# Fast Detectors Viewed from a Different Angle: Scintillators and SiPMs for Photon-Counting CT

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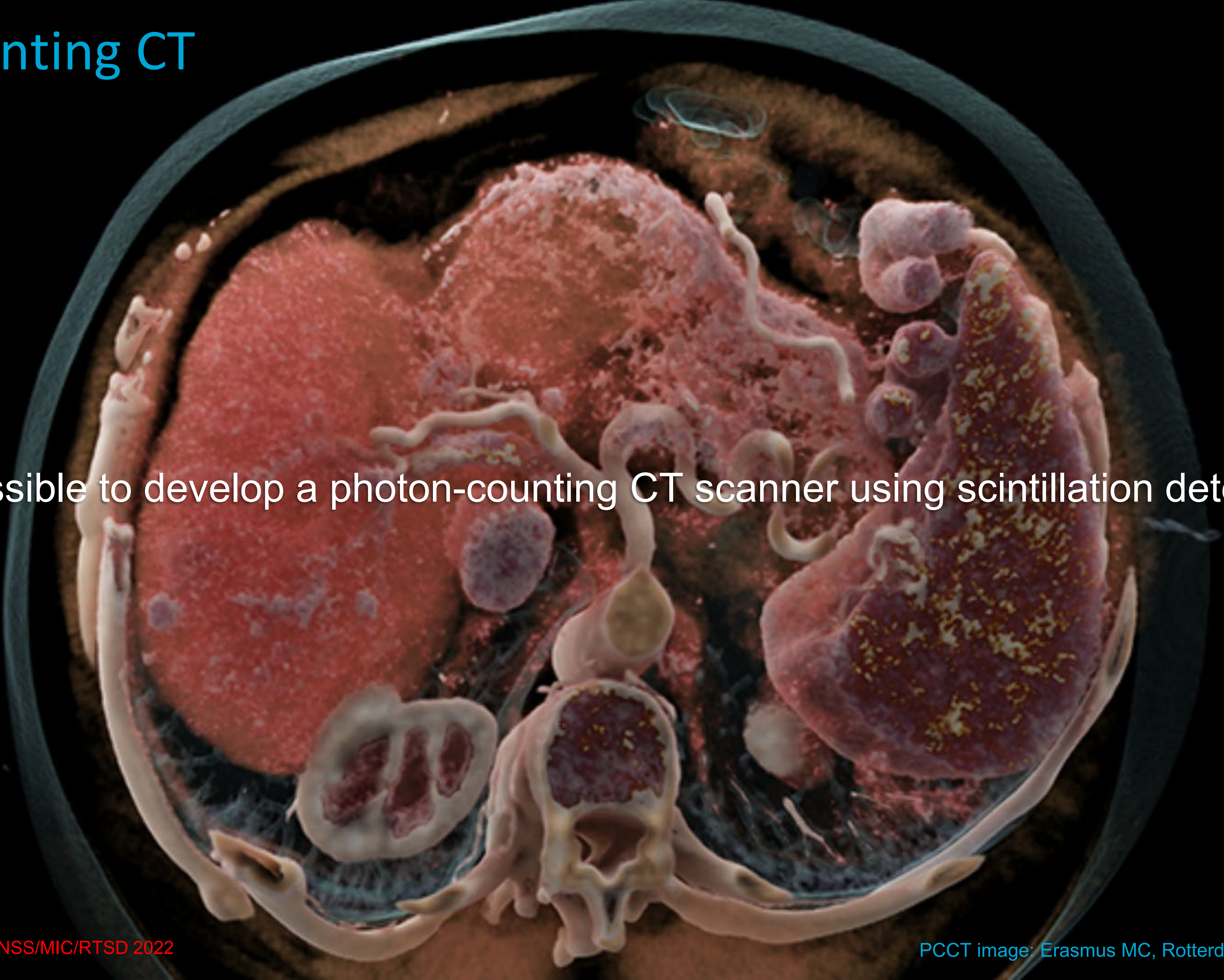
# Photon-counting CT



“It is ~~not~~ possible to develop a photon-counting CT scanner using scintillation detectors”

From: S.J. van der Sar et al, IEEE NSS/MIC/RTSD 2022

PCCT image: Erasmus MC, Rotterdam, The Netherlands

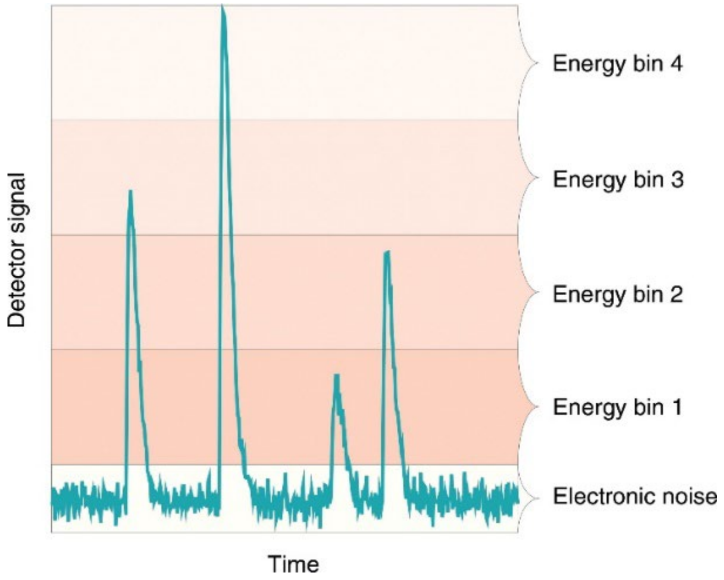
# X-ray photon counting

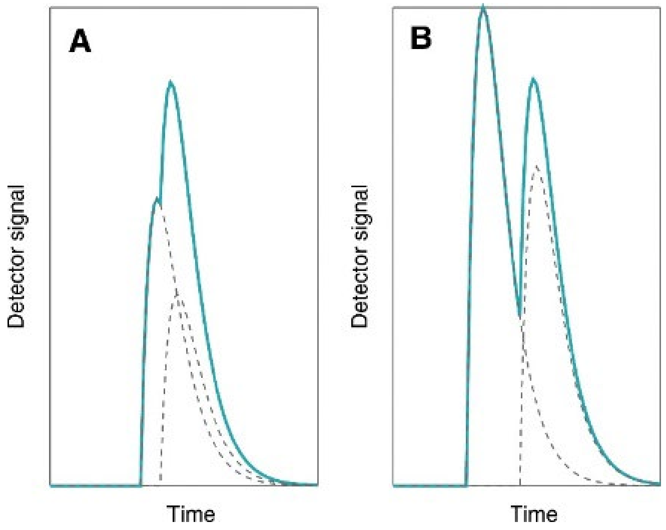
Photon-counting instead of energy-integrating detectors:

- Count individual photons & assign them to energy bins
- Current PCCT systems are based on room temperature semiconductor detectors (RTSD), such as CdTe, CZT or Si

Challenges:

- X-ray absorption efficiency (energies ≤ 150 keV)
- Pulse pile-up (fluence rate > 100 Mcps/mm$^2$ in clinical PCCT scanners)
- Cost-effective production; stable and reliable detector performance




Images: Willemink, M.J. et al., "Photon-counting CT: Technical …", Radiology 289(2), 293-312 (2018)

