The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1936-49

Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

7 - 25 April 2008

X- Ray Detectors (I)

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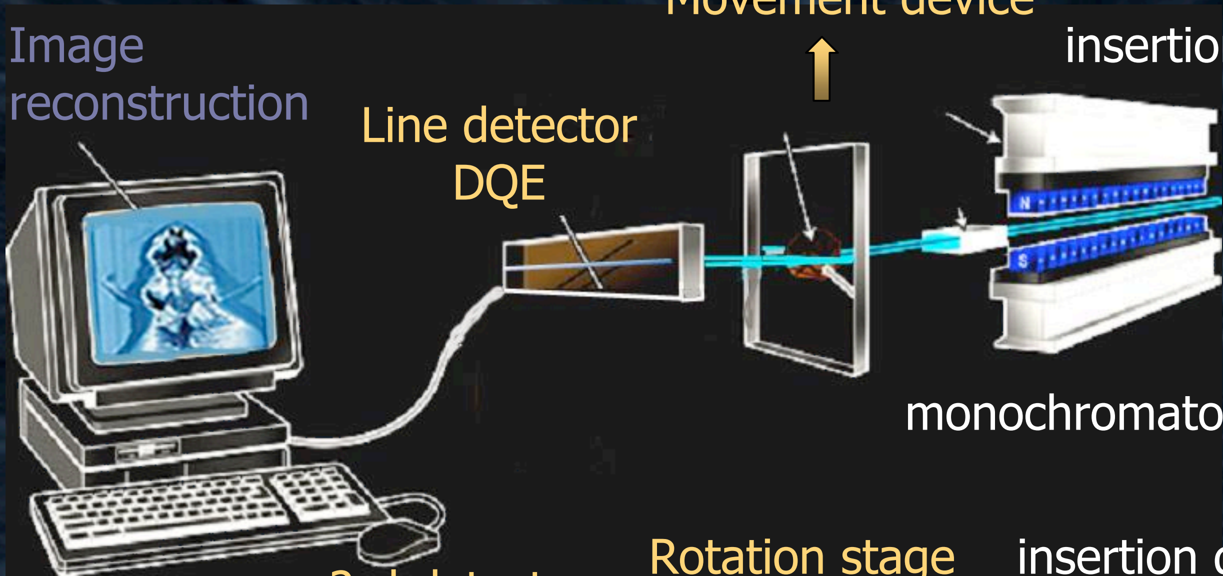
ICTP school 2008
X- Ray Detectors
Part 1

Ralf Hendrik Menk

Sincrotrone Trieste, Italy

Imaging set up with X-rays



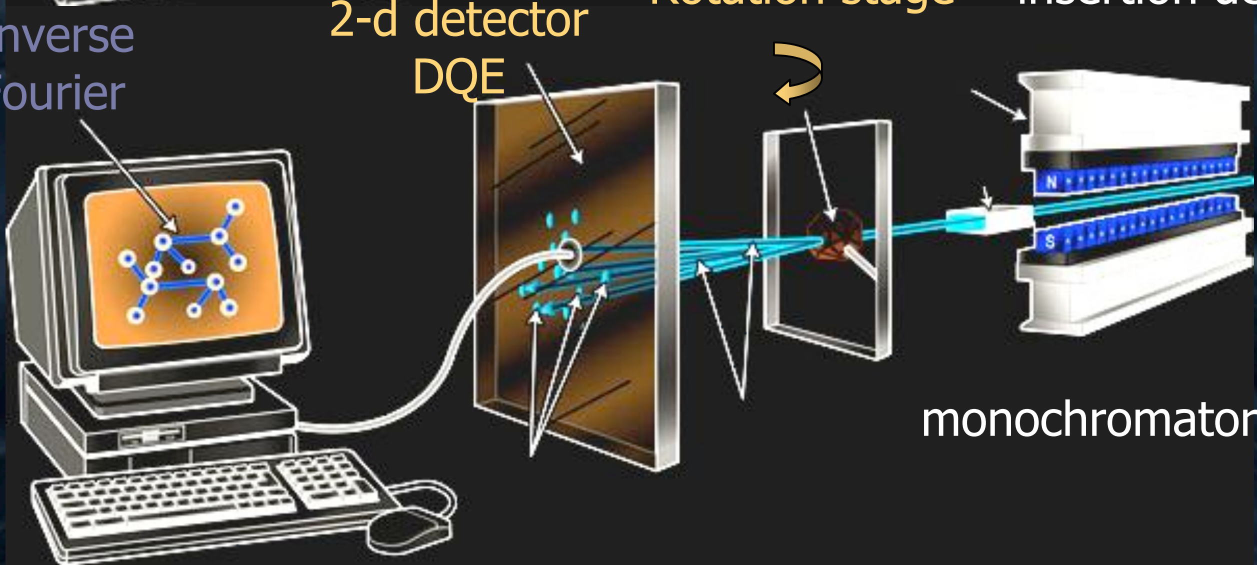
Direct imaging

Length scale

0.5 μm – 30 cm

most of pixels see approx same photon

~ 10^4 for 0.1%



Fourier indirect imaging

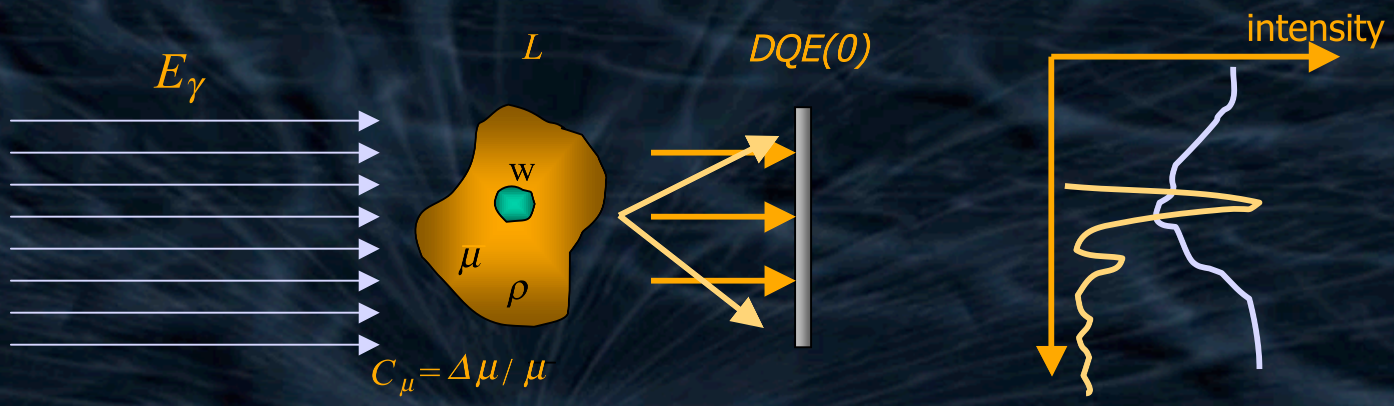
Length scale

15 Å –5000Å

most of pixels see

~ 0 photons

Dose considerations



Direct Imaging

$$D_{skin} = \frac{2 \cdot L \cdot e^{\mu \cdot L} \cdot SNR_{out}^2}{DQE(f) \cdot \mu^2 \cdot w^4 \cdot C_\mu^2} \cdot E_\gamma \cdot \left(\frac{\mu}{\rho} \right)$$

$$D_{sample} = \frac{\mu \cdot P \cdot h \cdot \nu}{DQE(f) \cdot \rho^2 \cdot w^4 \cdot \lambda^2 \cdot r_e^2}$$

$$\approx \frac{1}{w^4 \cdot DQE(f)}$$

Indirect imaging

Signal to noise & Detective Quantum Efficiency DQE

$$SNR \equiv \frac{Signal}{noise} = \frac{S}{\sigma}$$

Detector

In case of photons > Poisson statistics

SNR$_{in}$ → DQE(f) → SNR$_{out}$

$$S = N, \;\; \sigma = \sqrt{N} \;\; \Rightarrow SNR^2 = N$$

$$DQE(f) \equiv \frac{SNR^2_{out}}{SNR^2_{in}} = \frac{SNR^2_{out}}{N}$$

Your measurement!

To be or not to be in nature

is here the question of the detector….

$$DQE \subset [0,1]$$

Detective Quantum Efficiency DQE

What looks DQE like?

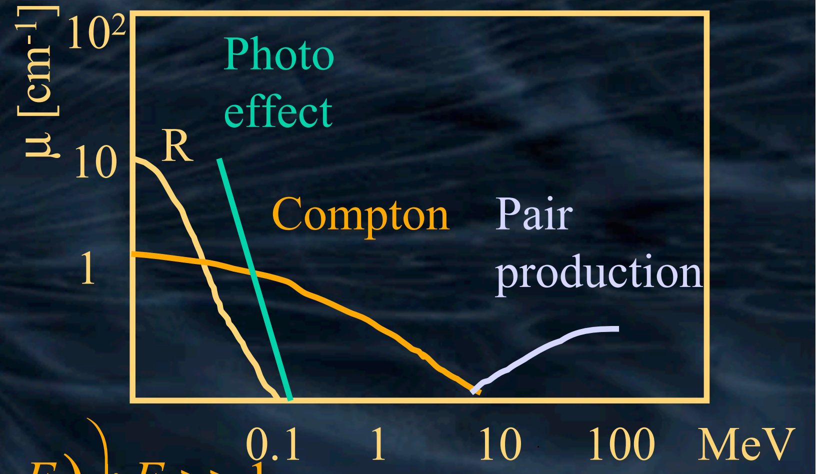
To answer this questions one as to understand the underlying detection principle

Bottom line: Convert photons to free charges and measure those

$$\mu \approx \frac{Z^5}{E^{\frac{7}{2}}}$$

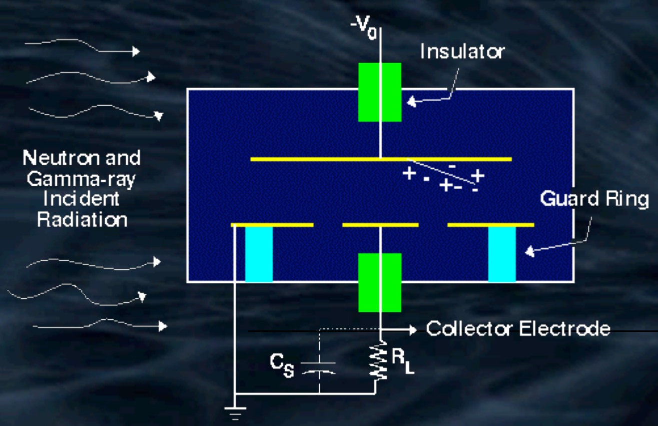
$$\mu \approx Z \cdot \frac{1}{E} \cdot \left(\frac{1}{2} + \ln(2 \cdot E) \right); E >> 1$$

$$\mu \approx Z^2 \cdot \left(\ln(2 \cdot E) \right); 1 < E < \frac{137}{Z^{1/3}}$$



Charge Collection

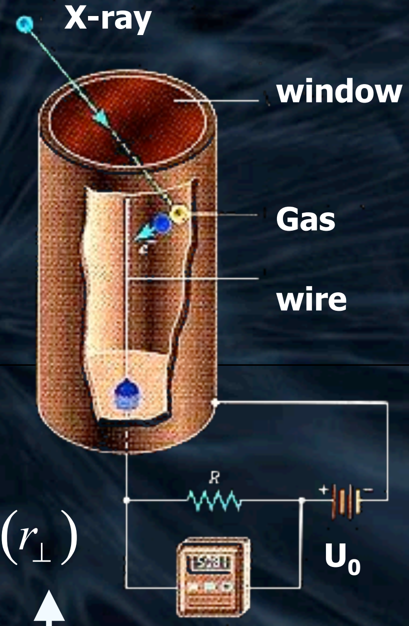
Integrating detectors



Gas	W_{ion}[eV]
Ar	26
Kr	24
Xe	22

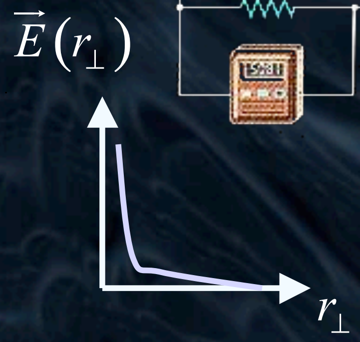
$$Q(E_\gamma) = \frac{E_\gamma}{W_{ion}} \cdot \varepsilon(E_\gamma) \cdot N \cdot e^-$$

Counting detectors



$$\Delta E_{kin} = e^- \cdot \int_{r_1}^{r_2} \vec{E}(\vec{r}_\perp) \cdot d\vec{r}_\perp$$

$$= e^- \cdot U_0 \cdot \frac{\ln\left(\frac{r_2}{r_1}\right)}{\ln\left(\frac{r_a}{r_i}\right)}$$



$\Delta E_{kin} > W_{ion} \Rightarrow$

gas amplification

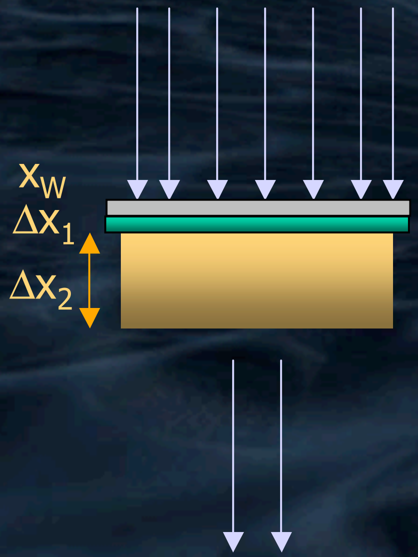
$$A = e^{\int \alpha(r_\perp) \cdot dr_\perp}$$

α Townsend Coefficient

$$Q(E_\gamma) = \varepsilon(E_\gamma) \cdot \frac{E_\gamma}{W_{ion}} \cdot e^- \cdot A \cdot \delta(t)$$

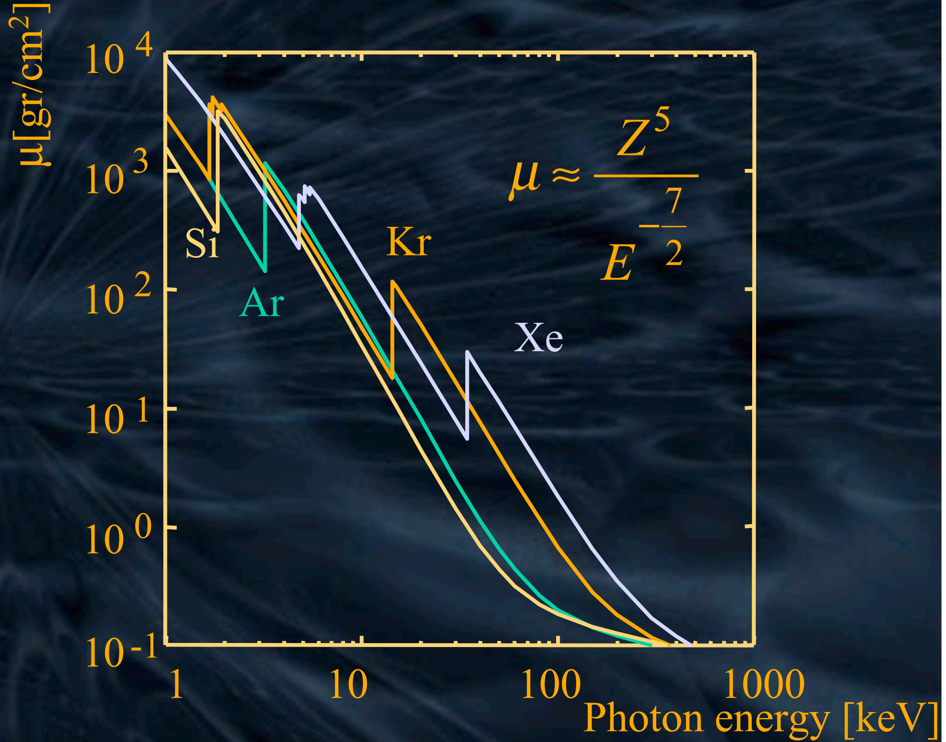
Quantum efficiency ε

$$\varepsilon := \frac{\text{no of photons that interact in the detector volume}}{\text{no of photons in front of the detector}}$$



Detector window and/or 'dead volume'

Conversion volume defined by ρ and μ

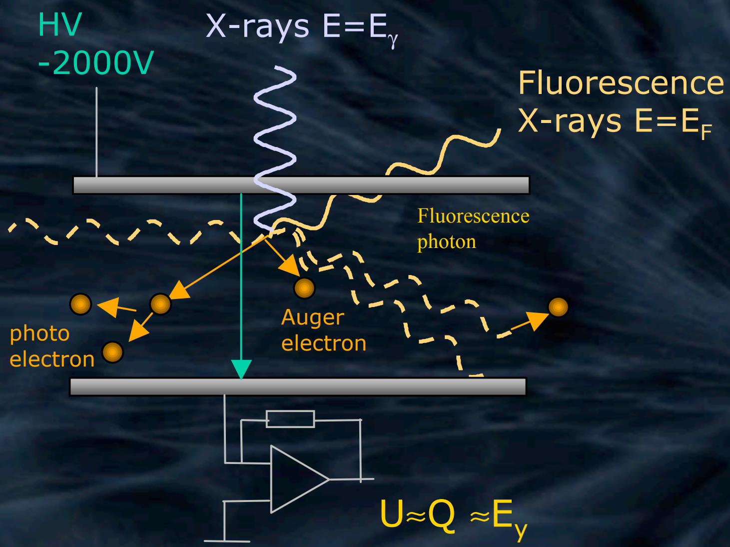


$$\varepsilon(E_\gamma) = \underbrace{e^{-\mu_w(E_\gamma)\rho_w \cdot x_w}}_{\text{Transmission window}} \cdot \underbrace{e^{-\mu_d(E_\gamma)\rho_d \cdot \Delta x_1}}_{\text{Transmission dead volume}} \cdot \Big(\underbrace{1 - e^{-\mu(E_\gamma)\rho \cdot \Delta x_2}}_{\text{Absorption in detector volume}} \Big)$$

