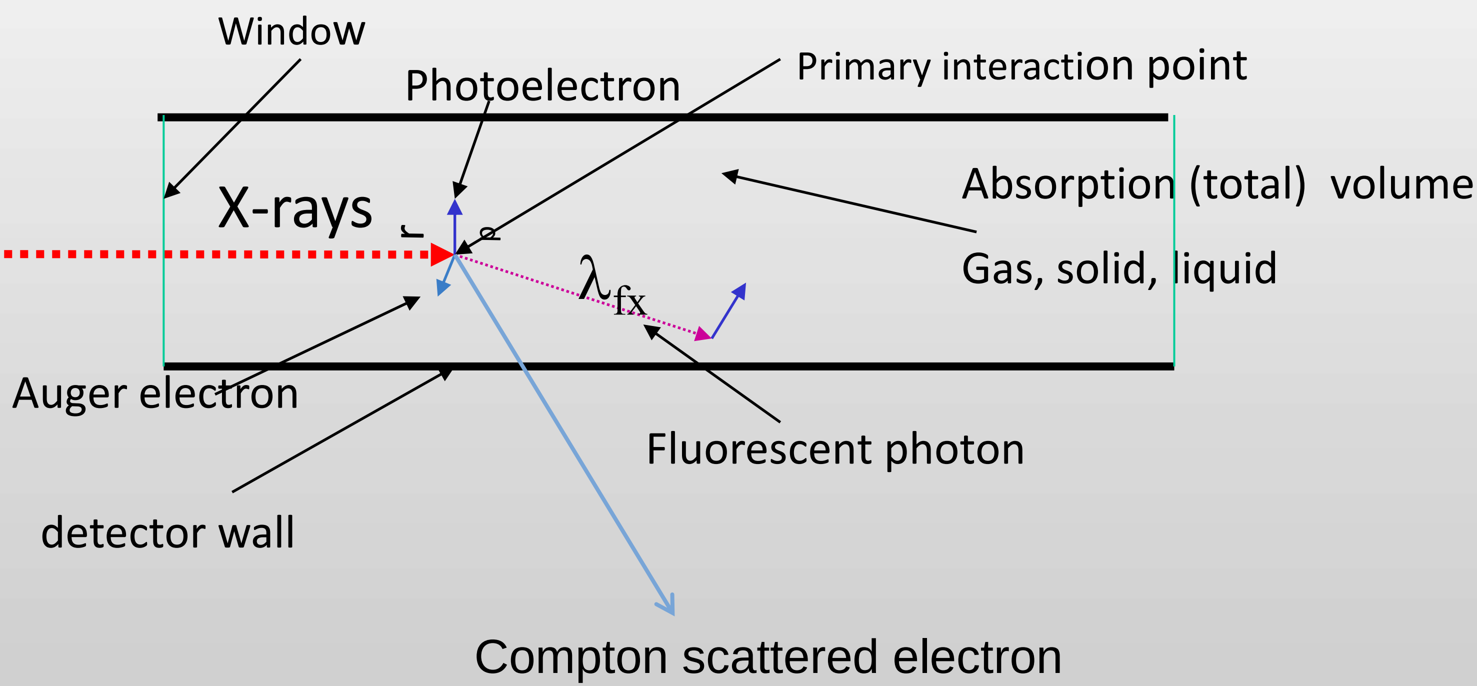
A Light for Science

ESRF

European Synchrotron Radiation Facility

Detectors at ESRF

INTERACTION X-rays – matter



Detectors at ESRF

- Effects du to X-ray absorption

Ionization

creation of charge carriers of opposite sign

Scintillation

exciting metastable states, than return to the fundamental state which is accompanied by the emission of a short flash of light

Bolometric effect

the deposited energy is transformed to heat

Braking of Cooper pairs

Detectors at ESRF

- Radiation detector can determine
  - Energy
    - Energy range, resolution
  - Event timing
    - Timing resolution,
  - Event position
    - Position resolution, point spread function
  - Event counting
    - Rate capability

Detectors at ESRF

- Detectors based on ionization
- Photoeffect

$$\delta = \text{constant x } \frac{Z^n}{E^3}$$

δ -cross section

Z – atomic number (Pb - 82, Si -14, Ge – 32)

E - energy

4<n<5

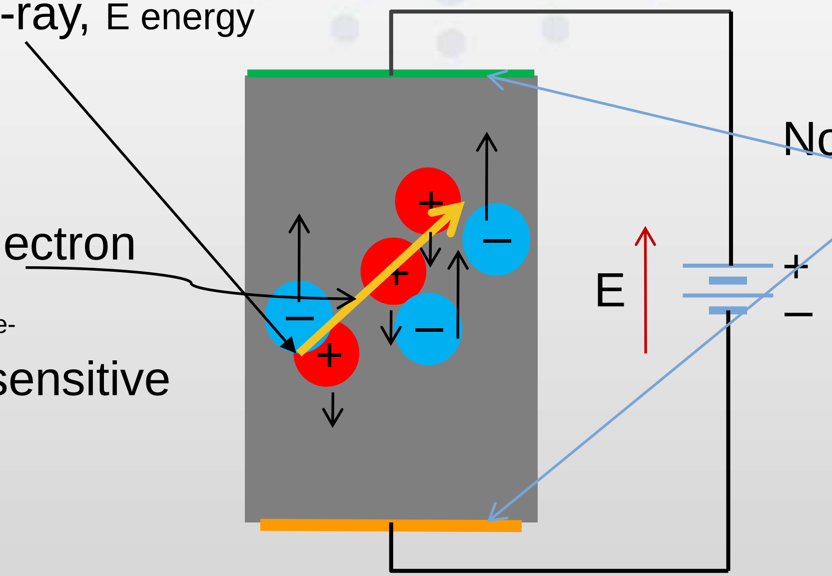
Detectors at ESRF

- **QE= quantum efficiency = fraction of incoming photons detected (<1.0).**
- **DQE= detective quantum efficiency**

$$DQE=(S/N)^2_{out}/(SN)^2_{in}<1$$

Detectors at ESRF

Ionization based detectors – general principle



+ Positive charge carrier

– Negative charge carrier

$$E_e = E - E_b$$

Detectors at ESRF

- Ionization based detectors – charge separation
- N = number of released ion pairs

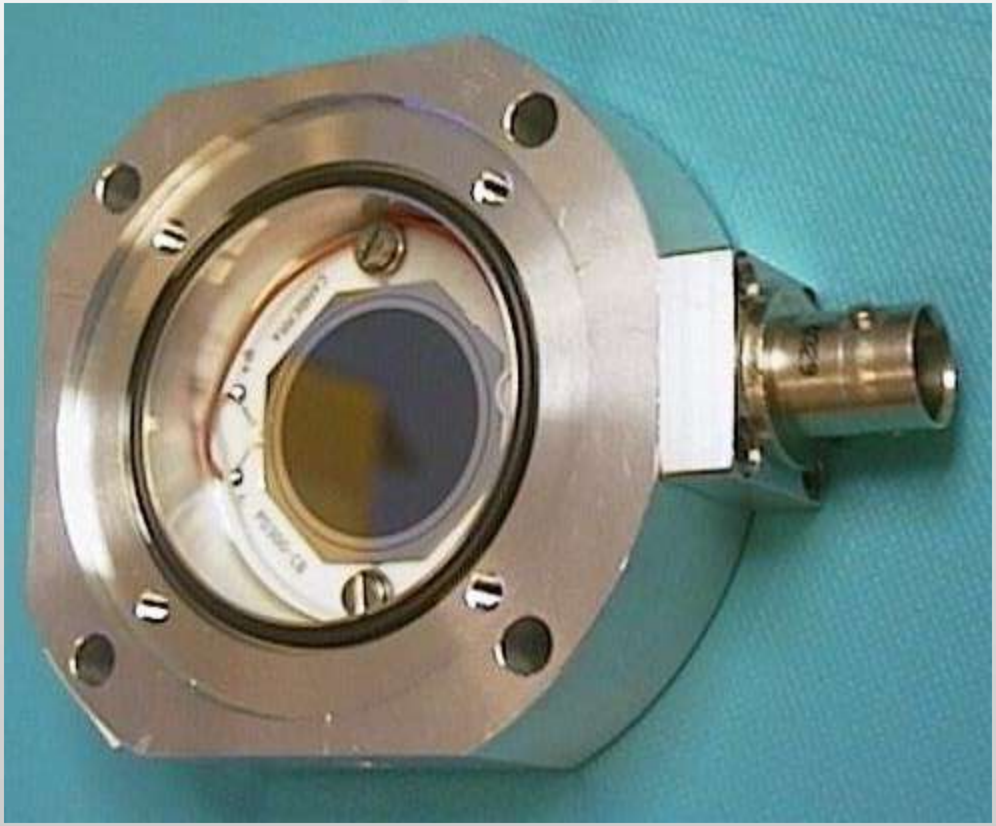
$$N=E/\varepsilon$$

$\varepsilon \approx 2.35 \times E_g$ for solids

$\varepsilon = w$ for gases (Argon 25 eV, Xenon 21.5 eV)

material	Atomic number	Band gap E_g [eV]	E [eV]	Density [g/cm3]
Si	14	1.12	3.62	2.33
Ge	32	0.67	2.96	5.33
CdTe	48,52	1.44	4.43	6.2
diamond	6	5.4	13.25	3.51

Detectors at ESRF



Detectors at ESRF

Central limit theorem

“If a large number of different fluctuations affect the measurement, than the fluctuation of the measured value will be described by Gaussian distribution”

$$\mathbf{FWHM^2}_{\textit{measured}} = \mathbf{FWHM^2}_{\textit{statistical}} + \mathbf{FWHM^2}_{\textit{electronics noise}} + \mathbf{FWHM^2}_{\textit{other}}$$

Detectors at ESRF

Energy resolution

Charge carrier production is a Poissonian process

$N=E/\varepsilon$

Standard deviation of N = $\pm\sqrt{N}$

Energy resolution = $\delta E/E = \sqrt{N}/N = 1/\sqrt{N} = \sqrt{\varepsilon/E}$

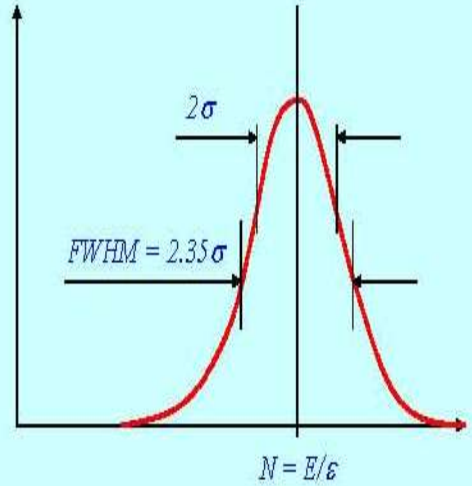
Full **W**idth at **H**alf **M**aximun- FWHM = $2.35 \times \delta E$

Real world: $\delta E/E = \sqrt{N}/N \leq 1/\sqrt{N} = \sqrt{F/N}$ correlated statistics F Fano factor - empirical correction . Gas ion chambers F~0.1, Si~ 0.12 !!

Detectors at ESRF

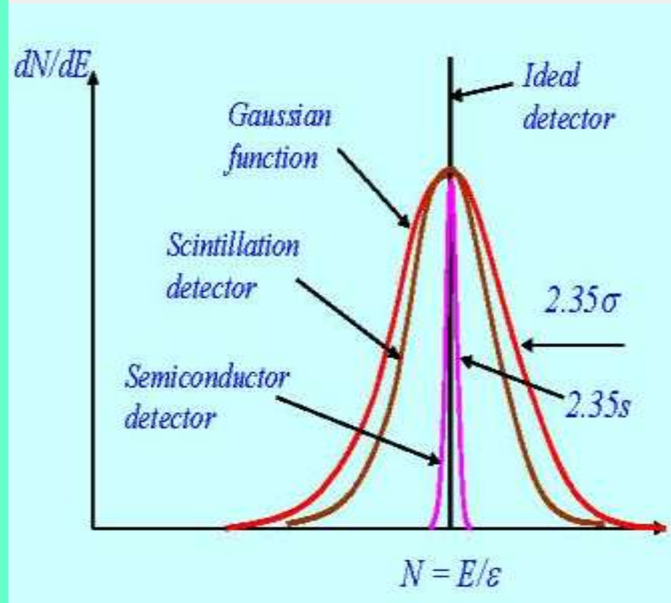
Energy resolution

Theoretical resolution
$\delta E/E = \sqrt{\varepsilon/E}$



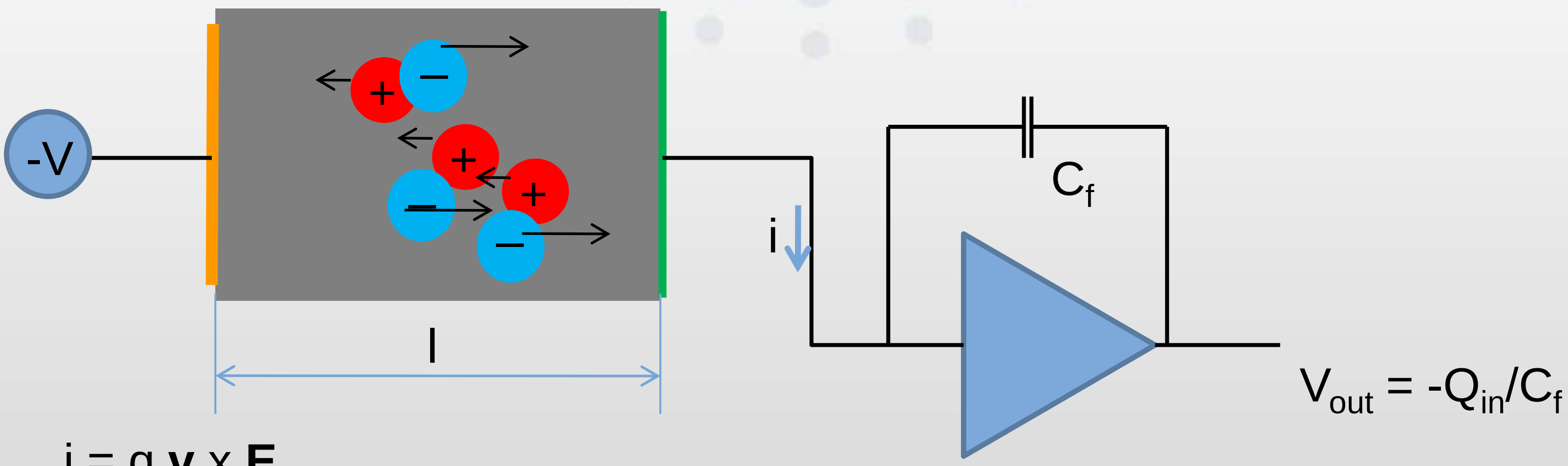
Detectors at ESRF

F- Fano factor (empirical)
E resolution = FWHM/N
= 2.35√(F/N)
F~0.1, Si~ 0.12
F~1 NaI(Tl)



Detectors at ESRF

Ionization based detectors – signal creation



$i = q\,\mathbf{v} \times \mathbf{E}$

$Q_{in} = \int_0^t i\,dt = Nq_e = N \times 1.6 \times 10^{-19} C$

$t = l / v$

Example: E = 10 keV, Si, Cf = 1 pF
$Q = 10^4 / 3.62 \times 1.6 \times 10^{-19} C = 0.44 pC$
Vout = -0.44pC/1pF = 0.442 mV

