PAUL SCHERRER INSTITUT

PSI

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

Bernd Schmitt

Jungfrau, Mönch and Eiger: Detector Development at the Swiss Light Source

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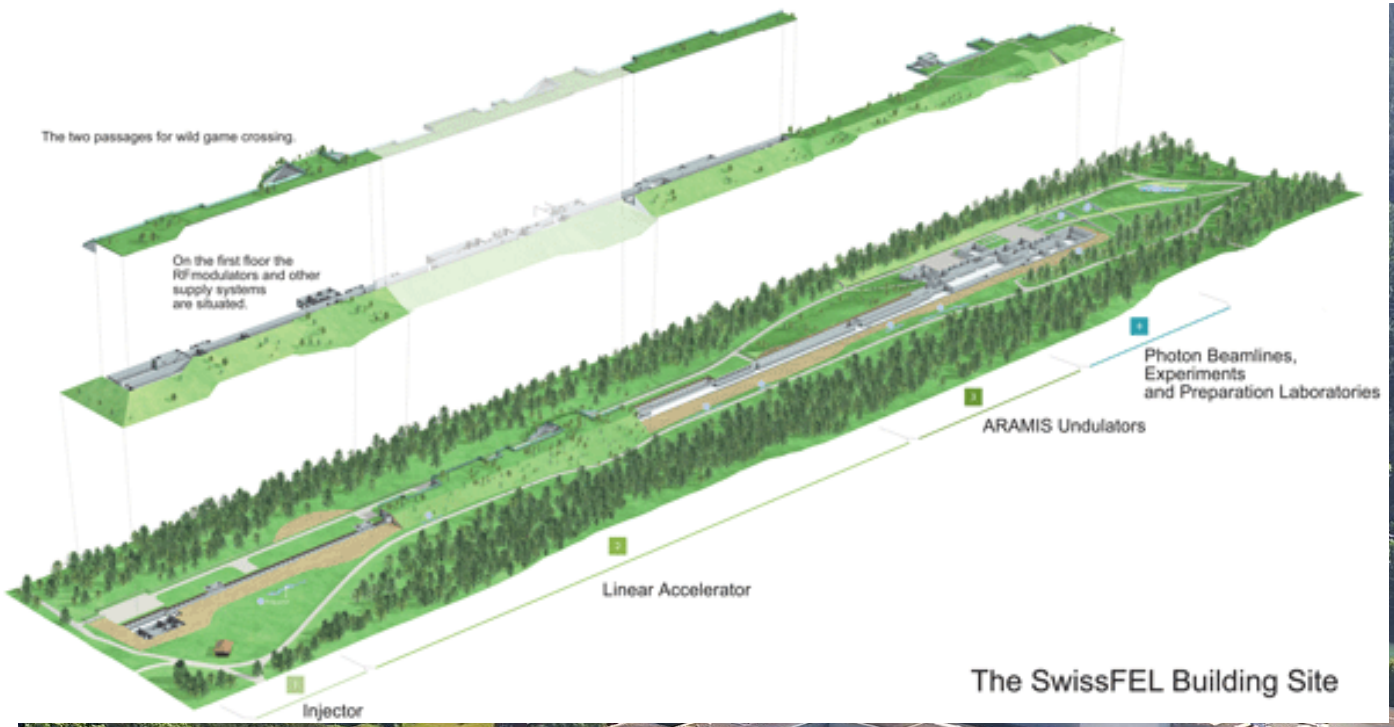
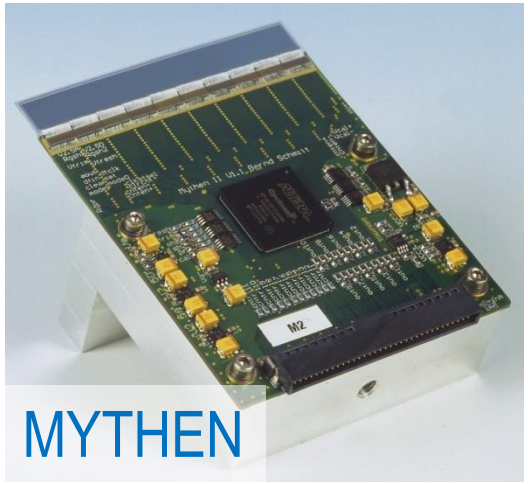
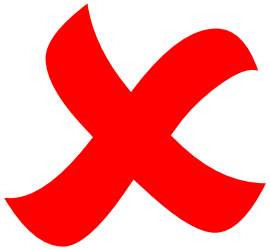
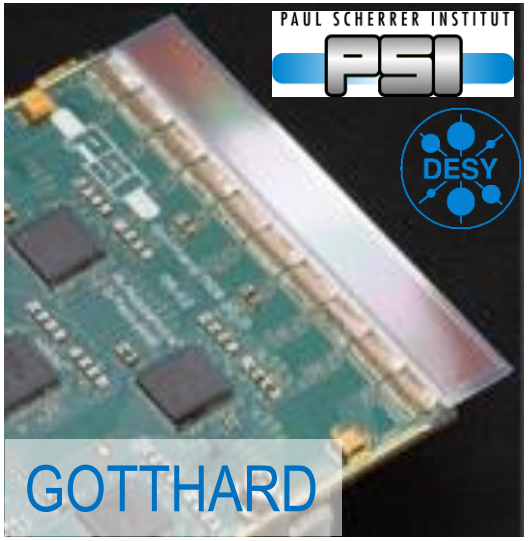
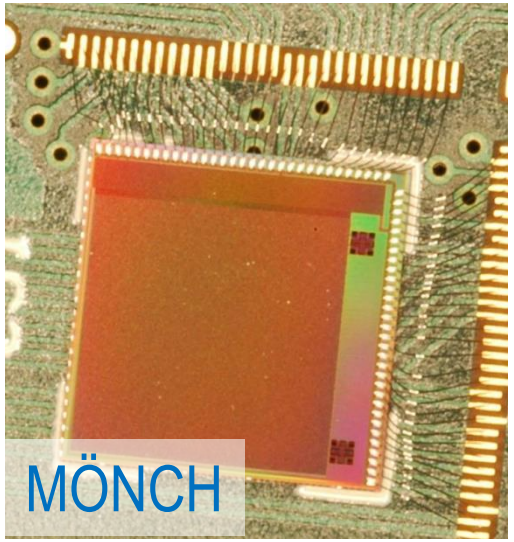


Our group is part of the SLS and our job is
to build detectors for specific applications at the SLS
and SwissFEL to allow users to do new or better science

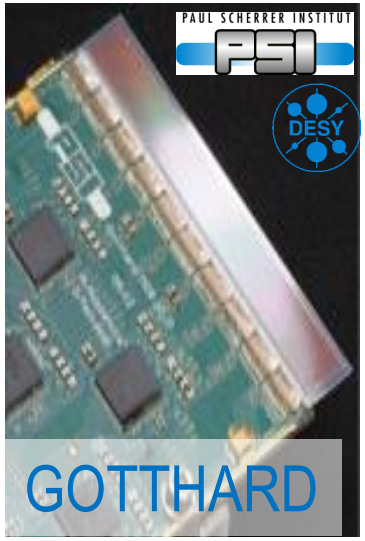
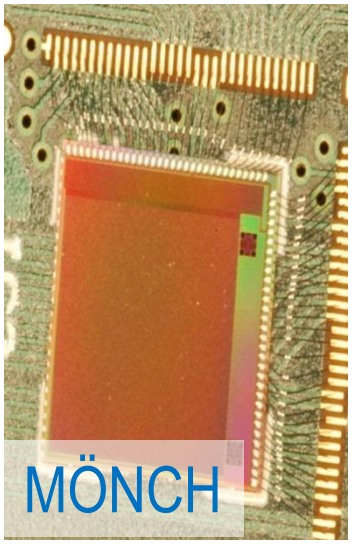
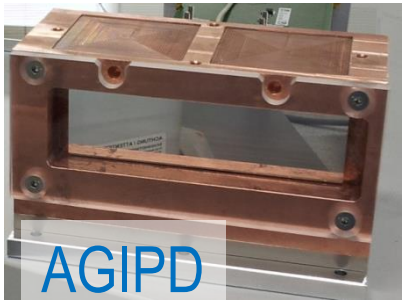
uSR, SINQ, SLS

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

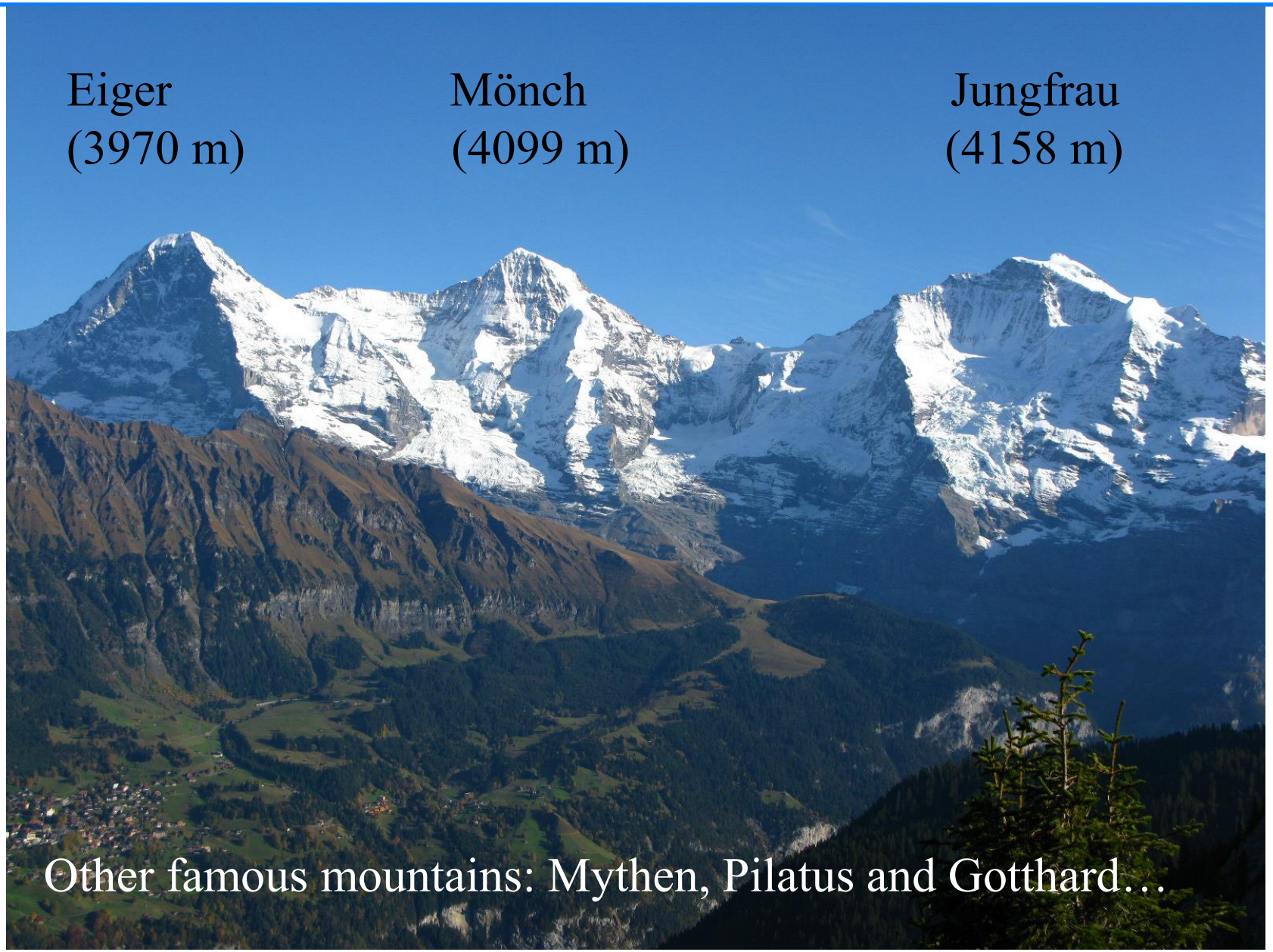
Hybrid Detectors @ SLS

	Microstrips 50 um	Pixels 75 um	25 um
Single Photon Counting	 MYTHEN	 EIGER	
Charge Integrating	 GOTTHARD	 JUNGFRAU	 MÖNCH

Hybrid Detectors @ SLS

	Microstrips 50 um	Microstrips 75 um	Pixels 25 um	Pixels 200 um
Single Photon Counting	 MYTHEN	 EIGER	✗	✗ See talk Alexander Klyuev
Charge Integrating	 GOTTHARD	 JUNGFRAU	 MÖNCH	 AGIPD

Swiss Mountains



Outline

Example Application: Protein Crystallography

Detector principles:

- single photon counting for synchrotrons
- charge integrating for XFELs and synchrotrons

The Eiger detector

The Jungfrau detector

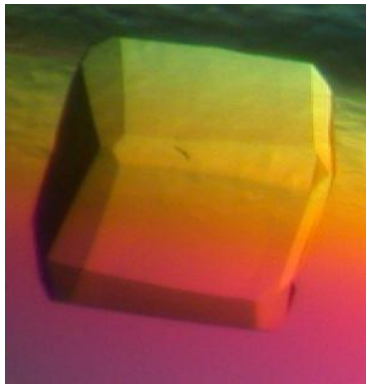
The Mönch detector

Conclusions

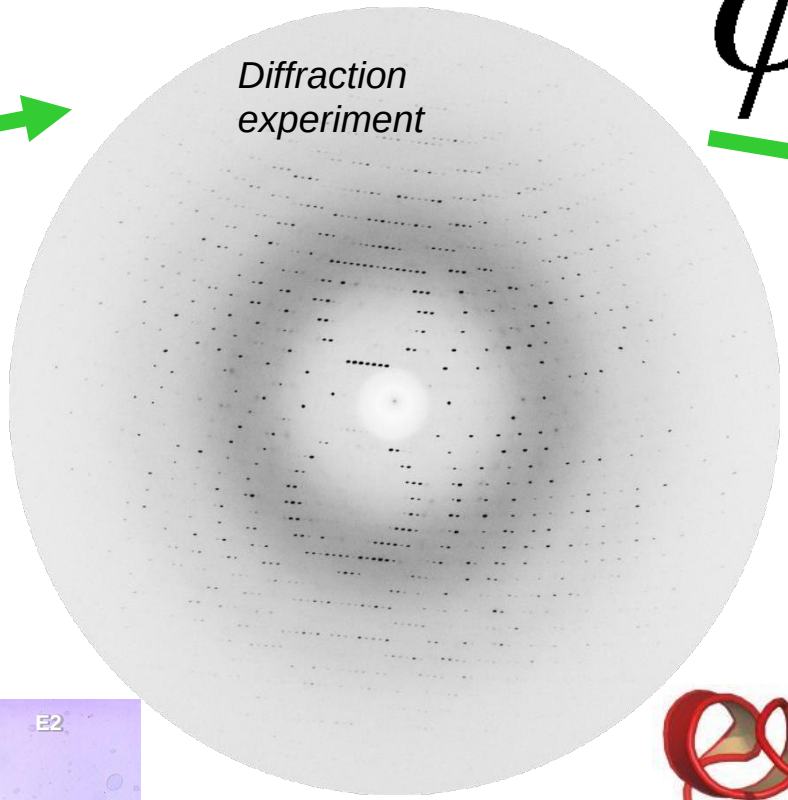
Protein Crystallography

From protein to structure

Crystallization (cubic Insulin)

