Aldo Mozzanica :: Photon Science Detector Group :: Paul Scherrer Institute

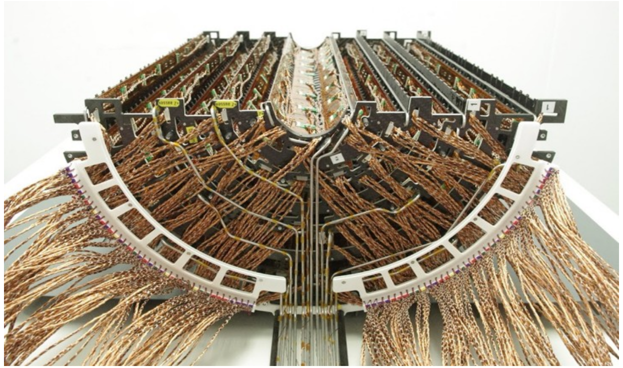
Photon science detector developments at PSI

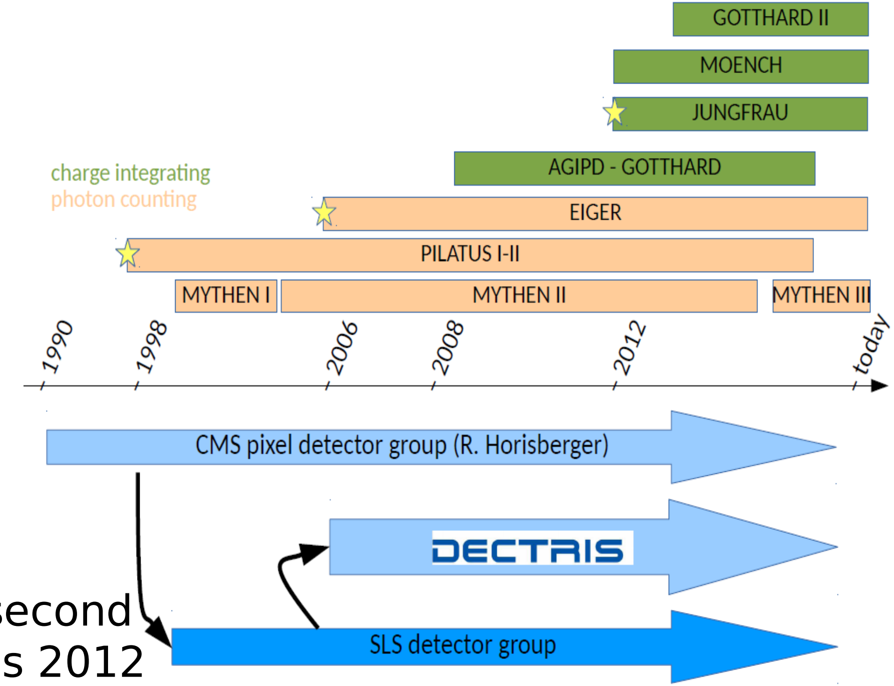
HPXM 2023 :: Frascati :: June 2023

Outlook

- Introduction to our group activities
- Our single photon counting and charge integrating detectors
  - why do we have two architectures?
  - status and applications
  - Jungfrau at FELs and Syncrothron sources
  - Dealing with the data
- Challenges from next generation sources and experimental techniques
- Our next steps:
  - Charge integrating ASIC with high frame rate
  - Photon counting ASIC with high(er) count rates
  - Low noise applications

The Photon Science Detector Group - History





CMS pixel detector at the LHC, CERN

- 48 million pixels, 40 million images per second
- 1992 proposal, 2008 first collisions, Higgs 2012

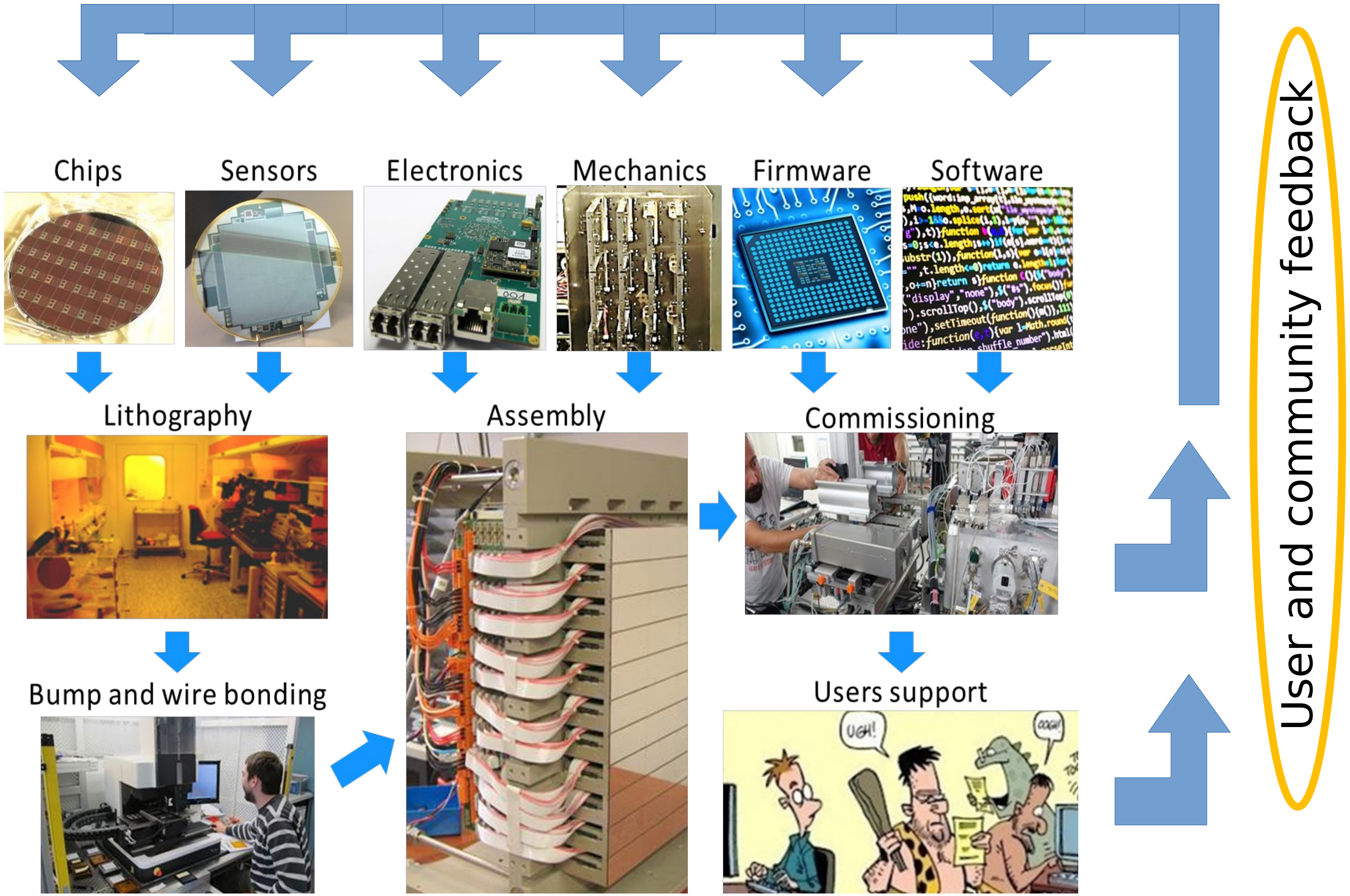
X-ray detector development:

- Late 90s, photon detectors at the time were too slow, bottleneck for SLS
- Technology transferred from CMS group → our group was born

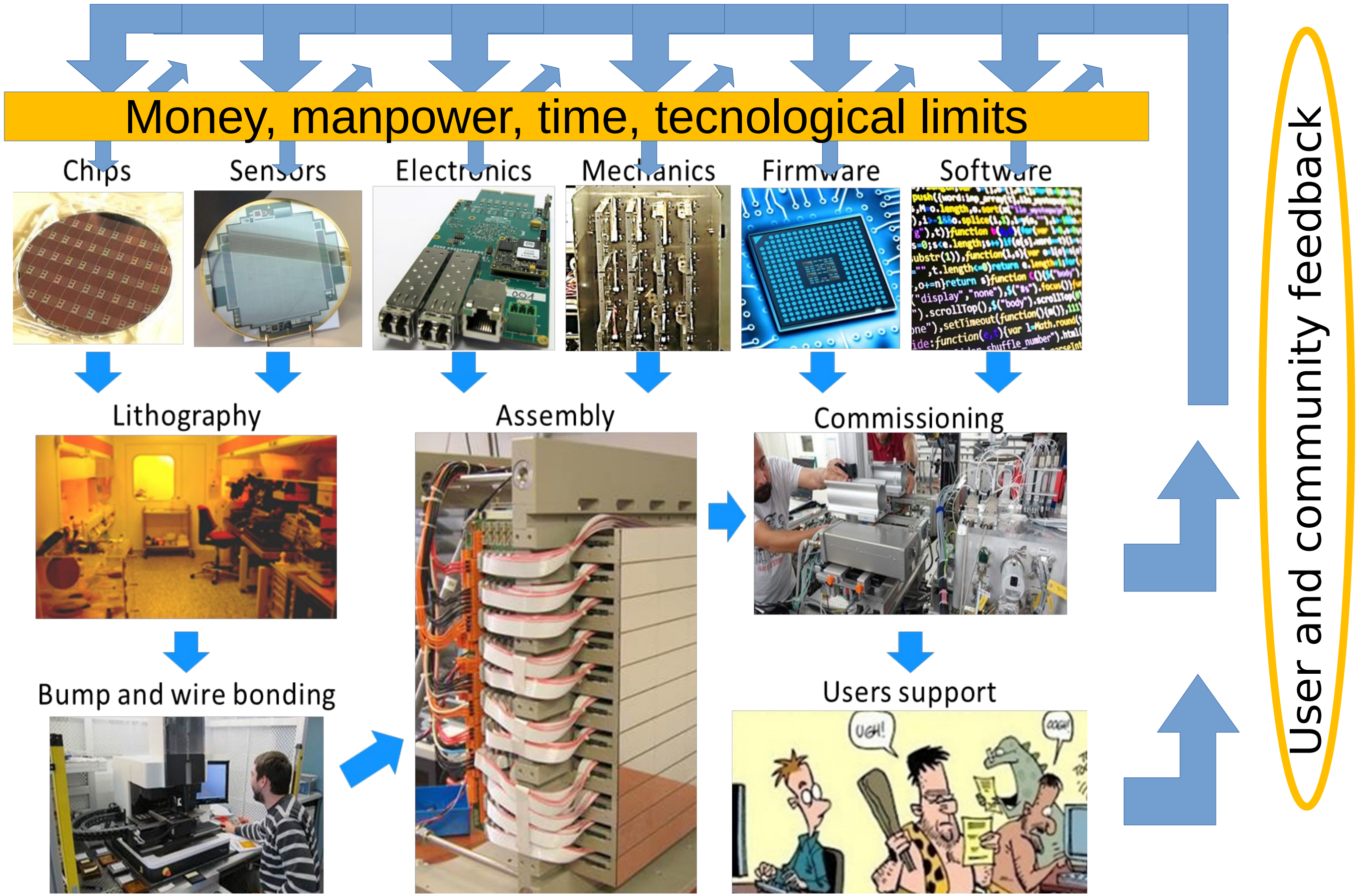
The Photon Science (PSD) Detector Group

- Bernd Schmitt
- Rebecca Barten
- Anna Bergamaschi
- Carlos Lopez Cuenca
- Maria Carulla
- Sabina Chiriotti
- Simon Ebner
- Shquipe Hasanaj
- Roberto Dinapoli
- Erik Fröjdh
- Dominic Greiffenberg
- Thattil Dhanya
- Julian Heymes
- Viktoria Hinger
- Thomas King
- Davide Mezza
- Kostantinos Moustakas
- Kirsty Paton
- Christian Ruder
- Jiaguo Zhang
- Xie Xiangyu