Detectors at ESRF

Noise in electronic circuits

Thermal noise → V^2_{noise} **(rms)= $4k_bTR\Delta f$**

Shot noise → Statistical fluctuation of the electric current

Flicker noise → **1/f** noise

Burst noise

Avalanche noise

Reset noise a capacitors → $Q^2_n = k_bTC$

1kΩ ~ 4.07nV/√Hz

1fF ~ 12.5 e^-

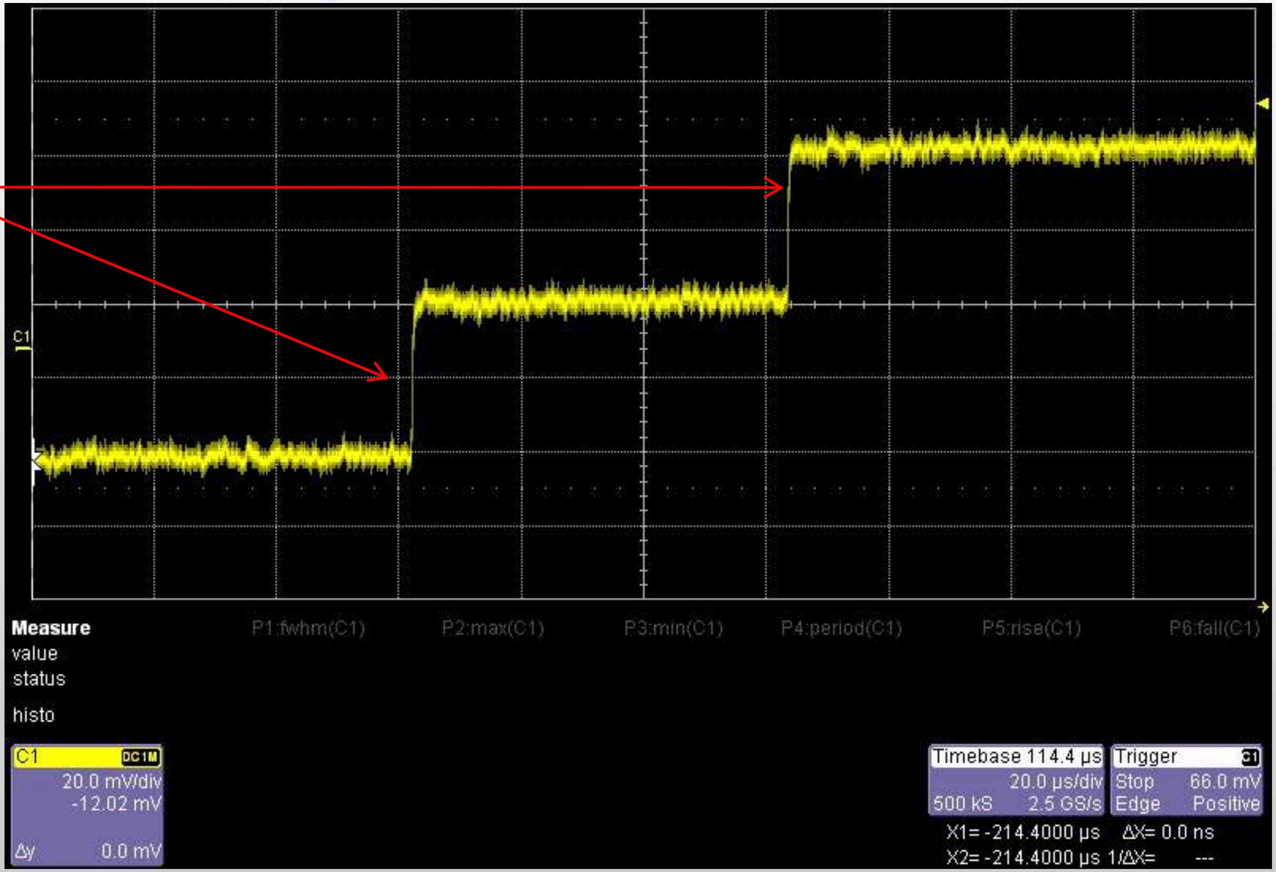
1pF ~ 400 e^-

1nF ~ 12500 e^-

Detectors at ESRF

Ionization based detectors – signal from PA

Ge detector
Step due to 5.9 keV photons

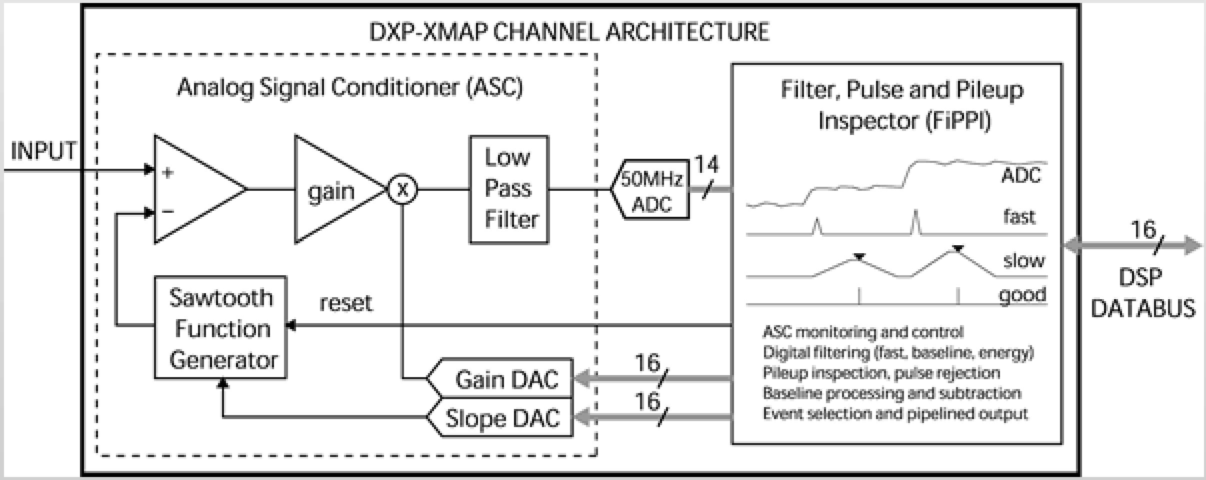


Reset of PA after 10V/20mV=500 (!) photons

Detectors at ESRF

Detectors at ESRF

XIA DAQ channel



Detectors at ESRF

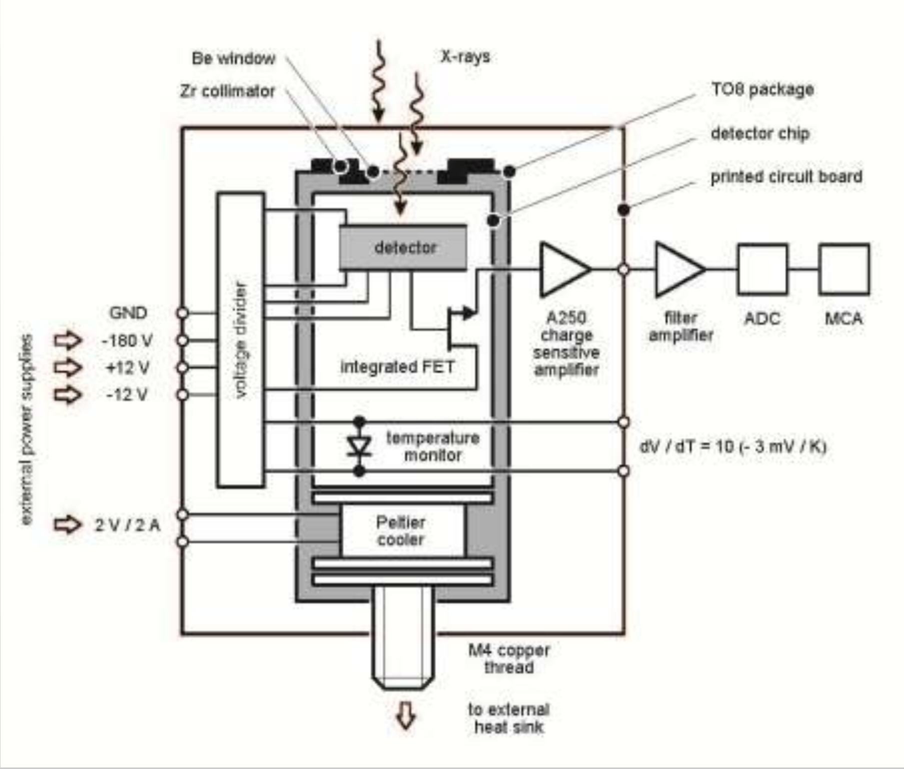
XIA

Single PXI/CompactPCI module contains 4 channels of pulse processing electronics with full MCA per channel.
4 MB of high-speed memory allows ample storage for timing applications such as mapping with full spectra or multiple ROI's. Memory can be read at the full PCI speed.
Peak PCI transfer rates exceed 100 MB/sec.
Peaking time range: 0.1 to 100 microsec
Maximum throughput up to 1,000,000 counts/sec/channel.
Digitization: 14 bits at 50 MHz
Low noise front end offers excellent resolution, and provides excellent performance in the soft x-ray region (150 - 1500 eV).
Operates with virtually any x-ray detector. Preamplifier type is computer controlled.
16 bit gain DAC and input offset are computer controlled.
Pileup inspection criteria are computer selectable.
Accurate ICR and livetime for precise deadtime correction and count rate linearity.
Multi-channel analysis for each channel allows optimal use of data.
Facilitates automated gain setting and calibration to simplify tuning array detectors.
External Gate allows data acquisition on all channels to be synchronized.
All runs can be synchronized between modules using the LBUS signal connecting all the modules together.

Detectors at ESRF

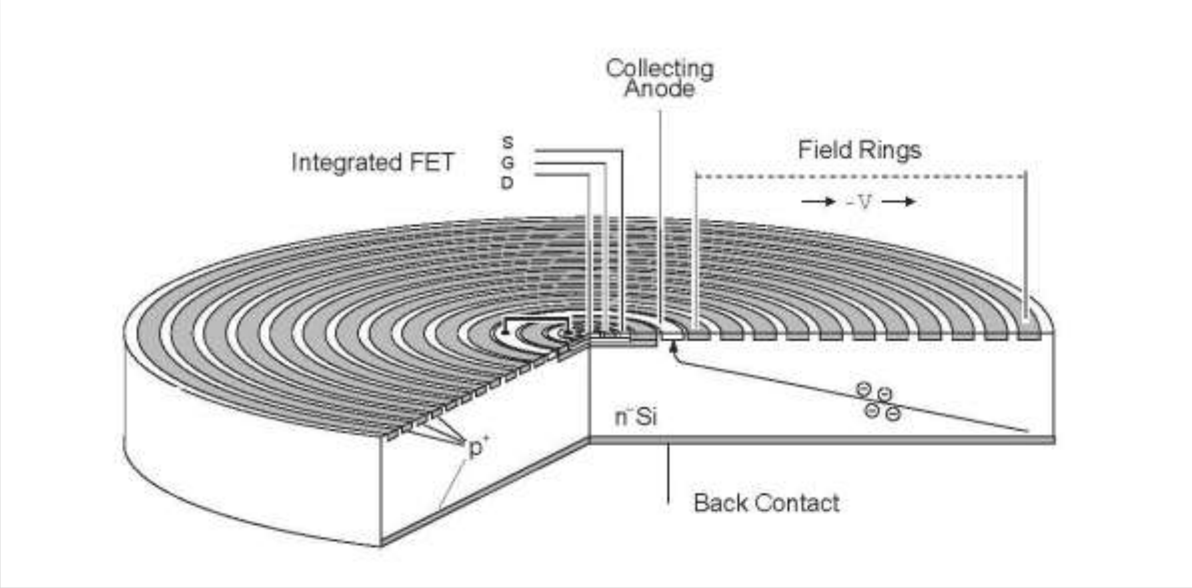
Detectors at ESRF

Silicon Drift Diode-SDD



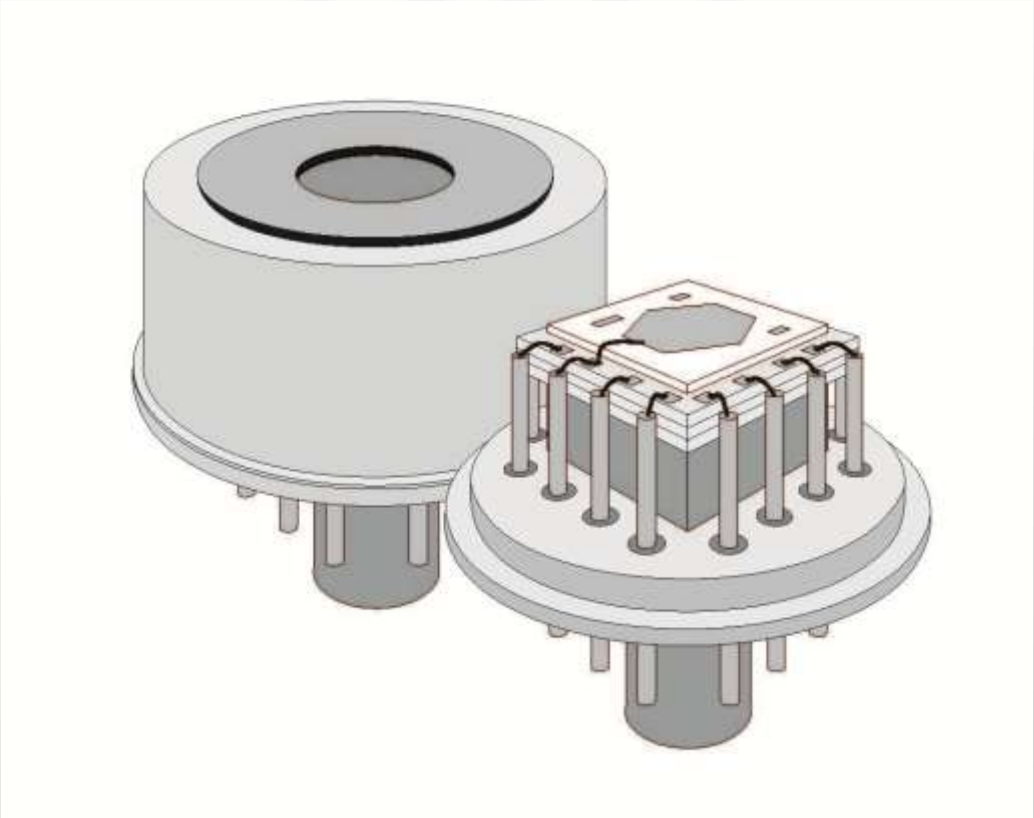
Detectors at ESRF

SDD



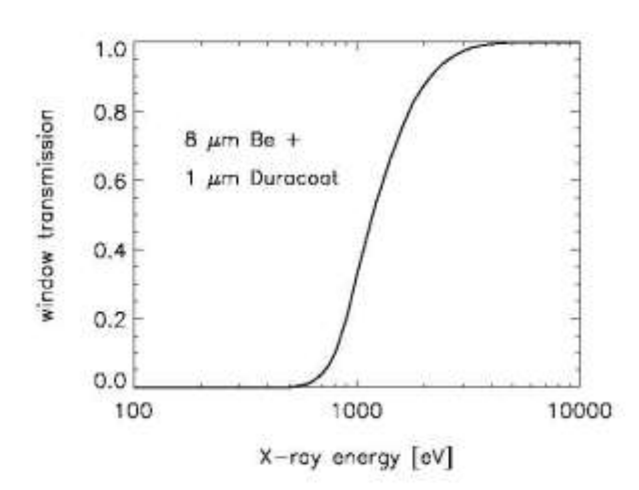
Detectors at ESRF

SDD



Detectors at ESRF

SDD



Detectors at ESRF

SDD

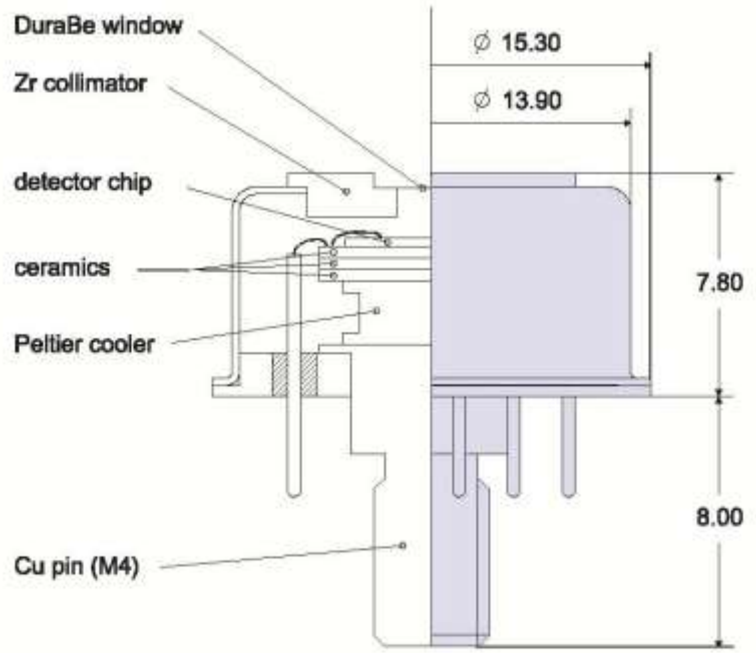
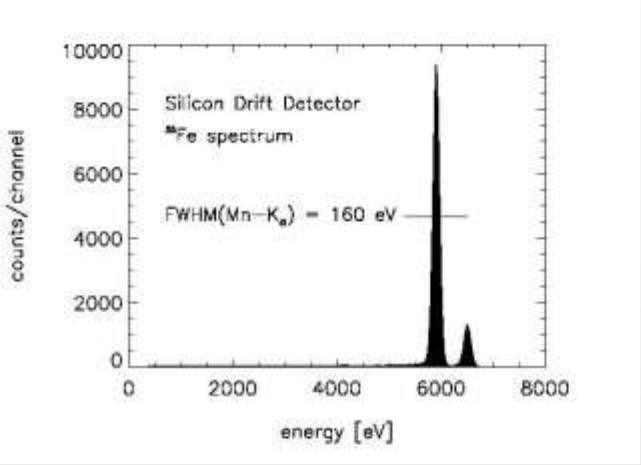


Fig. 5.
Dimensions of the TO8 detector package.

