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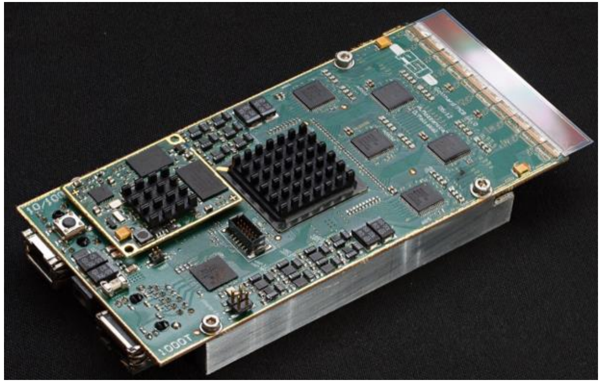
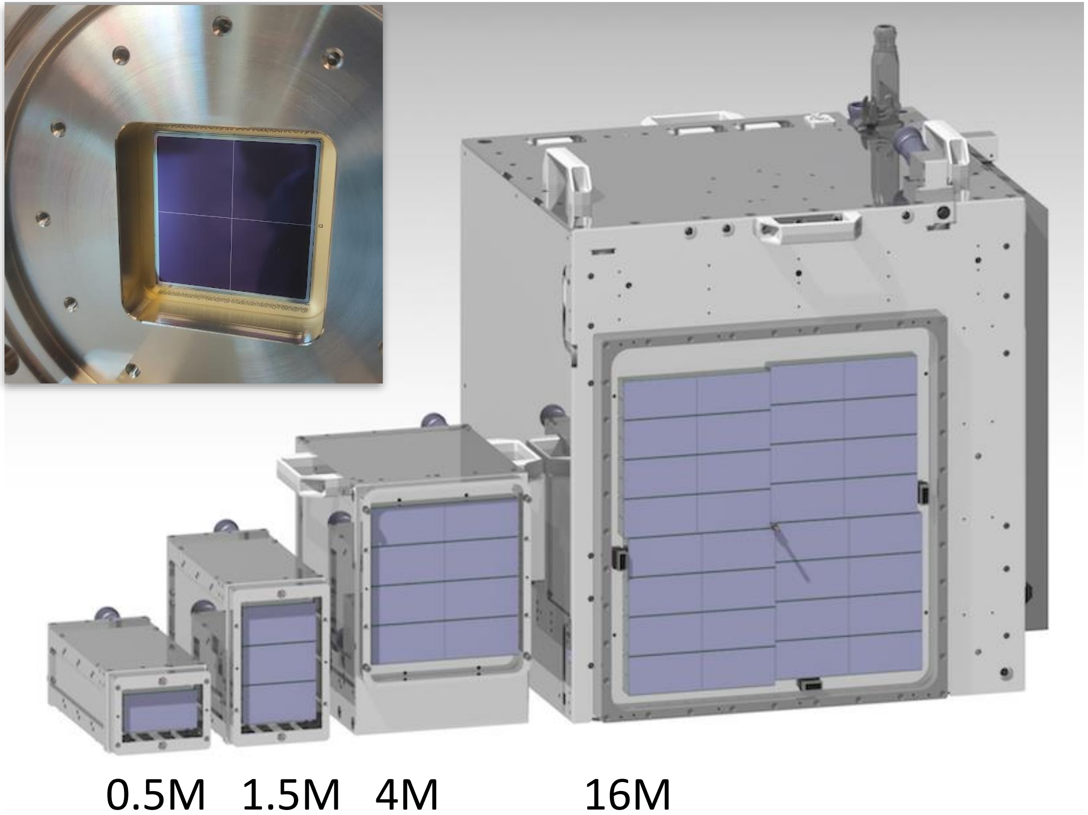
Erik Fröjdh :: PSD Detector Group :: Paul Scherrer Institute

A look at single photon counting detectors for SLS2.0

PSD13 – Oxford, UK – 3-8th September 2023

PSD Detector Group at PSI





SLS2.0 – a 4th generation light source

- Increased brilliance [1]:
  - >100x at 10 keV
  - Up to 1000x at 20 keV

- Dark period starting end of September 2023
- First light planned 2025 with user operation in later part of the year

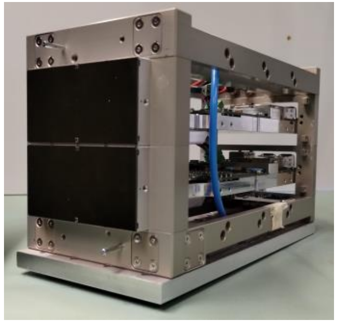
> - More photons
> - Higher energies
> - Lower energies

[1] SLS 2.0 Storage Ring Technical Design Report PSI Bericht Nr. 21-02 November 2021

New light source, new detector (Matterhorn)

- 75x75 μm^2 pixel size
- 4 thresholds (w. 16 bit counters)
- Energy range: 250 eV-
- Electron and hole colle
- 100Gbit/s readout boa
- 160 kHz in 1 bit mode
- <20ns gating
- ~20M photons/pixel/s tracking)

First results of Matterhorn v0.1



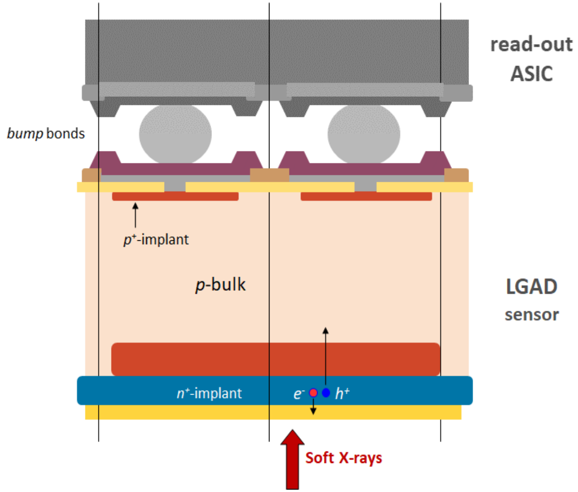
1M Jungfrau GaAs
500 μm thick
8x4 cm^2

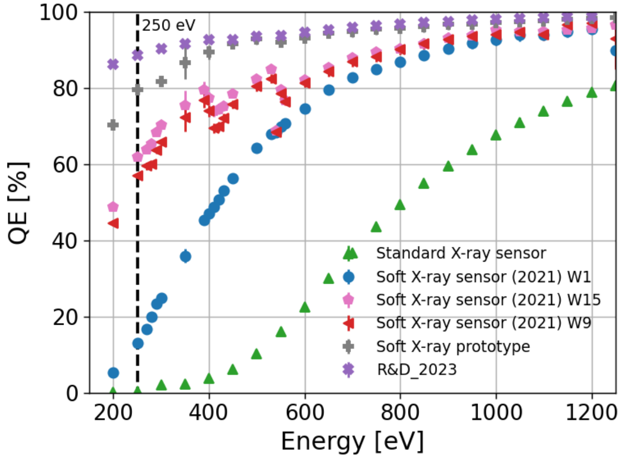
Reaching 250 eV - iLGADs

- Thin entrance window (QE)
- Signal amplification in the sensor

- Collaboration with FBK started 2019
  - Optimized entrance window
  - iLGAD design with shallow gain layer

- QE @ 250 eV increased:
  - < 5% **conventional sensor**
  - ~ 60% **current TEW**
  - ~ 80% **thinner passivation**
  - *~ 90% future new process*
- Gain 3-7 (tested on Eiger)





