PAUL SCHERRER INSTITUT PSI

Paul Scherrer Institut
Bernd Schmitt

Potential of strip and pixel applications at synchrotron light sources

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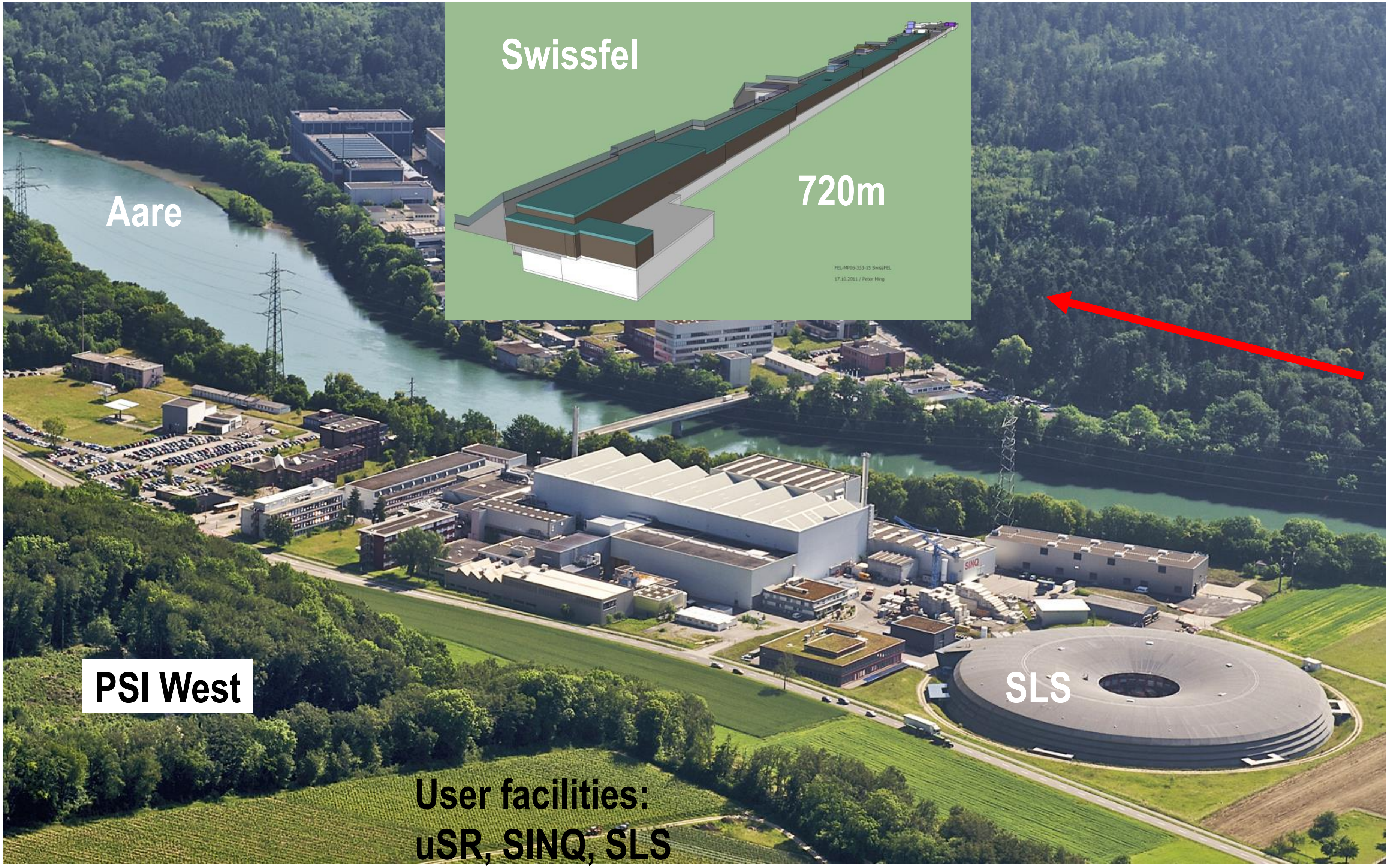


~1500 Staff employees; 30Km from Zurich, task in ETH domain: run large scale user facilities

Outline

Detector principles:

- hybrid detectors
- single photon counting
- charge integrating

Detectors and Applications at Synchrotrons:

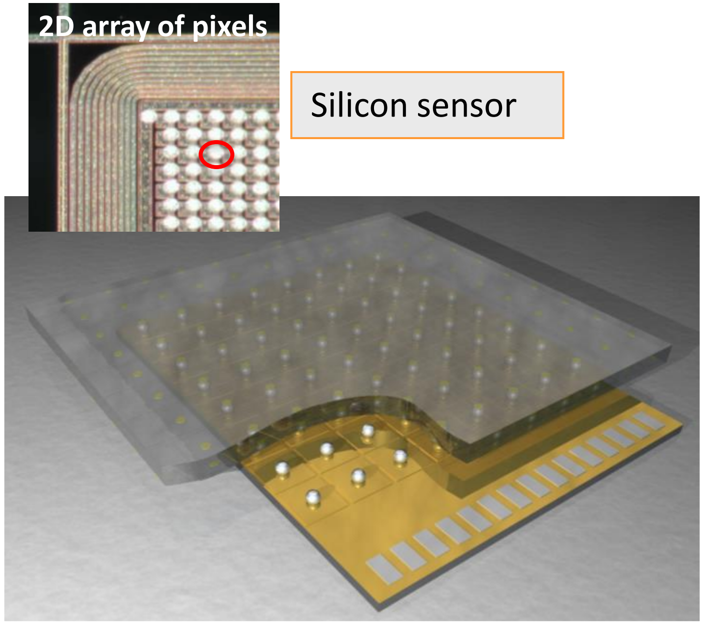
- powder diffraction: the Mythen detector
- protein crystallography: the Pilatus Detector

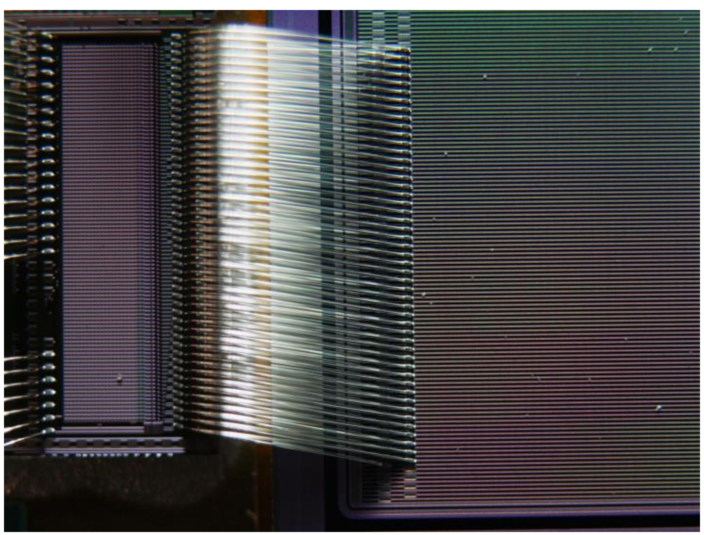
Overview of current Detector Developments

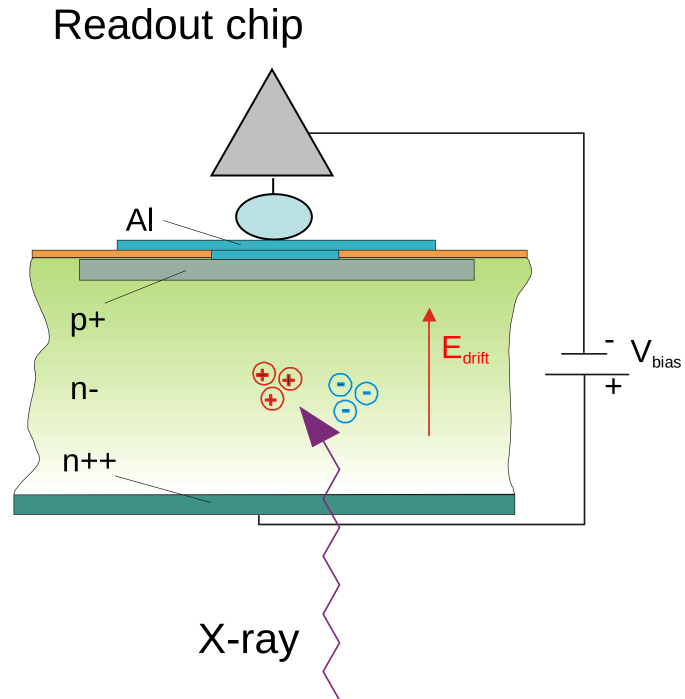
Developments at PSI: Jungfrau, Mönch and Eiger

New possibilities with charge integrating systems

Hybrid Silicon Detectors



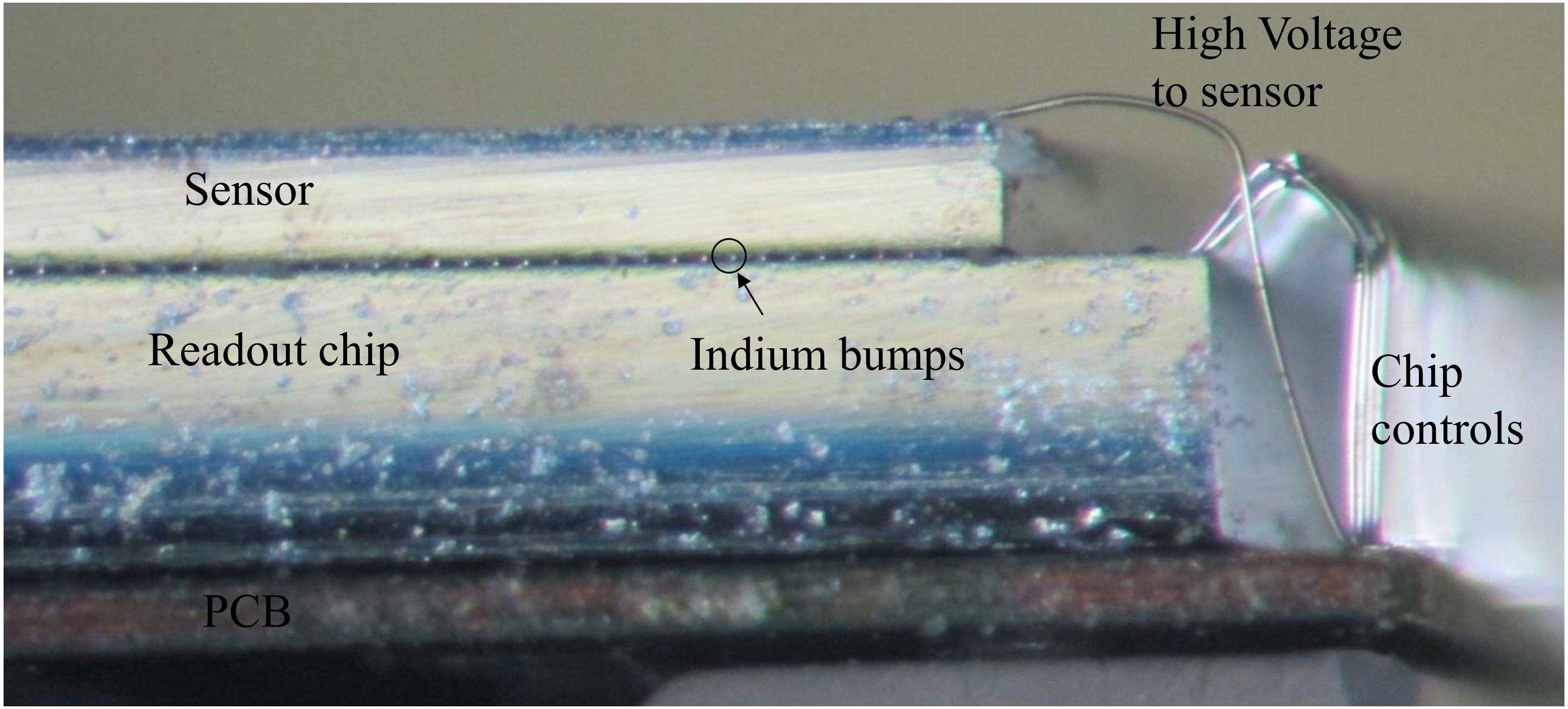




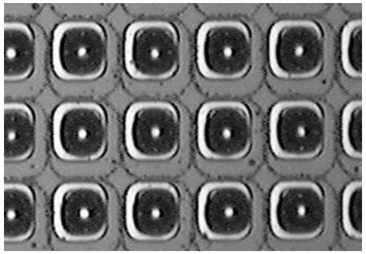
3.6eV per eh pair in Si

Charge for 12keV=3300 electrons = 0.5 fC

Bump bonded pixel sensor



•Bump bonding require additional processing of the chip and sensor surface to deposit an under-bump-metallization and the indium



SENSOR

Absorbs the radiation and converts it into electric charge

READOUT

Translates the electronic signal into information for the user

1D: strip

2D: pixel

Detector properties

→ Absorption efficiency

→ Spatial resolution

→ Dynamic range

→ Energy resolution

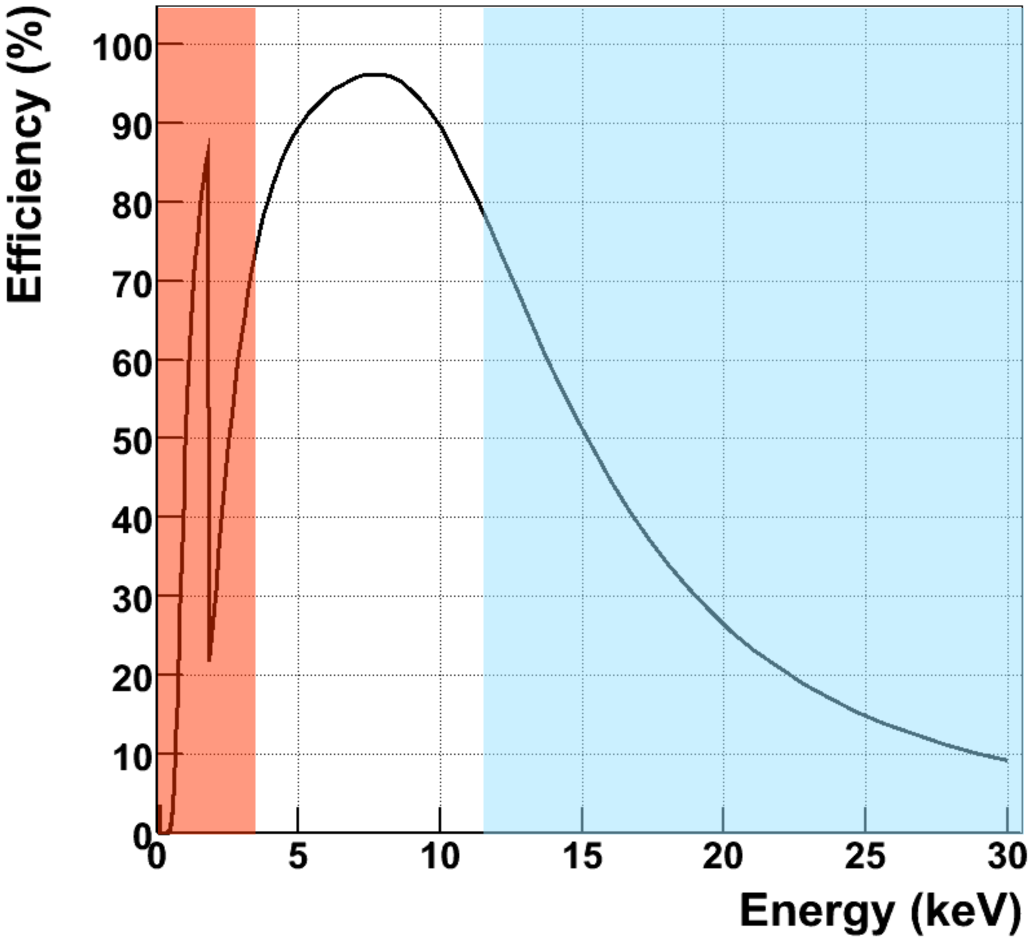
→ Time resolution

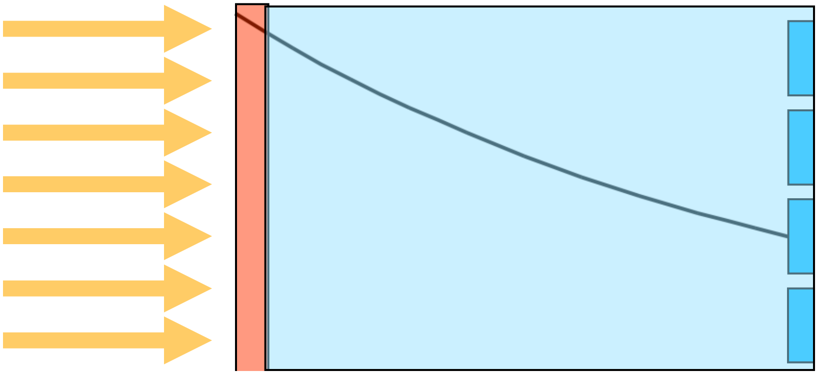
frame rate

Efficiency for X-rays

Energy range: 250eV-150keV

Standard silicon sensors:
300um thick, 2um backplane

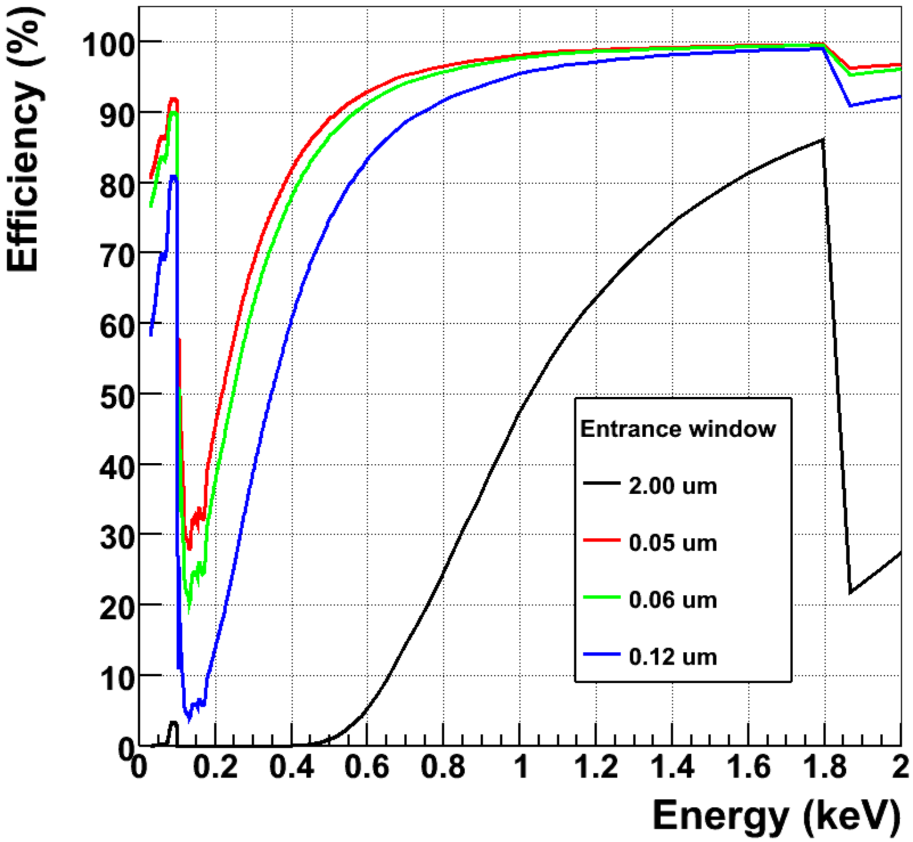




➔Soft X-rays: transmission of the entrance window

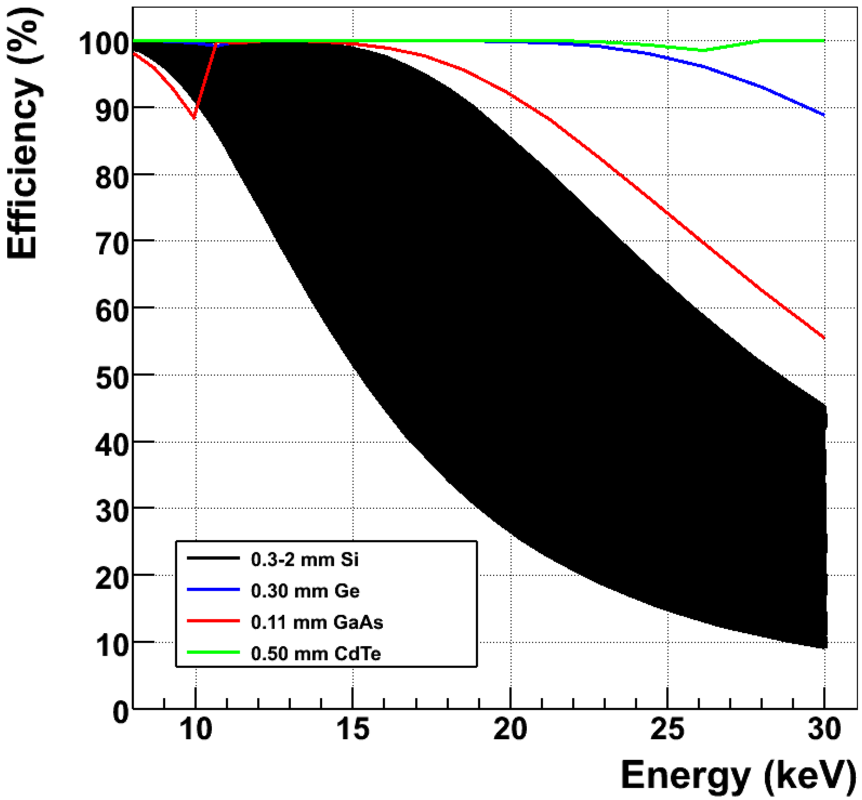
➔Hard X-rays: absorption in the depleted region

