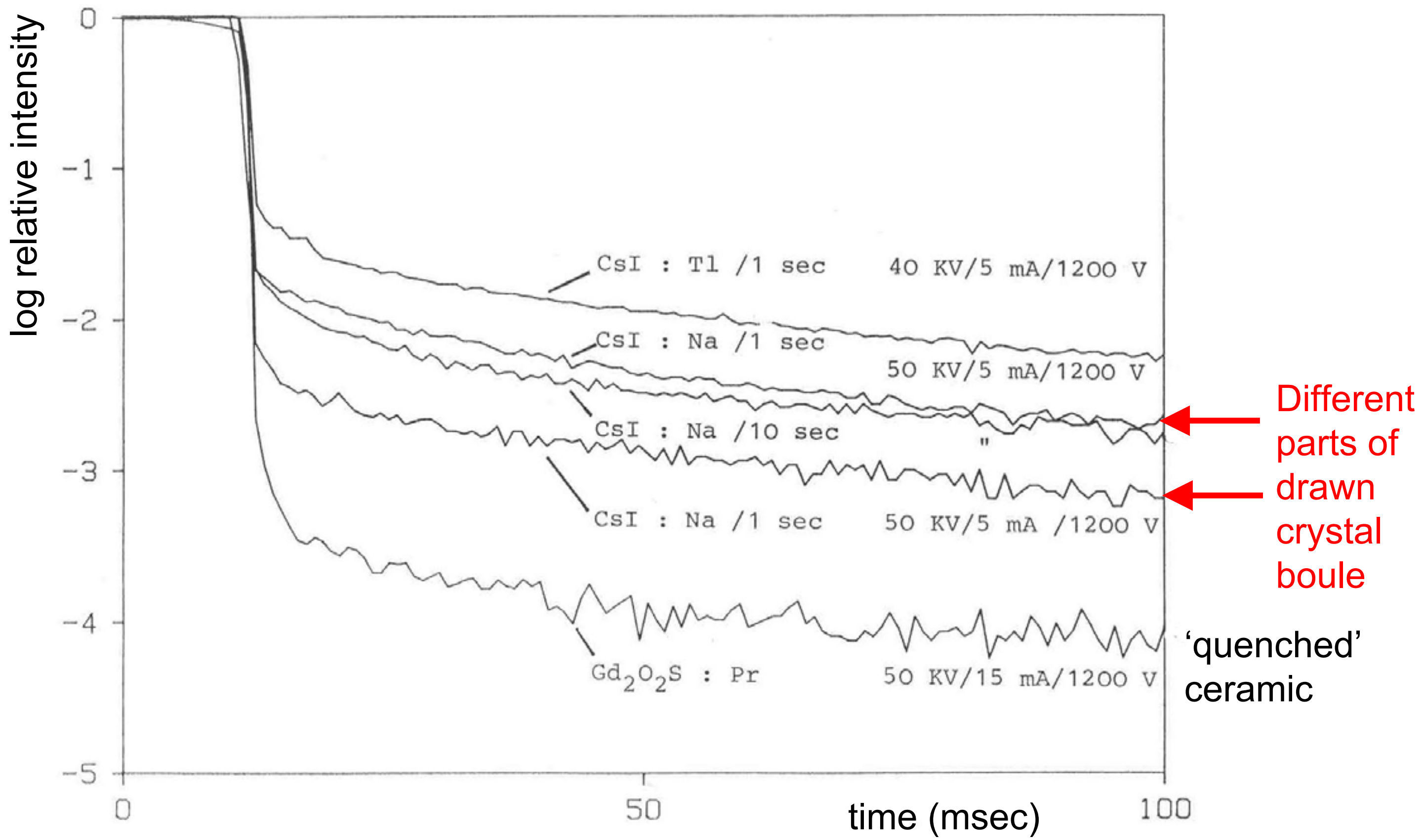


Scintillator time response…



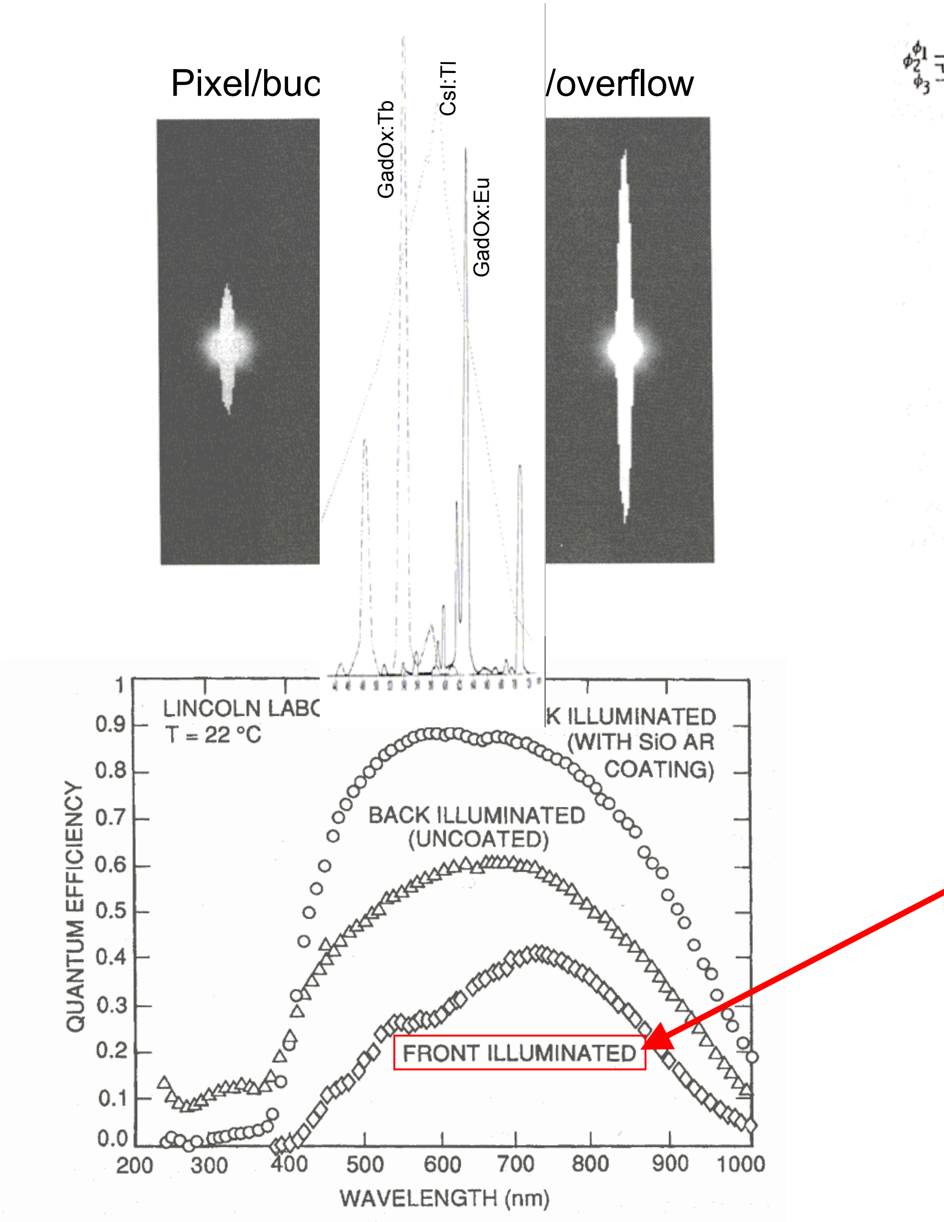
JP Moy et al, NIM A326(1993) 581-586

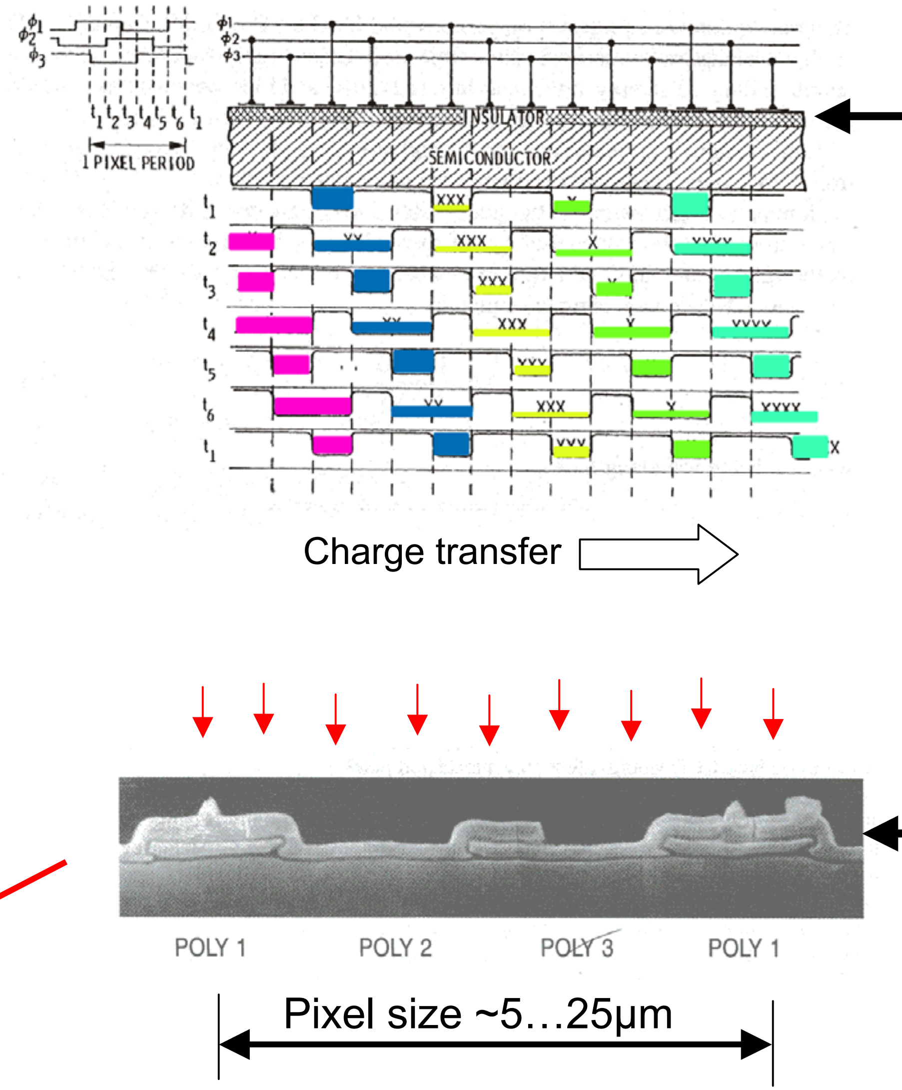
… the 'afterglow' problem



After BC Grabmaier, Siemens 1991

CCD imager basics

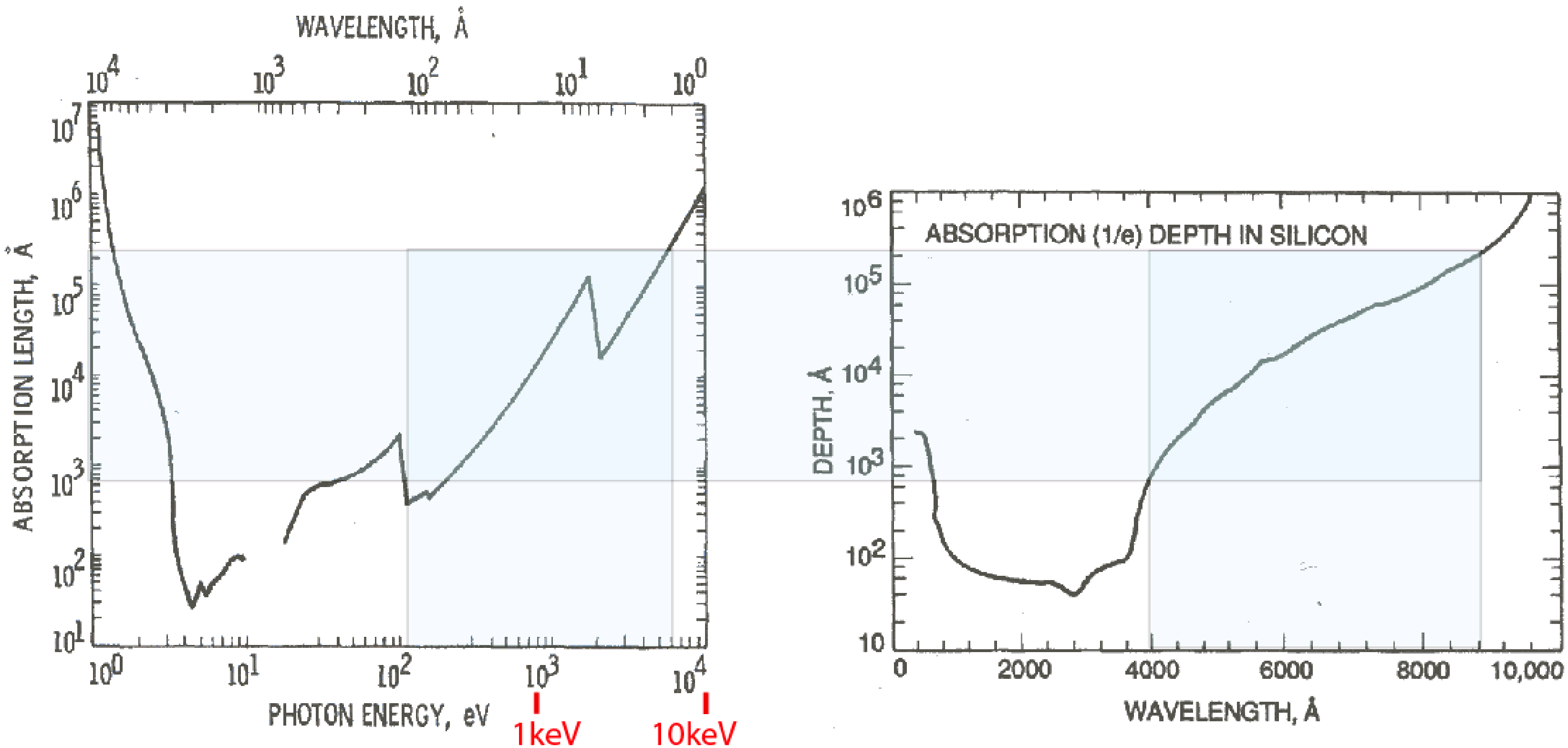




after J Janesick

CCD: direct X-ray sensitivity

‘Fortuitous’ overlap of Si absorption length in optical and X-ray bands

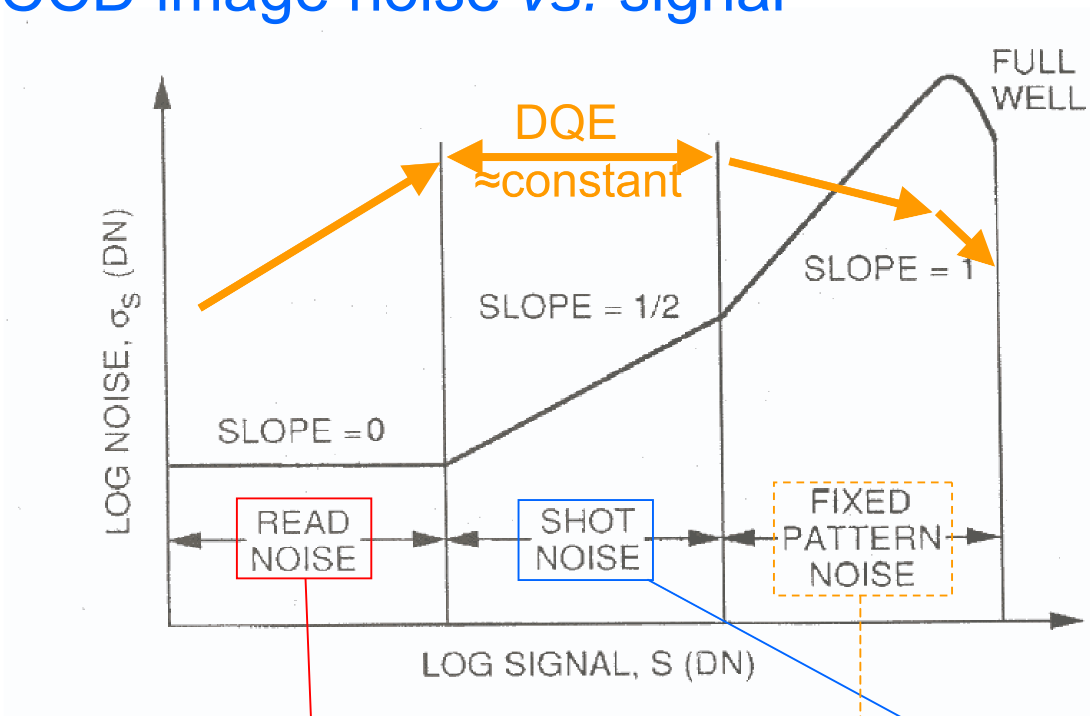


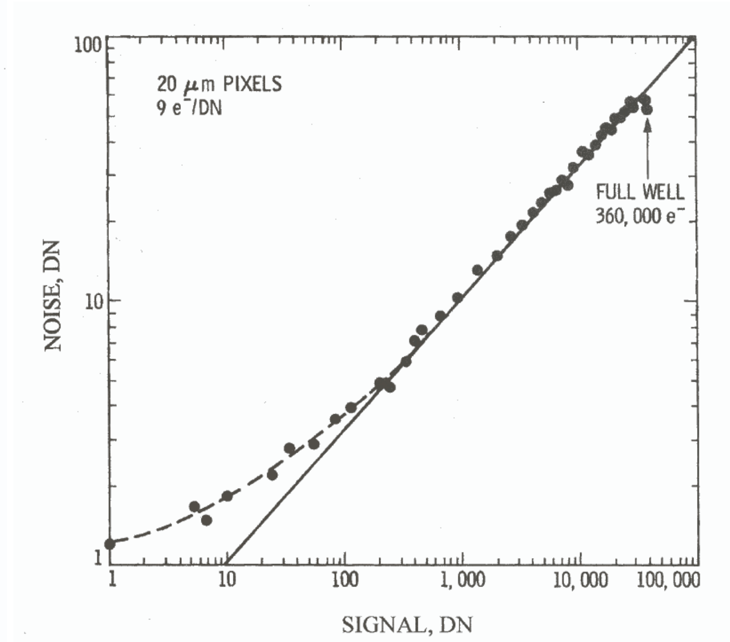
For X-ray sensitive CMOS CCDs, ~100 µm ‘active’ high resistivity (QE 50%@10keV)
~300µm for p-n CCD stuctures

10keV X-ray generates ~ 2800e$^-$ in silicon , ~10% saturation of pixel capacity

⇨ *dynamic range limitation…*

