PSI Center for Photon Science

Matterhorn, a high flux, single photon counting detector for 4th generation synchrotrons

Roberto Dinapoli, Aldo Mozzanica, Anna Bergamaschi, Bernd Schmitt, Carlos Lopez Cuenca, Christian Rueder,Davide Mezza, Dhanya Thattil, Dominic Greiffenberg, Erik Fröjdh, Filippo Baruffaldi, Jiaguo Zhang, Jonathan Mulvey, Julian Heymes, Khalil Daniel Ferjaoui, Kirsty Paton, Konstantinos Moustakas, Mar Carulla Areste, Martin Brückner, Martin Mueller, Partick Sieberer, Saverio Silletta, Shuqui Li, Simon Ebner, Thomas King, Vadym Kedych, Viktoria Hinger, Viveka Gautam, Xiangyu Xie.

11th PIXEL conference, Strasbourg France, 18-22 November 2024

SLS 2.0 – a 4th generation synchrotron

Increased coherent flux [1]:

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

Increased electron energy (2.4 → 2.7 GeV)

- Higher energy photons (80 keV)

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

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LGADs PAUL SCHERRER INSTITUT PSI + FONDAZIONE BRUNO KESSLER

High Z

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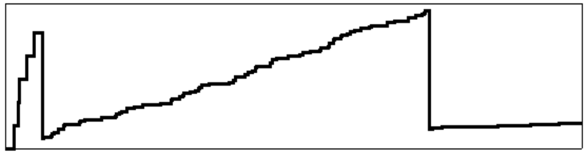
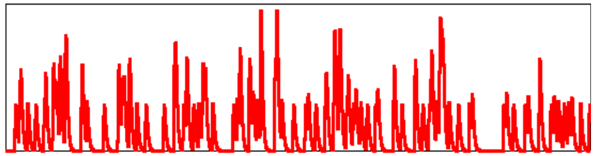


Charge integration



Single Photon Counting

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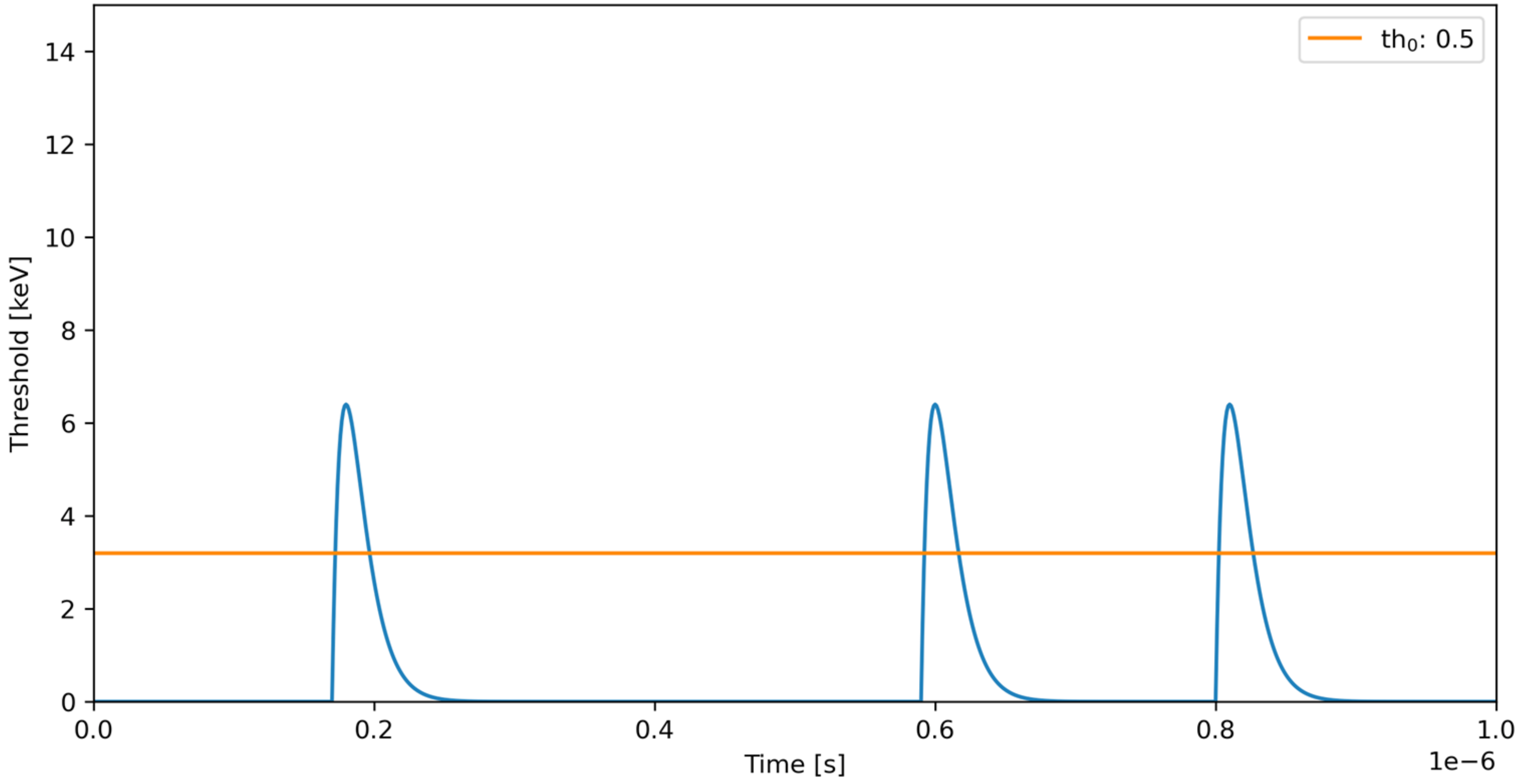
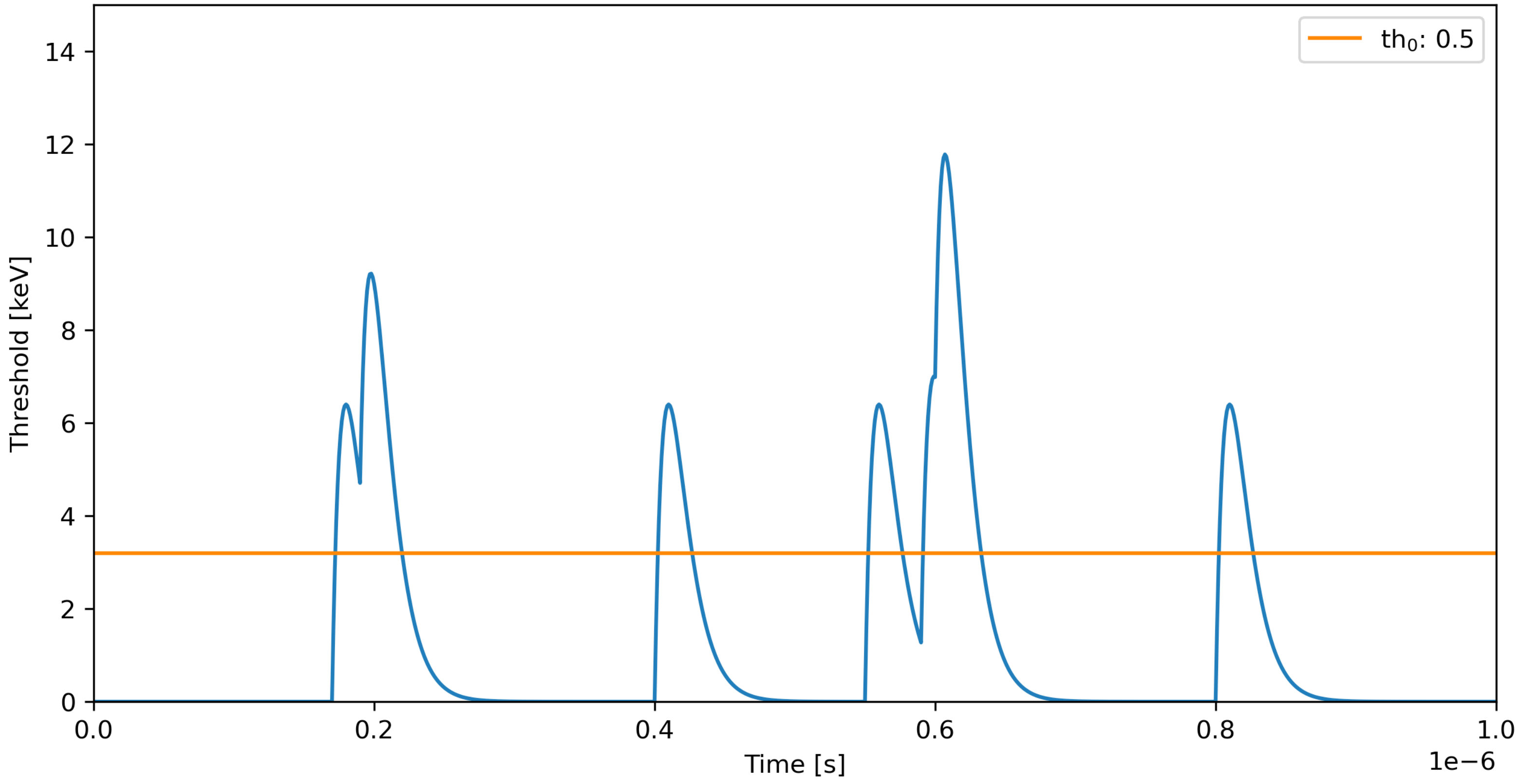
PSI Bericht Nr. 21-02 November 2021

The “speed challenge”: high photon flux



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

The “speed challenge”: high photon flux



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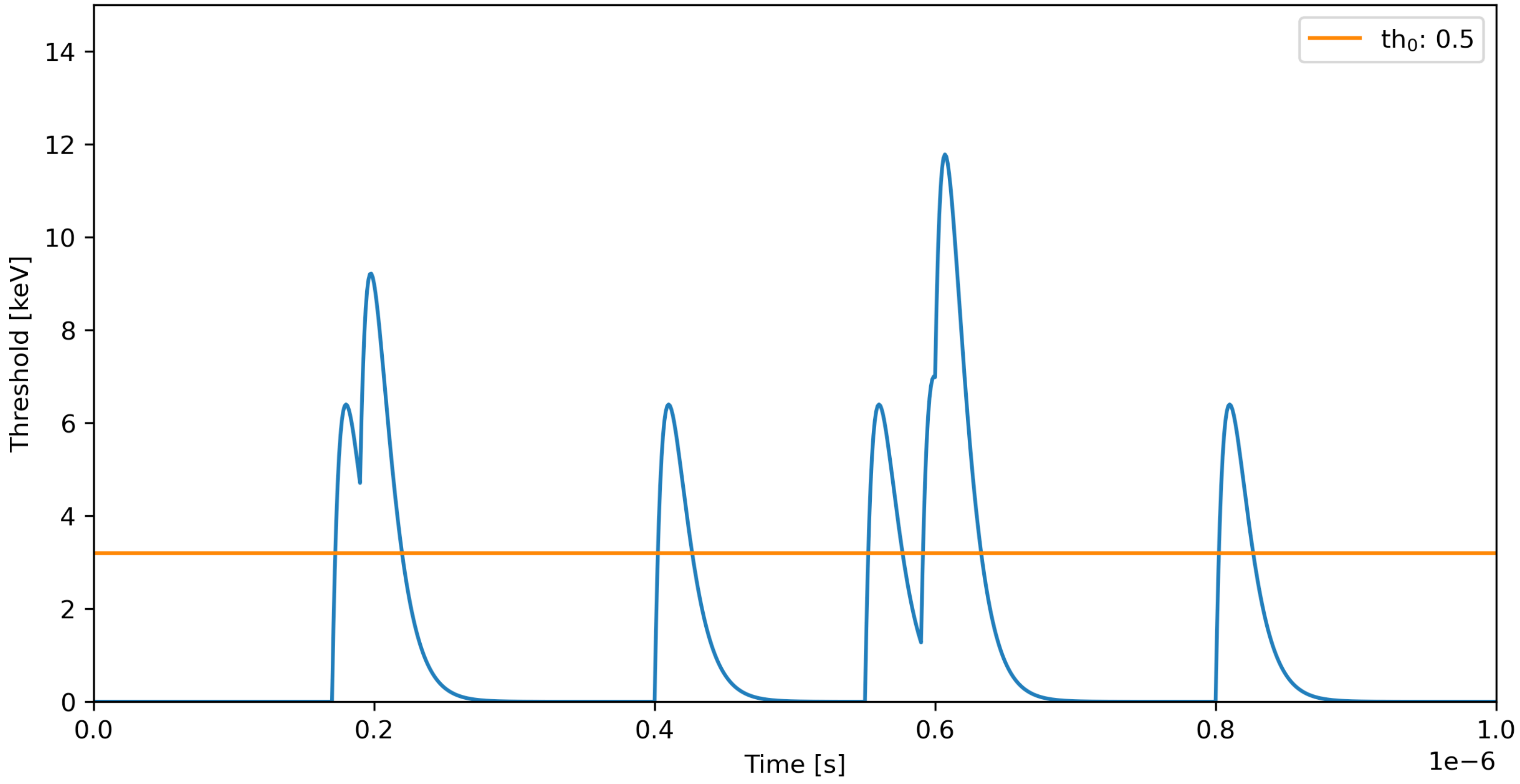
But as the rate increases we lose efficiency due to pulse pileup

The "speed challenge": high photon flux



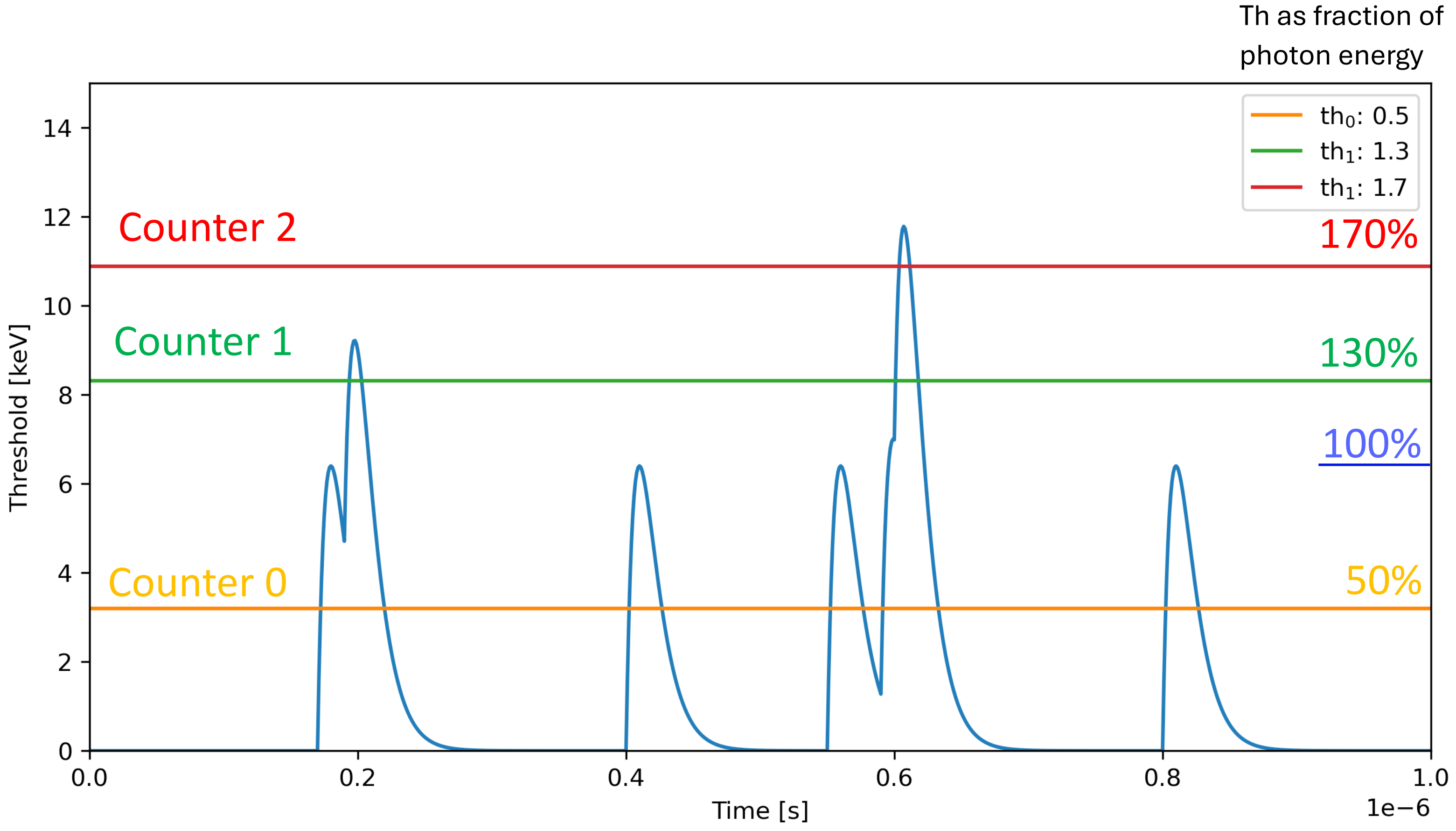
Single photon counting works extremely well if the incoming photon rate is reasonable low

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

Pile-up mitigation techniques for SPC:

- Time over threshold
- Retriggering
- …

Pile-up counting with multiple thresholds



100%: Energy of the monochromatic incoming photons

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

Probablility of two and three events pile-up:

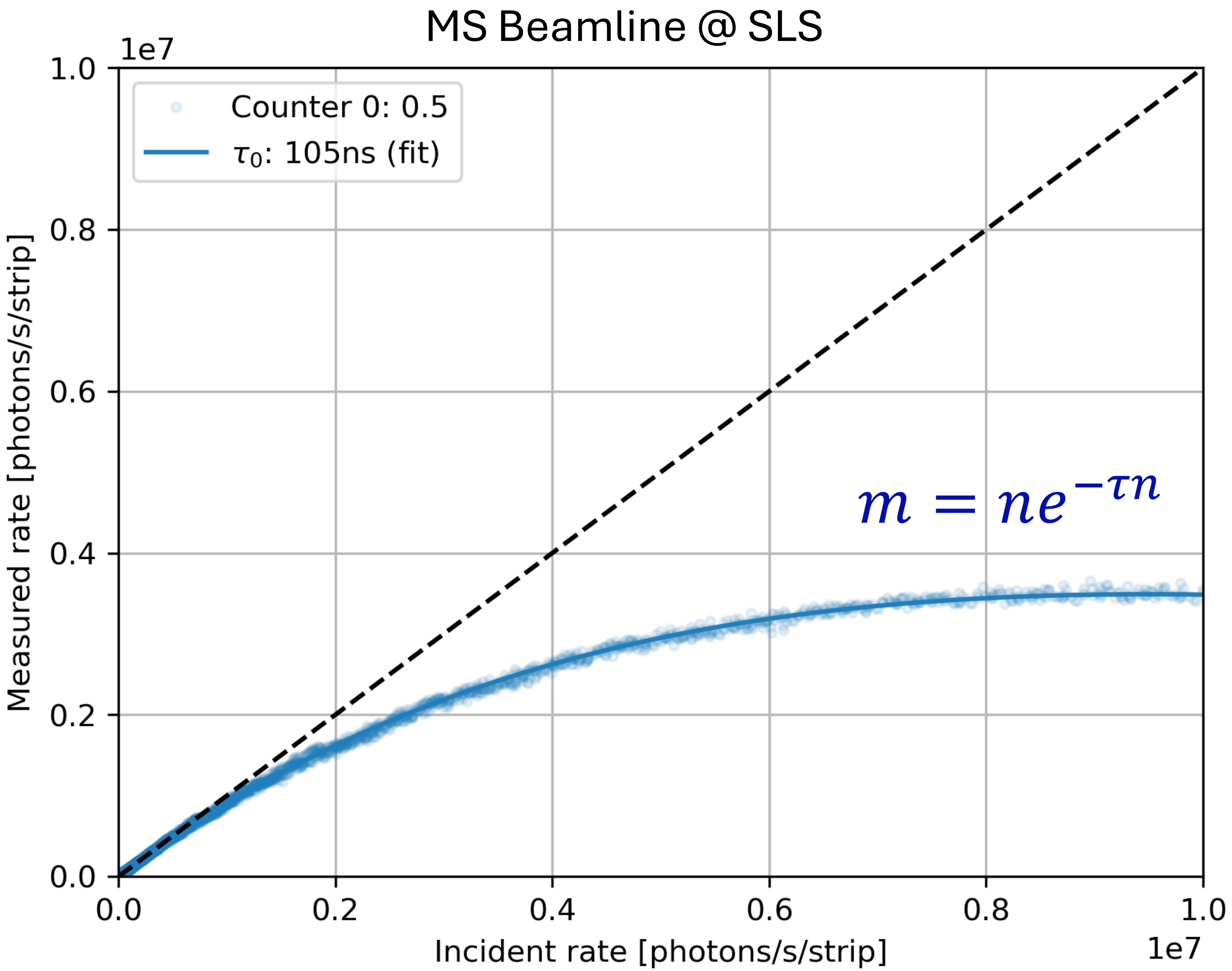
- $p_2 = e^{-\tau n}(1 - e^{-\tau n})$
- $p_3 = e^{-\tau n}\,(1 - e^{-\tau n})^2$

$$m_s = m + m_2 + m_3$$

[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

Multi-thresholding : proof of concept with Mythen3.02 (1D)



Settings: standard

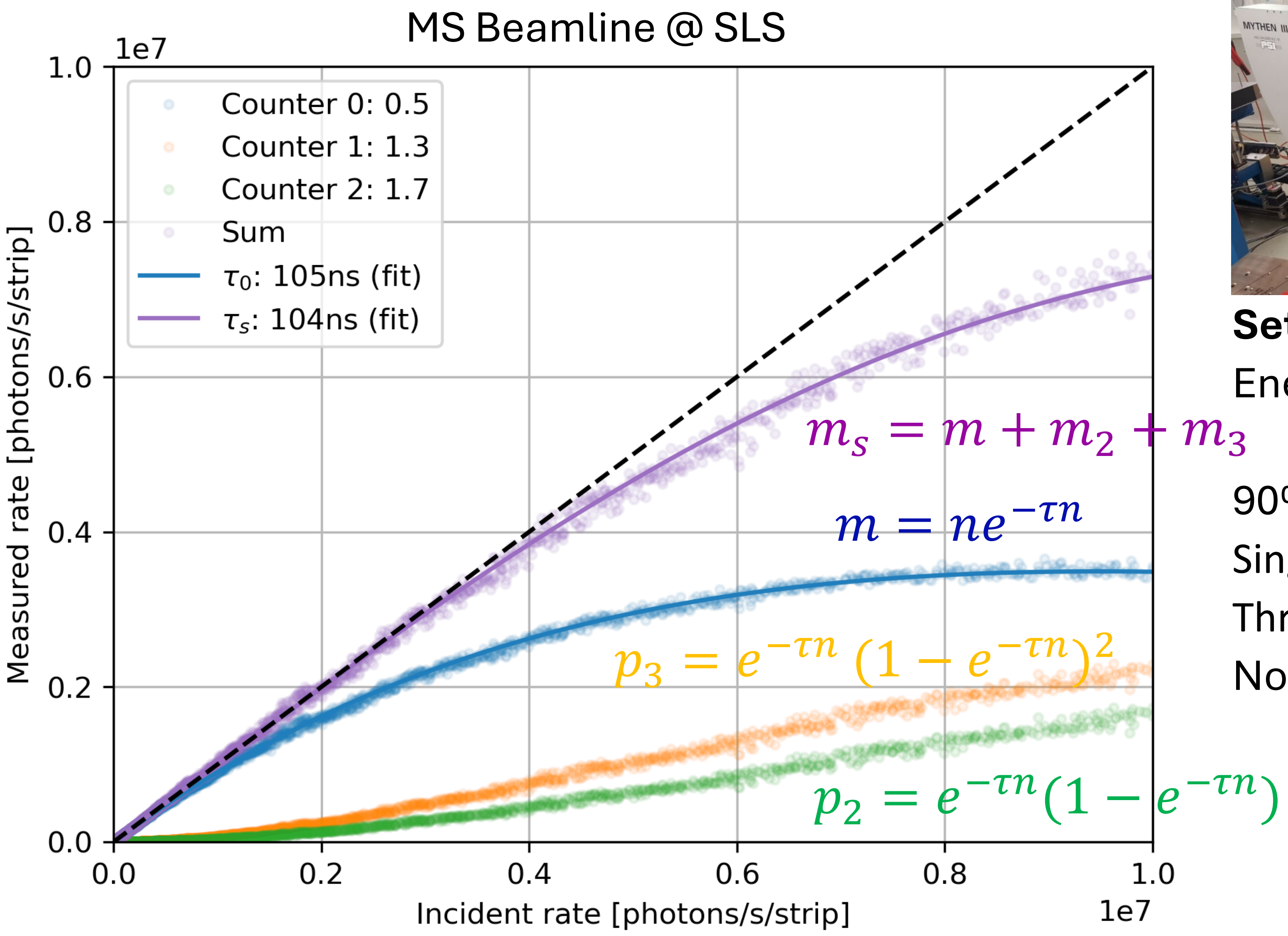
Energy: 15 keV

90% efficiency at:

Single counter : 1.03Mcps

Multi-thresholding : proof of concept with Mythen3.02 (1D)

PSI



Settings: standard

Energy: 15 keV

90% efficiency at:

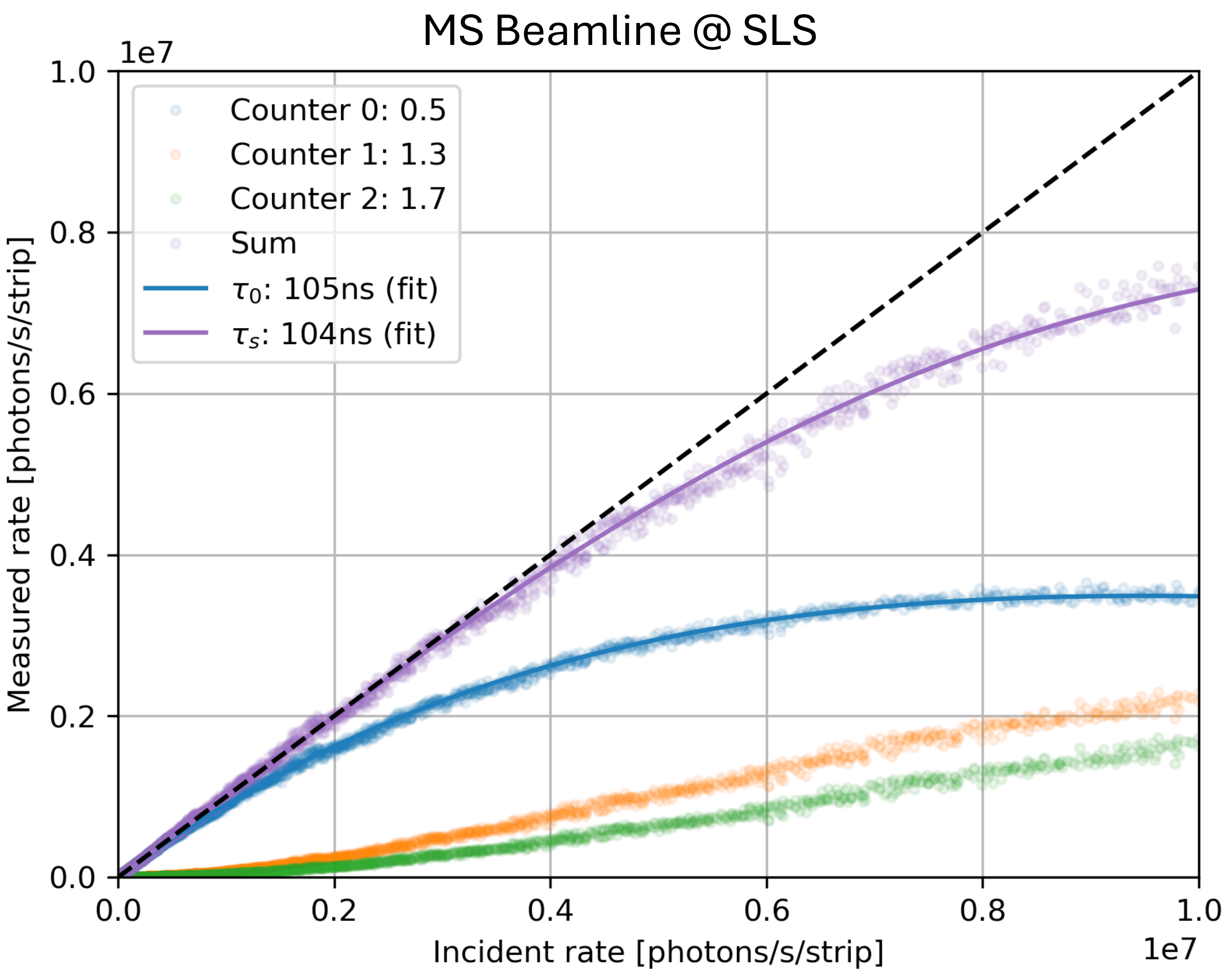
Single counter : 1.03Mcps

Three counters : 6 Mcps

Noise: 175e- RMS

Multi-thresholding : proof of concept with Mythen3.02 (1D)

PSI



Settings: standard

Energy: 15 keV

90% efficiency at:

Single counter : 1.03Mcps

Three counters : 6 Mcps

Noise: 175e- RMS

x6

Settings: Fast [1]

Single counter 3.52 Mcps

Three counters 20.87 Mcps

Noise:~250e-

x6

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

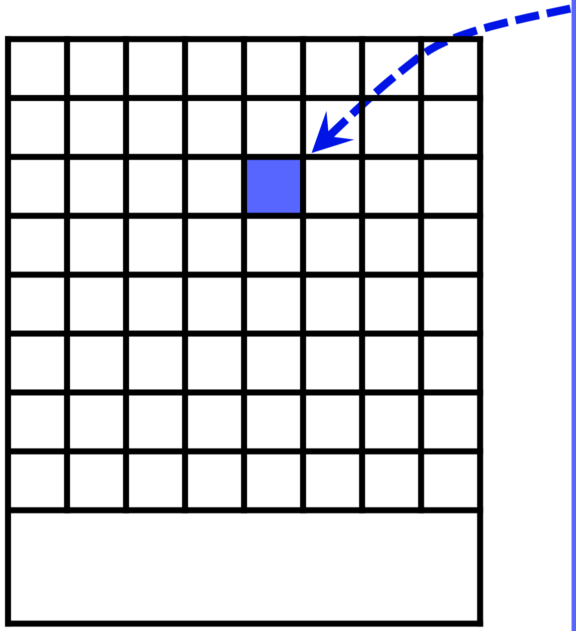
Matterhorn – a new single photon counter for SLS2.0

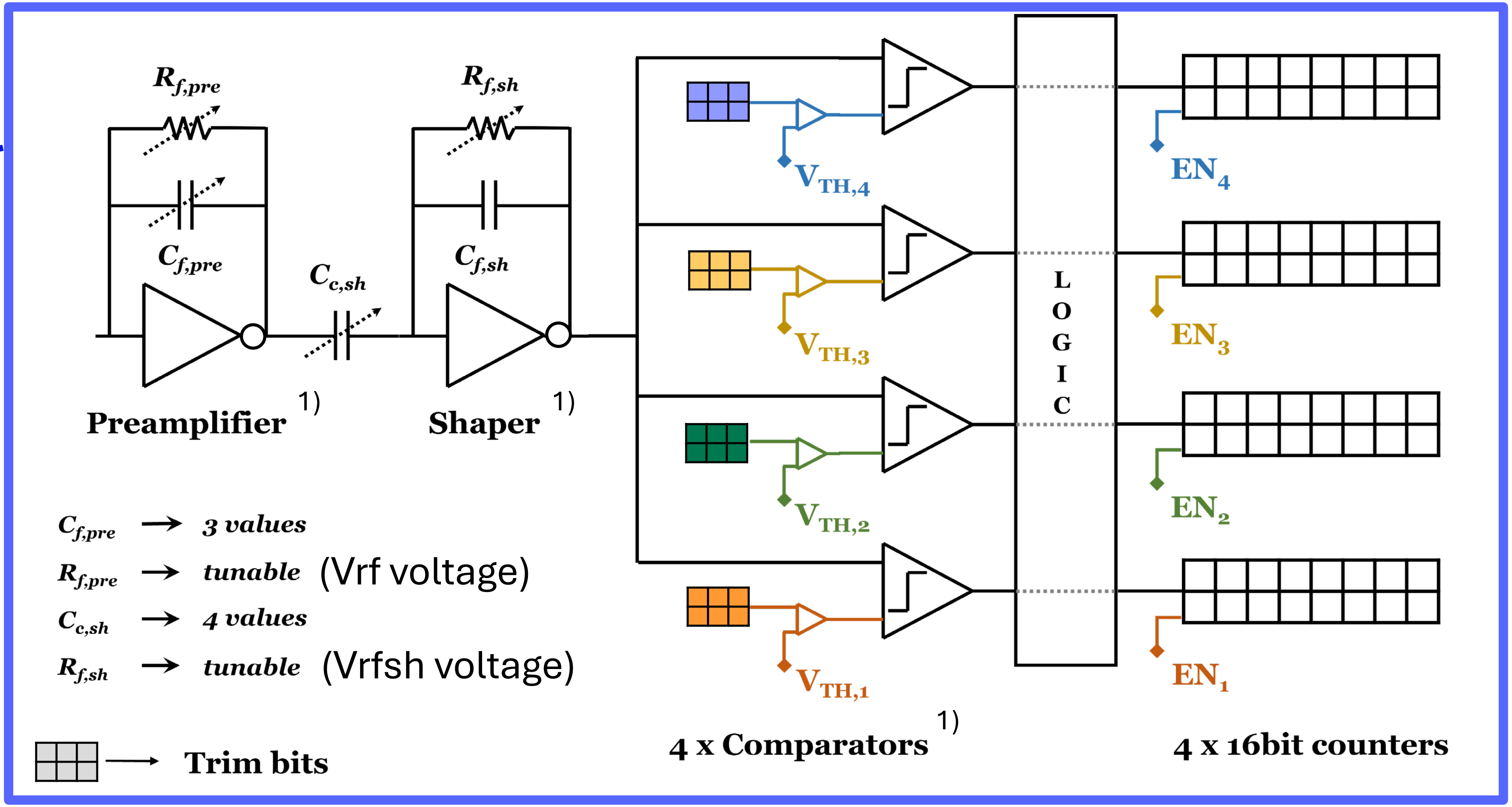
	EIGER	MATTERHORN
Technology	UMC 250 nm	UMC 110 nm
Pixel size	75 x 75 um^2	75 x 75 um^2
Thresholds	1	4
Counter depth	12 bit (3x4)	4x16 bit
90% efficiency	350k counts/pixel/s*	15-20M counts/pixel/s
Module size	4x8cm^2	4x8cm^2
HighZ/LGAD	No	Yes

