



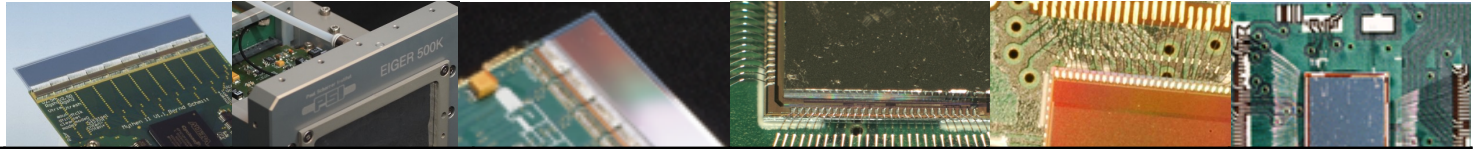
Gemma Tinti for the Swiss Light Source Detector Group

EIGER: high frame rate pixel detector for synchrotron and electron microscopy applications

PIXEL 2018

2018/12/11

SLS-detector group detectors



	MYTHEN II&III	EIGER	GOTTHARD I & II	JUNGFRAU	MÖNCH	AGIPD
1D/2D	Strip	Pixel	Strip	Pixel	Pixel	Pixel
Working Mechanism	Photon Counting	Photon Counting	Charge Integrating	Charge Integrating	Charge Integrating	Charge Integrating
Strip/Pixel size [μm]	50	75×75	25/50	75×75	25×25	200×200

Poster X.Shi

R. Dinapoli
on Thursday

PSI EIGER: high frame rate pixel detector:

1) synchrotron

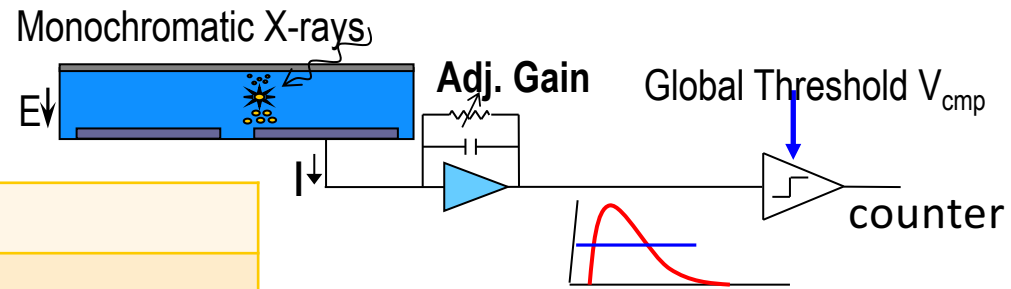
2) electron microscopy

EIGER: ASIC characteristics

Single photon counter

Pixel size	75 x 75 μm^2
Pixel matrix	256 x 256
Counter	4/8/12 bit
Frame rate	23/12/8 kHz
Data rate	6 Gb/s
Threshold adj. bits	6
Threshold dispersion (after trimming)	$<10\text{ e}^-$
Noise	100-200* e^- RMS
Rate capabilities (10% deviation)*	500 k counts/pixel/s \rightarrow 90 Mphotons/ mm^2/s
Dead time	4 μs (with buffering)

*Depending on gain setting



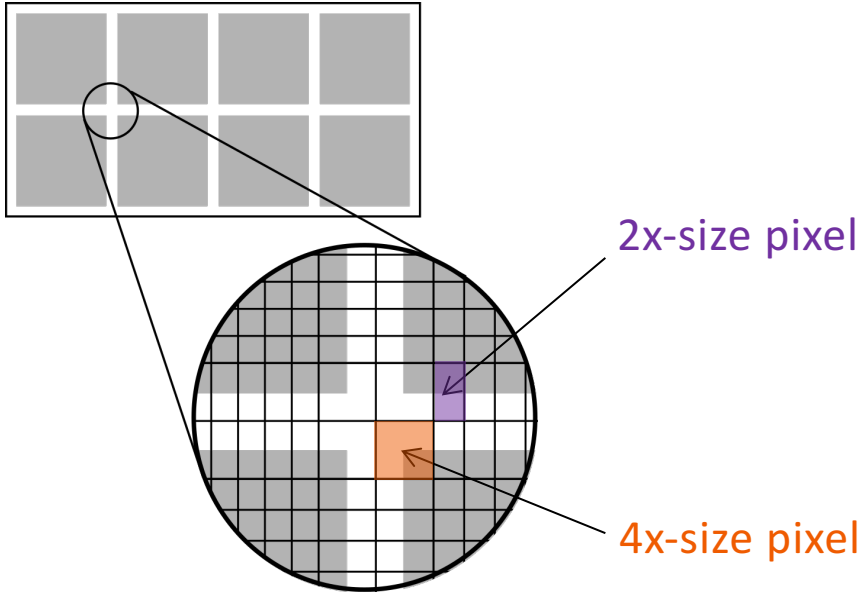
Single photon counting detector



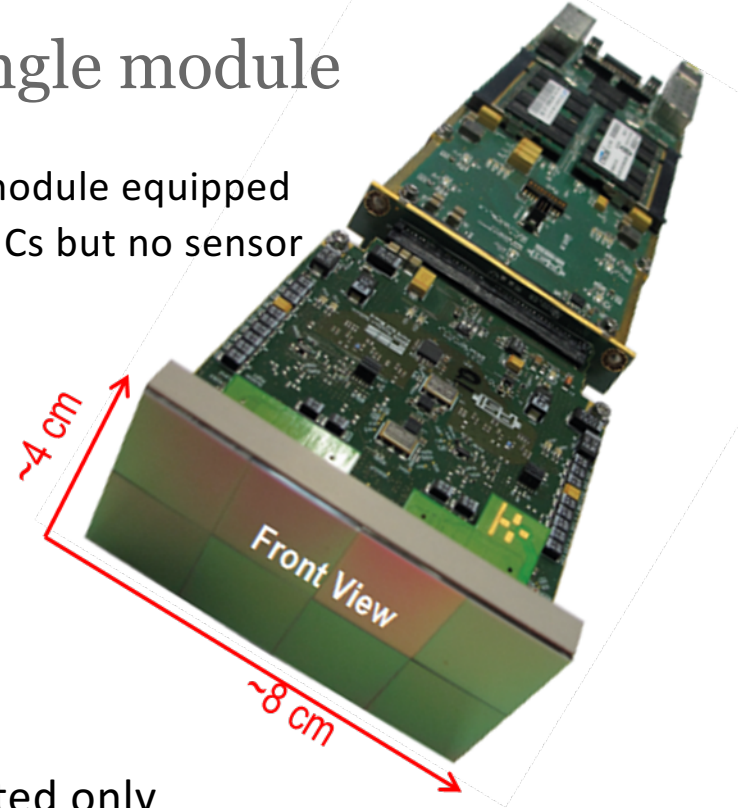
EIGER: 500k pixel single module

- 2x4 chips
- Single 4x8 cm² silicon sensor
- Sensor thickness 320 μm

No dead area in a single module!

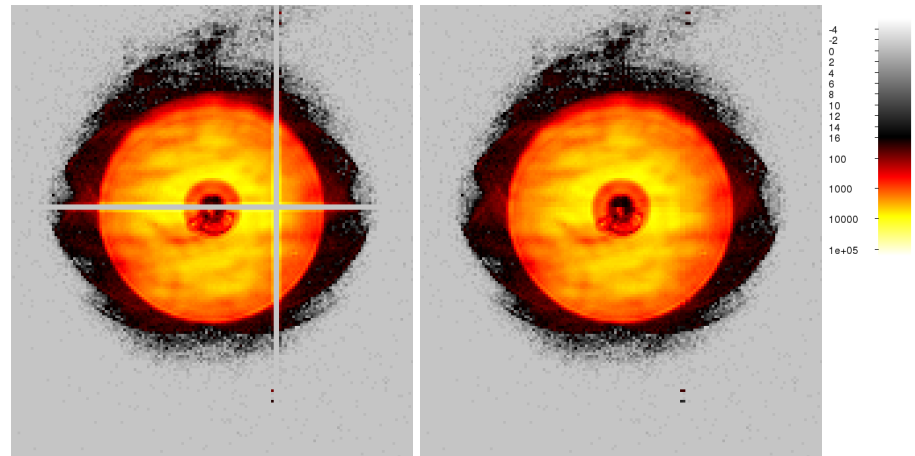


EIGER module equipped with ASICs but no sensor



Corrected only
for geometry

interpolated

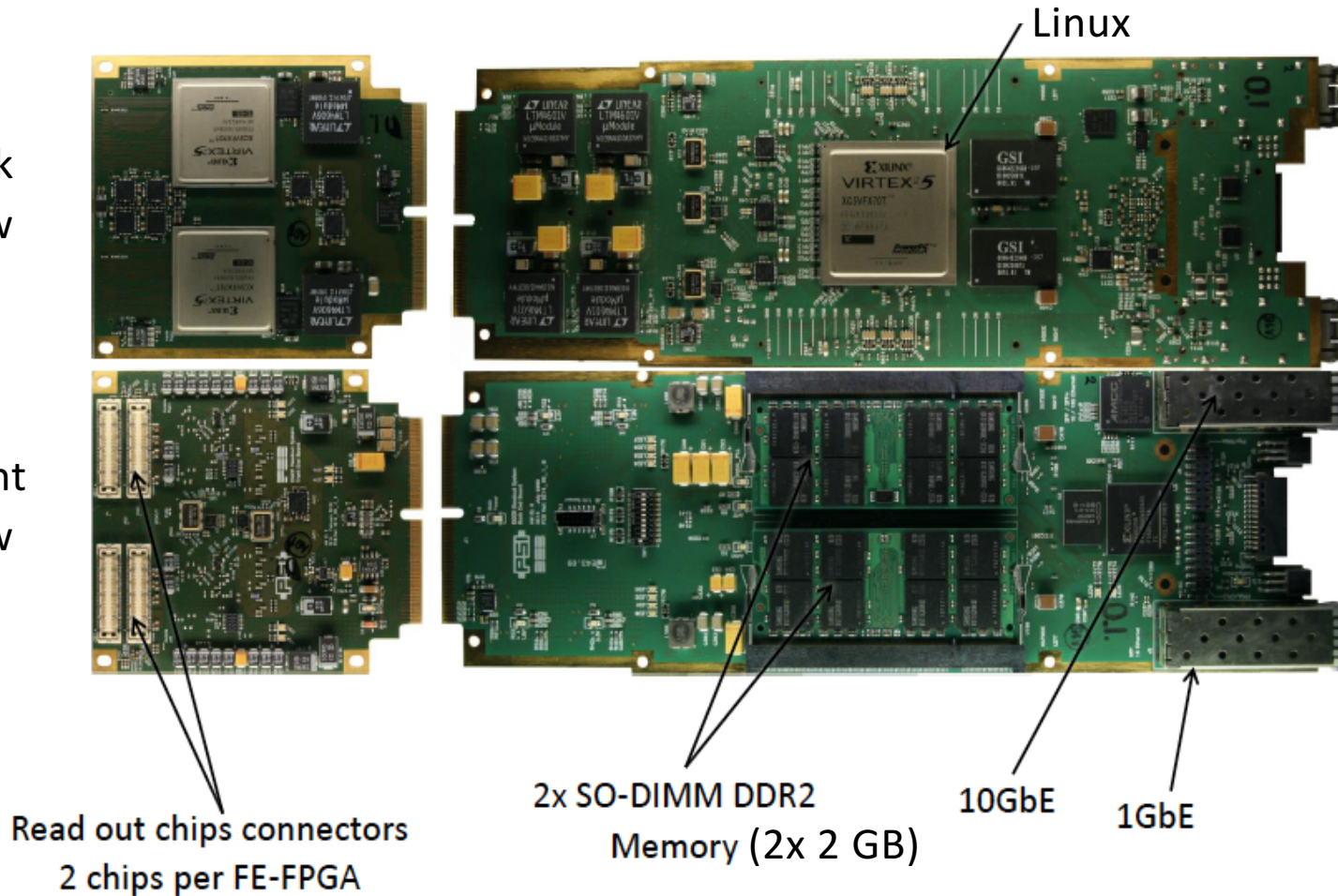


EIGER: Readout System

Back
view

4 chips

Front
view



- Image summation 12 → 32 bit
- Data buffering
→ preserve high frame rate capability
- Possibility to apply corrections