M.Carulla

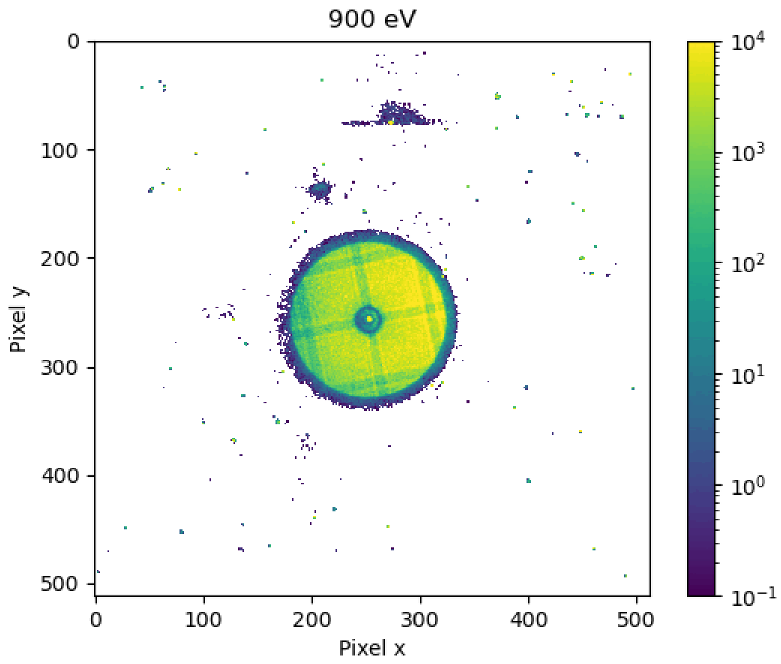
References: PSI-FBK sensor development

[1] Andrä et. al. *Development of low-energy X-ray detectors using LGAD sensors*. J. Synchrotron Rad. 26, 1226–1237.

[2] Zhang et. al. *Development of LGAD sensors with a thin entrance window for soft X-ray detection* JINST 17. 2022

[3] Carulla et. al*. Study of the internal quantum efficiency of FBK sensors with optimized entrance windows* JINST 18 2023

Eiger with iLGADs

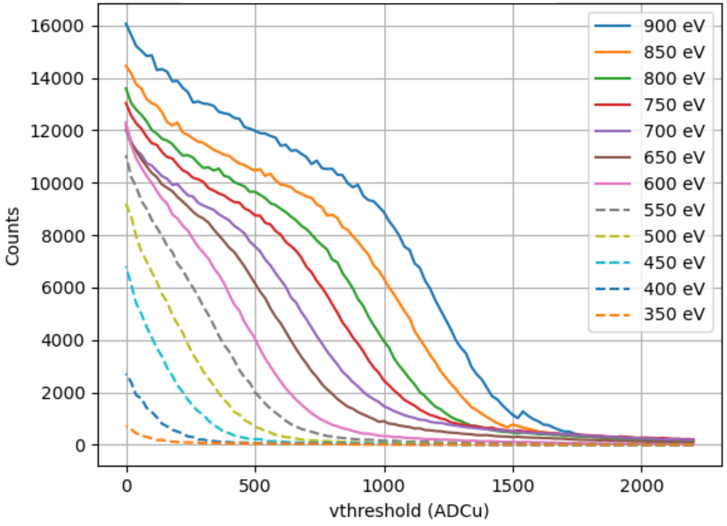


- Single photon counting
- 512x512 pixels at 75 µm^2

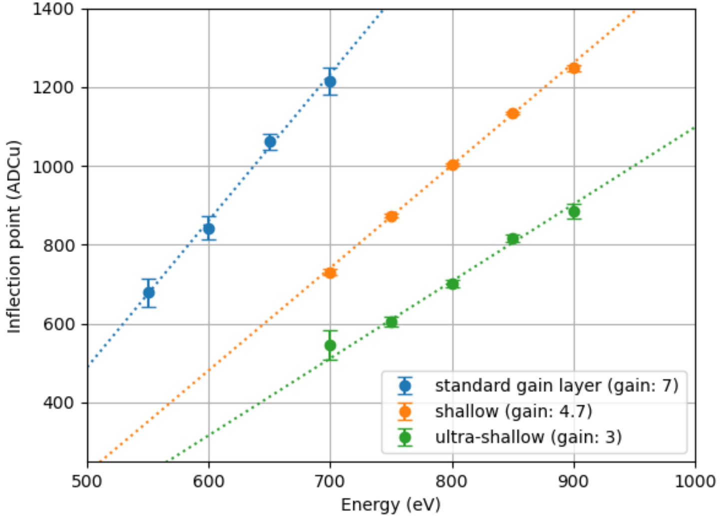
- Diffraction pattern from *Fresnel zone plate*
- 900 eV – 250 eV
- Lower energies → larger diffraction angle
- Higher harmonics visible in the center

