Pushing the Limits of TOF-PET Detectors: Advancements in Timing and DOI Evaluation

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19th February 2025 - Medical Applications

VCI2025 – The 17th Vienna Conference on Instrumentation

Positron Emission Tomography

Fundamental requirements

To obtain as many counts as possible:

- High **sensitivity**

To characterize them as accurate as possible:

- High **spatial resolution**

- High **timing resolution**

- High **energy resolution**

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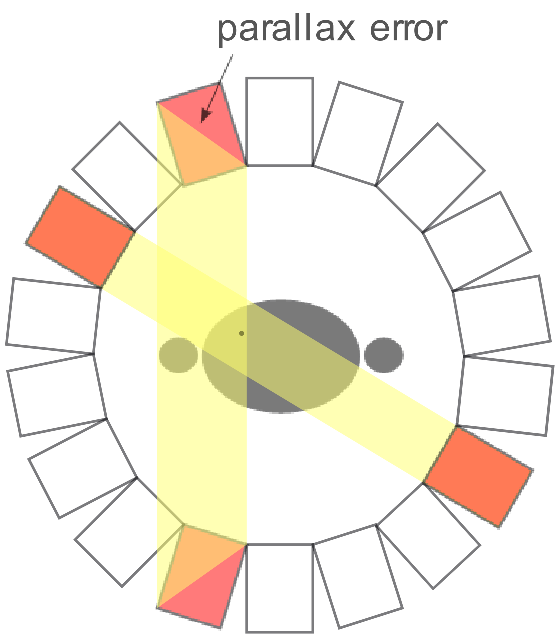

Long scintillator maximize sensitivity

But

Parallax effect degrades the spatial resolution

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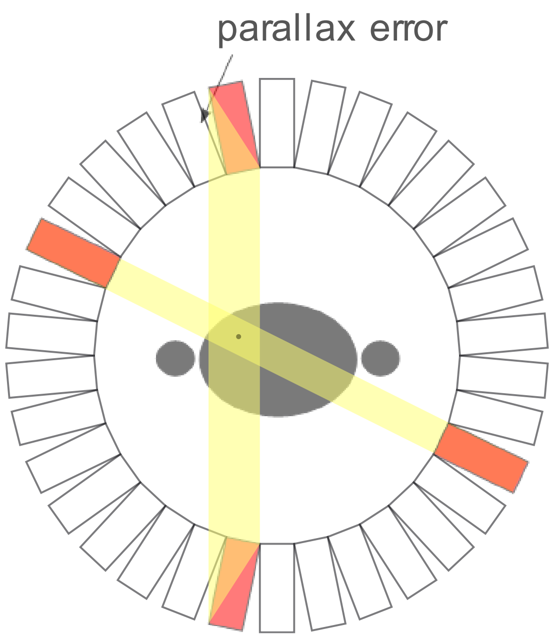

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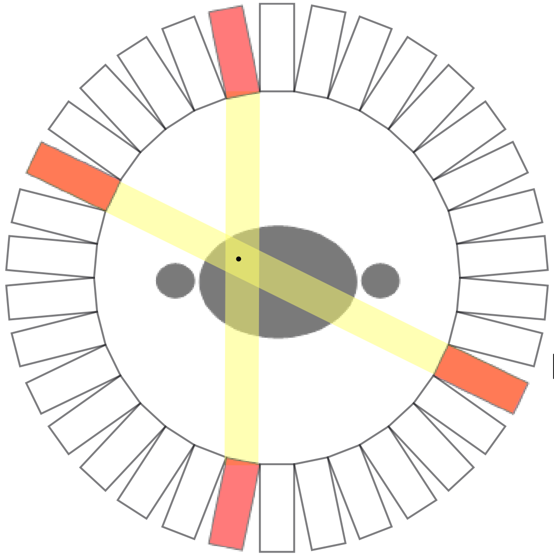

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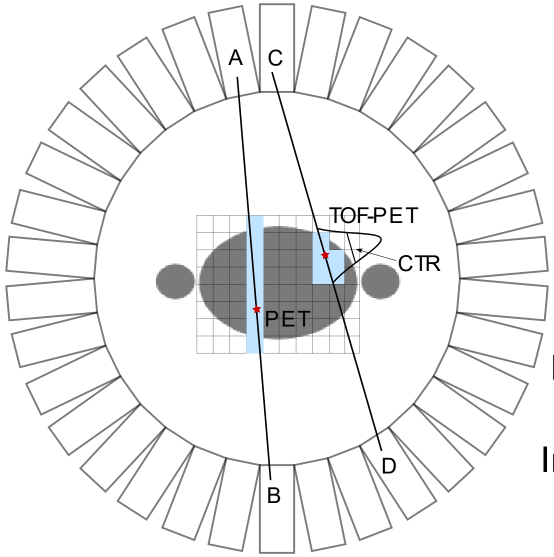

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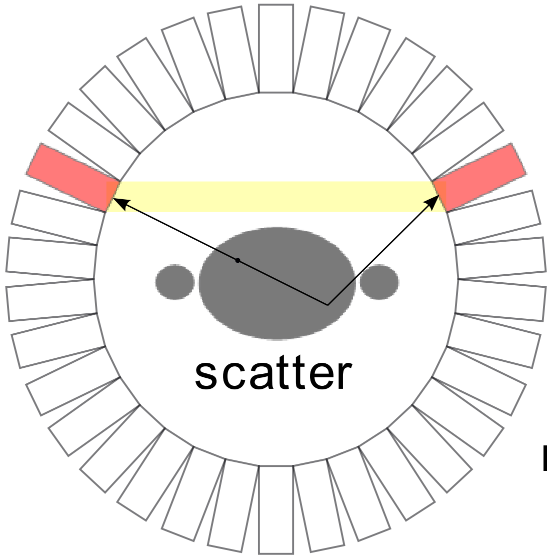

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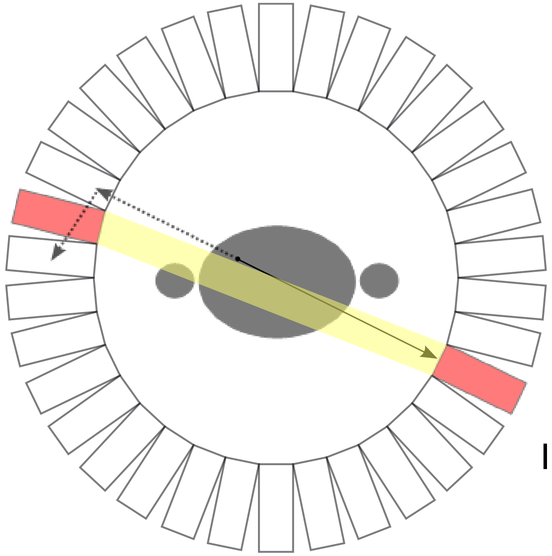

