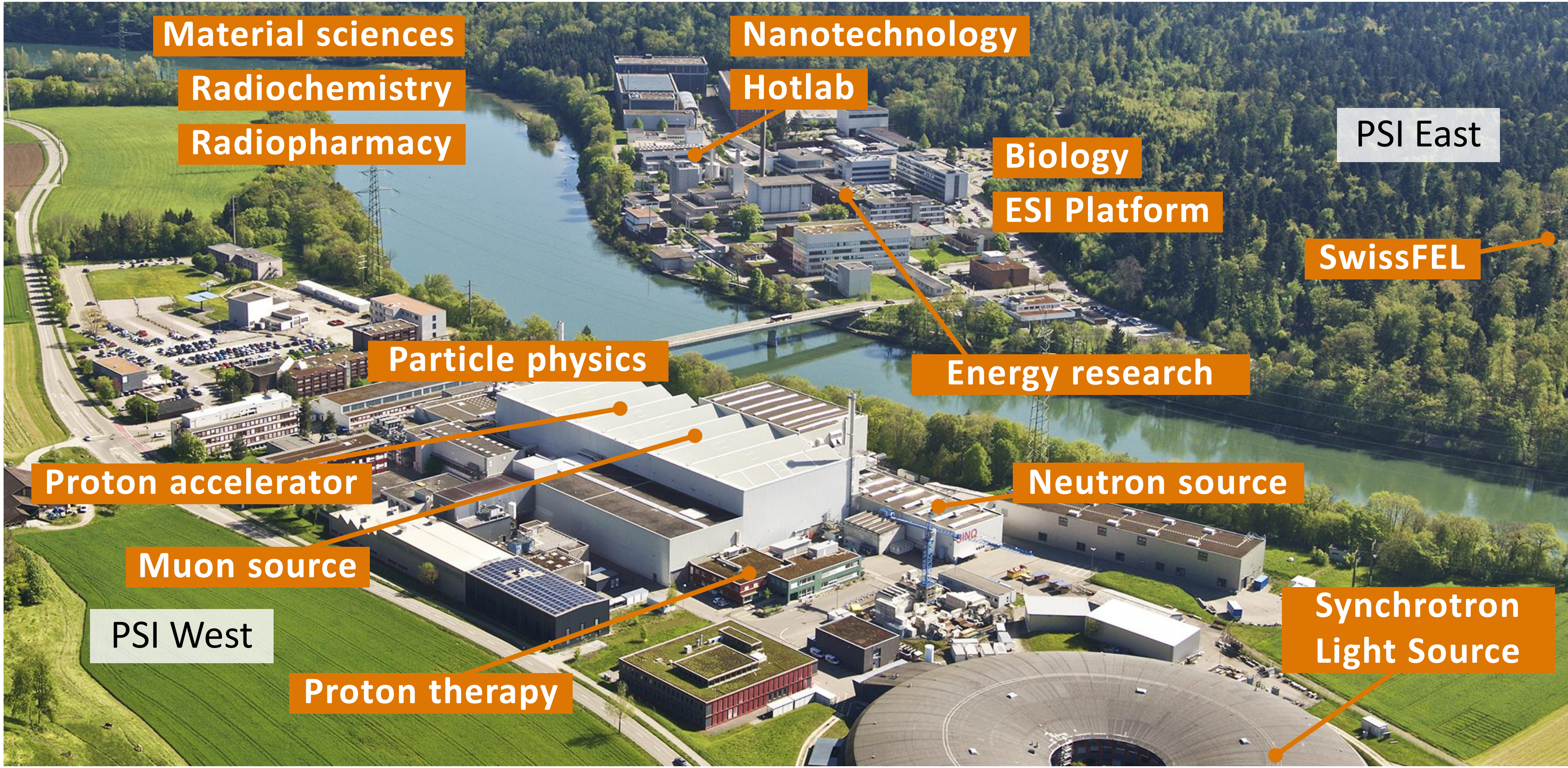
Roberto Dinapoli:: Electronics and Photon Science Detector Groups :: Paul Scherrer Institut

IC design and detector development for Photon Science

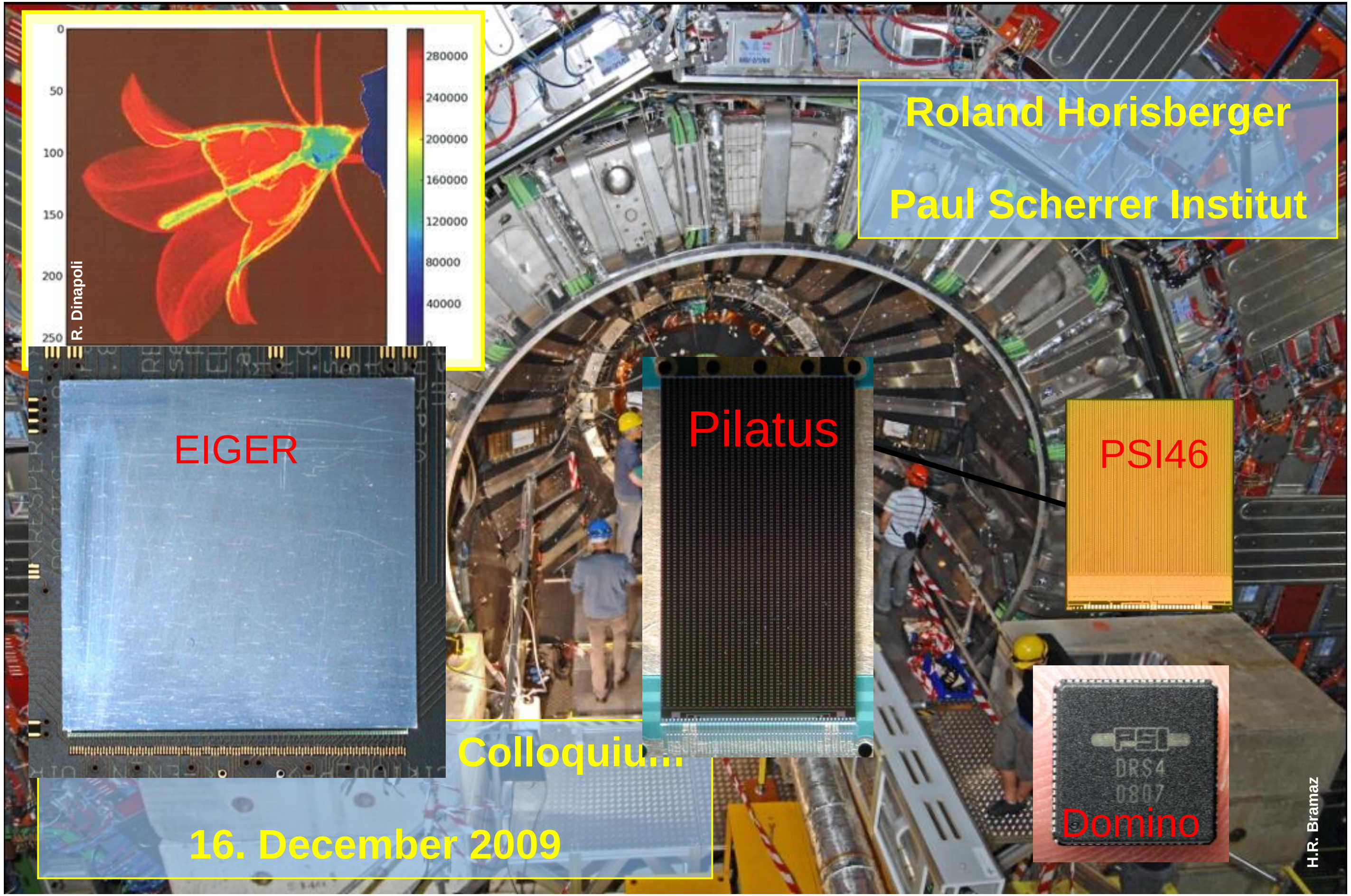
PIXEL 2022:: Santa Fe:: 14th December 2022

Paul Scherrer Institut

← Basel   Germany ↑   Aarau/Bern ↓   Zurich →



Pixels for Beauty



The Photon Science detector group

- We are a very diverse group bringing together experts from many different fields,~20 people
- Development of hybrid detectors for Photon Science

Chip Design Team

Photon Science (PS):
R. Dinapoli (NUM)
K. Moustakas (PSD)
A. Mozzanica (PSD)
D. Mezza (PSD)

High energy physics (HEP):
B. Meier (NUM)

Back: J. Zhang, **A. Mozzanica**, T. King, **D. Mezza**, A. Bergamaschi, J. Heymes; *Middle:* E. Fröjdh, C. Lopez, M. Brückner, C. Ruder, B. Schmitt, **K. Moustakas**, D. Greiffenberg; *Front:* V. Hinger, D. Thattil, **R. Dinapoli**, S. Hasanaj, M. Carulla, S. Ebner; Missing: R. Barten, P. Kozlowski, F. Baruffaldi

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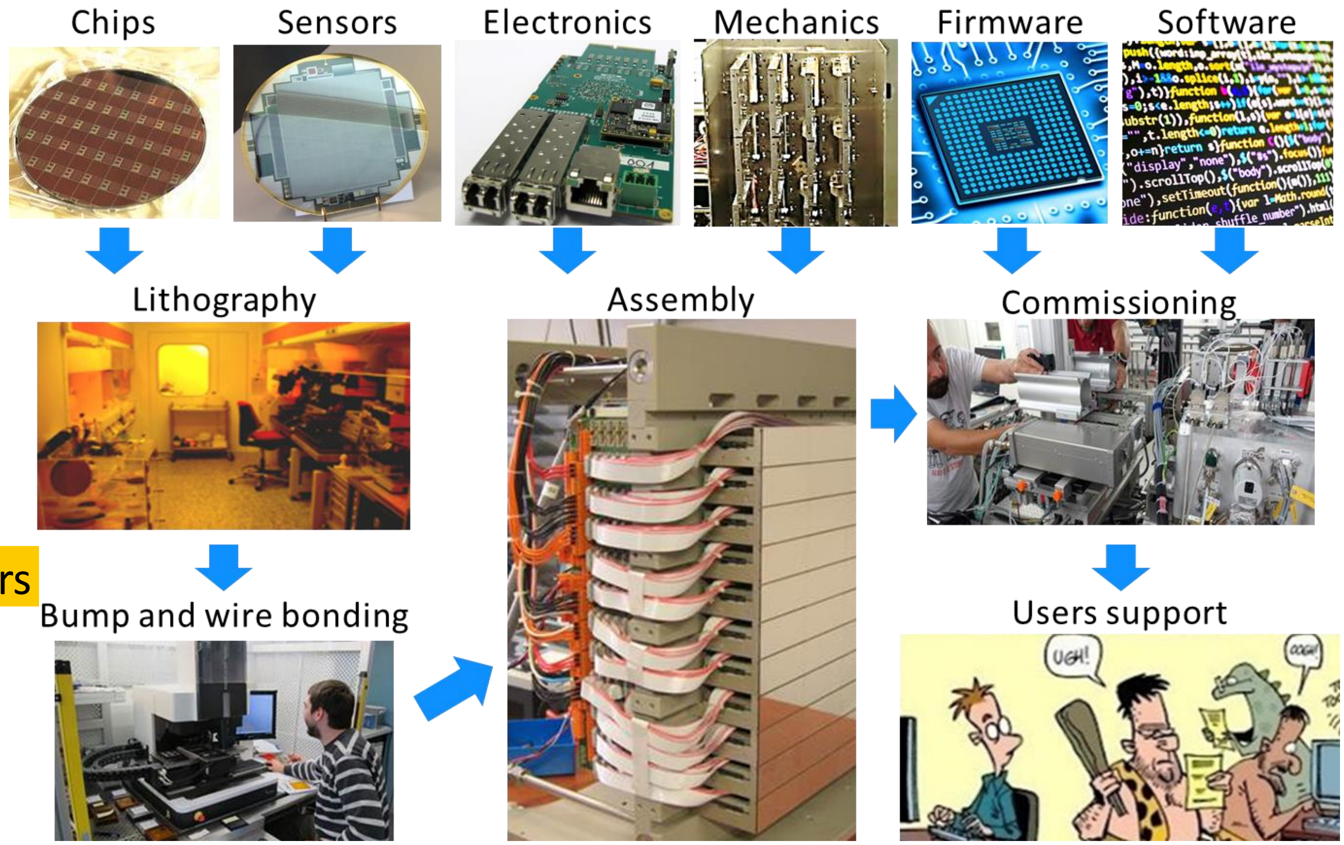
Everything developed in-house