# Photon-counting detectors: state of the art

| Requirements (medical: [25, 150] keV) | RTSDs (CdTe/CZT) |
|---|---|
| Count rates > 100 Mcps/mm$^2$ | Short pulses (10s of ns) & small pixels (≤500 µm) |
| Sufficient energy resolution | ~8-20% @ 60 keV |
| X-ray detection efficiency | $\rho = 5.8$ g cm$^{-3}$ & $Z_{eff} \approx 50$ (1.5 – 3.0 mm) |
| Room temperature | Yes |

- Stable and reliable operation:
  - High purity materials
  - Low defect concentration
  - Optimized anode contacts

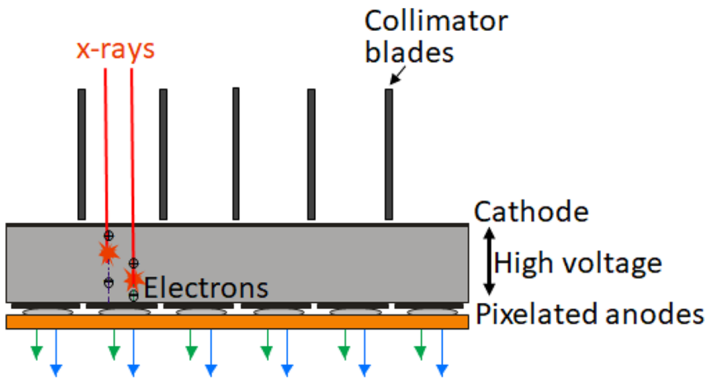



Image from: Flohr, T. *et al. Chin J Acad Radiol* **3,** 19–34 (2020)

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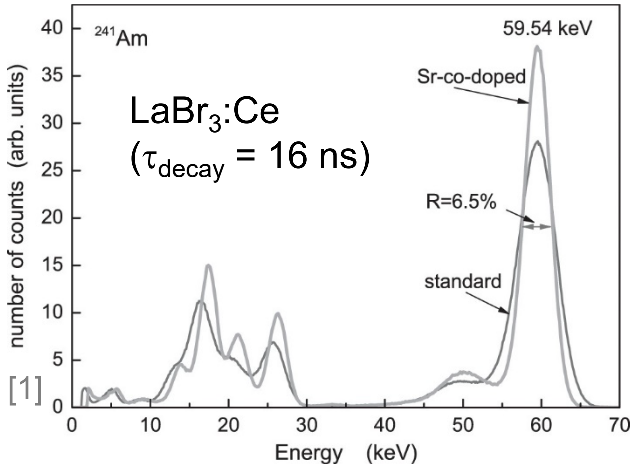
# Why scintillation detectors are a rational choice for PCCT

- Inorganic scintillators
  - Widely used in X-ray and nuclear imaging systems
  - High mass density and atomic number
  - Fast response & high energy resolution available
  - Sub-mm pixels are possible
- Silicon photomultiplier (SiPM)
  - SiPMs are state-of-the-art in PET
  - High internal gain (> $10^5$)
  - Fast response ($\tau_{recharge}$ < 10 ns is possible)
  - SiPMs can be miniaturized to sub-mm level

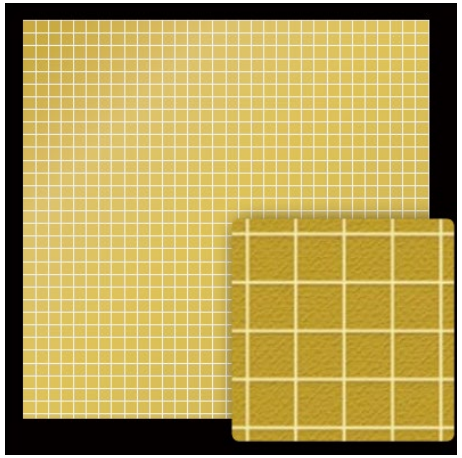

Images: Philips.com

[1]




$LaBr_3$:Ce energy spectrum @ 60 keV

[2]



0.25 mm scintillator array

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[1] Alekhin et al, "Improvement of γ-ray energy resolution of $LaBr_3:Ce^{3+}$…:, Appl. Phys. Lett. 102, 161915 (2013)
[2] Canon, "Aquilion Precision CT", https://global.medical.canon/products/computed-tomography/aq_precision

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# Finely pixelated scintillation detectors

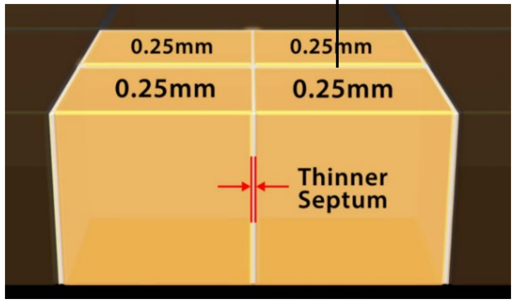
Example of a commercial system with a finely pixelated detector:

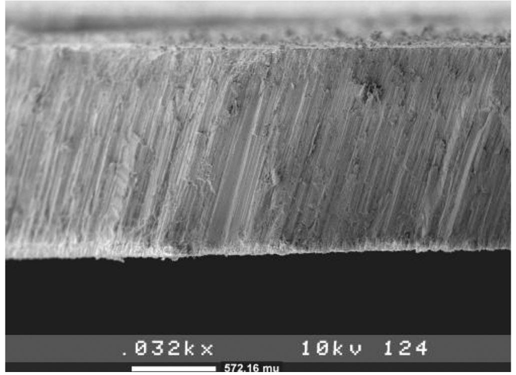
- Canon's Aquilion Precision (energy-integrating) CT scanner
- 50% finer scintillator pixel, reflective septa, and collimator blades
- Dose-efficiency of conventional systems therefore maintained

- More examples of finely pixelated detectors in research projects:
  - 430 × 430 μm$^2$ pixels with a 50 μm thick reflector [2]
  - 220 × 220 μm$^2$ pixels with a 63 μm thick reflector [3]
  - 312.5 × 312.5 μm$^2$ pixels with a 38 μm thick reflector [4]
  - 250 x 250 μm$^2$ pixels with a 50 μm thick reflector [5]
  - Laser-induced optical barriers [6]
  - Columnar microstructure [7]

Measured at the isocenter

[1]



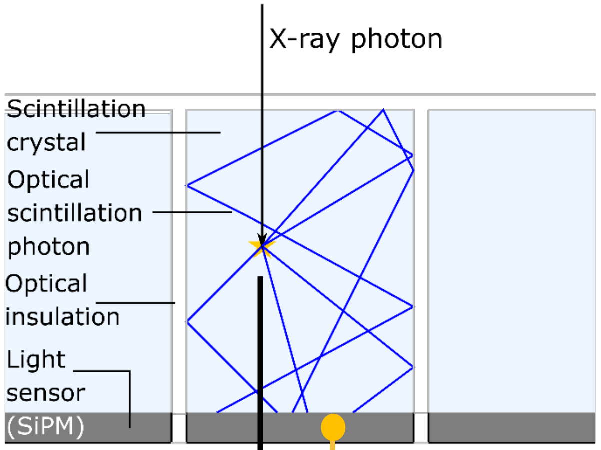




[1] Canon, "Aquilion Precision CT", https://global.medical.canon/products/computed-tomography/aq_precision. (24 Jan 2022)
[2] Godinez, F. et al., "Development of an ultra …, IEEE TRPMS 2:7-16 (2017). doi: 10.1109/TRPMS.2017.2765486
[3] Cherry, S.R. et al., "High resolution PET with 250 …, (2012), https://www.osti.gov/servlets/purl/1032741 (8 June 2022)
[4] Imai, Y. et al., "Development and performance …, Medical Physics 36:1120-1127 (2009). doi: 10.1118/1.3086117
[5] Shimadzoe, K. et al, "Performance of custom fine-pitch SiPM-scintillator based photon counting detectors," IEEE NSS-MIC 2024
[6] Bläckberg, L. et al "Exploring light …", Phys Med Biol 64: 095020 (2019). doi: 10.1088/1361-6560/ab1213
[7] Bhandari, H.B. et al, "Large-Area Crystalline …", IEEE TNS 60(1), 3-8 (2013). doi: 10.1109/TNS.2012.2213612

