PAUL SCHERRER INSTITUT

PSI

Viktoria Hinger :: Photon Science Detector Group :: Paul Scherrer Institute

Advancing the JUNGFRAU detector toward low-energy X-ray applications

PSD12 :: 13 September 2021 :: University of Birmingham

Outline

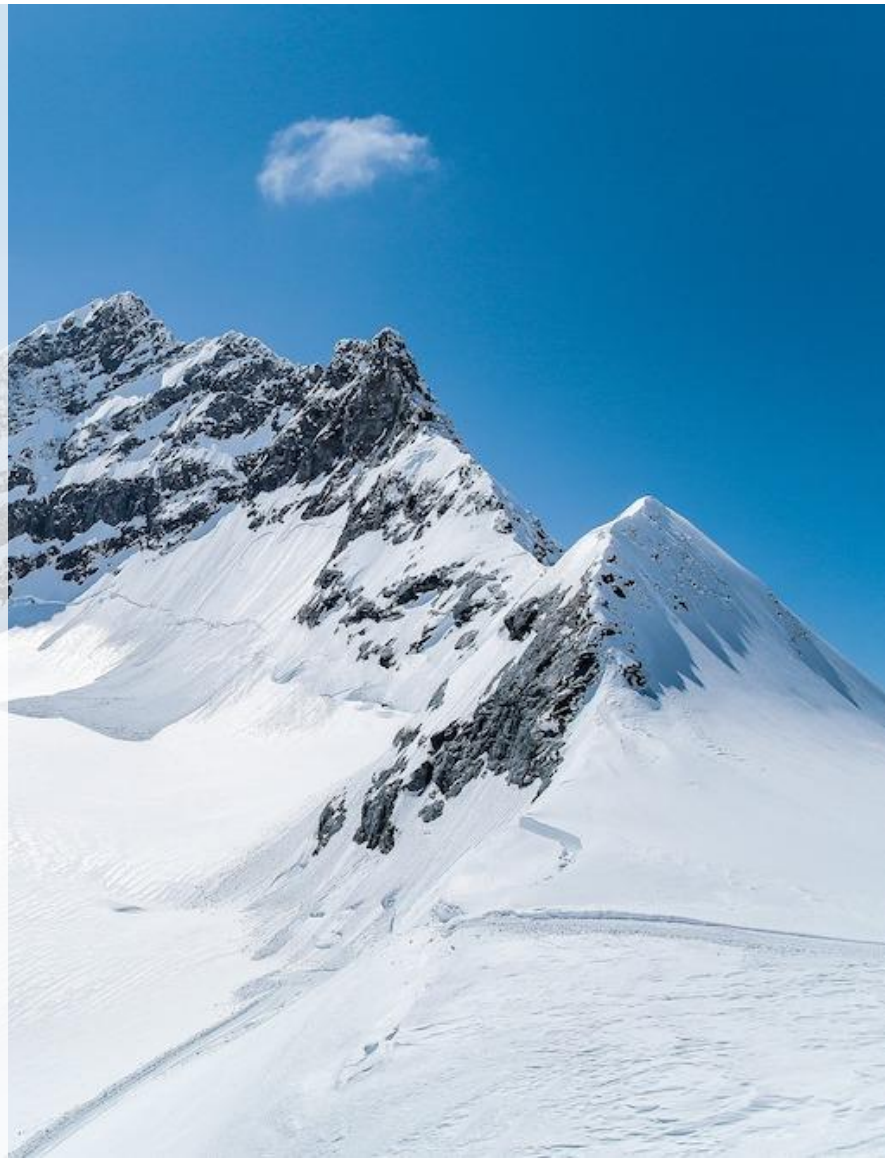
The JUNGFRAU detector
- current applications
- working principle

Toward low-energy X-rays
- Why JUNGFRAU?
- improvements of the system

JUNGFRAU at the SwissFEL Maloja end station
- setup at the beamline
- first results

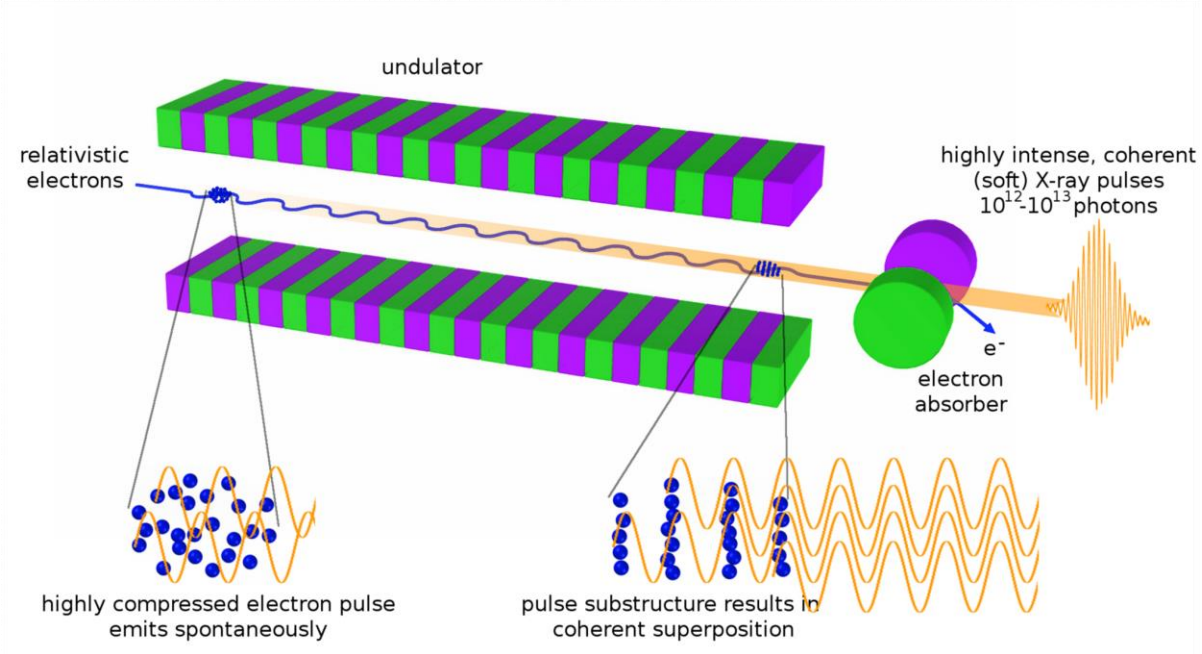
Outlook – JUNGFRAU meets LGADs
- LGAD principle
- advantages and critical points
- development at PSI

Summary



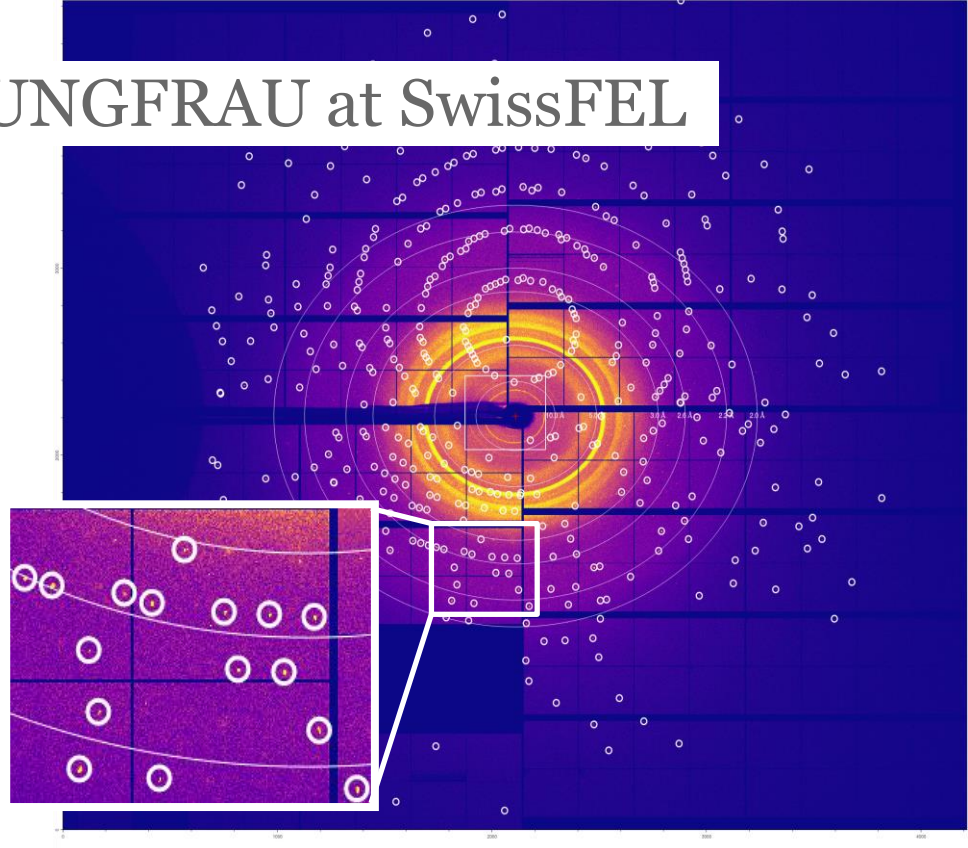
X-ray free electron laser (XFEL)

- **Short, intense, laser-like X-ray pulses**
  - Observe extremely **fast processes**
  - Probe **electronic structure** of materials

