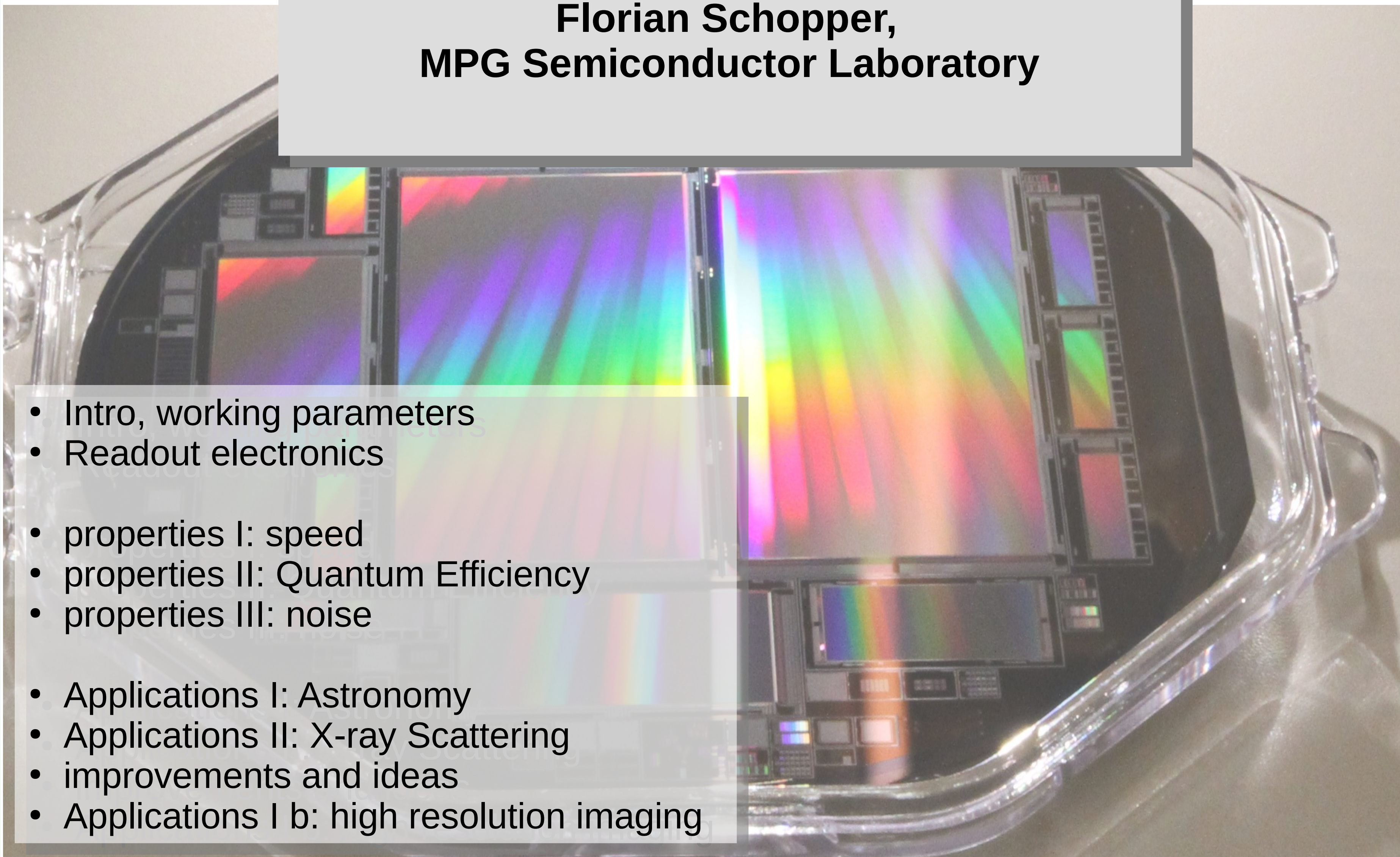
Status of pn-CCDs

Florian Schopper,
MPG Semiconductor Laboratory



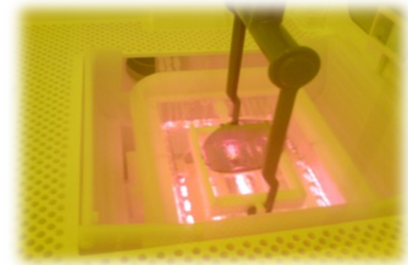
- Intro, working parameters
- Readout electronics

- properties I: speed
- properties II: Quantum Efficiency
- properties III: noise

- Applications I: Astronomy
- Applications II: X-ray Scattering
- improvements and ideas
- Applications I b: high resolution imaging

Max-Planck Semiconductor Laboratory

wet chemistry

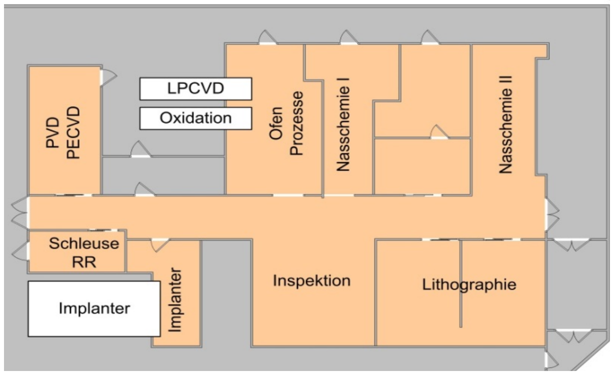


lithography

implantation

inspection

thermal



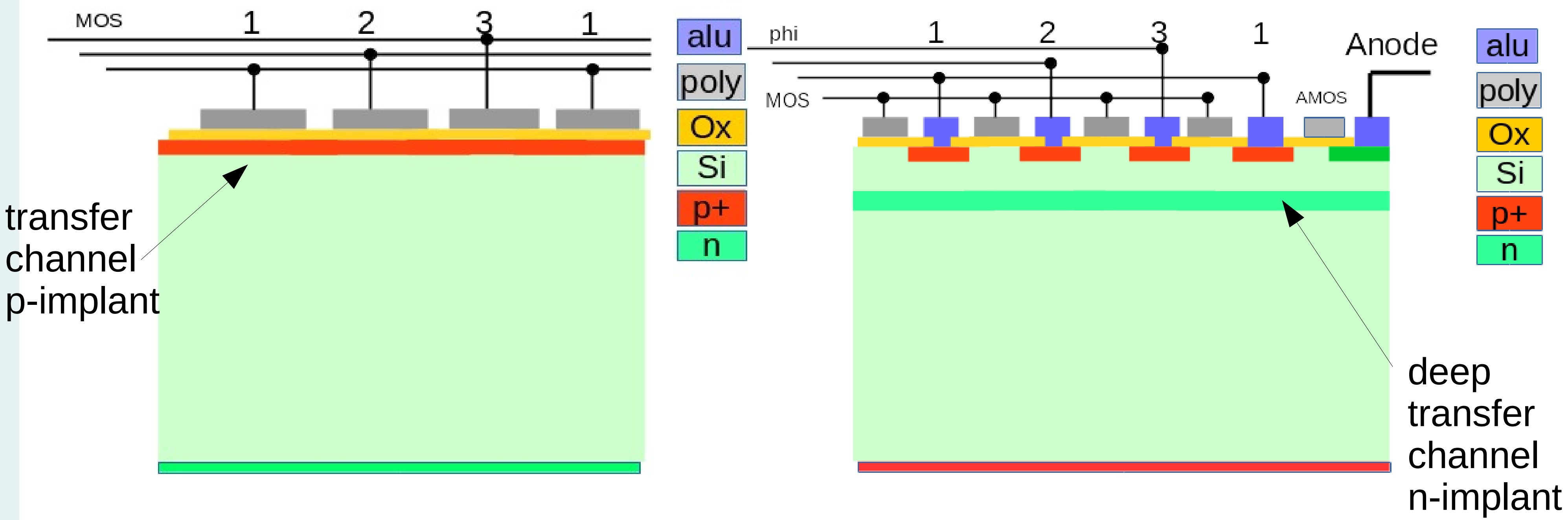
advantages of pnCCDs

- backside illumination -> 100% QE possible
- low leakage current -> low noise (~ 2 e^- ENC)
- large Charge Handling Capacity (up to ~ 10^6 e^- / 50µm²)
- fast transfer (~ 100ns/line)

Disadvantages

- transfer = image area -> Out Of Time Events
- charge trapping during transfer possible
- area needed for framestore

types of depleted CCDs



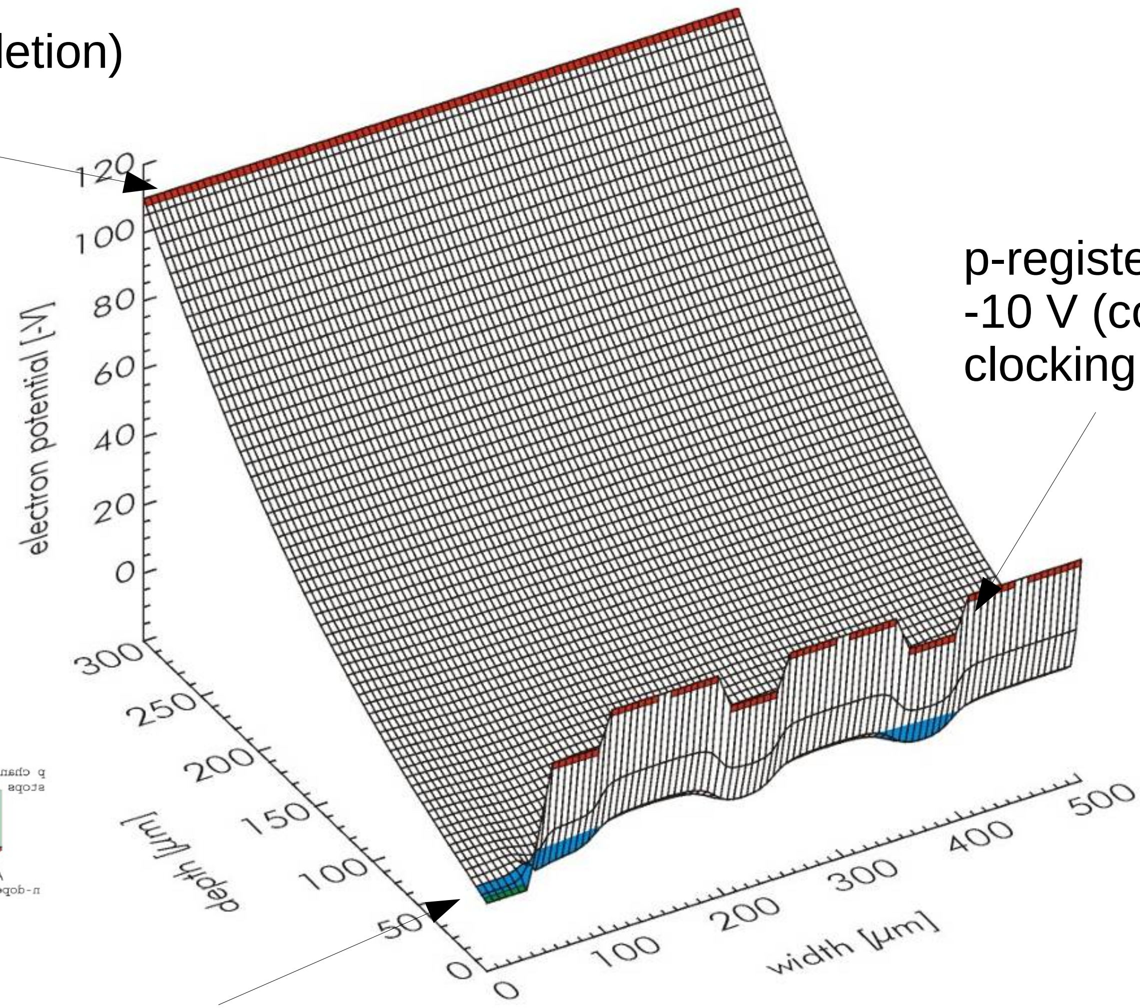
fully depleted MOS-CCD
is derived from a Diode structure
and collects holes.
(LBNL, Dalsa)

fully depleted pn-CCD
is derived from a Driftsensor structure
and collects electrons.
(HLL, pnSensor)

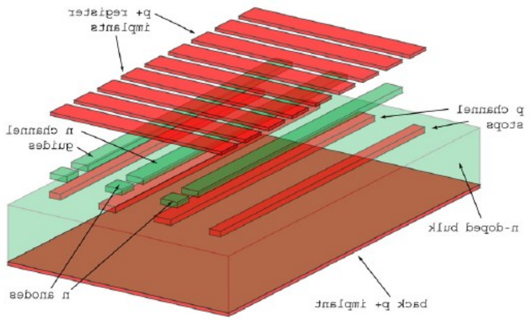
working parameters, Potential

Backside-Bias:
from -120V (depletion)
up to ~ -600V

can control
charge diffusion
during drift

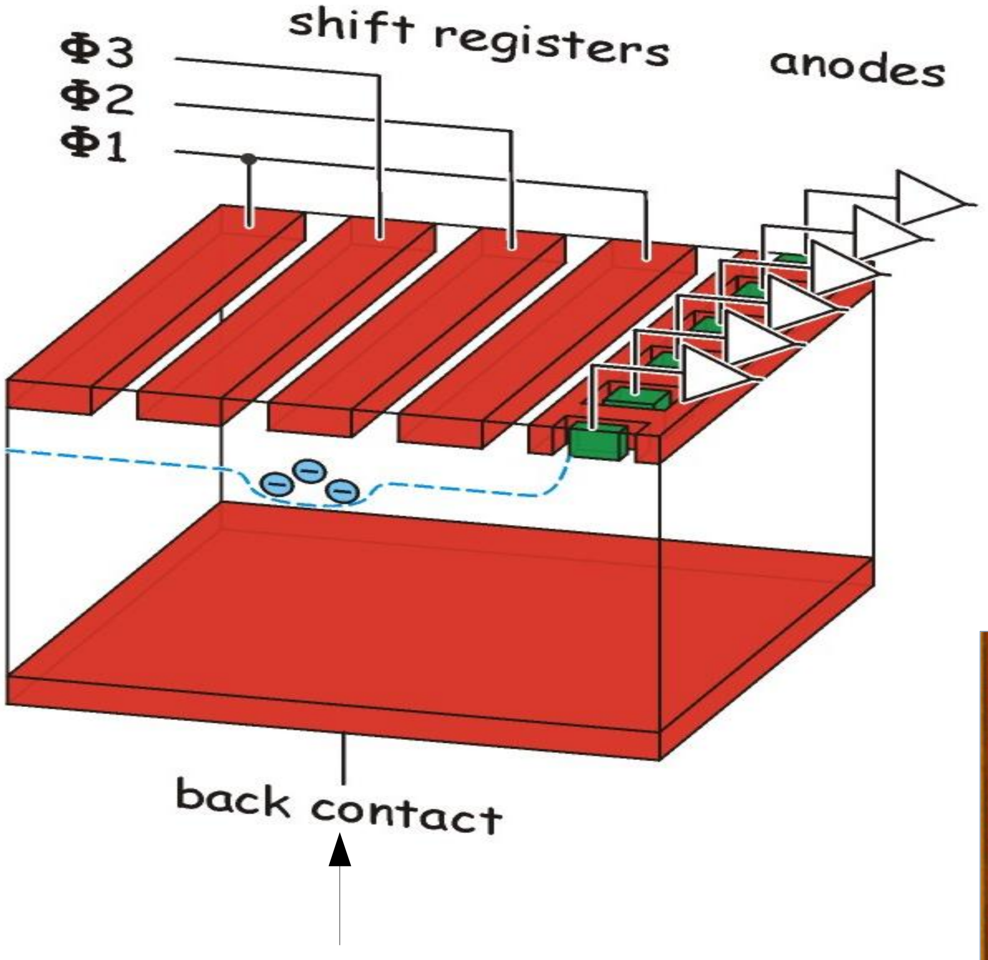


p-registers:
-10 V (collecting),
clocking to -20V

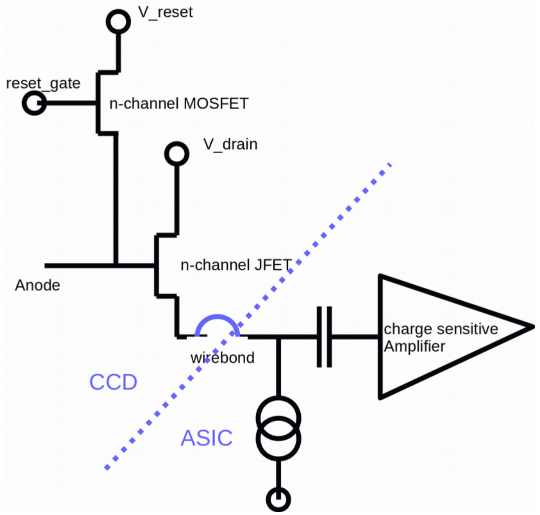


substrate,Anode: ~0V set by JFET reset

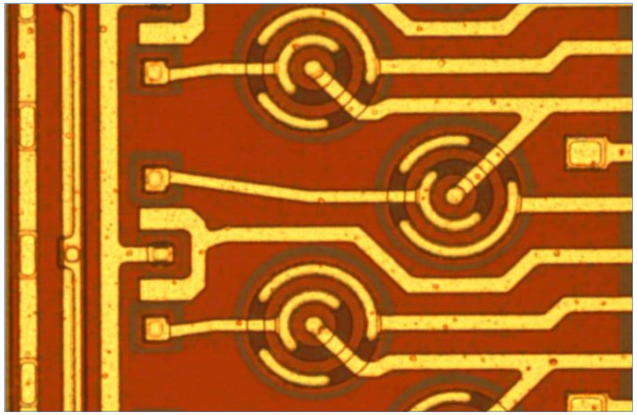
Signal Readout



Radiation entrance window



Anode+Reset+JFET capacitance
~ 30 fF -> 5.3 µV/e⁻



For 36 µm pixelsize, JFETs (large version) need to be staggered

Readout ASICs

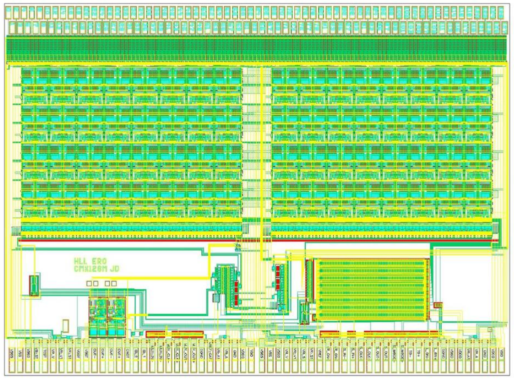
CAMEX

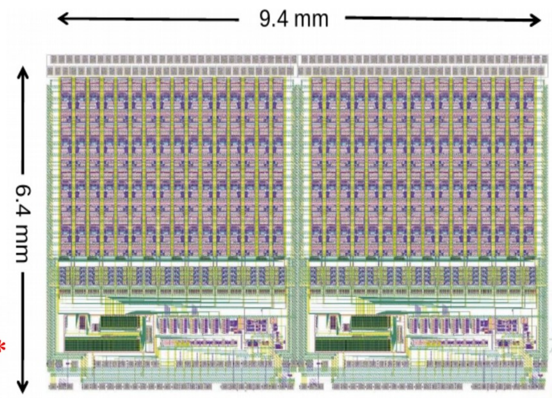
MCDS-filter, 128 channels, S/H, serial output
Processing time: 20 µs/line 5 mW / channel

