PSI Center for Photon Science

Characterization of inverse LGADs in the soft X-ray energy range

Shuqi Li[1*], A. Bergamaschi[1], A. Bisht[2], M. Boscardin[2], M. Brückner[1], M. Carulla[1], R. Dinapoli[1], S. Ebner[1], S. Emiliani[1], K. Ferjaoui[1], E. Fröjdh[1], V. Gautam[1], D. Greiffenberg, S. Hasanaj[1], V. Hinger[1], M. Hürst[1], V. Kedych[1], T. King[1], C. Lopez-Cuenca[1], L. Lunin[1], A. Mazzoleni[1], D. Mezza[1], S. Moses[1], K. Moustakas[1], A. Mozzanica[1], J. Mulvey[1], M. Müller[1], G. Paternoster[2], C. Ruder[1], B. Schmitt[1], S. Silletta[1], D. Thattil[1], M. Vignali[2], X. Xie[1], J. Zhang[1]

[1] PSI Center for Photon Science, 5232 Villigen PSI, Switzerland
[2] Fondazione Bruno Kesler (FBK), Via Sommarive 18, 38123 Trento, Italy

The 14th International Conference on Position Sensitive Detectors
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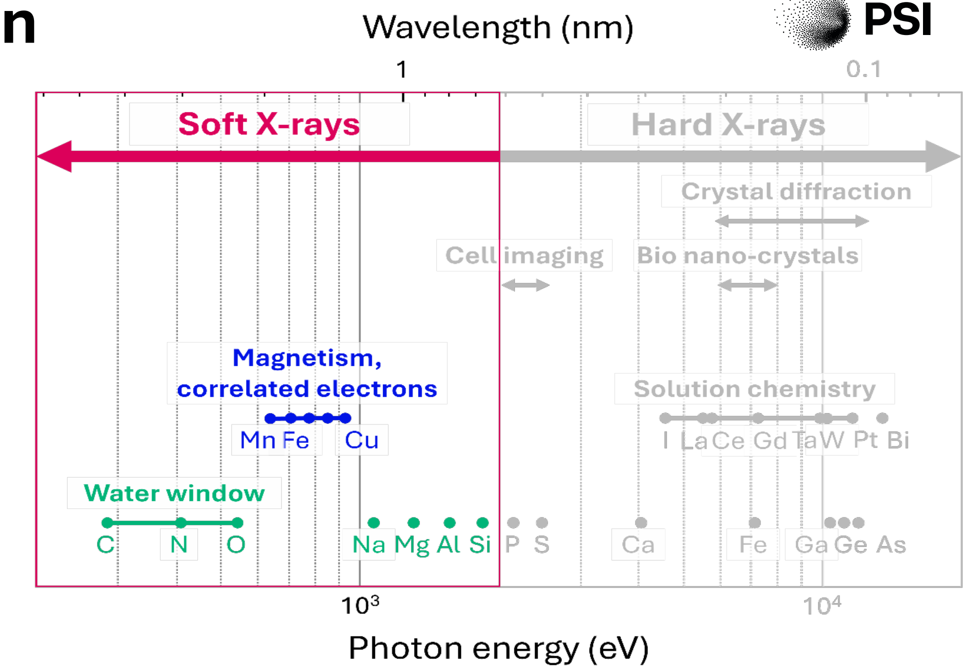
*shuqi.li@psi.ch

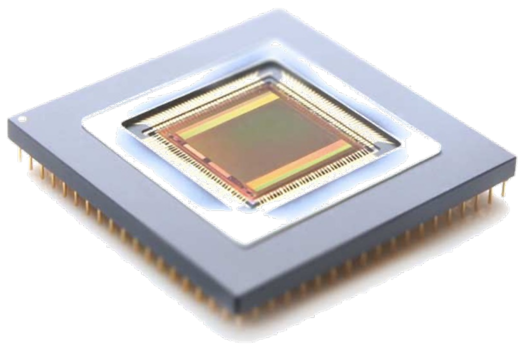
Detectors for Soft X-ray detection

- Science enabled by soft X-rays
  - L-edges of many **important metals**
    Mn, Fe, Cu ... (600 – 1000 eV)
  - **“Water window”** and **light elements**
    C and O *K*-edges (282 – 543 eV)
    Na, Mg ... (1-2 keV)

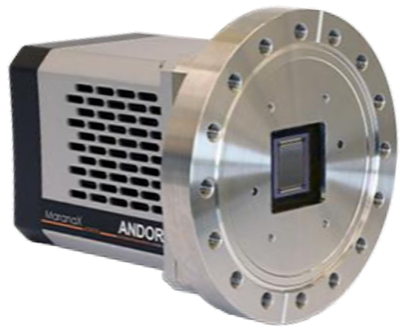
    ...
- State-of-art detectors for soft X-rays



CCD



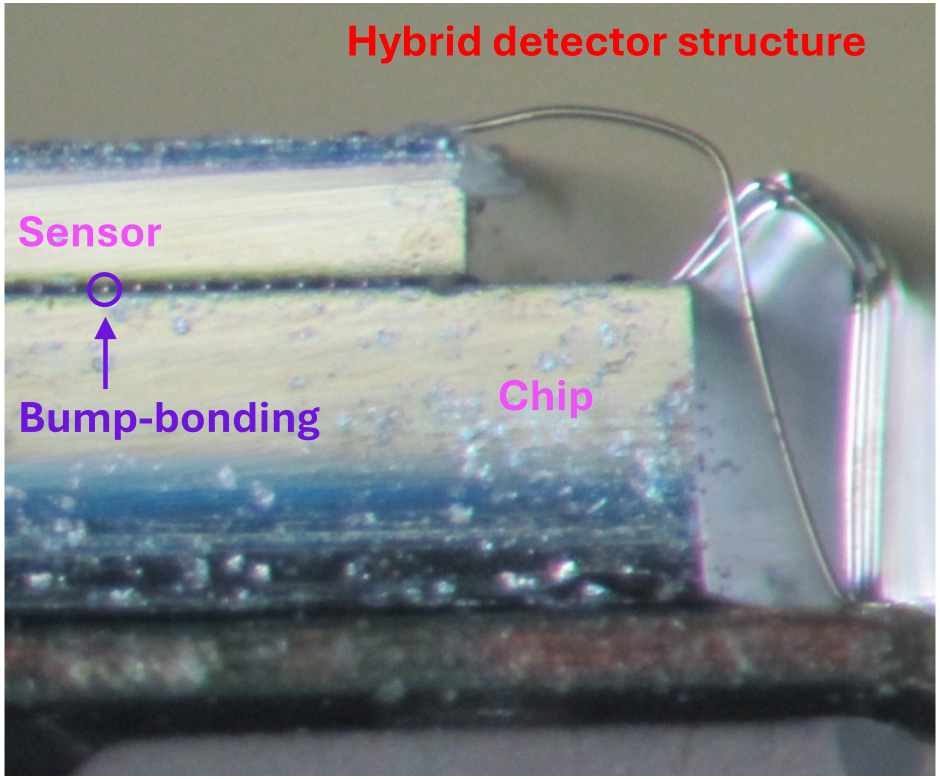
CMOS imager



Readout speed ~ 1 Hz – 70 Hz

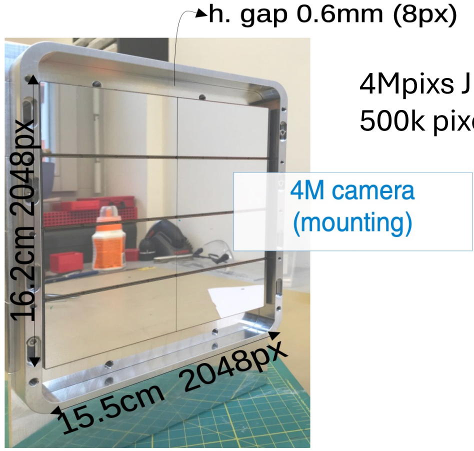
Area ~ 2x2 – 4x4 cm^2

A Viable Solution: Hybrid Pixel Detectors (HPD)



Advantages:

- High frame rate (> 2 kHz)
- Large detection area (4 x 8 cm^2, tileable)
- Wide dynamic range (up to 35 M e-)
- **We can optimize sensor and chip separately**



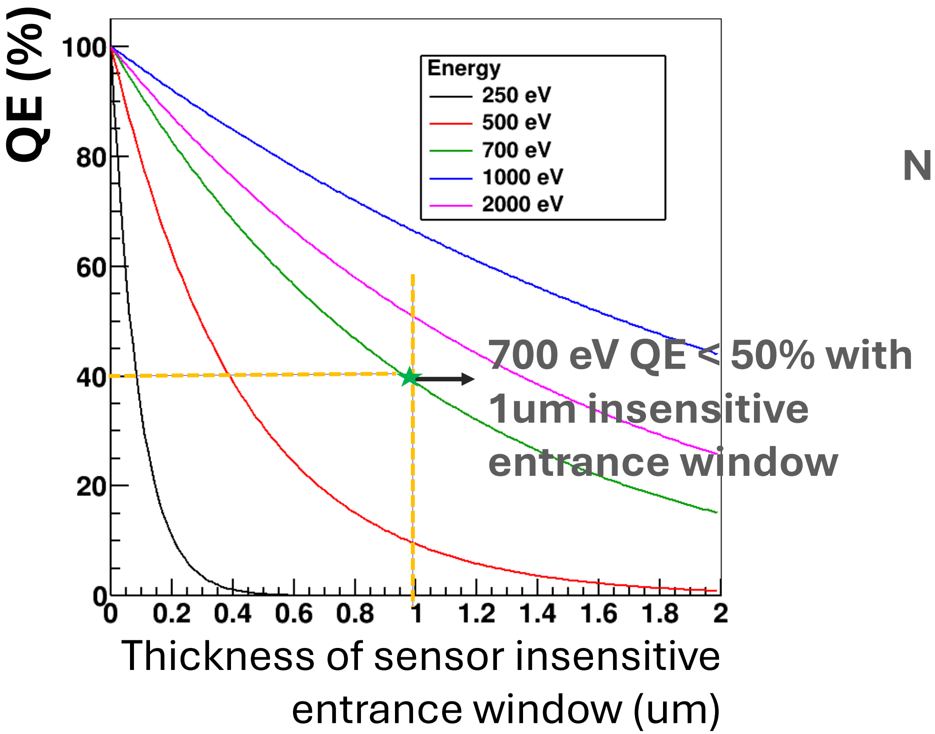
4Mpixs JUNGFRAU detector
500k pixels for one 4 x 8 cm^2 module

Challenges for HPD in the Soft X-ray Range

Shallow photon absorption of low energy photon

→ Low quantum efficiency(QE)