***DECTRIS EIGER2 90% efficiency at ~2 Mcps (UMC 110nm)**

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

Matterhorn pixel architecture

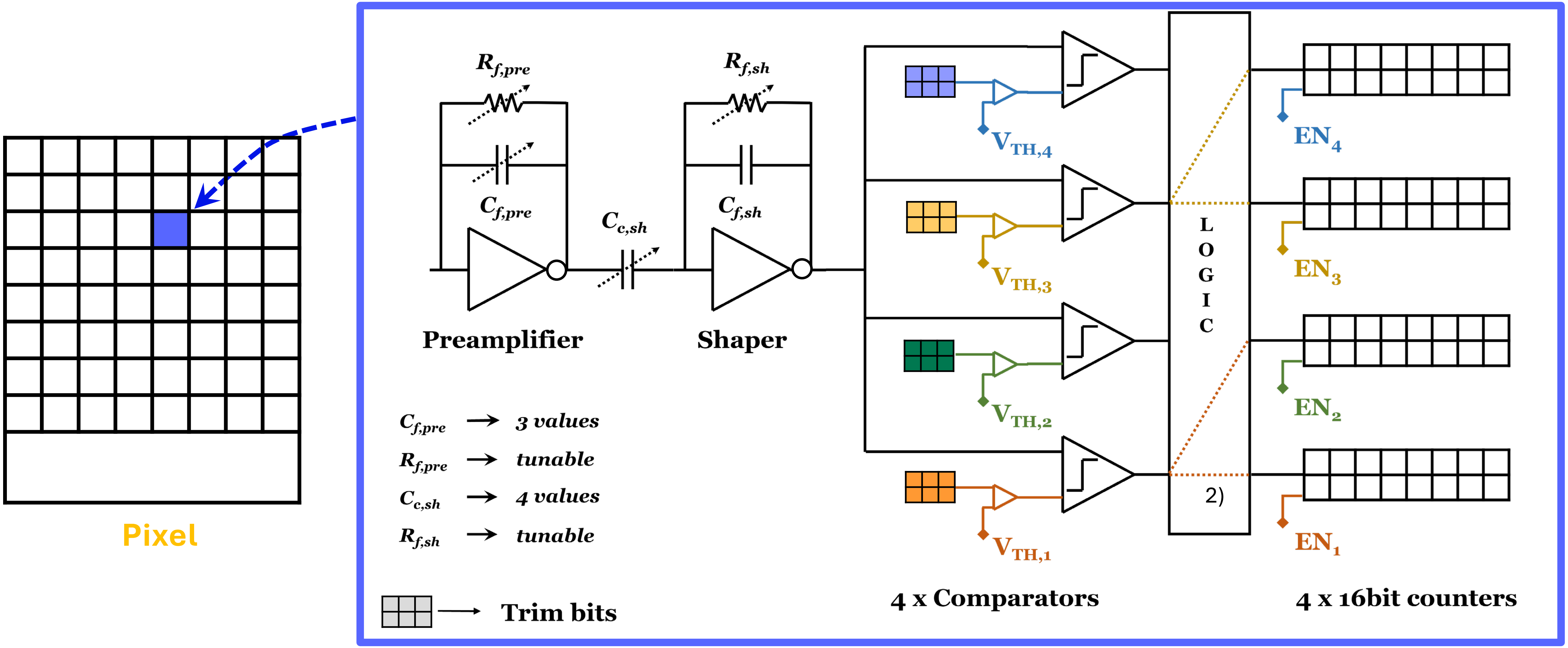




1) Both e^- and h^+ readout possible

Static power/pixel (4 comparators)	9.6μW

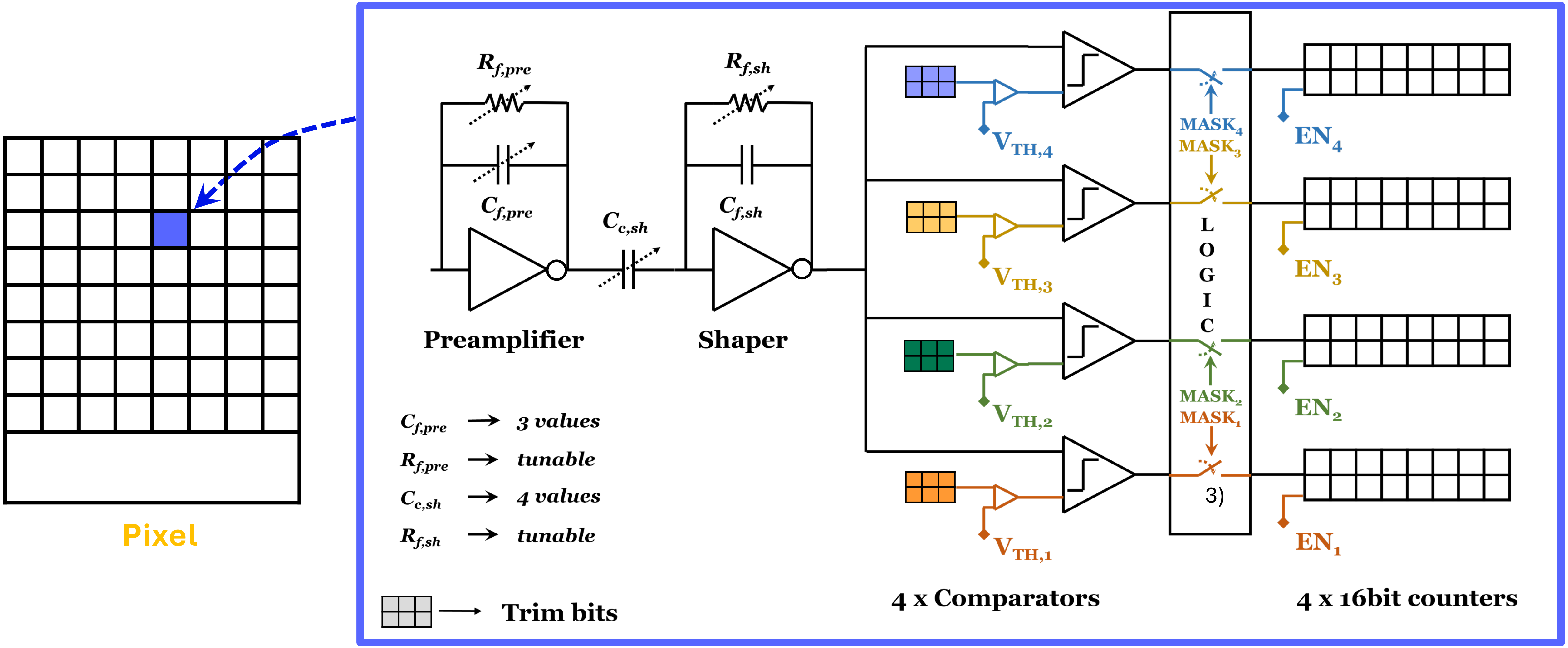
Matterhorn pixel architecture



[2] One comparator can be connected to two counters (pump-probe)

Matterhorn pixel architecture

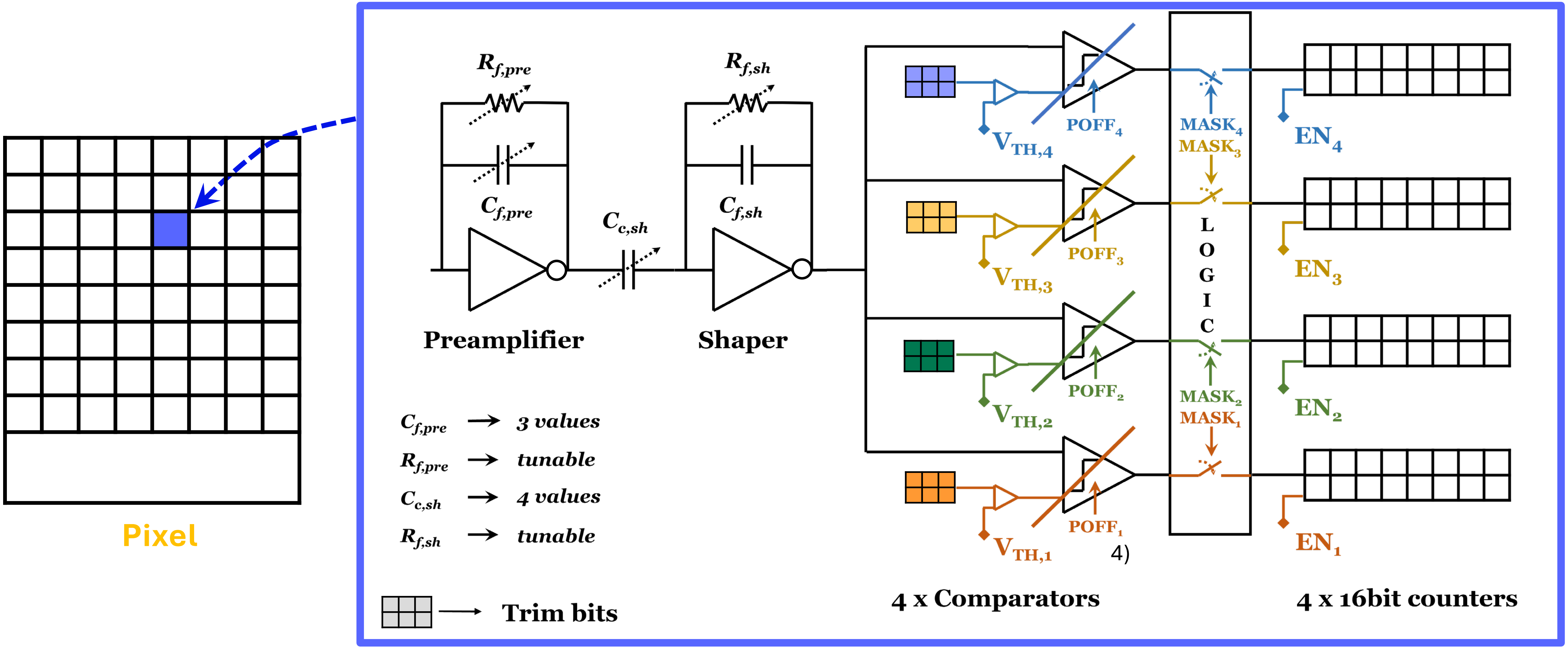
PSI



[3] Each comparator can individually be 'masked' (disconnected from the counter)

→ reduce switching for noisy channels

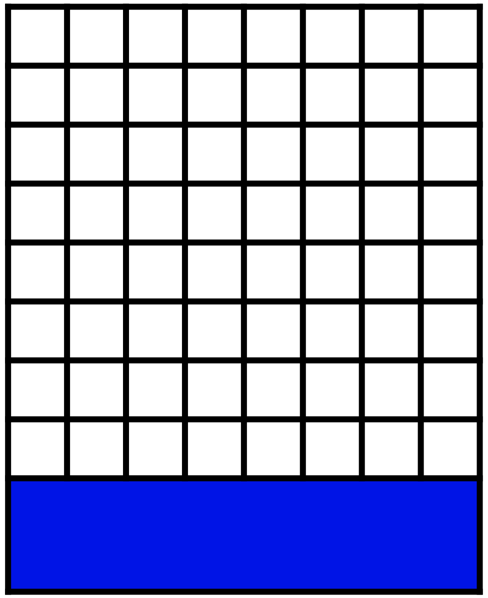
Matterhorn pixel architecture



[4] Each comparator can individually be powered-off when noisy or not used

Periphery blocks

- **PLL**
  - Locking range: 930 MHz ÷ 2600 MHz
  - Power: 18 mW
- **Pixel & counter selector**
  - Pixel/counter addressing logic
  - Pixel/counter readout logic (includes 16 or 8 bit mode)
  - 8b/10b encoding
  - High speed serializers
- **CML driver**
  - Main driver and pre-emphasis current tunable (3 bits): 3 mA ÷ 15 mA
  - Pre-emphasis delay tunable (2 bits)

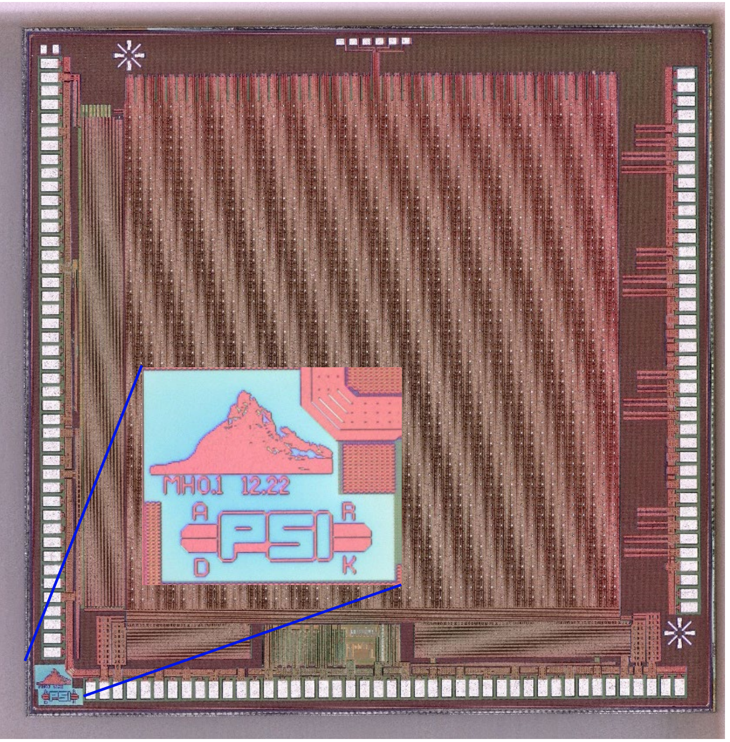


All periphery logic synthesized with digital tools for the first time!

Matterhorn prototypes

PSI

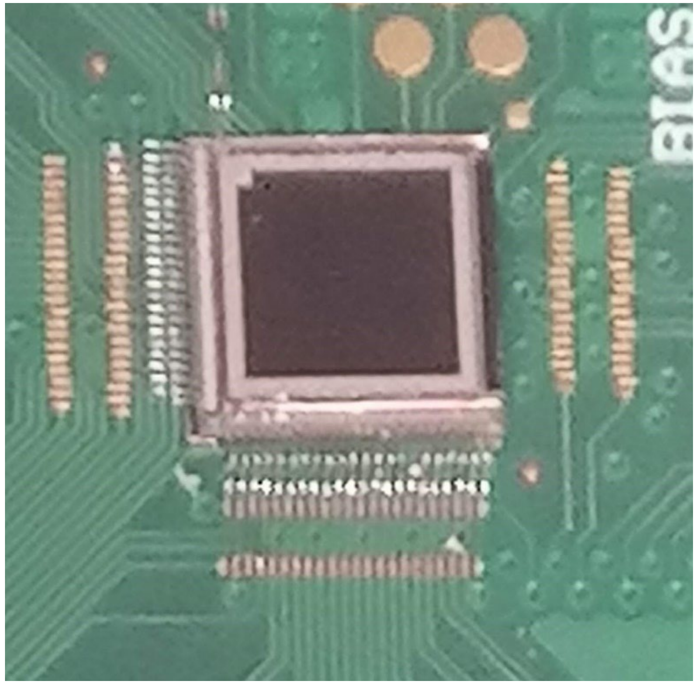
Matterhorn 0.1, 12.2022



- **2 Pre/shaper variations**
- **2 Comparator variations**
- **2x 1.6 GHz serializers**
- **1.6 GHz CML driver (with pre-emphasis)**

- ASICs: ~5x5 mm^2 (3.6x3.6 active=48x48=2304 pixels)
- MPW chips bump-bonded to sensor

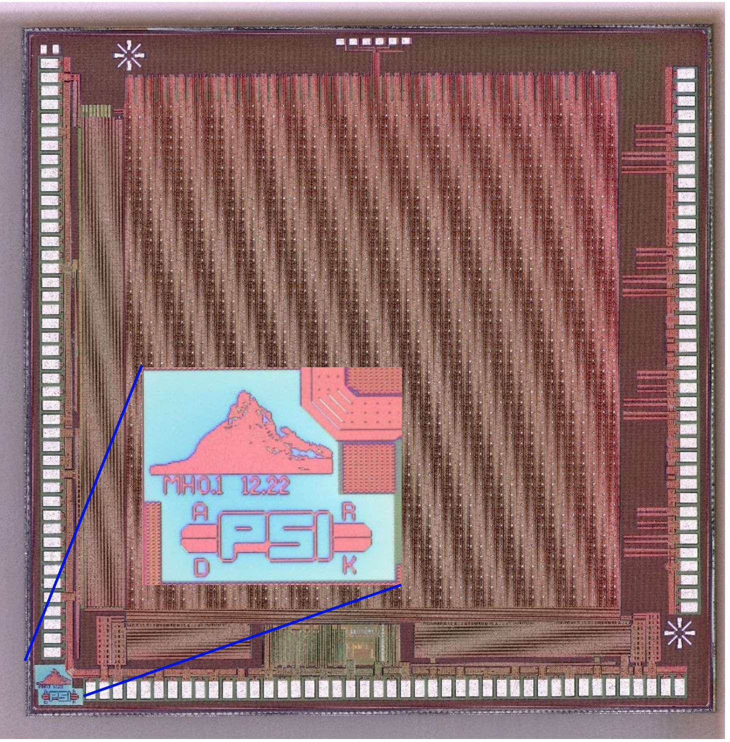
Matterhorn 0.2,10.2023



- **One pixel version only**
- **2x 3.125 GHz serializers**
- **3.125 GHz CML driver**
- **Internal DACs for biasing**
- **Some "features" fixed**

