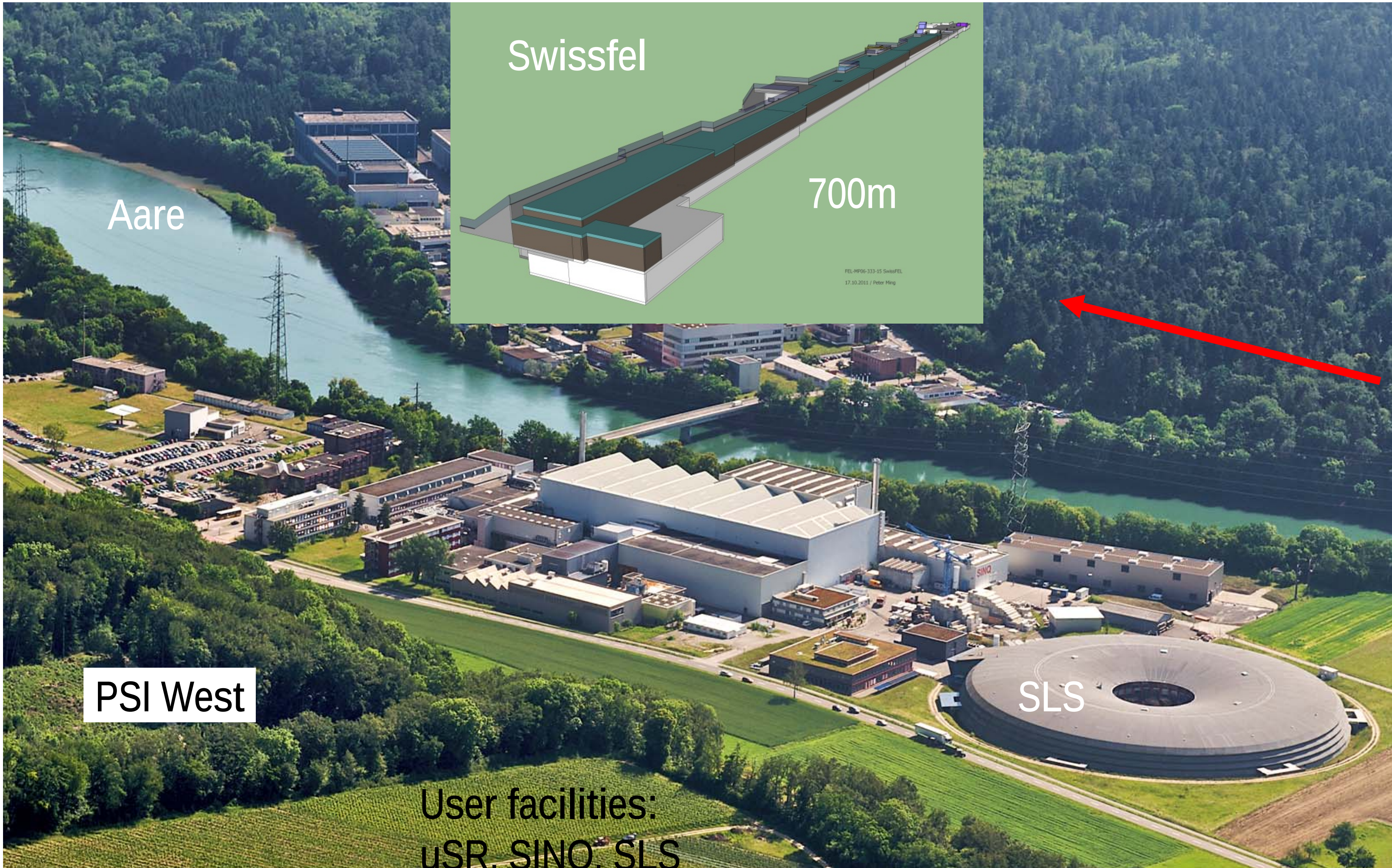
PAUL SCHERRER INSTITUT

Paul Scherrer Institut
Bernd Schmitt

X-ray Detector Development at the Swiss Light Source

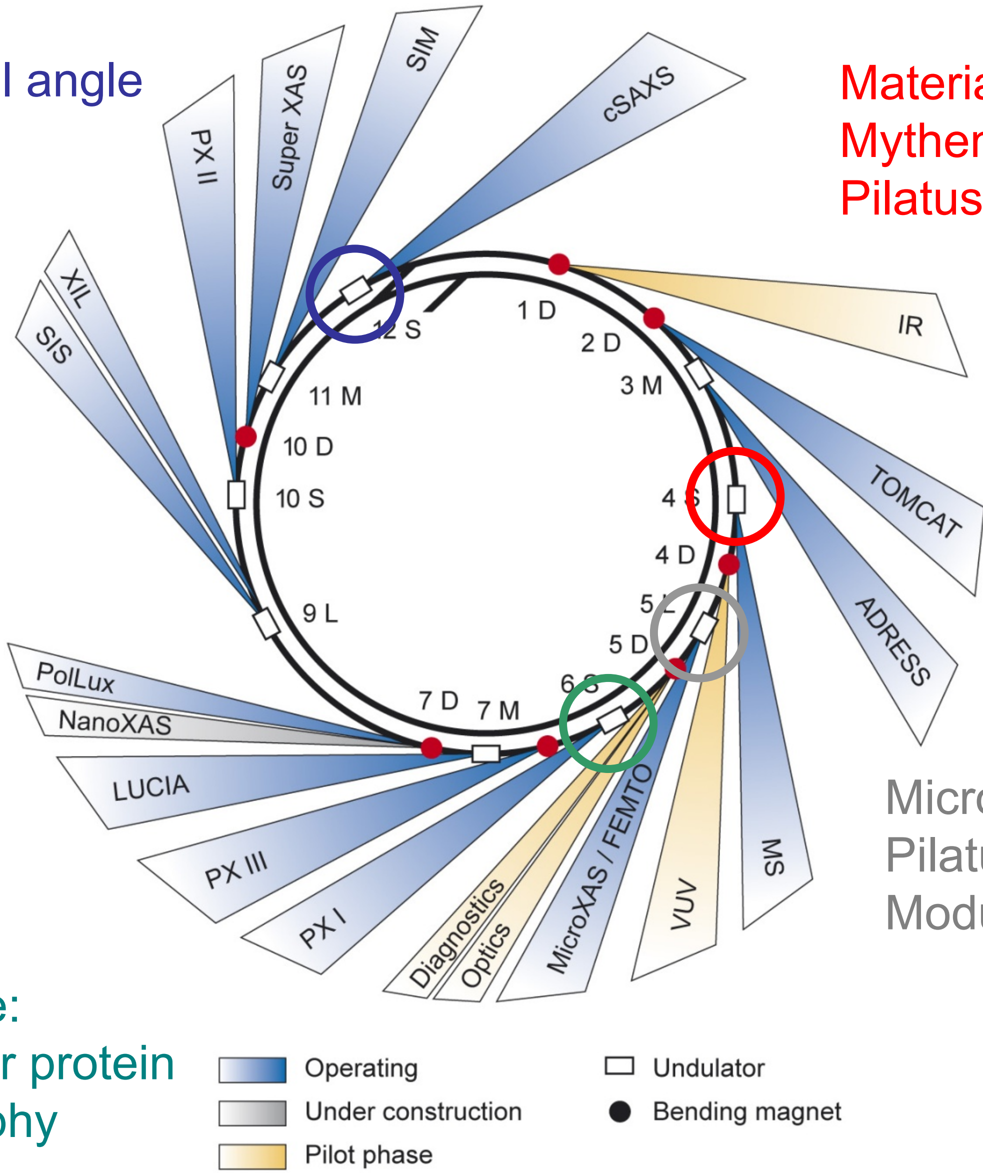
PAUL SCHERRER INSTITUT (2011)



~1500 Staff employees; 30Km from Zurich, task in ETH domain: run large scale facilities

csax beamline:
Pilatus2M for small angle scattering

Material science beamline:
Mythen for powder diffraction
Pilatus for surface diffraction

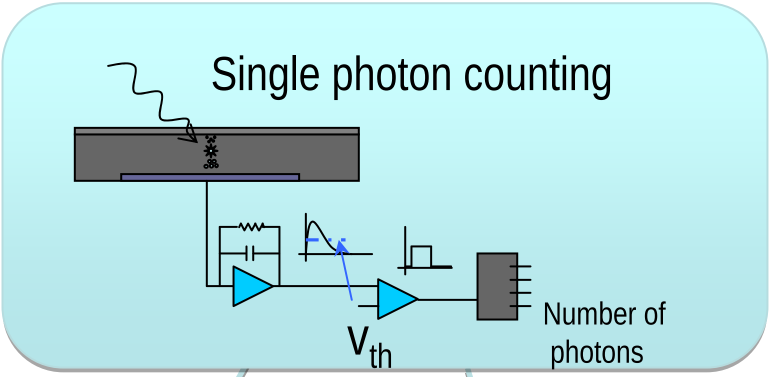


MicroXAS/Femto:
Pilatus and Mythen single Module Systems

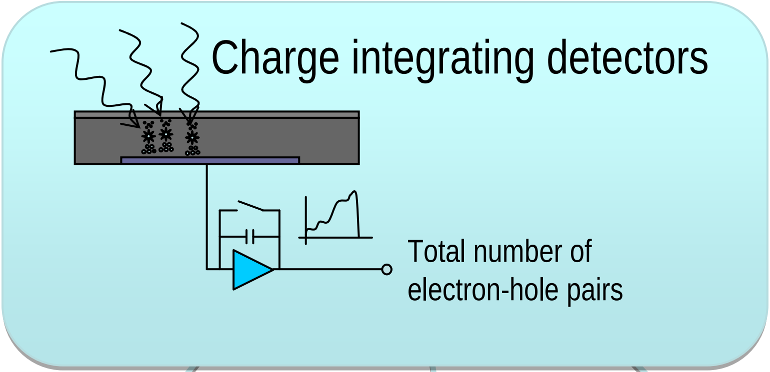
PX beamline:
Pilatus6M for protein crystallography

X-ray Detector Development at SLS

Synchrotron detectors



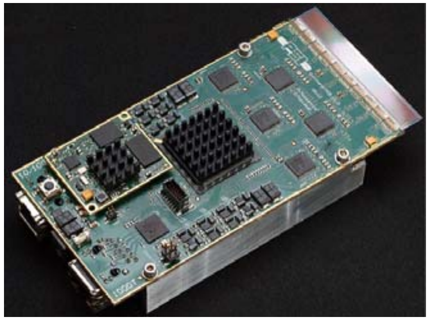
X-ray free-electron laser detectors



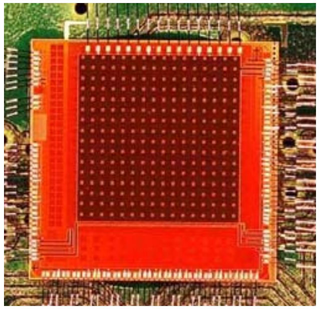
Mythen II

Eiger

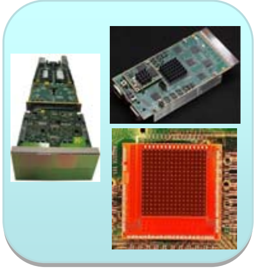
Gotthard



AGIPD



SwissFEL



Outline

Detector principles:

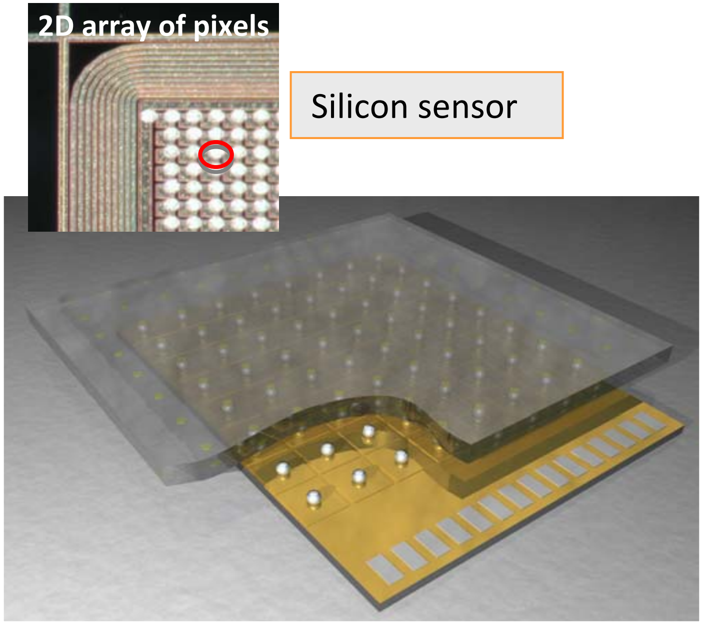
- hybrid detectors
- single photon counting
- charge integrating

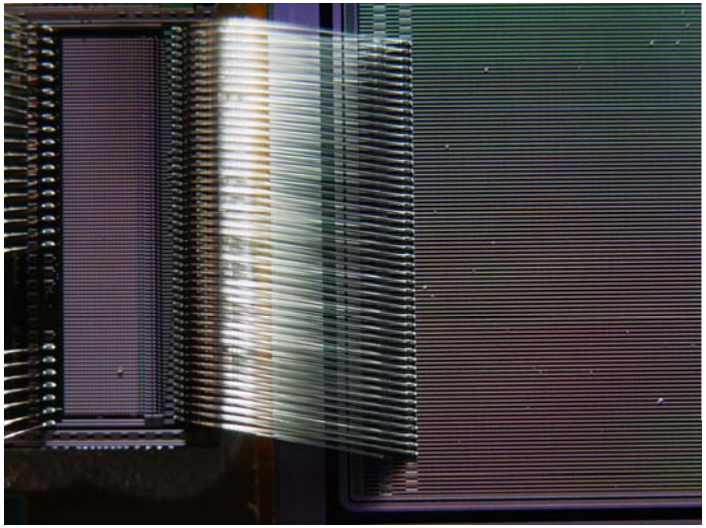
Single Photon counting: Mythen, Eiger

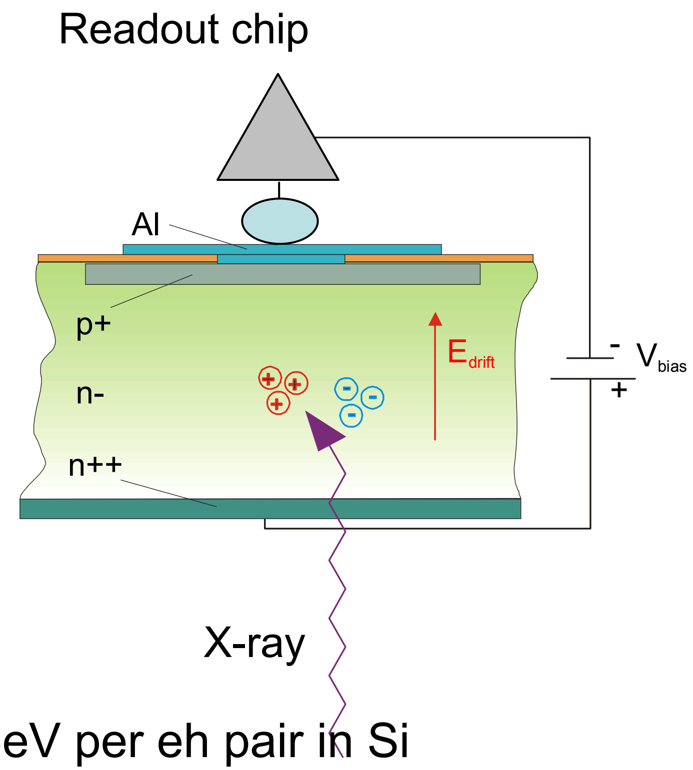
Charge integrating: Gotthard, Swissfel

Detector research: What are the limits in pixels size?
How can one reach the highest position resolution?

Hybrid Silicon Detectors







3.6eV per eh pair in Si

Charge for 12keV=3300 electrons = 0.5 fC

From single photon counting detectors at PSI…

MYTHEN

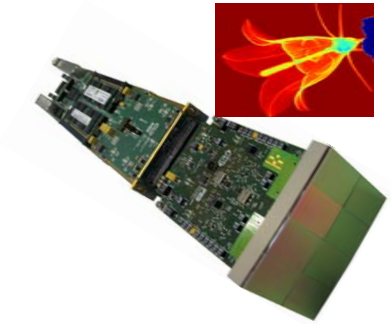
1k to 30k 50µm strips for powder diffraction, small angle scattering, medical imaging…

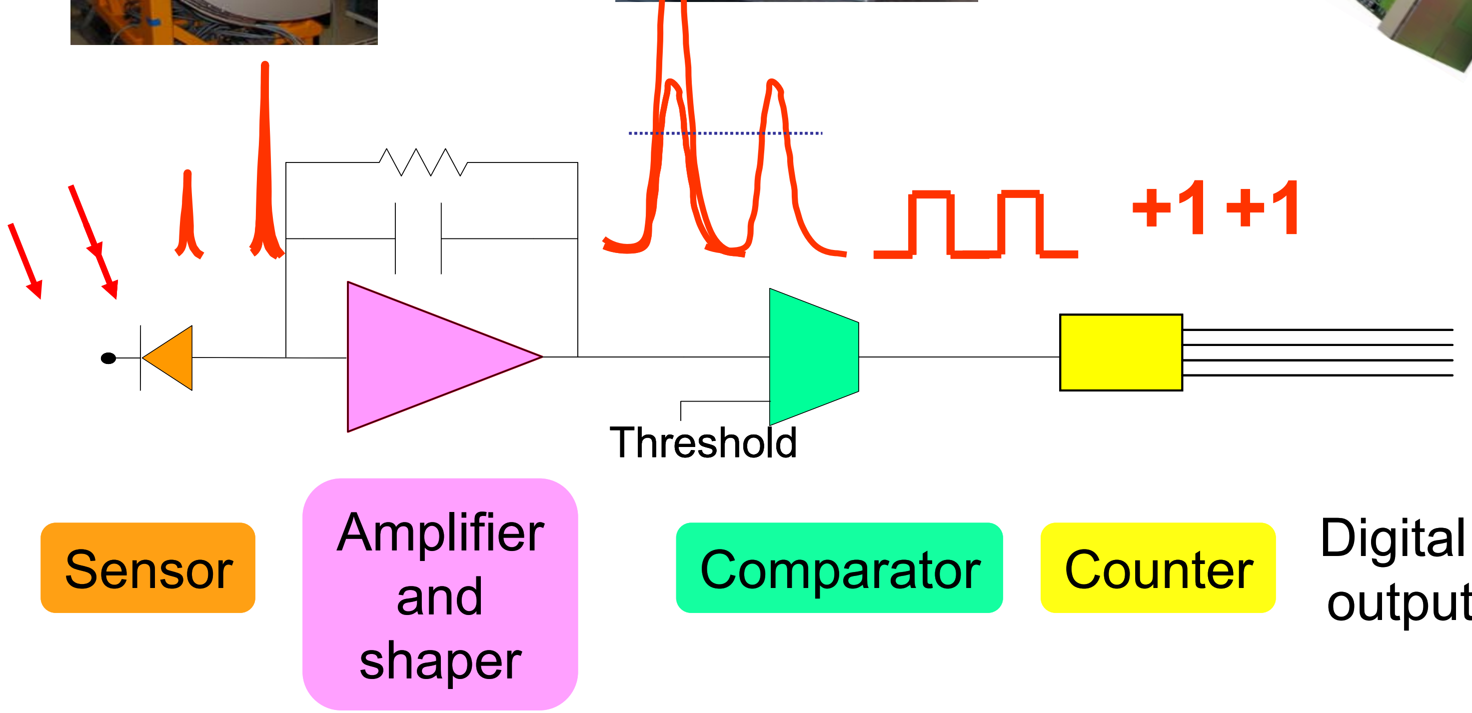
PILATUS

100k to 6M 172µm pixels for protein crystallography, small angle scattering, imaging …

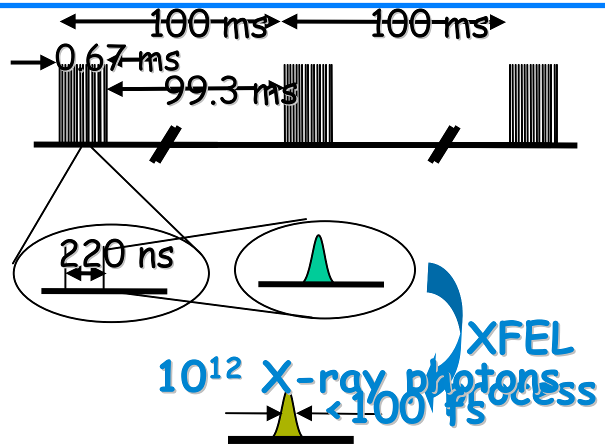
EIGER

500k to 9M 75µm pixels, for small angle scattering, CDI, XPCS, protein crystallography, imaging ....