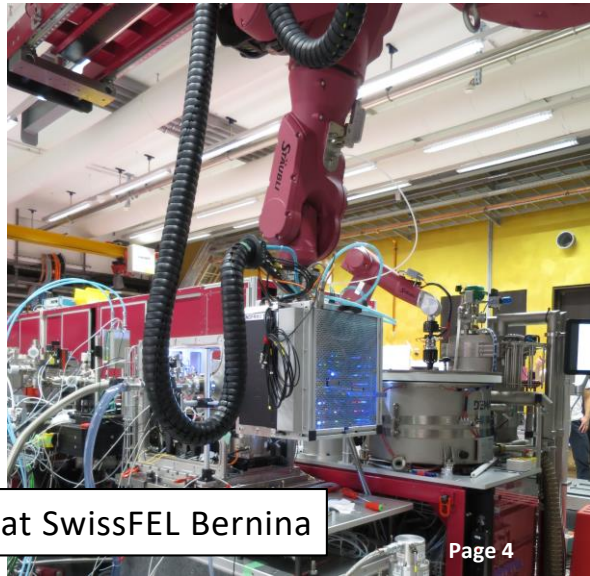


JUNGFRAU detector is optimized for high photon rates at XFELs

Applications of JUNGFRAU at SwissFEL



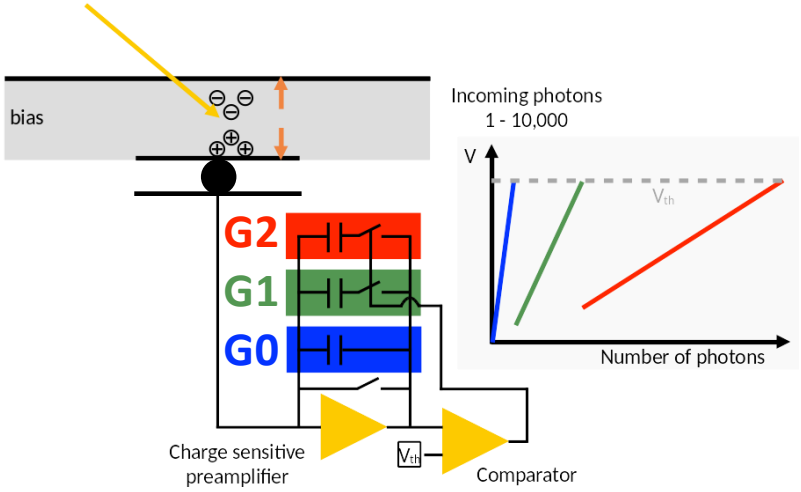
- Covers all needs of SwissFEL
- **Hard X-rays (2 keV—16 keV):**
  15 systems in operation
  - (serial) femtosecond crystallography
  - X-ray emission spectroscopy
  - X-ray diffraction
  - beam diagnostics
  - …
- **Soft X-rays (250 eV—2 keV):**
  1 system in operation **(Maloja)**, more in planning
  - coherent diffractive imaging (CDI)
  - resonant inelastic X-ray scattering
  - plasmonic dynamics
  - transient resonance scattering
  - …

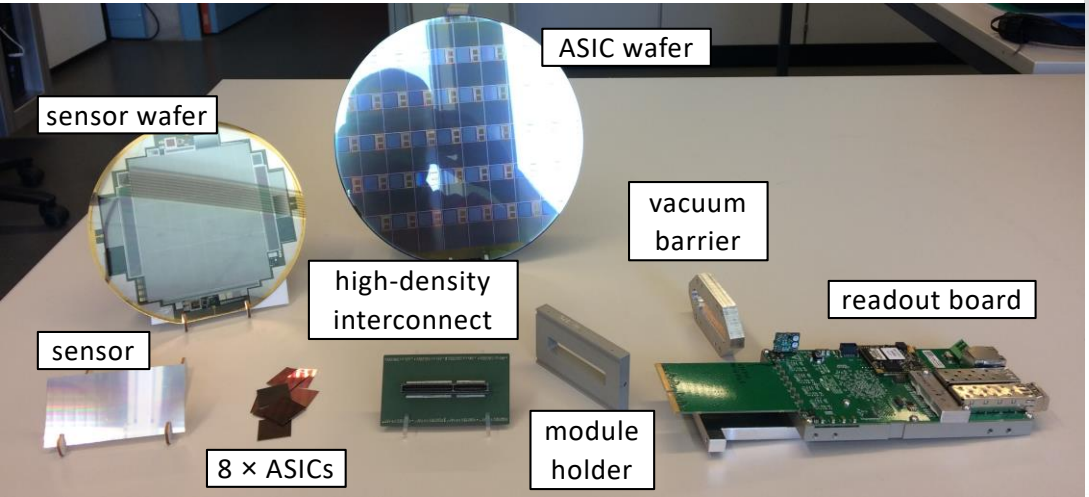


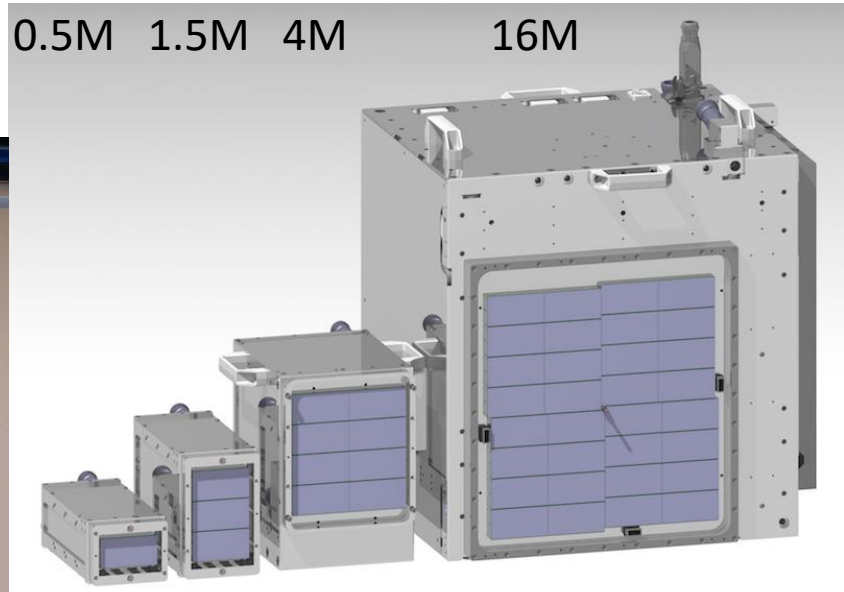
JUNGFRAU at SwissFEL Bernina

The JUNGFRAU detector

- **Charge integrating** hybrid pixel detector (75 × 75 μm^2)
- **3 dynamic switching linear gains** per pixel
- Low noise (< 52 e$^-$ ENC in high gain)
- Dynamic range of 10^4 12 keV photons
- Maximum frame rate 2.2 kHz
- **Modular hardware** → scalability for large-area detectors



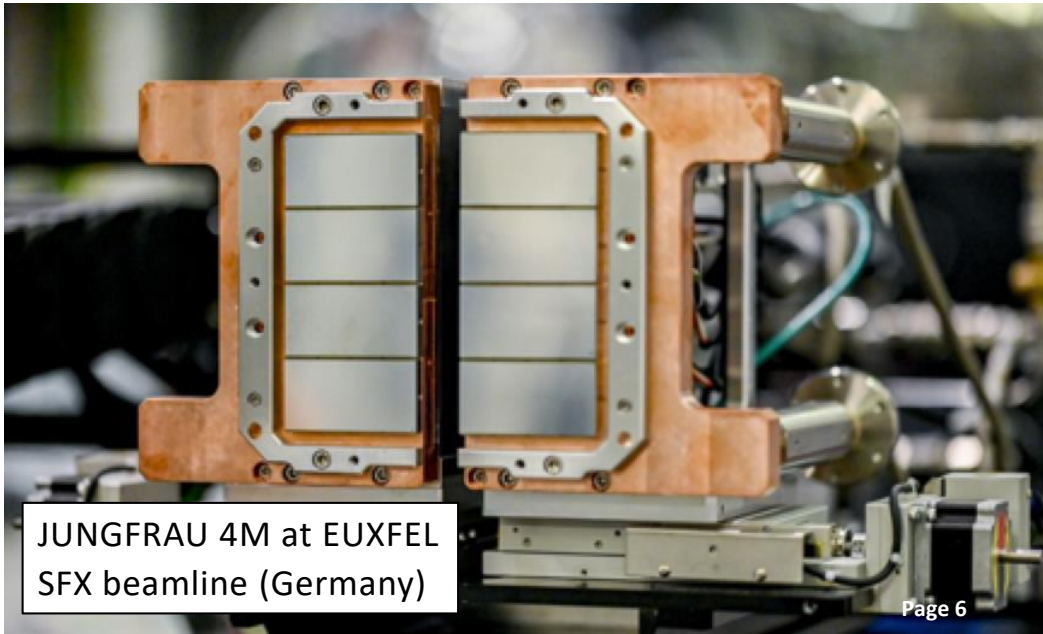




JUNGFRAU at other FEL facilities

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

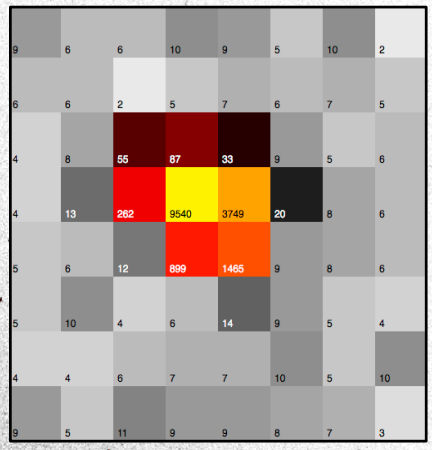
JUNGFRAU 4M at PAL (South Korea)



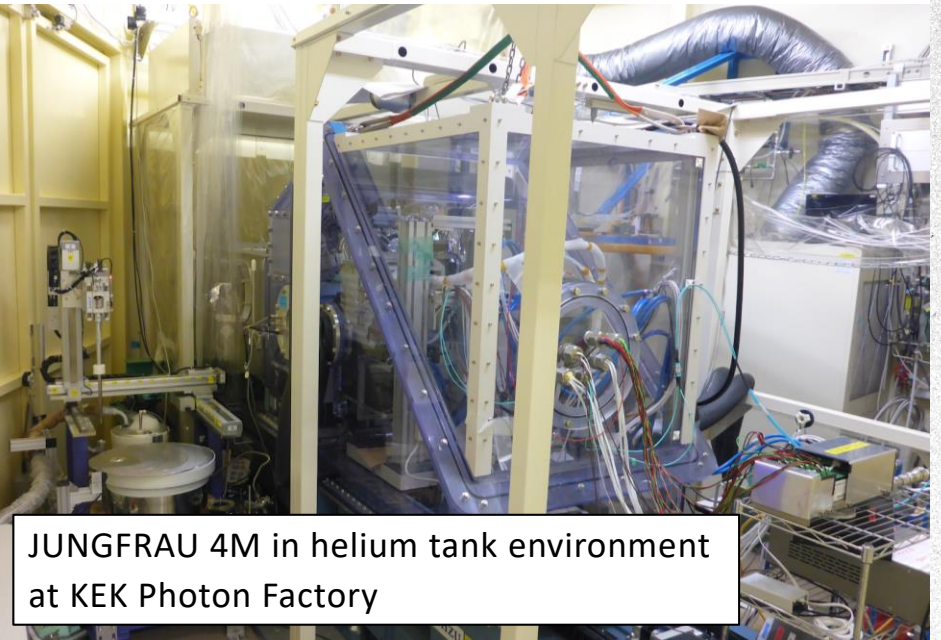
JUNGFRAU 4M at EUXFEL SFX beamline (Germany)