Thin entrance window



- Silicon sensors with a backplane thinner than 0.1um are available
- Acceptable efficiency can be obtained down to 0.3-0.5 keV
- The noise of the readout electronics can limit the detection of single photons

High-Z materials



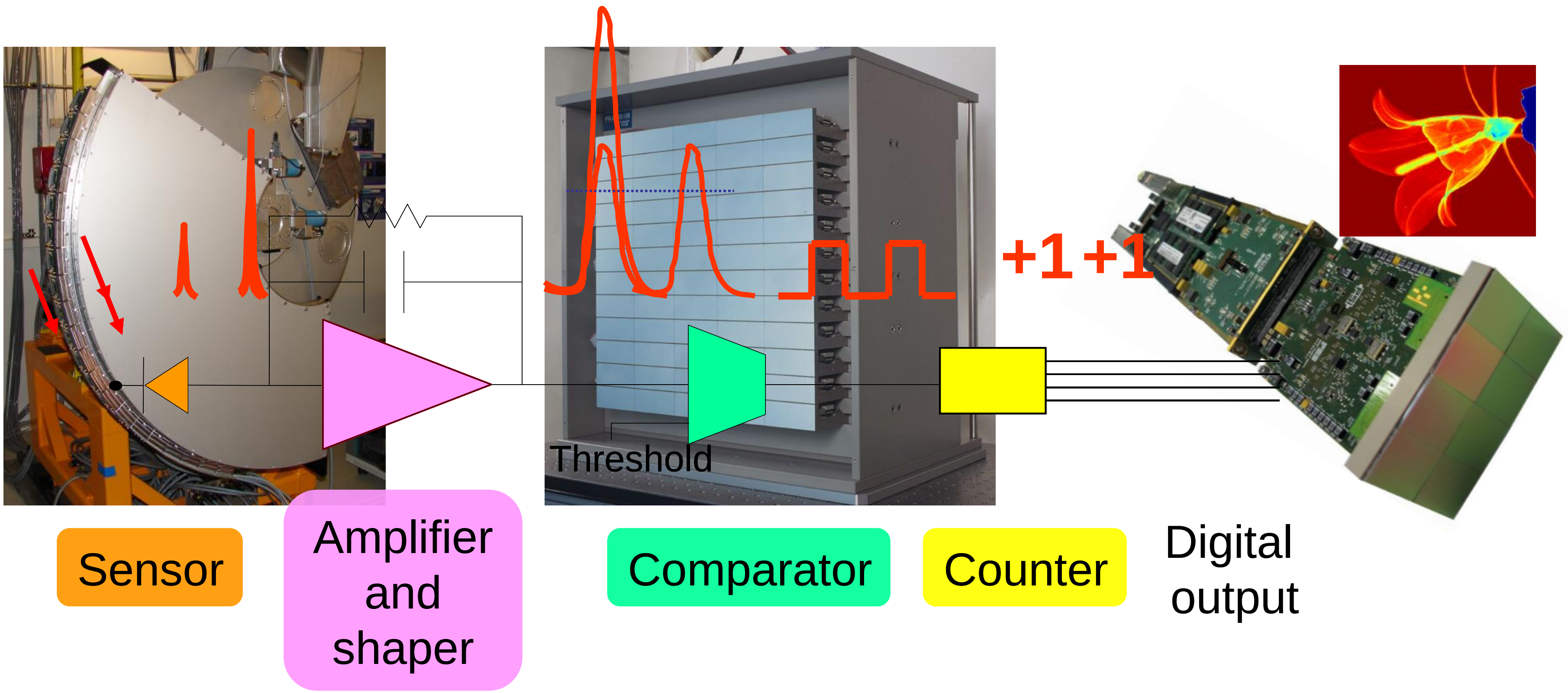
- Silicon
  - ✓Very mature technology
  - ×Relatively low Z
- Germanium
  - ✓Good spectroscopic properties
  - ×Cooling and fabrication issues
- Gallium Arsenide
  - ✓Good charge collection properties
  - ×Poor crystal quality
  - ×Fluorescence around 10 keV
- Cadmium Telluride
  - ✓High absorption efficiency up to 100keV
  - ▪Crystal quality is improving but it is available only in small wafers
  - ×Poor charge collection properties
  - ×Fluorescence at 23 and 27 keV
  - ×Interconnection issues

From single photon counting detectors at PSI…

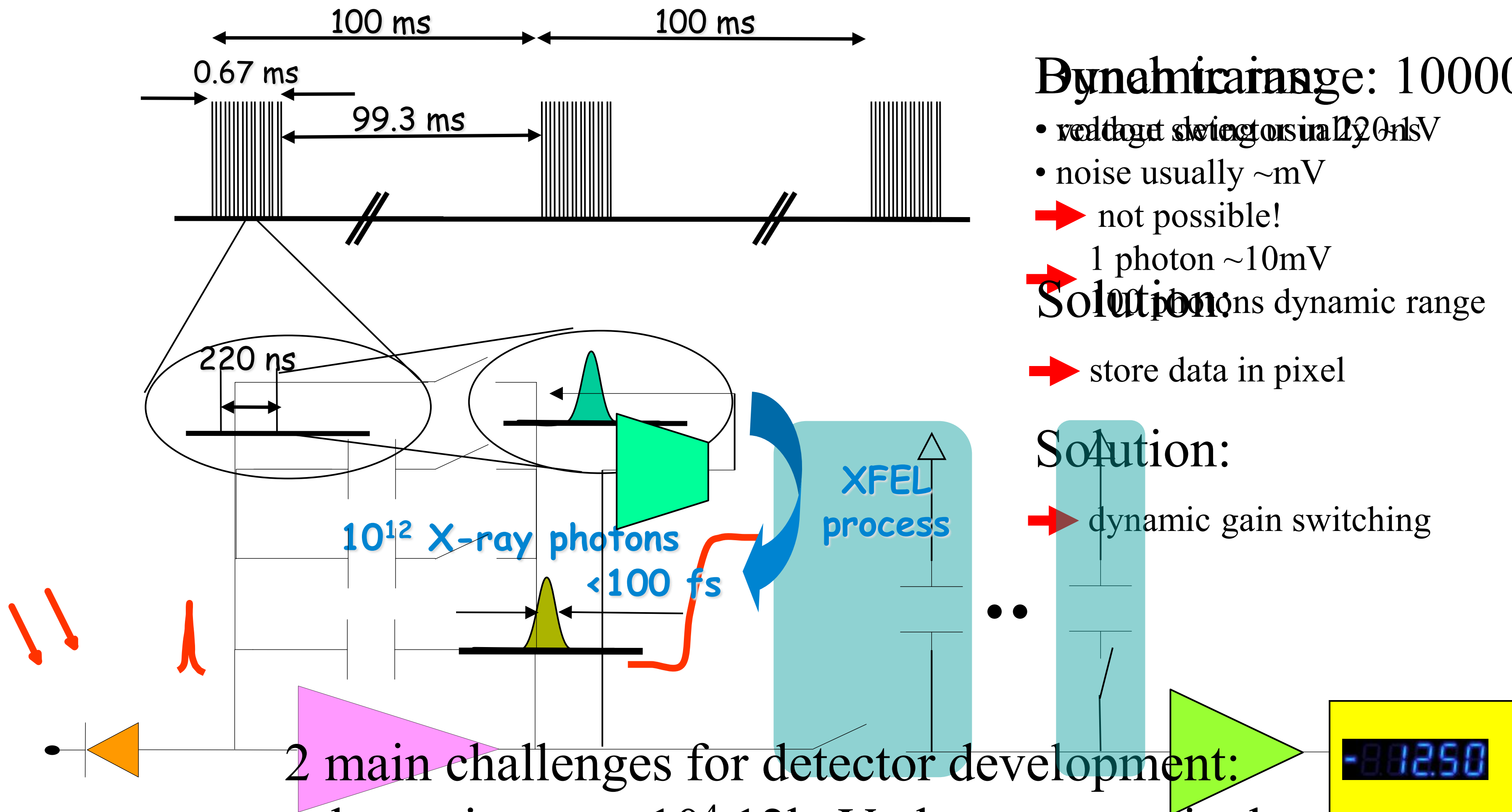
MYTHEN
1k to 30k 50µm strips for powder diffraction, small angle scattering, medical imaging…

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

→ not possible!

1 photon ~10mV

→ 100 photons dynamic range

Solution:

→ dynamic gain switching

Bunch trains:

- read out detector in 220 ns

Solution:

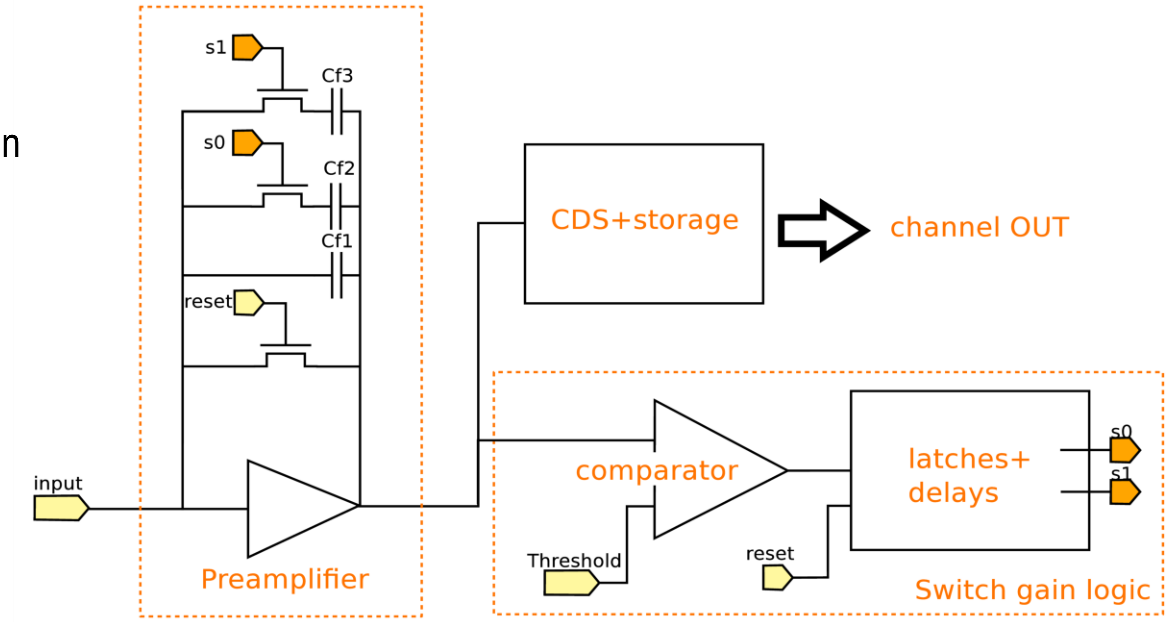
→ store data in pixel

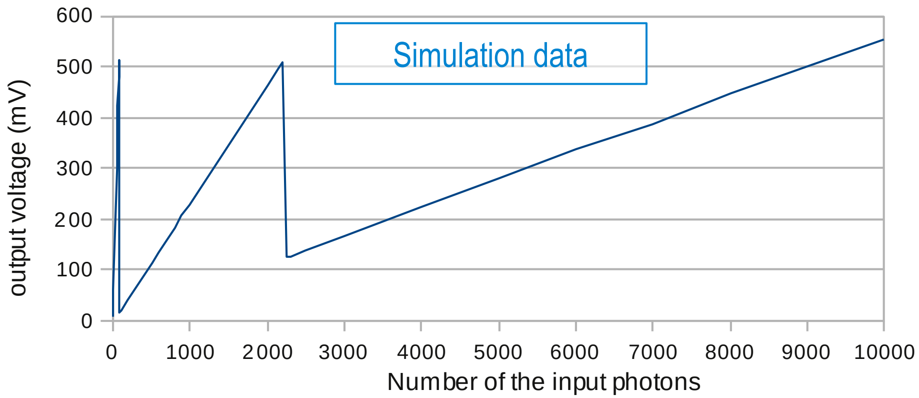
2 main challenges for detector development:

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

Preamplifier with gain switching

- Common for 1D and 2D
- CSA in charge integrating configuration
- 3 feedback capacitors

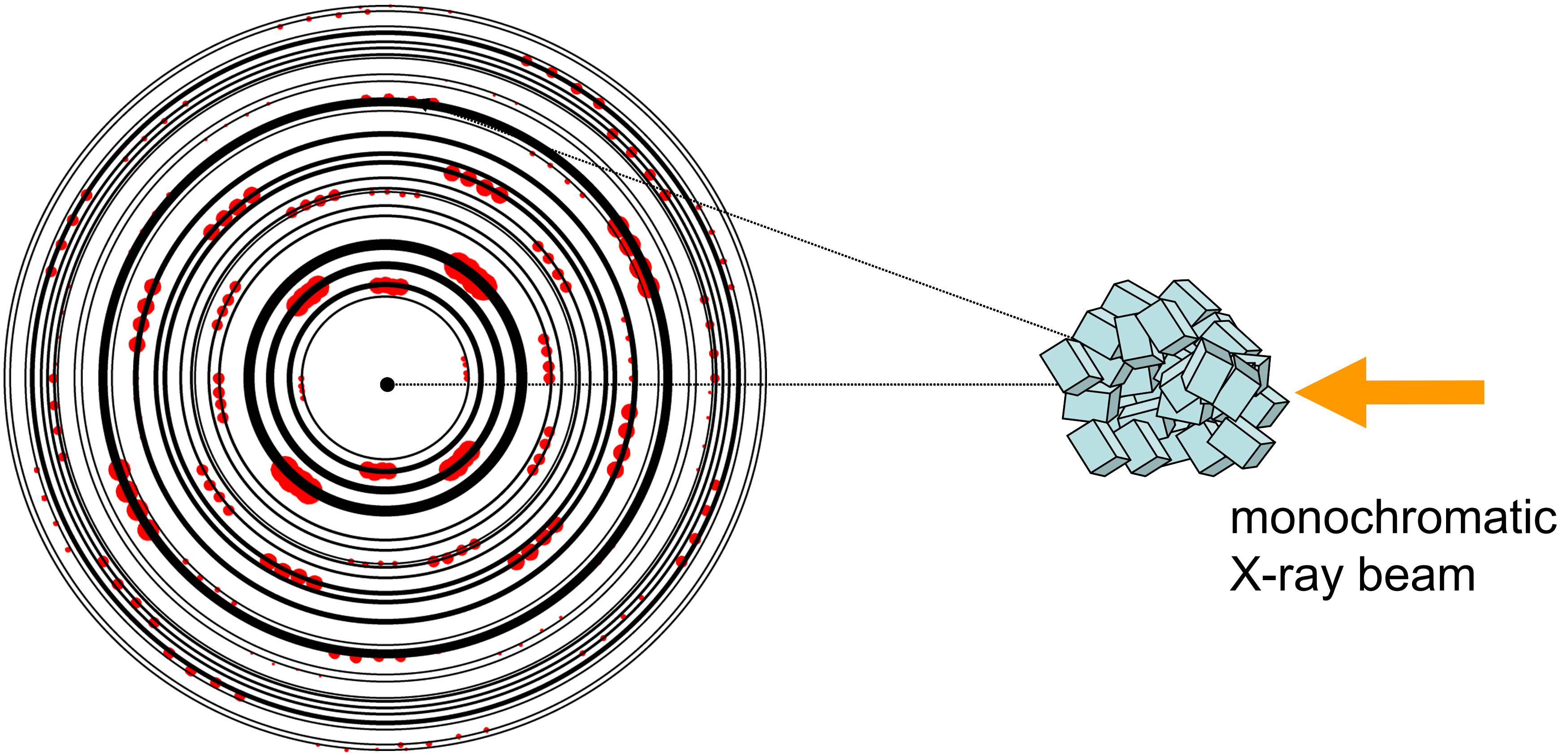




- Logic after comparator to:
  - Switch a 2nd time if 1st switch not enough
  - Avoid a 2nd switch on spikes due to the 1st one
- Switching has to be FAST (<10ns)

Powder Diffraction: the Mythen Detector

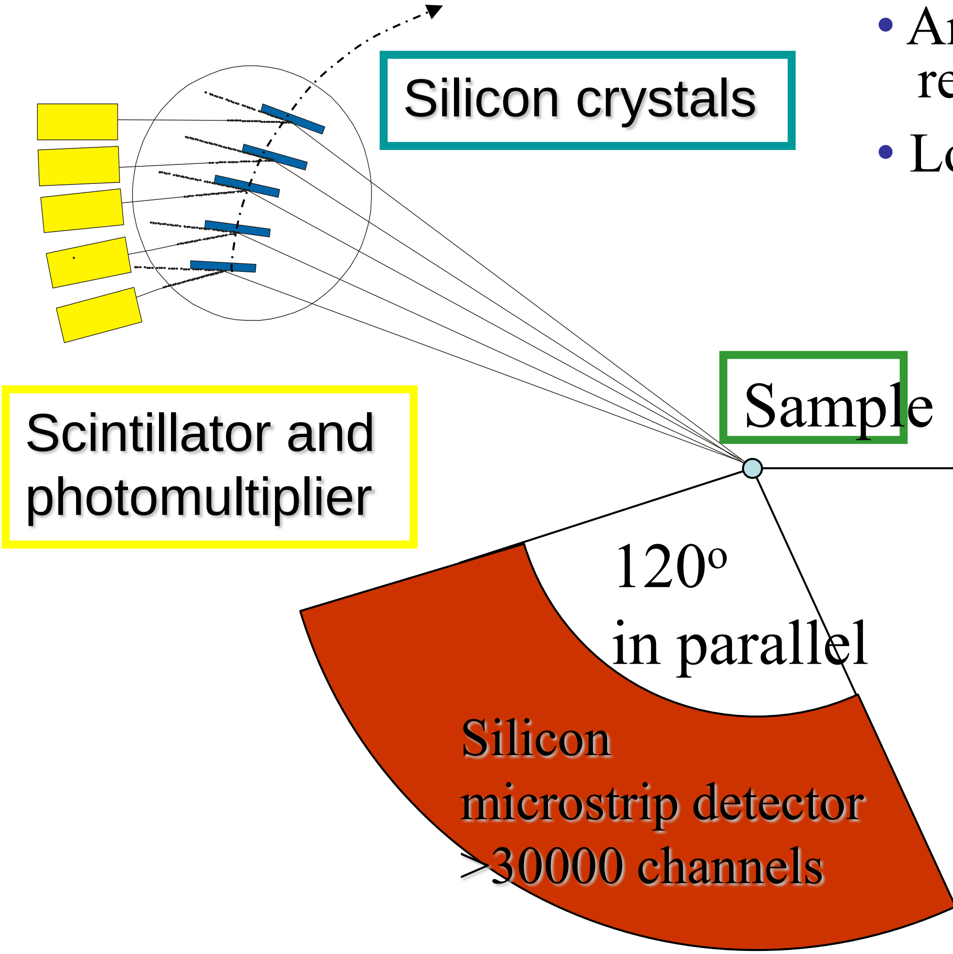
Powder diffraction: principle



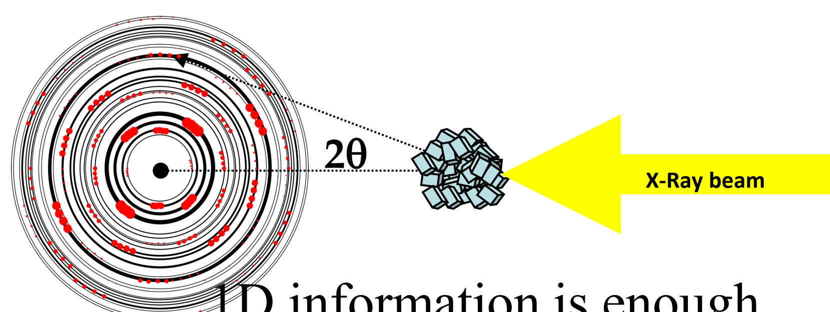
Powder diffraction: principle

Crystal analyzer detector

- few channels (max 45)
- Angular selectivity: better than 0.003° resolution
- Long measurement times: 15 min-several hours