… to charge integrating detectors for the E-XFEL



Dynamic range: 10000

- voltage swing usually ~1V
- noise usually ~mV

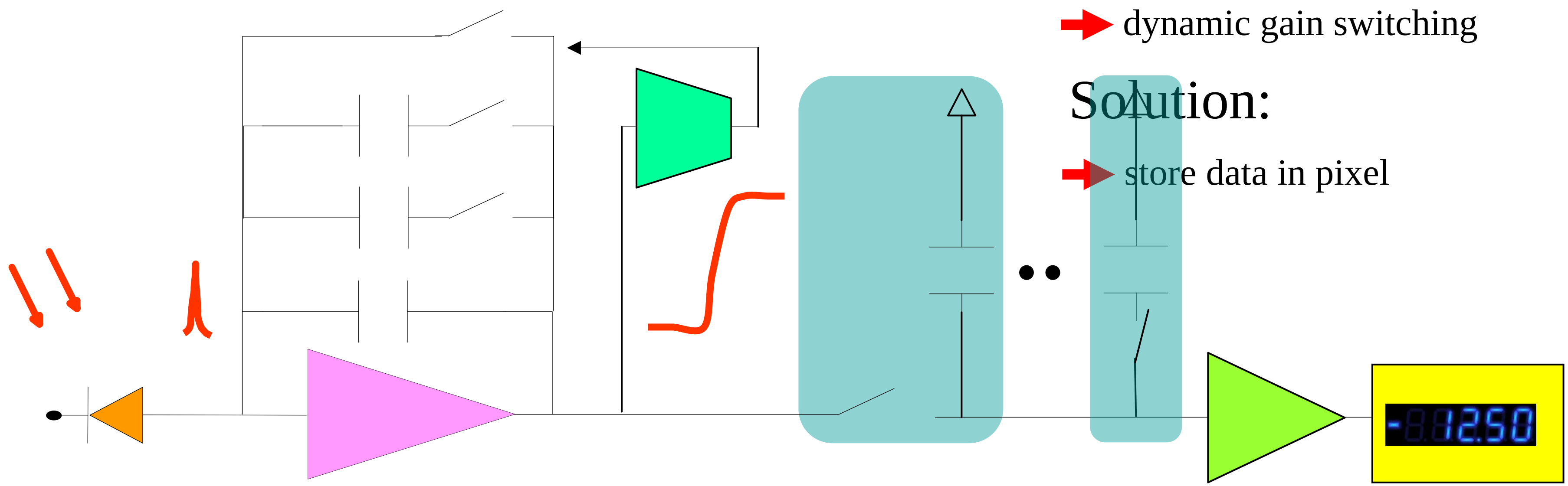
➡ 1 photon ~10mV
100 photons dynamic range

Solution:

➡ dynamic gain switching

Solution:

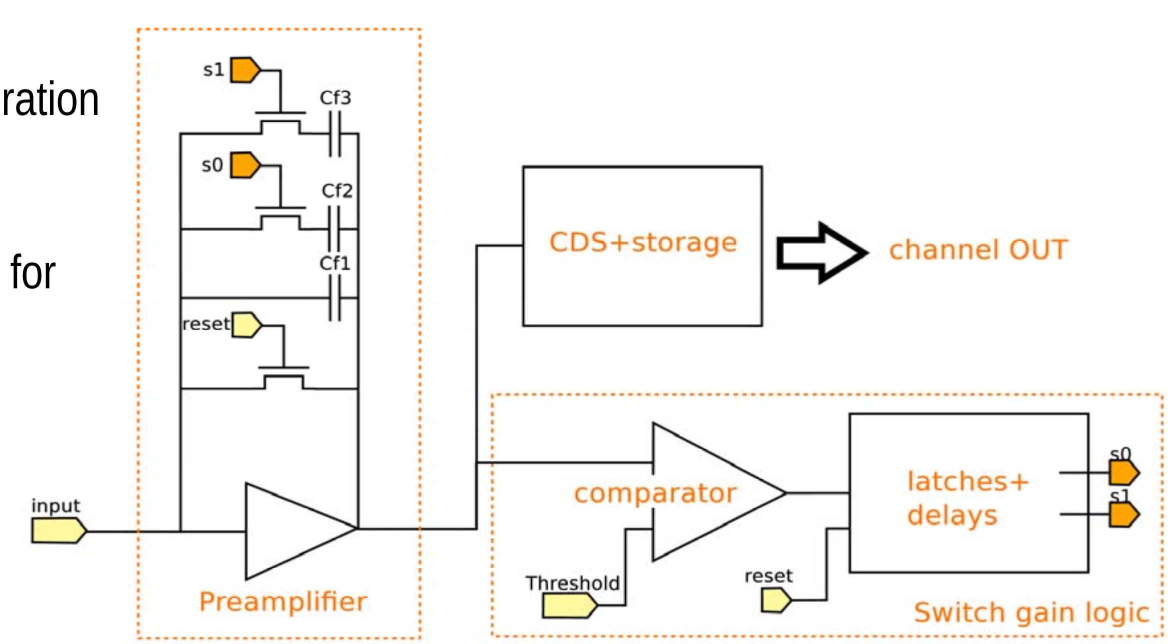
➡ store data in pixel

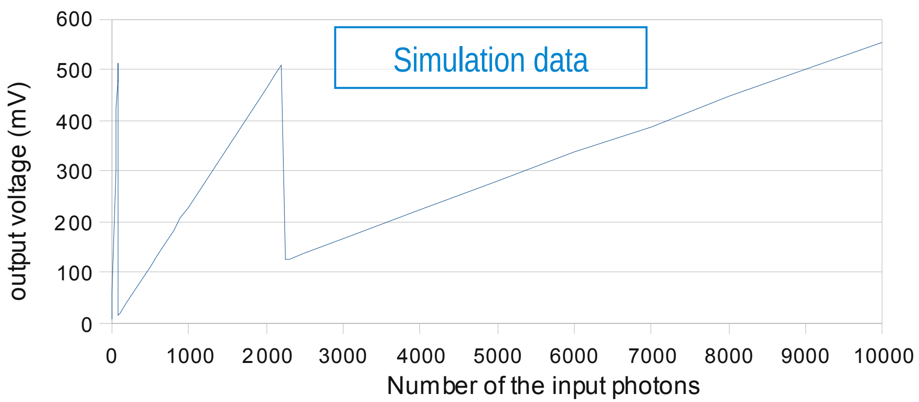


Sensor | Amplifier and reset | Gain switching | Sample and hold | Analog output | External ADC

Preamplifier with gain switching

- CSA in charge integrating configuration
- 3 feedback capacitors
- Common for 1D and 2D, baseline for AGIPD, Gotthard and Swissfel





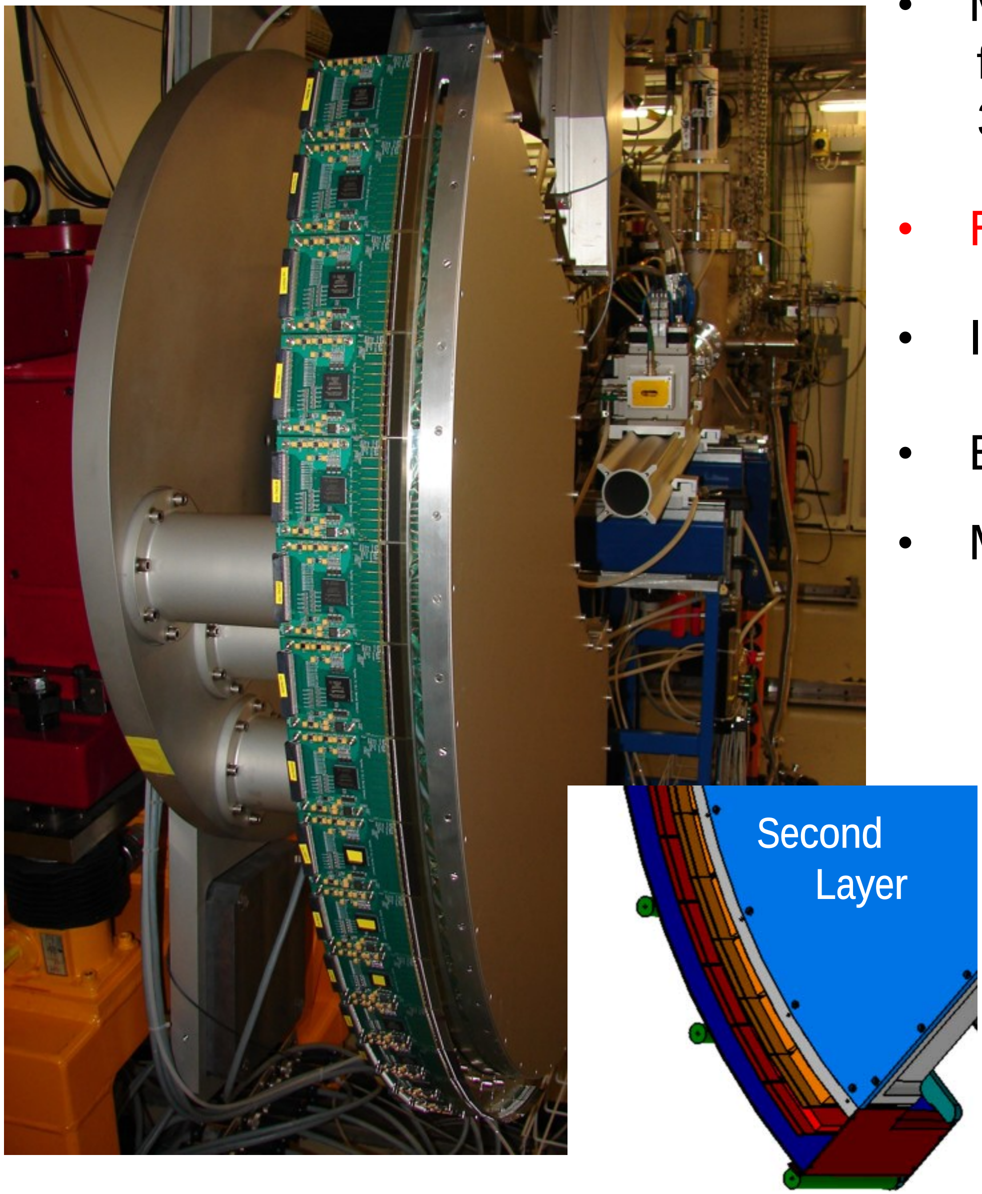
- Logic after comparator to:
  - Switch a 2nd time if 1st switch not enough
  - Avoid a 2nd switch on spikes due to the 1st one
- Switching has to be FAST (<10ns)

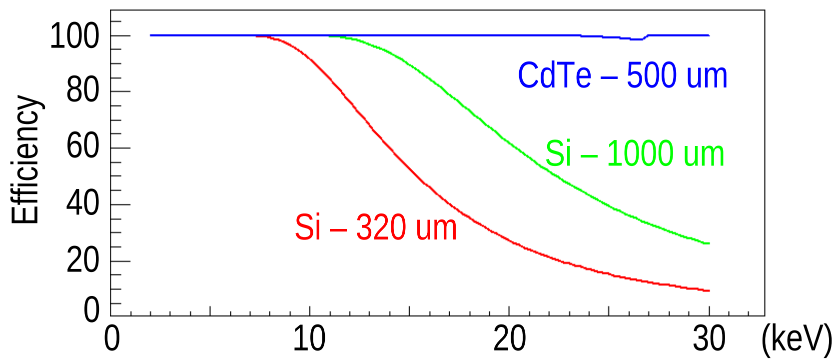
Single photon counting detectors: Mythen, Eiger

+1 +1 +1……

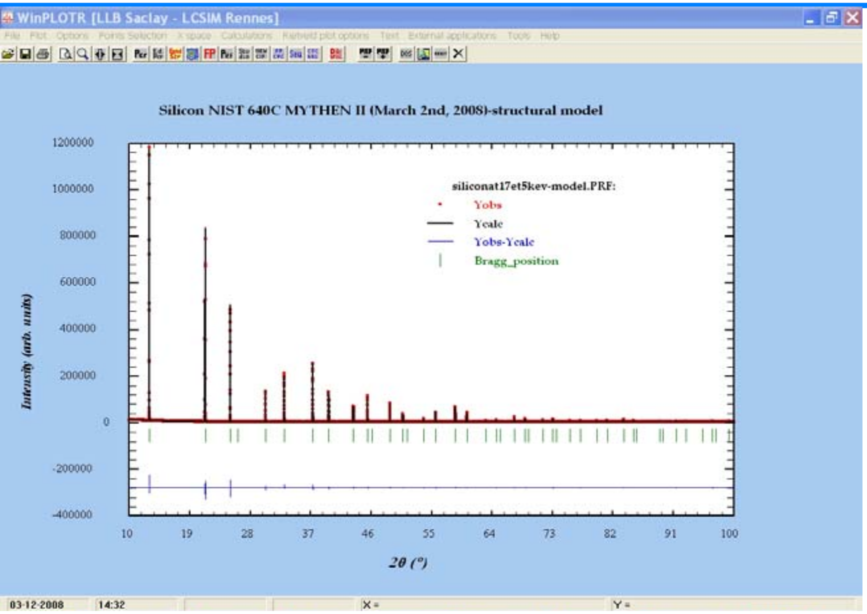
MythenII at the Powder Diffraction Station

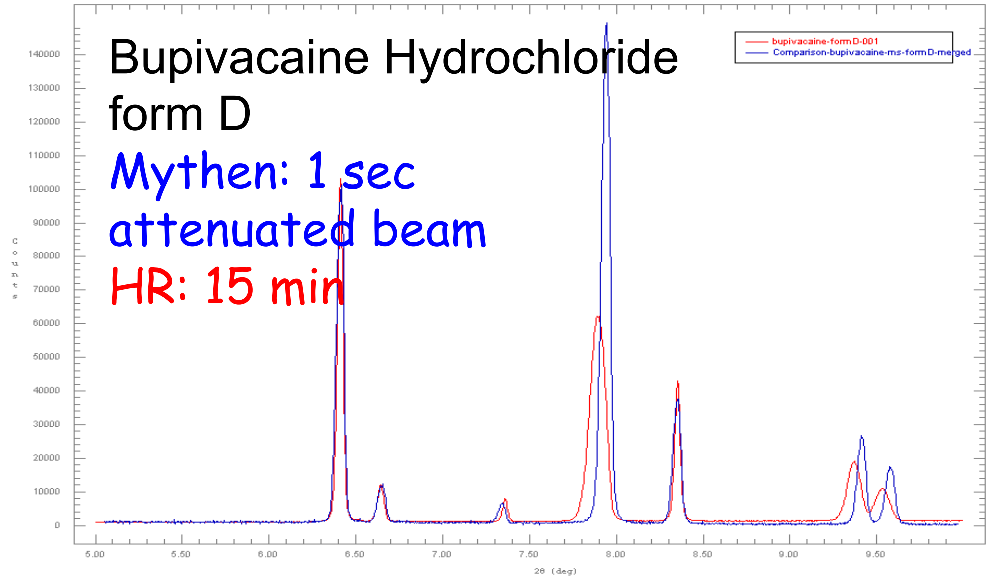
- Modular system: 1 to 24 modules,
  for PD at SLS 24 modules covering 120°
  30k channels ⇨ gain factor of 30k
- Full 120° PD spectrum in <1s, typically 0.1s
- Intrinsic angular resolution 0.004° (0.01°)
- Energy range: 5-40 keV (at SLS PD)
- Main applications:
  - Time resolved, in Situ measurements
  - Temperature scans
  - Organic Materials (reduces radiation damage dramatically)