Matterhorn prototypes

Matterhorn 0.1, 12.2022



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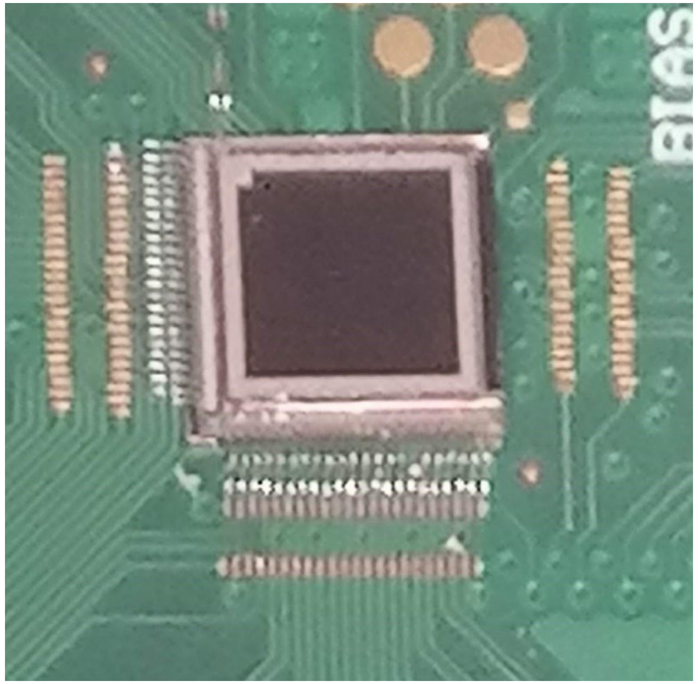
- PLL working
  - Jitter < 5 ps (limited by measurement setup)
- HS logic/data transmission working
  - BER< 10^{-15} (limited by measurement time)
- DACs working
  - 8 bits

Matterhorn 0.2,10.2023



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- **Internal DACs for biasing**
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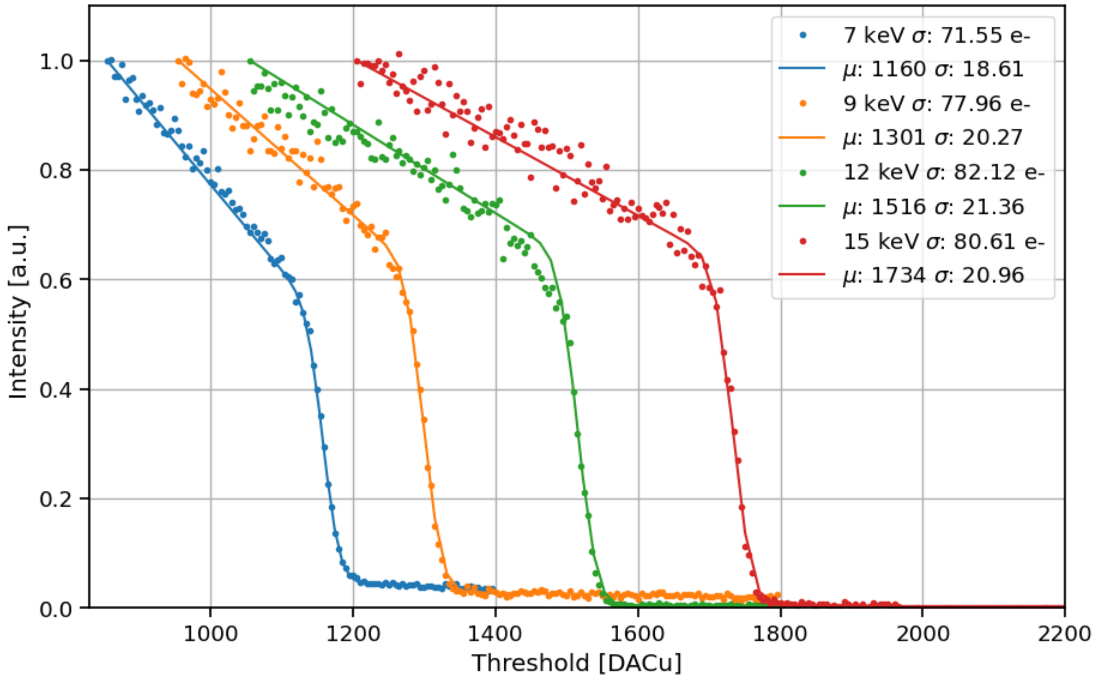
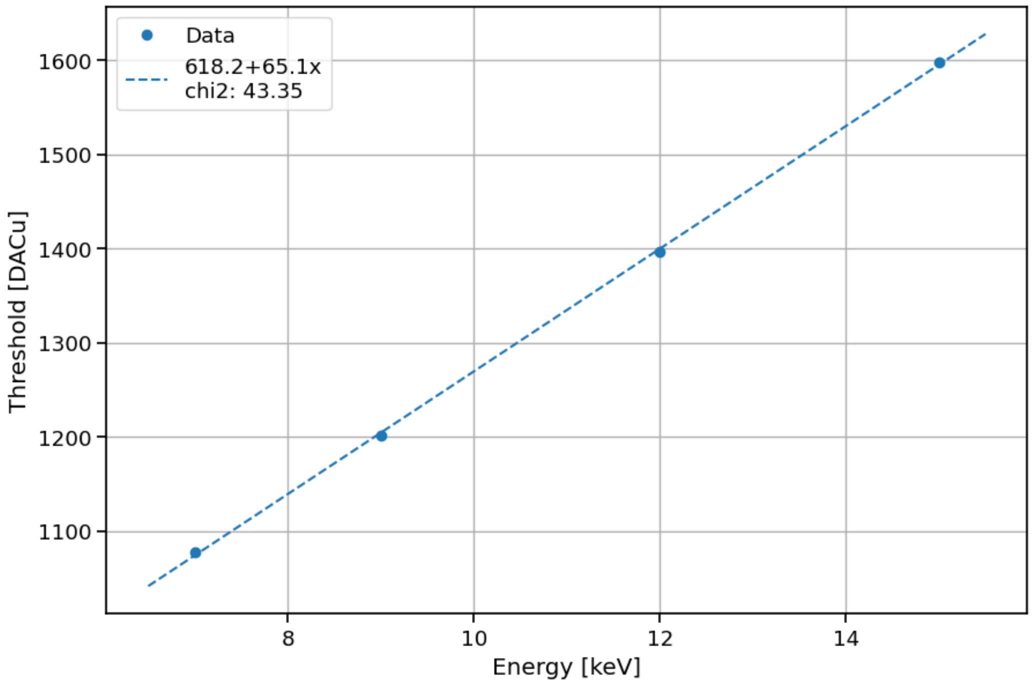
Basic characterization of MH02

- Calibration at: 7, 9, 12, 15 keV
- Threshold scans fitted with analytical model:
- $f(x) = (p_0 + p_1 x) + 0.5\left(1 + Erf\left(\frac{x-\mu}{\sqrt{2}\cdot\sigma}\right)\right)(A + C(x-\mu))$

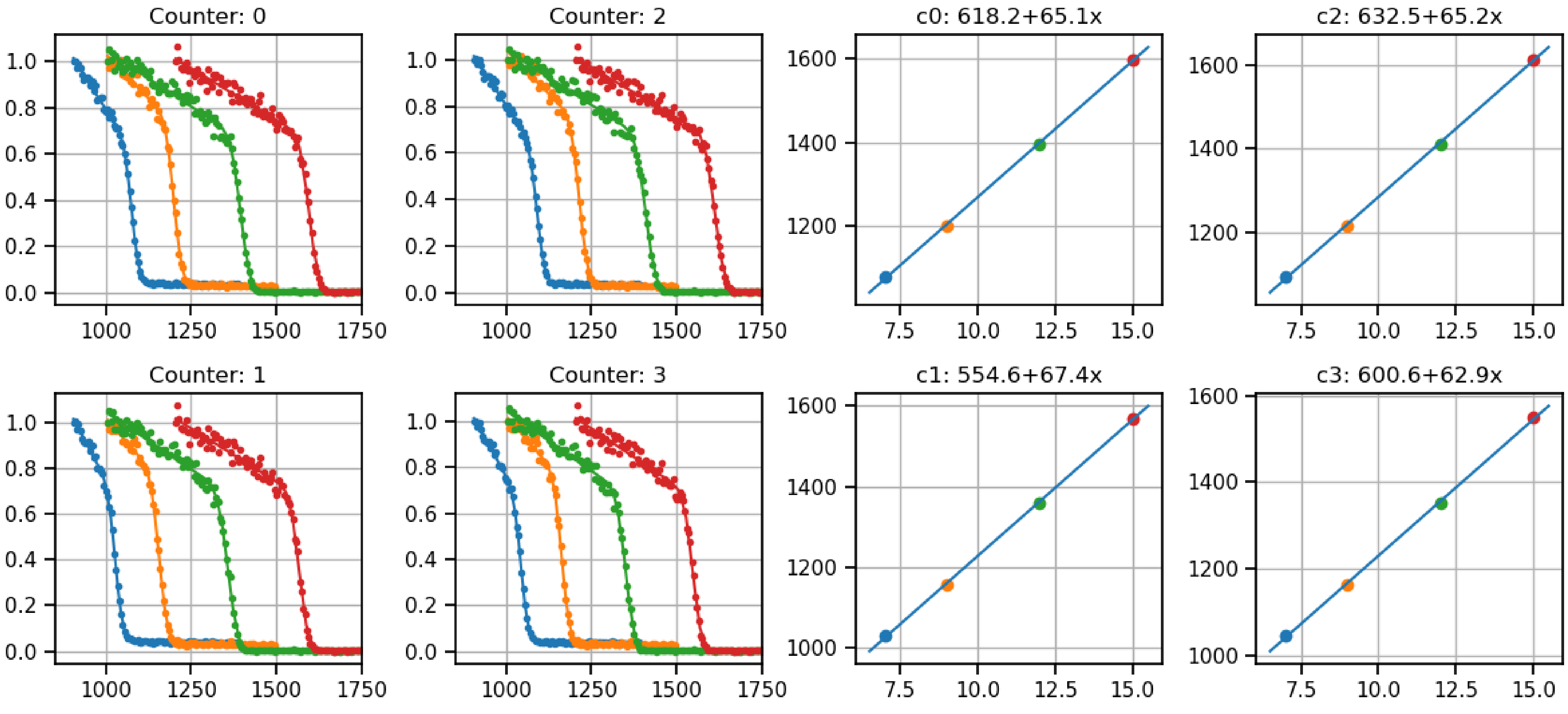
- Metrologie beamline at SOLEIL with help from: Marie Andrä and Arkadiusz Dawiec





