ScintLaCHARM: A Scintillator Compton Camera

Detector concept, optical simulation, and scalable SiPM readout

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K. Kooshk, A. Deisting, Th. Hahn, U. Oberlack[1]

[1]Johannes Gutenberg University Mainz, Experimental Particle and Astroparticle Physics (ETAP)

1 From MeV Astronomy to Decommissioning

Compton imaging is a key technique for MeV gamma-ray astronomy. Missions such as COSI [1] use the energies and three-dimensional positions of successive photon interactions to reconstruct the gamma-ray direction while providing spectroscopy and polarimetry. The same physical principle can address a terrestrial challenge: locating radioactive material during nuclear decommissioning. ScintLaCHARM transfers this astroparticle-physics approach to a portable, modular scintillator camera. Fast plastic scatterers, $CeBr_3$ absorbers, and SiPM readout provide directional imaging and spectroscopy without a mechanical collimator.

Research Objective

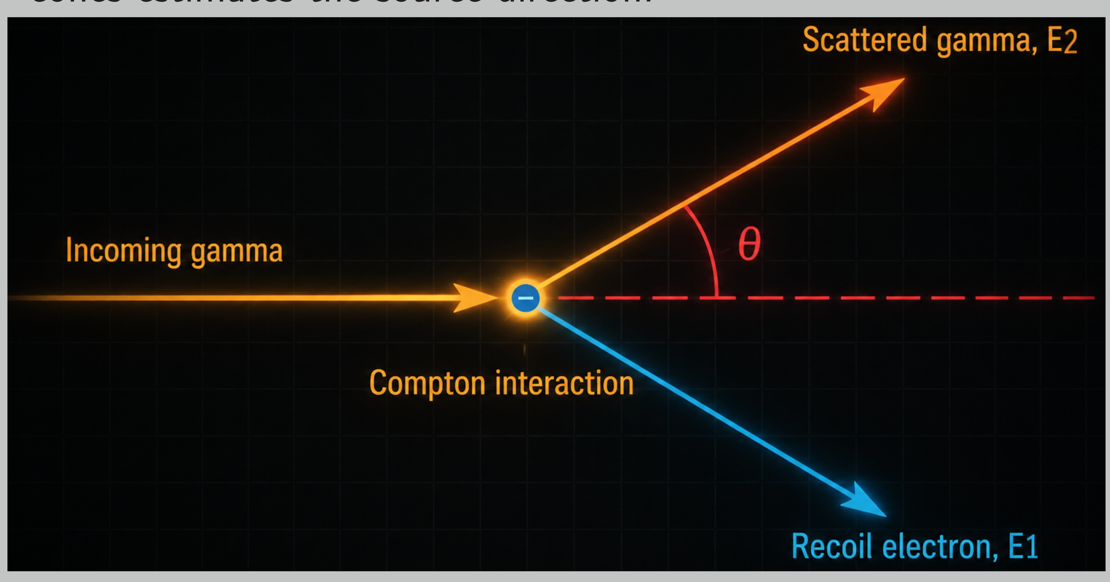
Optimise the detector geometry and optical response, qualify the scalable readout, and validate the complete chain from gamma interaction to reconstructed source image.

2 Compton Imaging Principle

For a photon depositing energies E_1 and E_2 in two interactions, the first-scatter angle is