CCD image noise *vs.* signal





after J Janesick

output MOSFETamplifier white noise and
1/f 'flicker' noise (f < 1MHz)
+ *possible 'dark current' offset noise*

For a 'gain' 8μV/e^-,
noise ~ 10 e^- @1 MHz = ?? X rays

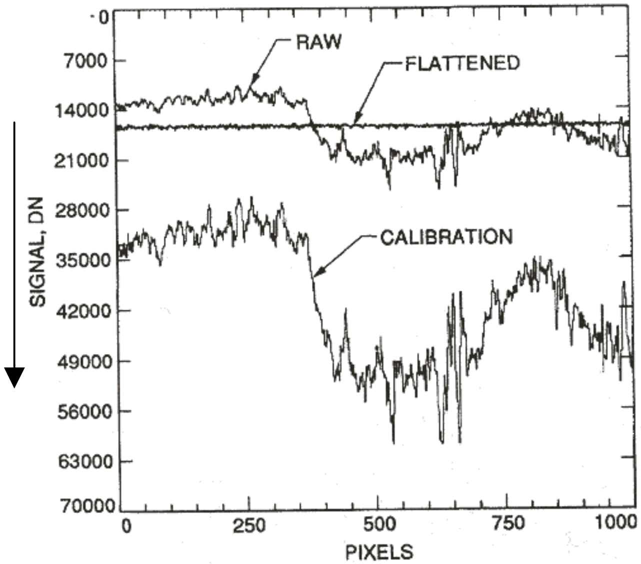
Reset 'kT/C' noise eliminated
by CDS signal processing

shot noise ~ √N signal electrons

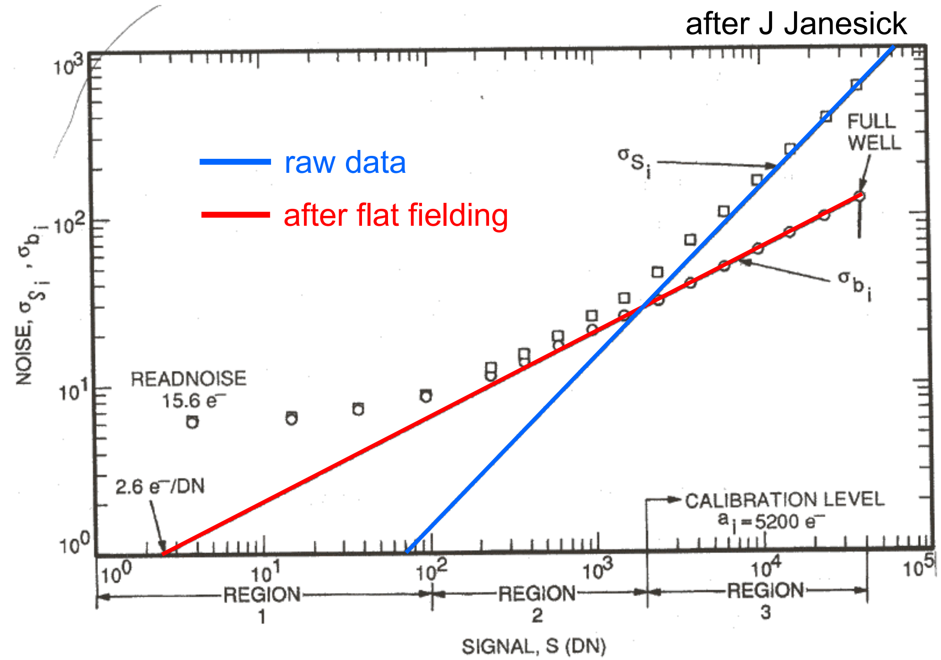
e.g. at 10 000e^- (~5% max. CCD signal)
shot noise = 100 (e^-) = 'signal / noise' ratio

Pixel-pixel efficiency variations
e.g. pixel area variations from CCD
fabrication (mask alignment precision…)

Reduction of CCD (and system) image noise by ‘flat field’



after J Janesick



multiple (~16) frames acquired and averaged:

-- ‘dark field’ to subtract spatial variations in ‘zero’ offsets (leakage current offsets)

--‘ reference’ flat intensity image (ideally, in same exposure conditions as final data image)

Flat fielding errors usually dominant noise for low contrast images

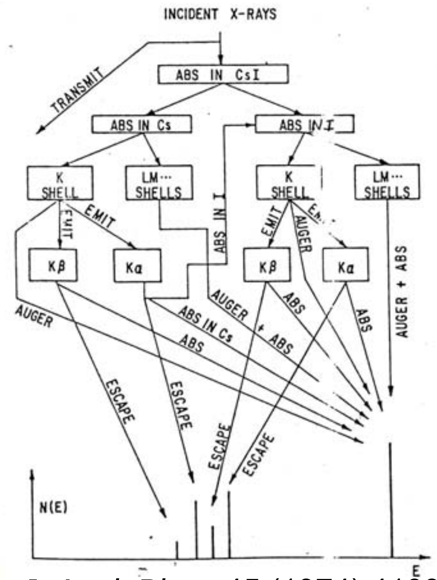
-- difficulty in acquiring accurate reference images:

beam I_o normalization errors, spatial movements, alignment drifts…

Detective Quantum Efficiency

Often quoted 'overall figure of merit' for *any* detector system ('integrating' or photon counting)

$$DQE \equiv \frac{SNR^2_{out}}{SNR^2_{in}}$$



R Swank, *J. Appl. Phys.* 45 (1974) 4109–203

SNR_{in} is the input signal-to-noise ratio (e.g. photon shot noise).

Beware! the effective DQE is a function of many parameters: e.g.