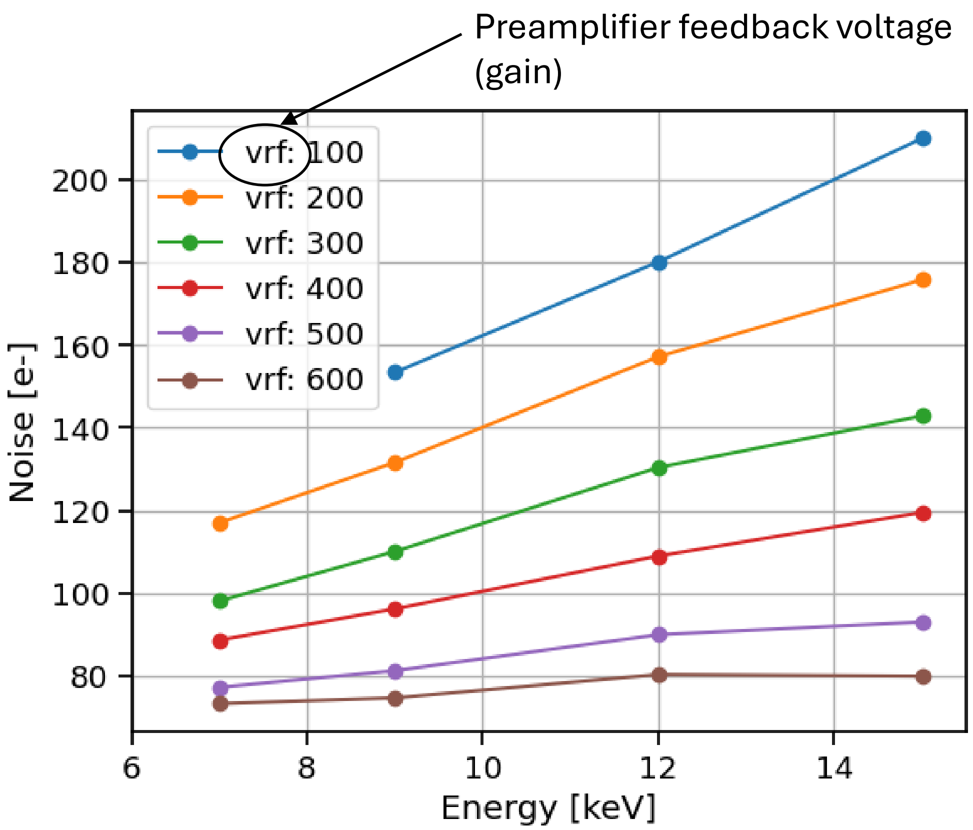
Single pixel data

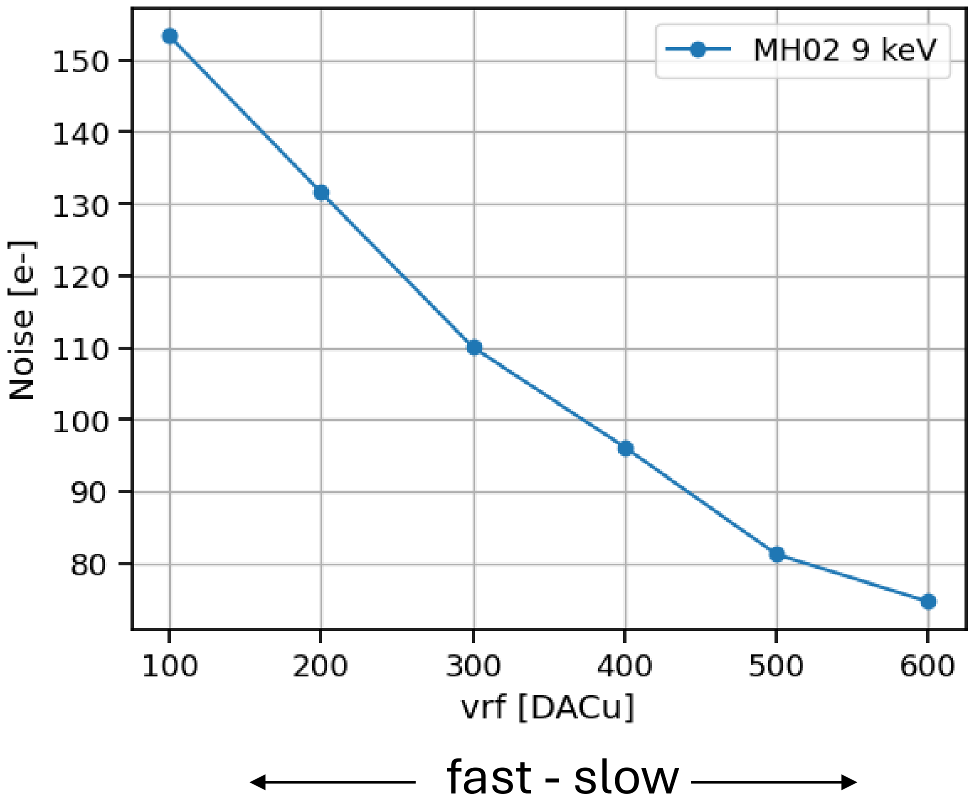
Four counters scan



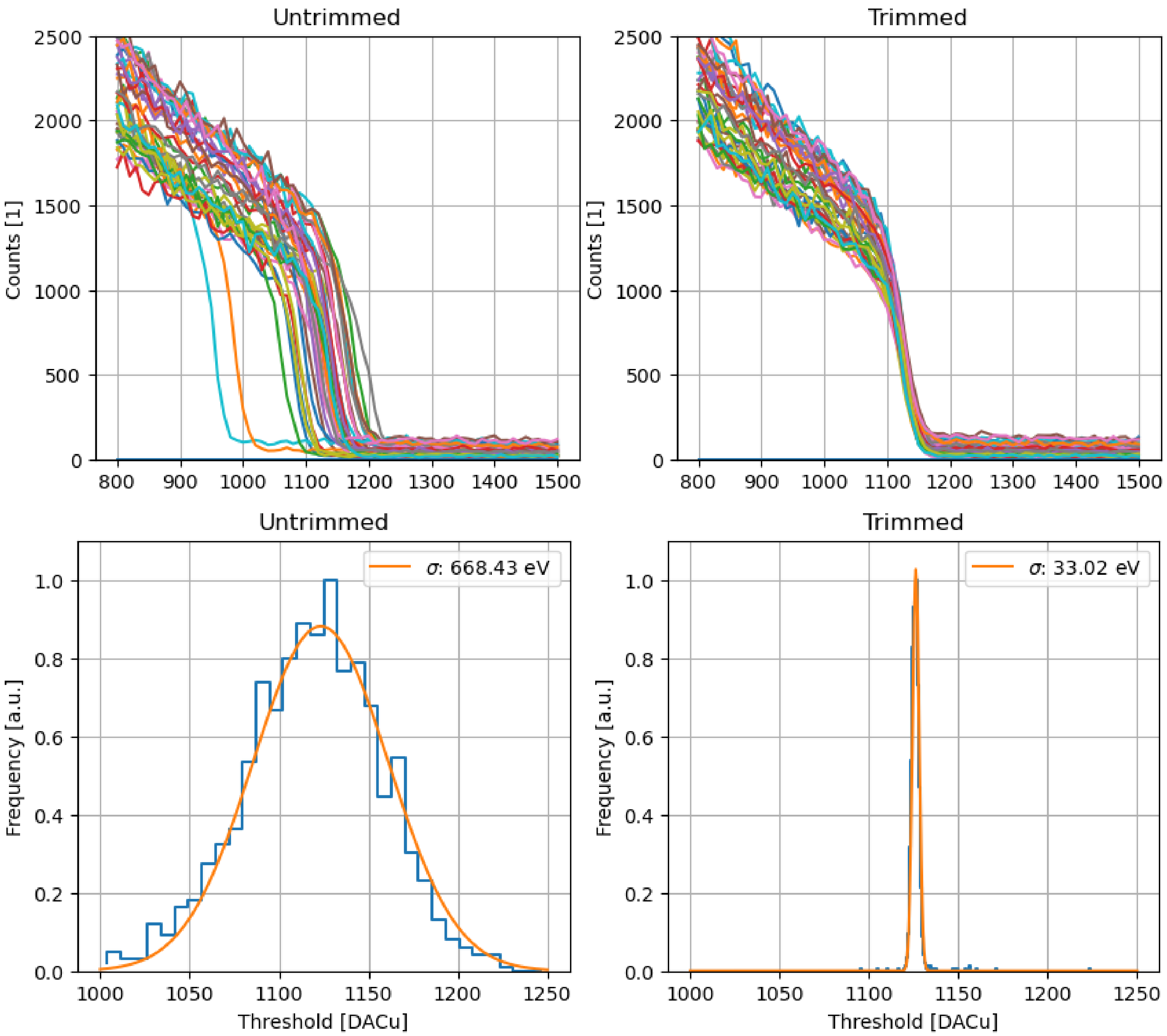
Scanned at the same time

Noise performance of MH02





Threshold dispersion at 9 keV



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

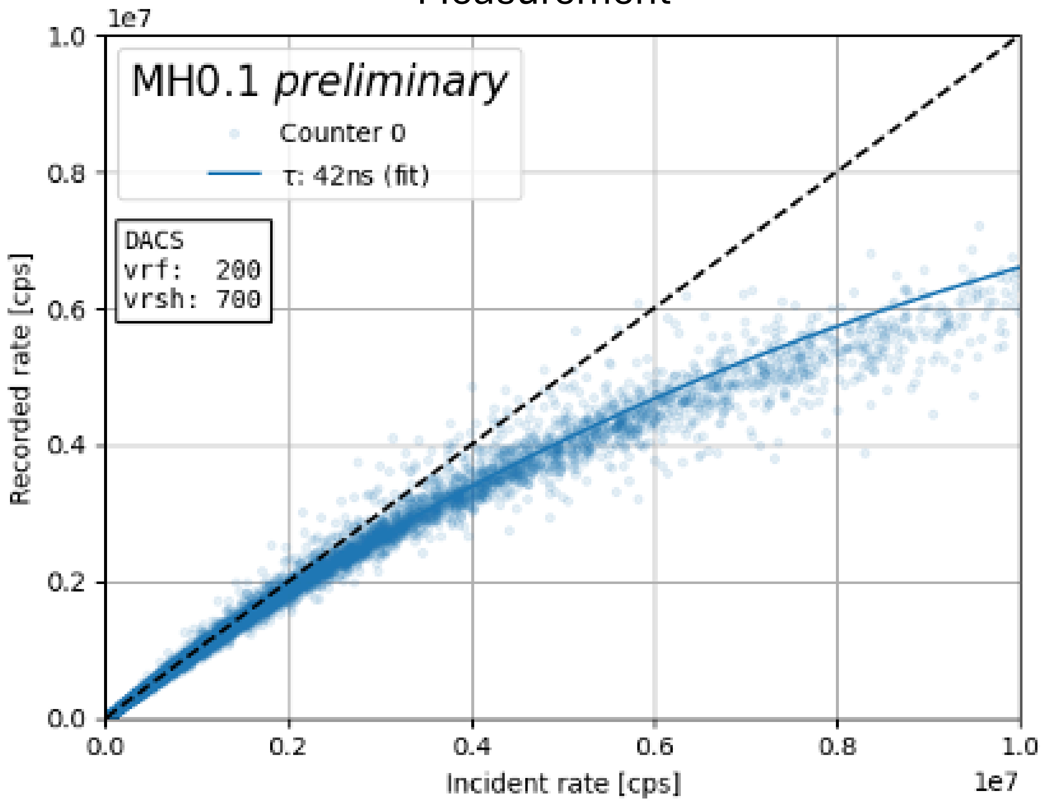
:16 to 20

8e-

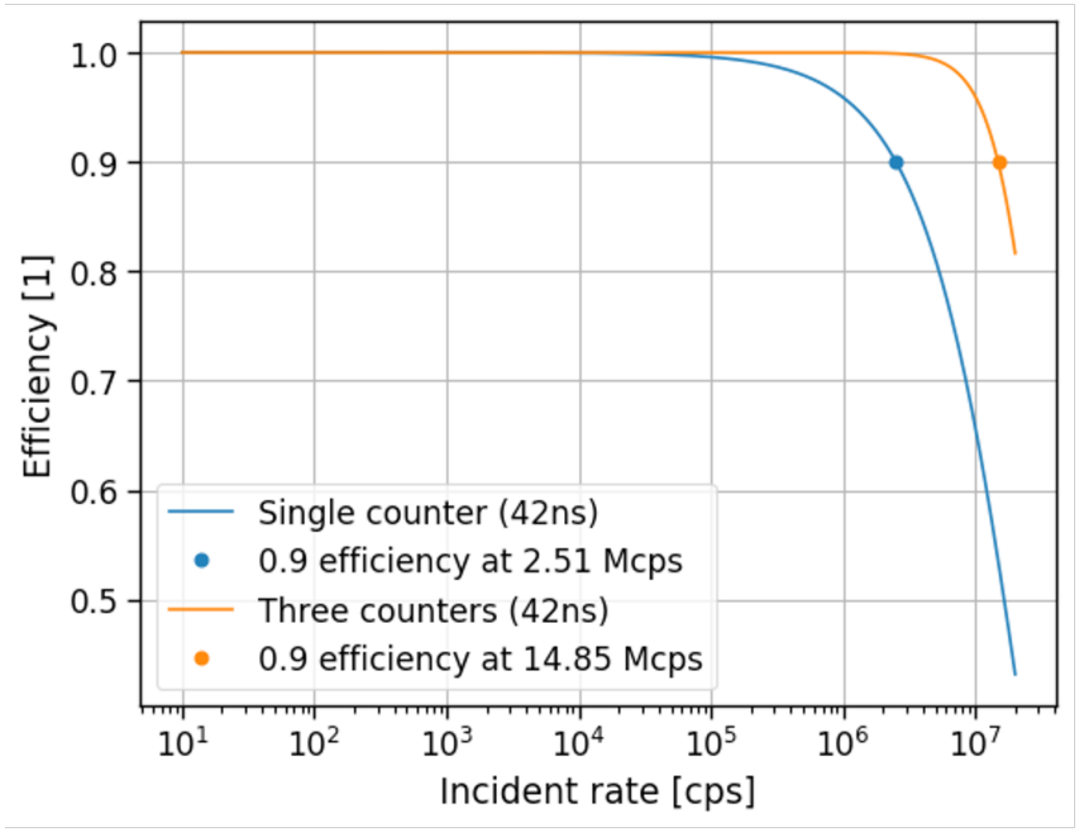
- Small chip (48x48 pixels)
- Non optimized trimming procedure

Single counter rate tests at MS beamline - MH01

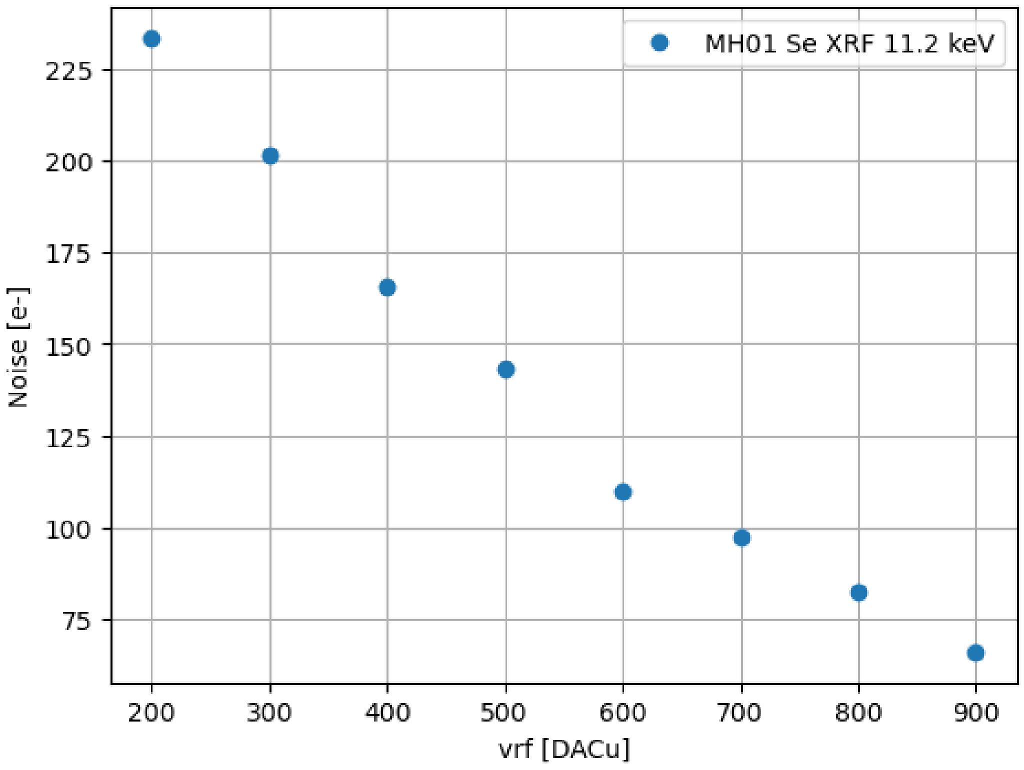
Measurement



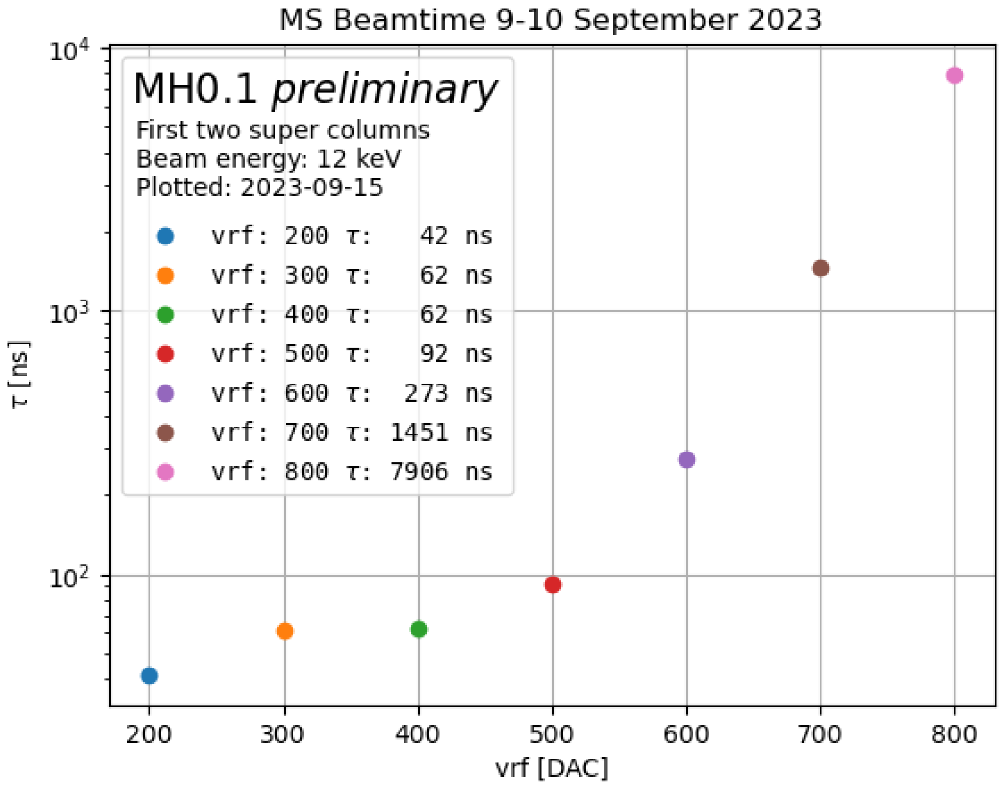
Predicted rate capability using analytical model



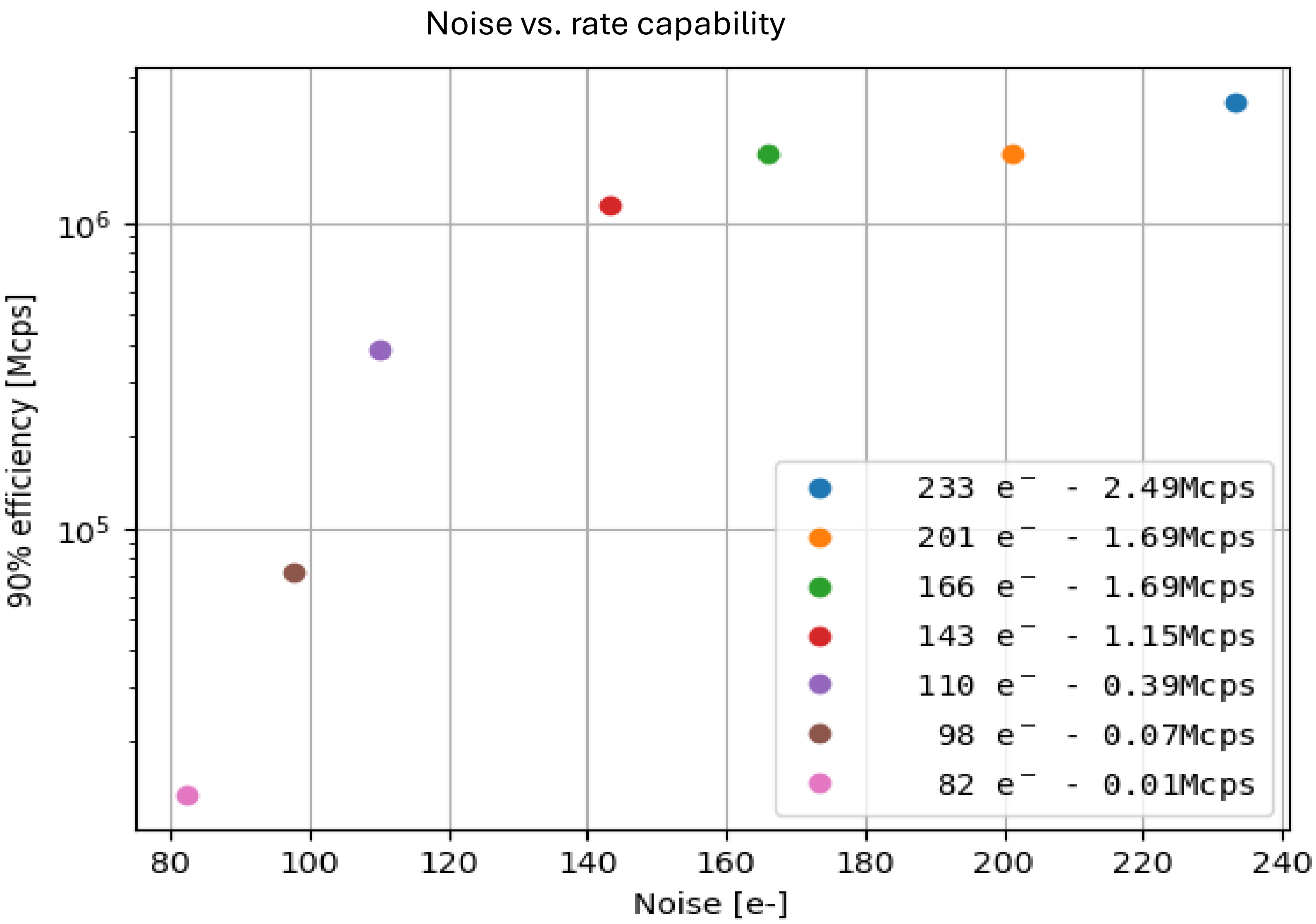
Single counter rate tests at MS beamline – MH01