Eiger with iLGADs

- Threshold scans: 450 eV – 900 eV
- Shallow gain layer design

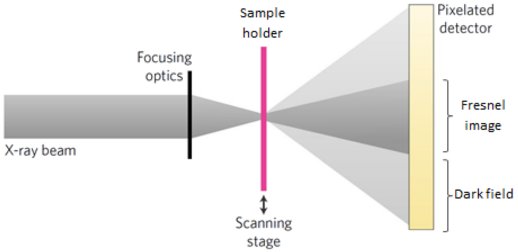


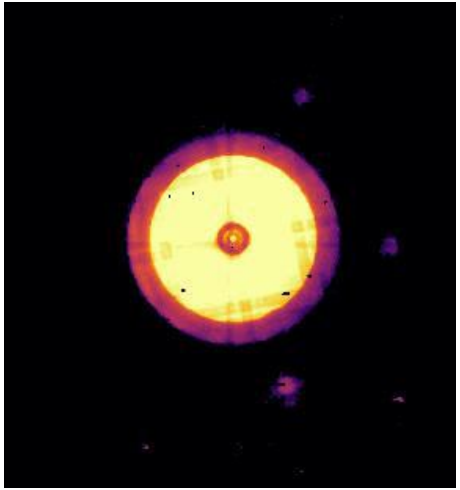
- Calibration curves



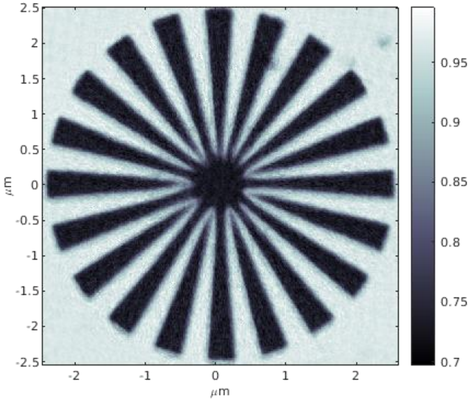
F. Baruffaldi

Ptychographic Scan of a Siemens Star

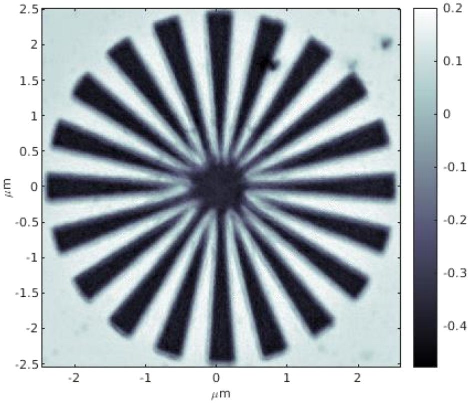




Amplitude



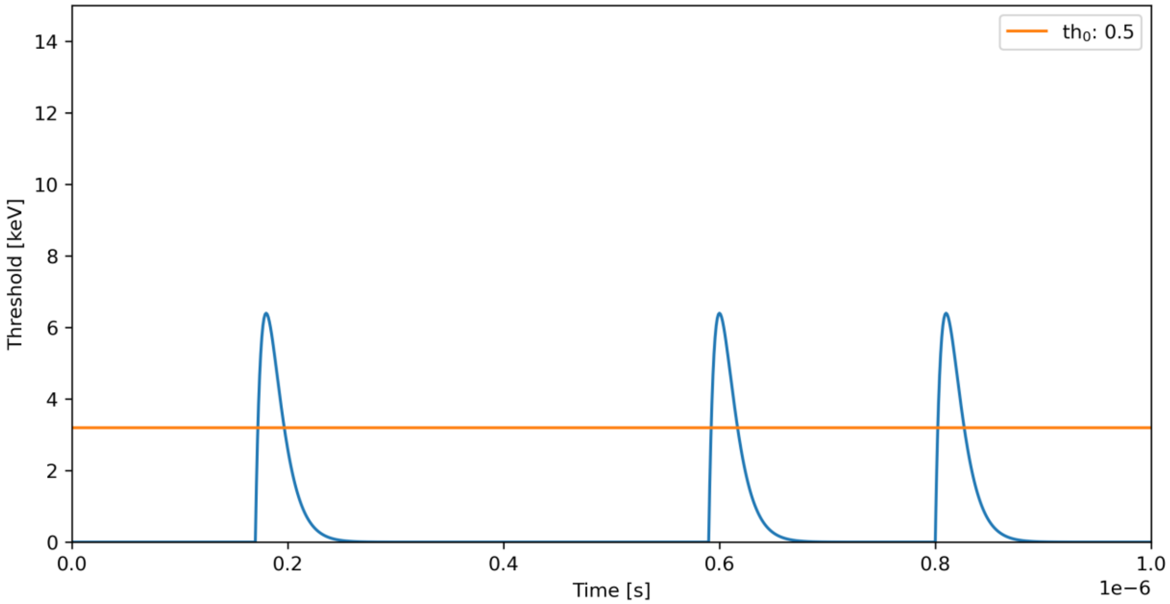
Phase



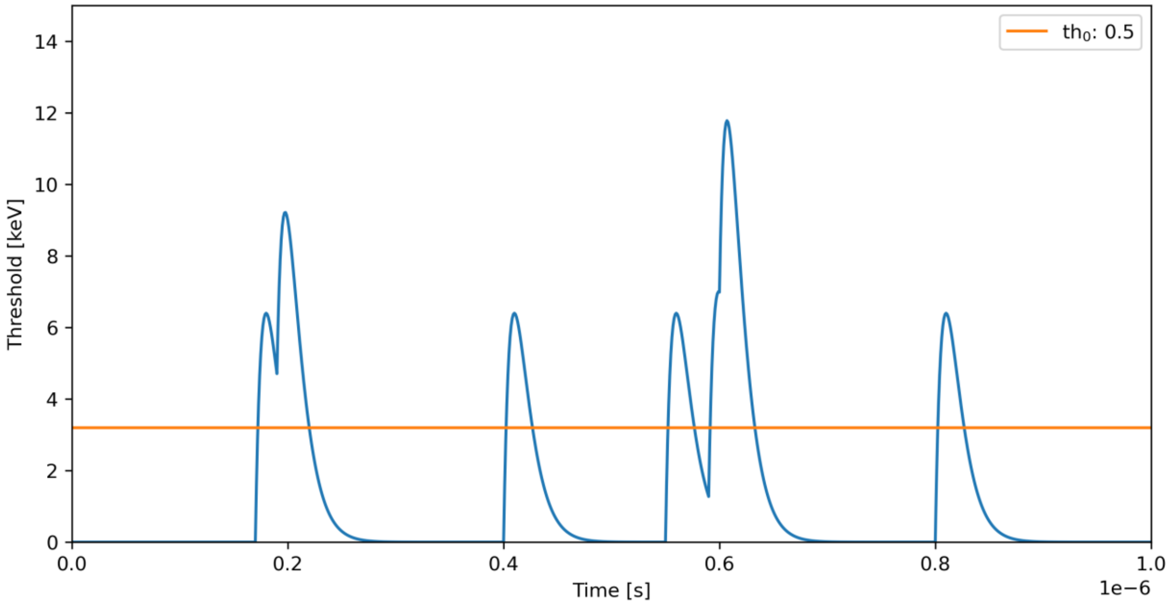
LGAD Eiger (standard gain layer)
at **712.5 eV** Spatial resolution ~8 nm

Butcher et. al. *Ptychographic nanoscale imaging of the magnetoelectric coupling in freestanding BiFeO3*
https://arxiv.org/abs/2308.13465

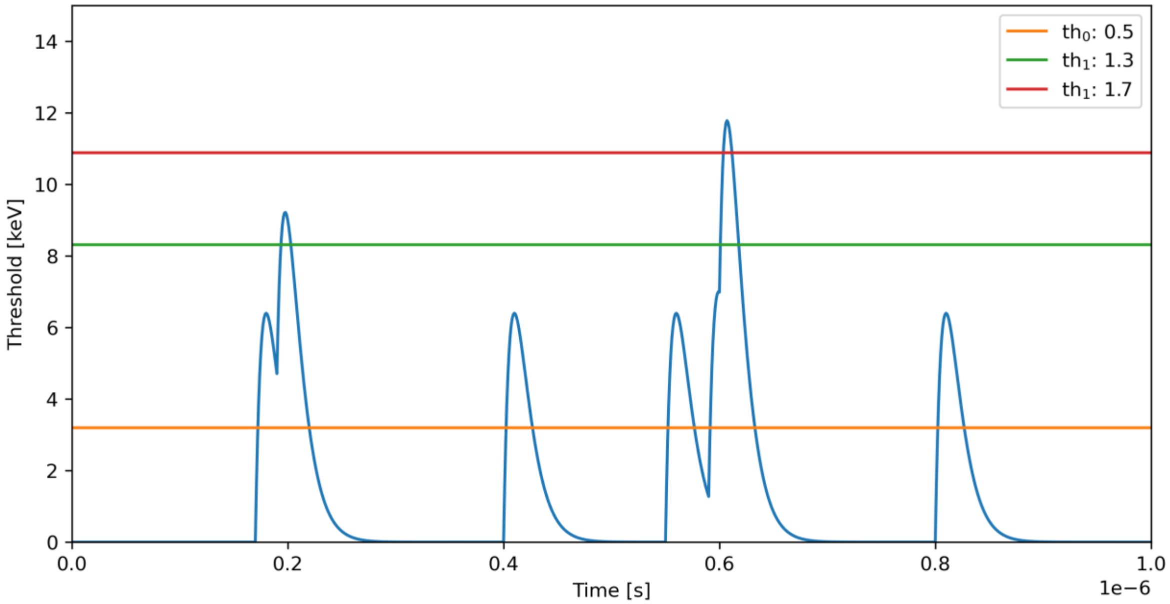
Reaching 20Mcps



Reaching 20Mcps



Reaching 20Mcps – pileup tracking



Counting pile-up

- Paralyzable counter: $m = ne^{-\tau n}$
- Probablility of two and three events pile-up:
  - $p_2 = e^{-\tau n}(1 - e^{-\tau n})$
  - $p_3 = e^{-\tau n}\,(1 - e^{-\tau n})^2$