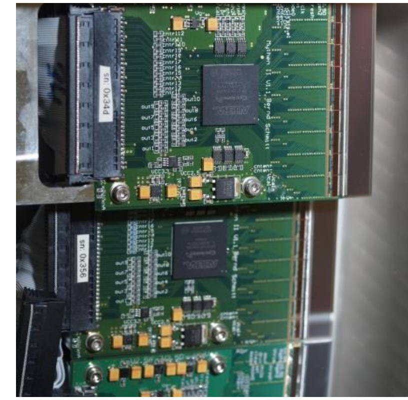
monochromatic X-ray beam



1D information is enough
Large angular range required

MYTHEN

Microstrip sYstem for Time rEsolved experimeNts



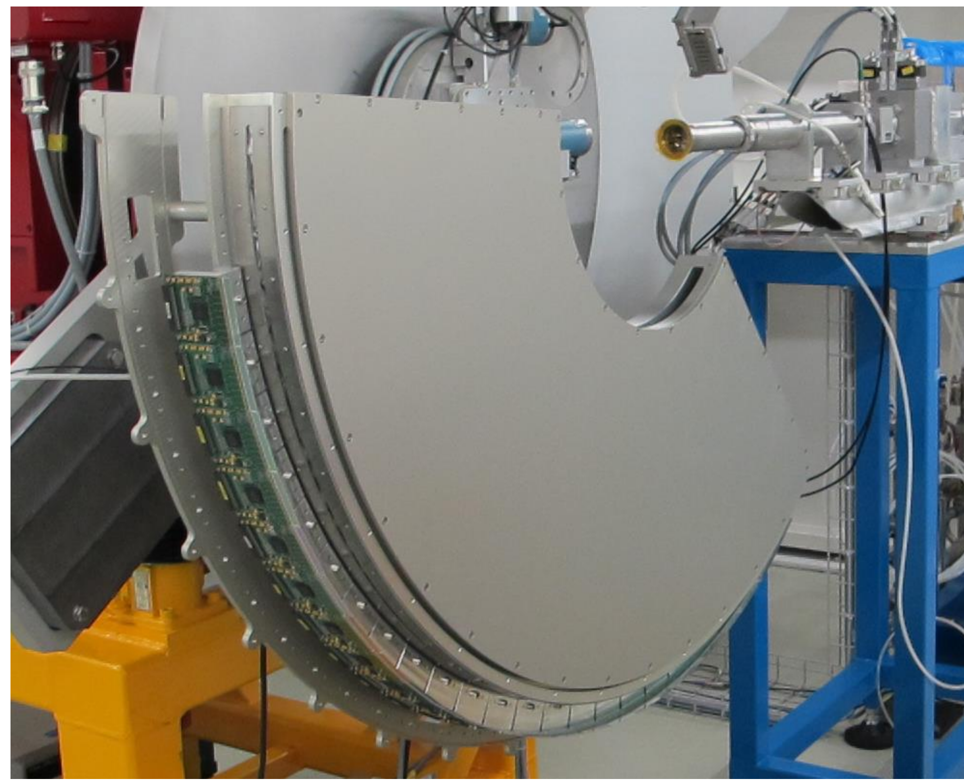
- Single photon counting microstrip

- Covers 120 degrees with 0.004° angular resolution
  - > 40k independent channels
  - 50 um pitch, 8 mm long

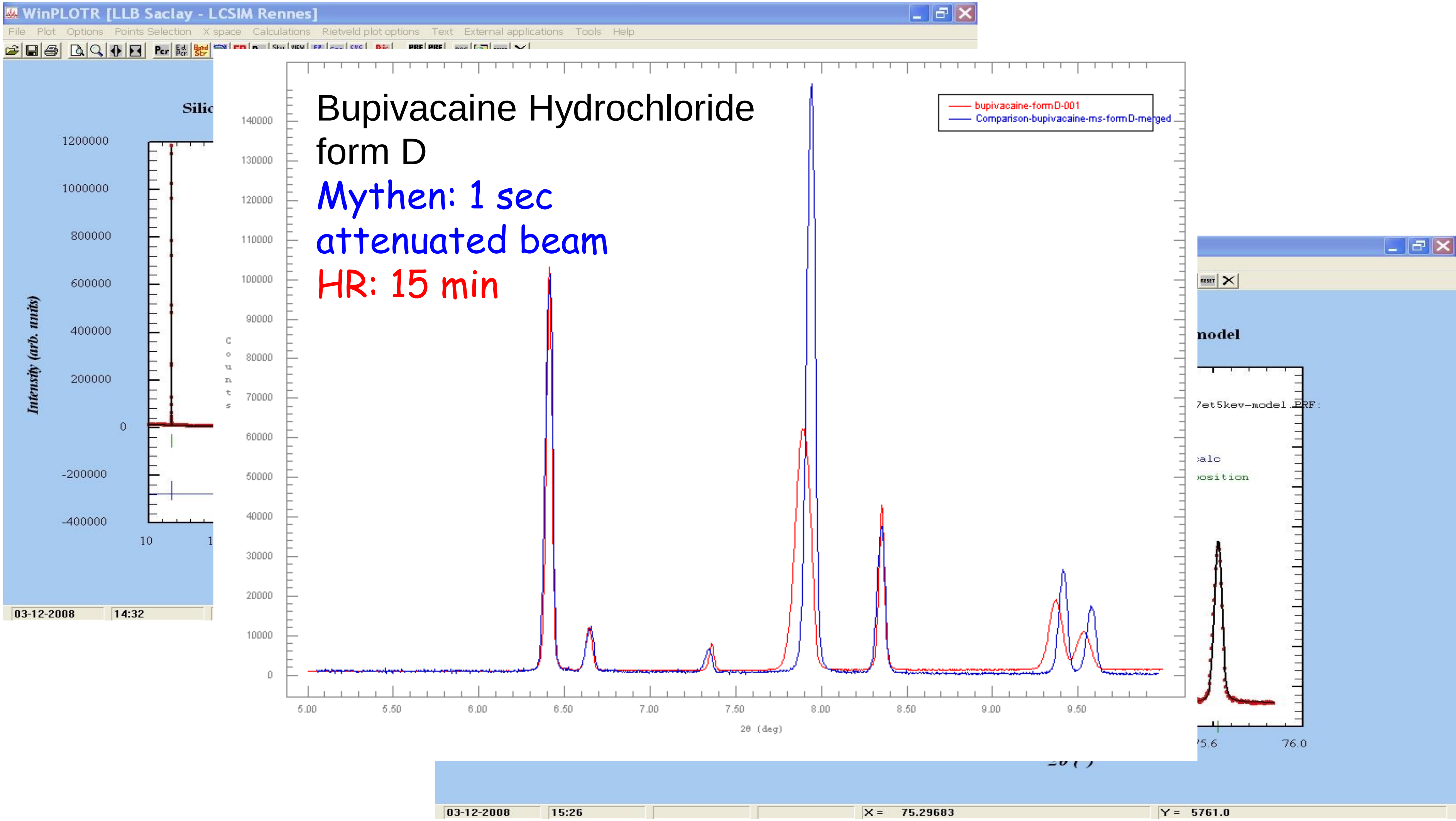
- Second detector layer to detect the transmitted photons
  - Efficiency almost doubled
  - above 12 keV

- Frame rate up to 20 Hz - 1 kHz
  - Depending on dynamic
  - and angular range

- Users operation since 2007
  - In-situ measurements
  - Pump-probe experiments
  - Monitoring of radiation damage



Standard powder samples



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

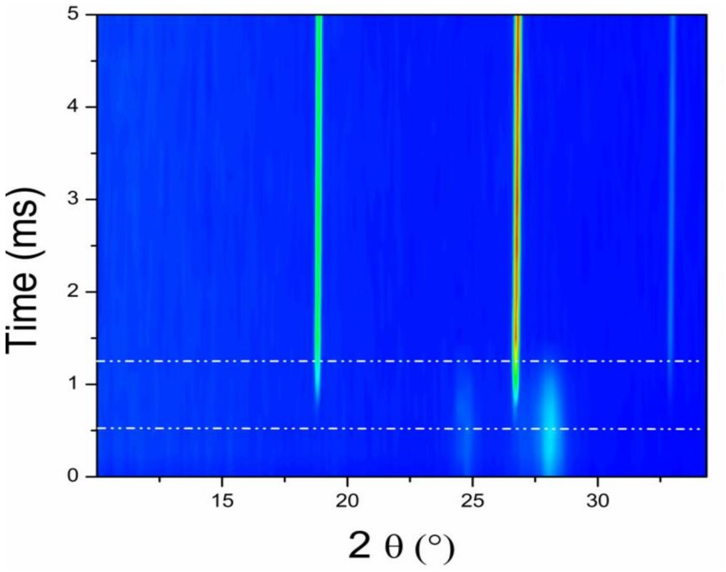
In situ self propagating exotermic reactions

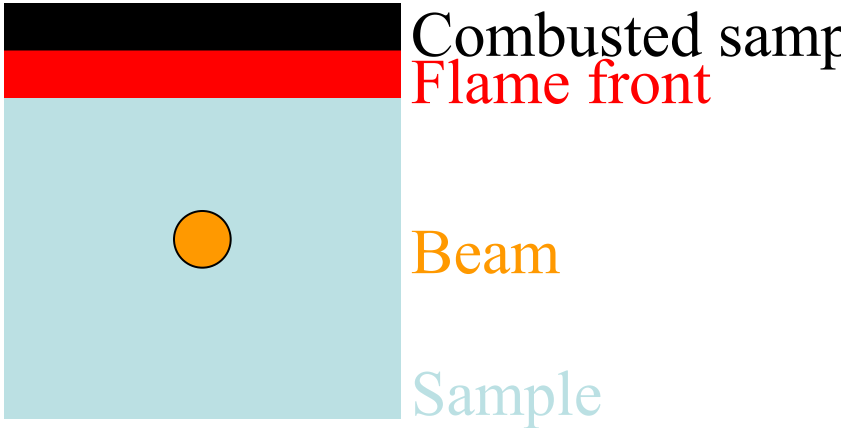
Sputtered NiAl multilayer foils

Beam size 500x500 μm^2 defines the time resolution

Synchronization of equipment via digital signals

- Ignition using a spark while triggering the detector
- High-speed Recording Camera
- In-situ XRPD using MYTHEN
  - 125us acquisition/125us readout time
  - 8bits dynamic range
  - 16 consecutive frames





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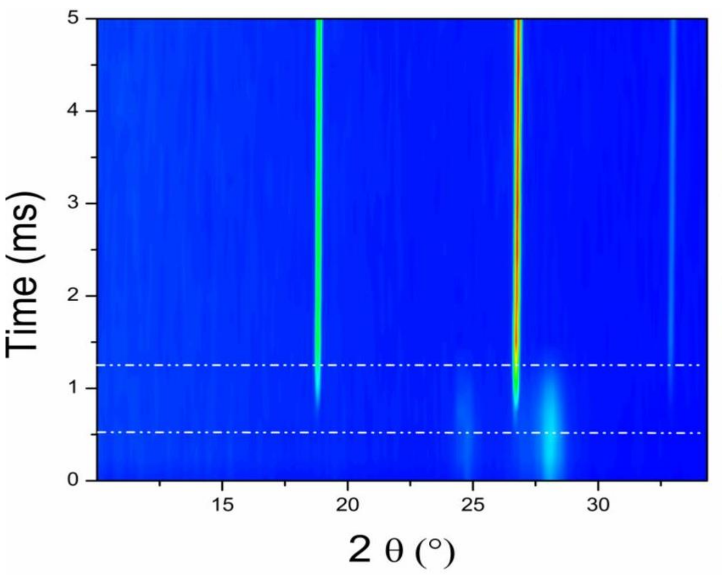

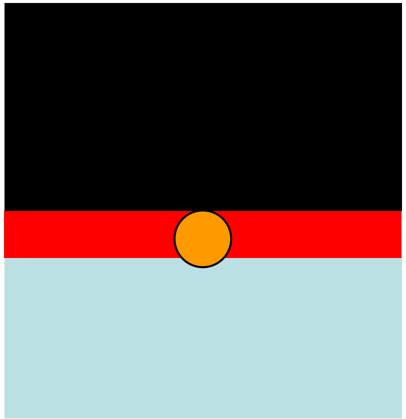

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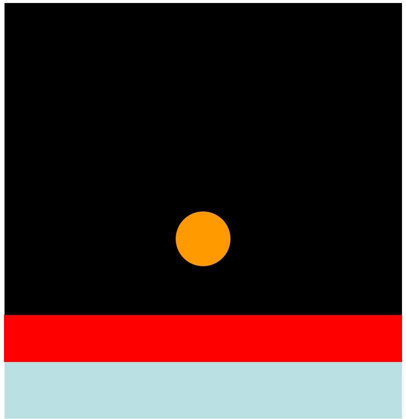
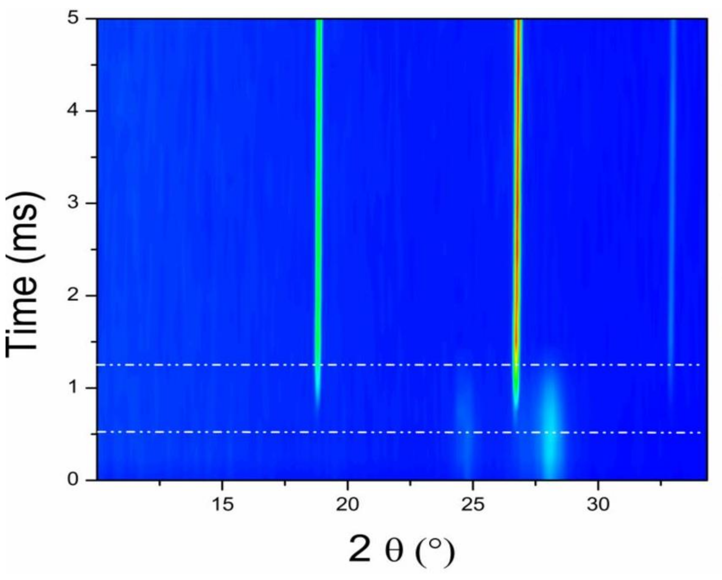
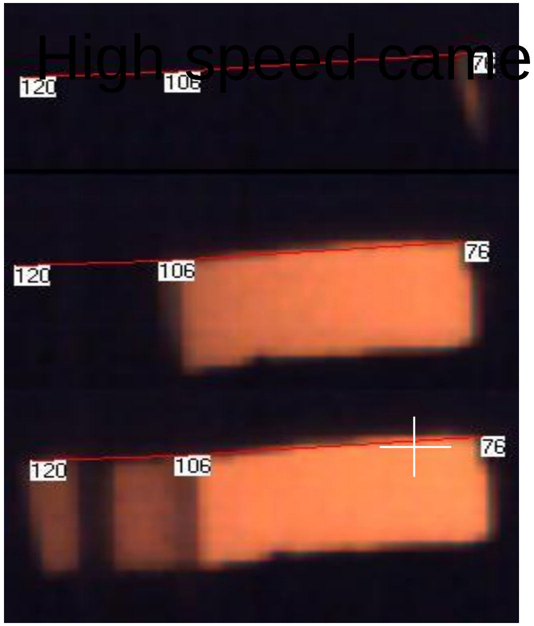


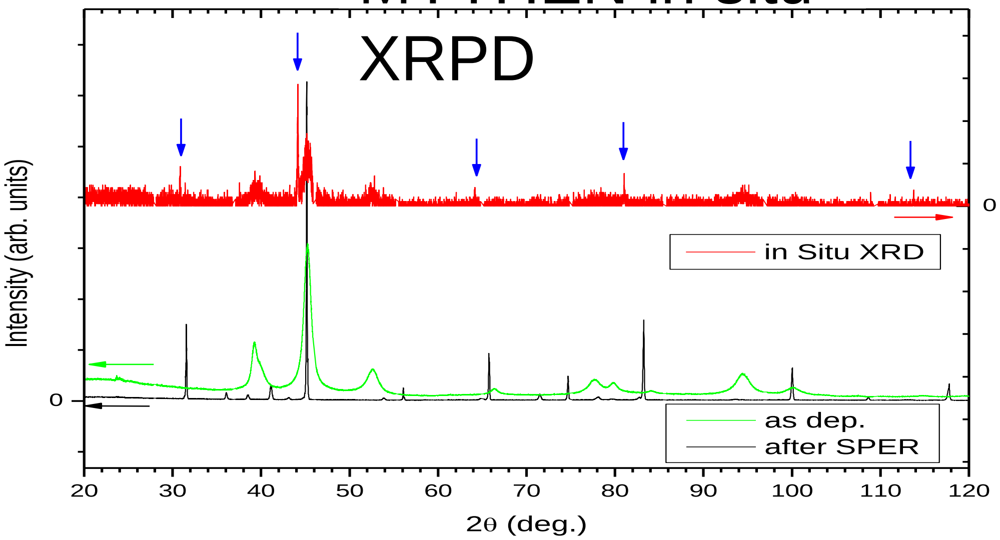


Experimental proof of intermediate structure

High speed camera



MYTHEN in situ XRPD



Proof of principle for investigations of reactions with high flame front velocities

Experimental proof for the formation of an intermediate intermetallic phase

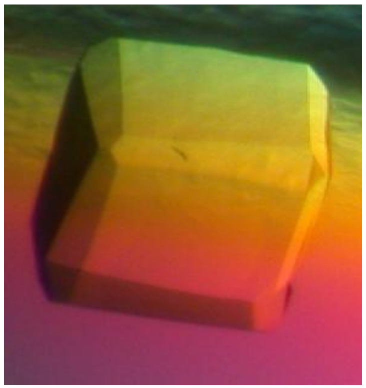
Without Mythen no transient structure could have been measured

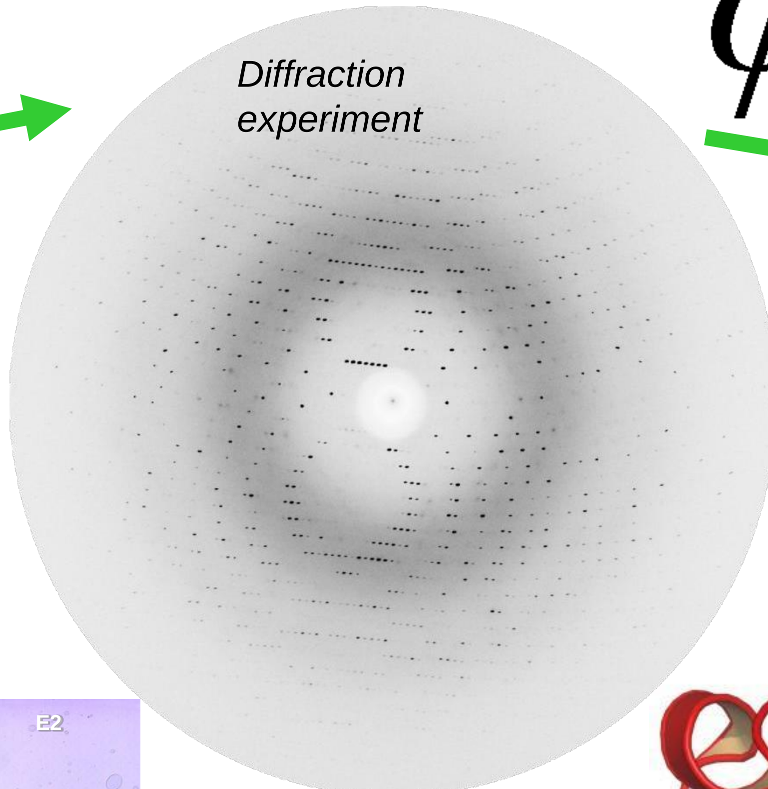
K. Fadenberger (Uni Cyprus)

Protein Crystallography: the Pilatus Detector

From protein to structure

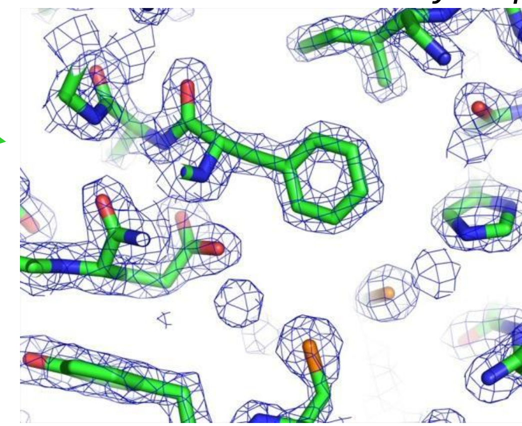
Crystallization (cubic Insulin)