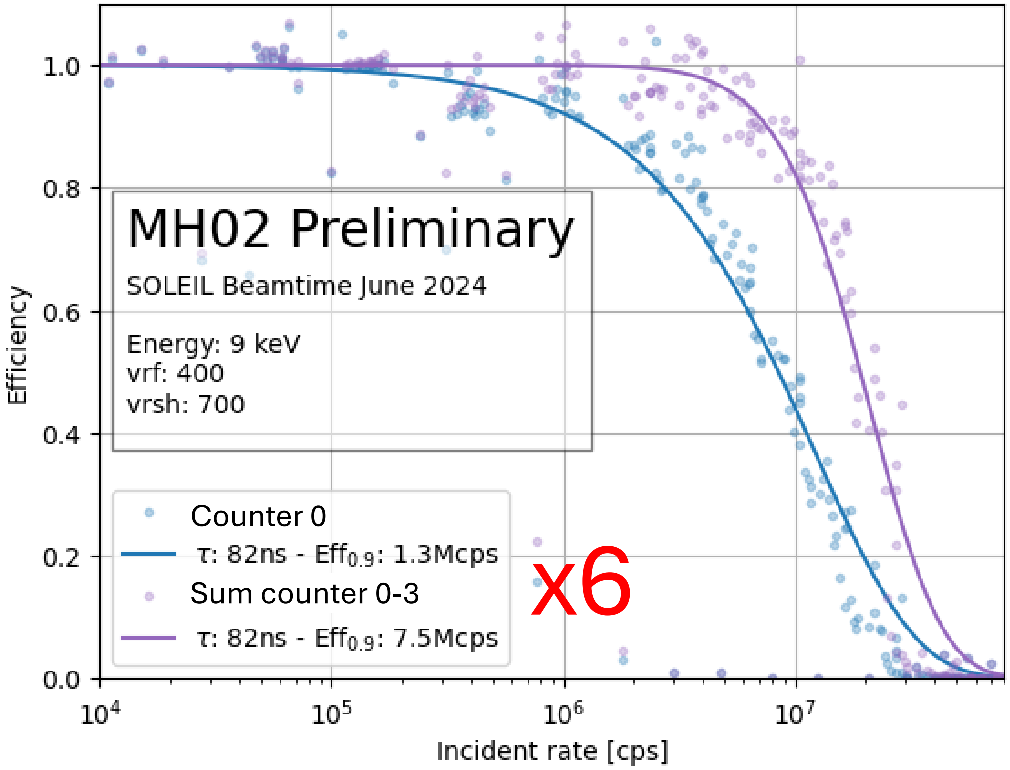
Note: slightly over estimated due to kB peak



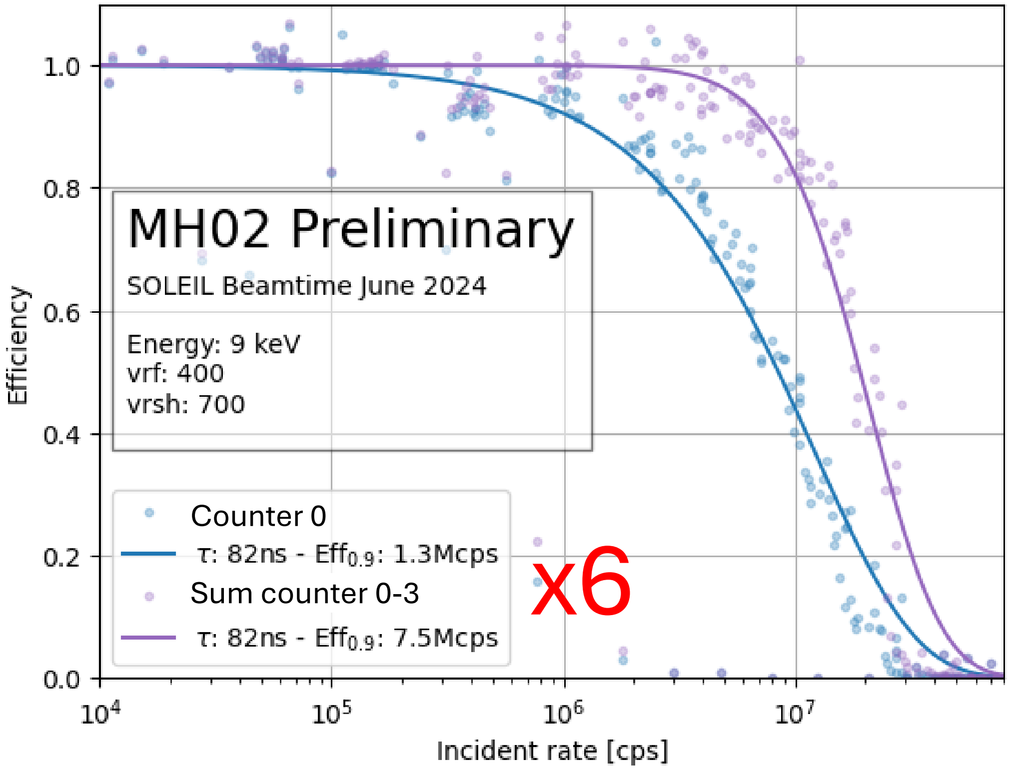
Single counter rate tests at MS beamline – MH01

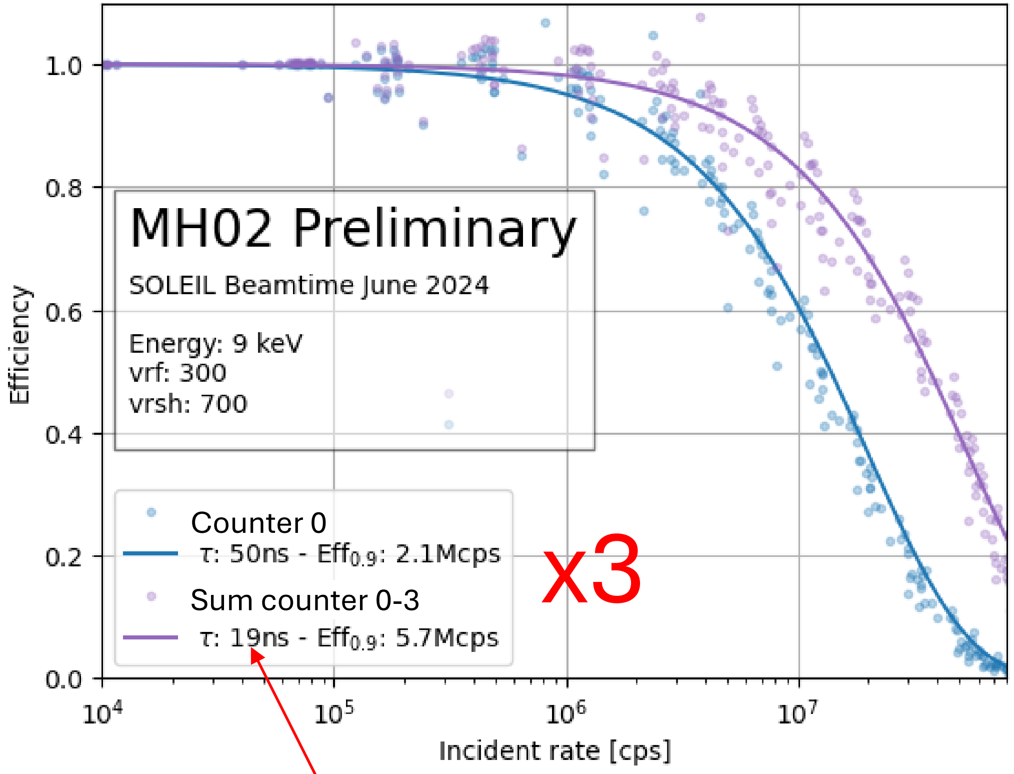


Multi threshold rate tests at SOLEIL with MH02



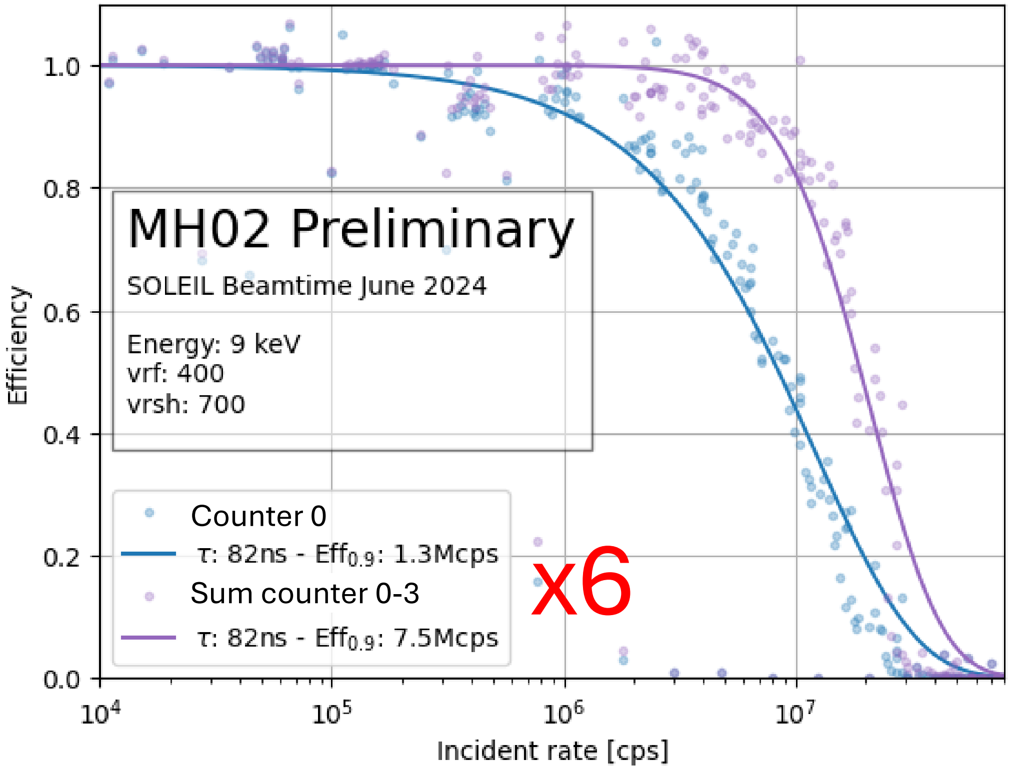
Multi threshold rate tests at SOLEIL with MH02

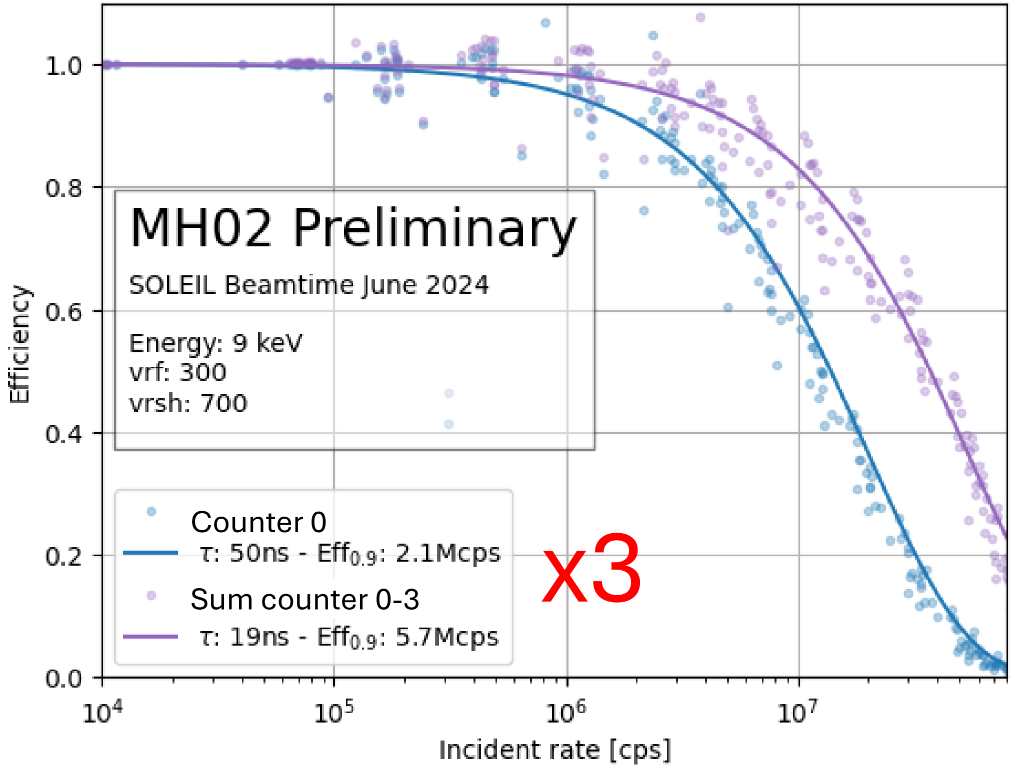




Note: fitted with simple paralyzable function

Multi threshold rate tests at SOLEIL with MH02



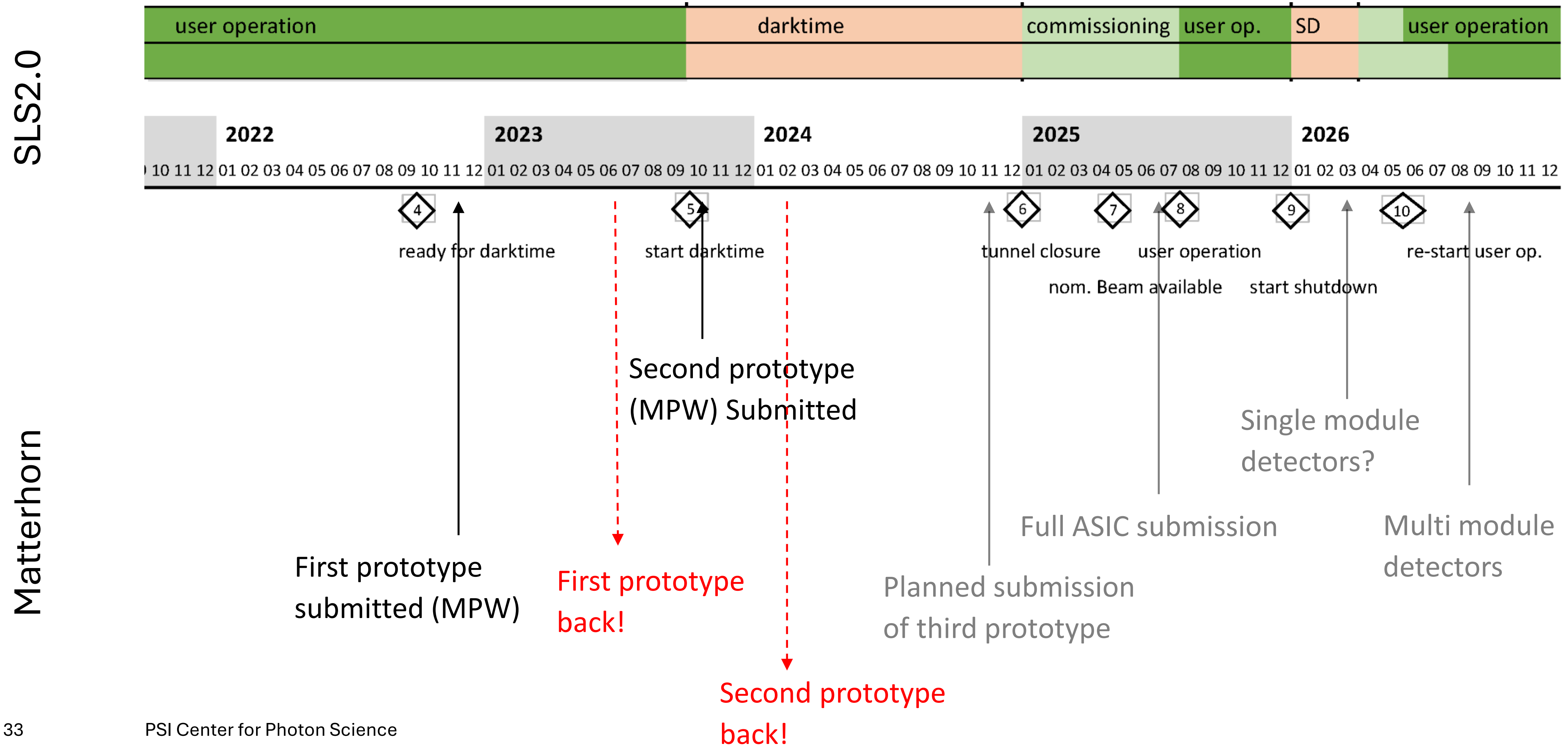


- Comparator biased in "low power" mode
- Vrf can be set even lower (100-150)
- Preamp/shaper biases can be further tuned