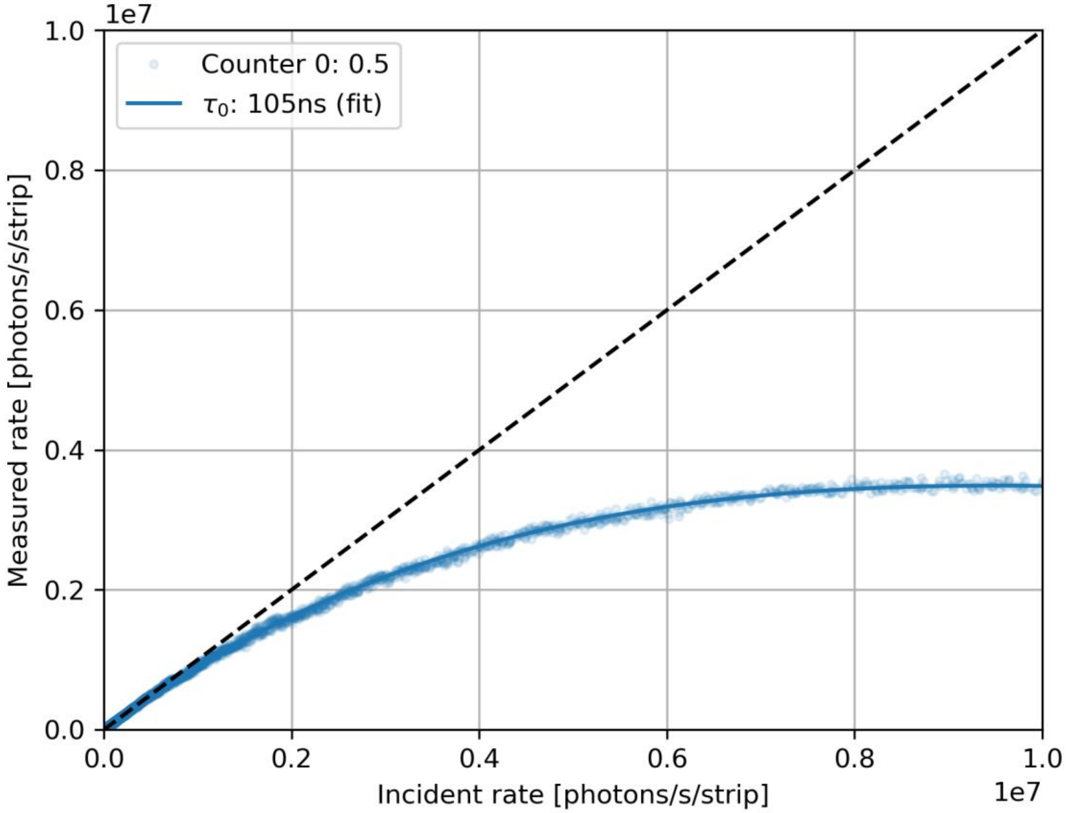
- $m_s = m + m_2 + m_3$

For characterization:

- Fit first counter with the paralyzable model
- Fit sum of counter 1,2 and 3 with the pile-up model

Glenn F. Knoll, *Radiation Detector and Measurement* 4th Edition, Wiley
M. Andrae The MYTHEN III Detector System - A single photon-counting microstrip detector for powder diffraction experiments ETHZ Doctoral Thesis

Mythen 3 (strips)

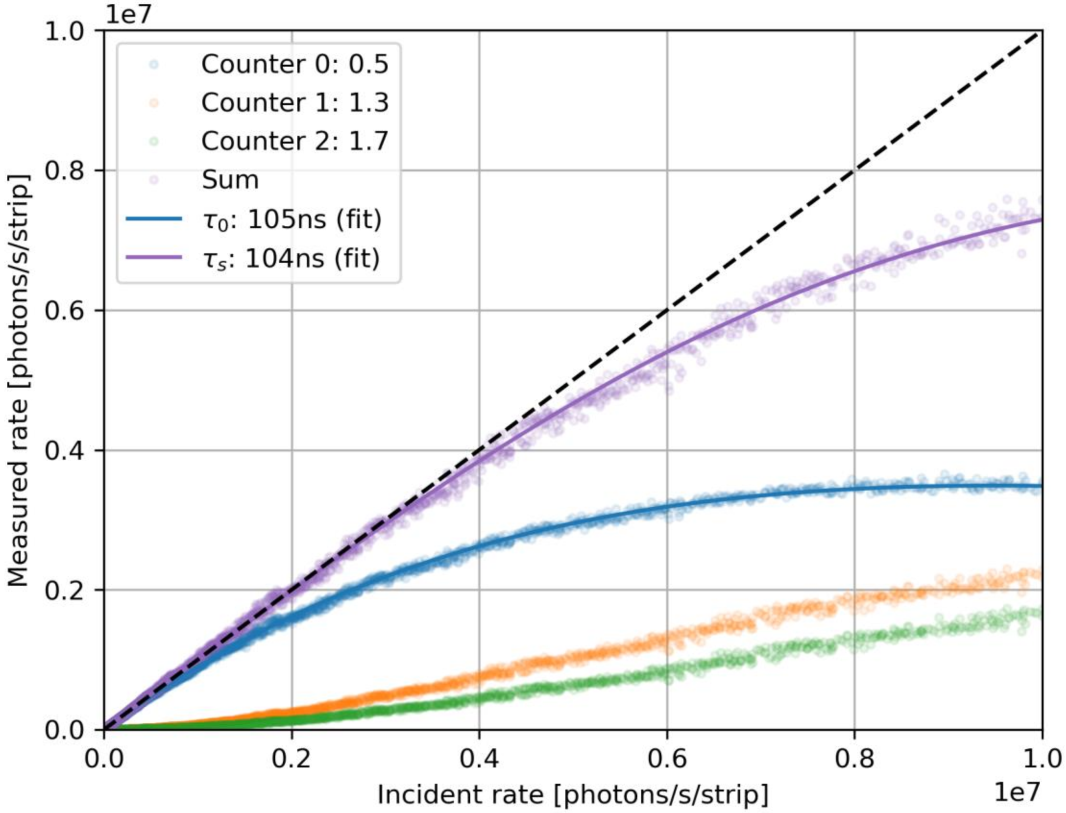


Settings: standard

Energy: 15 keV

MS beamline@SLS

Mythen 3 (strips)



Settings: standard

Energy: 15 keV

10% lost counts at:

th_0: 1.03M

th_{sum}: 6 M

Noise 175e- RMS standard settings

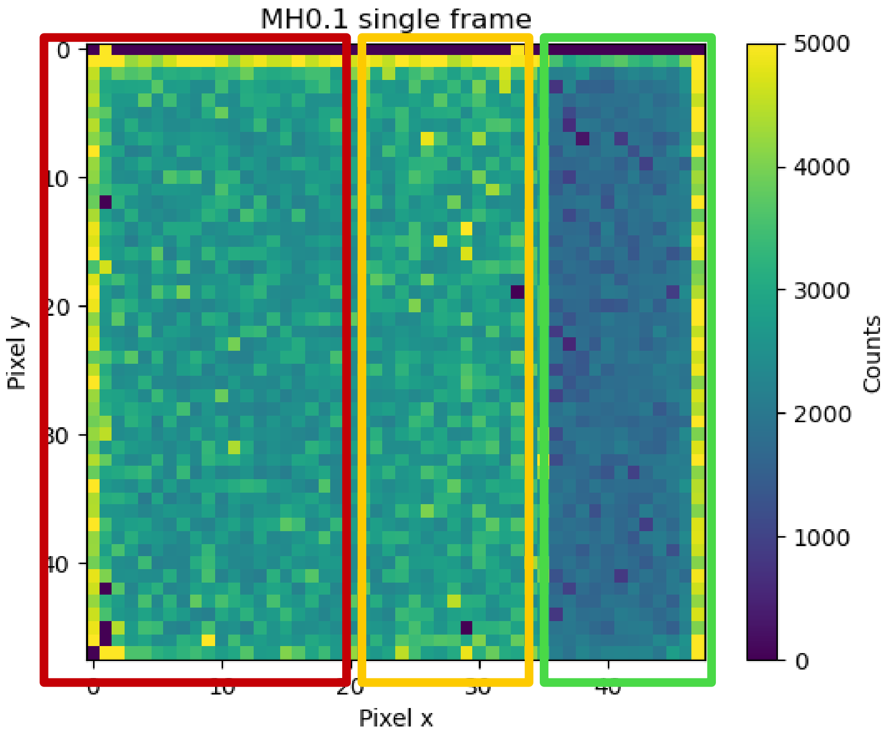
Settings: Fast [1]