Hybrid detectors

Talk focuses on Single Photon Counters only

What is not going to be covered…

A different challenge: detectors for free electron lasers

- Photons arrive simultaneusly: no SPC possible
- Dynamic range 10^4 photons with single photon sensitivity at few keV

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Charge integrating detectors (since 2008)

	GOTTHARD[1]	AGIPD[2]	JUNGFRAU	MÖNCH
				
Status	In operation at EuXFEL	At beamline (EUXFEL)	2x 16M at SwissFEL	At beamline
Pixel size	50 µm (Strips)	200 x 200 μm^2	**75 x 75 μm^2**	**25 x 25 μm^2**
Maximum system size	Modules (=10 ASICs)	1Mpixel (=16 Modules)	16Mpixel (=32 Modules)	Single Chips (=2x3 cm^2)
Noise (r.m.s.)	<300 e^- ENC	< 322 e^- ENC < 214 e^- ENC (HG)	**< 100 e^- ENC (G0)** **< 35 e^- ENC (HG0)**	**<35 e^- ENC**
Dynamic range	**< $1\cdot10^4$ x 12.4 keV** **(3 gain stages)**	**< $1\cdot10^4$ x 12.4 keV** **(3 gain stages)**	**< $1\cdot10^4$ x 12.4 keV** **(3 gain stages)**	< 500 x 12.4 keV (2 gain stages)
Maximum frame rate	40 kHz (cont.) 1 MHz (burst)	**< 5 MHz (burst*)** *** 352 frames**	**2.4 kHz (cont.)** **< 1 MHz (burst)**	**6-8 kHz (cont.)**

2) Common development with University of Bonn (GER), University of Hamburg (GER) and DESY (GER), 1) Common development with Desy

Studies on high-Z materials

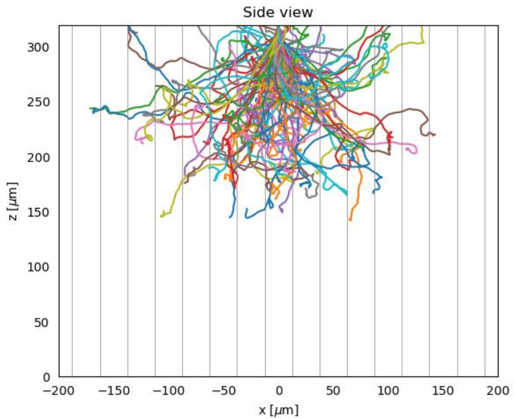
The «energy challenge», part 2

	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 seems to be the material of choice at the moment** as alternative to silicon to extend the photon energy range
😐 **Still some issues with uniformity and defects**
😐 **Sensor yield relatively low (≈40 %)**
☹ **Biggest problem is the availability of larger sensors (>4×4 cm²)**

Other applications

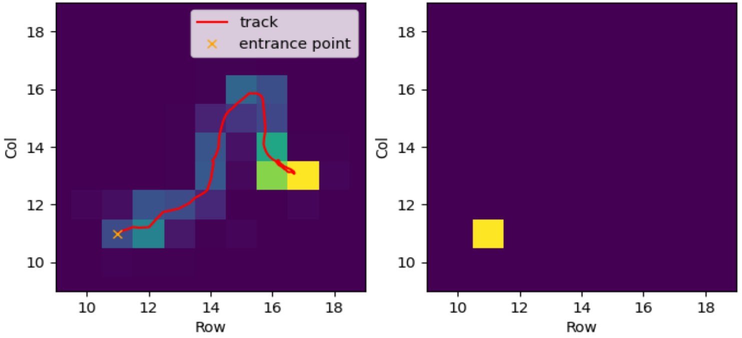
- **Example:** Improving spatial resolution in electron microscopy with Mönch and ML
- Postod working on using machine learning to find the entrance point of the electron
- Information encoded in the track by physical processes



200 keV electron tracks

Simulated signal with track overlaid

All signal assigned to the correct pixel



Simulated MÖNCH 25µm pixel

J. P. van Schayck et al. “Sub-pixel electron detection using a convolutional neural network”. Ultramicroscopy 218 (2020), p. 113091.

Moving from HEP to Synchrotrons

Similarities with HEP:

- Detect charge generated by particles entering your detector
- Sensitive to single particles
- Detect all particles impinging on your detector
- Large area detectors
- Harsh conditions, in particular radiation tolerance

Moving from HEP to Synchrotrons

Differences with HEP:

– EASIER

- No timing information required
- Radiation tolerance requirements less stringent: no SEUs, SELs or SEFIs
- Much easier access to the detector, no cooldown.
- Area not as big

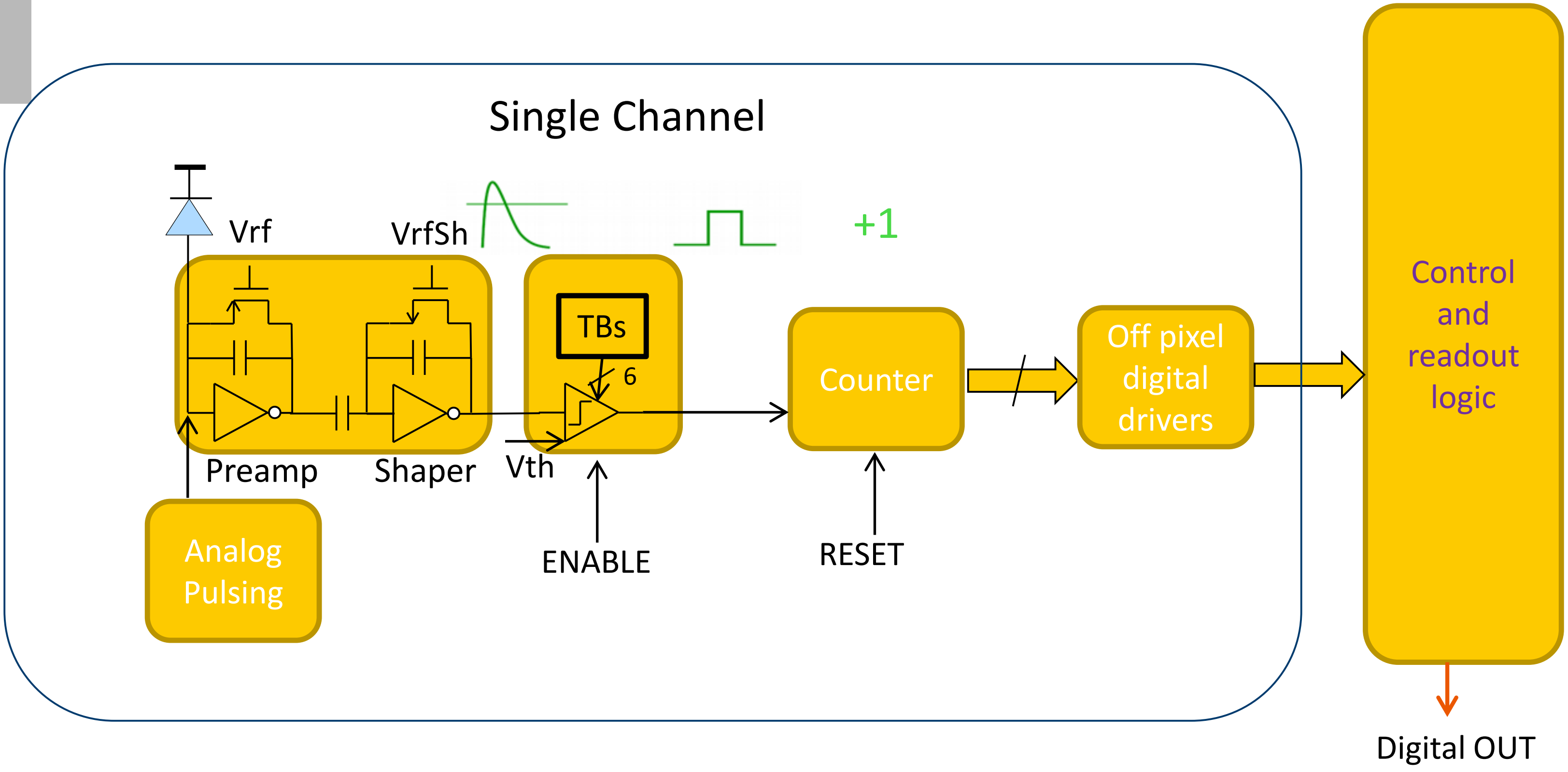
Moving from HEP to Synchrotrons

Differences with HEP:

– MORE DIFFICULT

- High dynamic range
- Energies from 2-3 keV to 20keV

Single photon counting (SPC) at synchrotrons

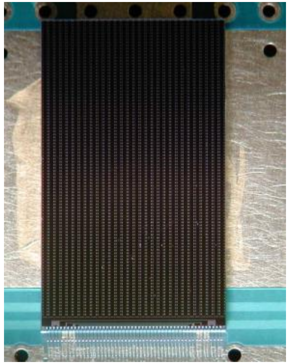


Requirements for an ideal X-ray pixel detector

1st generation

- Single photon resolution
- No spatial distortion and uniform response
- Large dynamic range
- Large area

→ PILATUS



Moving from HEP to Synchrotrons

Differences with HEP:

- MORE DIFFICULT

- High dynamic range
- Incoming particle rate >2 orders of magnitude(Mcnts/pixel/s)
- Complete frame readout at:
  - High frame rates
  - Negligible dead time

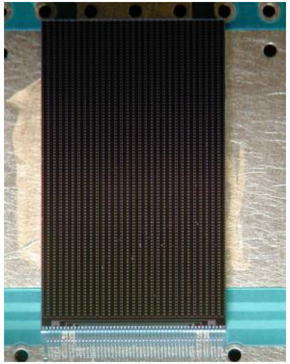
=>Much higher data throughput (x15)