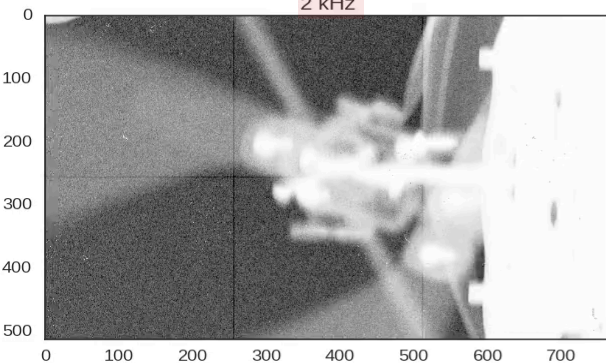
Half module is basic readout unit.
A **module** is readout as **2 half modules**
(20 Gb/s)

Very high frame rate detector

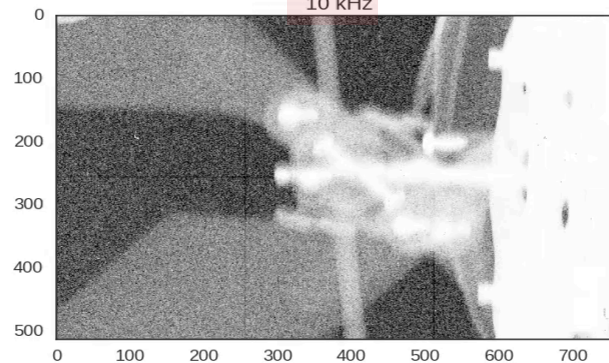
Dynamic range (bit)	Buffered max frame rate (kHz)	Data buffered (# images)
4	22	30000
8	11	15000
12	6	7600
32	2	Online sum



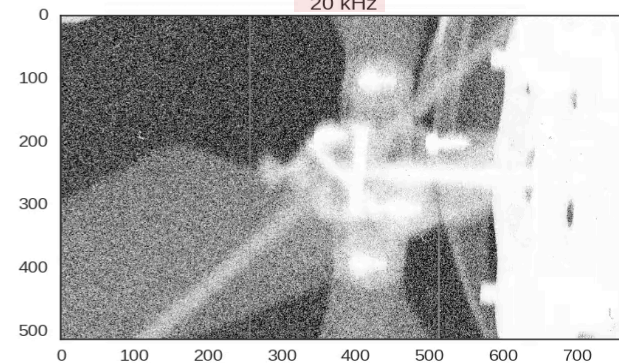
2 kHz



10 kHz

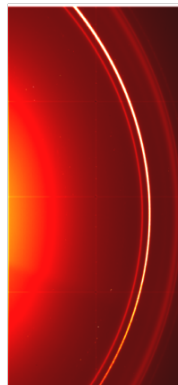
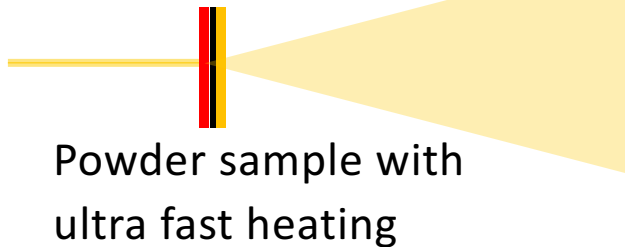


20 kHz

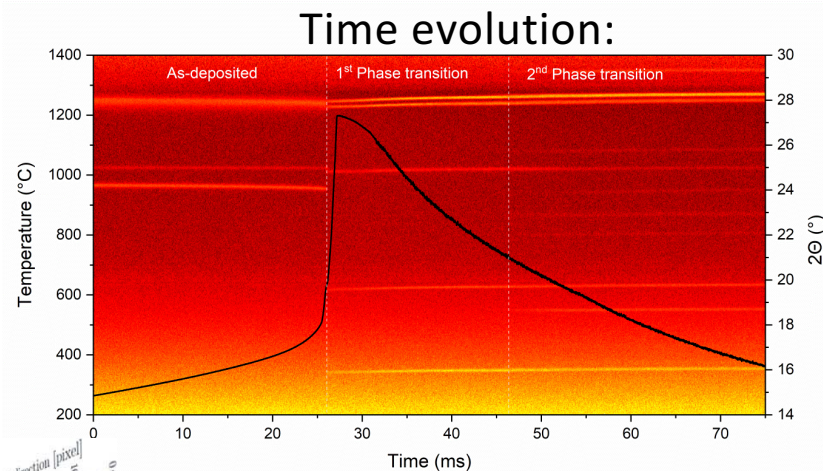


Displayed normalized to 30 imgs/s

K. Woll's group (KIT)

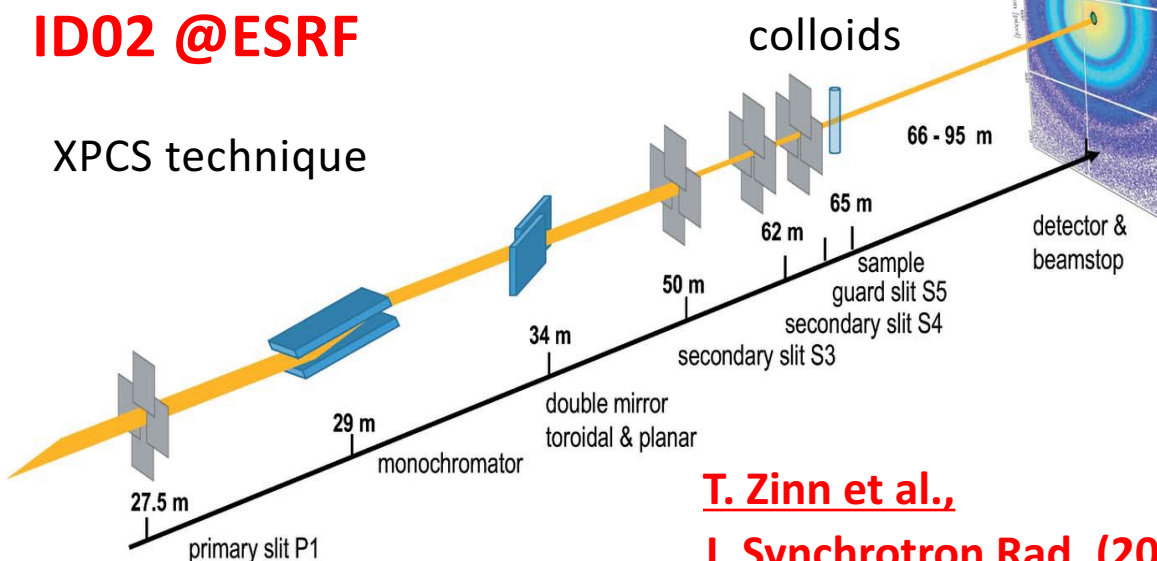


MS + microXAS beamlines @ SLS



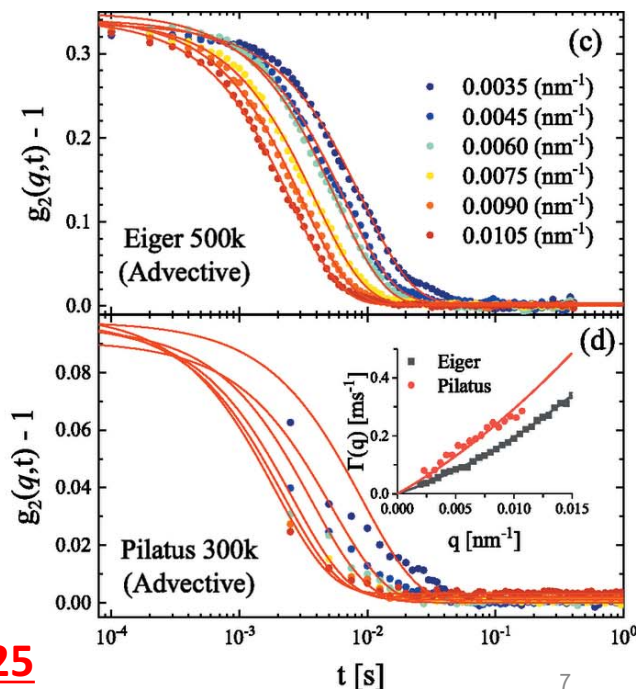
ID02 @ESRF

XPCS technique



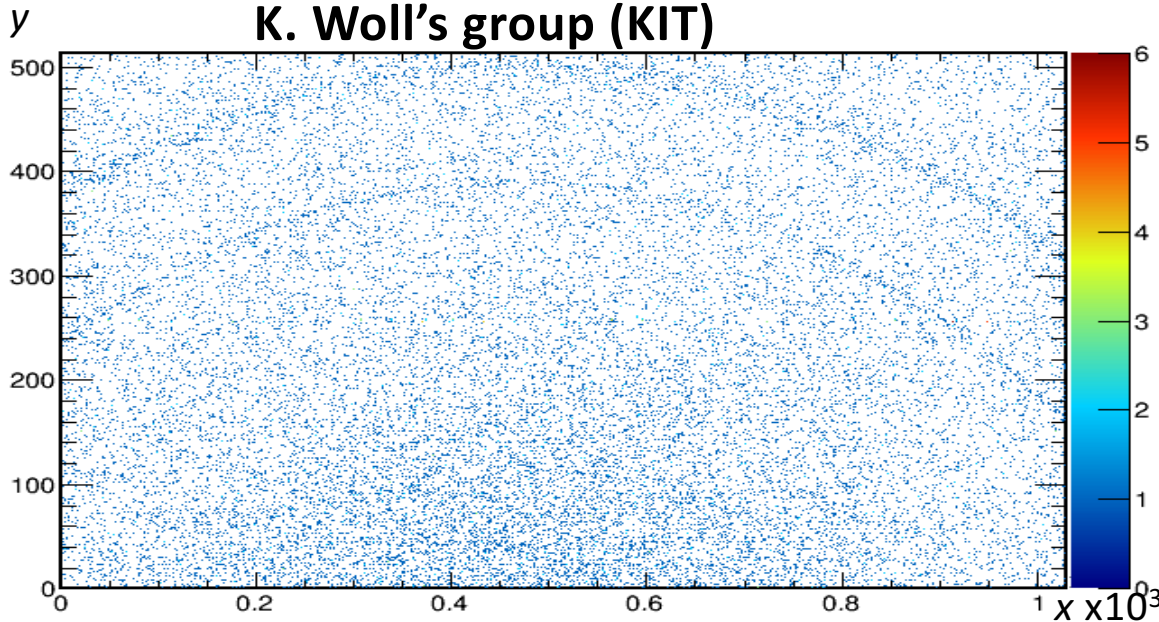
T. Zinn et al.,

J. Synchrotron Rad. (2018). 25



Detector occupancy **POWDER DIFFRACTION**

K. Woll's group (KIT)

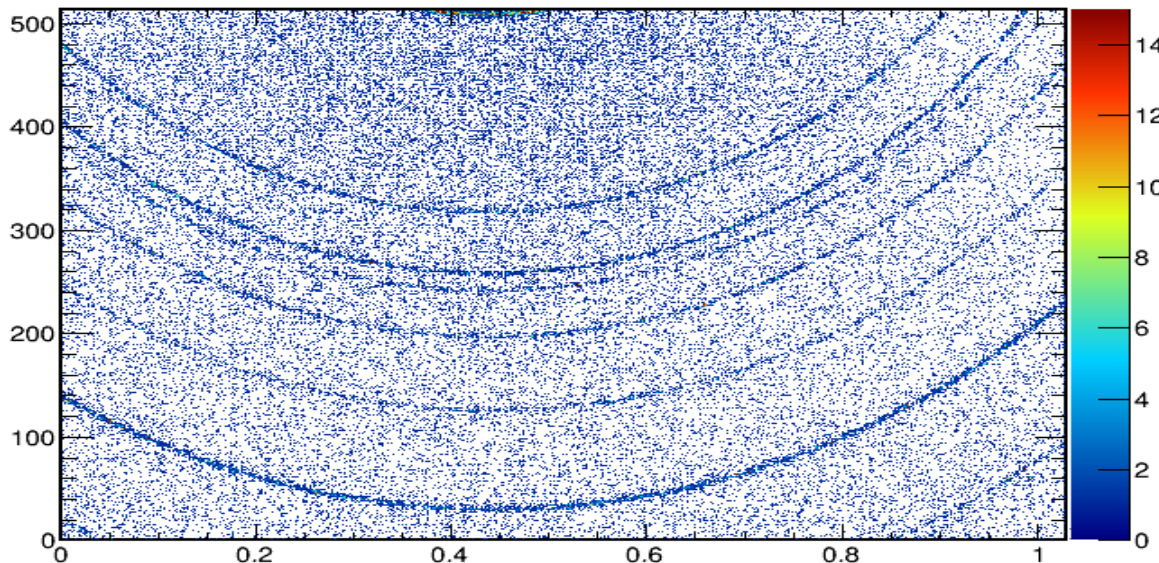


Diffraction pattern recorded at 20kHz (45 μ s exposure + 5 μ s)