# SiPM-based scintillation detector array (analog case)

Side view [1]

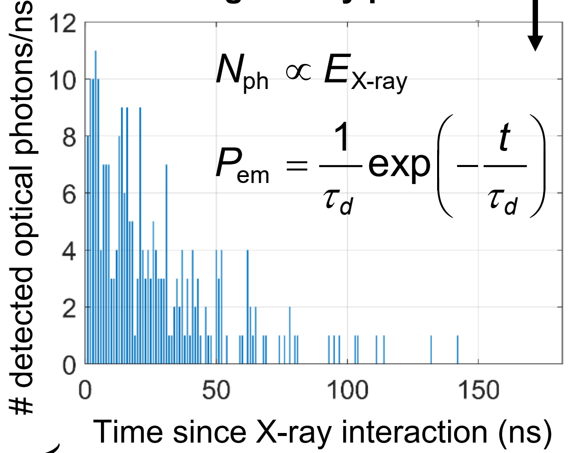
Typically tens of photons per keV of energy deposited




Pulse width mainly determined by two parameters:

- Scintillator decay time $\tau_d$ (e.g. 16 ns for $LaBr_3$:Ce)
- SiPM recharge time $\tau_r$ (< 10 ns is possible)

**Scintillator response to single X-ray photon**

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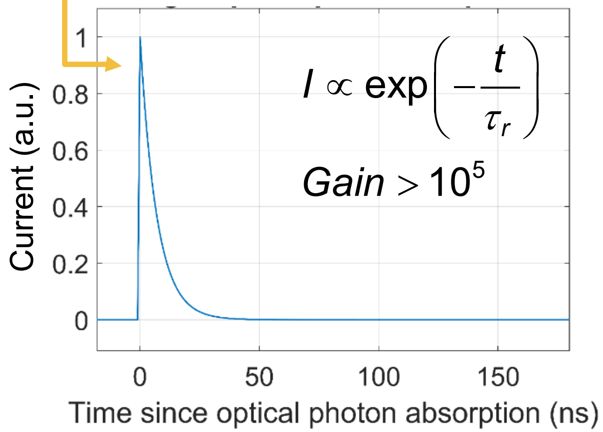
**SiPM response to single optical photon**

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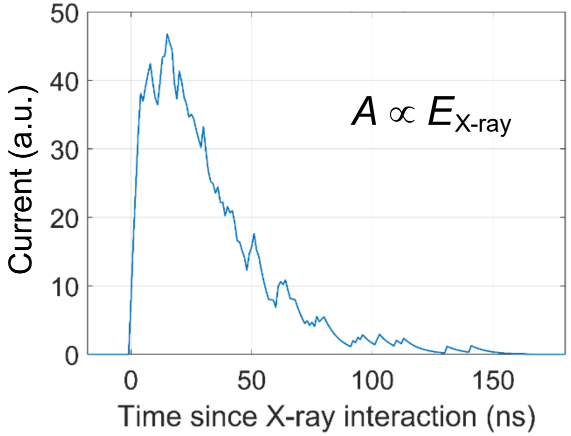
**Detector response to single X-ray photon**

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[1] Van der Sar, S.J. et al, "Silicon photomultiplier-based scintillation detectors for photon-counting CT, a feasibility study", Medical Physics 48(10), 6324-6338 (2021)


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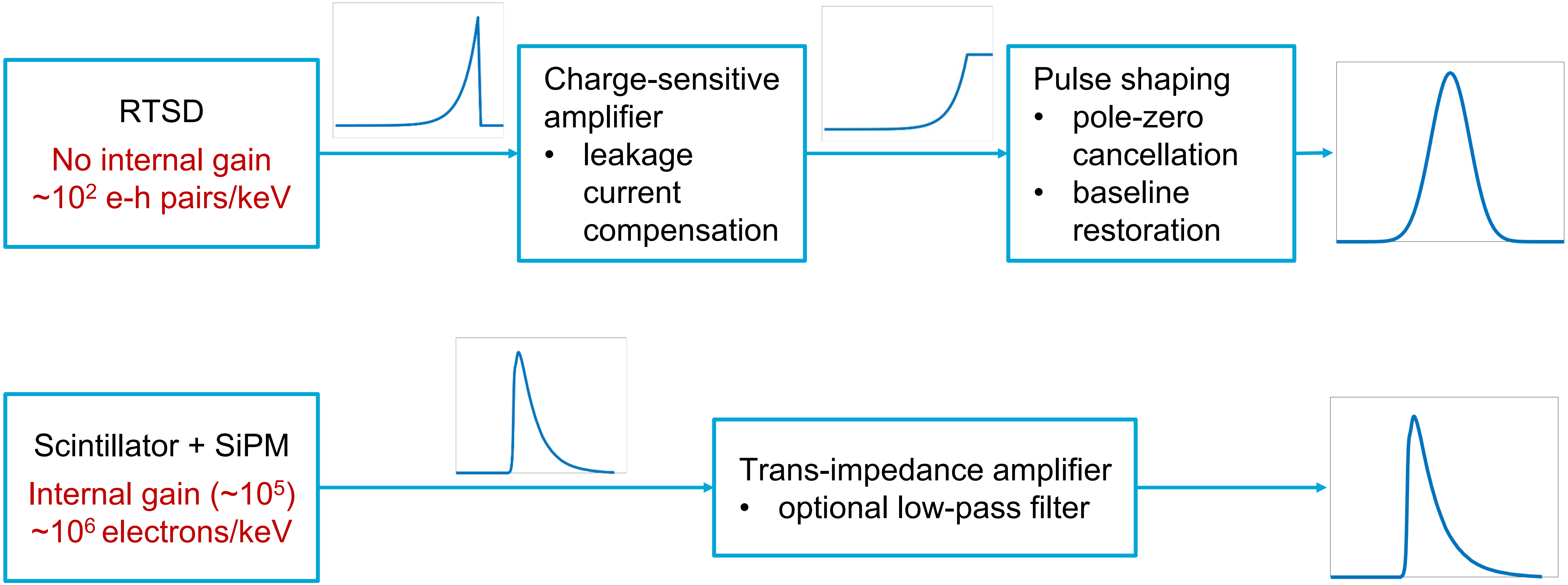
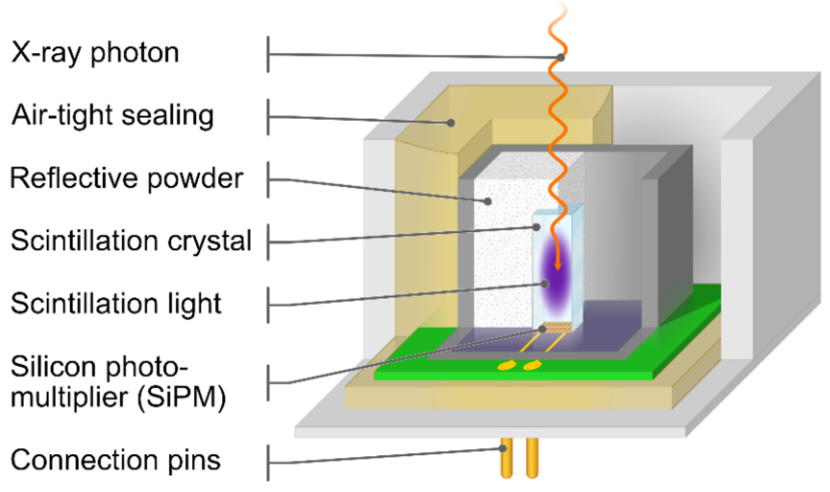
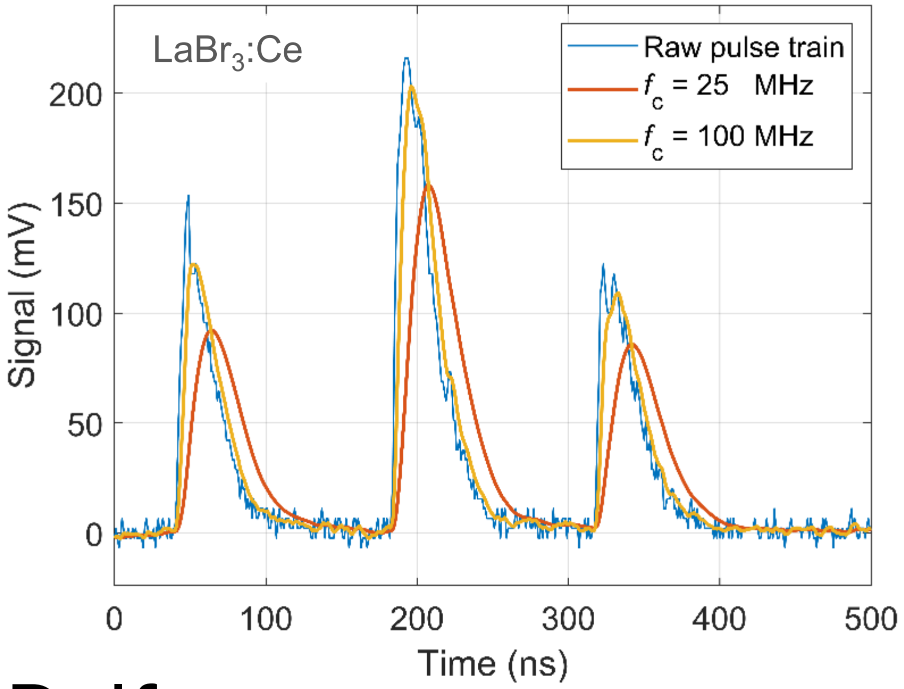
# RTSD vs SiPM-based detection chains