- X-ray energy (phosphor absorption efficiency and *statistics* of cascade processes)
- optical coupling and CCD QE photon-loss statistics
- spatial resolution (MTF) *vs.* feature integration area
- signal intensity relative to useful *dynamic range*…

dynamic range:

For an integrating detector (e.g. CCD), $$\mathbf{DR} = \frac{\text{signal saturation level}}{\text{(zero signal) r.m.s. noise}}$$

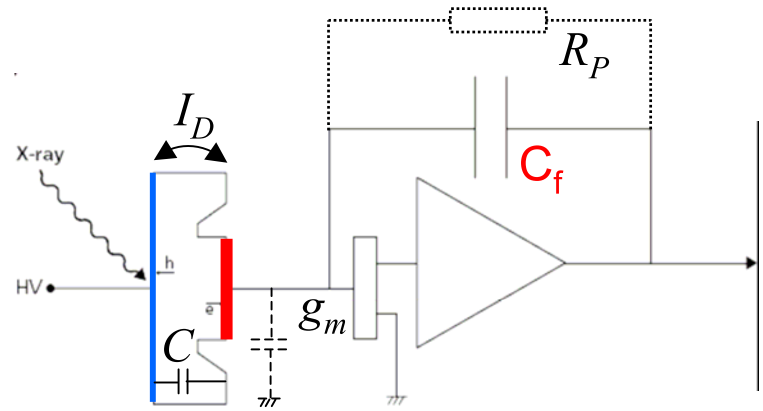
Do not confuse device dynamic range with obtainable 'signal/noise' :

e.g. for a CCD with pixel saturation level 300ke$^-$ and readout noise 10e$^-$, DR = 30 000
but measuring a 10ke$^-$/pixel signal over a 10 pixel-cluster , **CCD signal/noise ≤300**

…while for a true 16bit full scale ADC, signal level is coded with a resolution of ~1 part in 2000

Spectroscopy: semiconductor detector basics

Cooled crystal of Si or Ge with X-ray transparent rectifying/ohmic contact pair. Strong reverse field completely depletes bulk. Charge **q** created by X-ray absorption causes step voltage in output of FET charge preamplifier.



SiLi or Ge crystal FET-charge preamp signal

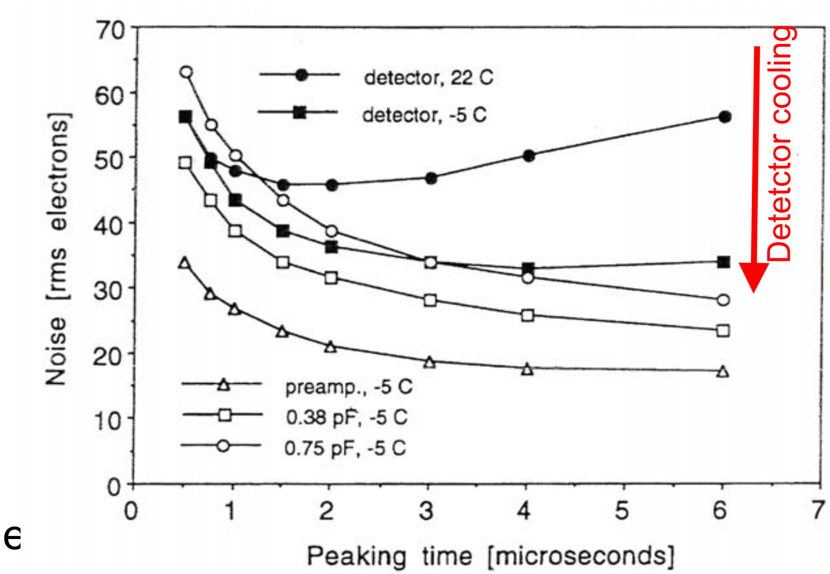
$\mathbf{q} = 1.6 \times 10^{-19}\, E_{xray}(eV)/3.63$ (Si, Coulombs)

e.g. for preamp' feedback C_f=0.1pF, a 10keV Xray gives only a 0.5mV signal…

problem is electronic *NOISE*

Equivalent noise charge ENC (e^-) analysis gives

$$ENC \approx \sqrt{\left(\frac{kT}{2R_P} + \frac{eI_D}{4}\right)\tau + \left(\frac{kTC^2}{2g_m}\right)\frac{1}{\tau} + AC^2}$$



Need to:

-maximize R_P (->∞ for 'pulse restore' preamp)

-minimize I_D, T (cooling of detector)

-minimize C (crystal geometry, 'drift diode')

-*optimize choice of* τ (pulse shaping (peaking) time

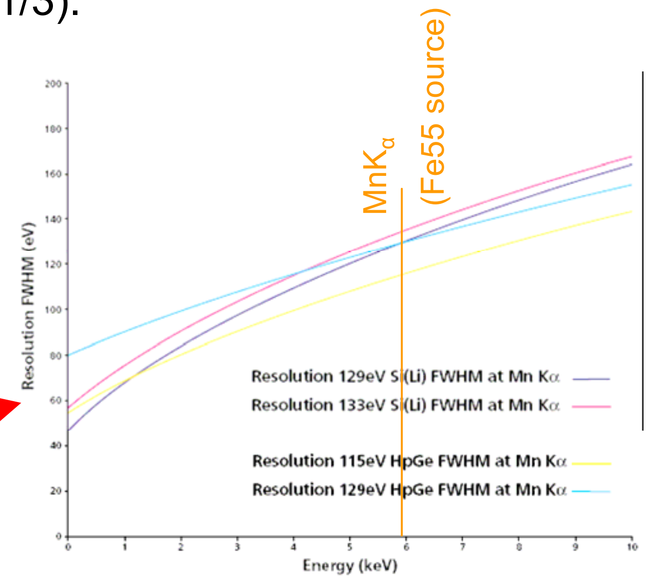
Energy resolution

Generation of electron and hole charges is *statistical process*: energy is shared between lattice excitations (~2/3) and generation of charge carriers(~1/3).

Resultant spread in energy is

$$\mathbf{FWHM} = \mathbf{2.35}\,\sqrt{\mathbf{F}\varepsilon\mathbf{E}} \qquad \varepsilon = 3.63 \text{ eV/e-h for Si}$$

Fano factor **F** ≈0.12 for Si and Ge (**F** is *not* a constant)



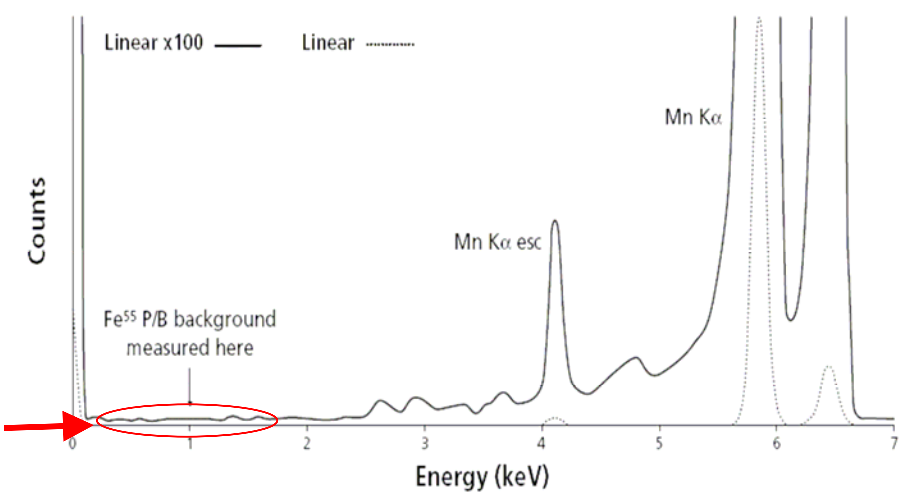
Measured spectral resolution is quadrature-sum of electronic noise and Fano statistics:

$$\mathbf{R} = \sqrt{(\textbf{electronic noise})^2 + (\textbf{Fano})^2}$$

R should have Gaussian shape, but rarely does at ≤ 1% level… multiple causes:

- near surface X-ray absorptions with incomplete charge collection
- ‘ballistic deficit’ associited with pulse shaping time
- pulse processor (pile-up and baseline degradation at high count rates)

Peak-valley performance should not be ignored

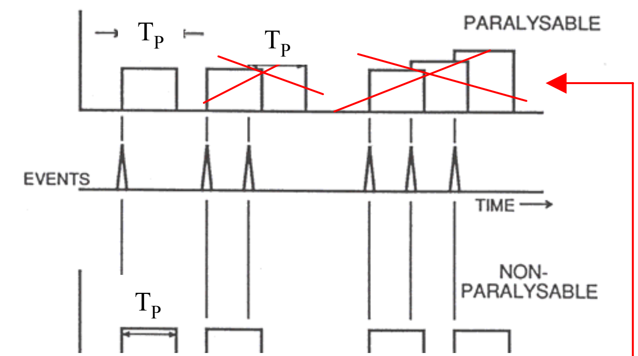


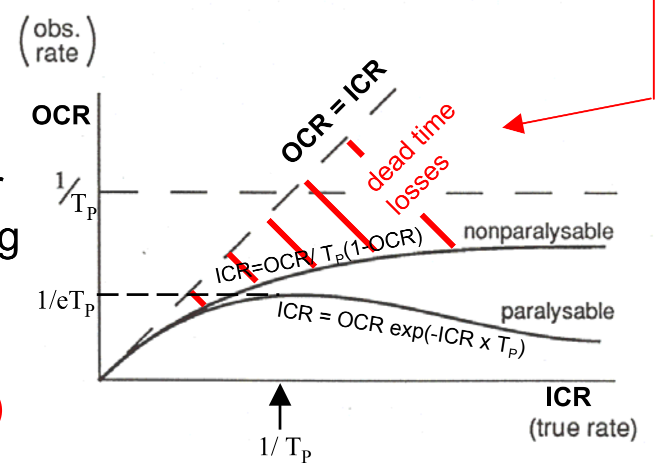
Pulse processing

Spectroscopy pulse processors are ‘paralysable’: for Poisson time-distributed (?synchrotron?) X-ray events, measured spectrum output count rate can be obtained from