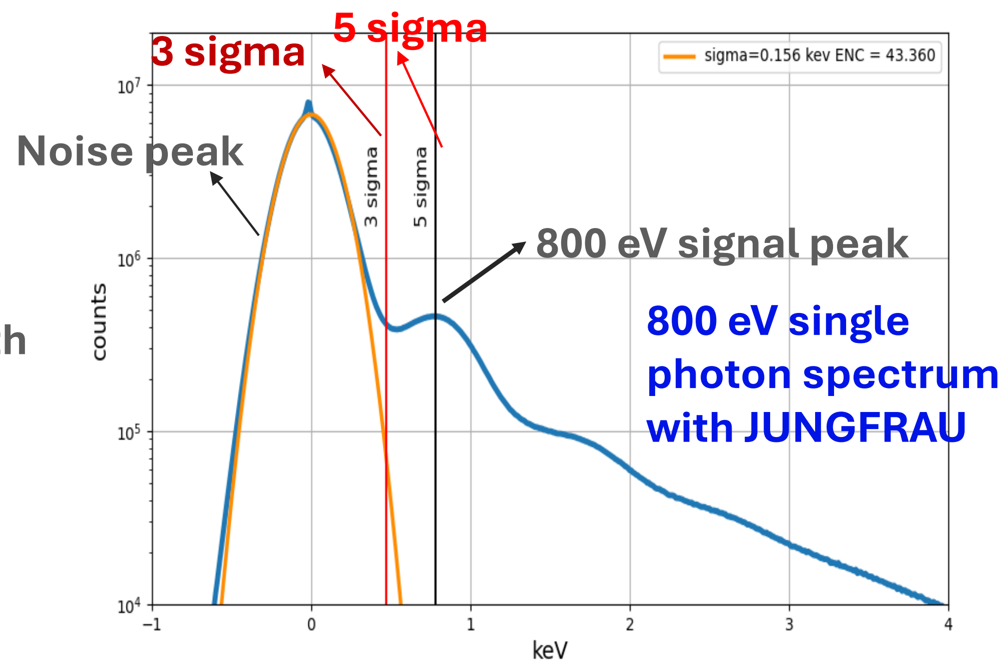
QE < 50 % at 700 eV



Small signal compared to electronic noise

-> Low signal-to-noise ratio (SNR)

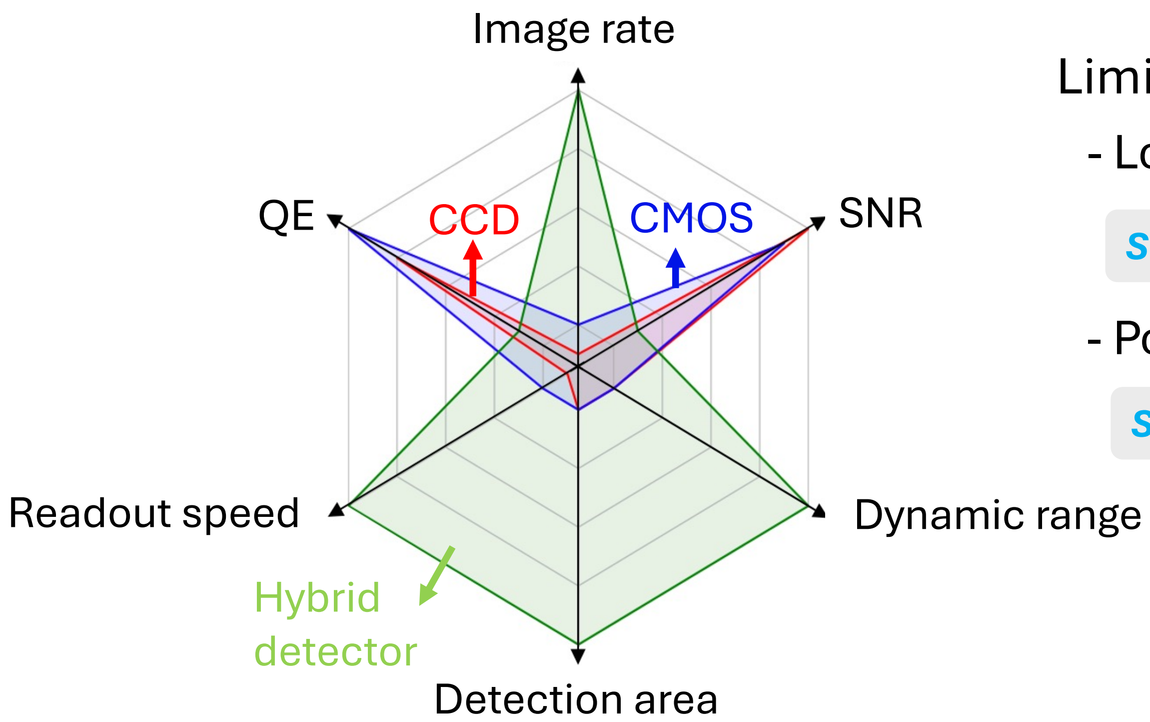
Minimum detectable energy: 800 eV



Solutions for HPD in the Soft X-ray Range

FONDAZIONE BRUNO KESSLER + PSI

Optimize sensor



Limitations:

- Low Quantum Efficiency (QE)

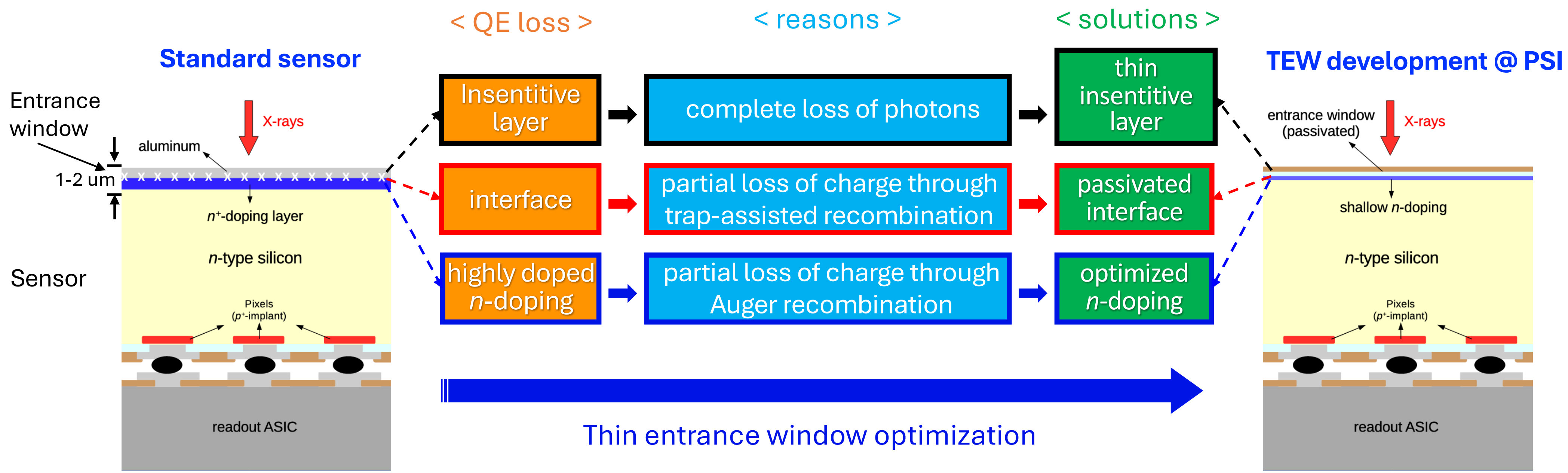
Solution: Thin Entrance Window (TEW) technology

- Poor Signal to Noise Ratio (SNR)

Solution: Low Gain Avalanche Diode (LGAD)

Thin Entrance Window (TEW) Technology

- To improve quantum efficiency (QE)



J. Zhang et al., *JINST* **17**, C11011 (2022)

TEW for high QE

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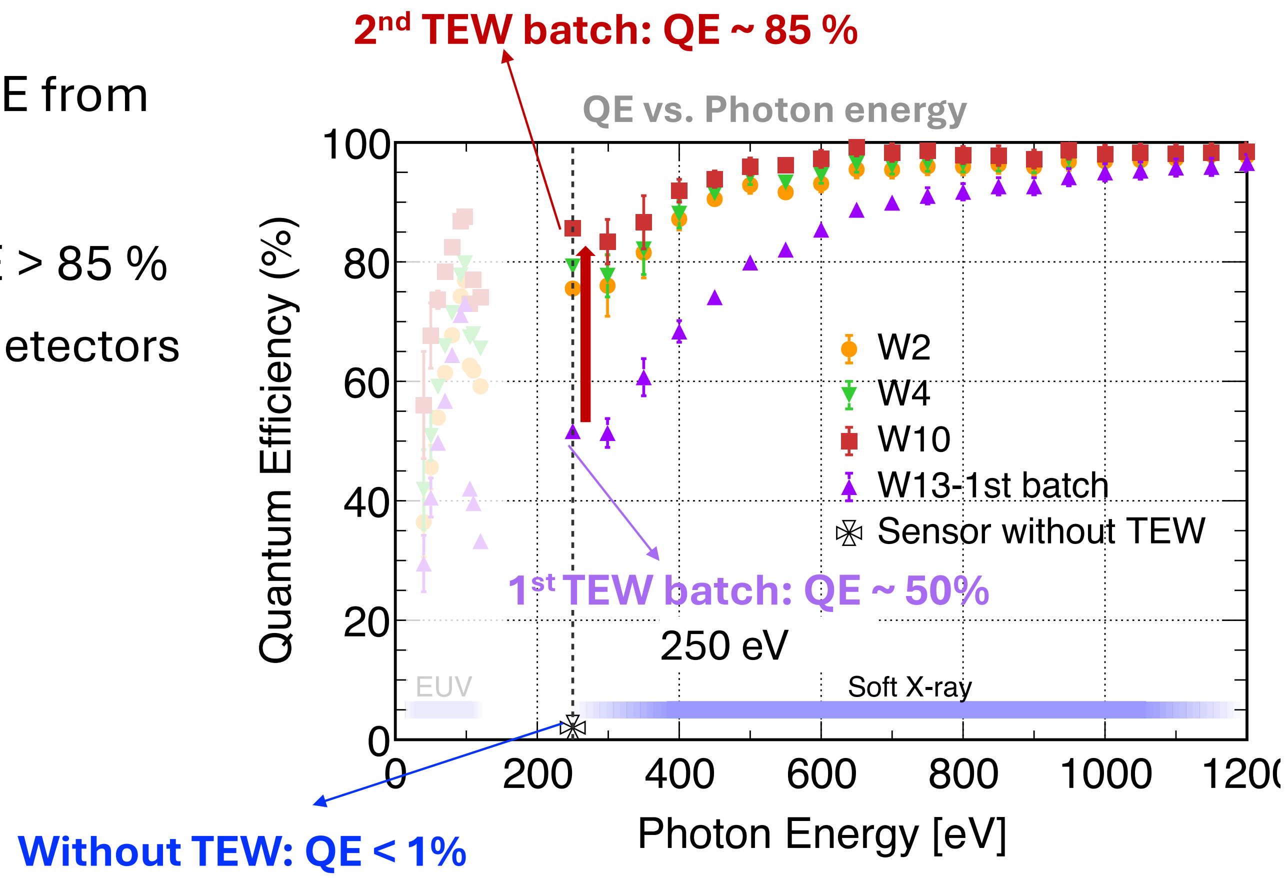
- 1st TEW R&D batch improves QE from < 1% to ~ 50 % at 250 eV