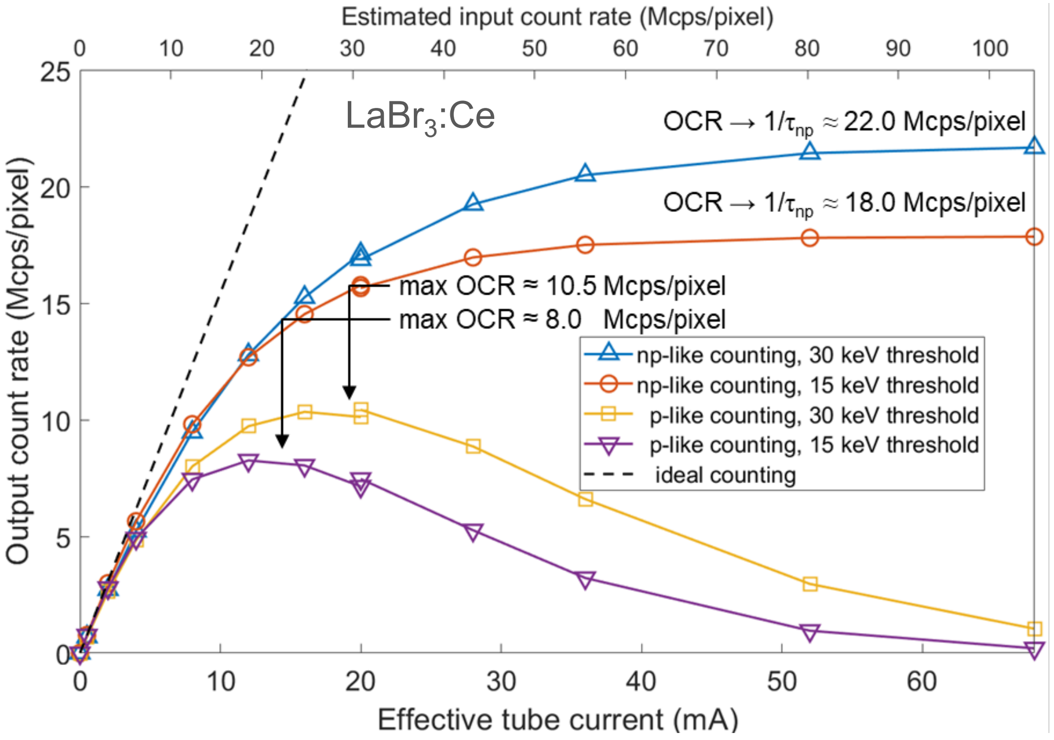


# Single-pixel experiments

- $0.9 \times 0.9 \times 3.5$ mm$^3$ $LaBr_3$:Ce ($\rho$ = 5.1 g/cm$^3$, $\tau_{decay}$ = 16 ns)
- Ultrafast SiPM prototypes: 15 μm SPADS, PDE 20-30%, $\tau_{recharge}$ = 7 ns
- Trans-impedance amplifier → digital scope
- 2$^{nd}$ order low-pass filter with various cut-off frequencies
- X-ray tube (120 kVp, tungsten target, 3.0 mm Be, 7.5 mm Al)
- **~20 Mcps/pixel x ~10 pixels/mm$^2$ = ~200 Mcps/mm$^2$**