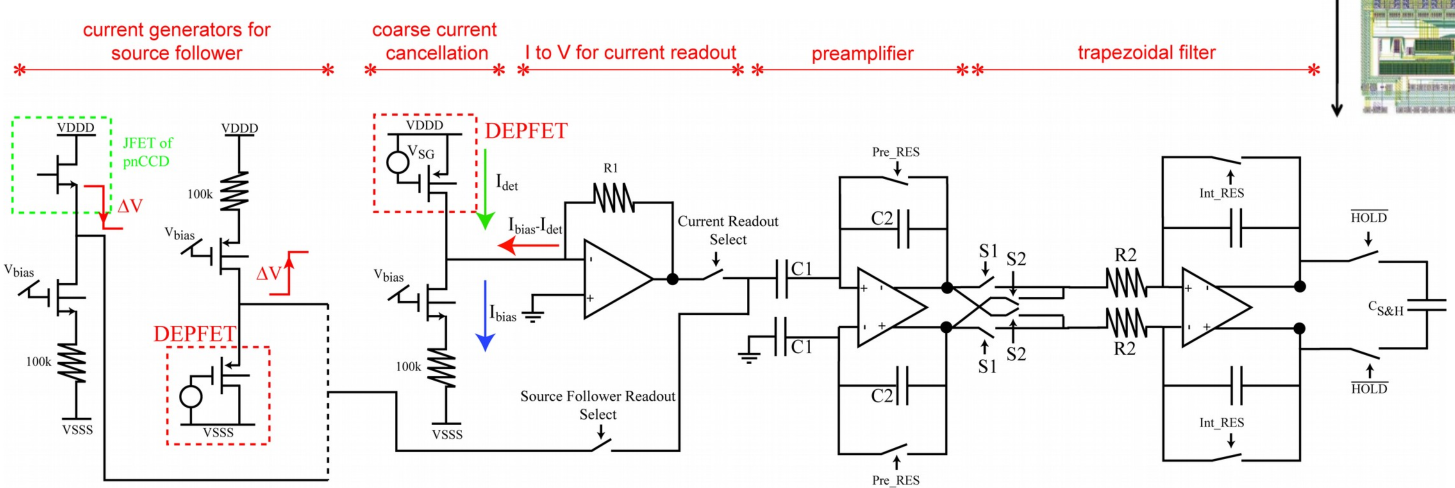
Veritas I and II

trapezoidal filter, 128/64 channels, S/H, serial output
Processing time: 2-4 µs/line 6 mW / channel

II: pnCCD n-JFet, Depfet p-mos source/drain readout







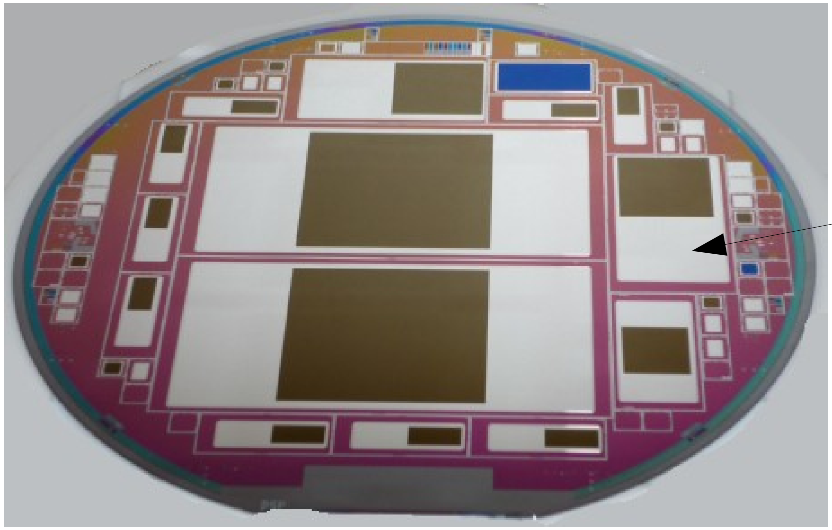
Framestore

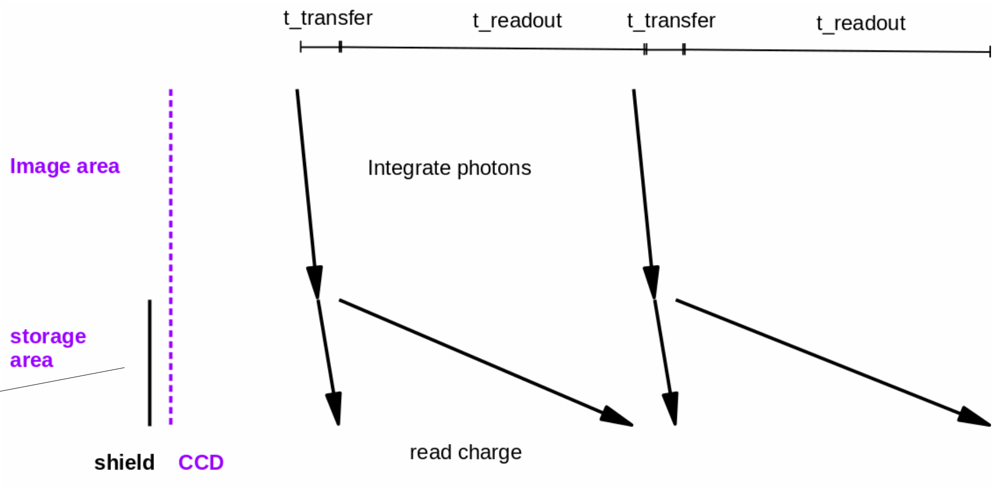
The percentage of Out-of-Time events:

without framestore : $$\frac{t_{Readout}}{t_{integration}}$$

with framestore : $$\frac{t_{Transfer}}{t_{Readout}}$$

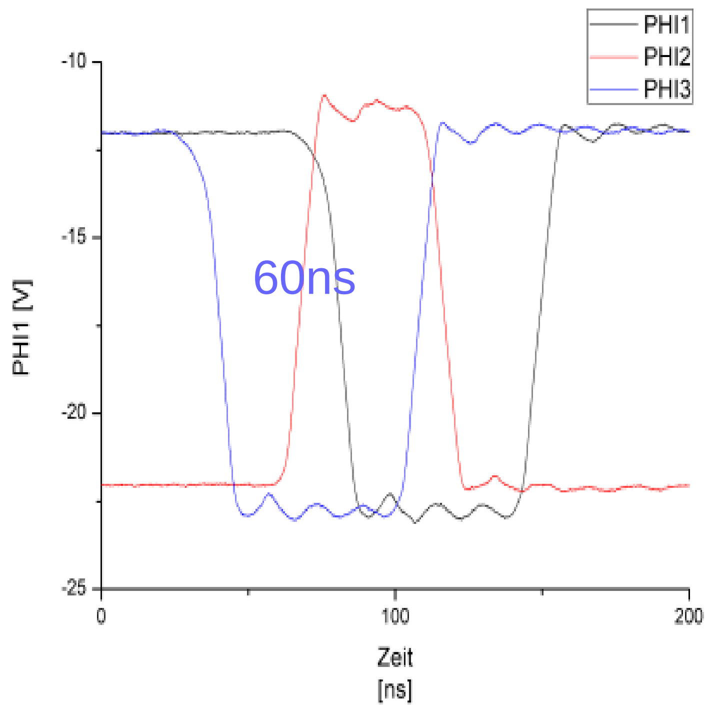
Spectroscopic reading means:
$t_{readout} = t_{integration}$ -> framestore is necessary



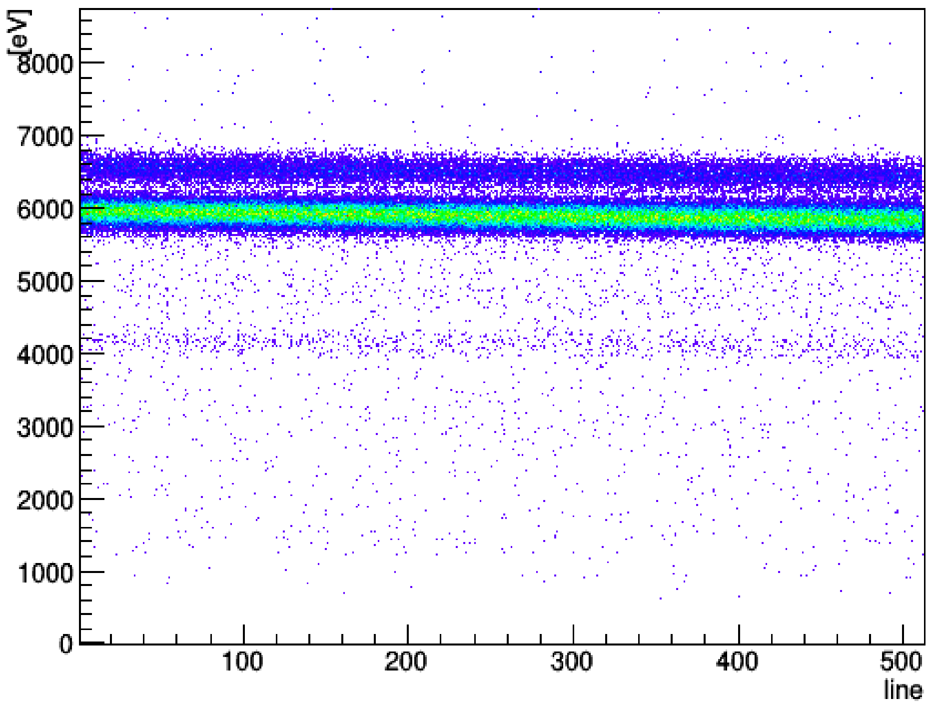


Properties I: speed

readout/line: 20µs -> 4µs
frame transfer/line: 300ns -> 60ns



Charge Transfer Inefficiency at 120 ns/row is $3 * 10^{-5}$



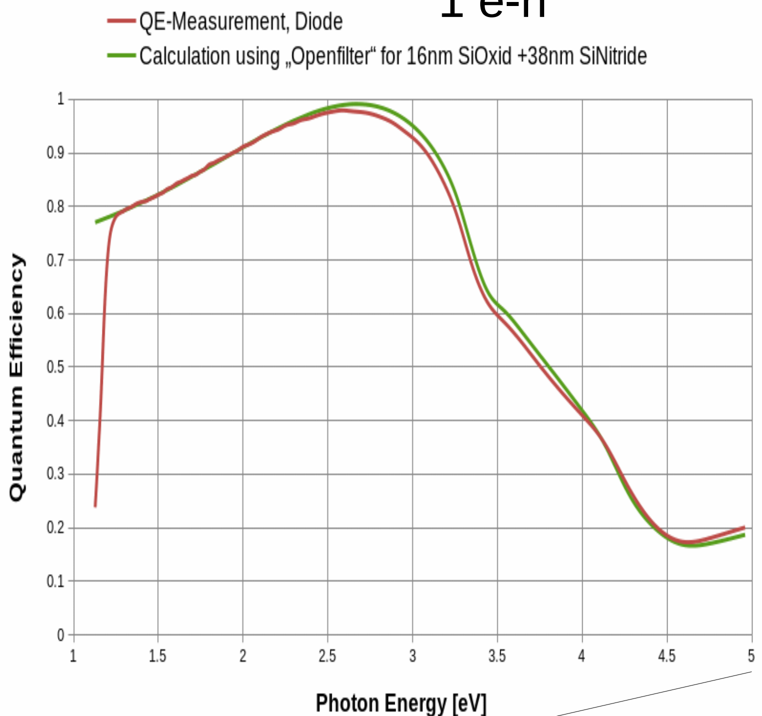
first row

last row

Floating/resistively biased MOS registers allow fast clocking also for large CCDs with narrow lines.

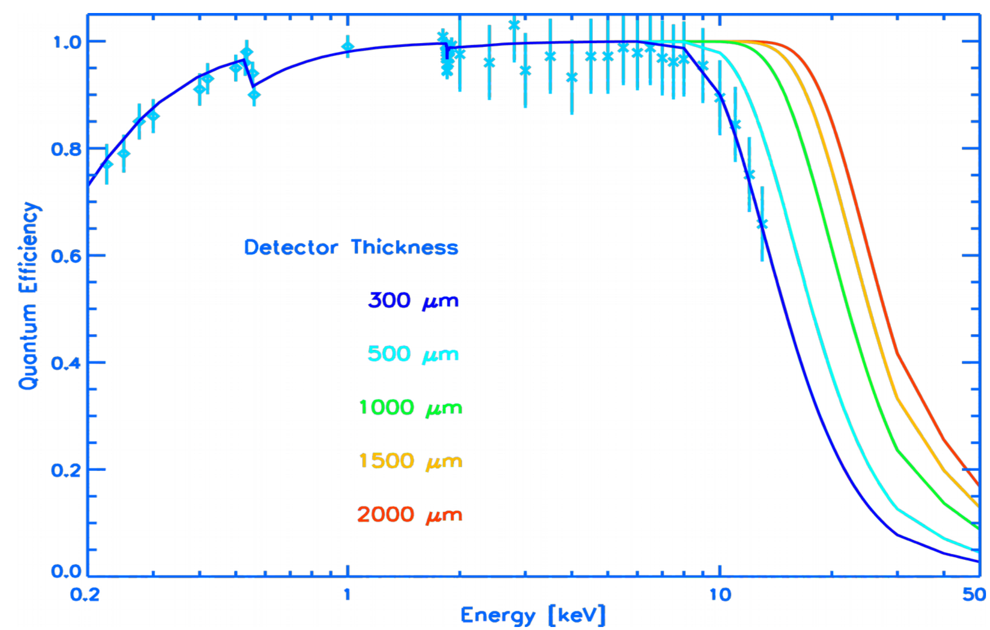
Properties II: QE of photon detection

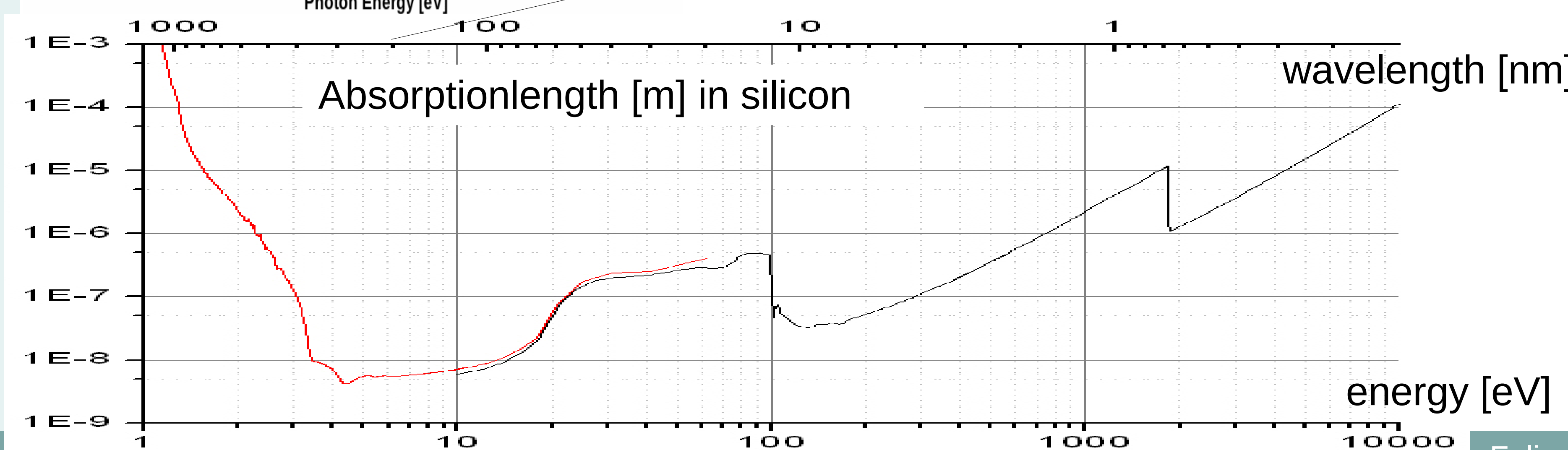
1 e-h



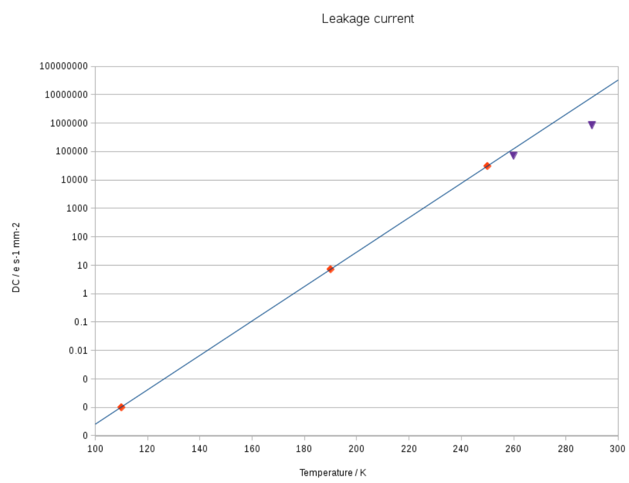
54 e-h pairs

2800 e-h pairs





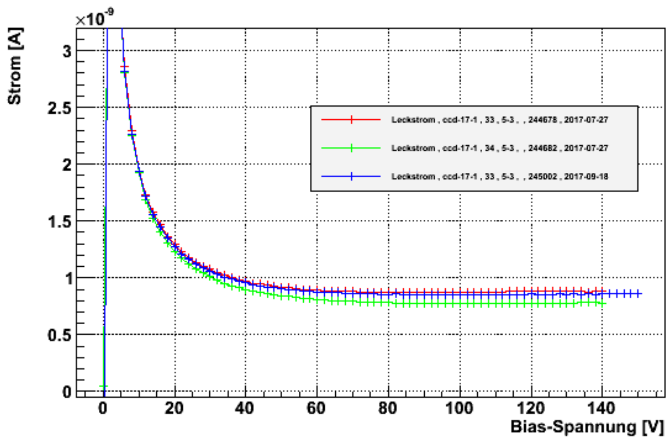
properties III: noise/leakage current

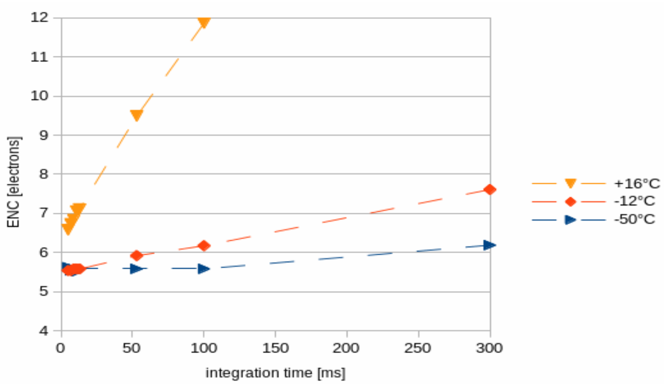


When does leakage current matter?