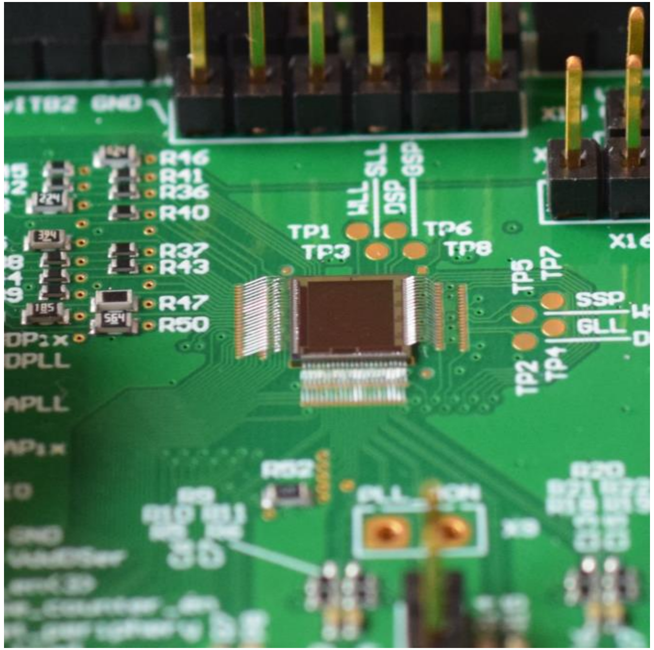
Single counter 3.52 M

Three counters 20.87 M

[1] M Andrä The MYTHEN III Detector System - A single photon-counting microstrip detector for powder diffraction experiments ETHZ PhD Thesis 2021

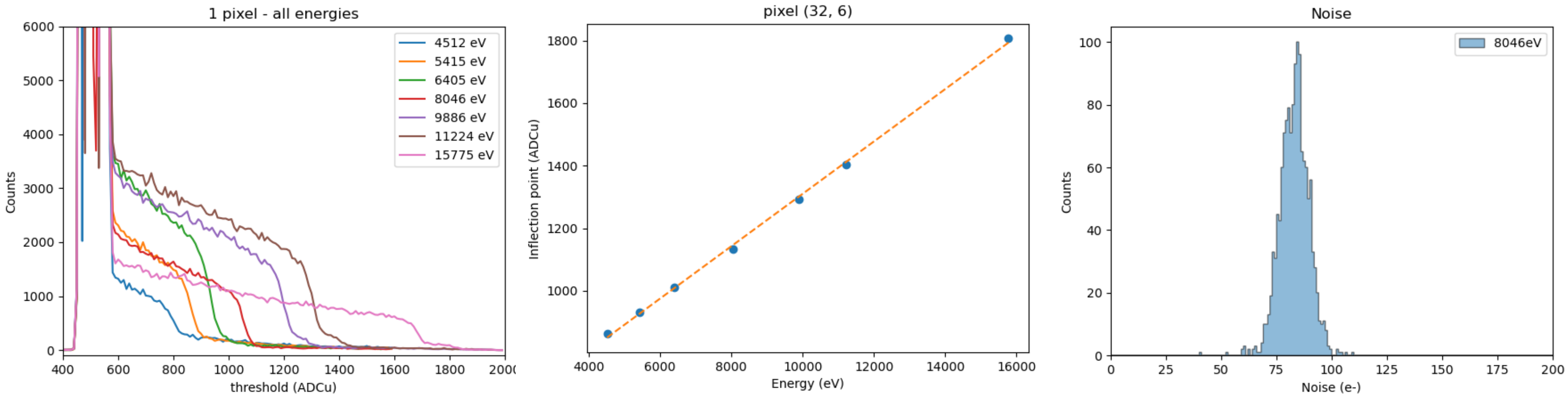
Matterhorn v0.1



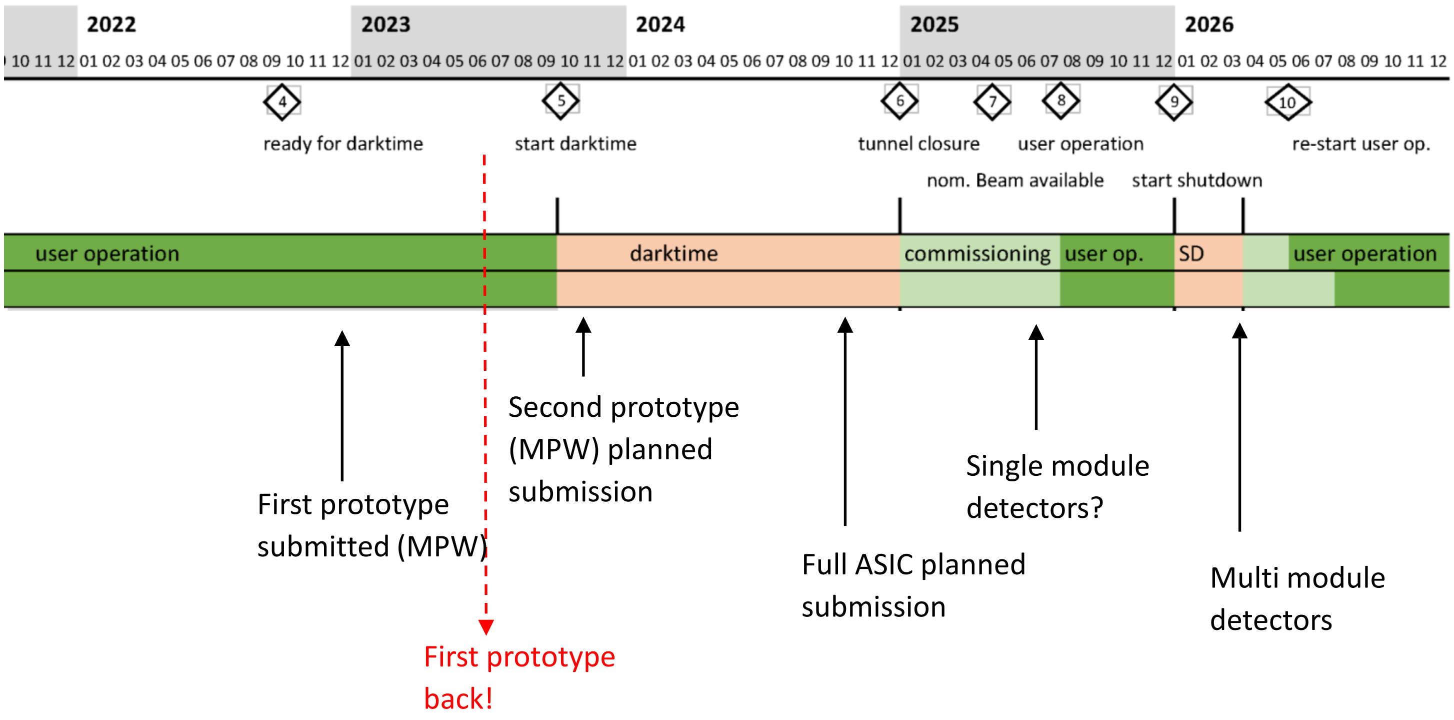


Matterhorn v0.1 characterization

- First results with X-rays (XRF)
- ~80e- RMS noise (preliminary!)
- Beamtime planned: calibration and rate



MATTERHORN and SLS2.0



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Summary and outlook

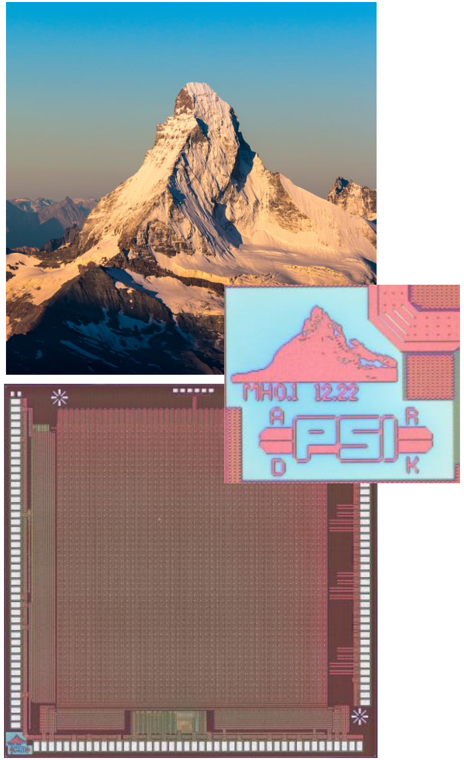
Increased flux at SLS2.0 will be be a challenge for single photon counting detectors

- Extend rate capabilities (e.g. pileup tracking)
- Faster frame rates (to use the photons)

Extended energy range

- iLGADs 250eV single photon counting looks realistic
- High Z sensor materials

Charge integrating with dynamic gain switching for the extremly high (or low fluxes)



Count if you can, integrate if you have to

Jungfrau for synchrotron use

[1] F. Leonarski et al. *Fast and accurate data collection for macromolecular crystallography using the JUNGFRAU detector*. Nature methods 15.10 (2018), pp. 799–804.