Detectors at ESRF

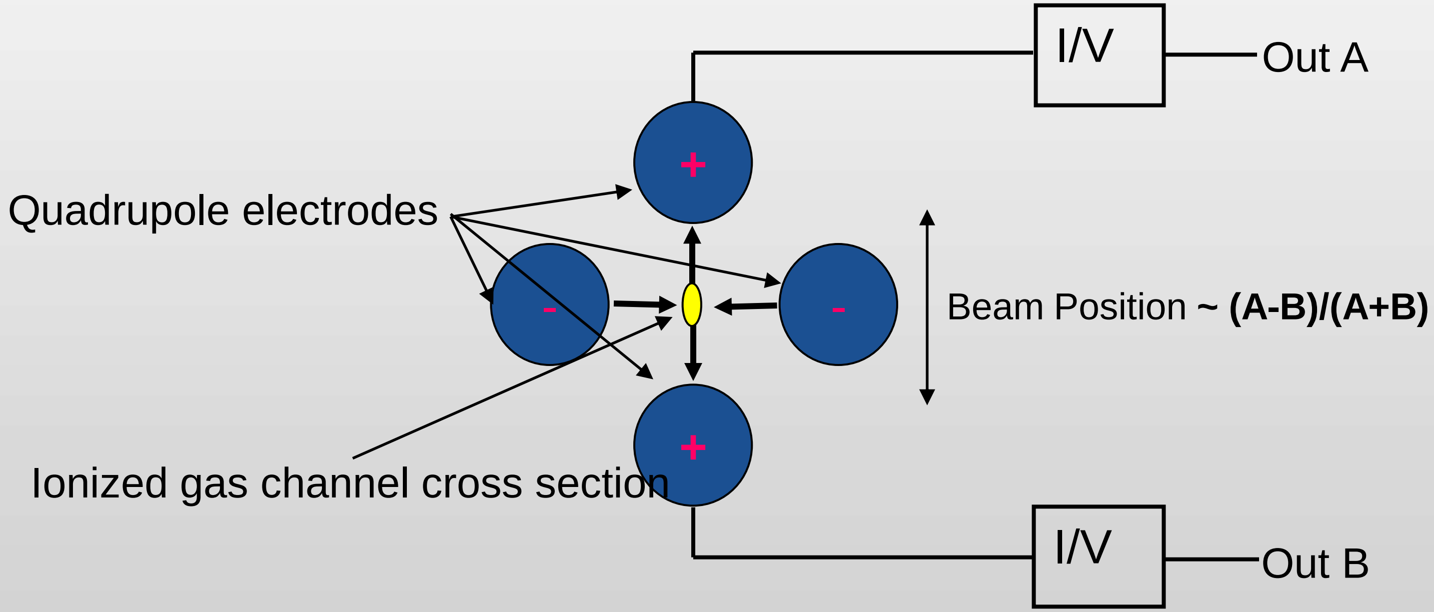


Detectors at ESRF

SDD

Detectors at ESRF

Position sensitive quadrupole ionization chamber



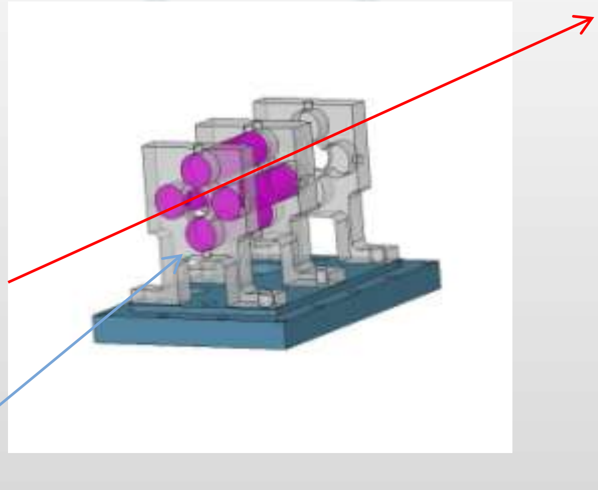
Separated electron/ion trajectories → lower recombination and space charge

Sensitive *only* to one direction

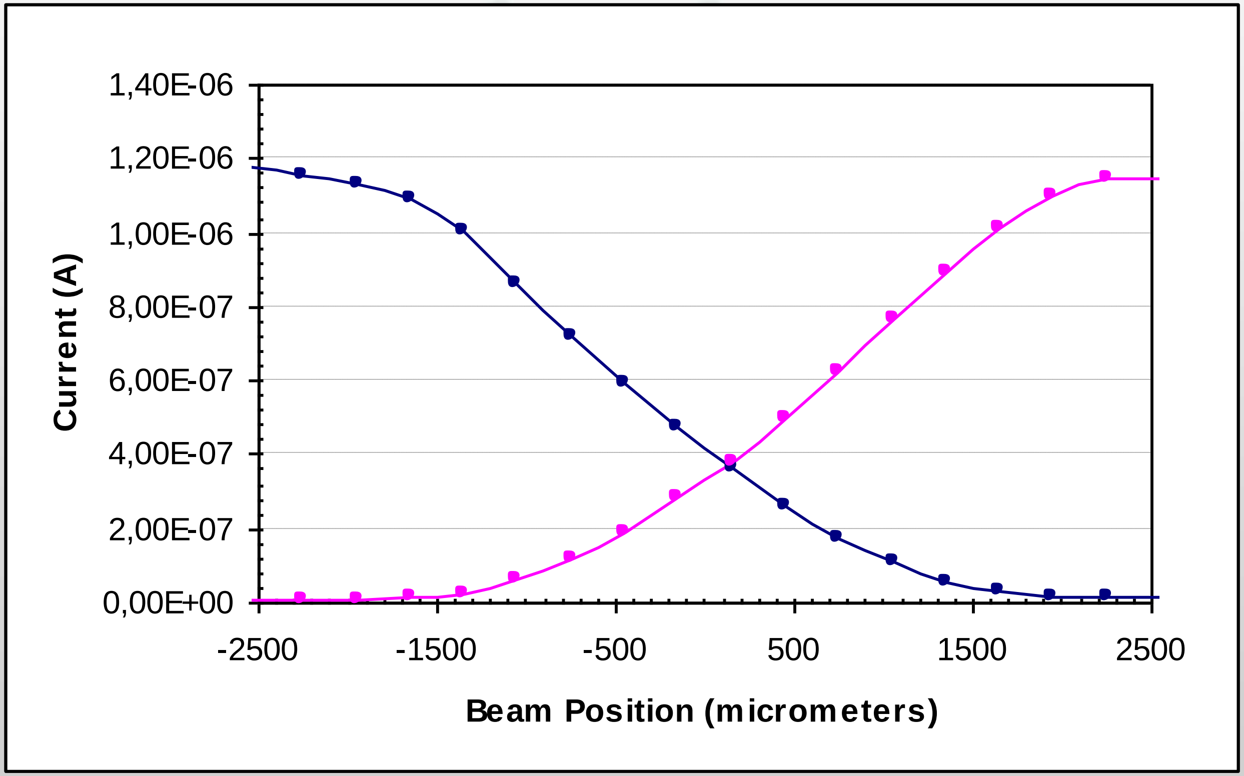
Simple and robust construction

Detectors at ESRF

QBPM

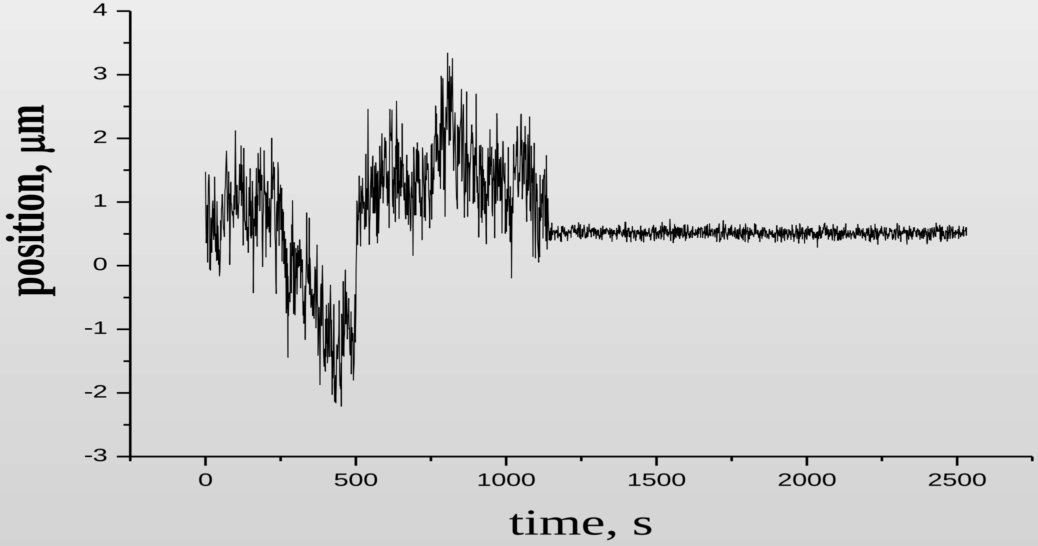


Detectors at ESRF



Detectors at ESRF

QBPM – beam stabilization



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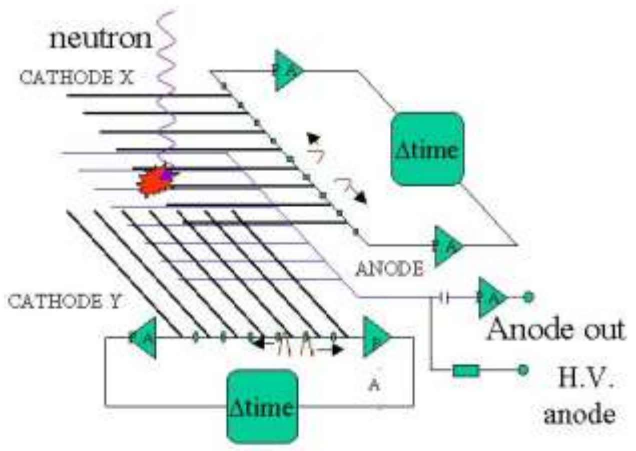
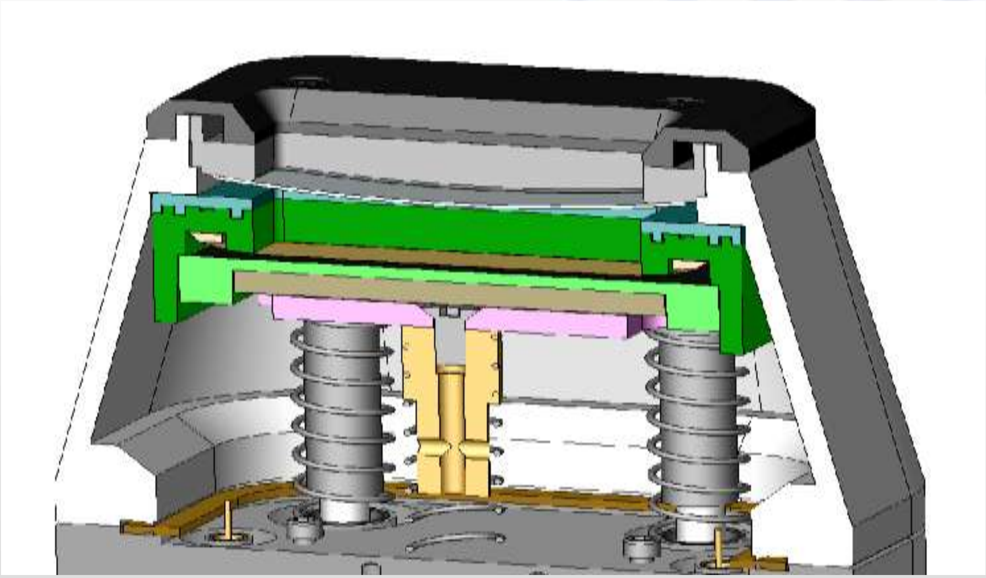


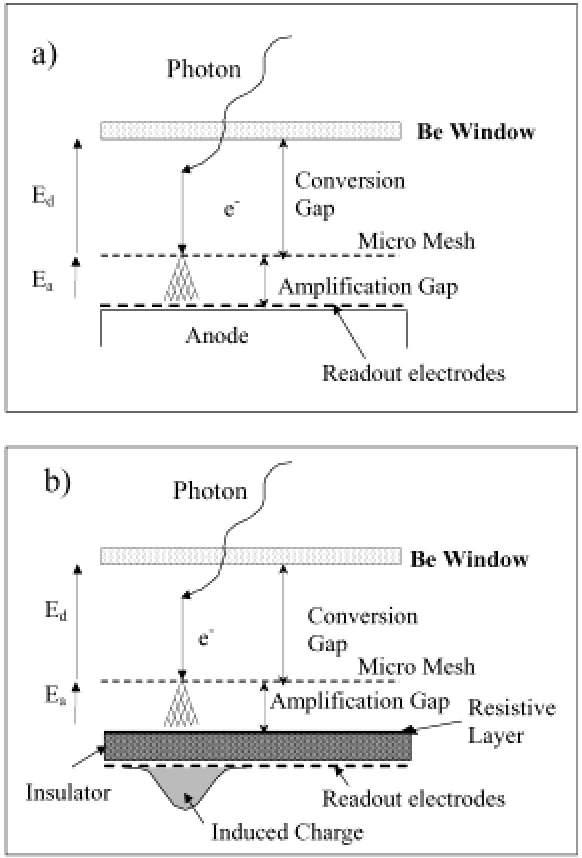
Detectors at ESRF

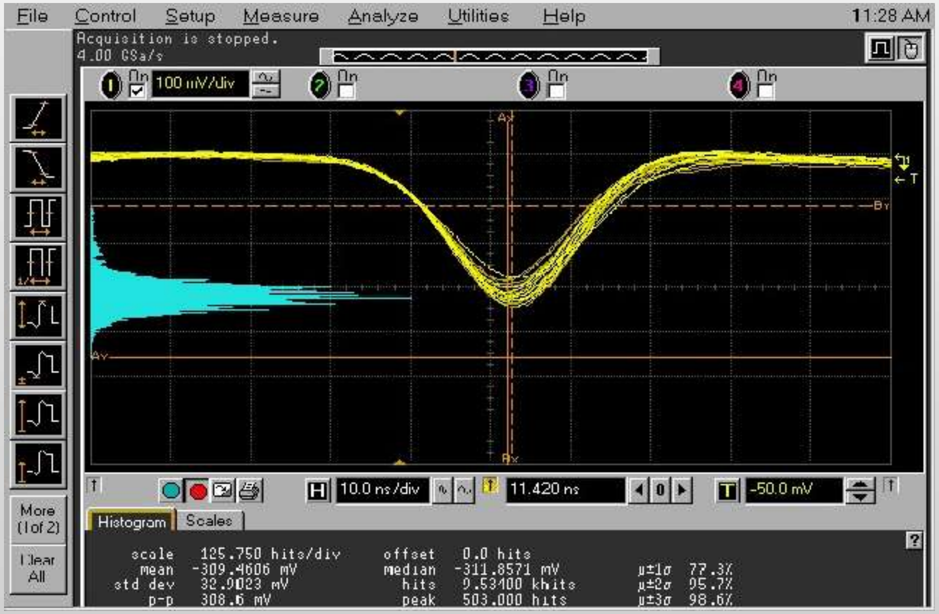
Detectors at ESRF



Radiation hard!