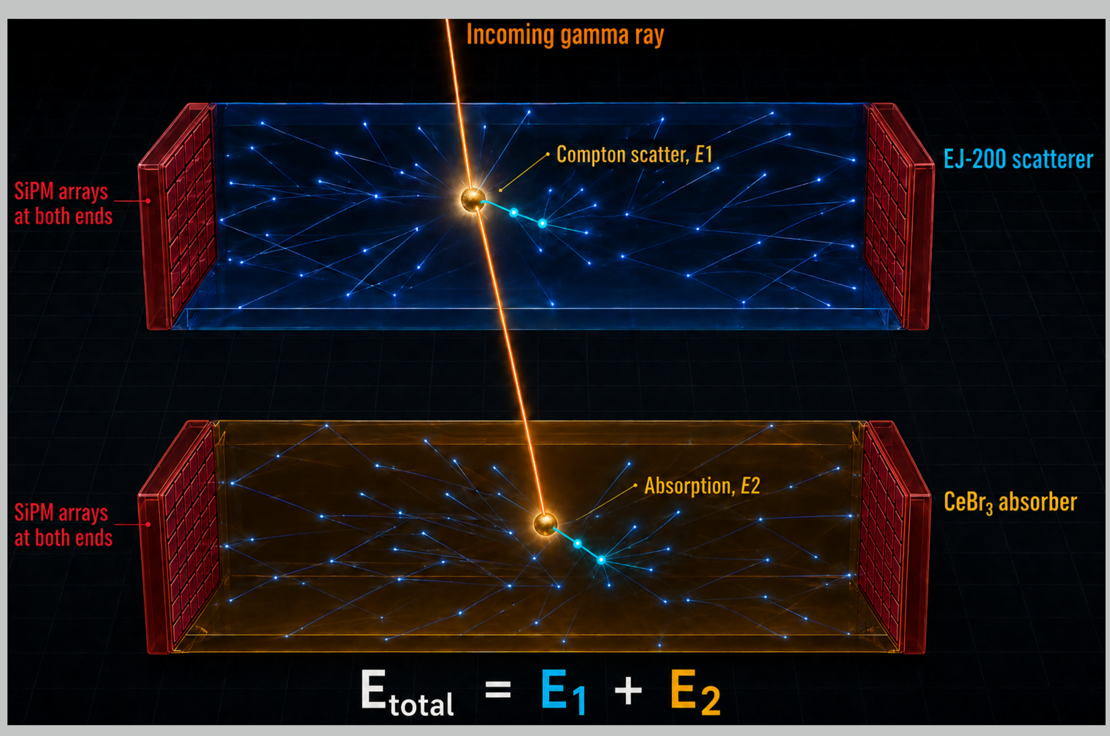
$$\cos\theta = 1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1+E_2}\right).$$

Each coincident event defines a cone. The intersection of many cones estimates the source direction.



Compton-scattering kinematics used to reconstruct the incident gamma direction.

3 Detector Concept



Compton Event in the Dual-Ended PVT/$CeBr_3$ Detector Concept

PVT scatterer: Its low Z favours Compton scattering; ~2.1 ns decay, long optical attenuation, and mechanical robustness support fast, modular scatter layers [3].

$CeBr_3$ absorber: High stopping power (effective Z~46), ~60,000 photons/MeV, ~20 ns decay, and emission near 380 nm support efficient photopeak spectroscopy [2]. The hygroscopic crystal requires a sealed optical module.

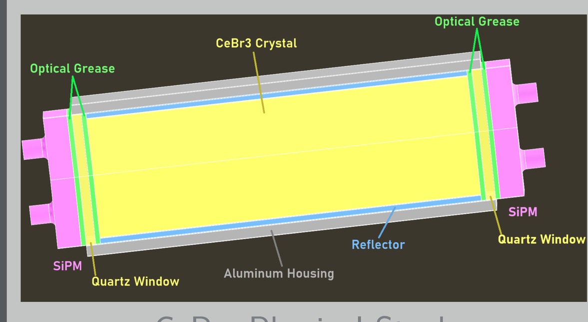
Dual-ended multi-SiPM readout: SiPM arrays provide energy, timing, and longitudinal-position observables. Scaling to a camera multiplies the channel count and demands pedestal/gain equalisation, stable bias and temperature, synchronised acquisition, coincidence triggering, and event building. This motivates the FERS A5204 evaluation in Sections 6–7; optical simulations select the crystal dimensions and interfaces.