[2] F. Leonarski et. al. *Jungfraujoch: hardware-accelerated data-acquisition system for kilohertz pixel-array X-ray detectors* Journal of Synchrotron Radiation 30, 2023

[3] Mozzanica et. al. *The JUNGFRAU Detector for Applications at Synchrotron Light Sources and XFELs* Synchrotron Radiation News 31 2018

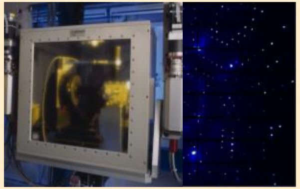
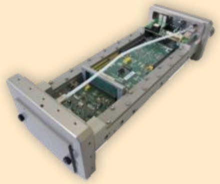
Backup slides

What about integrating detectors?

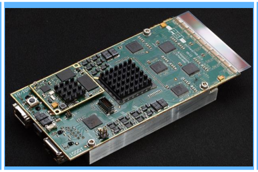
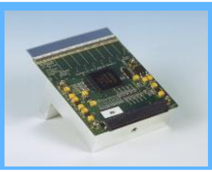
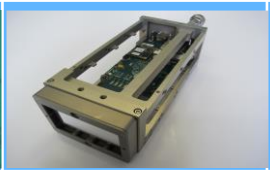
- Charge integrating detector with dynamic gain switching (e.g. Jungfrau) can outperform single photon counters at high rates [1]
  - Linear up to 20M 12keV photons/pixel/s (Jungfrau2 100M 12 keV photons?)
  - Rate capabilities scales with photon energy and frame rate
  - (Almost) no corner effect
- Provides more information about photons in the sparse regime (interpolation)
- Higher demands on the readout system
  - Needs to run at maximum frame rate for optimal data quality
  - Pedestal subtraction and conversion into energy

[1] F. Leonarski et al. “Fast and accurate data collection for macromolecular crystallography using the JUNGFRAU detector”. In: Nature methods 15.10 (2018), pp. 799–804.

Detector portfolio: Single photon counting

	MYTHEN3	PILATUS	EIGER	MATTERHORN
				
Technology	UMC 250 nm	UMC 250 nm	UMC 250 nm	UMC 110 nm
Status	Commercially available	Commercially available	Commercially available	Prototyping phase
Pixel size	**50 µm (Strips)**	172 x 172 µm^2	**75 x 75 µm^2**	**75 x 75 µm^2**
Maximum system size	**120° (=48 modules)**	**6M (=42 x 43 cm^2)**	**9M (=23 x 23 cm^2)**	4 x 4 mm^2
Minimum threshold	< 4 keV	**< 2 keV**	**< 2.5 keV**	**< 1 keV** with **iLGAD technology**
Count rate capability	>2 MHz/Strip (10% deviation, Standard)	0.5-1.0 MHz/Pixel (10% deviation)	0.2-0.7 MHz/Pixel (10% deviation)	**20 MHz/Pixel** (20% deviation)
Maximum frame rate	**100 kHz (8-bit)**	300 Hz/Module	**23 kHz (1-bit)**	**10 kHz (16-bit)**
Applications **(Examples)**	• Powder Diffraction • Energy dispersives spectrometer	• Protein Crystallography • Time-resolved experiments	• Protein Crystallography • XPCS • Coherent X-Ray Imaging	• **Optimized for high count-rates** • **Electron collection**

Detector portfolio: Charge integrating

	GOTTHARD	GOTTHARD2	AGIPD[1]	JUNGFRAU	MÖNCH
					
Technology	IBM 130 nm	UMC 110 nm	IBM 130 nm	UMC 110 nm	UMC 110 nm
Status	Modules available	Modules available	Modules available	Modules available	(Advanced) Prototyping
Pixel size	50 µm (Strips)	50 µm (Strips)	200 x 200 μm^2	**75 x 75 μm^2**	**25 x 25 μm^2**
Maximum system size	Modules (=10 ASICs)	Modules (=10 ASICs)	1Mpixel (=16 Modules)	16Mpixel (=32 Modules)	Single Chip (=1x1 cm^2)
Noise (r.m.s.)	<200 e^- ENC	~300 e^- ENC @ 4.5 MHz	< 322 e^- ENC < 214 e^- ENC (HG)	**< 100 e^- ENC (G0) < 55 e^- ENC (HG0)**	**<35 e^- ENC**
Dynamic range	**< $1 \cdot 10^4$ x 12.4 keV (3 gain stages)**	**> $8 \cdot 10^3$ x 12.4 keV (3 gain stages)**	**< $1 \cdot 10^4$ x 12.4 keV (3 gain stages)**	**< $1 \cdot 10^4$ x 12.4 keV (3 gain stages)**	< 500 x 12.4 keV (2 gain stages)
Maximum frame rate	40 kHz (cont.) 1 MHz (burst)	**400 kHz (cont.) 4.5 MHz (burst*) *2720 frames**	**< 5 MHz (burst*) * 352 frames**	**2.4 kHz (cont.) < 1 MHz (burst*) *16 frames**	**6-8 kHz (cont.)**

[1] Developed with the University of Bonn (GER), the University of Hamburg (GER) and DESY (GER)

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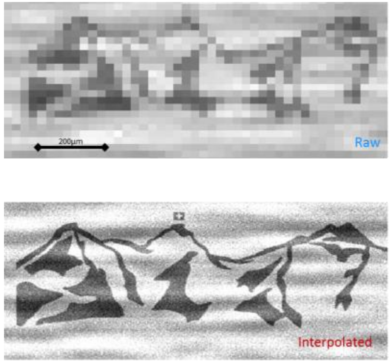
Where does counters fit in?

Interpolation

(<< 1 photon/pixel/frame)