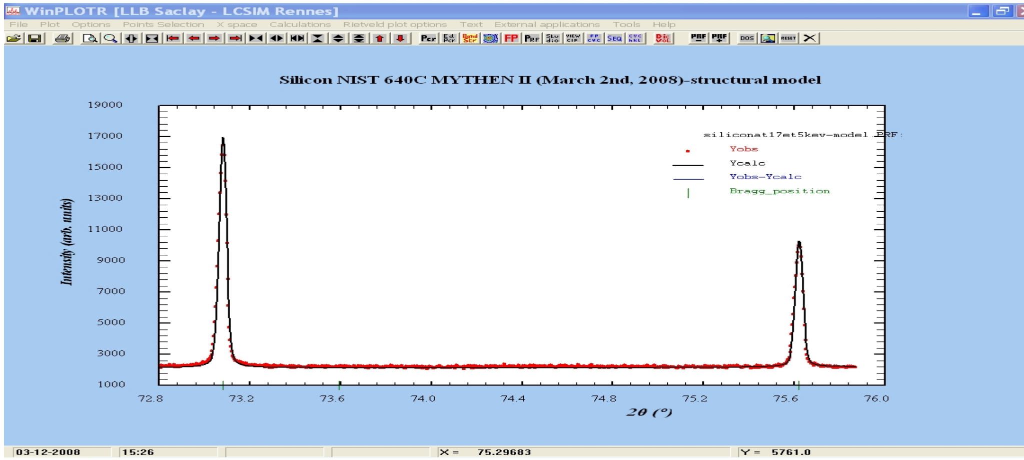




Standard powder samples





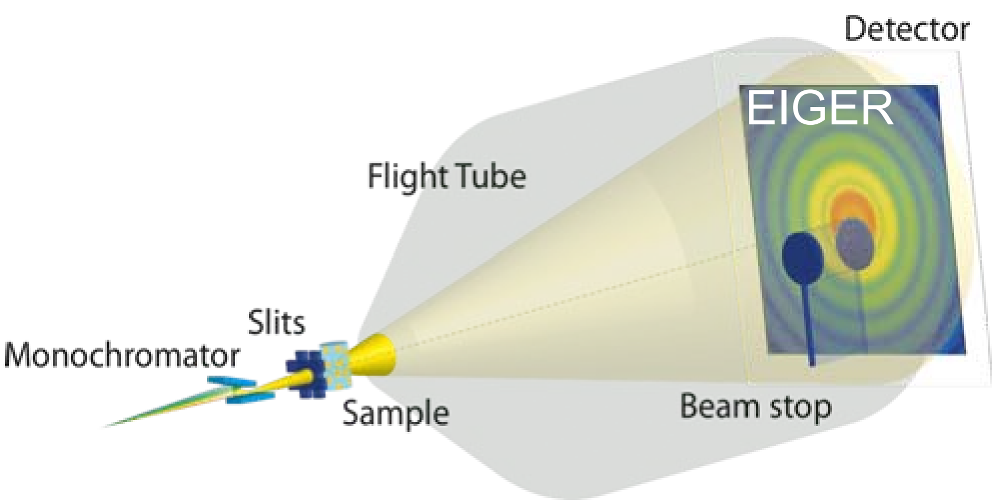


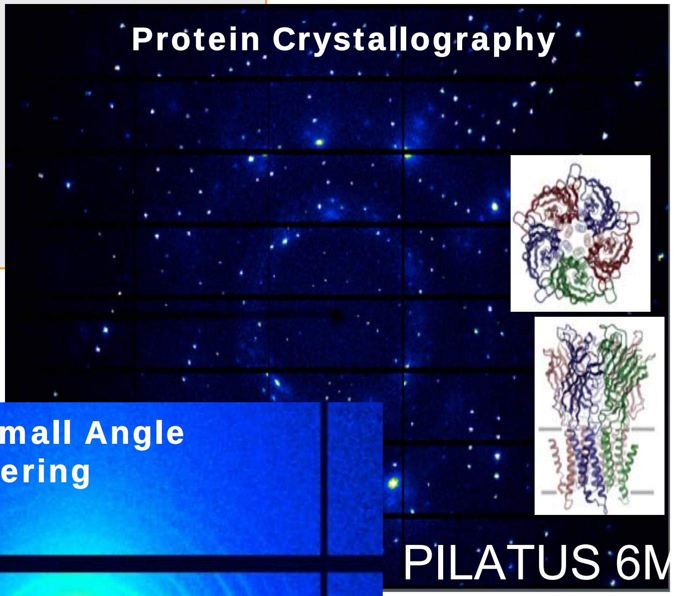
The data quality allows structural solution and refinement!
Measurement several orders of magnitudes faster!

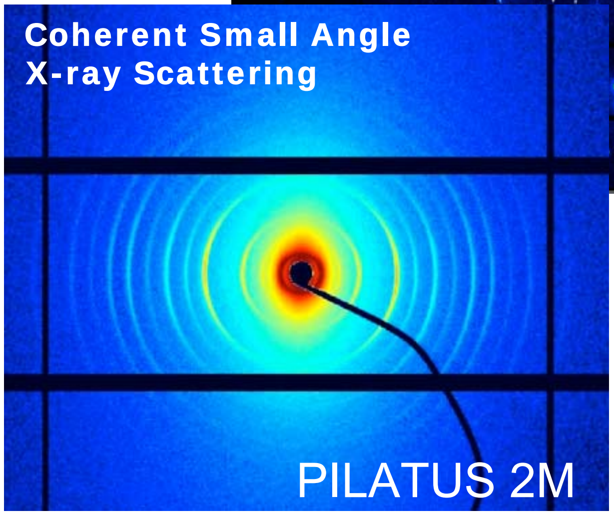
The Eiger Detector

Single photon counting hybrid pixel detectors for synchrotron applications are aimed towards diffraction experiments

- Applications at CSAXs:
  - Scanning Coherent Small Angle X-ray Scattering
  - Coherent Diffractive Imaging
  - X-ray Photon Correlation Spectroscopy
- Protein Crystallography

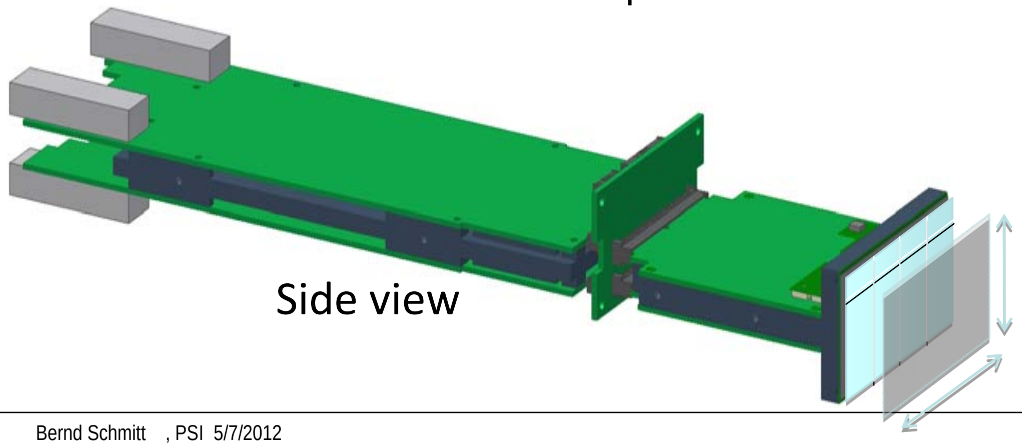


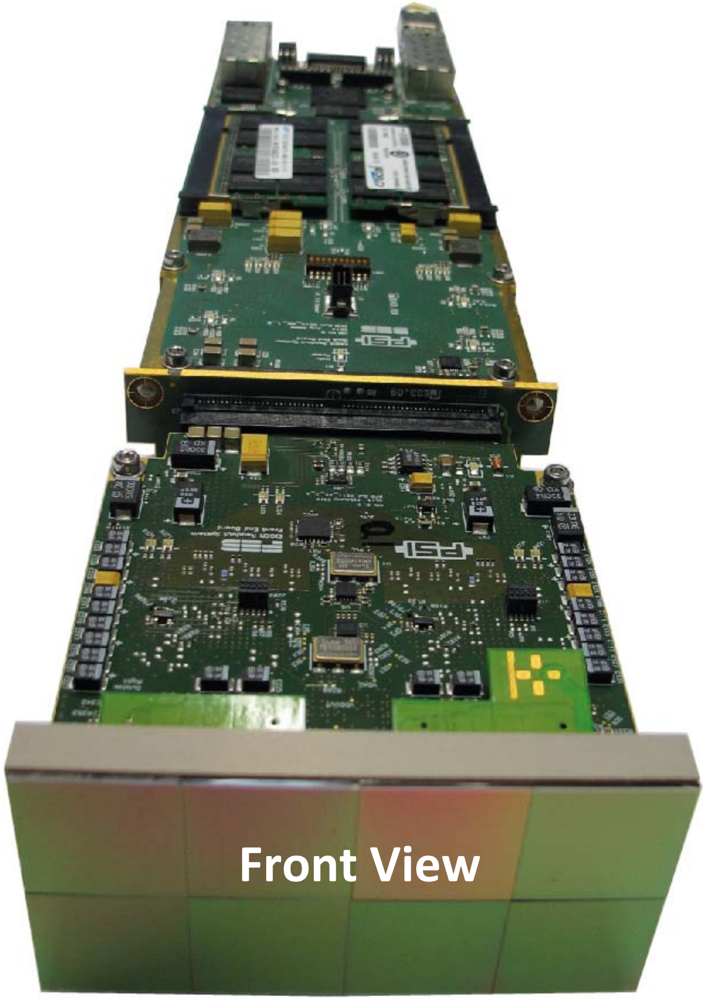


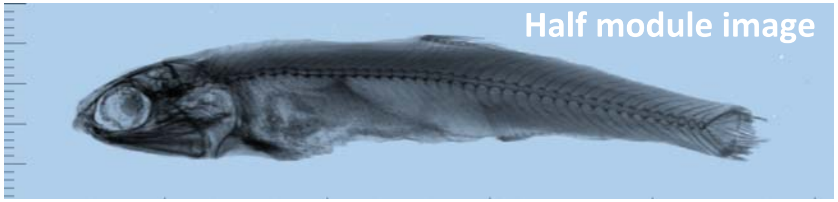


Eiger, the next generation pixel detector

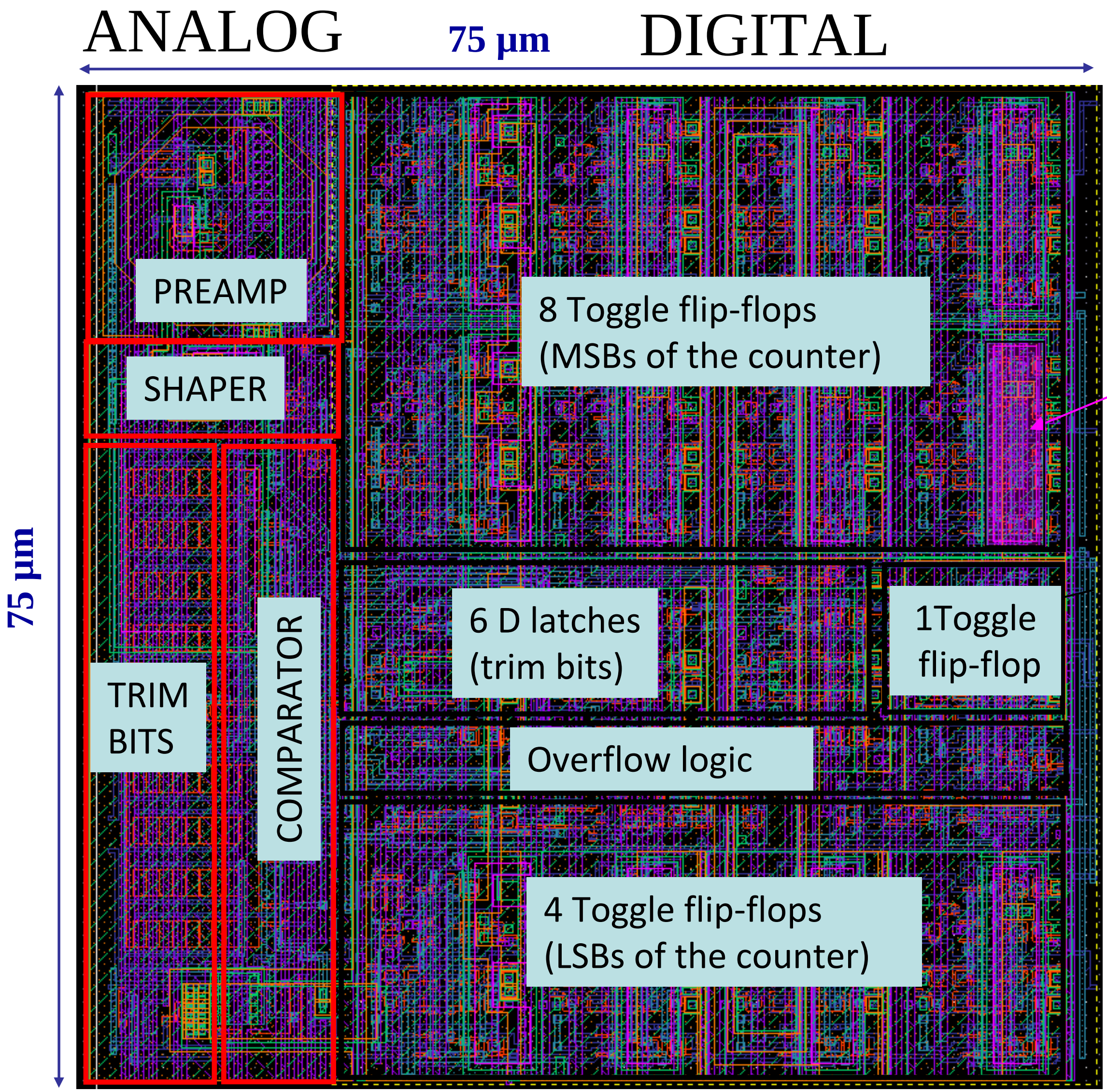
- Single photon counting pixel detector
- Sensitive area of 38 X 77 mm^2
- 524k pixel module
  - 2 x 4 chip array
- Dead time free mode of operation
- Maximum frame rates
  - 23 kHz in 4 bit mode
  - 12 kHz in 8 bit mode
  - 8 kHz in 12 bit mode
- Maximum data rates on the readout boards
  - 25 Gb/s for a half module
  - 50 Gb/s for a module
- On board in hardware data processing
- 8 GB of memory on a module
- Two 10 GbE data links per module

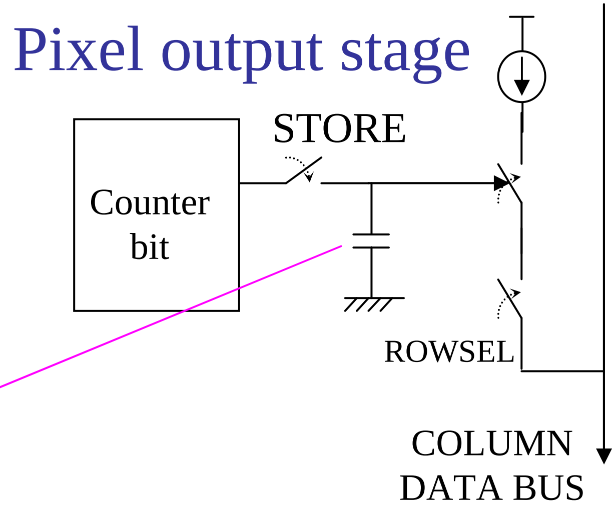






The EIGER pixel on silicon





UMC 0.25 µm Technology, full radiation tolerant layout

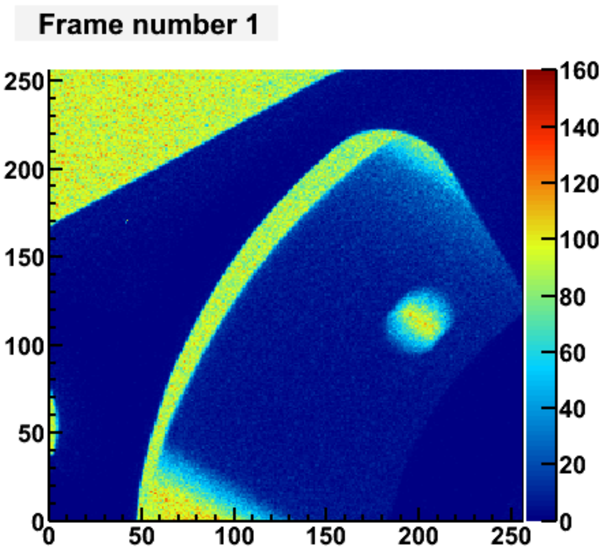
EIGER main features

Technological process	UMC 0.25 µm
Radiation tolerance	Full radiation tolerant design (>4Mrad)
Chip size	19.3 x 20.1 mm^2 (active 19.2x19.2mm^2) > 2 x
Pixel size	75 x 75 μm^2 = / 5.3
Pixel per chip	256 x 256 = 65536 = 11.3 x
Counter	12 bits, binary, configurable (4,8,12 bit mode), double buffered
Count rate	3.4 x 10^9 x-rays/mm^2/s = 5.3 x
Dead time free readout	yes
Detector readout speed	~12 KHz @ 8 bit mode (Detector size doesn't matter) = up to ~2000 x (Clock=100 MHz DDR)
Threshold adjustment	6 bit DAC

In red:
Improvement factor with respect to PILATUS

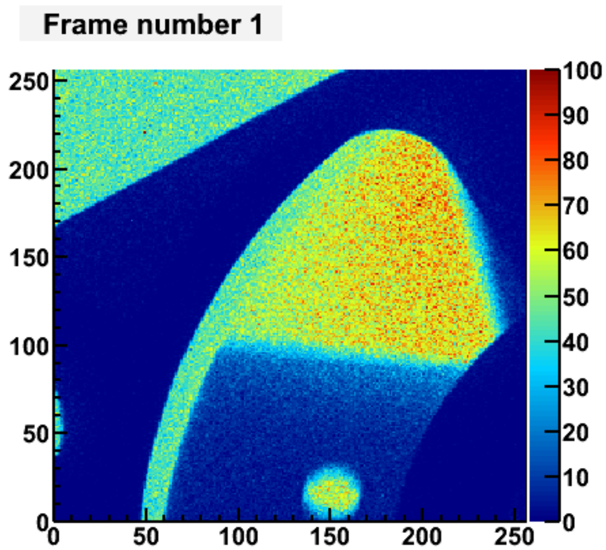
EIGER high frame rate Demo

V = 50KV, I = 0.4mA



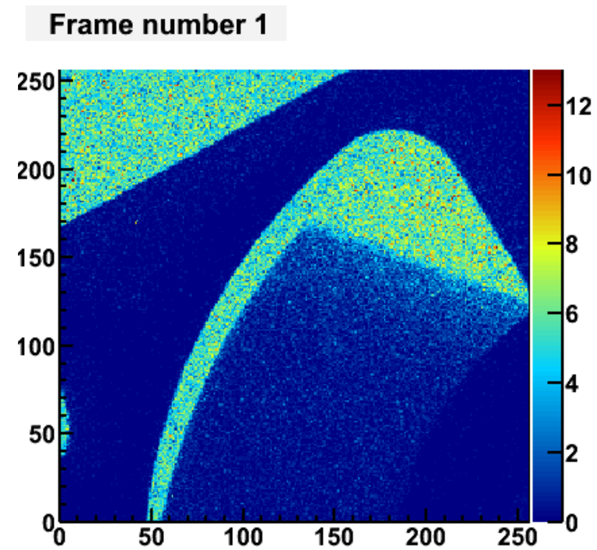
Chip in 12 bit Mode
Exposure time 125μs
Dead time 3μs
Frame rate 7.8 kHz