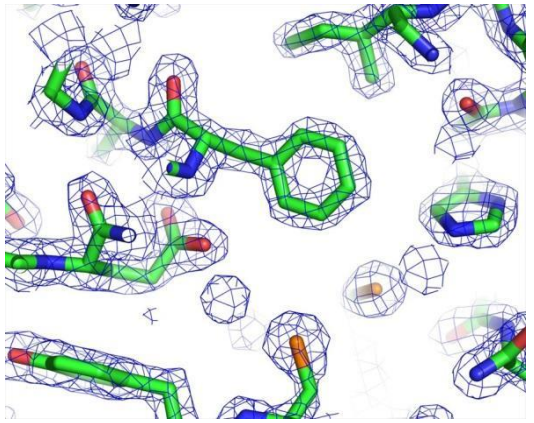


Diffraction experiment

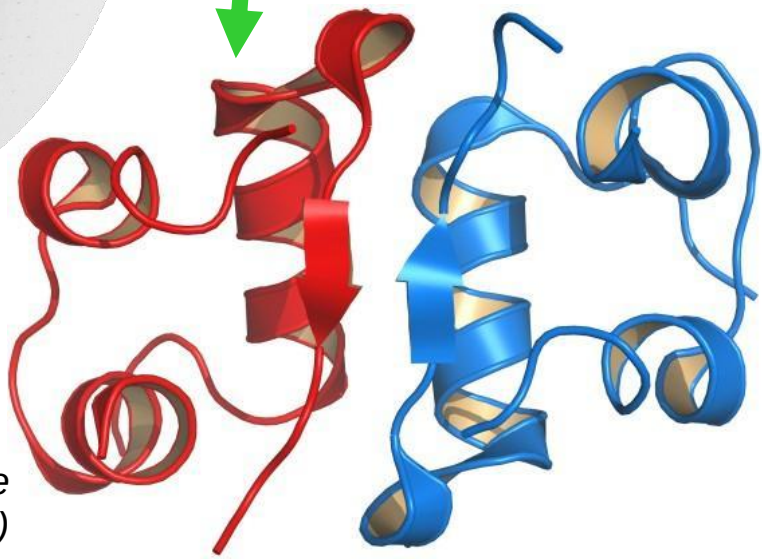


Phasing φ

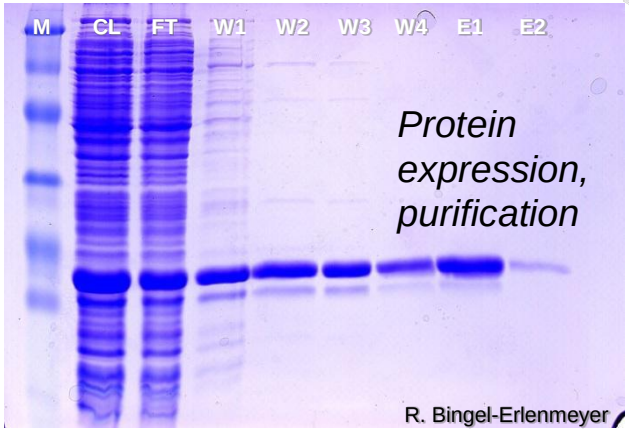
Electron density map



Model building, refinement

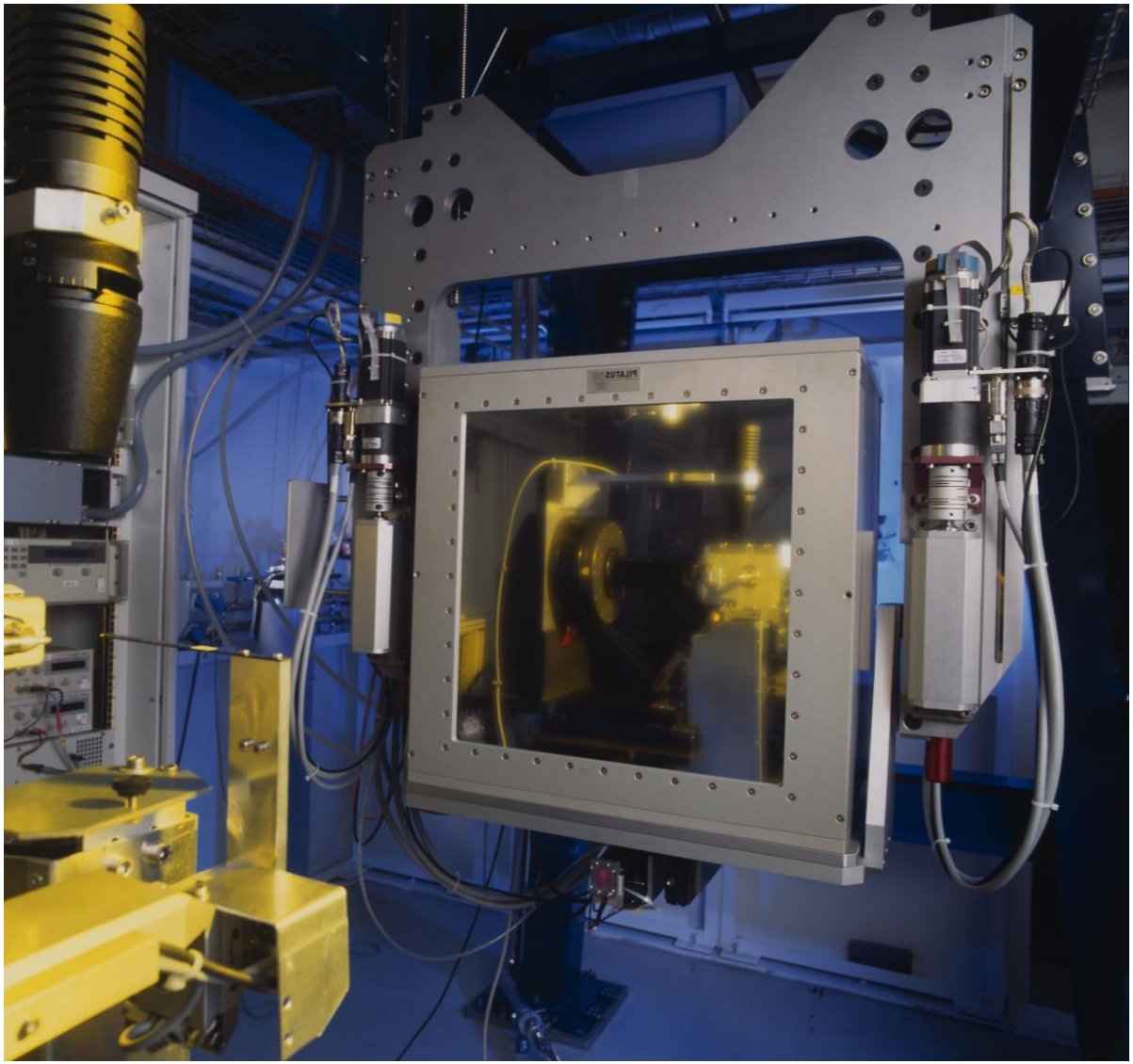


Structure (Insulin)



PilatusII6M at the Protein Crystallography Station

No of Modules	60, 12 x 5
Detector Size [mm]	431 x 448
Format	6’224’001 pixels
Pixel size	172 x 172 μm^2
Dynamic range/pixel	20bits
Count rate/pixel	~ 1-3 MHz
Readout time	3.5 ms
Frame rate	12.5 Hz



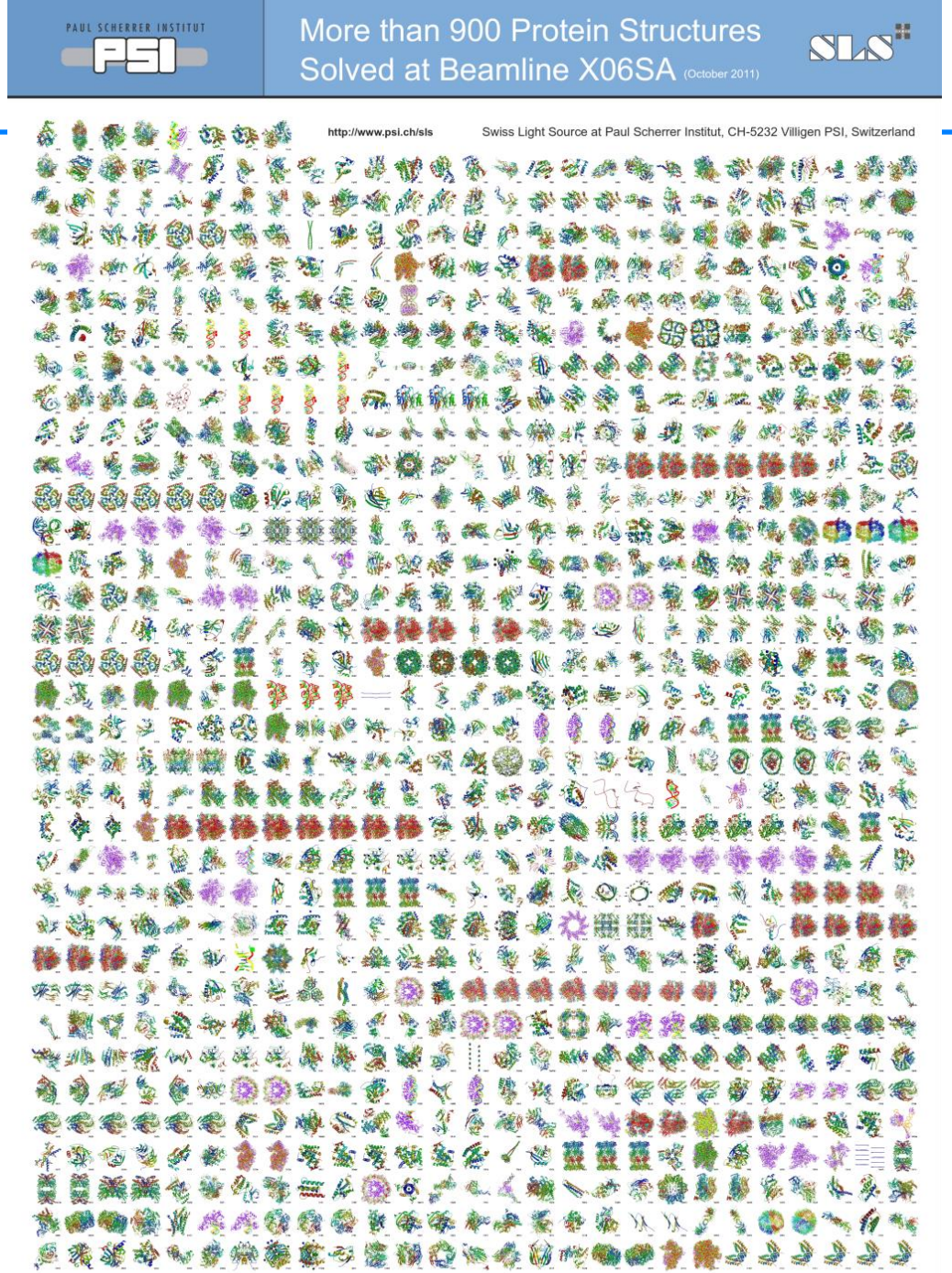
made continuous shutter-less operation possible at PX