Application	I/cm² [pA]	pixelsize [µm]	T	t/row [µs]	#rows	added noise [e⁻]
LAMP 120 Hz framerate	**20**	75	RT	16	512	7.6
	20	75	-10°C	16	512	1.4
Fast pnCCD (Veritas)	**20**	36	RT	4	512	2.2
BELLE SVD	**2000**	60	RT	0.25	768	2.9
eROSITA	**20**	75	RT	20	384	7.3
	20	75	-80°C	20	384	0.2

+ all „long integrating" CCDs like for Dark Matter search

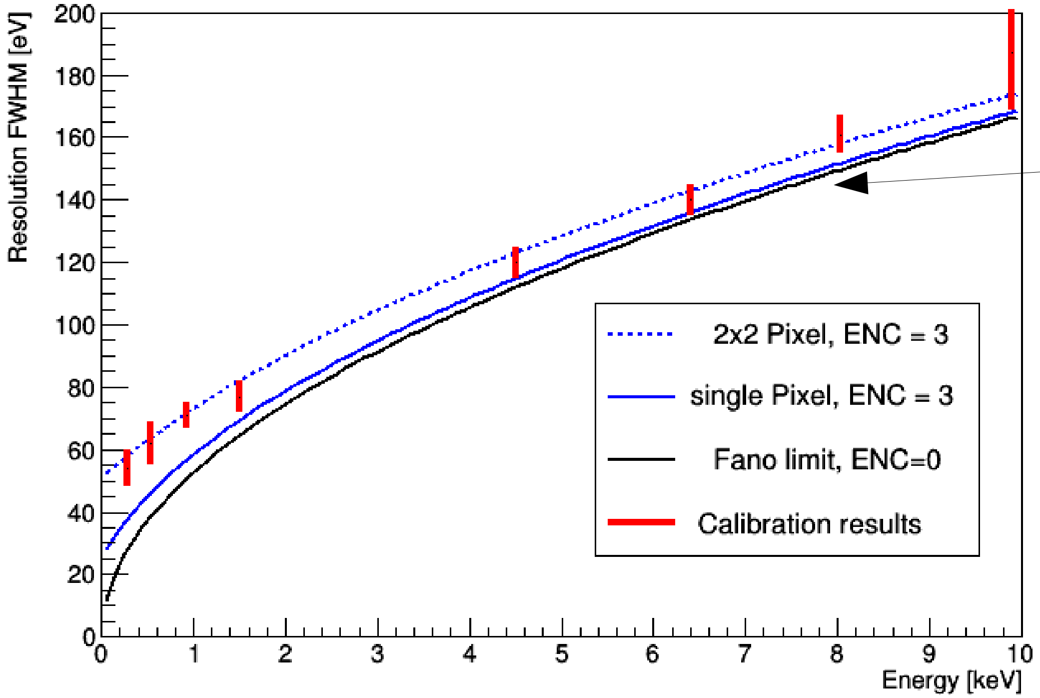




Leakage current at RT for 30cm² CCDs
-> 20pA/cm²

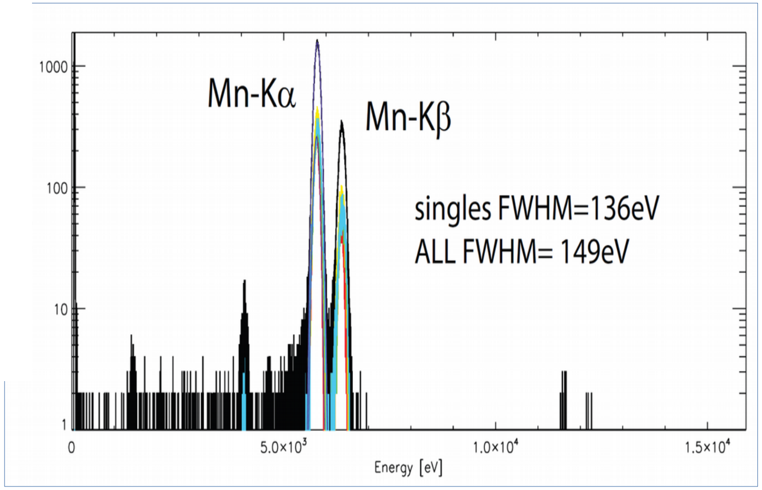
at RT ~ 1000 electron /s pixel
at -50°C ~ 1 electron / s pixel

properties III: noise/energy resolution



Limiting energy resolution in silicon:

$$FWHM_{Fano} = 2.35 \cdot \sqrt{(0.12 \cdot E / 3.69)}$$

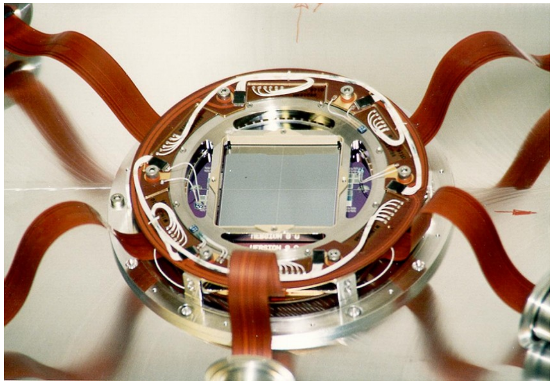


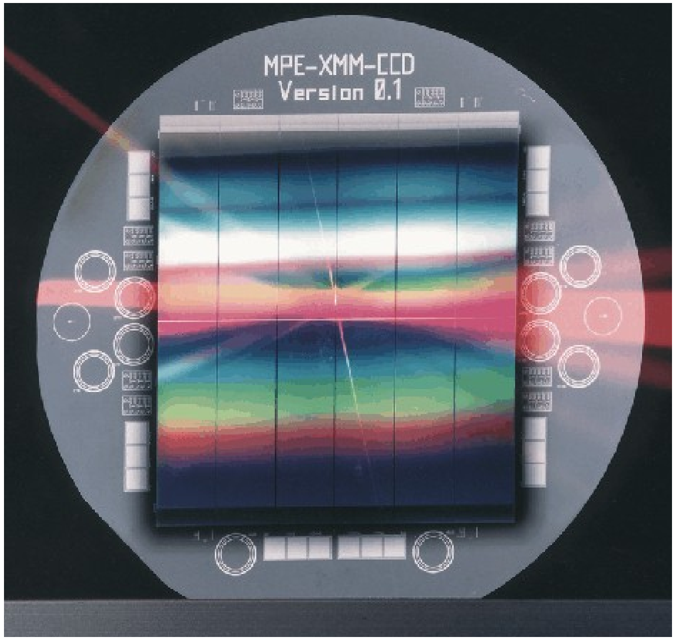
Calibration results from X-ray satellite eROSITA
2.5 e⁻ ENC @ 20µs/row

3.3 e⁻ ENC @ 4.2µs/row

data from:
Proceedings of IACHE-Conference 2017, Vadim Burwitz, MPE

Applications I: Astronomy

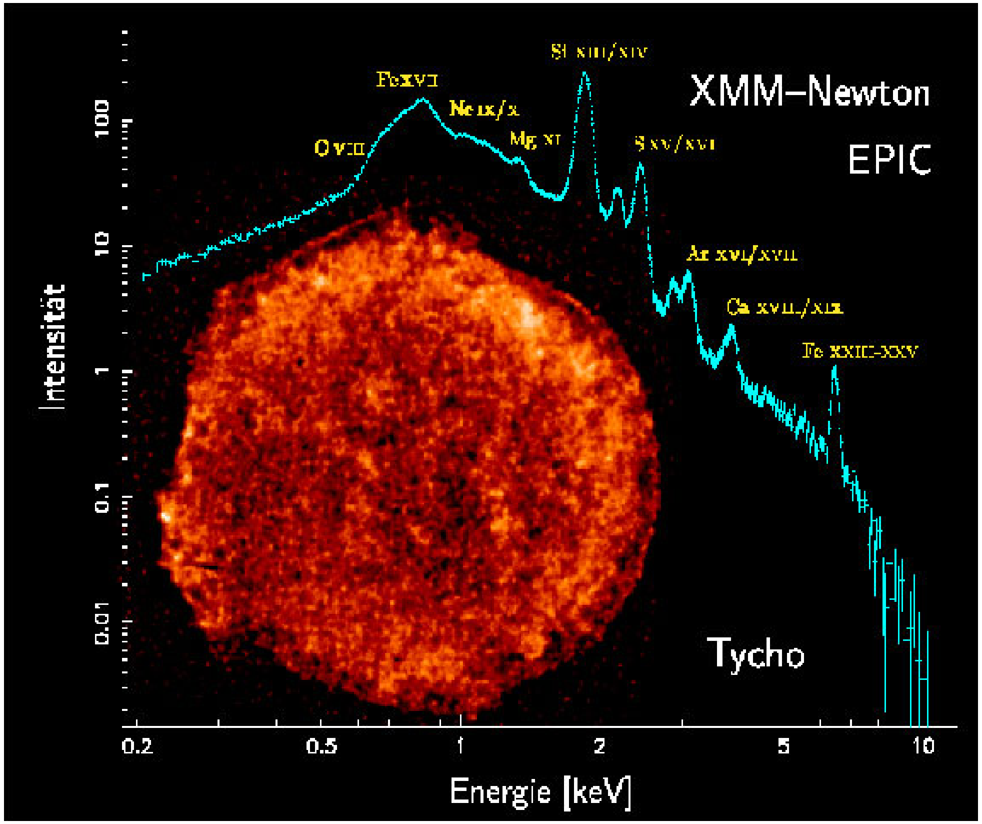


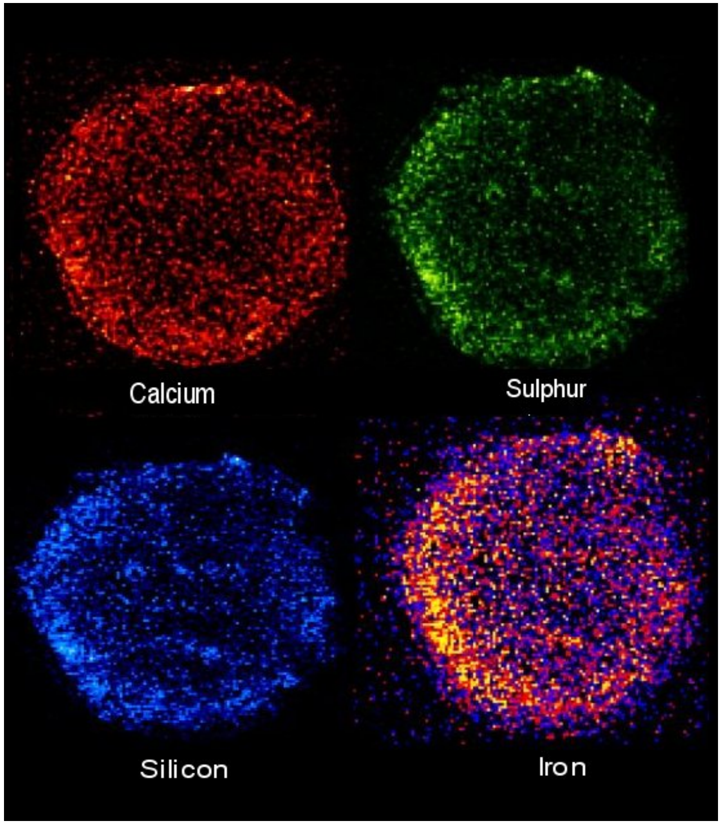


XMM-Newton: Launch 1999 by ESA
150 µm pixelsize, 280 µm thick
no Framestore
resolution 140eV@5,9keV, degrading by 2,5eV/year

until today > 5800 reviewed papers, still growing

Applications I: Astronomy

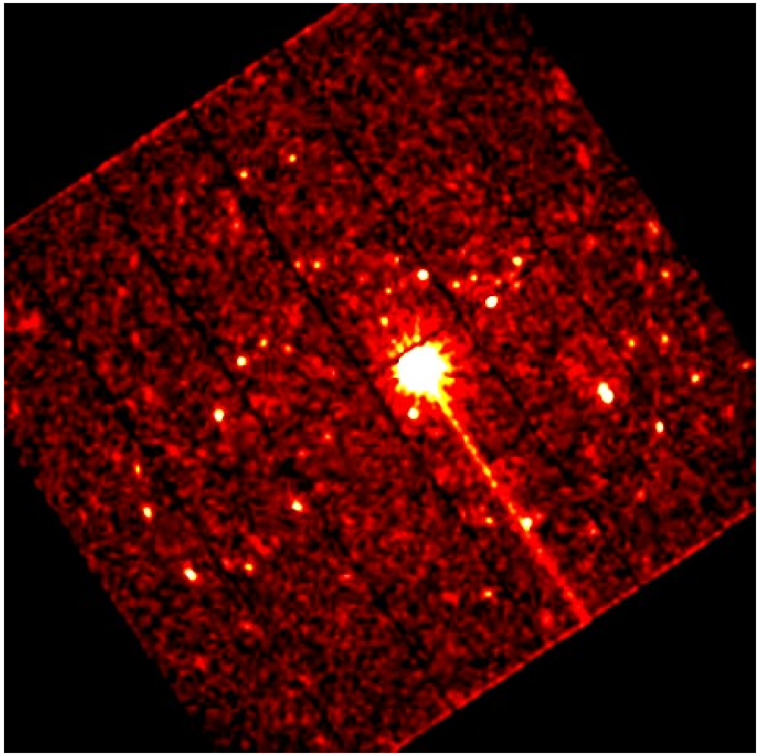




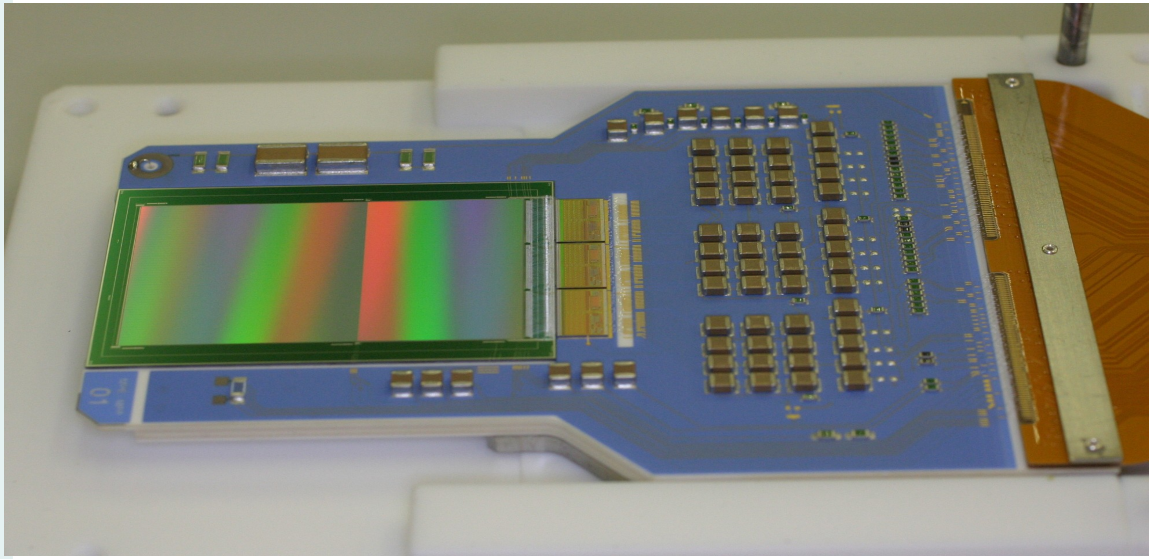
Applications I: Astronomy

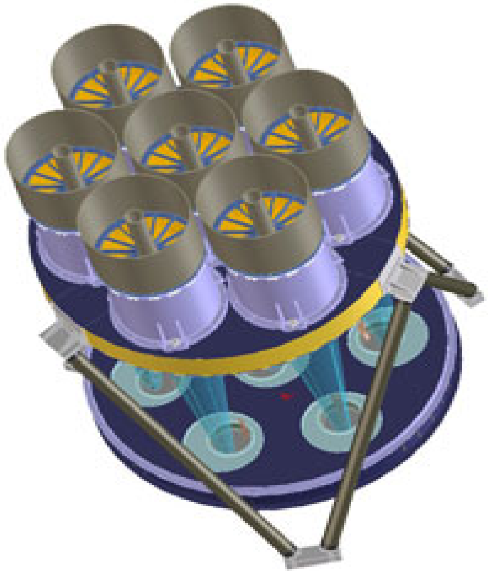
´out of time´ events increase with source strength if there is no framestore

EPIC pn-CCD: ~ 6 %



Applications I: Astronomy



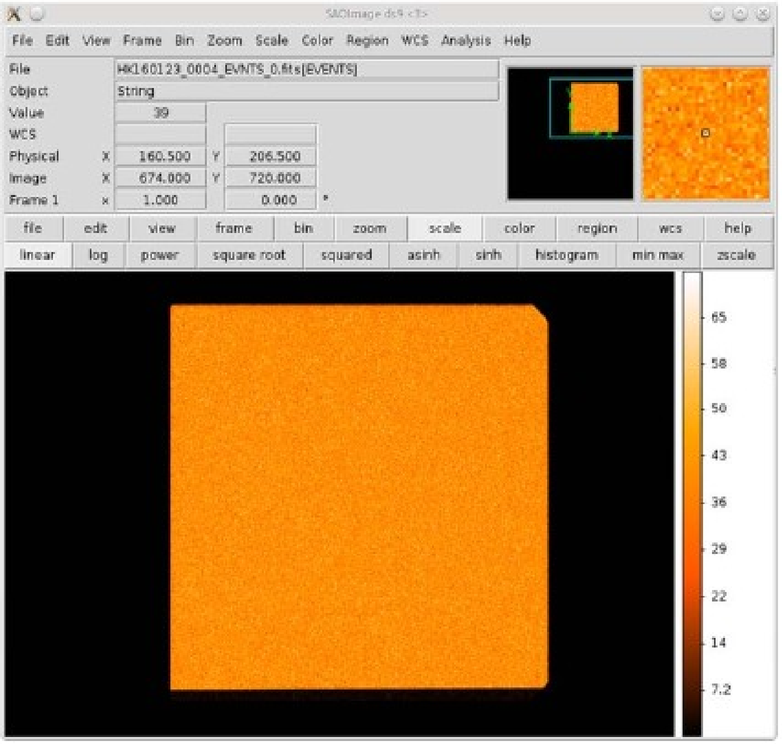


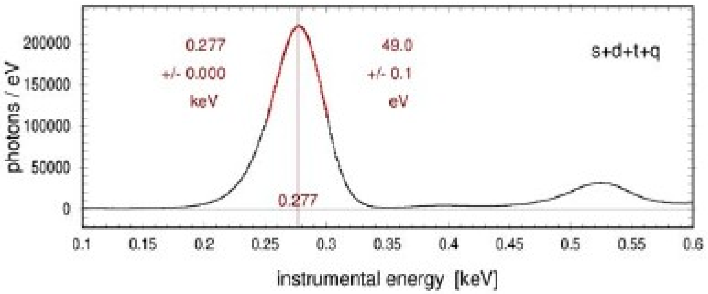
Russian/German Satellite, launch 2018

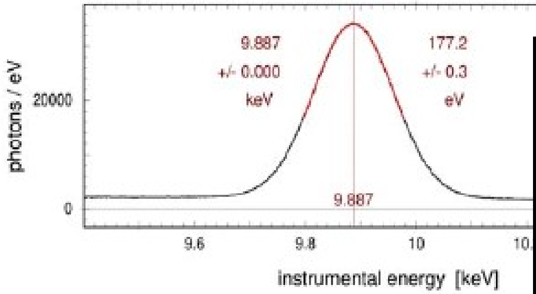
- 7 pn-CCDs with framestore
- 75µm pixelsize, 450 µm thick
- 2,5 e^- ENC
- Energy resolution **at the limit** of Si

eROSITA calibration before launch

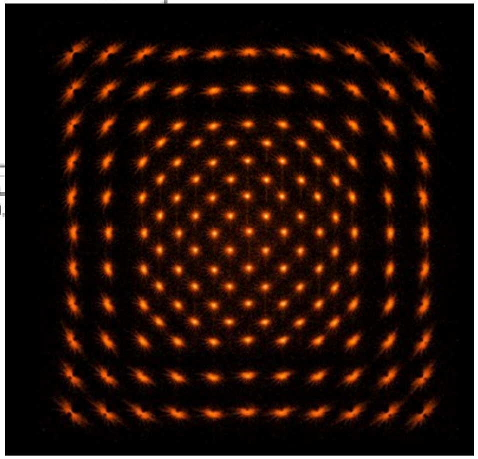
- Spectral resolution at all 9 measured energies well within specification
- Extremely good uniformity
- Only weak dependence on temperature of CCD and electronics (unlike XMM-EPIC!)