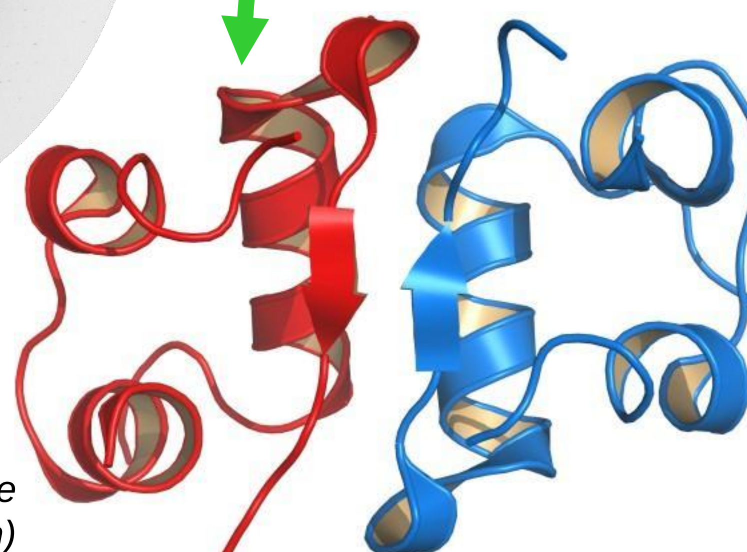


Phasing φ

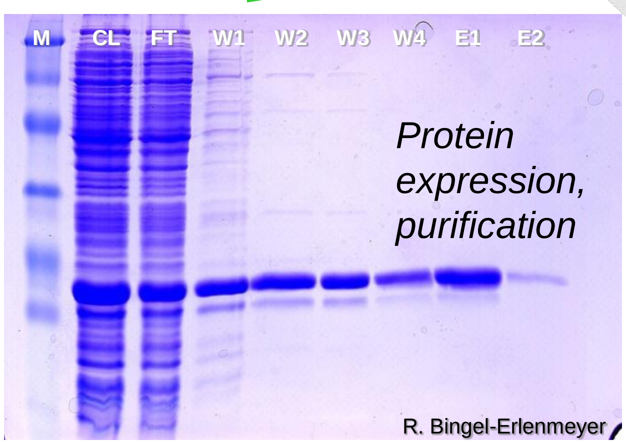
Electron density map



Model building, refinement

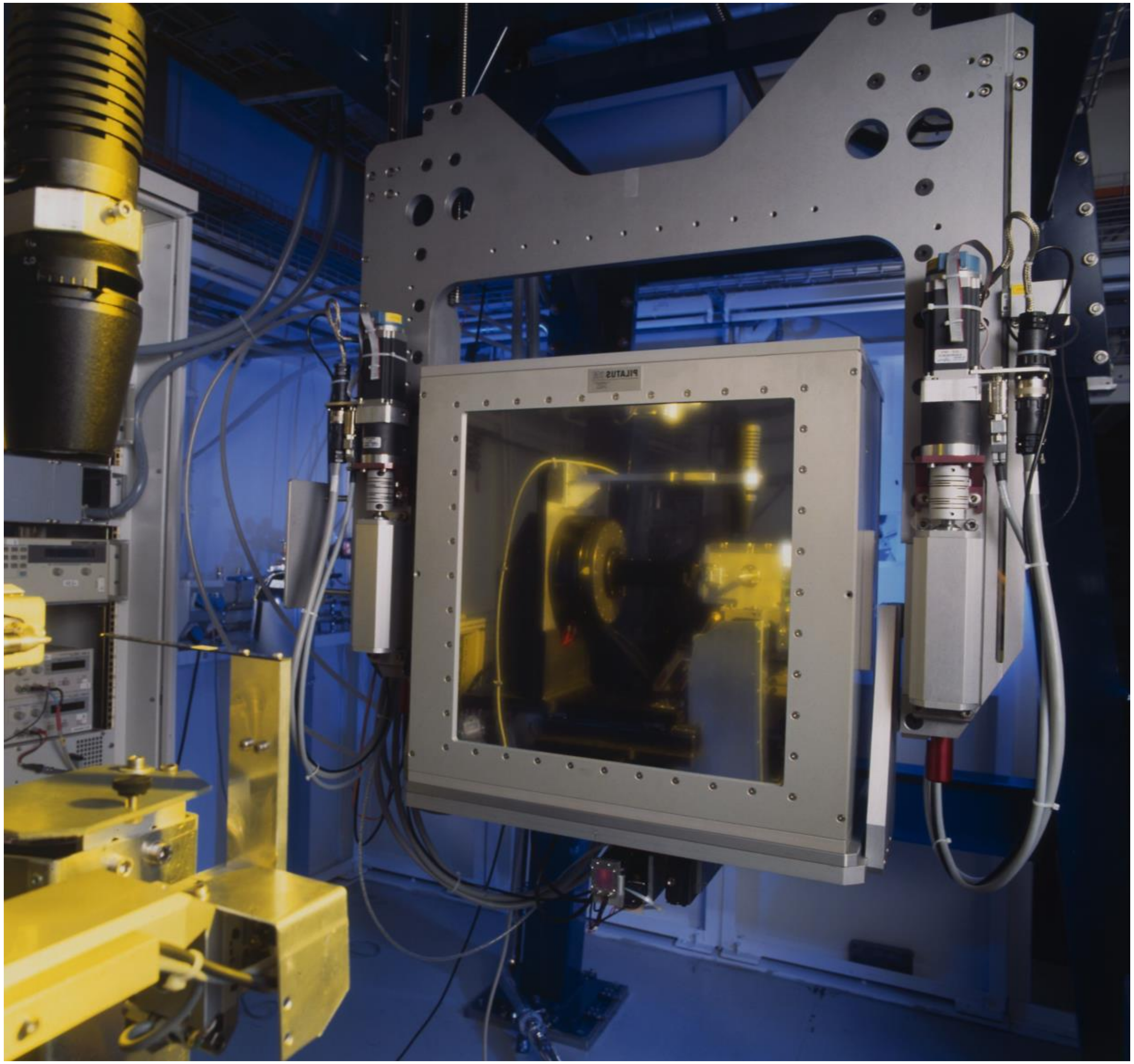


Structure (Insulin)



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 3000 protein structures solved at PX beamline at SLS

~2/3 using PilatusII 6M

compiled by Sandro Waltersperger
Dec 20113

Current developments

Point of view of a Synchrotron person:

- detector must be big > 1 Mpixel
- well calibrated, usable, available and affordable

Developments in the US:

- Berkeley: P. Denes CCDs
- Cornell: Sol Grunners group (mixed mode pad)
- SLAC: LCLS, CSPAD, epix
- APS: CCDs, energy resolving detectors

Developments in Japan:

- SPring8 H. Toyokawa, T. Hirono CdTe pixel and strip
- Sacla T. Hatsui multi via pixel based on SOI

Developments in France:

ImXpad (Spin-off CPPM Marseille)

ESRF (FRELON CCD, MAXIPIX)

Current developments

Medipix based developments:
- Lamda at Desy
- Excalibur at Diamond

Developments for EU-XFEL:
- AGIPD, LPD, DSSC

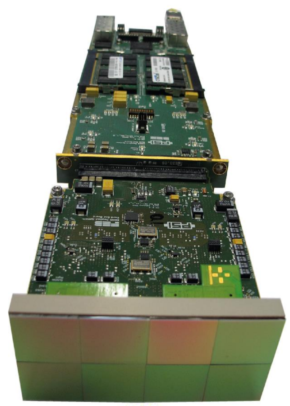
Developments from Dectris: PilatusIII

Developments from HLL, PN Sensor PN Detector:
- Depfets, PN-CCD, Si Drift

Low energies:
- Percival (Desy, RAL, Elettra)

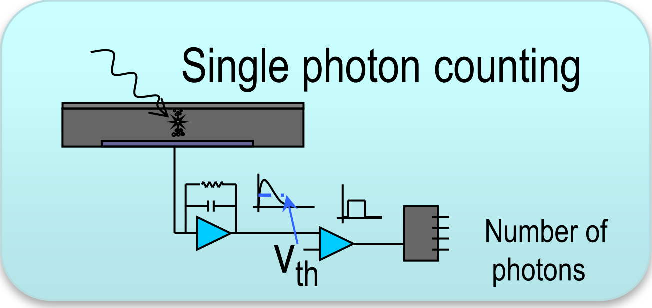
Current X-ray Detector Development at SLS

Eiger

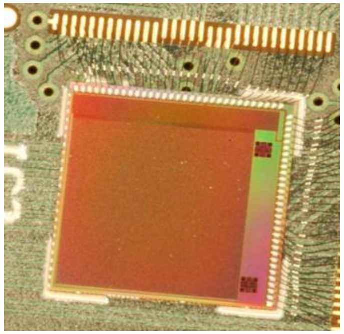


Mythen II

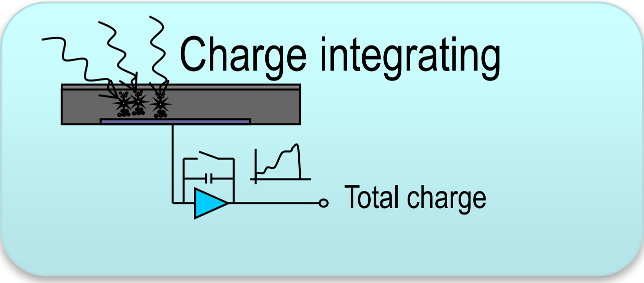
Synchrotron detectors



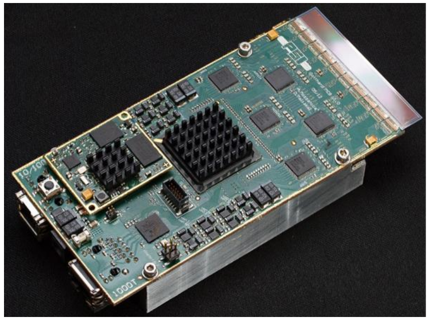
Mönch



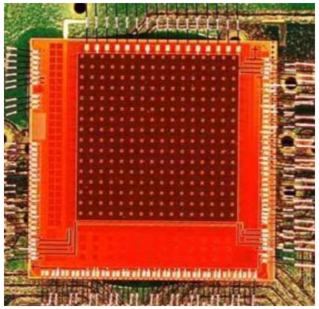
Synchrotrons and XFEL detectors



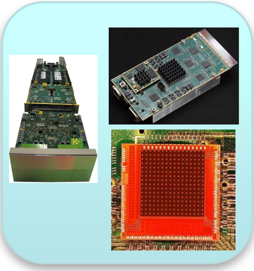
Gotthard



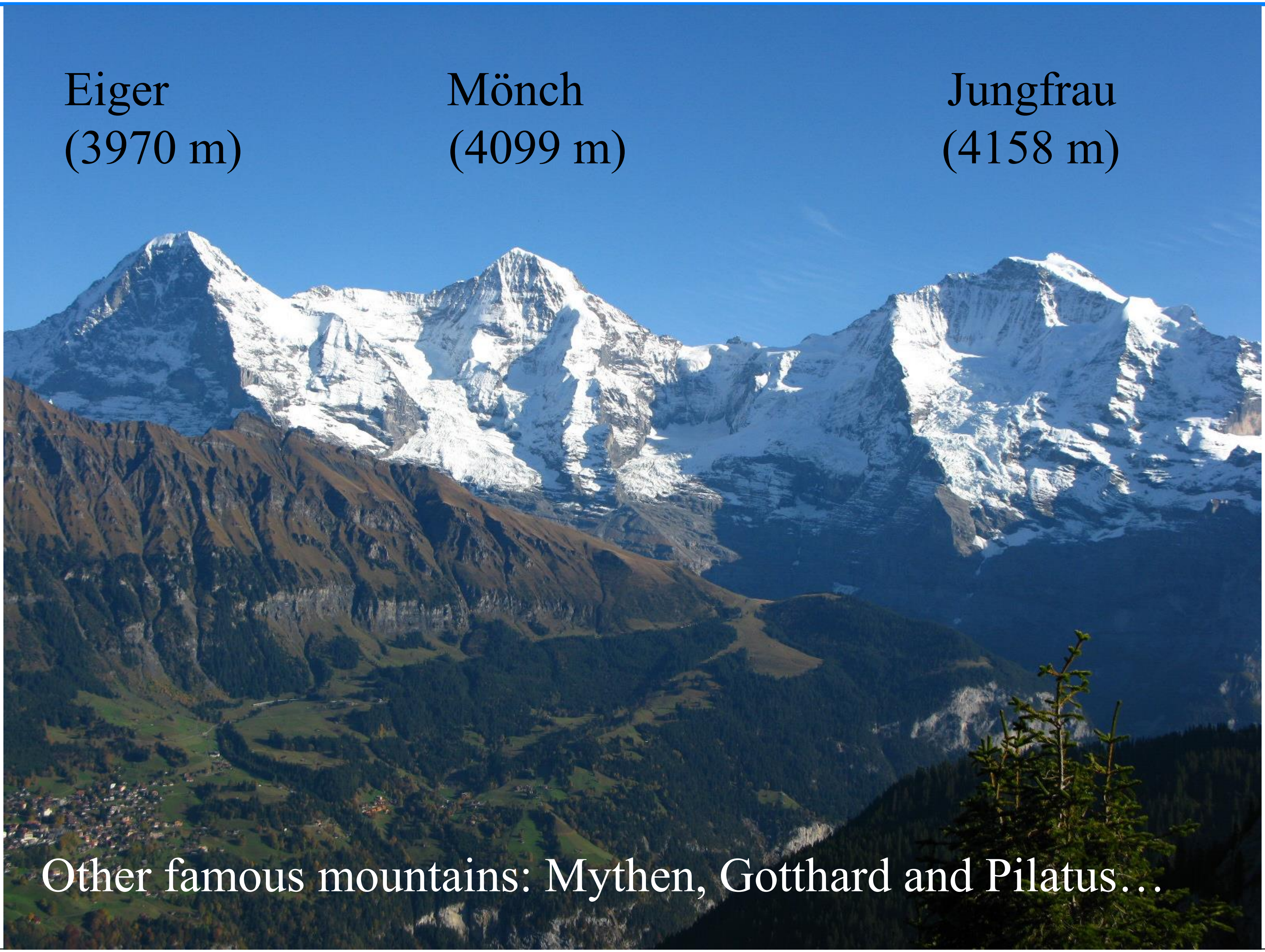
AGIPD: EU-XFEL



Jungfrau: SwissFEL



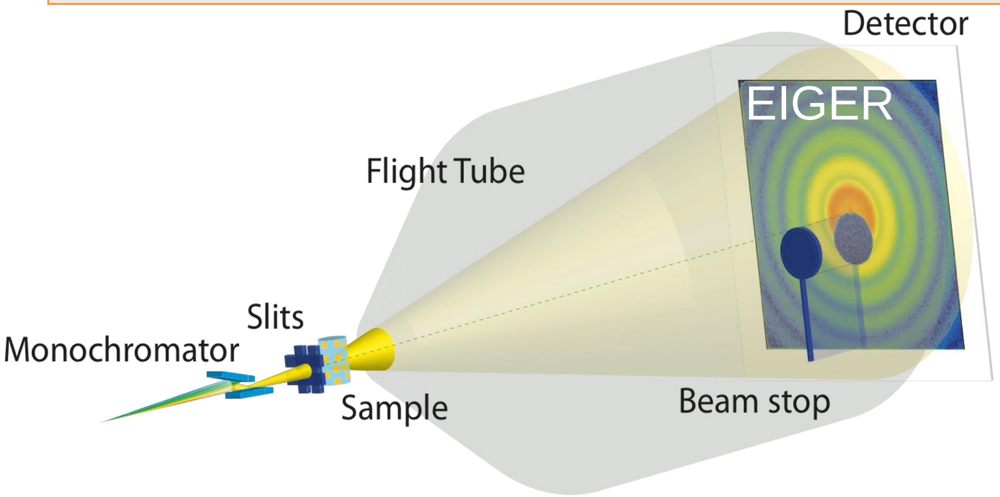
Swiss Mountains

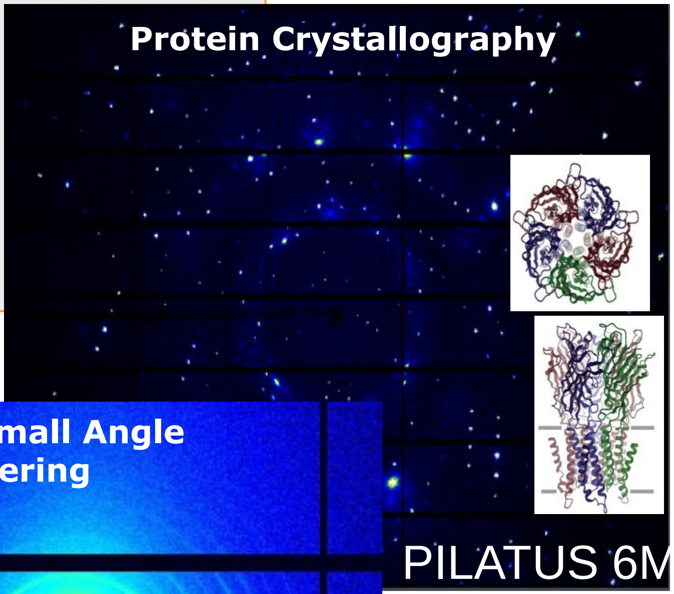


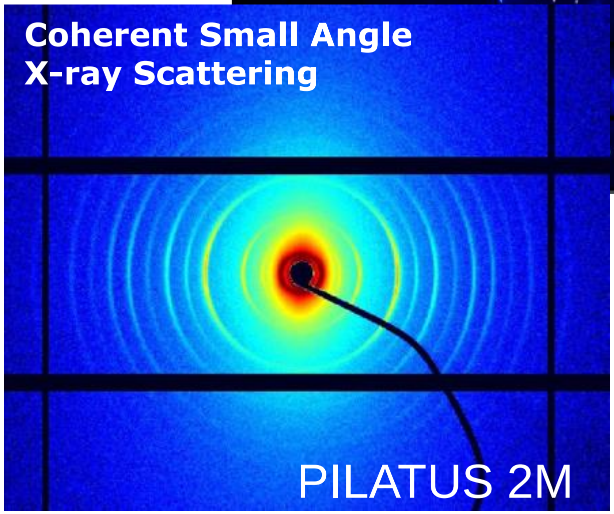
The Eiger Detector

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
  - X-ray Photon Correlation Spectroscopy
- Protein Crystallography

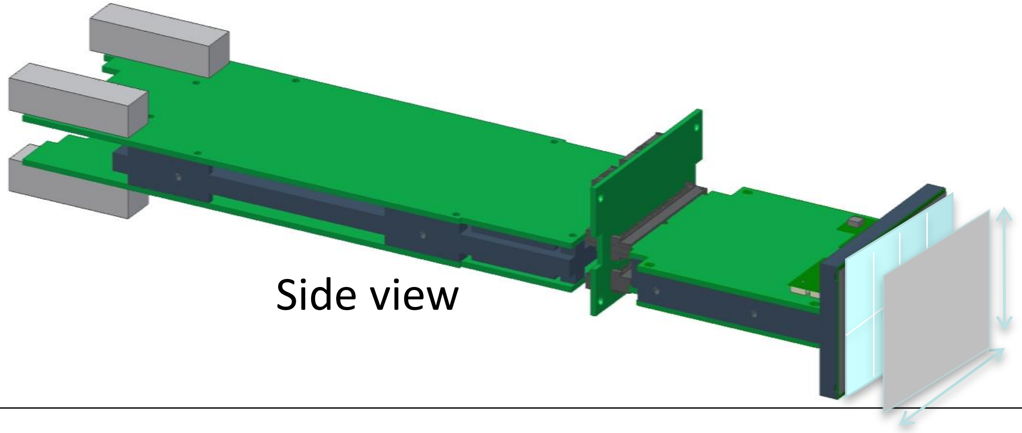






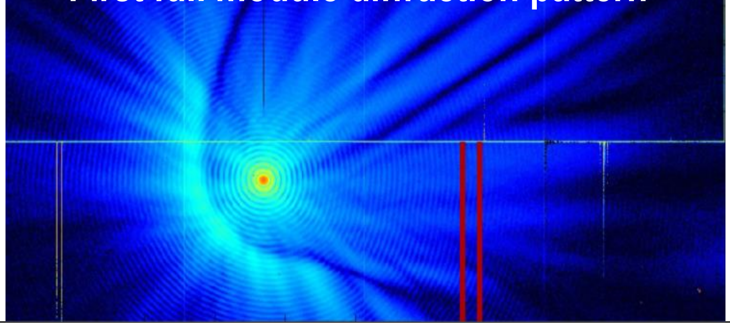
Eiger, the next generation pixel detector

- Single photon counting pixel detector
- Sensitive area of 38 X 77 mm^2
- Pixel size 75 μm
- 524k pixel module
- 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
- 8 GB of memory on a module
- Two 10 GbE data links per module