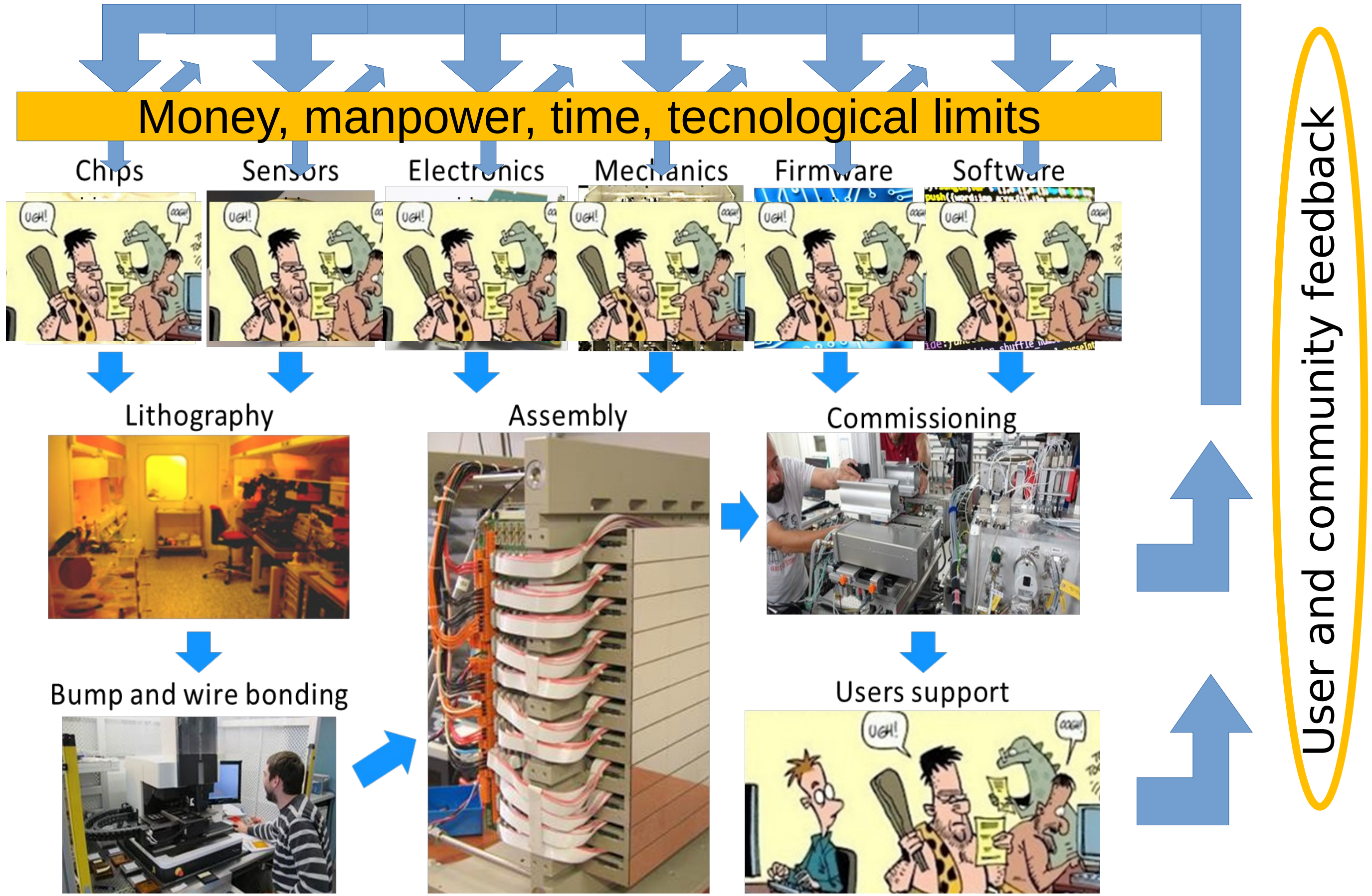
The PSD Detector Group - How



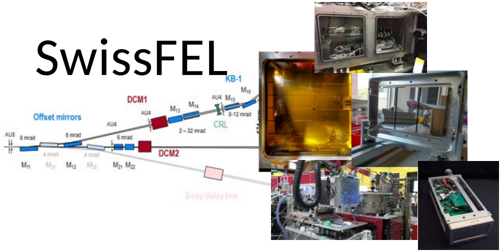
The PSD Detector Group - How

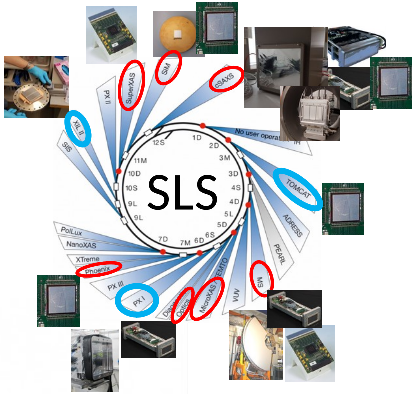


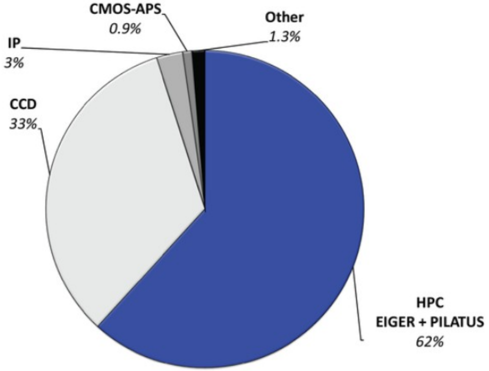
The PSD Detector Group - How



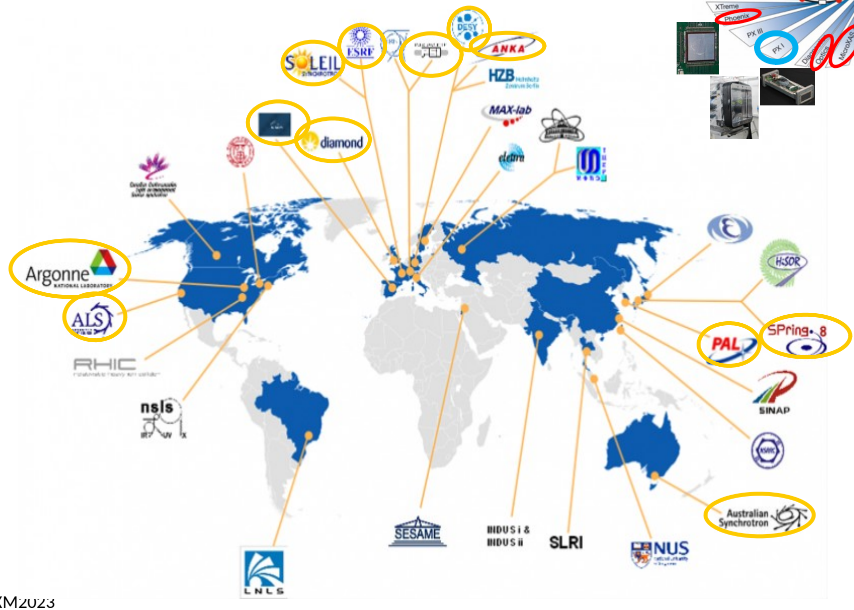
The PSD Detector Group - Impact







. Contribution of detectors to PDB entries released in 2019.



Systems built by us:

- main detectors for SwissFEL
- extensively used at SLS
- Operated in tens of facilities.

Systems from Dectris of PSI legacy:

- In all facilities, often mayority of beamlines
- Used for more than 60% of solved structures

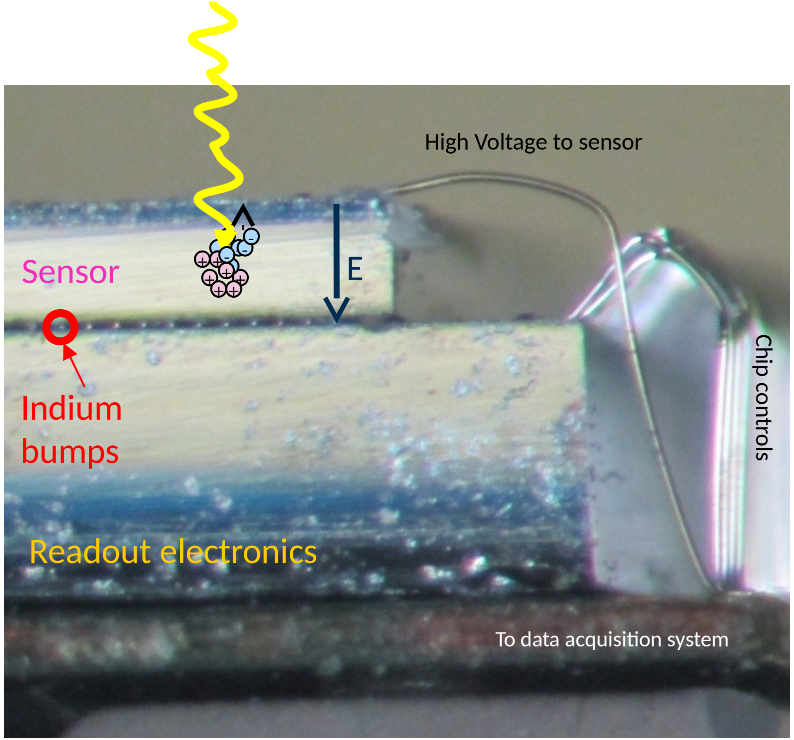
The PSD Detector Group - Technology

Hybrid detectors for imaging

Sensor and readout electronics optimized separately

- ☺ Direct conversion in semiconductor
- ☺ Fast drifting of charge to the pixel
- ☺ Room temperature operation
- ☺ Fast highly parallelized readout

- ☹ Interconnection (bump bonding) limits the pixel pitch
- ☹ Costs (?)
- ☹ Input capacitance increases the electronic noise (vs. monolithic)



Our detectors

Microstrips

Pixels

50 µm

MYTHEN 2/3

GOTTHARD I and II

25 µm

MÖNCH

75 µm

EIGER/ Matterhor

JUNGFRAU

> 150 µm

PILATUS (172 µm)

200 um

AGIPD (200 µm)

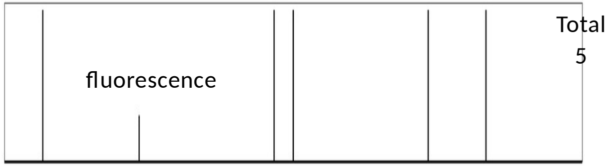
Single Photon Counting

Why two architectures?
Historically, SPC for SRs
CI for FEL

Charge Integrating

The two architectures

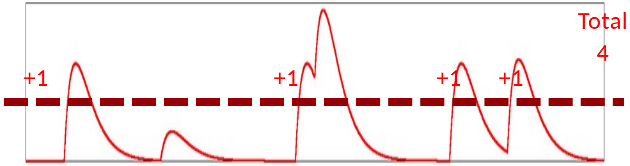
Photons



Low flux on the detector*
(<1MHz per pixel)

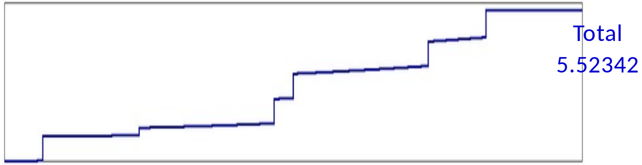
*some applications already exceed this at gen3 sources

Single Photon Counter (SPC)



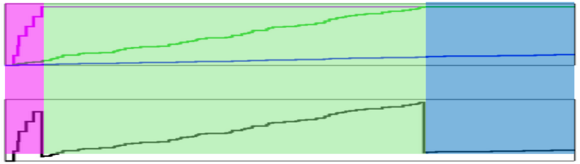
- ☺ Large dynamic range
- ☺ Fluorescence rejection
- ☹ Pile-up at high fluxes
- ☹ No energy information

Charge Integrating



- ☺ No flux limitation
- ☹ Limited dynamic range
- ☹ No energy information if more than one ph.