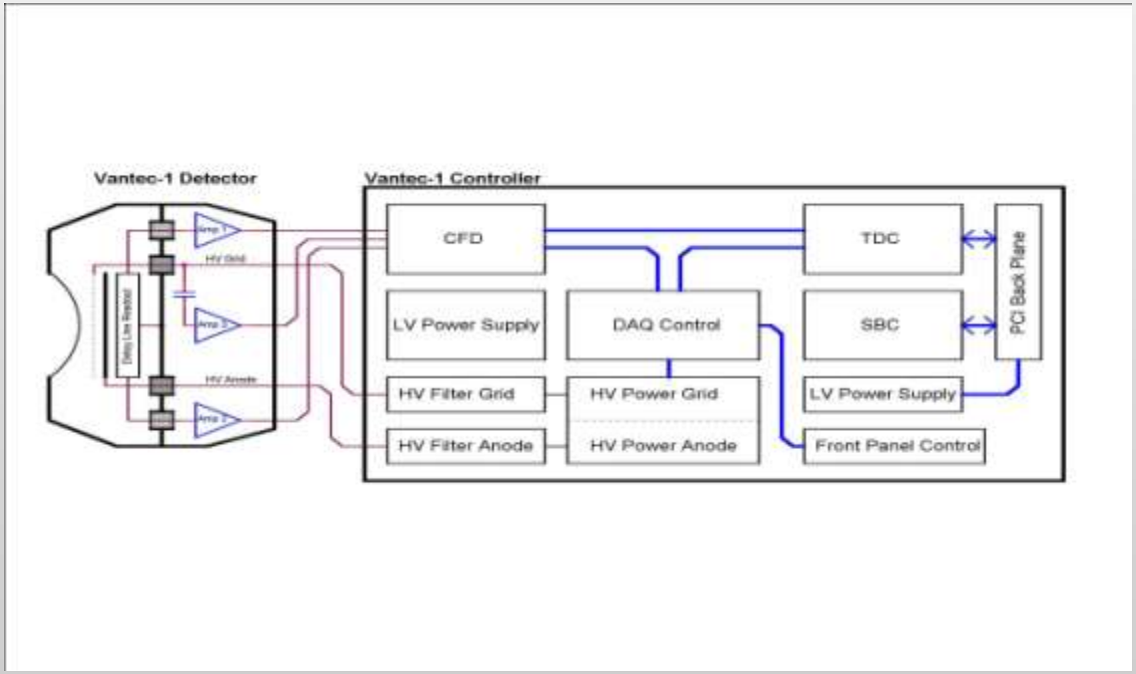
Detectors at ESRF



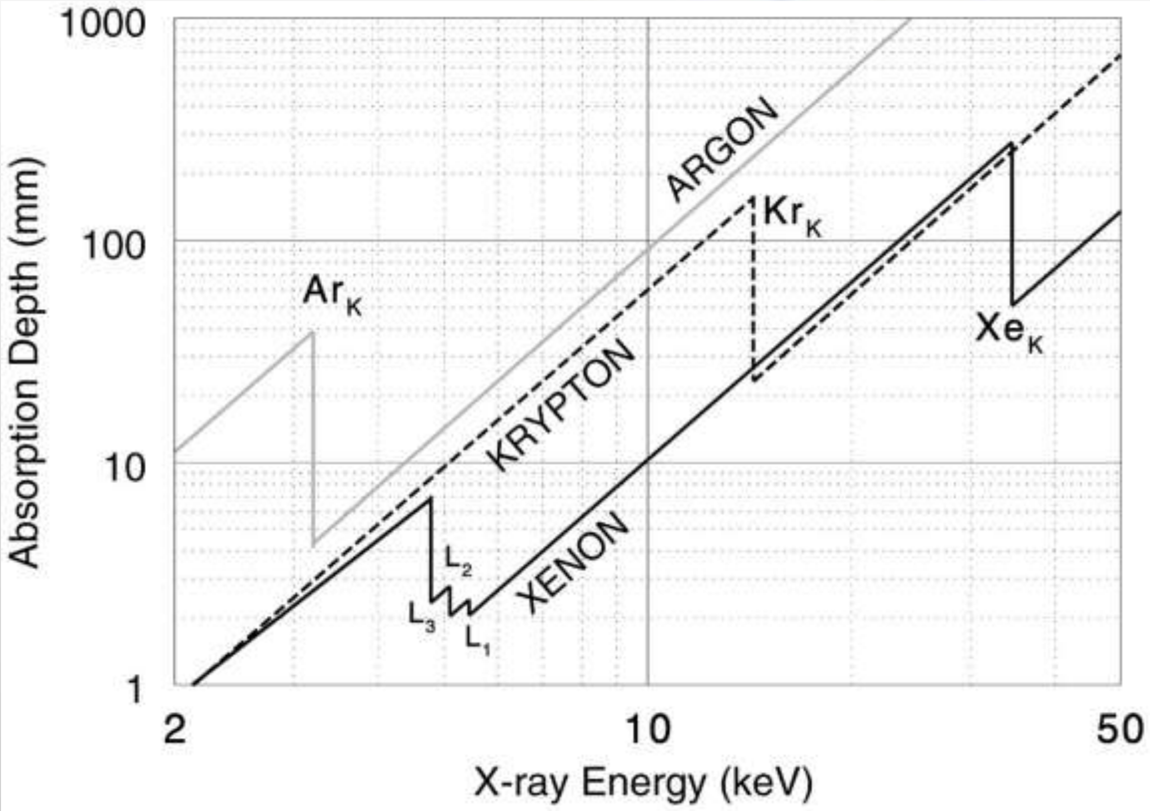


Detectors at ESRF

- Gas-filled detector

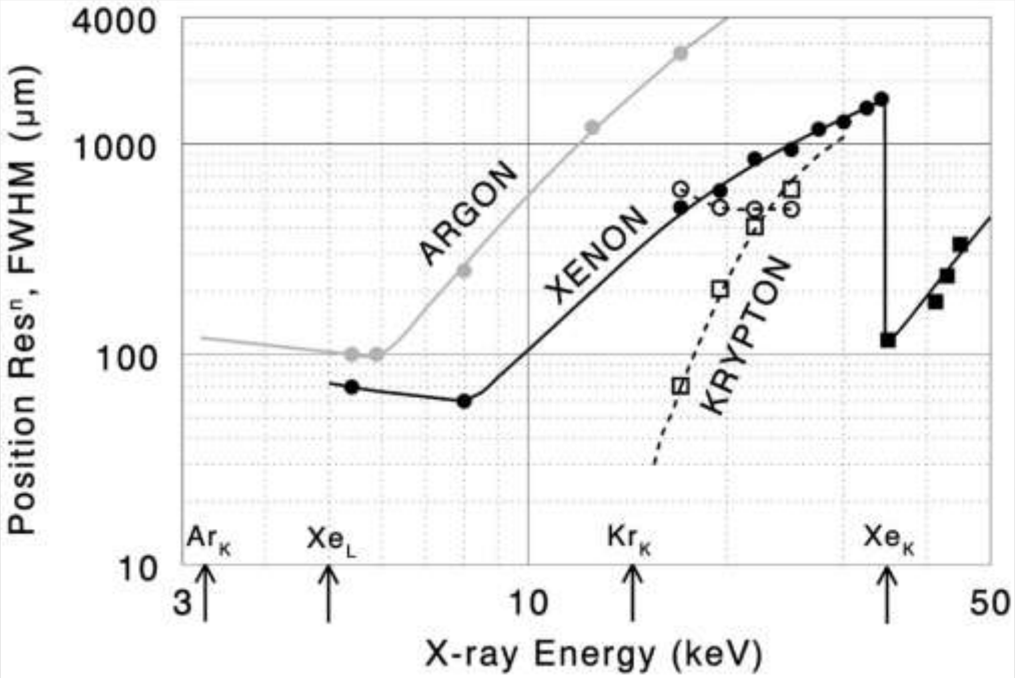


Detectors at ESRF



J. Synchrotron Rad. (2006). 13, 172–179, G. Smith

Detectors at ESRF



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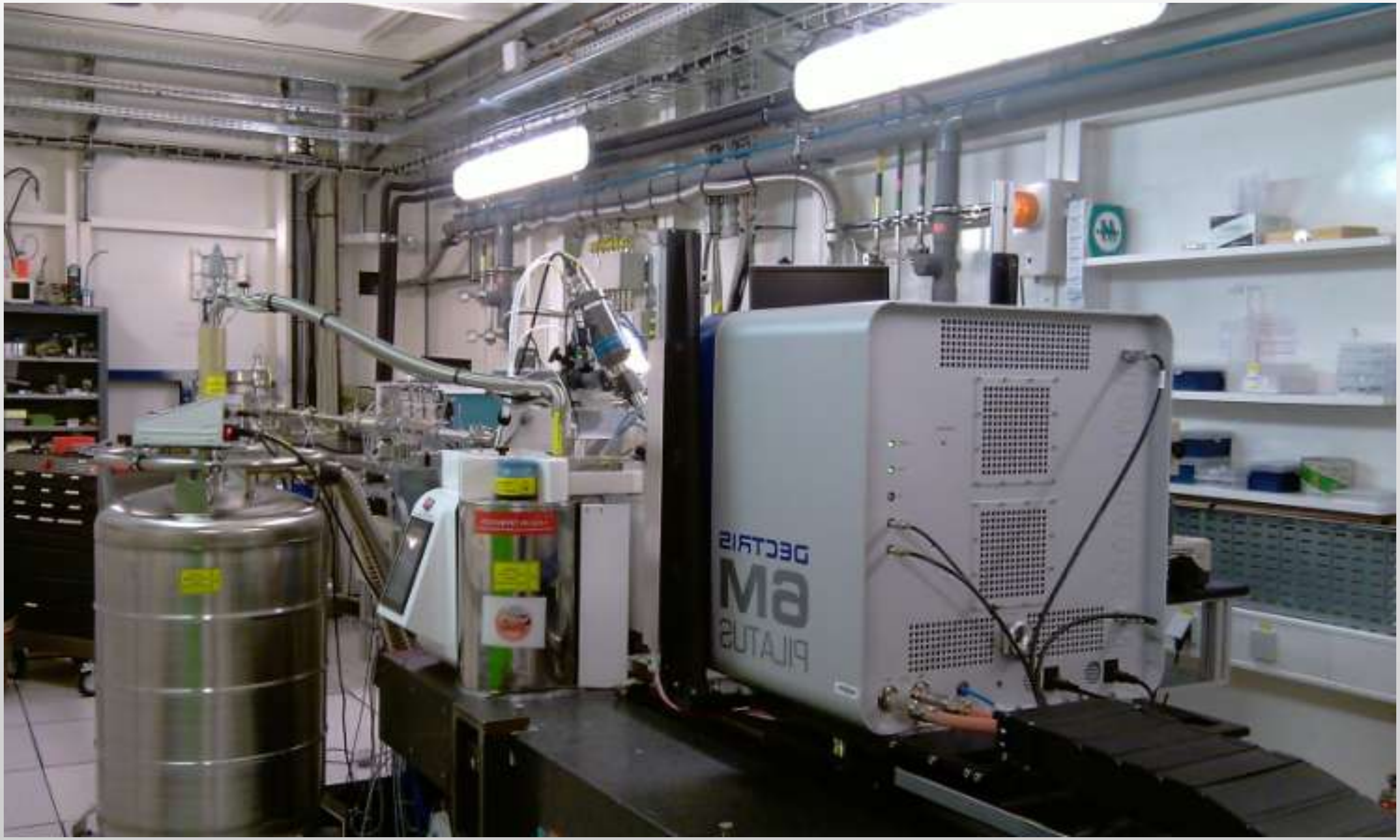
Detectors at ESRF



Detectors at ESRF

Detectors at ESRF

Detectors at ESRF

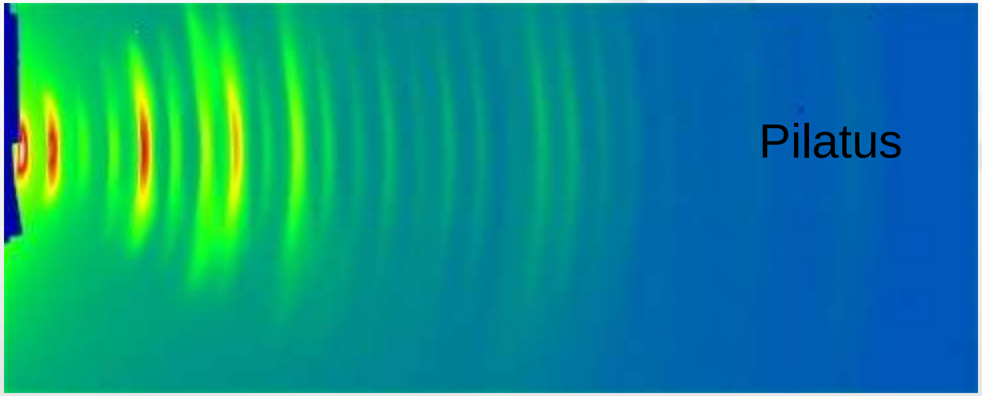
Technical specifications
Number of modules 5 × 12 = 60
Sensor Reverse-biased silicon diode array
Sensor thickness 320 µm
Pixel size 172 × 172 µm2
Format 2463 × 2527 = 6,224,001 pixels
Area 424 × 435 mm2
Intermodule gap x: 7 pixels, y: 17 pixels, 8.4 % of total area
Dynamic range 20 bits (1:1,048,576)
Counting rate per pixel > 2 × 106 X-ray/s
Energy range 3 – 30 keV
Quantum efficiency 3 keV: 80 % (calculated) 8 keV: 99 % 15 keV: 55 %
Energy resolution 500 eV
Adjustable threshold range 2 – 20 keV
Threshold dispersion 50 eV
Readout time 2.3 ms
Framing rate 12 Hz
Point-spread function 1 pixel
Data formats Raw data, TIF, EDF, CBF
External trigger/gate 5V, 3 different modes
Software interface Through socket connection; clients for EPICS, SPEC and stand-alone operation are available
Cooling Closed circuit cooling unit for temperature stabilization
Power consumption 400 W
Dimensions (WHD) 590 × 603 × 455 mm
Weight Approx. 95 kg