Requirements for an ideal X-ray pixel detector

1st generation

- Single photon resolution
- No spatial distortion and uniform response
- Large dynamic range
- Large area

PILATUS



2nd generation

Small pixel size (172x172um^2->75x75 µm^2)

Small dead area

Fast Frame Rate (10Hz->23kHz)

Simultaneous exposure and readout

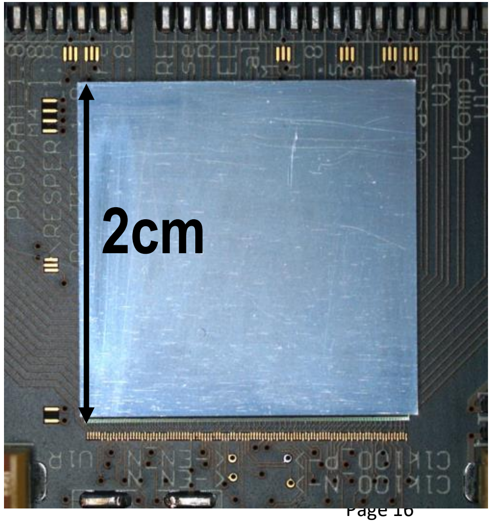
Negligible dead time (100ms->3µs)

High count rate of incoming photons

(30 counts/(s*µm^2)-> 200 counts/(s*µm^2))

Low noise at high speed O(150e$^-$@150ns τ))

EIGER



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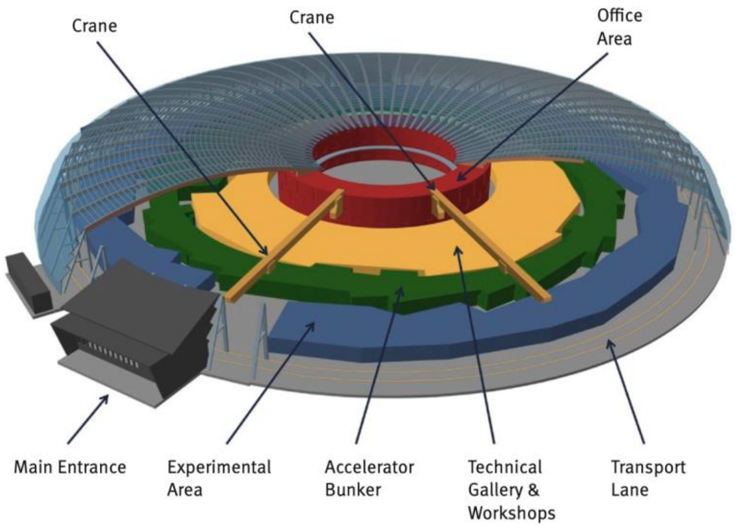
Diffraction limited sources, SLS 2.0

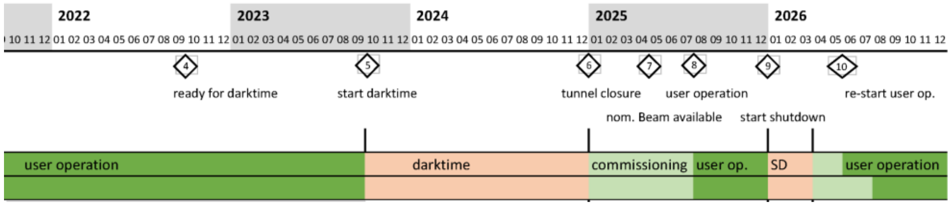
The «speed challenge»

- Depending on beamline ~ 1000x flux
- Dark period form autum 2023
- First light planned 2025 with user operation in later part of the year

- This requires ~20MHz/pix/s
- More flexibility for more applications

Can SPCs get there?



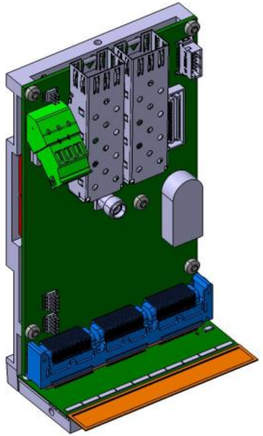


Mythen 3

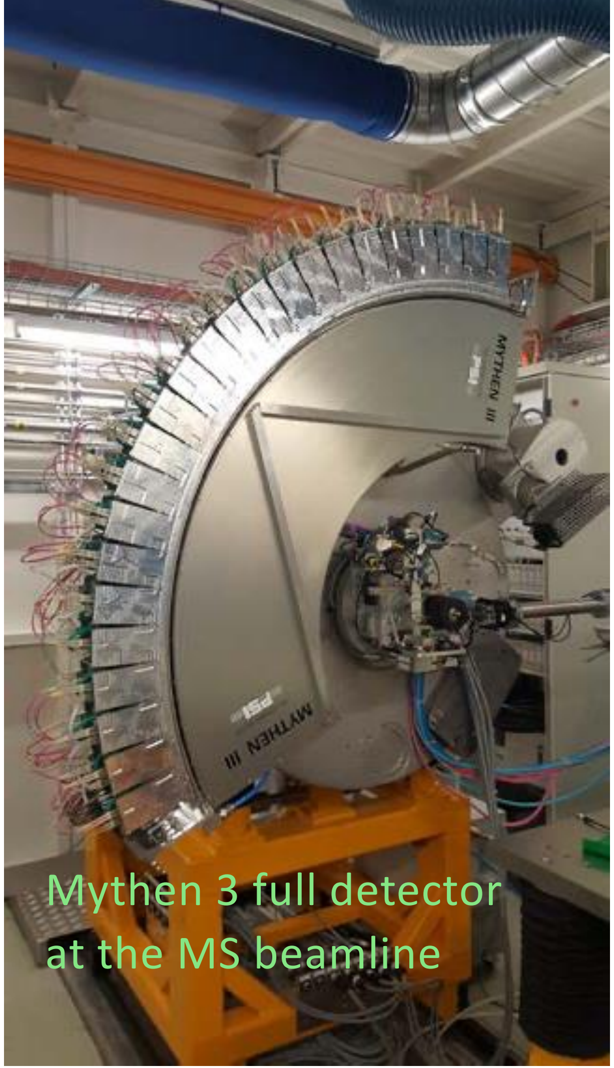
3rd generation

- Hybrid strip detector
- 100/175e- RMS noise (high/standard gain)
- Trimmed threshold dispersion < 6e-
- 300kHz frame rate
  - 8bits, 1 counter
  - limited by RO electronics