4 Optical Simulation and Crystal Optimisation

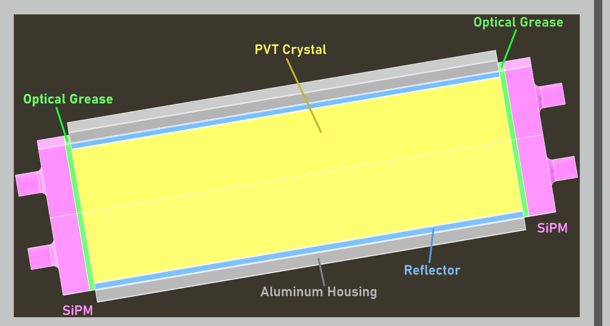
The optical study isolates light collection from the preceding gamma interaction. Monoenergetic electrons are generated throughout configurable $CeBr_3$ and PVT scintillators, and the resulting scintillation photons are transported to SiPMs at both ends.

- Crystal dimensions, reflector (PTFE, TiO_2 or ESR), and an optional air gap are selected for each simulation campaign.
- The readout stack follows the material: $CeBr_3$ uses crystal–grease–quartz–grease–SiPM [3], while PVT is coupled directly through grease to the SiPM.
- A wavelength-dependent PDE is applied when photons enter either SiPM; event, track, reflection and hit information is written to ROOT for analysis.

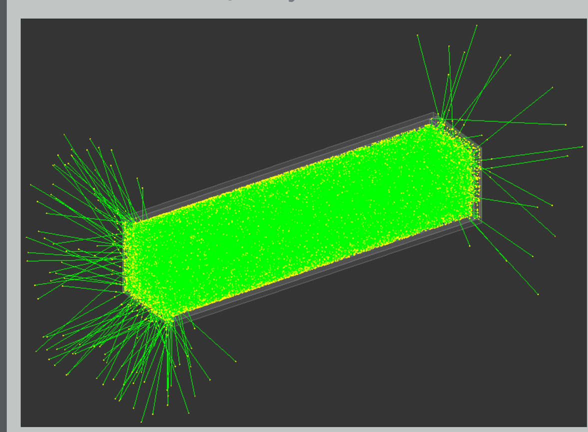
4 Optical Simulation (continued)