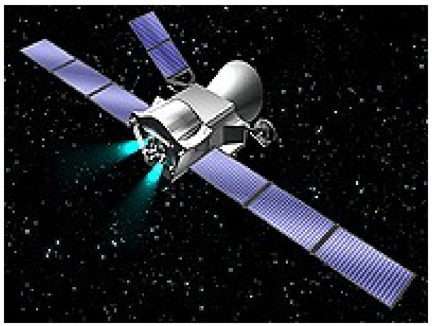


Focal plane map Al Kα

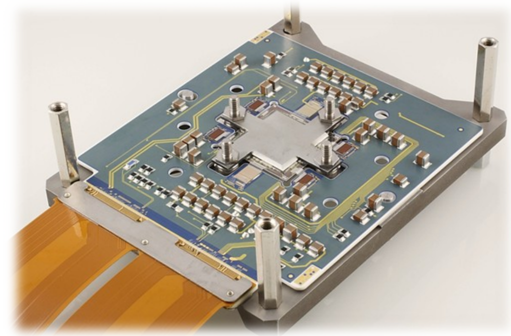


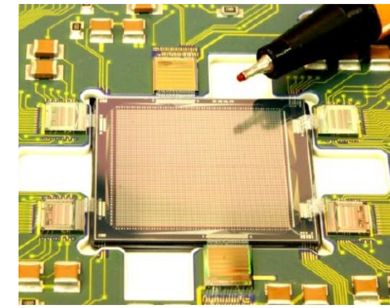
Proceedings of IACHE-Conference 2017, Vadim Burwitz, MPE)

Next generation spectroscopic X-ray imagers will not be CCDs but DEPFETs.

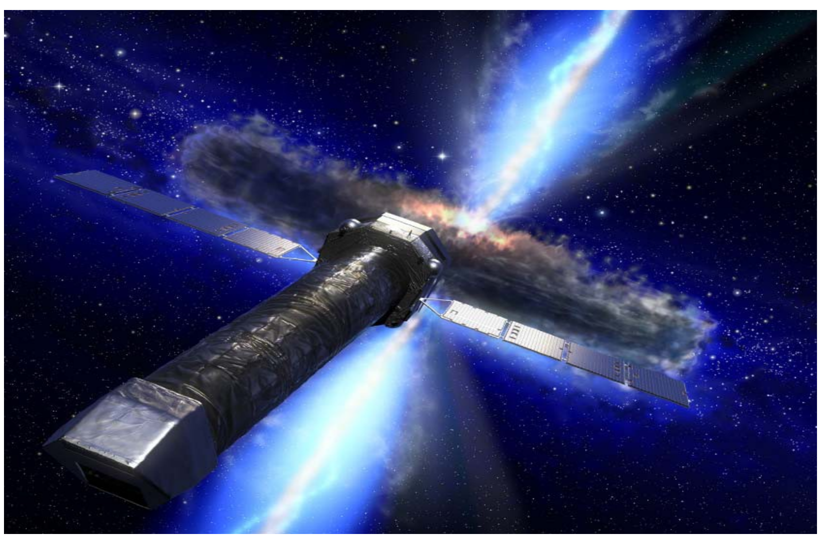


BepiColombo,ESA, launched only 4days ago, on its way to mercury

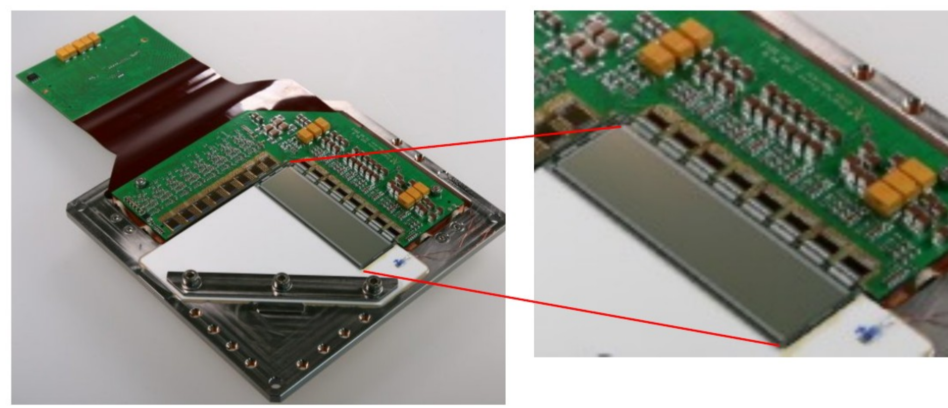




The MIXS instrument contains an array of SDDs (300x300 μm²) with DEPFET readout nodes



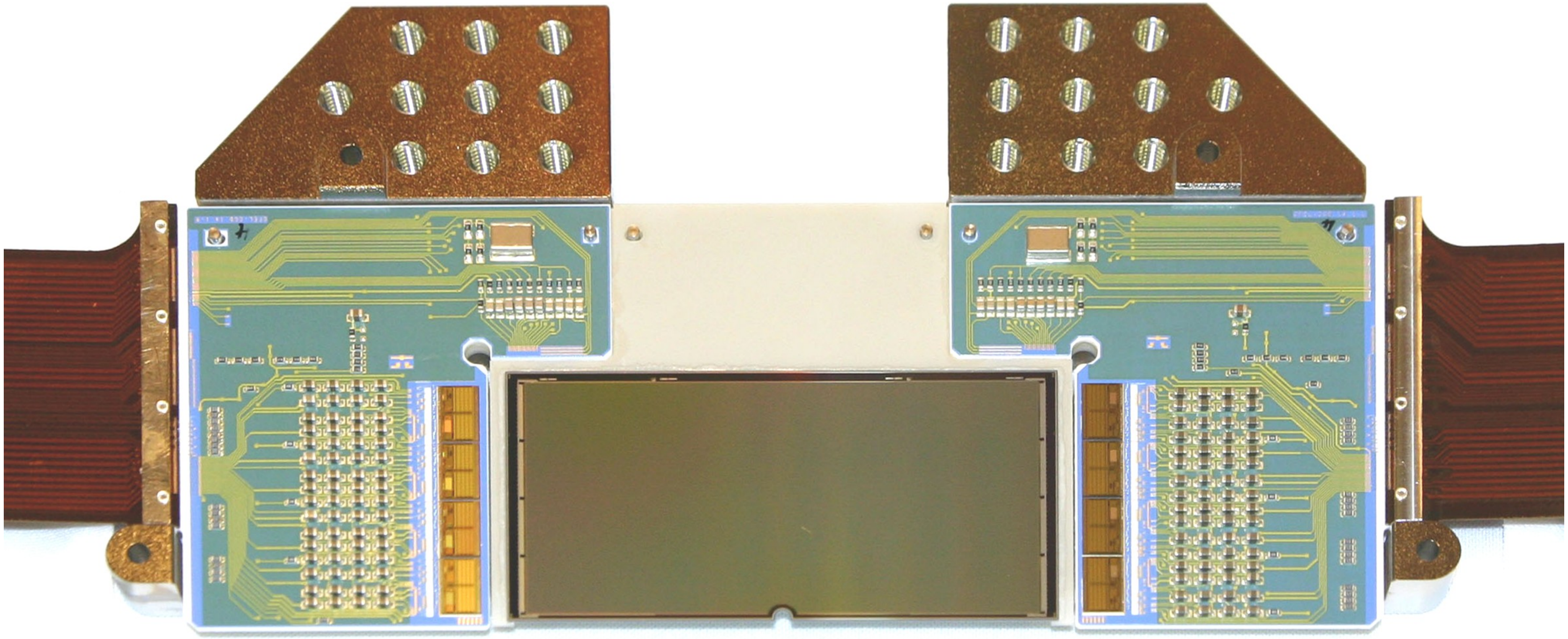
ATHENA, launch 2028



Wide Field Imager (WFI) DepFet array.

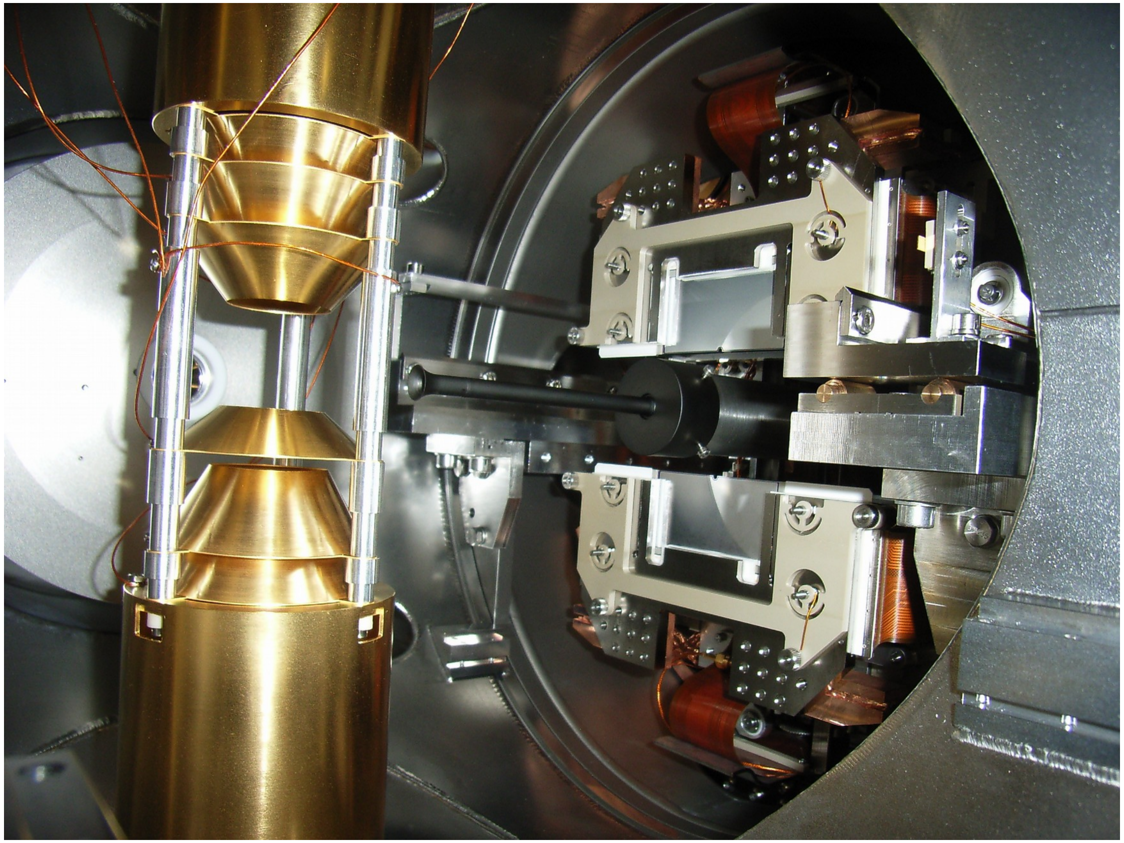
1 MPix with 120x120 μm² pixel

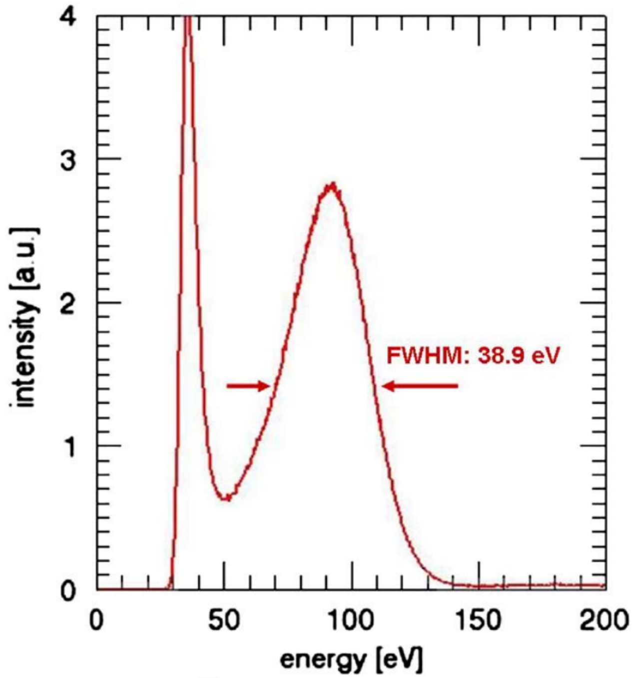
Applications II: X-ray scattering



Pulsed source with known energy -> Read integrated Flux, not spectroscopic
Framerate has to cope with repetition rate.

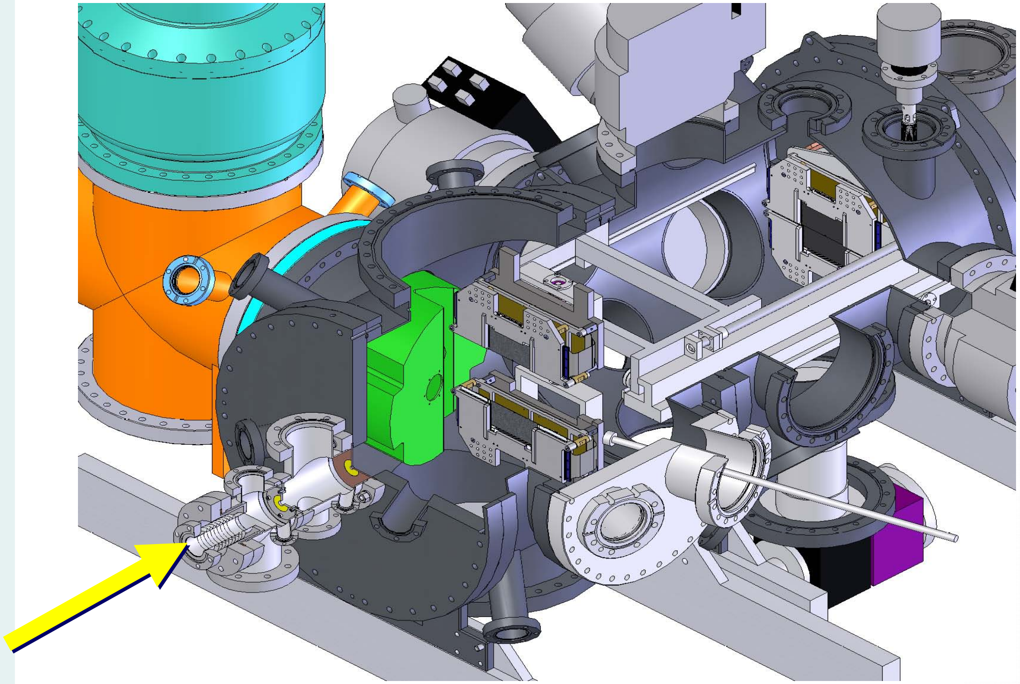
Applications II: X-ray scattering





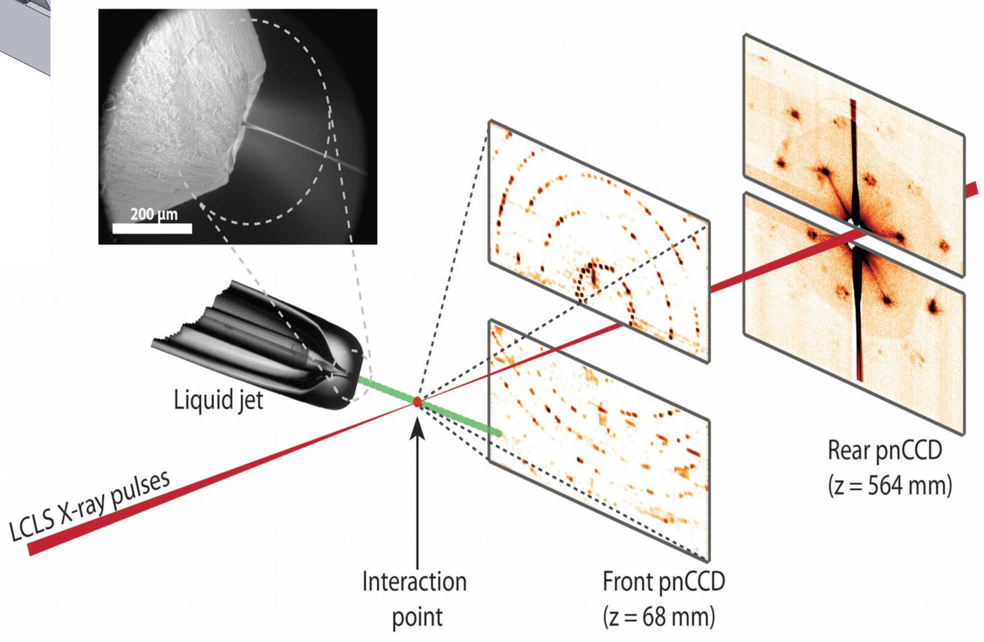
CAMP chamber at FLASH with 90 eV photon's spectrum

Applications II: X-ray scattering



FEL Photon beam

LAMP and CAMP chambers
in Stanford-LCLS and DESY-Flash

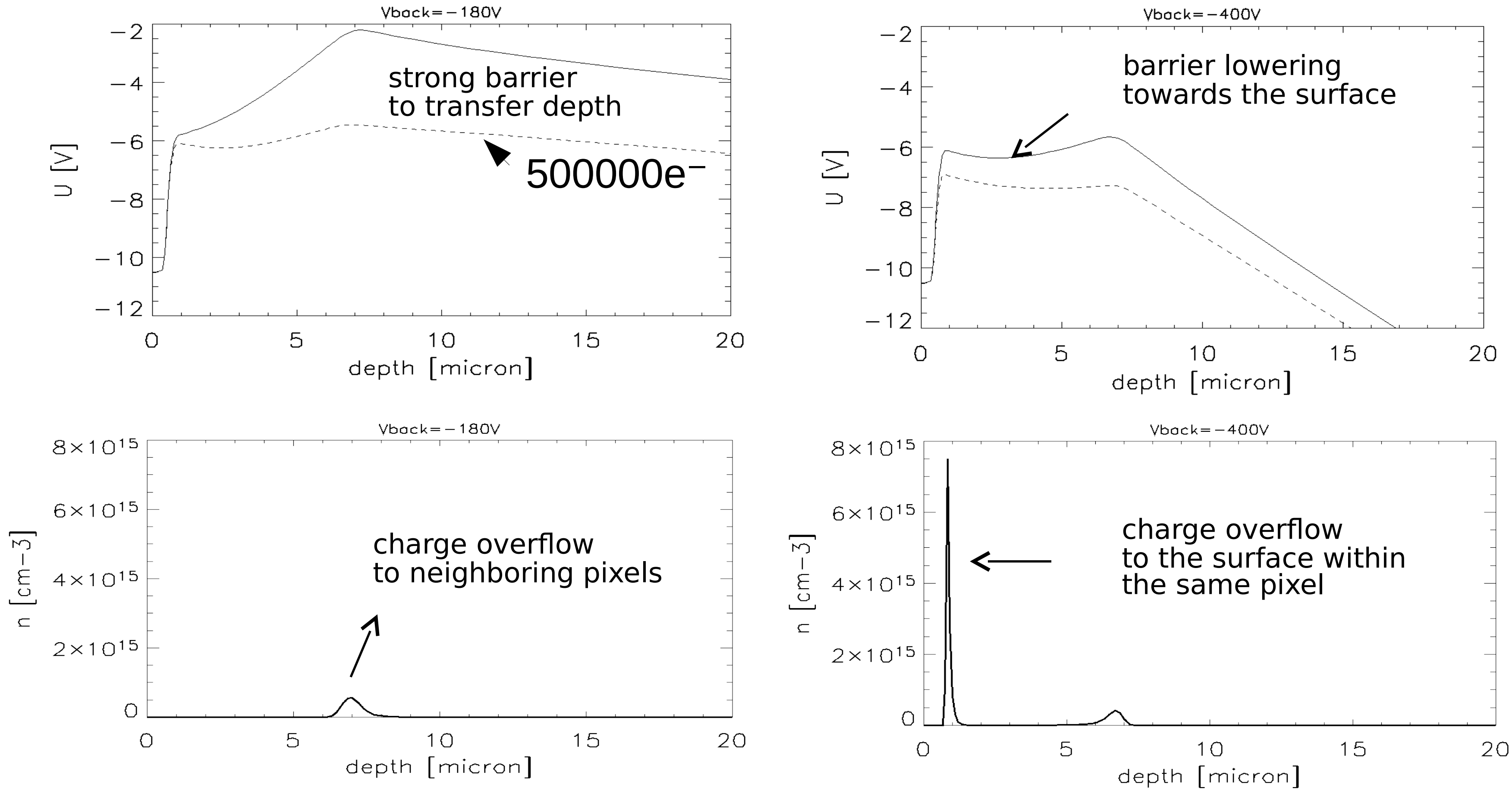


Henry Chapman, *Nature* 470, 73–77 (03 February 2011)