- 320um thick silicon sensor
- 50um strips



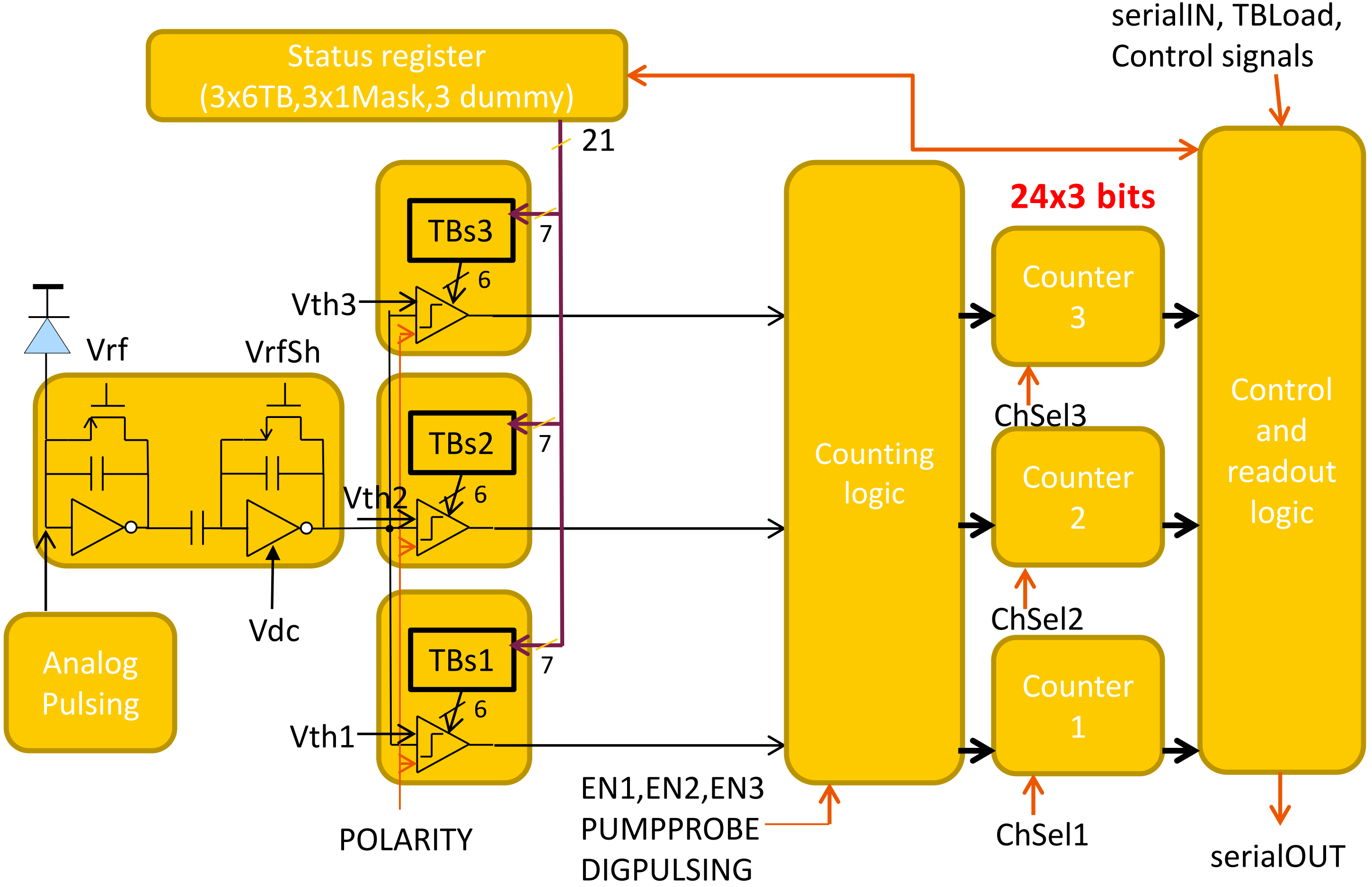
Mythen 3 module



Mythen 3 full detector at the MS beamline

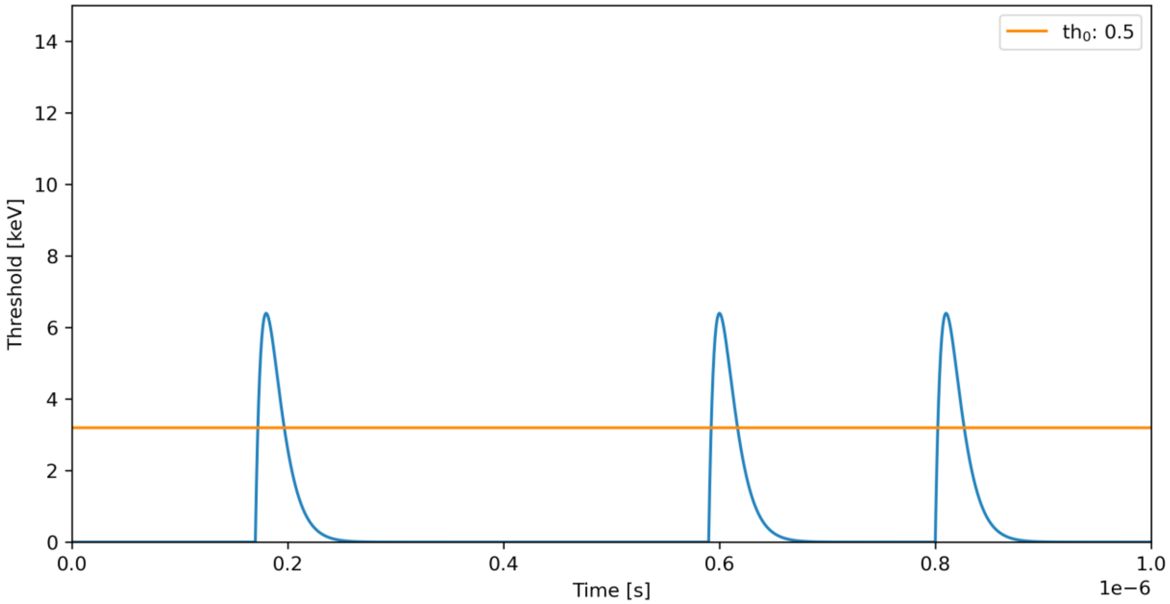
MYTHEN 3, the channel

3rd generation

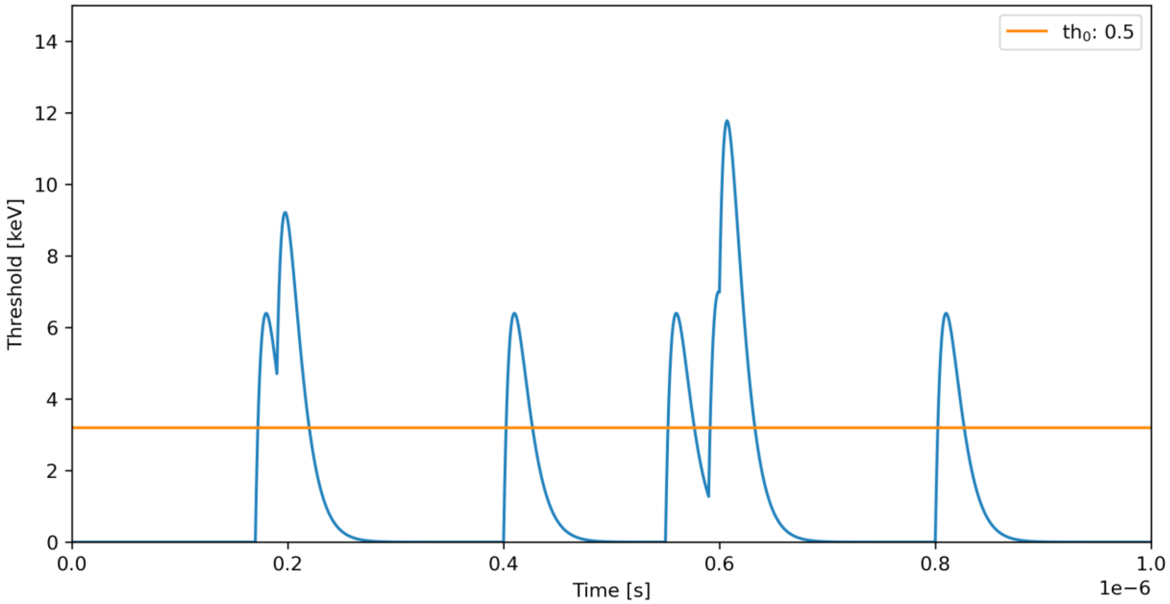


Roberto Dinapoli

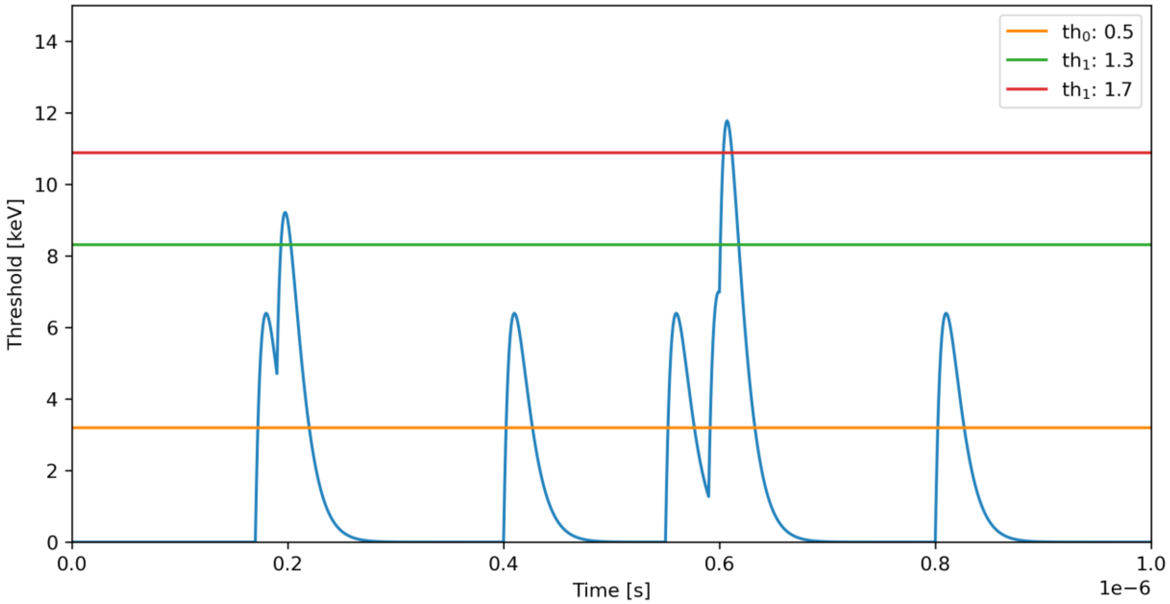
Improving rate capabilities: multithresholding



Improving rate capabilities: multithresholding

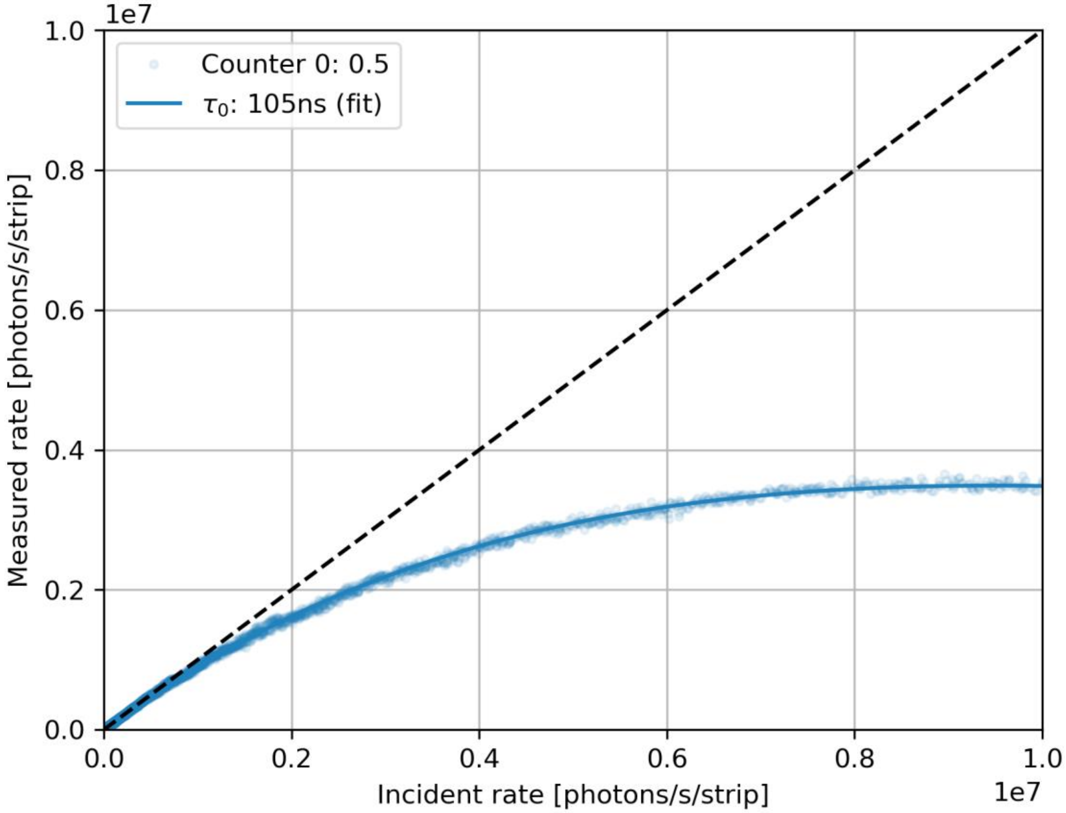


Improving rate capabilities: multithresholding



Mythen 3 (strips)

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



Settings: standard

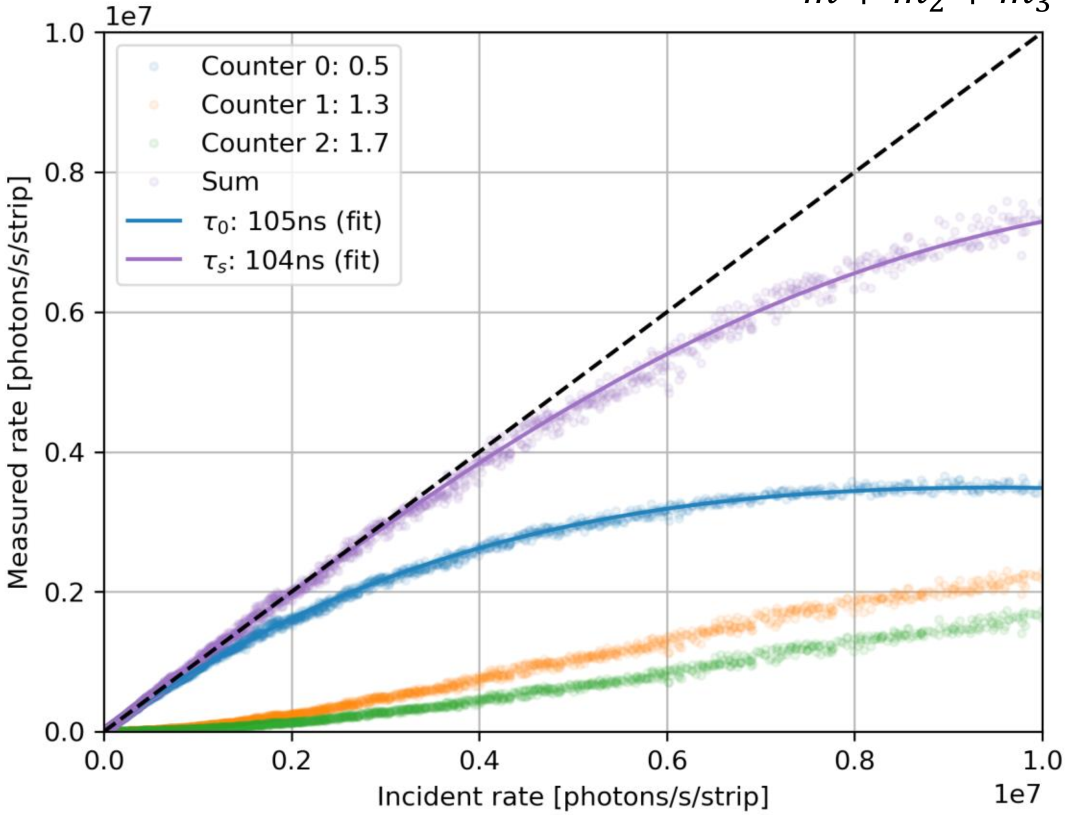
Energy: 15 keV

Noise 175e- RMS

MS beamline@SLS

Mythen 3 (strips)