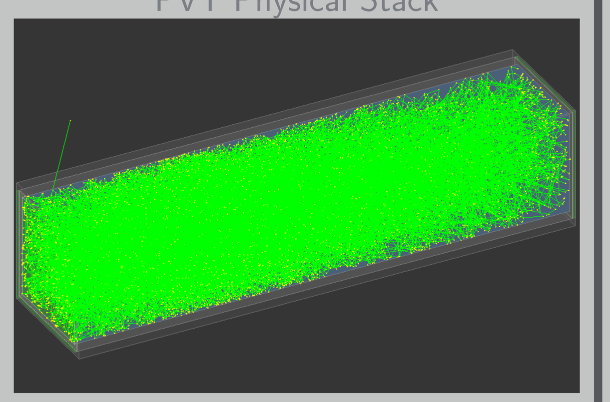
$CeBr_3$ Physical Stack



PVT Physical Stack



$CeBr_3$ 100keV Simulation

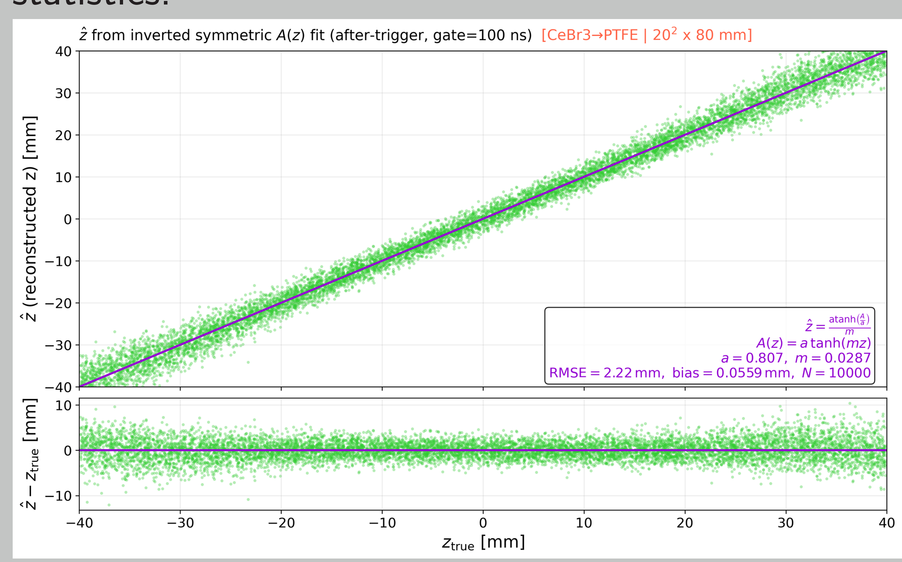


PVT 100keV Simulation

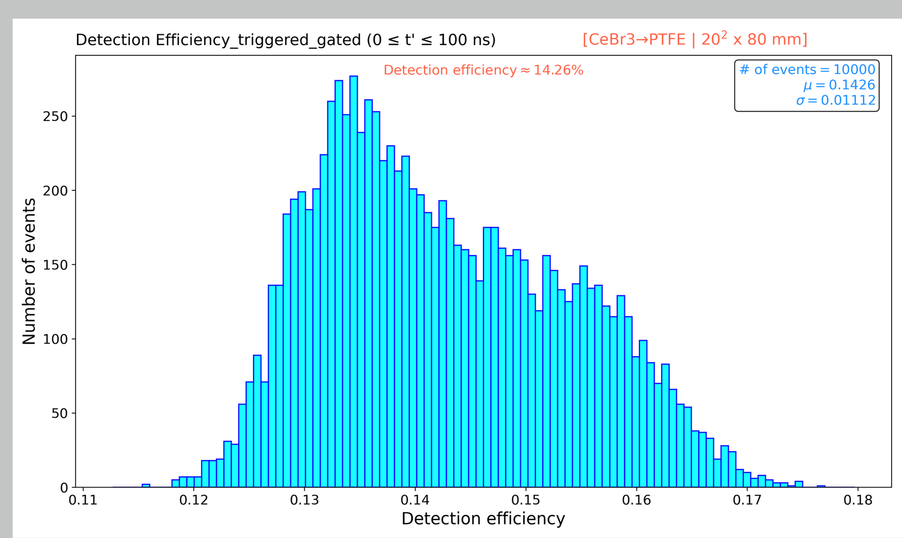
Analysis: Asymmetry and CNN Reconstruction

Asymmetry: the dual-ended light balance $A = (N_1 - N_2)/(N_1 + N_2)$ is calibrated against the true interaction depth to reconstruct z and correct its position-dependent light yield.