Sold and further developed By Dectris

more than 900 protein structures solved at PXI beamline at SLS

~2/3 using PilatusII 6M

compiled by Sandro Waltersperger
Oct 2011

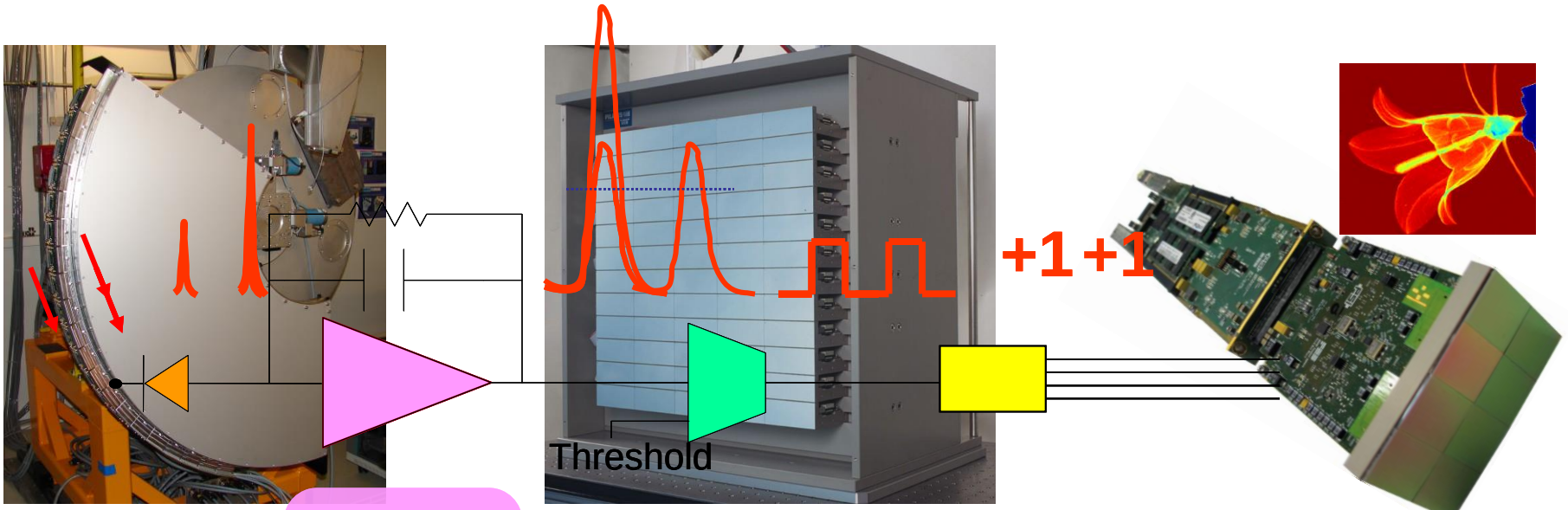


From single photon counting detectors at PSI…

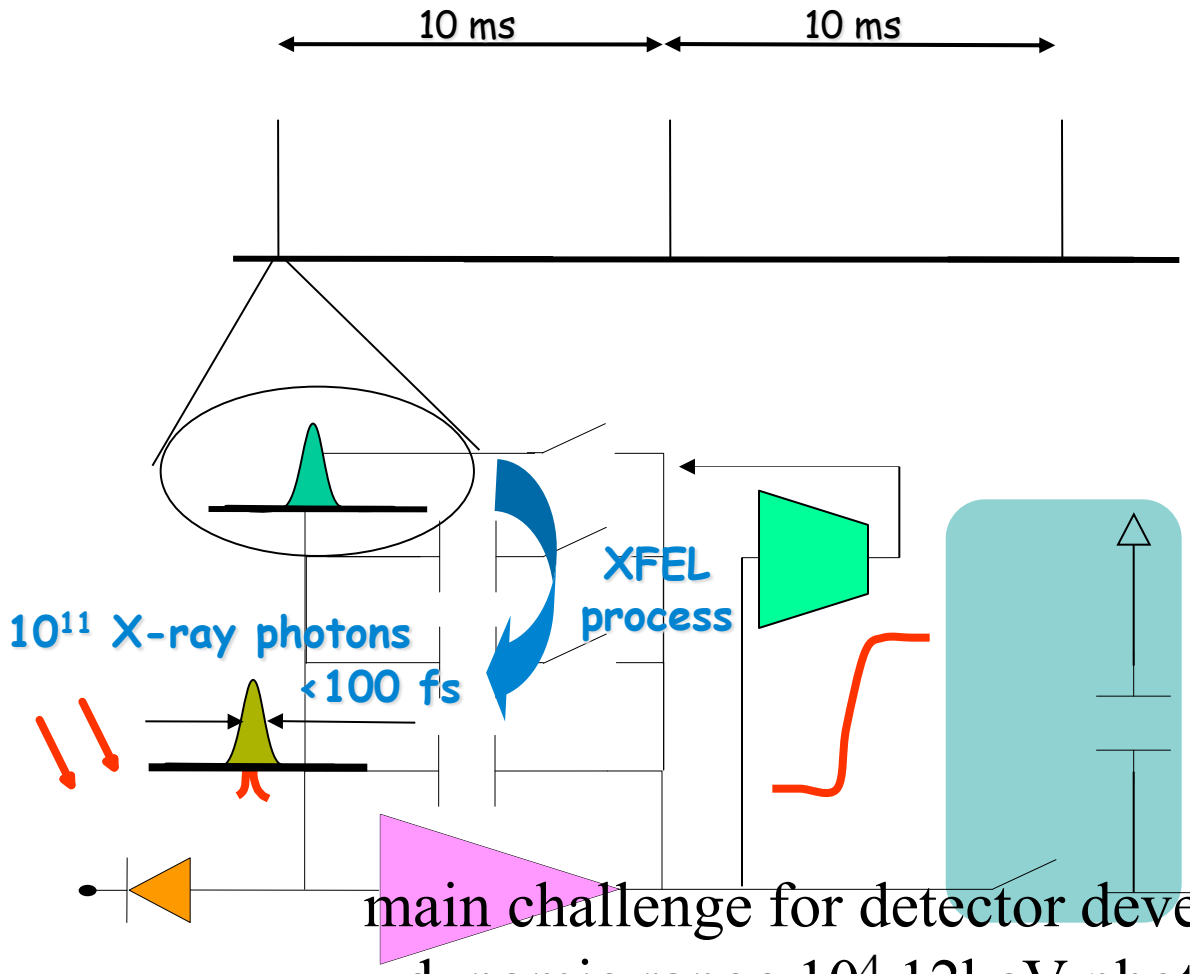
MYTHEN
1k to 30k 50µm strips for powder diffraction, small angle scattering, medical imaging…

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

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



… to charge integrating detectors



Dynamic range: 10000

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

→ 1 photon ~10mV
100 photons dynamic range

Solution:

→ dynamic gain switching

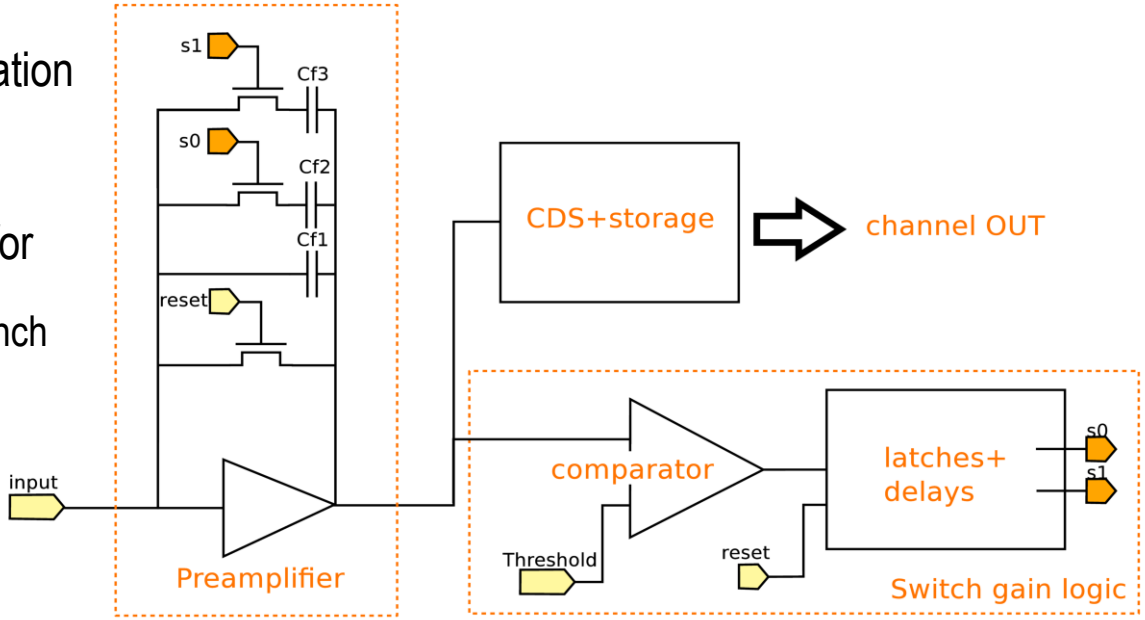
main challenge for detector development:

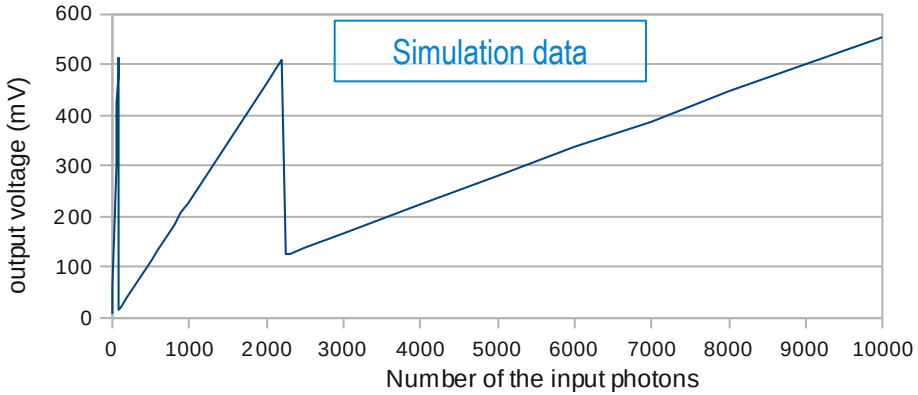
- dynamic range 10^4 12keV photons per pixel
- still with single photon resolution

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, Jungfrau and Mönch



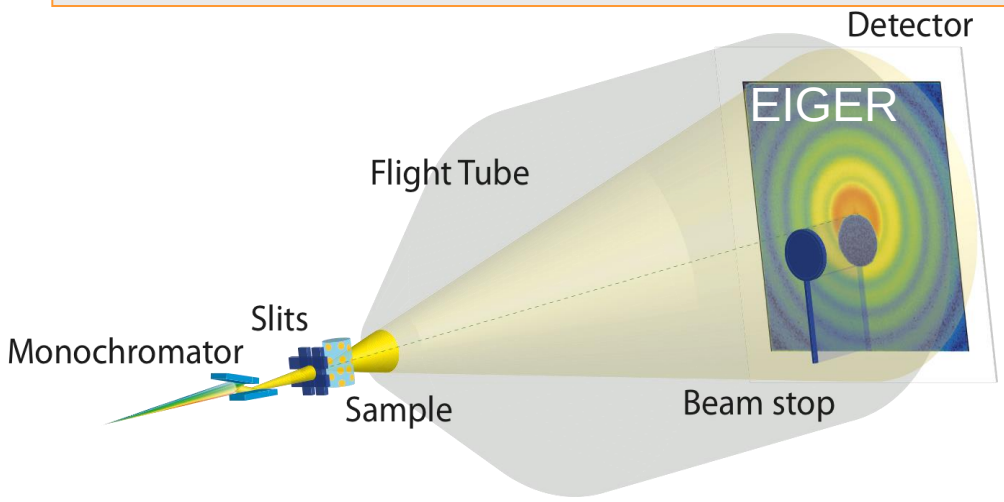


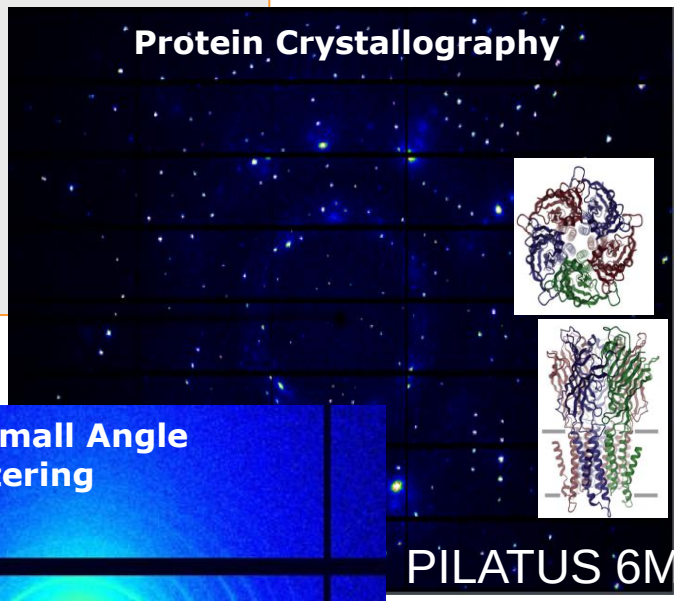
- Logic after comparator to:
  - Switch a 2nd time if 1st switch not enough
  - Avoid a 2nd switch on spikes due to the 1st one
- Switching has to be FAST (<10ns)

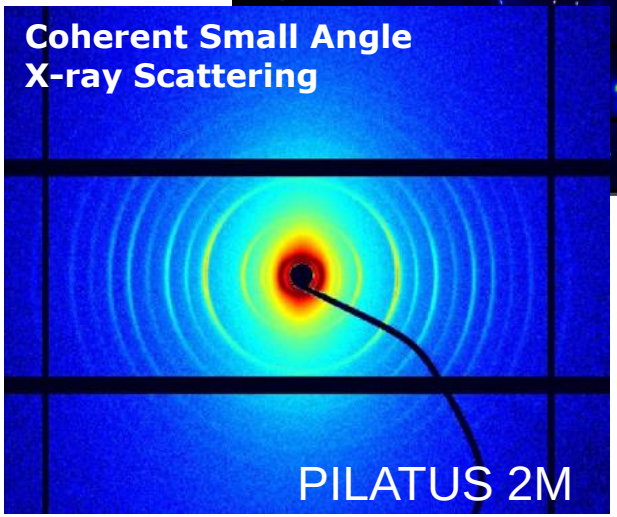
The Eiger Detector

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

- Applications at cSAXS:
  - Scanning Coherent Small Angle X-ray Scattering
  - Coherent Diffractive Imaging
- Protein Crystallography







EIGER: R. Dinapoli et al., Nucl. Instrum. Meth. A., 650, 11, 79-83, 2011

The Eiger Module: Eiger 500k

- Sensor 4cm x 8cm,524k pixels
- 75 micron pixel size
- Dead time free mode of operation

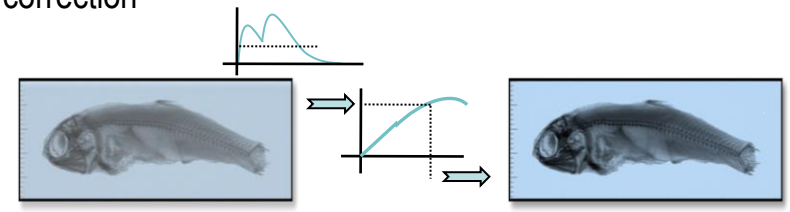
- Electronics is separated in 2 half-modules
  - High frame rates: up to 24 kHz at 4 bit
    12 kHz at 8 bit
    8 kHz at 12 bit

- Readout architecture
  - High speed data transfer: data is sent over 10 GbE connections, one per half module

Image summation

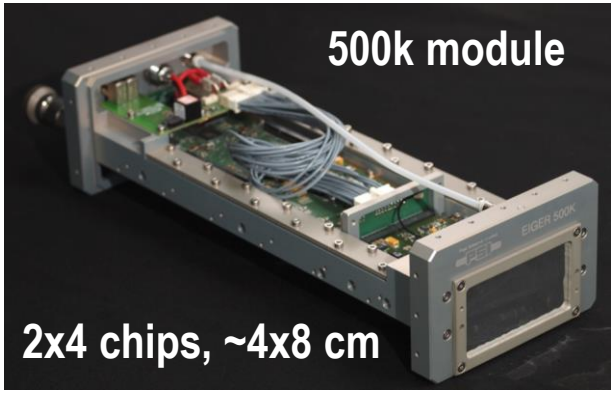
- Data buffering
  - 8 GB of on board memory per module
  - 32 k frames for 4 counter bits

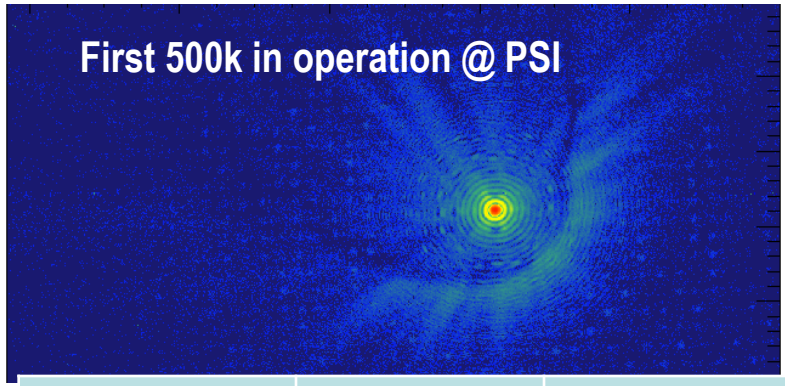
Rate correction



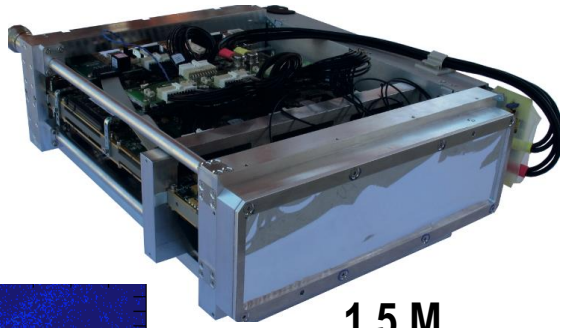
- Firmware data processing
  - Image summation
    - **extends the dynamic range from 4096 (12 bits) to $4x10^9$ (32 bits)**
  - Rate correction

