PSI Center for Photon Science

Count rate measurements of a new single photon counting hybrid pixel detector prototype

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25th iWoRiD, Lisbon Portugal, 01 July 2024

SLS 2.0 – a 4th generation synchrotron

Increased brilliance [1]:

- >100x at 10 keV
- Up to 1000x at 20 keV

Increased electron energy (2.4 → 2.7 GeV)

- Higher energy photons (80 keV)

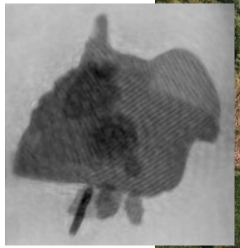
For the detector this means:

- Faster count rate - 20 M photons/pixel/second
- Higher frame rate - 20 kHz continuous frame rate
- Wider energy range - 250 eV – 80 keV

Kirsty Paton- Tuesday 15.10
Evaluation of a Novel Large-Area GaAs:Cr Sensor for Photon Science Applications

Mar Carulla - Tuesday 11.00
Characterization of charge integrating detectors with iLGAD sensors in the soft X-ray energy range

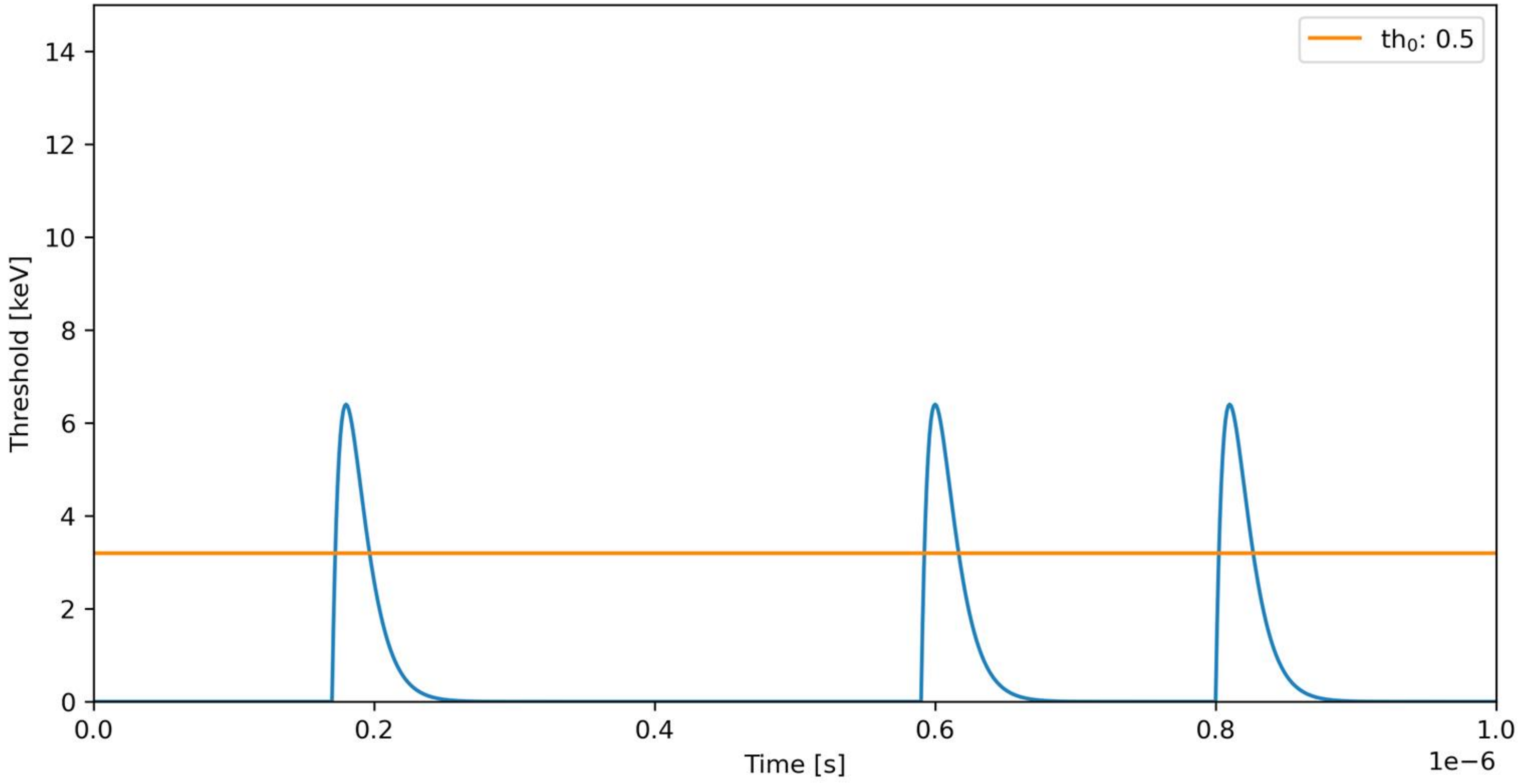
Viktoria Hinger - Thursday 12.20
First applications of the JUNGFRAU detector with iLGAD technology for Resonant Inelastic X-ray Scattering



Photon counting with EIGER and LGADs at ~700 eV
T.Butcher et.al. *Ptychographic nanoscale imaging of the magnetoelectric coupling in freestanding BiFeO3 Advanced Materials 36, 23 2024*
https://doi.org/10.1002/adma.202311157

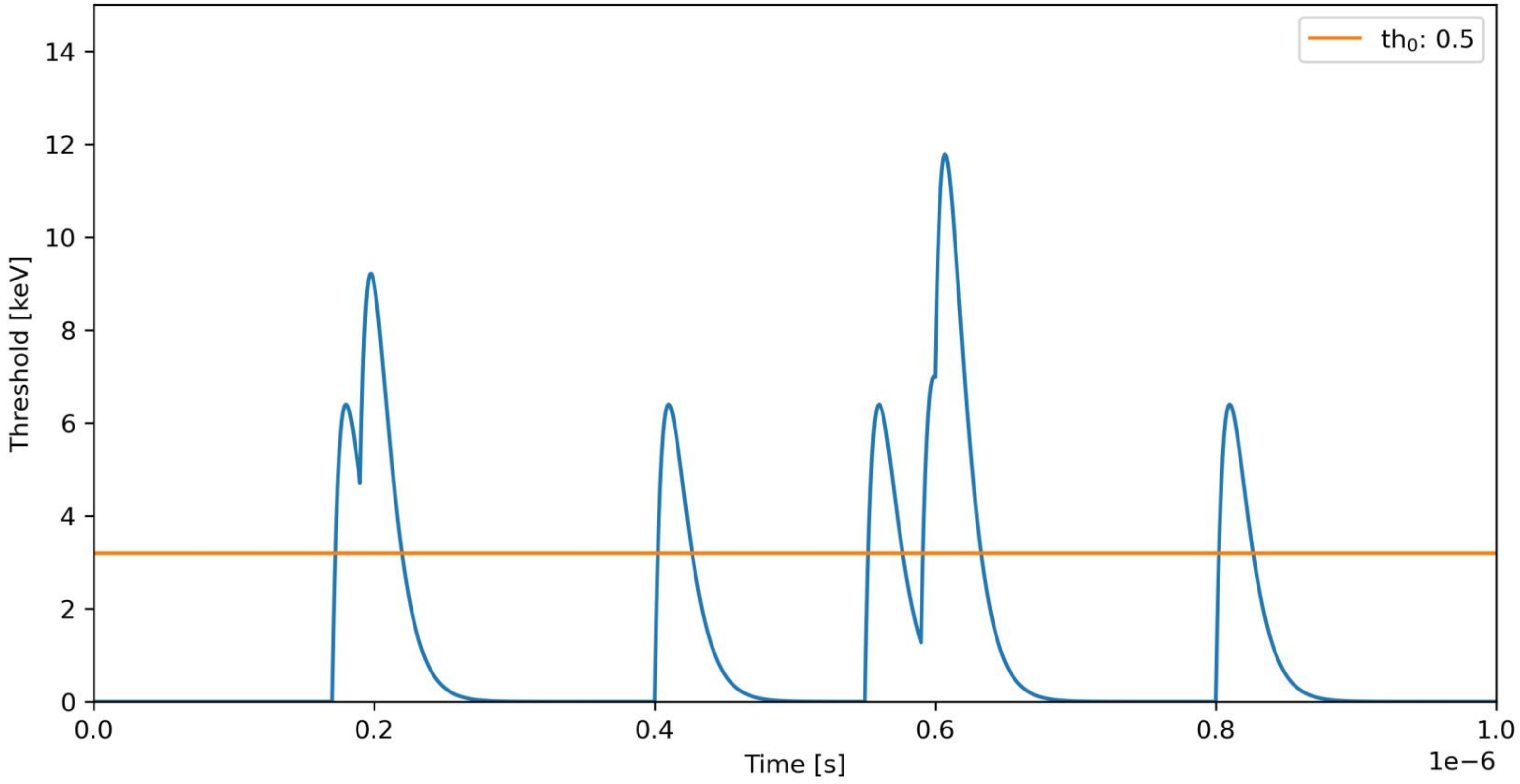
[1] SLS 2.0 Storage Ring Technical Design Report PSI Bericht Nr. 21-02 November 2021

Can we reach 20 M photons/pixel/second?