Application II: dynamic range matters

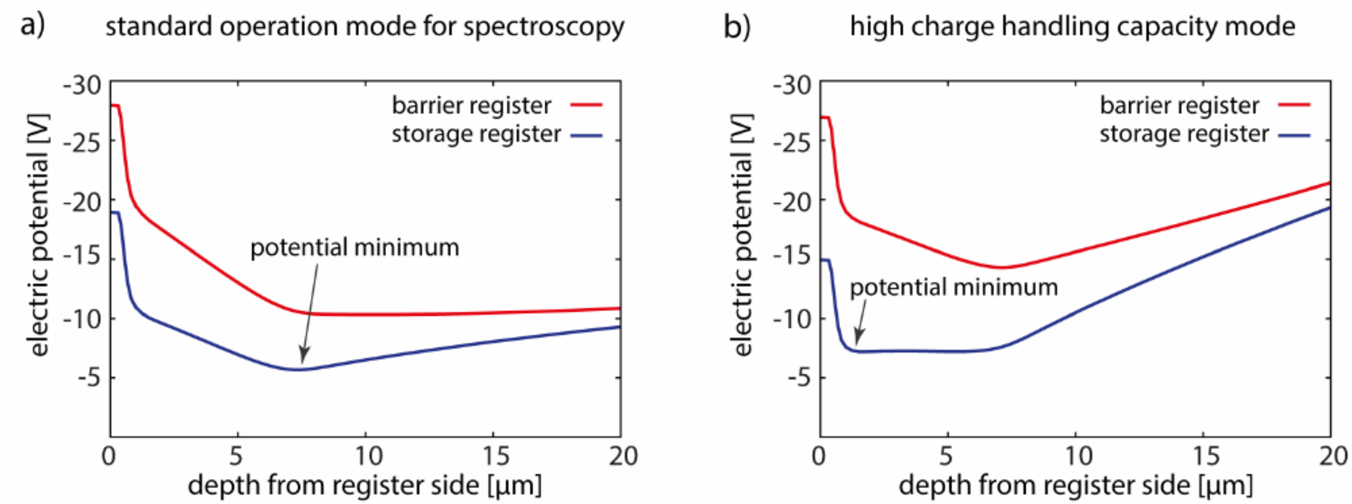
Perpendicular cross section through a register (top to back)

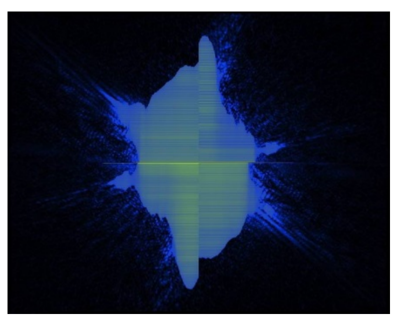
Normal operation **HDR operation**



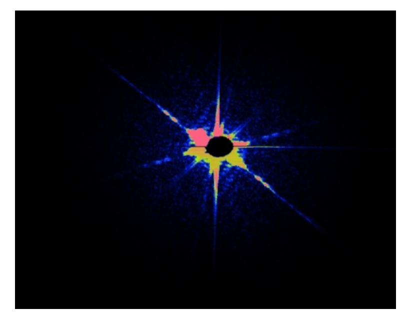
Very high charge handling capacity (1-2 Mio e-) has been found by using large negative backside bias and positive MOS bias.

Application II: dynamic range matters





200 ke- dynamic range



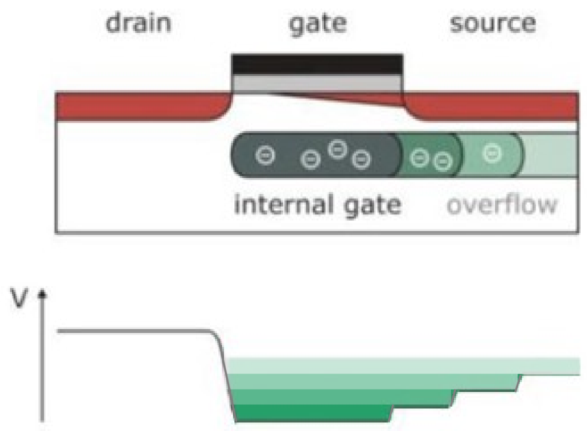
800 ke- dynamic range

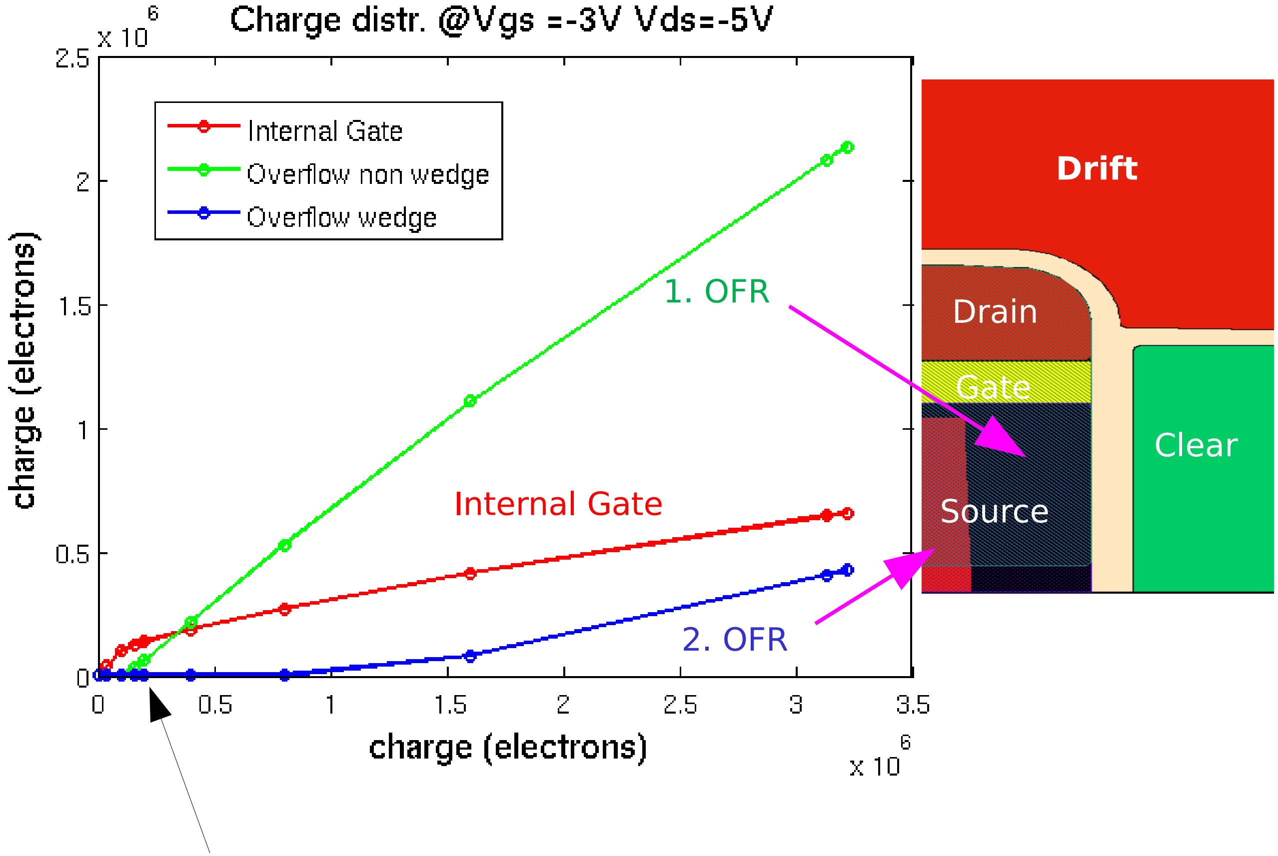
- 2Mio e with 2 e ENC   requires 20bit resolution ADC
- Source follower (SSJFET, C360 fF) 5µV/e- -> 10V at output. Gain can't be reduced without sacrificing noise level.

Replace JFET by non-linear, low-noise DEPFET

Create Overflow regions below the source:

Each Overflow Region has a different (smaller) gain.



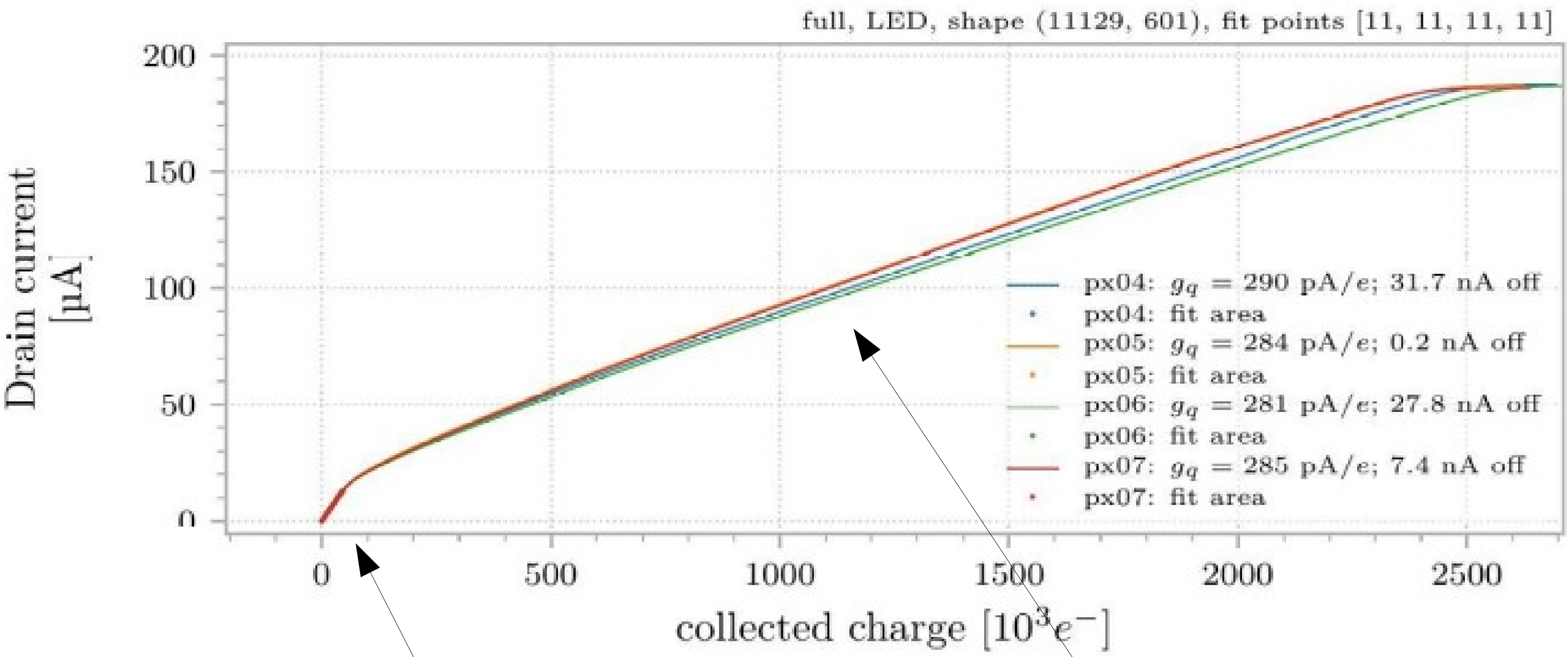


Onset of overflow

= onset of signal compression

Replace JFET by non-linear, low-noise DEPFET

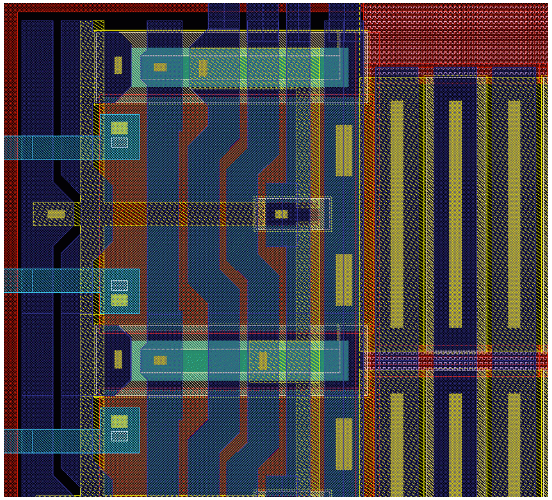
works well for „true“ Depfets, but still needs to be shown to work in pnCCDs.

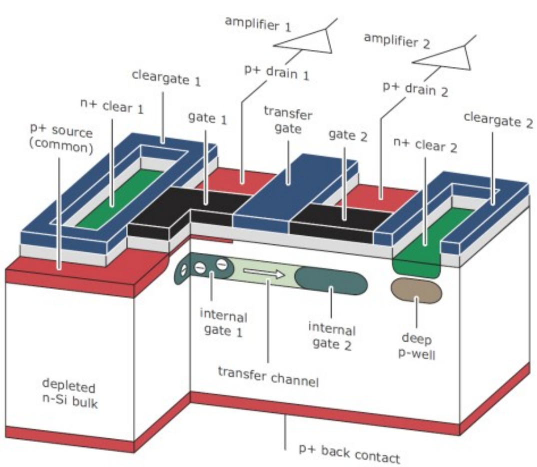


high gain (300pA/e-h) for the first 50.000 electrons.

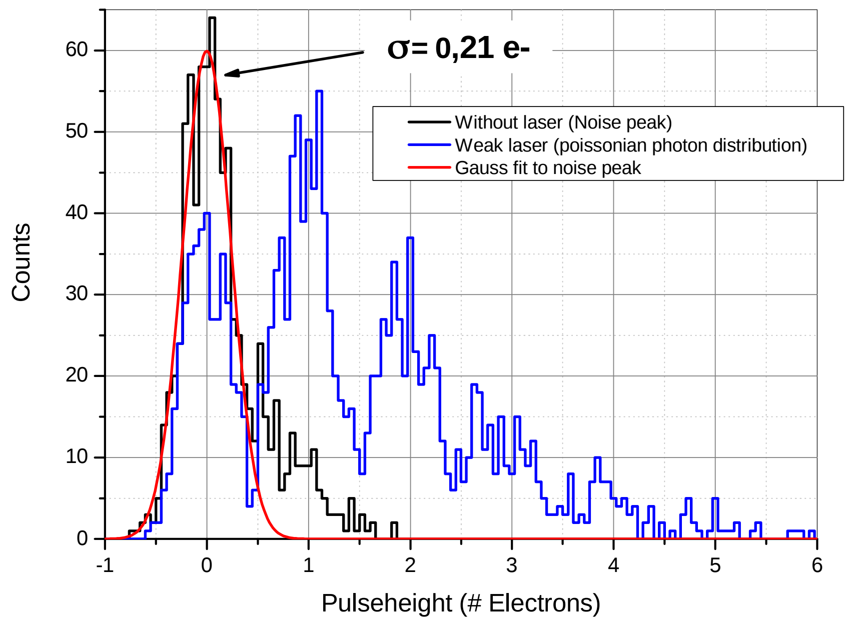
Low gain (70pA/e-h) up to 2.5 Mio. electrons.

Repetitive Non Destructive Readout (RNDR)



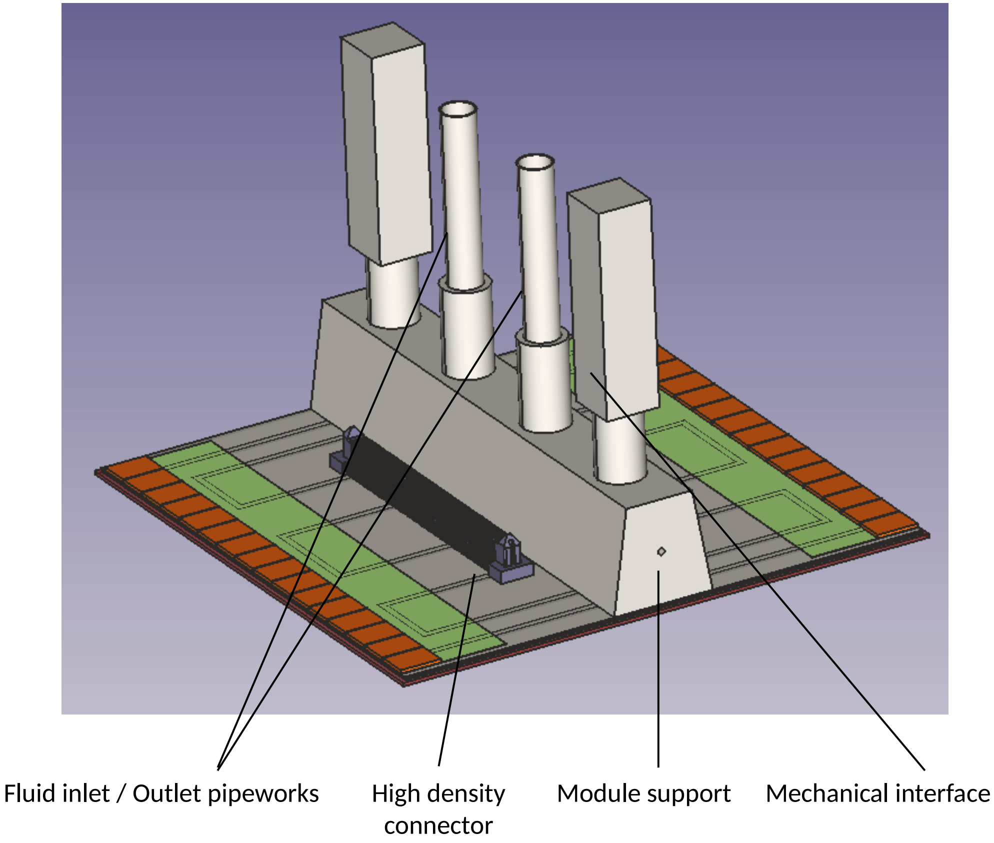


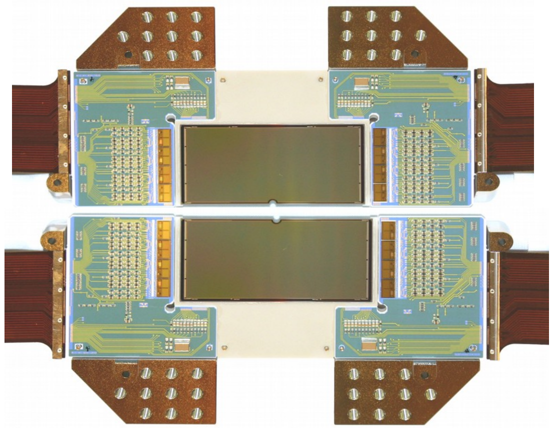
- By measuring the charge multiple (n) time the "effective noise" can be reduced by 1/n .
- Because the collected charge is stored during readout in the DEPFET-RNDR, the very same charge can be measured multiple times.