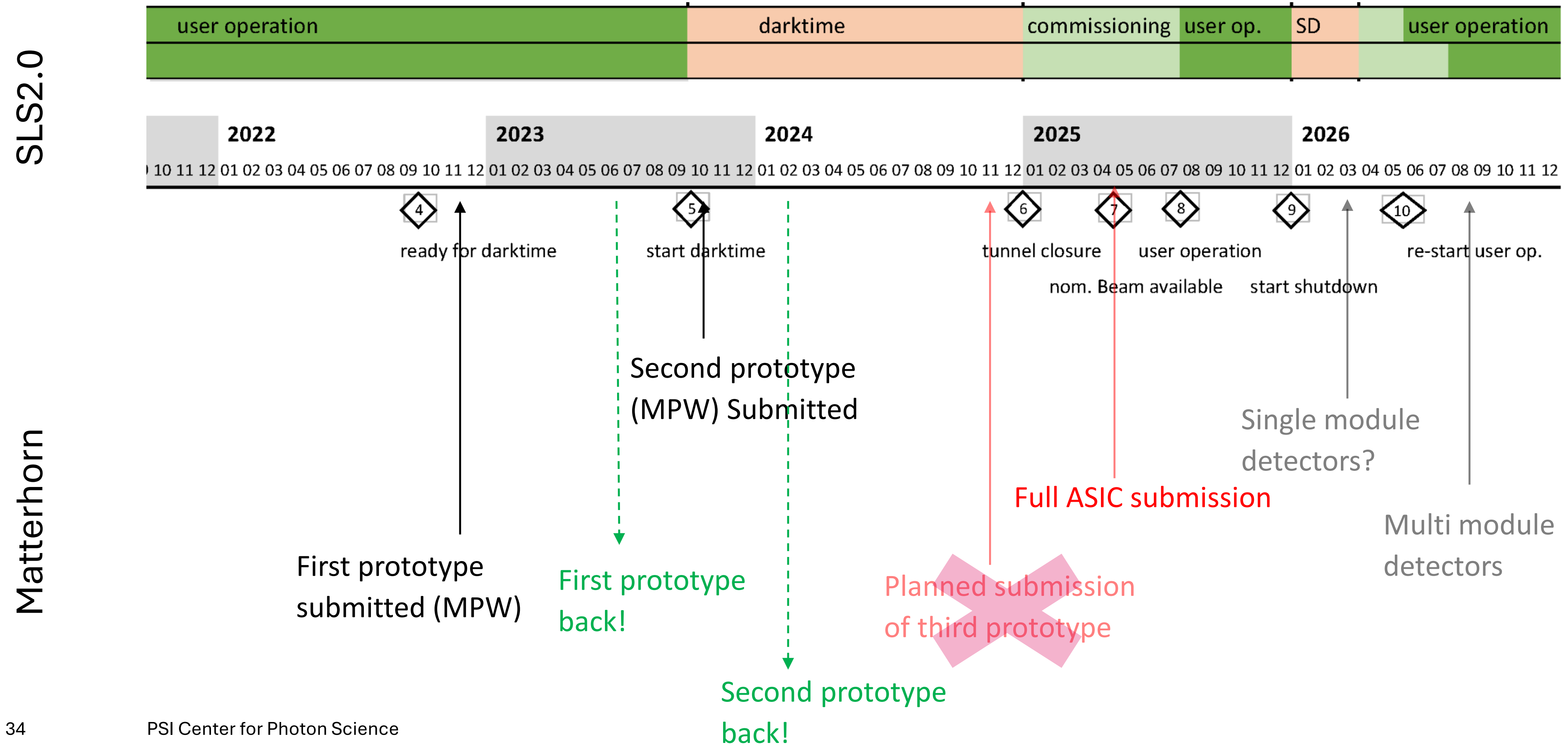
The “speed challenge”: high frame rate

	EIGER	MATTERHORN 1
Technology	250 nm	110 nm
Chip outputs	32xCMOS, 200 Mb/s	4xCML, 3.125 Gb/s
Single chip	6.4 Gb/s	12.5 Gb/s
Module (8 chips)	51.2 Gb/s	100 Gb/s
Readout channels/module	2x10Gbit/s	1x100Gbit/s
Frame rate	~10 kHz 8bit (burst)	~20 kHz 8bit (continuous)
Continuous R/W	Yes	Yes

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!

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
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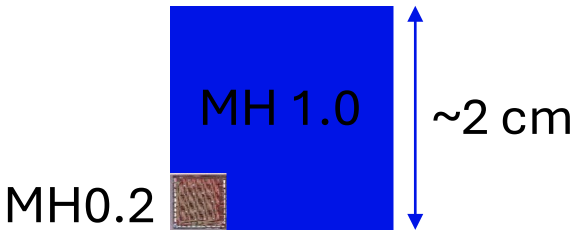
Matterhorn
Second prototype (MPW) Submitted
Single module detectors?
Full ASIC submission
Multi module detectors
First prototype submitted (MPW)
First prototype back!
Planned submission of third prototype
Second prototype back!

Matterhorn 1, the full-size chip



Same pixel as Matterhorn 0.2

	MATTERHORN 1
Technology	110 nm
Chip active area	1.92x1.92 cm^2 256x256 pixels
Pixel size	75 x 75 um^2
Thresholds	4
Counter depth	4x16 bit
Trim bits/compar.	6
Static power/pixel (4 comparators)	9.6μW
HighZ/LGAD	Yes

New features

- Pixel data transfer:
  - Current mode signal distribution (to pixel periphery)
- New periphery, additional features:
  - Global signals distribution (RES,STO,EN<0:3>)
  - Counter summing mode
  - 4 bit mode
  - 64b/66b encoder for serializers
  - SPI interface for configuration/slow control
- Gating (4 independent EN) <20ns
- No active circuitry on the chip sides (less dead area)

Conclusion and outlook

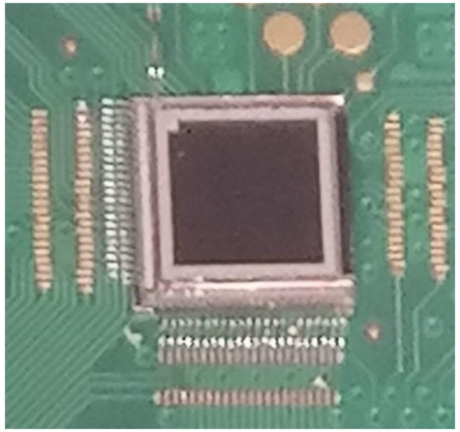
Matterhorn is a new SPC detector for SLS2.0 targeting:

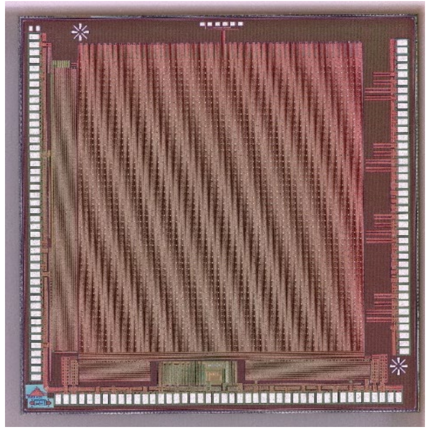
- 20Mcps count rate with 10% loss of efficiency
- 250 eV – 80 keV energy range (with LGADs and HighZ)
- 20kHz frame rate; <20 ns gating

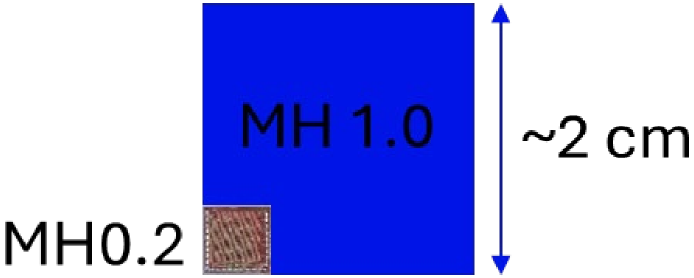
Results from MH01 and MH02:

- Noise down to <~80e- 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 spring 2025...







THANKS!

Left to right: Jiaguo Zhang, Bechir Braham, Konstantinos Moustakas, Viktoria Hinger, Christian Ruder, Shqipe Hasanaj, Dominic Greiffenberg, Julian Heymes, Anna Bergamaschi, Khalil Ferajoui, Carlos Lopez-Cuenca, Xiangyu Xie, Pawel Kozłowski, Martin Brückner, Roberto Dinapoli, Kirsty A. Paton, Filippo Baruffaldi, Mar Carulla, Bernd Schmitt, Thomas King, Patrick Sieberer

Not in the picture: Simon Ebner, Erik Fröjdh, Davide Mezza, Aldo Mozzanica, Dhanya Thattil, Viveka Gautam, Vadym Kedych, Shuqui Li, Martin Mueller, Saverio Silletta

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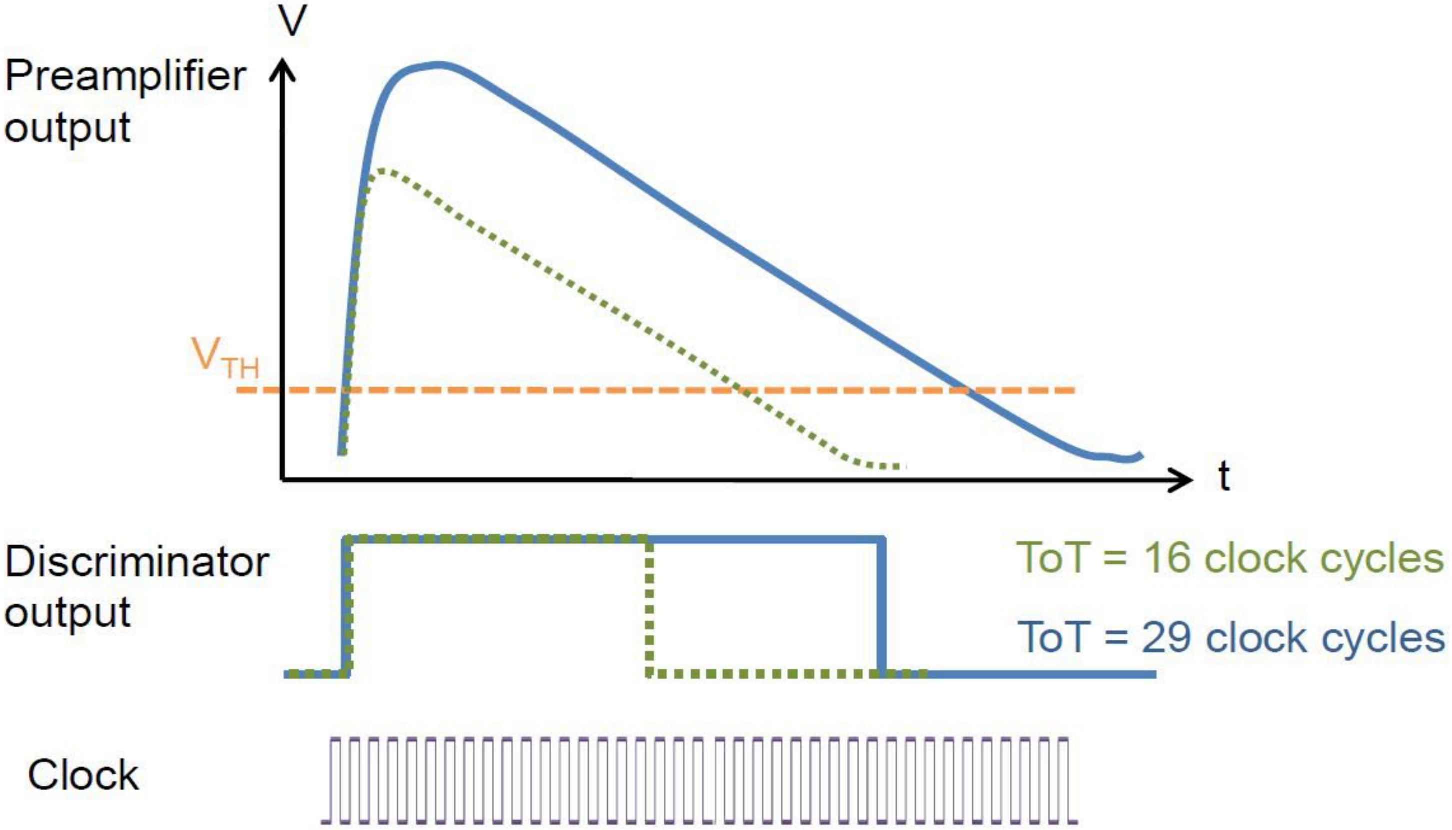
Not in the picture: Simon Ebner, Erik Fröjdh, Davide Mezza, Aldo Mozzanica, Dhanya Thattil, Viveka Gautam, Vadym Kedych, Shuqui Li, Martin Mueller, Saverio Silletta

Backup slides

Pile-up mitigation techniques

PSI

- Use charge integration with dynamic gain switching (Jungfrau, Jungfrau 2)
- Time over threshold/retriggering



Credit: R. Ballabriga

Operating modes of a single photon “counter”

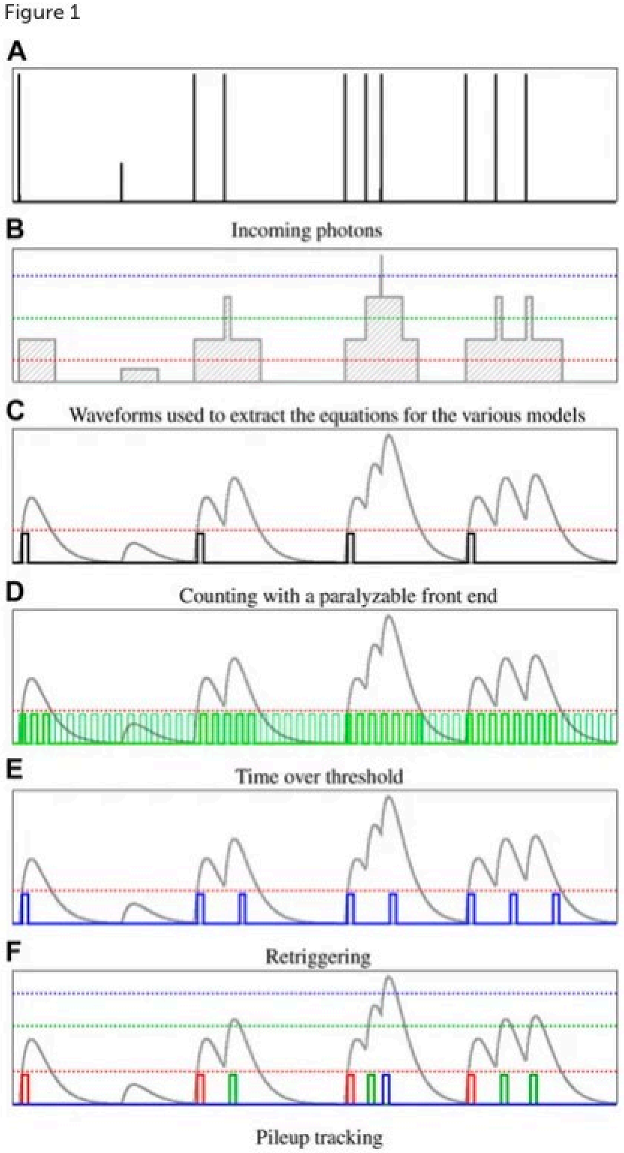


FIGURE 1. **(A,B)** Method to compare different strategies for mitigating the pulse pileup: **(C)** normal counting (reference), **(D)** time-over-threshold, **(E)** retriggering, and **(F)** pileup tracking. The *x*-axis refers to time, while the *y*-axis represents the height of the analog signal.

Comparison of pileup mitigation

Figure 2

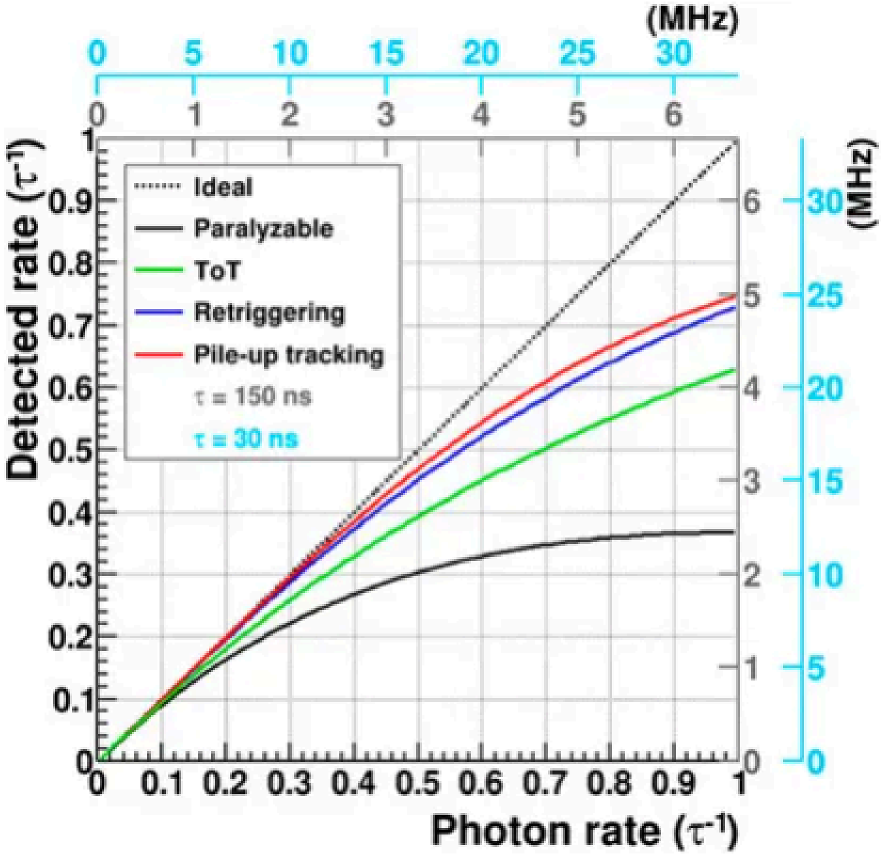
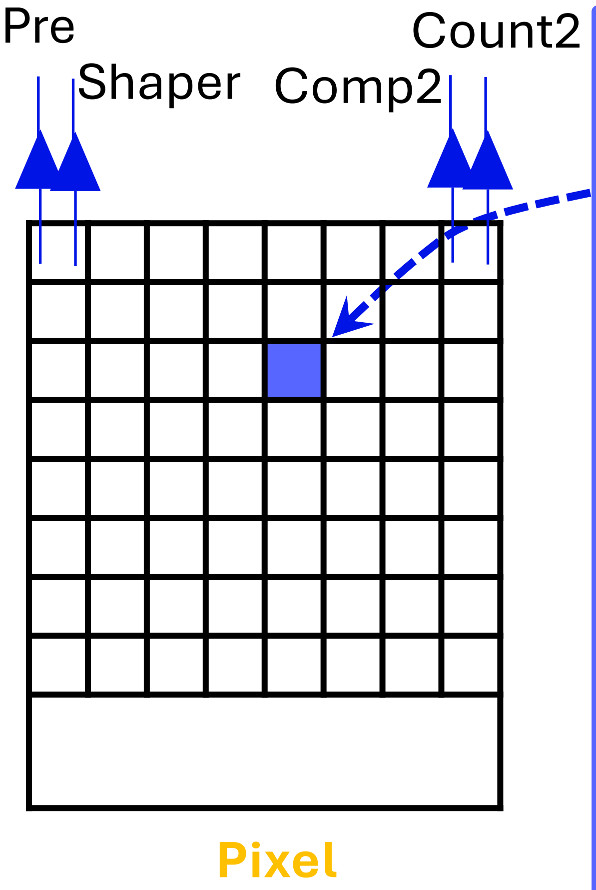