Single photon counting works extremely well if the incoming photon rate is reasonable low

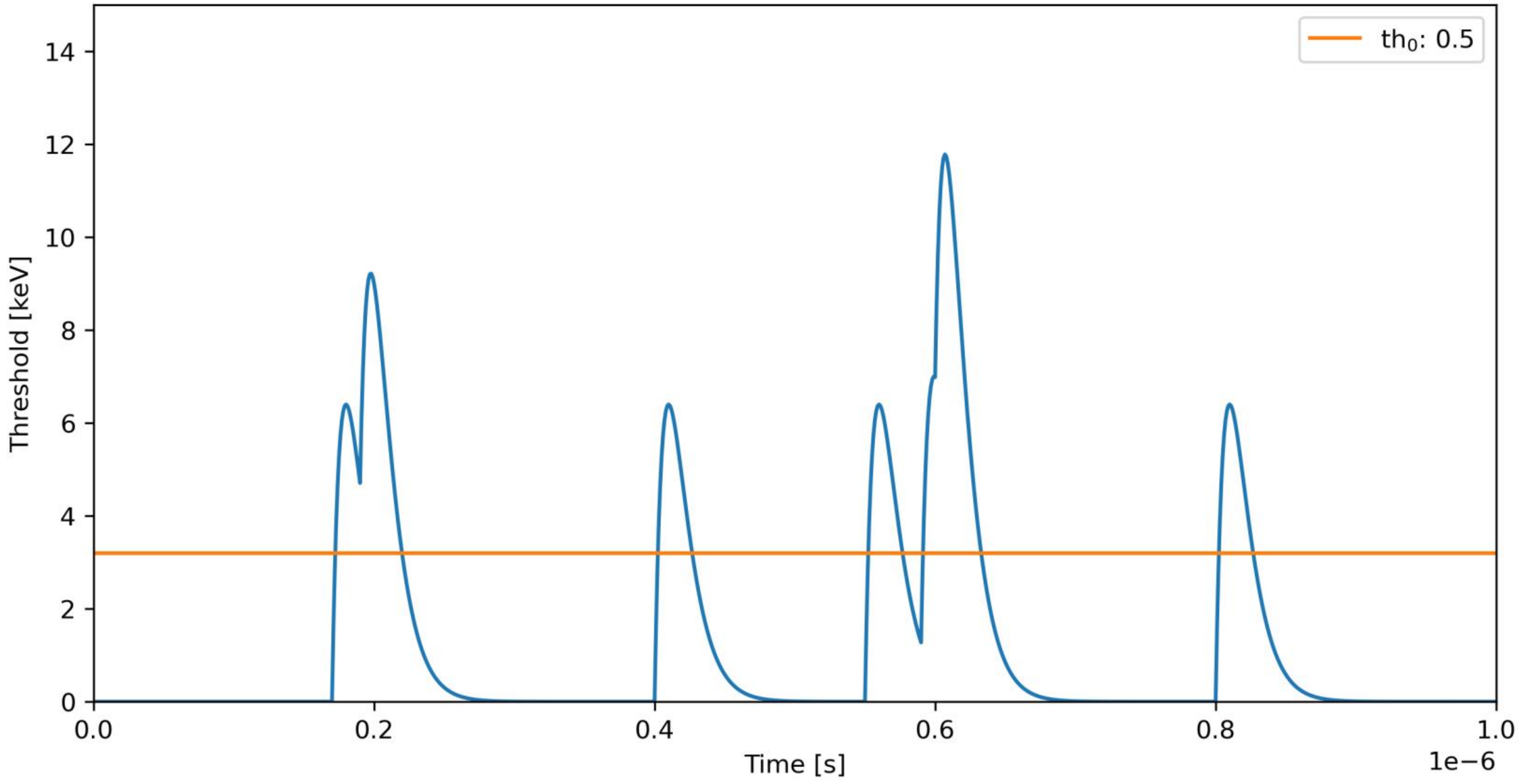
Can we reach 20 M photons/pixel/second?



Single photon counting works extremely well if the incoming photon rate is reasonable low

But as the rate increases we lose efficiency due to pulse pileup

Can we reach 20 M photons/pixel/second?

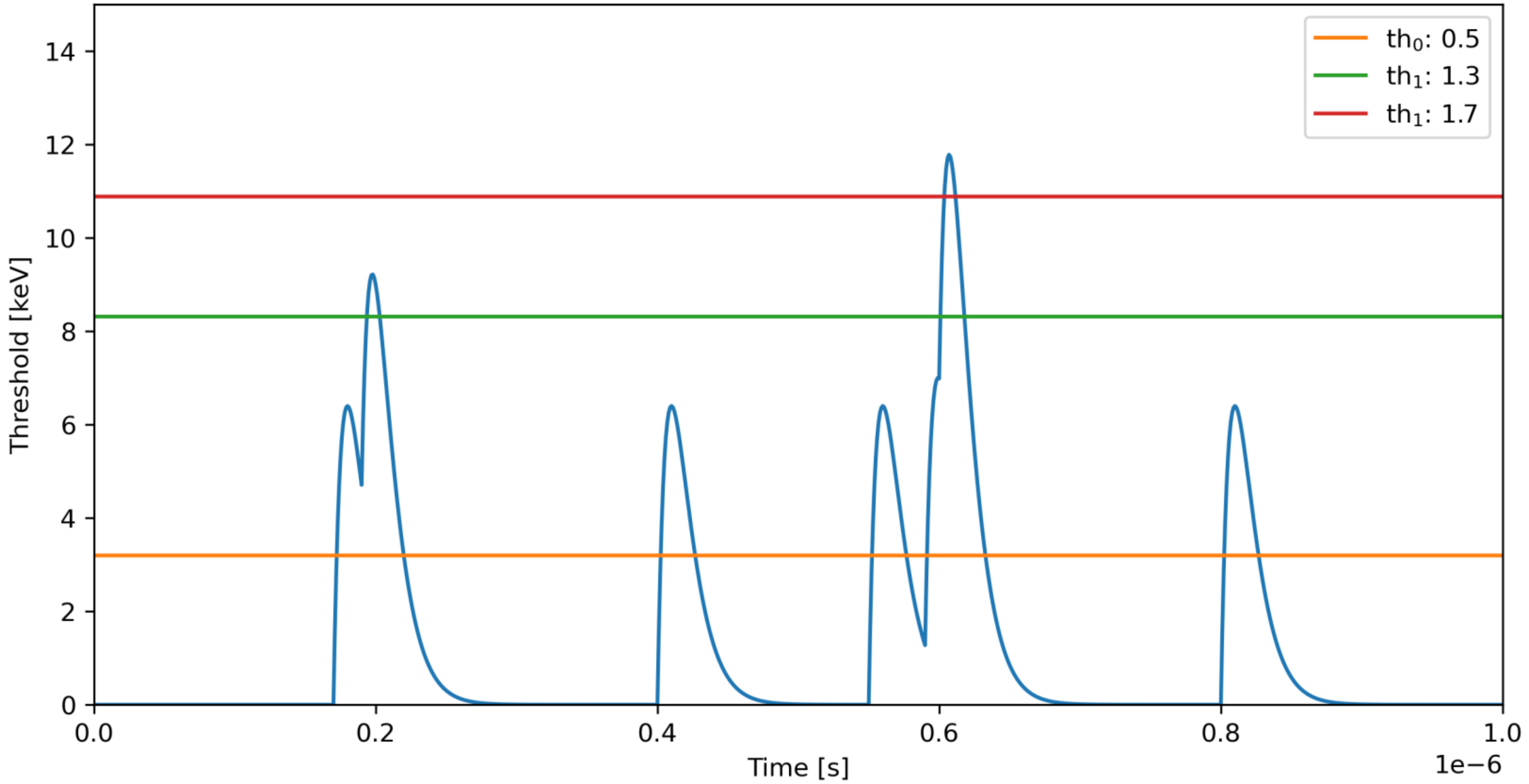


Possible mitigations

- ToT
- Retriggering
- Charge integrating with dynamic gain switching (i.e. Jungfrau)

Can we reach 20 M photons/pixel/second?

Th as fraction of photon energy



Paralyzable counter: $m = ne^{-\tau n}$

Probablility of two and three events pile-up:

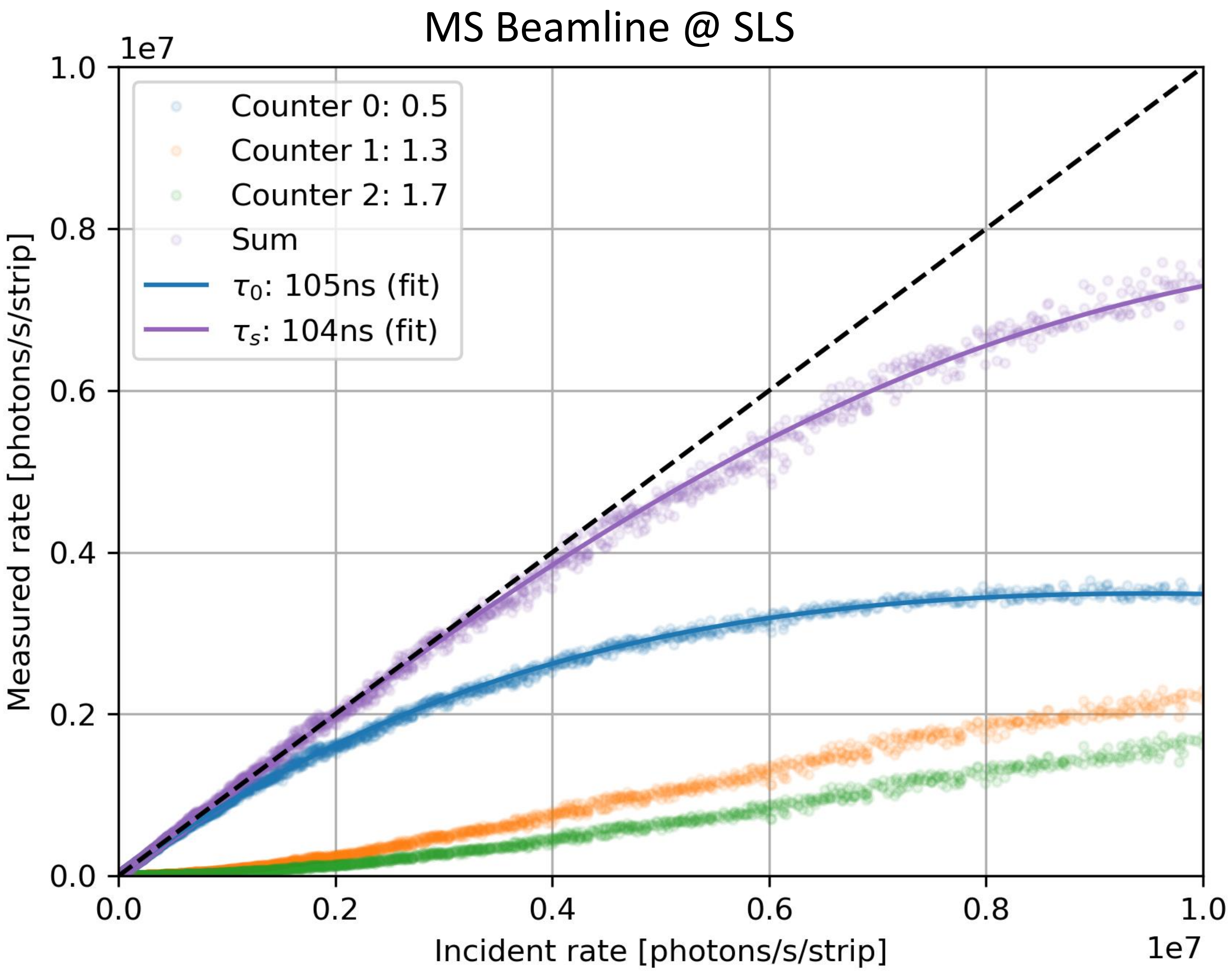
- $p_2 = e^{-\tau n}(1 - e^{-\tau n})$
- $p_3 = e^{-\tau n}\,(1 - e^{-\tau n})^2$

$$m_s = m + m_2 + m_3$$

[1] Glenn F. Knoll, *Radiation Detector and Measurement* 4th Edition, Wiley

[2] M. Andrae The MYTHEN III Detector System - A single photon counting microstrip detector for powder diffraction experiments ETHZ Doctoral Thesis