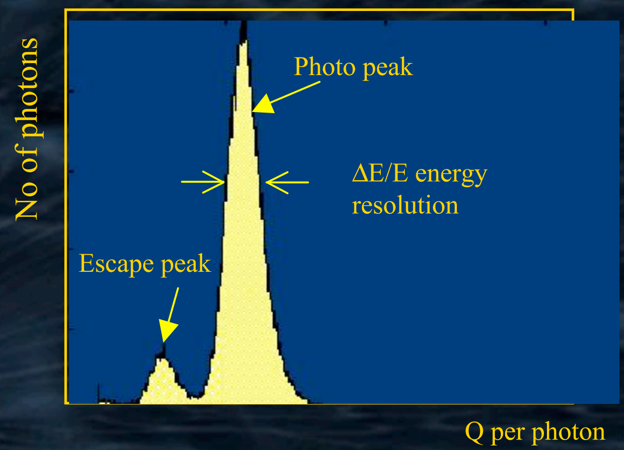
Energy resolution

Energy resolution for gaseous detectors $\Delta E/E \sim 10\%$

Example: gaseous detector-. Proportional counter



Typical 'energy spectrum'

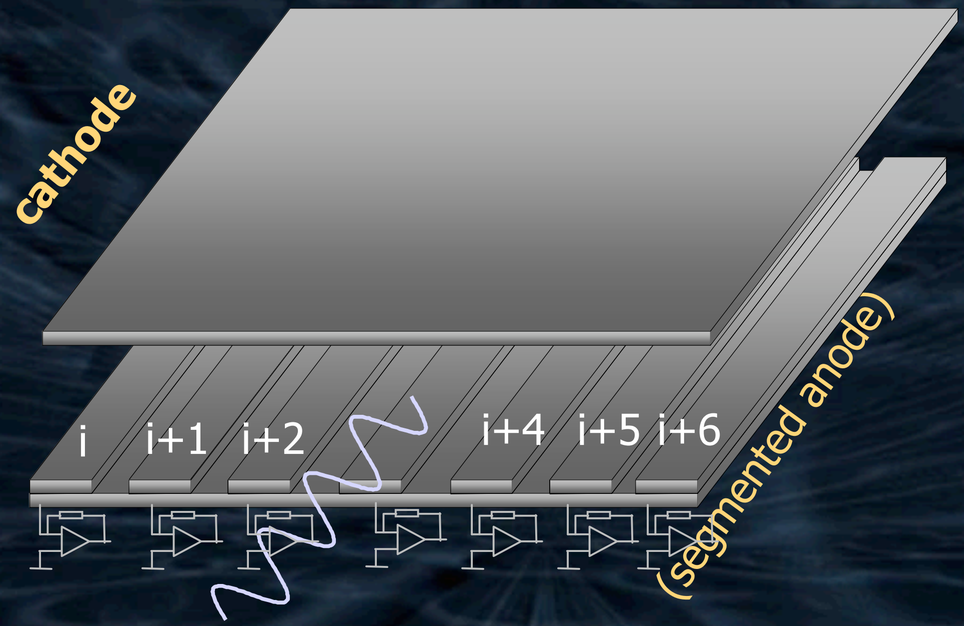


Process	Energy
photo electron	$E_p = E_\gamma - E_b$
Fluorescence photon	$E_f = E_i - E_j$
Auger electron	$E_a = E_k - 2E_l$ for photo effect on k-shell

$$\frac{\Delta E}{E} = \frac{\int_0^\infty n(E)\cdot E^2 \cdot dE - \left(\int_0^\infty n(E)\cdot E \cdot dE\right)^2}{\left(\int_0^\infty n(E)\cdot E \cdot dE\right)^2}$$

$= single\ event\ energy\ resolution$

Spatial resolution



Bottom line: connect each strip to pream. and collect charges release

Integrating detectors

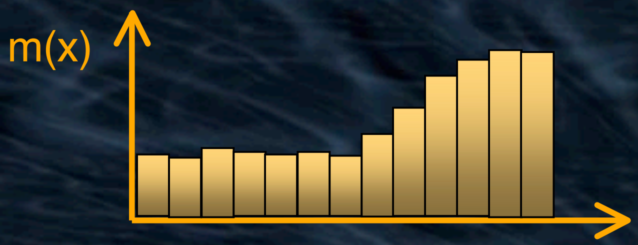
$$Q_i\left(E_\gamma\right) = \frac{E_\gamma}{W_{ion}} \cdot \varepsilon\left(E_\gamma\right) \cdot N \cdot e^-$$

Counting detectors

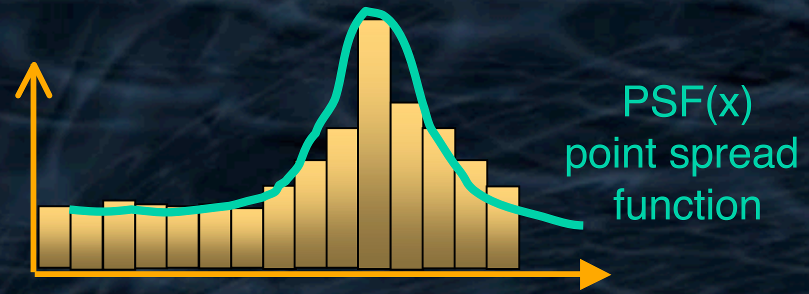
$$Q_i\left(E_\gamma\right) = \varepsilon\left(E_\gamma\right) \cdot N \cdot \frac{E_\gamma}{W_{ion}} \cdot e^- \cdot A \cdot \delta\left(t\right)$$

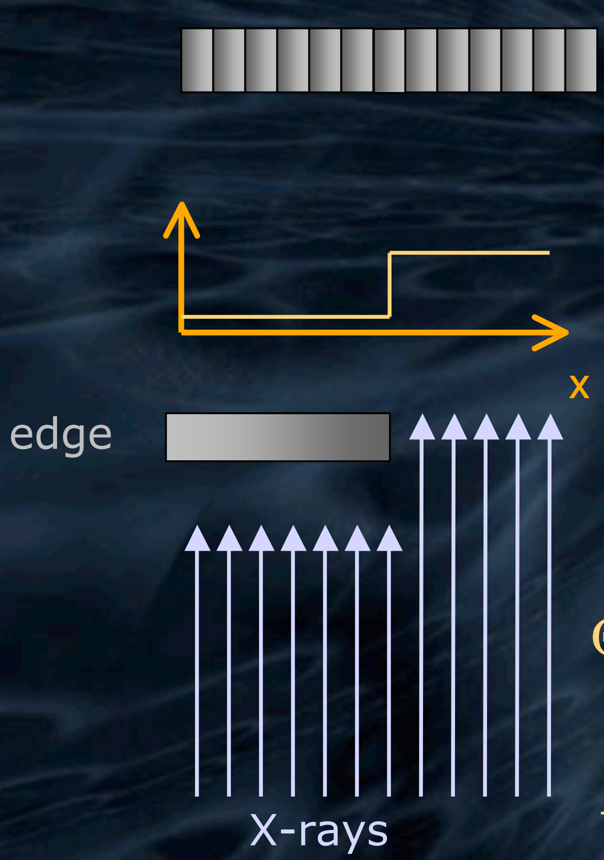
$$\left\langle x \right\rangle = \sum_i i \cdot Q_i\left(E_\gamma\right) \Big/ \sum_i Q_i\left(E_\gamma\right)$$

Spatial resolution: PSF



$$\frac{\partial m}{\partial x} \rightarrow$$





$$m(x) = \int_{-\infty}^{\infty} PSF(x') \cdot \Theta(x-x') \cdot dx'$$

$$\frac{\partial m(x)}{\partial x} = \int_{-\infty}^{\infty} \frac{\partial}{\partial x}\left(PSF(x')\right) \cdot \Theta(x-x') \cdot dx' + \int_{-\infty}^{\infty} PSF(x') \cdot \frac{\partial}{\partial x}\Theta(x-x') \cdot dx'$$

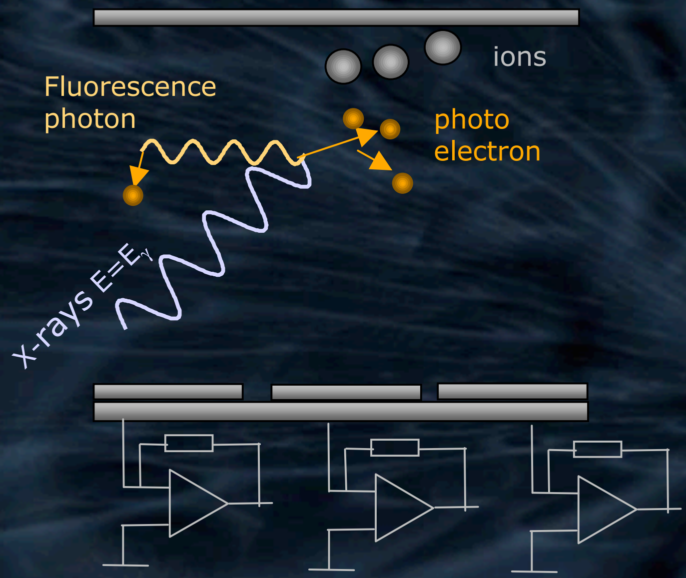
$$= \int_{-\infty}^{\infty} PSF(x') \cdot \delta(x-x') \cdot dx' = PSF(x)$$

$$\Theta(x-x') = \begin{cases} 0 & for\ x < x' \\ 1 & else \end{cases};$$

$$\frac{\partial \Theta(x-x')}{\partial x} = \delta(x-x')$$

Signal smearing is due to
- the process of charge generation
- and the discrete pixel size

Spatial resolution: PSF



Contributions to the spatial resolution

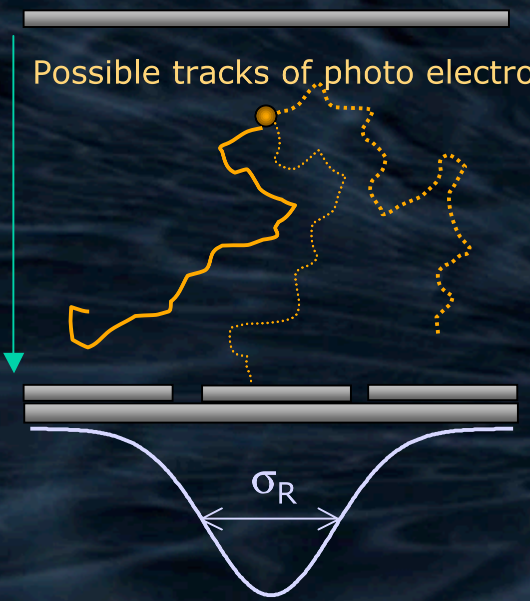
- Range of photo electrons
- diffusion of the electron components
- range of the fluorescence
- pixel size of the segmentation
- electronics cross talk
- induction of ion component
- etc

$$PSF(x) = \int_{-\infty}^{\infty} ..[..[......\int_{-\infty}^{\infty} \delta\left(x^{'......'}\right)\cdot g_1\left(x^{'......'}\right) dx^{'......'} .]..]\cdot g_n\left(x - x'\right)\cdot dx'$$

$$= \delta * g_1 * .... * g_n$$

Point Spread Function /Line Spread Function

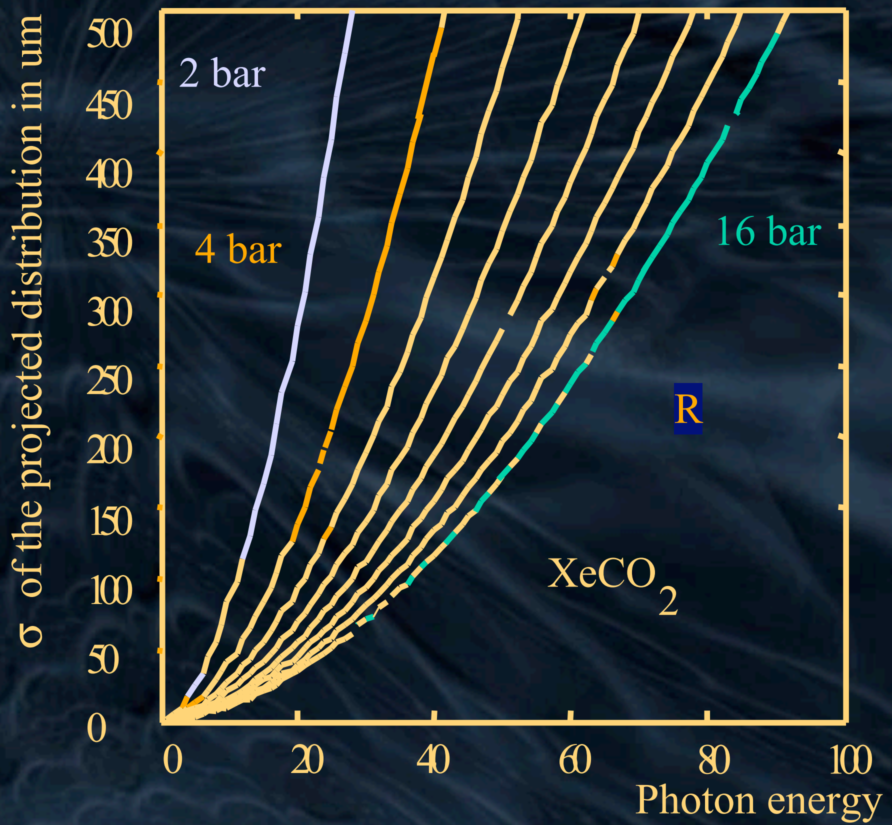
range of photo electrons



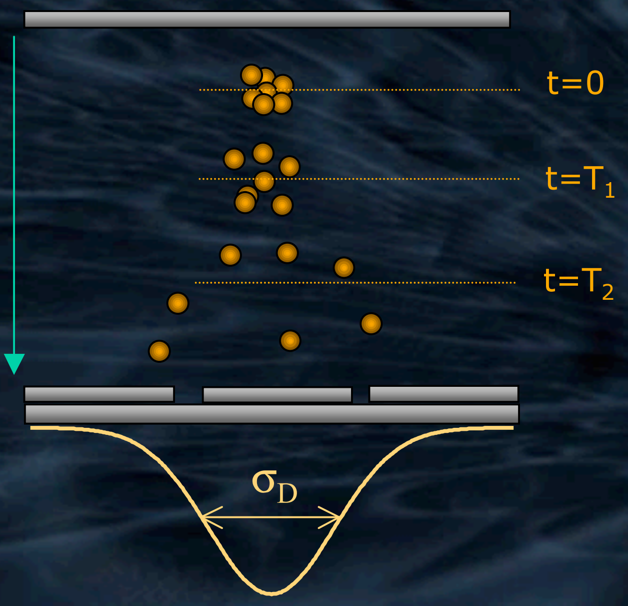
$\sigma_R = 1.5\ 10^{-3}\ E^{1.75}$ dim (σ_R) = [mgr/cm²] dim(E) = [keV]

Projected distribution of photo electrons
on the segmented electrode

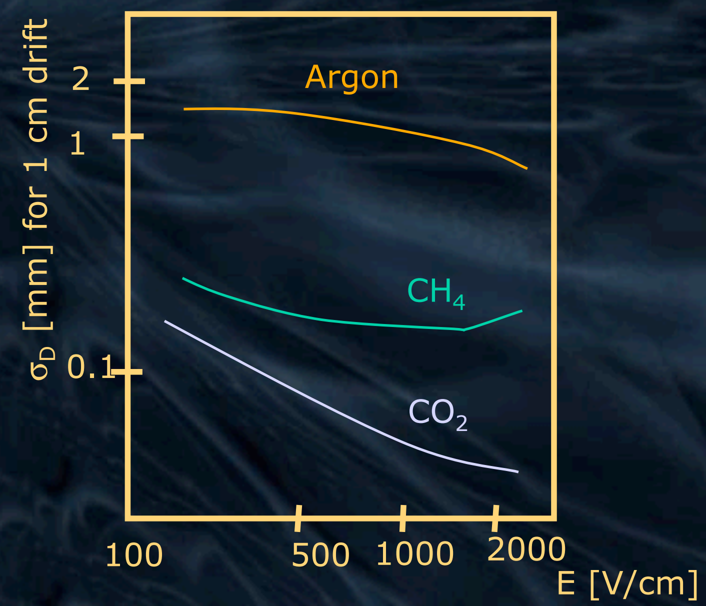
$$r_P(x) = e^{-\frac{x^2 \cdot \rho_{gas}^2}{2 \cdot \sigma_R^2}}$$



diffusion of electrons



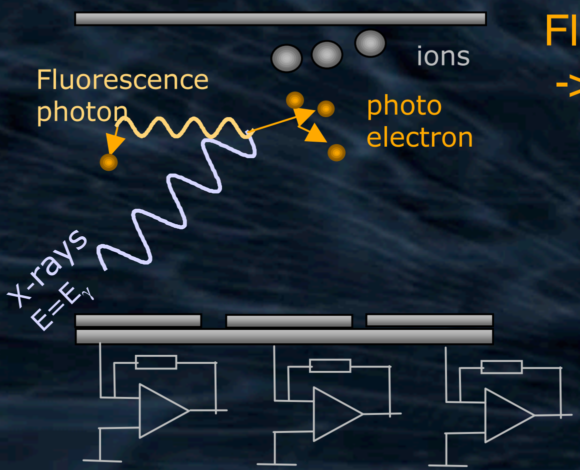
- D_t Diffusion constant
- E electrical field
- P pressure
- u- mobility
- z_{drift} drift distance
- t drift time



$$d(x) = e^{-\frac{x^2}{4 \cdot \sigma_D^2}}$$

$$\sigma_D = \sqrt{2 \cdot D_t \cdot t} = \sqrt{\frac{2 \cdot D_t \cdot z_{drift} \cdot P}{\mu^- \cdot E}}$$