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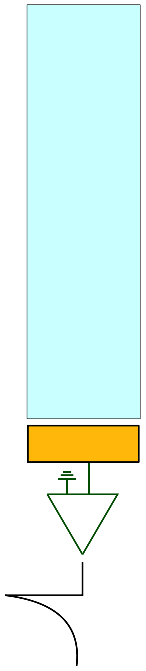
Objective: Achieving better timing resolution

Toward 100 ps

Every step of the detection chain needs to be **optimized**

while meeting the fundamental requirements of high sensitivity, and high spatial and energy resolution



Crystal pixel

Silicon Photomultiplier (SiPM)

Electronic readout

Search for materials with **fast light emission** mechanisms:

- Fast scintillation **LYSO:Ce, Plastic (EJ232)**
- Prompt Cherenkov production **BGO**

Improved photodetectors:

- **Metal-in-Trench (MT)** technology with high photon detection efficiency [1]

Faster electronics:

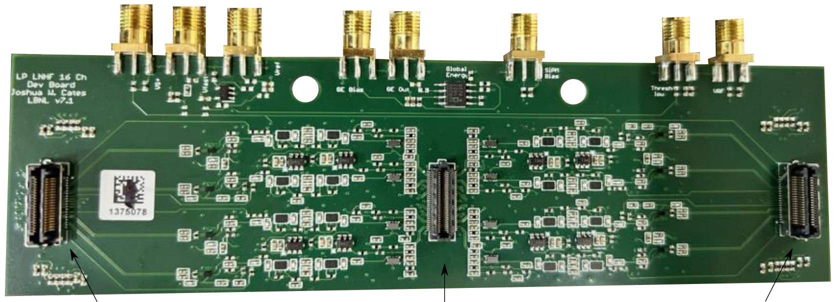
- **High-Frequency readout** to exploit fast-light production

[1] S. Merzi et al (2023) JINST 18 P05040.

Low-noise Low-power High-Frequency Readout

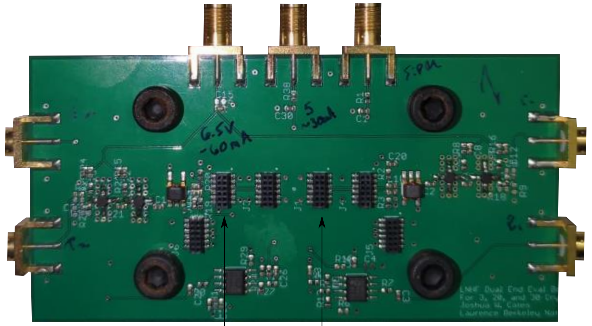
- Each SiPM output signal is split and processed by:
  - High-frequency circuit having a **low-noise amplifier** chain to extract a fast **time** signal [2]
  - **Low-power operational amplifier** to extract an analog **energy** signal [3-4]

New multi-channel development board [5]



- A **global energy output** to trigger two CAEN V1742 32-ch digitizers (5 Gs/s, 500 MHz bandwidth) for the digitization of the signals

Double-sided board [6]



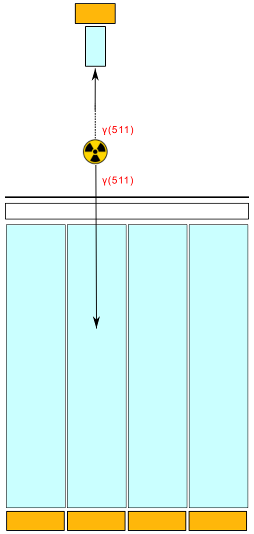
- Digitization performed using a Tektronix MSO68B-400 oscilloscope with 8 channels (12.5 GS/s, 8 GHz bandwidth)

[2] J. W. Cates et al. (2018) Phys. Med. Biol. p. 185022. [3] S. Gundacker et al. (2019) Phys. Med. Biol. p. 055012. [4] Cates & W. Choong (2022) Phys. Med. Biol. 67, 195009.
[5] J. Cates, W. Choong & E. Brubaker (2024) Phys. Med. Biol. 69, 045025. [6] Cates & W. Choong (2022) Phys. Med. Biol. 67, 195009.

DOI methods: Light sharing and Double-sided readout

- $4 \times 4 \times 20$ mm^3 LYSO:Ce crystals from Crystal Photonics Inc with **lateral depolished surfaces**
    - **Light-sharing method:** light guide on top to recirculate the light [7-9]
    - **Double-sided method:** readout of the two ends of a scintillator [10]
- Coupled to **Broadcom NUV-MT SiPMs**, each with 3.84×3.74 mm^2 active area and 4 mm pitch

Light-sharing method [7-9]

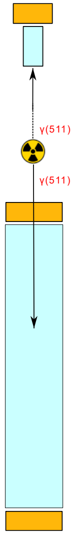


DOI parameters:

$$w = \frac{p_{max}}{P_{tot}}$$

$$c = \frac{p_f - p_b}{p_f + p_b}$$

Double-sided method [10]



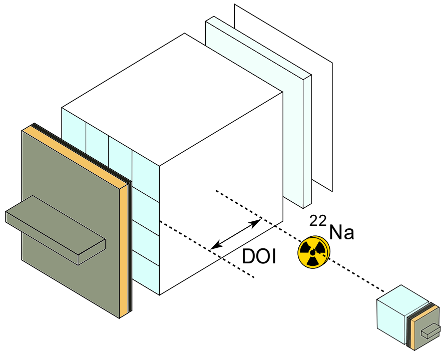
[7] M. Pizzichemi et al 2016 Phys. Med. Biol. 61 4679. [8] M. Pizzichemi et al 2019 Phys. Med. Biol. 64 155008. [9] G. Stringhini et al 2016 JINST 11 P11014.
[10] S. Seifert and D. R. Schaart 2015 IEEE TNS vol. 62, no. 1, pp. 3-11