Extended Paralyzable counter model:
$m + m_2 + m_3$



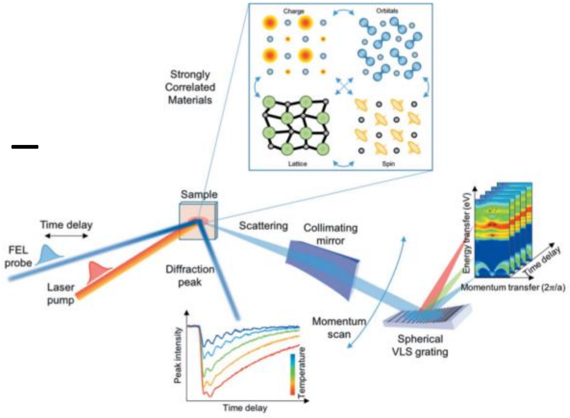
Settings: standard
Energy: 15 keV
Noise 175e- RMS

10% lost counts at:
th_0: 1.03M
th_{sum}: 6 M

MS beamline@SLS

The «energy challenge»

Time resolved resonant inelastic X-ray scattering (tr-RIXS)



doi: 10.1107/S1600577519003928

The «energy challenge», part 1

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

The «energy challenge», part 2

- Hard x-ray applications at Synchrotrons, 24-80keV

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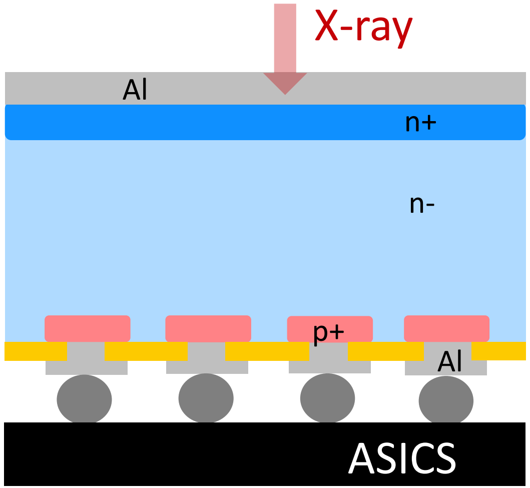
Challenges of soft x-ray single photon detection

- Single photon detection of X-ray in the energy range of 250 eV to 2keV:
  - Low quantum efficiency (QE): attenuation length of 250 eV photons is ~ 100 nm in silicon.
  - Low signal-to-noise ratio (SNR): small signal amplitude (~ 70 e-) with respect to the electronic noise (lowest noise pixel detector @ PSI -> 32 e- r.m.s equivalent noise charge).

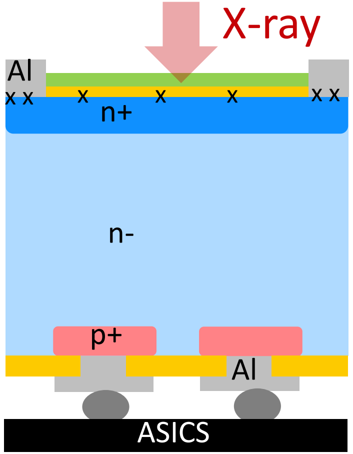


Both can be addressed at sensor level!

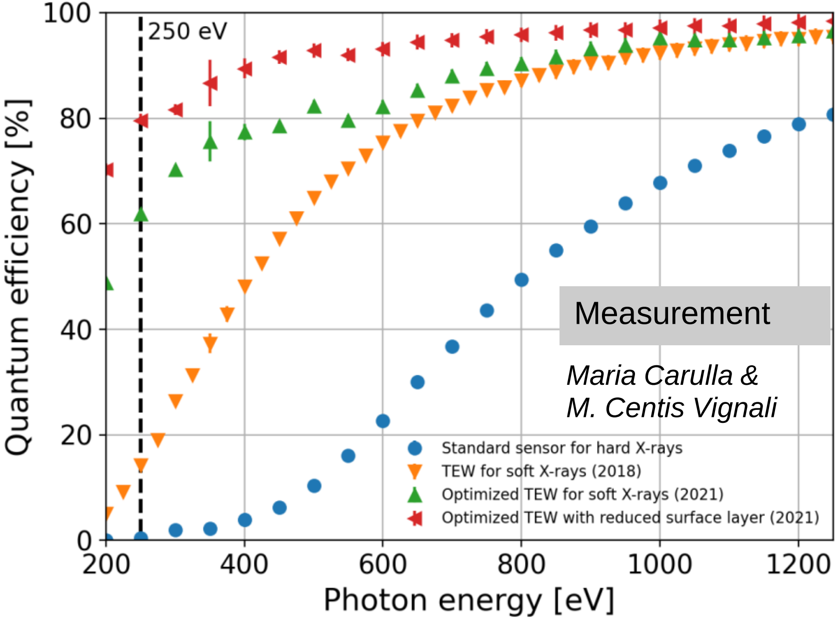
Challenges of soft x-ray single photon detection

- Improve the QE:
  - Reduce thickness of layers above Si
  - Decrease the charge recombination in the silicon/layer interface
  - Reduce the charge recombination in the highly doped implants

Opt. entrance window:



QE *vs.* X-ray photon energy



80 % QE for a planar pin diode @250eV

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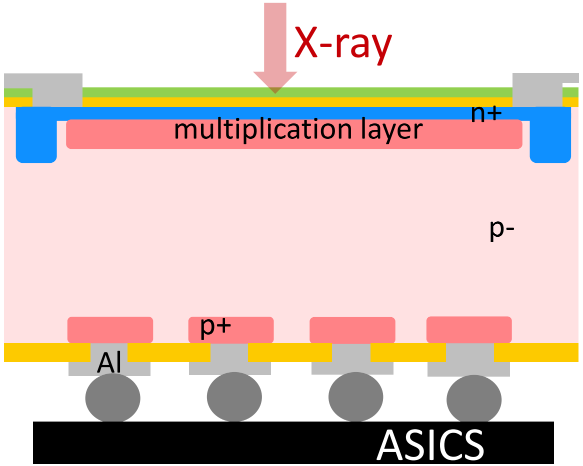
Challenges of soft x-ray single photon detection

- Improving the SNR:

  Increase the signal with Low Gain Avalanche Diodes (LGADs) with a multiplication factor 5-20
  ->Timing irrelevant for PS



=> iLGAD technology:

- Entrance window on the multip. layer
- Fill factor ☺
- Gain dependence on the photon energy ☹
- Leakage current ☹

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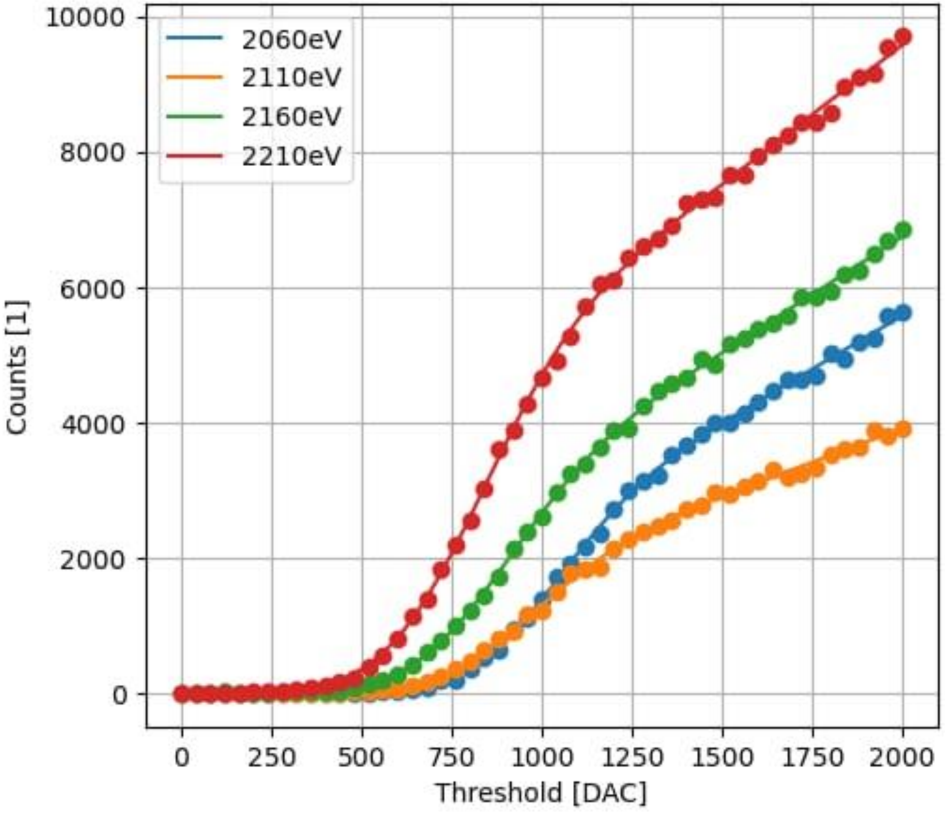
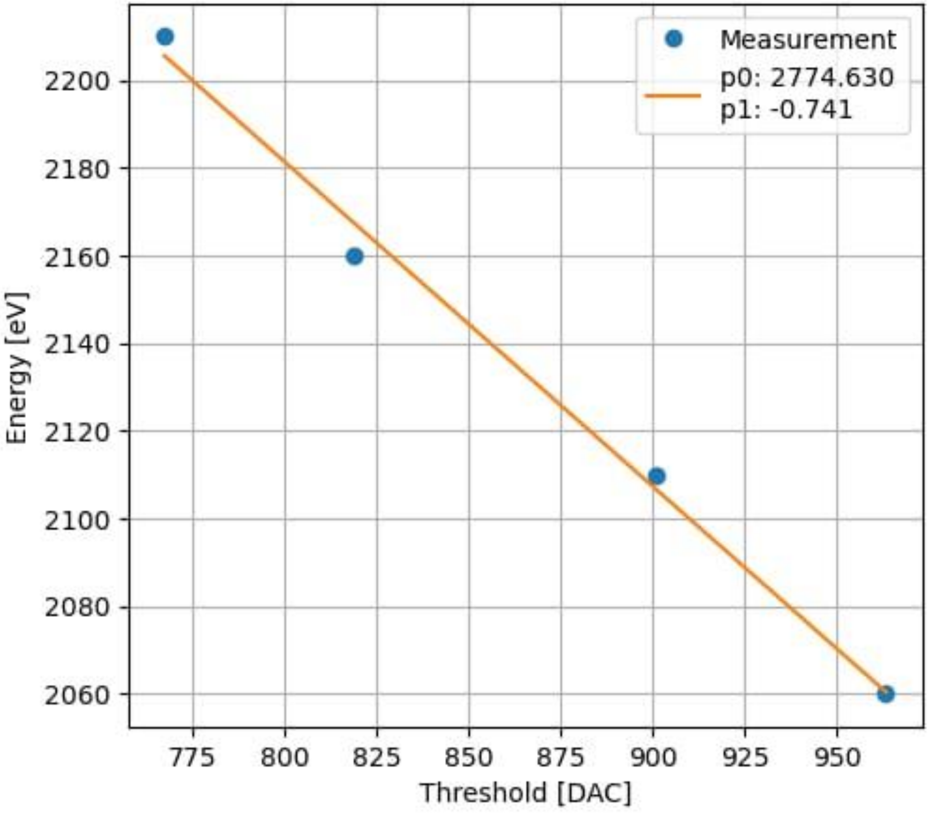
iLGADs with EIGER (Preliminary)