Proof of concept measurement with Mythen3 (1D)



Settings: standard

Energy: 15 keV

90% efficiency at:

Single counter : 1.03Mcps

Three counters : 6 Mcps

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

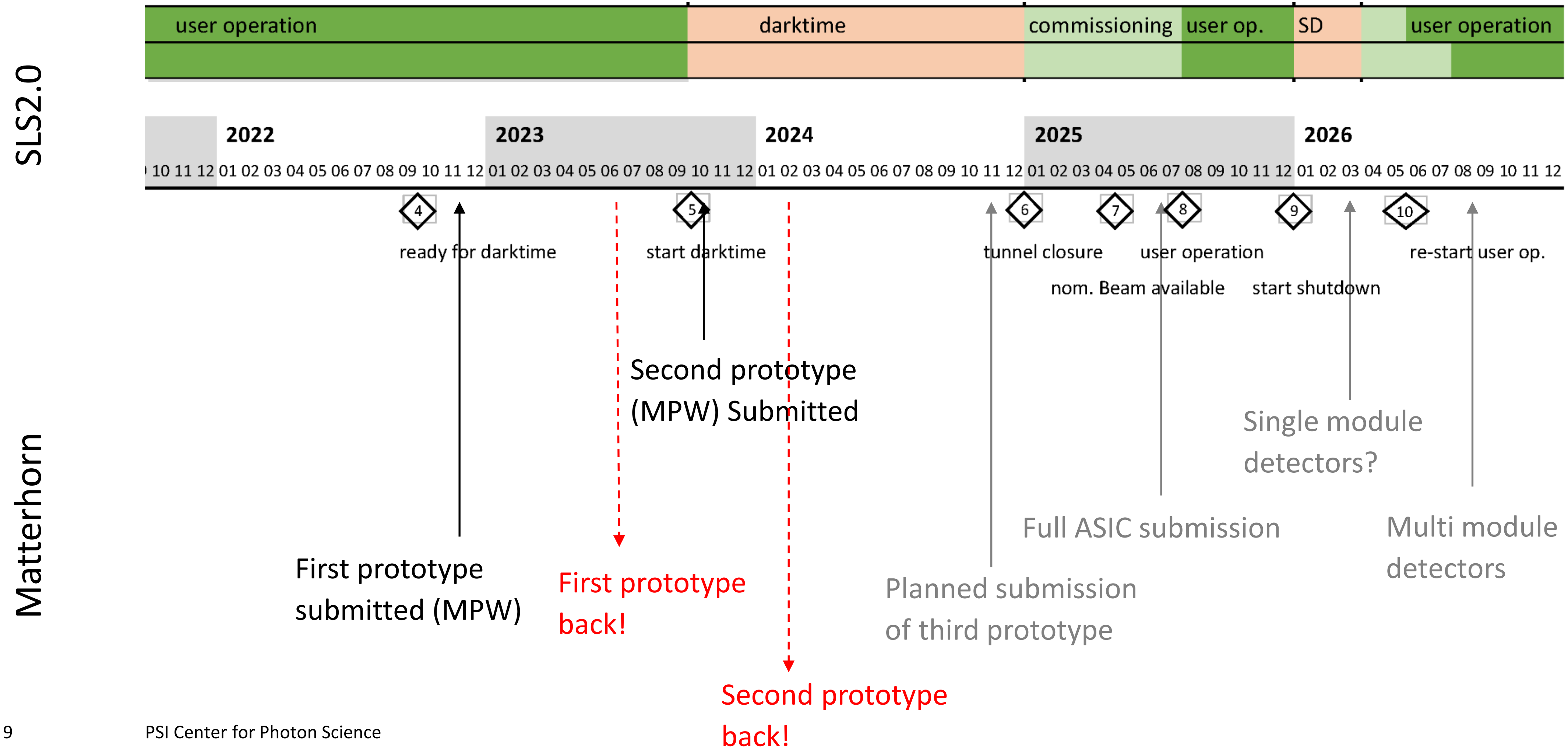
Matterhorn – a new single photon counter for SLS2.0

	EIGER	MATTERHORN
Technology	250 nm	110 nm
Pixel size	75 x 75 um^2	75 x 75 um^2
Thresholds	1	4
Counter depth	12 bit	4x16 bit
Module size	4x8cm^2	4x8cm^2
Readout	2x10Gbit/s	1x100Gbit/s
Frame rate	10 kHz 8bit (burst)	20 kHz 8bit (continuous)
90% efficiency	350k counts/pixel/s*	20M counts/pixel/s
Gating	~us	< 20ns (4 ind.)
Min th	~3 keV	~2 keV

***DECTRIS EIGER2 90% efficiency at ~2 Mcps**

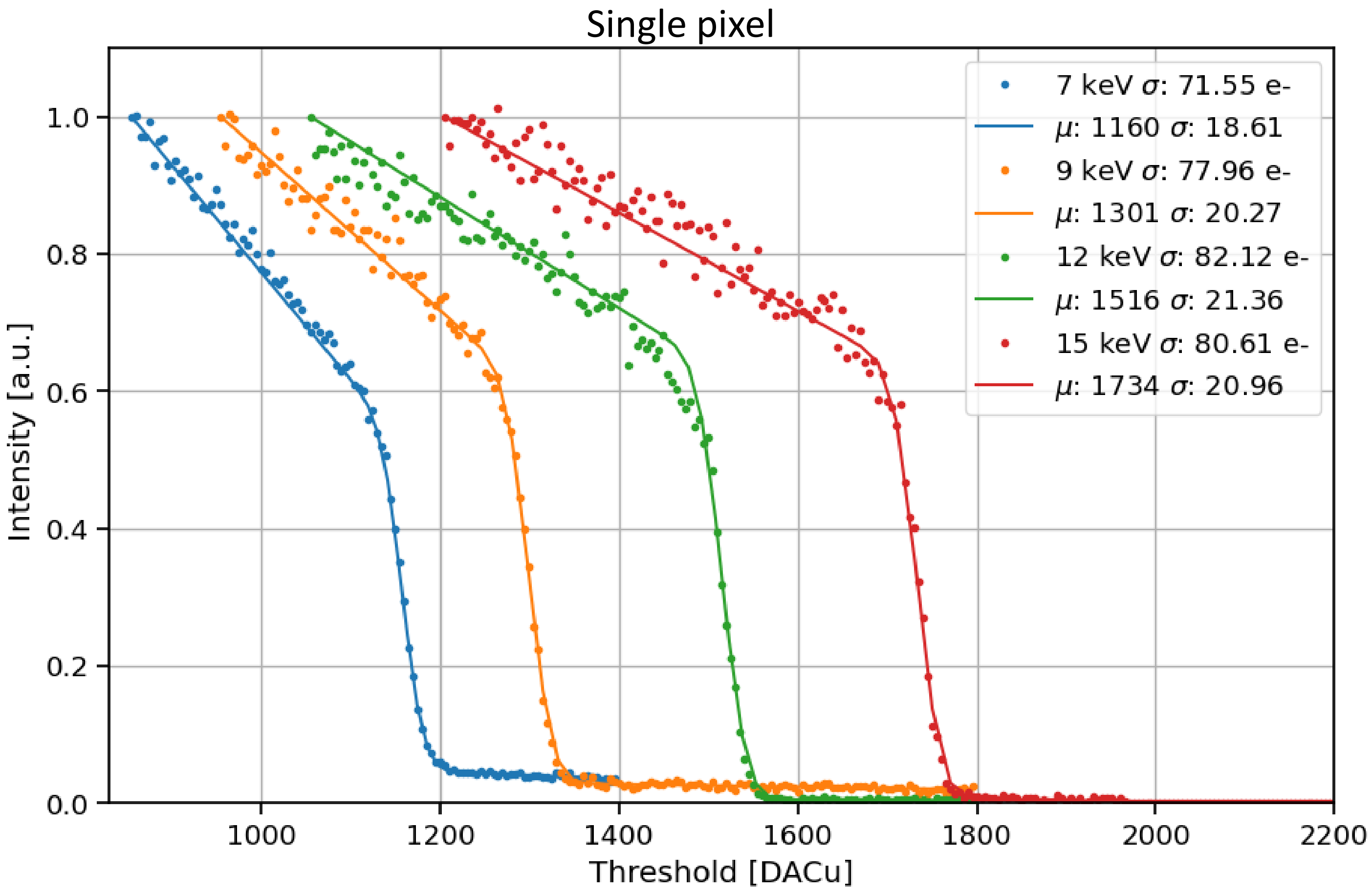
T. Donath et. al. *EIGER2 hybrid-photon-counting X-ray detectors for advanced synchrotron diffraction experiments* J. Synchrotron Rad. (2023). 30, 723-738

Timeline



SLS2.0
user operation
darktime
commissioning
user op.
SD
user operation
2022
2023
2024
2025
2026
10 11 12 01 02 03 04 05 06 07 08 09 10 11 12 01 02 03 04 05 06 07 08 09 10 11 12 01 02 03 04 05 06 07 08 09 10 11 12 01 02 03 04 05 06 07 08 09 10 11 12 01 02 03 04 05 06 07 08 09 10 11 12
4
5
6
7
8
9
10
ready for darktime
start darktime
tunnel closure
user operation
re-start user op.
nom. Beam available
start shutdown
Matterhorn
Second prototype (MPW) Submitted
Single module detectors?
Full ASIC submission
Multi module detectors
First prototype submitted (MPW)
First prototype back!
Planned submission of third prototype
Second prototype back!