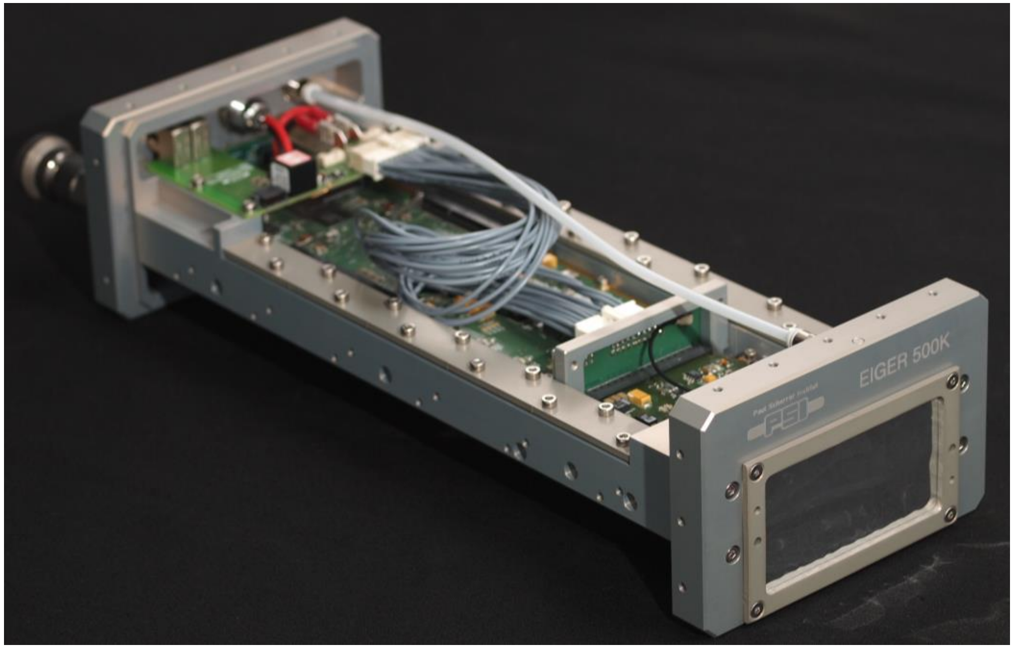
Side view

First full module diffraction pattern

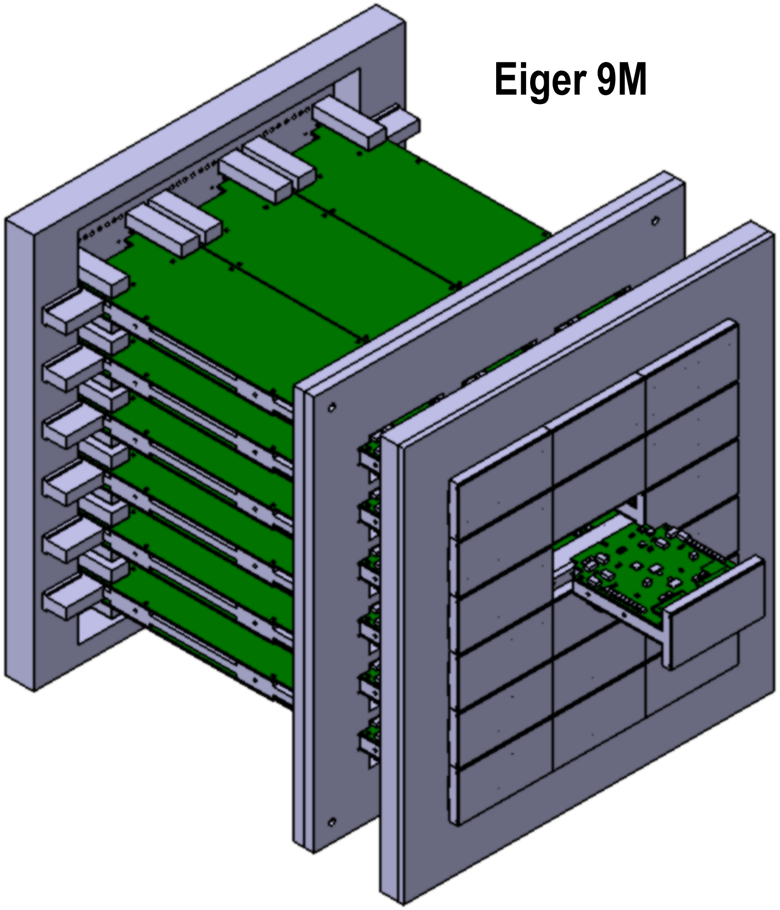


Eiger systems

500k single module



Eiger 9M

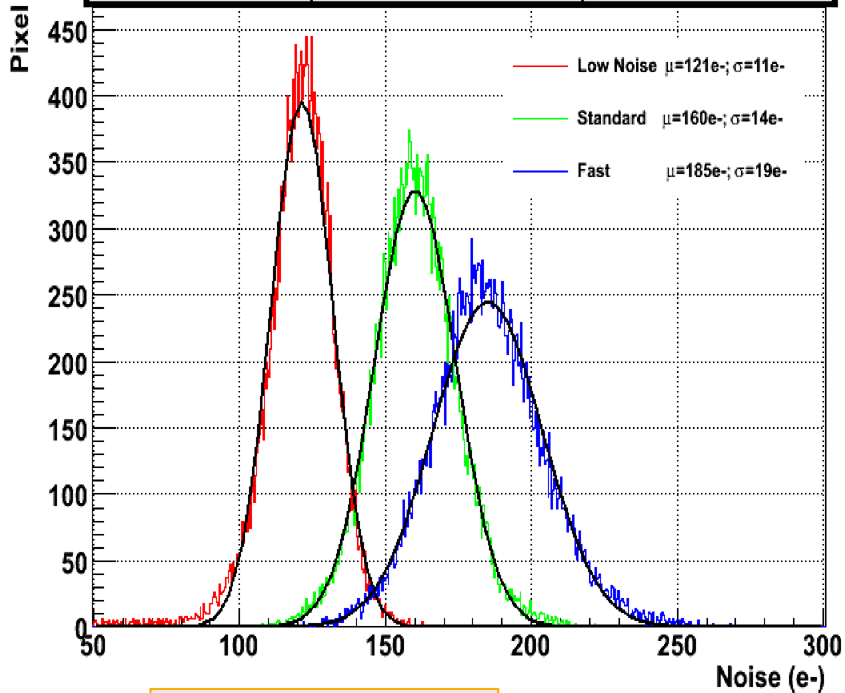


	Number of pixels	On board storage (frames/4 bits)	Data rate[1] @ 12 kHz	Data rate[2] @ 1kH	Data rate[3] @ 100 Hz	Data rate[4] @ 10 Hz
Module	524 k (512 x 1024)	~32,740	50.3 Gb/s	6.29 Gb/s*	839 Mb/s*	168 Mb/s*
9M Detector	9.44 M (3072x3072)	~32,740	906 Gb/s	113 Gb/s	15.1 Gb/s*	3.02 Gb/s*

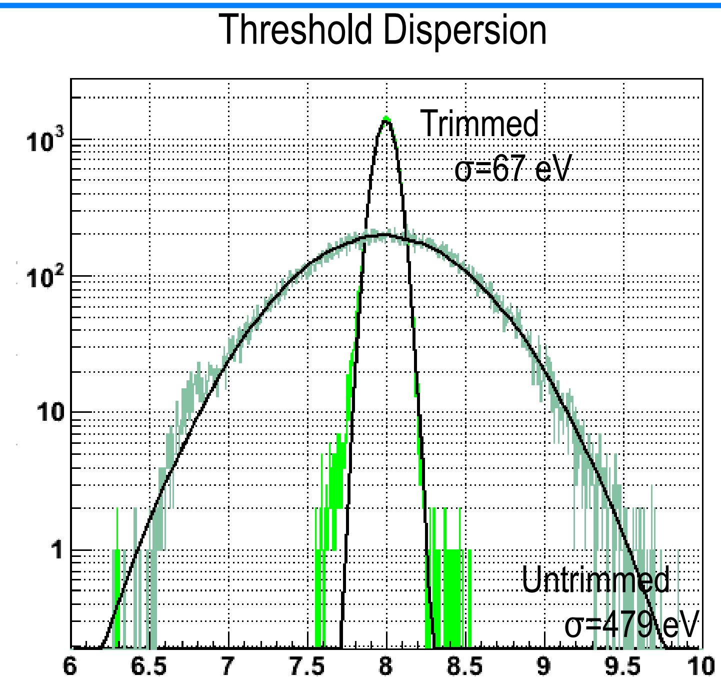
1) 8 bit, equivalent to ~4@23 kHz and 12@8 kHz. 2) 12 bit. 3) 16 bit. 4) 32 bit. *) Foreseeable continuous storage rates (~20 Gb/s).

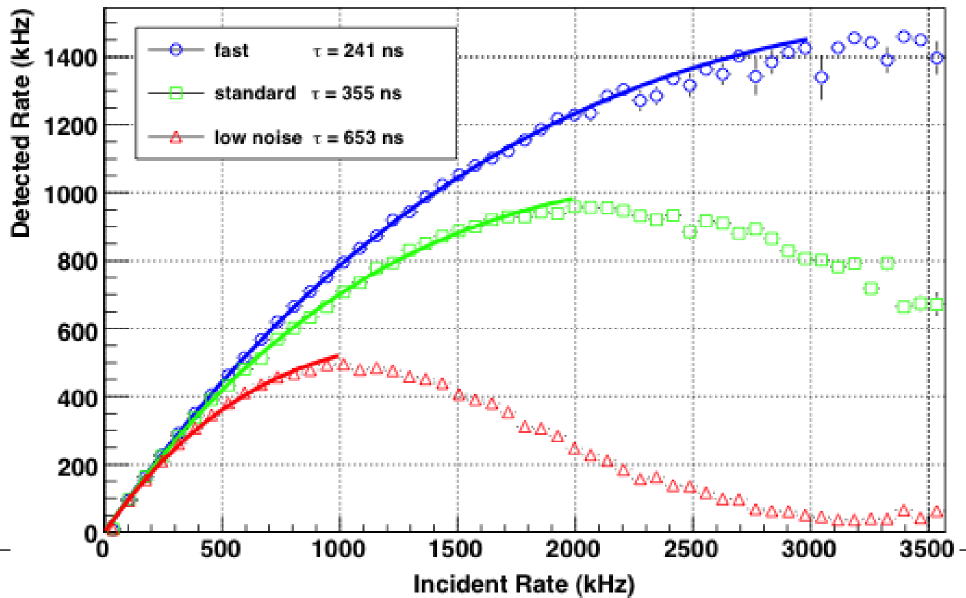
Noise and threshold dispersion

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

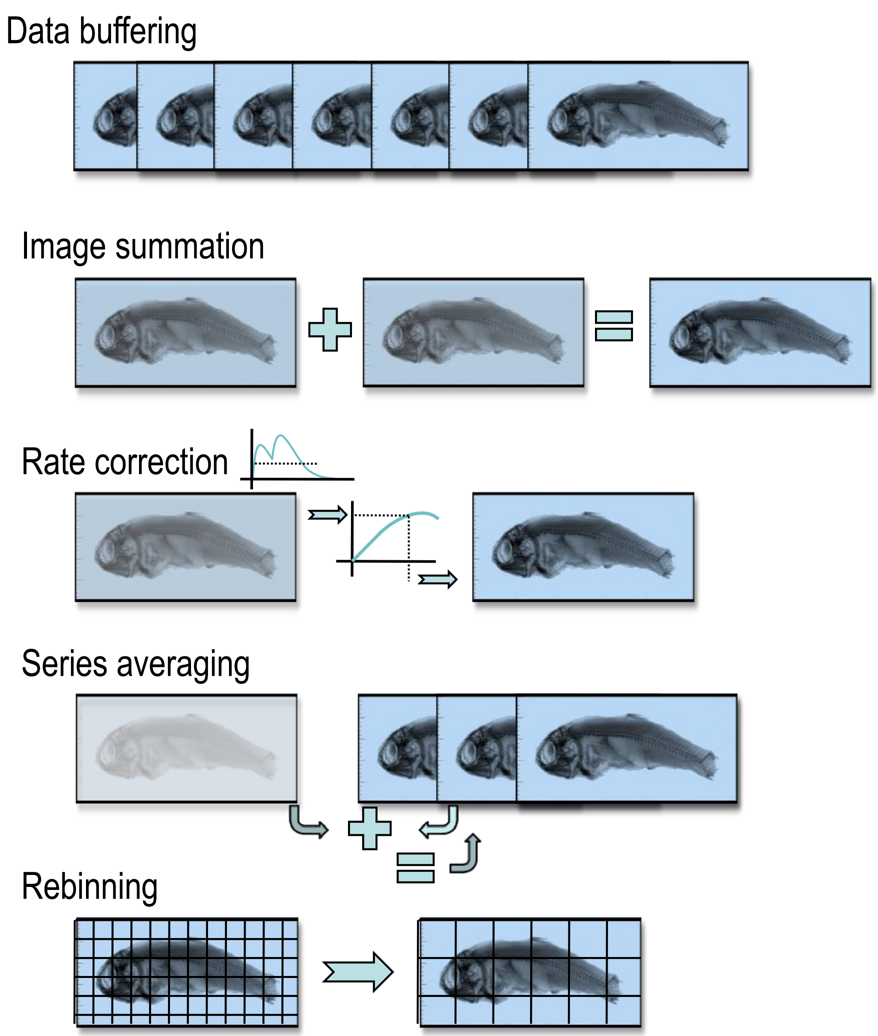


@14KeV



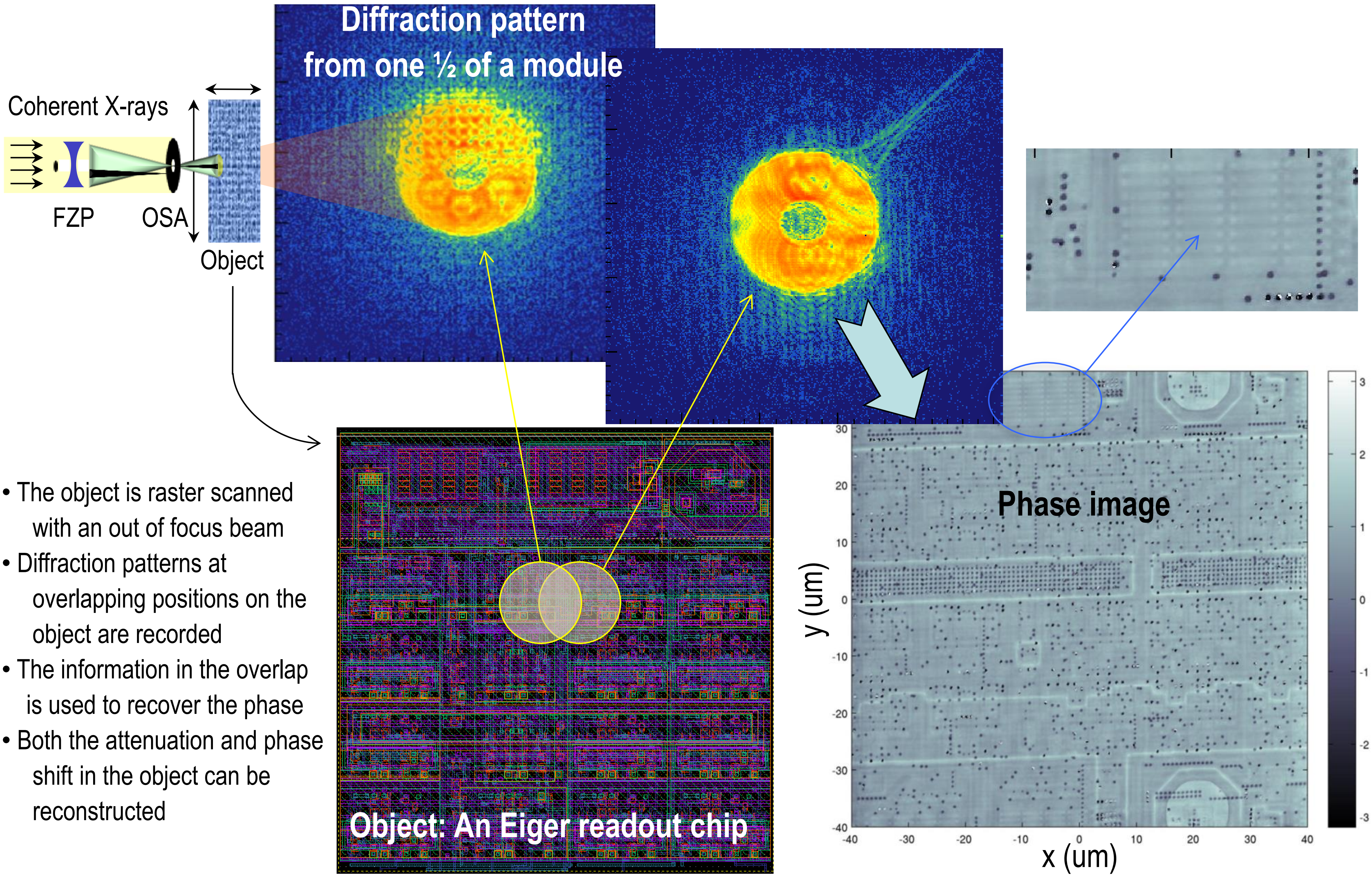


On board Intelligence (data processing in firmware)



- On board data processing is in parallel on multi-module systems
  - independent of the detector size
  - for modules reduces tens of Gb/s at the source
  - for a 9Ms, hundreds of Gb/s at the source
- Data buffering (8GB of memory)
- On the fly image summation
  - extends the dynamic range from 4096 to 4×10^9
  - makes high flux continuous data taking possible
  - combined with rate correction
- Rate correction
  - performed on sub-frames @ kHz frame rate
  - more precise, less sensitive to rate fluctuations
- Pump and probe series averaging
  - high frame rate exposure series summing
  - alternating pumped and un-pumped
- Data reduction
  - 2x2 pixel rebinning
  - SAXS ring intensity averaging (planned)
  - data compression (in thought, question of HDF5 compatibility)

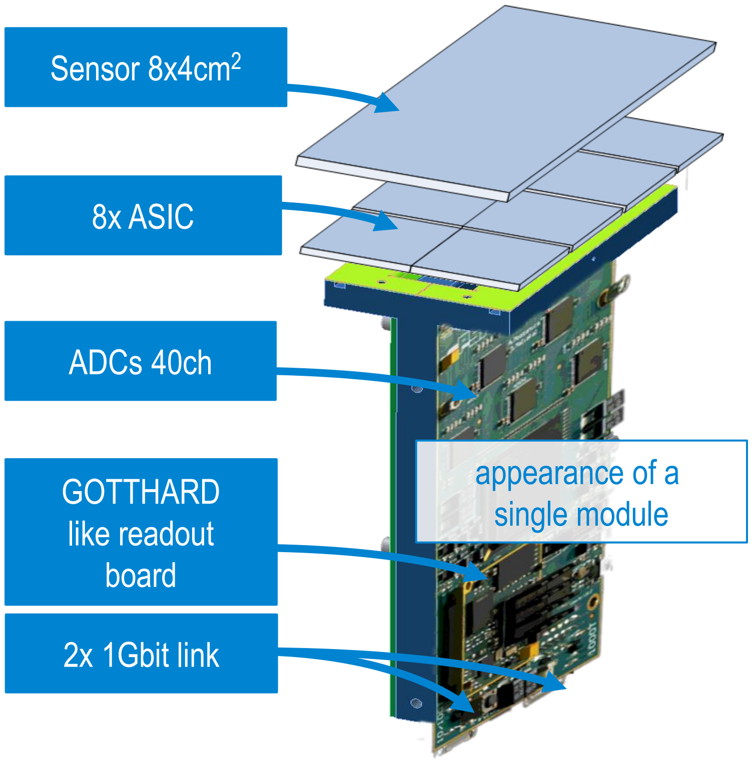
An Eiger self portrait (Ptychography)