Occupancy here defined as : # pixels with hits/# pixels

Occupancy ~ 4%

With optimization of the sample thickness it is expected to gain a factor 5-10 in hits



Diffraction recorded at 20kHz

Occupancy ~11%

Obtained from calibration sample: more representative occupancy

Online compression studies

Dynamic range (bit)	Continuous frame rate @10 Gb (kHz)	Buffered max frame rate (kHz)	Data buffered (images)
4	10.2	22	30000

2x10 GbE links/module are bottle neck

We need compression factor **x2.2** to go continuous

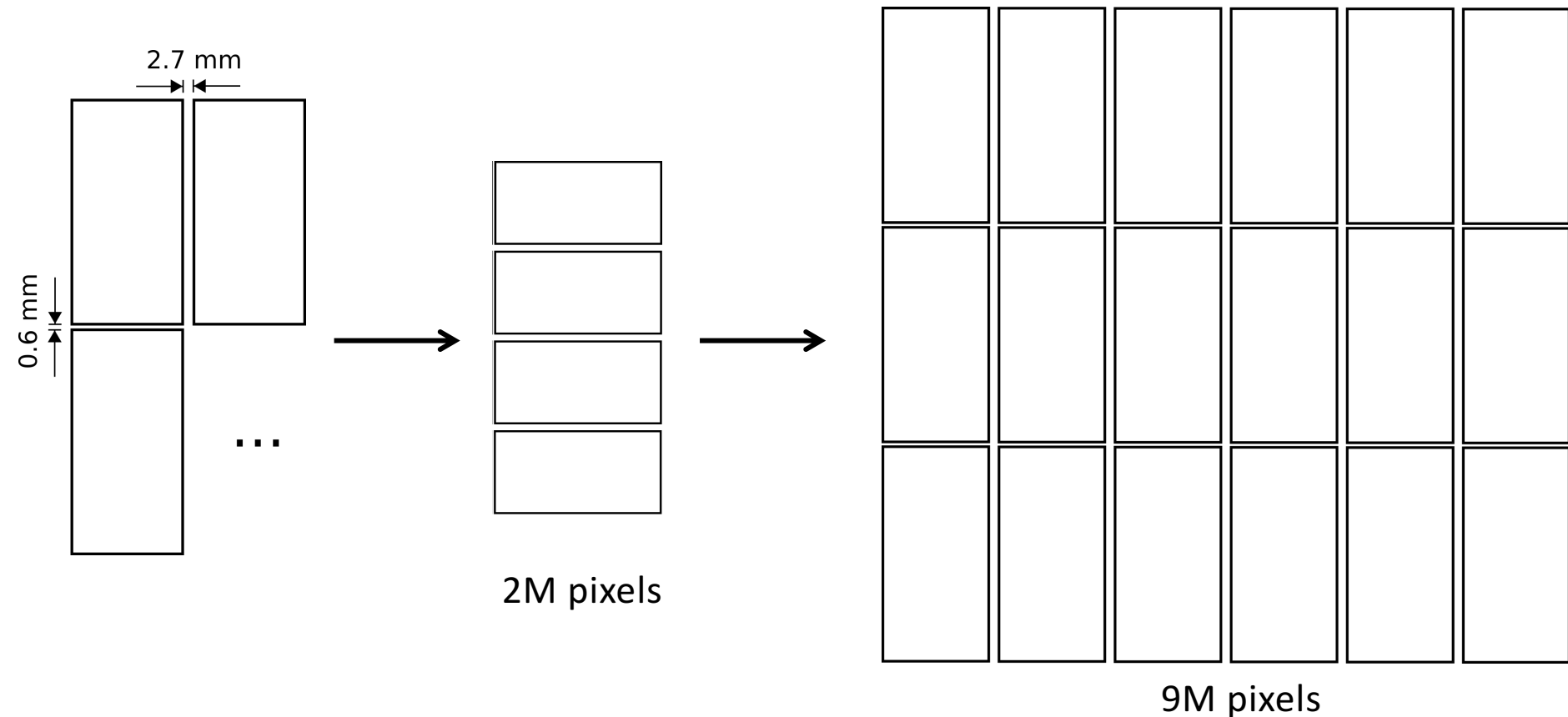
- **HIT BASED READOUT:** only if OCCUPANCY < 14% module
 - Send address and value only of pixel with hits
 - Typically we have a few % occupancy
- **ZERO COMPRESSION:** instead of writing all the half-bytes that are zeros, write a flag and #half-bytes that are zero:
 - 0000 0000 0000 0000 0001 -> 1111 0100 0001
 - Real 1111-> 1110, Real 1110-> 1111 0001

This study refers only to powder diffraction data

Dataset	Hit based readout	Zero compression	Reference GZIP, level 2 offline
Low occupancy	3.2	5.9	11.5 in 8 bit
High occupancy	1.4	3.4	6.9 in 8 bit

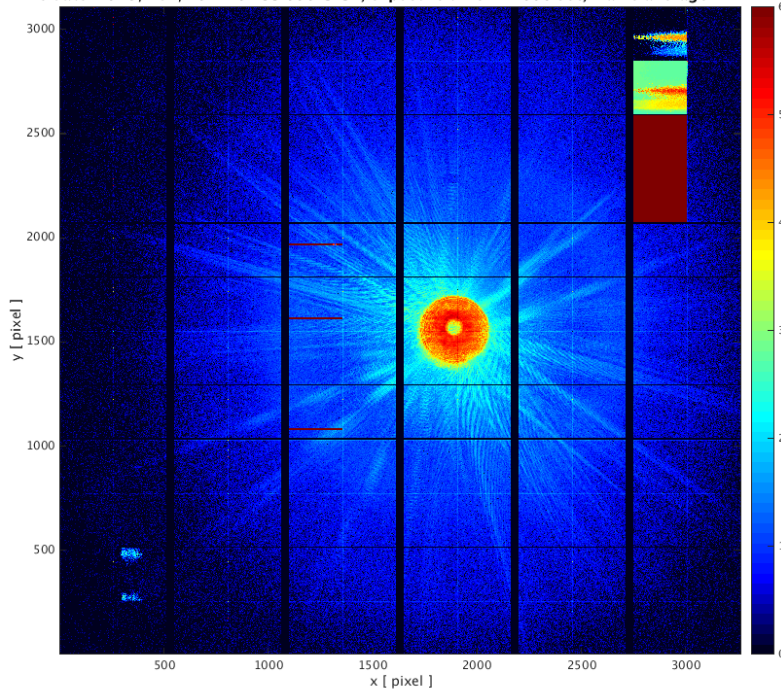
EIGER: Larger systems

- Modules can be tiled to large area detectors
- Due to the parallel design there is no penalty in performance when moving from a single module to multi module systems

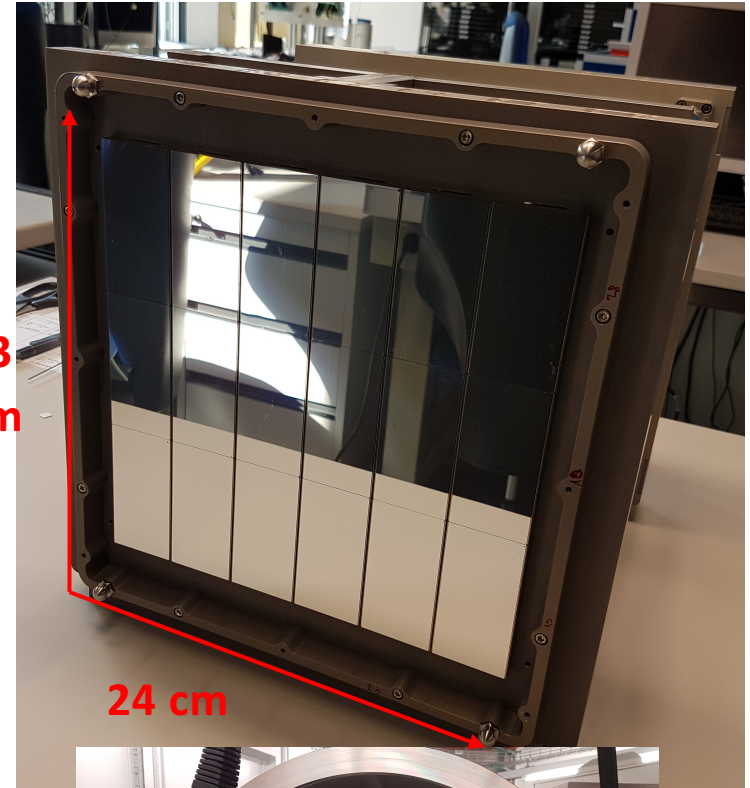


PSI Eiger 1.5 and 9M detectors for cSAXS beamline

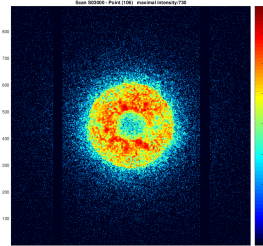
/sls/X12SA/data/x12saop/Data10/Eiger9M/20161110/run_00006_00001.cbf (log.) 14:21:58
file date: 2016/Nov/10 14:07:53.000 CEST, exposure time = 1.000 sec, frame average



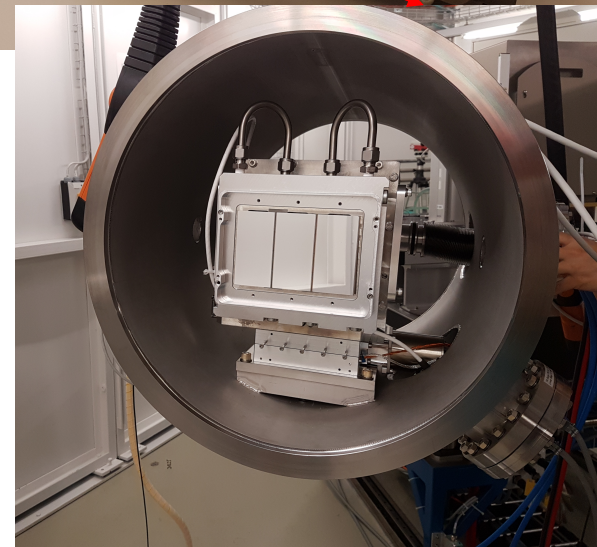
18 modules



- 1.5 M in user operation since April 2018
- 9M foreseen user operation Feb 2019



3 modules



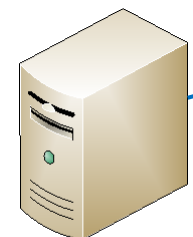
Detector integration concept

Detector: 18 modules

36x10GbE



TCP
x36



Control PC
beamline

UDP
stream
x36

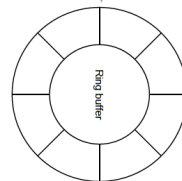


Receiver

x72
receivers
on a server

UDP stream

Receiver



Limited to
2GB/s

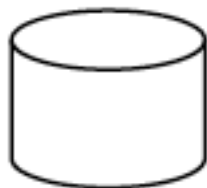
zmq

writer

data (metadata added from client)

Storage
(GPFS)

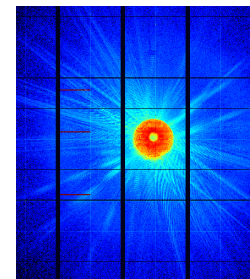
Limited to 1.6GB/s
currently



infiniband

38 MB/image

PREVIEW



- Independent half modules
- Parallel data processing/transmission
- 9 M with 36 half modules (18 modules) 360Gb/s

Phase I: User operation at minimum 25 Hz for 32-bit starting from Feb 2019

Expected: 42 Hz, 1.6GB/s. The detector can send out up to 45 GB/s

EIGER: high frame rate pixel detector:

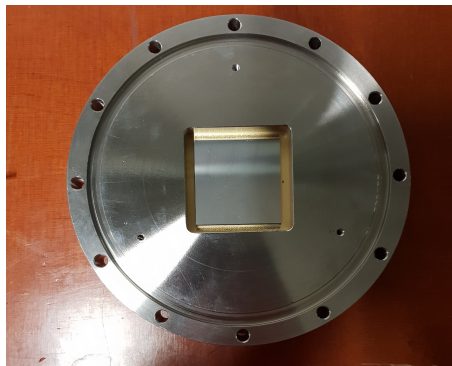
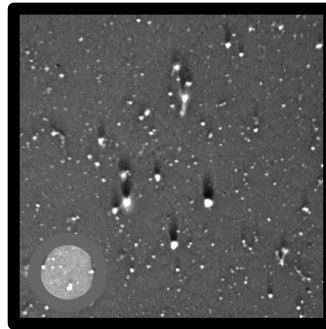
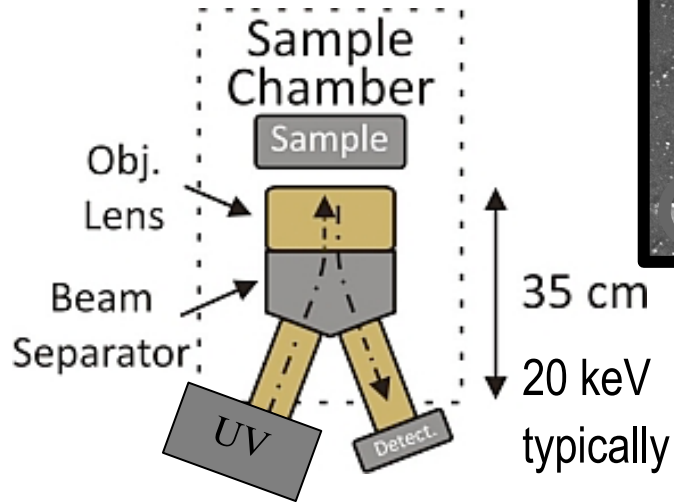
1) synchrotron

2) electron microscopy

EIGER in electron microscopy

- **PEEM - Photo Emission Electron Microscopy - Imaging**

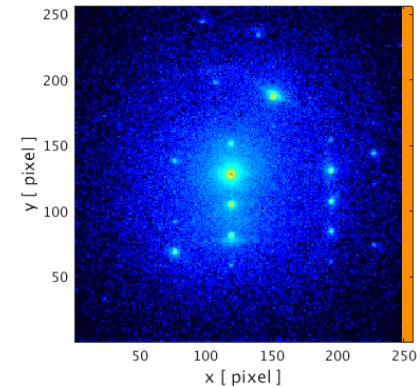
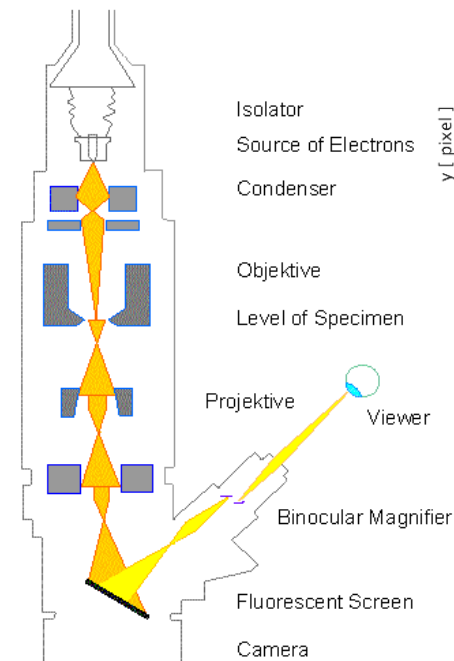
- ELMITEC, SIM Beamline SLS
- 20keV Electrons



- Quad:
active area
4x4 cm²
- In
vacuum

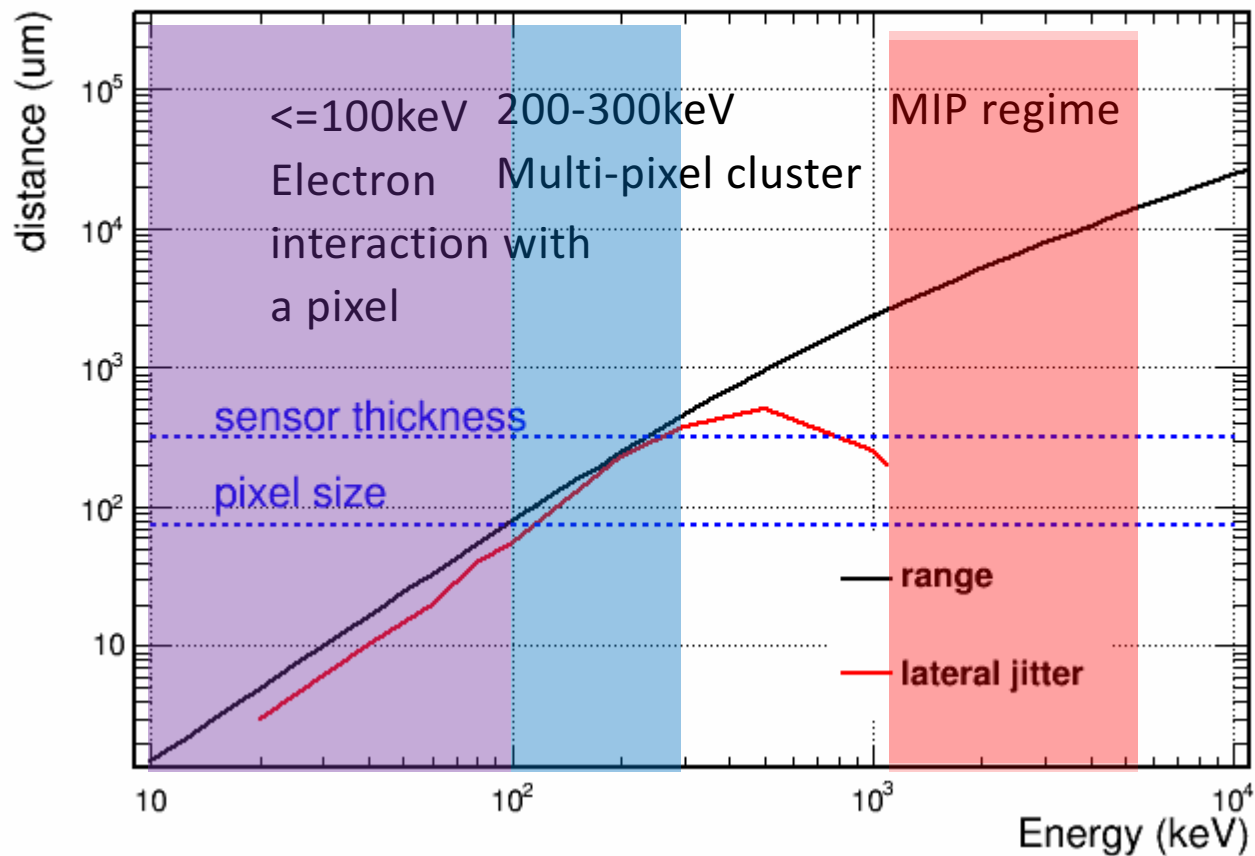
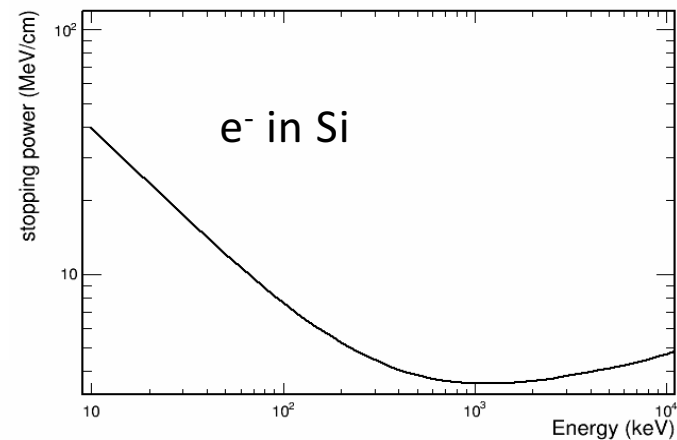
- **TEM - Transmission electron microscopy - Electron Diffraction/(Imaging)**

- Prof. Jan Pieter Abrahams C-CINA/PSI
- 100 – 300 keV

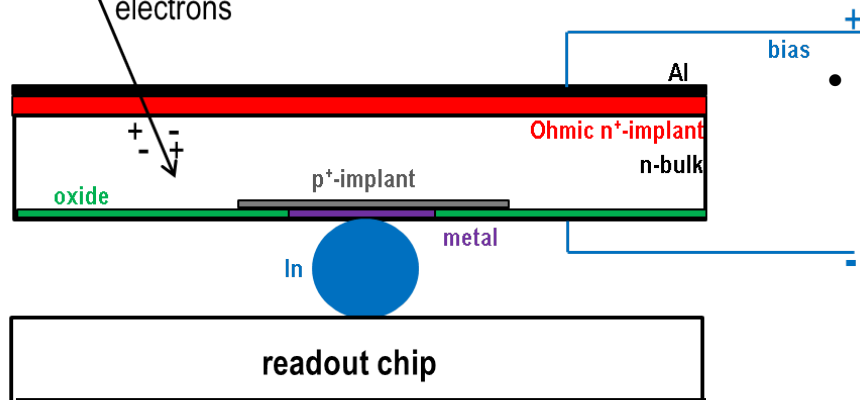


- For energies ≤ 100 keV, hybrid pixels are an “ideal detector”
- At higher energies, EIGER is appealing thanks to frame rate: scanning/rotation techniques, imaging single electrons, reducing sample drift

EIGER as an electron detector



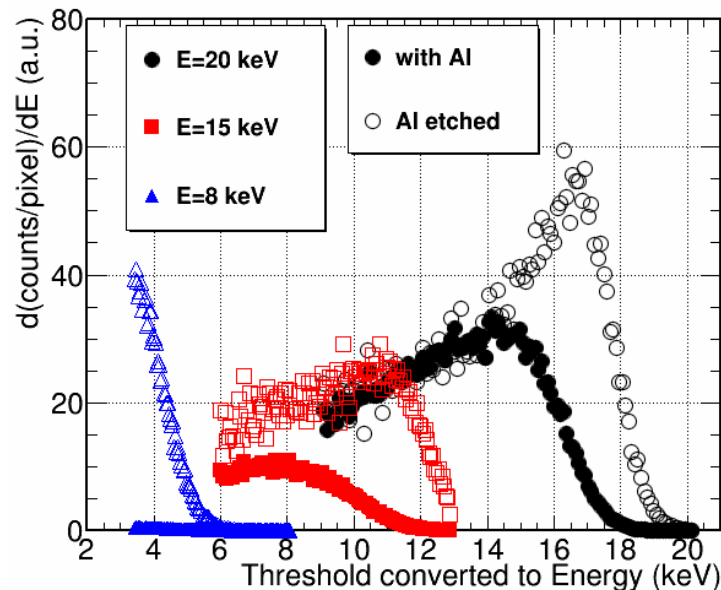
Low energy electron interaction ≤ 20 keV



e^- interaction:

- lose energy due to multiple collisions with atomic electrons
- Deposit energy in multiple points due to **multiple scattering**
- Al layer can be etched away
- e^- lose part of their energy in Si backplane

Completely rad hard for 8-20 keV e^-



Standard entrance window

Material crossed	20 keV e^-	10 keV e^-
Al 1 μm	2.6 keV	5.0 keV
Si 1.5 μm	3.0 keV	4.0 keV

FBK thin entrance window sensors

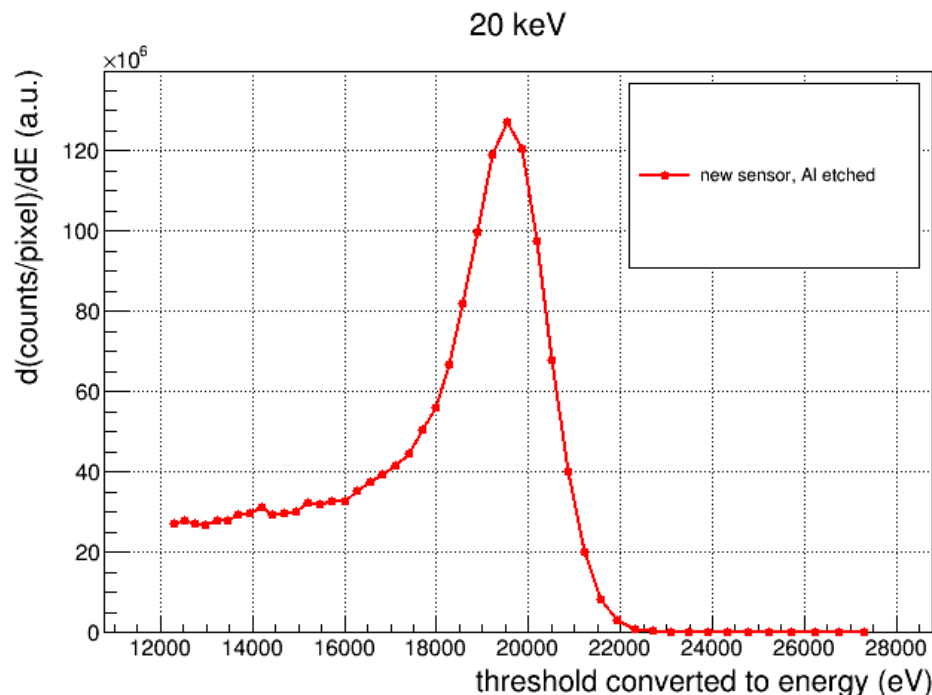
Sensor produced by FBK Trento:

Al has also been etched away

1. **As implant** tested (~ 200 nm)
2. As implant low energy still to be tested

Tested with a TEM from J.P. Abrahams's group

Material crossed	20 keV e^-	10 keV e^-
Si 500 nm	1.2 keV	2.0 keV
Si 200 nm	0.5 keV	0.9 keV

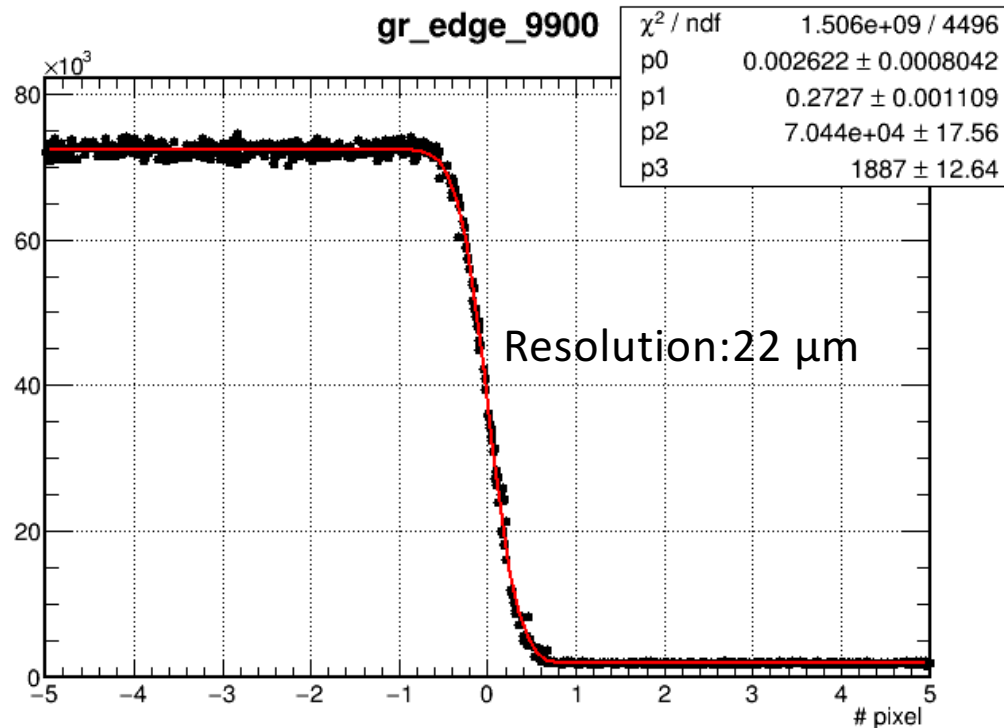


$19.5\text{keV} \pm 0.9\text{ keV RMS}$

0.5keV lost in entrance window

Spatial resolution with low energy electrons

20 keV electrons



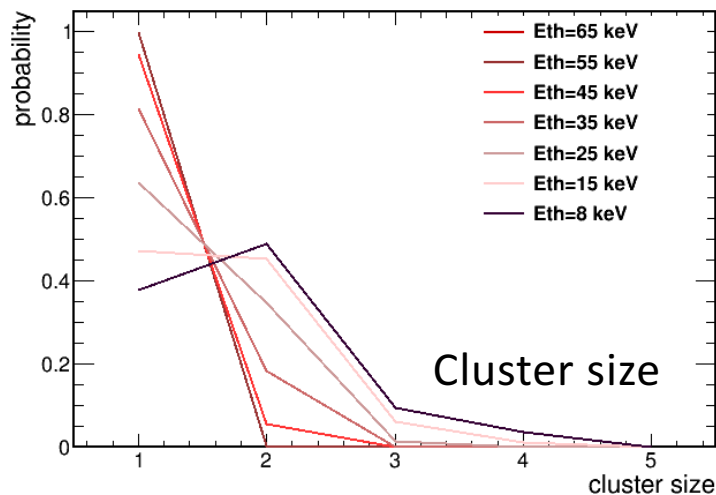
- When setting the threshold to half of the electron energy, we have single pixel resolution
- Fitting with a ErrFunction: resolution is 22 μm , compatible with 75 $\mu\text{m}/\sqrt{12}$

edge

100-300 keV electrons

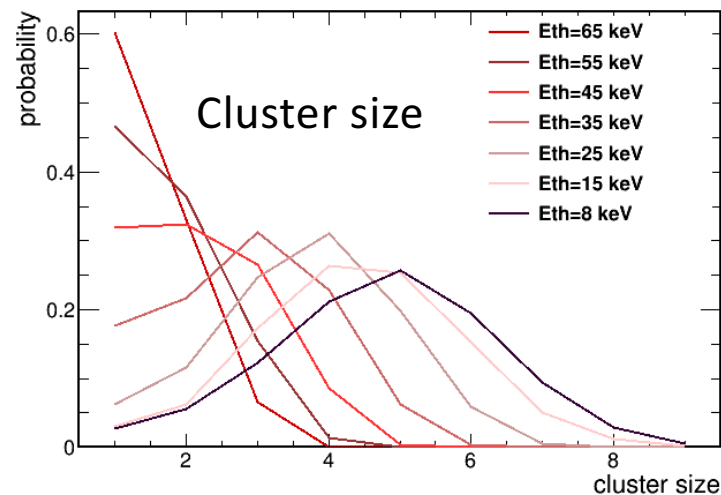
Tinti et al, IUCrJ 5(2) (2018)

100 keV



100 keV: Setting the threshold > 50%,
we recover single pixel resolution

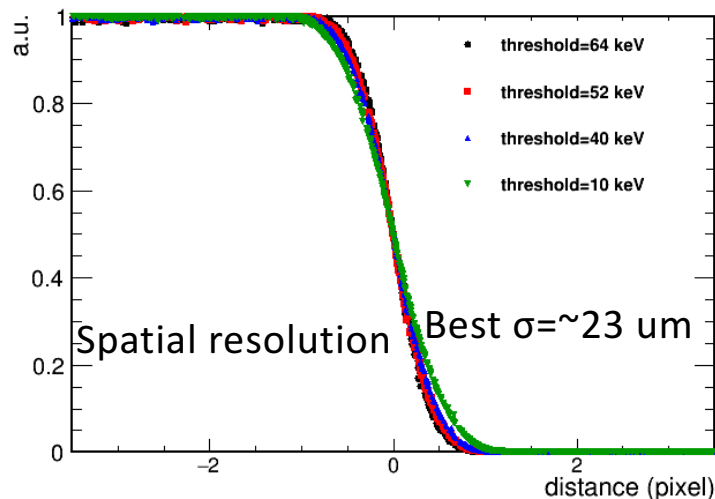
300 keV



The size of interaction is large: high
threshold records higher energy hit
but not entrance hit

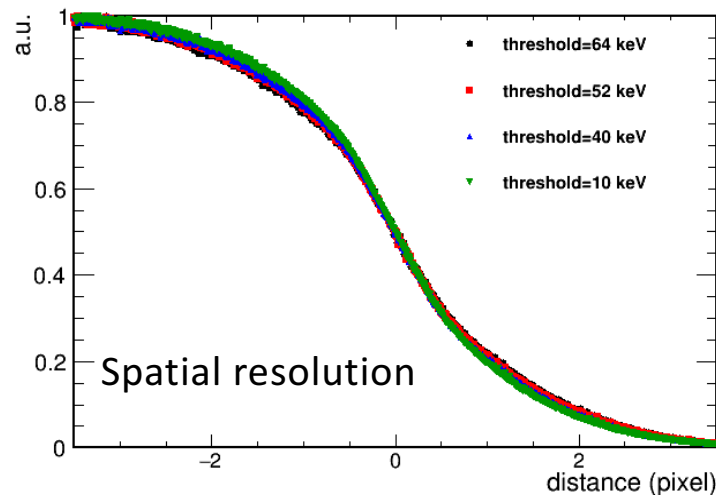
edge

E=100 keV



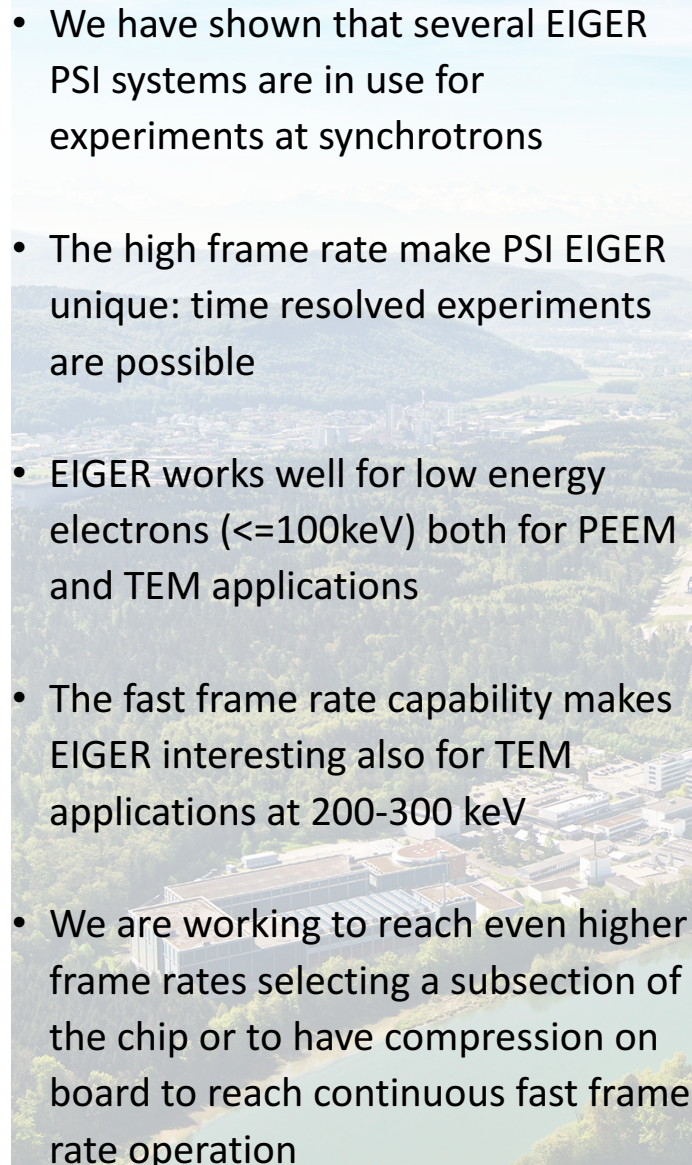
100keV: Good for imaging and diffraction