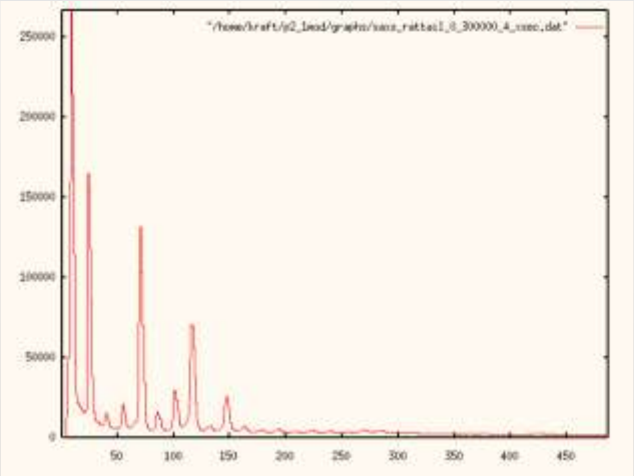
Detectors at ESRF

Pilatus 300k-W

Technical specifications
Number of modules 3 x 1
Sensor Reverse-biased silicon
diode array
Sensor thickness 320 µm
Pixel size 172 x 172 µm2
Format 1475 x 195 = 287,625 pixels
Area 254 x 33.5 mm2
Intermodule gap x: 7 pixels, 1 % of total range
Dynamic range 20 bits (1:1,048,576)
Counting rate per pixel > 2 x 106 X-ray/s
Energy range 3 – 30 keV
Quantum efficiency 3 keV: 80%
(calculated) 8 keV: 99%
15 keV: 55%
Energy resolution 500 eV
Adjustable threshold range 2 – 20 keV
Threshold dispersion 50 eV
Readout time Standard: 3.6 ms
Fast: 2.7 ms
Framing rate Standard: 100 Hz
Fast: 200 Hz
Point-spread function 1 pixel
Data formats Raw data, TIF, EDF, CBF
External trigger/gate 5V TTL, 3 different
modes
Software interface Through socket
connection;
clients for EPICS, SPEC
and stand-alone operation
are available
Cooling Air-cooled
Power consumption 50 W
Dimensions (WHD) Approx. 384 x 100 x 458
mm
Weight Approx. 12 kg