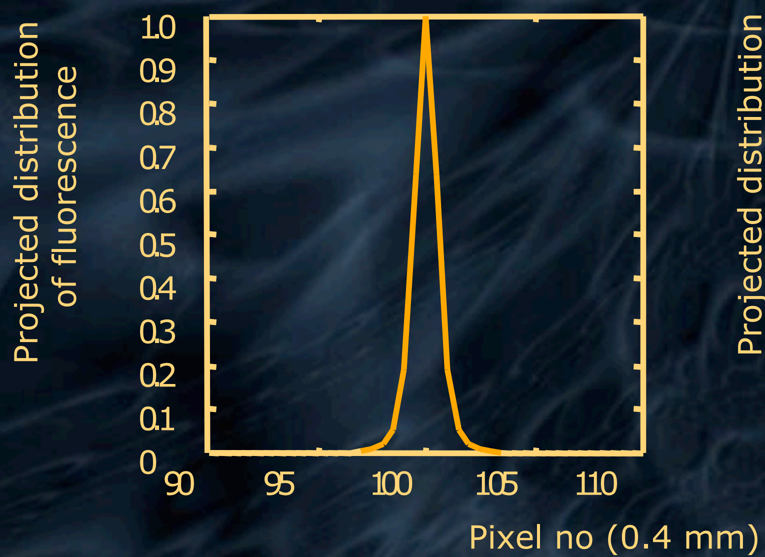
Fluorescence



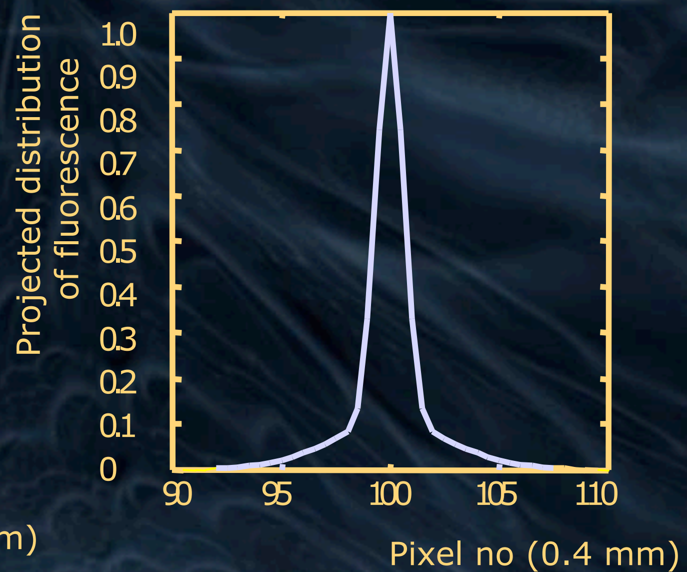
Fluorescence strongly depends on the geometry gas, energy etc.
-> no analytical expression -> Monte Carlo

- Dice position of incident photon
- Dice primary ionization $e^{-\mu\Delta z}$
- Dice effect (Auger or fluorescence
- If fluorescence
  - dice φ and $d\cos(\theta)$ [solid angle]
  - dice conversion position according to $e^{-\mu\Delta r}$
  - projection on x-axis
  - apply segmentation
- endif & go to beginning

For Kr-CO_2 filled Ionization chamber with a pixel size of 0.4mm and E_y= 33.174 keV

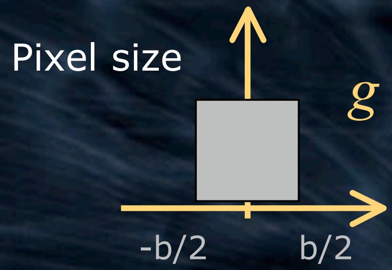


Distance anode -cathode = 3 mm



Distance anode -cathode = 10 mm

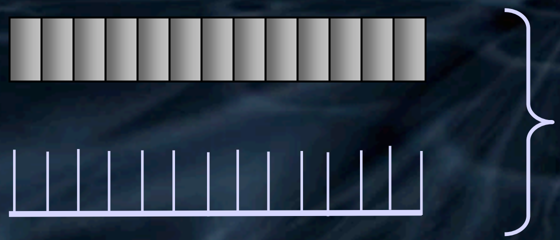
Spatial resolution: pixel size



$$g(x) = \begin{cases} \frac{1}{b} & for -\frac{b}{2} < x < \frac{b}{2} \\ 0 & else \end{cases}$$

$$\sigma_p = \frac{b}{\sqrt{12}}$$

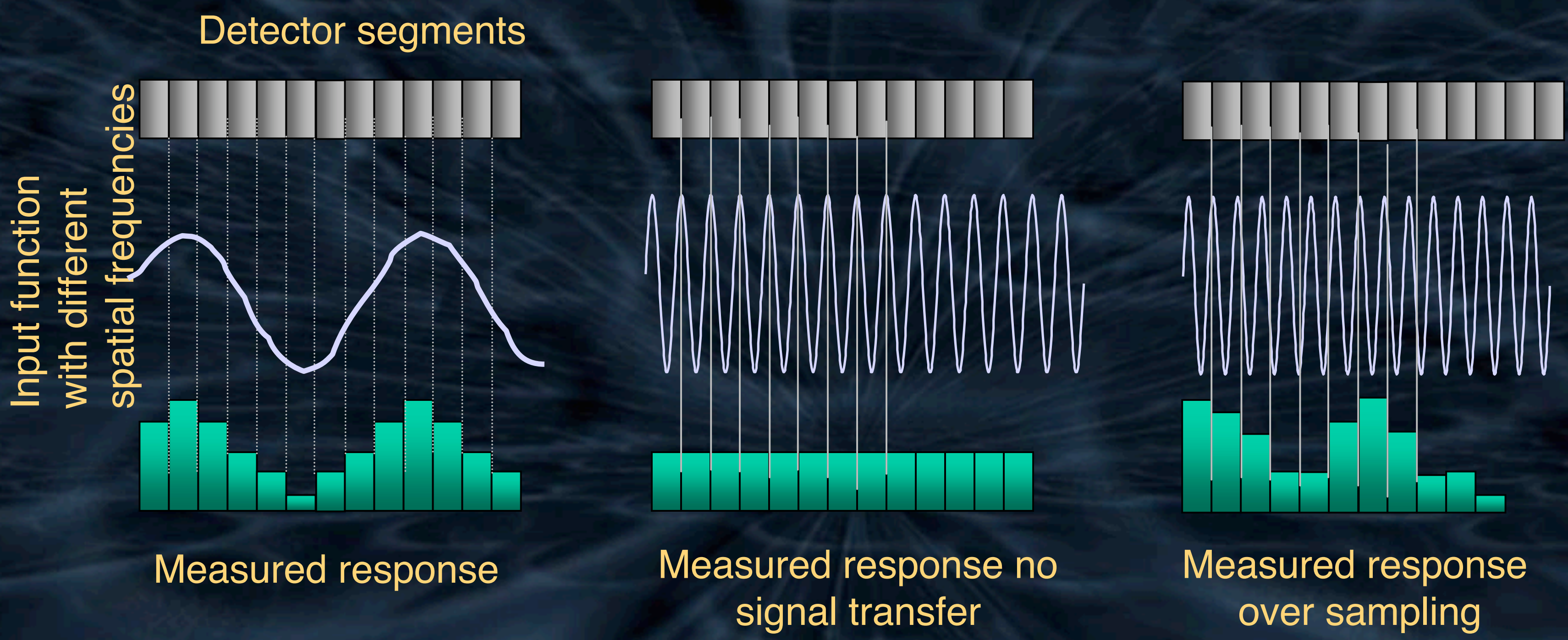
Periodic repetition of pixels in real detector



$$\sum_{i=-\infty}^{\infty} \delta(x - i \cdot b) \quad Dirac\ Comb$$

Segmentation is a convolution of g(x) with Dirac comb

Nyquist sampling theorem



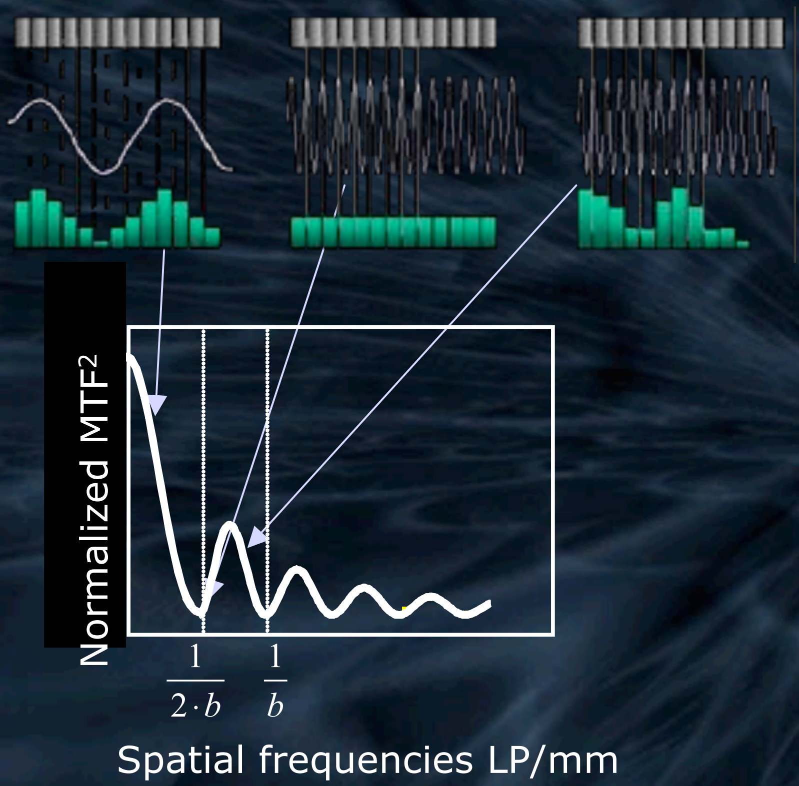
How good are different spatial frequencies transmitted (modulated) by the detector??

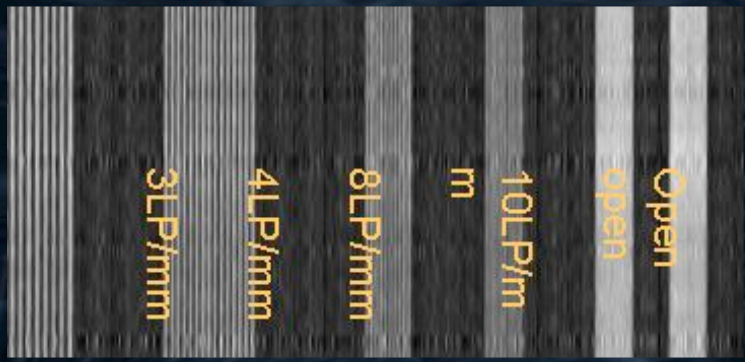
$$PSF(X) = \begin{cases} \frac{1}{b} & for -\frac{b}{2} < x < \frac{b}{2} \\ 0 & else \end{cases}$$

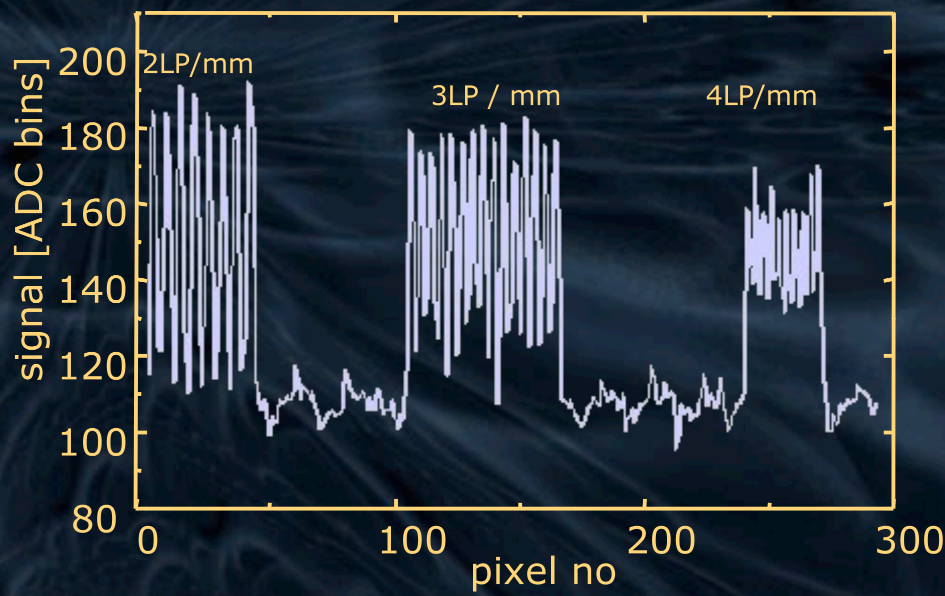
$$MTF(u) = \left| \int_{-\infty}^{\infty} PSF(x) \cdot e^{-2 \cdot i \cdot \pi \cdot u \cdot x} \cdot dx \right| = \left| \frac{\sin(2 \cdot \pi \cdot u \cdot b)}{2 \cdot \pi \cdot u \cdot b} \right|$$

MTF = Modulation Transfer Function

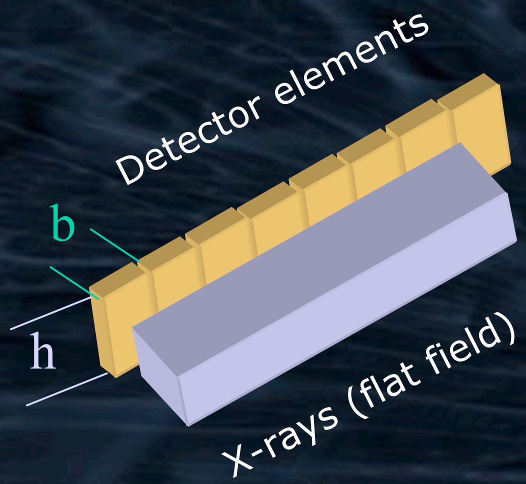
Modulation transfer function







Signal to noise ratio



$$\phi(x,y,t) = \phi_0 = const$$

$$\int_A da = \int_{-\frac{b}{2}}^{\frac{b}{2}} \int_{-\frac{h}{2}}^{\frac{h}{2}} dx \cdot dy$$

$$S_{in} = N_{in} = \int_A \int_T \phi(x,y,t) \cdot dt \cdot da = \phi_0 \cdot b \cdot h \cdot T$$

$$\sigma_{in} = \sqrt{\int_A \int_T \phi(x,y,t) \cdot dt \cdot da} = \sqrt{\phi_0 \cdot b \cdot h \cdot T}$$

$$SNR_{in} = \frac{\int_A \int_T \phi(x,y,t) \cdot dt \cdot da}{\sqrt{\int_A \int_T \phi(x,y,t) \cdot dt \cdot da}} = \frac{N}{\sqrt{N}} = \sqrt{N}$$

DQE: Signal to noise ratio for integrating detectors

$$S_{out} = \varepsilon \cdot S_{in}(x) \otimes PSF(x) = \varepsilon \cdot N(x) \otimes PSF(x)$$

$$\sigma_{out} = \sqrt{\underbrace{\varepsilon \cdot N(x) \otimes PSF(x)}_{\text{Poisson noise}} + \underbrace{\sigma^2_{out}}_{\text{Electronics noise of an integrating detector}}}$$