Energy resolution: ~150eV (~40 e-), room for improvement at lower E

iLGAD with MöENCH

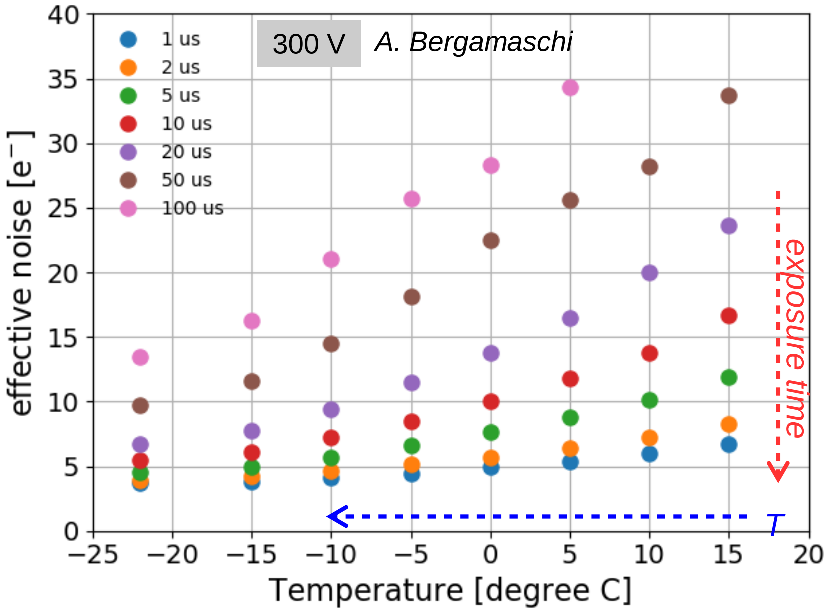
iLGAD pixel sensors of 25 um pitch with Moench readout chip:

–nominal noise of 35 e⁻ with standard sensor at RT (SNR=5 @ 700 eV)

–Various temperatures, RT down to -22 °C to reduce the “effective” noise

“Effective” noise *vs.* T & exposure time

down to 3.7 e^- at -22 °C with 1 μs exposure: SNR > 5 for soft X-rays above 67 eV (134 eV with 2x2 clustering).



$$\text{“effective” noise} = \frac{\text{noise [e}^- \text{ r.m.s.]}}{M}$$

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Preview: Matterhorn

3rd generation

- 75x75 um^2 pixel size
- 4 comparators
- 4x 16 bit counters
- 250 eV– 80 keV dynamic range
- Electron and hole collection
- 160 kHz in 1 bit mode
- <20ns gating speed
- 20 Mcts/pix/sec at 80% efficiency (with pileup tracking)
- *Corner effect mitigation, interpolation (future versions)*

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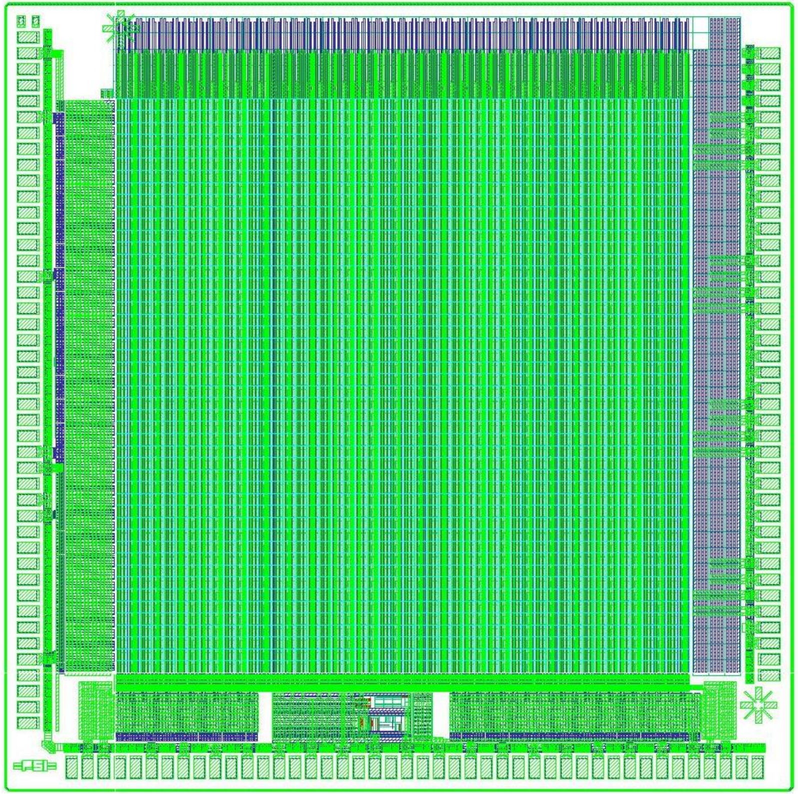


Prototype submitted last week

Conclusions

- Chip design design at PSI in HEP, precision physics, photon science
- Photon science detector group develops full detectors for synchrotrons and FELs
- Many chips and chip generations were developed for these purposes:
  - SPC for synchrotrons
    - Mythen (strip), Pilatus and Eiger (pixel)
  - CI for FELs
    - Agipd (pixels) and Gotthard for EuXFEL; Jungfrau, Mönch (pixel) for SwissFEL
- Research also in other fields (Electron microscopy, data science, …)
- Main challanges for new generation detectors:
  - High incoming photon rates of new light sources
    - SPC with fast shaping + multithresholding =>proven in Mythen 3, up to 20MHz/channel
    - Matterhorn development started, first MPW prototype submitted.
  - Expanding the energy range to low (down to 250eV) and high (>80keV) energy
    - First tests with FBK LGADs show 80%QE at 250eV, noise down to 5e-rms
    - Research on High Z materials


MYTHEN III


European XFEL
GOTTHARD II


EIGER


MÖNCH 0.3


Jungfrau 4M
JUNGFRAU 1.0/1.1

THANKS!


SwissFEL
SLS


SOLEIL
ESRF
DESY
ANKA
HZB
MAX-lab
diamond
elettra
Argonne
LCLS
ALS
RHIC
nsls
PAL
SPring-8
SINAP
Australian Synchrotron
NUS
SLRI
INDUS I & INDUS II
SESAME
LNLS

Chip characteristics: psi46dig and EIGER

psi46dig

EIGER

Technological process	IBM 0.25 µm Rad tol Design> 250 Mrad	UMC 0.25 µm; Rad tol. Design > 4 Mrad
Pixel array	80 x 52 = 4160 pixels	256 x 256 = 65536 pixels
Pixel size	100 x 150 μm^2	75 x 75 μm^2
Count rate	1.2 10^8 hits/cm^2/s	1.8 10^{10} photons/cm^2/s
Data rate	160 Mb/s	6 Gb/s
Transistors matrix Periphery Transistor density	1.26 M (304/pixel) 575 000 2.2 10^6/cm^2	28.44 M (430/pixel) 120 000 7.6 10^6/cm^2

Requirements for an ideal detector

EIGER, designed by PSI-SLS detector group, was optimized to satisfy the main requirements for an ideal detector for synchrotron radiation applications:

Single photons sensitivity and no intrinsic noise
- single photon counting detector

Good spatial resolution
- Small pixel size (75x75µm^2)

Fast Frame Rate ~tens kHz
- Simultaneous exposure and readout
- Negligible dead time (~ 3µs)
- Frame rate up to 22kHz in 4 bit mode

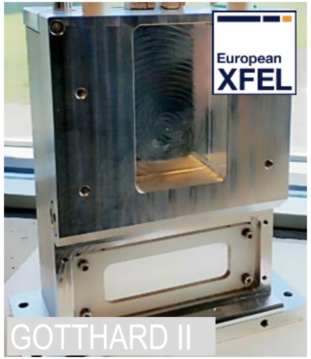
Detector that can be made as large as possible
- Modular detector system
- Data transfer parallel at half module level
- Projects for EIGER 16M Pixel (~32x32 cm^2)

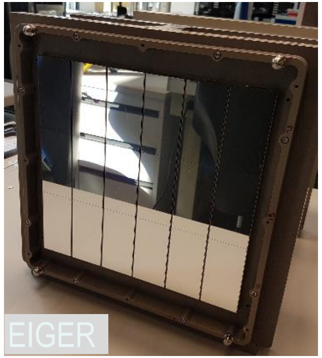
High count rate of incoming photons
- Count rates up to 1-2 million counts/pixel/second

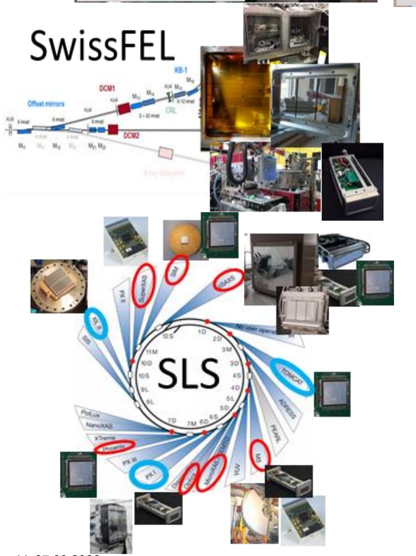
No spatial distortion and uniform response
- for X-ray energy range few keV to >20 keV