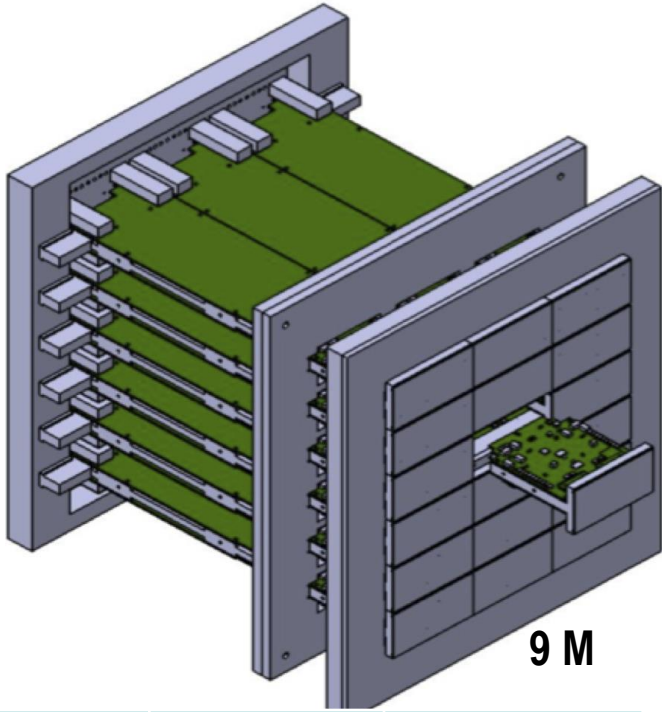
Eiger Systems





Multi-module detectors



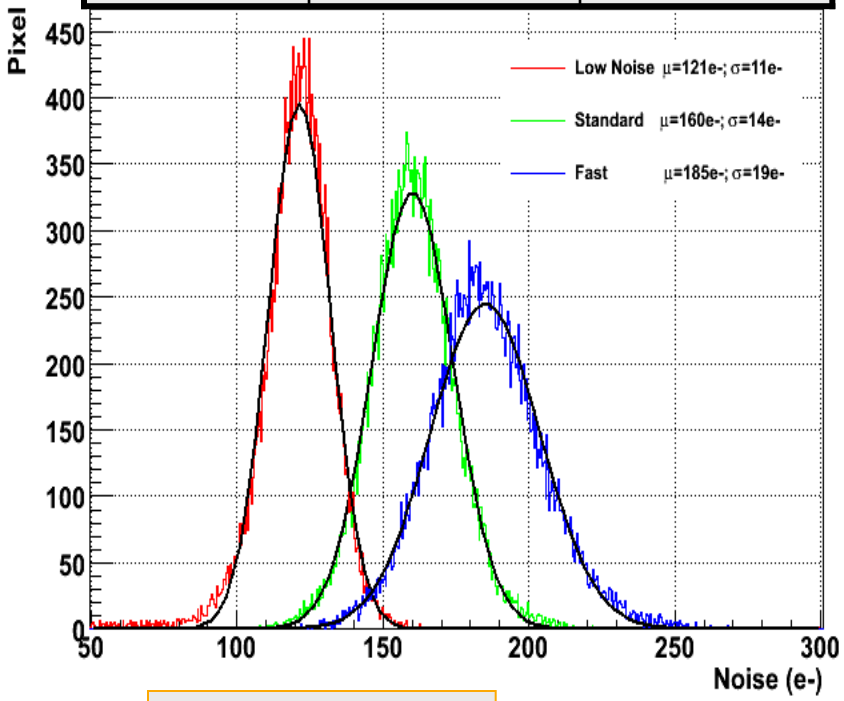


	Number of pixels	On board storage (frames/4 bits)	Data rate[1] @ 12 kHz	Data rate[2] @ 1kH	Data rate[3] @ 100 Hz	Data rate[4] @ 10 Hz
Module	524 k (512 x 1024)	~32,740	50.3 Gb/s	6.29 Gb/s*	839 Mb/s*	168 Mb/s*
9M Detector	9.44 M (3072x3072)	~32,740	906 Gb/s	113 Gb/s	15.1 Gb/s*	3.02 Gb/s*

1) 8 bit, equivalent to ~4@22 kHz or ~12@8kHz

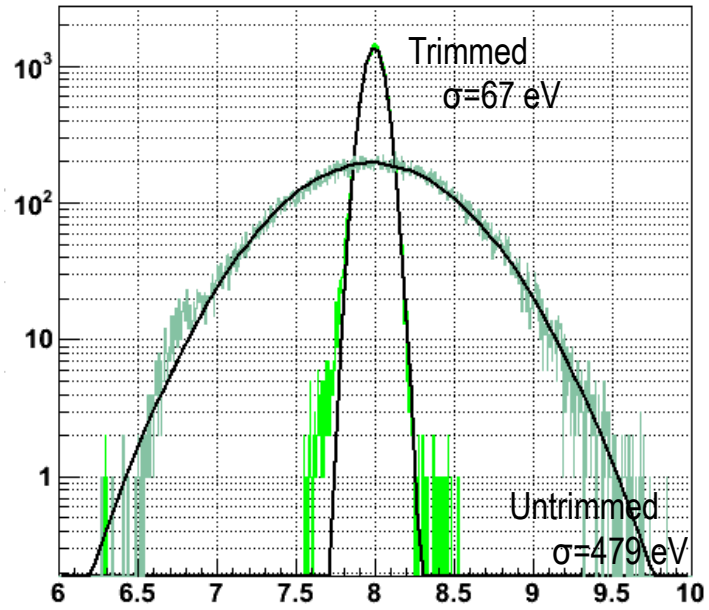
Electronic performance parameters

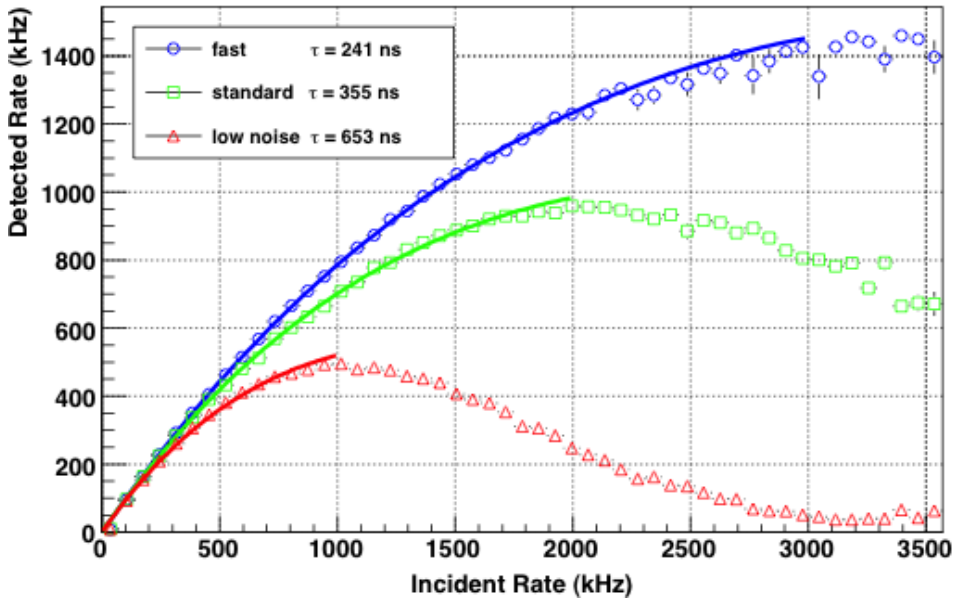
Operation Mode	Noise(e-)	Sigma (e-)
LowNoise	121.1±0.07	10.7±0.06
Standard	160.1±0.08	13.9±0.07
Fast	185.0±0.1	18.7±0.09



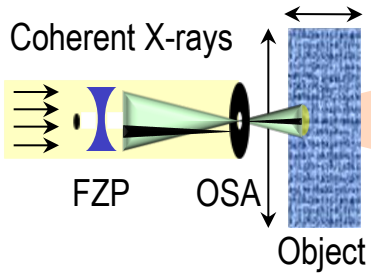
@14KeV

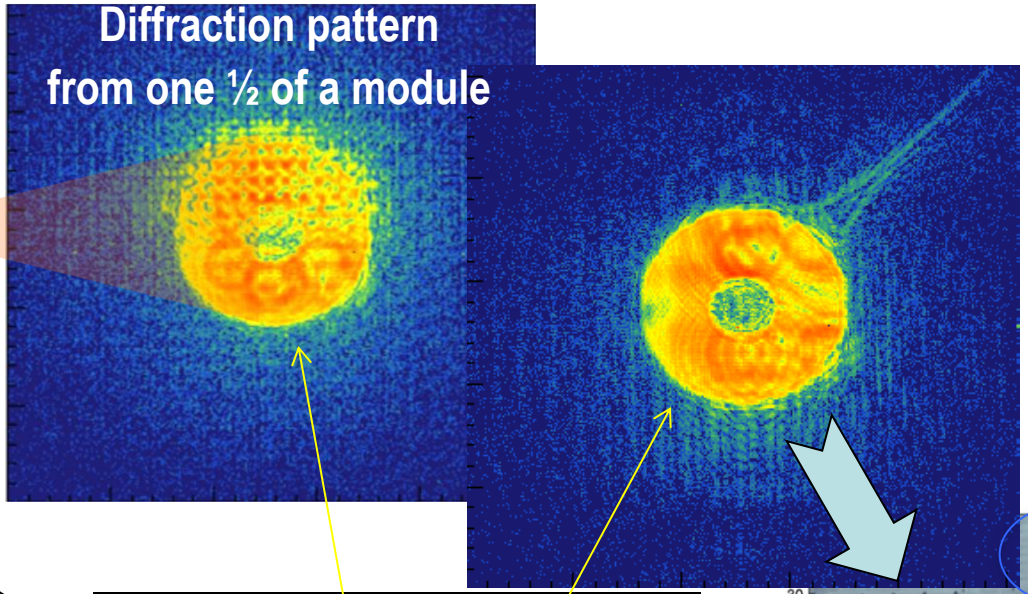
Threshold Dispersion

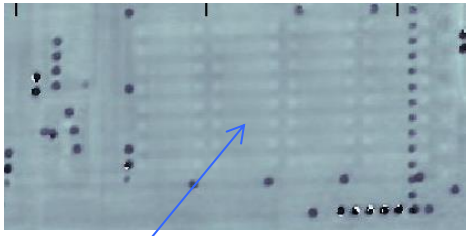


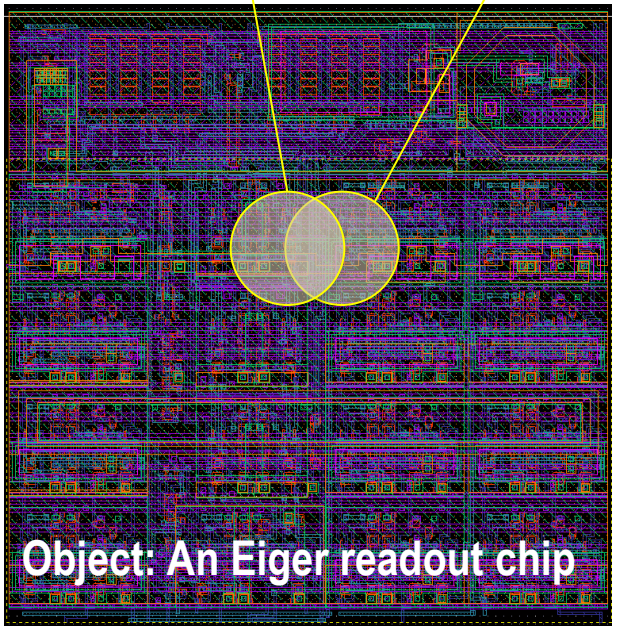


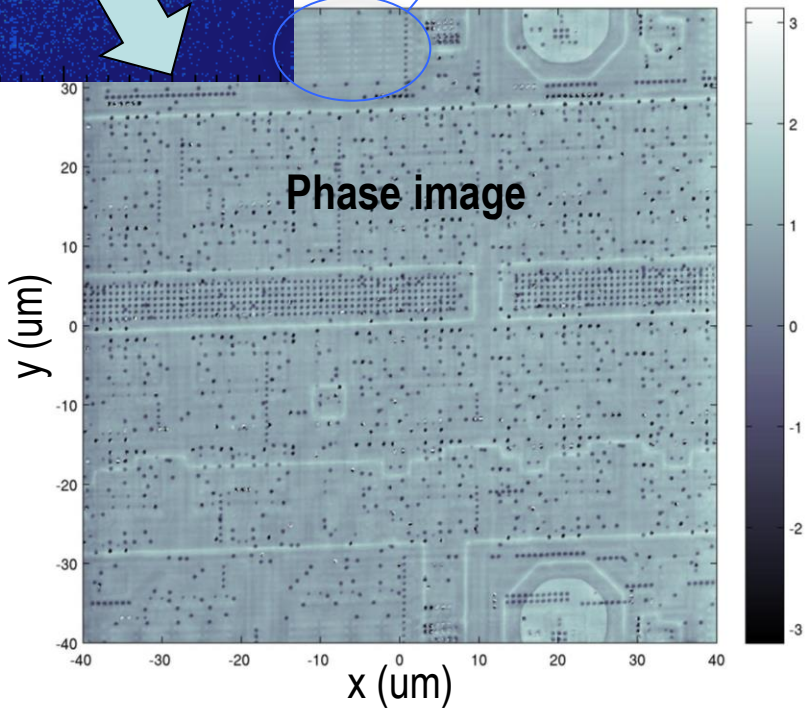
Eiger SELFIE: Ptychography of an Eiger chip











- The object is raster scanned with an out of focus beam
- Diffraction patterns at overlapping positions on the object are recorded
- The information in the overlap is used to recover the phase
- Both the attenuation and phase shift in the object can be reconstructed

Plans and summary for Eiger

- Eiger will be our work horse in the coming few years

- single module (an Eiger 500K) installed at cSAX beamline
- other single module systems foreseen at other beamlines

- 9M currently in production (modules), installation foreseen for early 2014
- will overcome frame rate and pixel size limitations of Pilatus

- we are thinking of a 49M detector in vacuum at a fixed distance

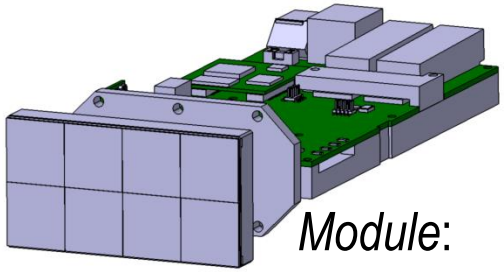
  for cSAXS not decided yet if this is an Eiger or Jungfrau detector

JUNGFRAU: a 2D detector for SwissFEL

adJUstiNg Gain detector FoR the Aramis User station

JUNGFRAU module:

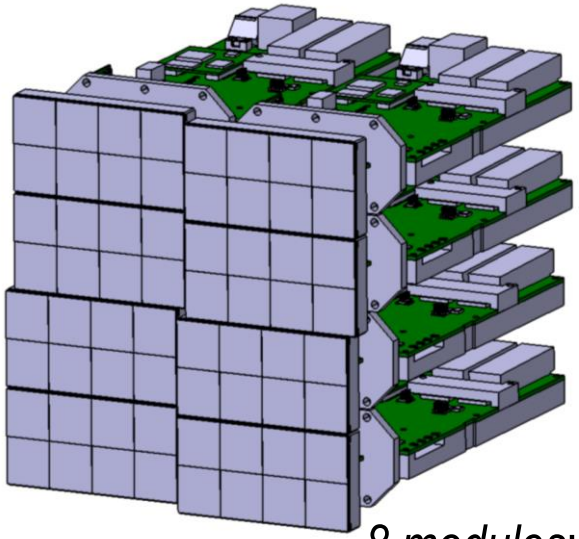
- *Chip:* 256 × 256 pixels, *Pixel:* 75 × 75 μm^2
- *Dynamic range: 10^4 12keV photons per pixel*
- *Module:* 2 × 4 chips, 4 cm × 8 cm
- Systems up to 16 Mpixel at SwissFEL



Module:
524 kPixel

Readout:

- Readout rate > 2 kHz
- Linear count rate capability @ synchrotron:
  25 MHz/pixel



8 modules:
4 MPixel

GOAL: detector for XFELs and synchrotrons

JUNGFRAU: A. Mozzanica et al., JINST, 9, C05010, 2014

Jungfrau pixel architecture

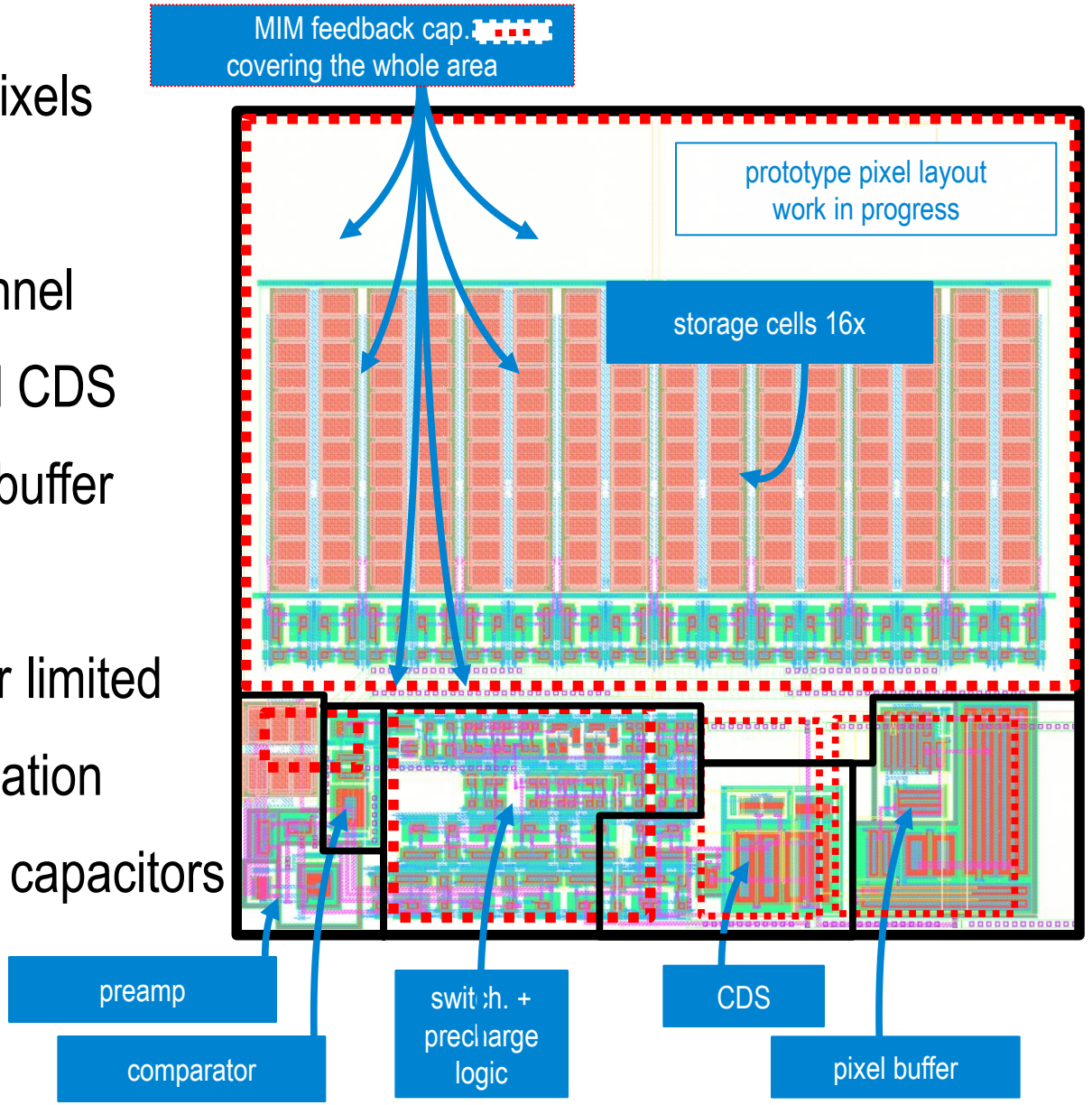
2 main challenges for small pixels

Power consumption per channel

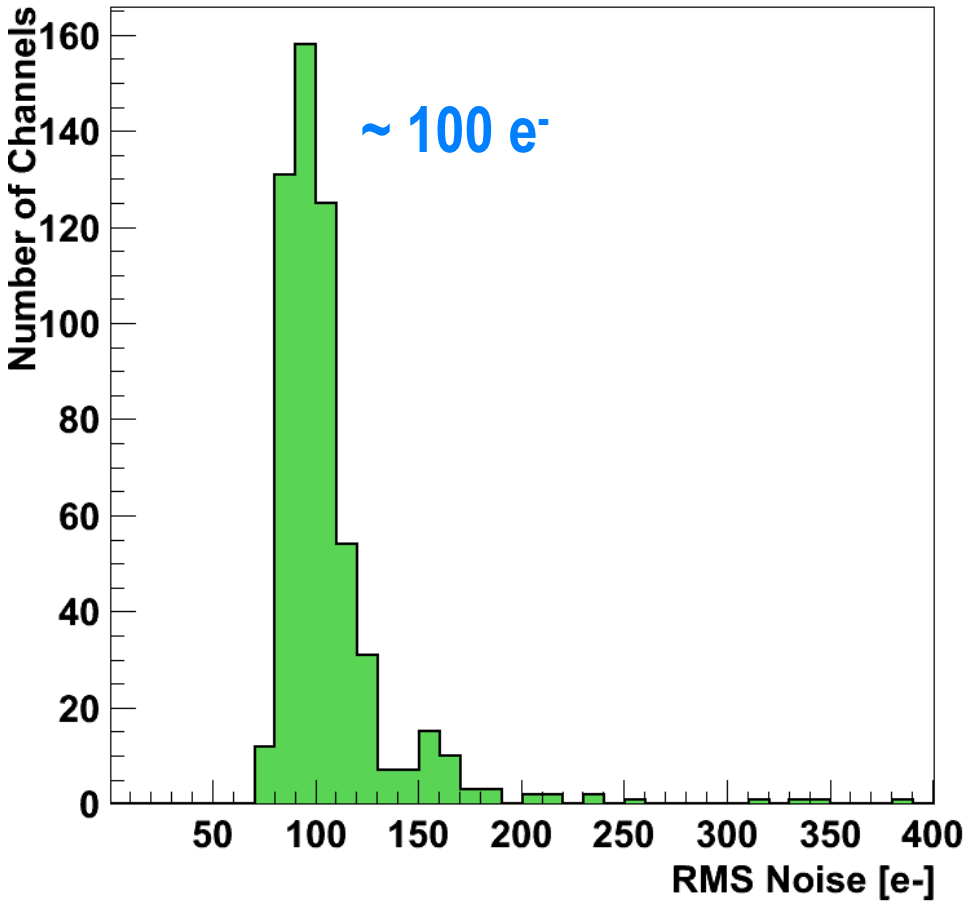
- low power preamp and CDS
- power cycled off-pixel buffer

Space for feedback capacitor limited

- amplifier range optimization
- precharge of feedback capacitors



Noise Characterization

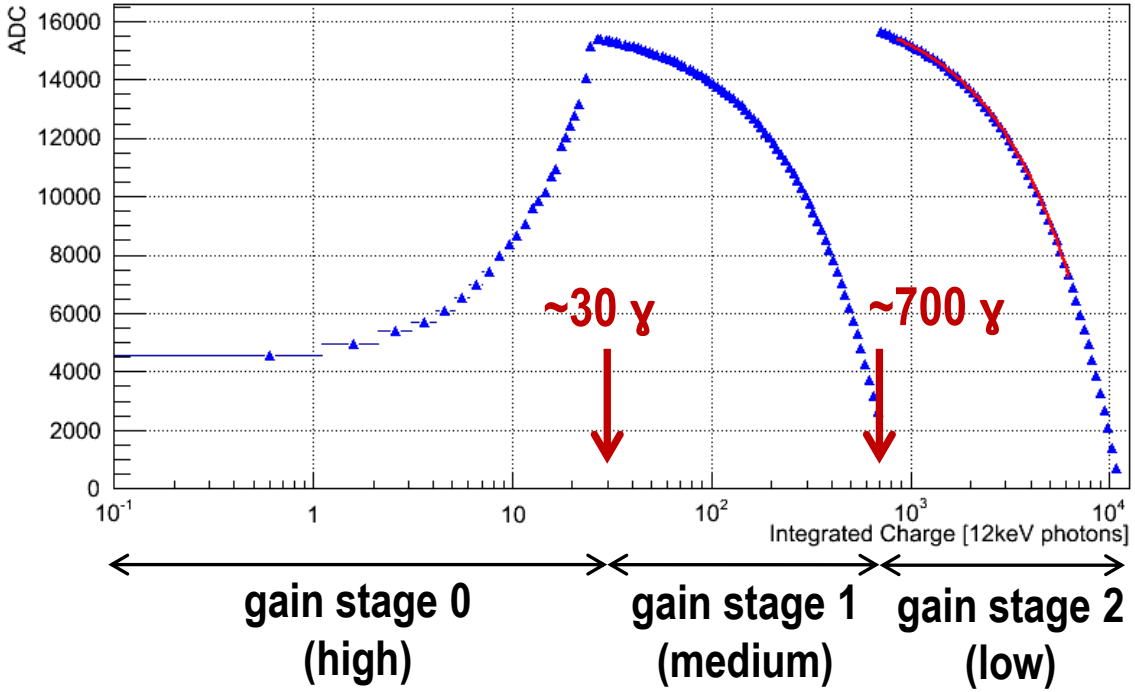


Total noise	~ 100 e-
Preamplifier	~ 91 e-
CDS	~ 25 e-
Readout	~ 31 e-

σ = 100 e- → <400 eV

→ 5 σ < 2 keV

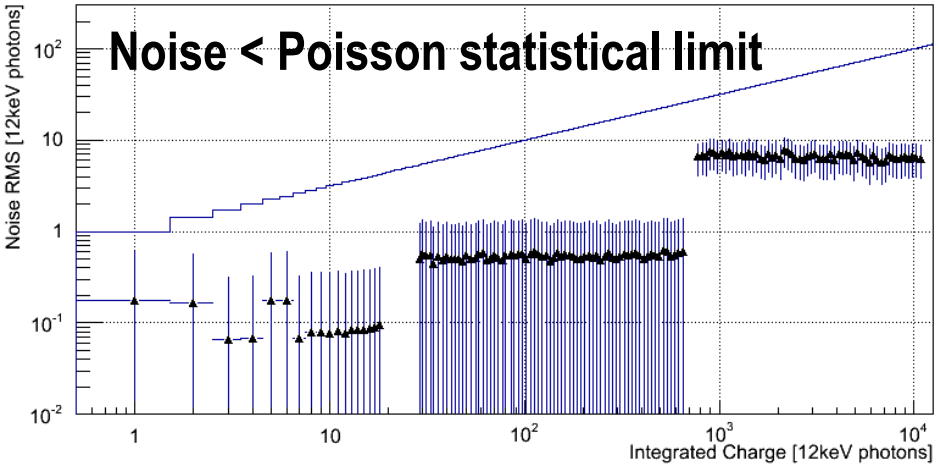
Automatic Gain Switching

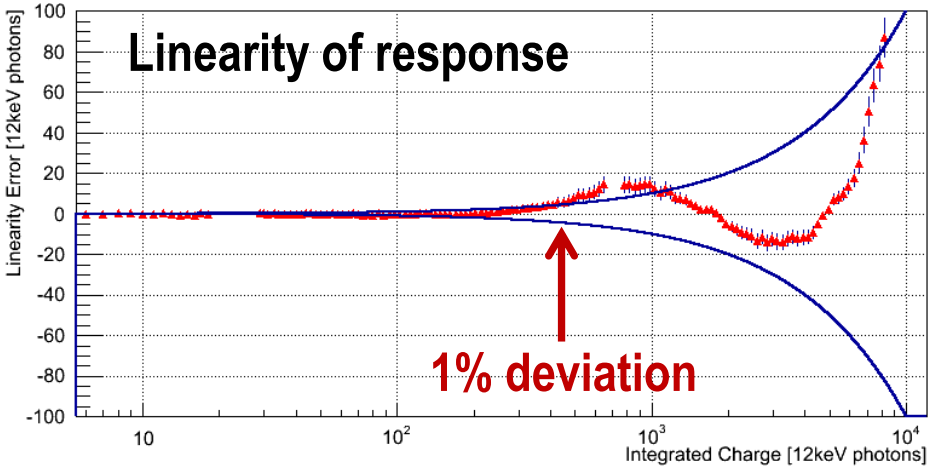


Automatic gain switching:

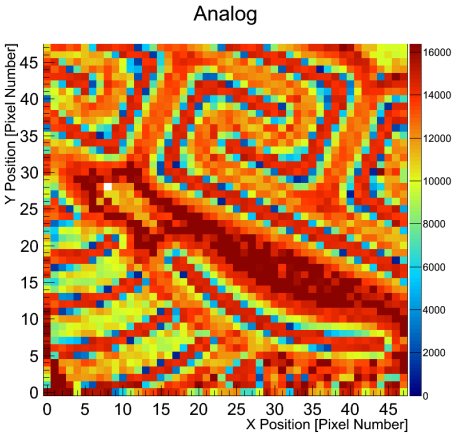
- White visible light illumination
- Increasing integration time

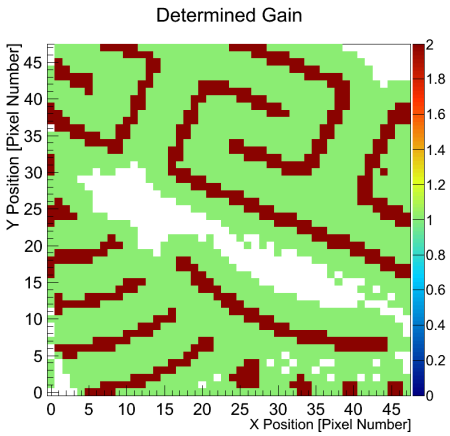
→ Covers ***dynamic range*** of ***> 4 orders of magnitude*** !