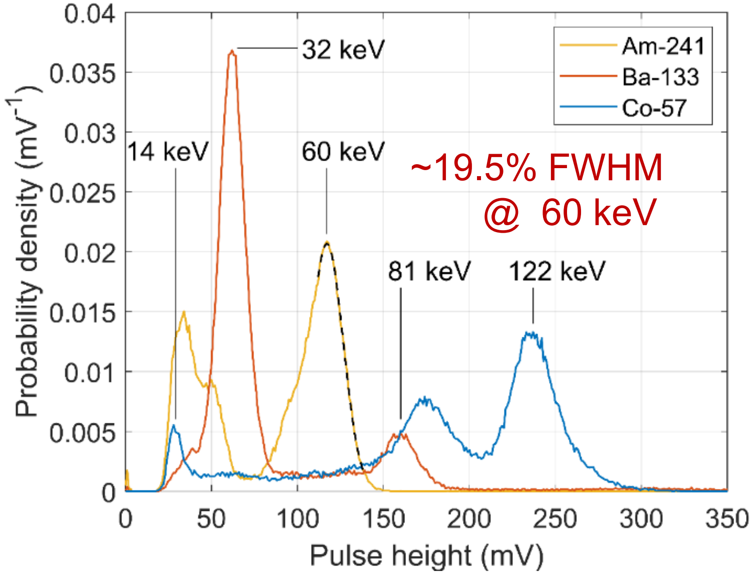



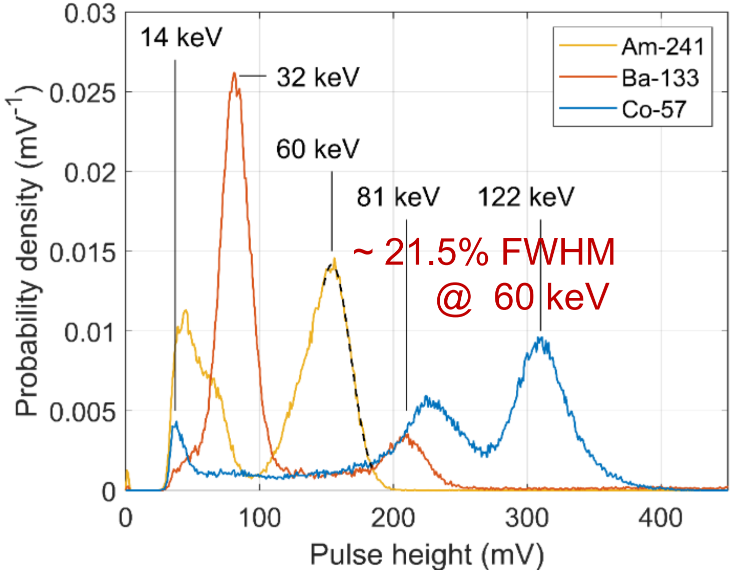

* Van der Sar et al, "SiPM-based scintillation detectors: a rational detector concept for photon-counting CT," IEEE NSS/MIC/RTSD 2022, Nov 5-12, Milano, Italy

# $LaBr_3$:Ce spectral performance

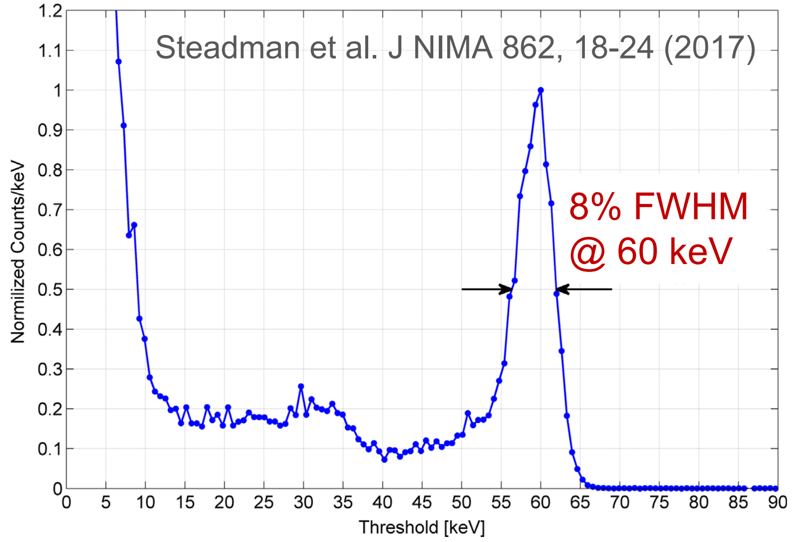
LaBr$_3$:Ce, $f_c$ = 25 MHz

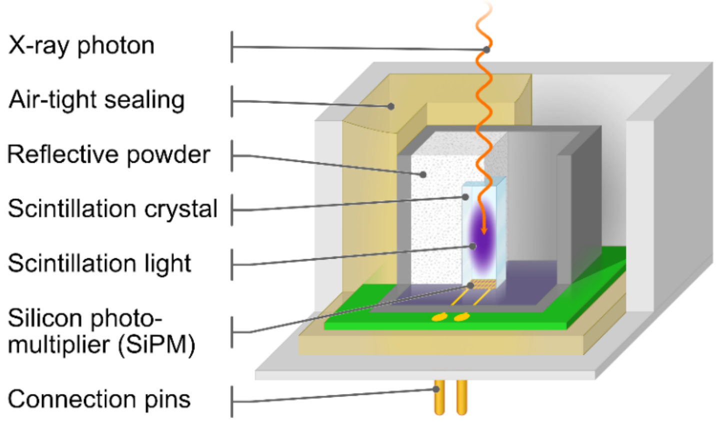



LaBr$_3$:Ce, $f_c$ = 100 MHz




0.5 x 0.5 x 2.0 mm$^3$ CZT pixel




Upgrade of SiPM: PDE x 2 ⇒ Energy resolution x 1/√2

Literature (Alekhin et al Appl. Phys. Lett. 102, 161915, 2013):

- 9.4% FWHM @ 60 keV for $LaBr_3$:Ce ($\tau_{decay}$ = 16 ns)
- 6.5% FWHM @ 60 keV for $LaBr_3$:Ce,Sr ($\tau_{decay}$ = 18 ns)

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* Van der Sar et al, "SiPM-based scintillation detectors: a rational detector concept for photon-counting CT," IEEE NSS/MIC/RTSD 2022, Nov 5-12, Milano, Italy