JUNGFRAU at synchrotrons

JUNGFRAU 1M at SLS:
thaumatin crystal diffraction

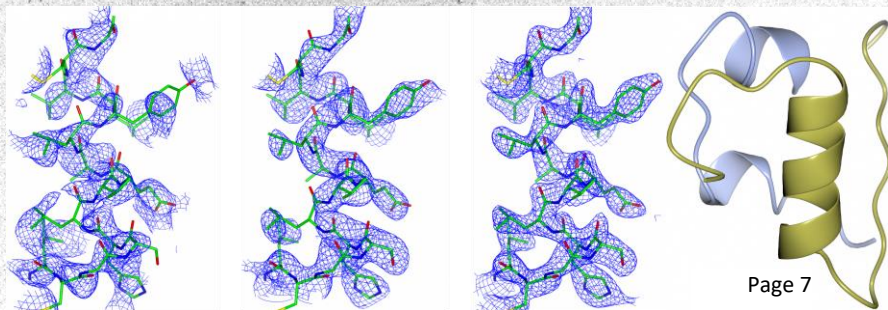


- **Swiss Light Source (SLS)**
  - "Fast and accurate data collection for macromolecular crystallography using the JUNGFRAU detector", *Nature Methods* volume 15, pages 799–804 (2018)
- **KEK Photon Factory (Japan)**



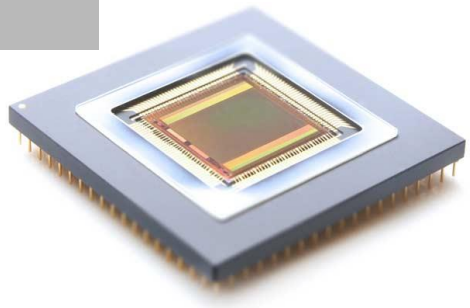
JUNGFRAU 4M in helium tank environment at KEK Photon Factory

First structure solved by JUNGFRAU: Insulin
October 2016 – credits K. Nass, S. Redford



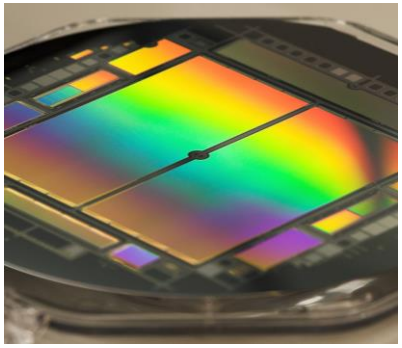
Toward low-energy X-rays – Why hybrid detectors?

Detector options in use now…have some shortcomings



CCD/EM-CCD

- readout speed
- active area
- radiation damage

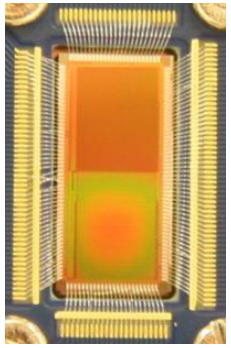


pn-CCD

- dynamic range
- active area
- availability

back side illuminated CMOS

- readout speed
- dynamic range
- active area
- radiation damage



Percival

- active area
- availability

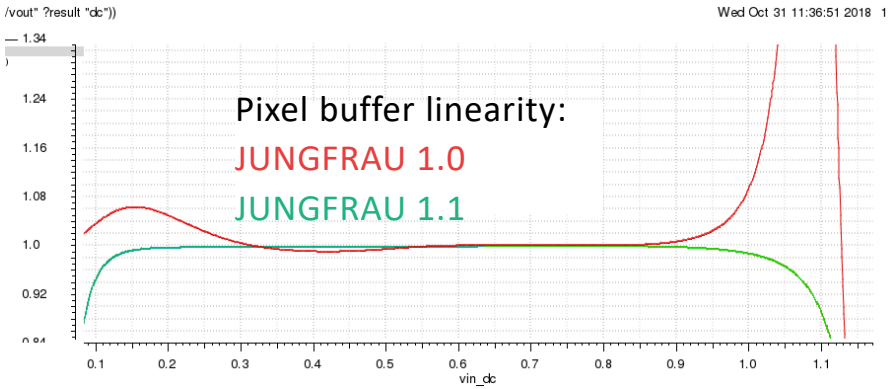
→**JUNGFRAU becomes attractive** because it provides

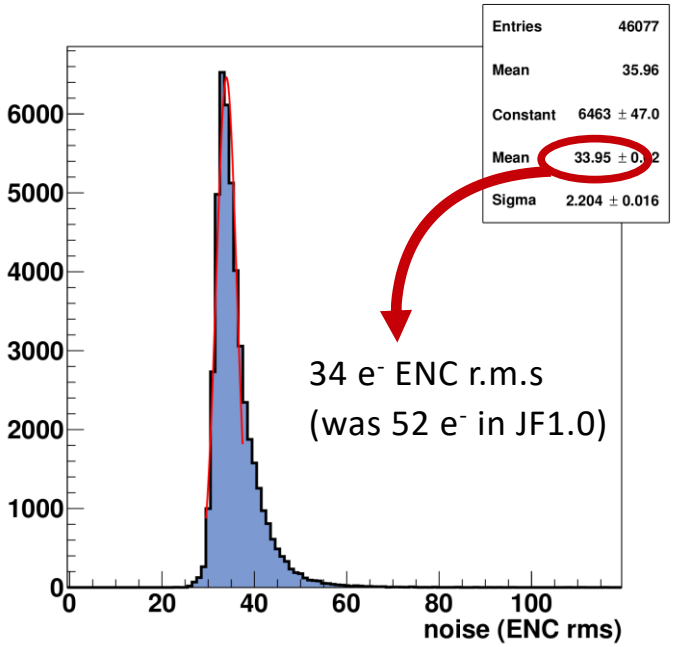
- fast readout
- high dynamic range
- (relatively) low noise
- scalable area
- radiation tolerance (measured to ~10 MGy)
- …and it is readily available for use at SwissFEL

Improving the JUNGFRAU system

- **Output linearity**
  - pixel buffer
- **Noise**
  - readout capacitance
  - amplifier