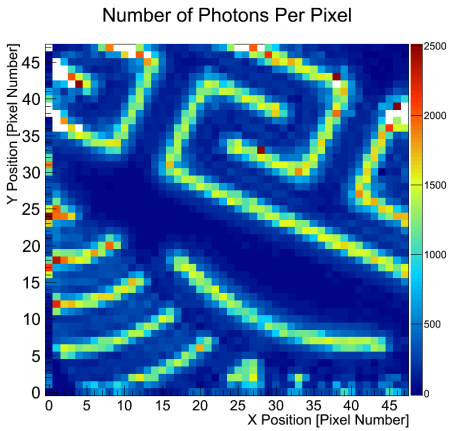




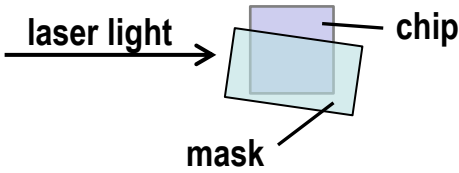
High Dynamic Range Imaging Via Gain Switching



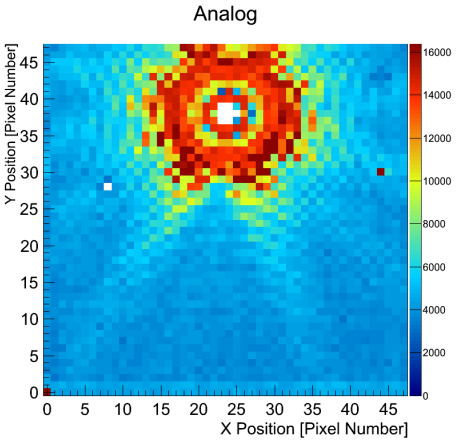


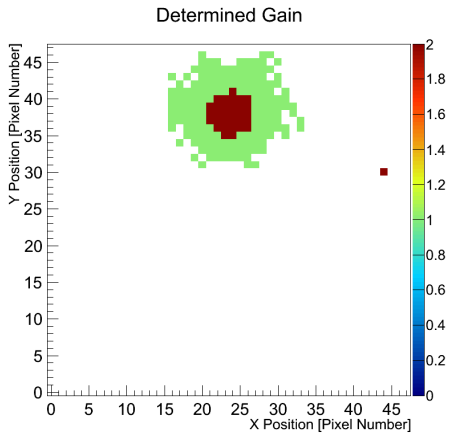


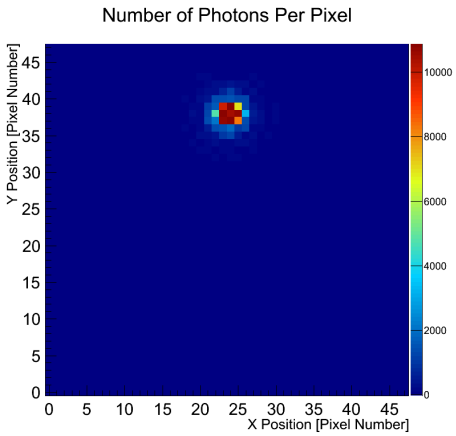
IR laser through mask

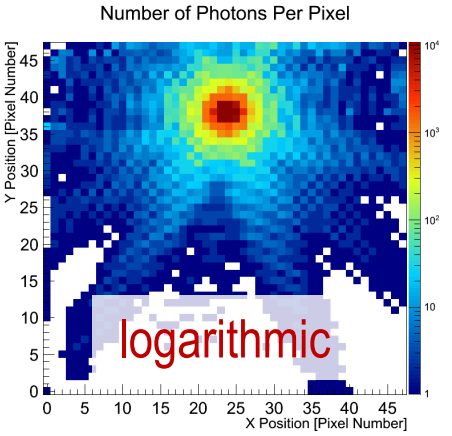


IR laser blurred









Works well whether signal is concentrated on part of the chip …

… or if distributed all over the chip!

Summary Jungfrau

Small pixel size: 75 microns

High frame rate: 2kHz

High linear count rate capability:

- Dead time free 24MHz
- Quasi infinite for smaller integration times
- First big not count rate limited hybrid pixel detector

Foresee up to 16M pixel systems for SwissFEL and SLS

Low noise of 120 e^- (434 eV) low energies accessible:

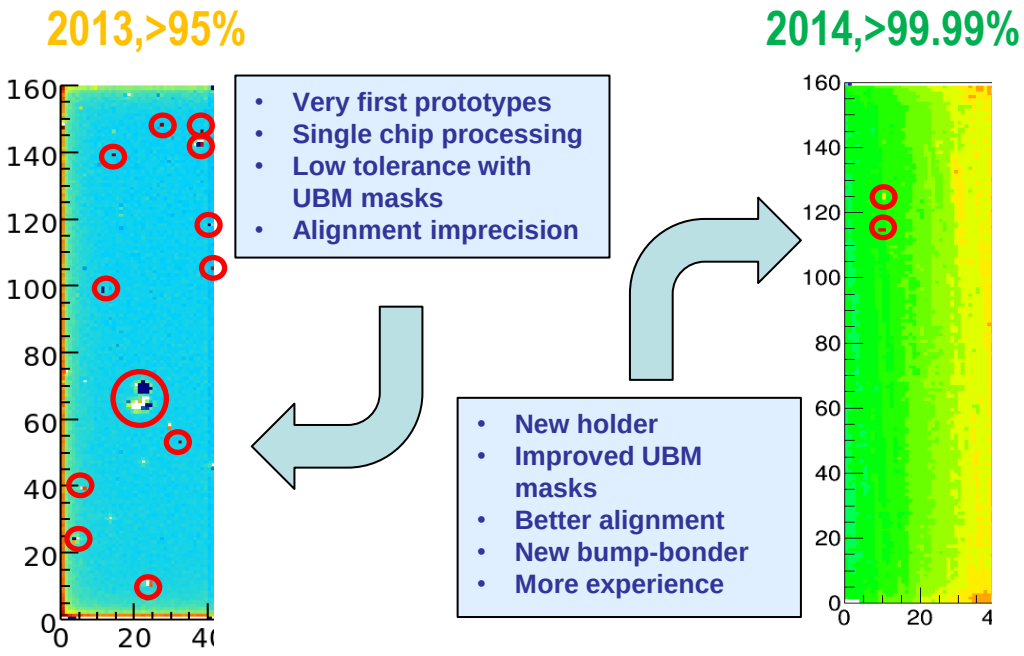
- 3 keV with single photon resolution
- Less without single photon resolution
  (sensor with thin entrance window)

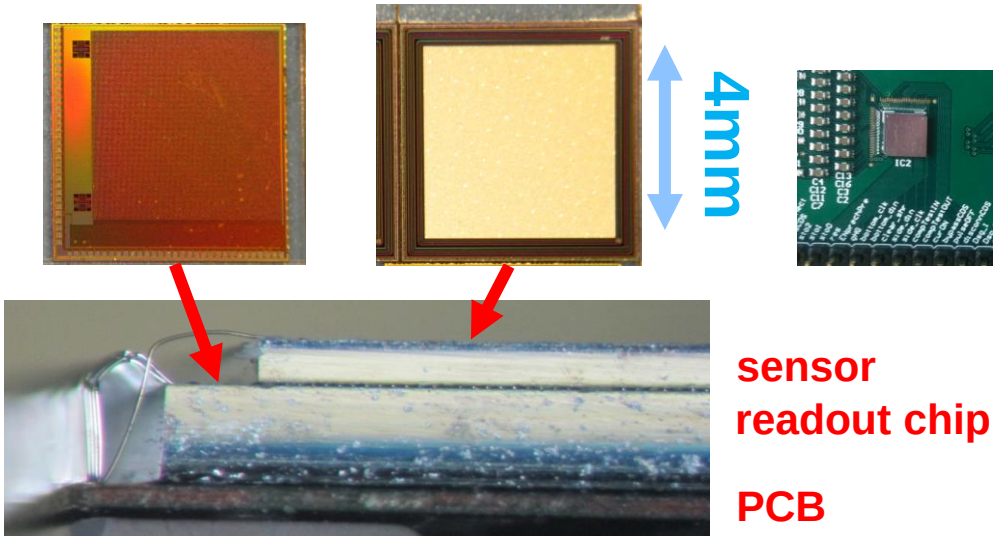
High energies with scintillators

MÖNCH detector system

- Hybrid pixel detector: 25x25 μm² pixel size
- goal: low noise and high dynamic range thanks to dynamic gain switching up to 600 12keV photons (or 2 x 10^4 400eV photons)

- Optimization for different application possible:
  - Imaging/Tomography
  - resonant and nonresonant inelastic X-ray scattering
  - Spectroscopy
  - Laue Diffraction

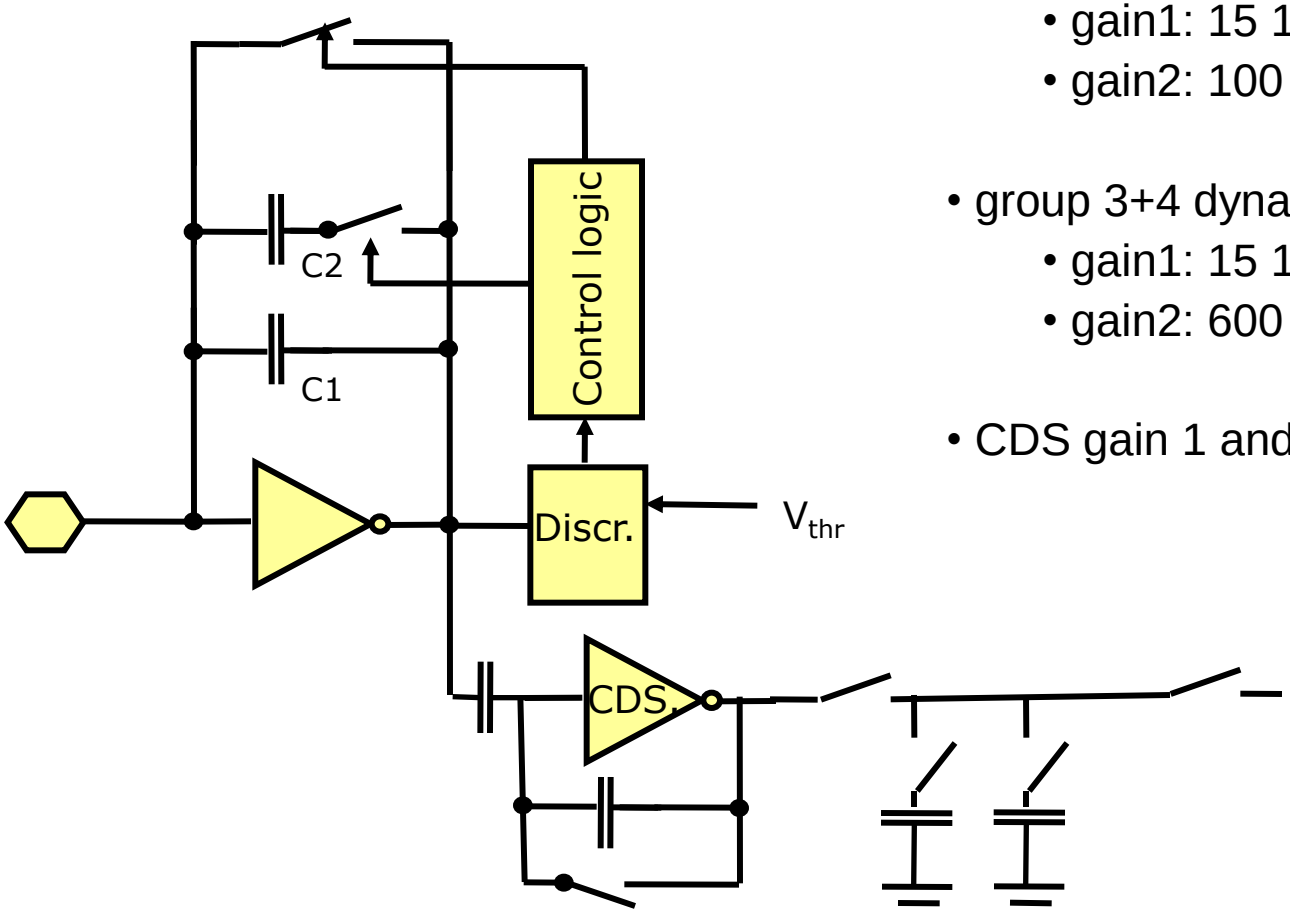




Current Prototype: MÖNCH 02

- Active area: 4x4 mm²
- 160x160 pixels
- 1x4 mm² optimized for Imaging

Mönch pixel schematics

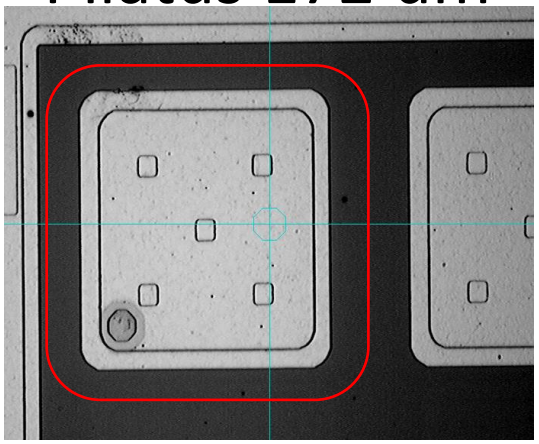


160 x 160 pixels divided into 4 groups:

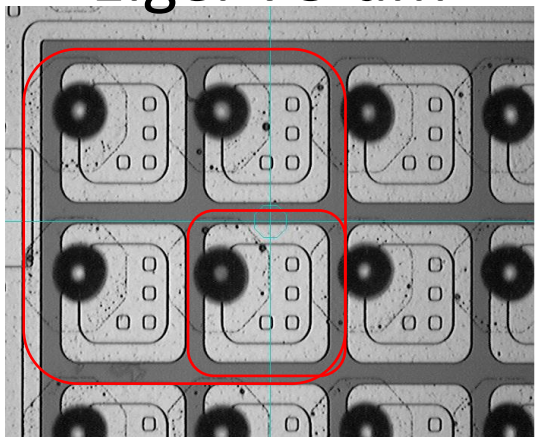
- group 1+2 fixed gains
  - gain1: 15 12keV photons
  - gain2: 100 12 keV photons
- group 3+4 dynamic gain switching
  - gain1: 15 12 keV photons
  - gain2: 600 12 keV photons
- CDS gain 1 and 4

The Mönch detector bump bonding

Pilatus 172 um

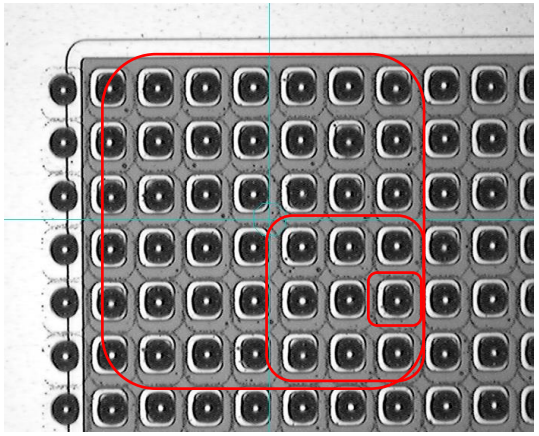


Eiger 75 um



x5.3

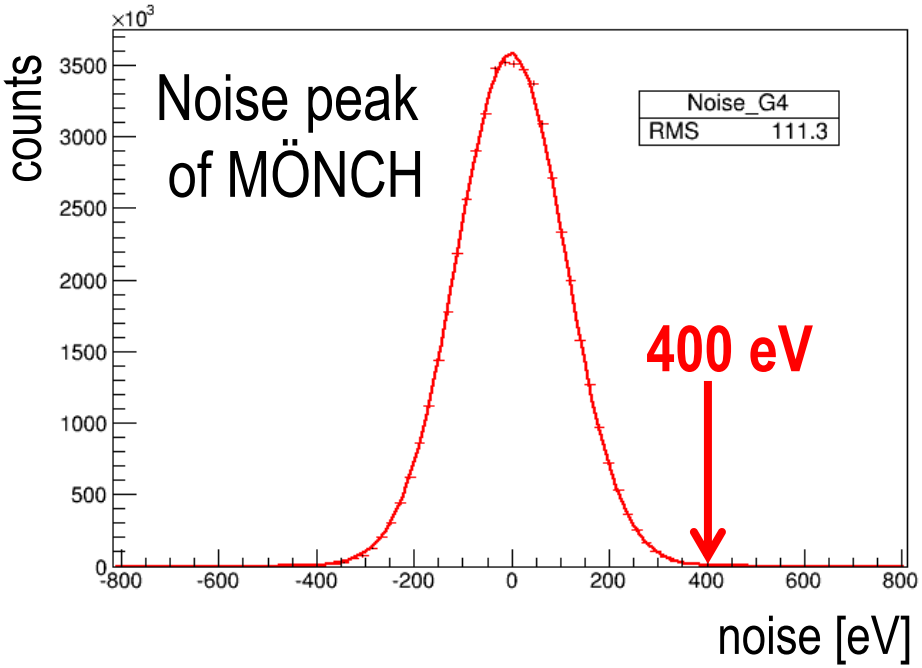
Mönch 25 um



x47

- Bump bonding of 25 micron pixel works well with PSI in-house process
- Limit: 20 microns