V = 50KV, I = 1 mA



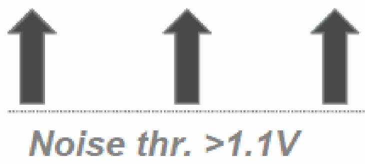
Chip in 8 bit Mode
Exposure time 85μs
Dead time 3μs
Frame rate 11.4 kHz

V = 50KV, I = 1 mA

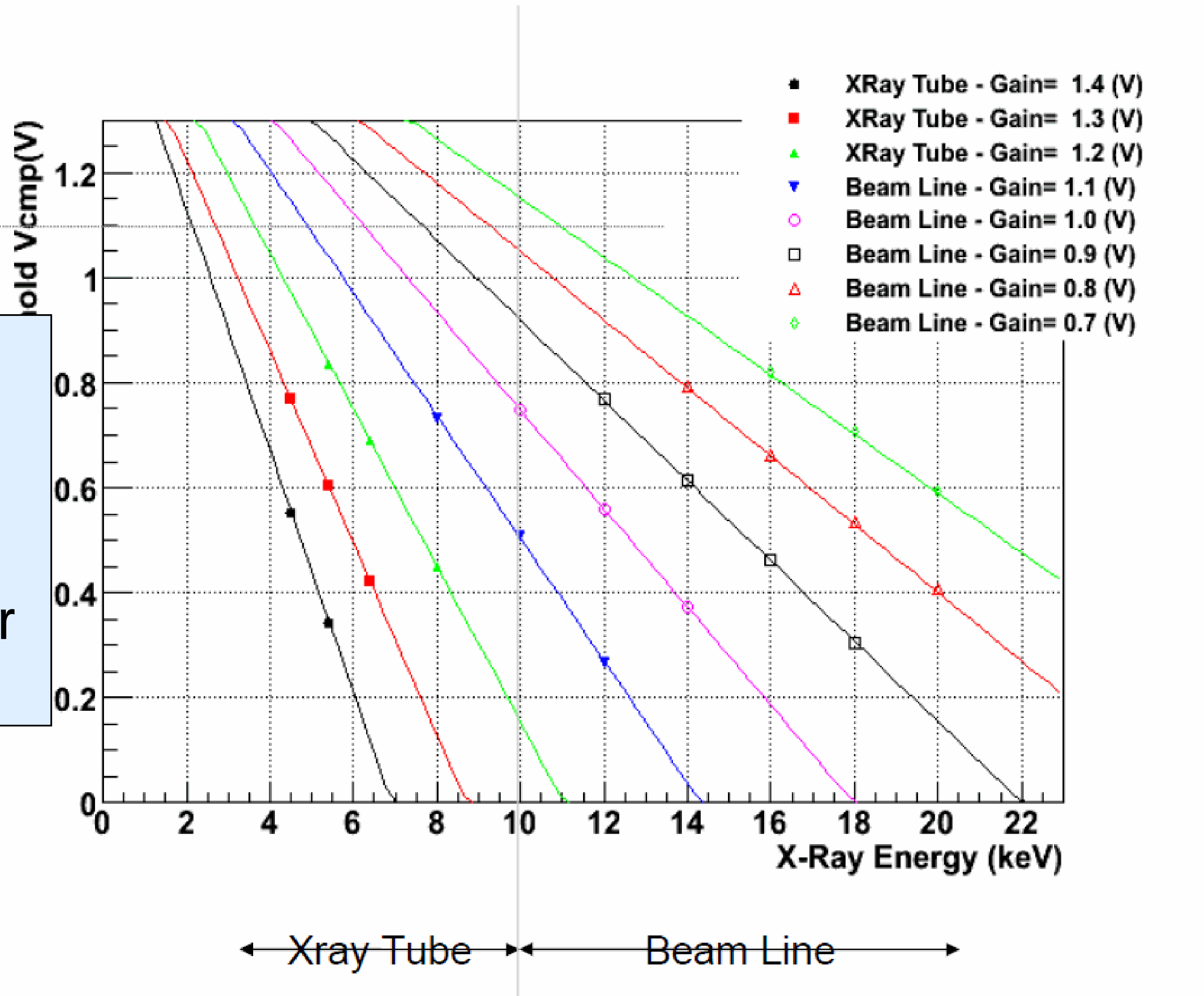


Chip in 4 bit Mode
Exposure time 45μs
Dead time 3μs
Frame rate 20.8 kHz

Energy calibration and definition of settings



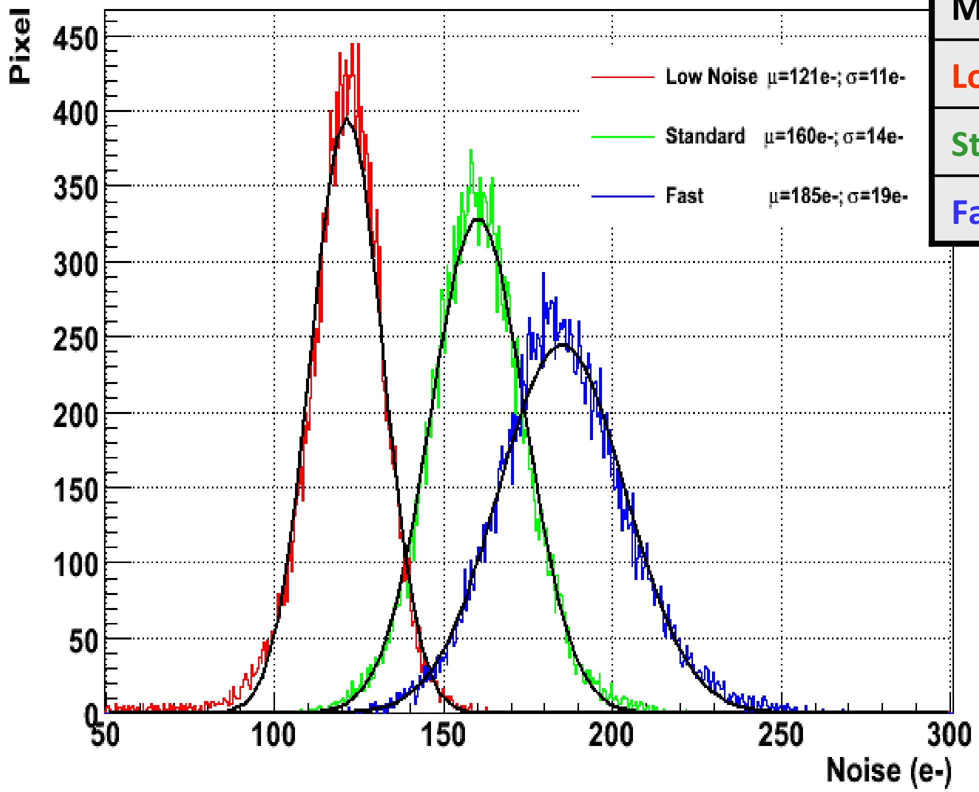
„Gain“ controls the feedback transistor bias. Increasing gain = less noise, slower ret. Zero.



Noise

- **Noise distributions:** monochromatic beam at the Beam line

@14KeV

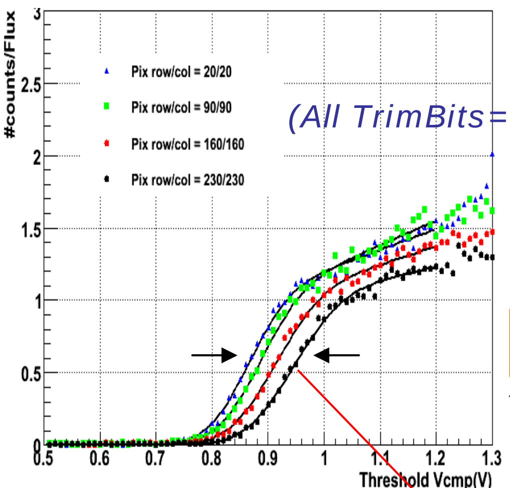


Operation Mode	Noise(e-)	Sigma (e-)
LowNoise	121.1±0.07	10.7±0.06
Standard	160.1±0.08	13.9±0.07
Fast	185.0±0.1	18.7±0.09

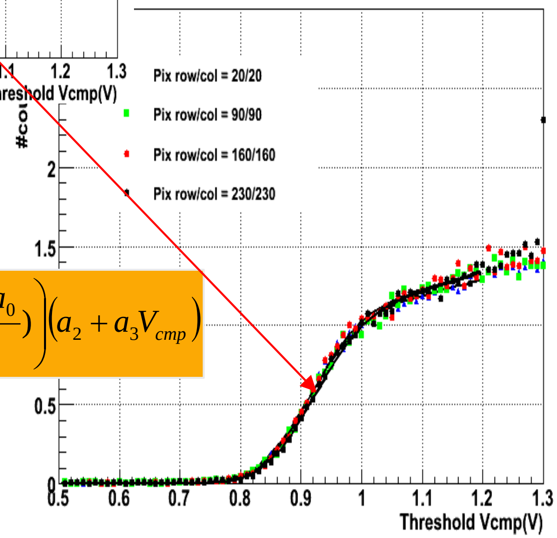
Trimming

- **Trimming**: XRay tube and Fluorescence screens (Cu Screen **8KeV**)
- **Threshold scans: Standard Mode** of operation

Before Trimming



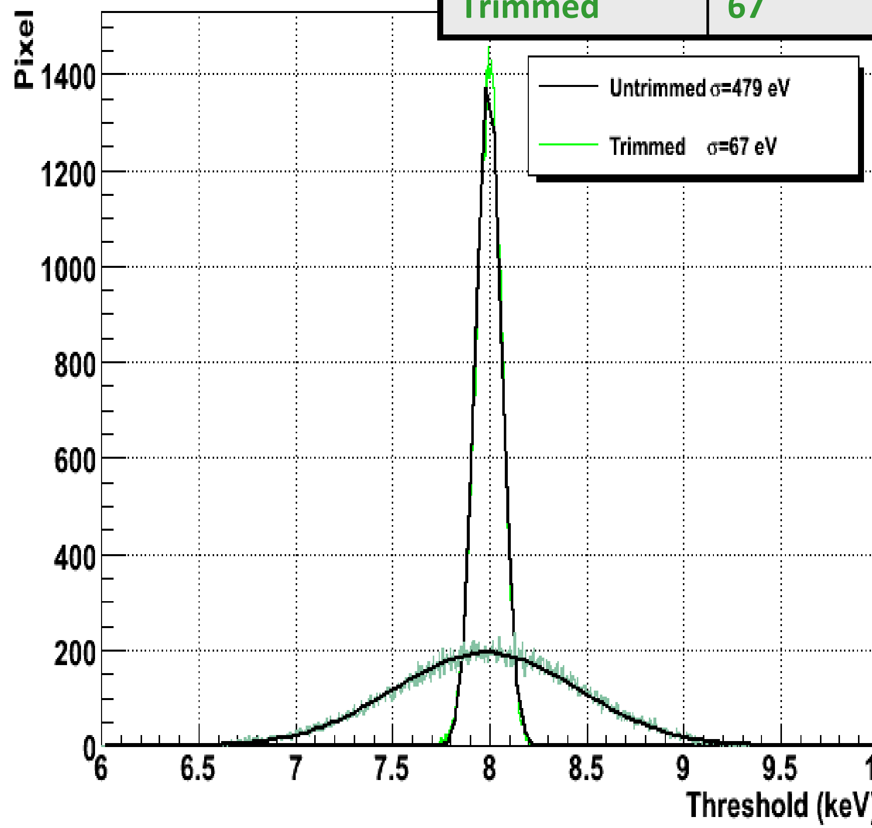
After Trimming



$$n(V_{cmp}) = \frac{1}{2}\left(1 + erf\left(\frac{V_{cmp} - a_0}{\sqrt{2}a_1}\right)\right)\left(a_2 + a_3 V_{cmp}\right)$$

Threshold dispersion

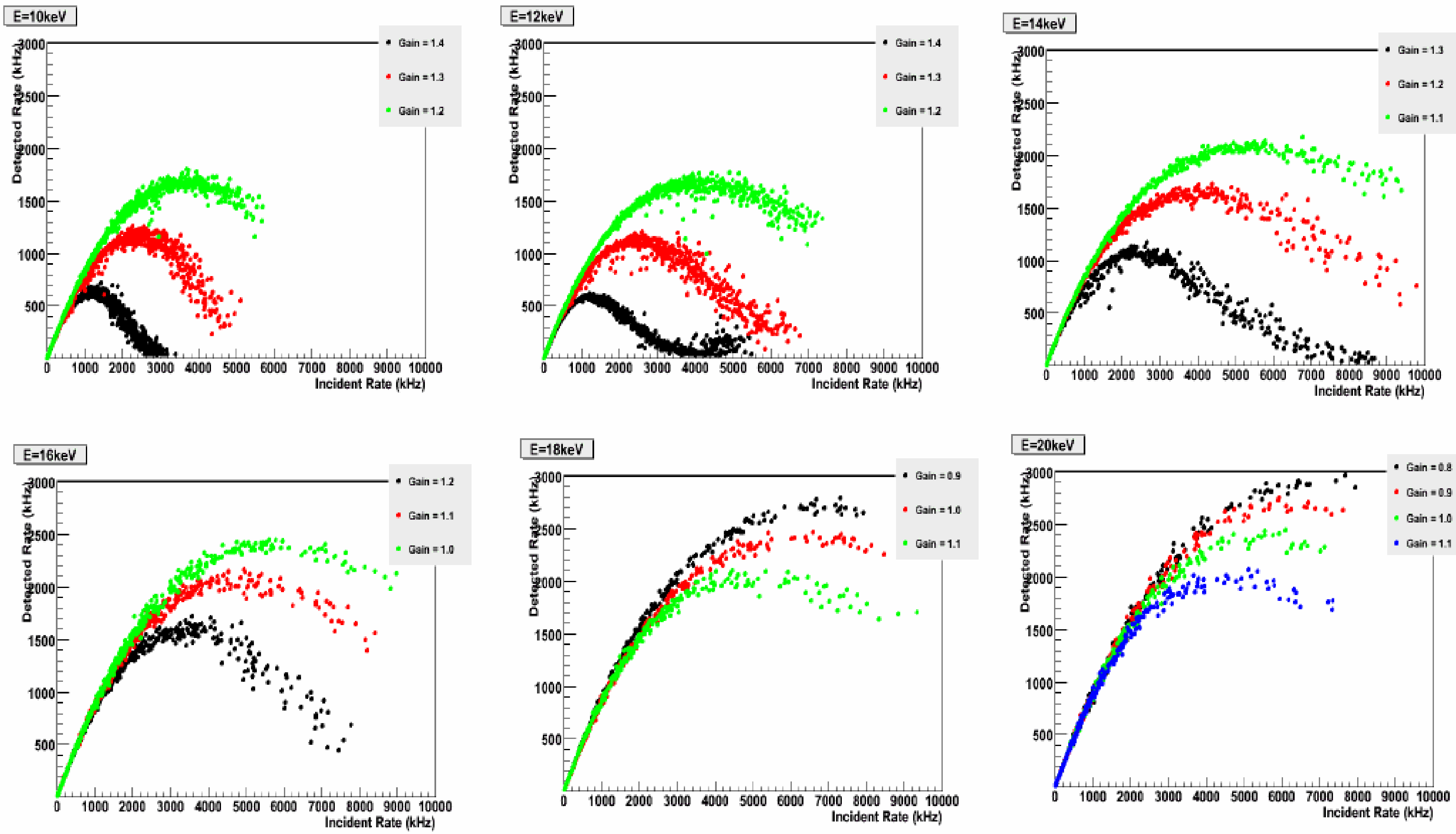
	σ(eV)
Untrimmed	479
Trimmed	67



Rate capability

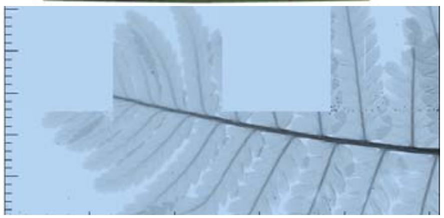
---- Very first curves: no fit, no errors !