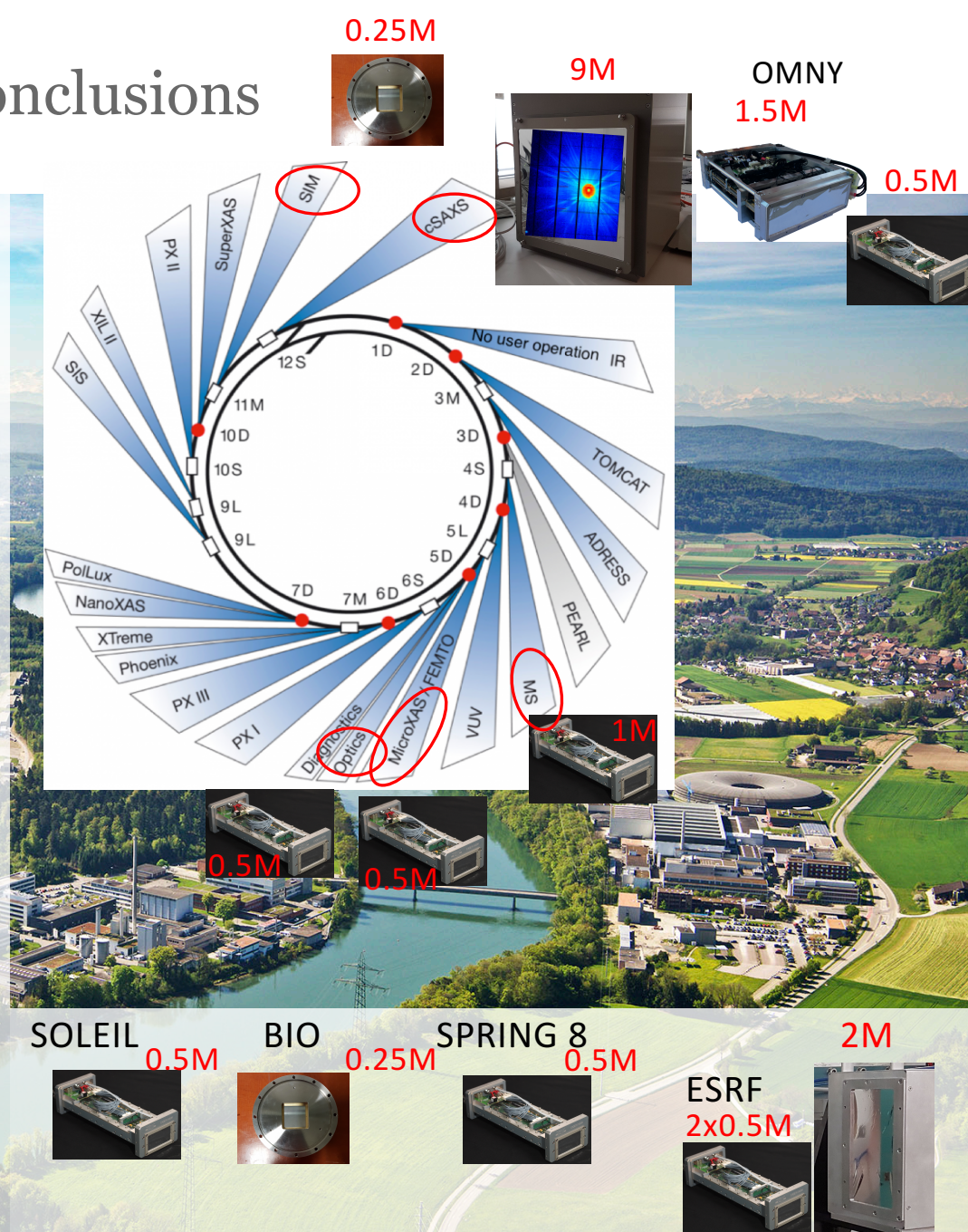
E=300 keV



200-300keV: Good for diffraction

Conclusions

- 
- We have shown that several EIGER PSI systems are in use for experiments at synchrotrons
 - The high frame rate make PSI EIGER unique: time resolved experiments are possible
 - EIGER works well for low energy electrons ($\leq 100\text{keV}$) both for PEEM and TEM applications
 - The fast frame rate capability makes EIGER interesting also for TEM applications at 200-300 keV
 - We are working to reach even higher frame rates selecting a subsection of the chip or to have compression on board to reach continuous fast frame rate operation



Acknowledgements



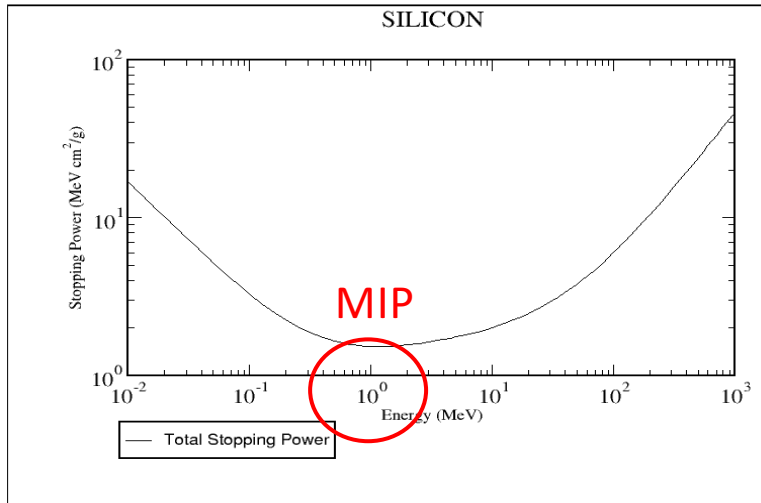
Back: (Marie Ruat,) **Bernd Schmitt**, Sophie Redford, Aldo Mozzanica, **Erik Fröjdh**.

Middle: Jiaguo Zhang, Carlos Lopez, Marie Andrä, **Rebecca Barten**, **Martin Brückner**, **Christian Ruder**, **Dominic Greiffenberg**, **Seraphin Vetter**.

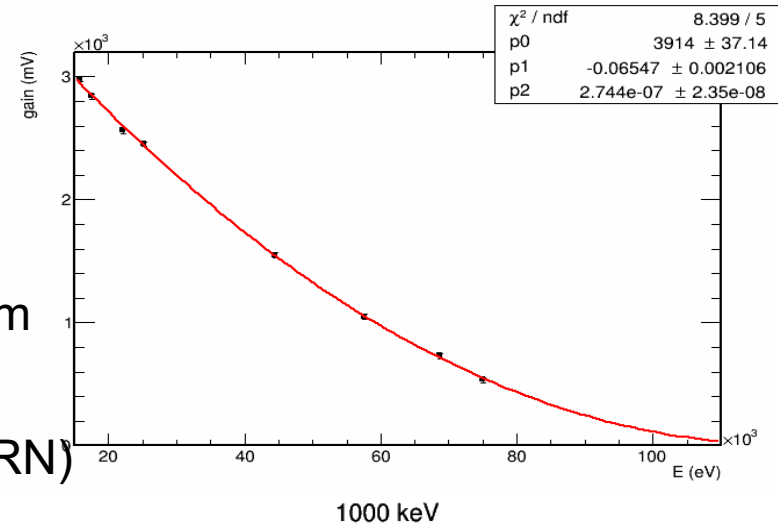
Front: Xintian Shi, **Dhanya Thattil**, Gemma Tinti, Anna Bergamaschi, (Marco Ramilli,) **Roberto Dinapoli**, Davide Mezza.

Not in picture: Sabina Chiriotti Alvarez

1MeV electrons



- We expect the peak of the Landau to be around 110 keV: 55 keV threshold
- Calibrated the detector threshold up to 110 keV

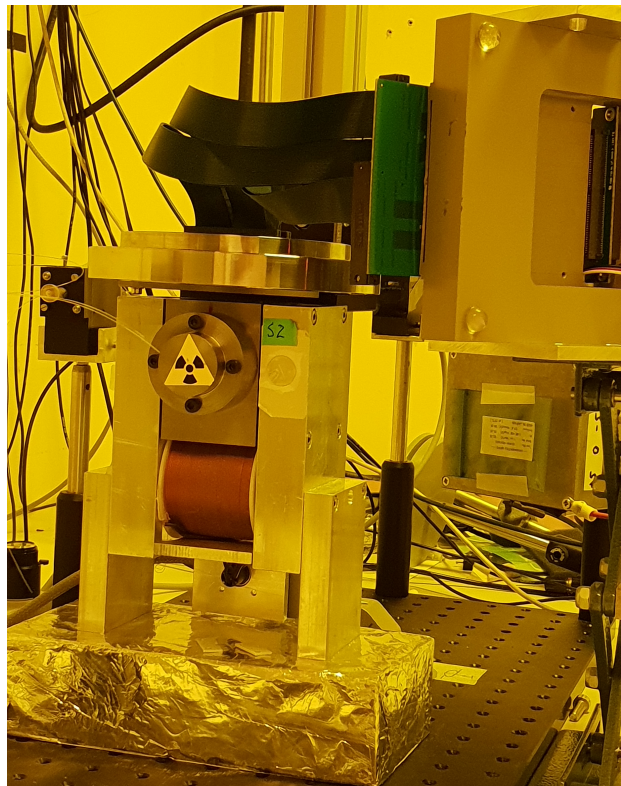
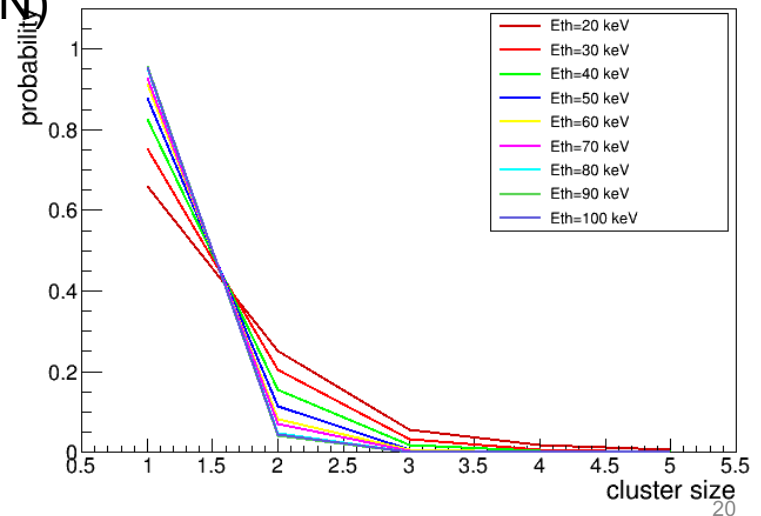


⁹⁰Sr with a momentum selector for electrons

Christian Joram (CERN)

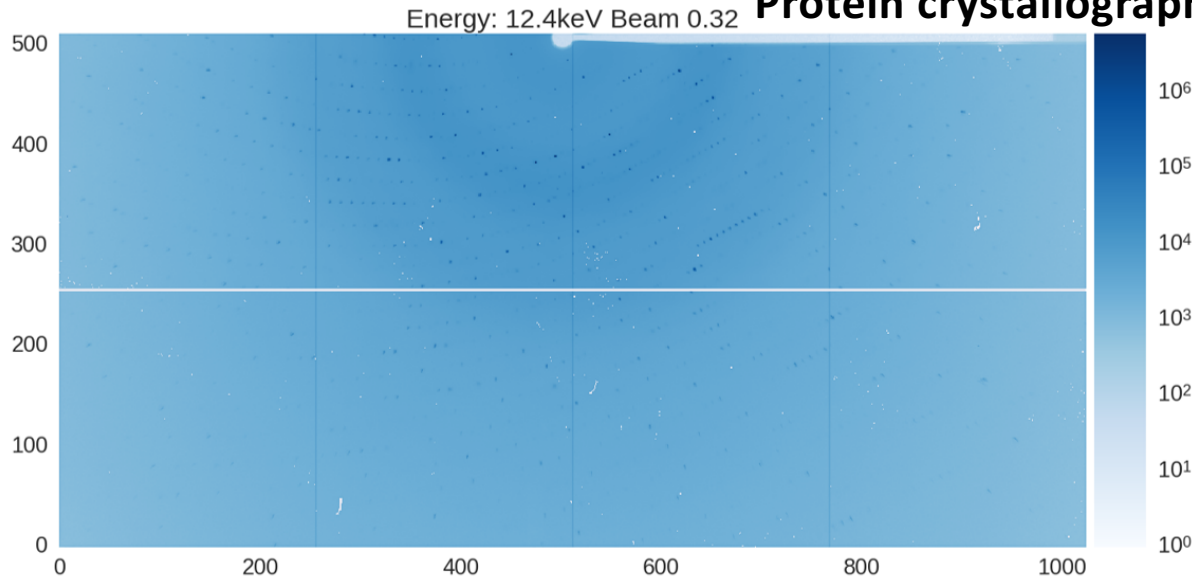
Lukas Gruber (CERN)

- At a threshold >60 keV, mainly single hits are recorded
- We expect a spatial resolution a bit worse than single pixel



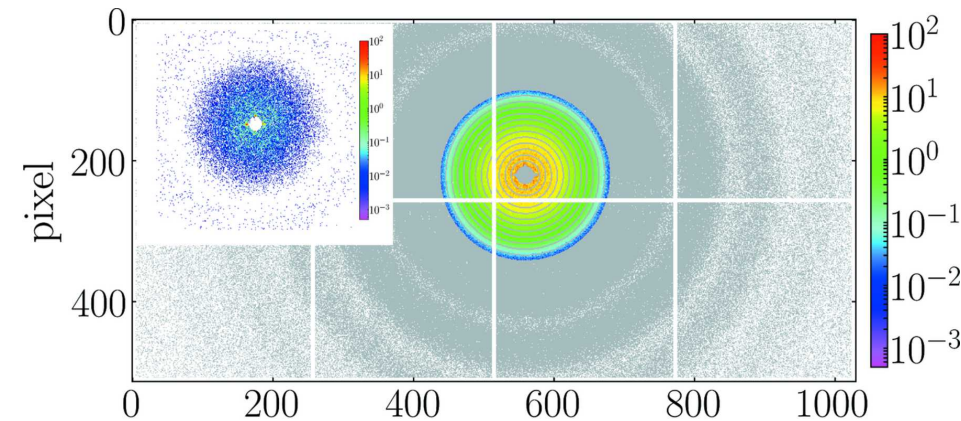
Experiments at synchrotrons

Protein crystallography PX beamlines



ALL compression findings for powder diffraction does not automatically apply to all experiments