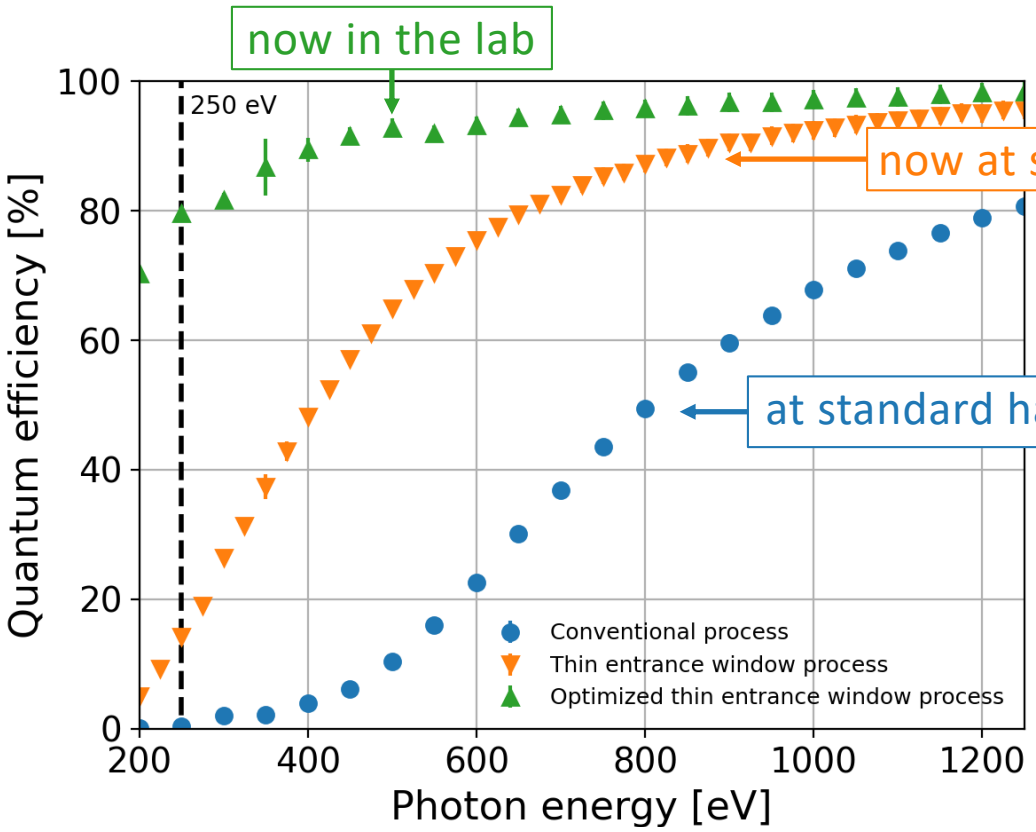
→ Improved for **new ASIC version 1.1**

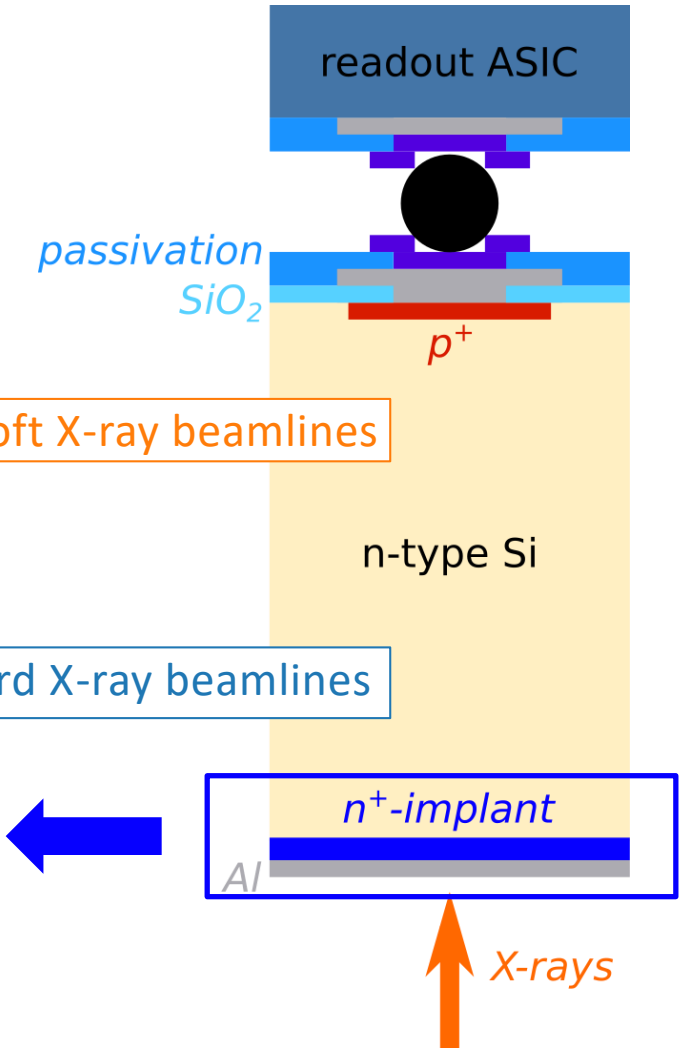




Improving the JUNGFRAU system

- **Quantum efficiency**
  - thickness and quality of the entrance window

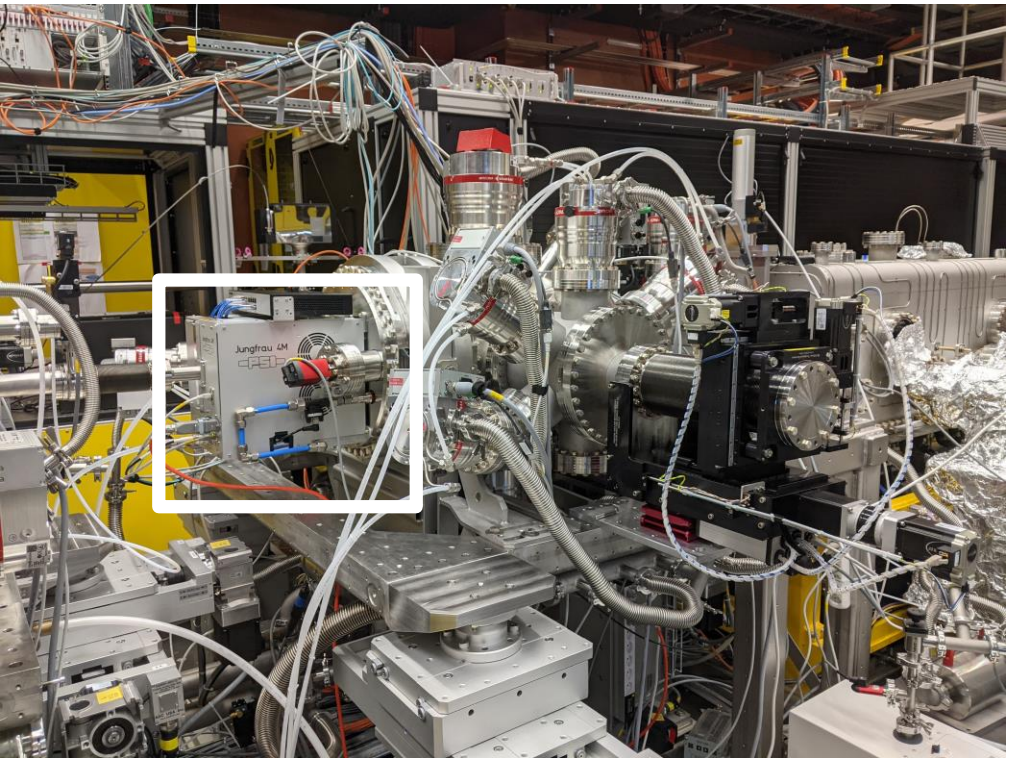


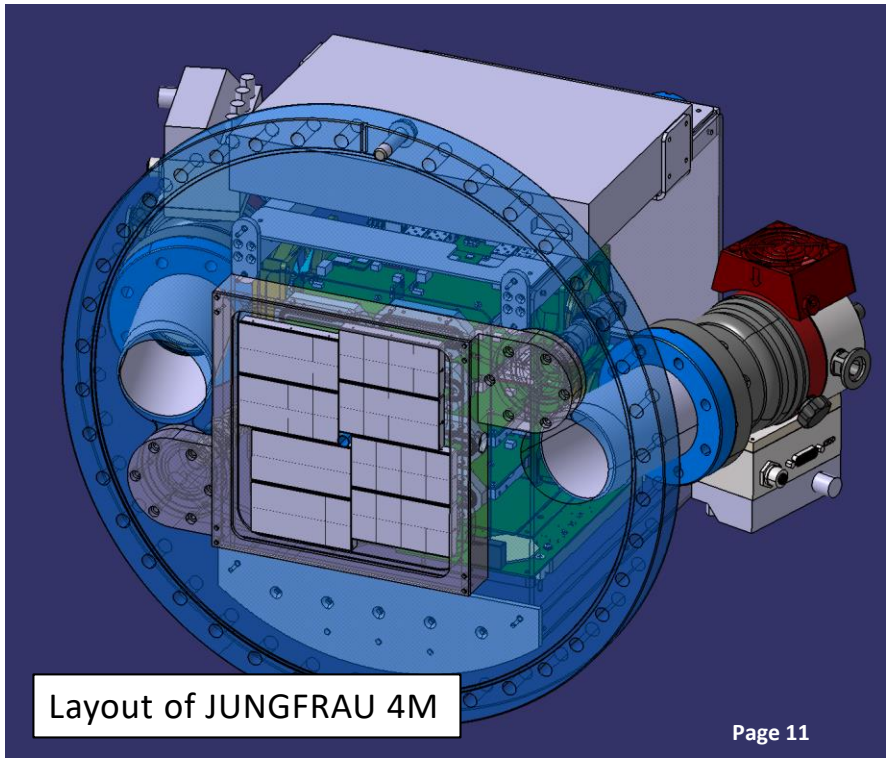


Measurement results of sensors with different back side processing

JUNGFRAU 4M at Maloja

- **Multi-purpose low-energy X-ray beamline** at SwissFEL
- **4M JUNGFRAU** installed
- 6M for larger angles in planning
- In planning for **Furka** end station
- **Commissioning** with xenon cluster target