- 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

Jungfrau: a 2D detector for Swissfel

adJUStiNg Gain detector FoR the Aramis User station



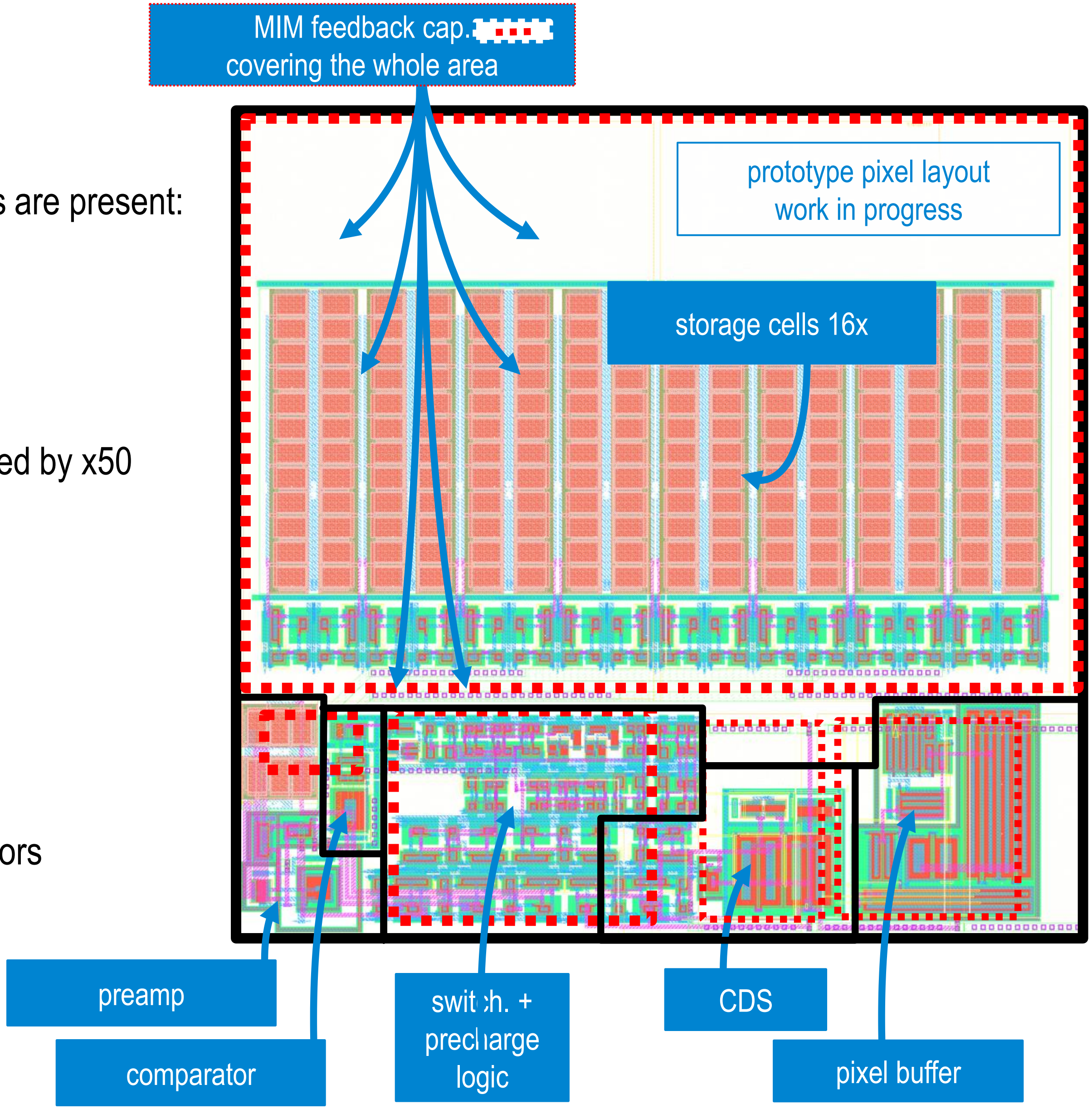
- ASIC and readout system based on GOTTHARD:
  - 3 gains automatic switching
  - Low noise high dynamic range (10^4 12keV photons)
  - UMC 110nm
- Dimensions, sensor and mechanics from EIGER:
  - 75 x 75 μm^2 pixel size
  - 4 x 8 cm^2 sensor size
- Frame rate: 2kHz

Jungfrau pixel architecture

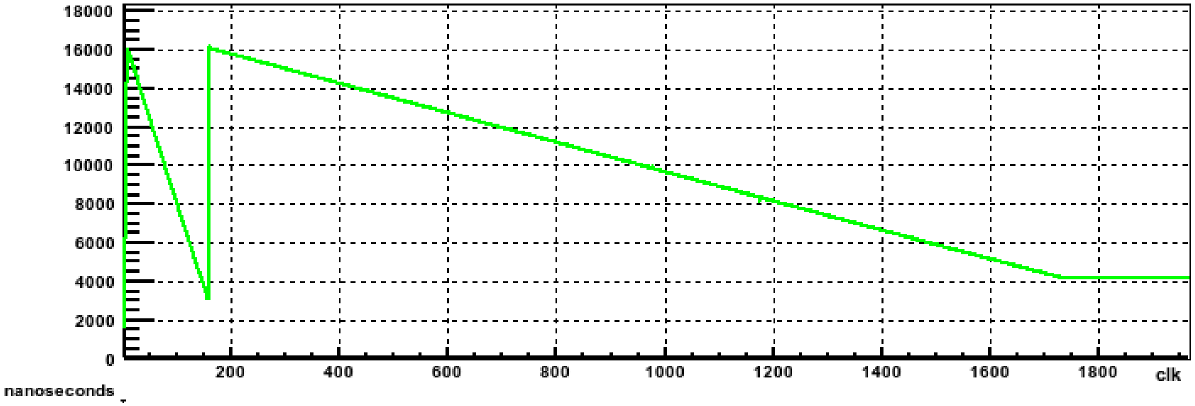
Basically a 2D version of Gotthard

In a pixel design the following challenges are present:

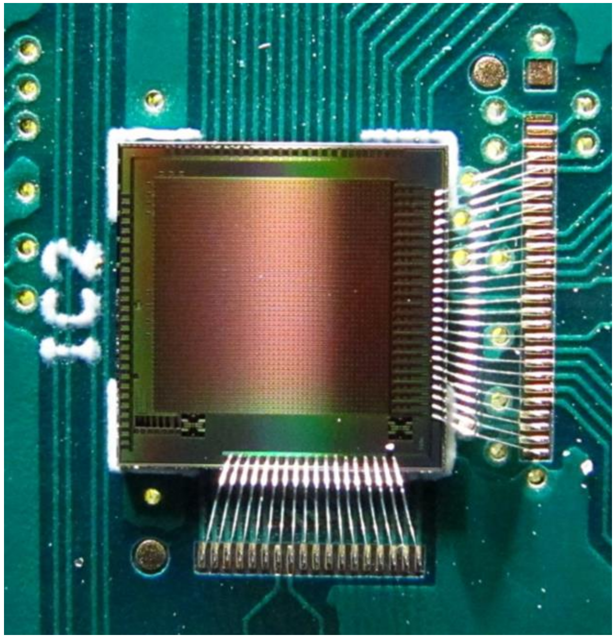
- Size reduced by a factor 5
- Power consumption per channel reduced by x50
    - low power preamp and CDS
    - power cycled off-pixel buffer
- Space for feedback capacitor limited,
    - amplifier range optimization
    - precharge of feedback capacitors



Dynamic gain switching response

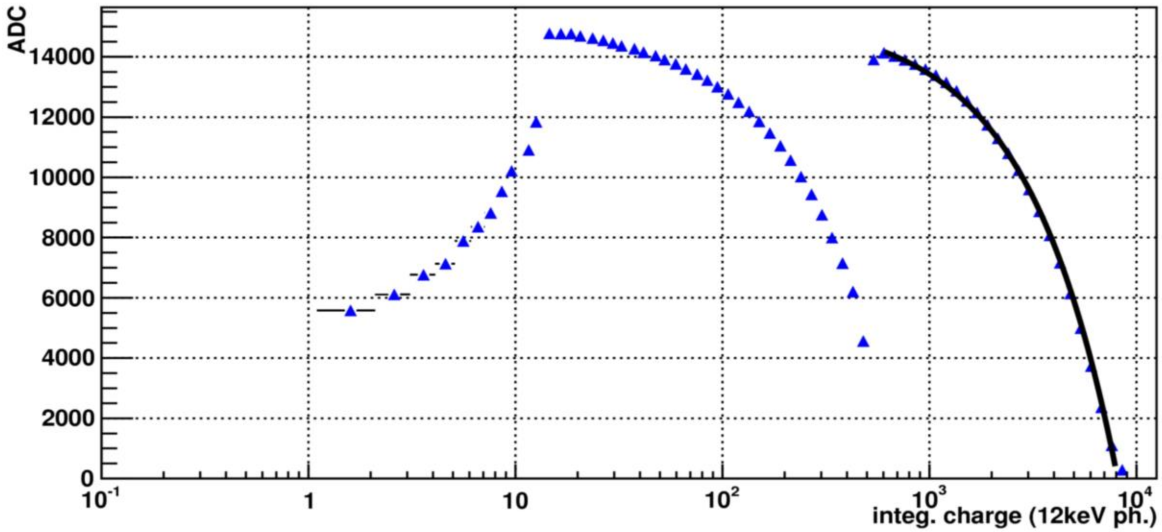


Prototype with 48 x 48 pixels



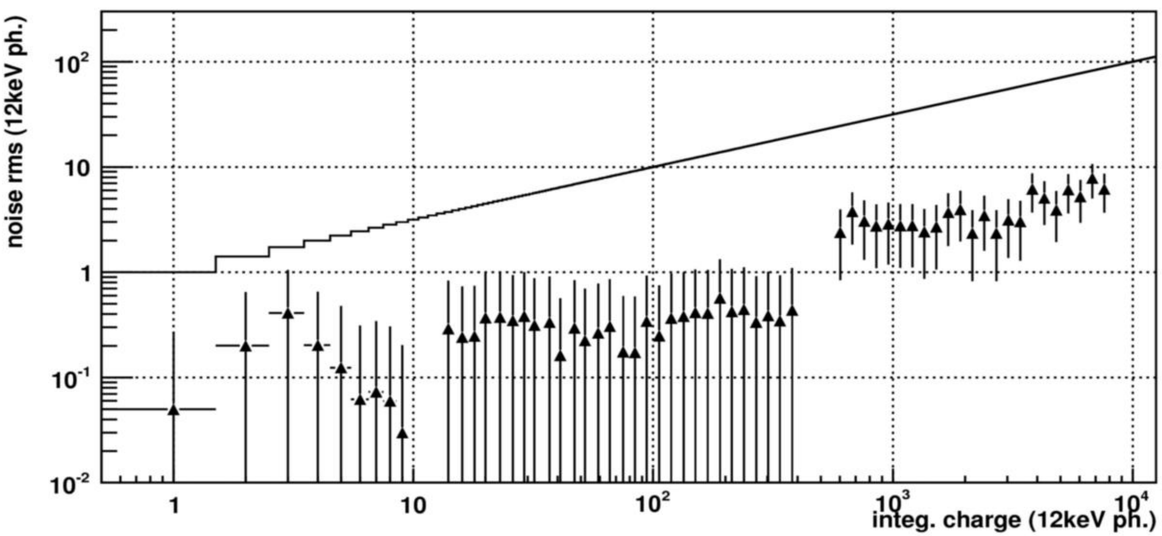
- measured with internal current source
- 1st gain switch at 25 ph. , 2nd at 600
- Linear up to >9500 12keV ph.
- Linearity err. <<1%

Noise with dynamic gain switching



Dynamic range

10^4 12 keV photons

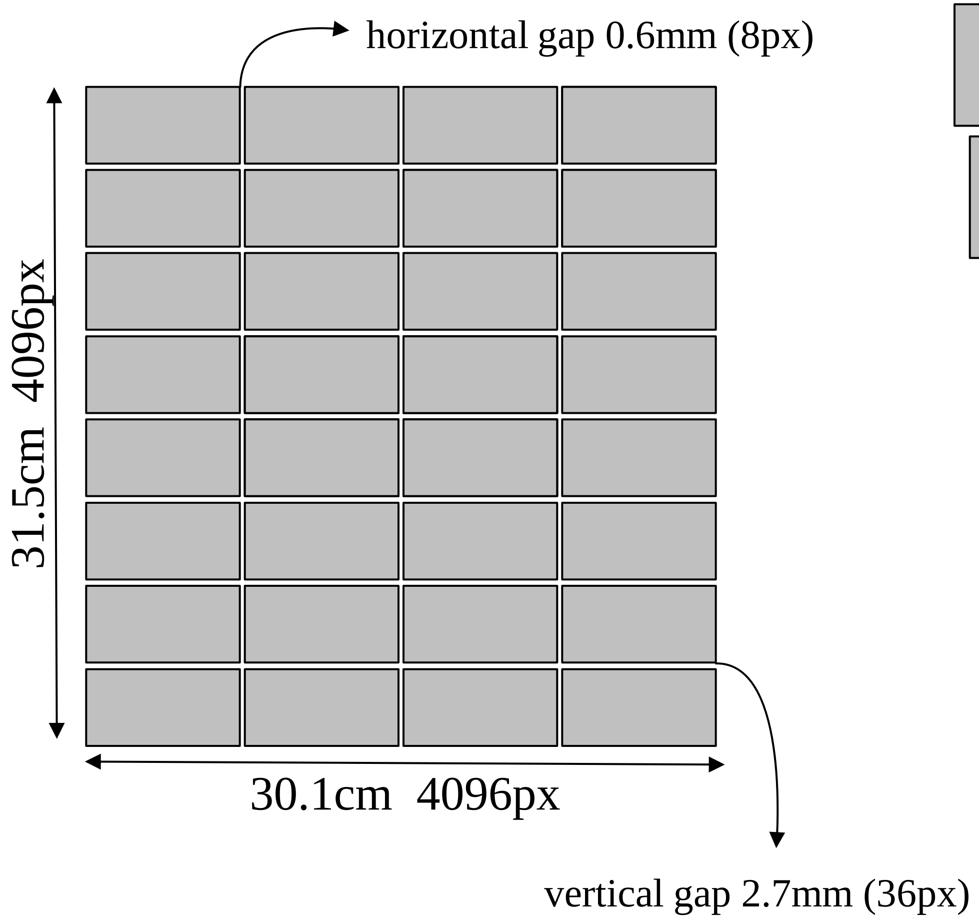


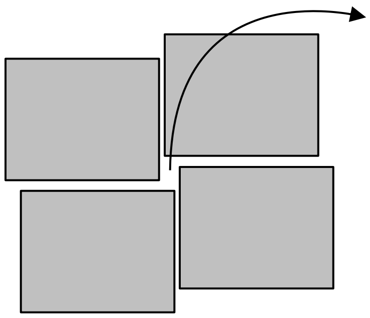
Noise always below

Poisson limit → Single photon counting

Data quality

From modules to systems





variable hole by moving quadrants (min. 1.2mm – max TBD) for the out of vacuum version

- 500k (one module), 1M (2 modules), 4M and 16M (ESA main instrument, 32 modules) systems are foreseen
- same geometry as the EIGER systems (gaps,etc..)
- compact (20-25cm) in the Z direction
- 16M @ 100Hz will generate ~1.6 GB/s

Conclusions/Benefits of Jungfrau

Timeline: full chip Mai, module end 2014, 4M detector mid 2015

Full chip and modules will be tested at Synchrotrons and XFELs

Small pixel size: 7

High frame rate: 2

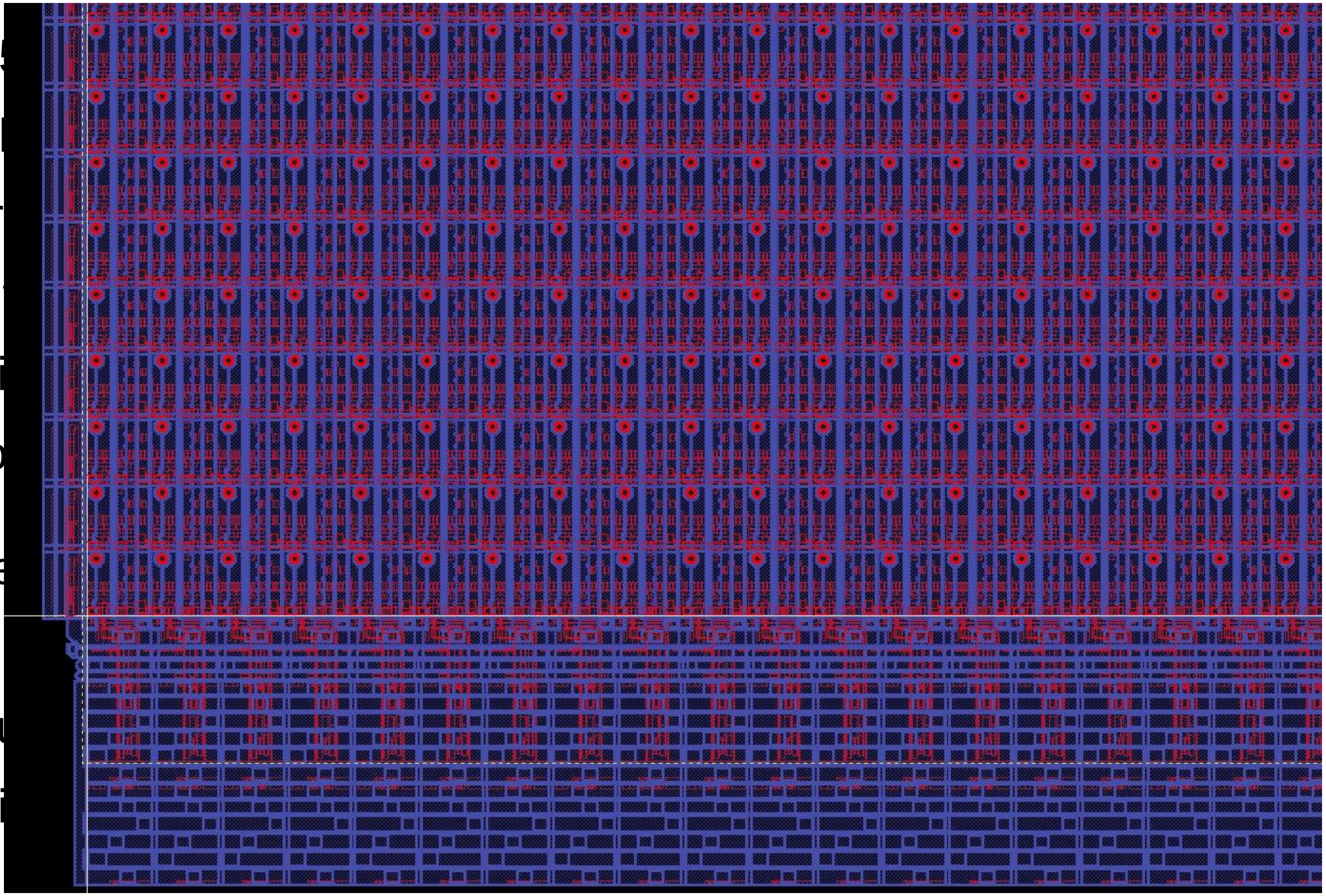
High linear count r

- Dead time
- Quasi infini
- First big no

Low noise of 120 e

- 3 keV with
- Less withou

  (sensor wi



High energies with scintillators

extremely good detector also for synchrotrons

The Mönch detector

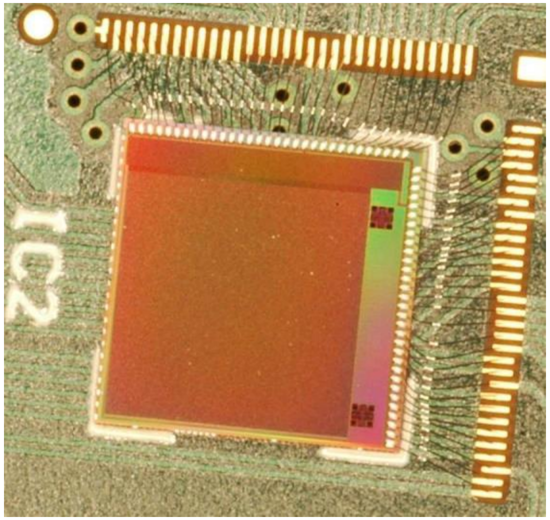
Micropixel with enhanced pOsition rEsolution usiNg CHarge integration