- 2nd TEW R&D batch achieve QE > 85 %

  - Comparable to the state-of-art detectors for soft X-ray detection



M. Carulla et al., *Sensors* **24**, 942 (2024)
M. Carulla et al., *JINST* **18**, C01073 (2023

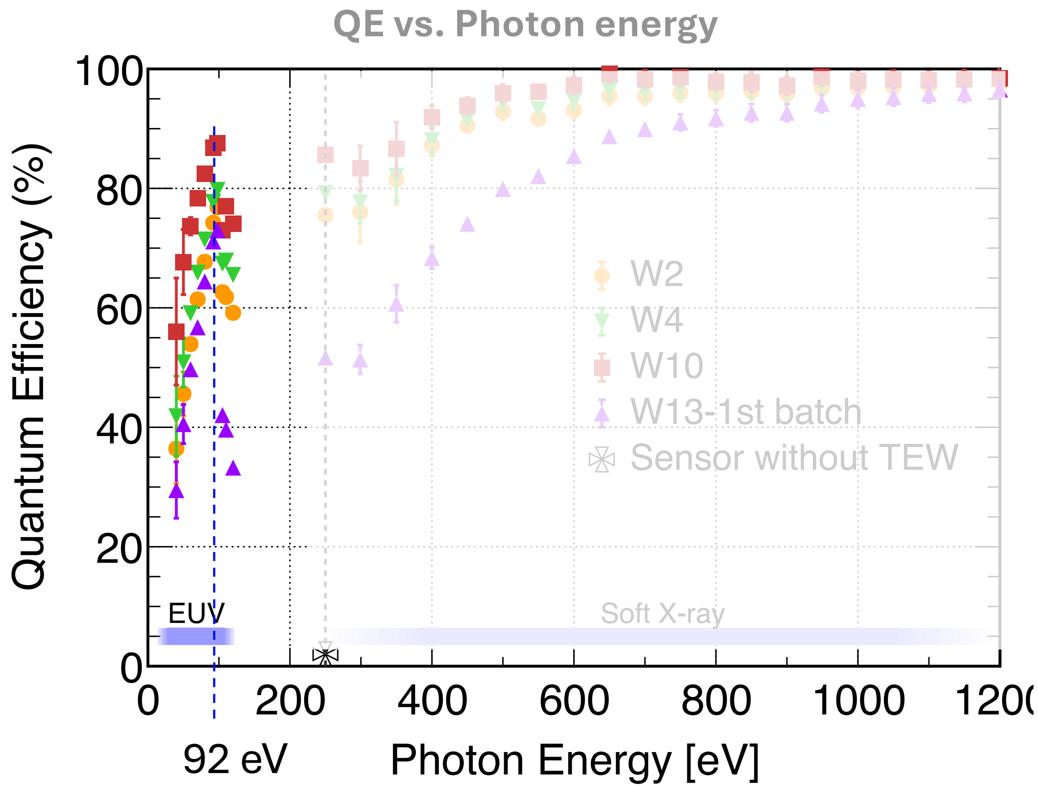
TEW for high QE

- 1st TEW R&D batch improves QE from < 1% to ~ 50 % at 250 eV
- 2nd TEW R&D batch achieve QE > 85 %

  - Comparable to the state-of-art detectors for soft X-ray detection
- QE: 90% at 92 eV
- High QE benefits for

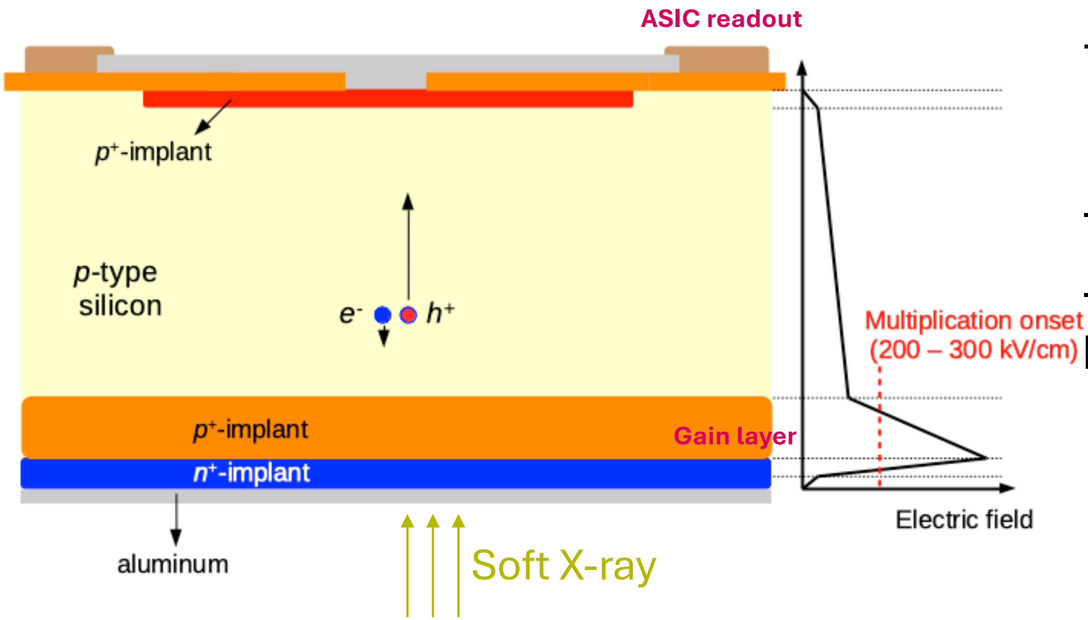
  - EUV photon detection

  - Electron detection down to 1-2 keV



LGADs for Soft X-ray Detection

- To improve SNR: inverse LGAD technology



- Uniform spatial response (100 % fill factor)

  → Charge interpolation → High spatial resolution

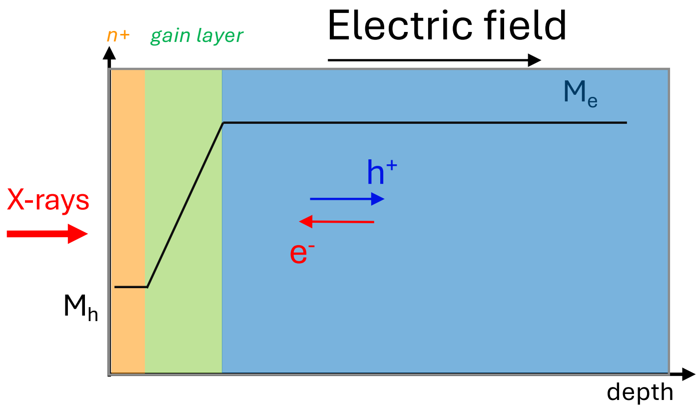
- Compatible with thin entrance window

- 2 iLGAD R&D batches integrated with TEW have been fabricated at FBK

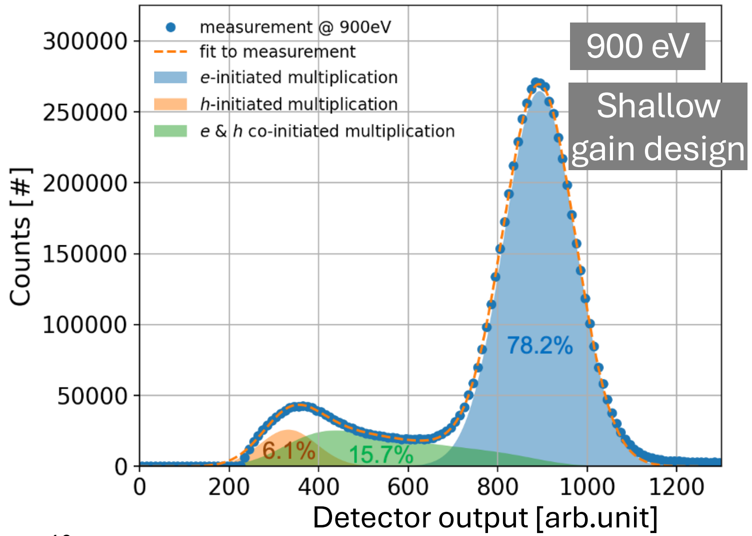
  → 1st batch: gain layer design optimization and TEW integration (this talk)

  → 2nd batch: SNR improvements down to the Carbon K-edge (280 eV) (under test)

Double-peak feature in iLGAD spectra



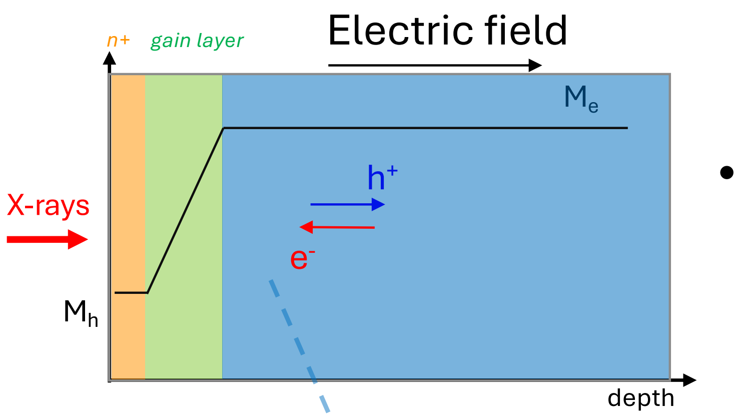
Spectrum measured with MOENCH chip



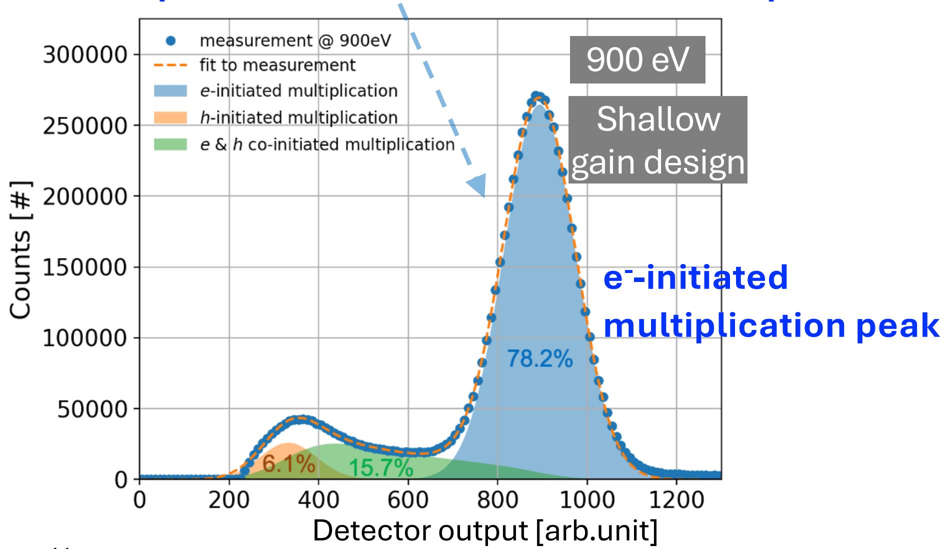
- Signals amplitude depend on photon absorption depth
  - Double-peak feature in iLGAD spectra
  - M_e (gain initiated by electron) > M_h (gain initiated by hole)