Basic characterization of MH02



- Metrologie [1] beamline at SOLEIL with help from: Marie Andrä and Arkadiusz Dawiec
- Calibration at: 7, 9, 12, 15 keV
- Threshold scans fitted with analytical model [2]:

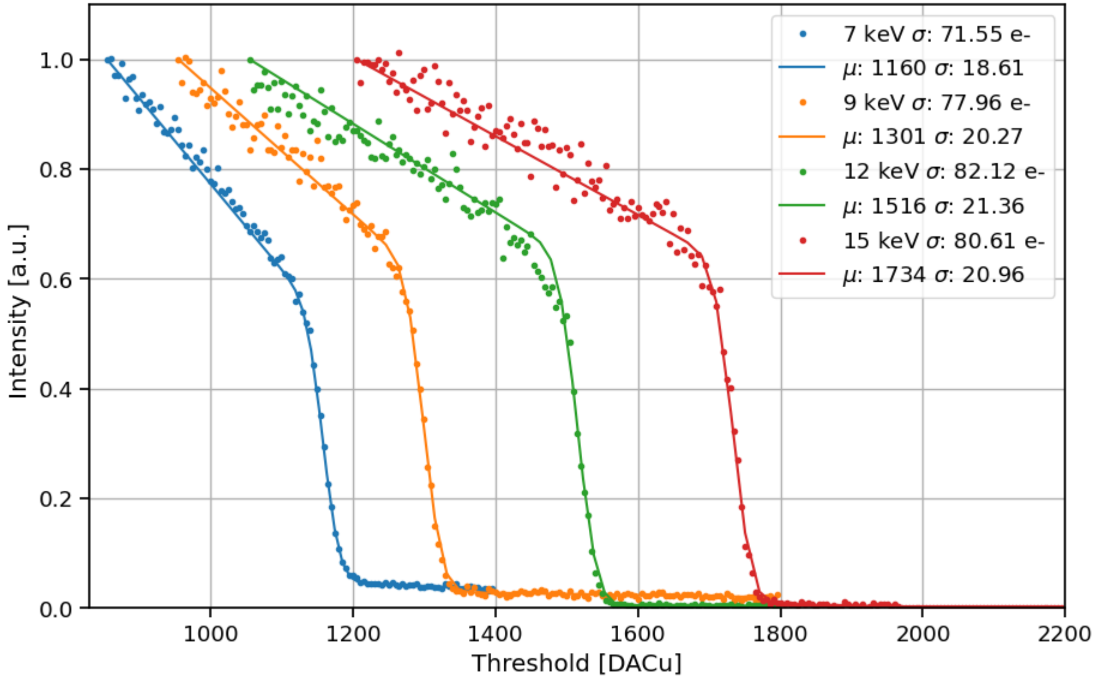
$$f(x) = (p_0 + p_1 x) + 0.5\left(1 + Erf\left(\frac{x-\mu}{\sqrt{2}\cdot\sigma}\right)\right)(A + C(x-\mu))$$

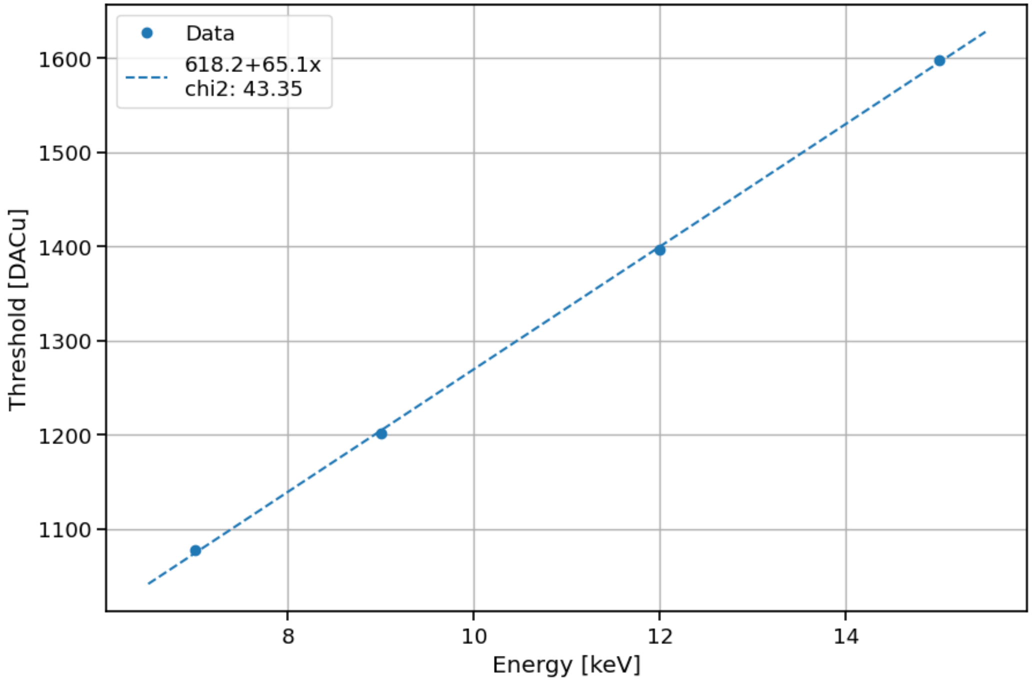
- Rate measurements at 9 keV

[1] https://www.synchrotron-soleil.fr/en/beamlines/metrologie

[2] Bergamaschi A. et. al. *Performance of a single photon counting microstrip detector for strip pitches down to 10 µm* NIMA 519/1 2008