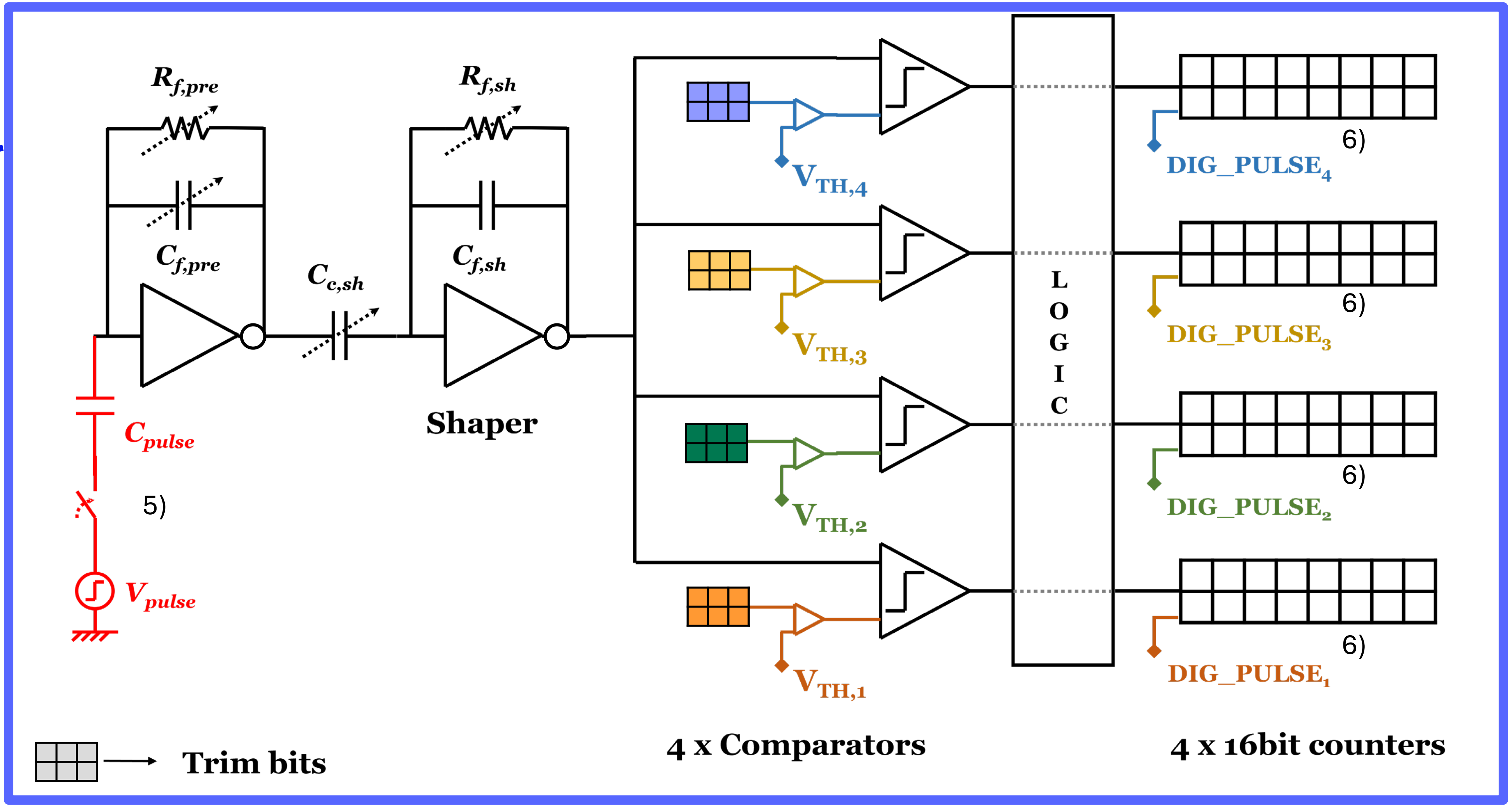
FIGURE 2. Detected rate as a function of the photon rate for a single-photon counting detector calculated using Eqs 1–4, covering the different solutions described in section 2.2. The rate is expressed as the reciprocal of the shaping time per pixel per second. The gray and the blue secondary axes compare 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

Pixel testability





5) The preamp can be pulsed with a programmable voltage step
Preamp and shaper outputs of pixel 0,0 can be monitored

6) Each counter can individually be pulsed
Comparator and "count" outputs of pixel 0,47 can be monitored

The «energy challenge»: low photon energies

- Soft X-ray applications at SwissFEL and SLS (250 eV – 2 keV)

– Low quantum efficiency (QE):

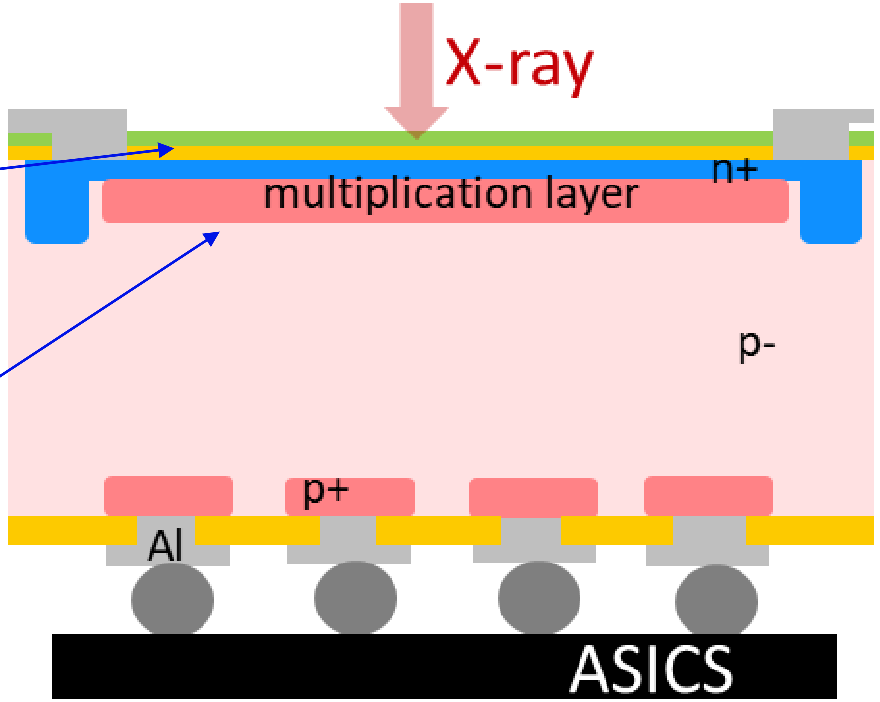
Development of "thin entrance window" sensor

Results: 80 % QE for a planar pin diode @250eV

– Low signal-to-noise ratio (SNR):

– Increase the signal with inverse Low Gain Avalanche Diodes (iLGADs) with a multiplication factor 5-20

Results: nominal noise of 35 e^- with standard sensor at RT down to 3.7 e^- at -22 °C with Moench



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The «energy challenge»: high photon energies

- Hard x-ray applications at Synchrotrons, 15-80keV

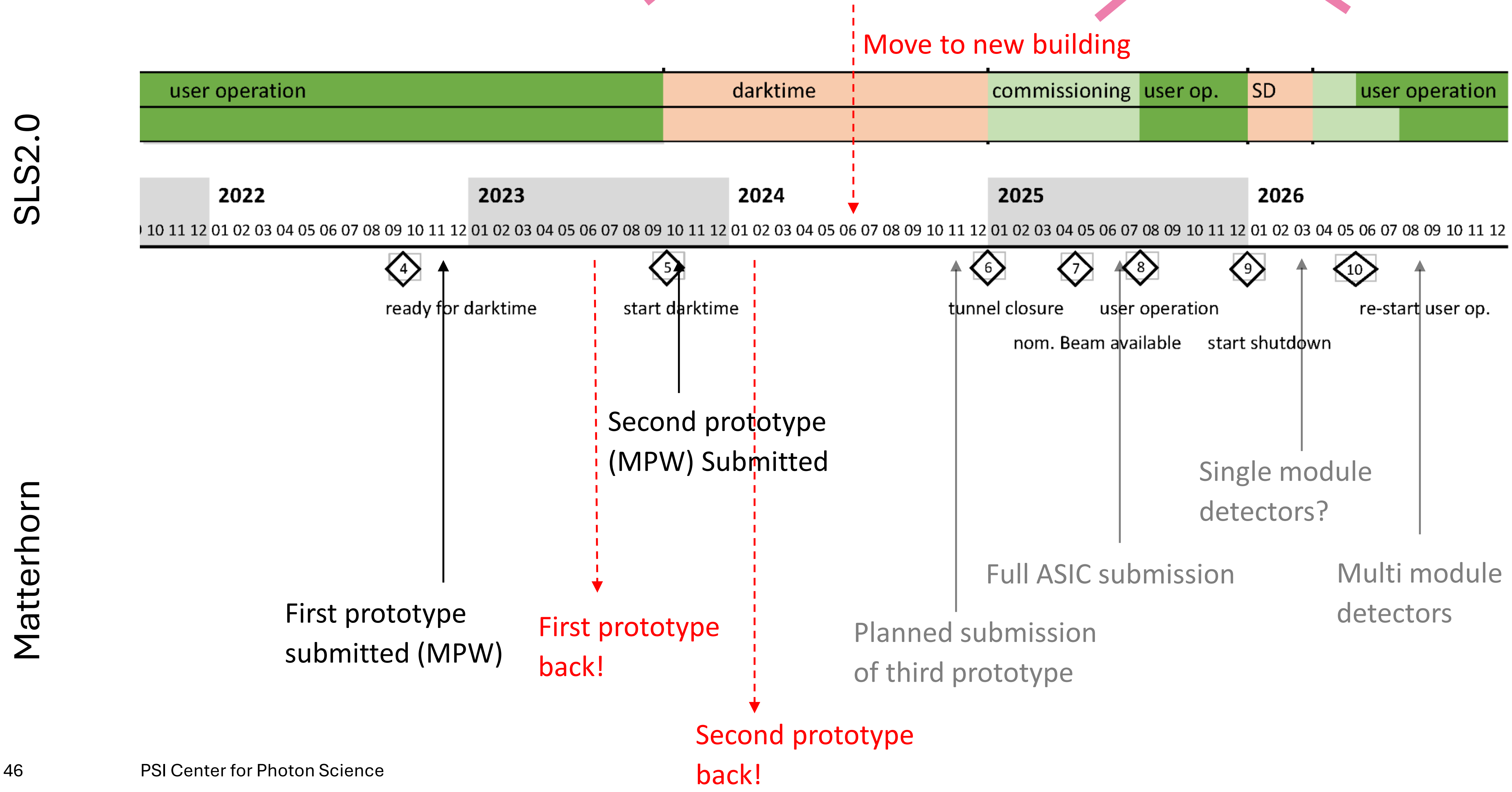
	Absorption efficiency	Signal stability	Afterglow	Spectral resolution capability	Dark current	Noise	Availability
Silicon	-	++	++	++	+	+	++
CdZnTe High Flux type	++	++	++	+	++	++	+
CdZnTe Spectroscopic type	++	+	+	+	++	++	+
CdTe e^- Schottky type	++	--	o	o	+	+	+
CdTe Ohmic tye	++	--	--	-	-	--	+
GaAs:Cr	+	o	o	+	--	-	+

- \+ **CdZnTe** is the **material of choice** above 15 keV
- \+ **4×4 cm^2 sensor commercially available**
- \+ **Dynamic behavior (signal stability, afterglow) close to silicon sensors**
  - → Higher photon energies need to be studied
- \- **Crystal defects** influence **sensor uniformity**
- \- Fluorescence photons with long absorption range

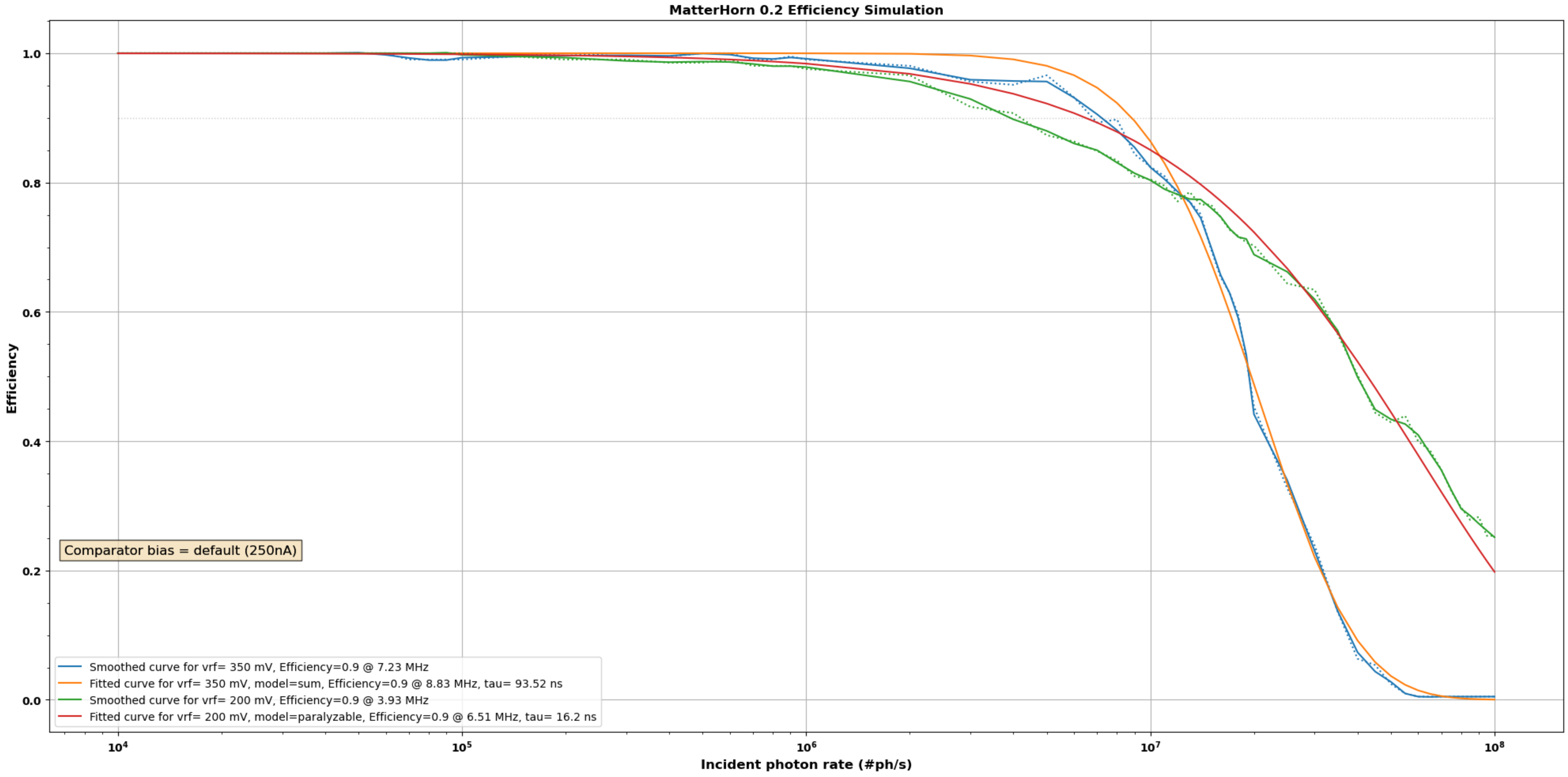
- \+ **GaAs:Cr** is **promising**, but doesn't perform as well as CdZnTe
- \+ **Two European suppliers, 8×4 cm^2 sensors available**
- o **Afterglow acceptable** up to photon fluxes
  - → Continuous: $<10^{(8\text{-}9)}$ $ph/mm^2 \cdot s$
  - → Pulsed: $<10^{(6\text{-}7)}$ $ph/mm^2 \cdot pulse$
- \- Some signal loss at photon fluxes above > 3×10^{10} $ph/mm^2 \cdot s$
- \- Crystal defects influence **sensor uniformity, variation of effective pixel size + Short hole lifetime** → Craters
- \- **High dark current** → For long exposure times: ideally SPC

Timeline





Move to new building
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!


MatterHorn 0.2 Efficiency Simulation
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0
Comparator bias = default (250nA)
Smoothed curve for vrf= 350 mV, Efficiency=0.9 @ 7.23 MHz
Fitted curve for vrf= 350 mV, model=sum, Efficiency=0.9 @ 8.83 MHz, tau= 93.52 ns
Smoothed curve for vrf= 200 mV, Efficiency=0.9 @ 3.93 MHz
Fitted curve for vrf= 200 mV, model=paralyzable, Efficiency=0.9 @ 6.51 MHz, tau= 16.2 ns
10^4
10^5
10^6
10^7
10^8
Incident photon rate (#ph/s)