  → More multiplication from electrons is desired

Double-peak feature in iLGAD spectra



Spectrum measured with MOENCH chip



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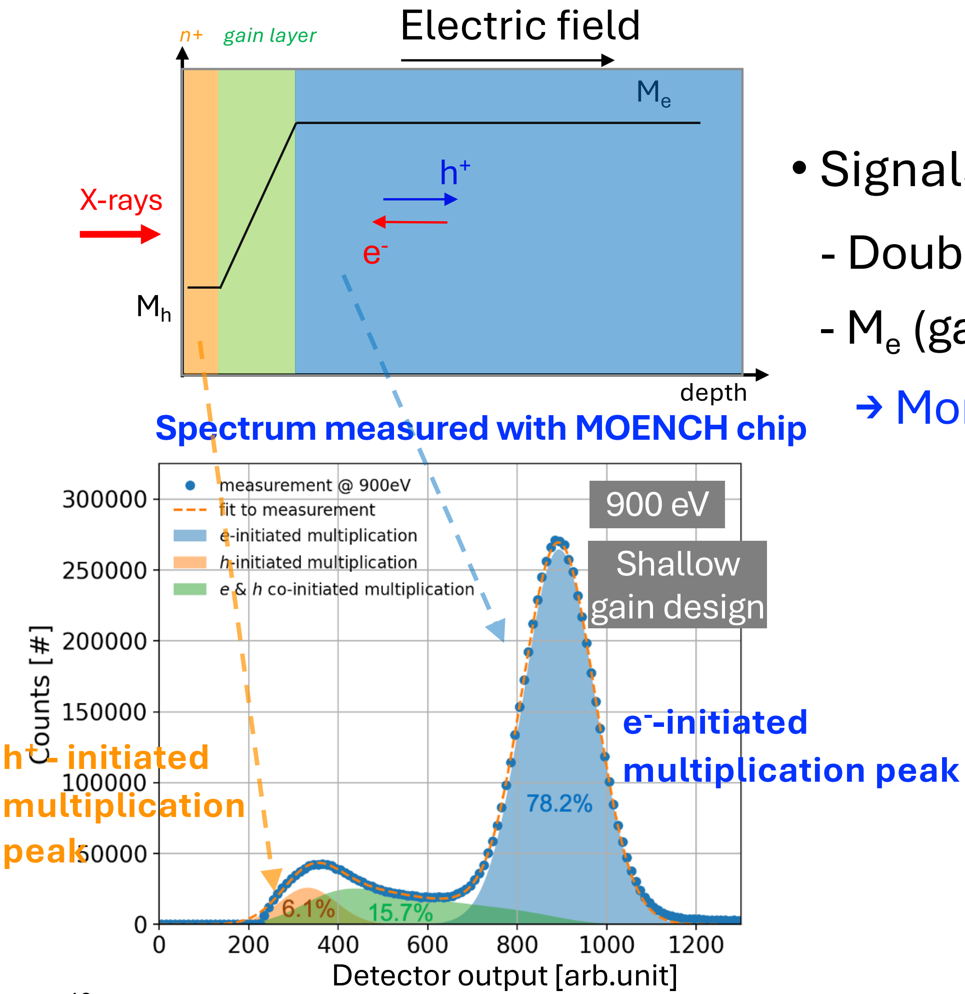

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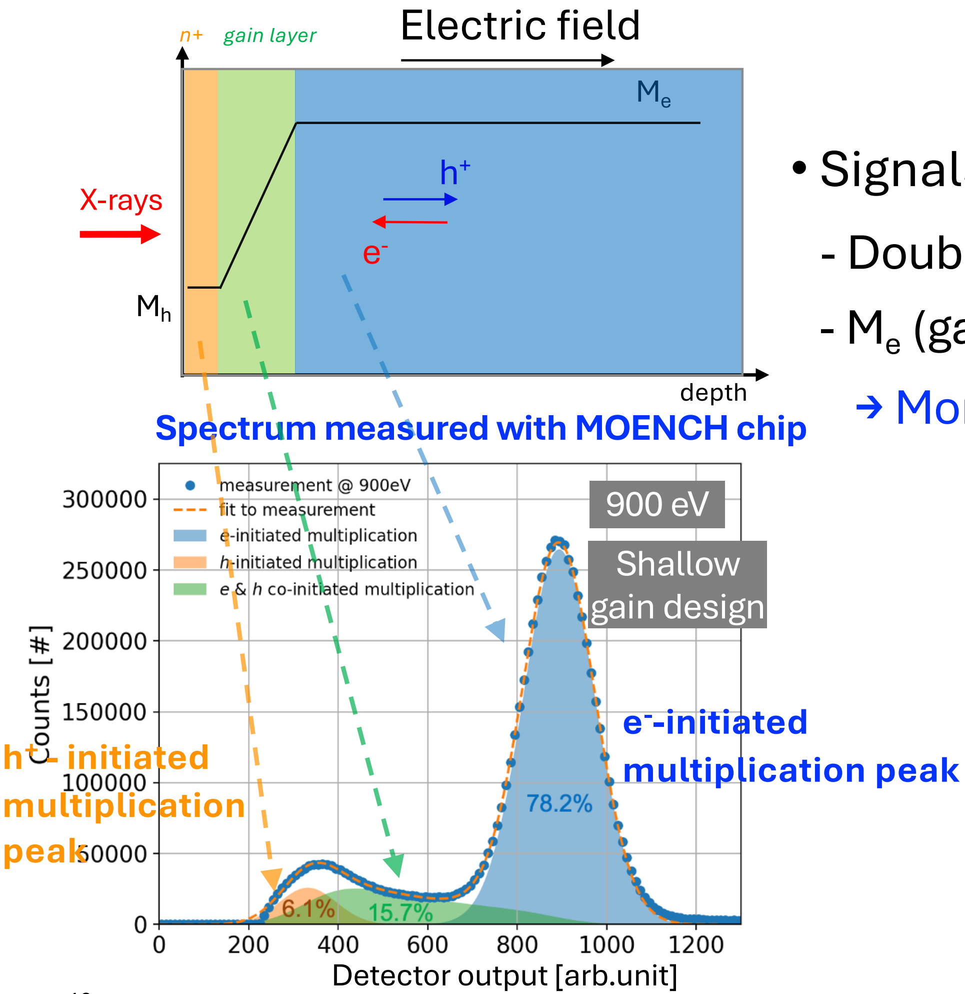

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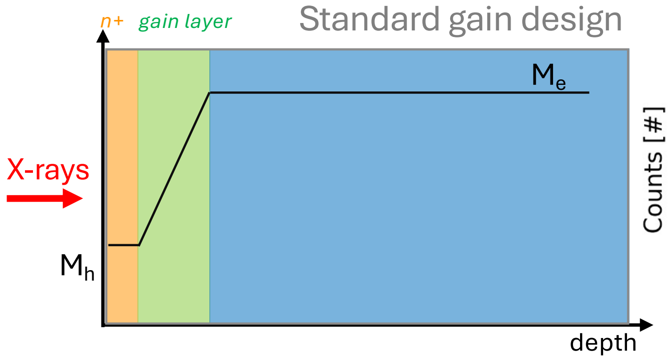
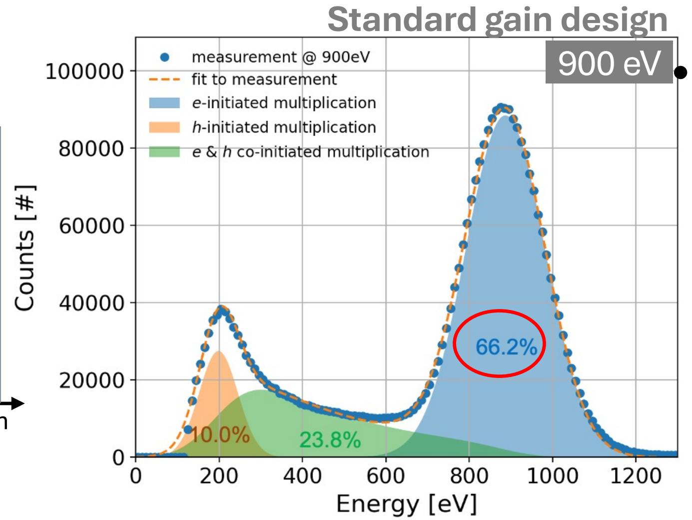
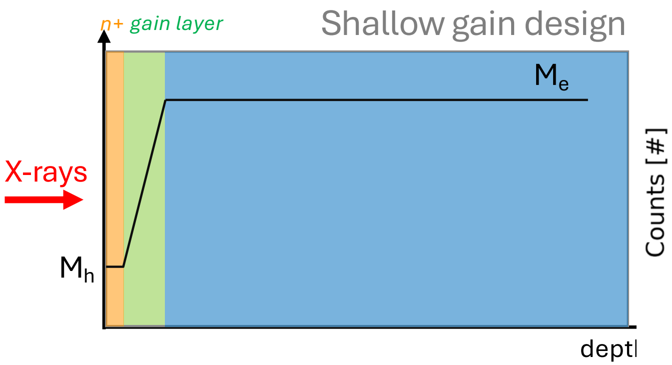
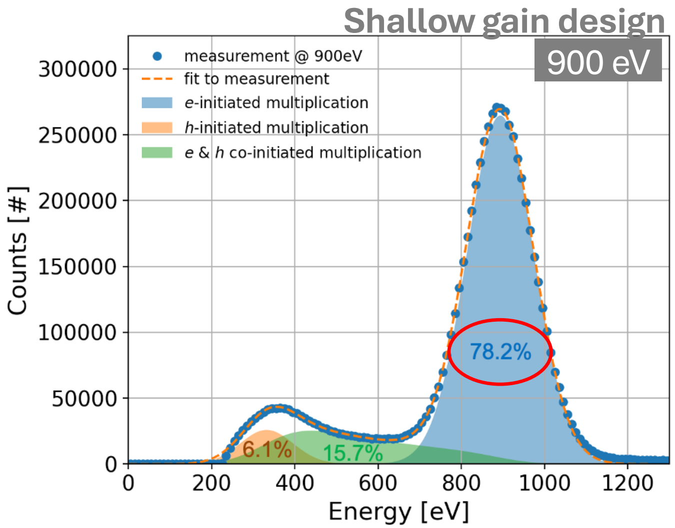
Gain layer optimization





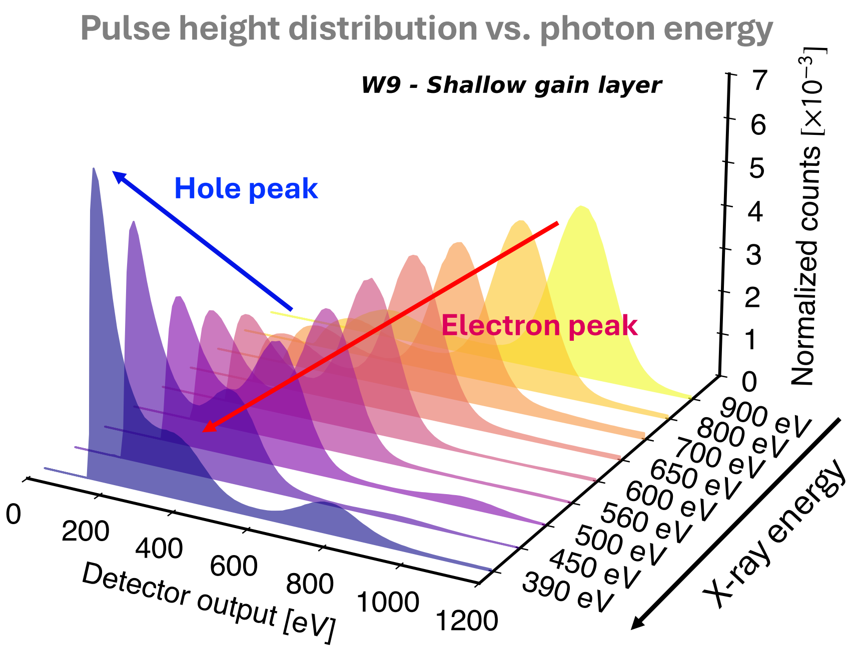
- Gain layer design optimization:
- Standard gain layer
- **Shallow gain layer**
  - → more photons abosorbed beyond gain layer
  - → higher probability of e$^-$-initiated multiplication
  - → selected for 2nd batch iLGAD