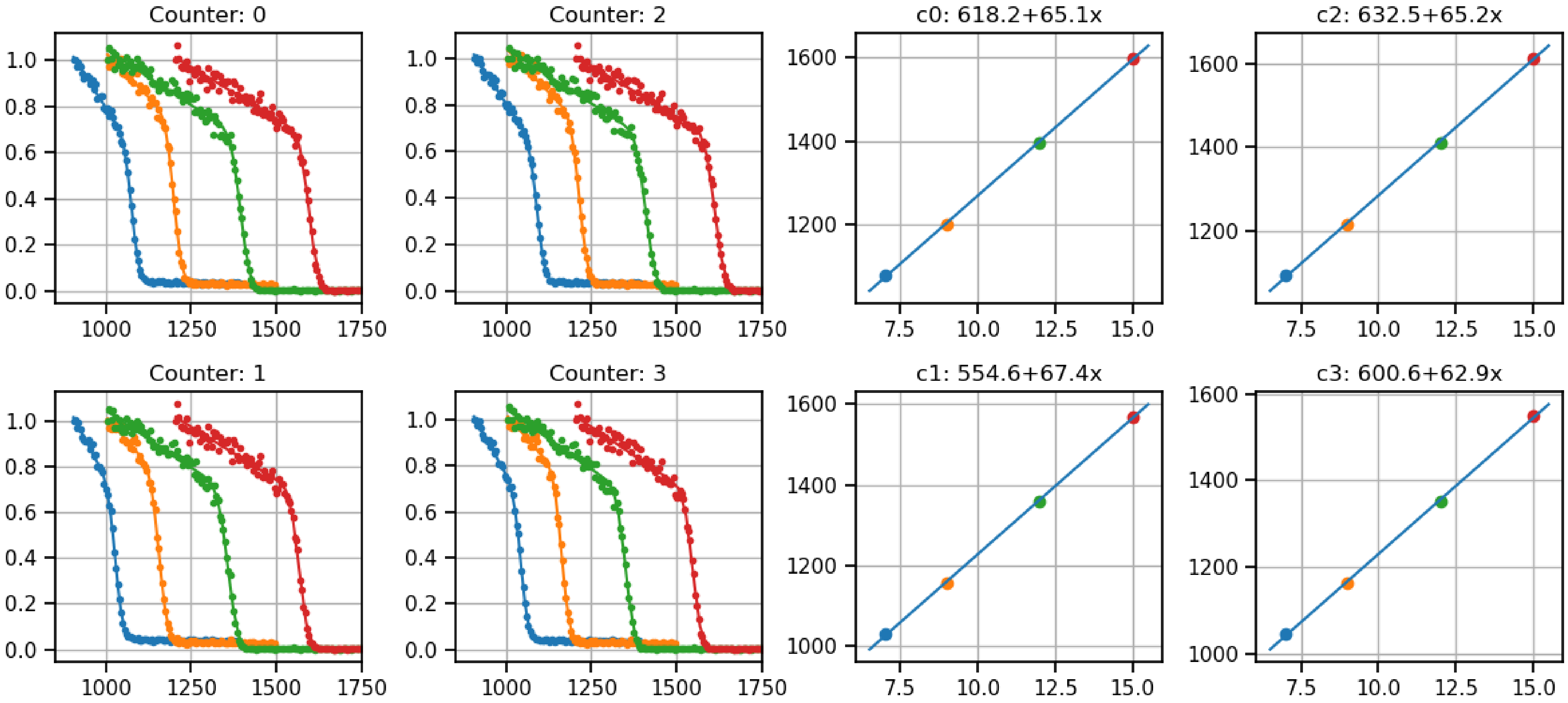
Basic characterization of MH02





Single pixel data

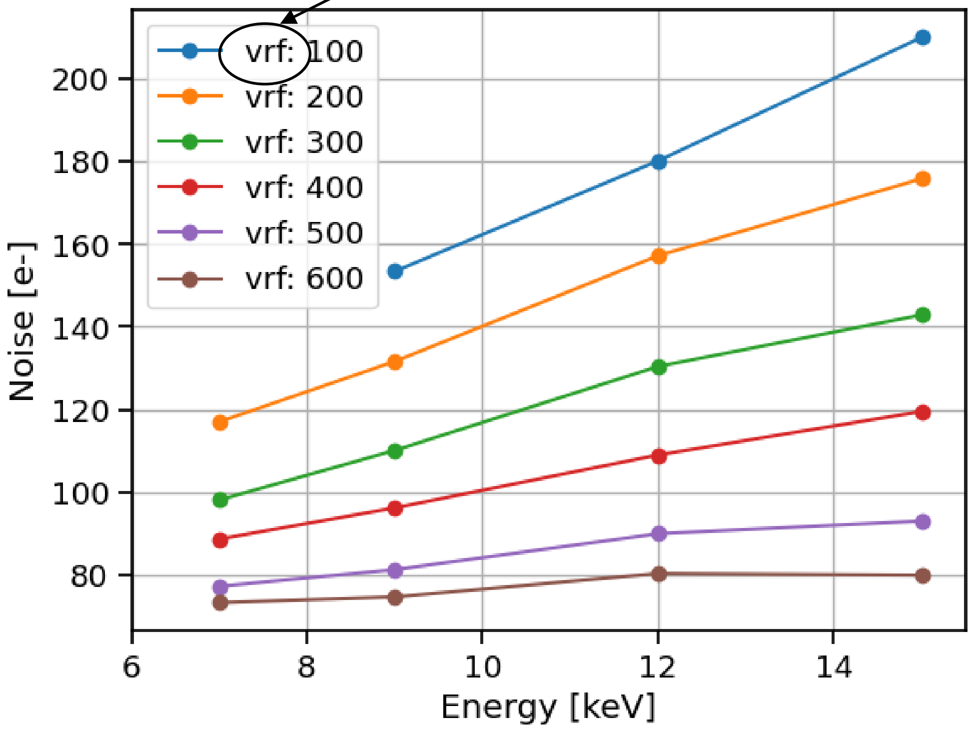
The four counters behave similarly

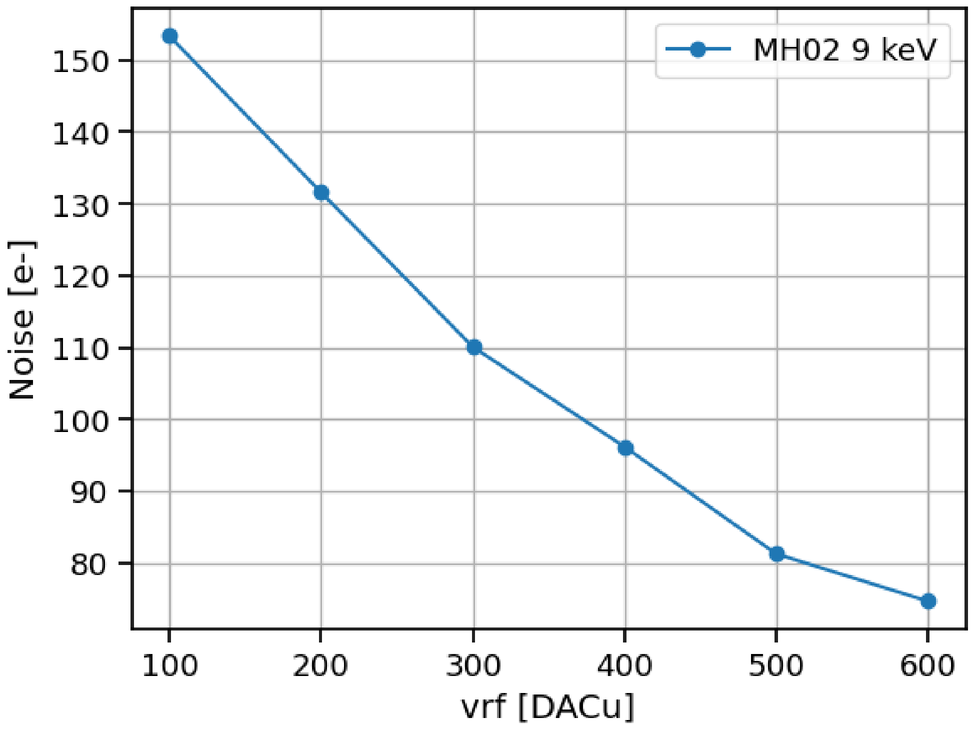


Scanned at the same time

Noise performance of MH02

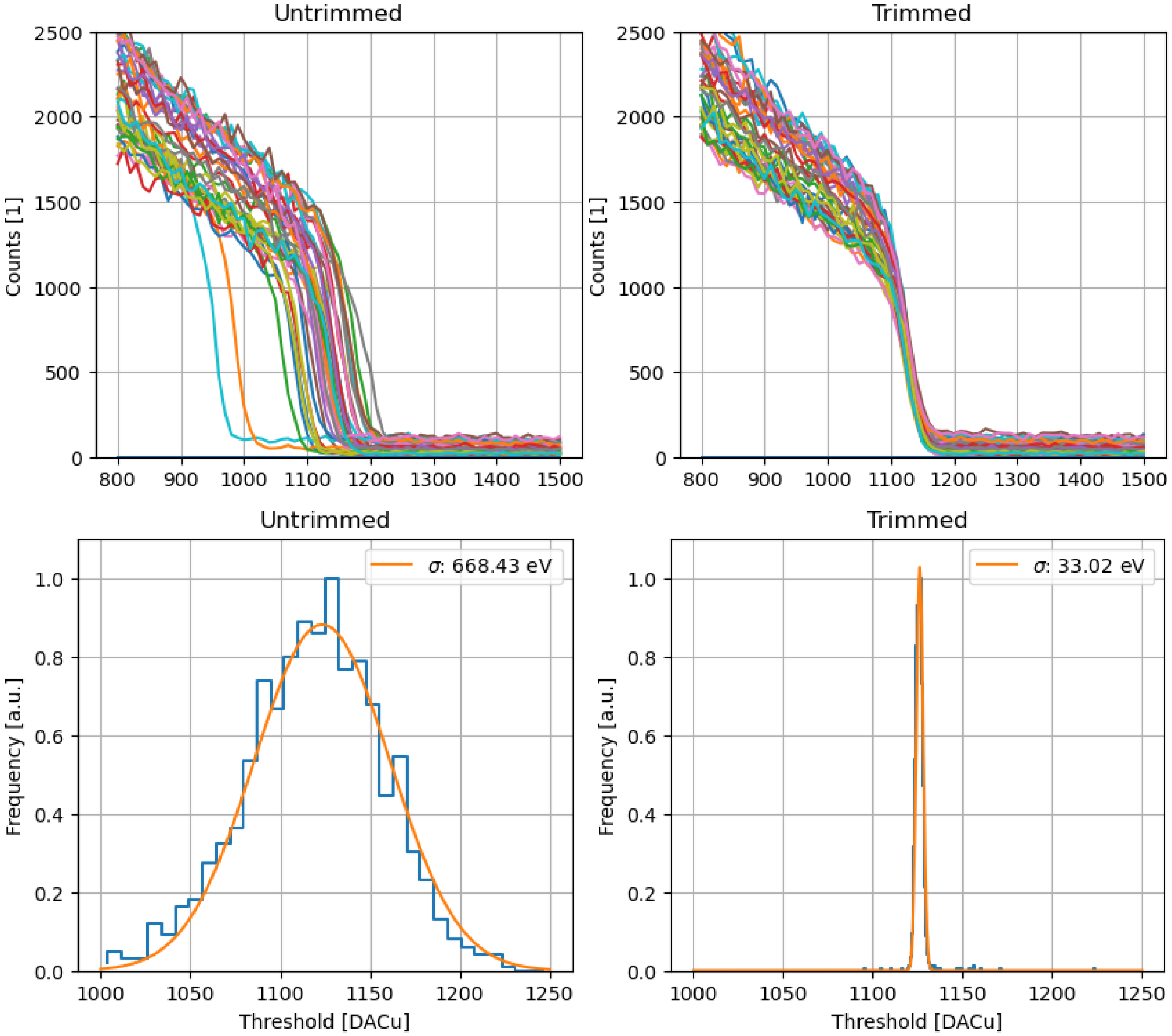
Preamplifier feedback voltage (gain)