Noise measurement



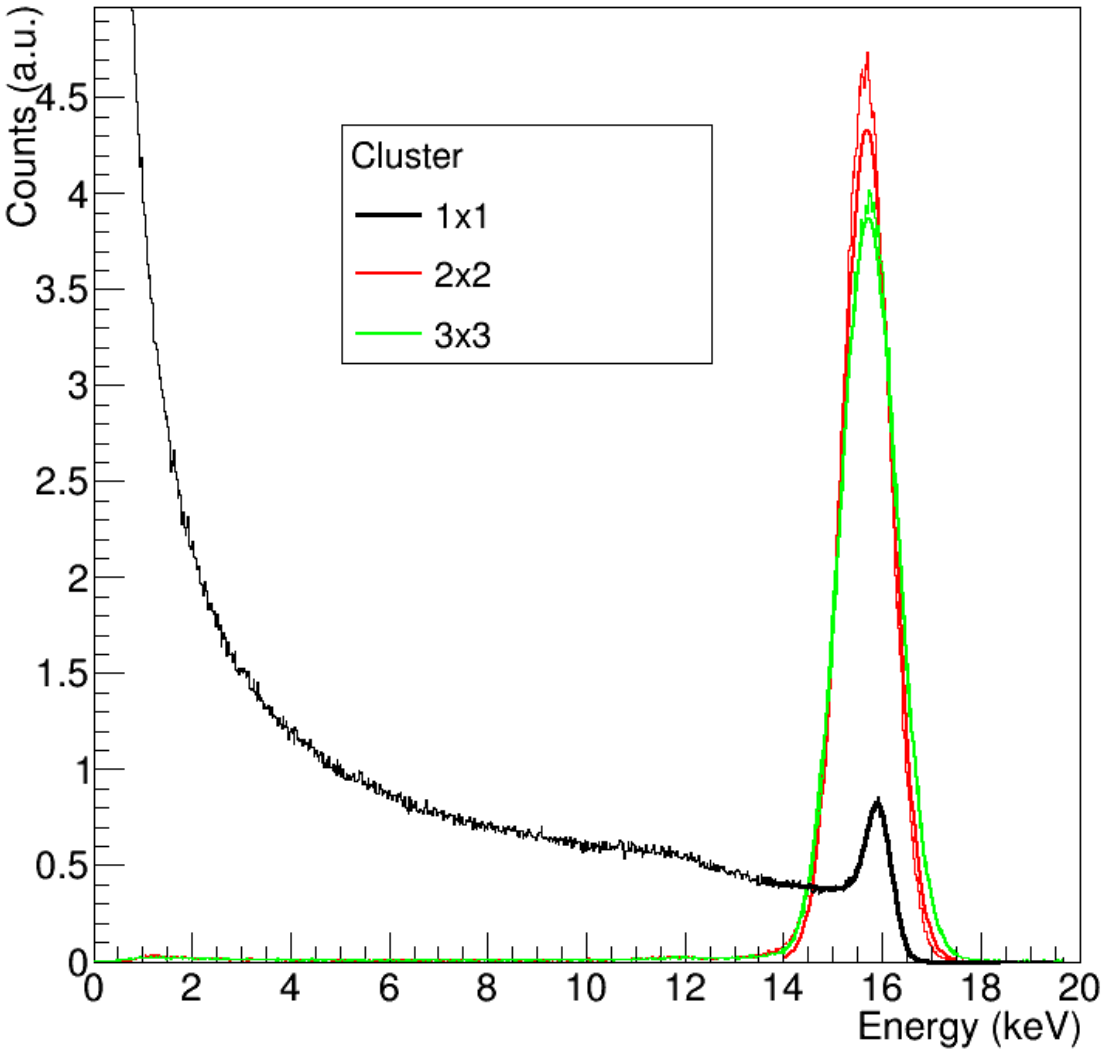
Lowest noise of hybrid pixel detectors:

Noise of 30 electrons rms

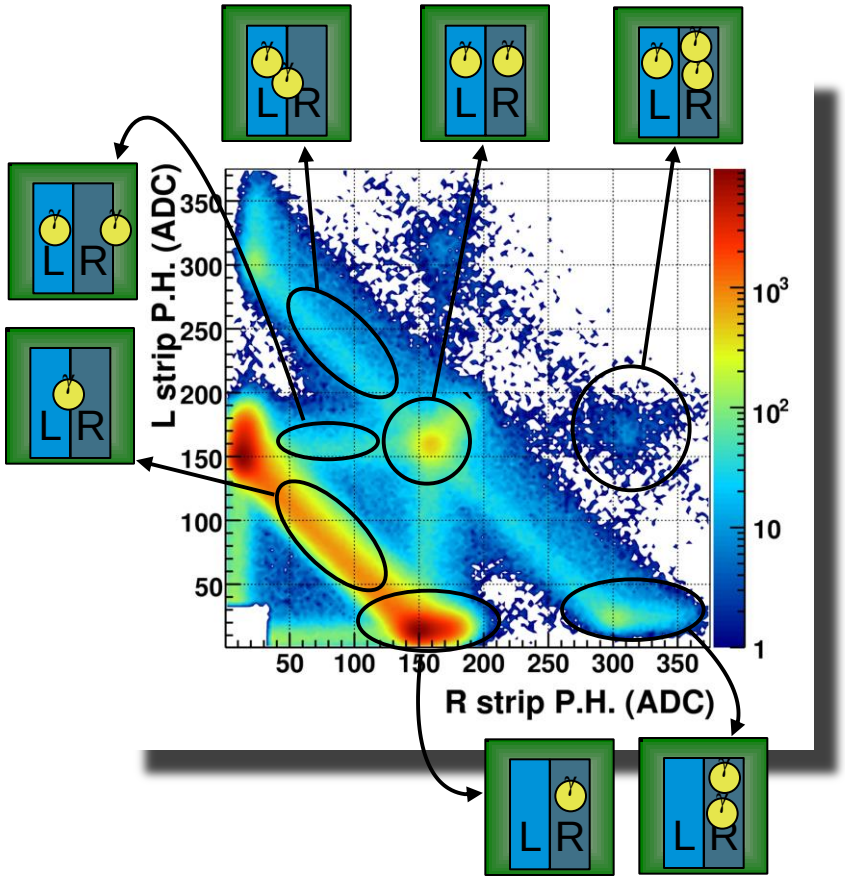
3.7 sigma at 400eV

5 sigma at 540eV

Cluster charge Distribution

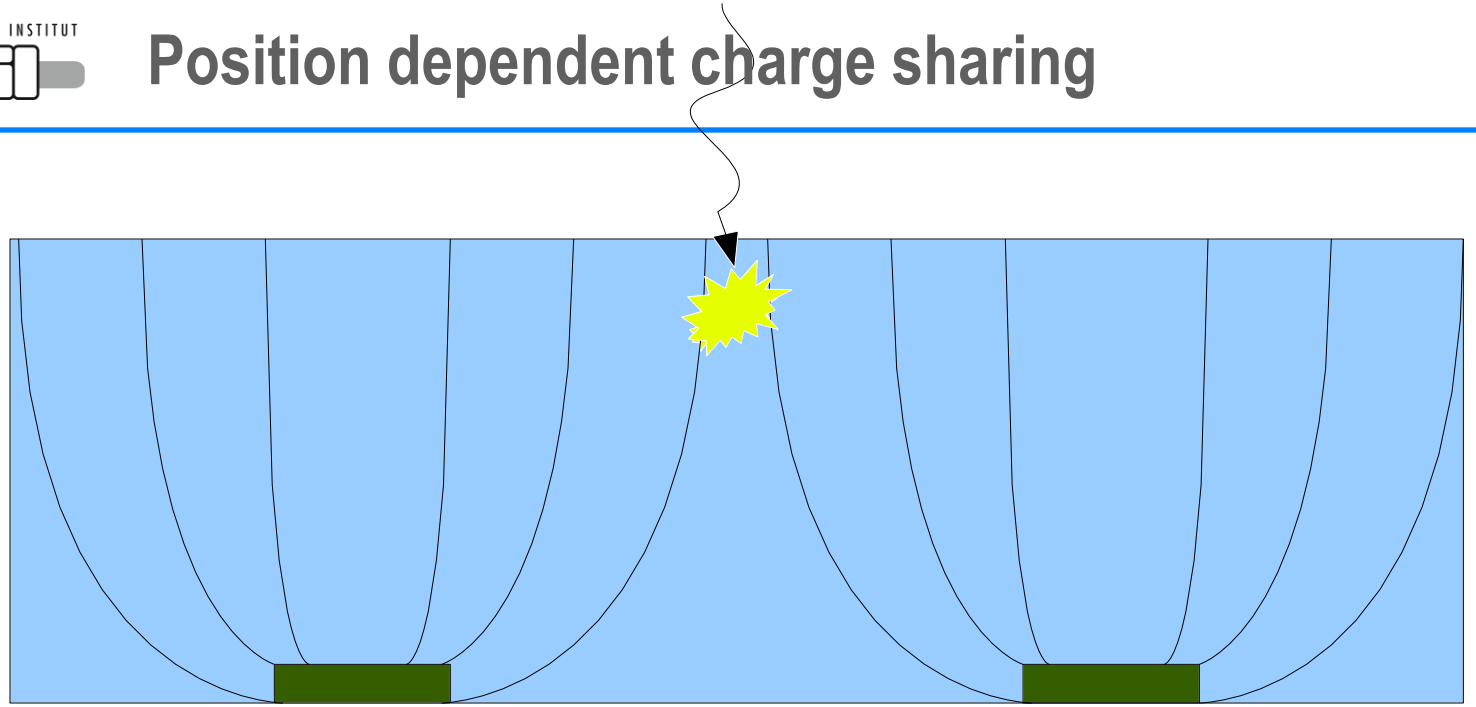


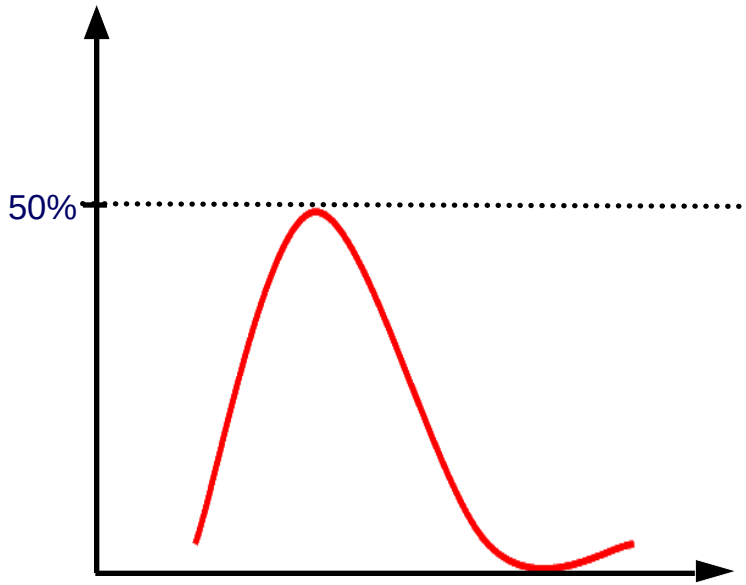
Charge integrating detectors: get full information