Poisson noise

Electronics noise
of an integrating detector

$$SNR_{out} = \frac{S_{out}}{\sigma_{out}} = \frac{\varepsilon \cdot S_{in}(x) \otimes PSF(x)}{\sqrt{\varepsilon \cdot N(x) \otimes PSF(x) + \sigma^2_{out}}} = \frac{\varepsilon \cdot N(x) \otimes PSF(x)}{\sqrt{\varepsilon \cdot N(x) \otimes PSF(x) + \sigma^2_{out}}}$$

$$SNR_{out} = \sqrt{DQE} \cdot SNR_{in}$$

$$DQE = \left(\frac{SNR_{out}}{SNR_{in}} \right)^2$$

DQE for integrating detectors

$$\Im(DQE) = \Im\left(\left(\frac{SNR_{out}}{SNR_{in}}\right)^2\right) = DQE(f);\ f\ spatial\ frequency$$

$$DQE(f,N) = \Im\left(\left(\frac{\varepsilon \cdot N(x) \otimes PSF(x)}{\sqrt{\varepsilon \cdot N(x) \otimes PSF(x) + \sigma_{out}^2}}\right)^2\right)$$

$$DQE(f,N) = \chi(N) \cdot \frac{\left|MTF(f)\right|^2}{NPS(f)};\ with\ \left|MTF(f=0)\right|^2 = 1\ and$$

$$NPS(f=0) = 1 + \frac{\sigma_{out}^2}{\varepsilon \cdot N}$$

$$DQE(f=0,N) = \frac{\varepsilon}{1 + \frac{\sigma_{out}^2}{\varepsilon \cdot N}}$$

MTF = modulation transfer function
NPS = noise power spectrum
$\chi(N)$ = zero spatial frequency DQE

DQE: Signal to noise ratio for counting detectors

m = measure rate
n = real rate
τ = dead time
Events in the detector

Non paralyzable

m = n/(1+n τ)

Paralyzable

m = ne$^{-n\tau}$

$$DQE(f=0)=\left(\frac{SNR_{out}}{SNR_{in}}\right)^2$$

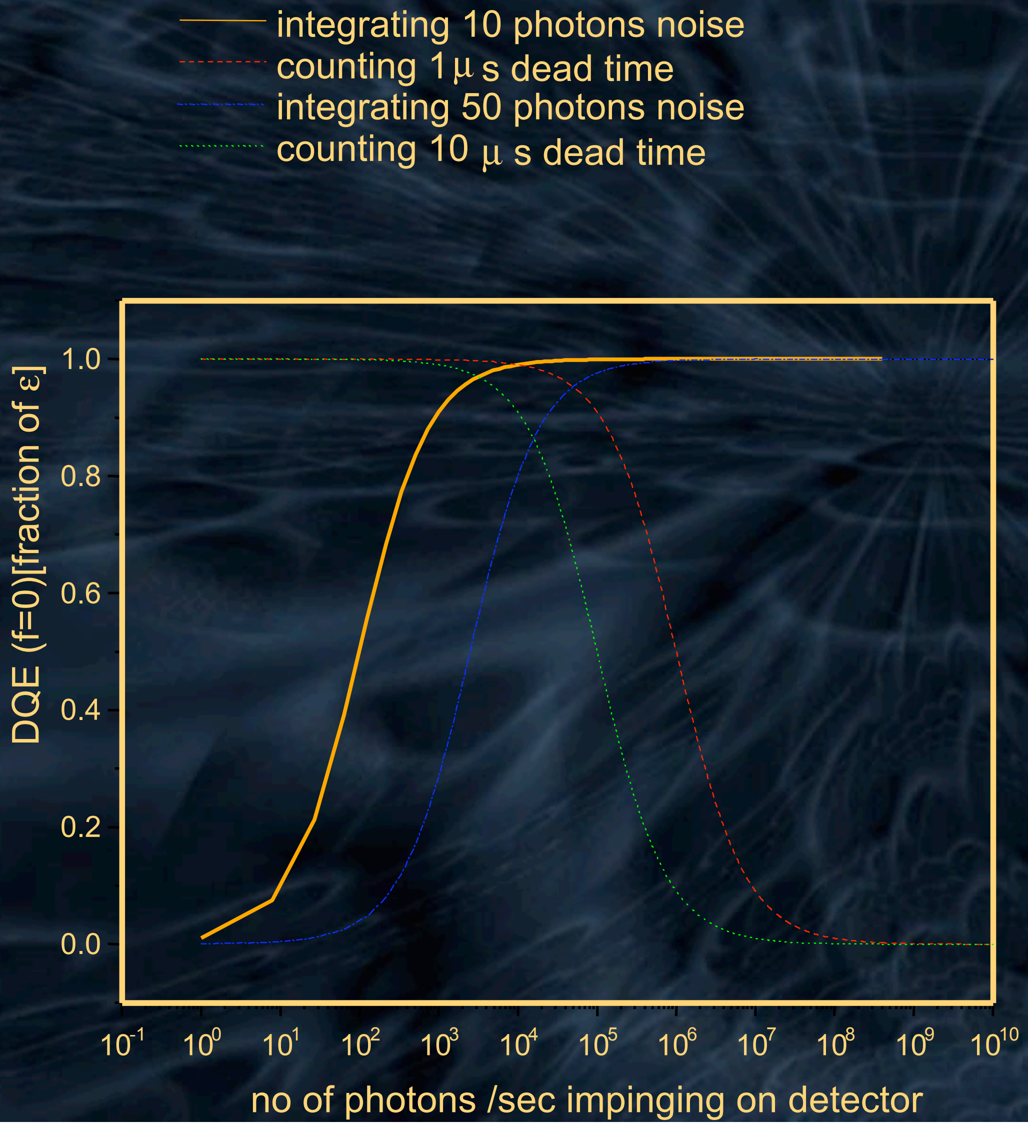
$$S_{out}=\frac{\varepsilon\cdot n}{1+n\cdot\tau};\ \sigma_{out}=\sqrt{\frac{\varepsilon\cdot n}{1+n\cdot\tau}}$$

$$SNR_{out}=\sqrt{\frac{\varepsilon\cdot n}{1+n\cdot\tau}}$$

$$SNR_{in}=\sqrt{n}$$

$$DQE(f=0)=\frac{\varepsilon}{1+n\tau}$$

Zero spatial frequency DQE



Counting detectors

$$DQE = \frac{\varepsilon}{1 + N \cdot \tau} \cdot |MTF|^2$$

Integrating detectors

$$DQE = \frac{\varepsilon}{1 + \frac{\sigma_{add}^2}{\varepsilon \cdot N}} \cdot |MTF|^2$$

DQE

Integrating detectors

$$DQE = \frac{\varepsilon}{1+\frac{\sigma_{add}^2}{\varepsilon \cdot N}} \cdot |MTF|^2$$

Counting detectors

$$\mathrm{DQE} = \frac{\varepsilon}{1+\mathrm{R}\cdot\tau} \cdot |MTF|^2$$

$$MTF = \Im(PSF)$$

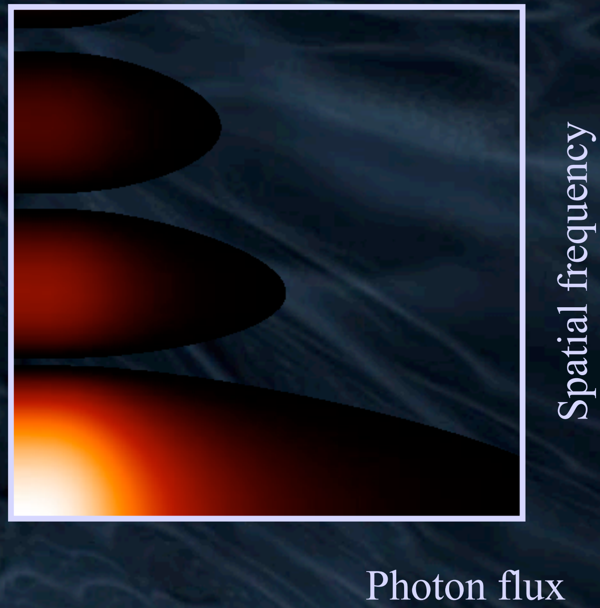
$$PSF = \begin{cases} 1 \text{ for } -b/2<x<b/2 \\ 0 \text{ else} \end{cases} \Rightarrow MTF \sim \frac{Sin(x)}{x}$$

Integrating: noise 10 photon

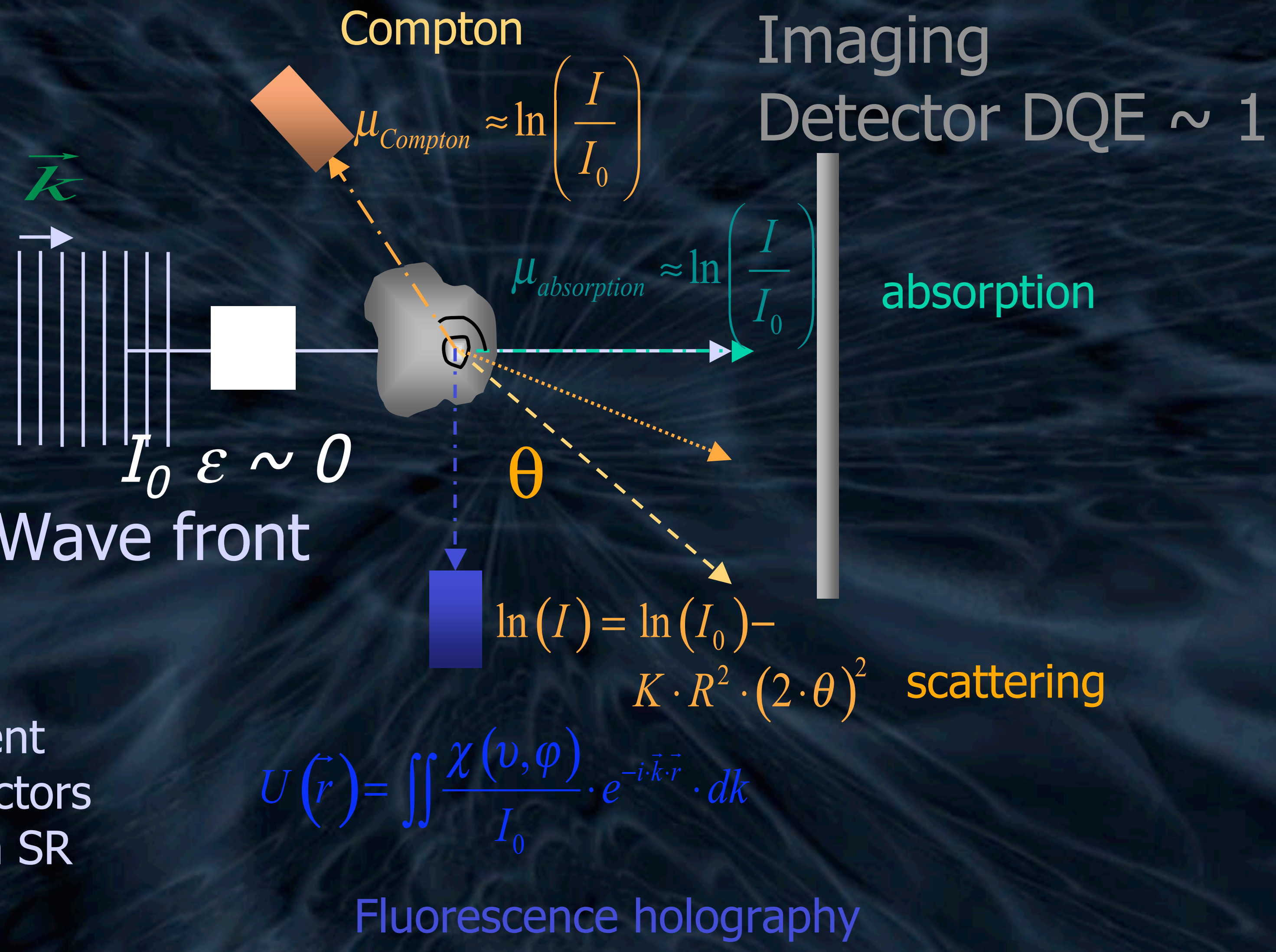
← $\frac{1}{4b}$ →

← $\frac{1}{2b}$ →

Counting: deadtime 10^{-6}s



SR & detectors



It needs both I_o and excellent imaging detectors for success in SR

SR & detectors

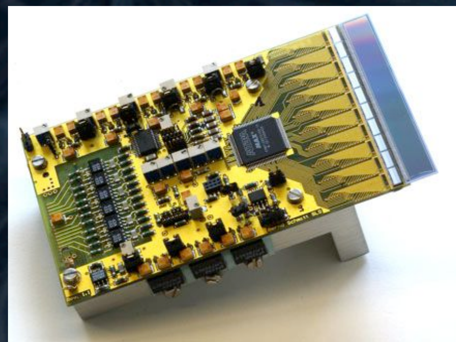
$I_0 \ \varepsilon \sim 0$

- should not alter incident beam
- precision $I_0 \sim$ ppm
- position resolution sub micron range

Elettra XBPM

Imaging Detector DQE ~ 1

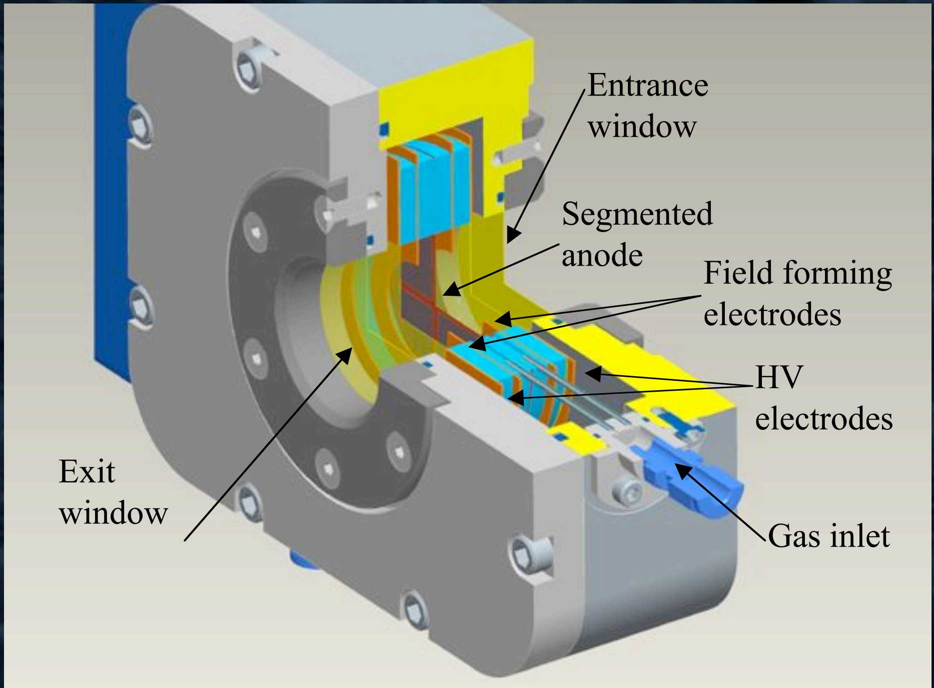
- should use every photon
- should not be a source of additional noise
- position resolution at least twice the smallest detail

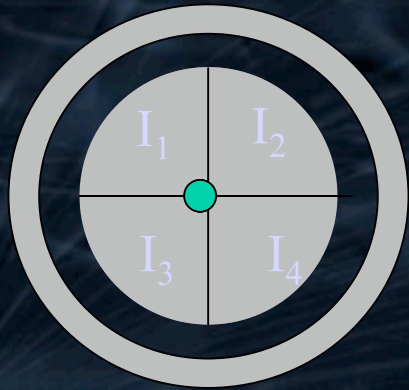


PSI Mythen
Si strip detector

DECTRIS Pilatus 100K

Low absorbing I_0 beam position monitors XBPM





Segmented Anode
Al on Kapton
"Mega pixel"

- 2 Burr Brown DDC 112 20 bit ADCs
- Micro controller state machine
- USB 2 readout
- Integration time programmable
- Programmable gain (min 50 pC FSR)
- Max 0.5 ms sampling rate

Simultaneous
- position encoding
- intensity measurement (< 0.3 %)

Low absorbing I_0 beam position monitors

$$\sum I_i = \sum \varepsilon \cdot \frac{E_\gamma}{W_{ion}} \cdot \phi_i \cdot c = \varepsilon \cdot \frac{E_\gamma}{W_{ion} \cdot \tau} \cdot c \sum N_i$$