fast - slow

Threshold dispersion at 9 keV

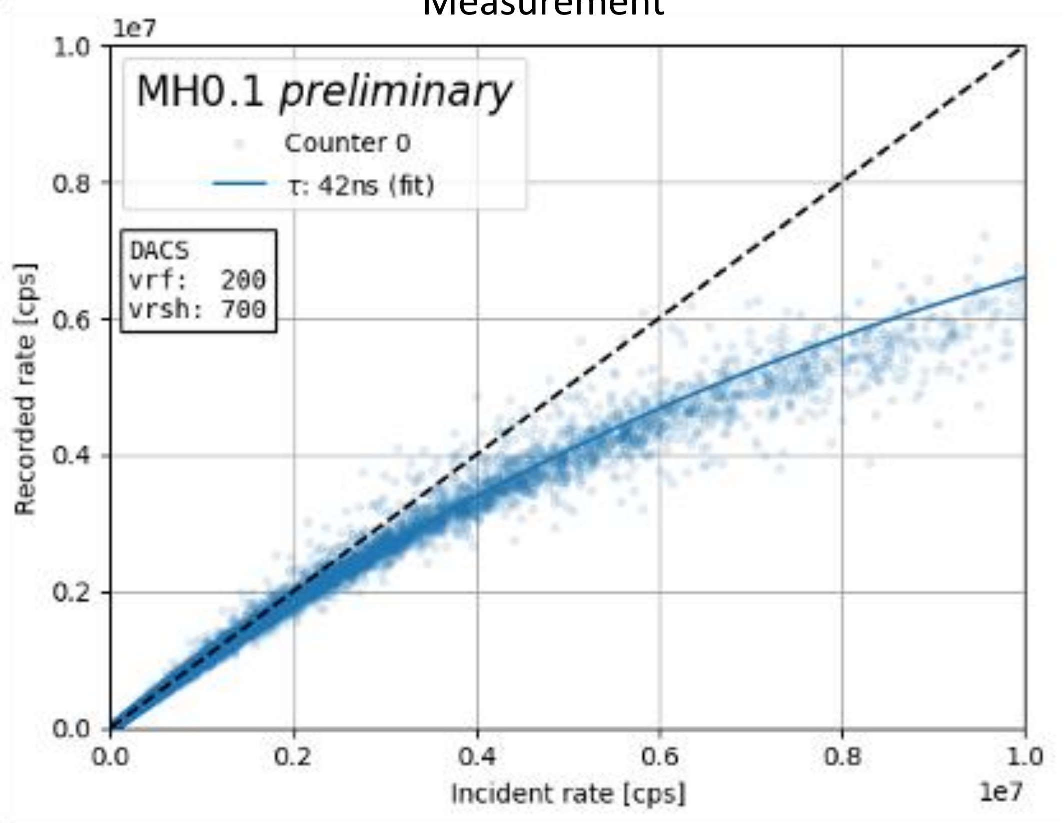


vrf	Untrimmed [eV]	Trimmed [eV]
200	998	59
300	905	43
400	668	33
500	477	29

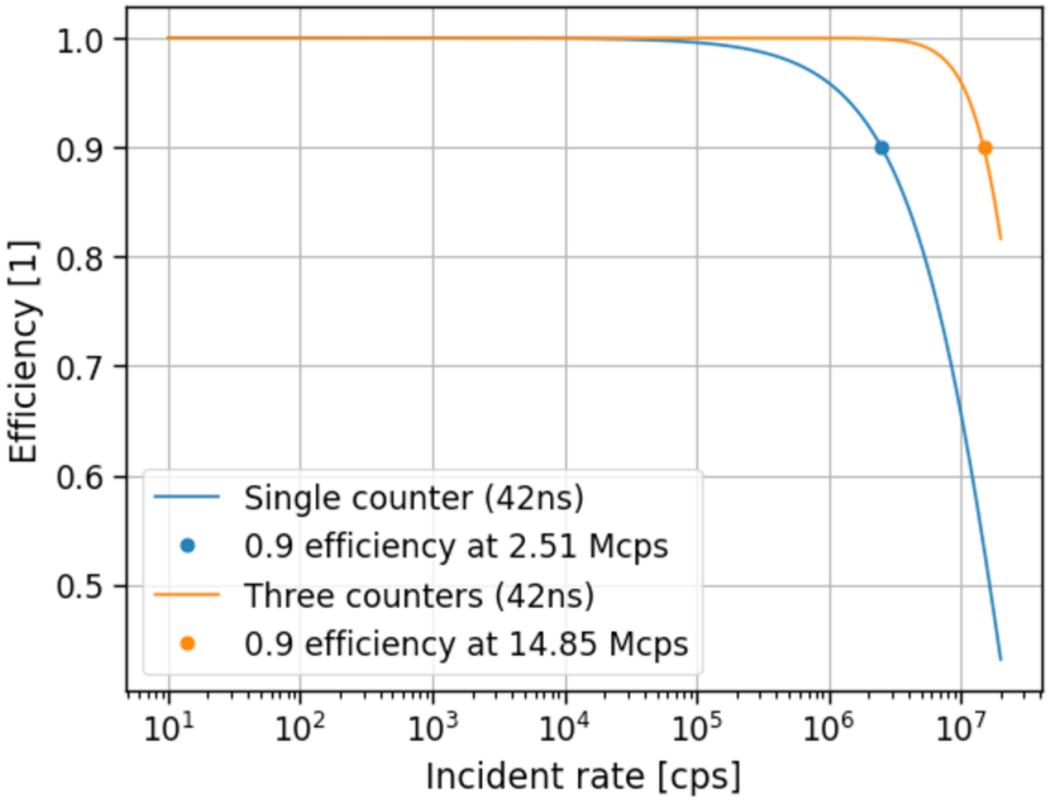
- Small chip (48x48 pixels)
- Non optimized trimming procedure

Single counter rate tests at MS beamline - MH01

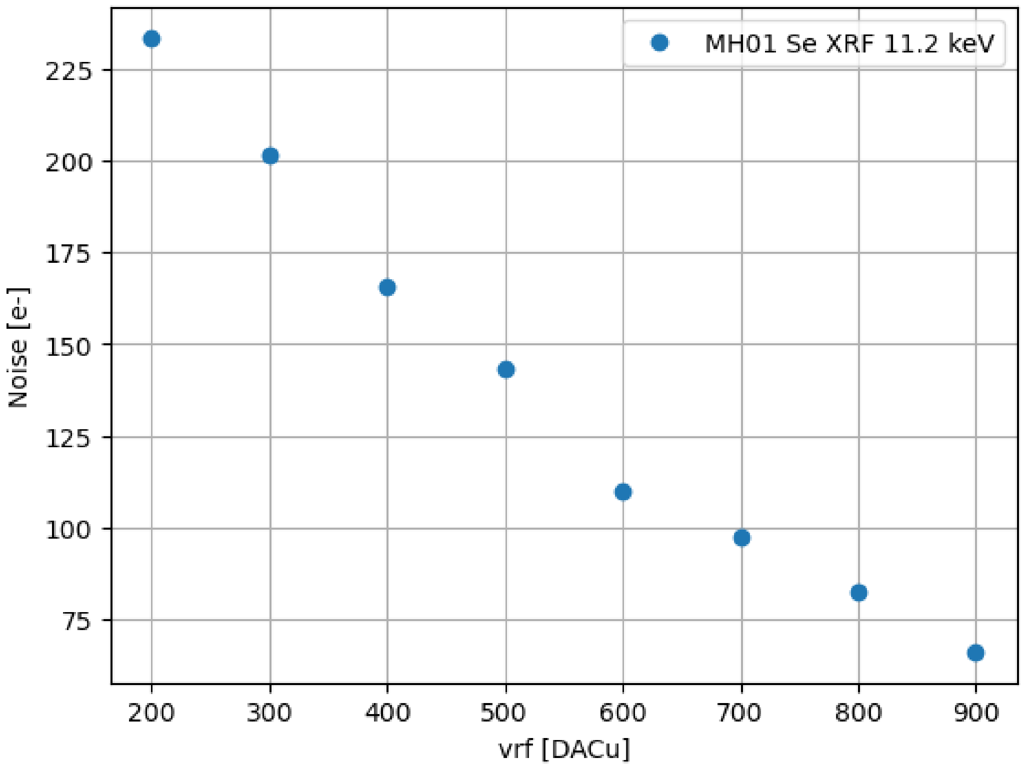
Measurement

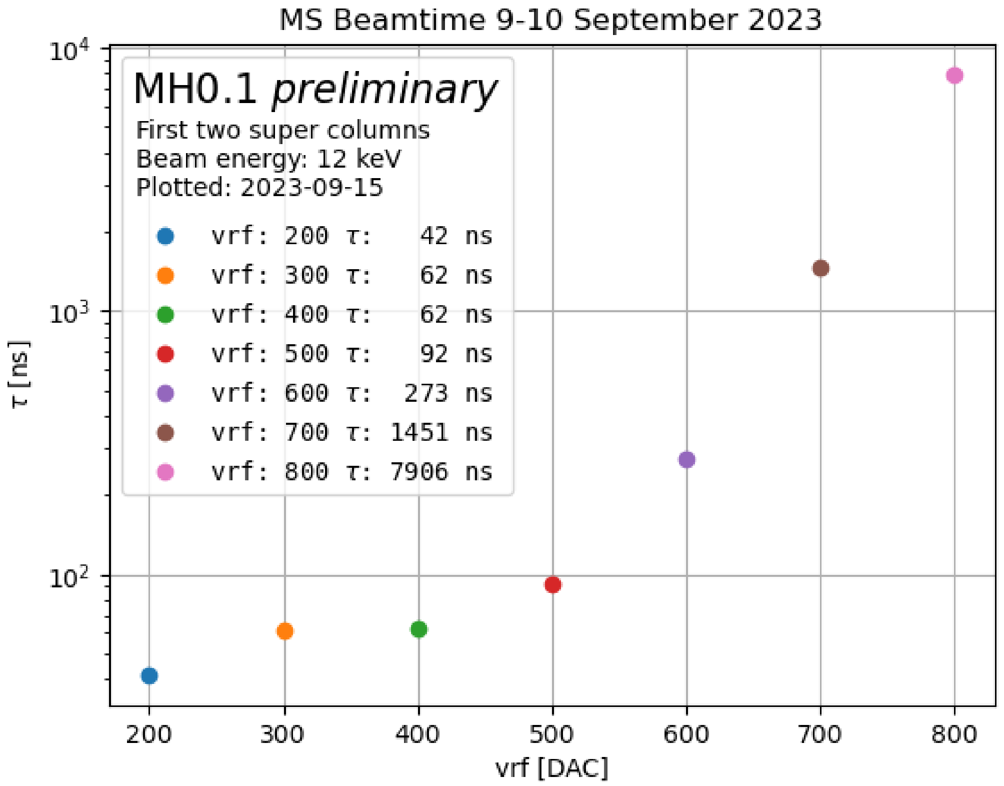


Predicted rate capability using analytical model



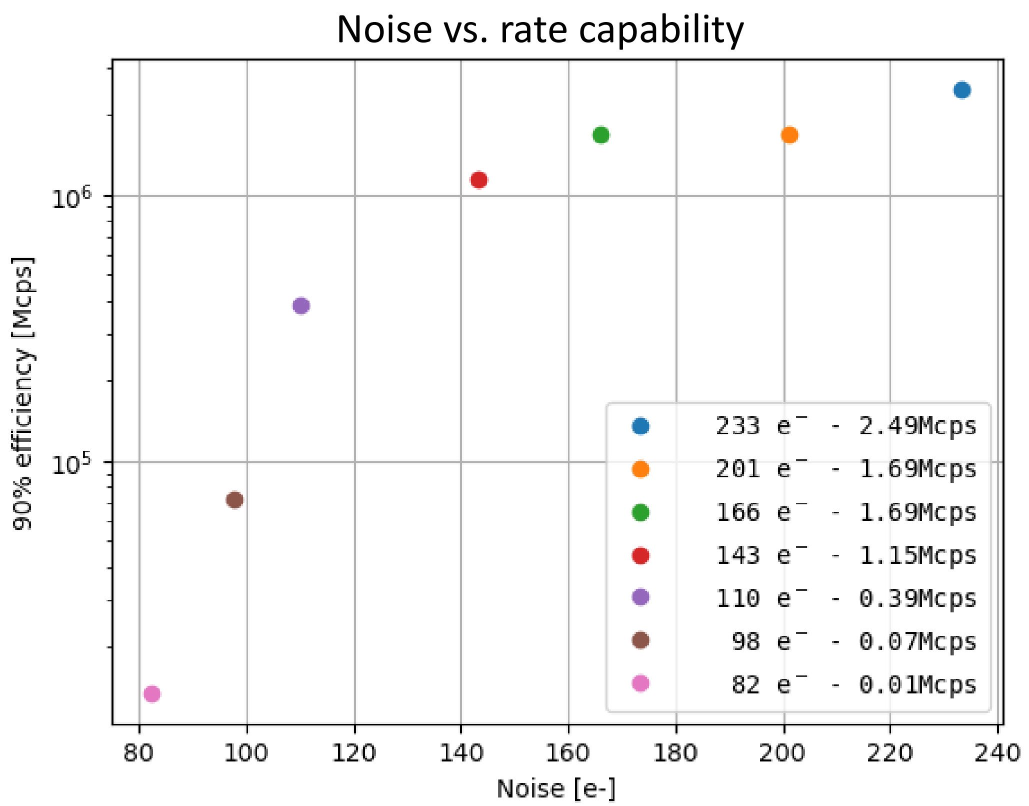
Single counter rate tests at MS beamline – MH01