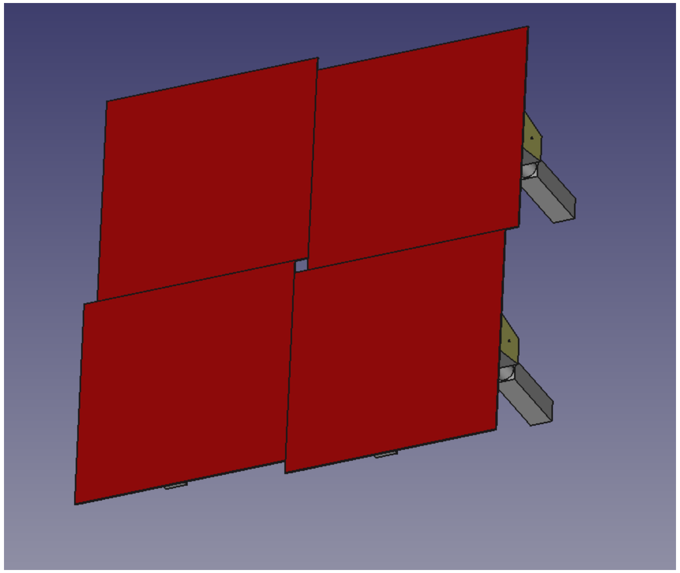


4 side buttable pnCCDs

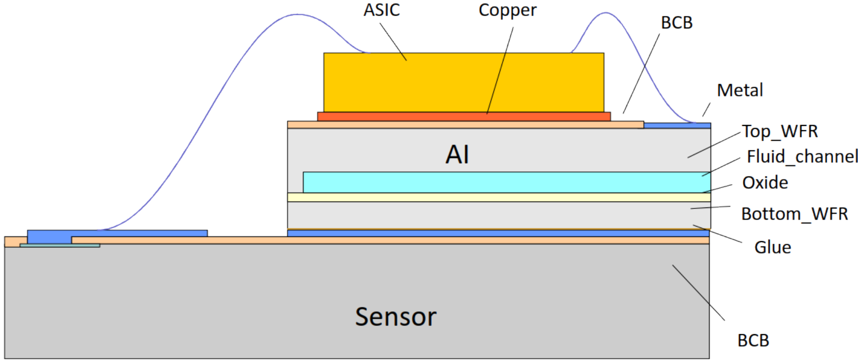
Current setup is only 1 side buttable



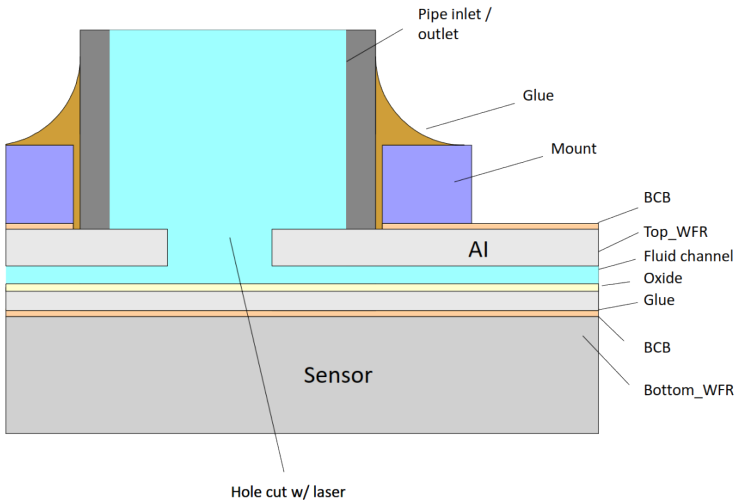


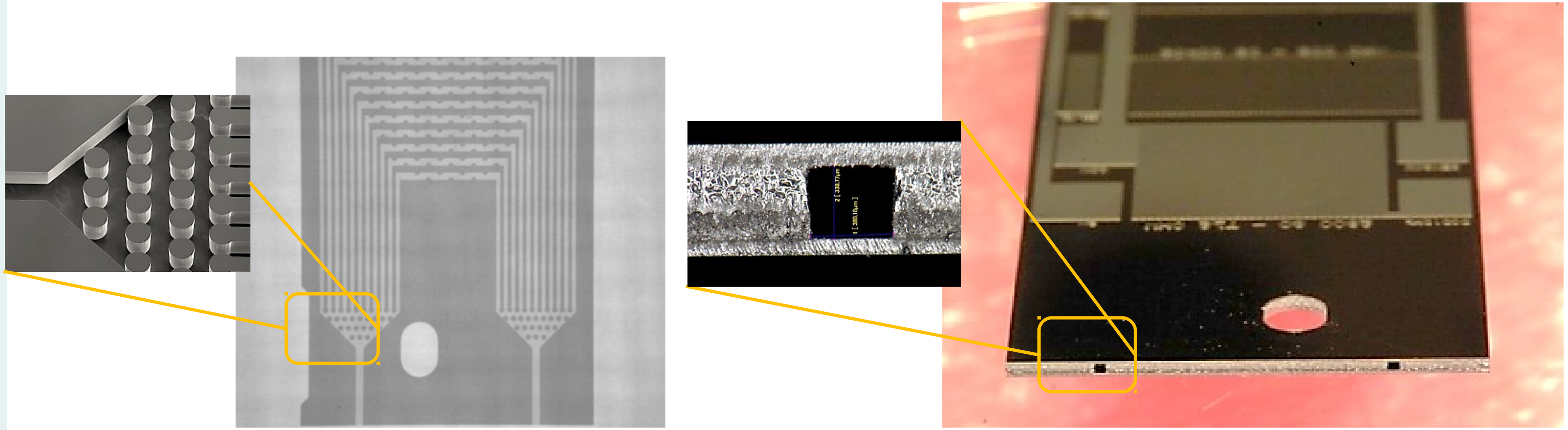


Active Interposer, combines Hybrid and cooling



Active Interposer (AI) approach

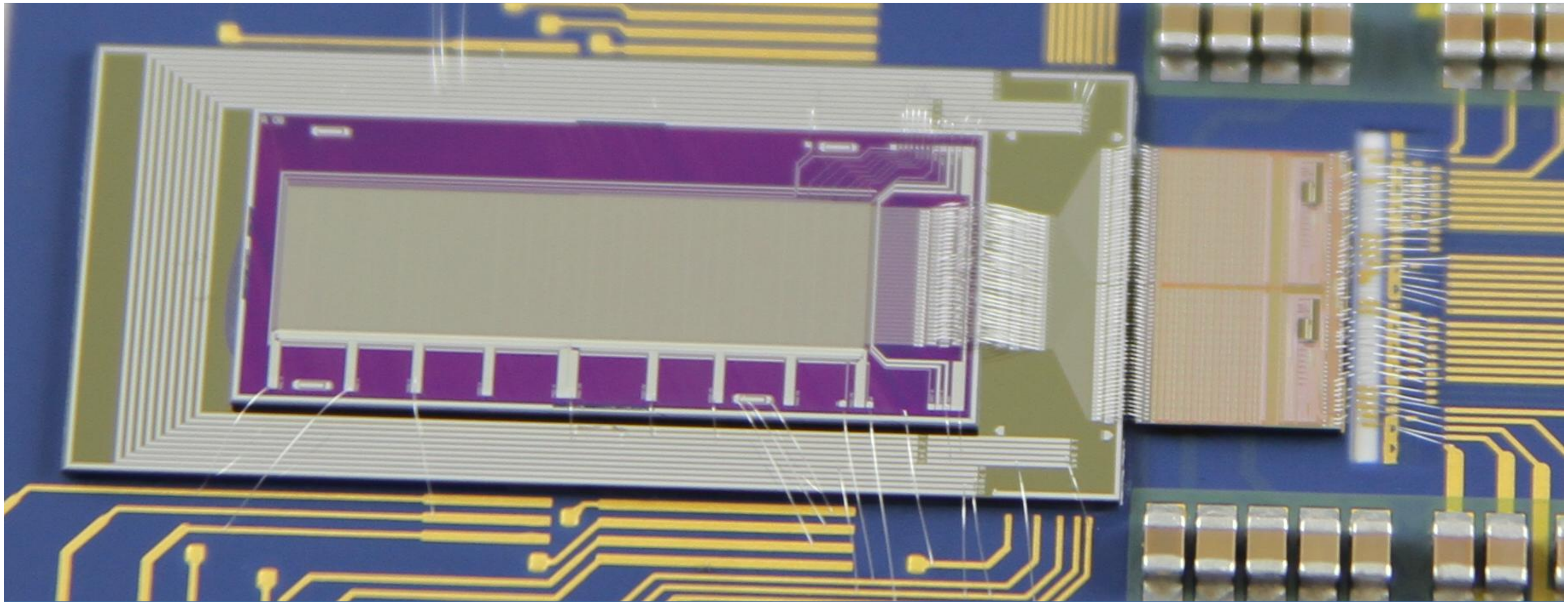




improvements and ideas

- floating MOS-registers (smaller pixels, higher speed)
- DEPFET readout node for pnCCDs
- two-phase pn-CCD (smaller pixels)

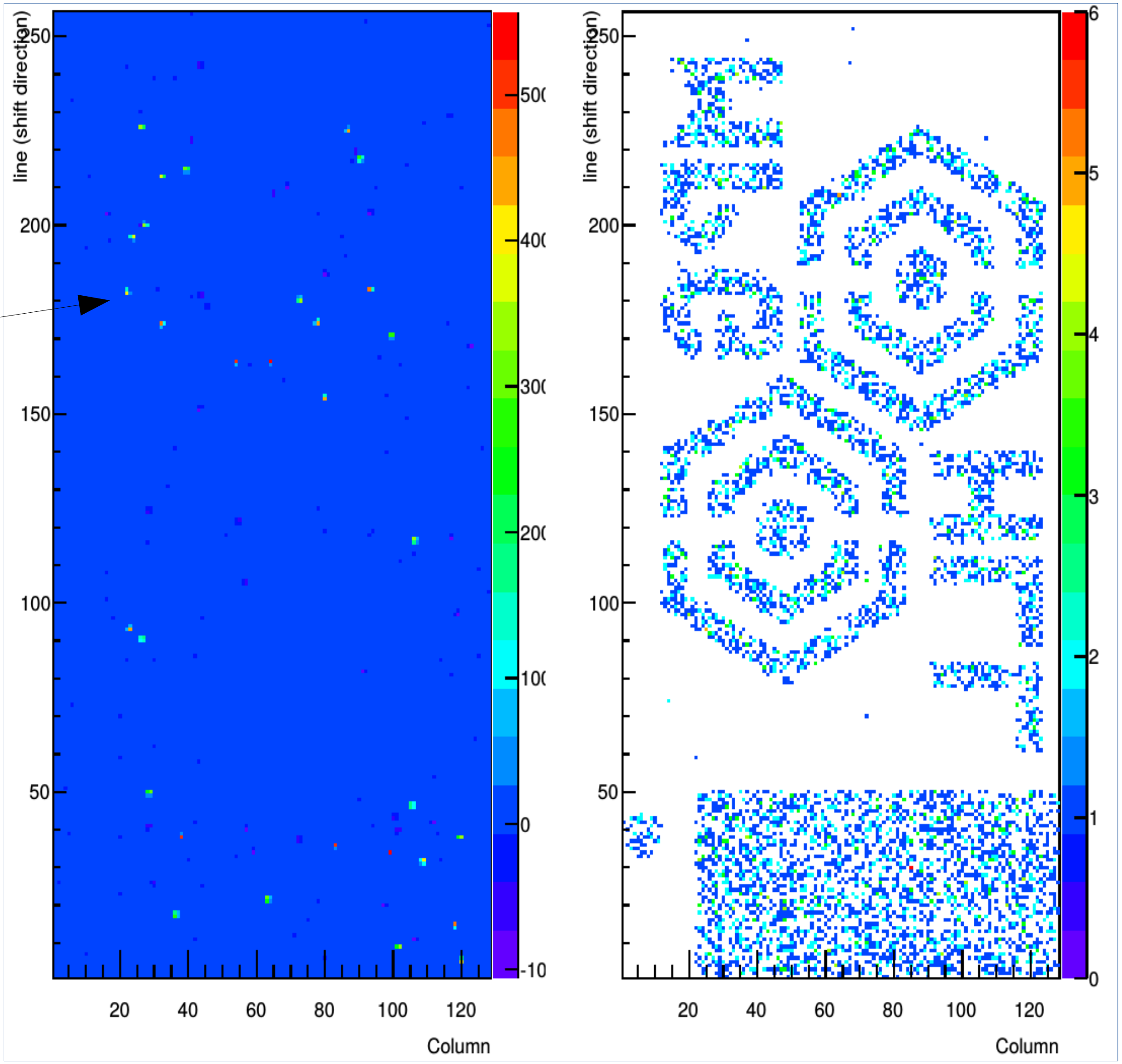
Test-CCDs 128x512 pixels, mounted to Veritas 1.0 ASIC



Applications Ib:
high resolution spectroscopic imaging

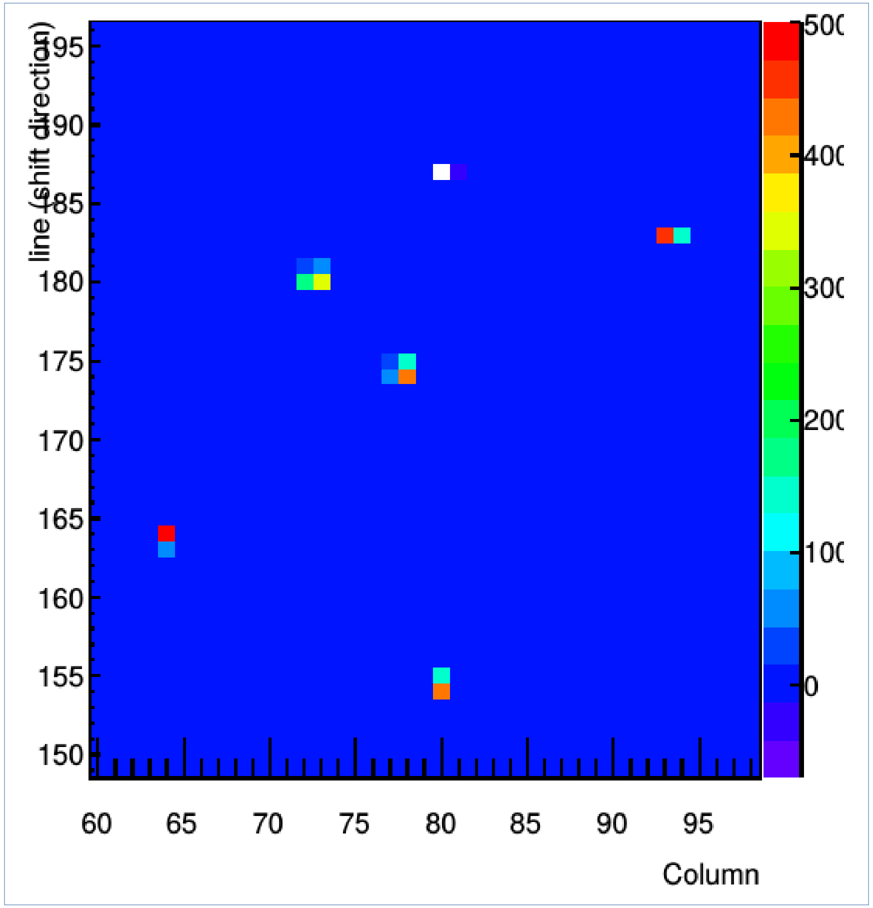
A single Frame | Events from many frames summed to form an image

Hits,
Events,
Photons

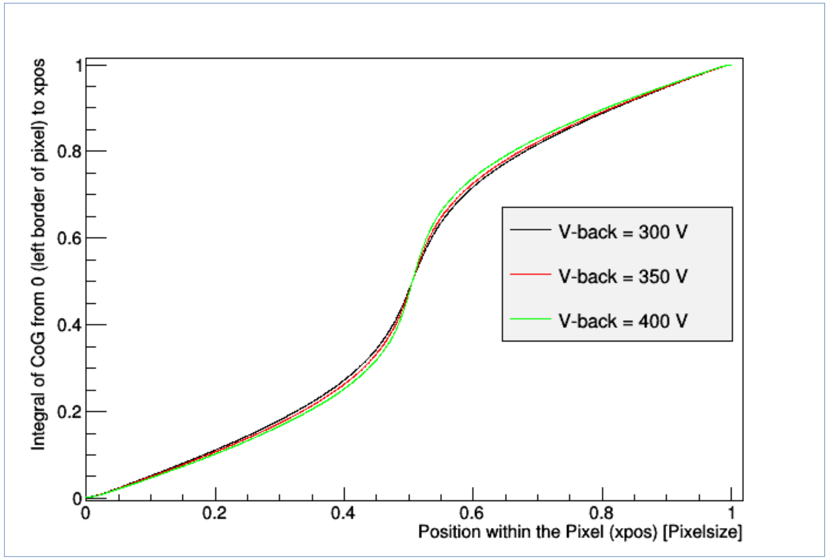


Applications Ib:
high resolution spectroscopic imaging

For 36 µm pixelsize, all photon events can be detected as clusters.



use the η-method as for si-stripdetectors but with 2-D clusters.

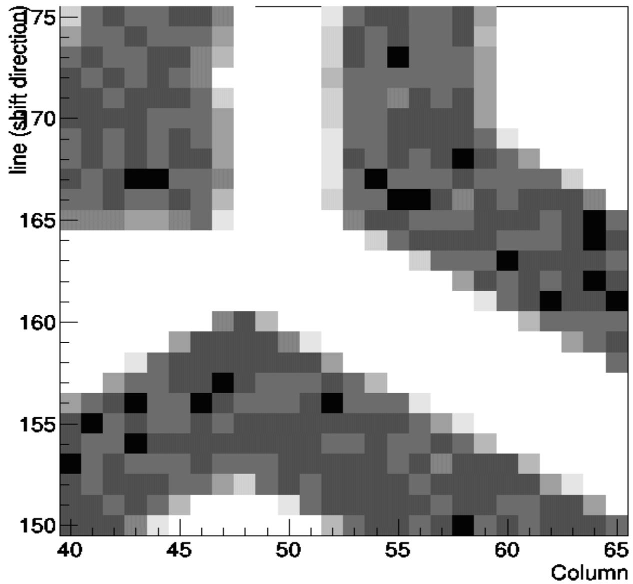


Drifttime and therefore CoG-distribution depends on backside voltage.