Charge Integrating with dynamic gain switching



- ☺ Large dynamic range
- ☺ No flux limitation
- ☹ Needs fast readout
- ☹ Challenging calibration

Single photon counting (SPC) detectors

- “Noiseless”, stable, reliable, user friendly, rad-hard, fluorescence suppression, large area systems, fast frame rate, pump-probe…

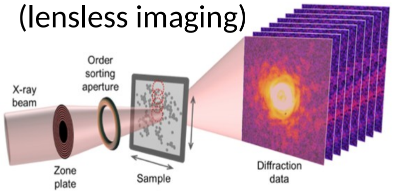
15 years ago

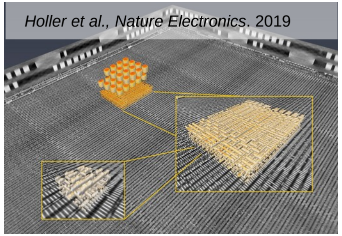
Replaced CCDs/Flat panels for PX

Thousands of protein structures solved using PILATUS/EIGER

10 years ago

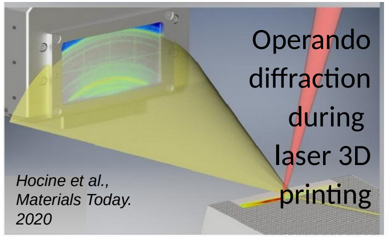
Enabled ptychography (lensless imaging)

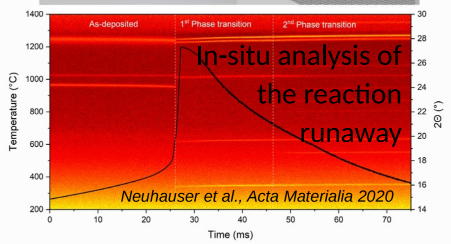




Now few nanometers resolution can be achieved in 3D

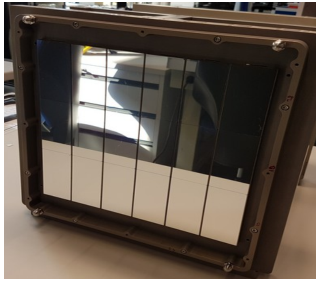
Time resolved experiments





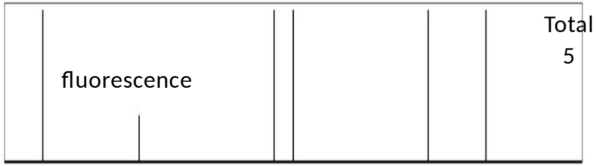
Time resolution better than 50(15)µs (20(70)kHz) possible with EIGER

9M EIGER
In operation at CSAXs
22kHz burst



The 2 architectures

Photons



Low flux on the detector*
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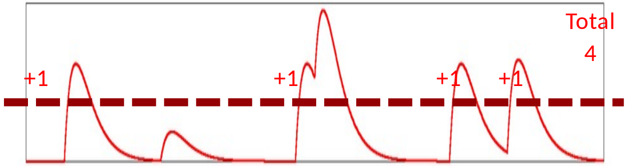
Single Photon Counter (SPC)



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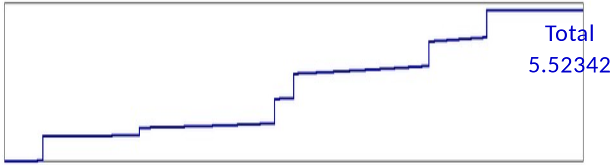
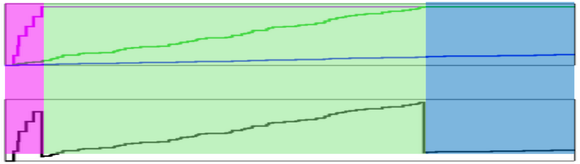
- ☹ No energy information

Charge Integrating



- ☺ No flux limitation
- ☹ Limited dynamic range
- ☹ No energy information if more than one ph.

Charge Integrating with dynamic gain switching



- ☺ Large dynamic range
- ☺ No flux limitation
- ☹ Needs fast readout
- ☹ Challenging calibration

Gain switching: theory of operation

Per pixel and per frame, JUNGFRAU automatically adjusts the gain to the input charge:

- small input charge: high gain
- medium input charge: medium gain
- high input charge: low gain

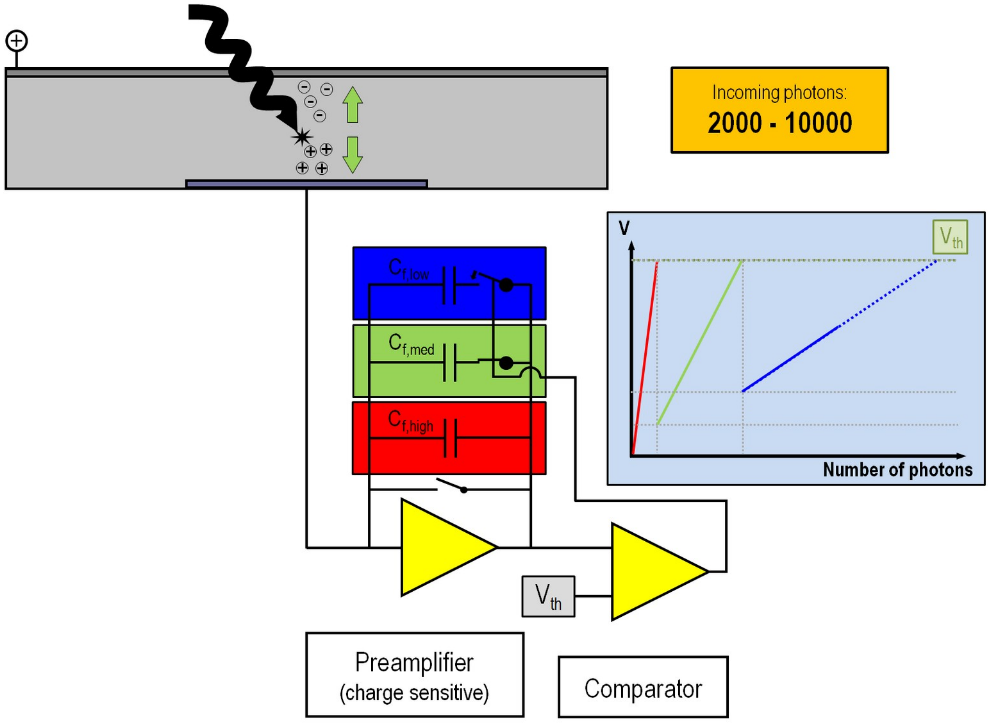
This achieves both

- single photon sensitivity
- high dynamic range

Per pixel and per frame, 16 bits output:

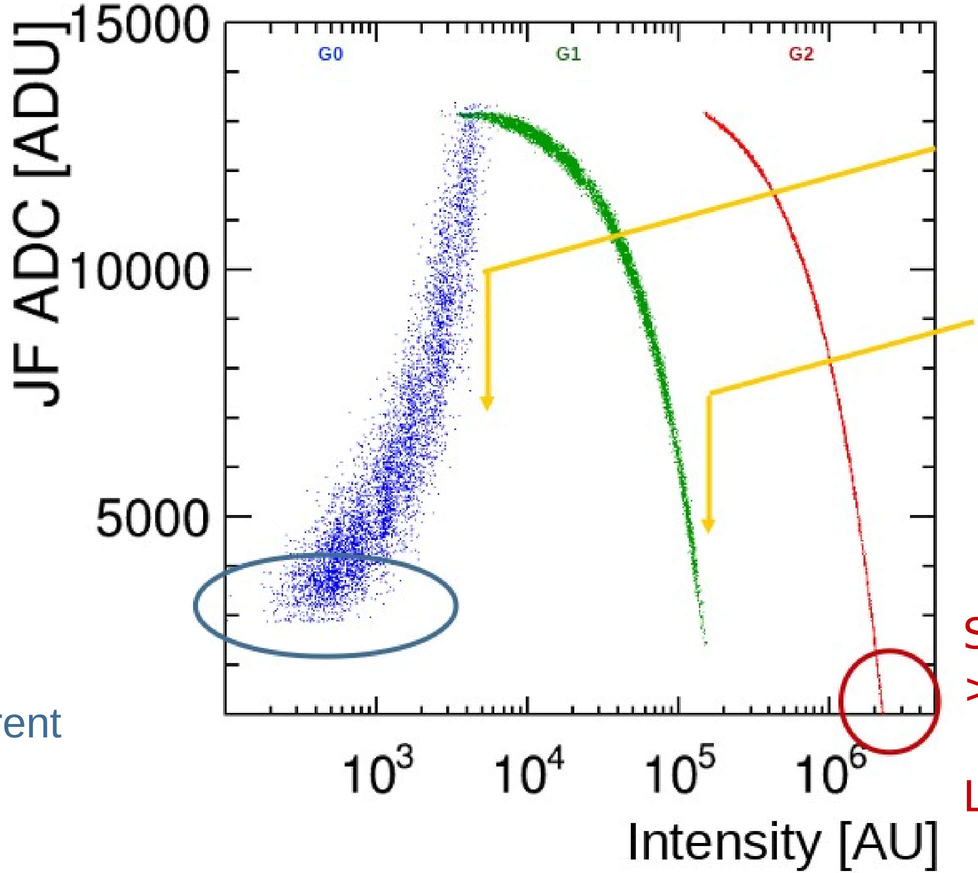
- 2 bits: what gain was used
- 14 bits: what was the amplified charge

This needs correcting to retrieve the number of photons detected



High (G0): **1 ... 20** x 12.4 keV photons
Medium (G1): *20* ... **700** x 12.4 keV photons
Low (G2): 700 ... **<10800** x 12.4 keV photons

Gain switching: practice.



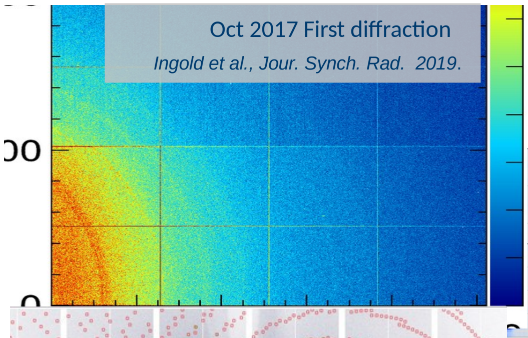
High -> medium gain switching:
20 x 12 keV photons

Medium ->low gain switching:
700 x 12 keV photons

Pedestal:
2000-3000 ADU
the leakage current
is integrated

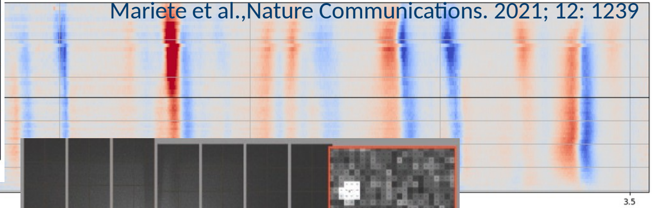
Saturation:
> 10,000 x 12 keV photons
Limited by capacitor size in 75 um pixels

Jungfrau at SwissFEL



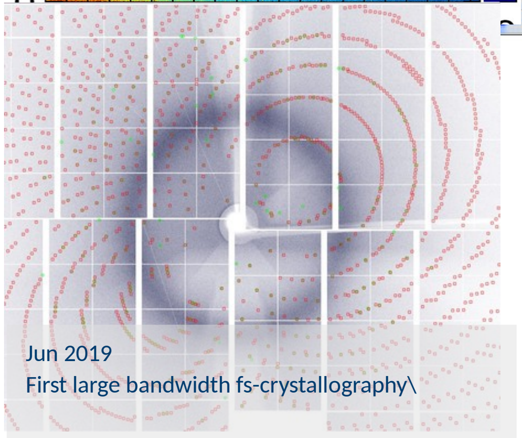
Oct 2017 First diffraction

Ingold et al., Jour. Synch. Rad. 2019.