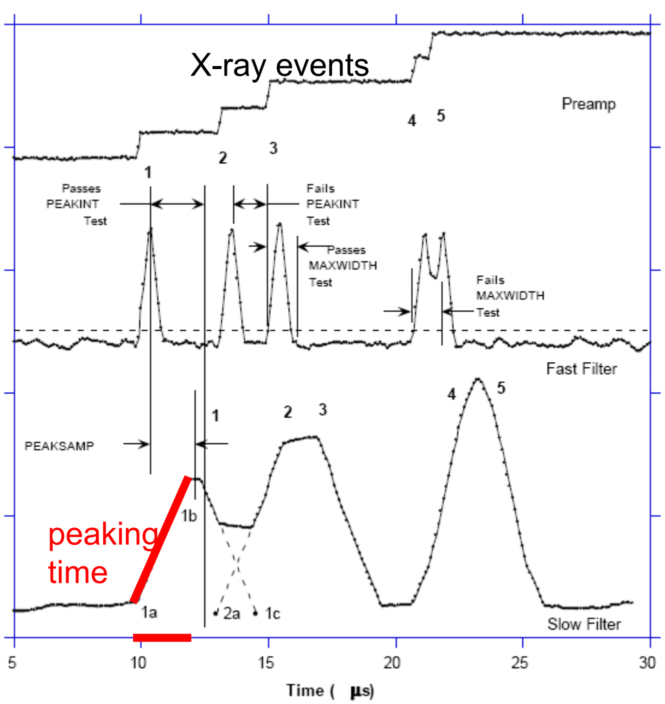
$$\mathbf{ICR = OCR\ exp(-ICR\ x\ T_P)}$$

T_P is processor ‘dead time’ associated with processing each event (≈5x pulse ‘shaping time’ or ≈2x ‘peaking time’).





Pulse processor optimizes signal/noise with appropriate filter peaking time, detects *pulse pile-up* events and corresponding dead time:



Limits to OCR usually:

- T_P (energy resolution!)
- detector solid angle

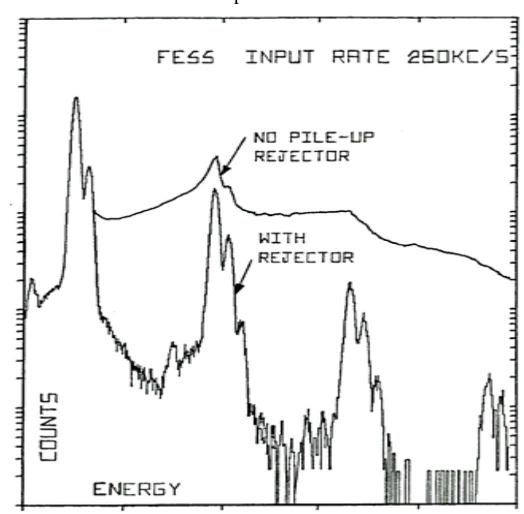
⇨ *multielement systems*

Fast channel (time info’)

‘slow’ channel (energy)

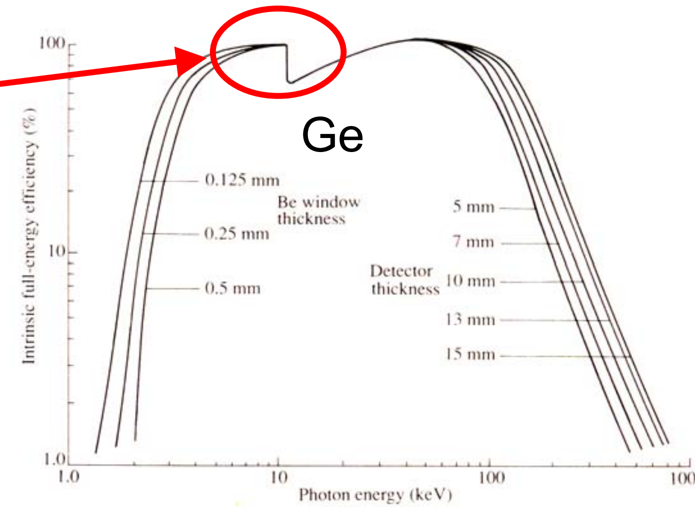
PUR

spectrum



Detector material choice: photopeak efficiency

Measured photopeak *intensity* may be reduced due to 'entrance window' (cryostat and detector crystal) absorption losses or fluorescence emission



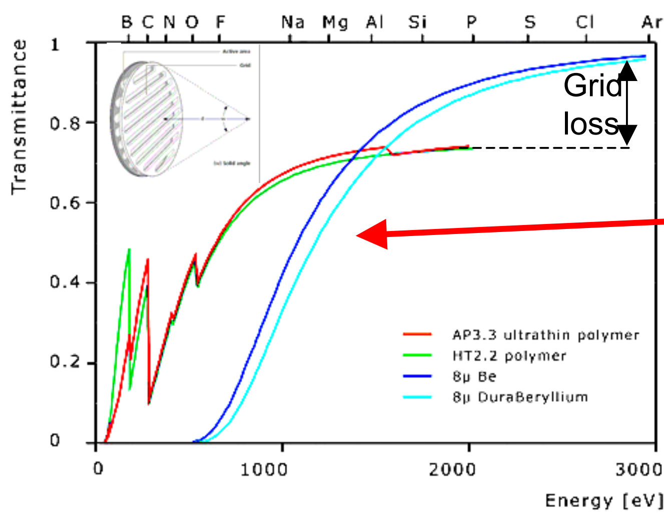
'Escape' peaks appear at energies (E_{Xray}- E_{fluo})

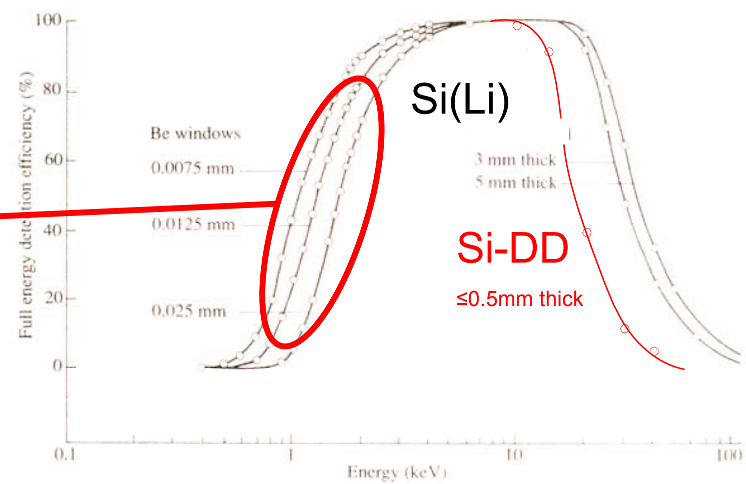
where $E_{fluo} \approx 9.9\ K_{\alpha}$, $1.2\ K_{\beta}$ Ge