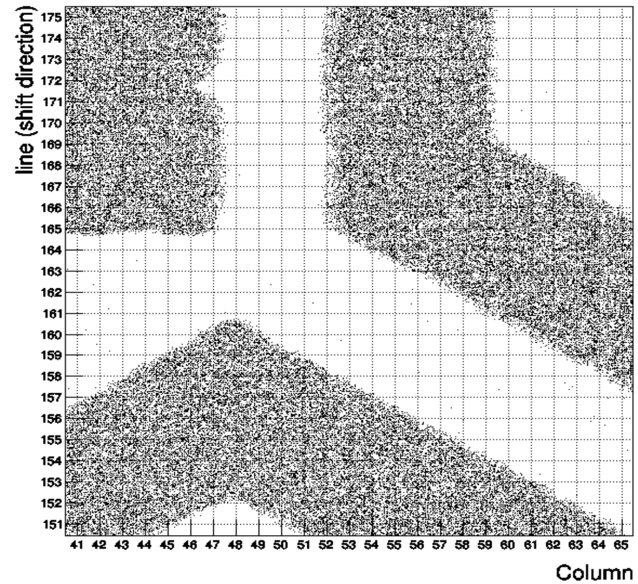
$$7.1\mu m < \sigma_{CDF} < 7.9\mu m$$

Applications Ib: high resolution spectroscopic imaging

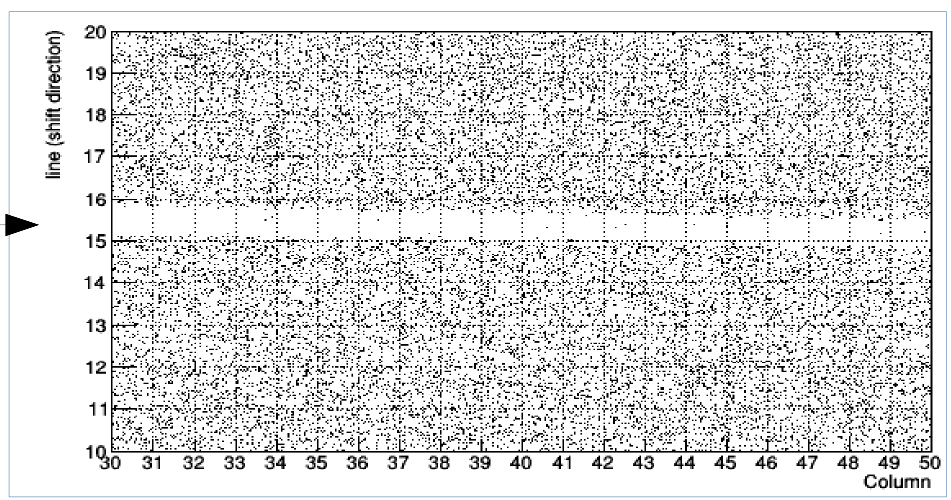
CCD pixels

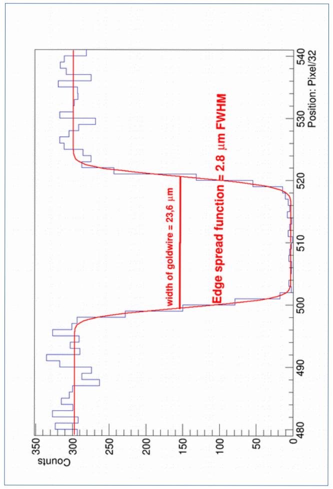


hit positions placed on 32x32 Subgrid



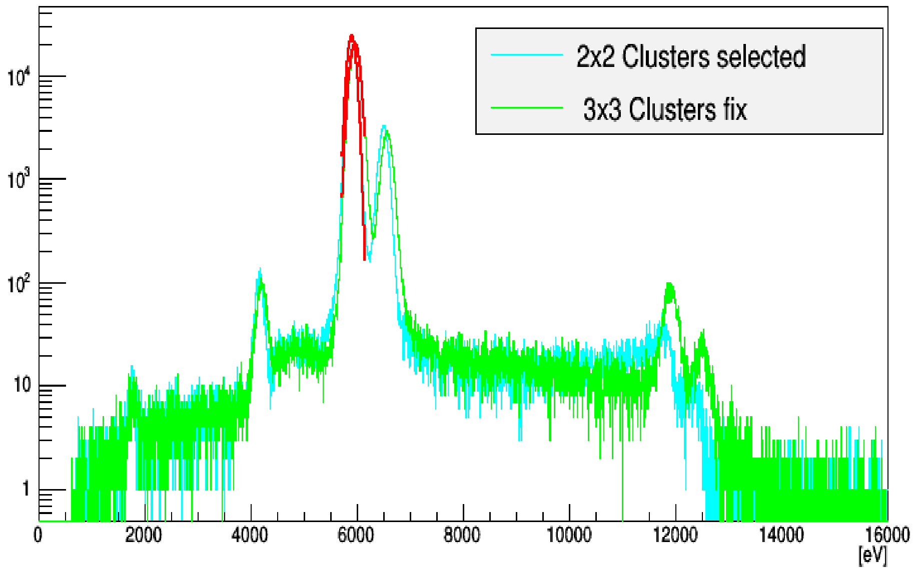
Goldwire
24 µm
diameter



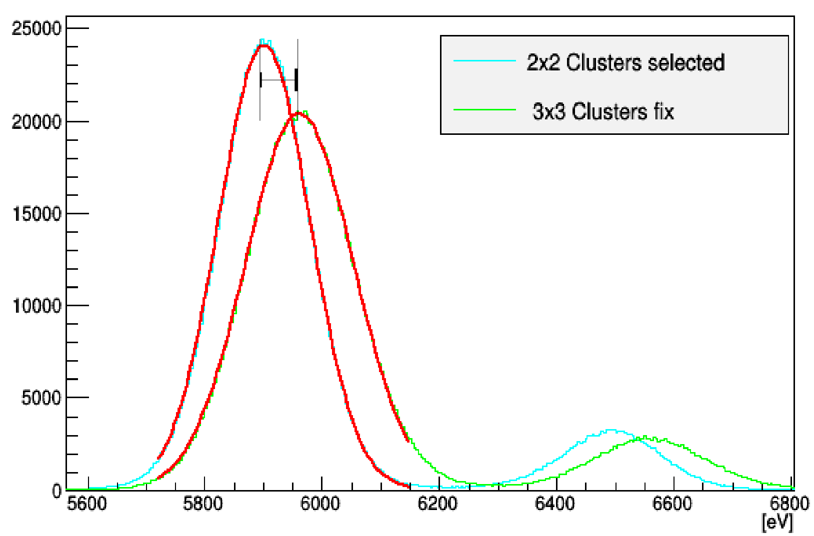


σ=1.2µm

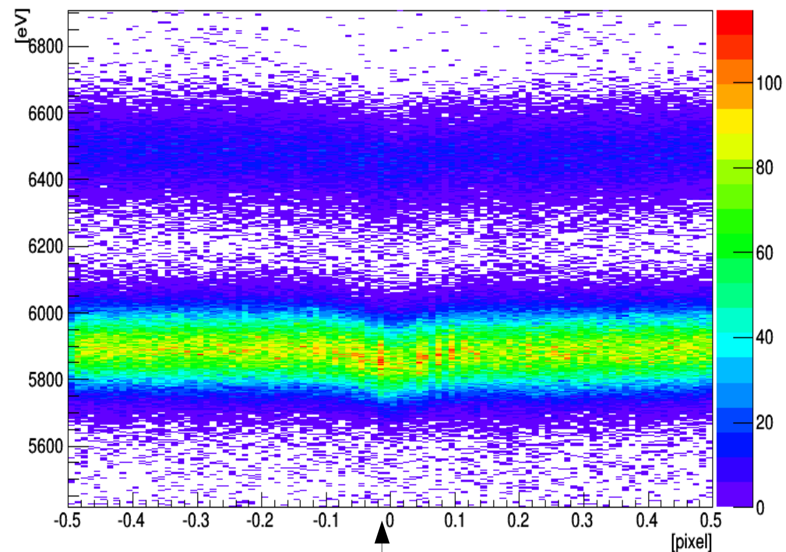
spectrum from 2x2 clustes, dependence on interaction position



Peakshift of 60 eV (~1%)



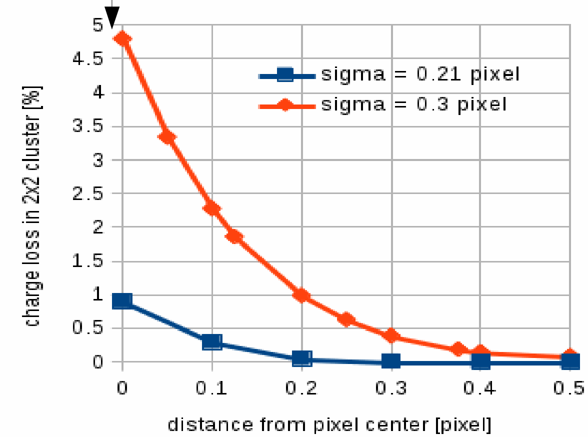
event position within pixel



pixel center

25 µm pixel

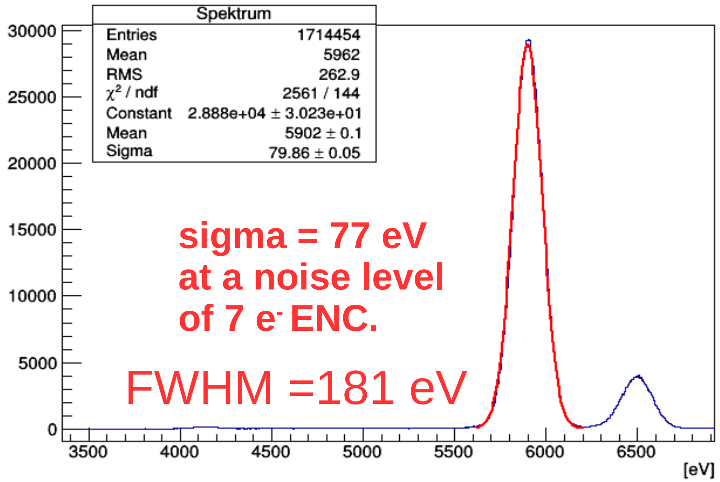
36 µm pixel



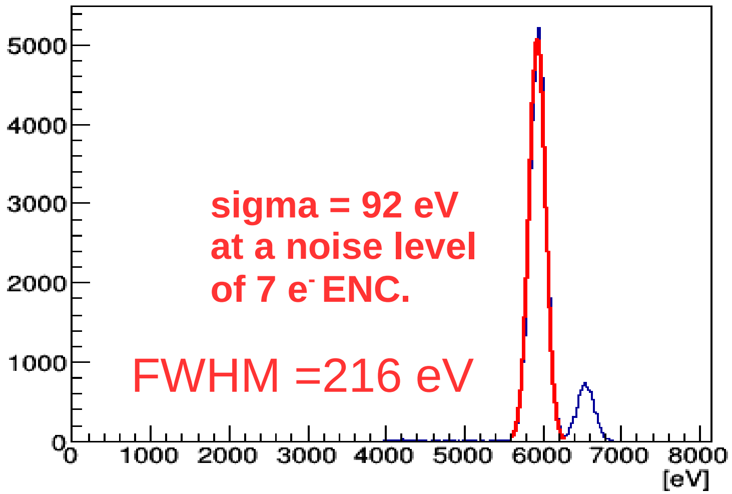
expected charge loss for 2-D CDF with σ=7.5µm

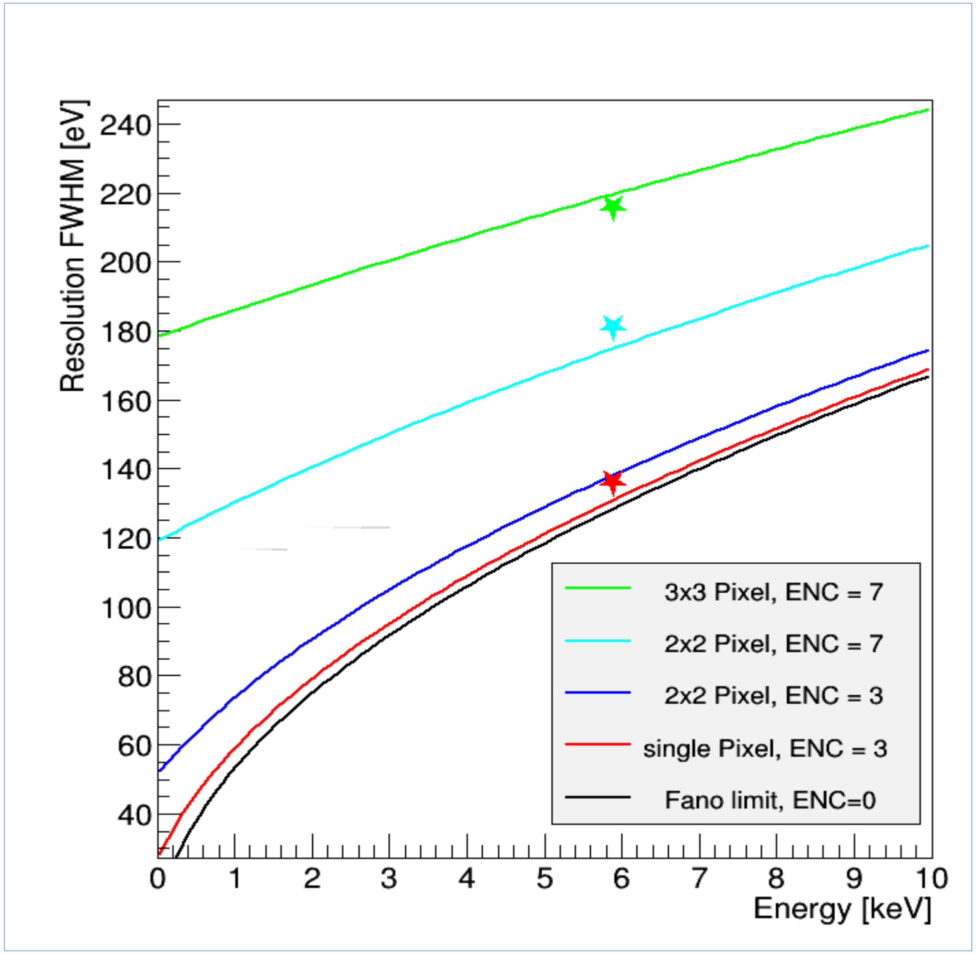
Applications Ib: charge sharing spoils the spectrum if S/N is poor

2x2 pixels are summed



3x3 pixels are summed

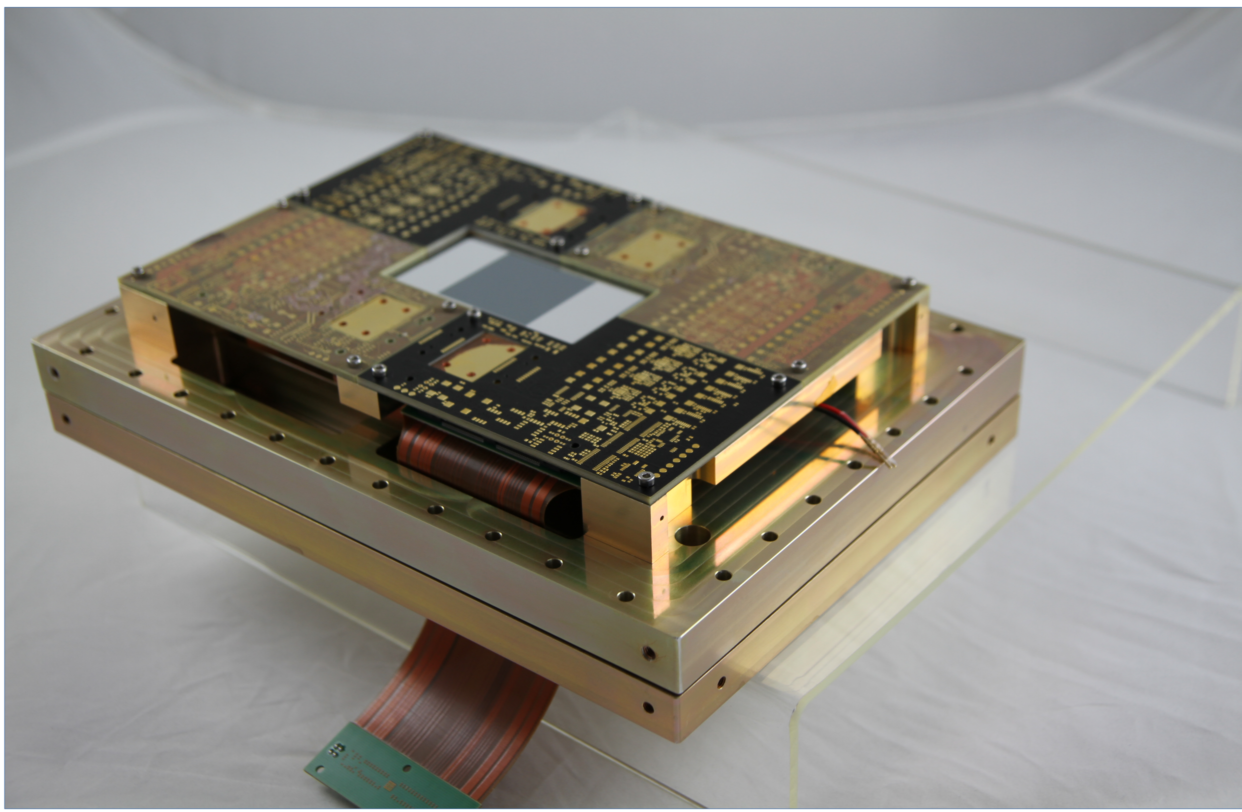


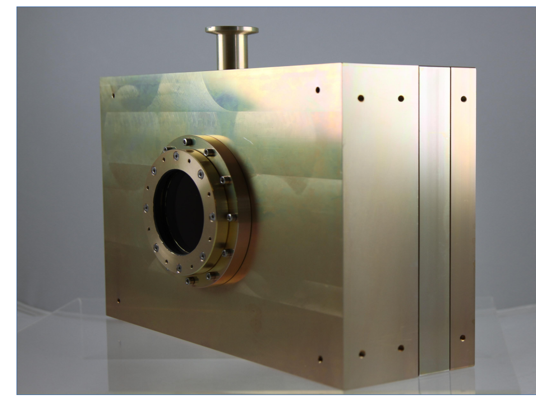


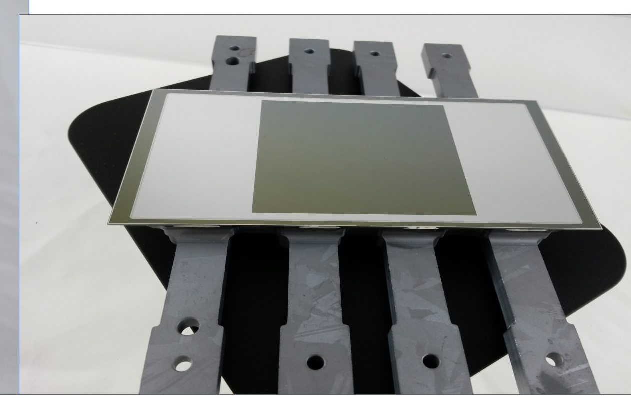
Under Construction, 2Mpix interpolating pnCCD

readout in two directions at 4µs/line -> **0.5 kHz Framerate at <3 e^- rms noise**

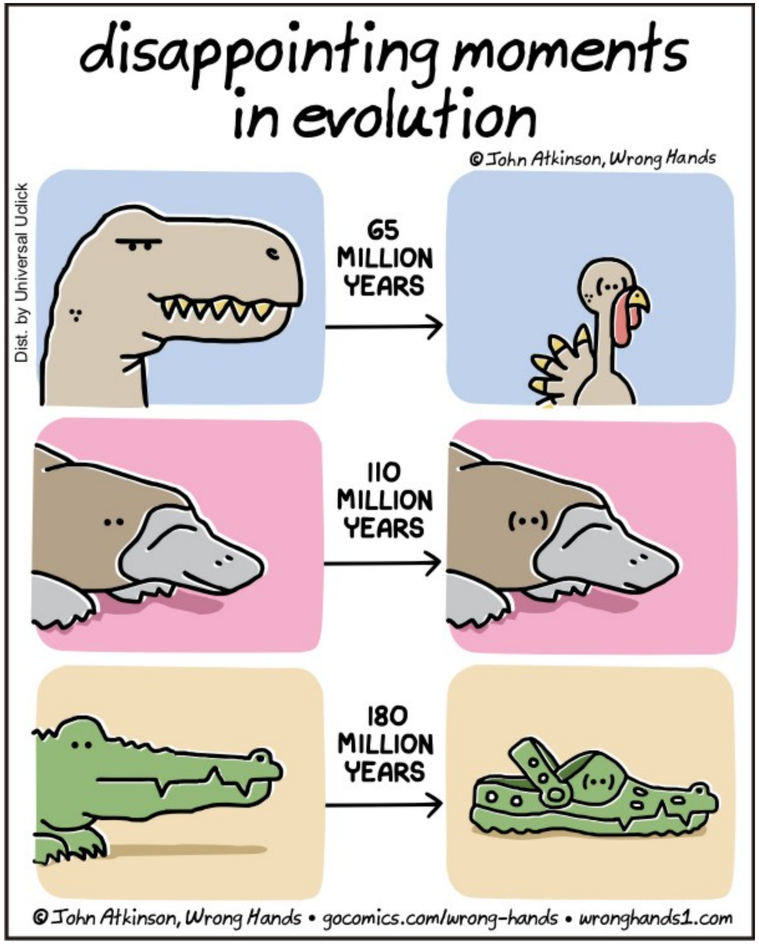
position interpolation of events corresponds to: **2,2 Gpix @ 1.12 µm size.**