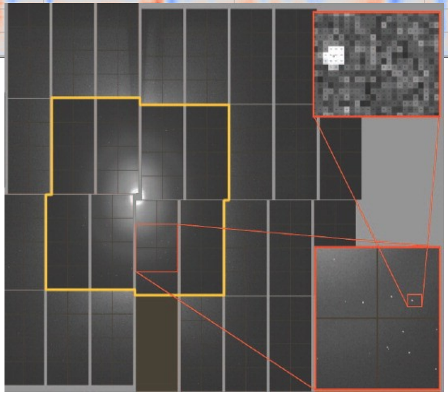
Nov 2017 First time resolved pilot experiment

Mariete et al.,Nature Communications. 2021; 12: 1239



Jun 2019

First large bandwidth fs-crystallography\

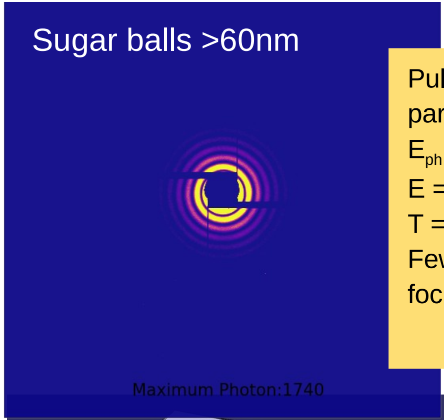


Aug 2018 First fs-crystallography

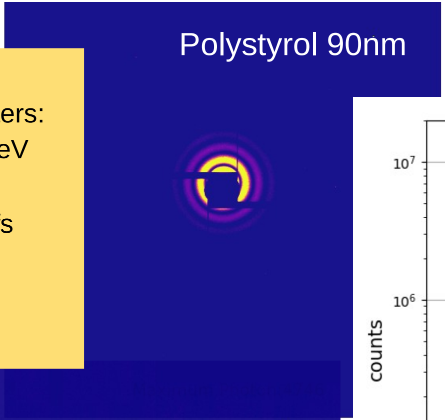
Nass et al., IUCrJ 2020.

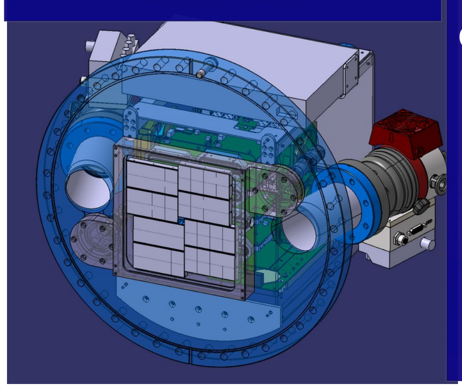
- 5y+ of operation
- More than 50Mpixels installed,
- 15 individual cameras
  - Complex experiments require up to 5 detector heads
- Running 24/7 with high stability:
  - Data always goes to a temporary buffer (>6h, 100s of TB)
  - Written to file as needed ex-post, at user request (pulse-id)

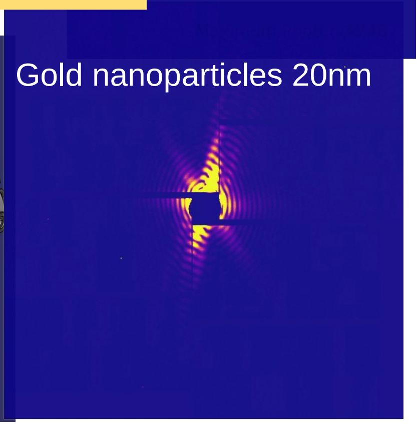
More recently: @Athos, the low energy branch

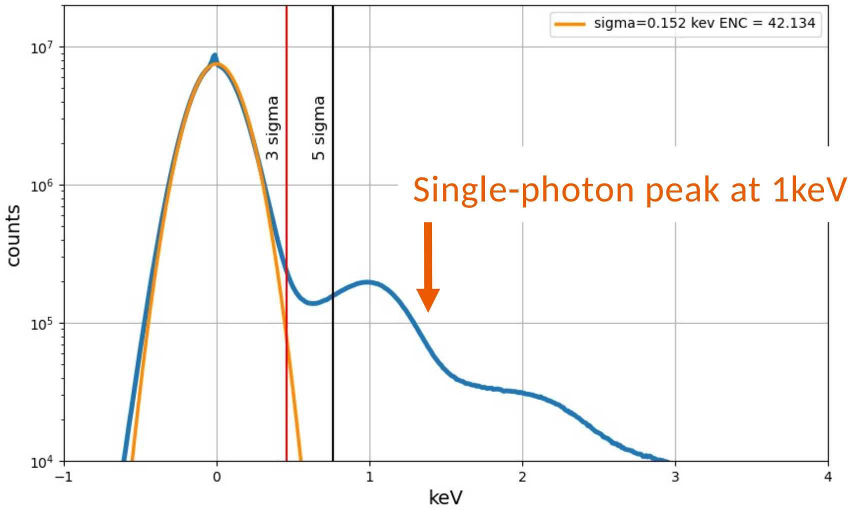


Pulse parameters:
E_{ph} = 1keV
E = 1mJ
T = 100fs
Few um focus









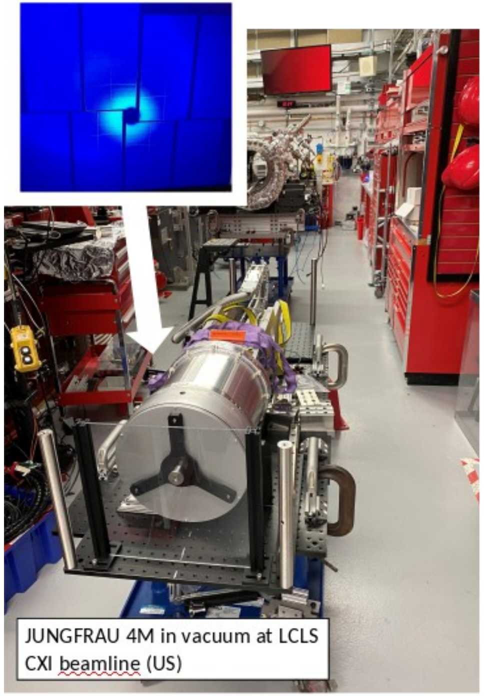
Cumulative energy spectrum (1000 frames all pixels)

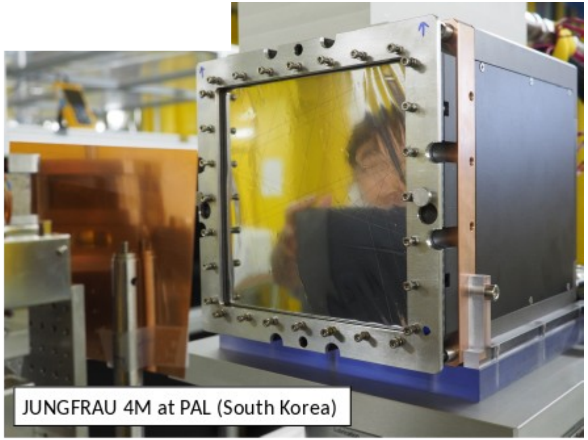
JUNGFRAU at other FELs

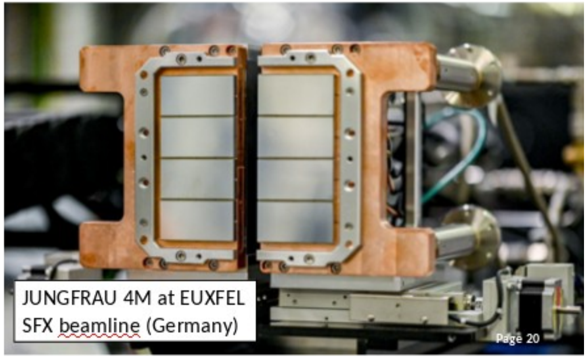
In operation:
LCLS 4M+1M+500k
PAL 16M+3x4M+5M
+6x500k
EU-XFEL 4M+2x1M+4x500k

To be delivered:
LCLS 16M
SHINE 4M

In addition: EMs, plasma sources, e-diffraction.


JUNGFRAU 4M in vacuum at LCLS CXI beamline (US)


JUNGFRAU 4M at PAL (South Korea)

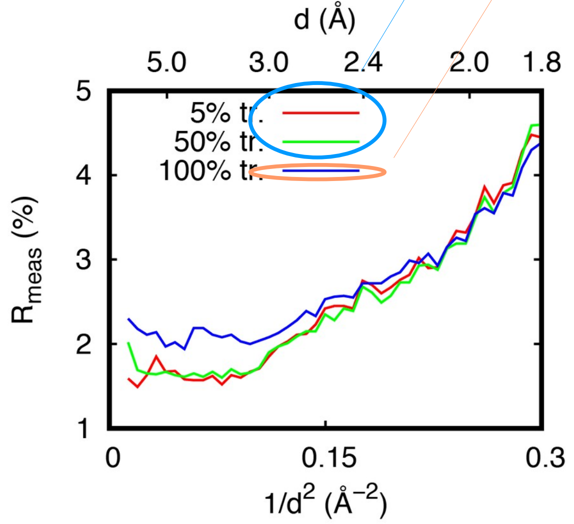


JUNGFRAU 4M at EUXFEL SFX beamline (Germany)

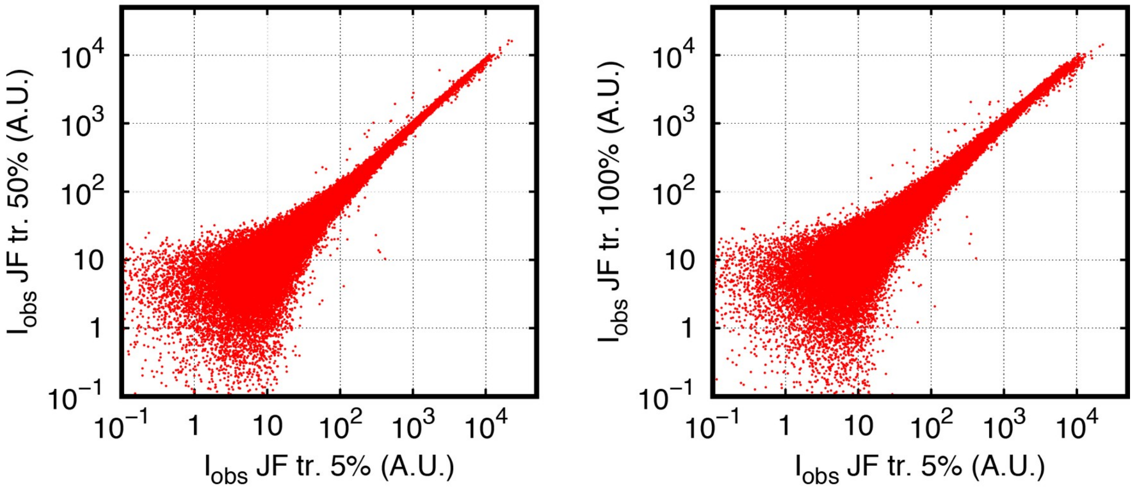
JUNGFRAU works well at Synchrotron

- data quality compares very well with state of the art PC detectors (EIGER)
- It allows faster data collection with strong beam
- Native SAD in 0.6s !

Data consistency



Integrated intensities

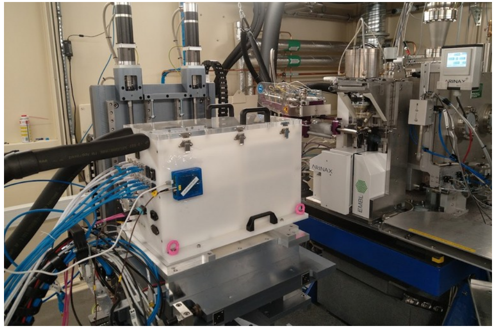


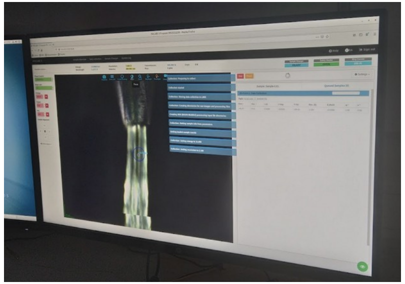
"JUNGFRAU Detector: Accurate Data for Macromolecular Crystallography", Nature Methods

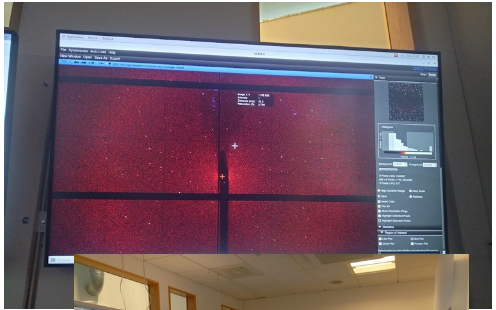
JF4M 2 kHz @ BioMAX

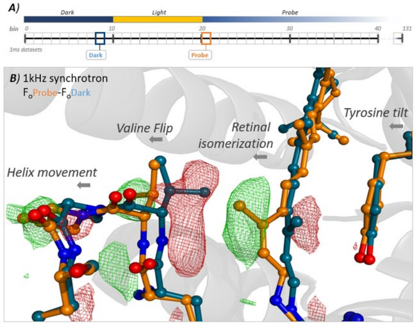
- Collaboration between MAX IV and PSI (MX + Detector + Bio
- JF 4Mpixel from PSI + MAX IV computing infrastructure with Jungfraujoch
- Demonstrated 1 ms time resolution at a synchrotron for a time resolved target (first to our knowledge)
- Continuous measurements up to 2 kHz (17 GB/s) frame rate on real biological target with good results
  - Consecutive 8 minute runs of 1 million frames