Chip Size	19.3x20.1 mm^2
Pixel Size	75x75 µm^2
Pixel Array	256x256 = 65536
Technological process	UMC 0.25µm; Rad tol. Design >4MRad
Sim. Analog Parameters	Gain: 44.6 µV/e- 30ns peaking time Timing: 151ns (Ret.to 0@1%) Noise: 135e-rms Static Power: 8.8µW/pixel(0.6W/chip)
Count Rate	3.4x10^9 xray/mm^2/s
Transistors Matrix Periphery Transistor density	28.44M >120 000 430/pix
Nom. power supplies	1.1V(analog), 2V(digital), 1.8V(I/O)
Counter	binary, configurable 4,8,12bit, double buffered
Readout speed	~22kHz@4bit mode
Threshold adjustment	Yes 6 Trim Bits
Analog out for testing	Yes
Overflow counter	Yes

Detector portfolio

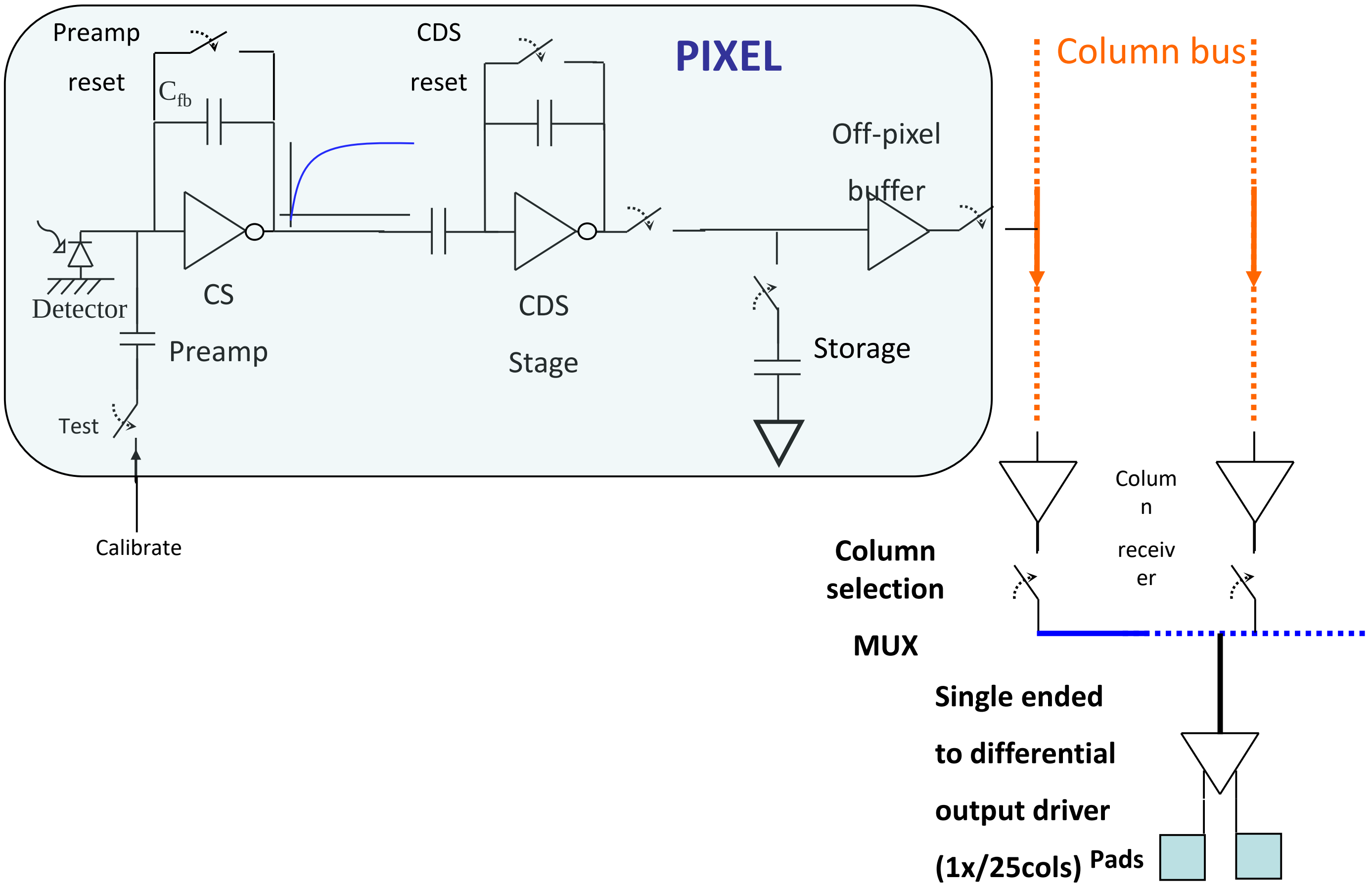






- Photon detectors
  - Synchrotrons, XFELs, Lab sources
- Electron detectors
  - Electron microscopes, Photoemission
- Anything depositing energy in a semiconductor

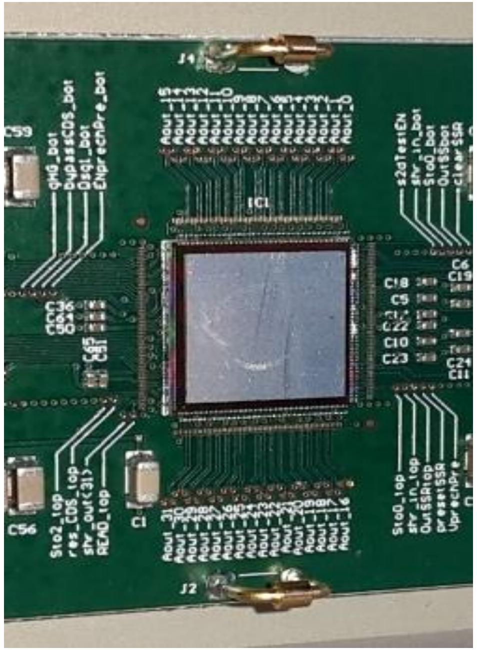
Charge integration with analog readout



MÖNCH

Micropixel with enhanced pOsition rEsolution usiNg CHarge integration

- Small pixels 25 x 25 μm^2
- Low noise
  - Single photon resolution >700 eV
    - 1.4 keV for clustering
  - 320 eV energy resolution FWHM
- Large dynamic range
  - Now static gain, will have switching
- Currently 1x1 cm^2 prototype available
  - 400x400=160 kpixel
- Fast frame rate (> kHz)
  - currently 3 kHz, by design 6 kHz
  - Ca. 20 TB/day
- Dead-time free operation possible



M. Ramilli, et al. (2017) J. Instr. 12, C01071.http://dx.doi.org/10.1088/1748-0221/12/01/C01071

EIGER vs. MATTERHORN

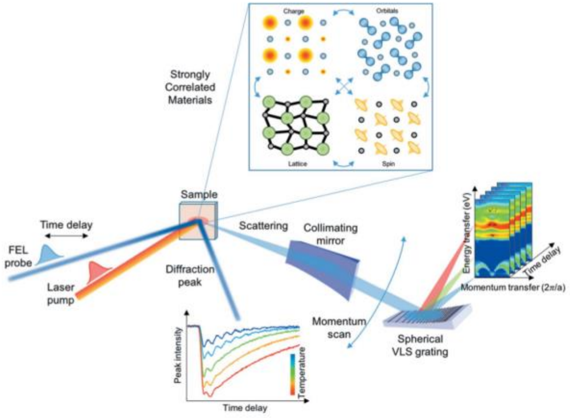
	EIGER	MATTERHORN
Node	0,25 um	110 nm
Pixel size	75 x 75 um^2	75 x 75 um^2
Comparators	1	4
Counter depth	4/8/12 bit	4x16 bit configurable
Energy range	5-25 keV	250eV – 80 keV
Module size	2x4 chips → 4x8cm	2x4 chips → 4x8cm
Maximum count rate	1M counts/pixel/s	20M counts/pixel/s
Frame rate	22 kHz	160 kHz
Gating	us	< 20ns

Soft X-ray applications at SwissFEL and SLS

The «energy challenge», part 1

- Soft X-ray applications at SwissFEL and SLS (250 eV – 2 keV)
  - Access K-edges of biologically important elements
    - e.g. water window 250-520 eV
  - L-edges of 3d transition metals, Fe, Cu, etc.
  - Possible applications:
    - RIXS at FELs and synchrotrons
  - Single photon detection necessary and interpolation desirable
    - Contrast enhanced imaging:
  - soft X-ray diffraction
  - ptychography
  - absorption spectroscopy

Time resolved resonant inelastic X-ray scattering (tr-RIXS)

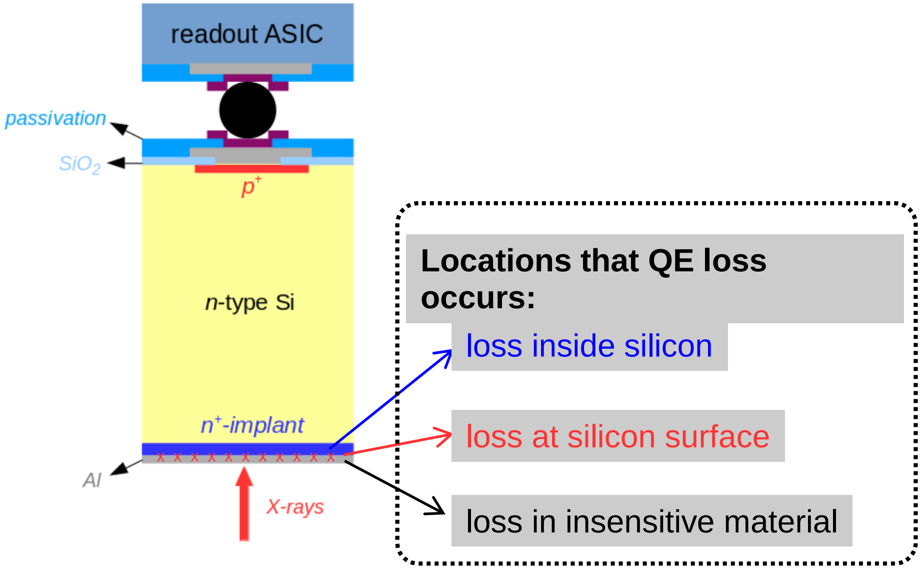


doi: 10.1107/S1600577519003928

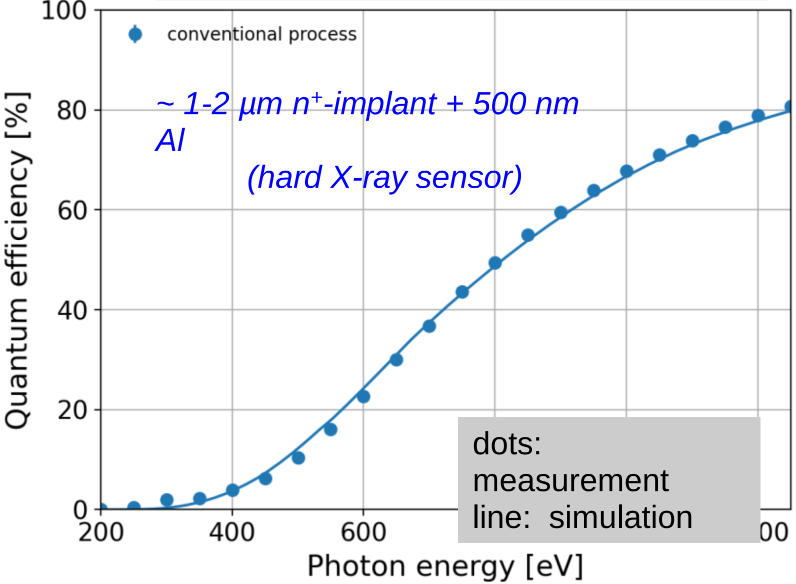
Quantum efficiency limit

- Soft X-rays (~ a few hundred eV) absorbed in the first micron of silicon sensor
  - For conventional process, e.g. p^+-n sensor: n^+-implant depth ≈ 1-2 micron + aluminum
- Significant efficiency loss for X-rays below 1.2 keV → not usable for soft X-rays! (< 50% below 800 eV)