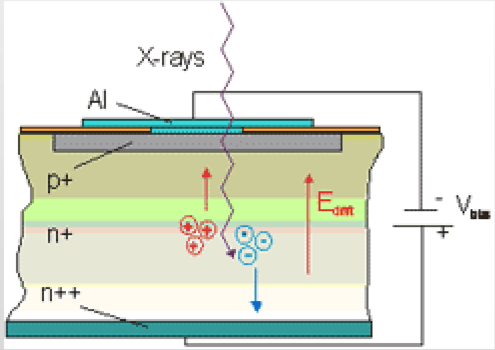
Detectors at ESRF

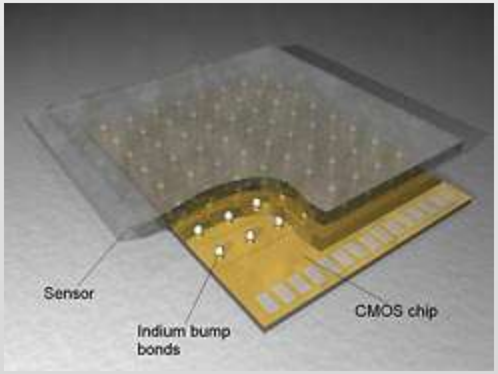


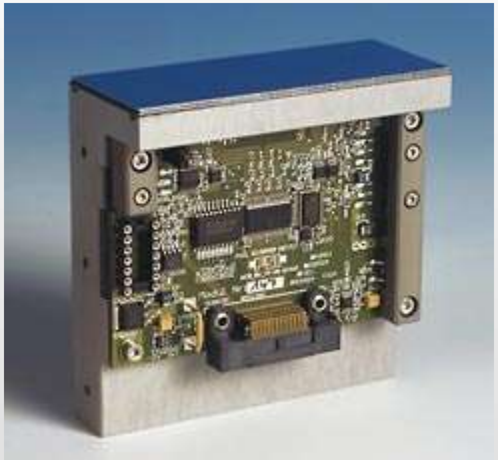


Detectors at ESRF

Pilatus – hybrid pixel detector





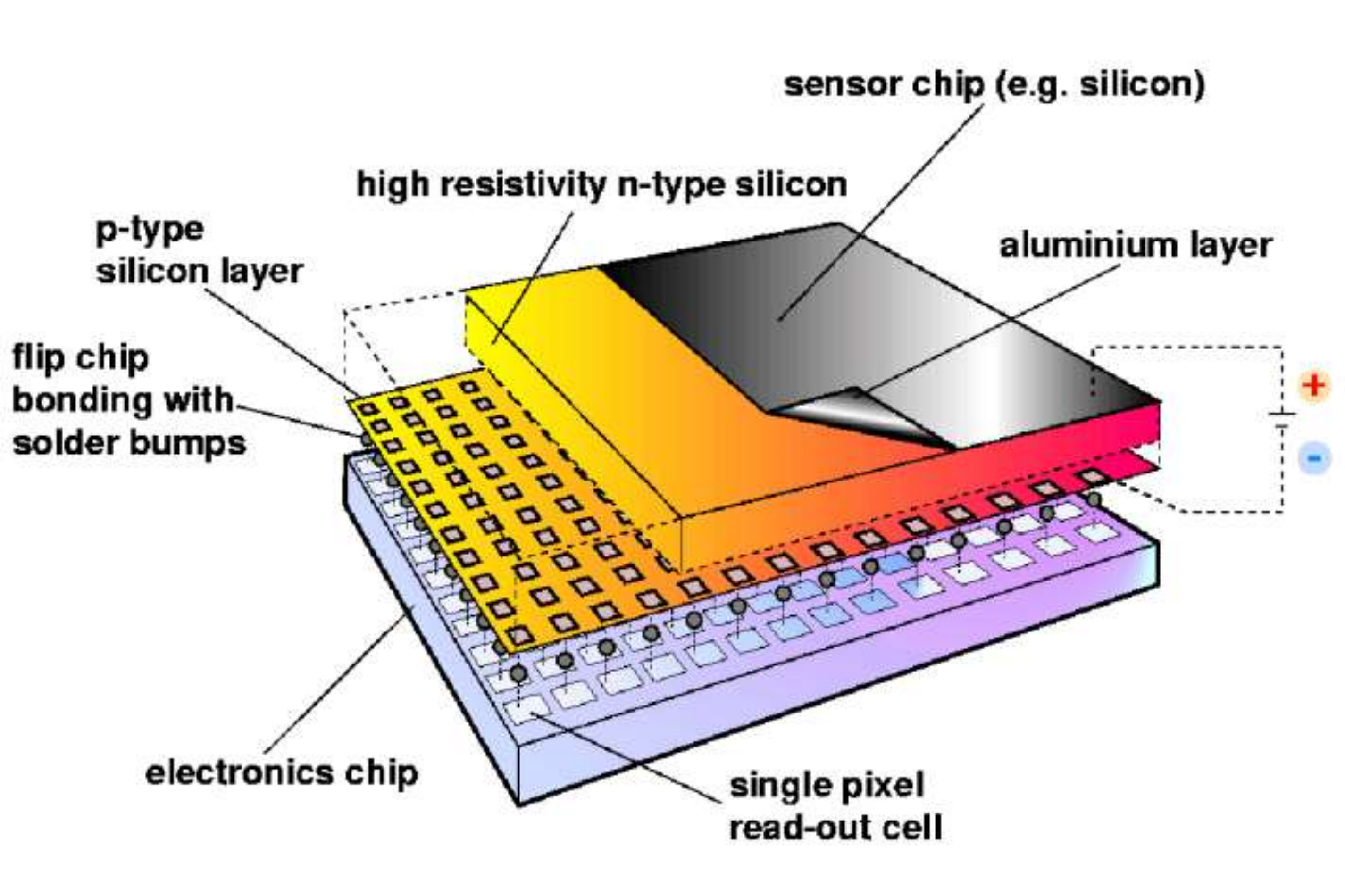


Detectors at ESRF

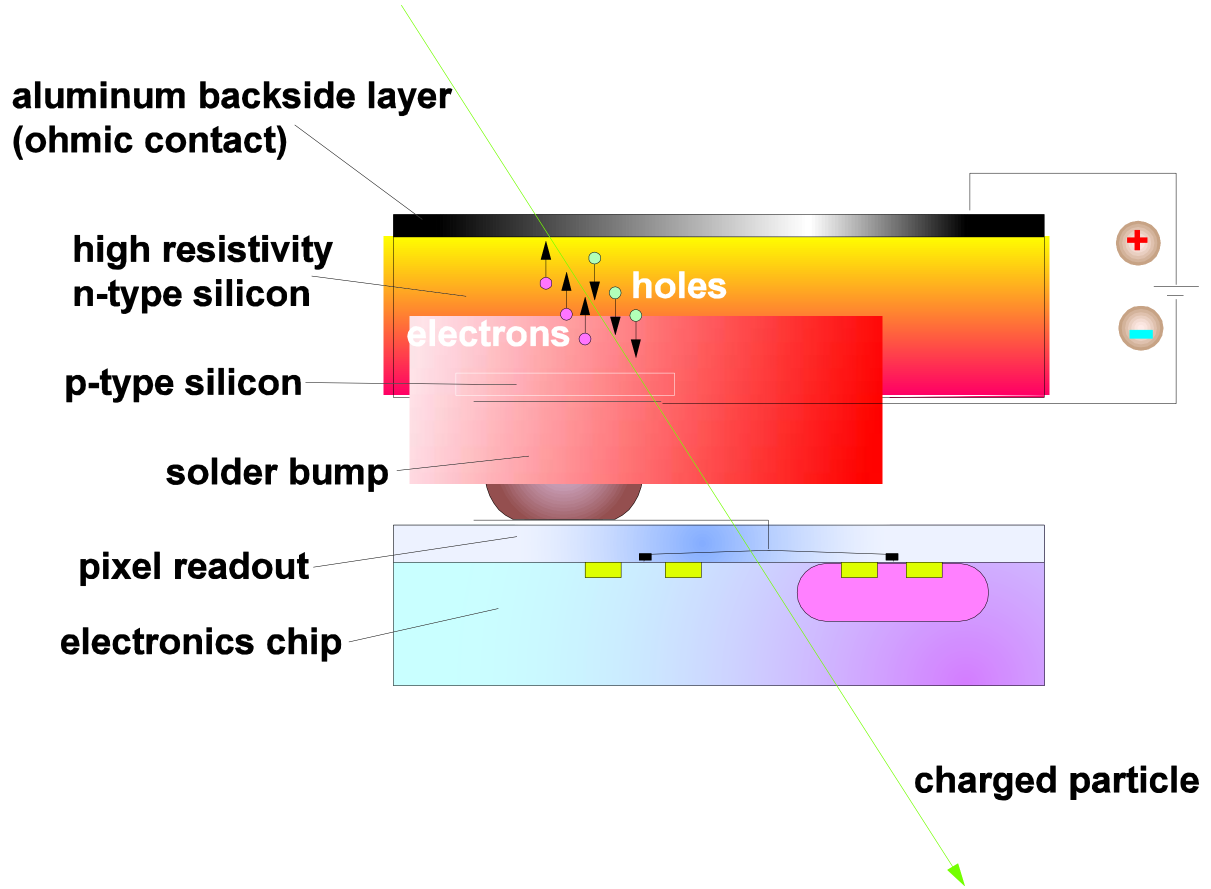
Pilatus 6M

Courtesy: Ch. Brönnimann, PSI SLS Detector Group

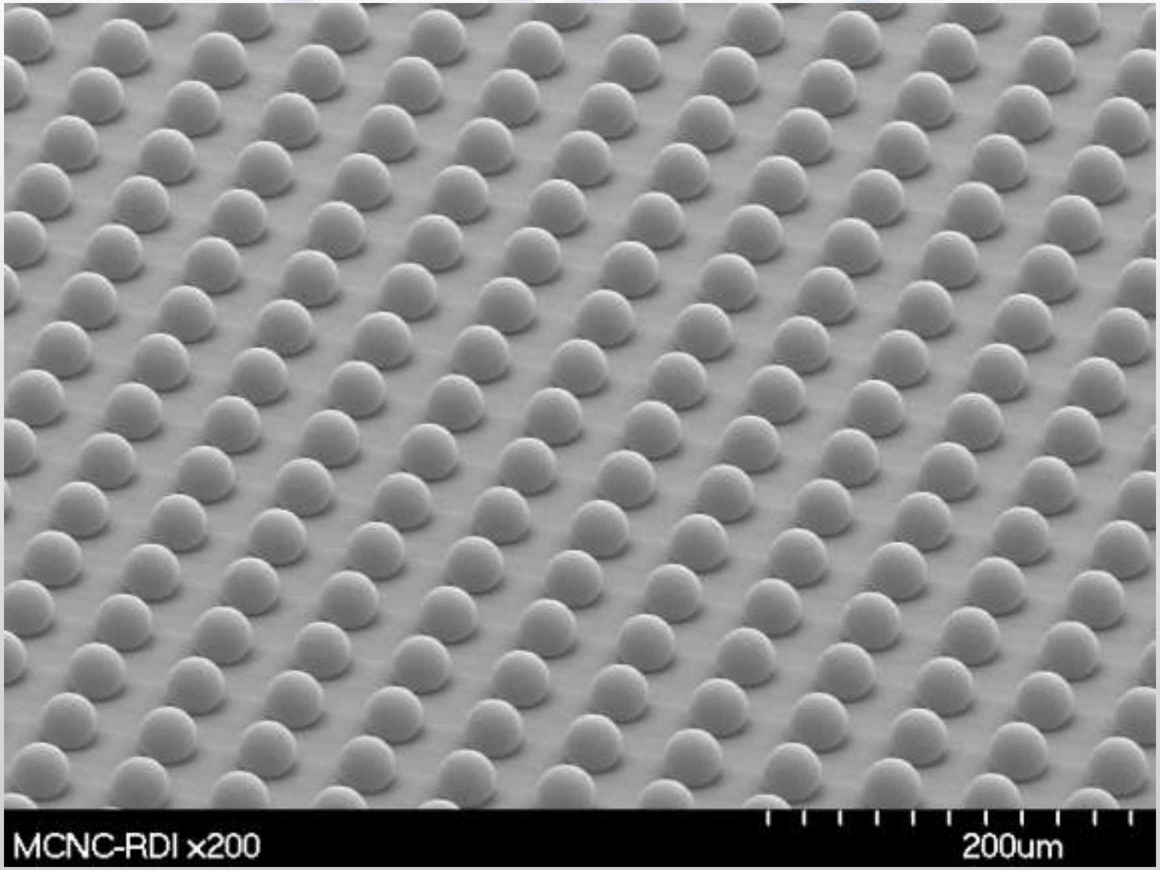
Detectors at ESRF



Detectors at ESRF



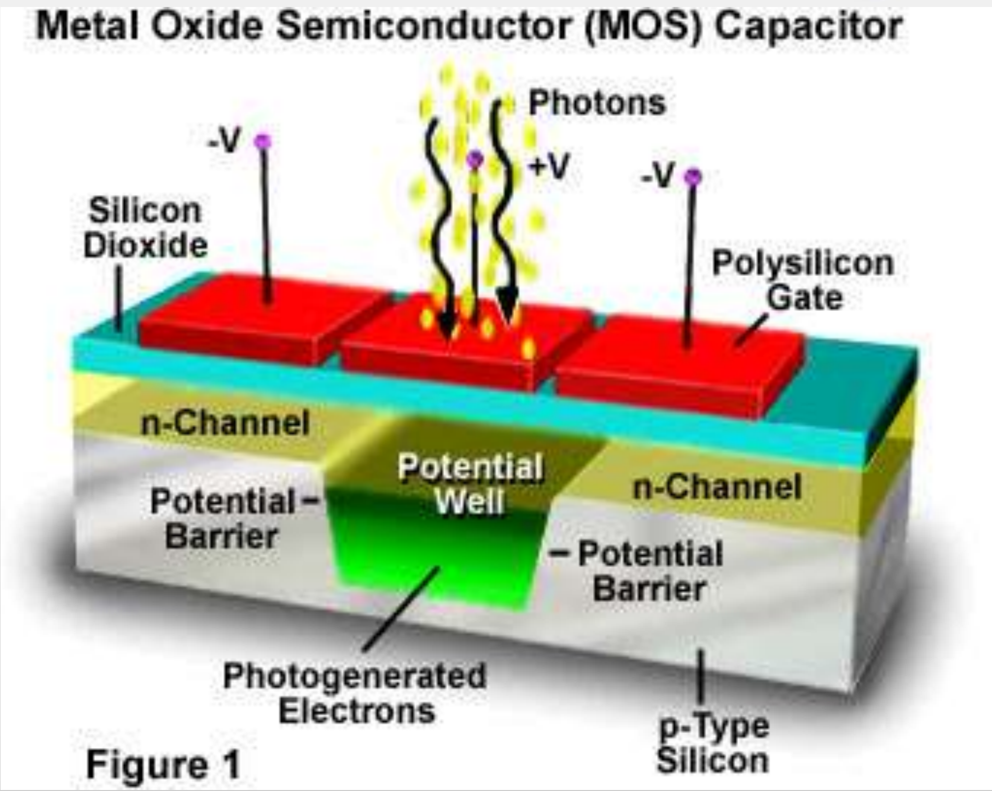
Detectors at ESRF

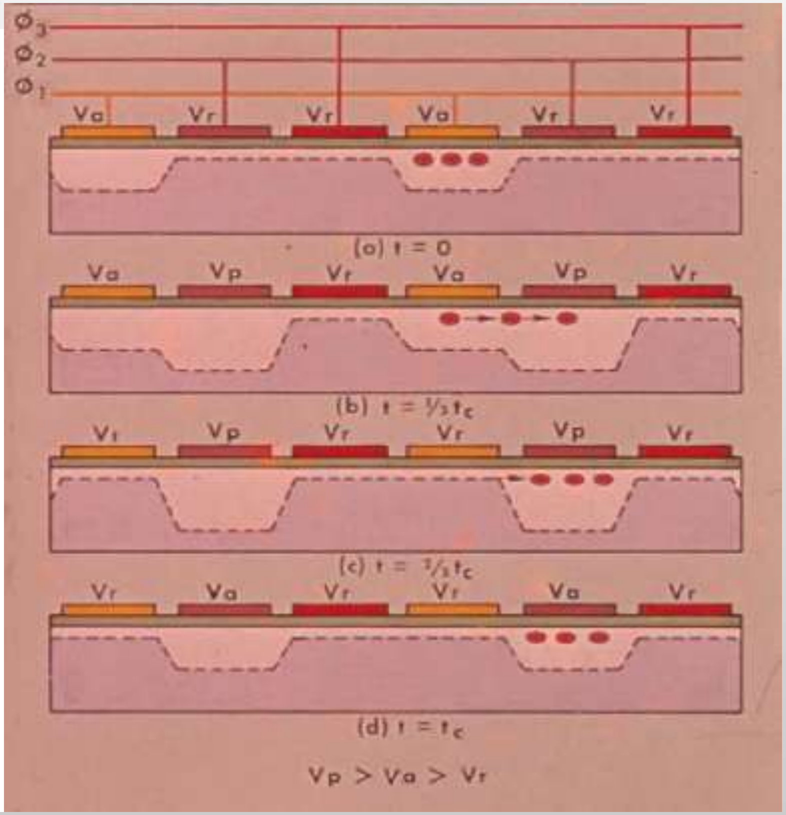


Detectors at ESRF

Detectors at ESRF

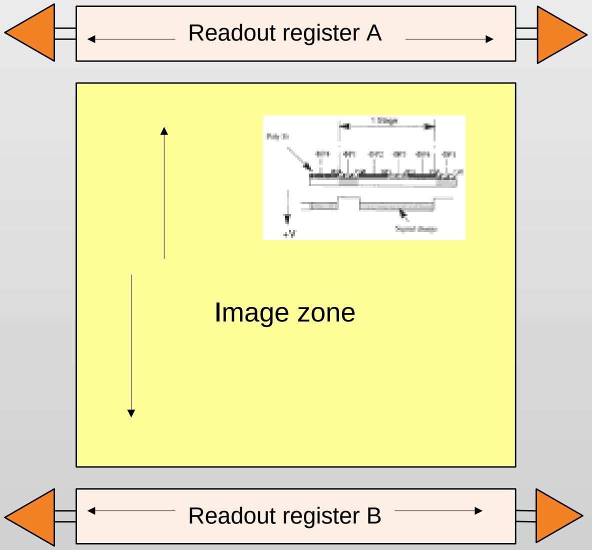
CCD basic principle





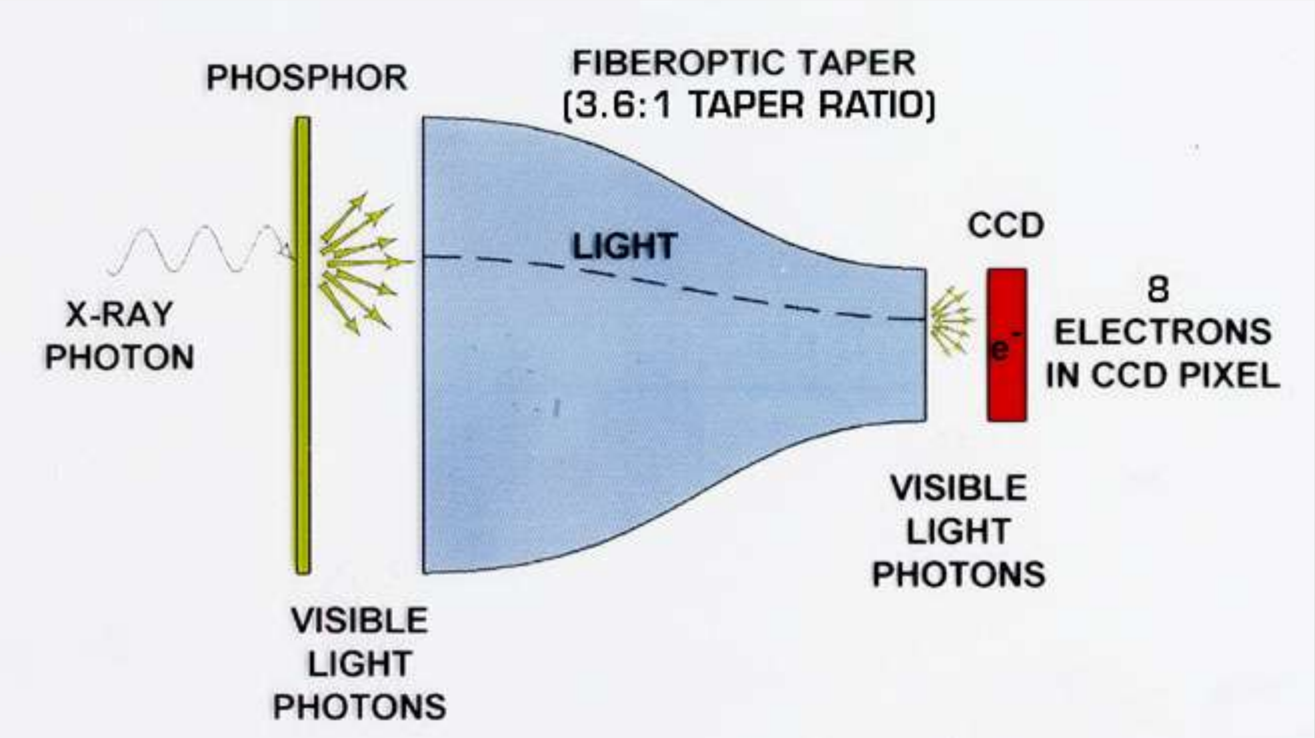
Detectors at ESRF

- **CCD**

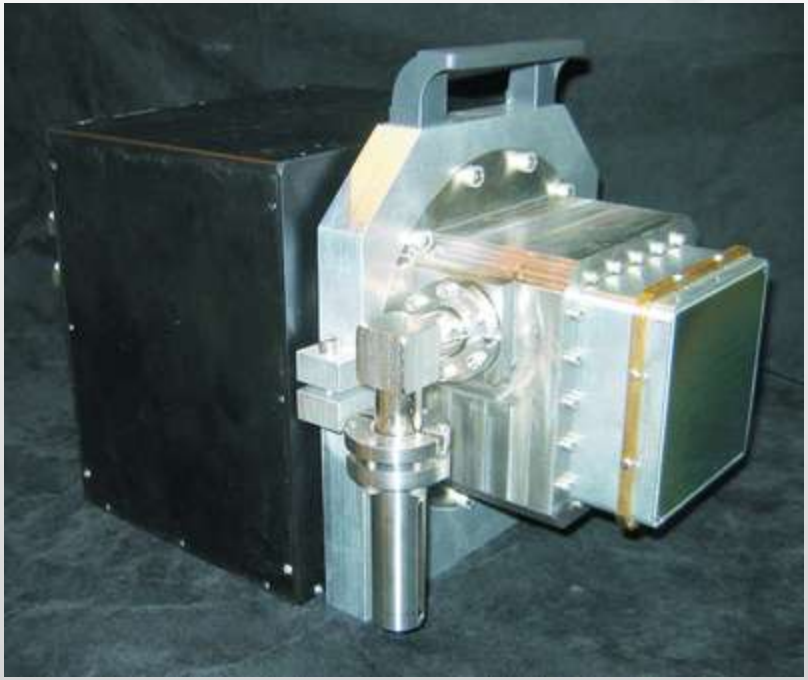


Detectors at ESRF

CCD-taper

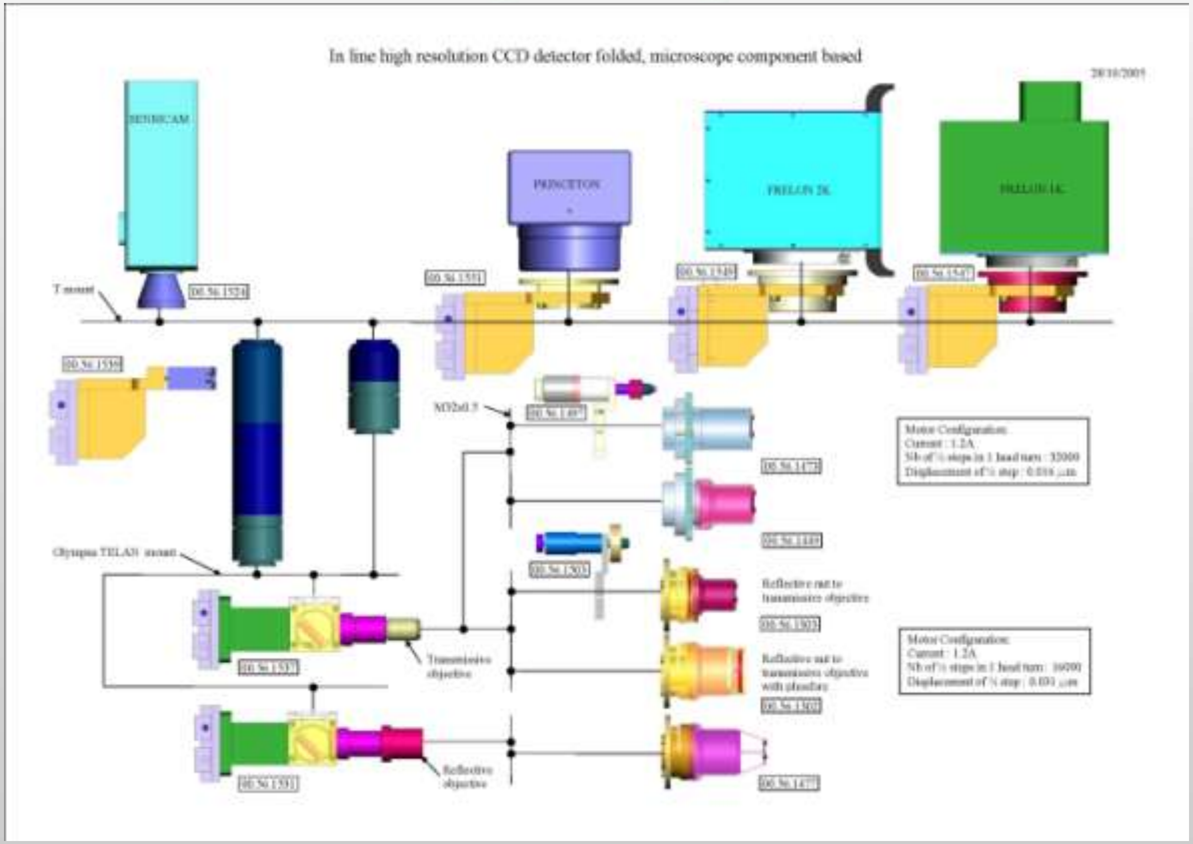


Detectors at ESRF

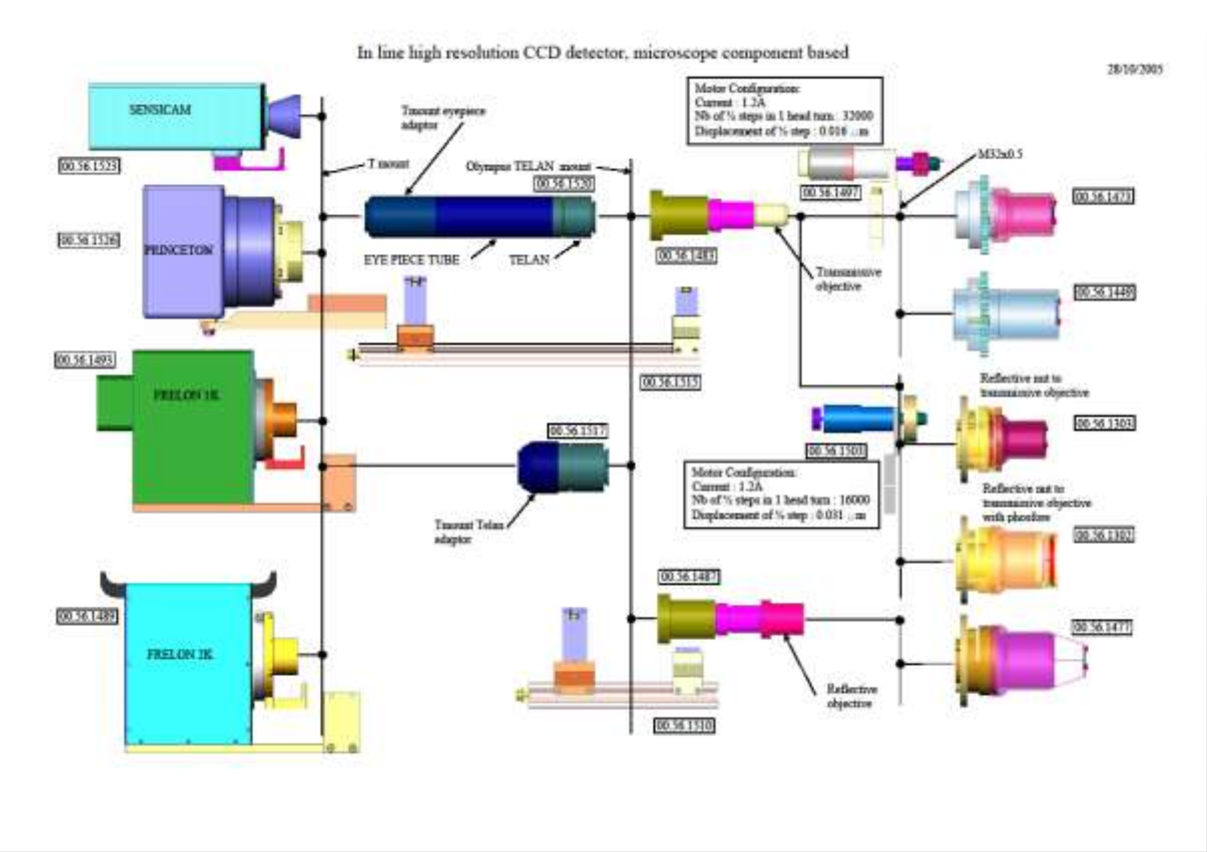


ESRF Frelon CCD

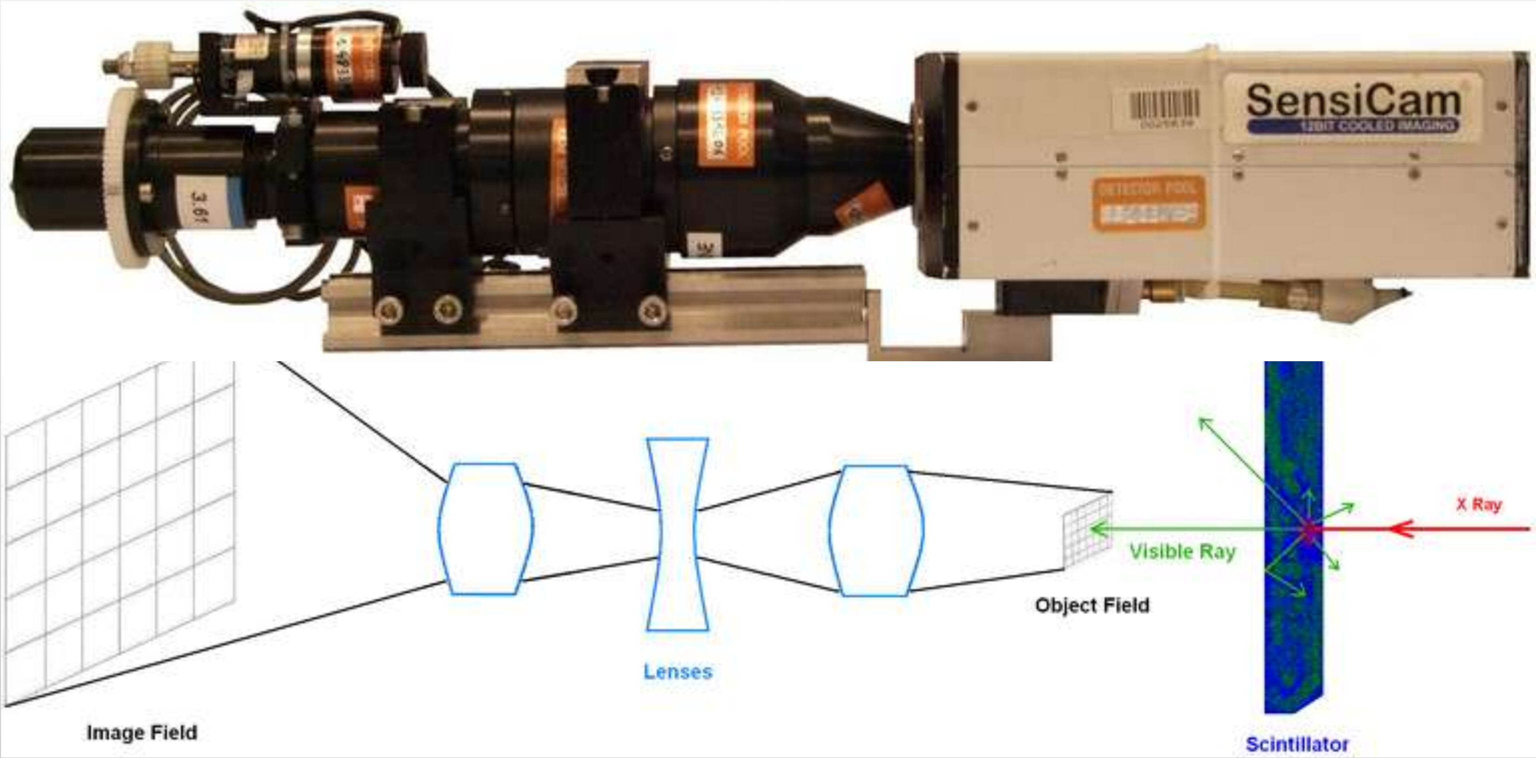
Detectors at ESRF



Detectors at ESRF



Detectors at ESRF



Detectors at ESRF

Lens coupled CCD

Detectors at ESRF

Objective	Theoretical magnification	Object field x (mm)	Object field y (mm)	Pixel size (μm^2)	Resolution of the scintillator