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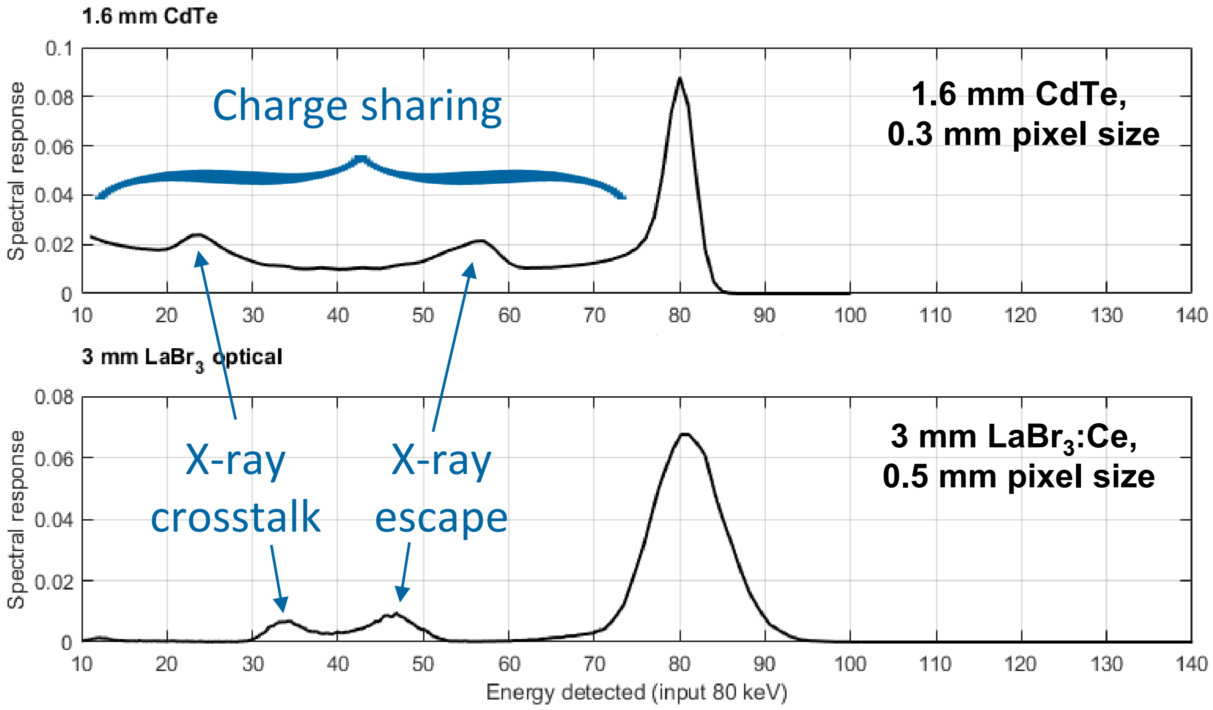
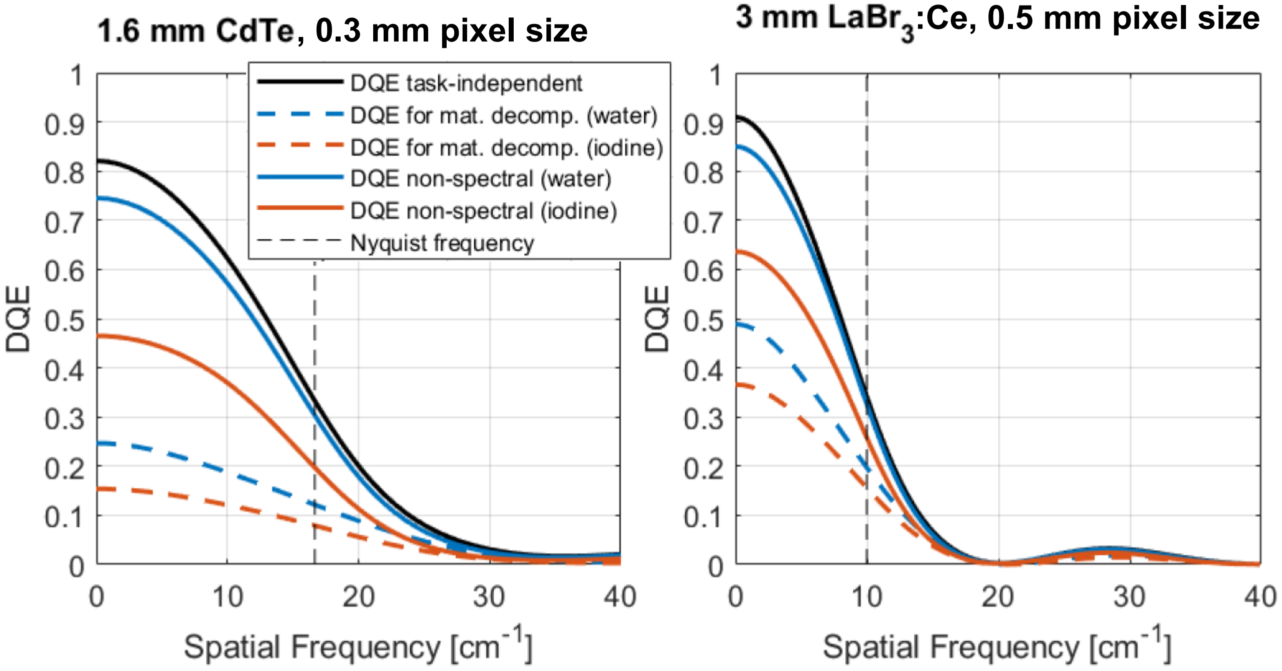
# A closer look at spectral performance: influence of crosstalk

Simulated pulse height spectra of 1.6 mm CdTe (top) and $LaBr_3$:Ce (bottom) upon irradiation with 80 keV X-rays [1]




Spectral DQE of 1.6 mm CdTe (left) and $LaBr_3$:Ce (right) [2]