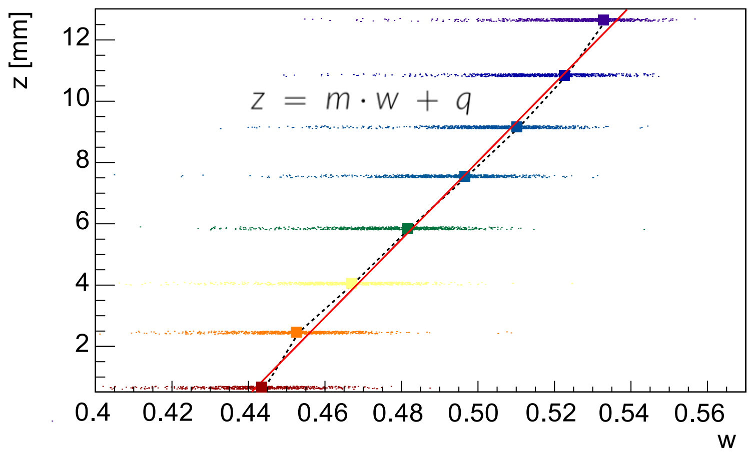
Light sharing matrix

DOI Resolution *__Lateral scan__ at fixed DOI positions to __estimate the resolution in the DOI evaluation__ by means of the w parameter*

- Depolished CPI LYSO:Ce crystals 4 x 4 x 20 mm^3
- Broadcom NUV-MT array

- Bias voltage 45 V
- Leading-edge threshold 20 mV





Crystals	DOI res. [mm]
Average on all	2.7 ± 0.2
Average on central	**2.2 ± 0.2**

Light sharing matrix

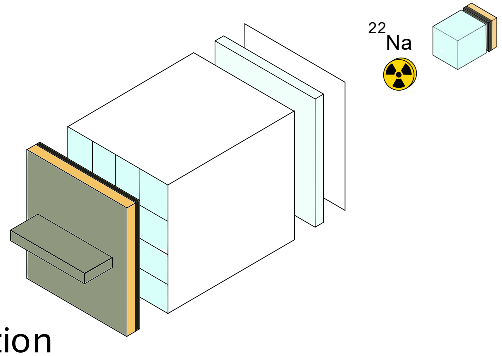
<u>Time Resolution</u>

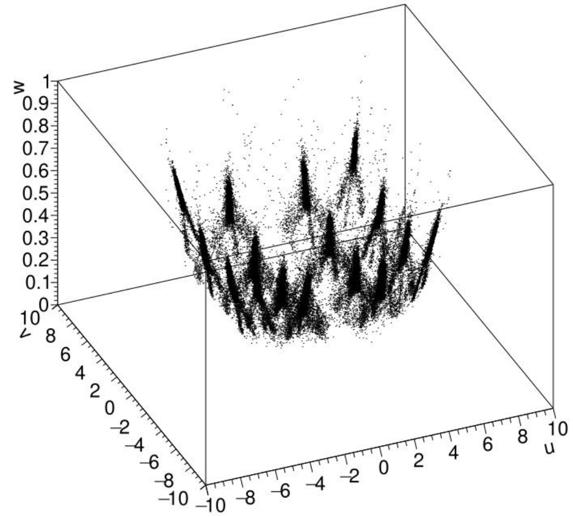
Front irradiation** of the entire crystal matrix to **estimate the coincidence timing resolution (CTR)

- Depolished CPI LYSO:Ce crystals 4 x 4 x 20 mm^3
- Broadcom NUV-MT array

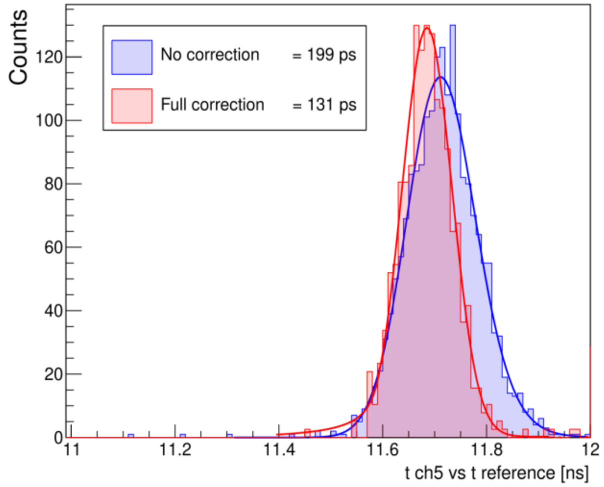
- Bias voltage 45 V
- Leading-edge threshold 20 mV

- **<u>CTR full correction</u>:** DOI-based timestamp correction and neighbouring channels timestamp combination





Crystals	DOI res. [mm]	CTR std. [ps]	CTR full corr. [ps]
Average on all	2.7 ± 0.2	189 ± 2	140 ± 2
Average on central	**2.2 ± 0.2**	195 ± 2	**133 ± 2**



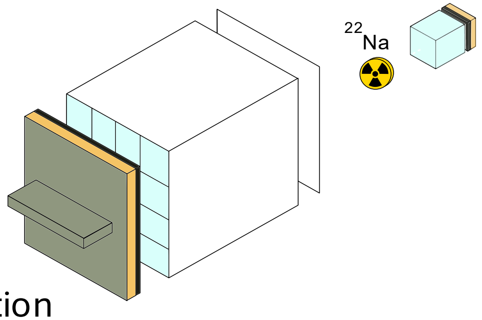
Standard matrix

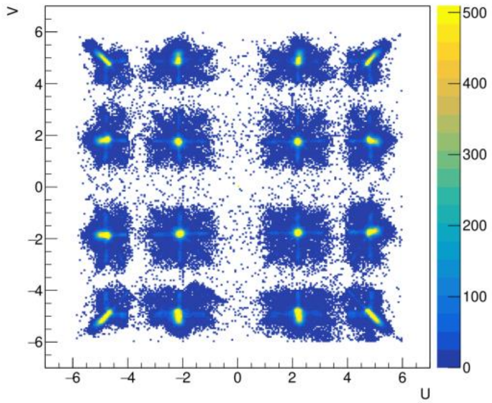
Time Resolution ***Front irradiation*** *of the entire crystal matrix to* ***estimate the coincidence timing resolution (CTR)***