---- 3 gains per Energy (4 @ 20keV) Vcmp @ ½ E

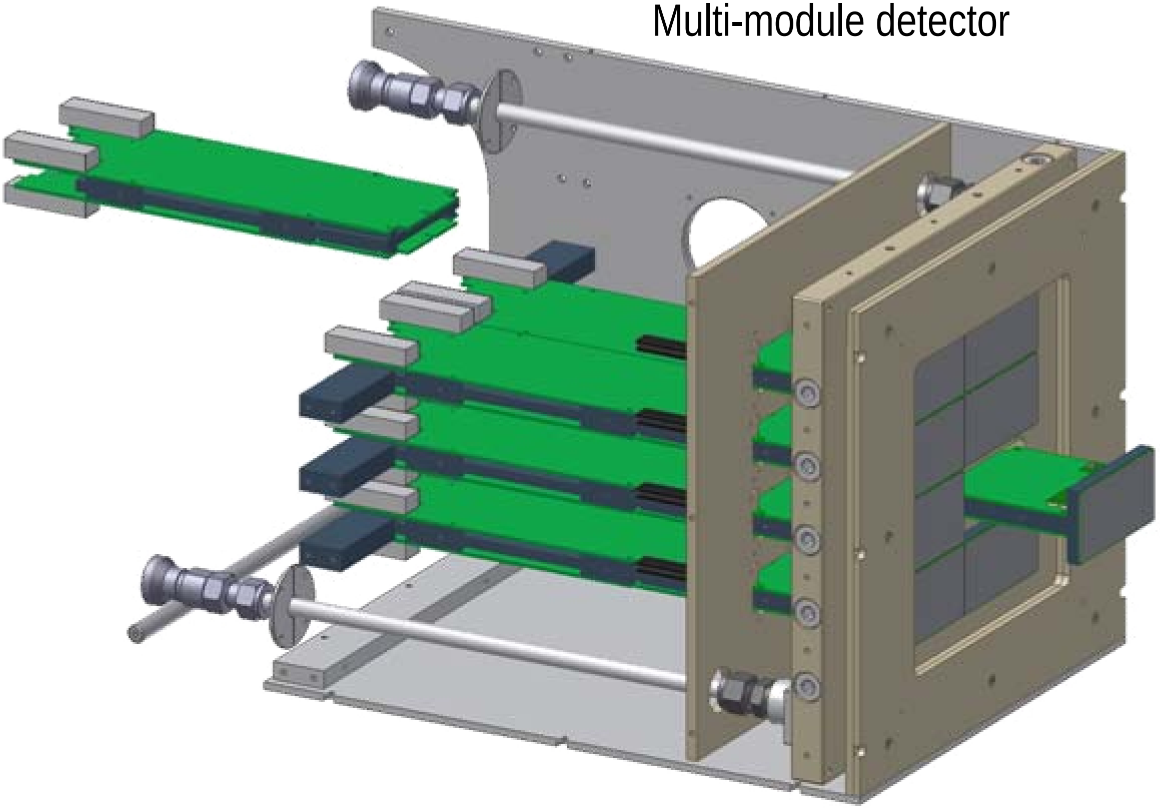


Eiger systems

500k single module



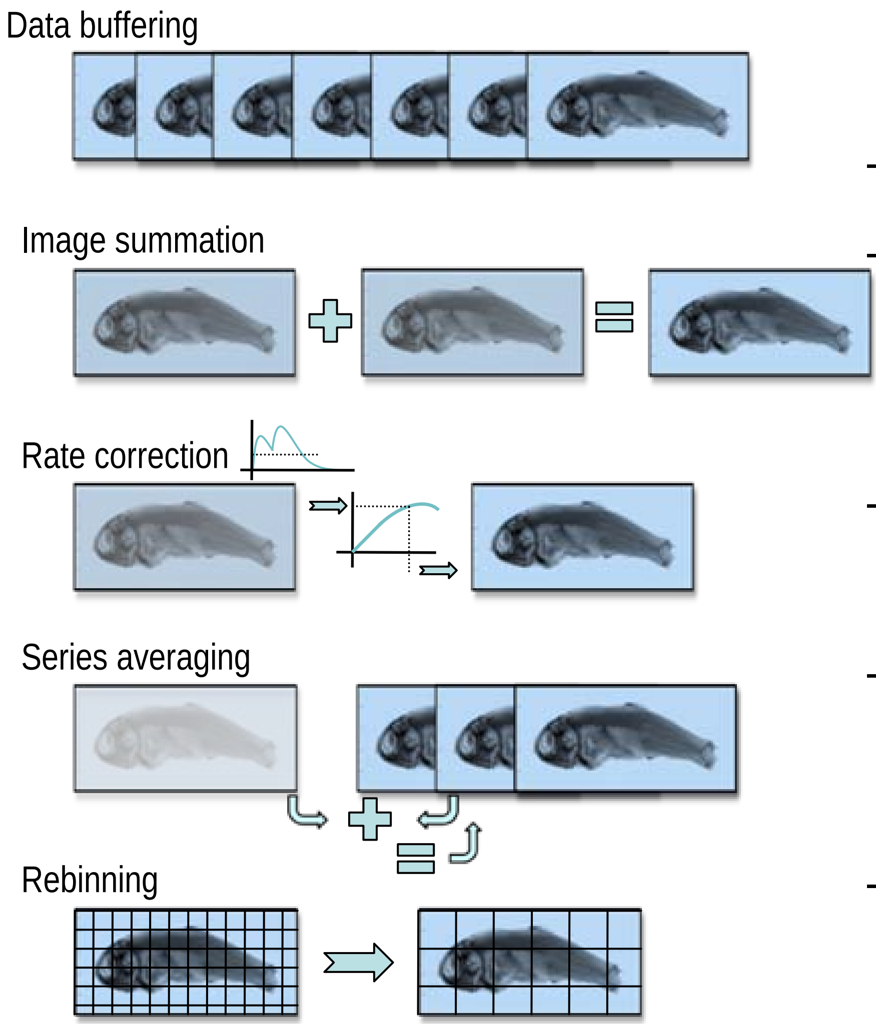
Multi-module detector



	Number of pixels	On board storage (frames/4 bits)	Data rate[1] @ 12 kHz	Data rate[2] @ 1kH	Data rate[3] @ 100 Hz	Data rate[4] @ 10 Hz
Module	524 k (512 x 1024)	~32,740	50.3 Gb/s	6.29 Gb/s*	839 Mb/s*	168 Mb/s*
9M Detector	9.44 M (3072x3072)	~32,740	906 Gb/s	113 Gb/s	15.1 Gb/s*	3.02 Gb/s*

1) 8 bit, equivalent to ~4@23 kHz and 12@8 kHz. 2) 12 bit. 3) 16 bit. 4) 32 bit. *) Foreseeable continuous storage rates (~20 Gb/s).

On board data processing (in firmware)

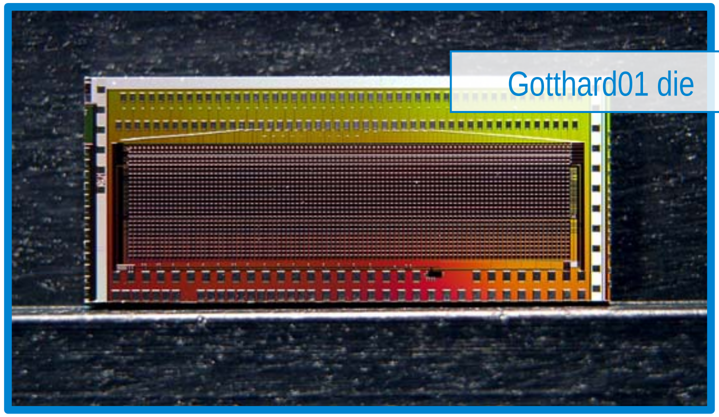


- On board data processing is in parallel on multi-module systems
  - independent of the detector size
  - reduces a modules tens of Gb/s at the source
  - or a 9Ms, hundreds of Gb/s at the source
- Data buffering
  - on board memory for 32 k frames per 4 counter bits
- Image summation
  - extends the dynamic range from 4096 to 4×10^9
  - ~1 k sub image frame rate (4 M counts/pixel/s)
  - transparent to the user
  - makes high flux continuous data taking possible
  - reduces the quantity of data at the source
- Rate correction
  - performed on sub-frames @ kHz frame rate
  - more precise, less sensitive to rate fluctuation
  - real-time processing
- Pump and probe series averaging
  - high frame rate exposure series summing
  - alternating pumped and un-pumped
  - no data transfer dead time between series
  - huge reduction of the quantity of data at the source
- Data reduction
  - 2x2 pixel rebinning
  - SAXS ring intensity averaging (planned)
  - data compression (in thought, question of HDF5 compatibility)

Charge integrating systems

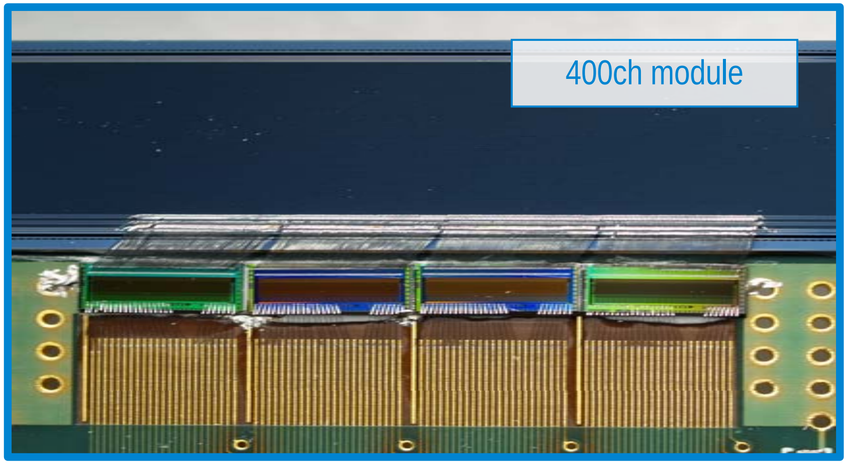
+1 +1000 +100……

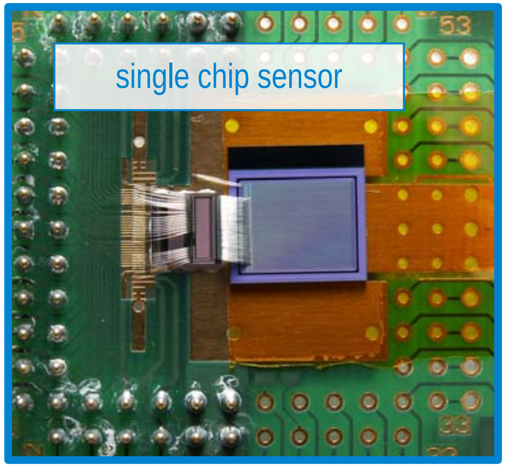
GOTTHARD 0.1 – the starting point



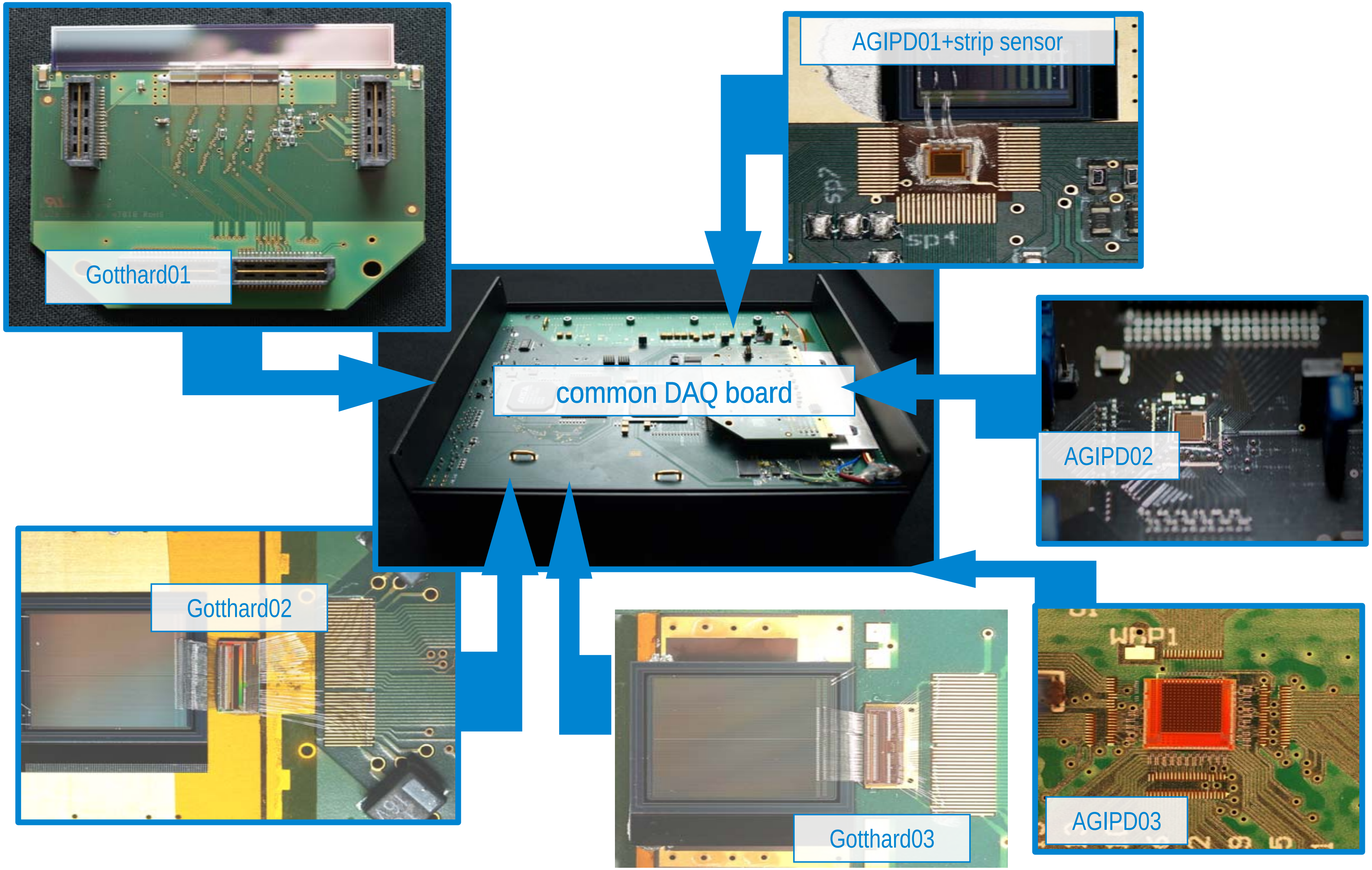
GOTTHARD:
Gain Optimizing microsTrip sysTem witH Analog ReaDout

- designed in 2004 in UMC0.25μm technology
- 100 channels
- 4 gain stages with automatic gain switching
- double sample and hold circuit to perform offline CDS



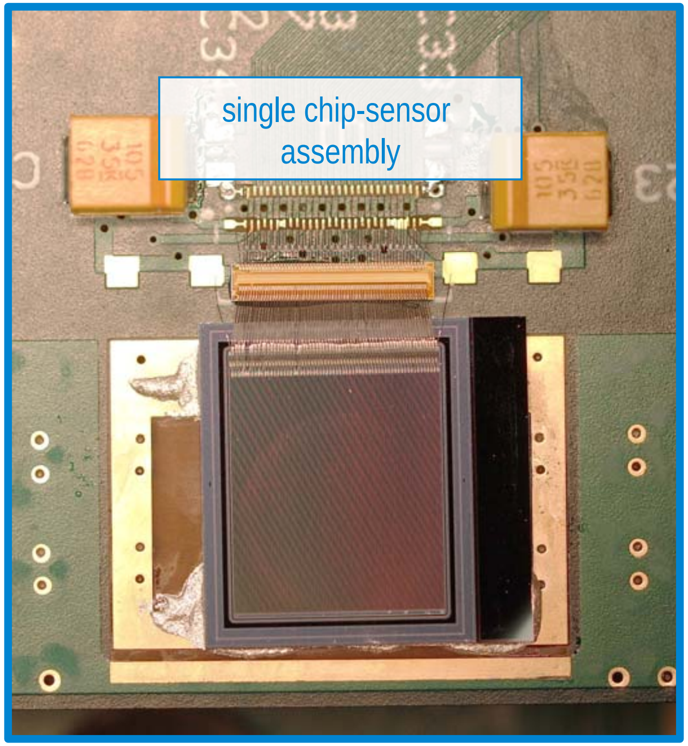


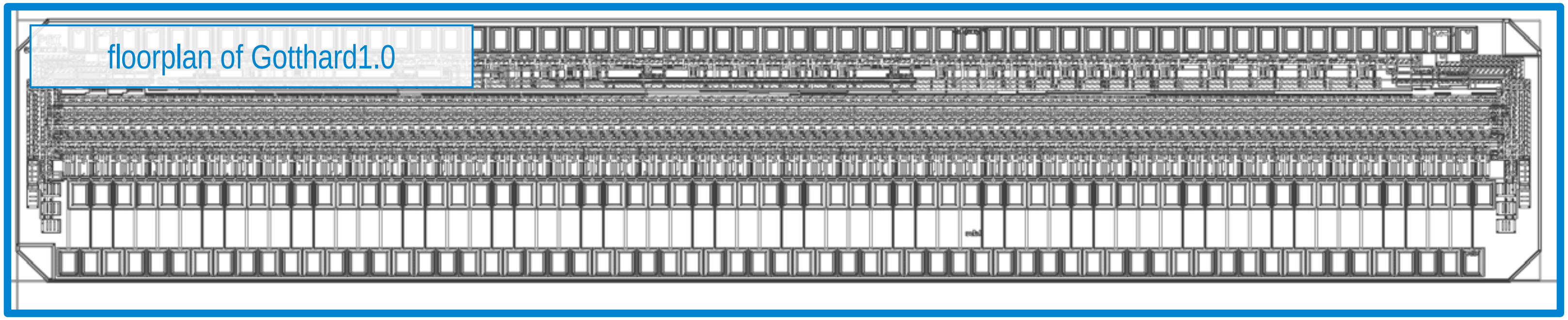
Prototypes (2008-2010)



GOTTHARD 1.0

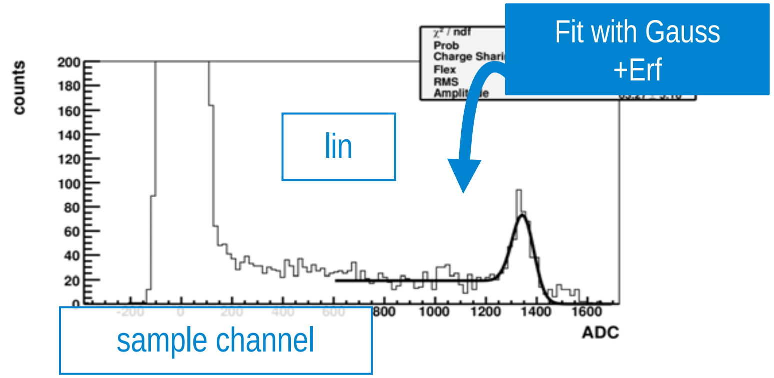
- 6.3x1.4mm^2 - 128 channels - 50μm pitch
- 3 automatic gain stages + 1 High Gain mode
- fast off pixel buffers, to sustain 32MHz readout
- 4 diff. analog outputs, 8 digital (gain) outputs
- ~ 1mW/ch.