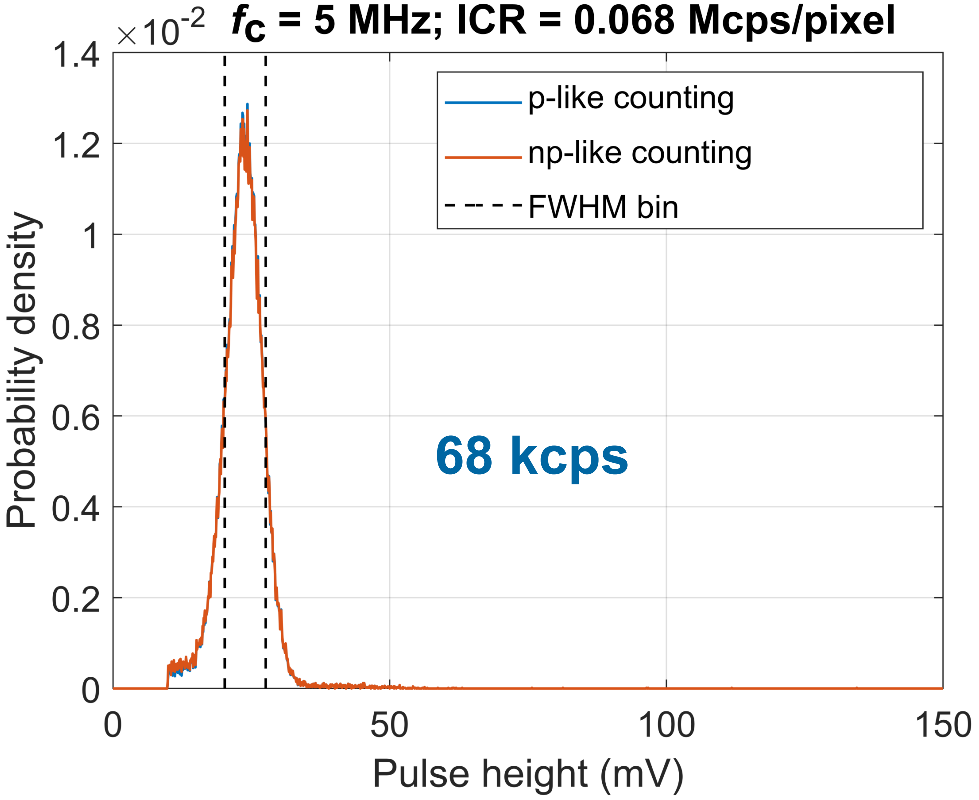


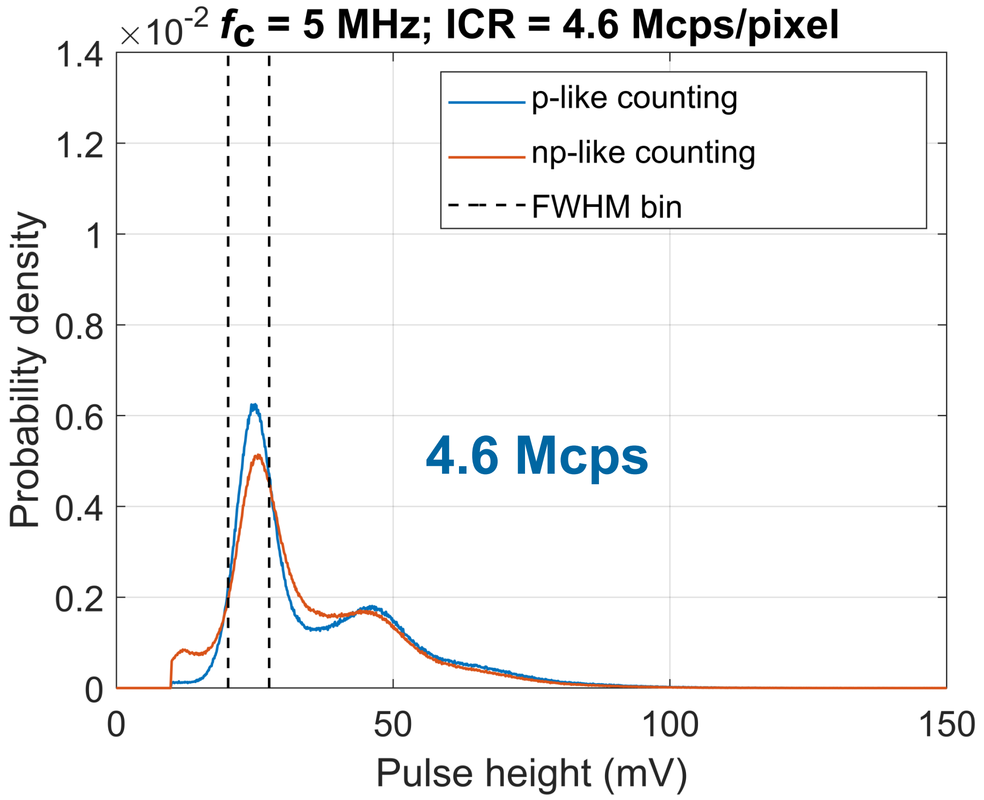


[1] Karl Stierstorfer & Martin Hupfer, Siemens Healthineers, private communication
[2] Karl Stierstorfer & Martin Hupfer, Siemens Healthineers, SPIE Medical Imaging, San Diego, Feb 2024.

# A closer look at spectral performance: influence of pile-up

Measured spectra of a LYSO:Ce detector upon irradtion with 60 keV X-rays at different incident count rates (ICR)

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Van der Sar et al, "Performance of X-ray photon-counting scintillation detectors under pile-up conditions at 60 keV…", in preparation

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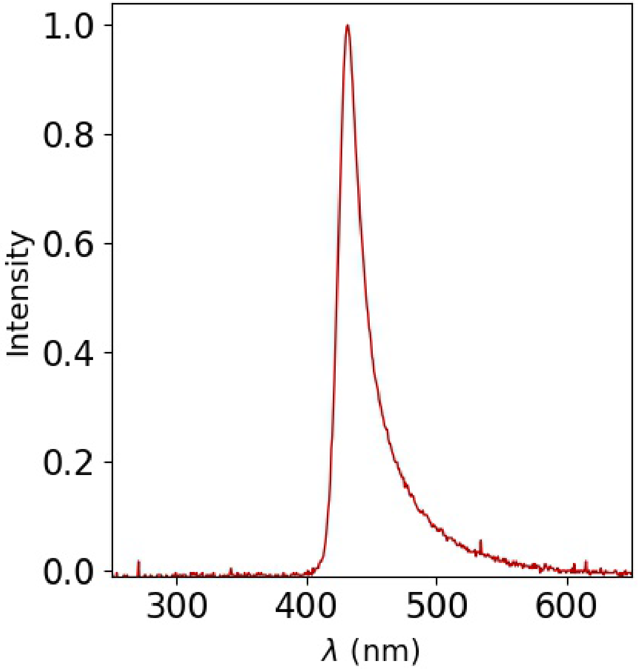
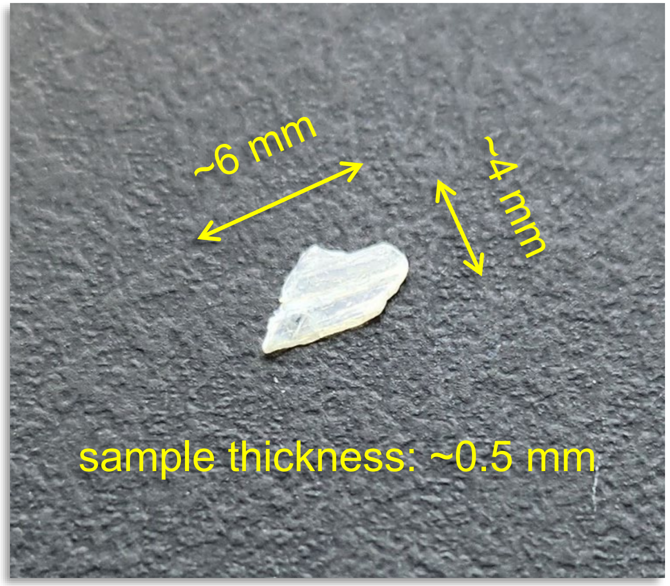
# Benzylamonium lead bromide - $(BZA)_2PbBr_4$




$(BZA)_2PbBr_4$ X-ray excited emission spectrum at 300K.




Photograph of the investigated sample.

| | |
|---|---|
| Material: | 2D hybrid organic-inorganic perovskite (HOIP) |
| Formula: | $(C7H10N)_2PbBr4$ |
| Emission: | 432 nm |
| Density: | 2.23 g/cm$^3$ |
| Hygroscopic: | No |
| Production: | Solution growth |

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* Van Blaaderen et al, "$(BZA)_2PbBr_4$: a potential scintillator for photon-counting computed tomography detectors," Journal of Luminescence 263, 120012, 2023