- **Polished** CPI LYSO:Ce crystals 4 x 4 x 20 mm^3
- Broadcom NUV-MT array

- Bias voltage 45 V
- Leading-edge threshold 20 mV

- **CTR full correction:** DOI-based timestamp correction and neighbouring channels timestamp combination





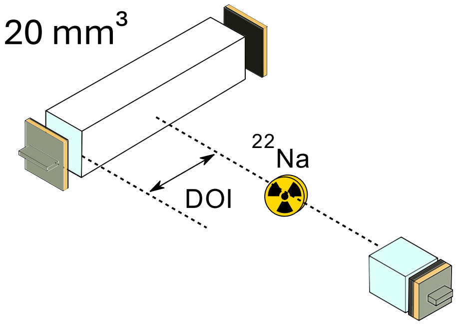
	TOF- and DOI- capable module			Standard module
Crystals	DOI res. [mm]	CTR std. [ps]	CTR full corr. [ps]	CTR std. [ps]
Average on all	2.7 ± 0.2	189 ± 2	140 ± 2	131 ± 2
Average on central	**2.2 ± 0.2**	195 ± 2	**133 ± 2**	**130 ± 2**

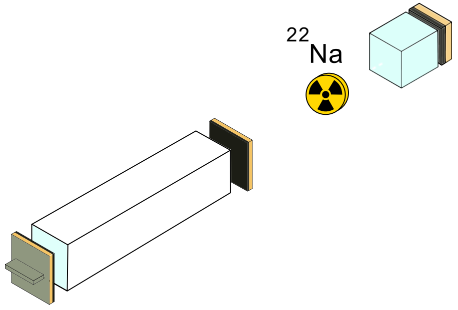
DOI-capable module achieves the **same CTR of the standard module (130 ps)**, with the added benefit of having **DOI resolution < 3 mm**!

Double-sided readout

- Depolished CPI LYSO:Ce crystal 4 x 4 x 20 mm^3
- 2 Broadcom NUV-MT SiPMs

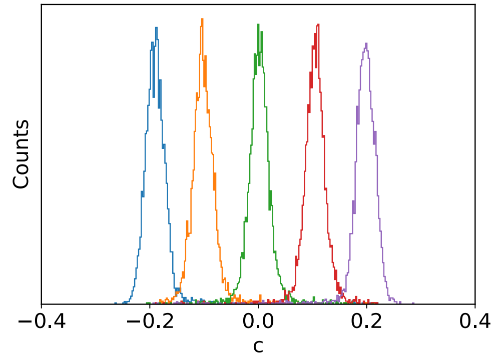
- Bias voltage 47 V
- Leading-edge threshold 20 mV

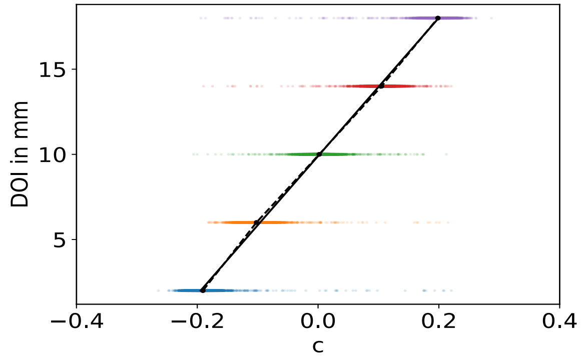




<u>DOI Resolution</u> ***Lateral irradiation*** *of the crystal.*

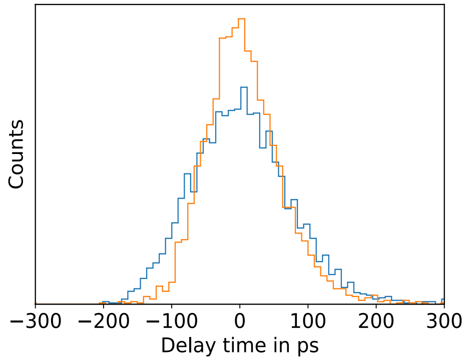
	DOI res. [mm]
Double-sided	**1.6 ± 0.1**
Light-sharing matrix	2.2 ± 0.2





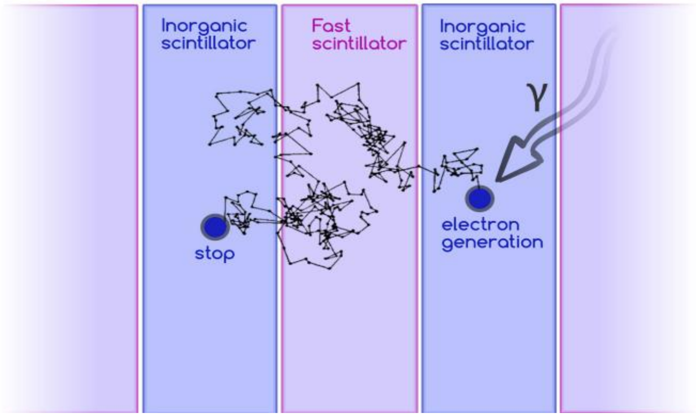
<u>CTR Evaluation</u> ***Front irradiation*** *of the crystal.*

	Polished	Depolished
Double-sided	**132 ± 9**	**103 ± 6**
Light-sharing matrix	130 ± 2	133 ± 2



Toward 10 ps: Cherenkov emission and Heterostructures

- **Inorganic scintillator** like **BGO**:
  - **High stopping power** for gamma rays at 511 keV
  - Emission of few **Cherenkov photons** in the first 10 ps
- **Fast scintillator** like **EJ232**:
  - **High photon density** (large number of photons in the first ns)



Energy sharing between inorganic and fast scintillator

- **Heterostructure** are made of combination of these two materials with complementary properties [8-11]

[8] ERC Advanced Grant TICAL (grant agreement No 338953, PI: P. Lecoq, CERN). [9] R. Martinez Turtos et al 2019 Phys. Med. Biol. 64.
[10] F. Pagano et al. Physics in Medicine & Biology, 2022, 67.13: 135010. [11] F. Pagano et al. 2023 IEEE Transactions on Nuclear Science.