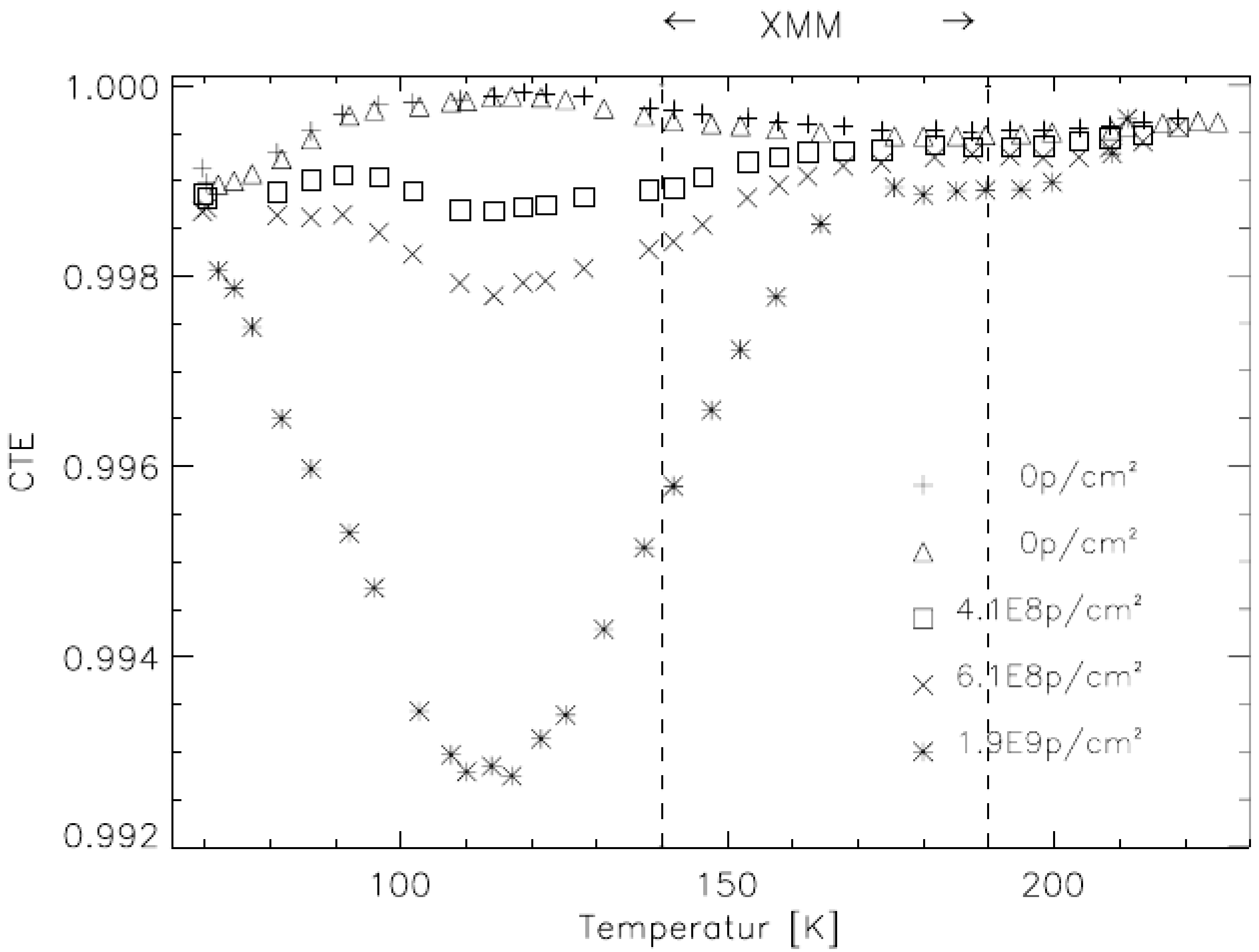


we hope to do better

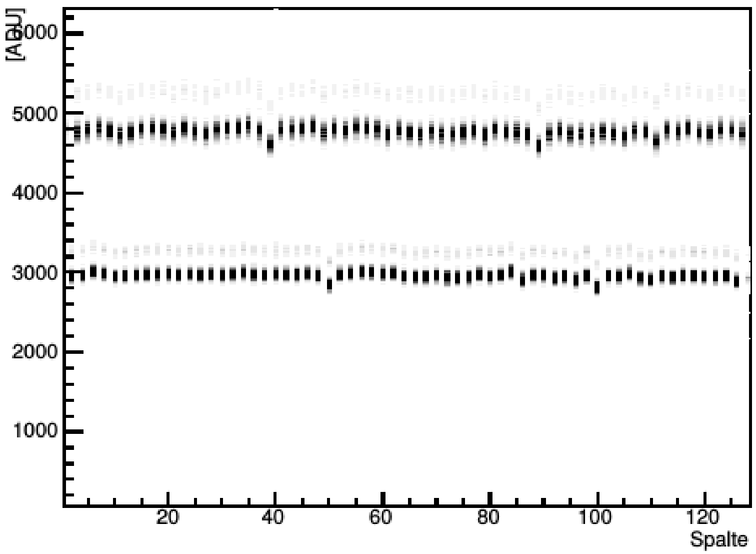


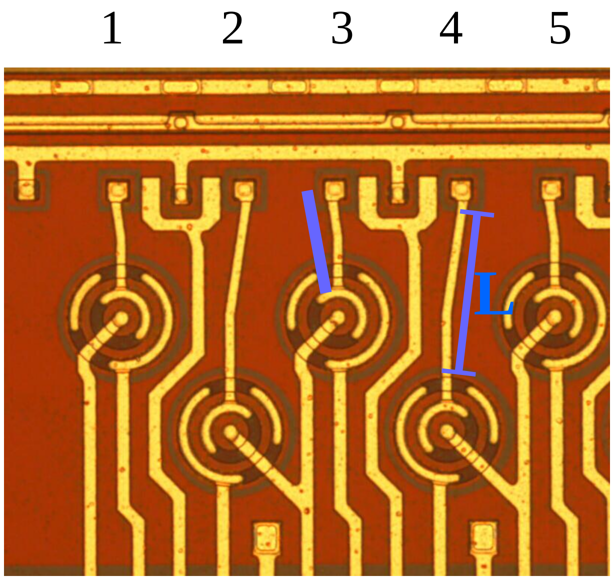
thanks for your attention

Radiation damage due to 10MeVprotons



Channel gain variation due to varying length of input lines

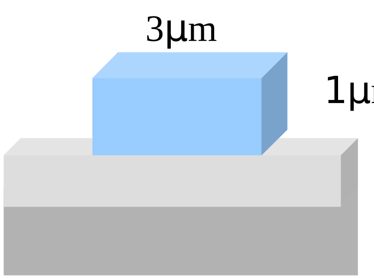




$$C = C_{fix} + C_L \cdot L$$

$$\frac{U_1}{U_2} = 0.625 = \frac{C_{fix} + C_L \cdot L_2}{C_{fix} + C_L \cdot L_1}$$

	length L	C_L L	C_{fix}	C
odd channels	21 µm	6,9 fF	13.9 fF	**20.8 fF**
even channels	59 µm	19,4 fF	13.9 fF	**33.3 fF**



From [„The design and Analysis of VLSI Circuits“ by L. Glaser]

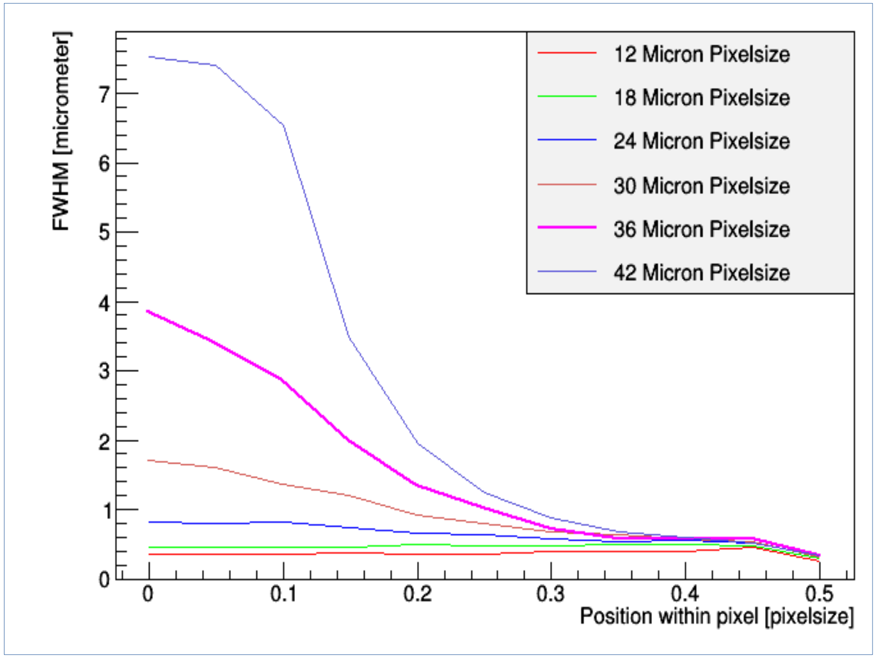
C_L = 0,33 fF/µm

We calculate **the same Values for C from the ASIC Gain** (51) on the 14 Bit / 2V ADC.

Applications Ib:
high resolution imaging needs good S/N, no limit by Fano-statistics

- define a position x and calculate signals from CCF(x,σ) for all pixels with **σ=7.5μm**
- add noise to each signal with **S/N = 1650e⁻ / 7e⁻ = 235**
- recalculate position from data

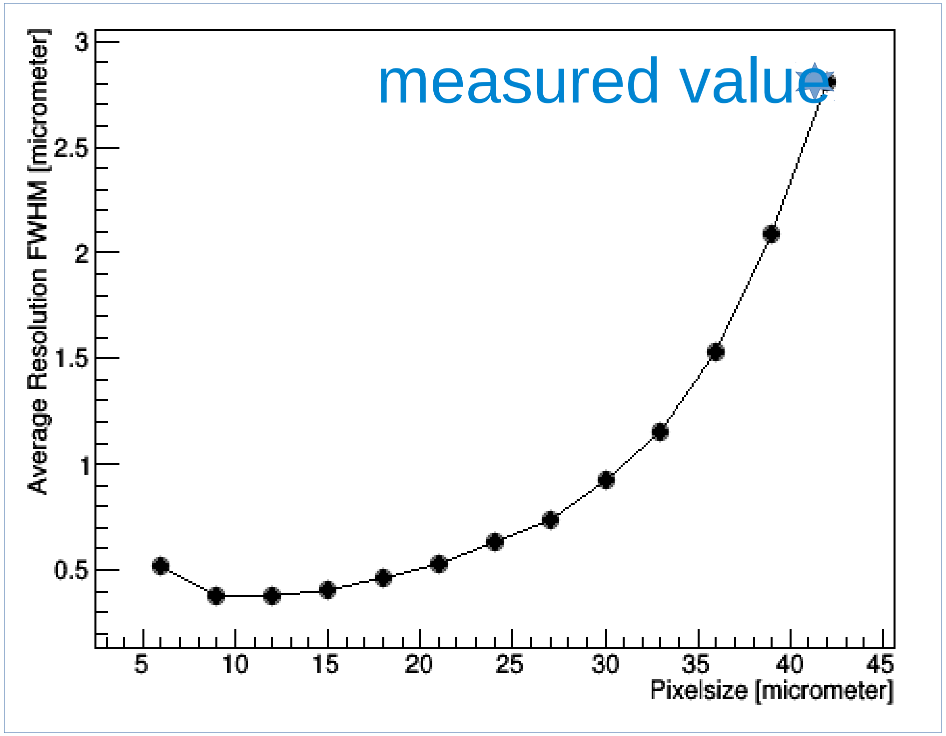
position resolution



pixel center

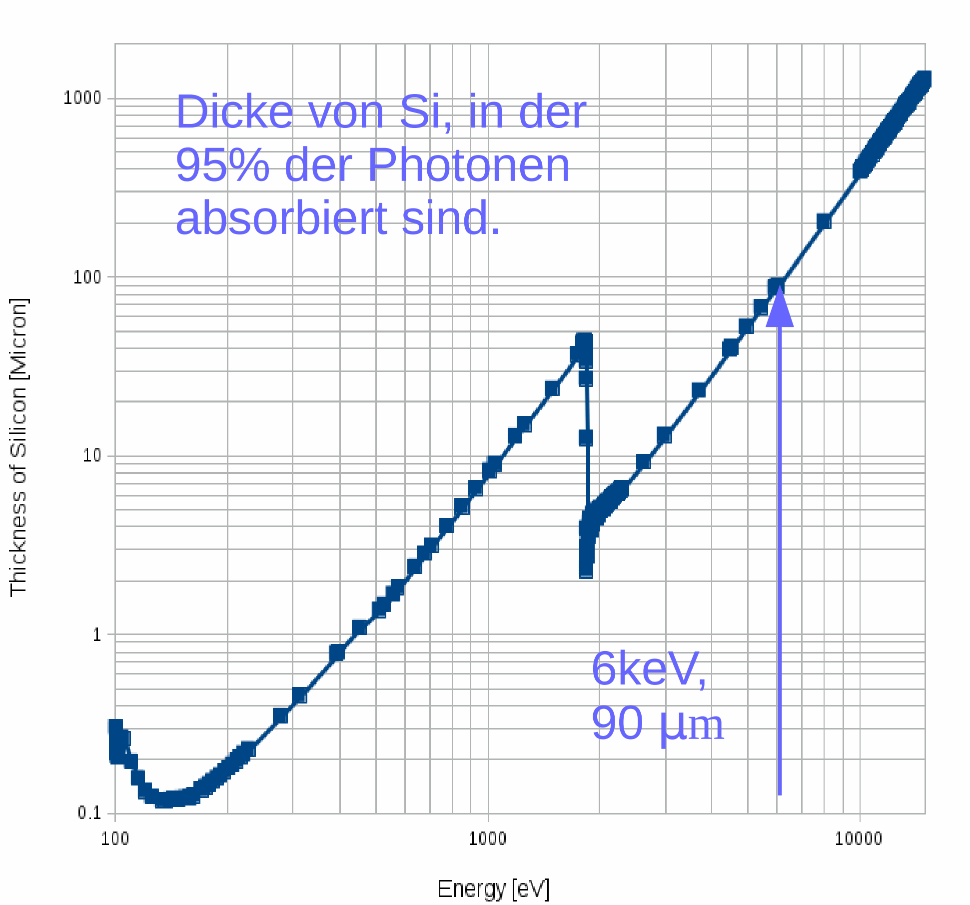
pixel end

average position resolution



Abhängigkeit der Breite von was ?

- **Driftzeit** <= Feldstärke <= Rückseitenspannung (only here, the drifttime matters !)
- **Tiefe der Wechselwirkung** -> Sensor sollte dick sein gegenüber der Eindringtiefe
- **Photonenenergie** (elektrostatische Abstoßung) kann -wenn nötig- berücksichtigt werden, weil spektroskopisch ausgelesen wird.

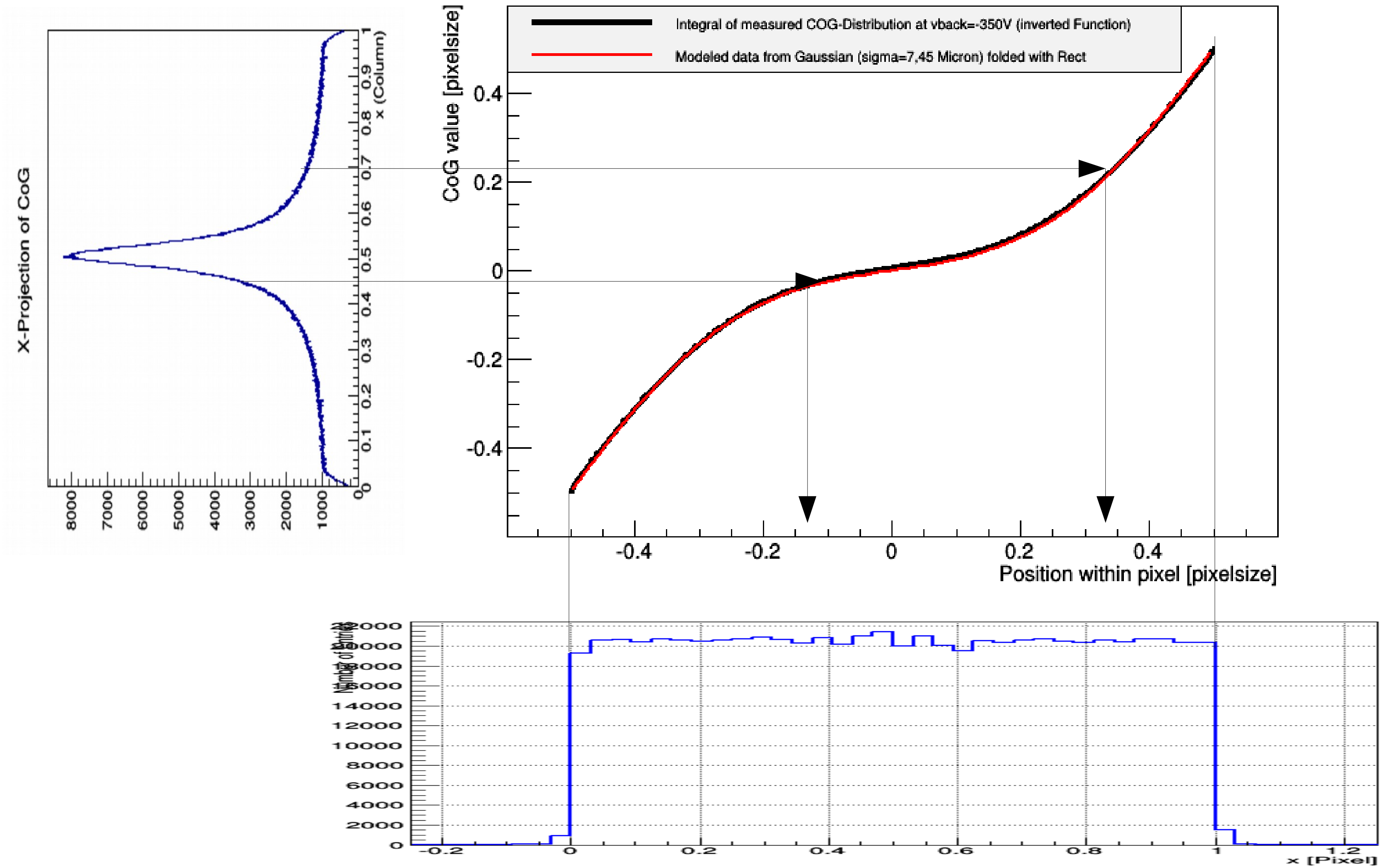


$$Breite_{Diffusion} \sim \sqrt[2]{D\,t}$$

$$Breite_{Abstoßung} \sim \sqrt[3]{\mu\, N_{signal}\, t}$$

Correction CoG -> interaction positions

The integrated CoG-distribution is inverted and each event is repositioned



left pixel border

right pixel border