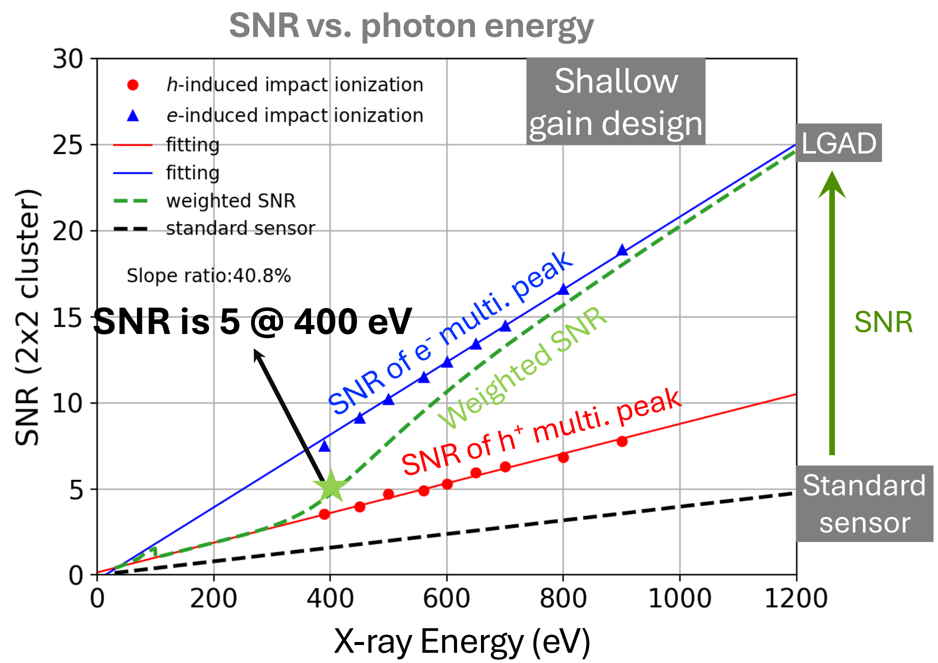




Single photon detection below 1 keV

- SNR > 5 for photon energy > 400 eV





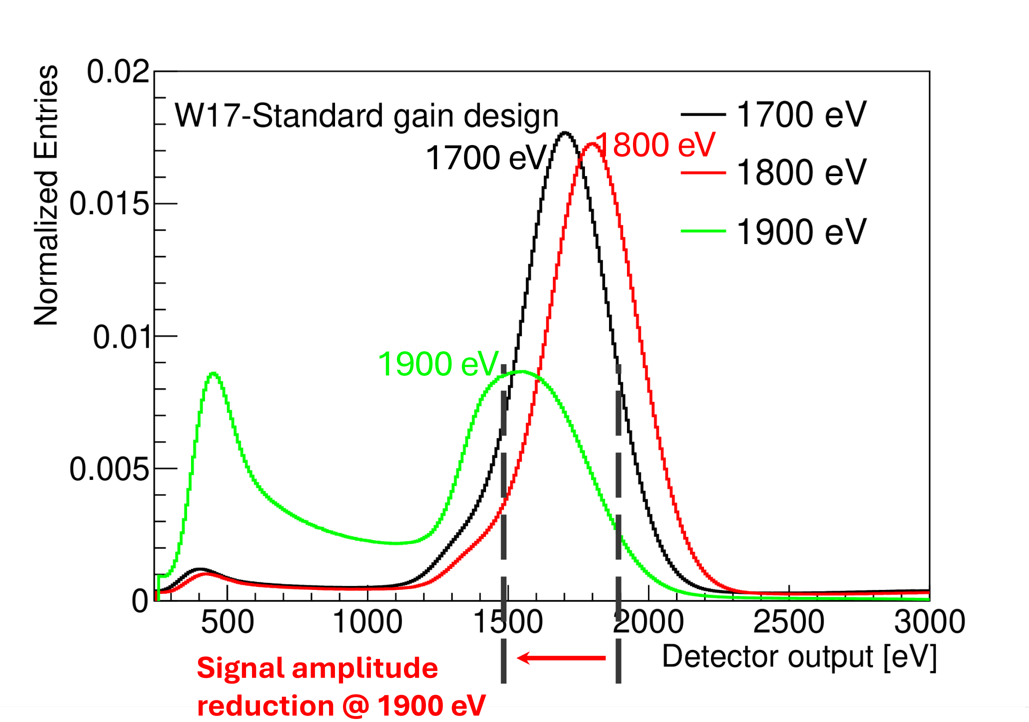
- 2nd batch iLGAD module will be tested in the coming months

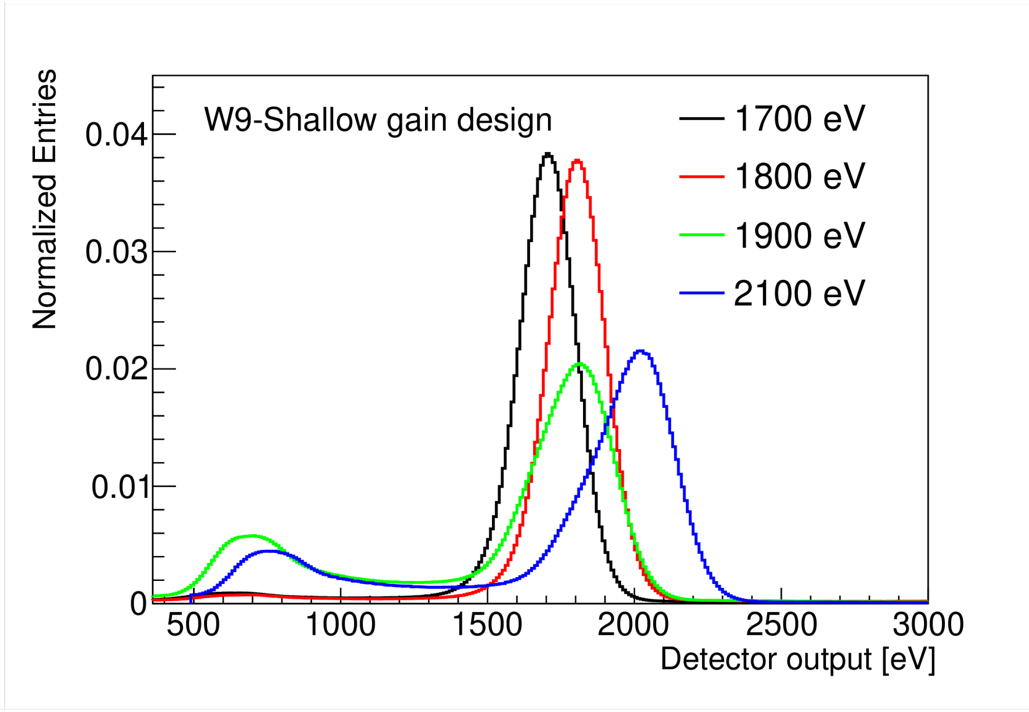
- Gain: **5 (1st batch) → 7.5-20 @ RT (2nd batch)**

- Potential for single-photon detection at 280 eV, benefiting “water window” experiments

Spectral Response of iLGAD above 1 keV

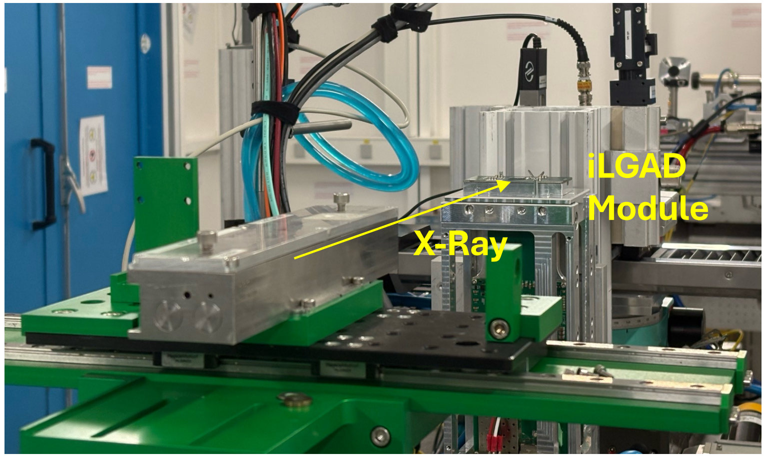
- Reduction in signal amplitude above the Si K-edge (1840 eV)
- The effect is much stronger in iLGADs with a standard gain layer and higher gain.
- Suspection: gain depends on photon absorption depth even beyond gain layer

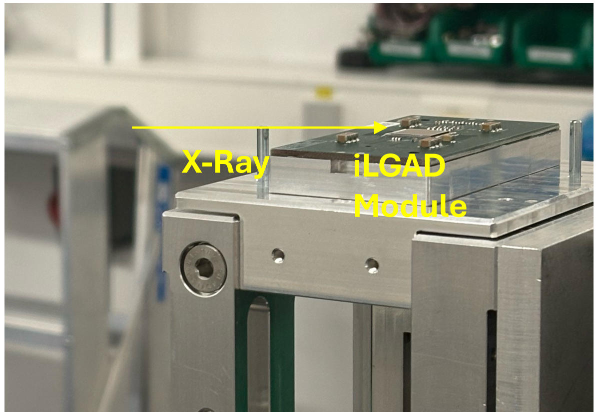


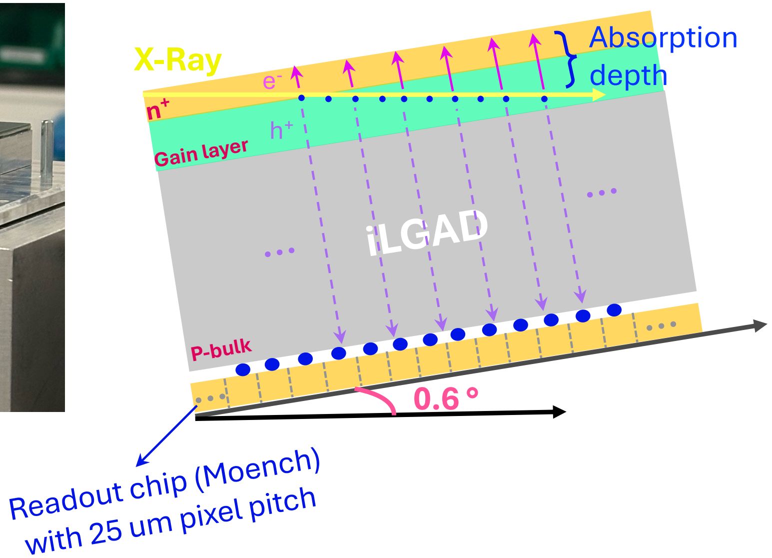


Investigations —— spectral response at different depth

- Grazing incidence beam test @ ESRF
  - Hard X-ray (17 keV) with focused beam (beam spot FWHM: ~ 4 um)
  - iLGAD module was tilted by ~ 0.6 °
    - → Shallow incidence angle leads to photon absorption mostly within the gain layer
    - → Random photon absorption at varying depth following Beer-Lamber law