2	**2.00**	**4.30**	**3.45**	3.35*3.35	24 2
4	**4.00**	**2.15**	**1.73**	1.68*1.68	24 2
10	**10.00**	**0.86**	**0.69**	0.67*0.67	24 2
20	**20.00**	**0.43**	**0.35**	0.34*0.34	24 2
40	**40.00**	**0.22**	**0.17**	0.17*0.17	24 2

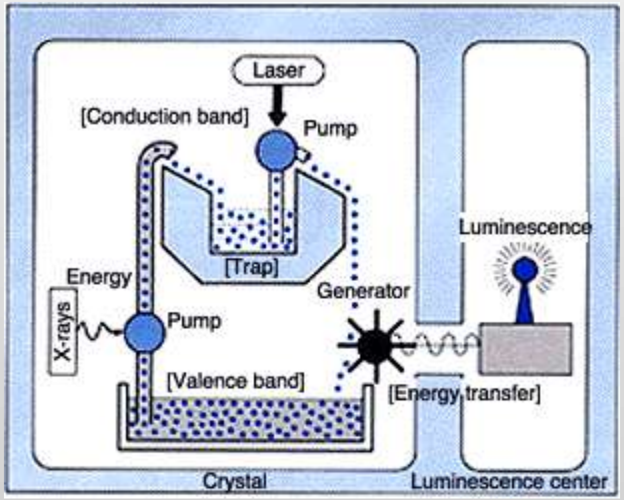
Sensicam in-line

Image Field : 6.9 mm x 8.6 mm

Detectors at ESRF

Specifications	
Usable detector area	93.480 mm²
Diameter of scanned area	Software selectable: 180, 240, 300 or 345mm
Pixel size (selectable by software)	150 x 150 µm² or 100 x 100 µm2
Sensitivity	1 X-ray photon per ADC-unit at 8 keV
Energy range:	4 keV to 100 keV X-ray photons
Intrinsic noise	< 1 photon equivalent
Dynamic range	0 : 131000 (17 bits)
Communication interface	Ethernet (RJ45), 10MB/s
Erase lamps	1 halogen lamp: R7S 11x118mm, 500W 2 halogen lamps: R7S 11x80mm, 250W Lifetime: 2000 hours (approx 100.000 scans)
Outside dimensions (H x W x L)	515 mm * 398 mm * 350 mm
Weight	53 kg
Energy consumption	approx. 1000 Watt
Electricity	120 / 240V (7.5 A)
Ambiental temperature	4 - 24 °
Maximum humidity:	70 %

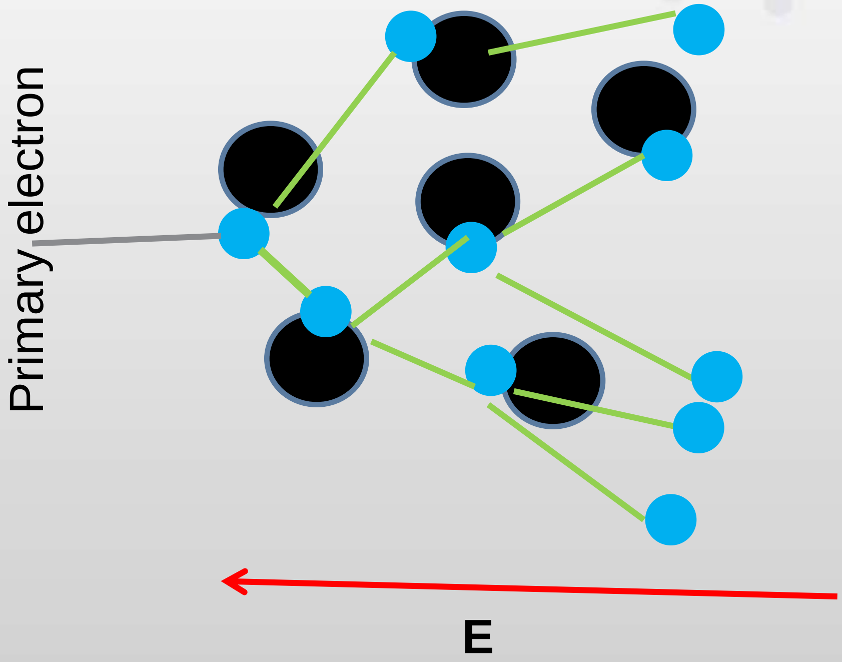
Detectors at ESRF



Fujifilm

Detectors at ESRF

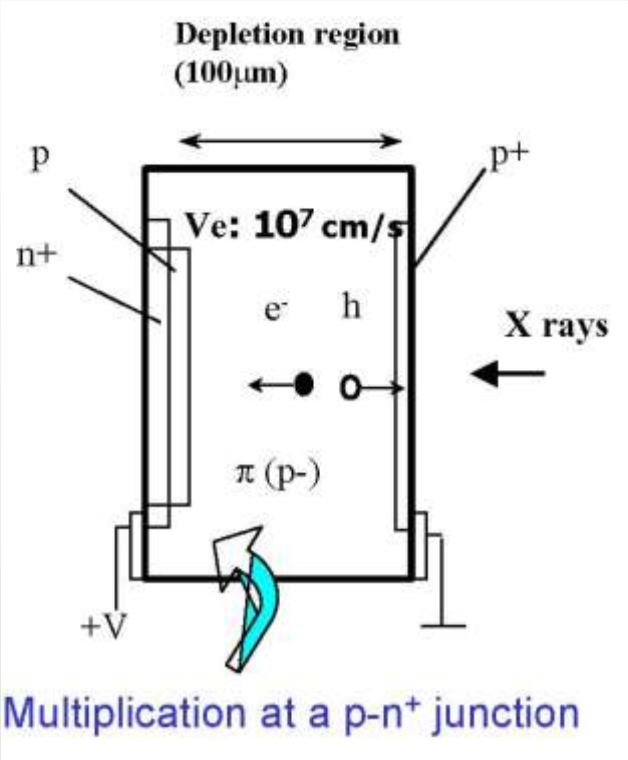
Ionization based detectors - charge multiplication