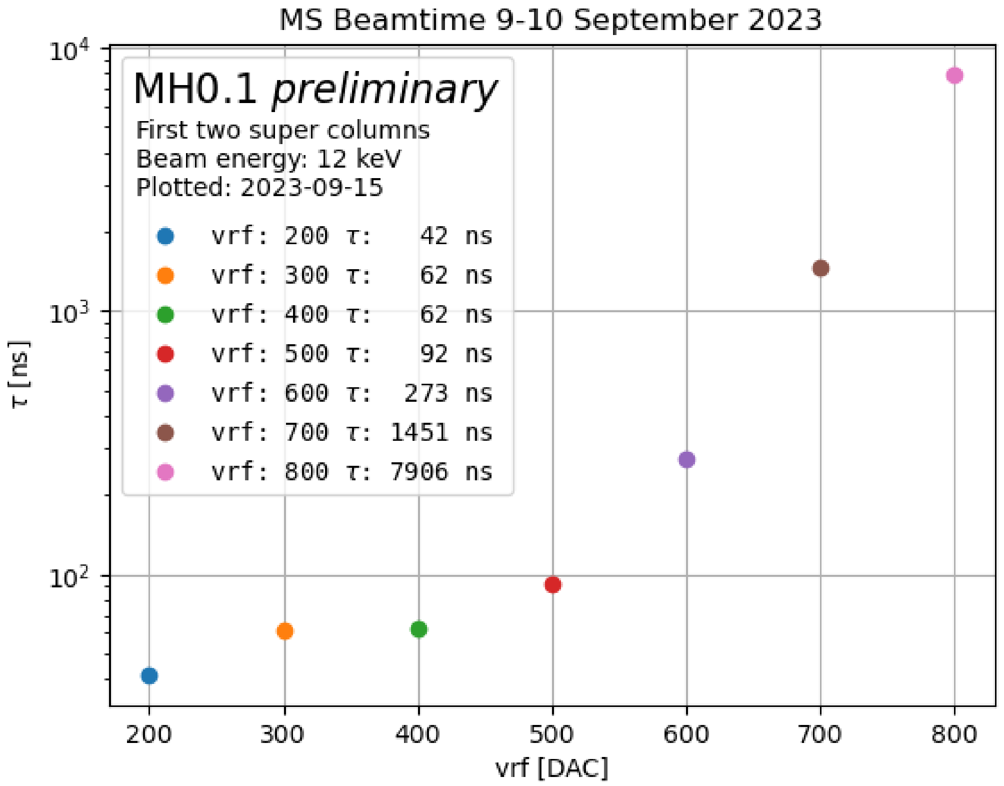




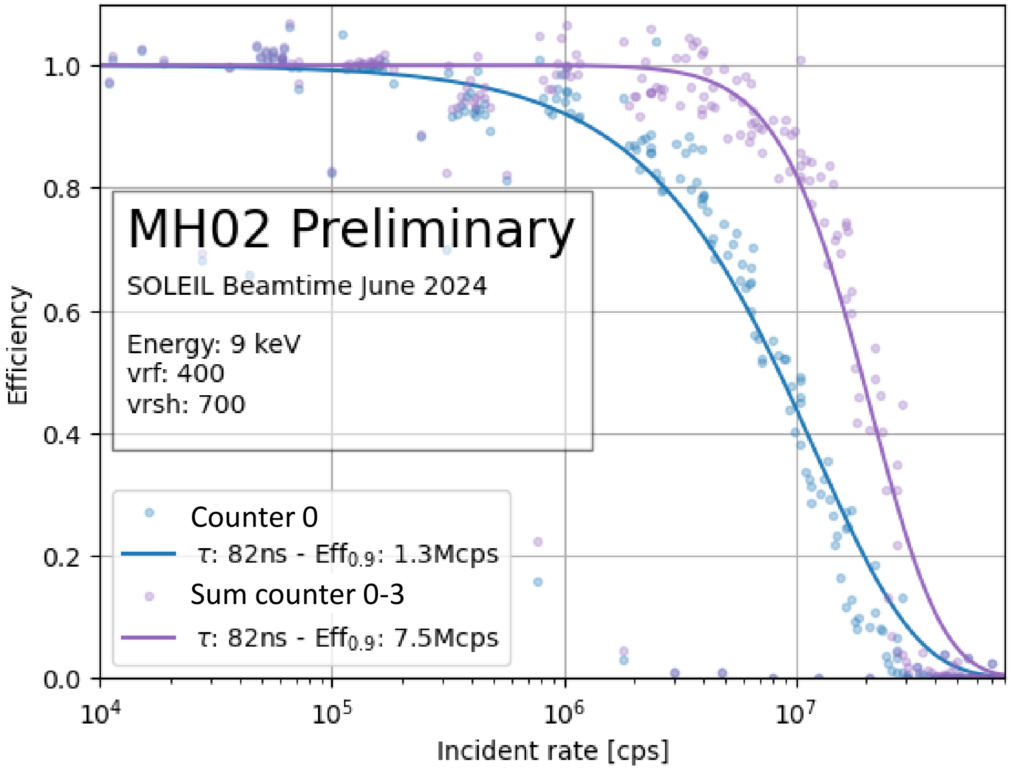
Note: slightly over estimated due to kB peak

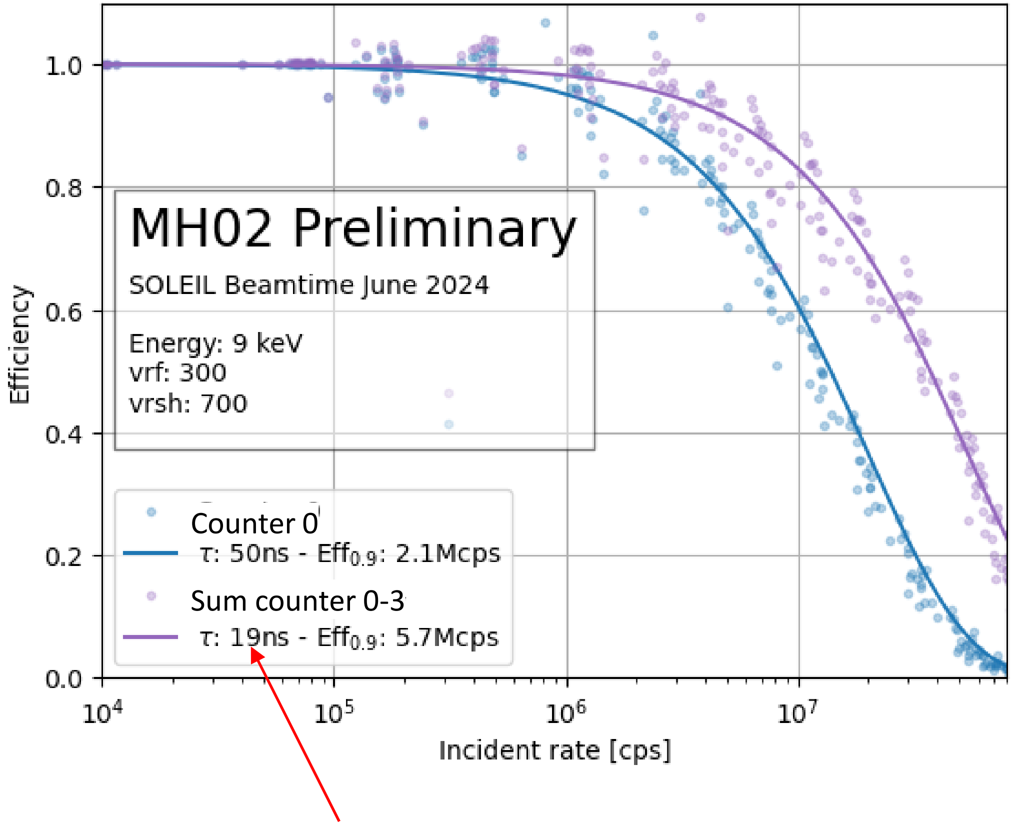
Single counter rate tests at MS beamline – MH01





Multi threshold rate tests at with MH02





Note: fitted with paralyzable function

Conclusion and outlook

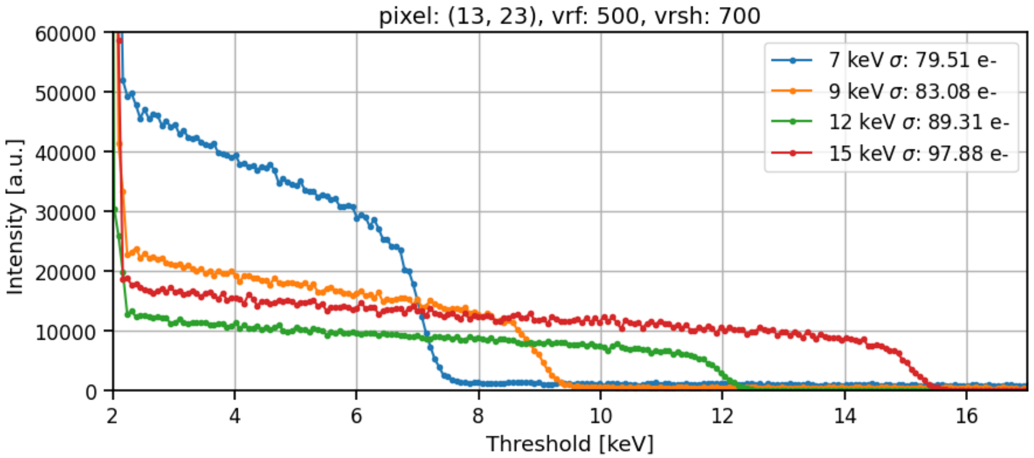
Matterhorn is a new SPC detector for SLS2.0 targeting:

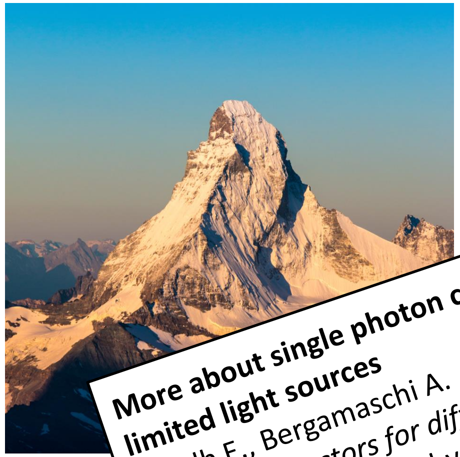
- 20Mcps count rate with 10% loss of efficiency
- 250 eV – 80 keV energy range
- <20 ns gating, multiple thresholds etc.