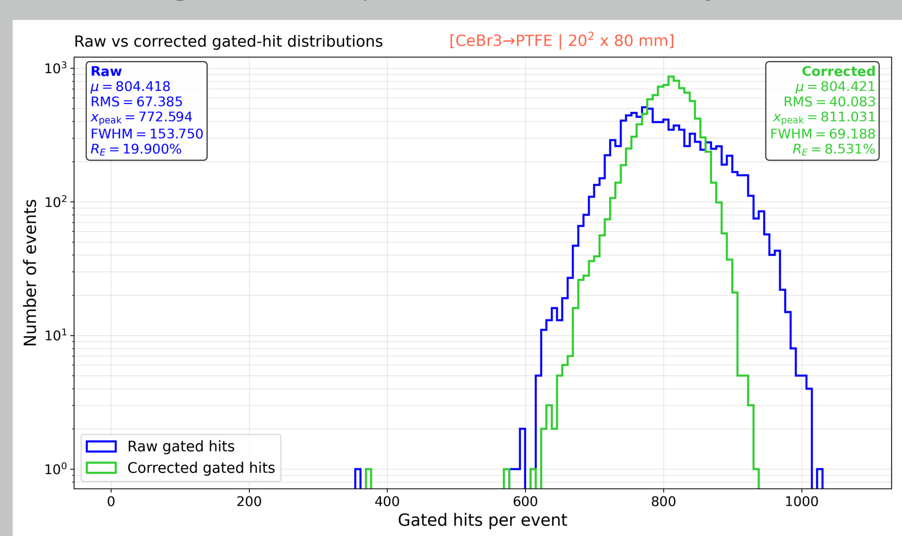
CNN: the SiPM response is used to reconstruct (x, y, z), while a PDE scan tests how robust the spatial resolution is to reduced photon statistics.



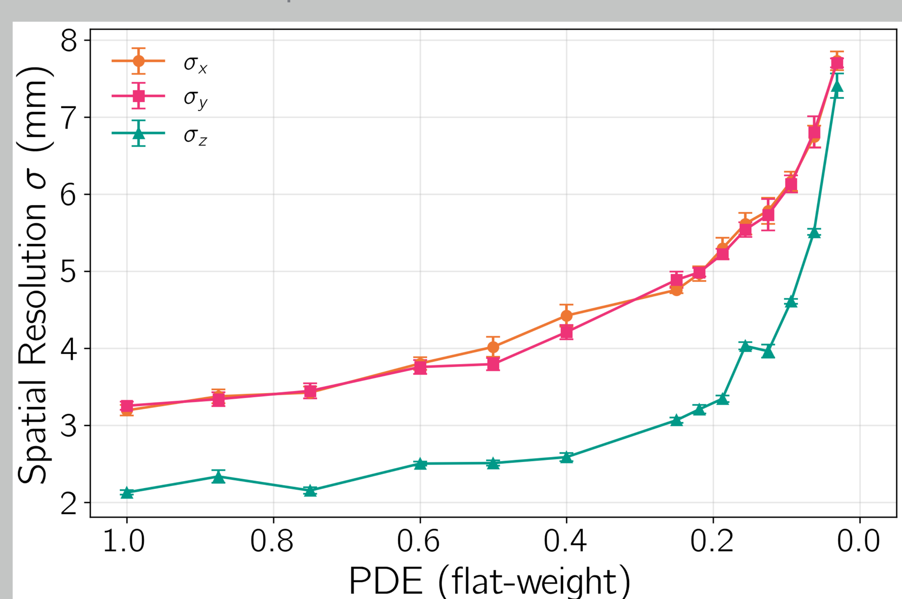
Asymmetry DOI: RMSE 2.22 mm; bias 0.056 mm (10^4 events).



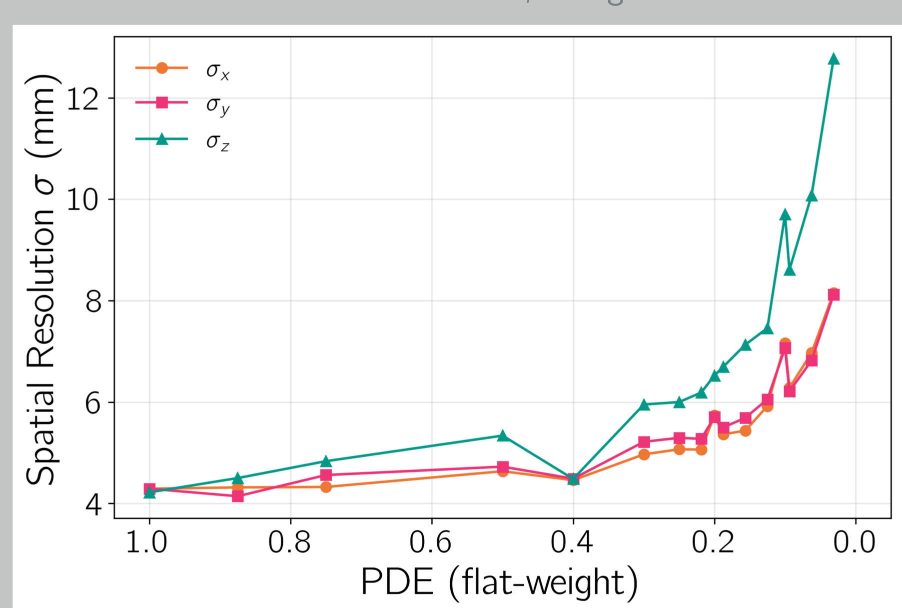
100 ns gate: mean optical detection efficiency 14.26%.