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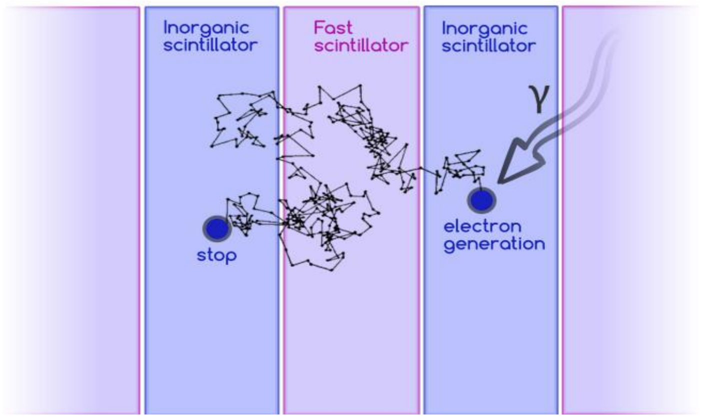

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For insights into R&D on materials faster than plastic - such as nanocomposites - check out

Poster of V. Zabloudil
"Enhancing Scintillation Efficiency of Scintillator Nanocomposites"

[8] ERC Advanced Grant TICAL (grant agreement No 338953, PI: P. Lecoq, CERN). [9] R. Martinez Turtos et al 2019 Phys. Med. Biol. 64.
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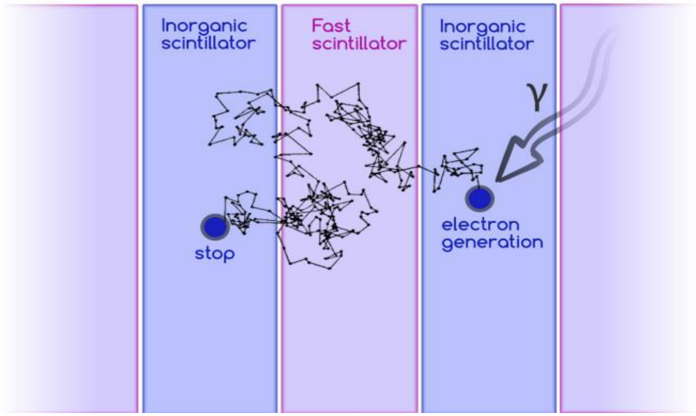

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DOI res. [mm]	LYSO:Ce	BGO	Heterostructure
Double-sided	1.6 ± 0.1	3.6 ± 0.1	4.3 ± 0.1
Light-sharing	2.2 ± 0.2	5.6 ± 0.1	-

CTR corr. [ps]	LYSO:Ce	BGO	Heterostructure
Double-sided	103 ± 6	370 ± 20	293 ± 15
Light-sharing	133 ± 2	362 ± 15	245 ± 4

[8] ERC Advanced Grant TICAL (grant agreement No 338953, PI: P. Lecoq, CERN) . [9] R. Martinez Turtos et al 2019 Phys. Med. Biol. 64.
[10] F. Pagano et al. Physics in Medicine & Biology, 2022, 67.13: 135010. [11] F. Pagano et al. 2023 IEEE Transactions on Nuclear Science.

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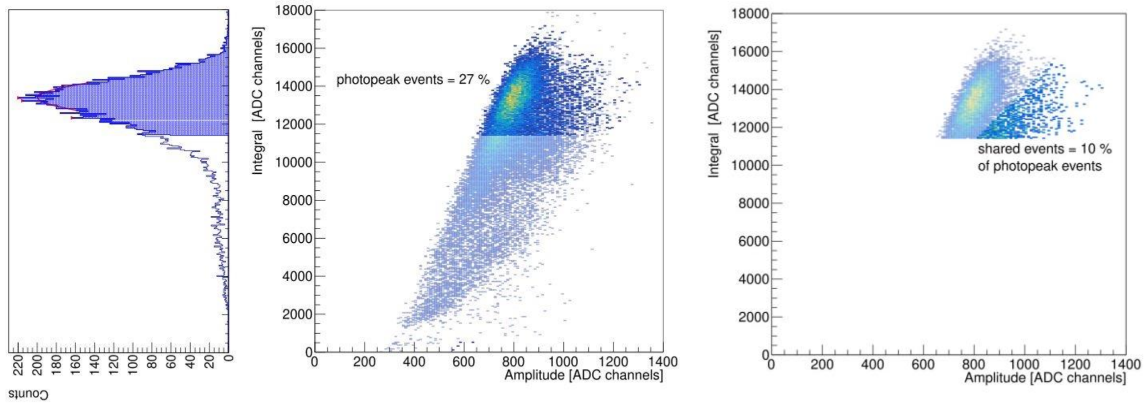

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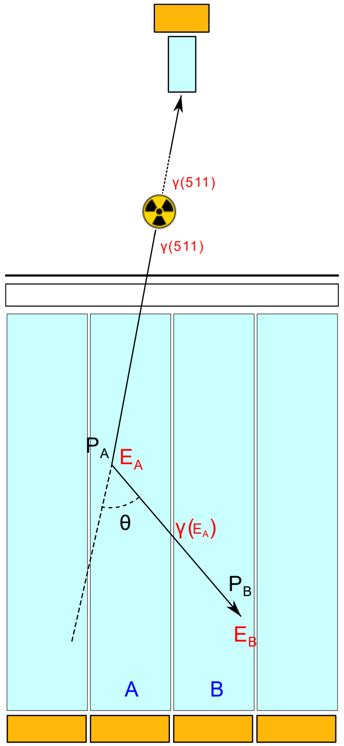
shared events
151 ± 8
178 ± 6

[8] ERC Advanced Grant TICAL (grant agreement No 338953, PI: P. Lecoq, CERN) . [9] R. Martinez Turtos et al 2019 Phys. Med. Biol. 64.
[10] F. Pagano et al. Physics in Medicine & Biology, 2022, 67.13: 135010. [11] F. Pagano et al. 2023 IEEE Transactions on Nuclear Science.