$\approx 1.74\ K_{\alpha}$ Si

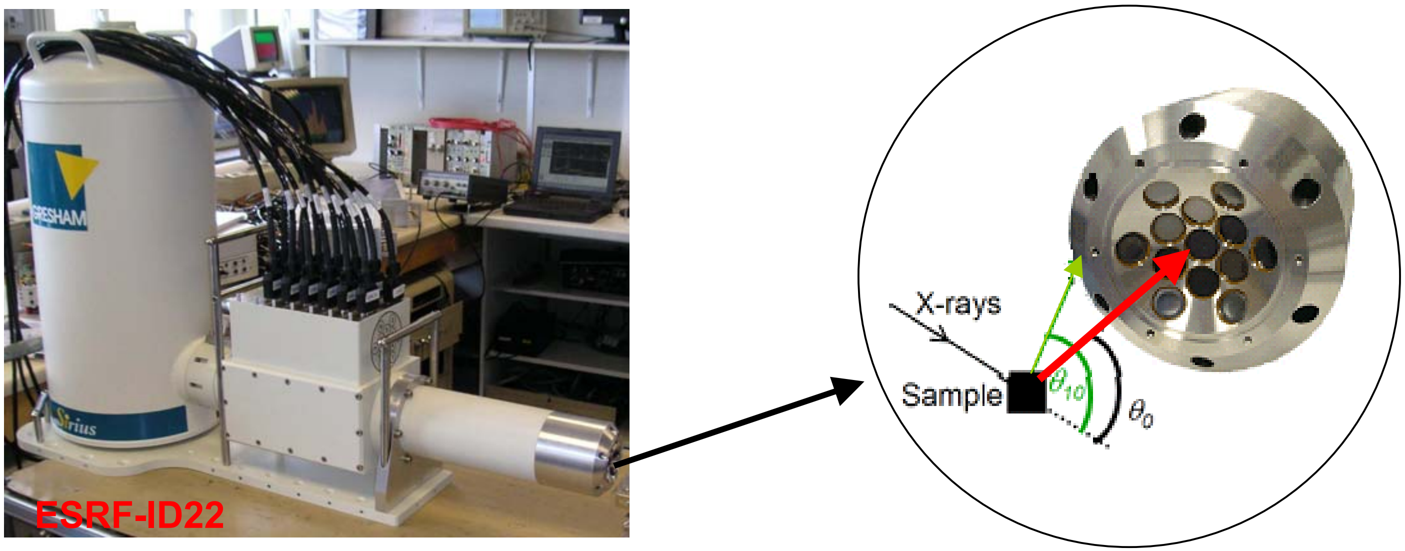
Photopeak intensity may be 'smeared' to low energies due to crystal contact/surface loss of electron charge

-> *ultrathin* metal Schottky or epitaxial doped-Si contact technologies



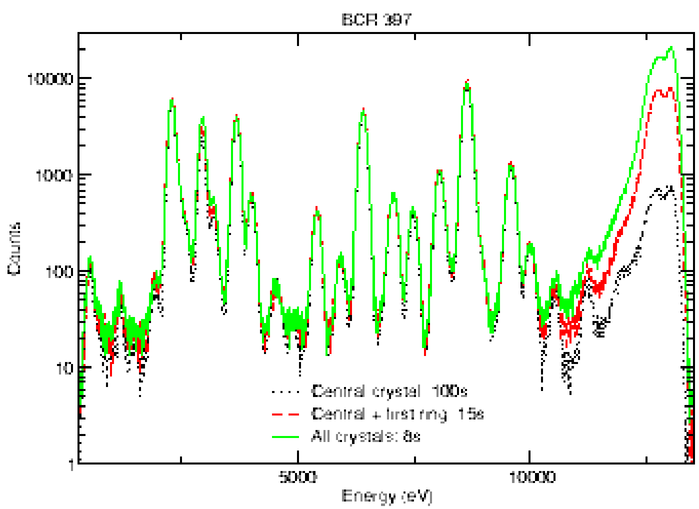


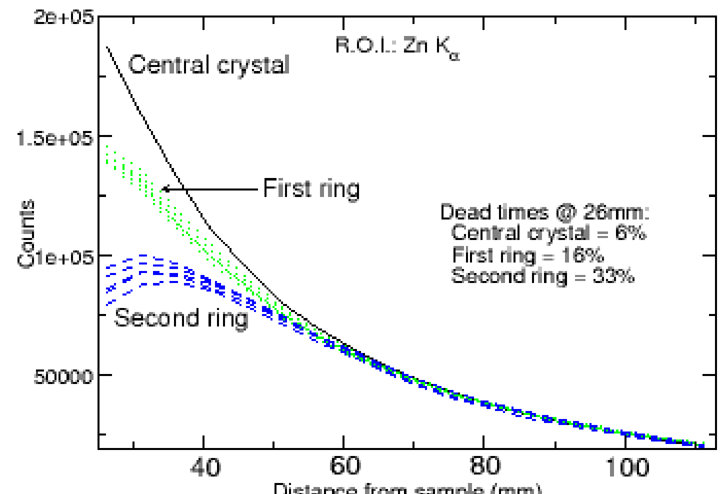
Collection solid angle and beam polarization



higher ratio scatter / fluorescence off- axis…
but overall ~10x counting gain

…higher *total* (fluo' + scatter count rate) on off-axis crystals ⇨ higher deadtime loss

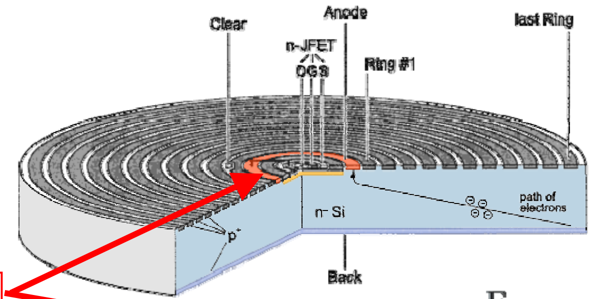




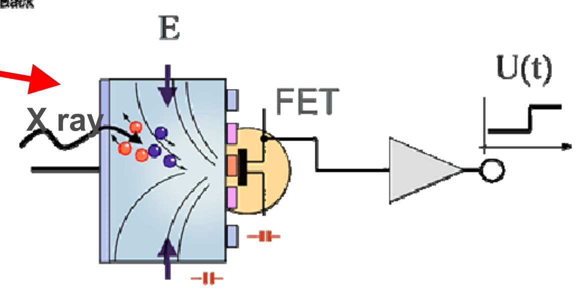
Letard et al, Rev. Sci. Instrum. 77, 063705 (2006)

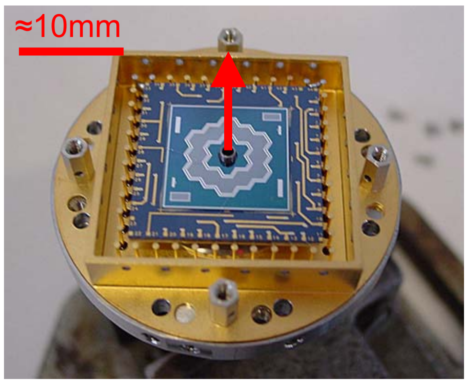
Silicon Drift Diodes

Planar silicon technology, multielectrodes establish transverse drift field , low capacity charge collecting anode / FET ~100fF



Preamp' may be (partly) integrated on detector





high resistivity silicon

⇨ low bulk leakage current

⇨ Peltier cooling suffcient -10ºC…-50ºC

⇨ *compact, lightweight systems*

Near wafer-scale lithographic processing

large, tightly-packed arrays possible

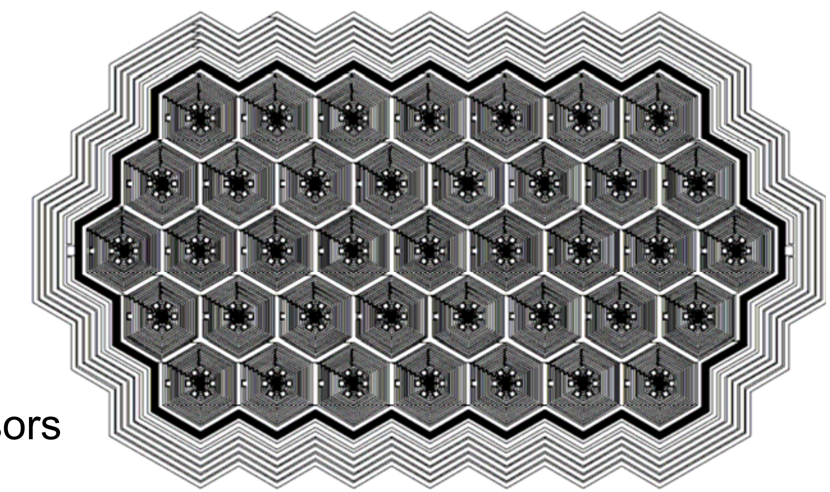
crosstalk issues

⇨ cell edge effects -> peak/valley limits

large cell counts ⇨ yield issues

⇨ multi channel pulse proccesors

⇨system cost



39 cell detector with on-chip FETs, total active area 195mm^2 (after Struder, MPI-Garching)