DOI correction improves relative FWHM: 19.90% → 8.53%.



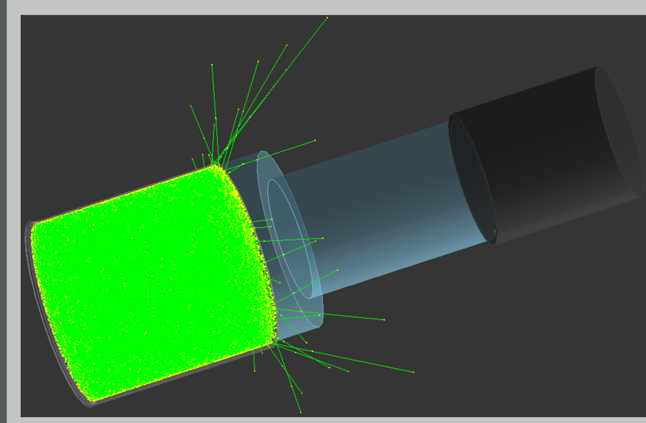
Single scatter CNN resolution versus PDE; z degrades fastest at low PDE.



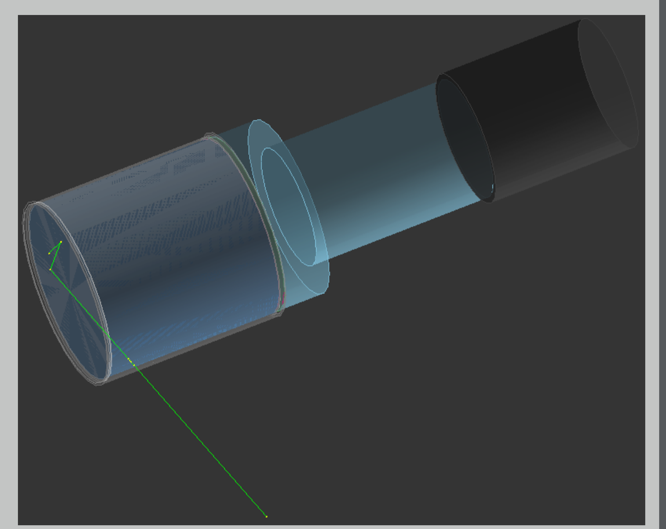
Multi scatter CNN resolution versus PDE; z degrades fastest at low PDE.

5 Gamma Simulation with the RSL7 Predecessor

Detector model: The RSL7 predecessor validates the simulation chain and provides the spatial scale of repeated gamma interactions. Its Geant4 model reproduces the fixed $76.2\,\mathrm{mm} \times 76.2\,\mathrm{mm}$ $CeBr_3$/PVT cylinder, reflector/housing, $CeBr_3$ quartz window, sealed rear face, and single-ended R6233-100 PMT. **Gamma-only mode:** FTFP_BERT/Livermore records ordered 3D interactions, secondaries, energy deposits, and exit or re-entry independently of the optical response. **Design metric:** For multi-scatter events, $d_i = |\mathbf{r}_{i+1} - \mathbf{r}_i|$ and its mean $\langle d \rangle$ guide ScintLaCHARM segmentation and spatial resolution.