Spectral response at different photon abosorption depths

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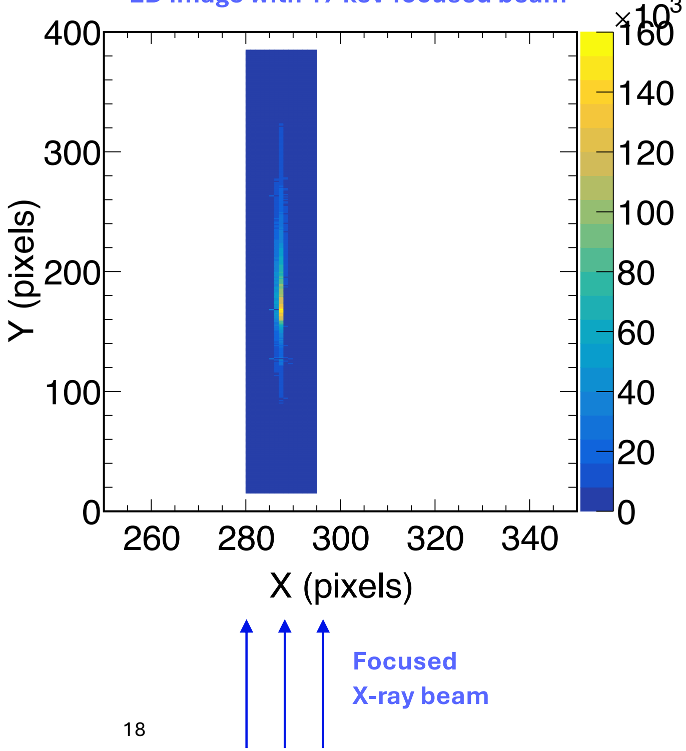
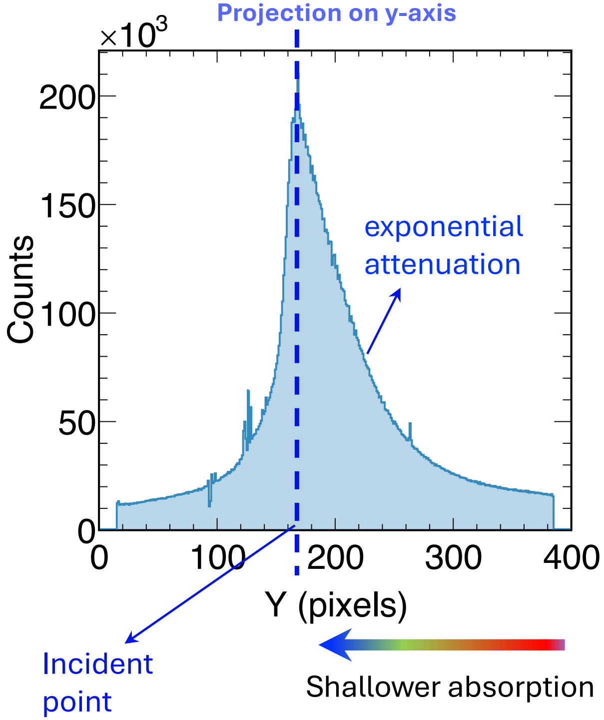
- Photon absorption depth-resolved spectra
  - Photons absorbed at different depths are mapped onto different pixels
  - Spectra were reconstructed in 5-pixel along the Y-axis

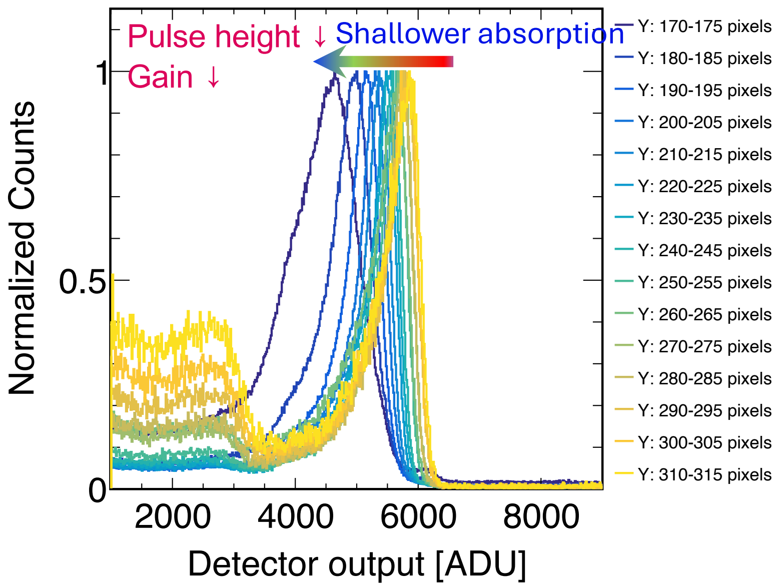
2D image with 17 keV focused beam



Projection on y-axis

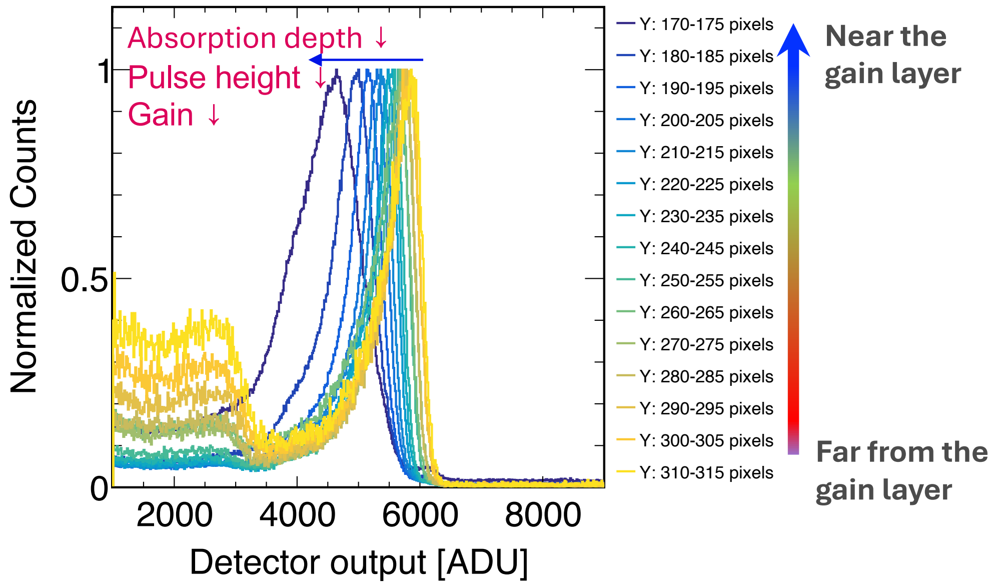


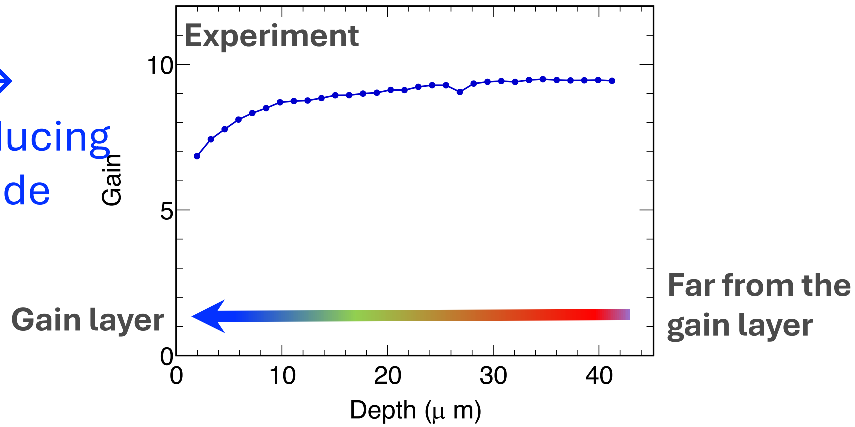
Spectrum at different ROI along y-axis (photon abosorption depth)

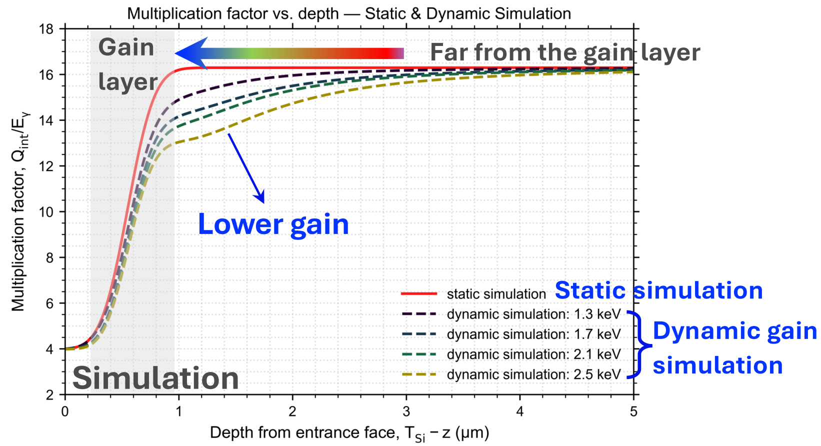


Gain vs. photon absorption depth

- Dynamic gain response: Near the gain layer < Far from the gain layer
- At Si K-edge, photon attenuation length drops to 1 um (comparable to gain layer depth)
  - Shorter distance and time to drift to the gain layer → smaller charge cloud → higher charge density → reducing electric field → reducing gain → lower signal amplitude







iLGAD with TEW Scientific Applications in Soft X-ray Regime

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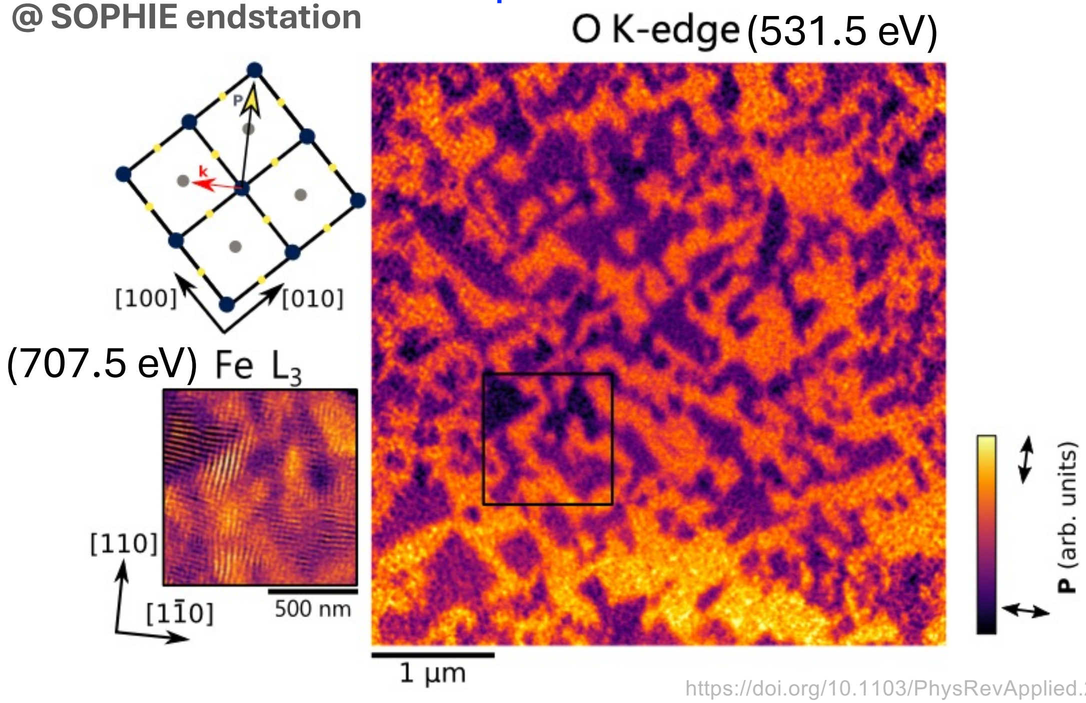
Ptychography with **iLGAD-Eiger**