- 25 x 25 μm^2 pixel integrating detector

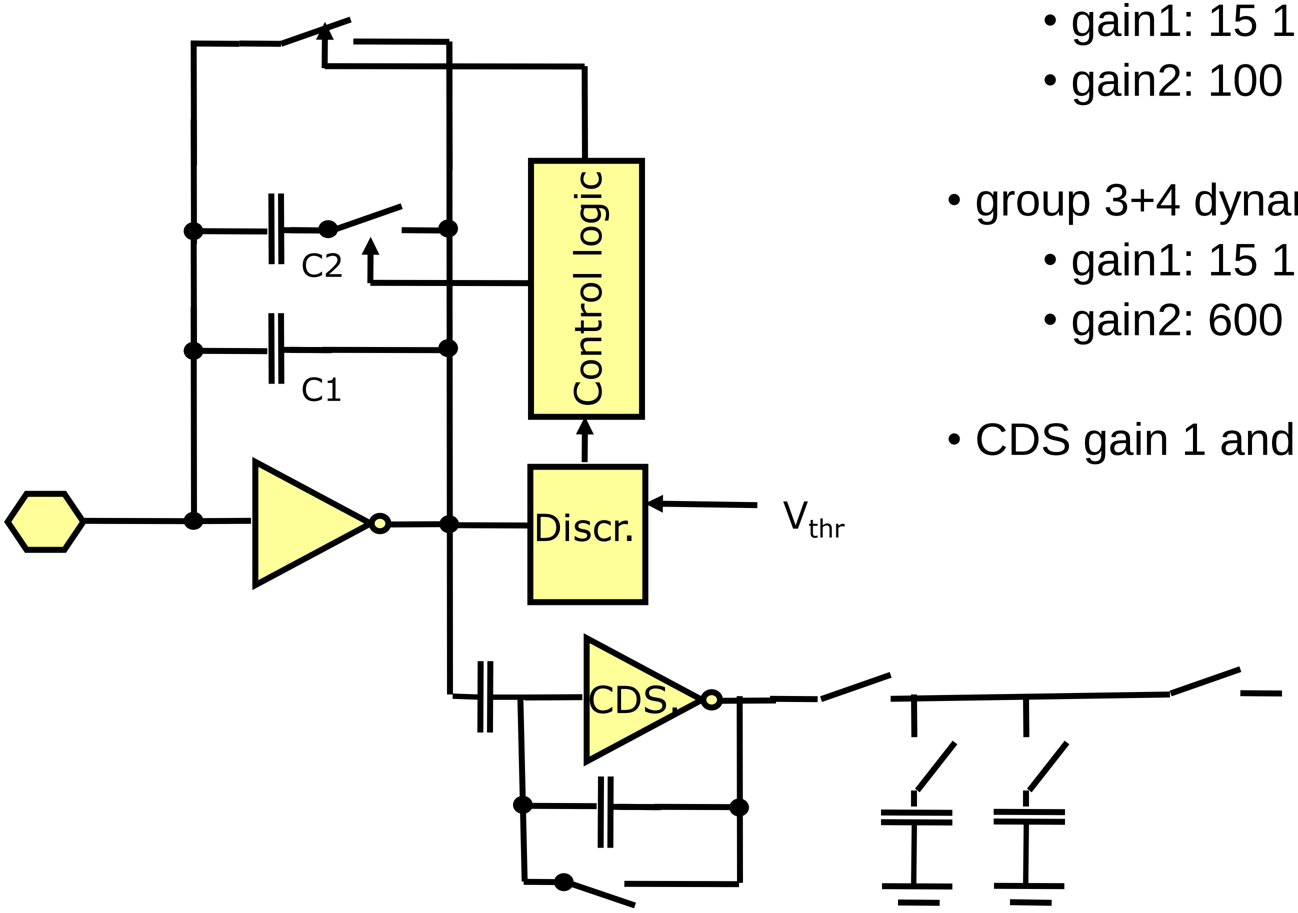
- currently research project (no big system defined yet)
- prototype with 160 x 160 pixels
- goal: low noise and high dynamic range thanks to the dynamic gain switching

- At single photon rates
- Interpolation gives 1 μm position resolution
- Spectral information is available by summing cluster charges

- Applications
- Tomography
- Laue Diffraction
- Imaging using X-ray tubes
  - Low rates, 1μm position resolution and energy resolution



Mönch pixel schematics

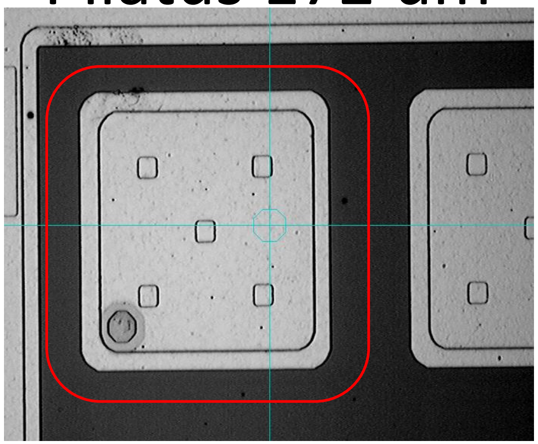


160 x 160 pixels divided into 4 groups:

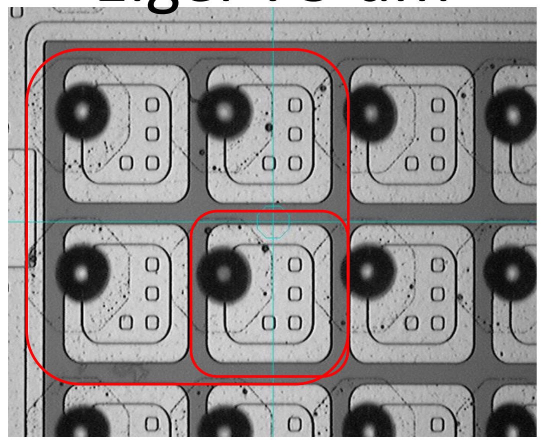
- group 1+2 fixed gains
  - gain1: 15 12keV photons
  - gain2: 100 12 keV photons
- group 3+4 dynamic gain switching
  - gain1: 15 12 keV photons
  - gain2: 600 12 keV photons
- CDS gain 1 and 4

The Mönch detector bump bonding

Pilatus 172 um

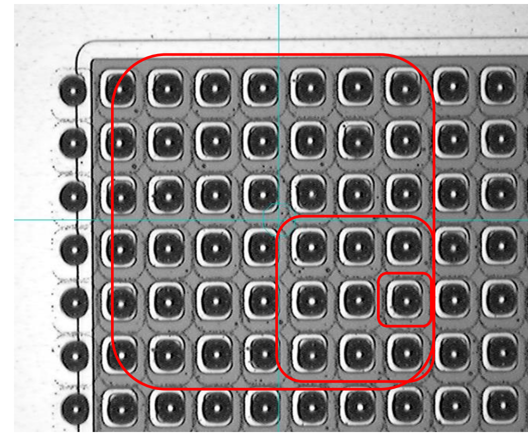


Eiger 75 um



x5.3

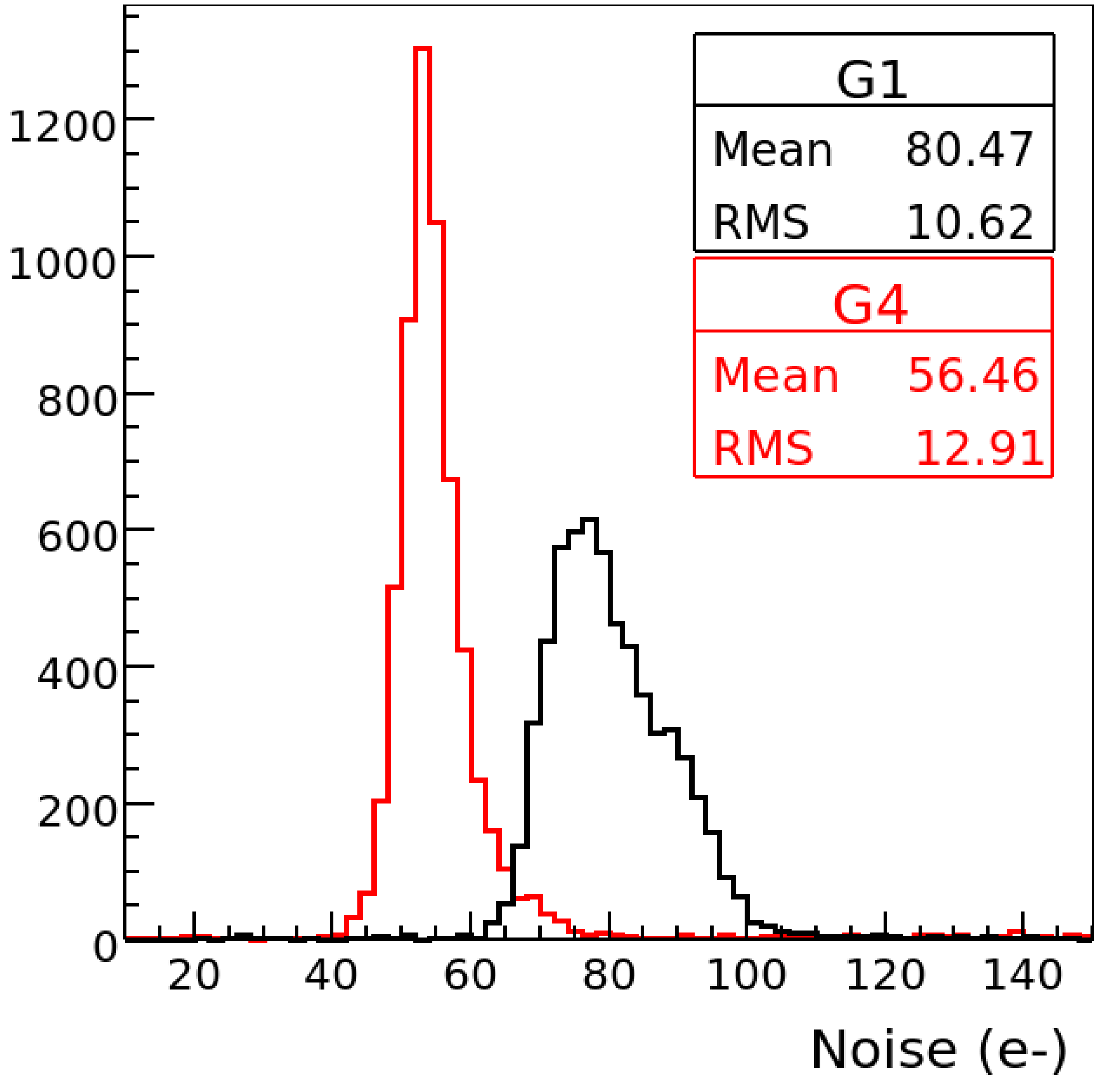
Mönch 25 um



x47

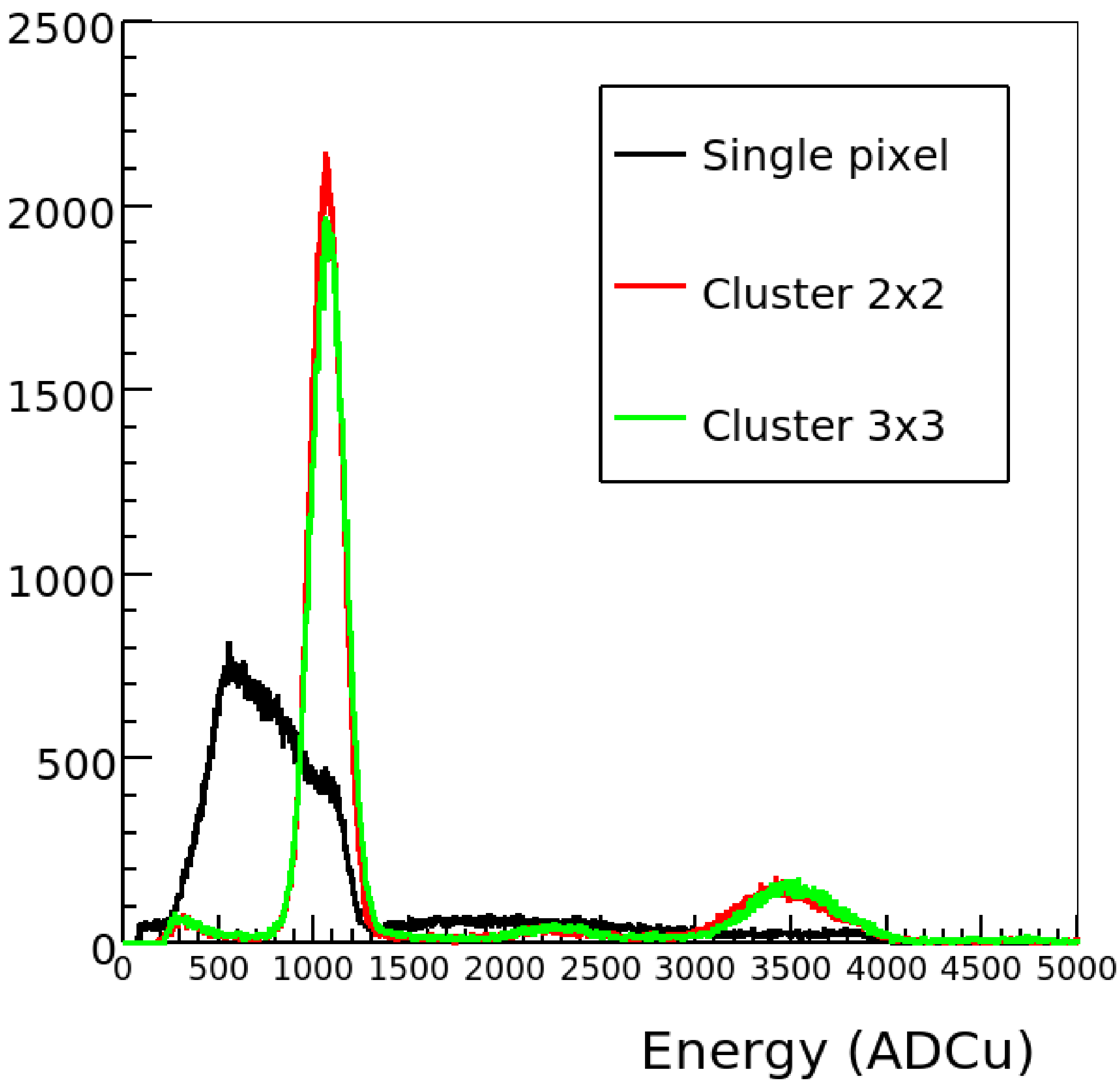
- Bump bonding of 25 micron pixel seems doable with PSI in-house process
- Need to work on photo lithography (optimization of masks)

Preliminary noise Distribution



Have reached 30 e^-

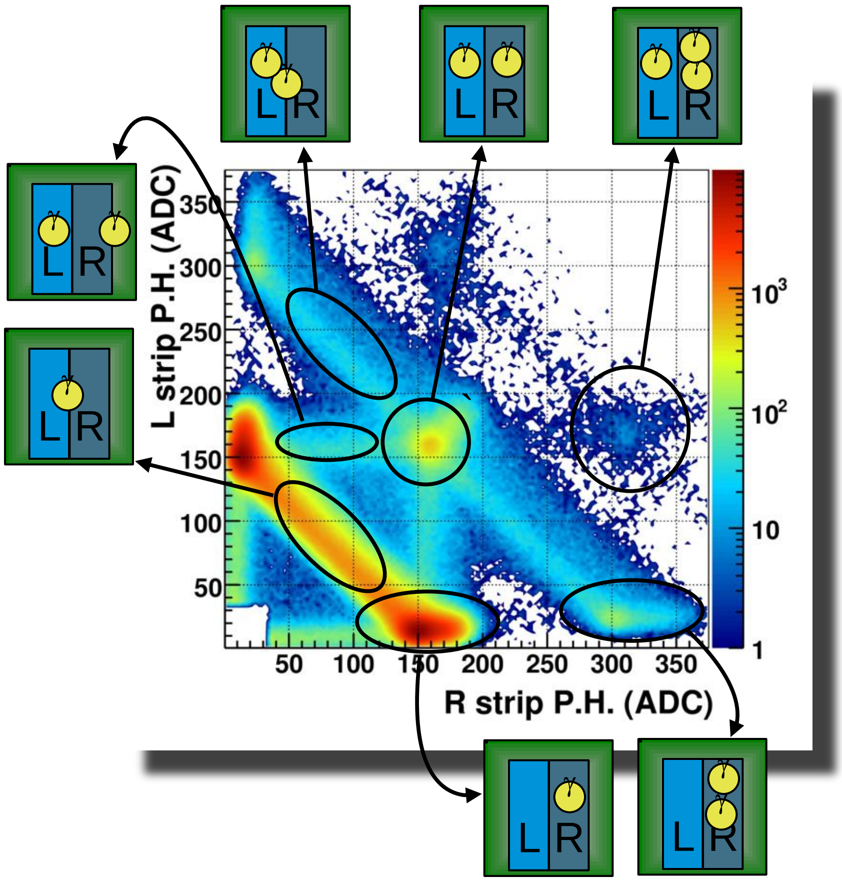
Cluster charge Distribution



PAUL SCHERRER INSTITUT

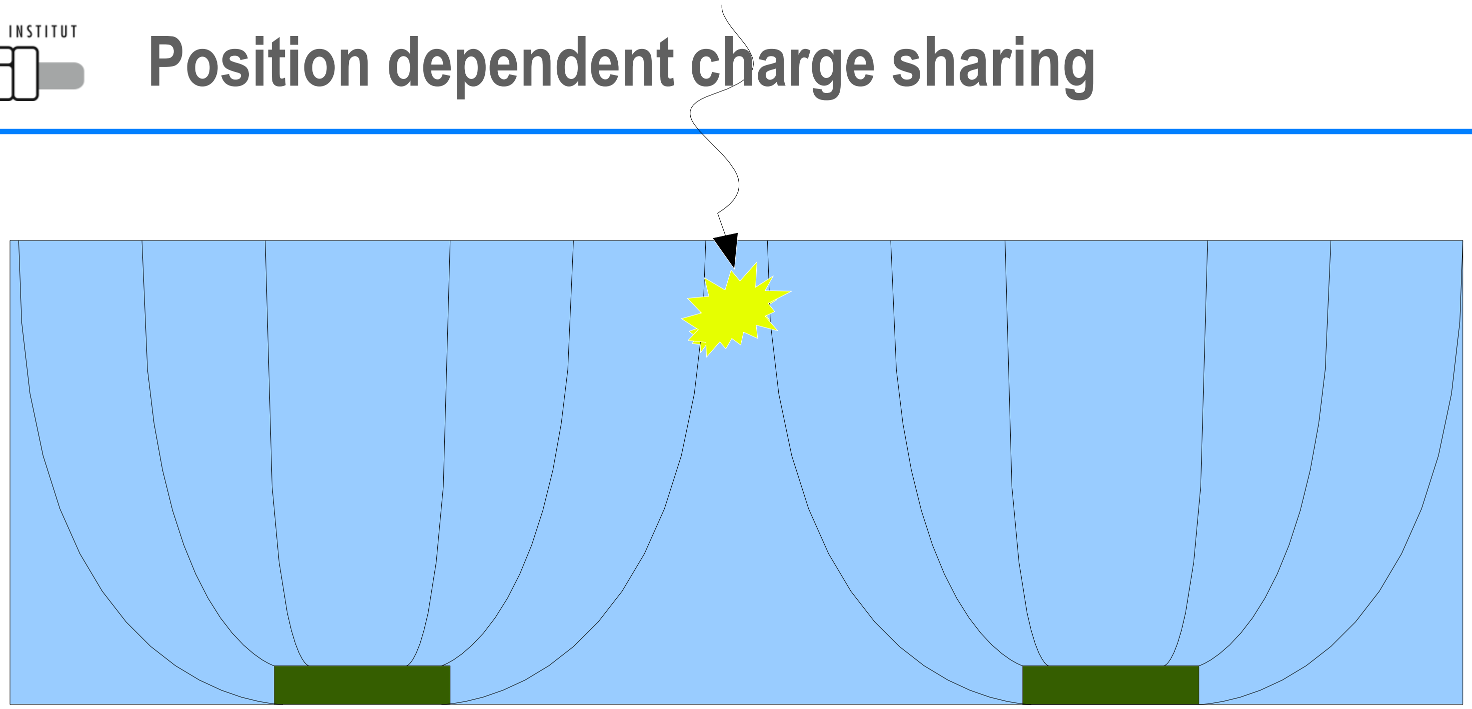
What can one do with charge integrating systems?