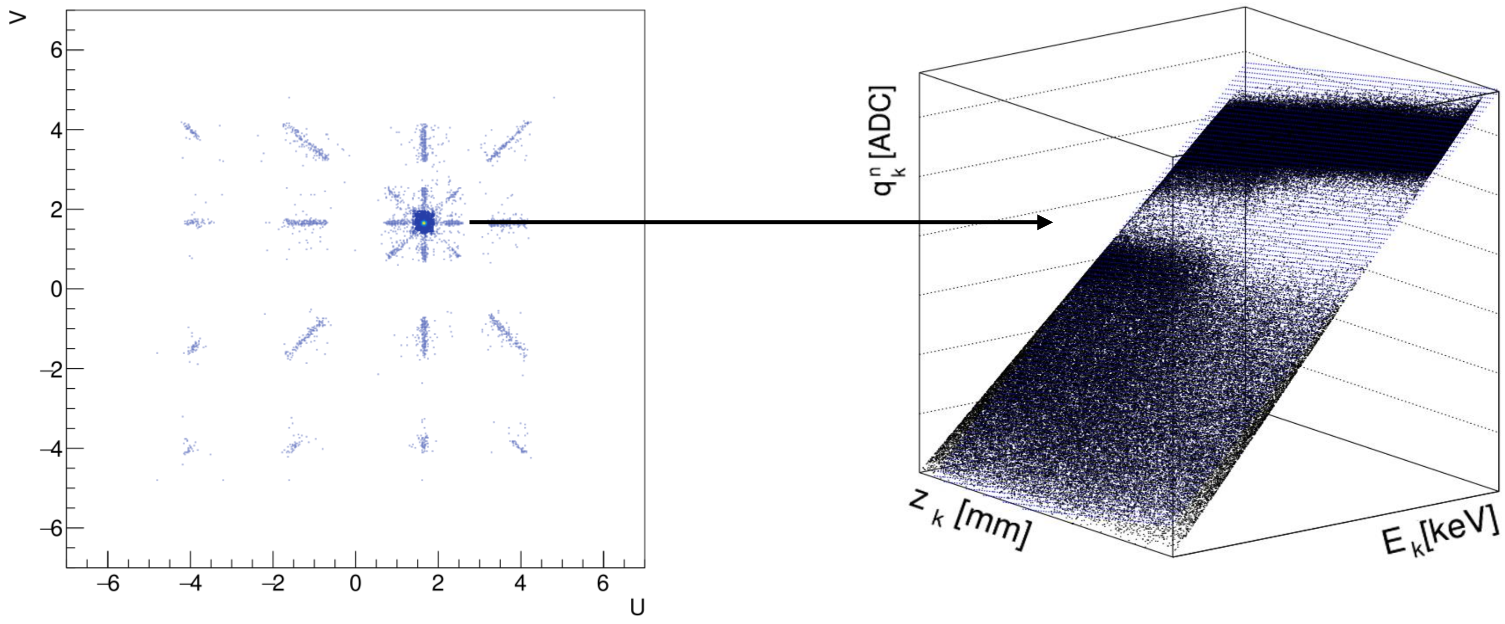
Inter-crystal scattering

<u>ICS problem</u>

In pixellated detectors, over half of the total coincidence events **deposit energy in two or more crystals**
*If not properly addressed, they can **degrade spatial resolution** due to the mispositioning of the crystal of first interaction*



1. **Selection of events** depositing energy in one crystal -> maps of the expected charge in each SiPM [12]



[12] A. Polesel, PhD thesis University of Milano-Bicocca 2021.

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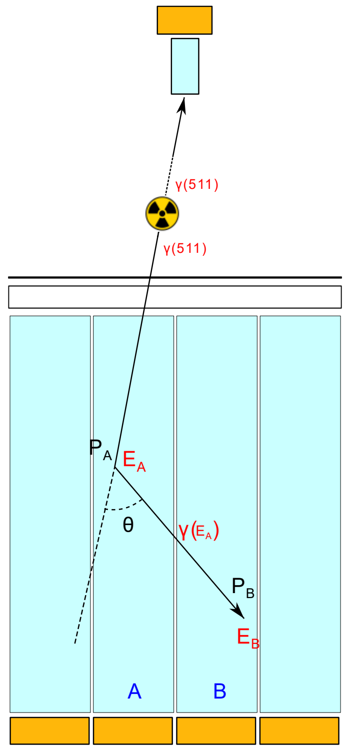
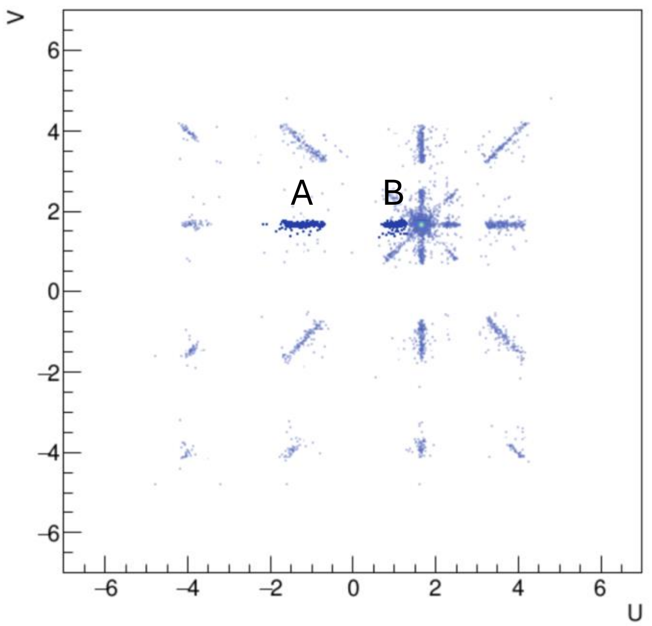


2. **Selection of ICS events** between two crystals A and B



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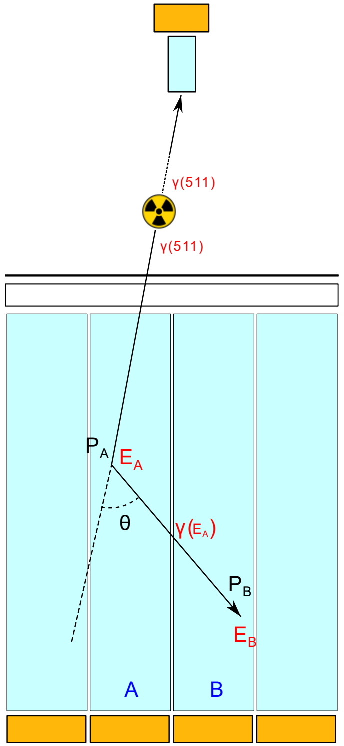
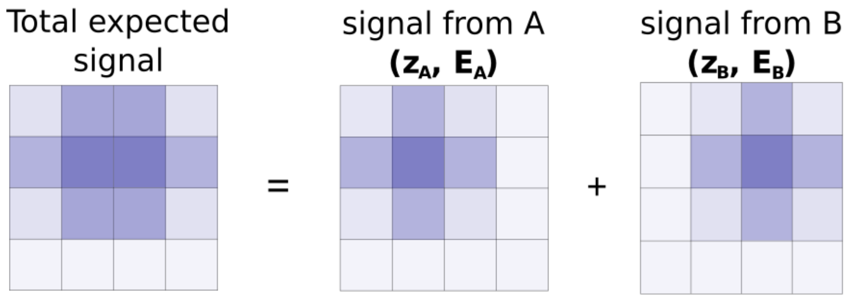