(will be replaced by **Matterhorn readout chip**)

impossible to achieve this using single-photon detectors with standard sensor

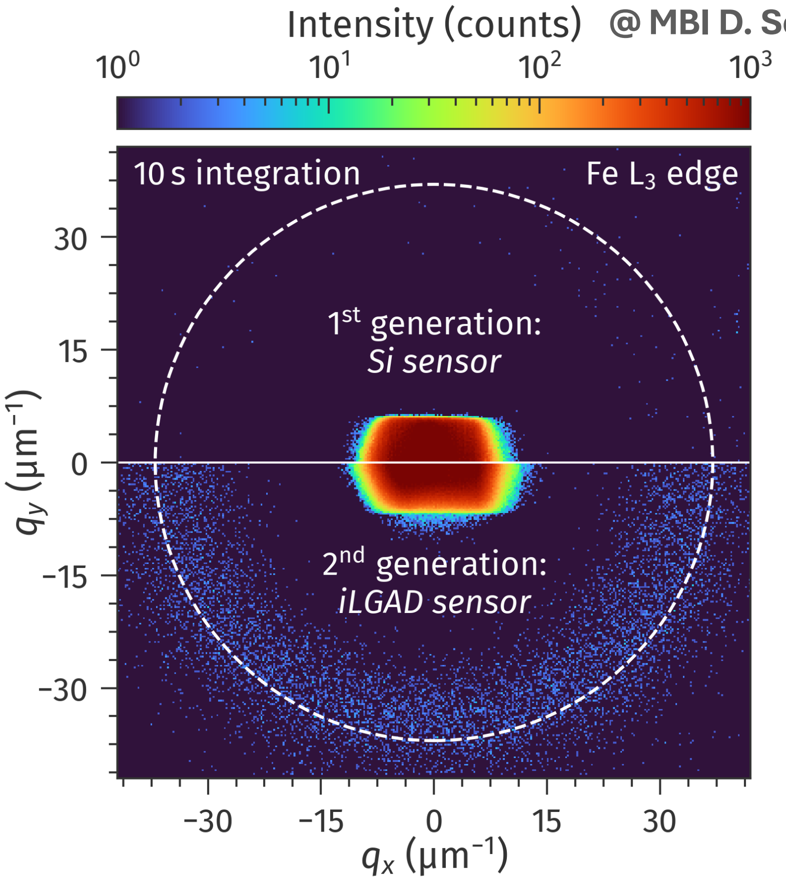
@ SOPHIE endstation



https://doi.org/10.1103/PhysRevApplied.23.L011002

mSAXS with **iLGAD/Standard sensor + MOENCH** using laser plasma source

@ MBI D. Schick



Summary

- QE > 50 % @ 250 eV (1st batch); QE > 85% @ 250 eV (2nd batch)
- SNR > 5 for single photon detection down to 400 eV with 1st batch iLGAD
- Signal amplitude reduction observed above Si K-edge (1.85 keV)

  - grazing incidence with a focused beam indirectly reproduces this phenomenon

  - gain transition region beyond the gain layer depends on photon absorption depth and energy

    → dynamic gain response: near the gain layer < far from the gain layer

Improvements on 2nd batch iLGAD

- Implement the TEW form 2nd R&D batch
- Increase gain to improve SNR > 5 at Carbon K-edge (280 eV)
- Will be tested at MAXIV in October

More sensor variants (nLGAD, MARTHA...) for soft X-rays are being explored

Acknowledgements

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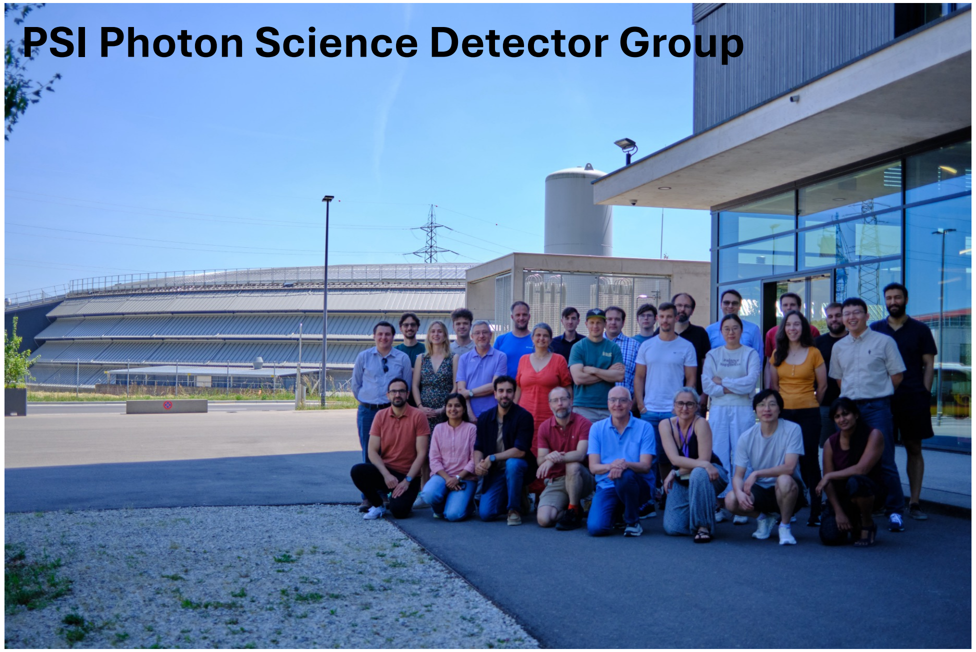
- Colleagues from FBK
- Beam line support from MAX IV, Soleil, ESRF

Fondazione Bruno Kessler

Ashish Bisht, Maurizio Boscardin, Matteo Centis Vignali, Francesco Ficorella, Omar Hammad Ali, Giovanni Paternoster, Sabina Ronchin



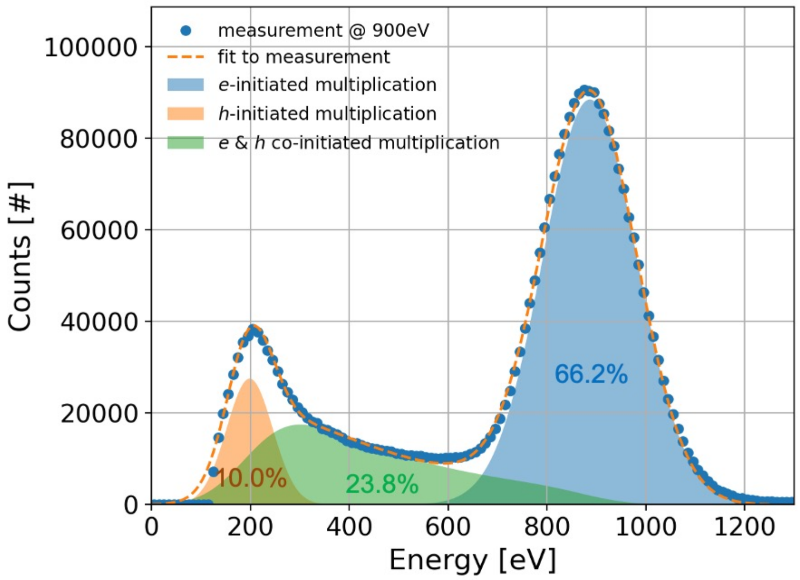
Michele Anastasi, Anna Bergamaschi, Martin Brückner, Maria Carulla, Roberto Dinapoli, Simon Ebner, Simone Emiliani, Khalil Ferjaoui, Erik Fröjdh, Viveka Gautam, Dominic Greiffenberg, Shqipe Hasanaj, Viktoria Hinger, Marius Hürst, Vadym Kedych, Thomas King, Shuqi Li, Carlos Lopez-Cuenca, Leonid Lunin, Alice Mazzoleni, Davide Mezza, Konstantinos Moustakas, Aldo Mozzanica, Martin Müller, Jonathan F. Mulvey, Christian Ruder, Bernd Schmitt, Saverio Silletta, Dhanya Thattil, Xiangyu Xie, Jiaguo Zhang

Fitting model for iLGAD spectrum

- Two Gaussian components: e^-/h^+-initiated multiplication peak
- Middle region modeled by:

$$f(x) = \frac{A}{2}\left[\mathrm{erf}\left(\frac{x-a}{\sqrt{2}\sigma}\right) - \mathrm{erf}\left(\frac{x-b}{\sqrt{2}\sigma}\right)\right] \cdot \exp\left(-\frac{x-b}{\tau}\right)$$

- a, b: the mean value of e^- and h^+-initiated multiplication peak
- σ: the width of error function
- τ: exponential decay constant
- A: amplitude



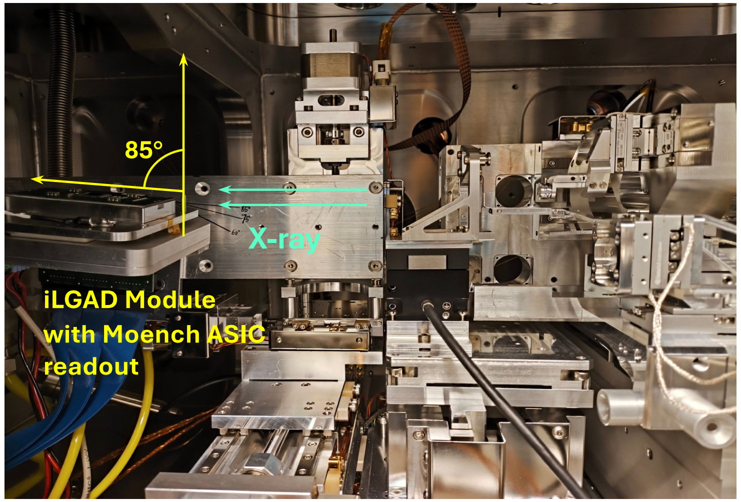
Investigation on signal amplitude reduction at Si K-edge

- Angular Dependence Characterization

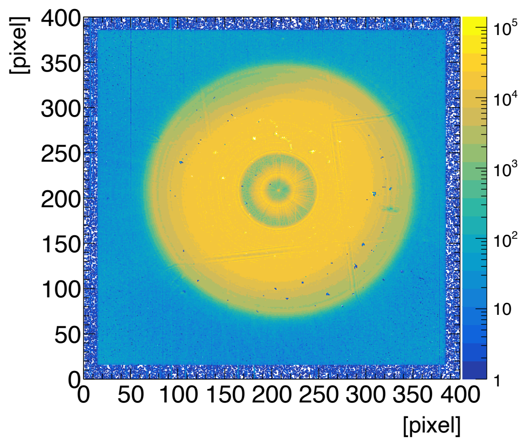
- Tilting the module mimics the sharp drop in absorption depth at Si K-edge (14 μm → 1μm)