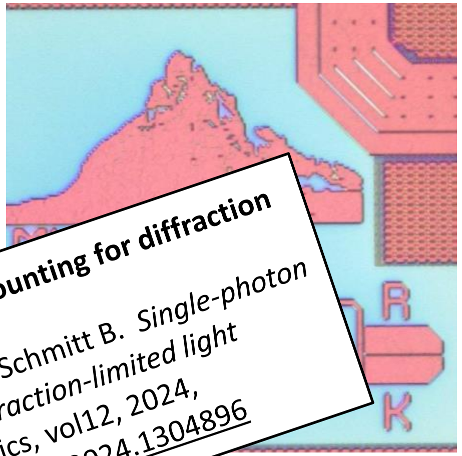
Results from MH01 and MH02:

- Noise down to ~70e- in slow settings
- Demonstrated ~7.5 Mcps at 90% efficiency using multiple thresholds
- Tau of 42ns in single counter mode indicates 15Mcps should be possible with pileup counting
- Tuning ASIC parameters

Submission of full ASIC summer 2025…







More about single photon counting for diffraction limited light sources
Fröjdh E., Bergamaschi A. , Schmitt B. *Single-photon counting detectors for diffraction-limited light sources*, Frontiers in Physics, vol12, 2024, https://doi.org/10.3389/fphy.2024.1304896

Backup slides

Comparison of pileup mitigation

Figure 2

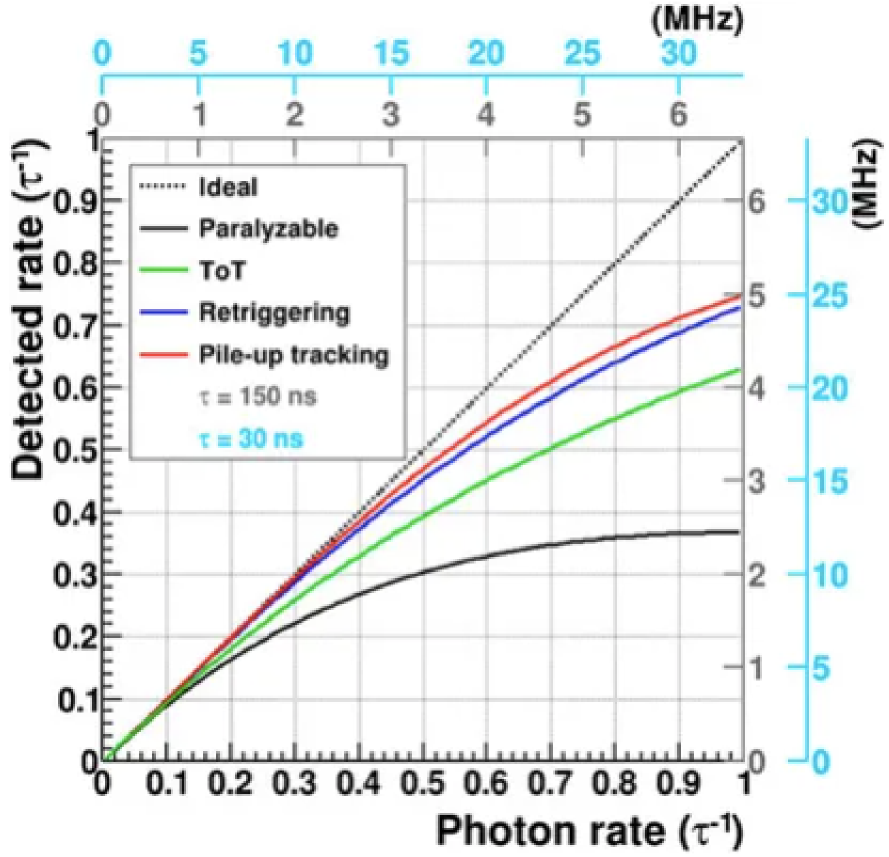


FIGURE 2. Detected rate as a function of the photon rate for a single-photon counting detector calculated using Eqs 1–4, covering the different solutions described in section 2.2. The rate is expressed as the reciprocal of the shaping time per pixel per second. The gray and the blue secondary axes compare the performance in Mphotons/pixel/s of SPC detectors with τ =150 ns and τ =30 ns, respectively.

[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

Operating modes of a single photon “counter”

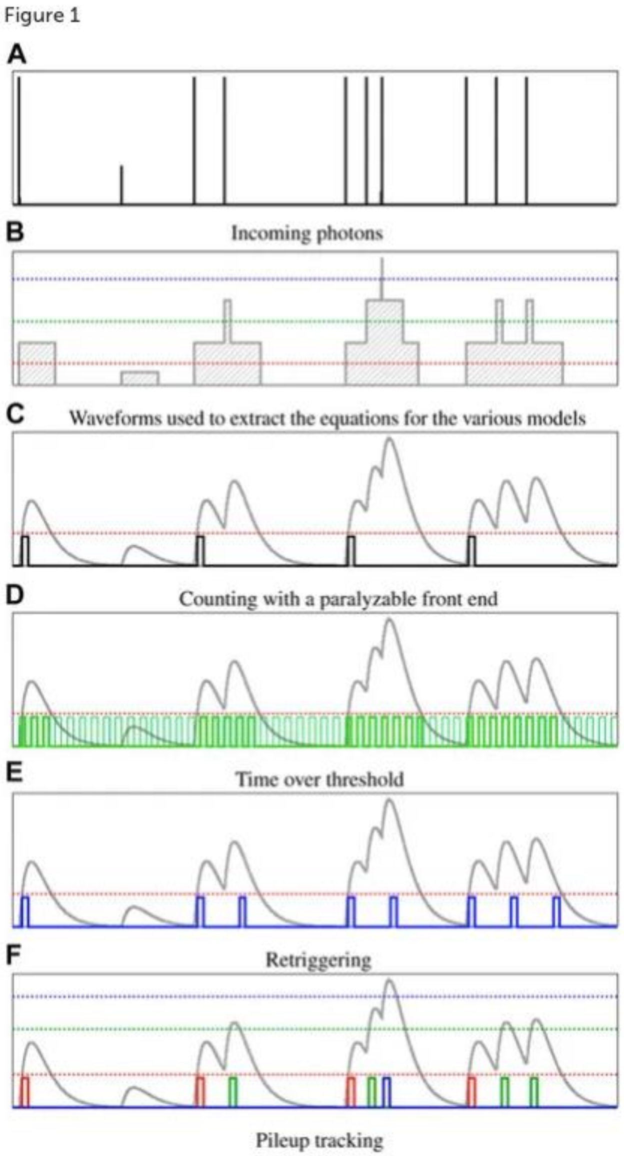
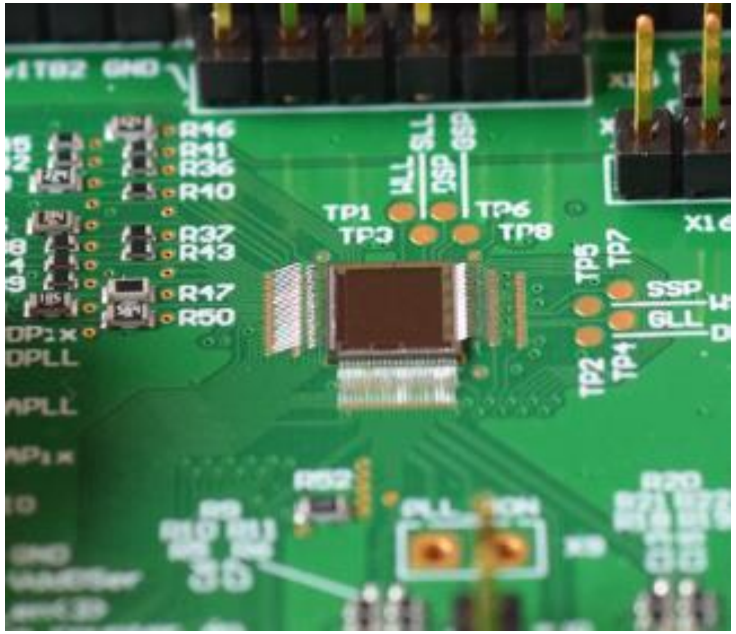


FIGURE 1. **(A,B)** Method to compare different strategies for mitigating the pulse pileup: **(C)** normal counting (reference), **(D)** time-over-threshold, **(E)** retriggering, and **(F)** pileup tracking. The *x*-axis refers to time, while the *y*-axis represents the height of the analog signal.

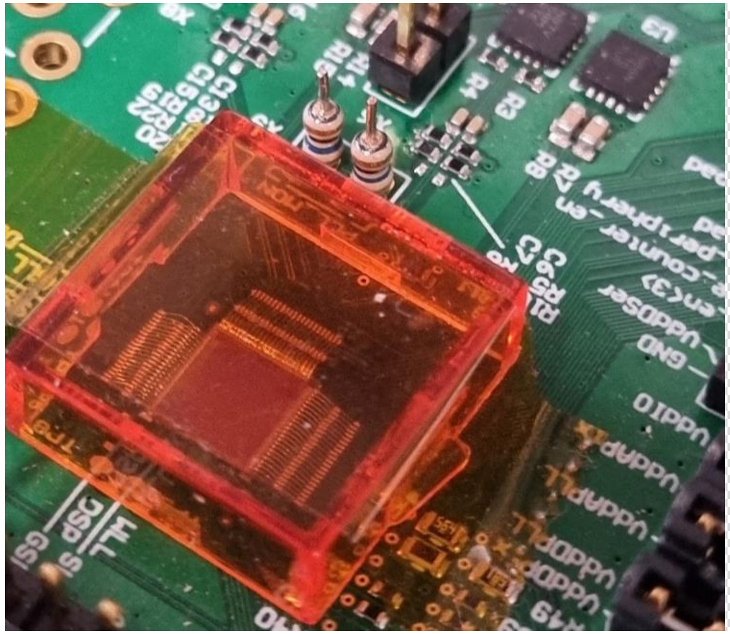
The Matterhorn prototypes

MH01



- 48x48 pixels
- Variations of the preamplifier and comparator

MH02



- DACs
- 3 Gbit/s serializers (8b/10b)
- Bugfixes: e.g. trimbit loading

MH03

- New periphery
- SPI interface for configuration
- 64b/66b encoder for serializers
- Current mode signal distribution (pixel periphery)