Intensity

$$x = \frac{(N_1 + N_4) - (N_2 + N_3)}{\sum N_i} \cdot \Delta x$$

$$and \;\; y = \frac{(N_1 + N_2) - (N_4 + N_3)}{\sum N_i} \cdot \Delta y$$

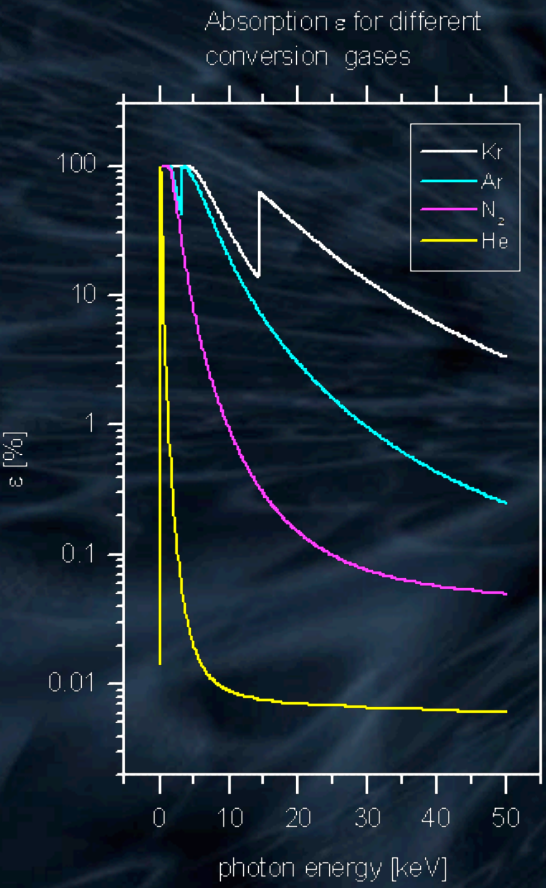
Position encoding

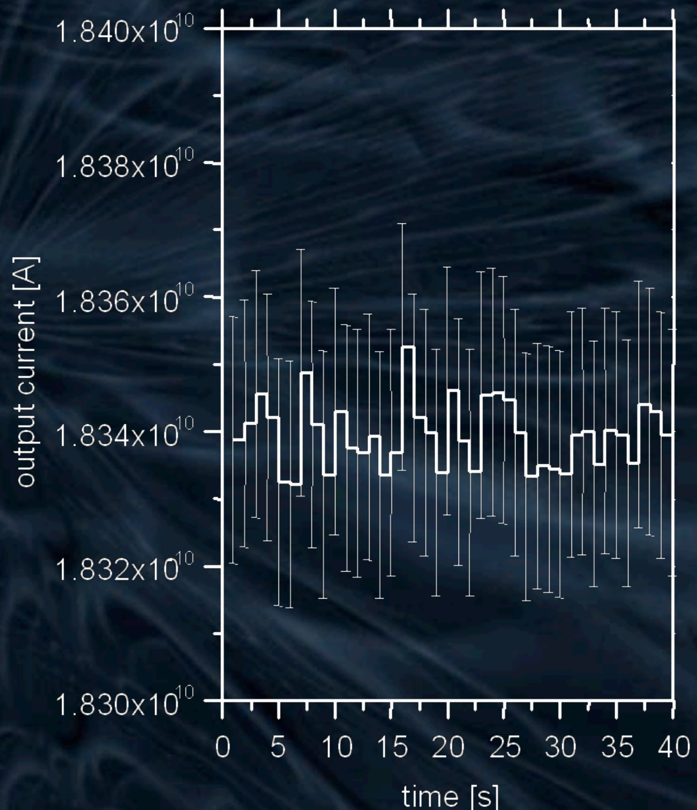
$$\Delta x \equiv \Delta y \approx \sigma_{tot} = \sqrt{\sigma^2_{range\ photo\ electrons} + \sigma^2_{diffusion} + \sigma^2_{stimulus}}$$

$$\approx 1.4mm \ for \ 9 \ KeV \ photons \ and \ 1mm \ aperature$$

XBPM intensity resolution

$$\sum I_i = \sum \varepsilon \cdot \frac{E_\gamma}{W_{ion}} \cdot \phi_i \cdot c = \varepsilon \cdot \frac{E_\gamma}{W_{ion} \cdot \tau} \cdot c \sum N_i$$





Precision in intensity better than 0.3%.
Measurements carried out at the Italian national bureau of standards

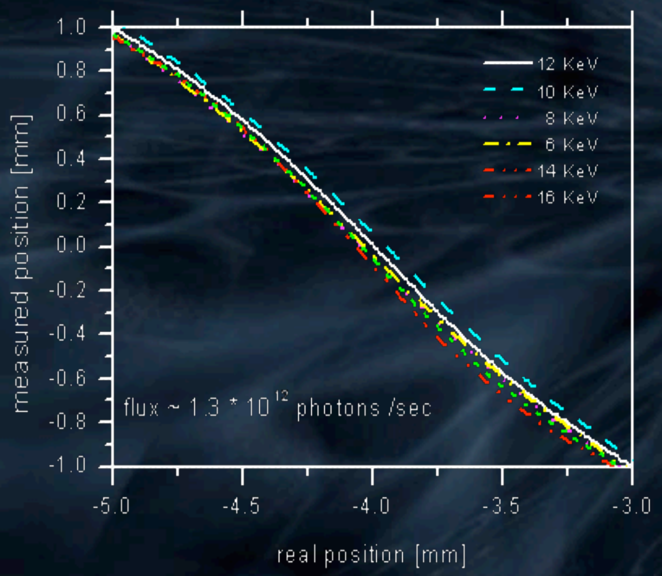
XBPM position resolution

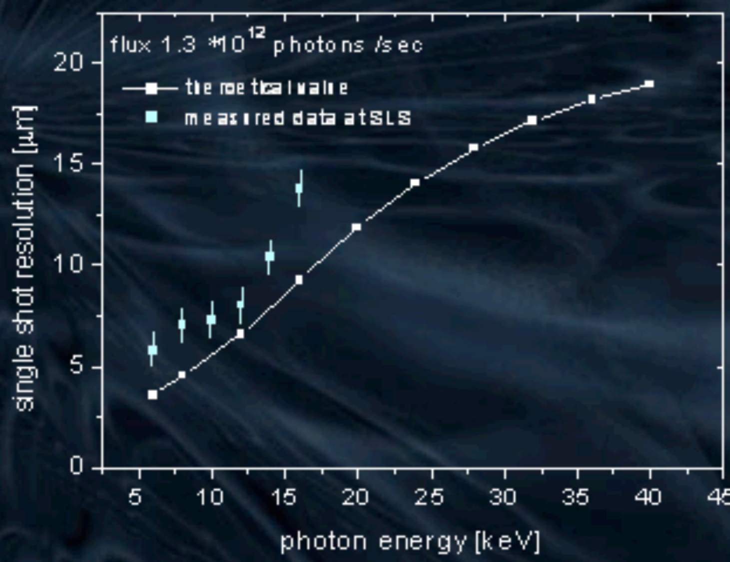
$$x = \frac{(N_1 + N_4) - (N_2 + N_3)}{\sum N_i} \cdot \Delta x$$

$$and \;\; y = \frac{(N_1 + N_2) - (N_4 + N_3)}{\sum N_i} \cdot \Delta y$$

$$\sigma_{x,y} = \frac{\Delta x, y}{2} \cdot \sqrt{\frac{\varepsilon \cdot N + \sigma_{el}^2}{\varepsilon^2 \cdot N^2}}$$

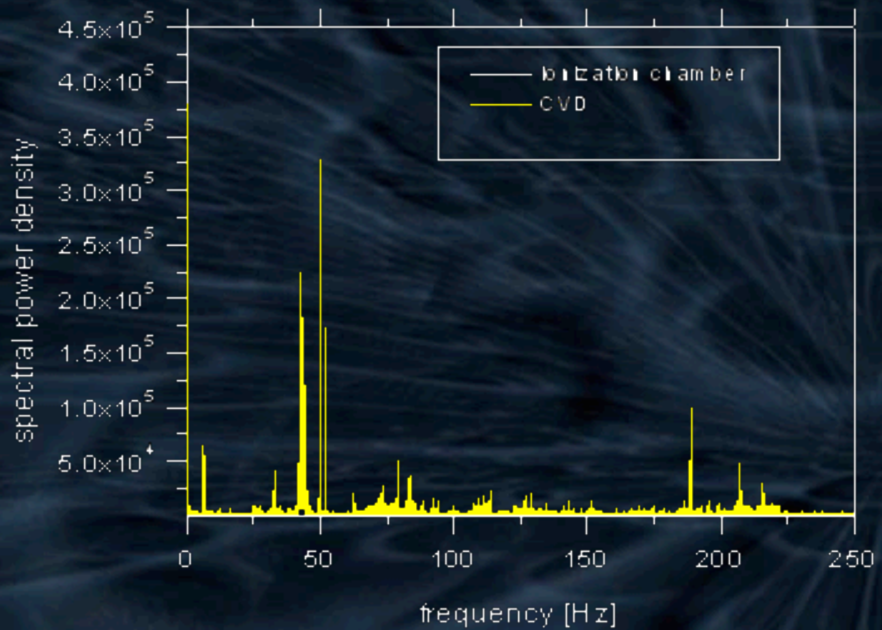
$$\Rightarrow \sigma \approx \frac{1}{SNR}$$





Better than 5μm per 1ms Integration .

XBPM real time measurements



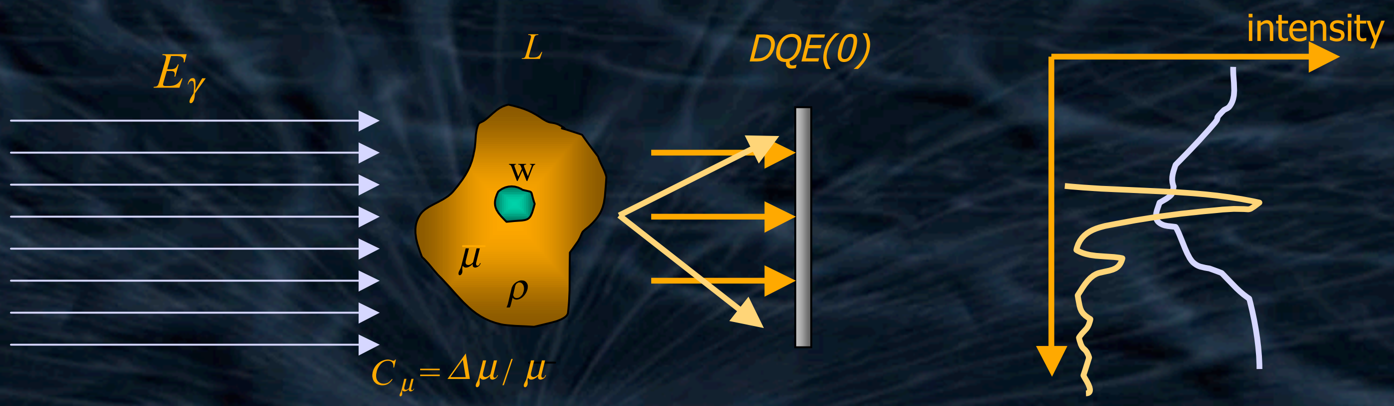
Real time measurements SLS
PX 1 beamline
1 ms integration time
Measured vertical beam fluctuations

$\sigma_{beam} = 4\mu m$

Note: For longer integration time τ precision in position encoding drops with $\sqrt{\tau}$. For τ = 1000ms

$$\sigma = \sqrt{1000} \cdot \sigma_{1ms} = 158nm$$

Dose considerations



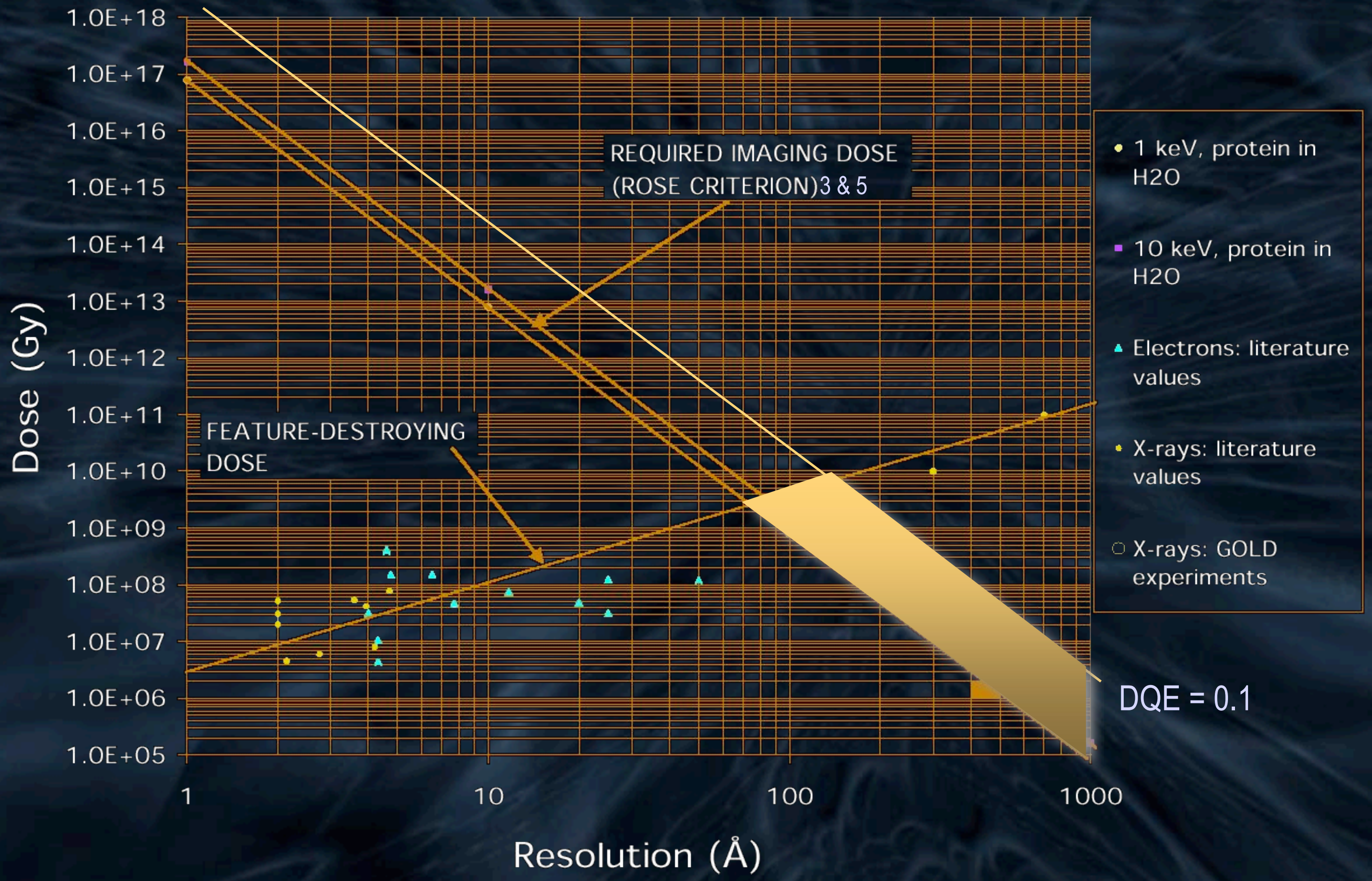
Direct Imaging

$$D_{skin} = \frac{2 \cdot L \cdot e^{\mu \cdot L} \cdot SNR_{out}^2}{DQE(f) \cdot \mu^2 \cdot w^4 \cdot C_\mu^2} \cdot E_\gamma \cdot \left(\frac{\mu}{\rho}\right)$$

$$D_{sample} = \frac{\mu \cdot P \cdot h \cdot \nu}{DQE(f) \cdot \rho^2 \cdot w^4 \cdot \lambda^2 \cdot r_e^2}$$

$$\approx \frac{1}{w^4 \cdot DQE(f)}$$

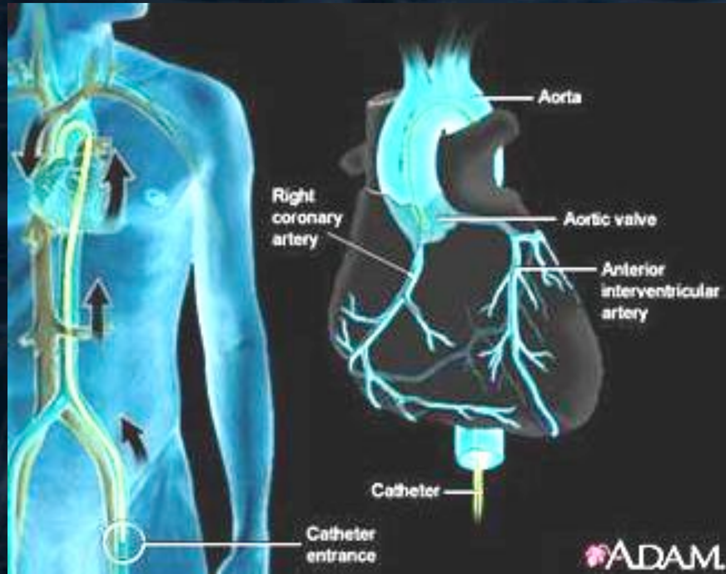
Indirect imaging



Source: Howell et al Coherence workshop Berkley 2003

Absorption contrast agents

$$D_{skin} = \frac{2 \cdot L \cdot e^{\mu \cdot L} \cdot SNR_{out}^2}{DQE(f) \cdot \mu^2 \cdot w^4 \cdot C_\mu^2} \cdot E_\gamma \cdot \left(\frac{\mu}{\rho} \right)$$



Increasing C_μ^2 utilizing contrast agents

Proc. Natl. Acad. Sci. USA
Vol. 83, pp. 9724–9728, December 1986
Medical Sciences

Transvenous injection of contrast agent

Detection of 20 fold diluted contrast agent

Transvenous coronary angiography in humans using synchrotron radiation

(arteriography/coronary artery disease/imaging)

Edward Rubenstein*, Robert Hofstadter†, Herbert D. Zeman†, Albert C. Thompson‡, John N. Otis†, George S. Brown§, John C. Giacomini*, Helen J. Gordon*, Robert S. Kernoff*, Donald C. Harrison*, and William Thomlinson¶