Conventional assembly and efficiency loss



Measured / simulated quantum efficiency



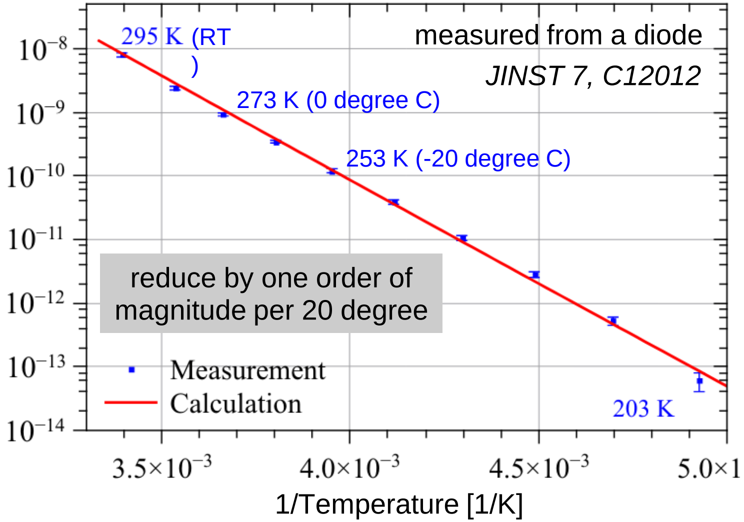
- For soft X-ray detection, it is necessary to develop a thin entrance window process to improve the quantum efficiency (QE) and the charge collection efficiency (CCE)

iLGAD with MOENCH

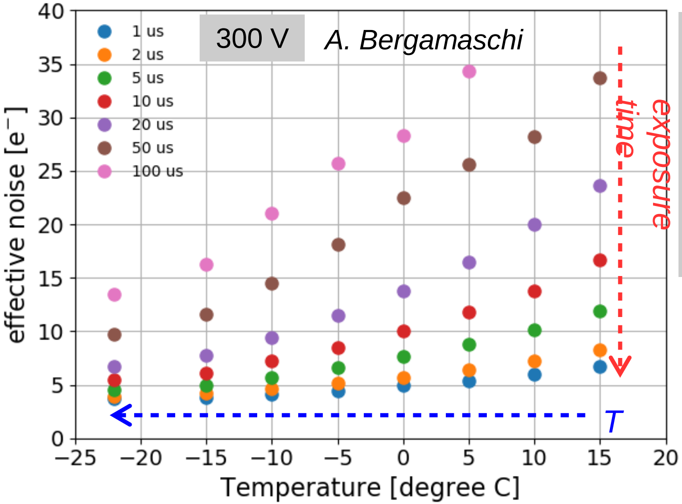
- Effect of the shot noise:
  - Shot noise: $i_{shot}^2 \sim \frac{2(I_{leakage}+I_{ph})M^2F}{q_0}$, *M* – multiplication factor, *F* – excess noise factor
  - Leakage current is sensitive to the temperature (T), reducing T and exposure helps with the noise
- iLGAD pixel sensors of 25 um pitch with Moench readout chip:
  - nominal noise of 35 e^- with standard sensor at RT (SNR=5 @ 700 eV)
  - Various temperatures, RT down to -22 ^oC to reduce the “effective” noise

“effective” noise = $\frac{\textit{noise } [e^- \textit{ r.m.s.}]}{M}$

Temperature dependence of leakage current



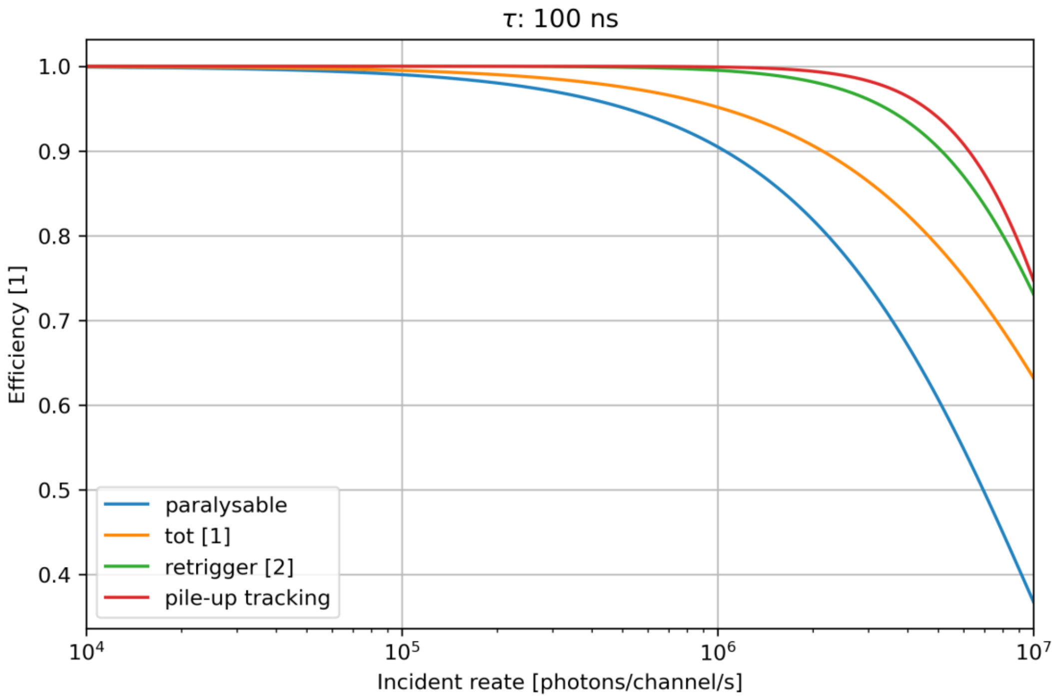
“Effective” noise *vs.* T & exposure time



down to 3.7 e^- at -22 ^oC with 1 µs exposure: SNR > 5 for soft X-rays above 67 eV (134 eV with 2x2 clustering).

* Operation at RT with long exposure requires low leakage current → to be optimized in next batch.

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

Counting pile-up

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

- $m_s = m + m_2 + m_3$

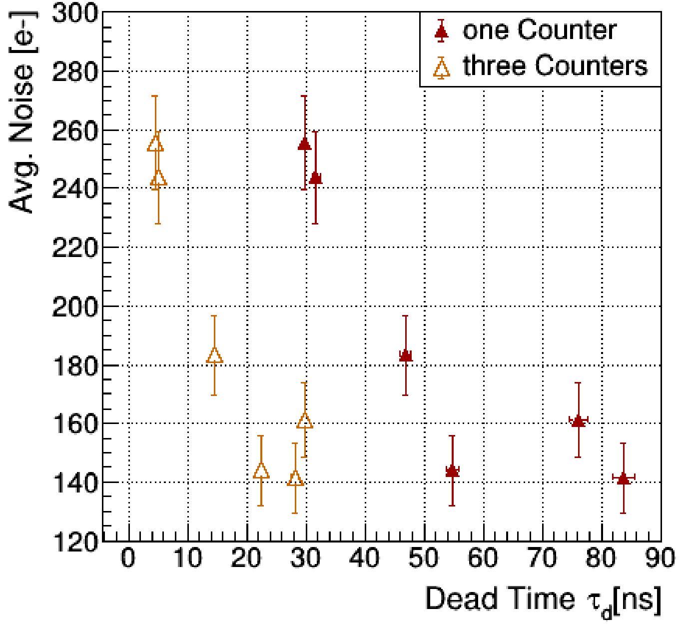
For characterization:

- 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

Rate Capability: Pile-up tracking with 3 counters



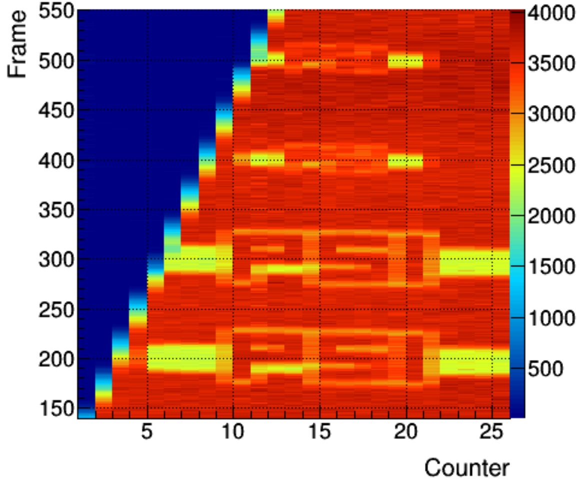
- Determine dead time and noise
  - If gain ↑ : noise ↓ and dead time ↑
- Calculate rate per strip at 90% efficiency:
  - $\varepsilon_{sum} = \varepsilon_1+\varepsilon_2+\varepsilon_3$

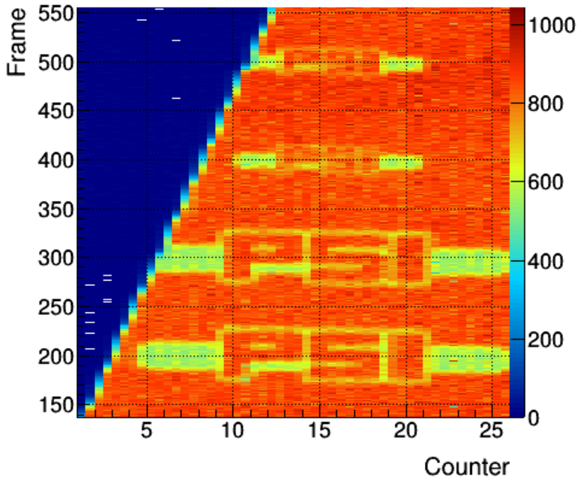
settings	1 counter	3 counters
Slow	1.3 MHz	7.4 MHz
Medium	1.4 MHz	8.2 MHz
Fast	3.5 MHz	20.9 MHz

Minimum achievable noise: 110 e- rms (not shown)

Interpolation: PSI logo

My 3.0.1





- Direct beam of X-ray tube with W-anode
- Threshold at 5 keV, 5 µm steps in vertical
- 2 µm Gold on 300 µm Silicon
- Large logo: 1064 µm x 274 µm, small logo: 532 µm x 137 µm

→ Interpolation mode shows many more details