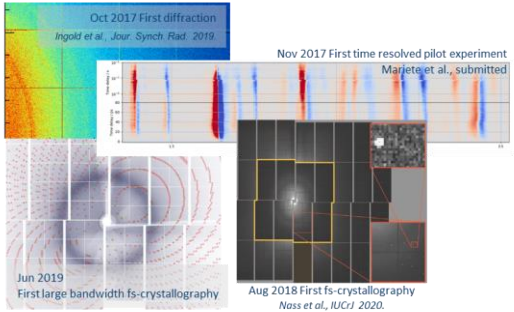


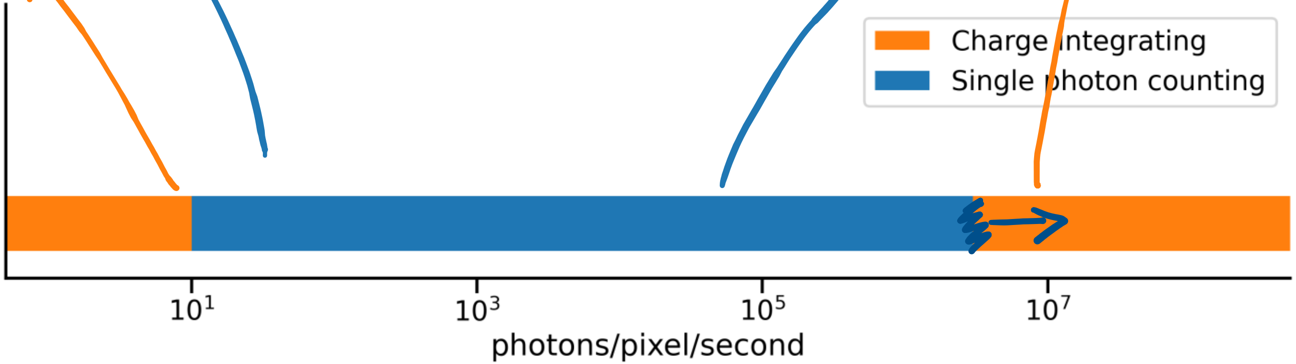
A. Bergamaschi

Single photon counting

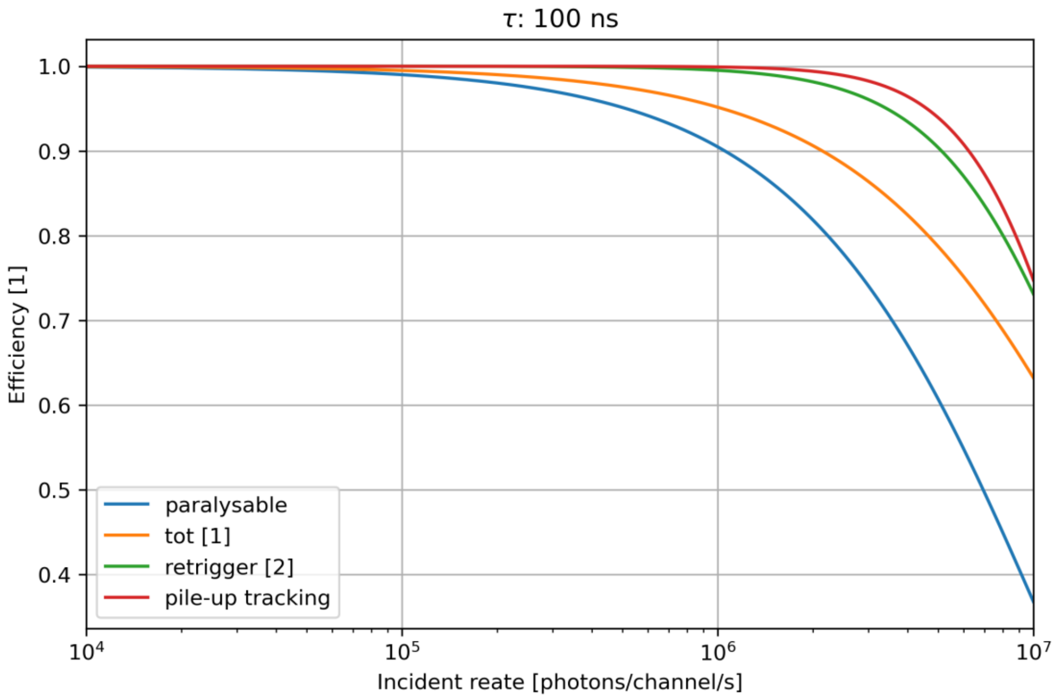
- Workhorse of the synchrotron
- ”Noise free” data
- Pre processed (1 photon - count)
- Gating possible
- Flexible exposure time (us->h)
- Reliable and proven technology

XFEL (all photons at once)





Comparing deadtime models

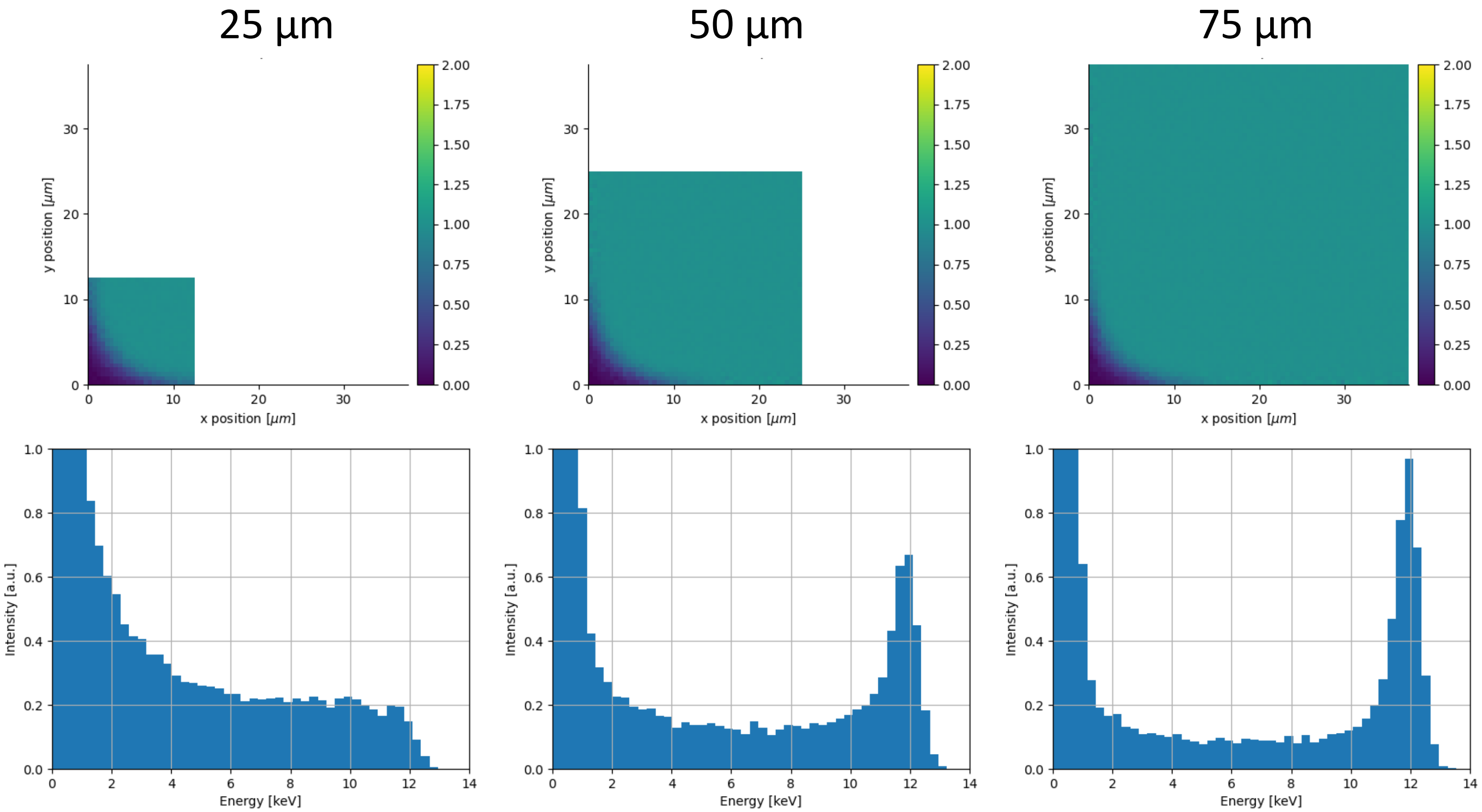


[1] A. Bergamaschi et. al. Time-over-threshold readout to enhance the high flux capabilities of single-photon-counting detectors J. Synchrotron Rad. 18, 923-929. 2011