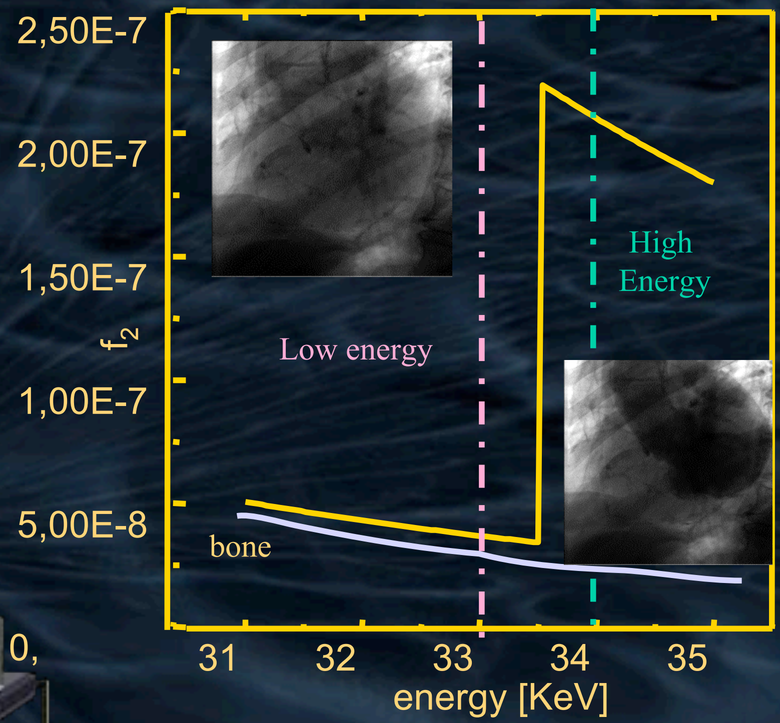
*Department of Medicine, School of Medicine, †Hansen Laboratories of Physics and Department of Physics, and §Stanford Synchrotron Radiation Laboratory, Stanford University, Stanford, CA 94305; ‡Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720; and ¶National Synchrotron Light Source, Brookhaven Laboratory, Long Island, NY 11973

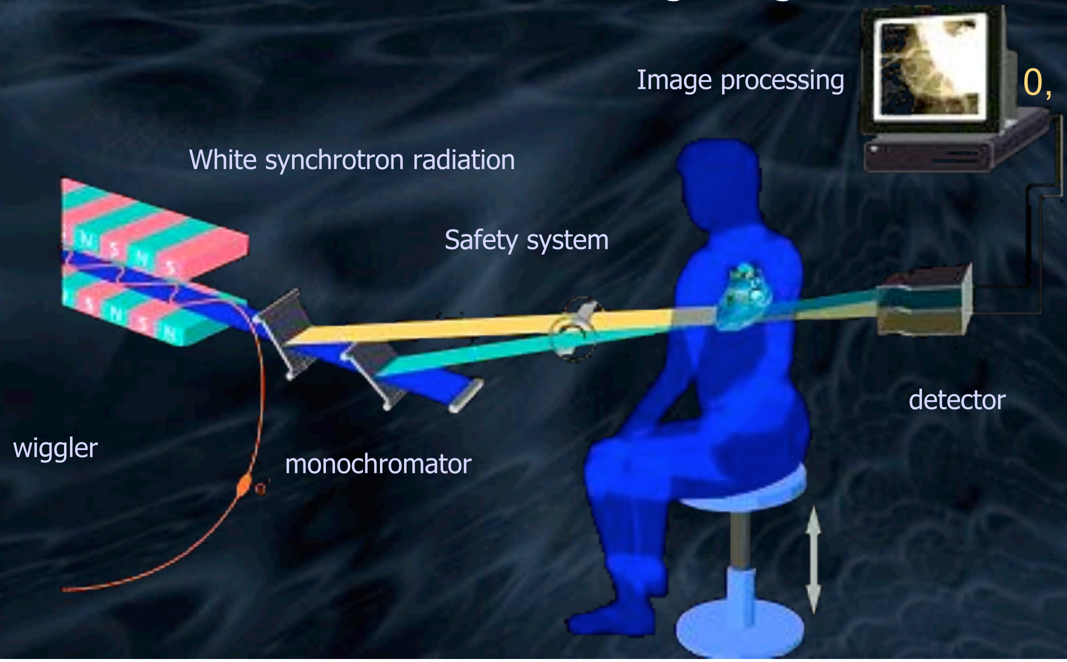
Contributed by Robert Hofstadter, August 18, 1986

Absorption contrast agents

DQE		as high as possible for 33 keV photons as low as possible or 99 keV photons
Active area		5mm * 15 cm
Spatial resolution		0.3 – 0.5 mm
Time resolution	τ	0.8 – 1 ms / line
Noise equivalent		< 10 photons / τ
Dynamic		>> 65000: 1
Max count rate		10^7 per pixel/ τ

> Integrating detectors

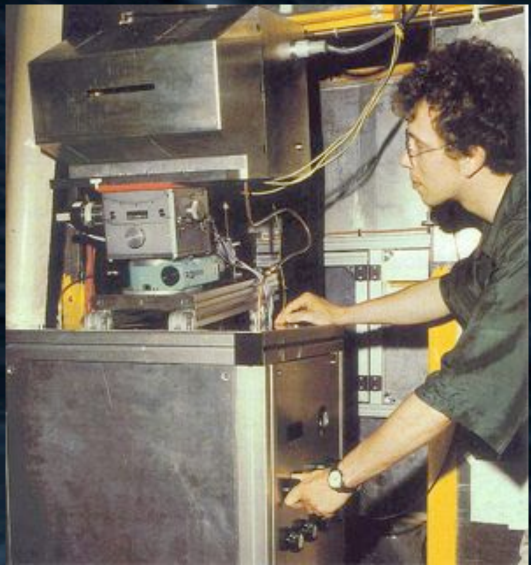




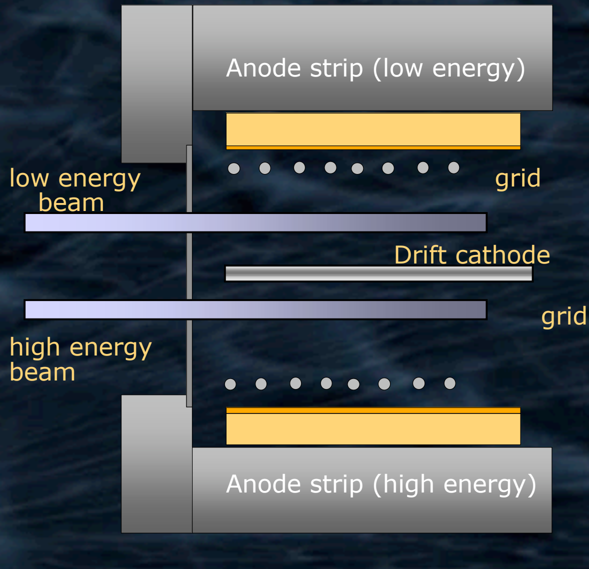
Transvenous coronary angiography

SF bay area NSLS	Li drifted Si detector (Al Thompson)
HASYLAB, DESY	Kr, Xe filled high pressure (10 bars) ionization chamber
ESRF, France	Ge detector (Eurosys)

Transvenous Coronary Angiography

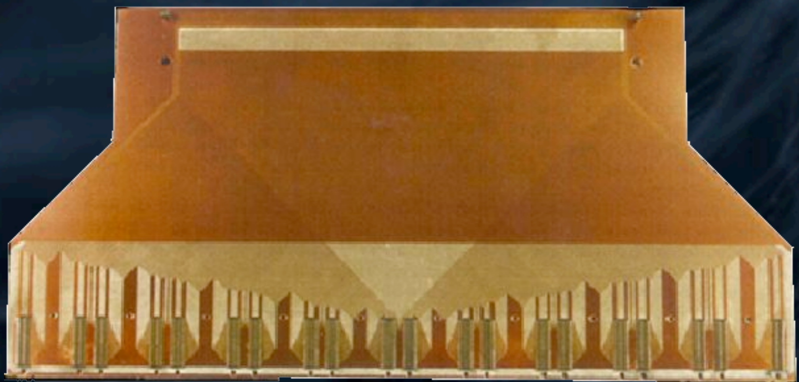


NIKOS IV



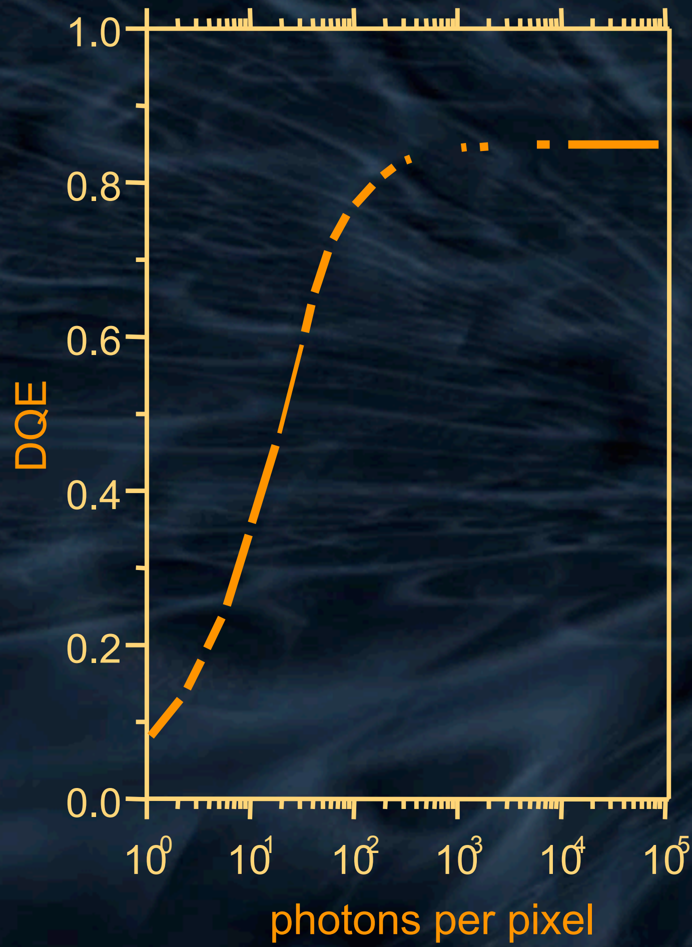
Detector HASYLAB
Segmented double line ionization chamber

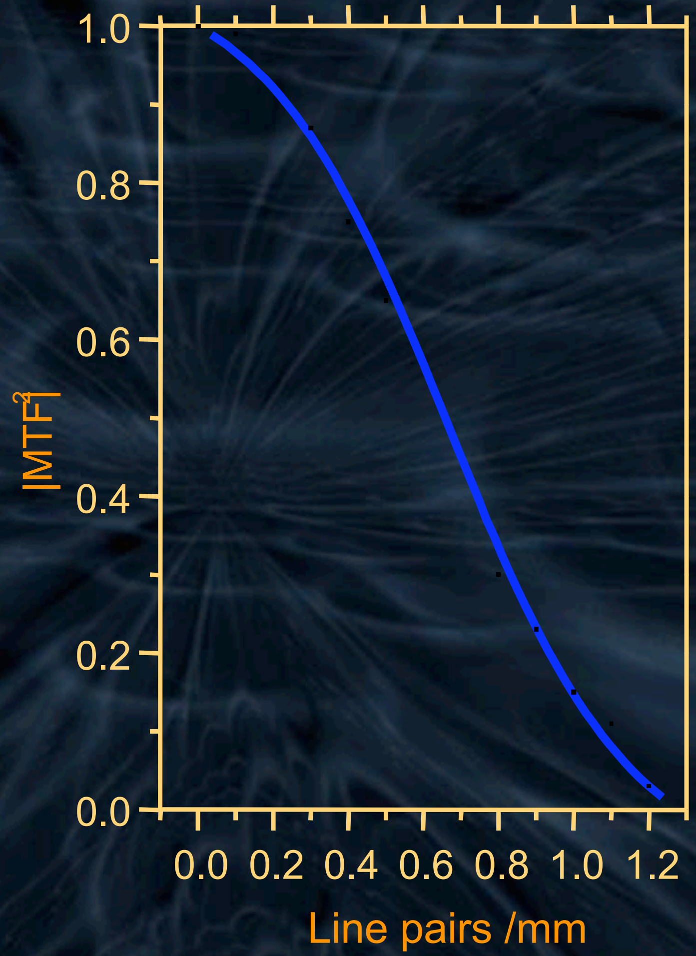
Frisch grid for fast e^- signal collection
length of the strips: 5 cm
distance drift cathode - anode: 3 mm



- two times 356 channels
- pitch 0.4mm
- integration time 0.8 ms
- 712 20 bit ADCs BB DDC 101
- optical fiber link

Detector performance

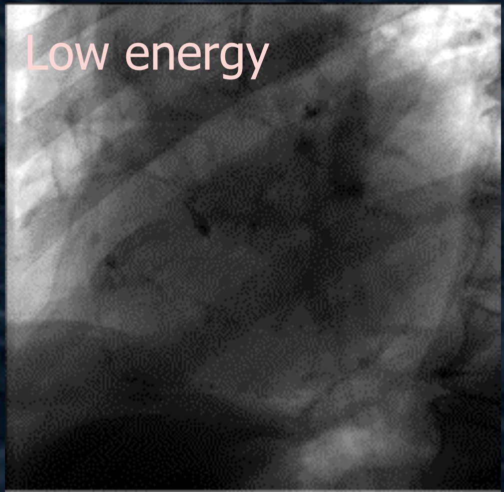


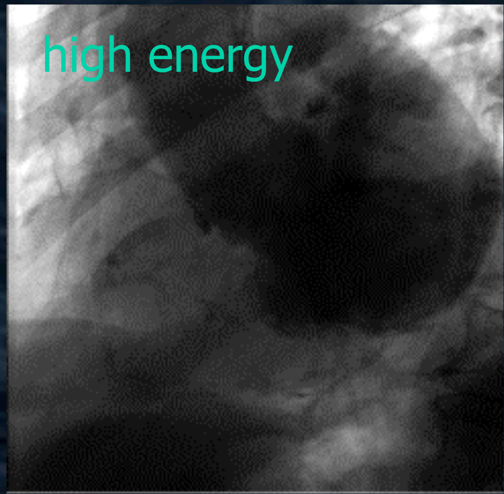


Dynamic 19 bit
DQE_{33} 0.83
Time res. 0.8 ms
Sp res 1 LP\mm
Noise 10 pho / t
No dead channels
With Kr suppression
of 3rd harmonics

1996 – 2001
376 patients
88% males
12% females

Non Invasive Coronary Angiography



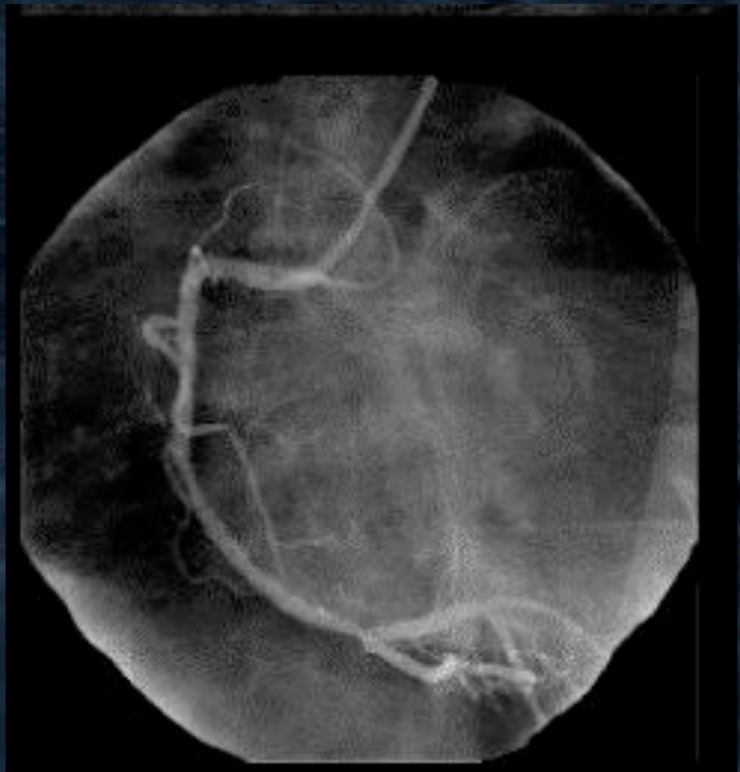


$$\begin{pmatrix} \mu_w^{>} & \mu_i^{>} \\ \mu_w^{<} & \mu_i^{<} \end{pmatrix}^{-1} \begin{pmatrix} -\ln\left(\dfrac{\phi_1}{\phi_{01}}\right) \\ -\ln\left(\dfrac{\phi_2}{\phi_{02}}\right) \end{pmatrix} = \begin{pmatrix} \rho_w \cdot \Delta x_w \\ \rho_i \cdot \Delta x_i \end{pmatrix}$$