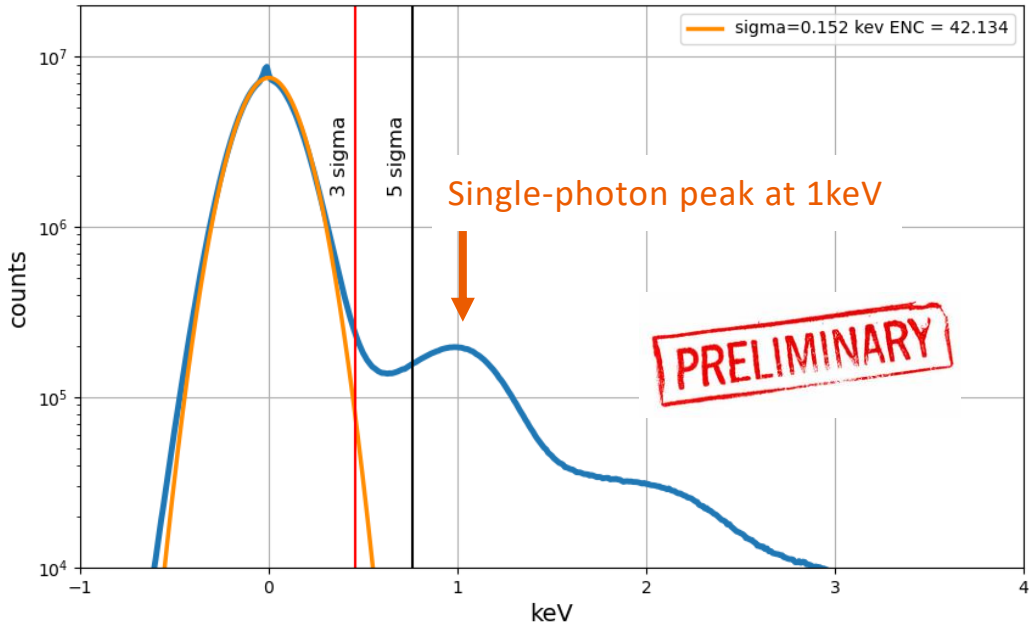


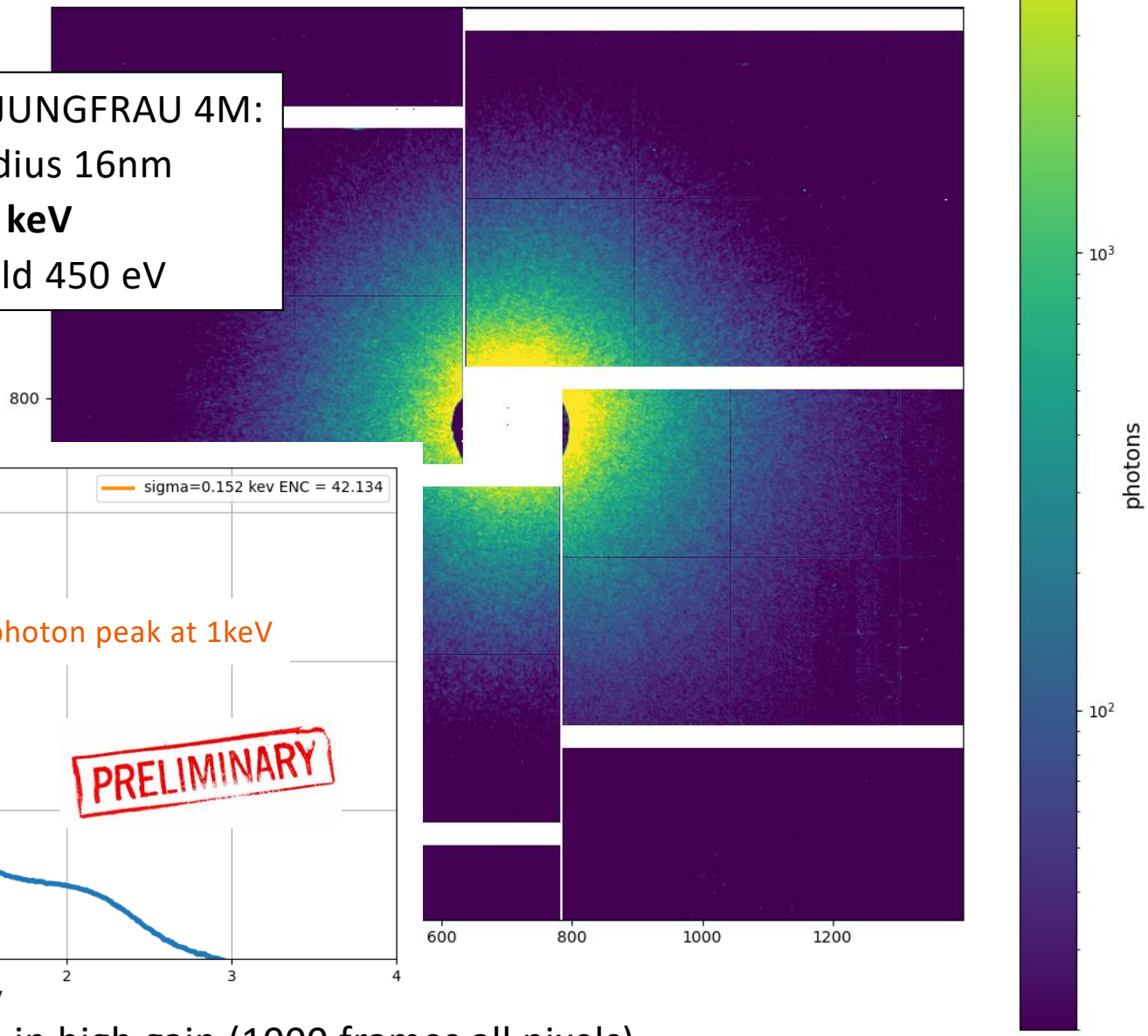
Layout of JUNGFRAU 4M

First results with JUNGFRAU at Maloja

Commissioning of JUNGFRAU 4M:

- xenon cluster, radius 16nm
- **photon energy 1 keV**
- counting threshold 450 eV



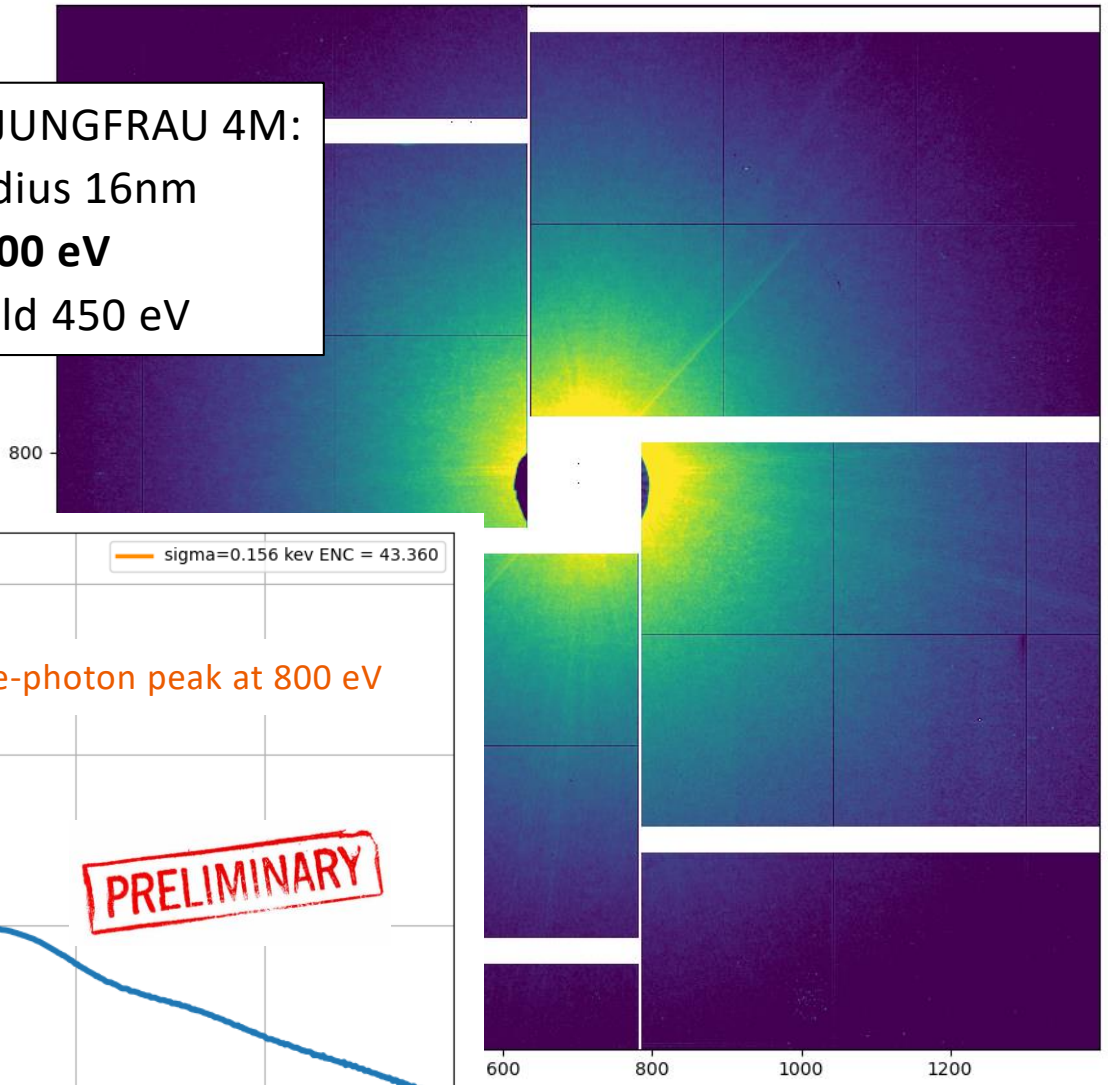


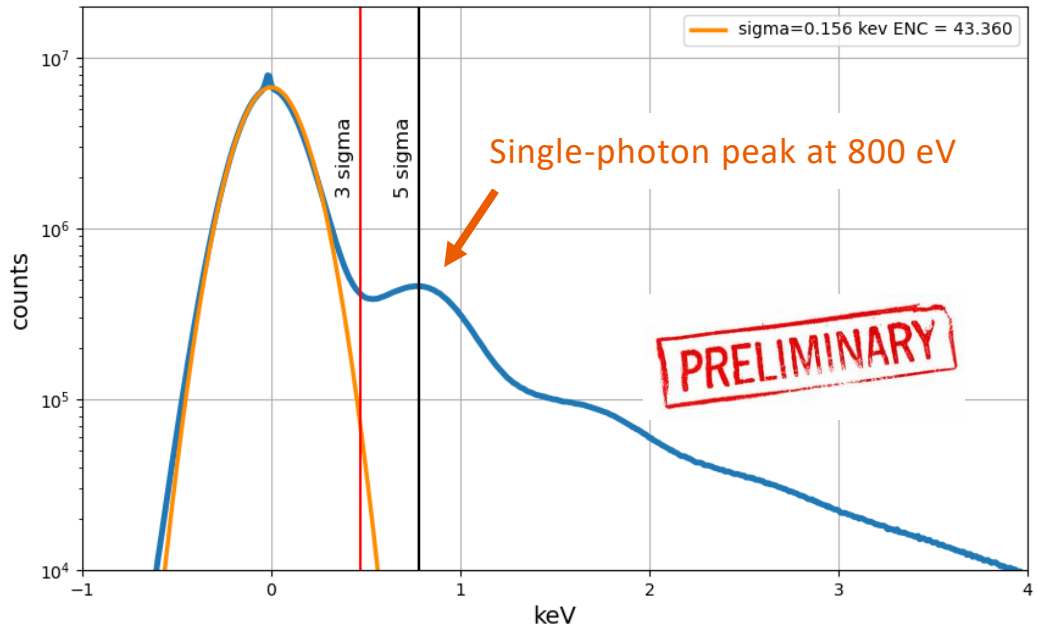
Cumulative energy spectrum in high gain (1000 frames all pixels)

First results with JUNGFRAU at Maloja

Commissioning of JUNGFRAU 4M:

- xenon cluster, radius 16nm
- **photon energy 800 eV**
- counting threshold 450 eV