3. **Determination of the (z, E)** combination that **best reproduces the signals measured on the SiPM** for both cases (A → B) and (B → A)



For each SiPM k, the expected charge is calculated as $q_k(z_A^h, z_B^r) = q_k^A + q_k^B$

And it is compared to the measured charges p_k $\chi^2 = \sum_{k=1}^{K} \frac{(p_k - q_k)^2}{q_k}$

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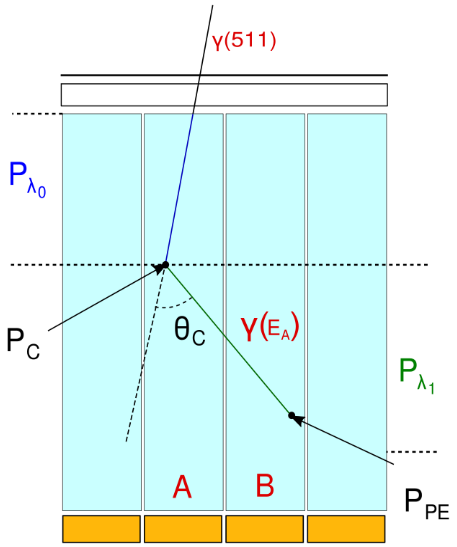

4. **Decide** what is more likely **between** the two cases **(A->B) or (B->A)**

For each case, the probability is calculated as:

$$P_\Lambda = P_{\lambda_0} \times P_C \times P_{\lambda_1} \times P_{PE} \times P_q$$

With P_q probability of the detected signal give the expected

The hypotesis with the highest probability between (A->B) or (B->A) is chosen

Inter-crystal scattering

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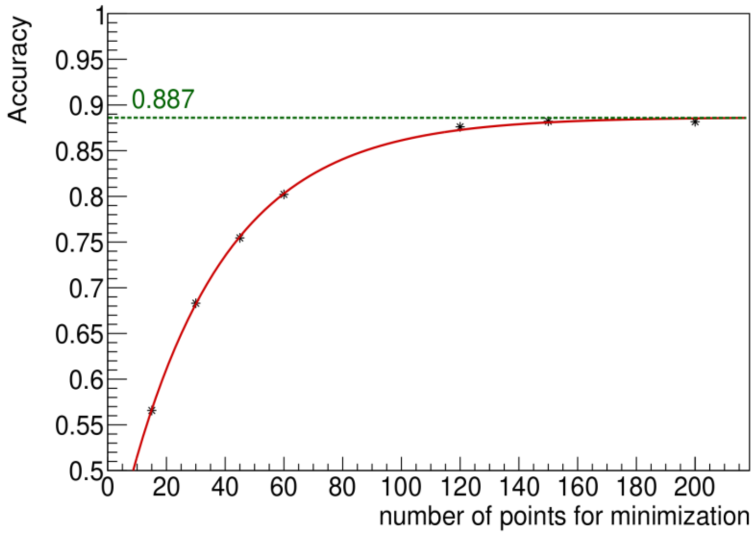
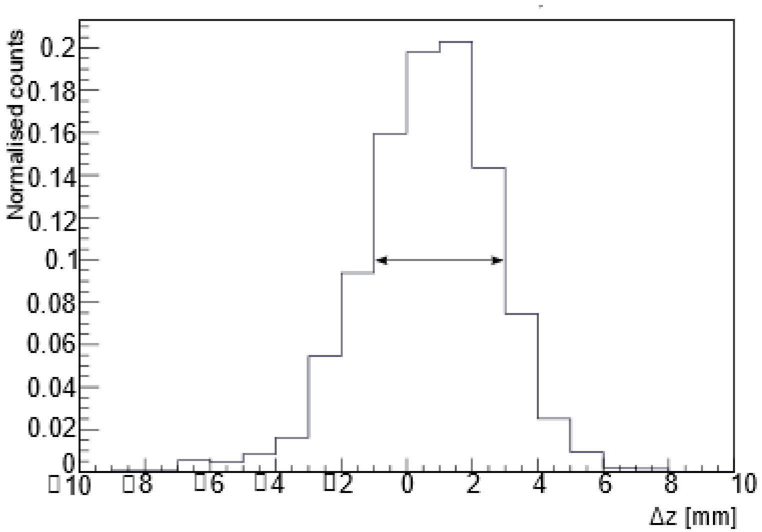


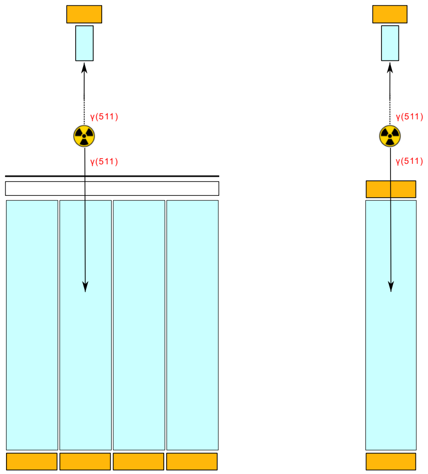
Accuracy = 89 ± 1 %



DOI res. = 4.6 ± 0.2 mm FWHM

Conclusions

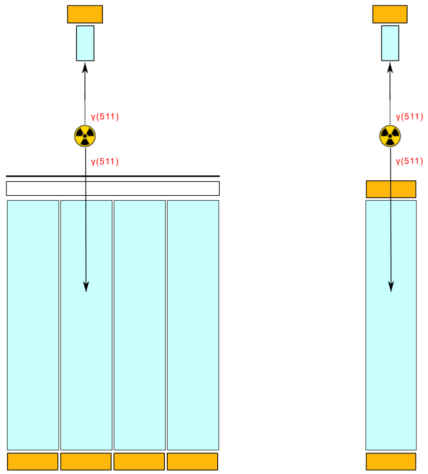
DOI capable detectors



LYSO	**DOI res. FWHM**
• Light-sharing matrix	**2.2 ± 0.2 mm**
• Double-sided readout	**1.6 ± 0.1 mm**