Online reduction and compression allowed to reduce initial 17 GB/s to below 4 GB/s (which is GPFS limit)



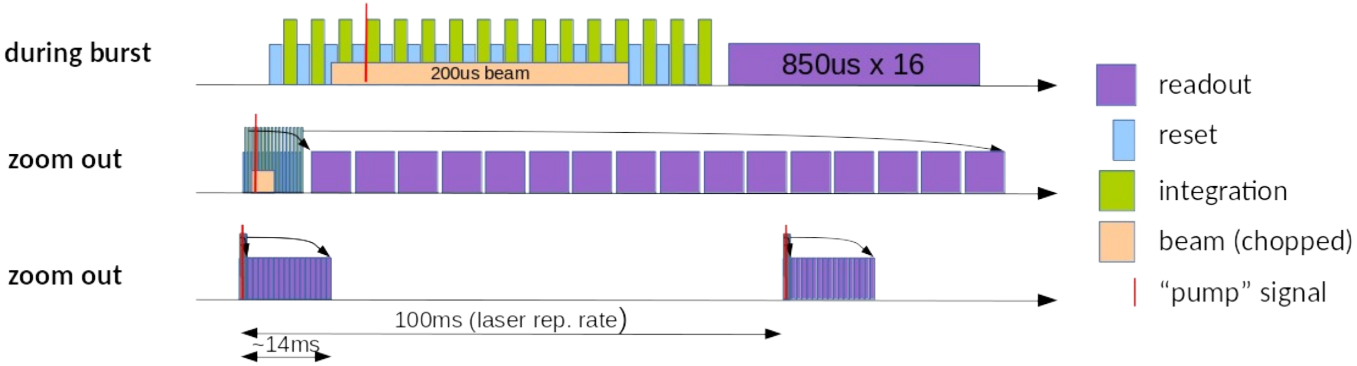


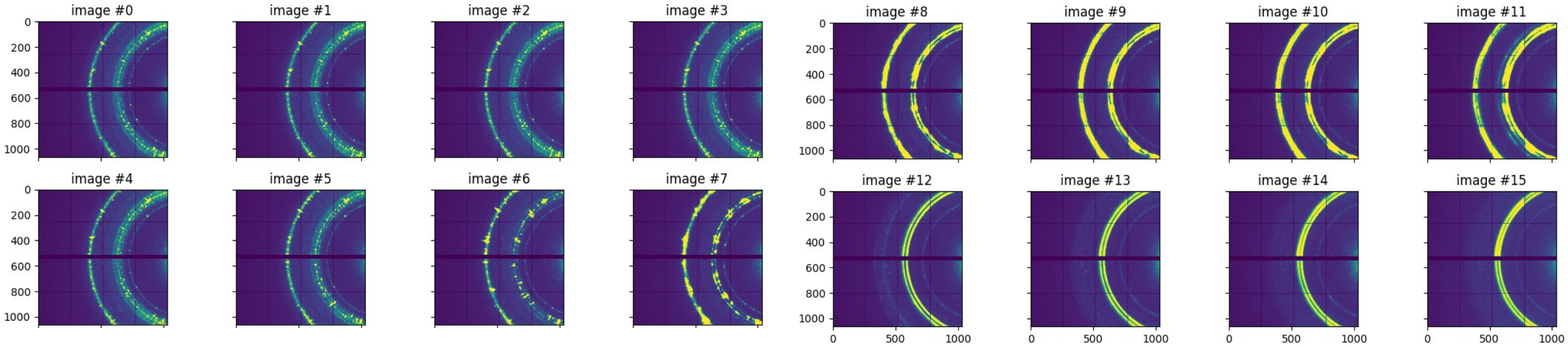




F. Leonarski, J. Nan, …, F. Dworkowski (submitted) «Kilohertz Serial Crystallography with the JUNGFRAU Detector at a 4th Generation Synchrotron Source»

Pink beam and burst mode applications





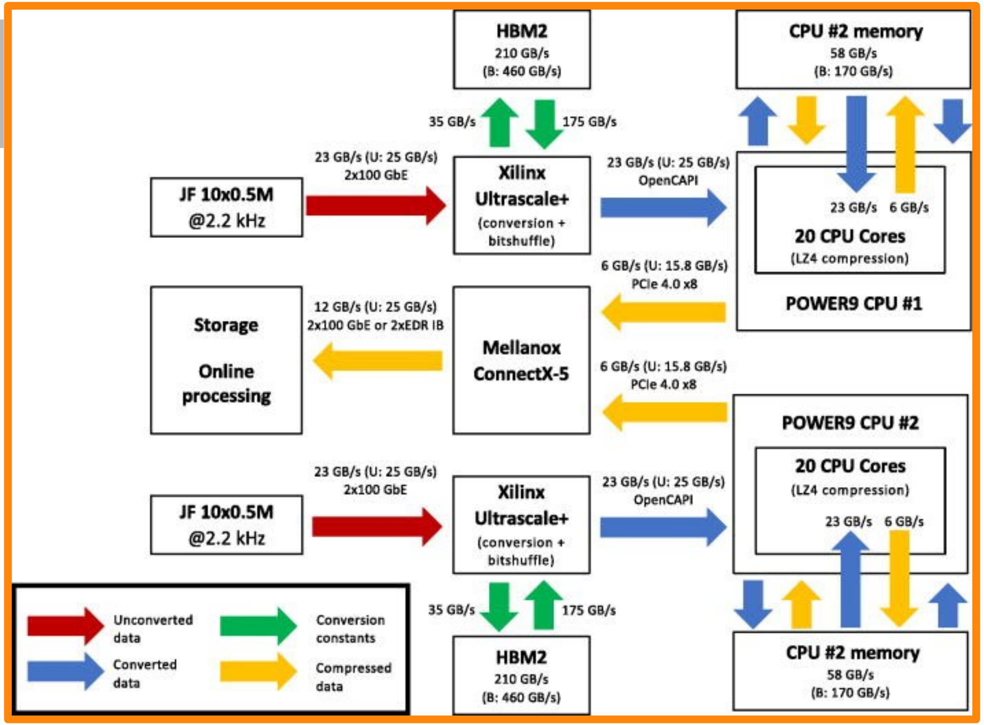
Charge integrating are great!

Then, why insist on SPC?

Pros of CI
- very high count rate limit: 24Mcps @ 12.4keV, 40Mcps at 8keV
can be extended 10x with a DR extension methods
or even higher if dead time is acceptable
- No “corner effect”
- low energies: single photon resolution at 2.5keV
- at low flux, JF gives energy information, without Th scan.
- works with strong single bunches, suitable for serial pink beam crystallography

BUT
huge data rates : we have to run full speed, always
- cooling
- Operation not as easy as a SPC
    - Calibration is more complex
    - Pedestals required

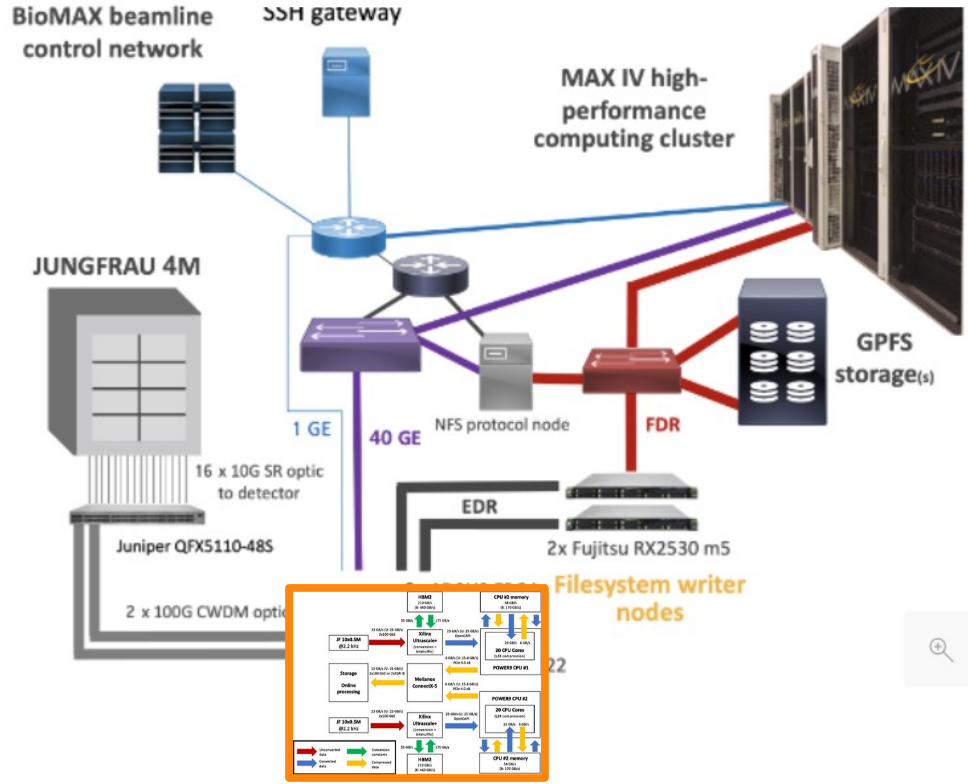
Data Rates!



F. Leonarsky Struct Dyn. 2020;7(1). doi:10.1063/1.5143480

This has been developed for the 10M at the SLS – PXIII beamline. It's a 2U server with dedicated FPGAs network card receivers. Downstream rate still many GB/s after compression/downsampling

Data Rates!

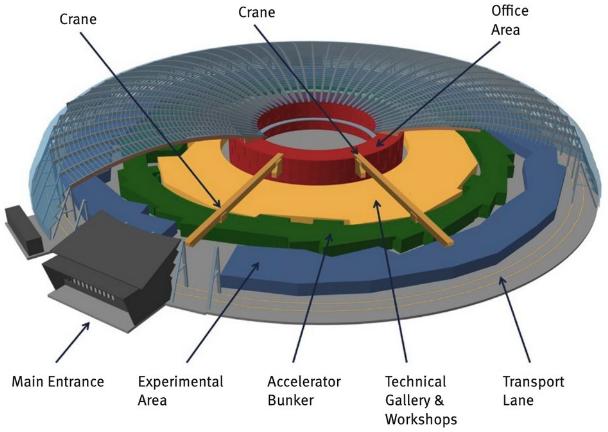


This has been developed for the 10M at the SLS – PXIII beamline. It’s a 2U server with dedicated FPGAs network card receivers. Downstream rate still many GB/s after compression/downsampling

To cope with that, more IT infrastructure needed (in the schema, the temporary MaxIV setup for the experiment shown)

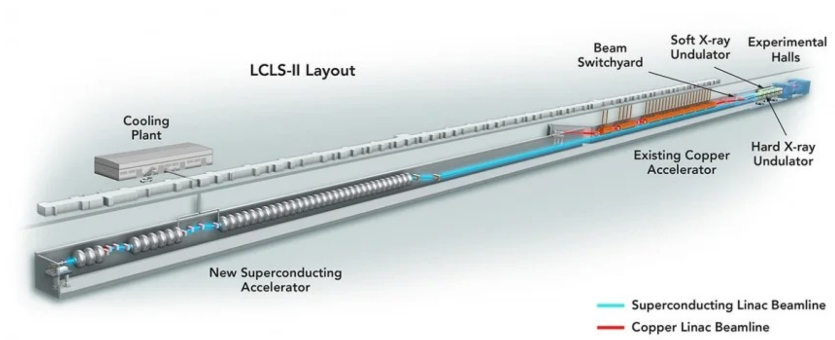
Clearly this is not something suitable for every beamline!

Next generation sources



Diffraction limited light sources:
MAXIV
ESRF
APS
And next year SLS
- huge increase in coherent flux
- more photons on the detectors!