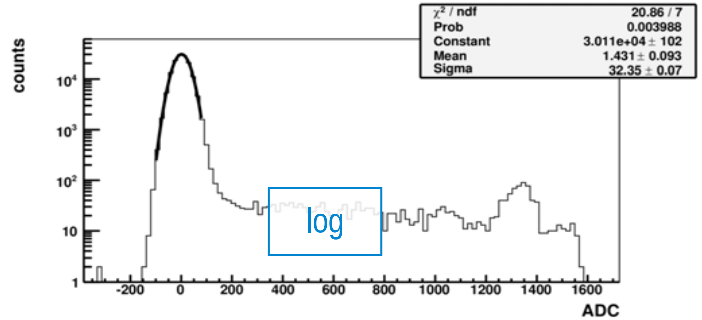

single chip-sensor assembly

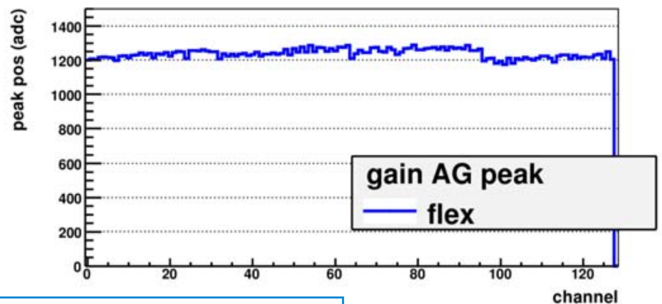

floorplan of Gotthard1.0

Noise – very high gain mode

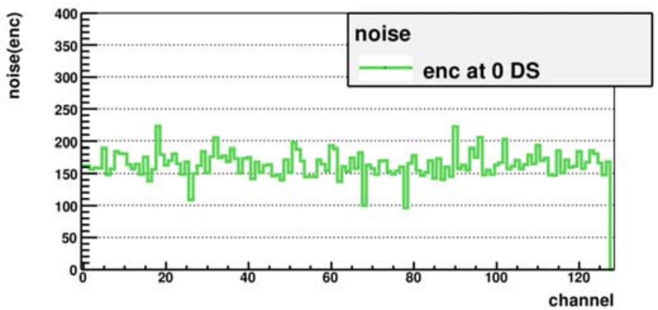
- measured with X-ray tube and Ag fluorescence (22 keV)
- ~ 1 us integration time





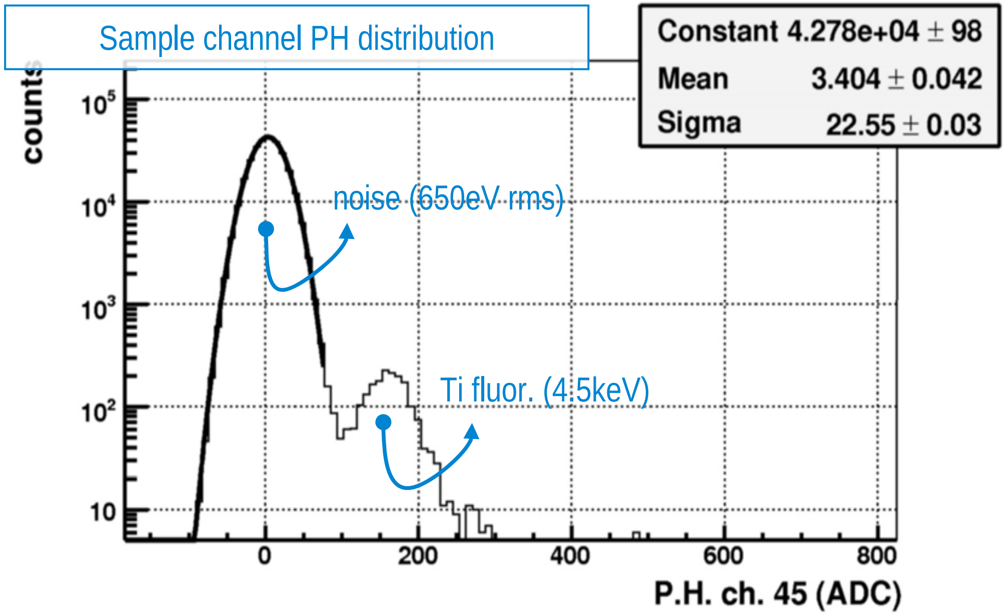


ch. to ch. variations



Noise ~ 160 e.n.c.

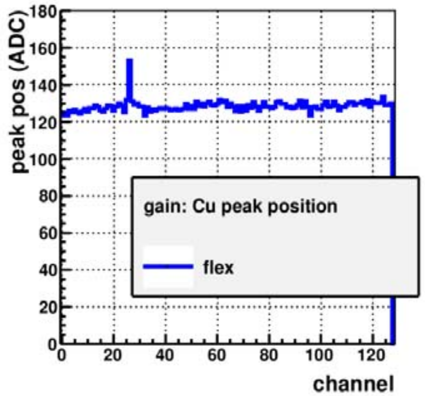
Low energy sensitivity

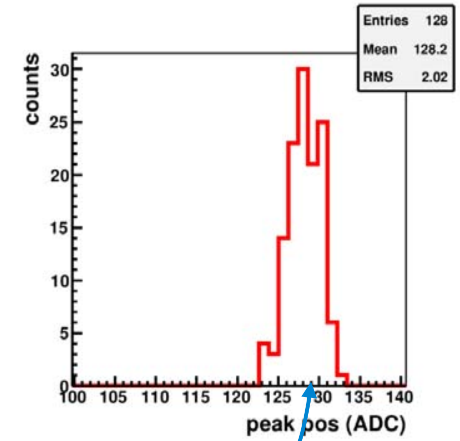


- single photon resolution down to ~3.5 keV
- At lower energy 2 or more γs can still be separated from the noise floor
- Sensors with thin “entrance window” needed

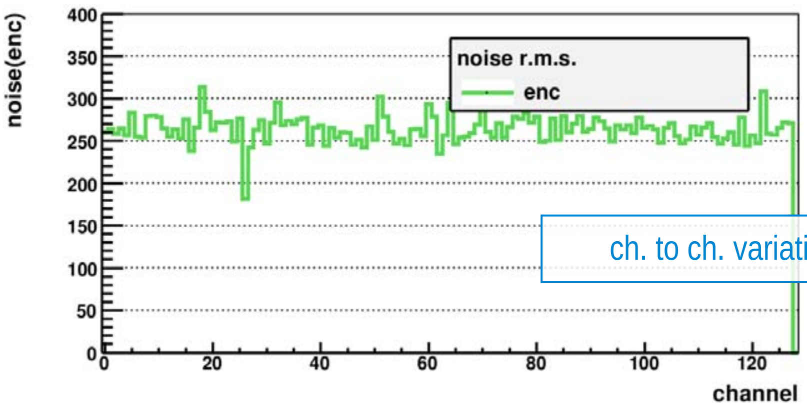
Noise – dynamic gain switching

- Gain1 is the starting gain for the switching mode
- measured with Cu fluorescence (8 keV)
- Average noise is 260 e.n.c.
- SNR=13 (for a 12 keV photon signal)
- Gain1 total range ~ 80 ph.

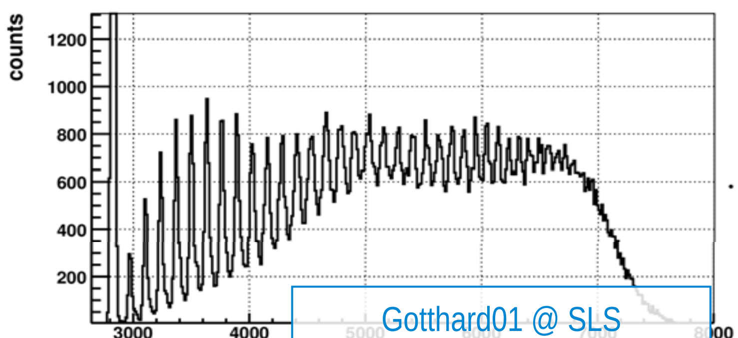




gain dispersion 1.5%

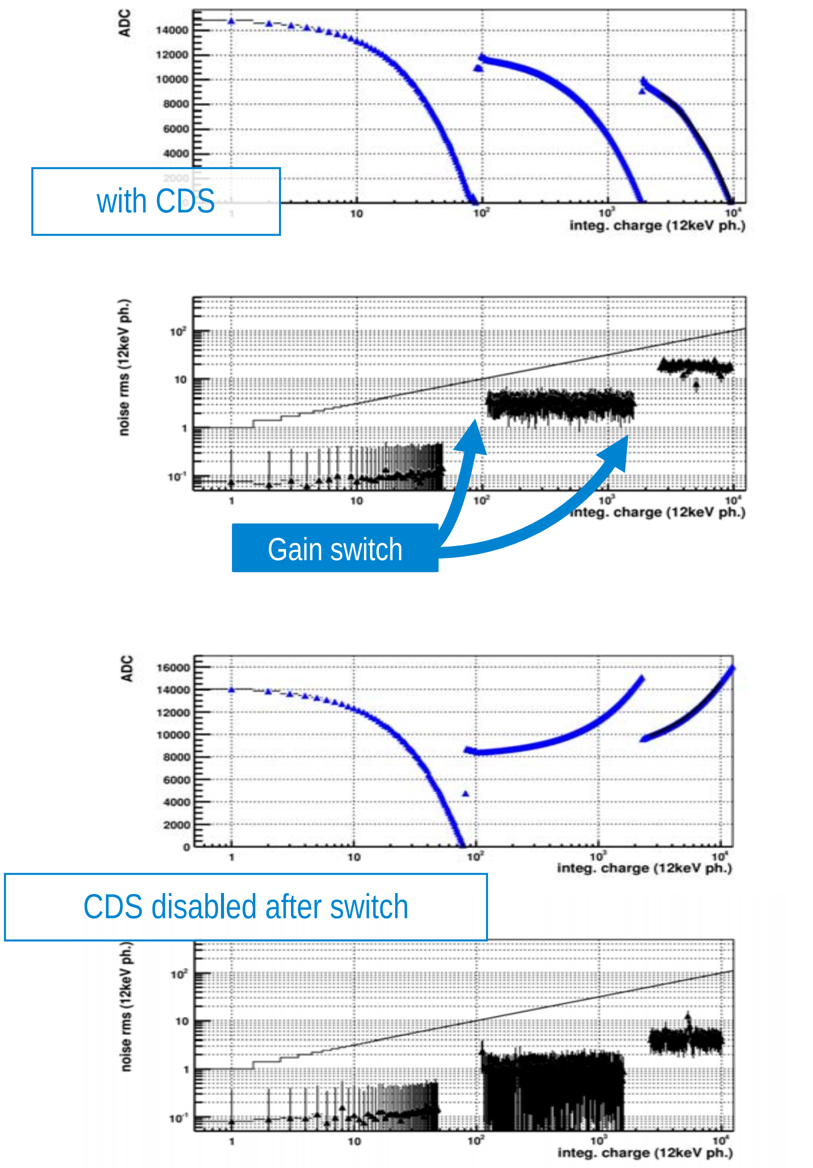


ch. to ch. variations



Gotthard01 @ SLS
charge sharing suppr.

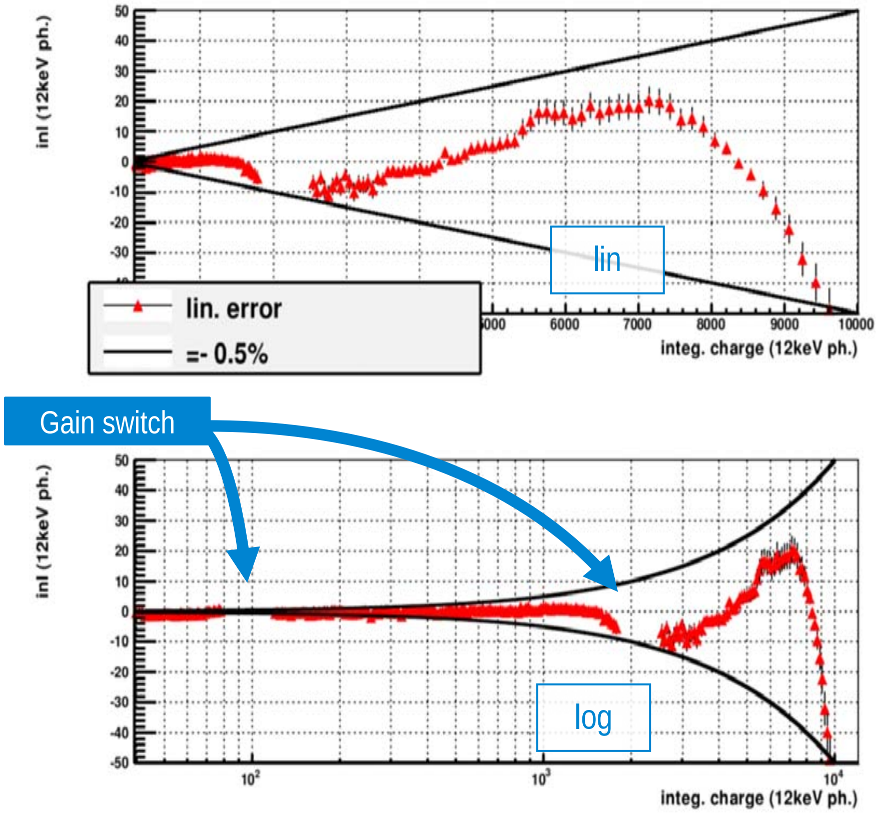
Noise – many photons



- an integration time scan at constant input current (visible light) was used to evaluate the noise at low gains
- CDS increases the noise of gain 2 and 3: a circuit to disable CDS after switch is present
- at all gains the electronic noise is well below the Poisson level
- Dynamic range of 10^4 ph.

Linearity

CDS disabled after switch



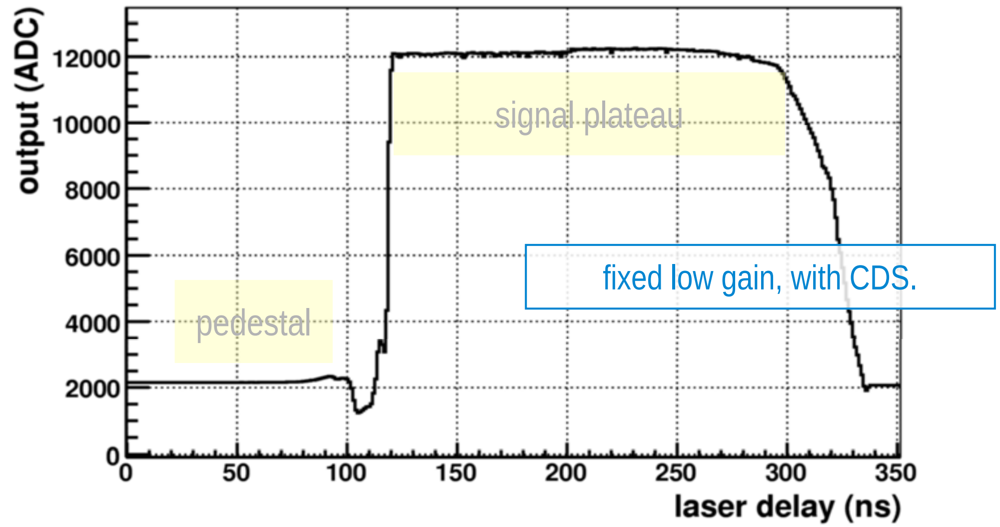
- linearity errors within +- 0.5% (source effects included) in the design input range (0-10^4 ph.)
- On smaller ranges better linearity can be achieved

Response to XFEL-like pulses

- ps laser setup UNI HH

- delay scan with a high intensity laser pulse (~500 12keV photons)
- 200ns integration time

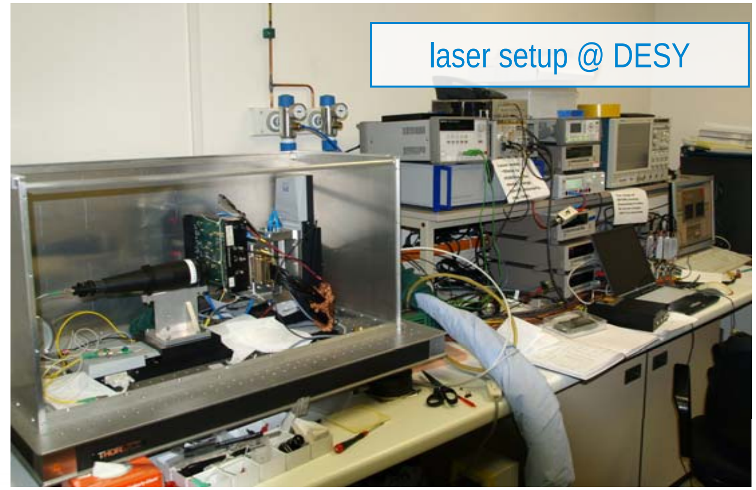
- CDS output settles in <30ns
- integration times as small as 80-50ns can be used

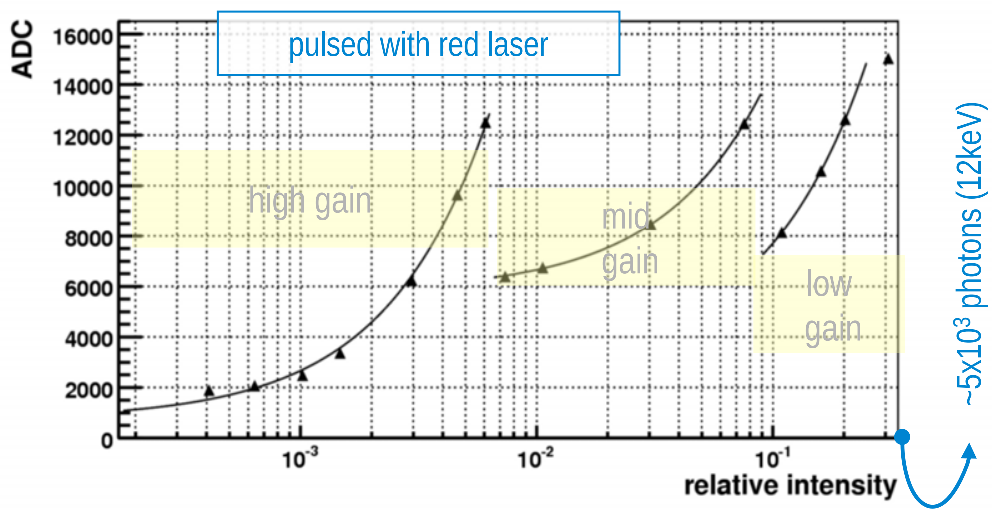


- similar result (in terms of speed) with or without automatic gain switching
- the preamplifier+switching circuitry can work at E-XFEL rates (4.5MHz)

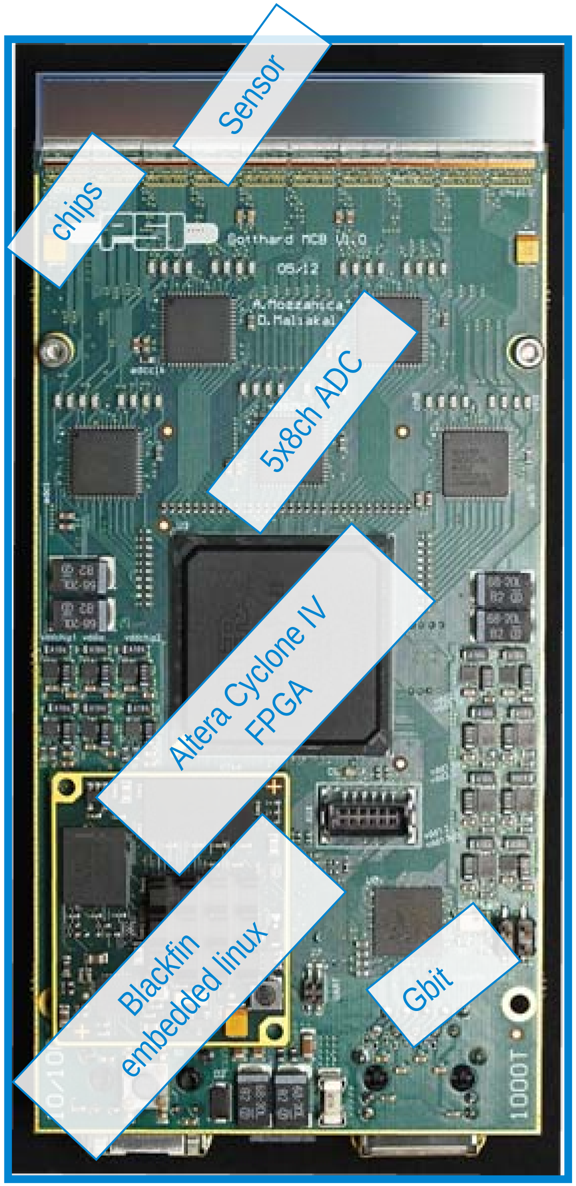
Linearity for XFEL-like pulses

- Measured with Gotthard0.3 prototype
- The switching has been tested with a sub-nanosecond laser pulse hitting the strip sensor
- Integration time 200ns, pulse in the middle of it
- Point dispersion mainly due to the uncertainty on the laser attenuation filters
- Switching works at the required speed