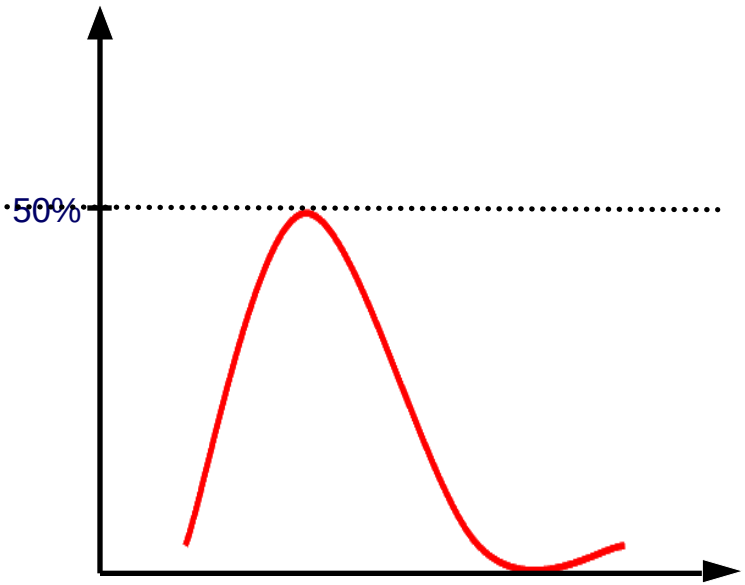


50 micron pitch, 25 keV

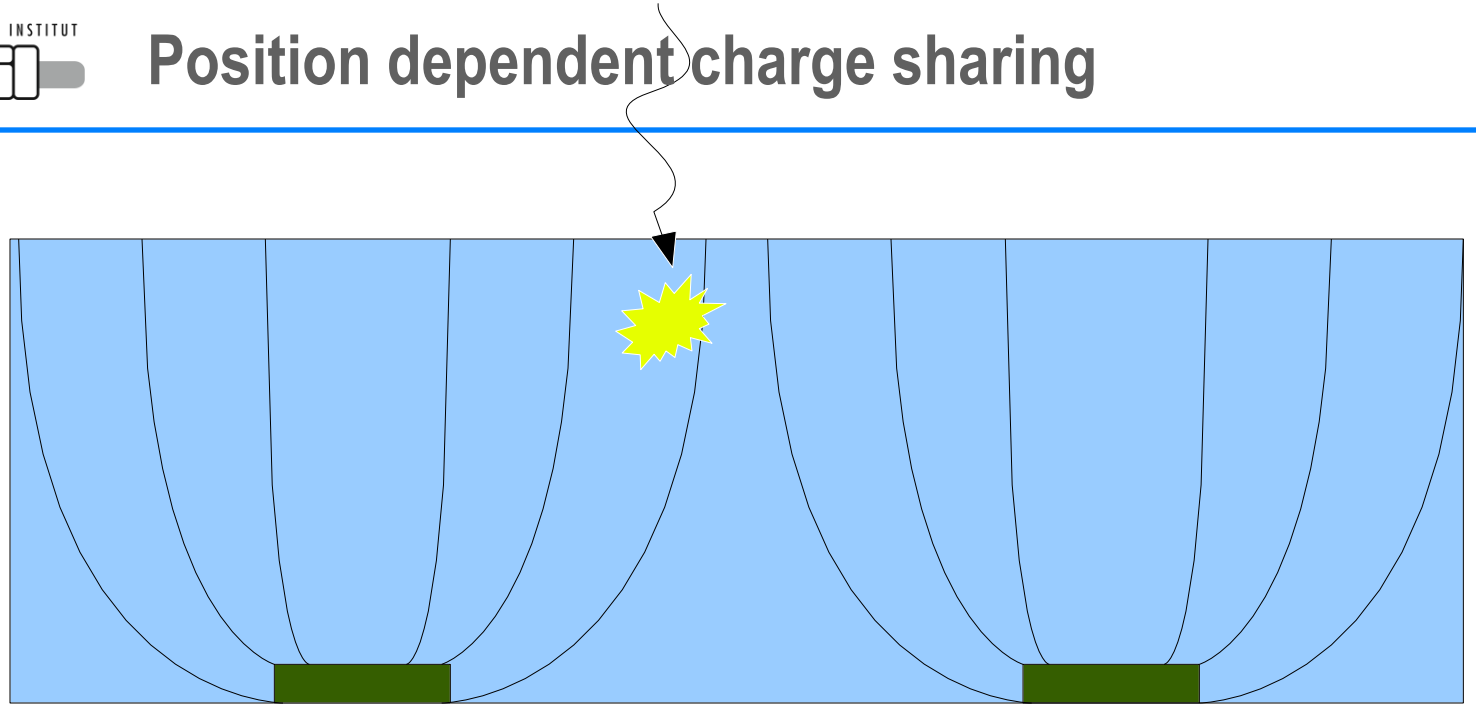
Position dependent charge sharing

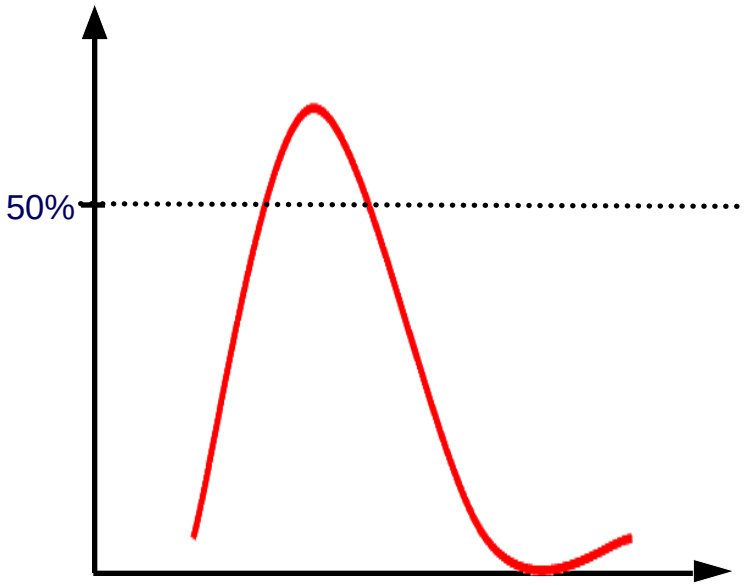


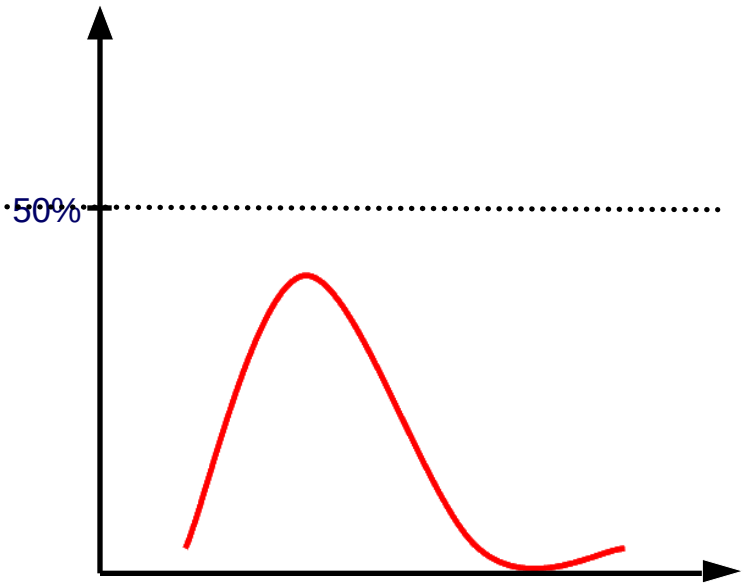




Position dependent charge sharing

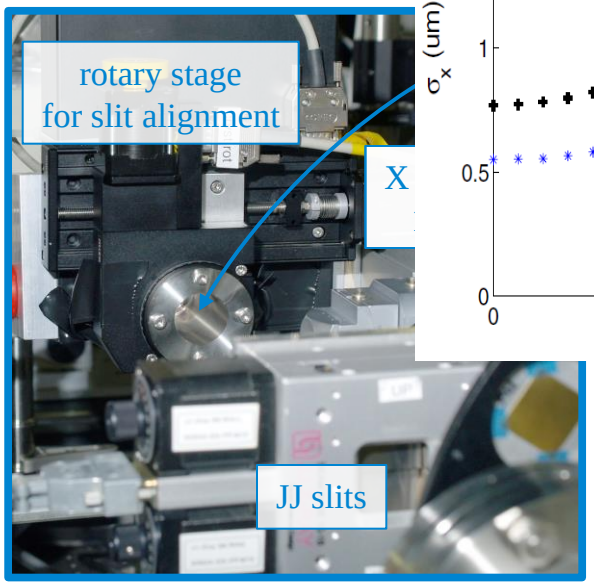


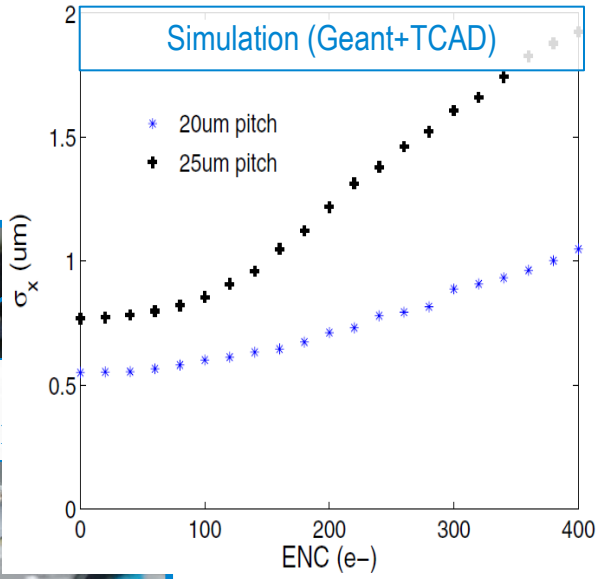




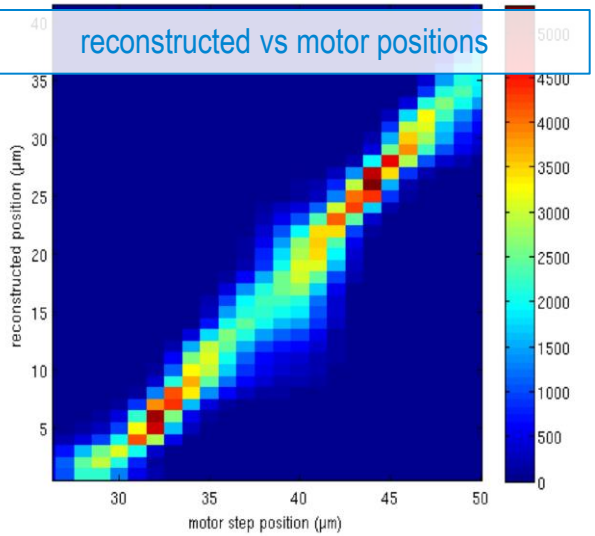
Gotthard: position interpolation

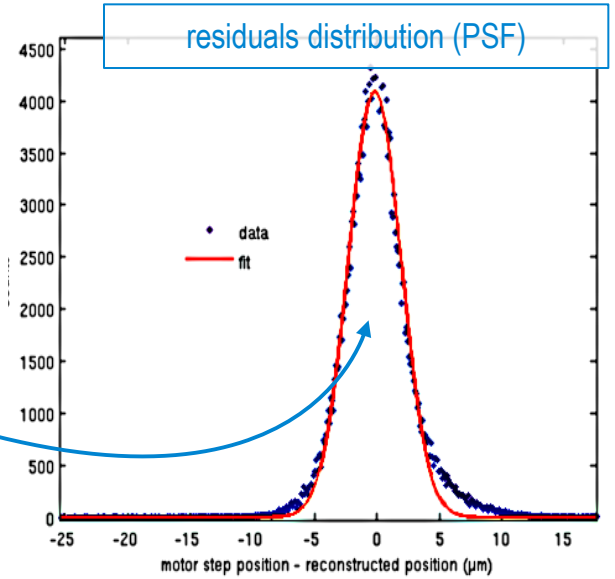
- To measure the spatial resolution a 2μm W slit has been scanned in 1μm steps in front of the strips
- slit parallel to strips
- Vertical beam size ~100μm
- Strip pitch 20μm, 15keV



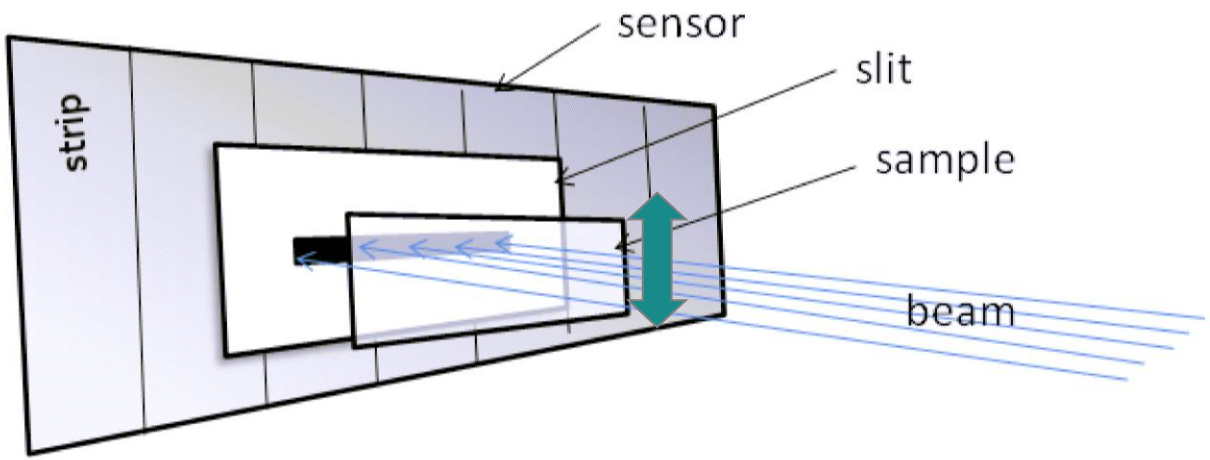


σ=1.8μm



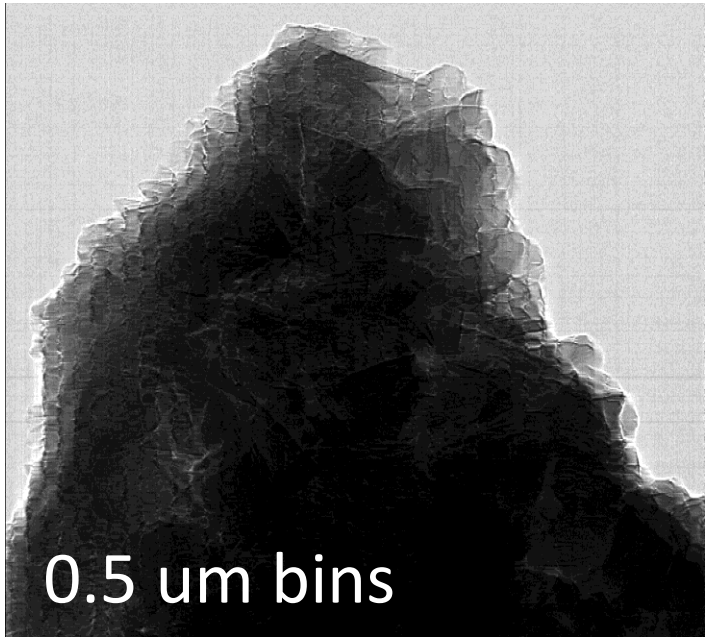


Interpolation in 1D



Kidney stone
12 keV beam
25 um pitch
with GOTTHARD

Interpolation
In 1D



Summary/Outlook Mönch

- Hybrid pixel detectors with 25 um (and less) pixel size are possible
- Extremely low noise: 30 e^- Noise (previously only accessible with CCDs and MAPS)
  - Single photon sensitivity down to ~ 400 eV

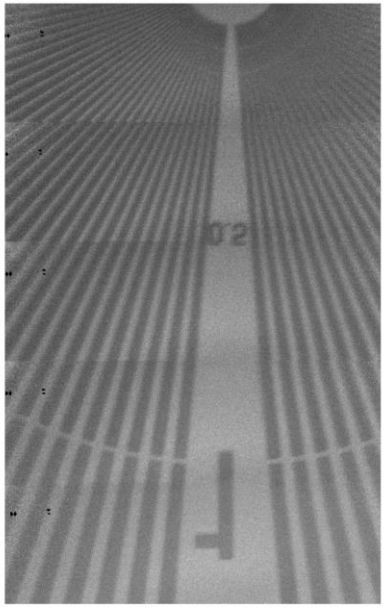
- Small pixels allow position interpolation
  - Current spatial resolution with interpolation: 3.3 um

Future MÖNCH developments:

- MÖNCH03 is a full 1 by 1 cm^2 detector optimized for imaging with the presented method
  - Up to 160k pixels
  - 5 kFrames/s

- MÖNCH 1.0 2 by 3 cm^2 tillable read-out chip for detector modules
  - Dynamic gain switching 20x10^3 photons (@400eV)

Moench



Summary

- Our single photon counting detectors are state of the art for many synchrotron applications thanks to large area and stability
  - EIGER in advanced commissioning phase
  - MYTHEN for XRPD

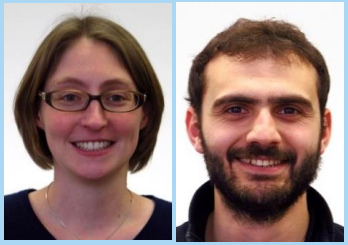
- Charge integrating detectors with dynamic gain switching offer performances close to photon counters and work at XFELs
  - Single photon resolution at high gain
  - Poisson limited over the full dynamic range
  - No count rate limitations for SR experiments
  - Low energies accessible with(out) single photon resolution
  - Still a lot of calibration, optimization, validation for real experiments

- Analog single photon readout expands the digital information
  - Work only with low flux
  - Energy dispersive detectors
  - (sub)Micron-resolution by interpolation
  - MÖNCH opens new possibilities in terms of energy and spatial resolution

http://www.psi.ch/detectors

The SLS Detector Group:
Anna Bergamaschi, Roberto Dinapoli, Dominic Greiffenberg, Dhanya Maliakal, Davide Mezza, Aldo Mozzanica, Christian Ruder, Lukas Schädler, Julia Smith, Bernd Schmitt, Xintian Shi, Gemma Tinti

Wir schaffen Wissen – heute für morgen



Open positions:
Postdoc for Mönch
Firmware for Eiger