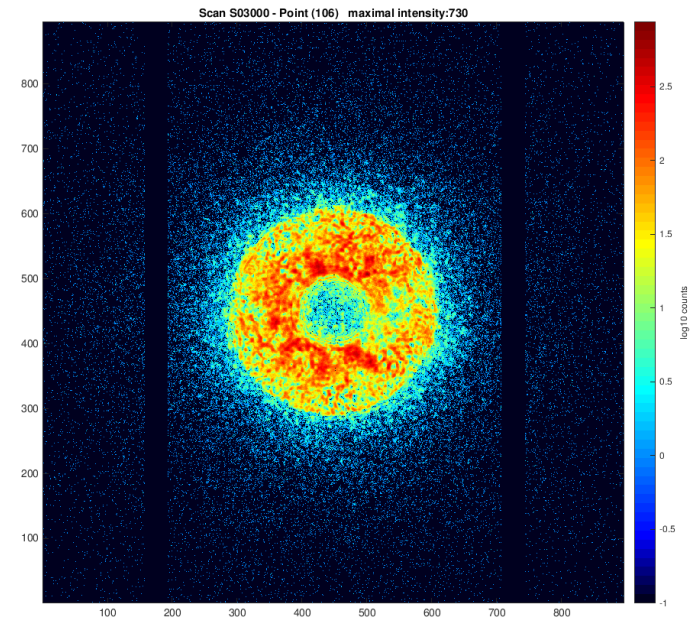
XPCS average and single ESRF ID02 beamline



T. Zinn et al., pixel

J. Synchrotron Rad. (2018). 25

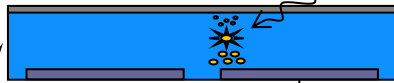
Ptychography cSAXS beamline



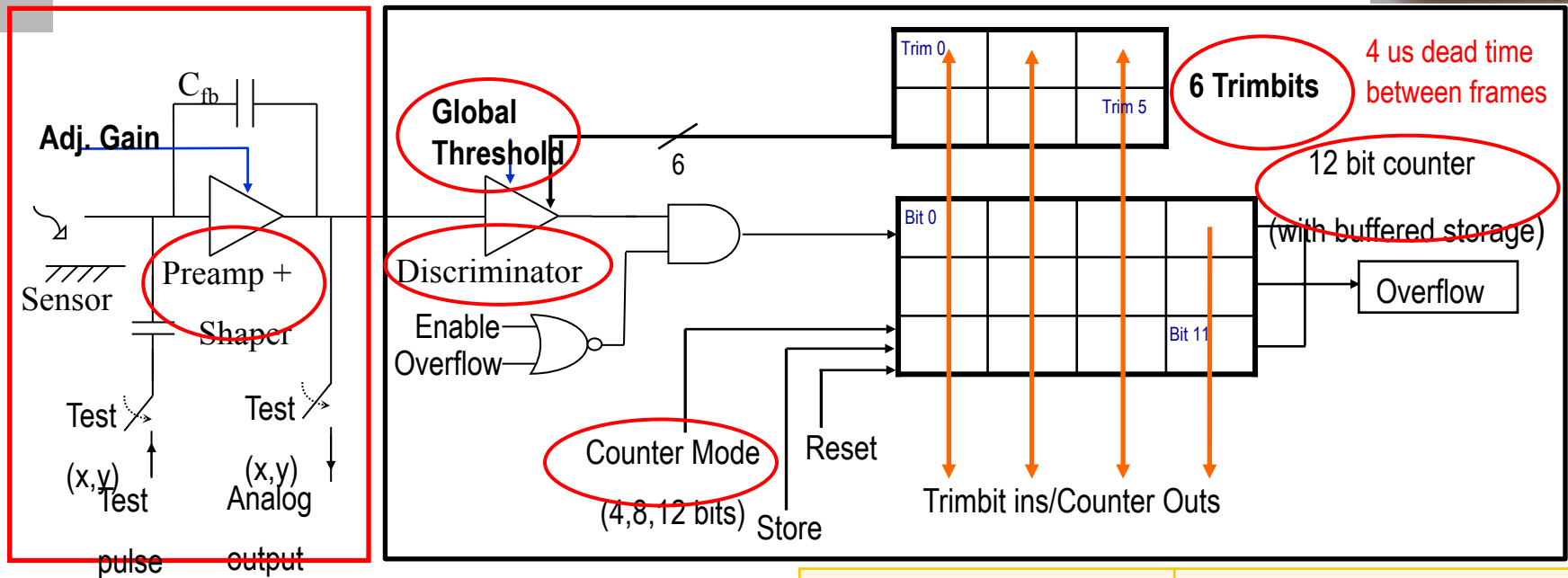
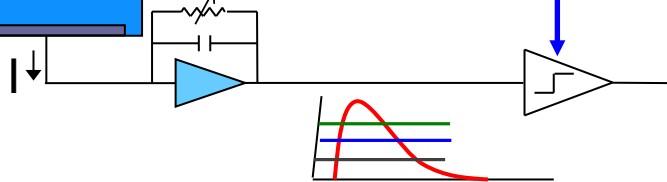
EIGER chip

Monochromatic X-rays

E↓



Adj. Gain

Global Threshold V_{cmp} 4 us dead time
between frames

6 Trimbits

12 bit counter

(with buffered storage)

Overflow

Counter Mode

(4, 8, 12 bits)

Threshold dispersion
(after trimming)<10 e^-

Noise

100-200* e^- RMSRate capabilities
(10% deviation)*500 k counts/pixel/s → 90
Mphotons/mm²/s

Dead time

4 us (with buffering)

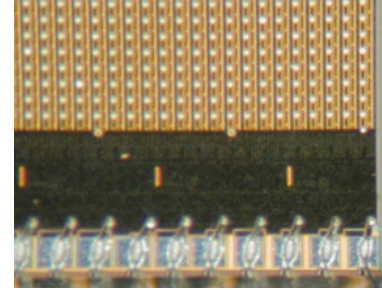
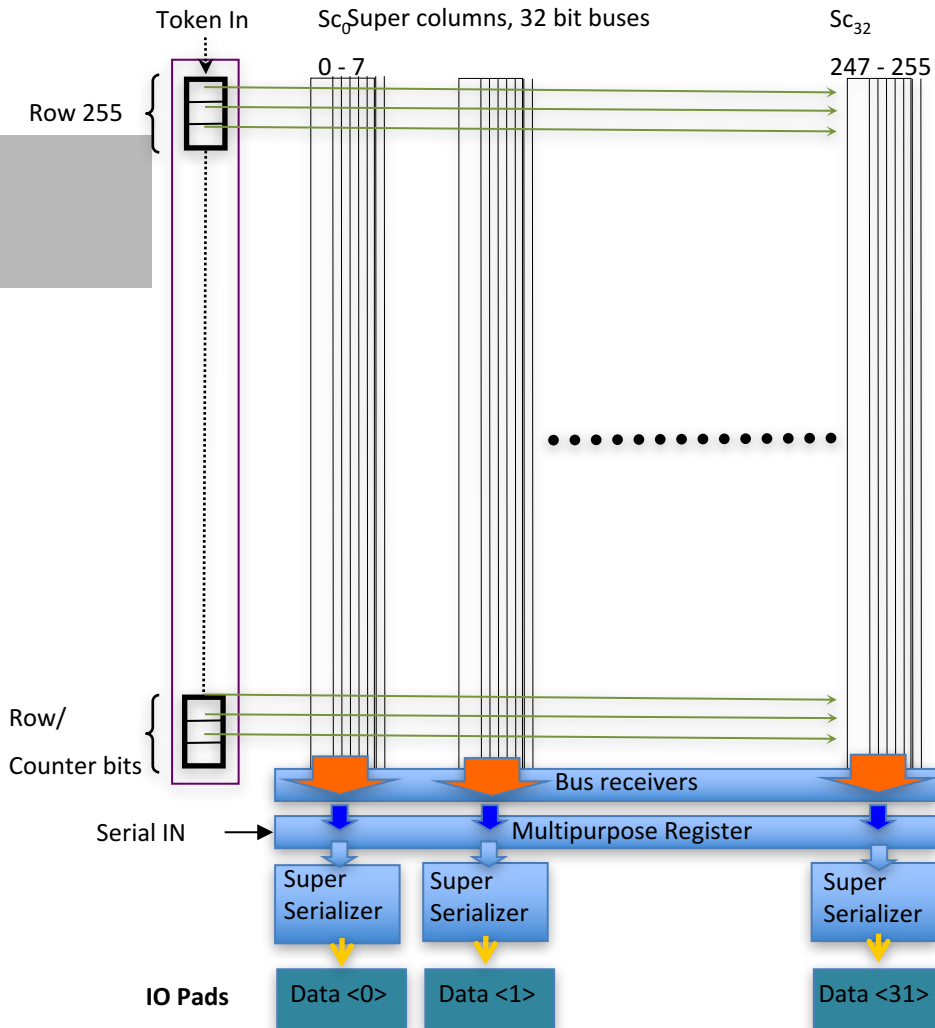
Pixel size 75 x 75 μm^2

Pixel matrix 256 x 256

Frame rate 23/12/8 kHz

Data rate 6 Gb/s

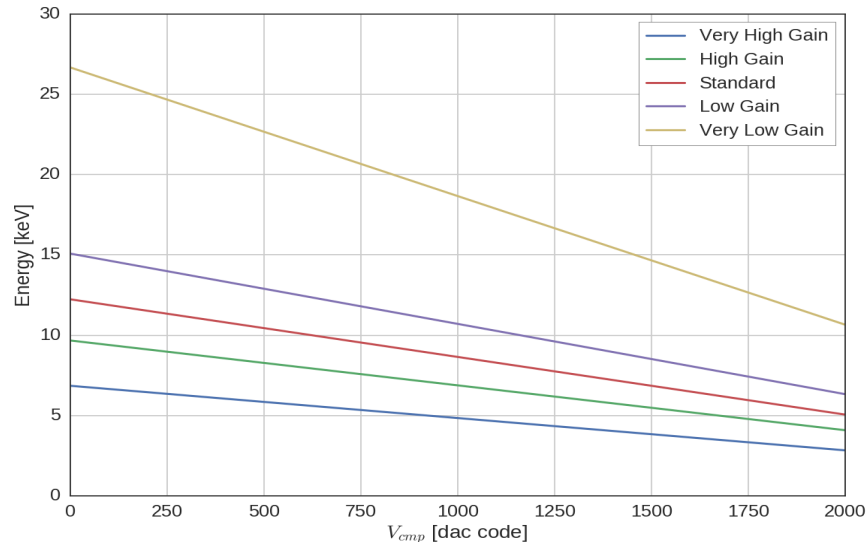
Very high frame rate



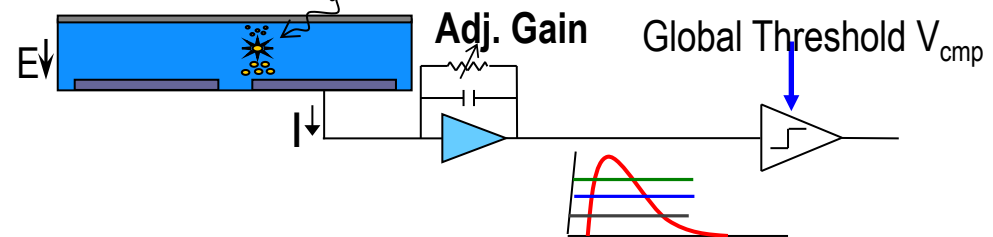
Threshold dispersion (after trimming)	<10 e ⁻
Noise	100-200* e ⁻ RMS
Rate capabilities (10% deviation)*	500 k counts/pixel/s → 90 Mphotons/mm ² /s
Dead time	4 us (with buffering)

Pixel size	75 x 75 um ²
Pixel matrix	256 x 256
Frame rate	23/12/8 kHz
Data rate	6 Gb/s