FELs:
LCLS-II HE: 1MHz soon
SHINE : 1MHz in 2026
EU-XFEL : 1MHz CW from early ‘30



Next generation sources

Diffraction limited light sources:
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ESRF
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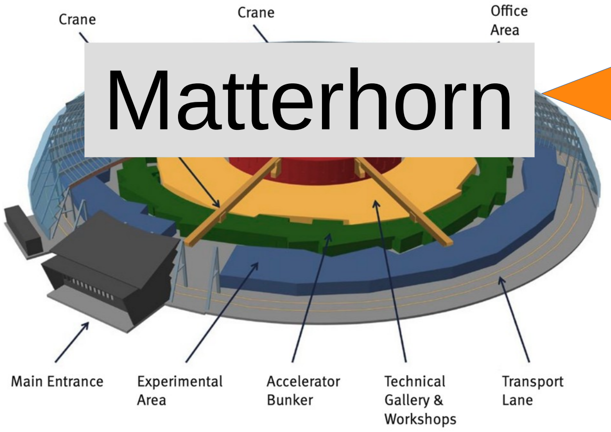
And next year SLS
huge increase in coherent flux
more photons on the detectors!

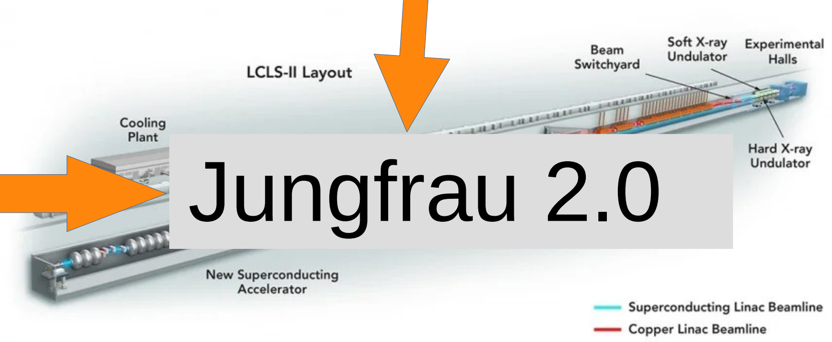
SPC detector with higher rate capability



Matterhorn

FELs:
LCLS-II HE: 1MHz soon
SHINE: 1MHz in 2026
EU-XFEL : 1MHz CW from mid '30

Charge integrating Detector with higher frame rate



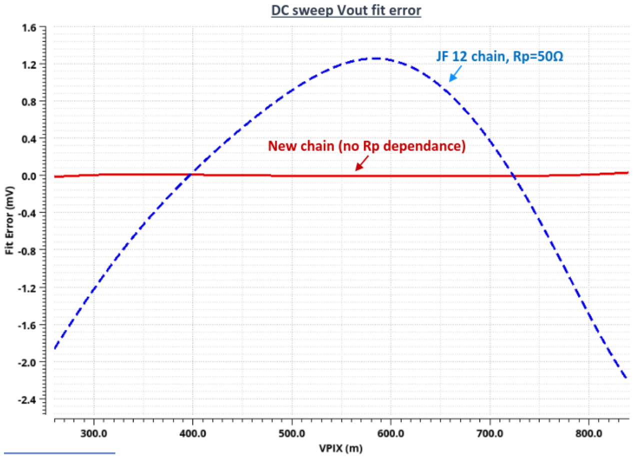
Jungfrau 2.0

Jungfrau 2.0 – faster and easier to use

- Same 75x75 um^2 pixel size
- Similar performance of the pixel frontend in terms of noise, DR
- Improved linearity (0.5%->0.05% i.n.l.) of the readout chain
- Improved pix-pix uniformity (helps calibration)
- Improved calibration capabilities (current sources) and pedestal collections modes

- Higher speed -> 10kHz readout target.

All this already
In layout. E.g.:



2 paths towards 10kHz

- Today, off chip ADCs, 4x40MS/s 14bit
- 2.2kHz

- Higher speed analog chain 80+MHz
- 80MHz external ADCs
- 2X the number of outputs per chip

  Challenges:
- Analog cross talk
- ADC-FPGA communication protocols

  Analog chain with 13bit precision @65MS/s already in silicon

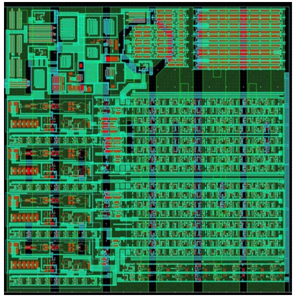
- On chip 20MS/s ADCs
- On chip data sorting and I/O via 3.25Gs/s serializers

  Challenges:
- Small footprint ADC with >11ENOB, obtained without complex ADC calibration

  Experience with the Gotthard II ADC.

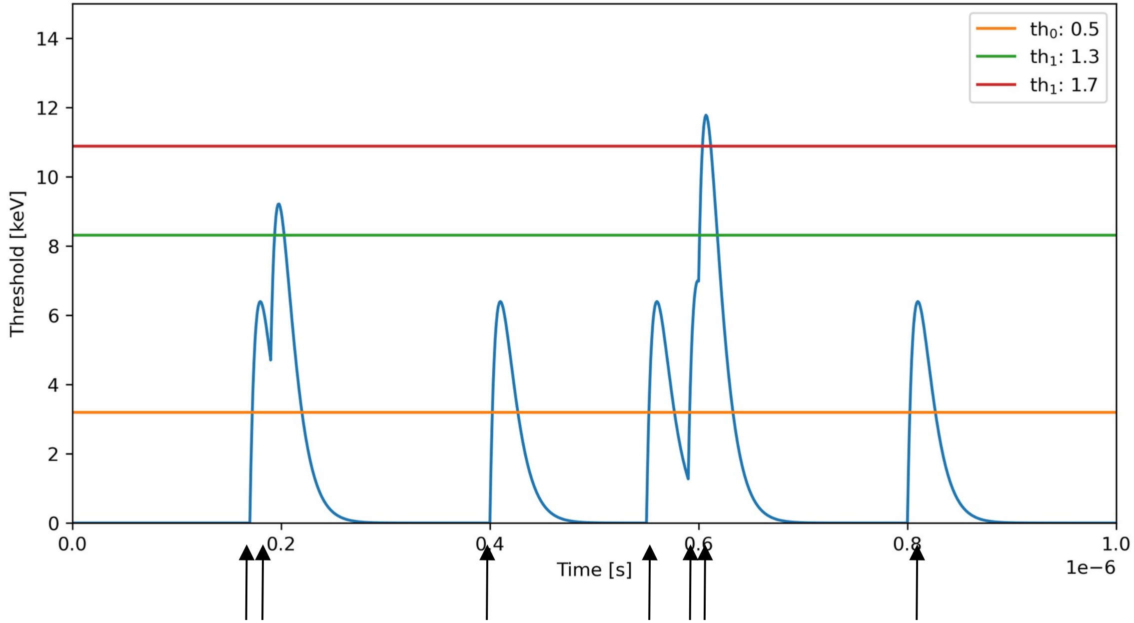
Matterhorn – fast and reliable SPC

- 75x75 um^2 pixel size
- 4 thresholds (w. 16 bit counters)
- Up to 80 keV frontend dynamic range
- Electron and hole collection
- 100Gbit/s readout board
- 160 kHz in 1 bit mode
- <20ns gating
- <20M photons/pixel/s (multithresholding)



Matterhorn MH0.1 pixel layout

Improving rate capabilities: multithresholding



Counter 2: 1

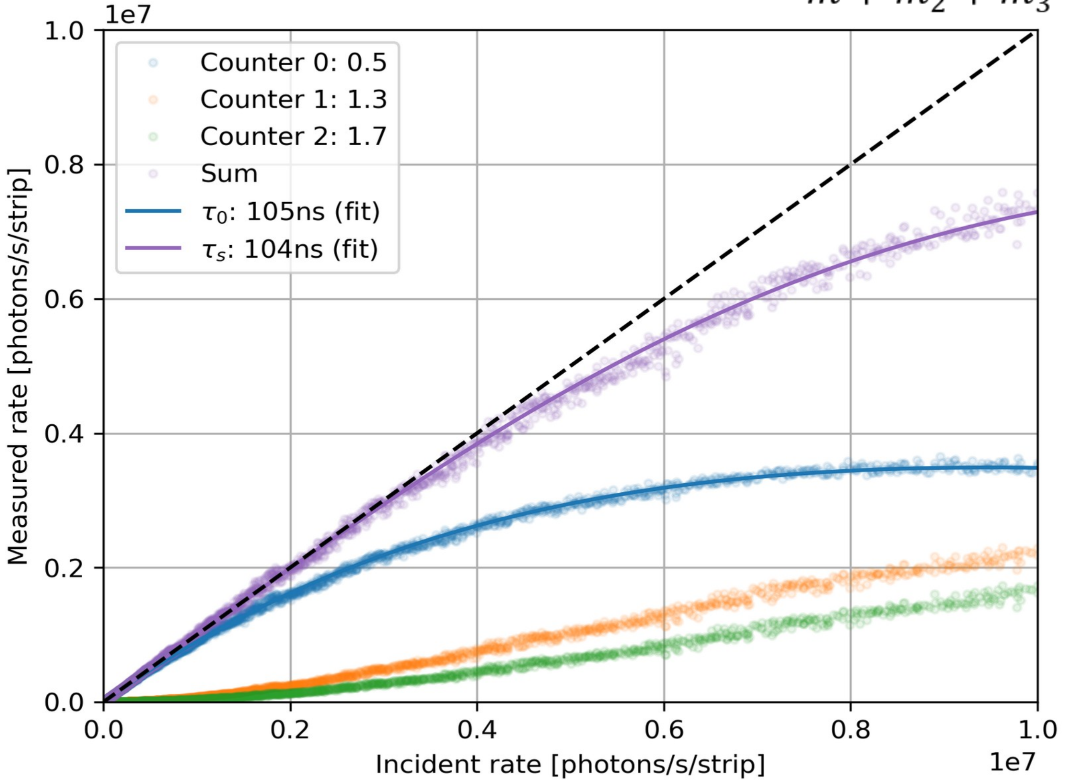
Counter 1: 2

Counter 0: 4

Total counts:7

Multithresholding (in Mythen3)

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



Andrä M, *et al.* *JINST* (2019) 14: C11028
https://doi.org/10.1088/1748-0221/14/11/C11028

Settings: standard

Energy: 15 keV

Noise 175e- RMS

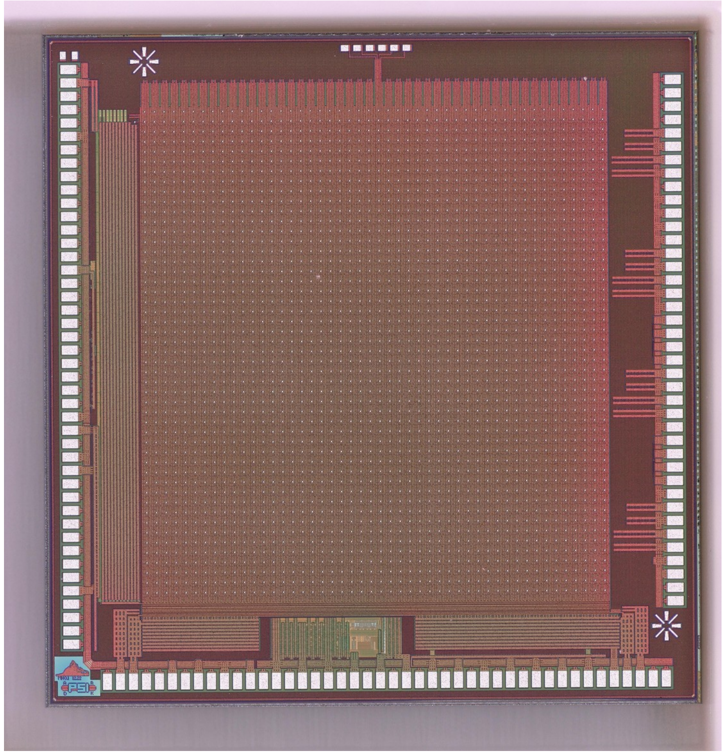
10% lost counts at:

th_0: 1.03M

th_{sum}: 6 M

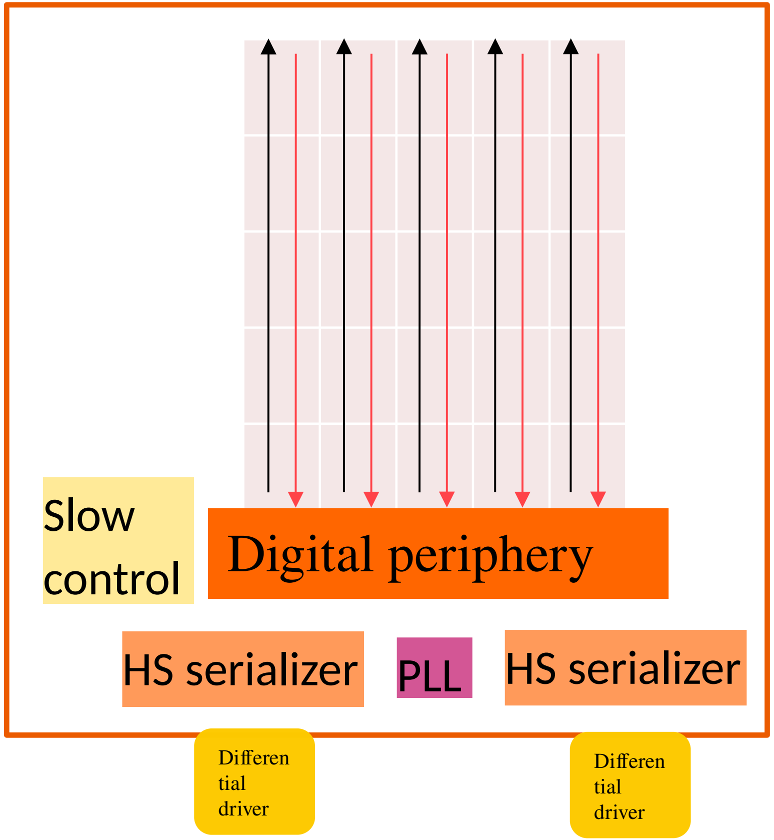
Matterhorn 0.1

- 75x75 µm^2 pixel size
- ASIC: ~5x5 mm^2 (3.6x3.6 active=48x48=2304 pixels)
- 4 comparators; 4x 16 bit counters
- 250 eV– 20 keV dynamic range
- Hole collection
- 17 kHz in 16bit/4cnt mode
- 140kHz in 8bit/1cnt mode
- <20ns gating speed (on small array)
- 20 Mcts/pix/sec at 80% efficiency (with pileup tracking)
- <100e- ENC for low photon rates



Prototype submitted 05.12.2022, received 07.06.2023

Matterhorn 0.1



Serializers:1.6GHz,
Data rate: 1.28Gbit/s including 10b/8b encoding

Slow control for chip configuration and debugging

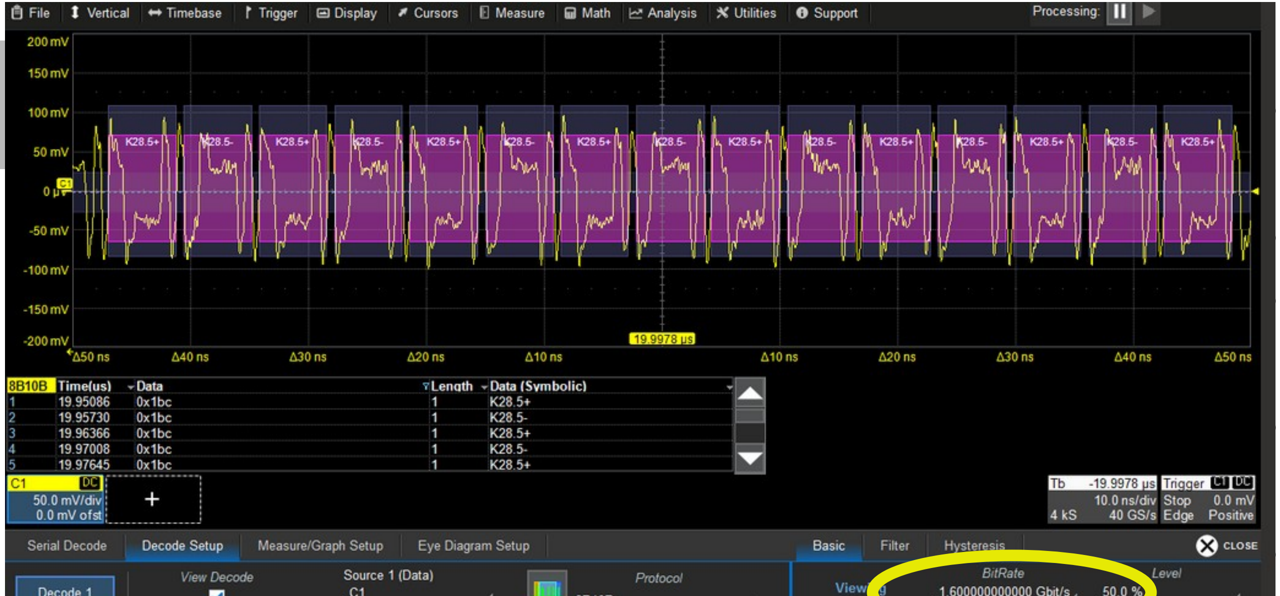
Addressing

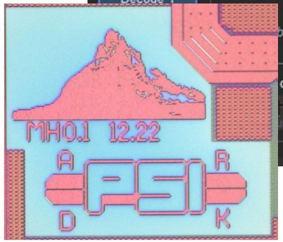
Readout

1152pixels/serializer
Serializer speed=1.28Gbit/s
@8 bit 1152x8= 9216bit
Frame rate: =138.9kHz
Target for full size= 20kHz @8bit, 160kHz @1bit

Preview: Matterhorn 0.1

PRELIMINARY





Basic configuration works

PLL works <10ps jitter

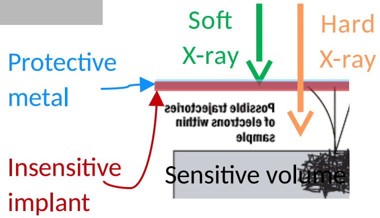
10b8b, Serializer, CML, all work

At 1.6 Gbps! (raw- 1.28 after 8b10b)

Pixel and pixel matrix still have to be tested.

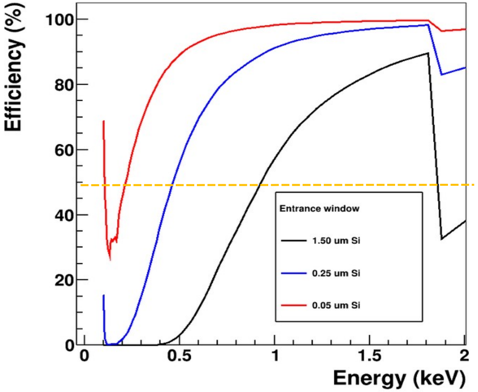
Sensor development for soft X-rays

- Improve quantum efficiency



Quantum Efficiency >50%

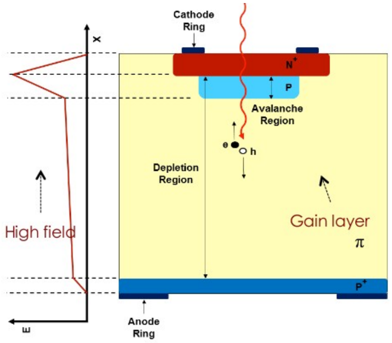
Standard	E>1 keV
Current	E>500 eV
Goal	E>250 eV

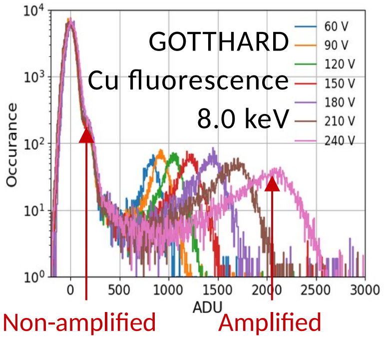


Collaboration with

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

- Enhance single photon resolution
  - Lower noise in readout electronic
  - Low Gain Avalanche Detectors (LGADs)
    - Improves SNR, no dark counts
    - Challenging thin entrance window and segmentation
    - Ideal for
      - Soft X-ray single photon counters
      - RIXS with MÖNCH

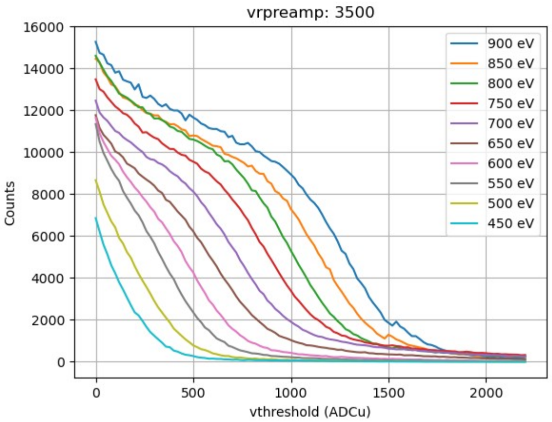




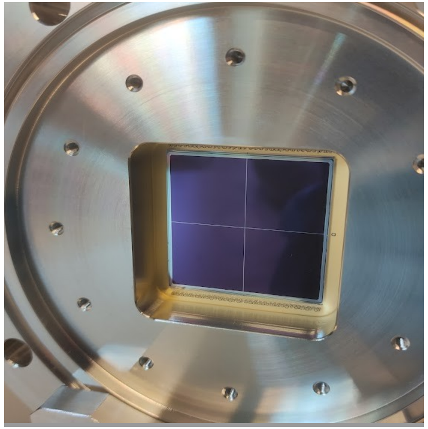
Andrä, Zhang et al., Jour. Synch. Rad. 2019.

ILGADs make SPC possible down to 500eV.

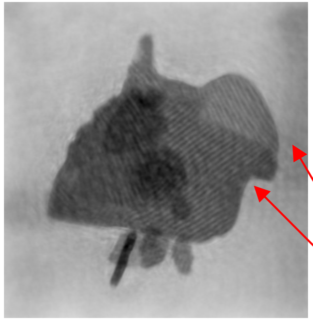
LGADs (450ev-2keV)



- Ptychographic Imaging $BiFeO_3$ at Fe L3 Edge (712 eV)
- Tim Butcher @ SIM beamline
- Current resolution ~8 nm



Eiger 512x512 with LGAD sensor in in a Vacuum flange setup.



Spin Cycloids

500 nm

Wir schaffen Wissen – heute für morgen

The Photon Science detector group at PSI…

… delivers state of the art detectors worldwide.

… strives to optimize hybrid detectors in every aspect.

Next challenges…

… soft X-ray detectors.

… a new single photon counting pixel detector for diffraction limited light sources.

… a faster frame rate charge integrating detector.

My thanks go to

- Bernd Schmitt
- Rebecca Barten
- Anna Bergamaschi
- Carlos Lopez Cuenca
- Maria Carulla
- Sabina Chiriotti
- Simon Ebner
- Shquipe Hasanaj
- Roberto Dinapoli
- Erik Fröjdh
- Dominic Greiffenberg
- Thattil Dhanya
- Julian Heymes
- Viktoria Hinger
- Thomas King
- Davide Mezza
- Kostantinos Moustakas
- Kirsty Paton
- Christian Ruder
- Jiaguo Zhang
- Xie Xiangyu

Thank you!