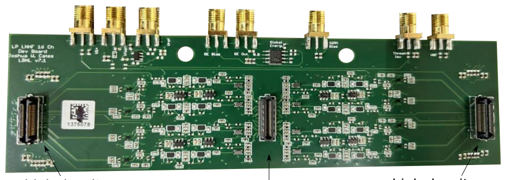
Conclusions

DOI capable detectors



LYSO	DOI res. FWHM
• Light-sharing matrix	**2.2 ± 0.2 mm**
• Double-sided readout	**1.6 ± 0.1 mm**

Low-noise low-power high-frequency electronics



HF-electronics to enhance time resolution

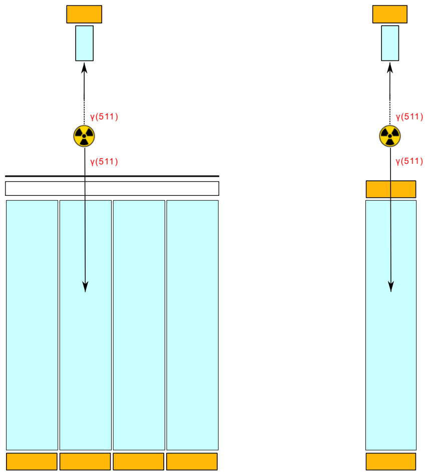
CTR corr. FWHM

LYSO

- **133 ± 2 ps**
- **103 ± 6 ps**

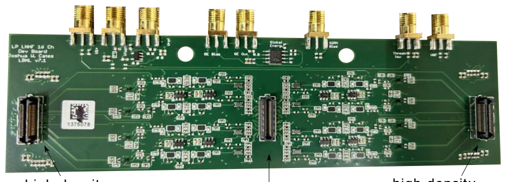
Conclusions

DOI capable detectors



LYSO	DOI res. FWHM
• Light-sharing matrix	2.2 ± 0.2 mm
• Double-sided readout	1.6 ± 0.1 mm

Low-noise low-power high-frequency electronics



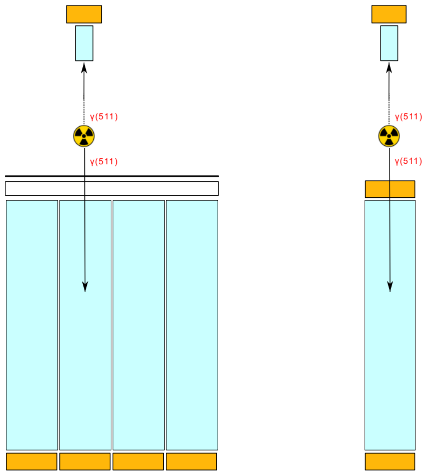
HF-electronics to enhance time resolution

CTR corr. FWHM

LYSO	BGO
• 133 ± 2 ps	362 ± 15 ps
• 103 ± 6 ps	370 ± 15 ps

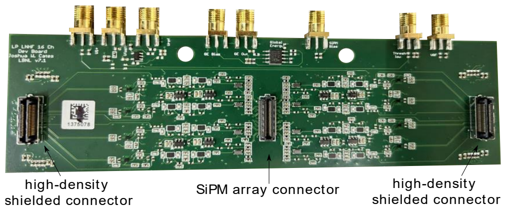
Conclusions

DOI capable detectors



LYSO	DOI res. FWHM
• Light-sharing matrix	**2.2 ± 0.2 mm**
• Double-sided readout	**1.6 ± 0.1 mm**

Low-noise low-power high-frequency electronics



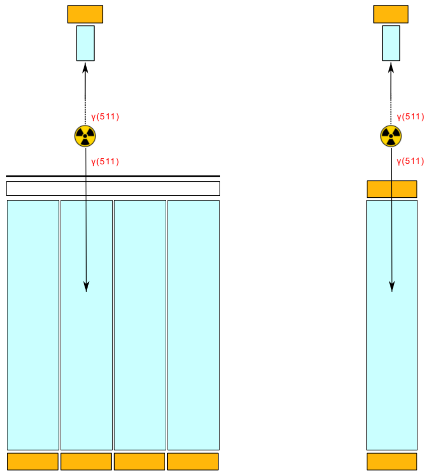
HF-electronics to enhance time resolution

CTR corr. FWHM

LYSO	BGO	Shared Het.
• **133 ± 2 ps**	**362 ± 15 ps**	**178 ± 6 ps**
• **103 ± 6 ps**	**370 ± 15 ps**	**151 ± 8 ps**

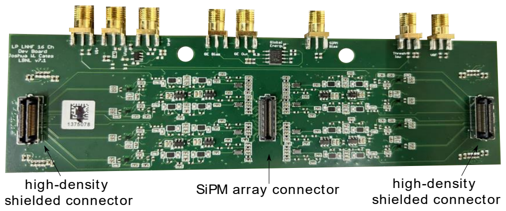
Conclusions

DOI capable detectors



LYSO	DOI res. FWHM
• Light-sharing matrix	**2.2 ± 0.2 mm**
• Double-sided readout	**1.6 ± 0.1 mm**

Low-noise low-power high-frequency electronics

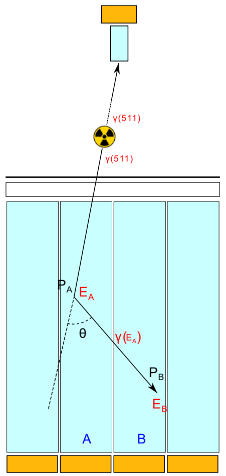


HF-electronics to enhance time resolution

CTR corr. FWHM

	LYSO	BGO	Shared Het.
•	**133 ± 2 ps**	**362 ± 15 ps**	**178 ± 6 ps**
•	**103 ± 6 ps**	**370 ± 15 ps**	**151 ± 8 ps**

Inter-Crystal scattering



- **90% accuracy** in selection of first crystal of interaction
- **4.6 ± 0.2 mm DOI resolution.**

Thank you for your attention!

Acknowledgements

This work is carried out in the framework of the Crystal Clear Collaboration.

It received support from CERN Austrian and Gentner (grant no. 13E18CHA) Doctoral Programmes and CERN Budget for Knowledge Transfer to Medical Applications.

The development of the readout boards is supported by the National Institute of Biomedical Imaging and Bioengineering under award R01EB028286.

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