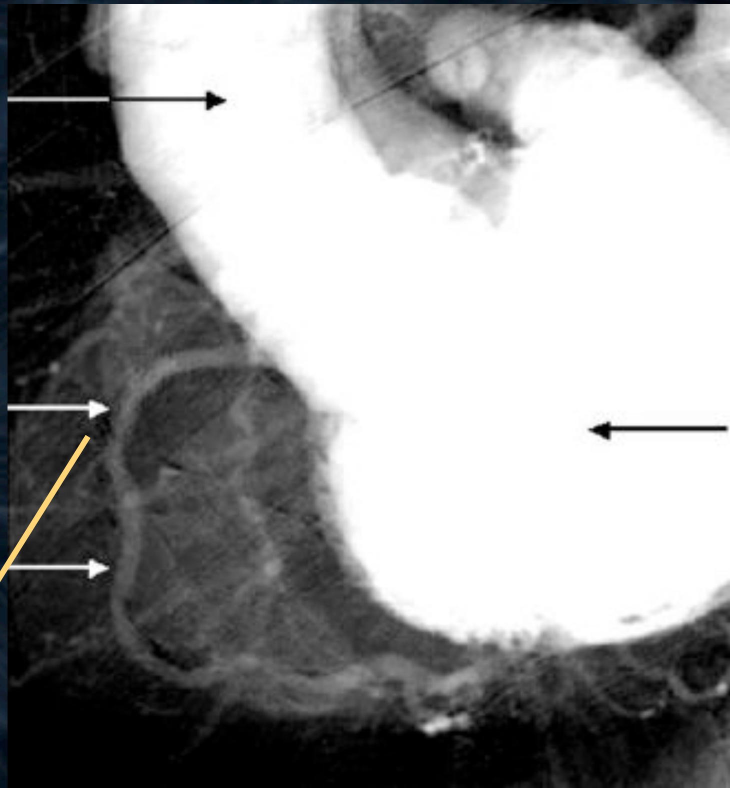
Works only for small contribution of 3rd harmonics

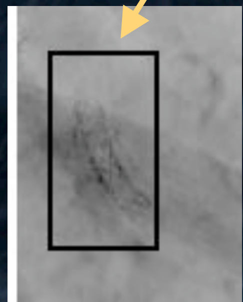
Non Invasive Coronary Angiography

Clinical angiography

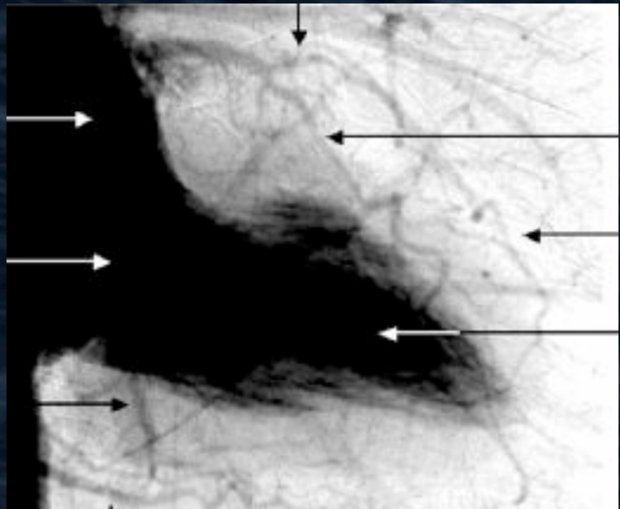


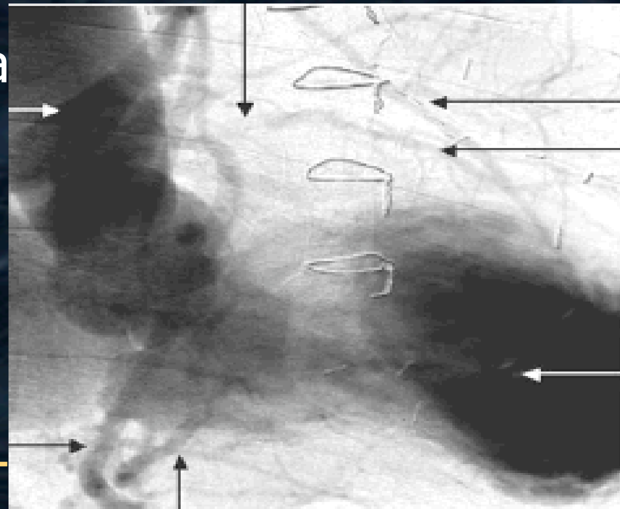
SR iodine image





Water image of stent



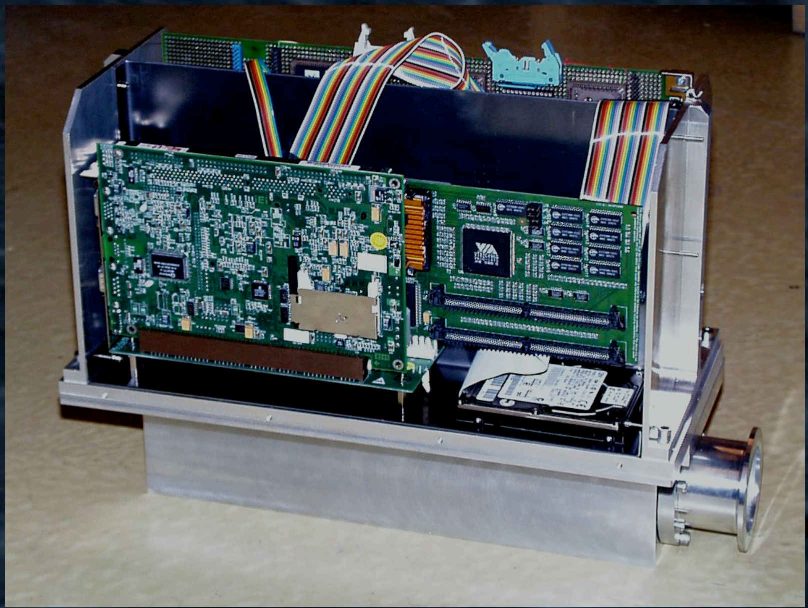


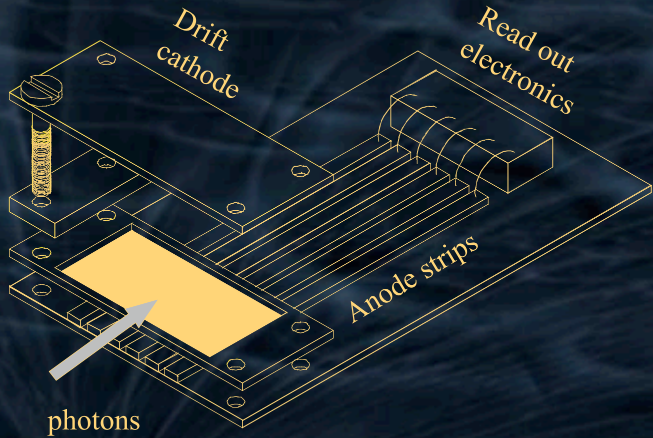
- 79% sensitivity (true positives) and 92% specificity (true negatives) for the RCA
- 45% sensitivity and 98% specificity for the LAD (superposition problem).

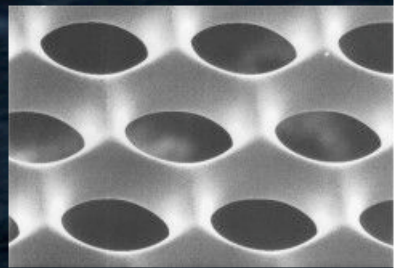
No further patients after 2002 (detector used as expensive thermometer)

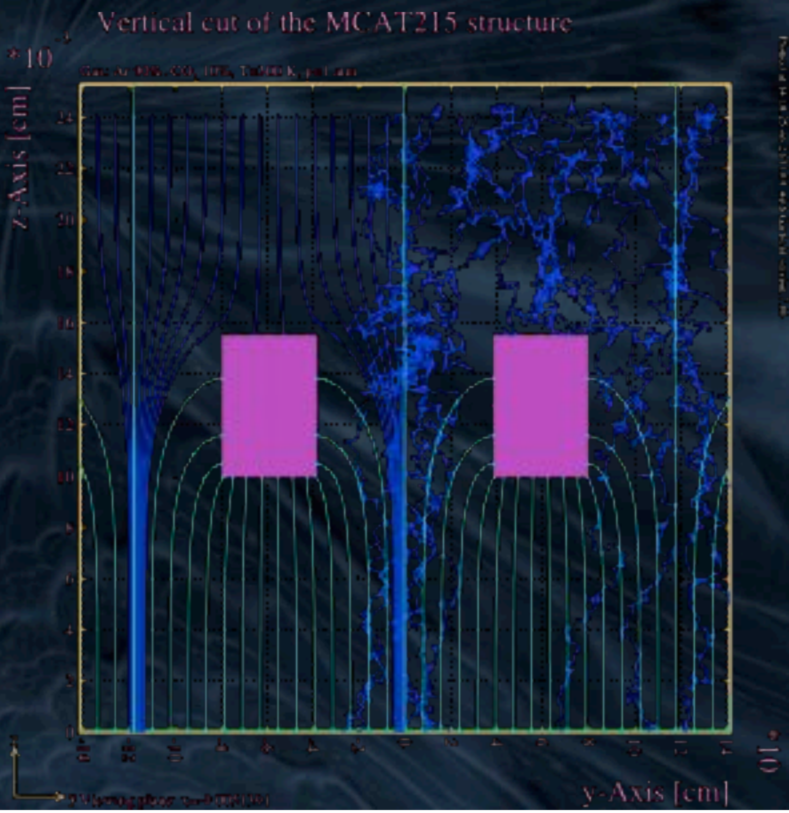
May be resurrection for a dedicated SR medical center in Germany
SR angiography and functional heart imaging with Gd based contrast agents

1-d integrating detector DQE shifter



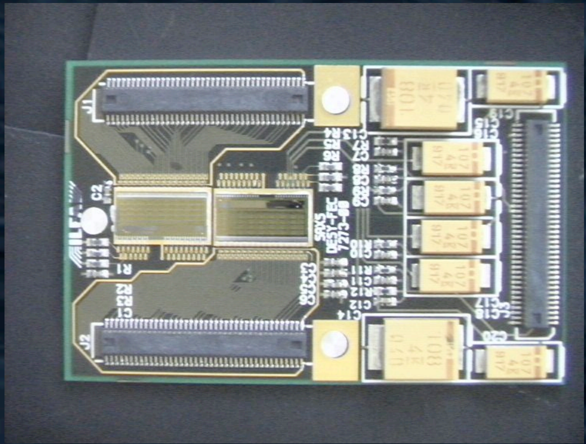






- Xe-CO_2 @ 4 bar
- 1500 strips/ channels
- adjustable gas gain (DQE shifter)
- precision < 0.1%
- frame rate 10 kHz
- spatial resolution < 100 micron

1-d SAXS detector integrating detector DQE shifter



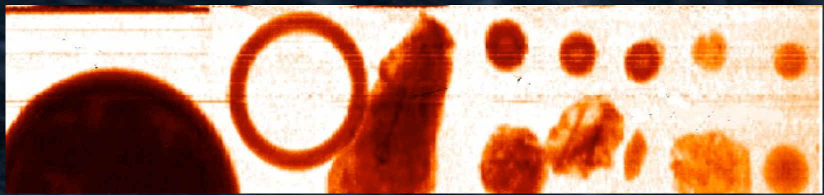
64 channel analog integrator (W Buttler)
8 gain settings
Correlated oversampling
Serial analog output
400 e^- noise (1 photon @ 8keV / integration time)

Mode of operation

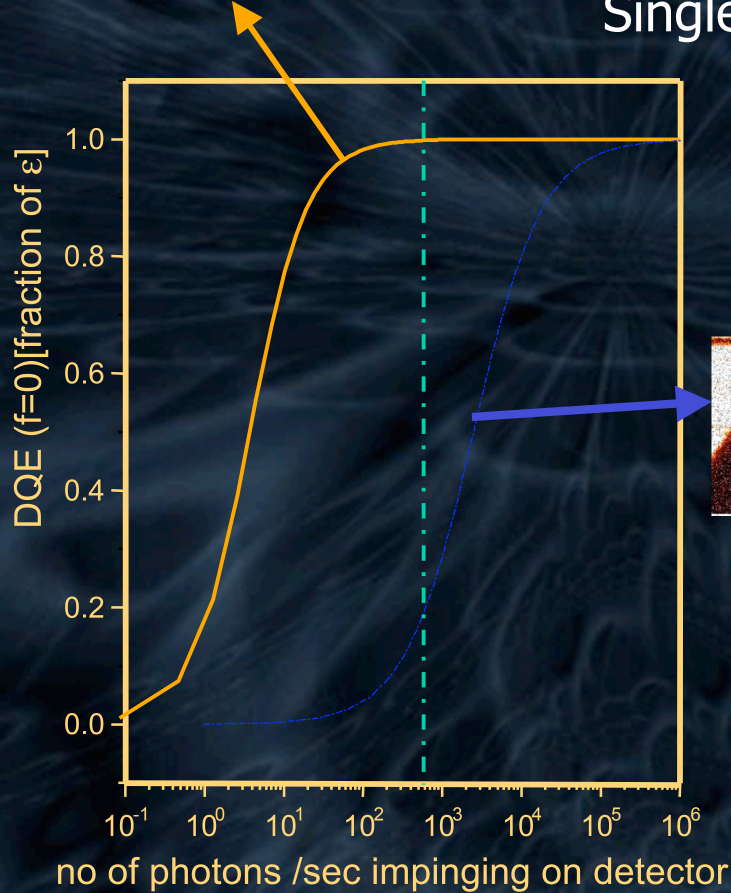
- ionization chamber mode (I_0 calibration)
- with gas gain single photon detection