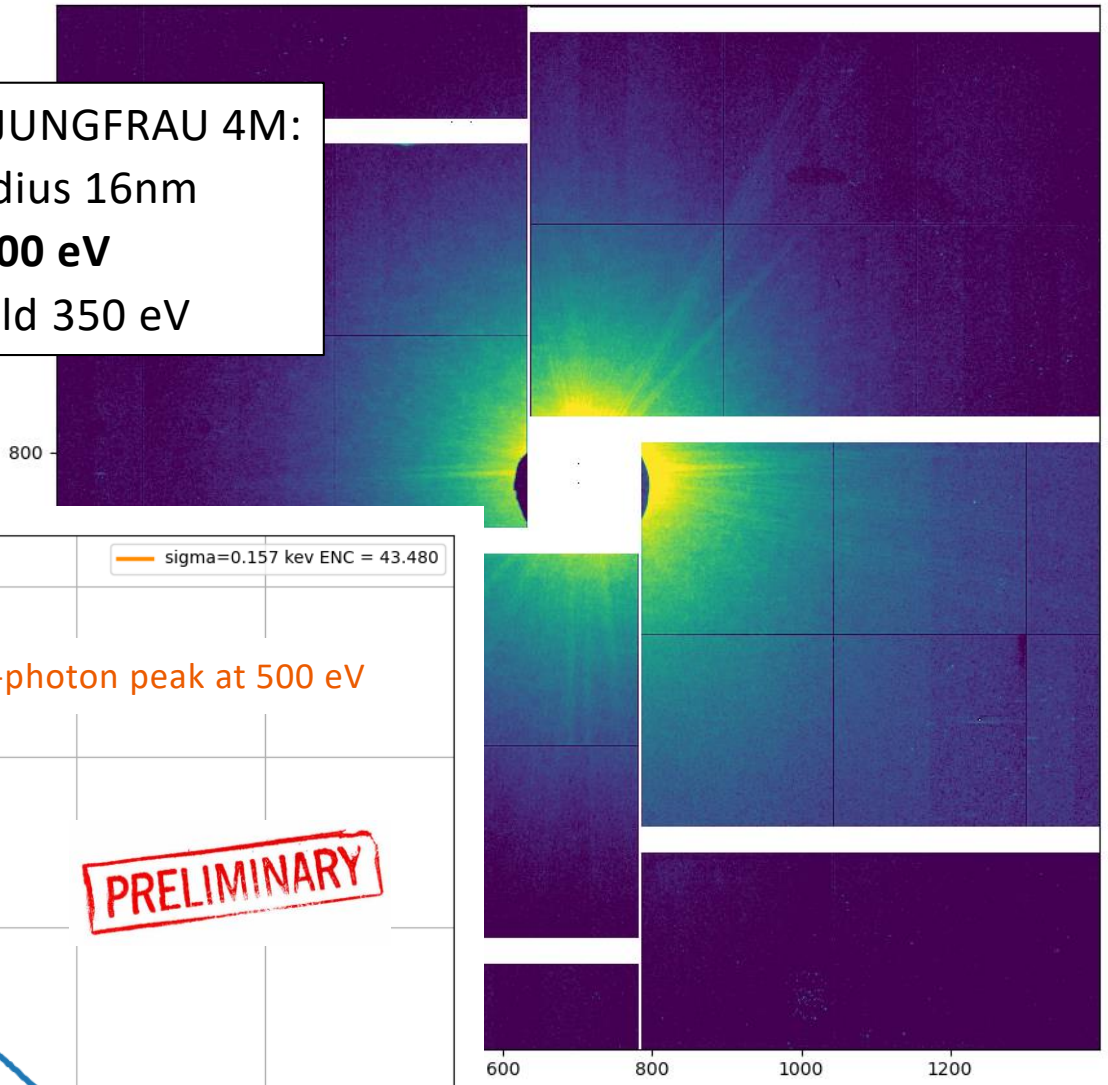


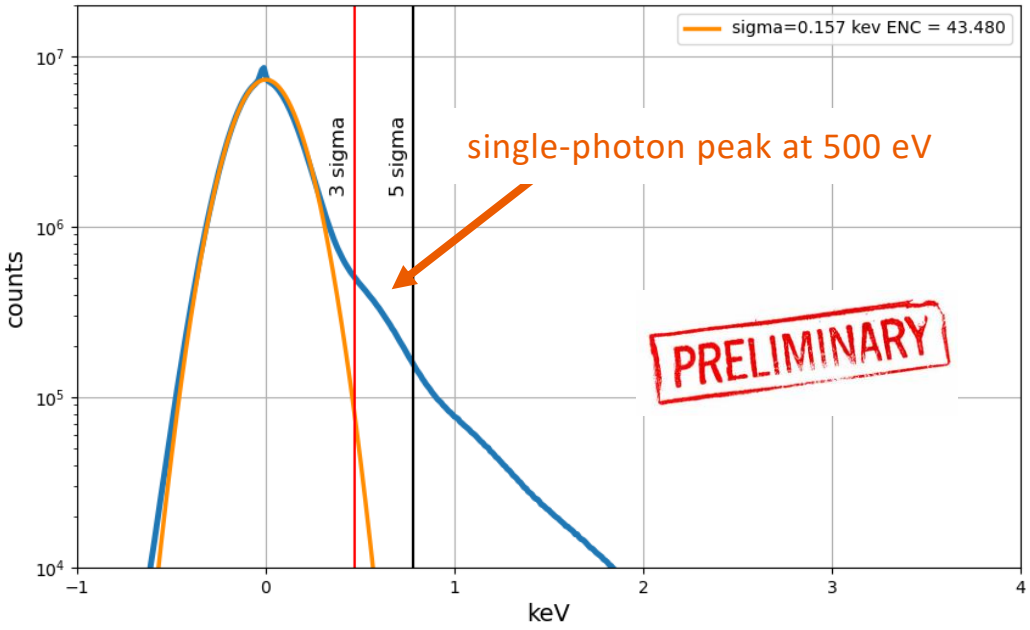
Cumulative energy spectrum in high gain (1000 frames all pixels)

First results with JUNGFRAU at Maloja

Commissioning of JUNGFRAU 4M:

- xenon cluster, radius 16nm
- **photon energy 500 eV**
- counting threshold 350 eV

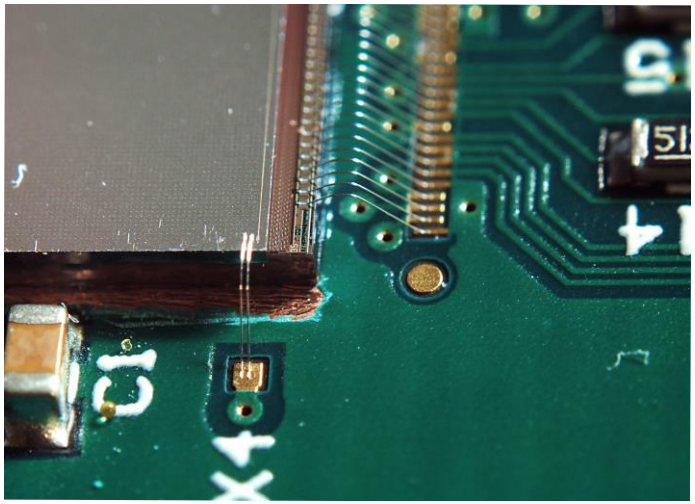




Cumulative energy spectrum in high gain (1000 frames all pixels)

Outlook – JUNGFRAU meets LGADs

JUNGFRAU
charge integrating ASIC



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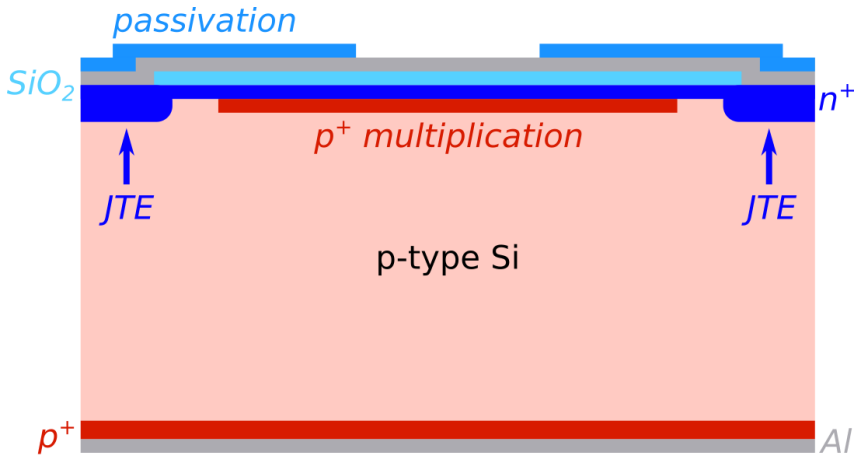
LGAD sensor



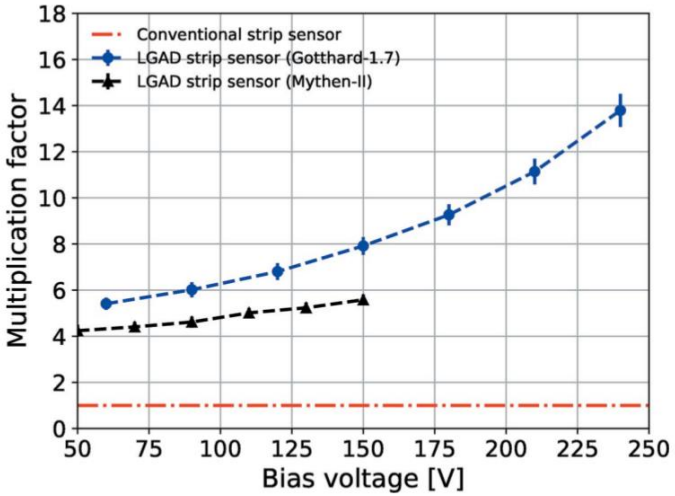
JTE: Junction-Termination-Extension

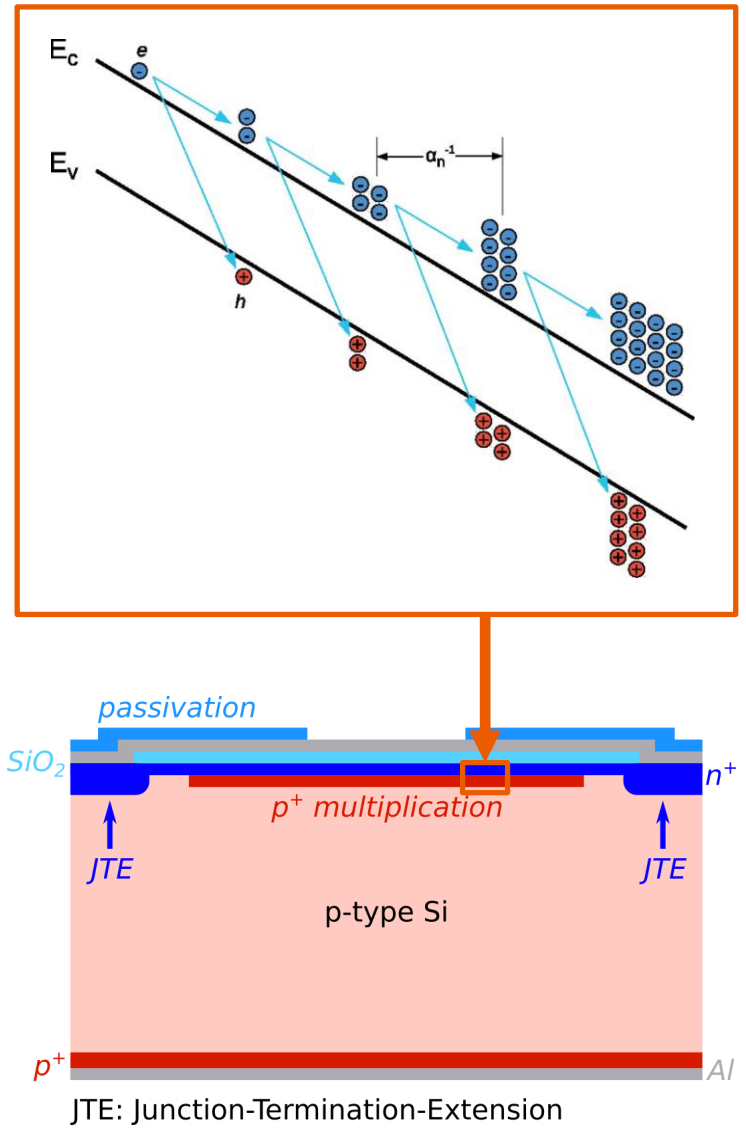
- **Low noise** readout (~ 34 e^- ENC)
- **Gain ~ 10**
- Output signal ∝ deposited energy