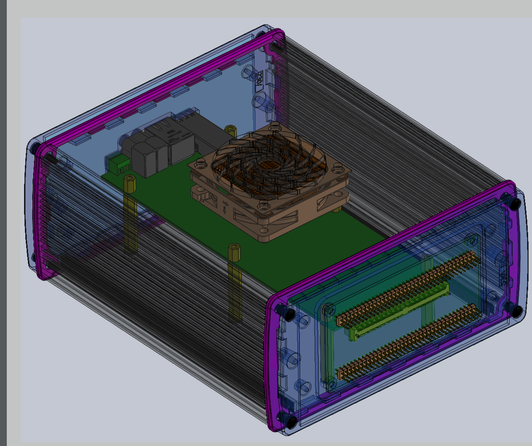
Optical-photon transport

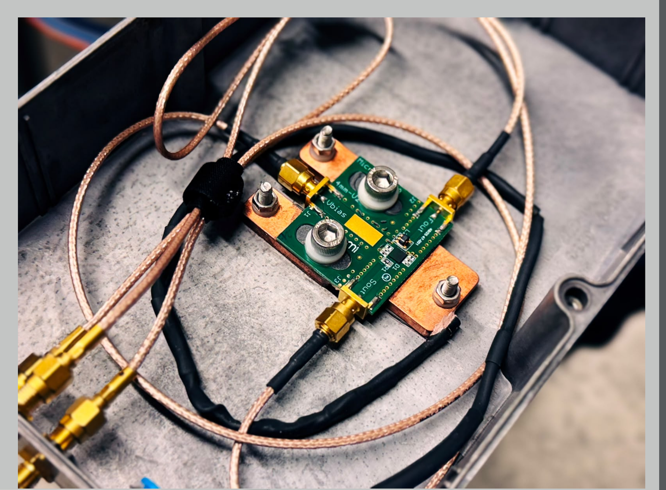


662 keV gamma-only event

6 Readout Evaluation: CAEN FERS A5204

The FERS A5204 [4], DT5800D emulator, and DSO9254A were used for HG/LG pedestal and PHA measurements. Separate aluminium Faraday cages were prepared for the sealed, nitrogen-filled SiPM detector and cooled A5204, including cabling, signal routing, and electrical/optical feedthroughs.





FERS and SiPM Faraday cages

7 Current Status and Development Roadmap

- **Completed:** $CeBr_3$/PVT optical simulation and position estimation, RSL7 gamma studies, and initial A5204 pedestal/PHA tests.
- **Module validation:** test one dual-ended $CeBr_3$ and one PVT module for light collection, energy, timing, position, and stability.
- **Readout pipeline:** integrate both modules with the A5204; establish calibration, triggering, coincidences, event building, and automated analysis.
- **Camera construction:** scale the validated modules and readout chain into the complete ScintLaCHARM camera.
- **Event reconstruction:** determine positions and energies, order coincidences, construct Compton cones, and image the source.

Next Experimental Milestone

Test simultaneous dual-ended SiPM readout of one $CeBr_3$ absorber and one PVT scatterer using the FERS A5204.

Acknowledgement

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References and Contact

[1] J. A. Tomsick et al., "The Compton Spectrometer and Imager," *PoS(ICRC2023)* 745 (2023).
[2] Hellma Materials GmbH, *Radiation Detection Materials*, product brochure, 2019.
[3] SCIONIX Holland B.V., "Properties and use of scintillation materials," *Scintillation Crystals*.
[4] CAEN, *FERS-5200 / A5204 documentation*.

Contact: kkooshkj@uni-mainz.de
Web: https://xenon.physik.uni-mainz.de/