SII-Vortex Silicon Drift Diode

50mm^2 area SDD, with discrete JFET

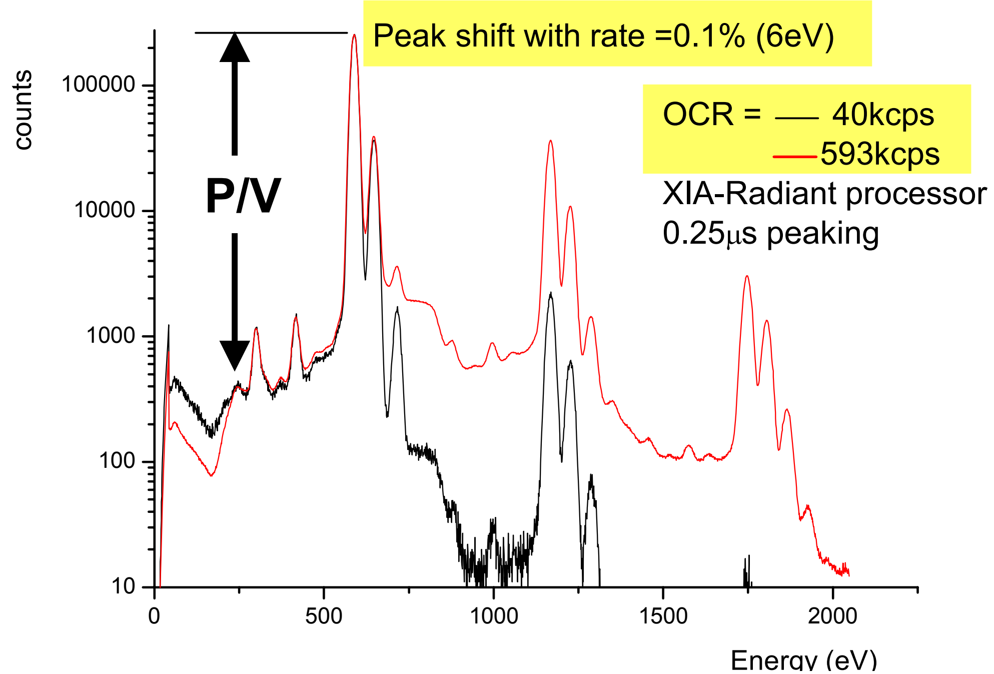
pulse restore operation (~no peak shift with rate)

Largest area SDD available for *high rate* applications, now a mature device:

Count rate to ~500kcps possible
(0.25us peaking, 230eV MnKα FWHM)

cf. Si(Li) detector ~25kcps
(5us peaking 160eV MnKα FWHM

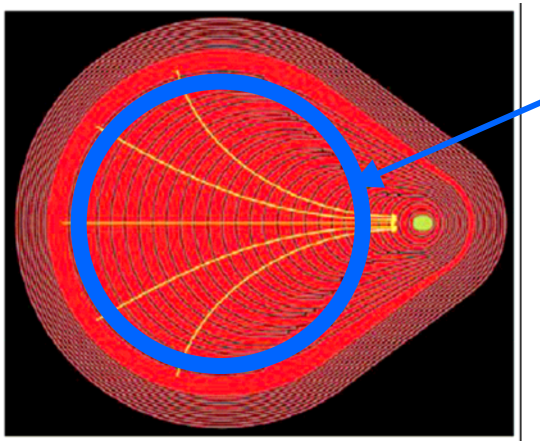
But peak /valley ≤ 700
cf. >5000 for Schottky Si(Li) or Schottky Ge

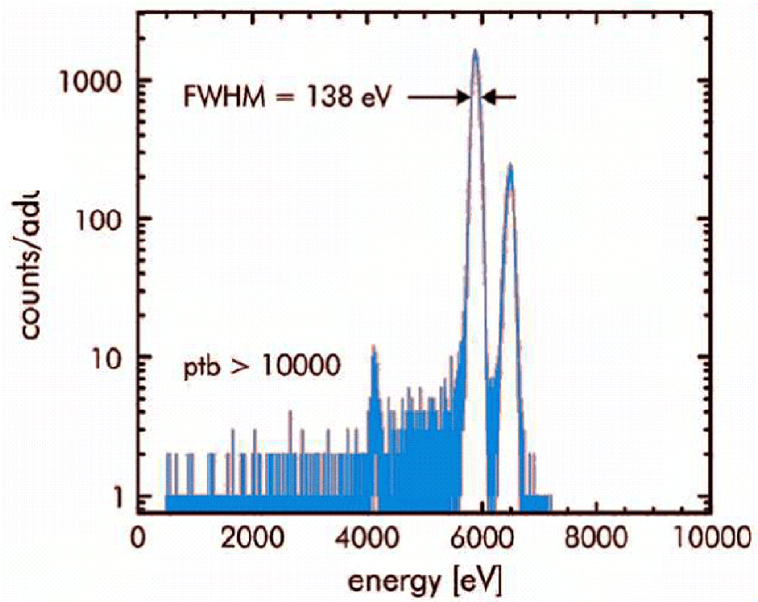


ID21 test data (Mn foil fluo'), ESRF-Diamond

pnSensor ‘teardrop’ Silicon Drift Diode

Integrated FET structure gives near Fano-limited resolution at low count rates
but ‘continuous’ reset mode (now) ⇨ noise increase with rate and possible peak shift





Collimator protection of FET

⇨ excellent peak / valley figures

geometry	active volume	energy resolution FWHM @ 5.9 keV at T = -10 °C	energy resolution FWHM @ 5.9 keV at T = -20 °C	peak/background ratio
symmetric	5 mm² x 450 µm	143 eV - 153 eV	138 eV - 143 eV	typ. 1.500
symmetric	10 mm² x 450 µm	148 eV - 158 eV	140 eV - 145 eV	typ. 3.000
symmetric	20 mm² x 450 µm	typ. 145 eV	typ. 135 eV	typ. 3.000 - 5.000
symmetric	30 mm² x 450 µm	typ. 150 eV	typ. 140 eV	typ. 3.000 - 5.000
asymmetric	5 mm² x 450 µm	typ. 145 eV	typ. 133 eV	typ. 7.000 - 10.000
asymmetric	10 mm² x 450 µm	typ. 135 eV	typ. 128 eV	typ. 7.000 - 10.000

Some bibliography

J Janesick ‘Scientific Charge Coupled Devices’, SPIE Press, Washington 2001

G Knoll ‘ Radiation Detection and Measurement’, Wiley , 2000

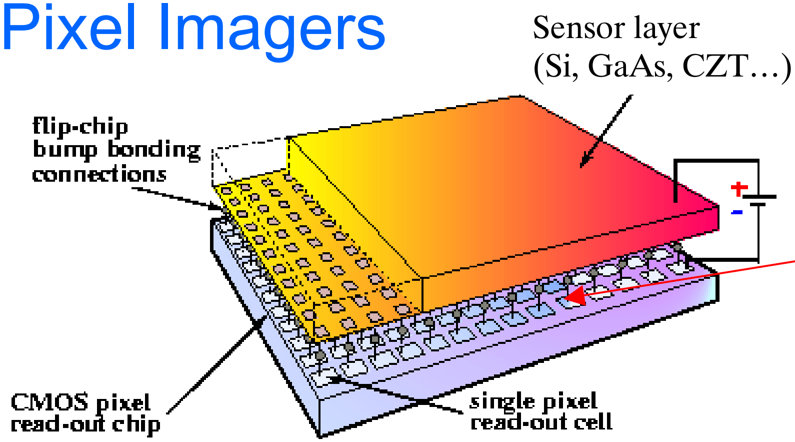
H Spieler, ‘Semiconductor Detector Systems’, OUP, 2005

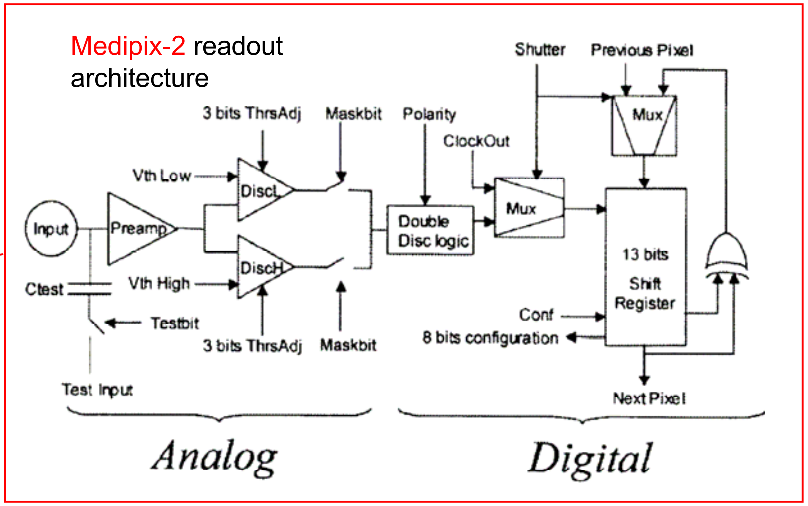
C Delaney, E Finch ‘Radiation Detectors: Physical Principles and Applications’, OUP 1992