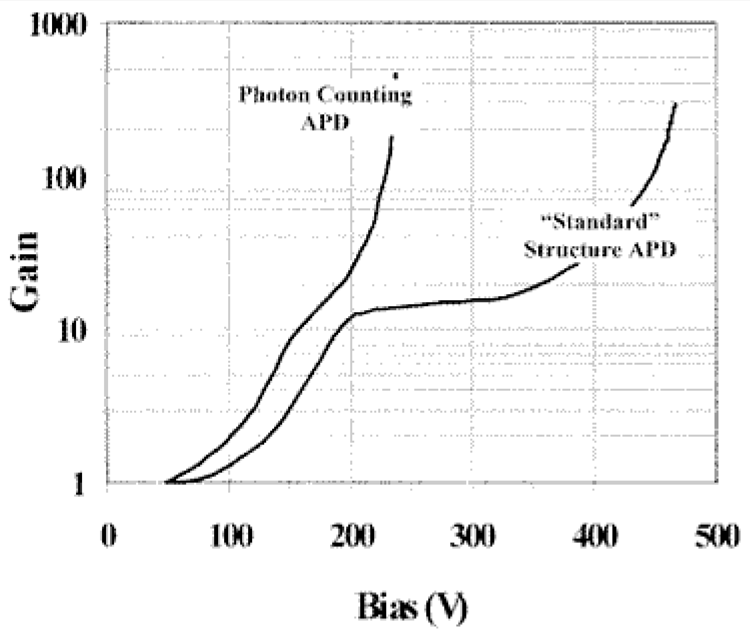


Multiplication factor M
Gases up to Raether limit n.M <10^8
Silicon M ~ few 100

Detectors at ESRF

- **APD** – working principle

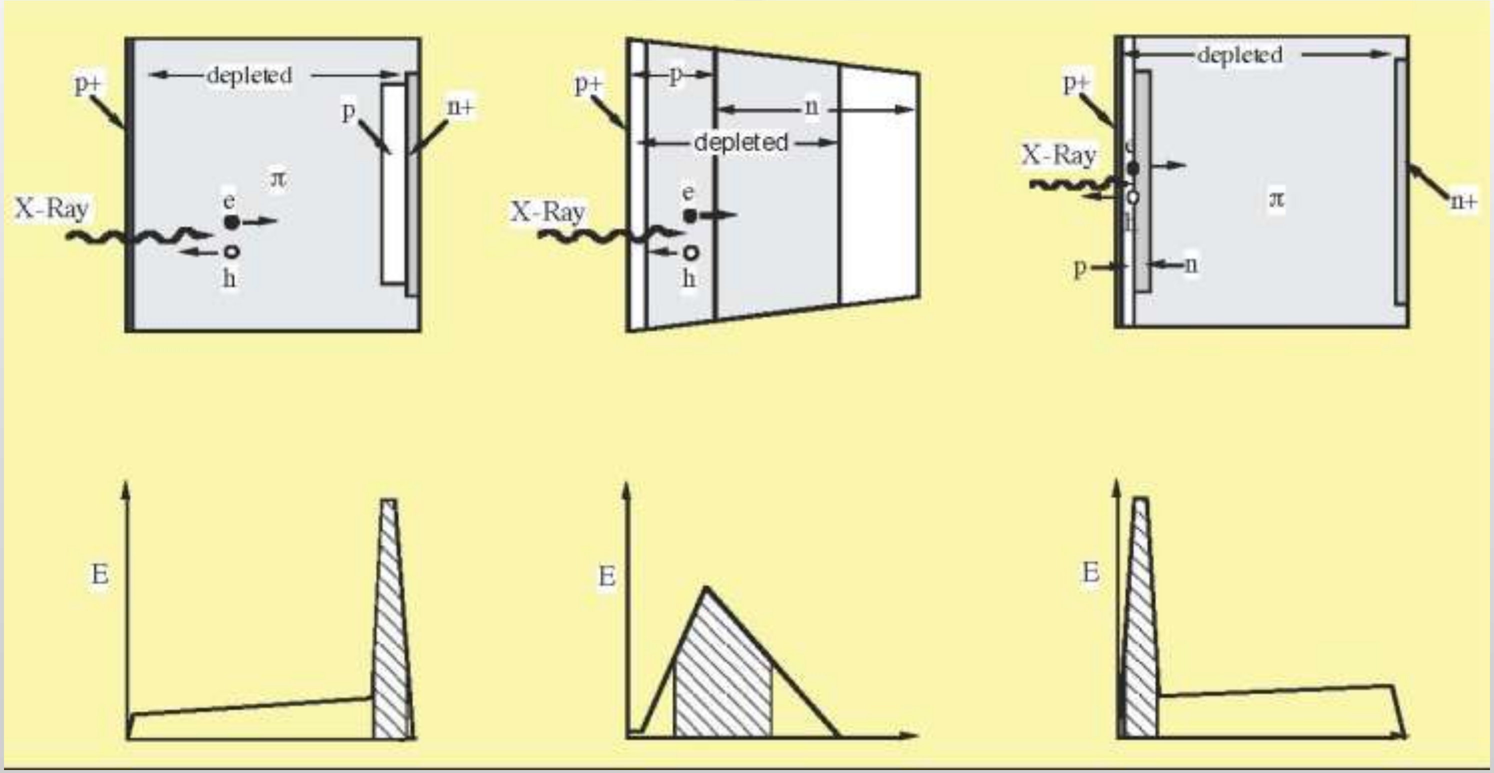




Detectors at ESRF

- **APD** structures

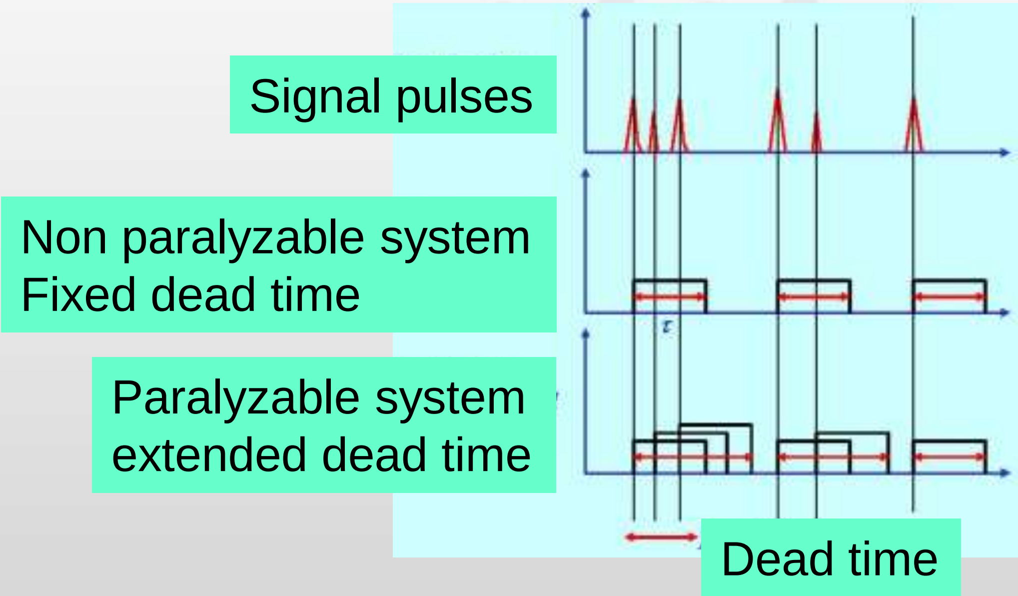
Reach through | Beveled edge | Reverse



Detectors at ESRF

APD

Detectors at ESRF



Detectors at ESRF

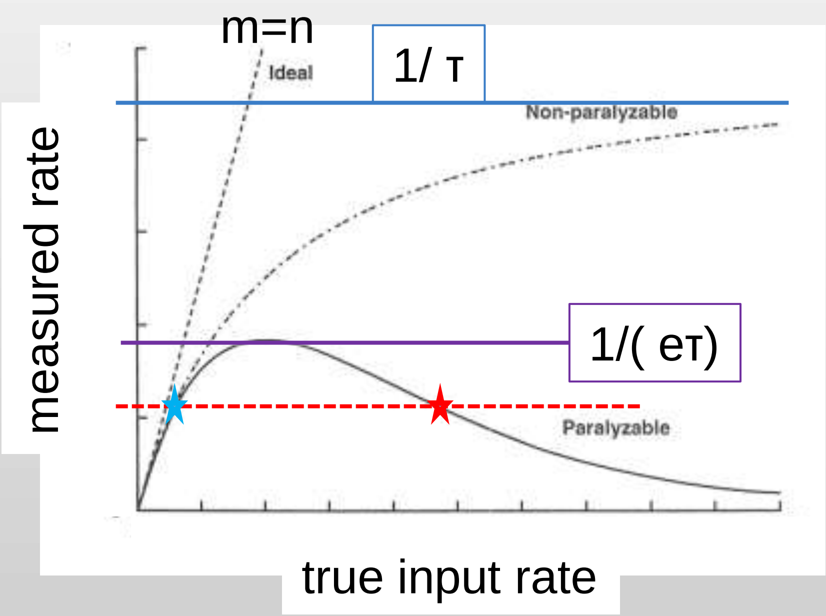
Dead time – model valid only for Poissonian sources!

Non paralyzable: $m=n/(1+n\tau)$

Paralyzable: $m=n_x\exp(-n\tau)$

n- true input rate
m- measured rate
τ - system dead time

★ Usually the fast detector destroyed here
Also problem for a pixel detector



Detectors at ESRF

Dead time – synchrotron, pulsed sources

$m = n.\exp(-n\tau)$ $\tau = T\,[\ln(\tau_D / T)+1]$

τ – “effective” dead time
T - separation of X-ray pulses
τ_D - system dead time

Detectors at ESRF

Dead time – ESRF a pulsed source

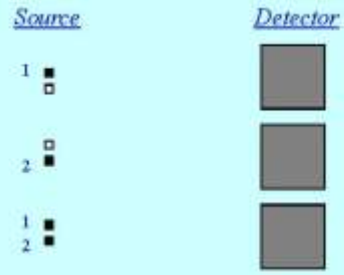
Filling mode	Filling pattern	T
Uniform	992 bunches are equally distributed around the whole circumference of the storage ring, rms bunch length 20ps	2.84 ns
Single	1 bunch 20mA, rms bunch length 73ps	2.8169 µs
2*1/3	2 times one third of the storage ring is filled. The 2 one thirds are separated by an empty gap of 1/6th of the ring	varying
7/8 + 1	A train of 868 bunches (7/8 of the Storage Ring circumference) filled with 200 mA (0.23 mA / bunch).Both edges of the train are filled with 1 mA single bunch	varying
Hybrid 24*8 + 1	One clean 4mA single bunch diametrically opposed to a ~ 196 mA multi-bunch beam composed of 24 groups of bunches spread over 3/4 of the storage ring circumference	varying
16 bunch	16 highly populated and equally spaced bunches, rms bunch length 48ps	176 ns
4*10	4 equidistant bunches, 10 mA/bunch	704 ns

Detectors at ESRF

$$m_1 = \frac{n_1}{1 + n_1 \tau}$$

$$m_2 = \frac{n_2}{1 + n_2 \tau}$$

$$m_{12} = \frac{n_1 + n_2}{1 + (n_1 + n_2)\tau}$$

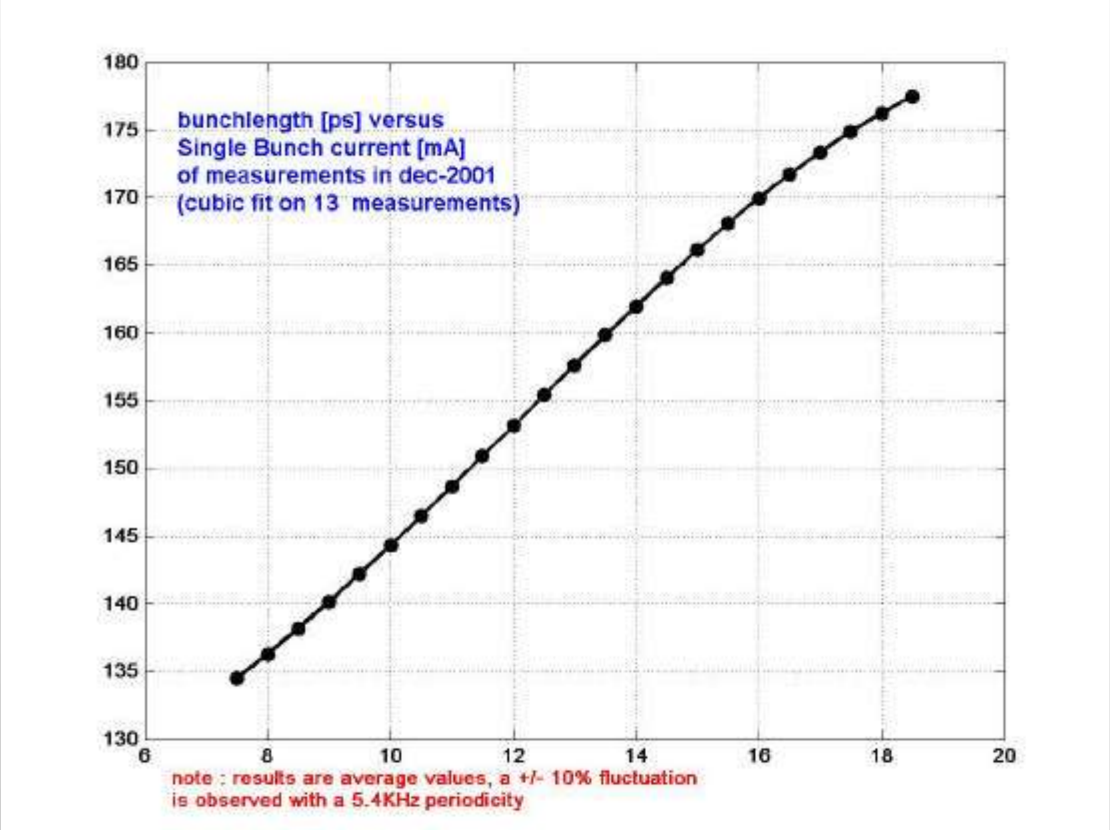


Known values: measured count rates m_1, m_2, m_{12}
Unknown values: true count rates and dead time n_1, n_2, τ

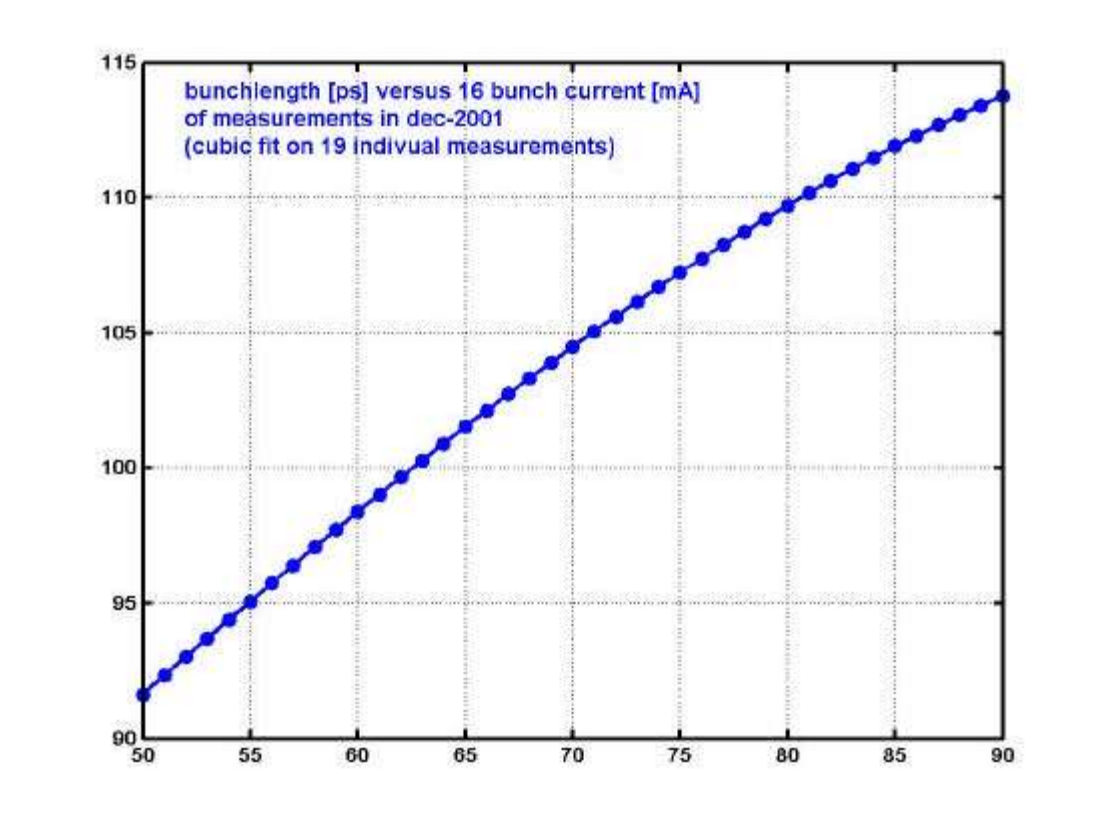
$$\tau = \frac{m_1 m_2 - [m_1 m_2 (m_{12} - m_1)(m_{12} - m_2)]^{1/2}}{m_1 m_2 m_{12}}$$

- ■ *Real source*
- □ *Phantom source with no activity*

Detectors at ESRF



Detectors at ESRF



Detectors at ESRF

Uniform Filling
The bunch length in uniform fill is about **46.5ps and independent of the** current (**150-200mA)**

Detectors at ESRF

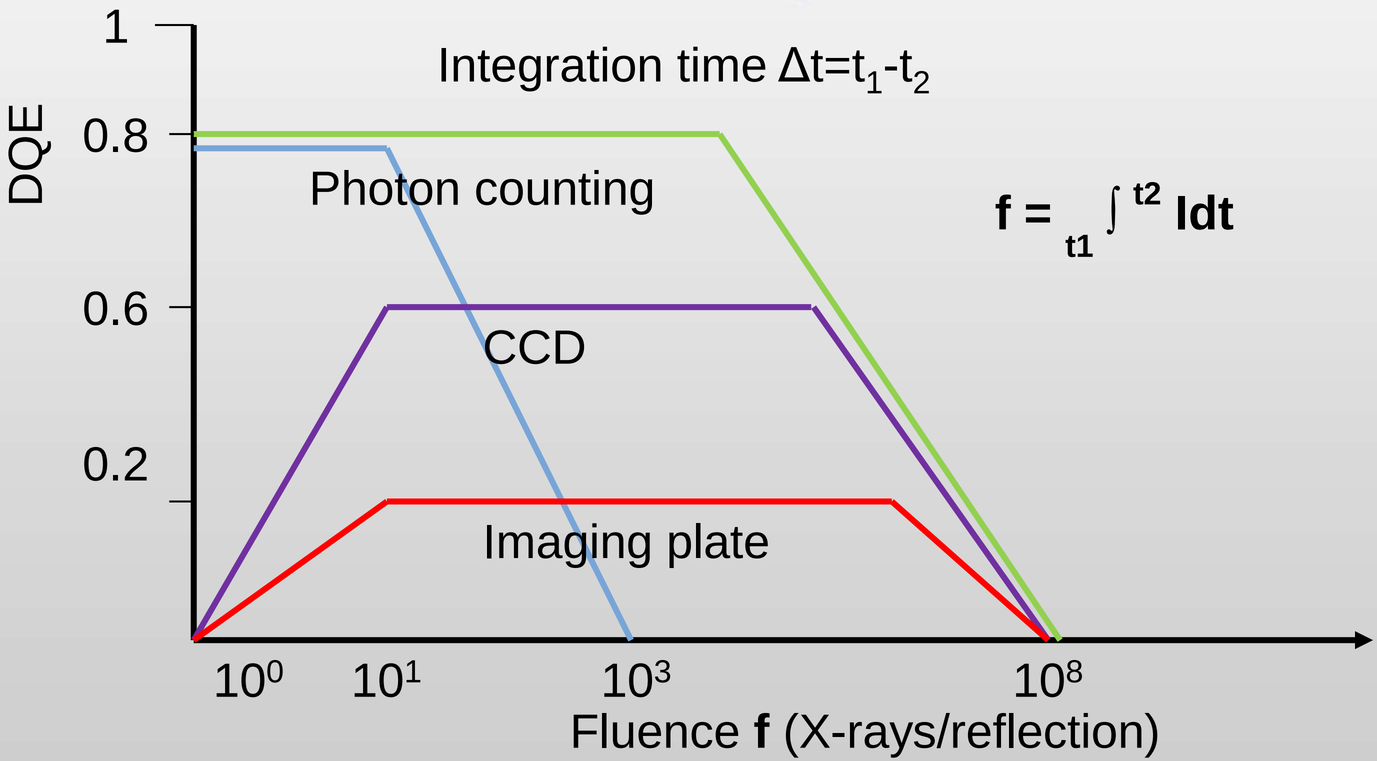
DQE

$$DQE = \frac{\left(\frac{S}{N}\right)^2_{Xabs}}{\left(\frac{S}{N}\right)^2_{IN}} \times \frac{\left(\frac{S}{N}\right)^2_{OUT}}{\left(\frac{S}{N}\right)^2_{Xabs}} = \frac{\left(\frac{S}{N}\right)^2_{Xabs}}{\left(\frac{S}{N}\right)^2_{IN}} \times \frac{1}{\frac{N^2_{OUT}}{N^2_{Xabs}}} = \eta_{abs} \times \frac{1}{\frac{N^2_{Xabs} + N^2_{phot} + N^2_{elec}}{N^2_{Xabs}}} = \eta_{abs} \times \frac{1}{1 + \frac{1}{n_{ph}} + \frac{1}{N^2_{Xabs} / N^2_{elec}}} =$$

$$= \eta_{abs} \times \frac{1}{1 + \frac{1}{n_{ph}}\left(1 + \frac{1}{\frac{n_{Xabs} \times n_{ph}}{\sigma^2_{elec}}}\right)}$$

Detectors at ESRF

DQE



$$f = \int_{t1}^{t2} I dt$$

Detectors at ESRF

Thank you for your attention