Tilt angle: 0°, 45°, 60°, 75°, 85°

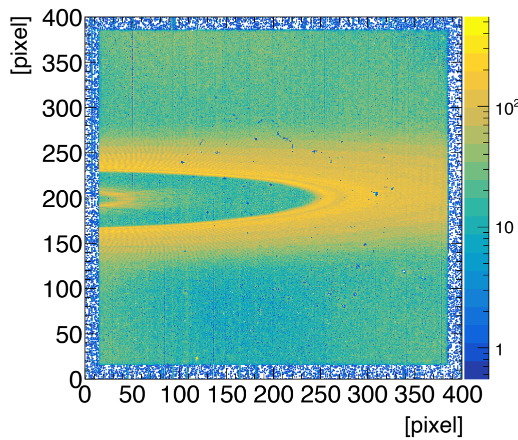
Effective attenuation length: λ, 0.71λ, 0.5λ, 0.25λ, 0.087λ



beam spot image @ 0°

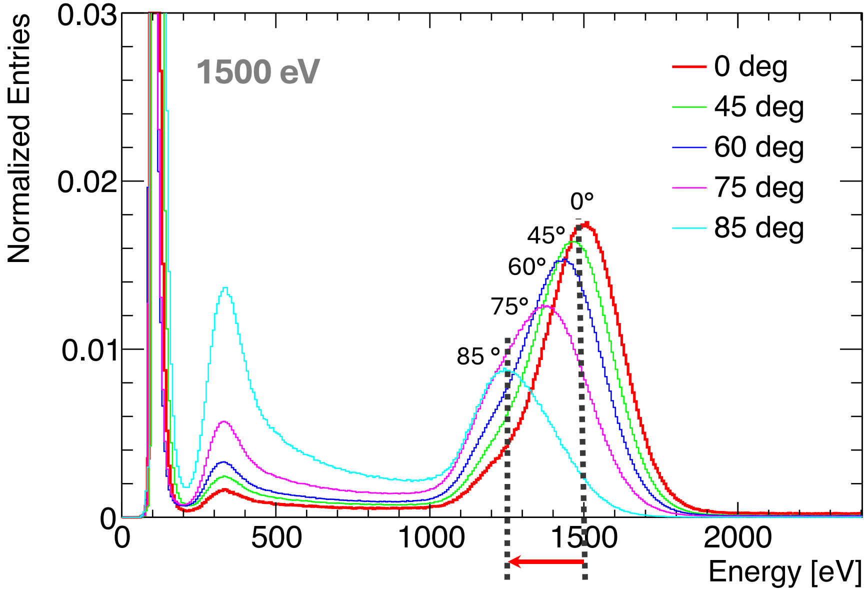


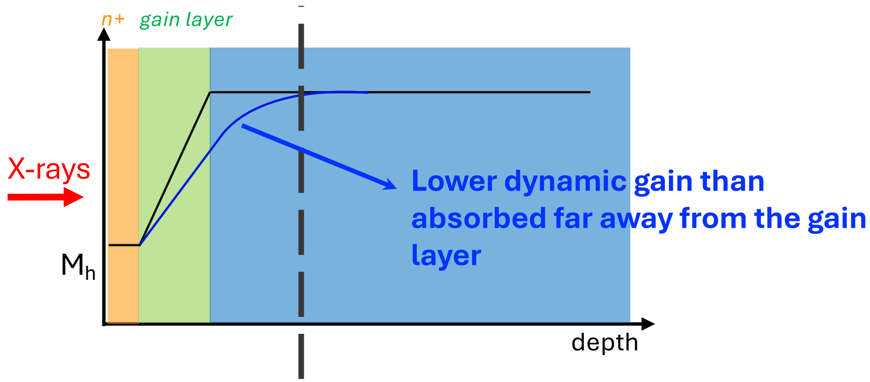
beam spot image @ 85°



Spectral response at different tilting angles

- Reproduced the reduction in signal amplitude observed near the Si K-edge
- Photons absorbed closer to the gain layer yield lower gain
  - The larger the tile angle, the more photons are absorbed near the gain layer





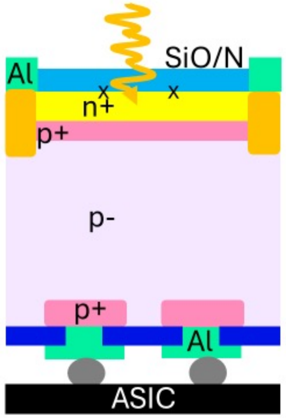
Ideal vs. Actual gain response to a single X-ray photon at different absorption depth

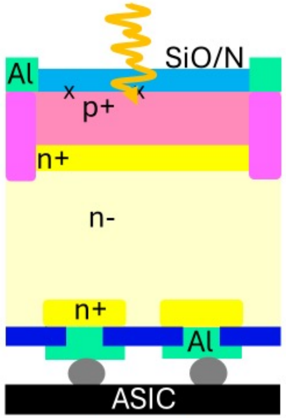
LGADs for photon science

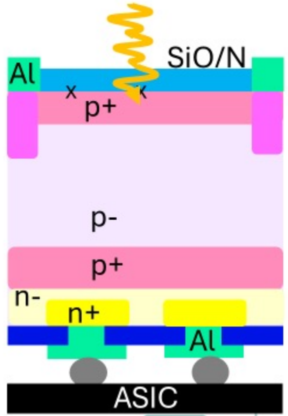
More sensor variants (nLGAD, MARTHA...) for soft X-rays are being explored

- Test different LGAD technologies
- iLGAD: improve yield
- nLGAD: higher gain at low energies
- MARTHA: constant gain

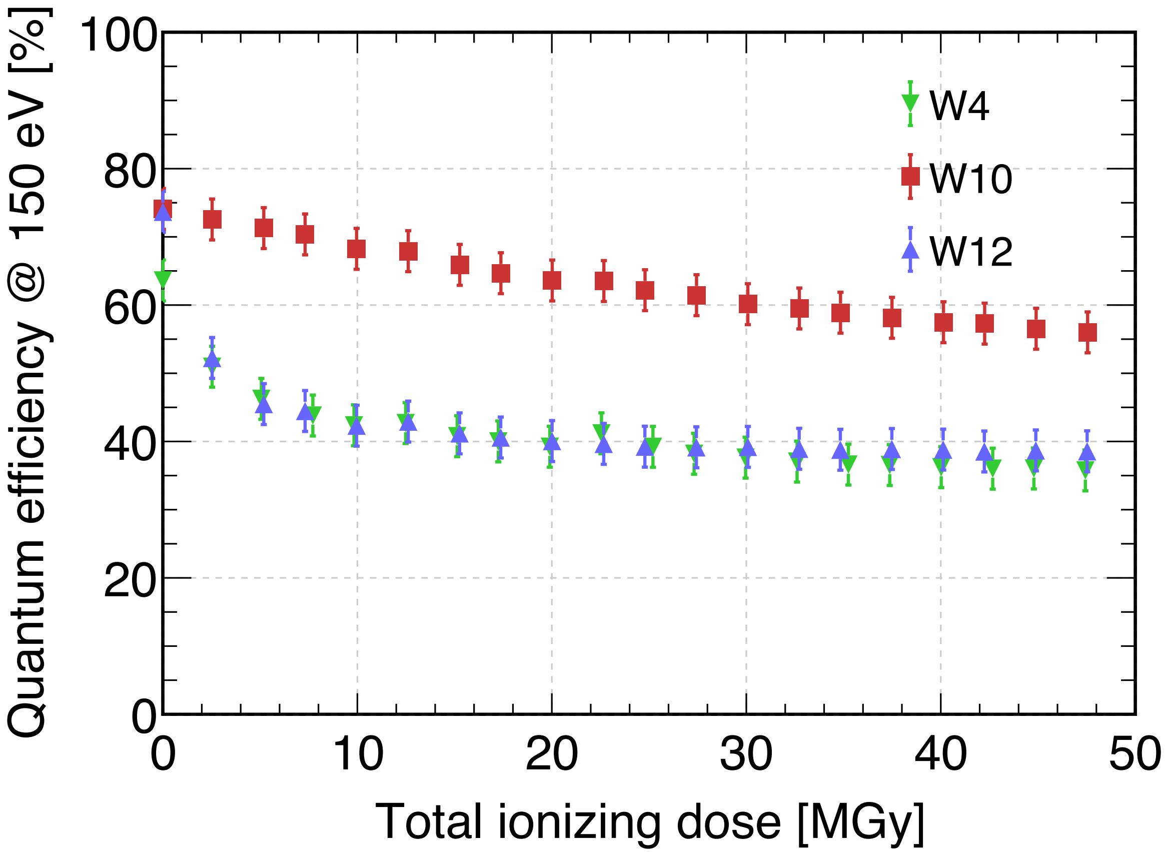
- Need for a better understanding
  - Improve simulations
  - Characterization with X-rays
- Collaborative effort required!

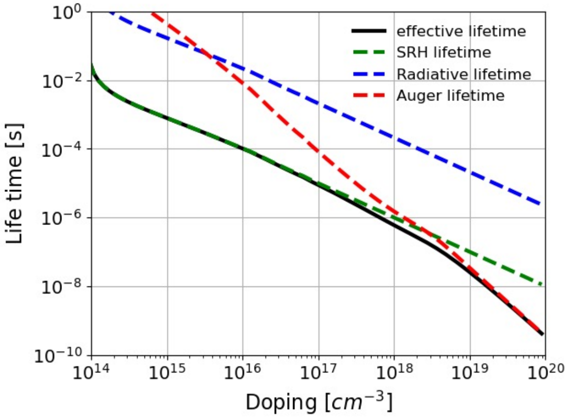


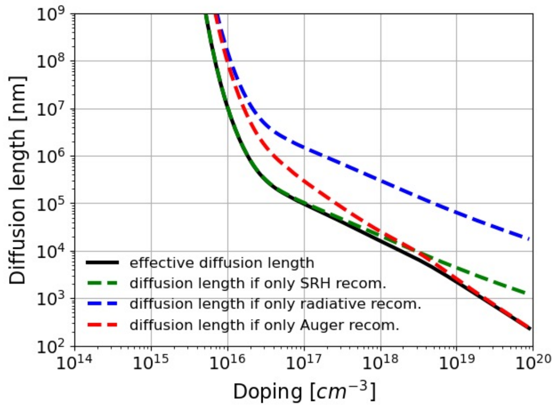


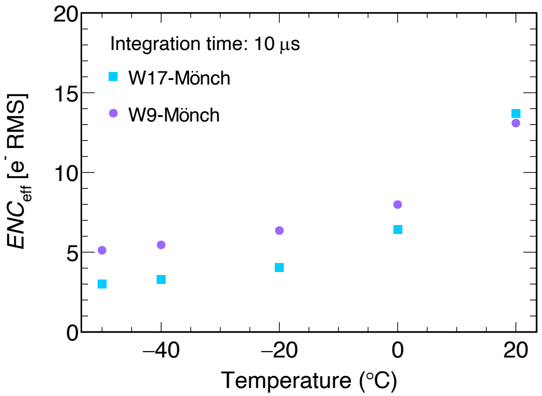


MAX PLANCK SEMICONDUCTOR LABORATORY


Quantum efficiency @ 150 eV [%]
100
80
60
40
20
0
0
10
20
30
40
50
Total ionizing dose [MGy]
W4
W10
W12


effective lifetime
SRH lifetime
Radiative lifetime
Auger lifetime
Life time [s]
Doping [cm^{-3}]


Diffusion length [nm]
effective diffusion length
diffusion length if only SRH recom.
diffusion length if only radiative recom.
diffusion length if only Auger recom.
Doping [cm^{-3}]


Integration time: 10 µs
W17-Mönch
W9-Mönch
ENC_{eff} [e⁻ RMS]
Temperature (°C)

Poisson’s equation

$$\nabla \mathrm{E} \propto \frac{\partial \rho}{\partial \mathrm{x}}$$