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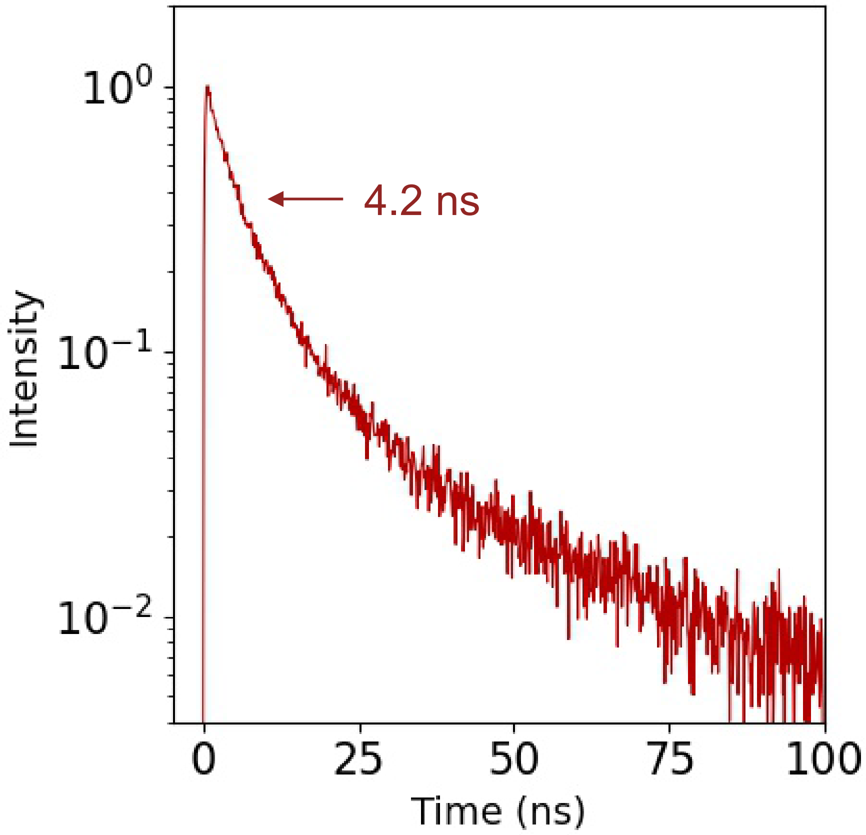
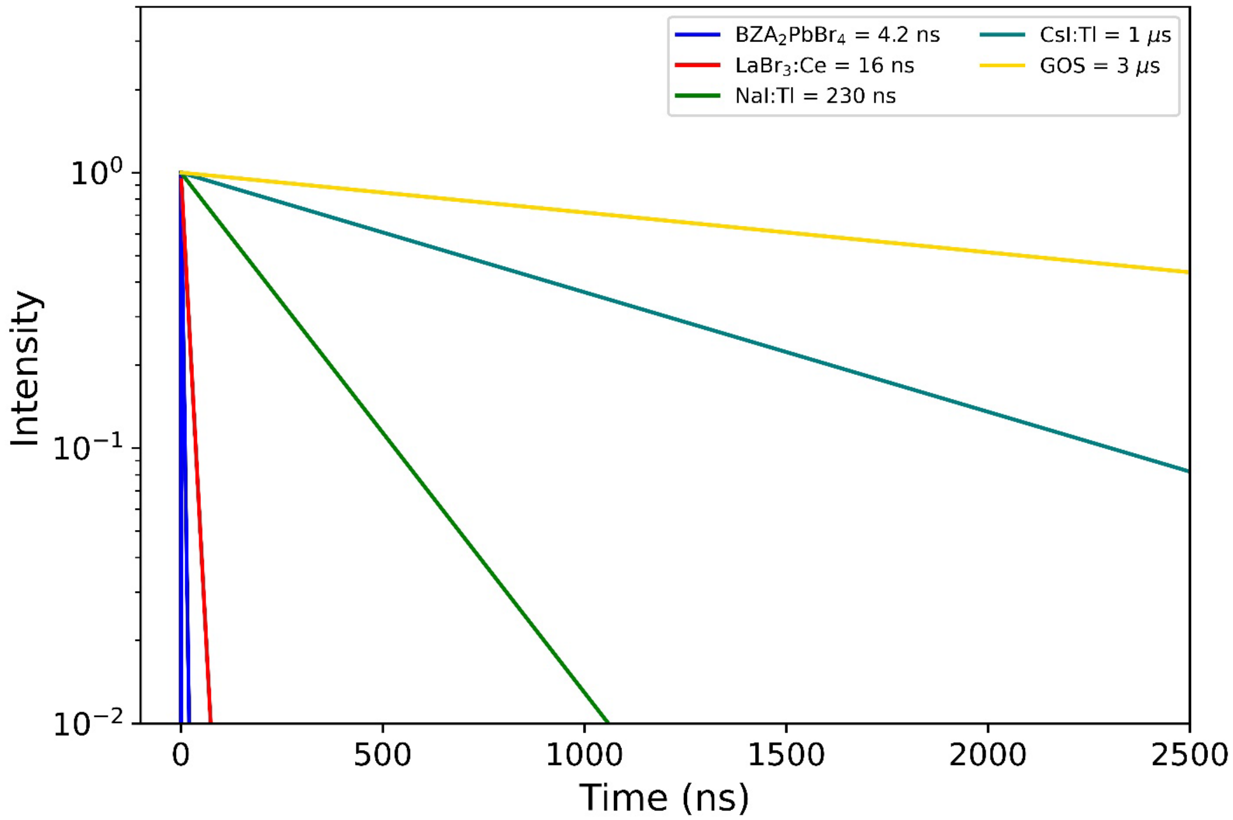
# $(BZA)_2PbBr_4$ X-ray excited decay




Pulsed X-ray excited decay spectrum of $(BZA)_2PbBr_4$ at 300 K




Decay spectrum of $(BZA)_2PbBr_4$ compared to other frequently used scintillators

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* Van Blaaderen et al, "$(BZA)_2PbBr_4$: a potential scintillator for photon-counting computed tomography detectors," Journal of Luminescence 263, 120012, 2023

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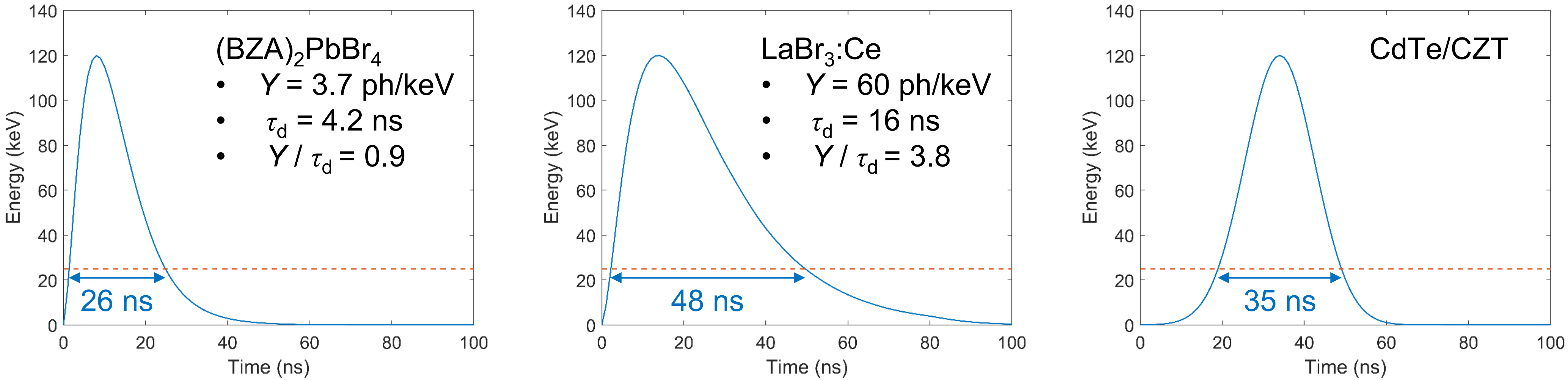
# Expected count rate performance

Comparison of simulated pulses ($E_{X\text{-ray}}$ = 120 keV, $f_c$ = 100 MHz, $E_{thr}$ = 25 keV)




| | $(BZA)_2PbBr_4$ | $LaBr_3$:Ce | CdTe / CZT |
|---|---|---|---|
| Max count rate with np-like counting | 38.5 Mcps/pixel ($\tau_{np}$ = 26 ns) | 20.8 Mcps/pixel ($\tau_{np}$ = 48 ns) | 28.6 Mcps/pixel ($\tau_{np}$ = 35 ns) [1] |

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* Van Blaaderen et al, "$(BZA)_2PbBr_4$: a potential scintillator for photon-counting computed tomography detectors," Journal of Luminescence 263, 120012, 2023

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# Conclusions

- Count rate of scintillator-based X-ray photon-counting detectors can be similar to that of CdTe/CZT detectors; potentially even better with new ultrafast scintillation materials
- The spectral fidelity of scintillator-based X-ray photon-counting detectors may be better than that of CdTe/CZT detectors due to the absence of charge sharing
- Scintillator-based X-ray photon-counting detectors may have a bright future!

# Thank you!