→ Improve signal-to-noise ratio and allow single photon detection down to ~ 250 eV

LGAD: Low Gain Avalanche Detector

- **Sensors with intrinsic gain**
- Deep p^+ implant serves as **charge multiplication** layer
- **Proof of principle for low-energy X-ray detection**
  - M. Andrä et al., "Development of low-energy X-ray detectors using LGAD sensors", *J. Synchrotron Rad.* (2019)

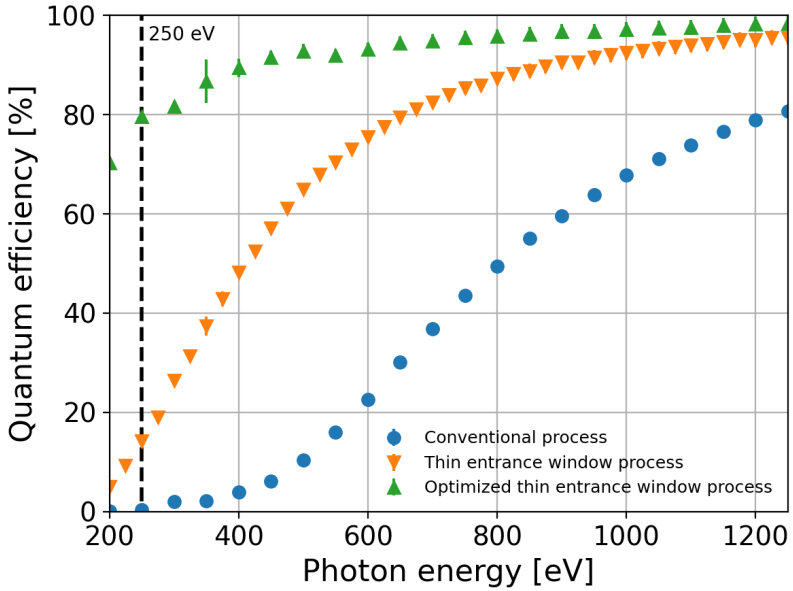




JTE: Junction-Termination-Extension

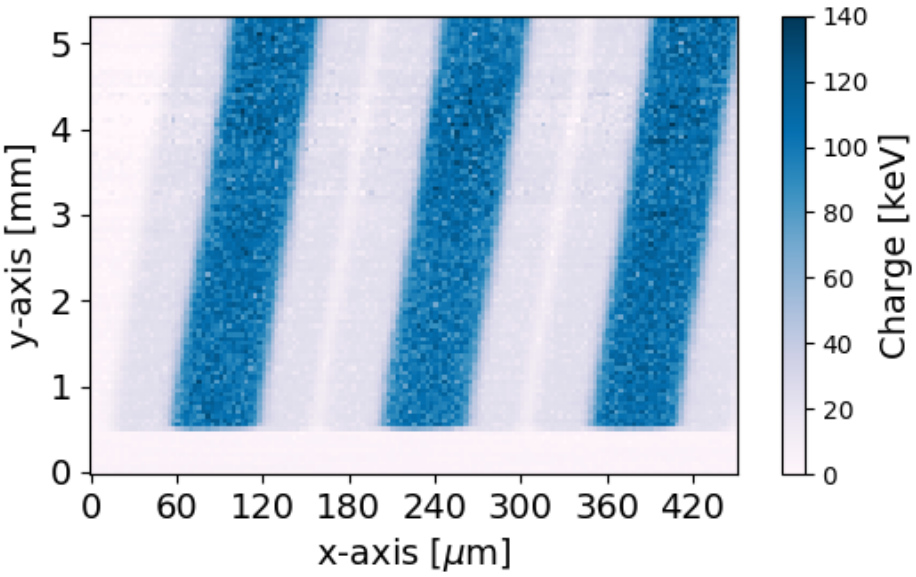
LGADs for low-energy X-rays – critical points

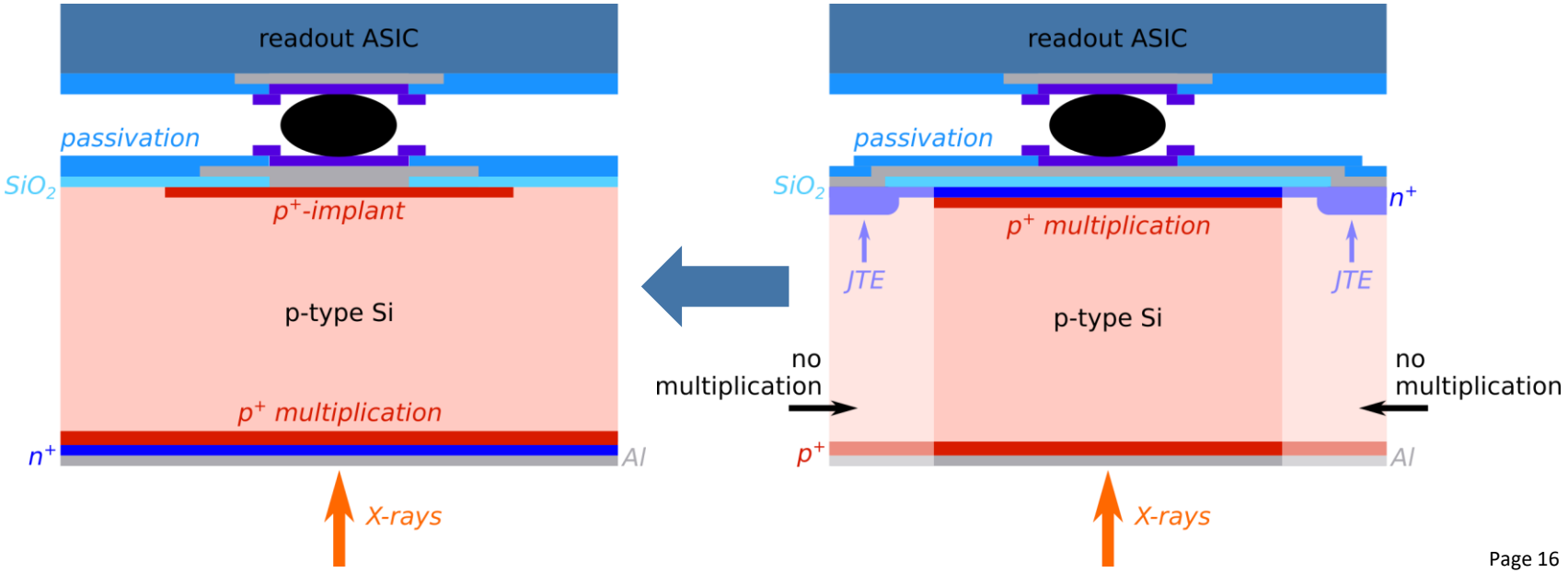
- **Quantum efficiency**
  - thickness and quality of entrance window



LGADs for low-energy X-rays – critical points

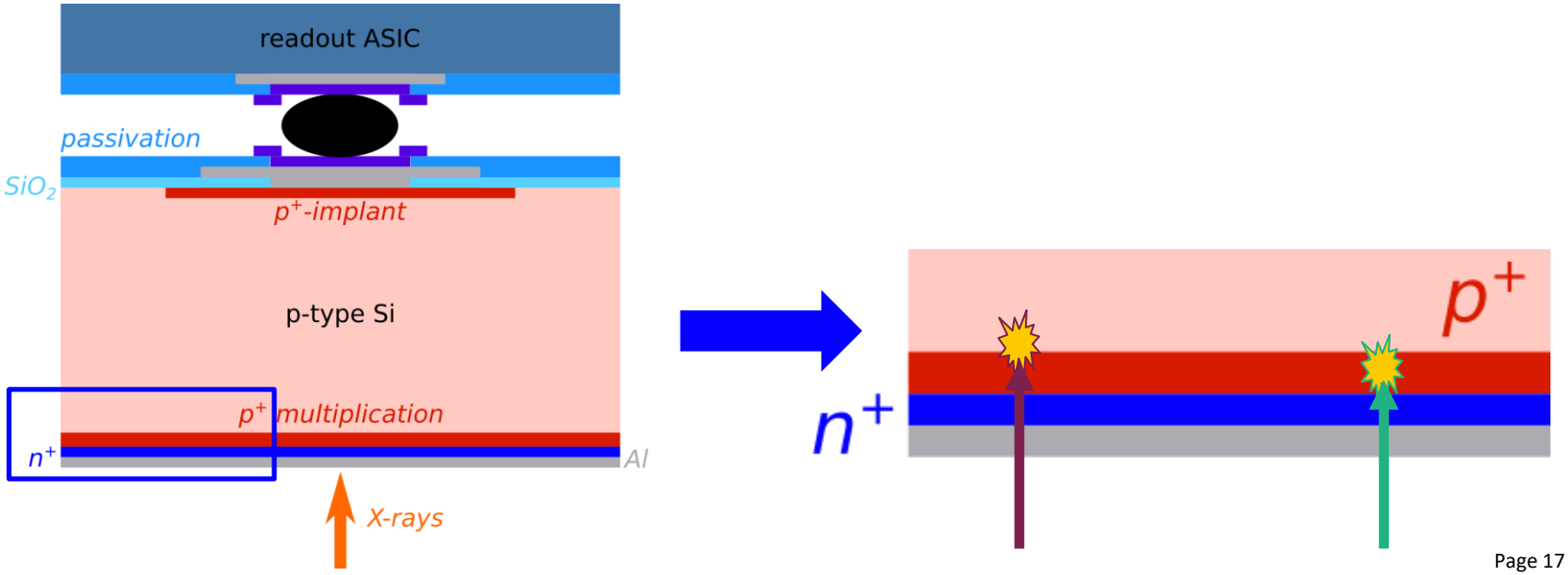
- **Quantum efficiency**
  - thickness and quality of entrance window
- **Fill factor**
  - inverted LGAD (iLGAD)