G Lutz, ‘Semiconductor Radiation Detectors: Device Physics’, Springer Berlin 1999

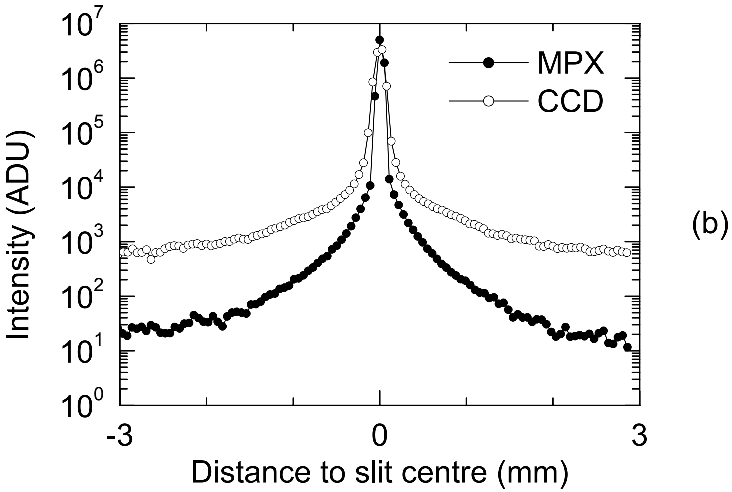
Postscript-- possible future devices

i. Pixel Imagers





LSF comparison with phosphor-lens coupled CCD(same effective pixel size)



Ponchut et al, IEEE TNS 52 (2005) 1760

55 x 55 μm^2 pixels, 256 x256 array

300 μm or 700 μm Si sensor layer

13 bits pseudo **counter** at 2MHz,
≈ 5 keV noise threshold, window discriminator

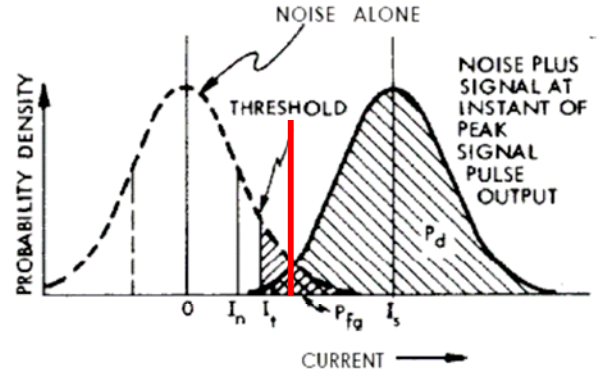
≈ up to 1000 frames/s with parallel readout

noise free (??)

Photon 'Counting' detectors, noise and background rate

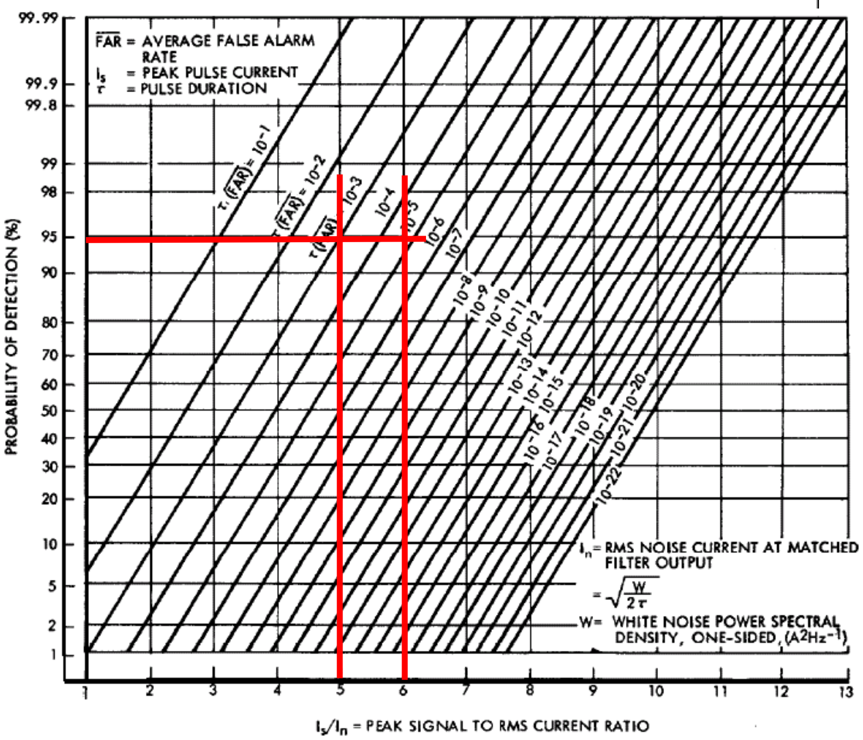
For a 'counting' detector: X-ray event is recognised if above some threshold level set above (electronic) noise floor.

Is it 'noise free' ?



The 'false alarm rate' of noise events is

$$FAR = \frac{1}{2\tau\sqrt{3}} \exp\left(\frac{-I_t^2}{2I_n^2}\right)$$

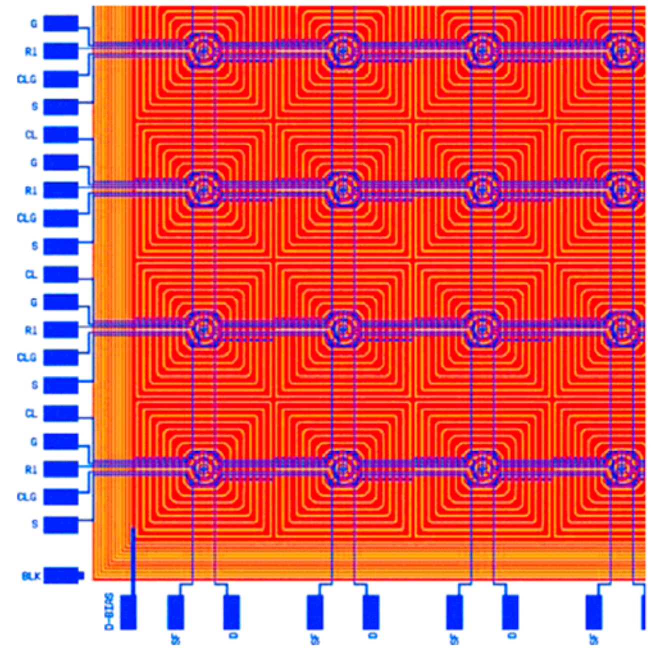


Consider a 1 sec integration, requiring >95% detection efficiency, for a *1μsec duration signal pulse* in a white noise background

FAR ~500 events/sec for 5σ threshold level
~10 events/sec for 6σ

(n.b. this is the 'optimum' case of white noise and matched filter of signal bandwidth =1/2τ)

ii. DEPFET-macropixel arrays



Matrix arrangement of DEPFET transistor amplifiers at centre of drift diode structure 'macropad' cells .

Various readout possibilities:

direct macropad addressing,

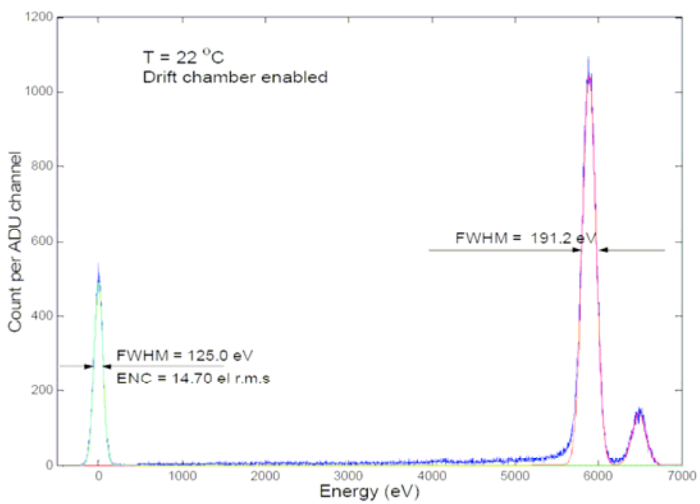
row-by-row readout through single node,

parallel readout of columns (very fast readout)

crosstalk issues?

$4 \times 4 \times 1 mm^2$ pixel prototype

Room temperature operation 191 eV !!



after G Lutz, MPI-Garching & Bonn University