1-d integrating detector DQE shifter

Mammographic phantom
E_γ = 17 keV, entrance dose xx mGy

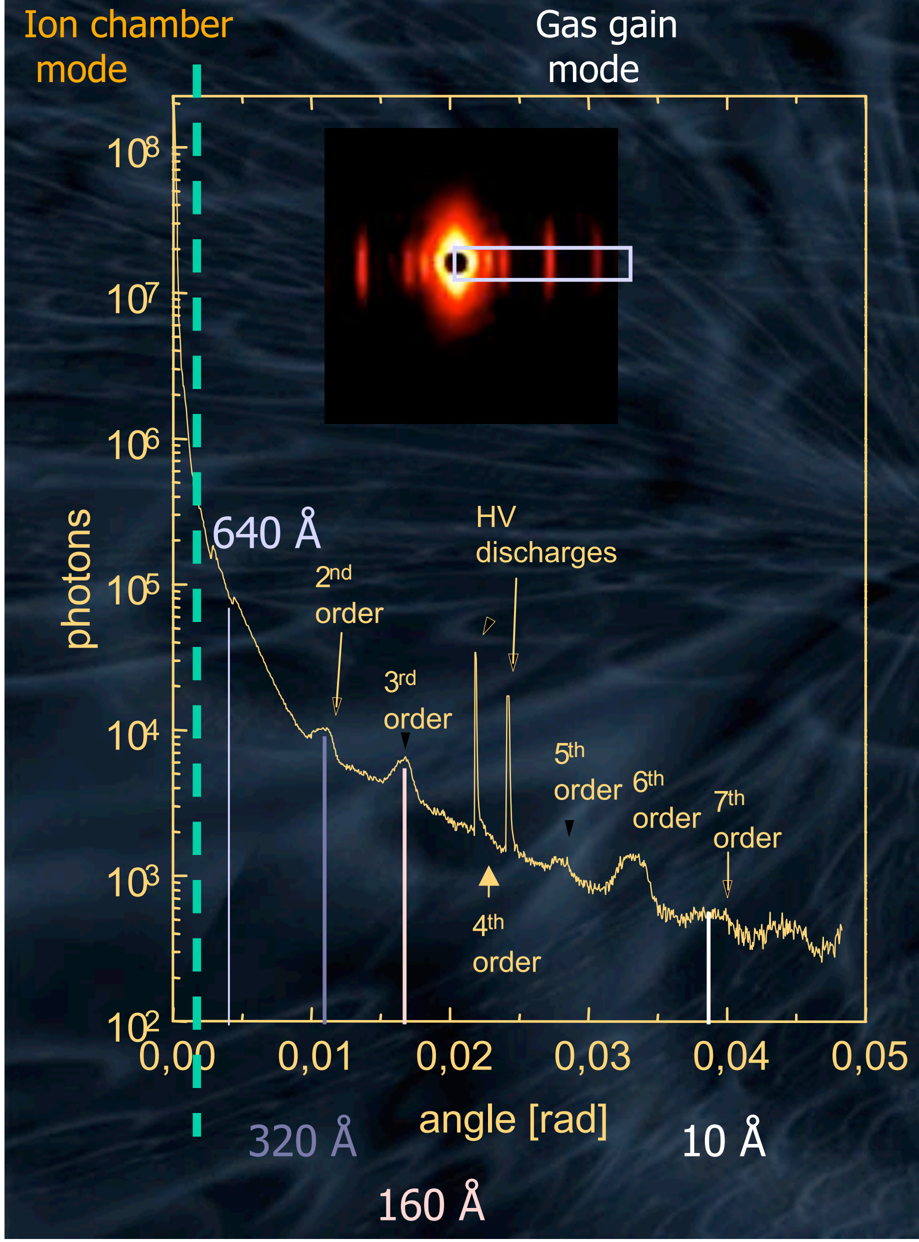


Integrating with gas gain
Single photon resolution

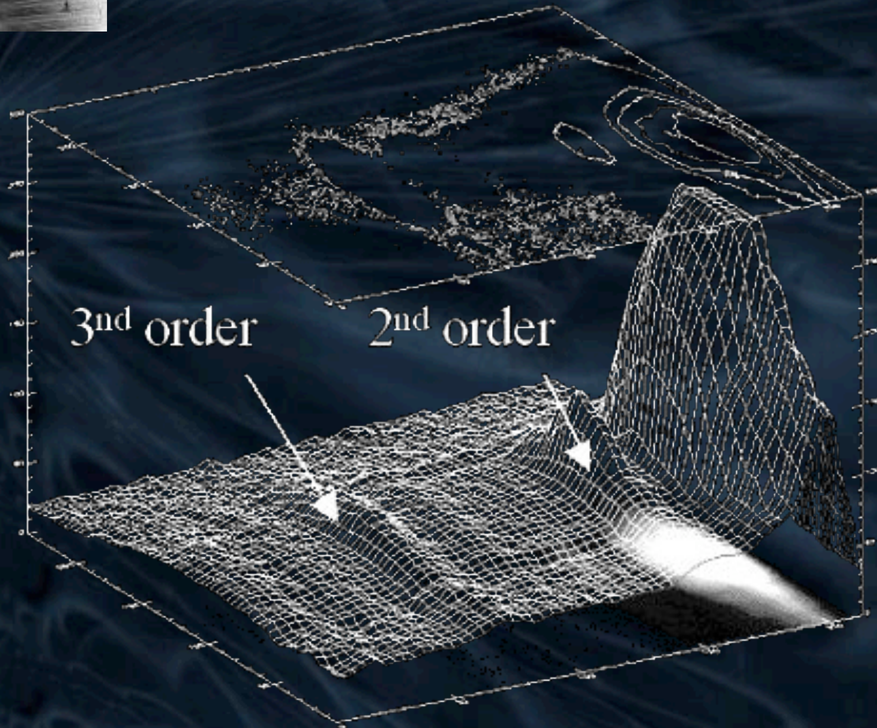


Ionization chamber mode

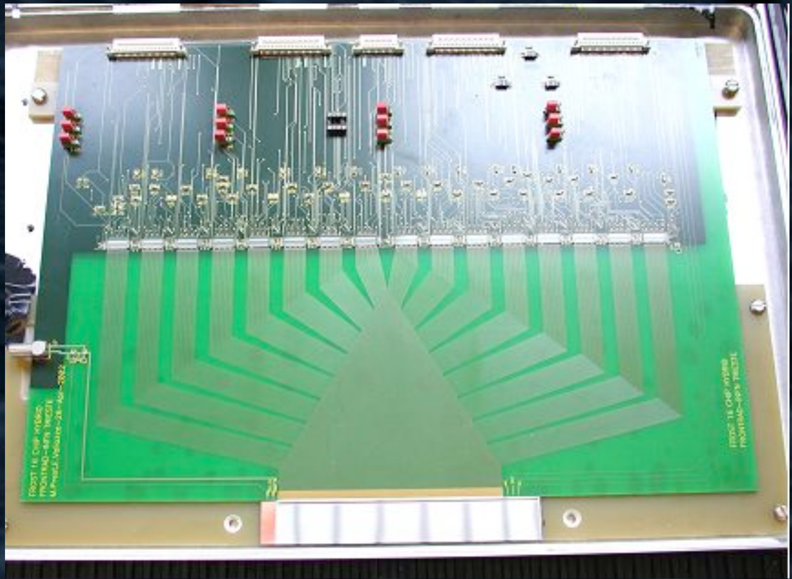
DQE shifter in SAXS

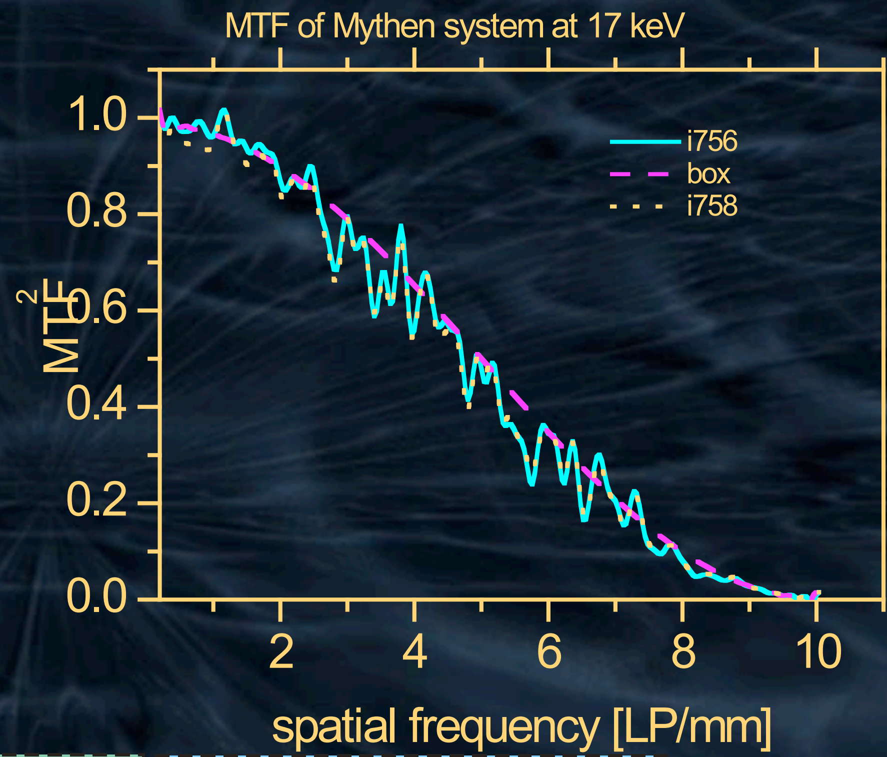


Rat tail collagen
Calibration standard

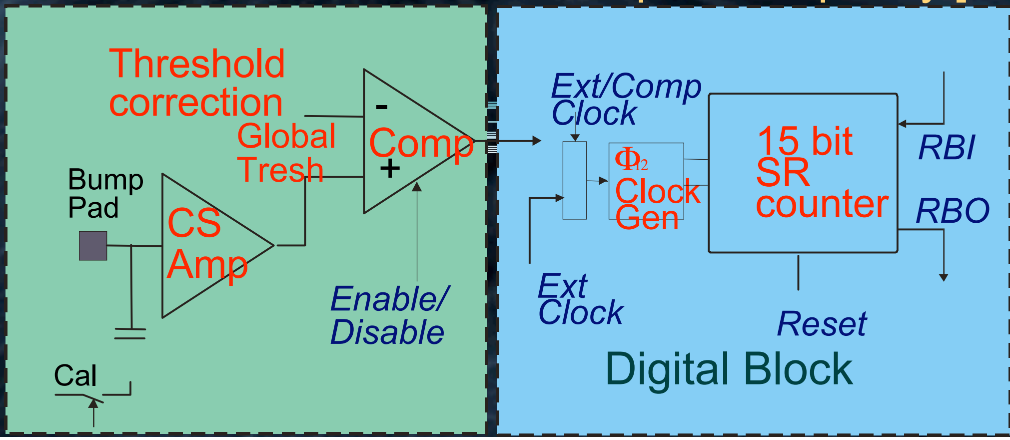


DQE Matisse coupled to Mythen
Single photon counting

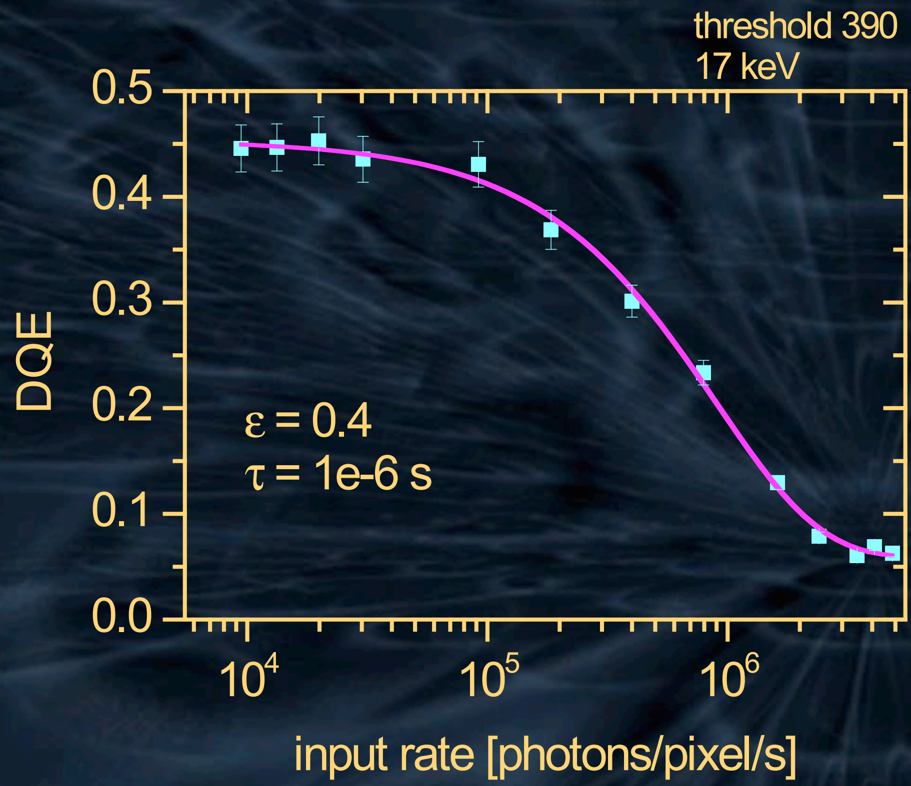




50 μm strip size
Edge on geometry
10 cm FOV

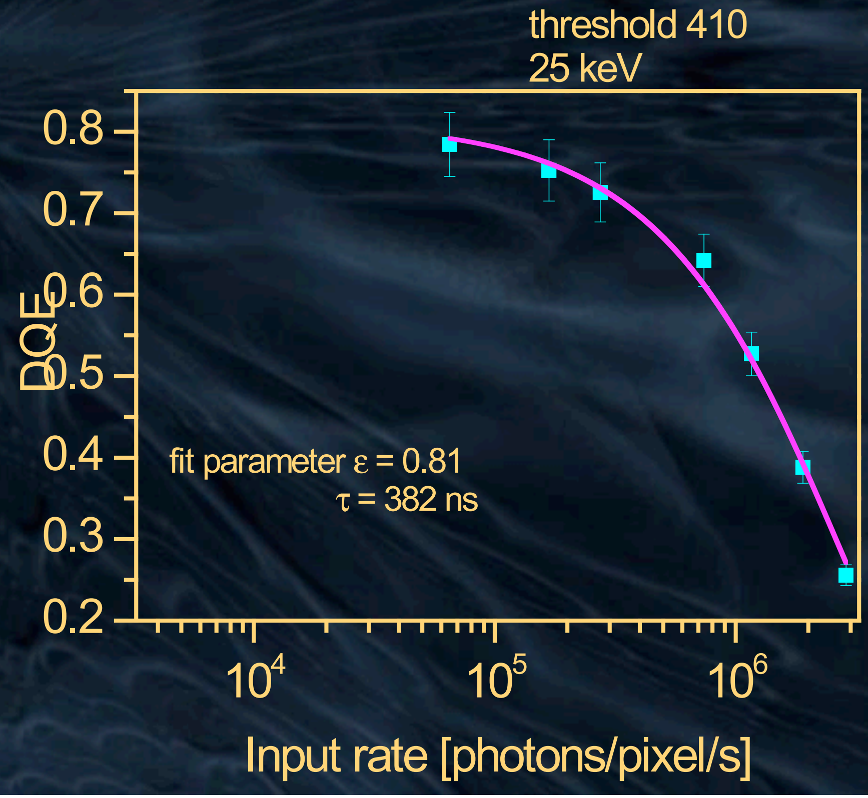


DQE Matisse coupled to Mythen



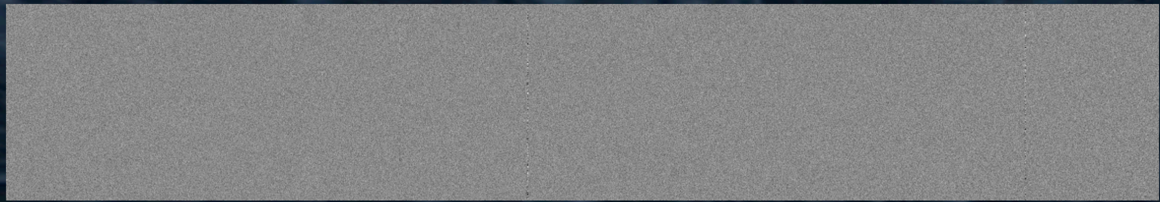
$$DQE(f=0)=\varepsilon \cdot e^{-n \cdot \tau}$$

DQE for paralyzed SPC



Imaging Matisse coupled to Mythen

Flat fields



9 kHz
Stochastic noise

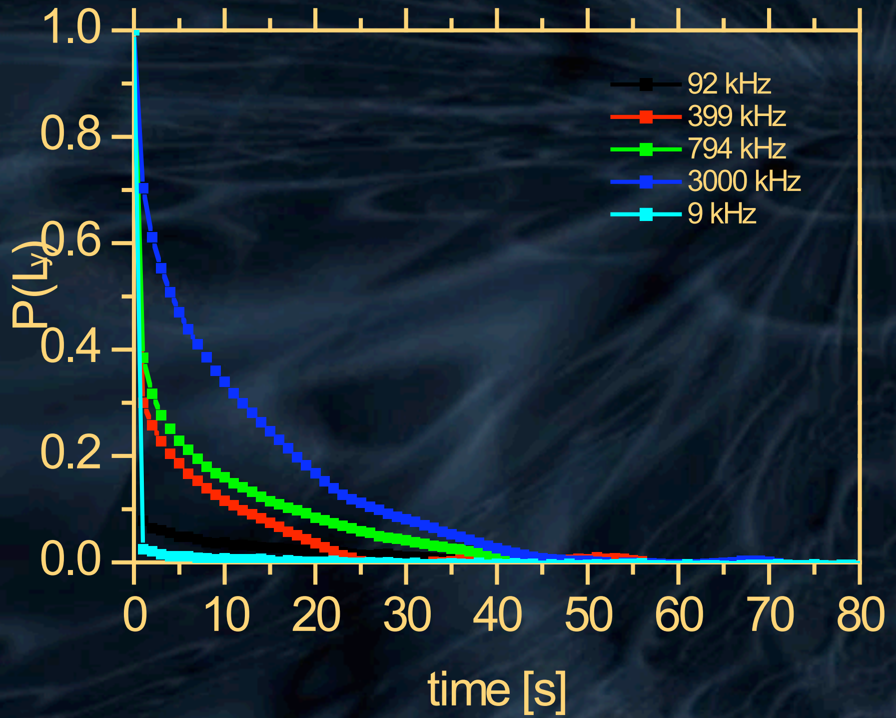
2.8 MHz
Non- stochastic noise

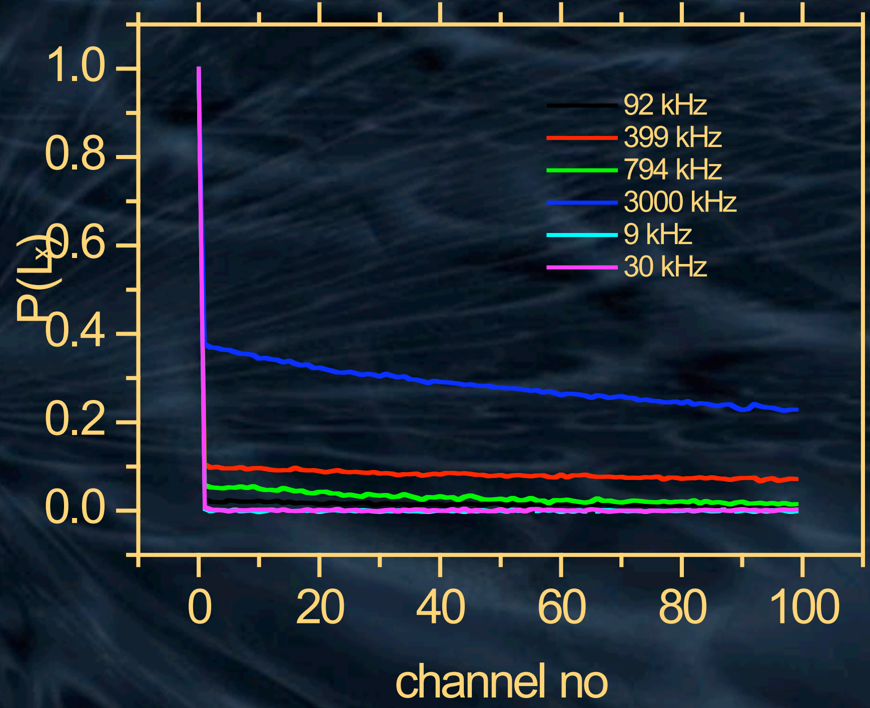
Fixed pattern = > Correlation / autocorrelation

$$P_x(L) = \frac{\sum_{k=0}^{N-L-1} \left(x_k - \bar{x}\right) \cdot \left(x_{k+L} - \bar{x}\right)}{\sum_{k=0}^{N-1} \left(x_k - \bar{x}\right)^2}$$

Imaging Matisse coupled to Mythen

$$P_x(L) = \frac{\sum_{k=0}^{N-L-1} \left(x_k - \bar{x}\right) \cdot \left(x_{k+L} - \bar{x}\right)}{\sum_{k=0}^{N-1} \left(x_k - \bar{x}\right)^2}$$





$$NPS(u,v) = \Im\left(P_{x,y}(L)\right)$$

$$DQE(u,v) = \frac{\left|MTF(u,v)\right|}{NPS(u,v)}$$

Imaging Matisse coupled to Mythen