GOTTHARD module: overview



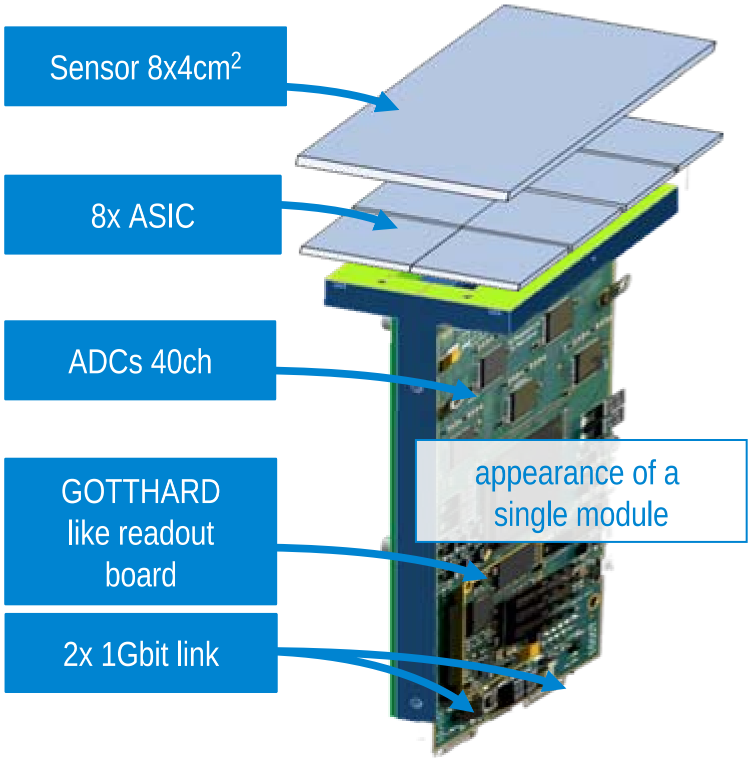
- 67mm x 130mm
- 50 µm pitch, 1280ch/module (same as MYTHEN)
- 10 chips, 4 analog outputs per chip
- 40 ADC channels @50Mhz,14bits
- Gbit Ethernet data transfer for readout
- 100T Ethernet for slow control/setup
- Fast readout (1MHz) with ~600 bunches per E-XFEL train measurable (memory for ~350)
- 60kHz continuous frame rate
- Integration in Mythen software (detector class)

GOTTHARD specification summary

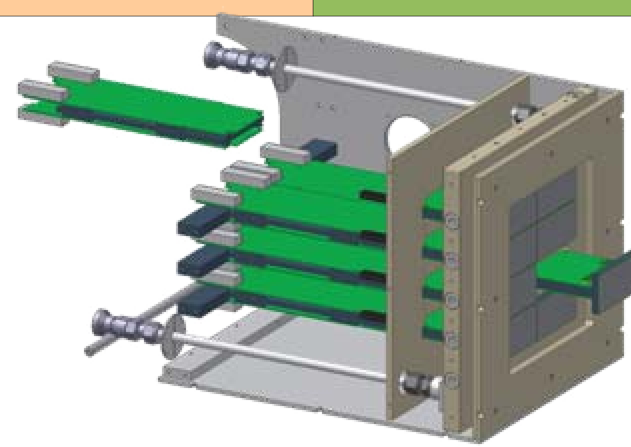
	Specifications
module size	6.7x13 cm
sensitive area	64x10mm
sensor thickness	320-500 μm
pitch	50 μm
dynamic range	10^4 12keV photons
min Energy	<3.5 keV
linearity	better than 0.5%
point spread function	O(pitch)
min int. time	80ns
dead time	<50ns
cooling	air (fan)
readout time = 1 / frame rate	>50kHz continuos 1MHz burst
XFEL ready	YES

Jungfrau: a 2D detector for Swissfel

adJUstiNg Gain detector FoR the Aramis User station



ASIC technology	UMC110nm
mudule pixel count	525k
mudule size	80x40 mm^2
sensor thickness	320-500 µm
pixel size	75x75 mm^2
dynamic range	up to 10^4 12keV photons
noise r.m.s.	<150 e.n.c.
min Energy	<3 keV
linearity	better than 1%
point spread function	1 pixel
dead time	<50ns
cooling	liquid
readout time = 1 / frame rate	400Hz



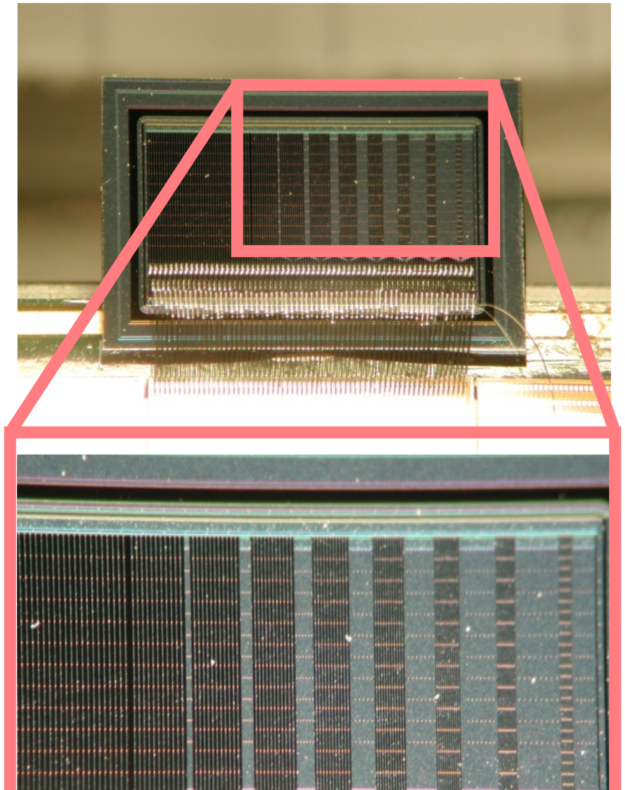
EIGER 4M detector mechanics – 4x2 modules

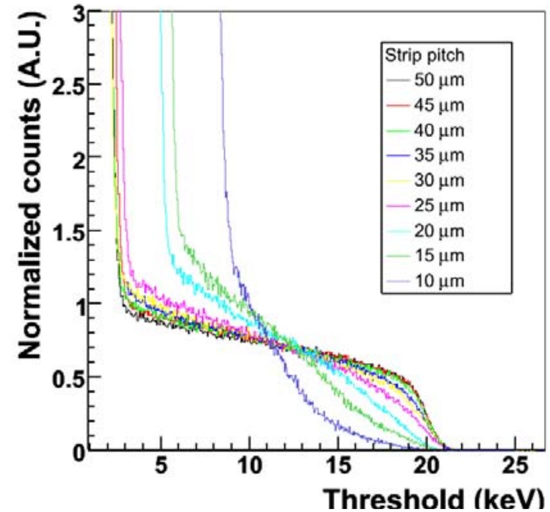
- ASIC and readout system based on GOTTHARD
- Dimensions, sensor and mechanics from EIGER
- chip 2013, module 2014, detector mid 2015

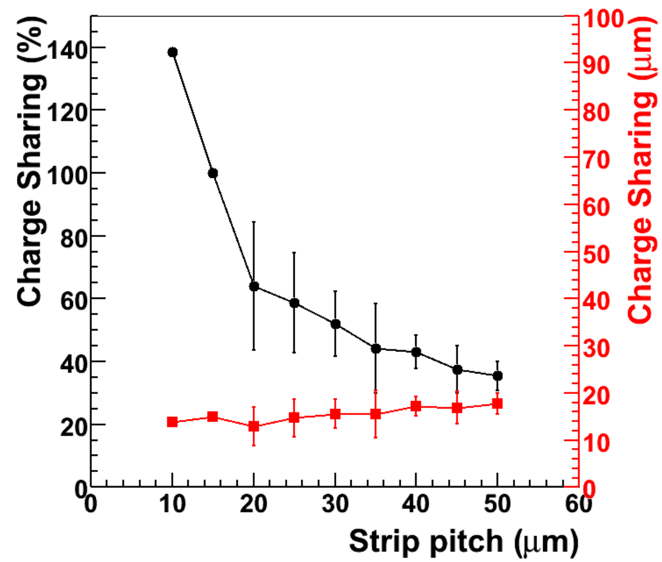
What are the limits for the pixel size and position resolution?

How can one achieve the highest resolution?

Single photon counting detectors at small pitches

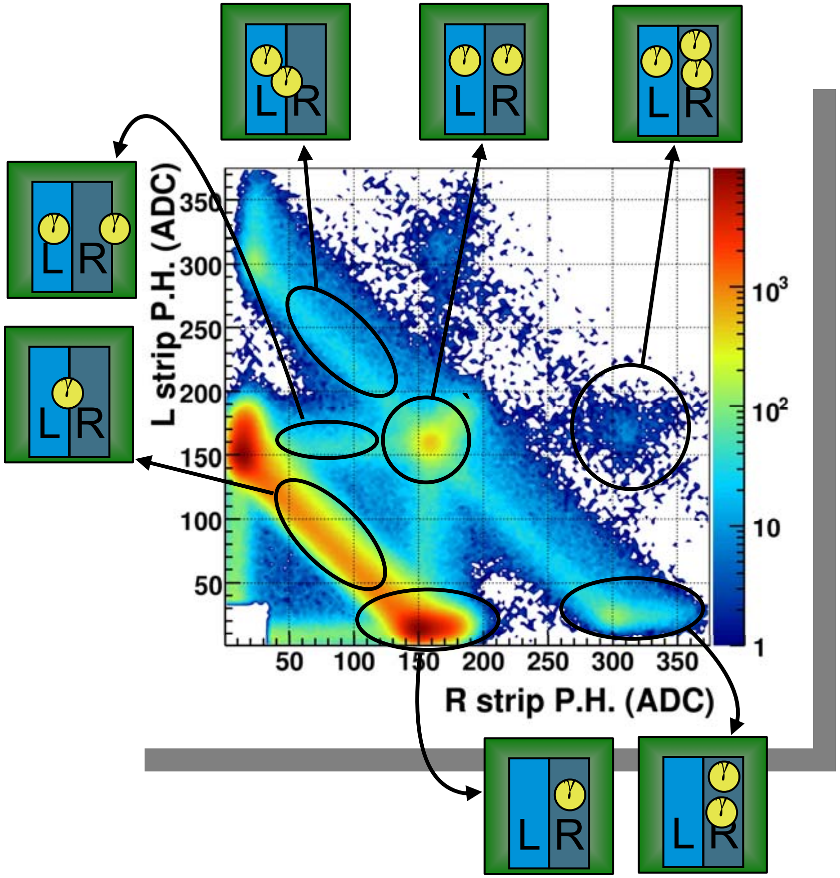






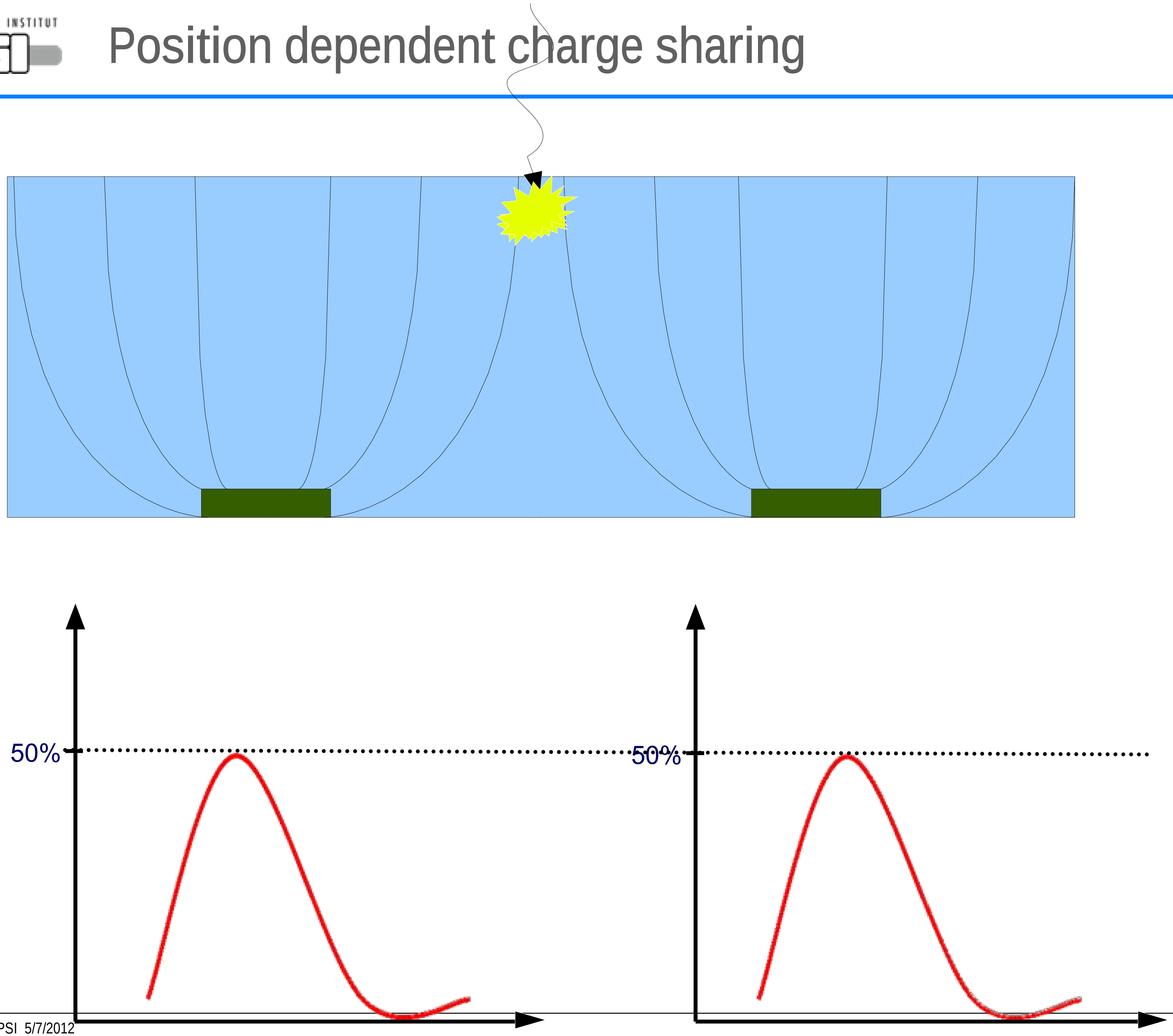
single photon counting possible down to about 25 µm
below 25 µm charge summation necessary
the region where the charge is shared is approximately constant