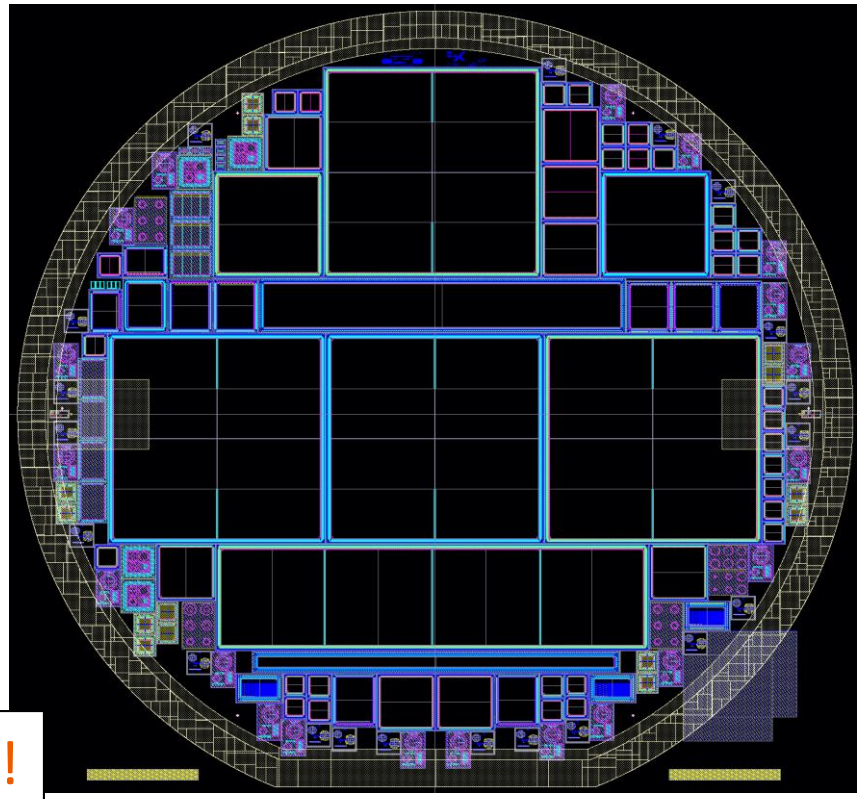
LGADs for low-energy X-rays – critical points

- **Quantum efficiency**
  - thickness and quality of entrance window
- **Fill factor**
  - inverted LGAD (iLGAD)
- **Gain uniformity**
  - dependency on absorption depth (caused by inverted design)



Development of LGAD sensors with FBK

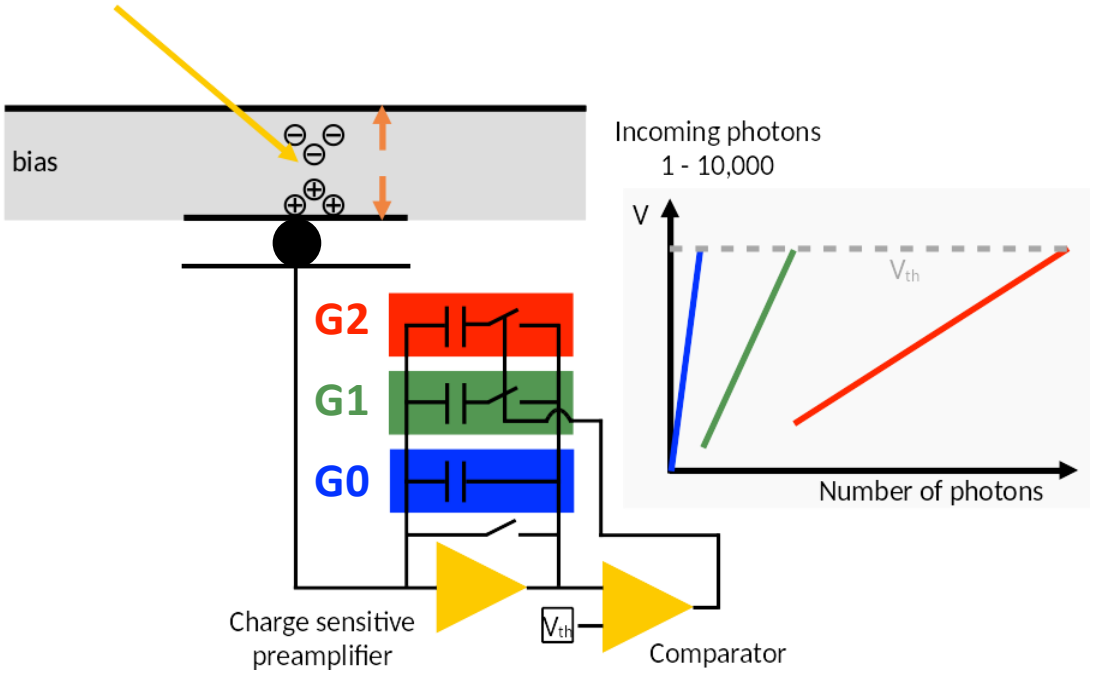
- **Wafer run with design variations** to be delivered **autumn 2021**
  - entrance window (also including the optimized process)
  - gain layers (doping concentration and depth)
  - iLGAD
  - sensor thickness 320 µm
- Characterization of **prototypes and full-scale modules**
- Assessment of performance in **real-life scenarios**



First results next year!

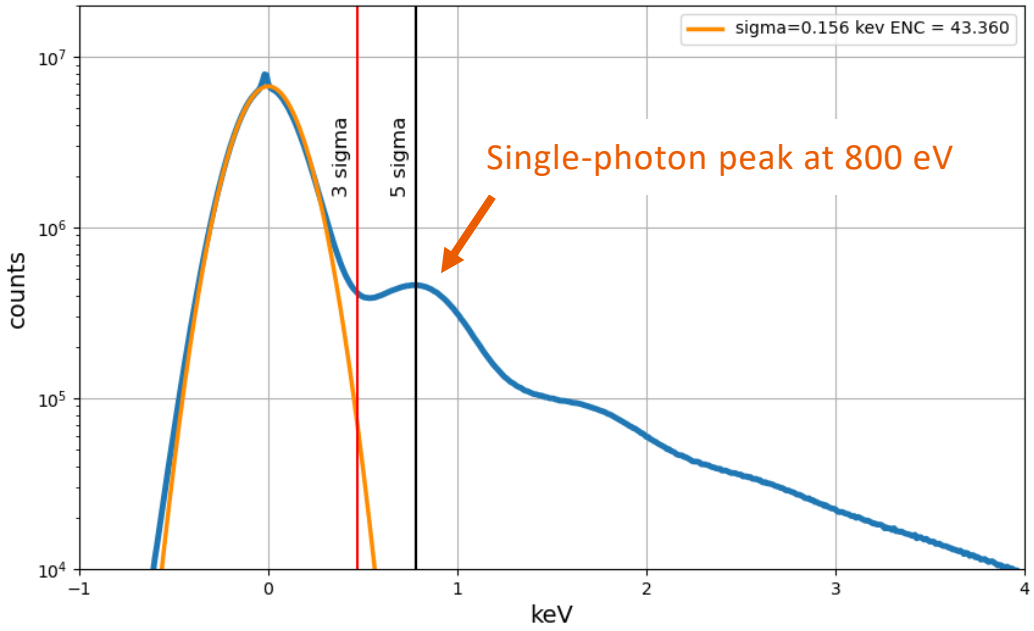
Summary

- **JUNGFRAU** is a **charge integrating hybrid pixel detector** for X-ray science at FELs and synchrotron sources.



Summary

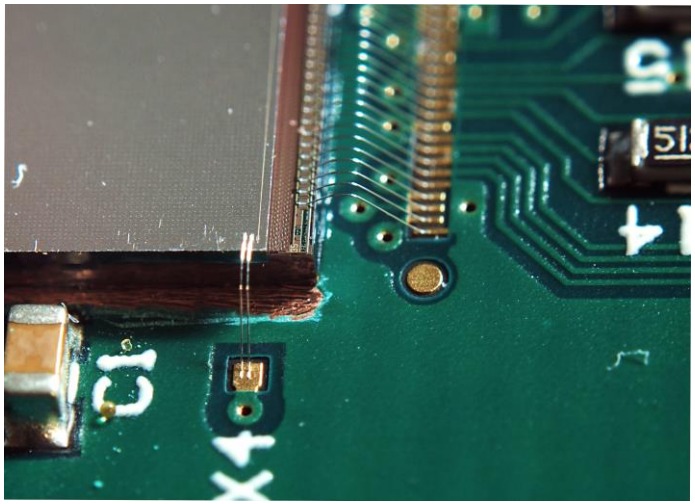
- **JUNGFRAU** is a **charge integrating hybrid pixel detector** for X-ray science at FELs and synchrotron sources.
- While **optimized for hard X-rays**, JUNGFRAU has successfully resolved **single photons at 800 eV** at the Maloja end station of SwissFEL.



Summary

- **JUNGFRAU** is a **charge integrating hybrid pixel detector** for X-ray science at FELs and synchrotron sources.
- While **optimized for hard X-rays**, JUNGFRAU has successfully resolved **single photons at 800 eV** at the Maloja end station of SwissFEL.
- In combination with **LGAD sensors**, JUNGFRAU presents a promising option as a photon detector for **low-energy X-rays down to 250 eV**, providing both single photon resolution and large dynamic range.

JUNGFRAU
charge integrating ASIC



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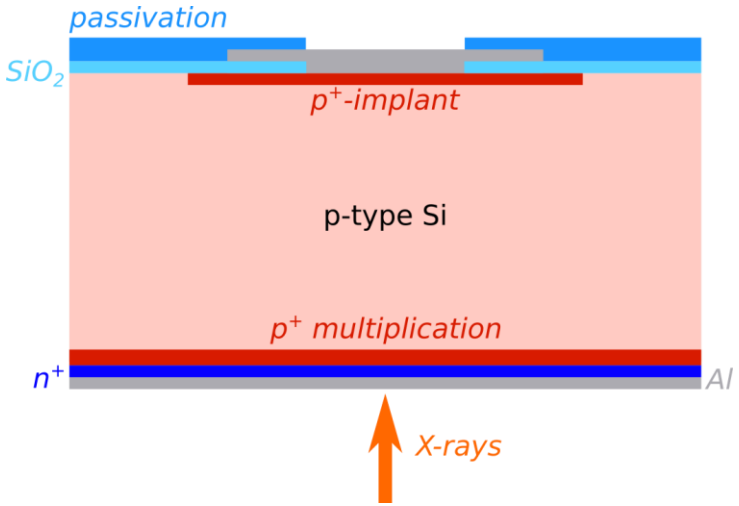
inverted LGAD sensor



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http://psi.ch/node/46984

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