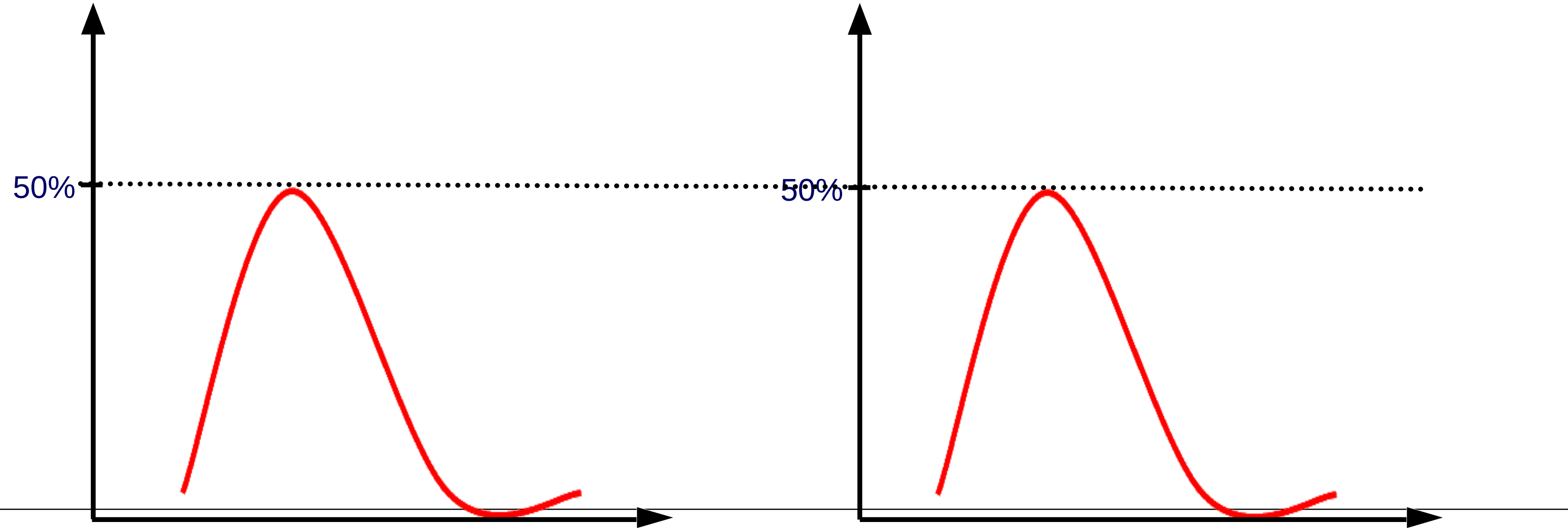
Charge integrating detectors: get full information



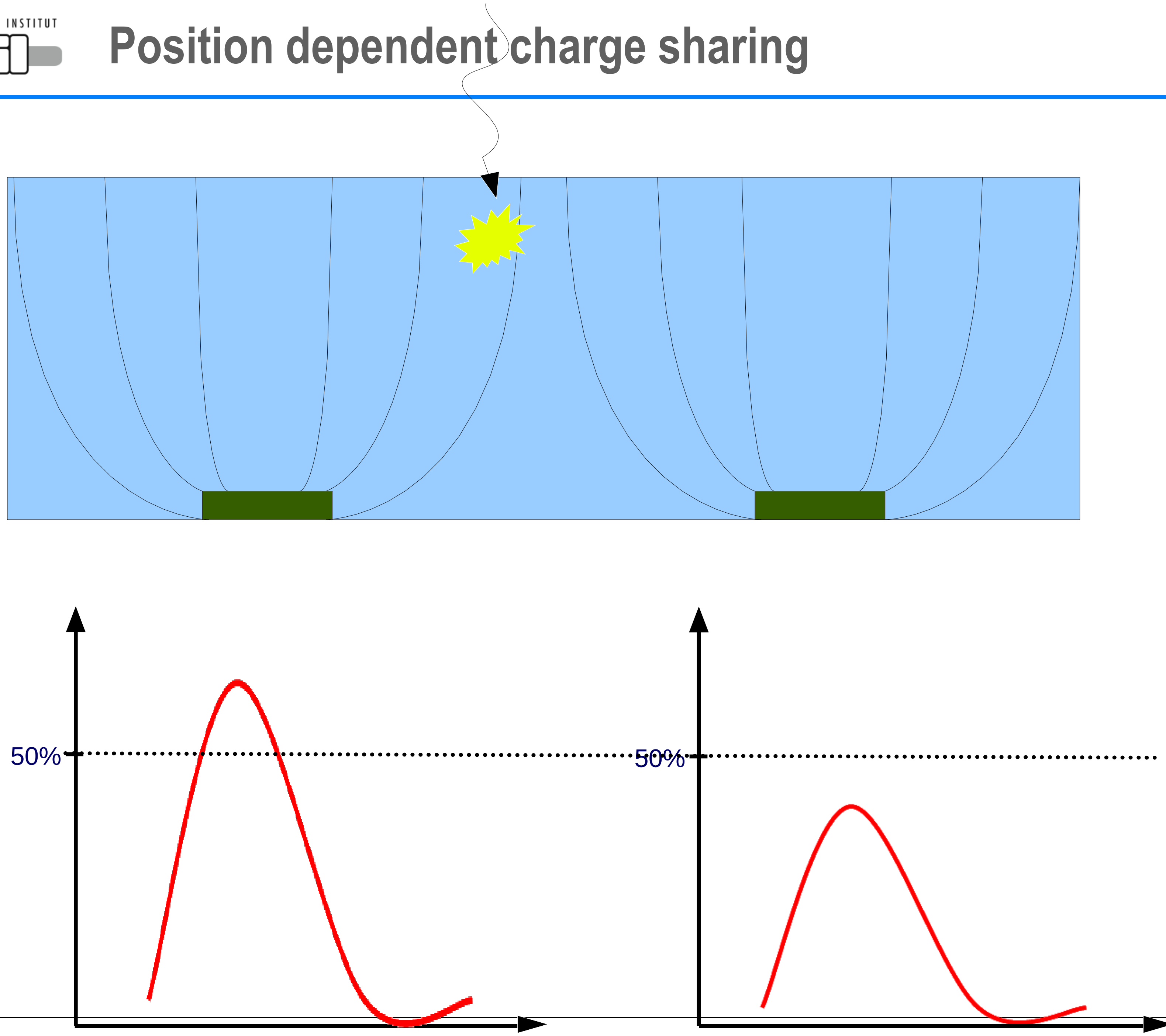
50 micron pitch, 25 keV

Position dependent charge sharing



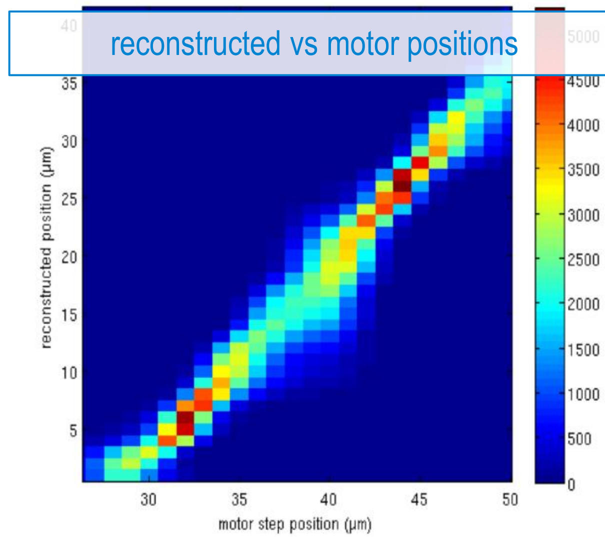


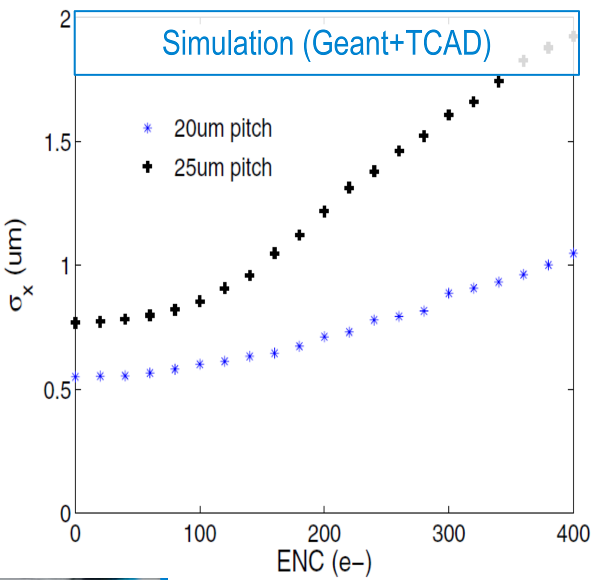
Position dependent charge sharing

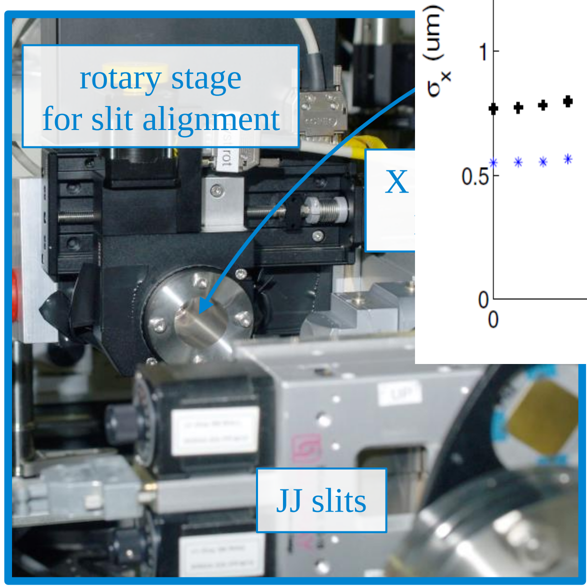


Gotthard: position interpolation

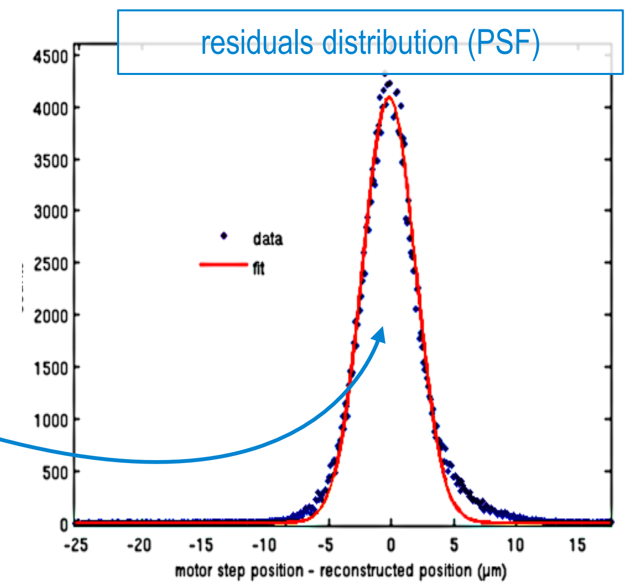
- To measure the spatial resolution a 2μm W slit has been scanned in 1μm steps in front of the strips
- slit parallel to strips
- Vertical beam size ~100μm
- Strip pitch 20μm, 15keV



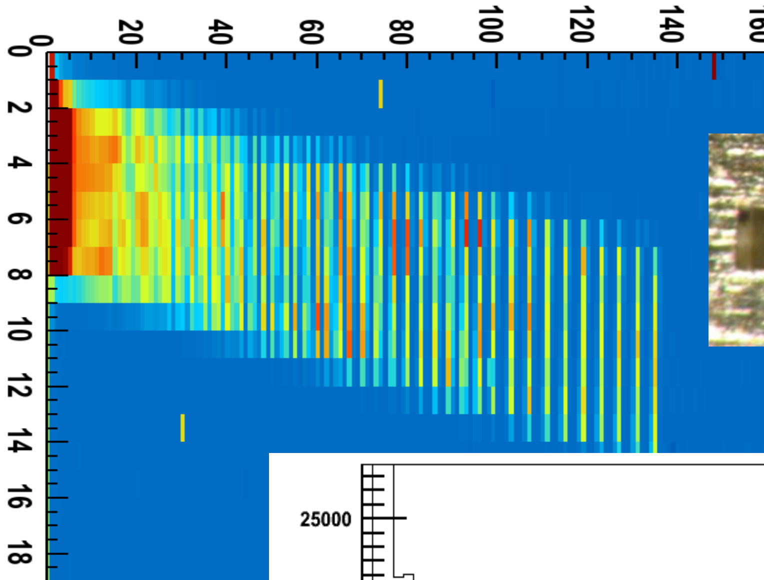


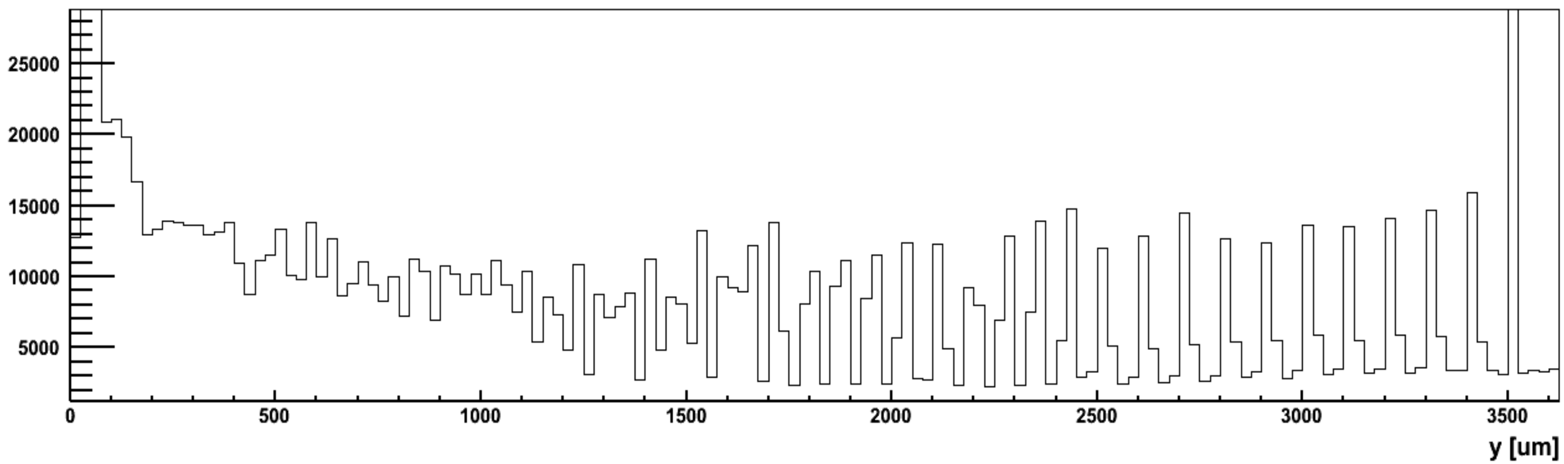


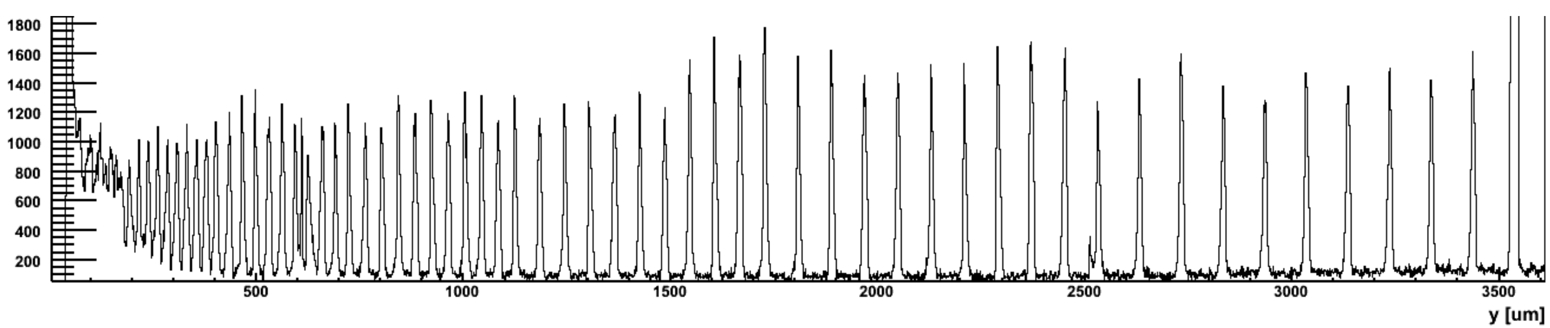
σ=1.8μm



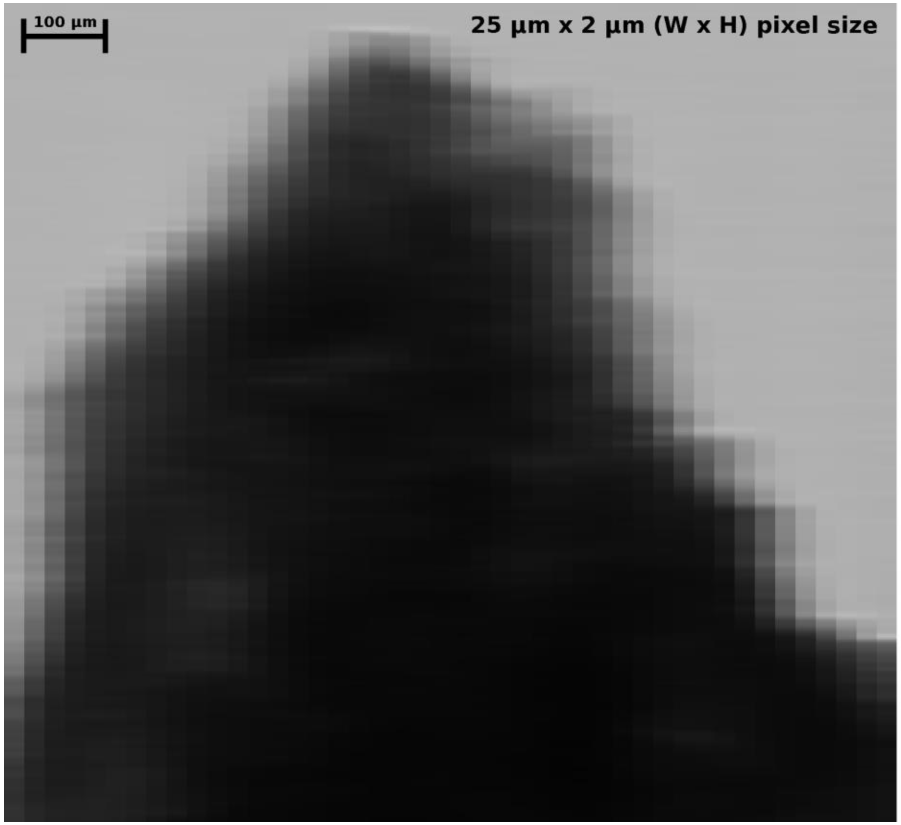
Mönch position interpolation

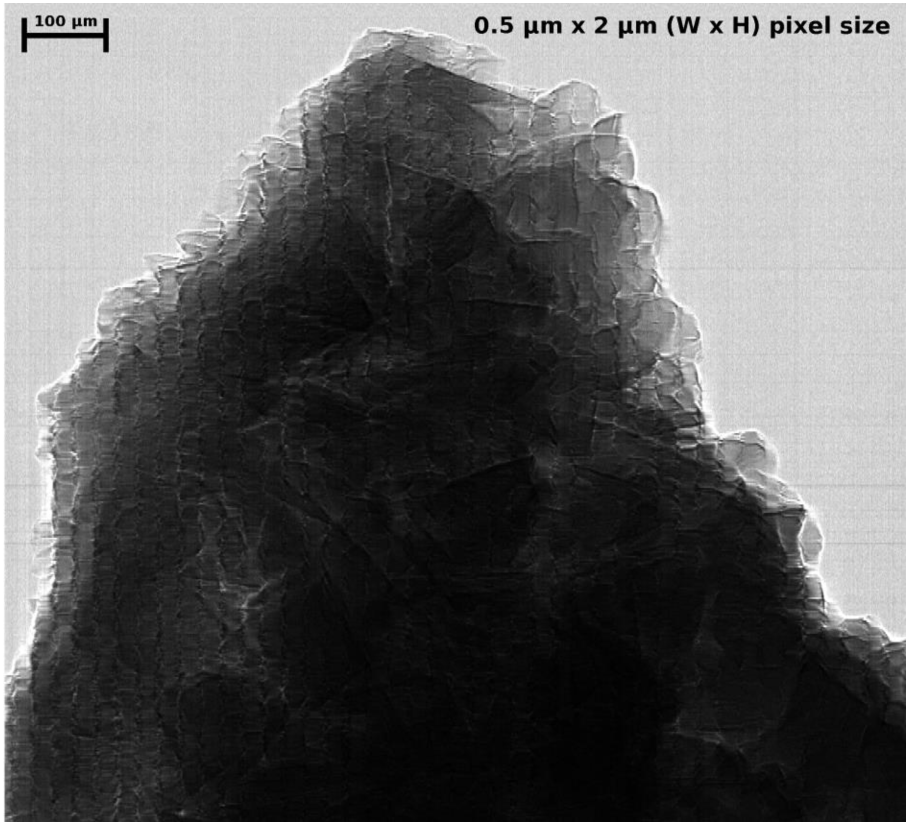






Using interpolation for a high resolution measurement





X-ray radiography of a kidney stone obtained at 15keV at the TOMCAT beamline of SLS using Gotthard with 25 micron strips and interpolation
(sample vertically scanned with a step size of 2 µm)

Conclusions

Mythen and Pilatus have become the standard detectors in their field

A lot of developments are currently going on in the Synchrotron field

Medipix systems will finally find their way into Synchrotrons

Eiger will advance many techniques which are today limited by Pilatus (scanning SAX, PX,..)

The developments for XFELs are also very important for Synchrotrons

Jungfrau will be the main detector for SwissFEL and probably similarly important for synchrotrons

- almost no count rate limitations

Percival will be a big step towards low energies, will replace many of todays CCDs

Low energy (> 400eV) hybrid pixel detectors are around the corner

Hybrid pixel detectors with small 25 μm pixels are possible

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

Wir schaffen Wissen – heute für morgen

Thank you!