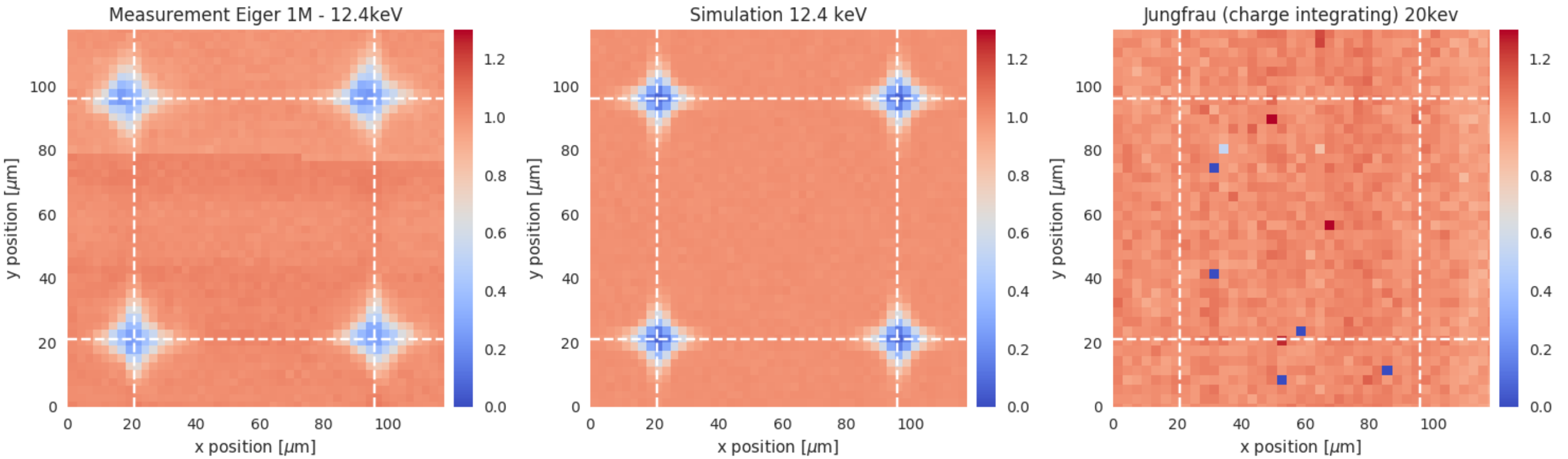
[2] P. Zambon, Dead time model for X-ray photon counting detectors with retrigger capability, NIMA 2021

Pixel size and the corner effect (sim)

Sensor 320 µm silicon

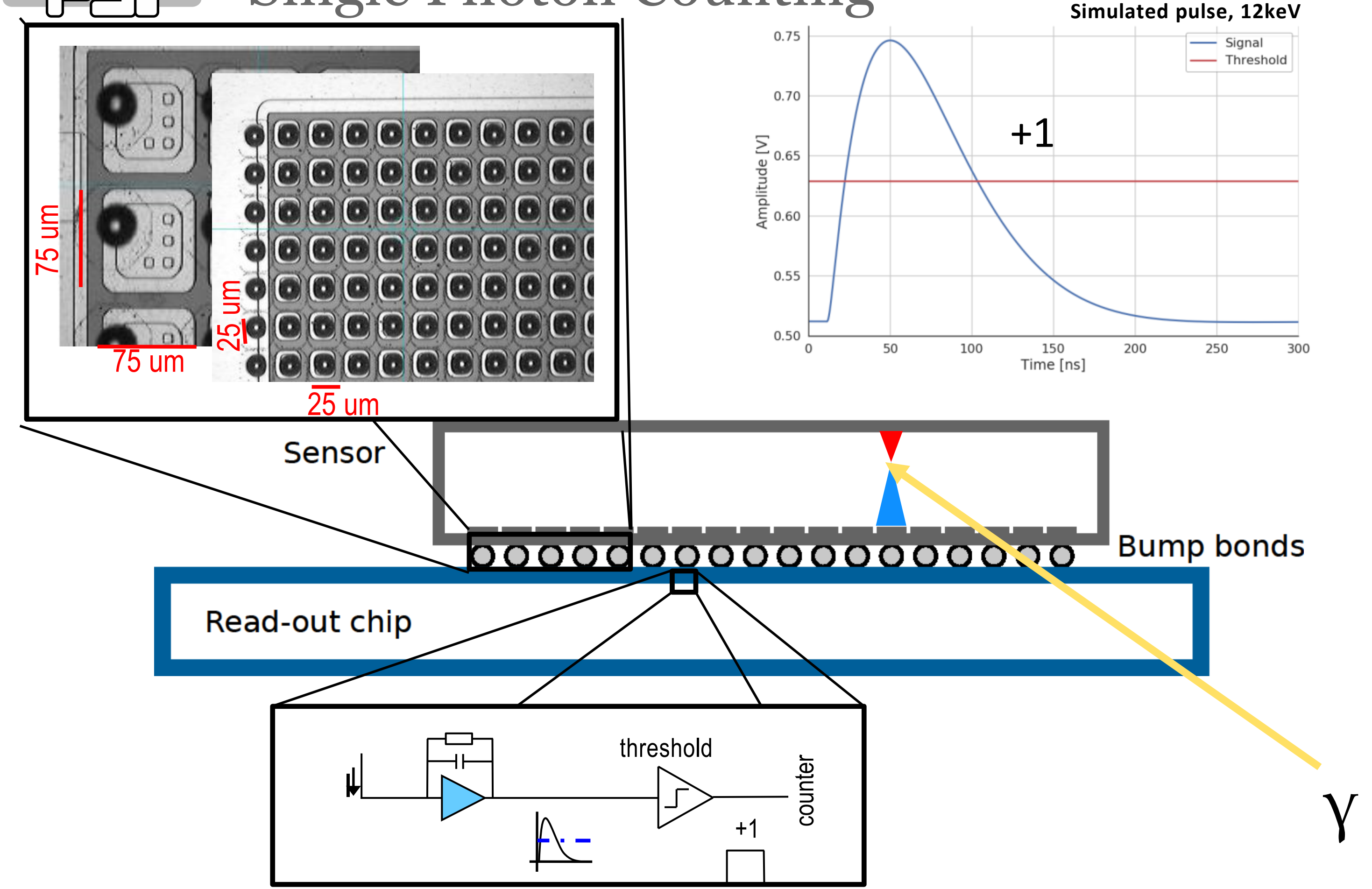


Comparing simulation and measurement



In collaboration with Filip Leonarski from the MX group. Jungfrau data from Aldo Mozzanica.

Single Photon Counting



Detector simulation

Radiation interaction in the sensor layer
- Cross section
- Secondaries

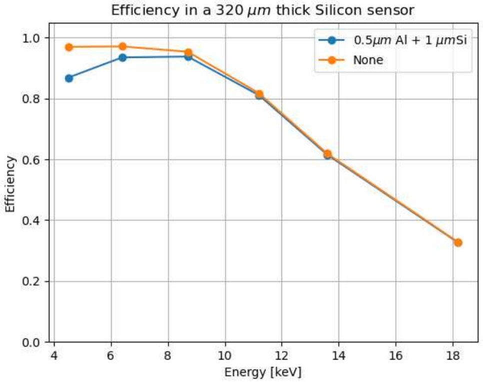
Charge transport
- Drift/diffusion
- Weighting field
- Traps/recombination

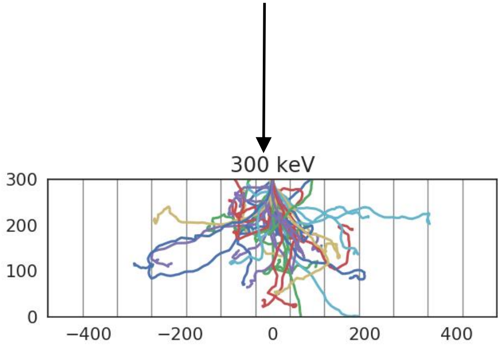
Geant4 + custom transport

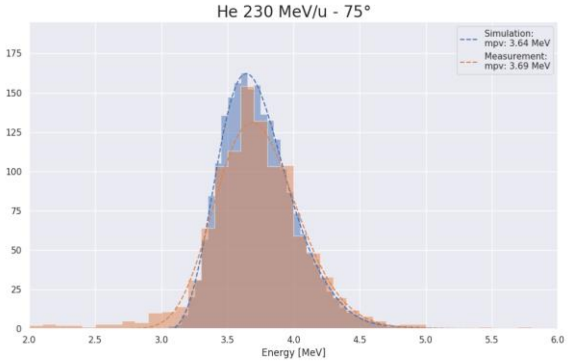
Time structure of beam

Readout ASIC
- Front end
- Digital logic

Analysis & Visualization
- Python & C++
- ROOT







A. Schübel, et.al. "A Geant4 based framework for pixel detector simulation". JINST 9.12 (2014), p. C12018.

D. Krapohl, et.al.. "Validation of Geant4 pixel detector simulation framework by measurements with the Medipix family detectors". TNS 63.3 (2016), pp. 1874–1881..