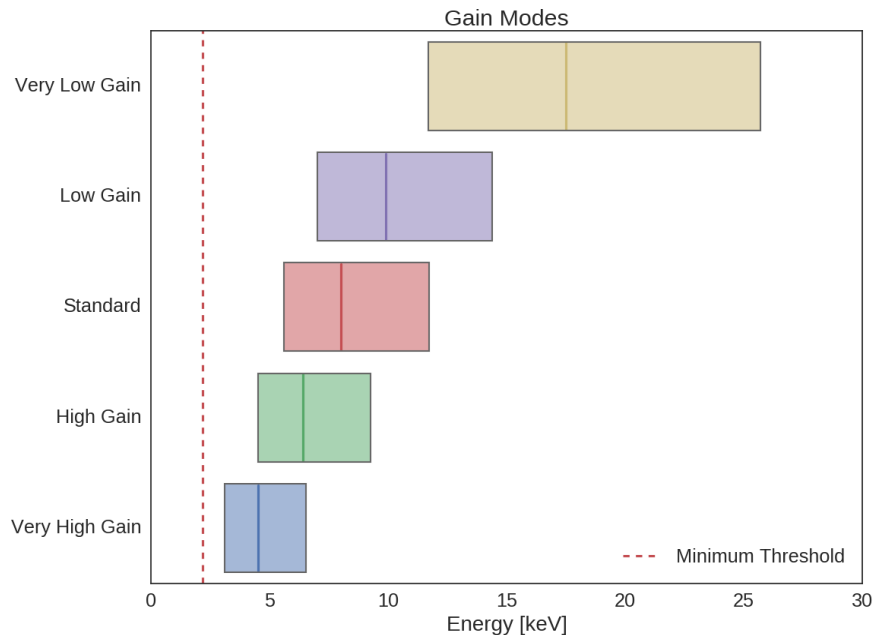
Threshold calibration



Monochromatic X-rays

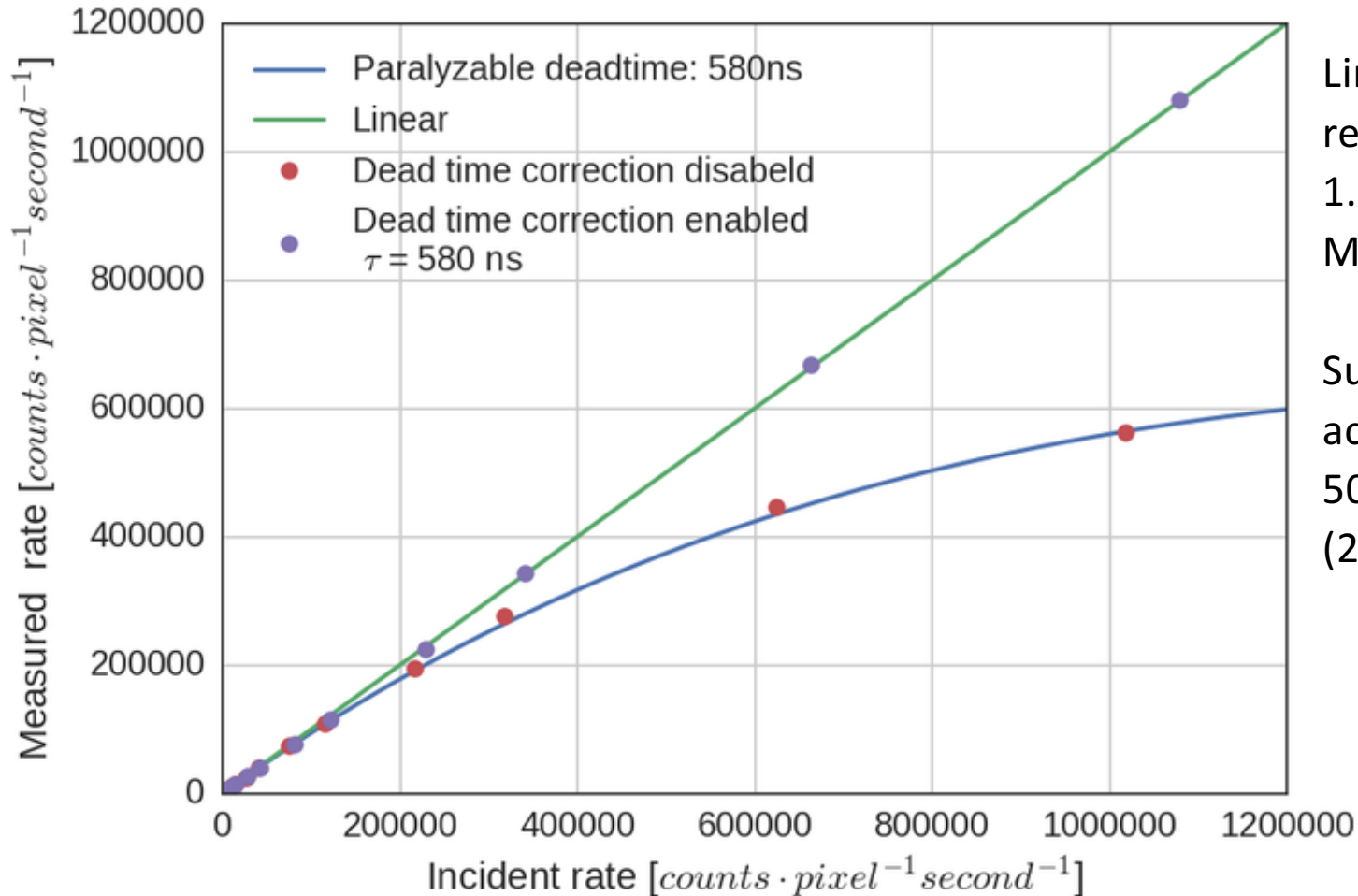


- Each **preamplifier gain** covers a different range of photon energies
- The **threshold setting** needs to be calibrated into photon energy
- Threshold is calibrated to be uniform in the detector and its dispersion is negligible (down to $10 e^-$) in comparison to noise
- The noise at high gain is $< 100 e^-$
- Threshold can be set at > 2 keV (depending on the readout settings)



Online rate correction

Single subframes recorded up to 2kHz frame rate can be corrected online, before summation



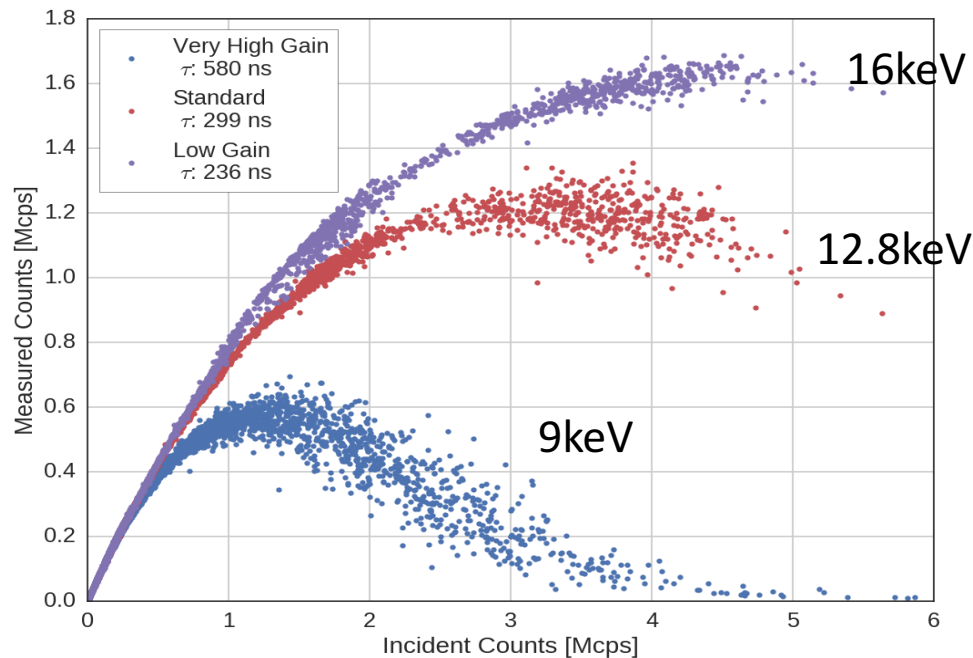
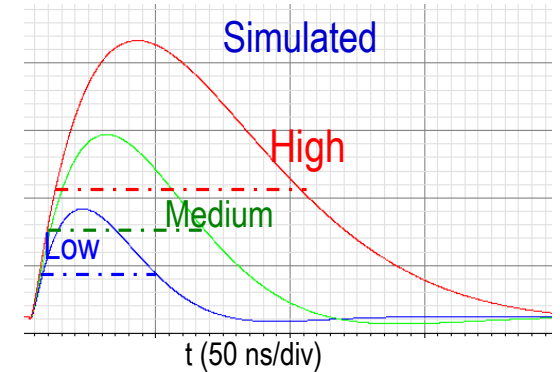
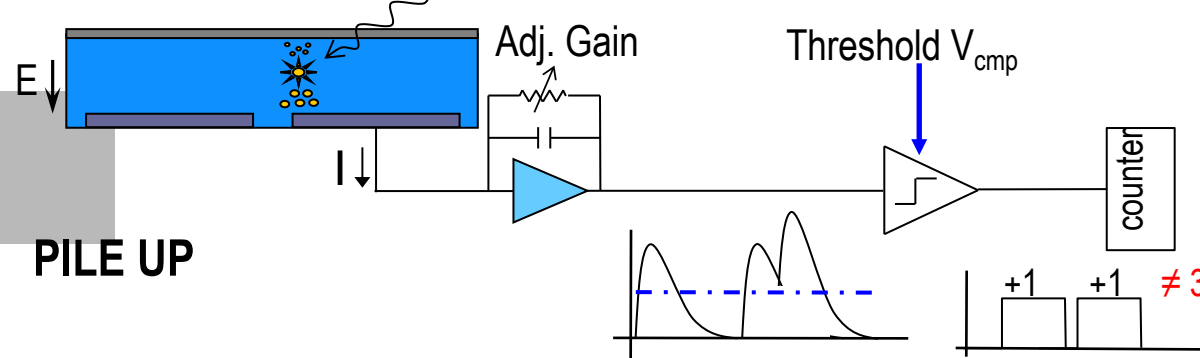
Linearity is restored up to 1.2

Mcounts/pix/s

Subframes acquired at 500Hz (2ms/subframe)

Rate correction as a function of energy

Monochromatic X-rays



For the same energy, lower gain improves the rate capabilities

Paralizable counter model:

$$N_{det} = N_{inc} \cdot e^{-N_{inc} \cdot \tau}$$

Linearity at 90% :

200 - 600

kcounts/pixel/s

Rate capability depend on the energy!

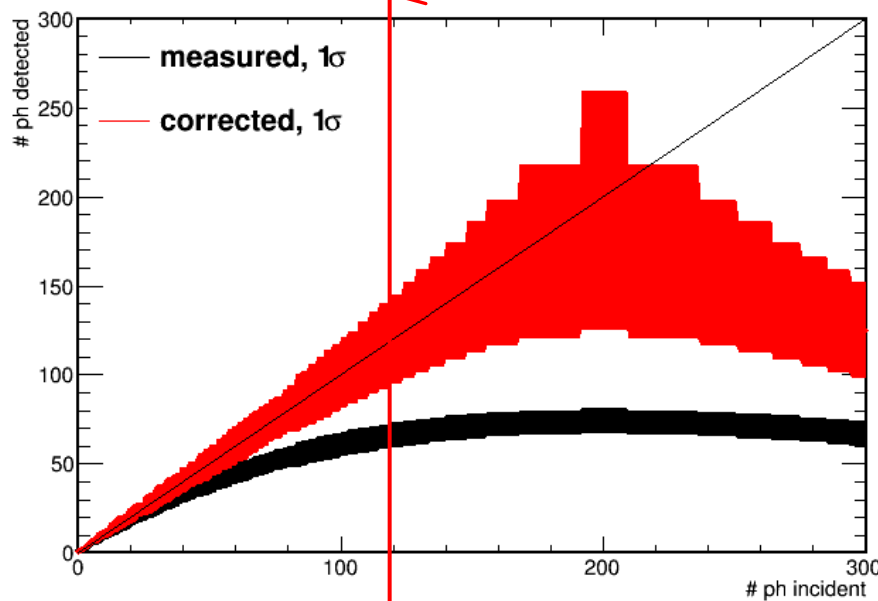
Rate corrections in 8 bit mode

$$N_{det} = N_{inc} \cdot e^{-N_{inc} \cdot \tau}$$

If $\Phi = 1.5 \text{ MHz/pix}$, $t = 80 \text{ us}$, $N_{inc} = 120$

Maximum flux
Chosen for linearity

Margin from 8bit
saturation



Errors on corrected value~ 20%:

- Statistical uncertainty in N_d :
 $\sigma = 20\%$
- Pixel to pixel differences in τ :
 $\sigma = 2 - 15\%$
- $\tau = 400 \text{ ns}$

- $N_{det} < N_{inc}$ Rate corrections can be applied to 8bit data as N_{inc} does not exceed 8bit depth (254)
- **Rate correction, if wanted in firmware, needs to be implemented for 8bit data**
- If more than 1 image taken in same condition → better to sum before and correct with higher statistics

Charge sharing