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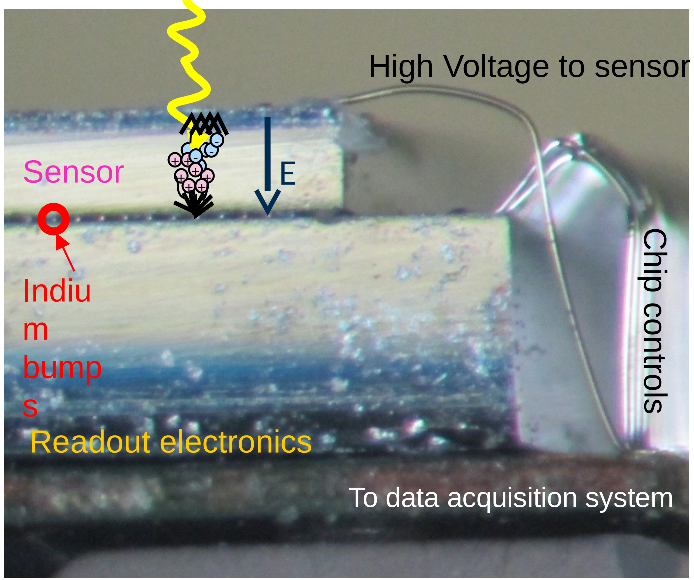
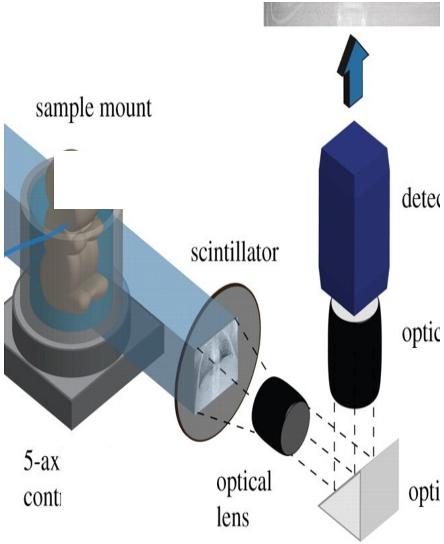
Backup Slides

Direct vs. Indirect conversion for hard X-





✓ Signal of single X-rays usually much larger than electronic noise
DQE ~ Quantum efficiency

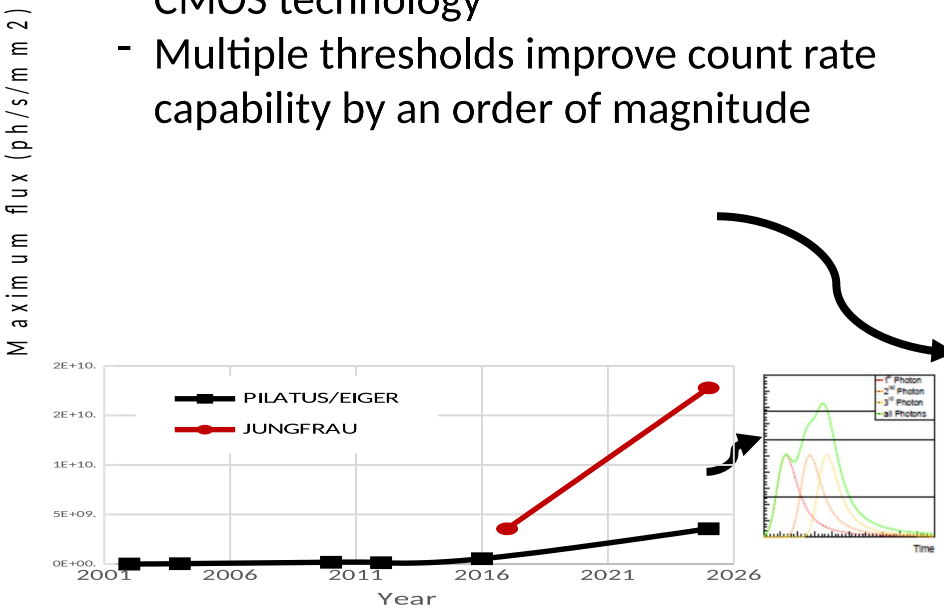
✘ Interconnection (bump bonding) limits the pixel pitch

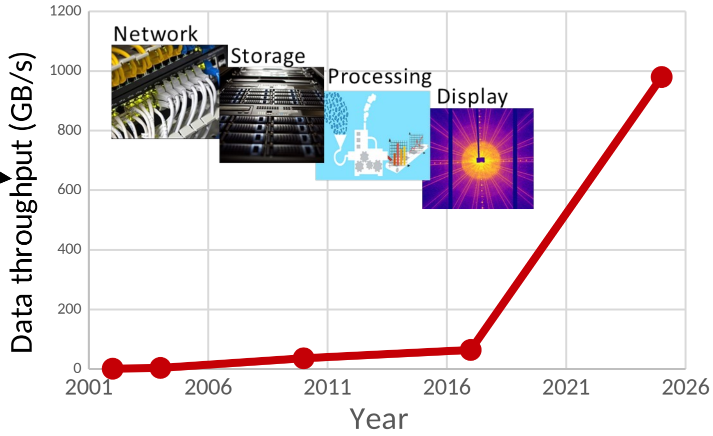
✓ No single photon resolution because of highly inefficient visible light conversion and collection
DQE << Quantum efficiency

✓ Optical magnification can increase the spatial resolution

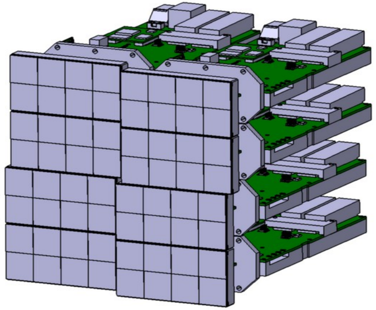
Faster detectors for SLS2.0 and XFELs

- Single photon counting detectors require higher count rate capability for experiments at SLS2.0
  - Faster shaping time thanks to new CMOS technology
  - Multiple thresholds improve count rate capability by an order of magnitude
- High frame rate readout
  - For charge integrating detectors
    - Larger dynamic range at synchrotrons
    - Higher flux for single photon experiments
    - CW-mode XFELs
  - Time resolved experiments
  - Huge amount of data
    - Almost 1 TB/s on the whole detector

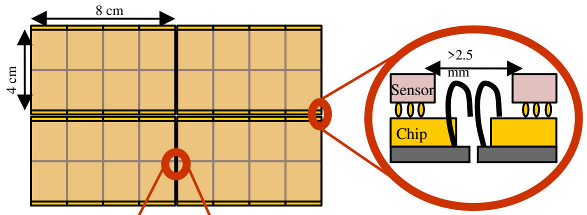


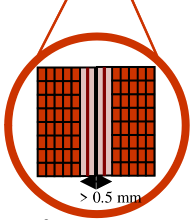


Large detectors



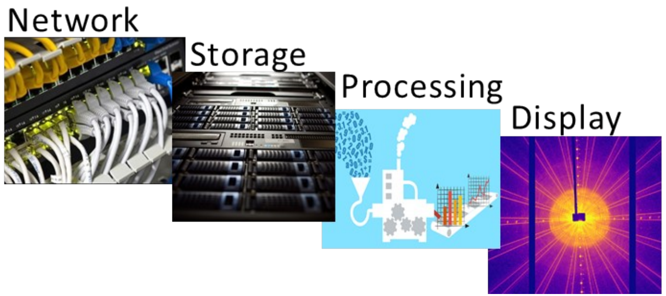
- Tiling of modules required for larger field of view





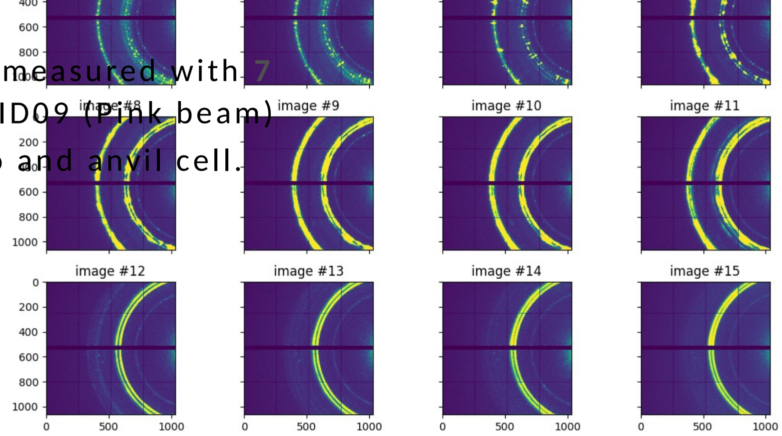
New techniques could reduce the gaps to <0.5 mm and avoid wirebonding

- More pixels more data
  - Fully parallel readout at full speed:
    - EIGER 9M 36 GB/s 0.4 PB/day
    - JUNGFRAU 16M 64 GB/s 0.7 PB/day
    - MÖNCH 0.3 160k 2 GB/s 170 TB/day
- Dedicated data backend required



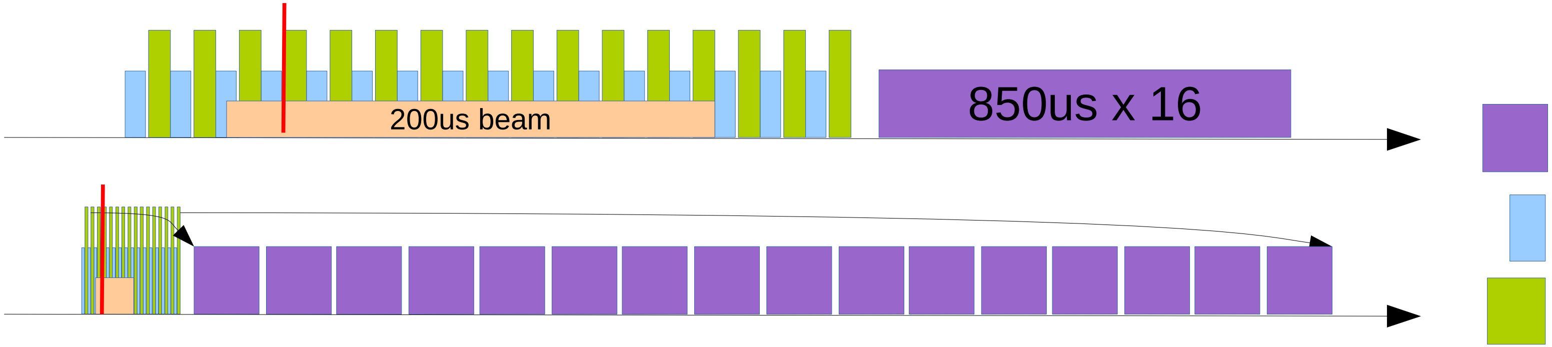
burst mode applications

n of Sn, measured with 7
at ESRF ID09 (Pink beam)
th piezo and anvil cell.

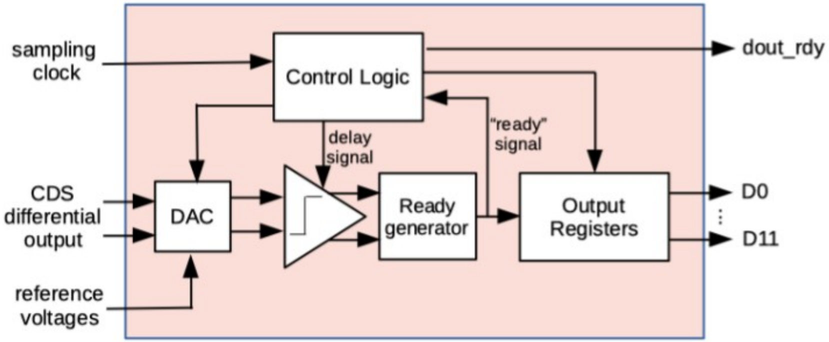


during burst

zoom out



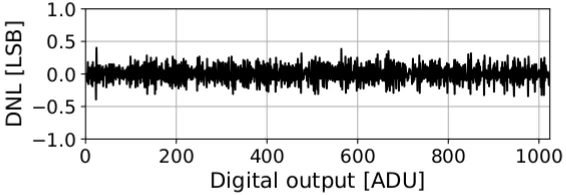
The Gotthard II ADC

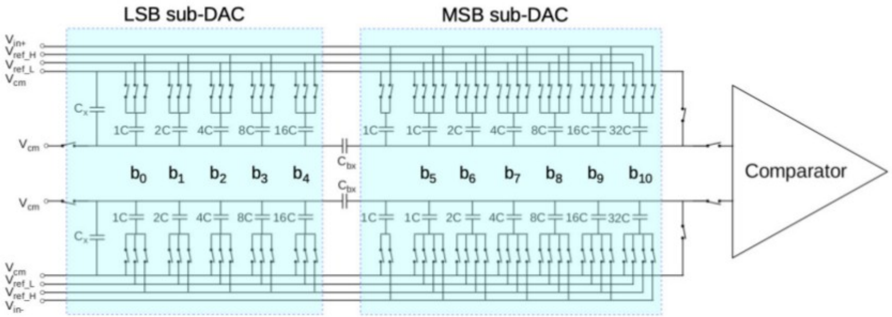


- 20MS/s12b operation
- 200x600um2
- Low power consumption

  BUT:
- ENOB = 10.1-10.3 bit
- Hard to calibrate.

DNL after calibration @10-bit





arXiv:2103.15405