Charge integrating detectors: get full information

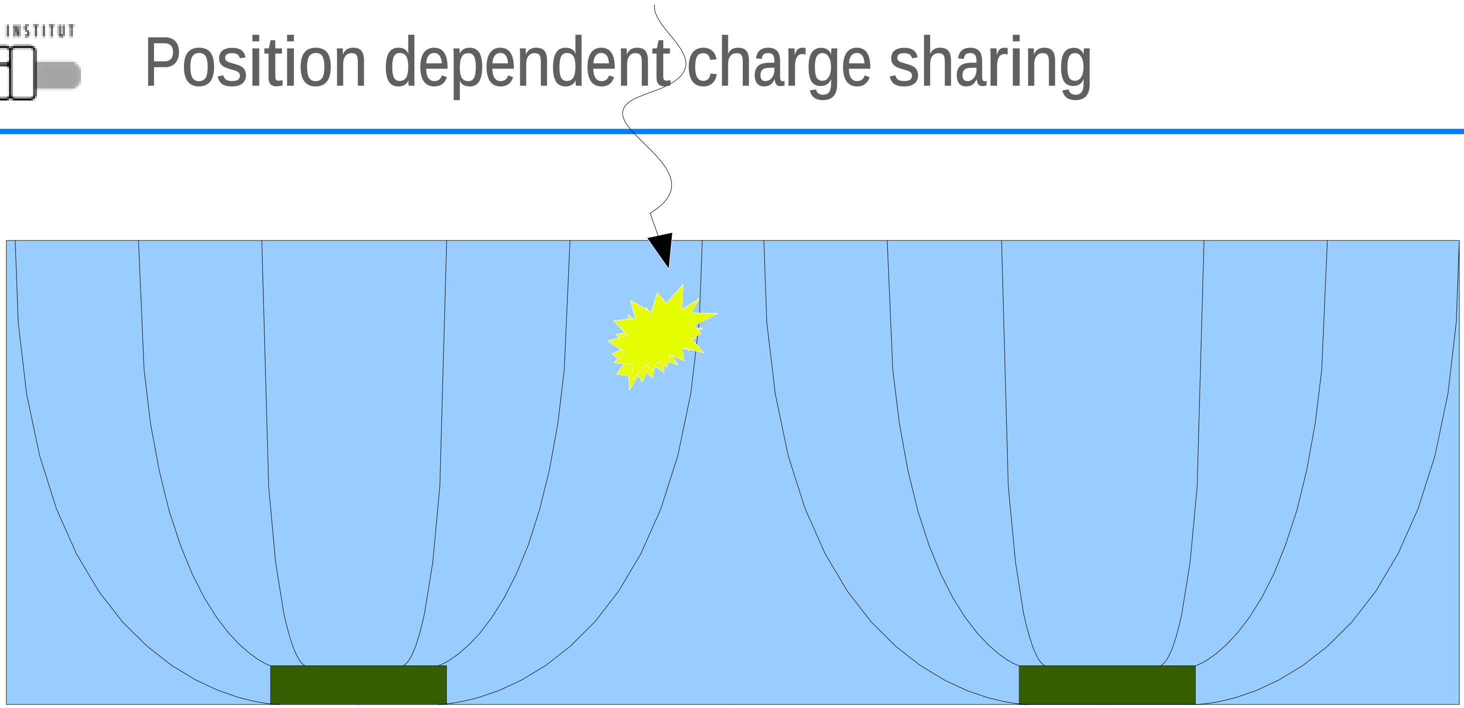


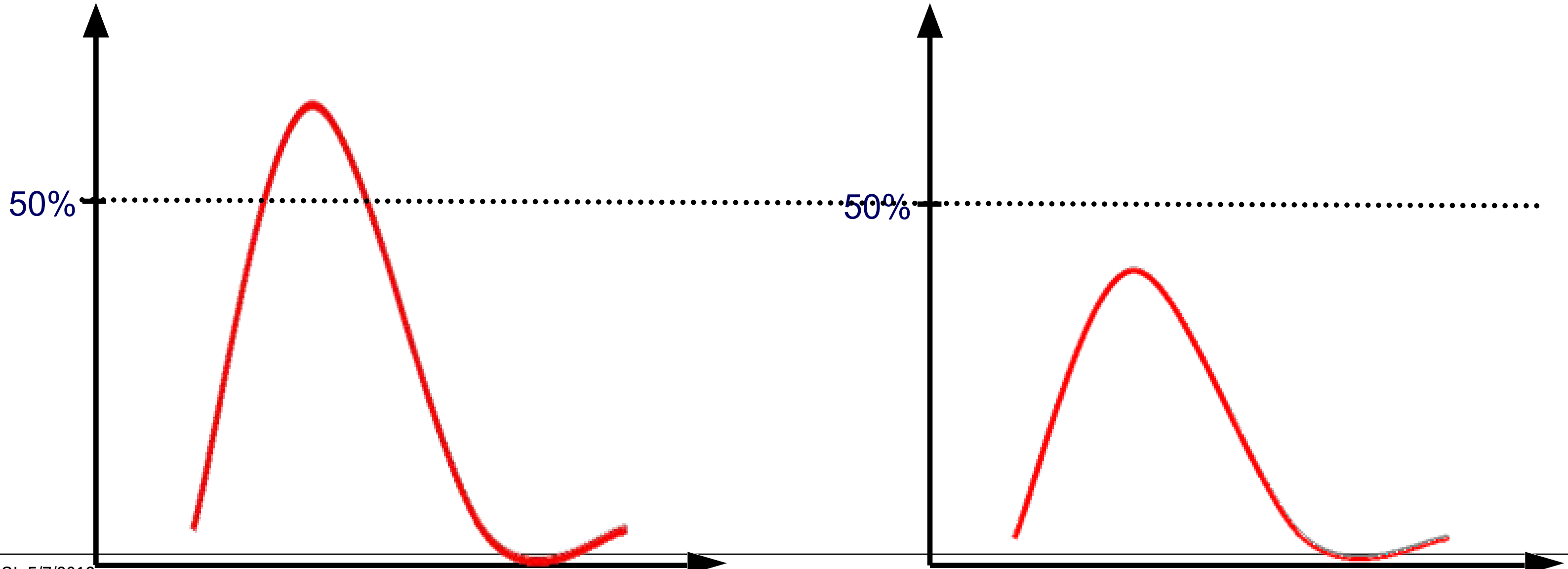
50 micron pitch, 25 keV

Position dependent charge sharing

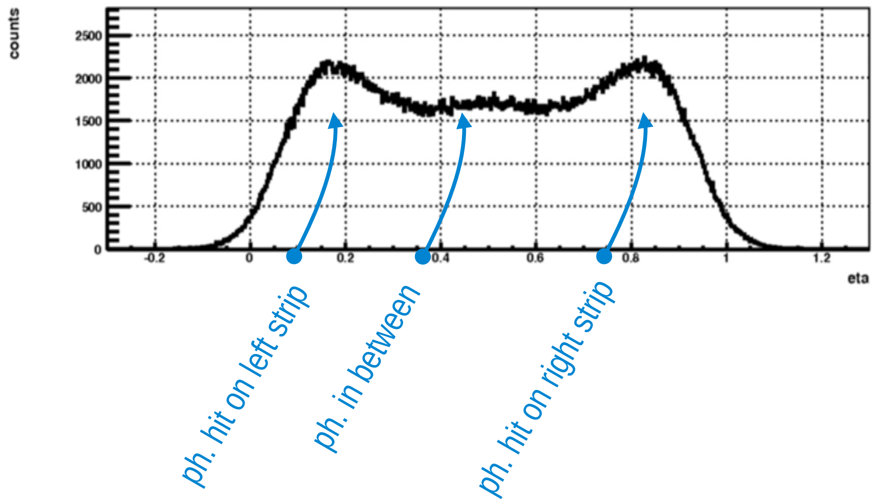


Position dependent charge sharing





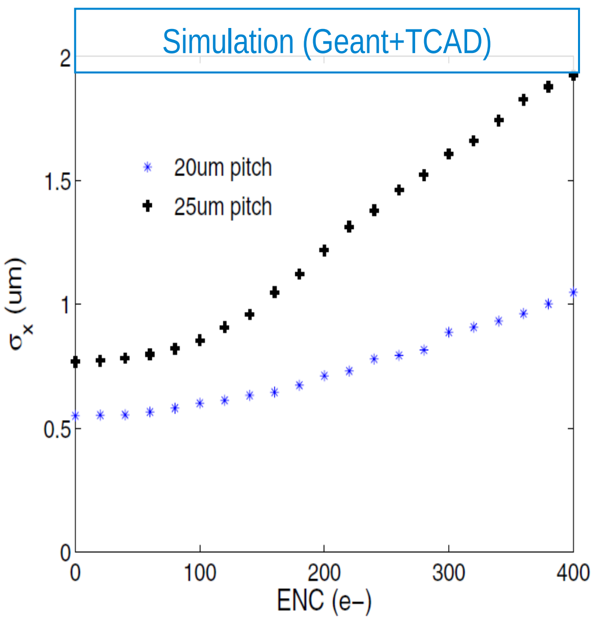
Gotthard: position interpolation

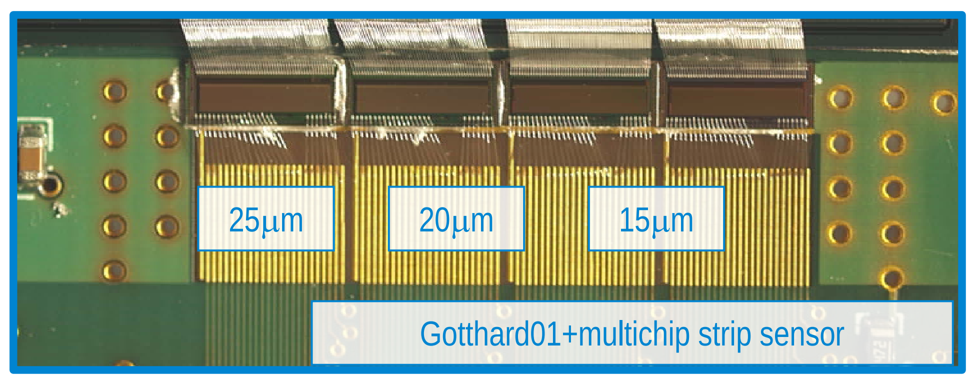


Eta algorithm for position reconstruction:

- $\eta = Q_R/(Q_L+Q_R)$
- eta distribution $N(\eta)$ are collected for a uniform photon field
- the hit position is then:

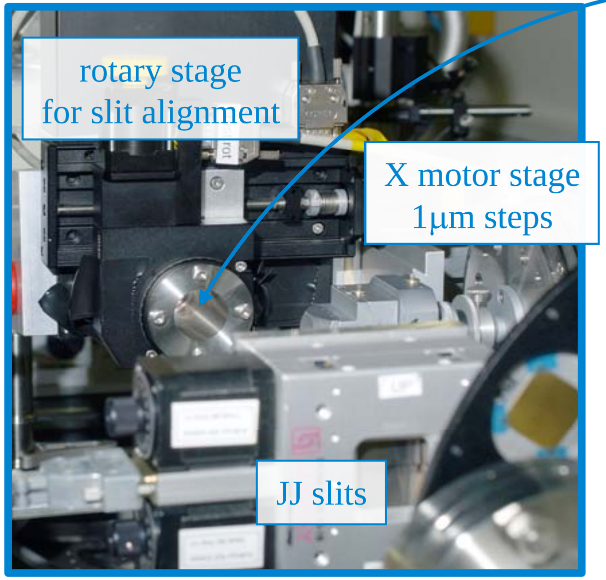
$$x_\eta = p\frac{\int_0^{\eta_0}\frac{dN}{d\eta}d\eta}{\int_0^{1}\frac{dN}{d\eta}d\eta}$$

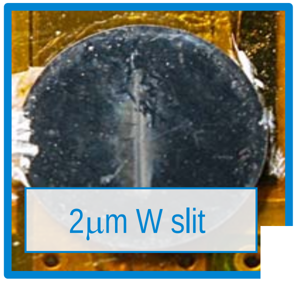


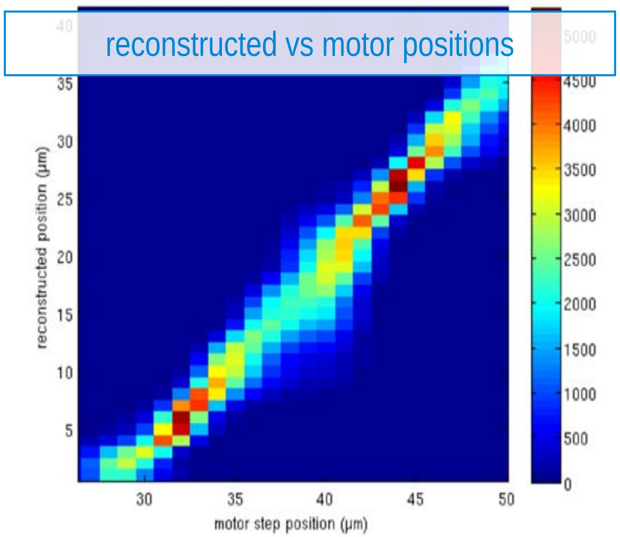


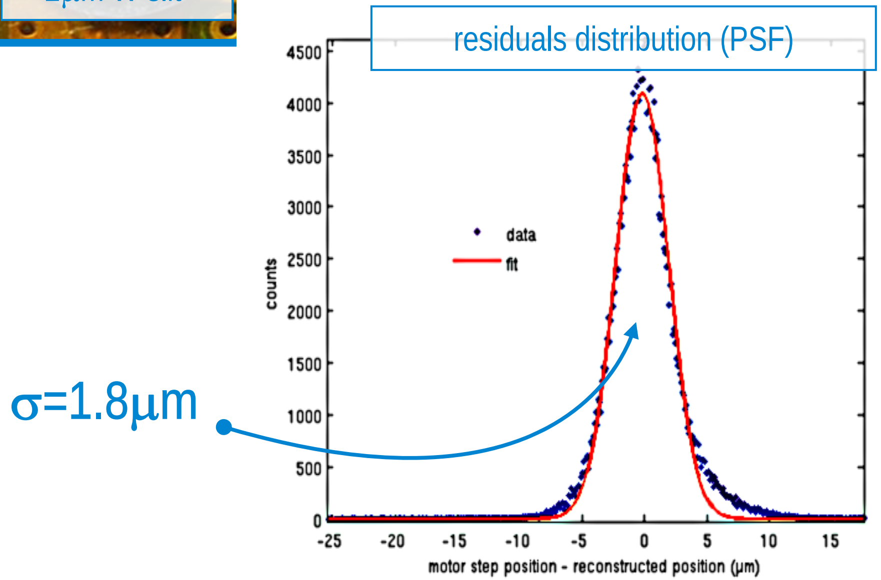
Gotthard: position interpolation II

- To measure the spatial resolution a 2μm W slit has been scanned in 1μm steps in front of the strips
- slit parallel to strips
- Vertical beam size ~100μm
- Strip pitch 20μm, 15keV beam

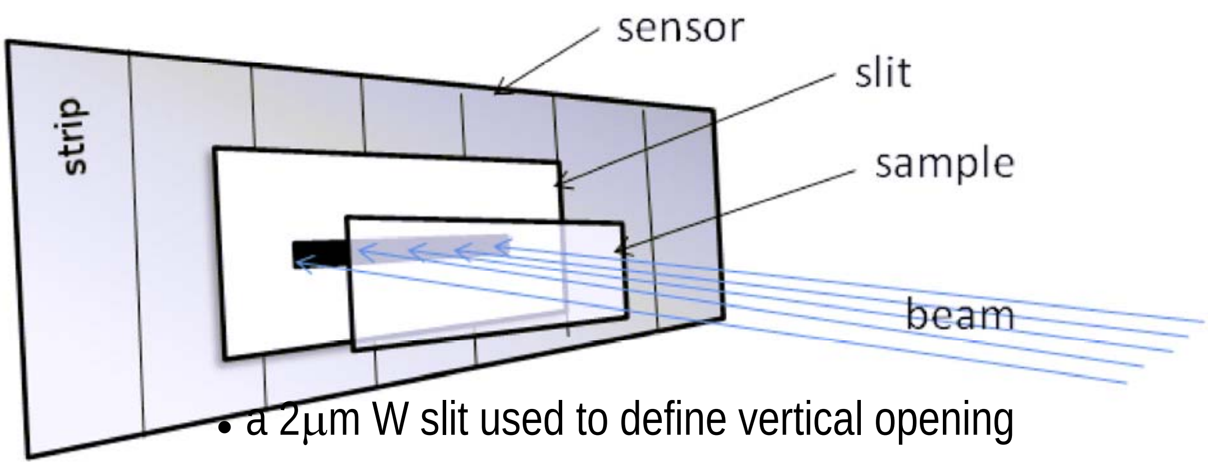






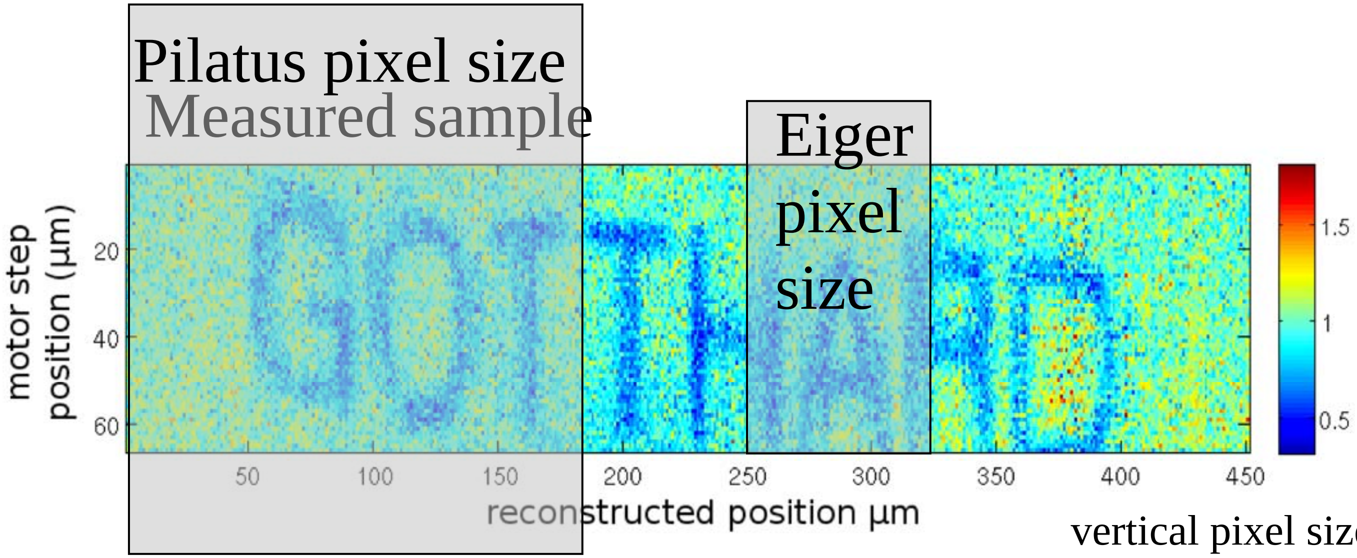


Gotthard: position interpolation III



- a 2μm W slit used to define vertical opening
- Sample scanned in 1μm steps in front of the strips
- Strip pitch 20μm, 15keV beam

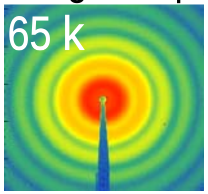
Sample 3μm thick gold on 300 μm Si substrate
➔ little contrast!



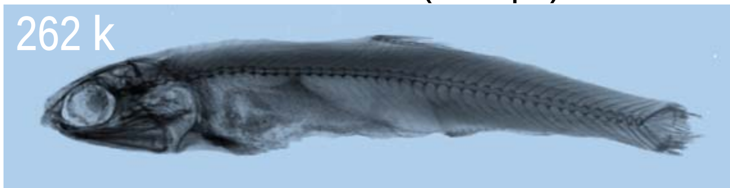
vertical pixel size not to scale

Conclusions Eiger

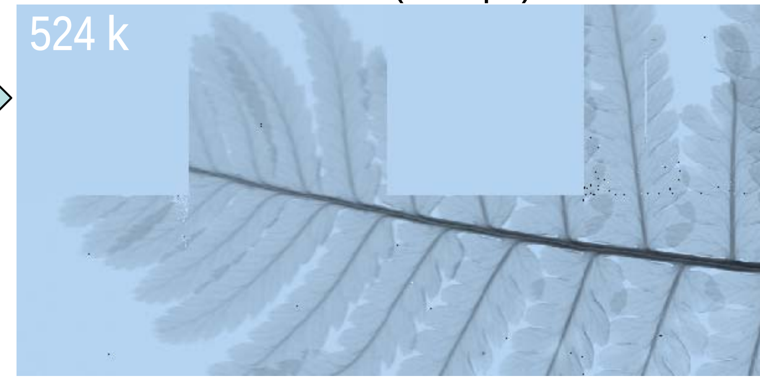
Single chip



Half module (4 chips)



Module (8 chips)



- First results
  - characterization of the chip
  - the first demonstration experiments
  - Currently work on firmware and software, soon module working
- Single module system @ cSAXS, surface diffraction station
  - summer this year
- High performance 9M Eiger @ cSAXS
  - on board memory (288 GB RAM) or 2.5 sec @ highest data rates
  - 100 Hz continuous operation and data to disk
  - Complex IT infrastructure and data storage needed
- Eiger licensed to Dectris

Conclusions charge integrating for XFELs

- Dynamic gain switching works well
  - Single photon resolution and 10^4 dynamic range
  - Electronic noise below poisson fluctuations

    → single photon counting data quality

- Gotthard works at 1MHz frame rate in burst and 50kHz continous
  - Well suited for diagnostics of XFELs and energy dispersive detectors

- Swissfel detector development just started (almost everything in hand) ready 2015
  - Based on Eiger sensor 75 micron pixel size
  - Frame rate up to 2kHz → well suited for PX (no rate limitation)

- Charge integrating system can have similarly low noise as single photon counting systems
  - No limit in pixel size due to charge sharing → position resolution on ~micron level can be reached

The SLS Detector Group:
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Wir schaffen Wissen – heute für morgen