New Radiation Detector Technologies for Time-of-Flight PET: Heterostructured Scintillators

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Work supported by CERN Knowledge Transfer for Medical Application

PET and TOF-PET

- **PET** = functional imaging technique that using radiotracers labeled with β^+ emitters to measure changes in metabolic processes
- β^+ decay $\rightarrow$ $e^+ - e^-$ annihilation $\rightarrow$ 2 back-to-back 511 keV γ-ray

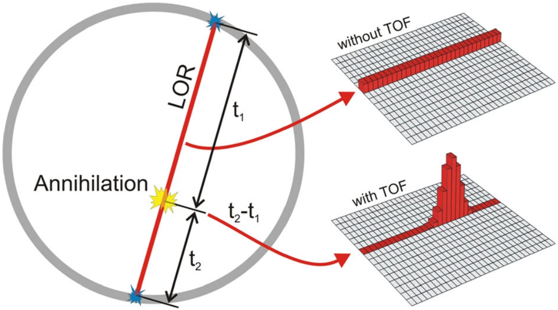

Figure: from: *10 ps Challenge webpage* (https://the10ps-challenge.org)

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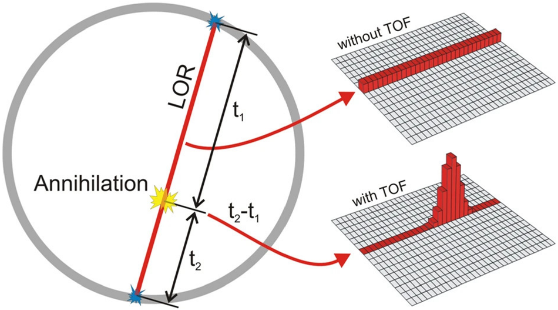

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Why **TOF-PET**?

- $SNR_{TOF} \propto \sqrt{\frac{1}{CTR}} \cdot SNR_{NON-TOF}$ [1]
  - ➜ Same SNR in shorter times or Better SNR in same time
  - ➜ Less delivered dose or Better image quality
  - ➜ Wider category of patients

[1] M. Conti 2009 Phys. Med. 25 1-11

Principle of Heterostructure in TOF-PET

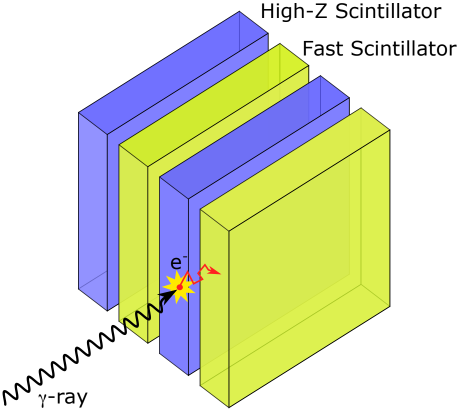


Figure: published in *F. Pagano et al (2022)*

Heterostructures are proposed as a solution to the dichotomy between **high sensitivity** and **fast timing** in TOF-PET [2] [3]

- Combination of two different materials with complementary properties
- The incident 511keV γ-ray is stopped most likely in the high-Z scintillator
- In a fraction of events the recoil photoelectron can deposit its energy in both materials (*Shared Events*)
- The more energy is deposited in the fast material, the more fast photons are produced

[2] ERC Advanced Grant TICAL (grant agreement No 338953, PI: P. Lecoq, CERN)

[3] R. Martinez Turtos et al 2019 Phys. Med. Biol. 64

BGO&Plastic Heterostructures

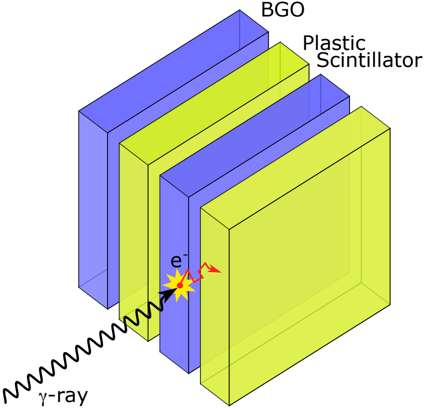


Figure: published in *F. Pagano et al (2022)*

BGO&Plastic Heterostructures constitute a simplified configuration allowing for a **comprehensive understanding** of the **fundamental properties** with experimental validation[4]

- ➜ Energy sharing
- ➜ Scintillation kinetics
- ➜ Timing improvement assessment
- ➜ Depth of Interaction (DOI) contribution

[4] F. Pagano et al 2022 Phys. Med. Biol.

Energy Sharing and Events Classification

Monte Carlo simulation on Energy Deposition

- **Photoelectric probability** for 511 keV γ-ray
- Fraction of **shared photopeak events**
- Mean **energy deposited in plastic**
  - ➜ Studied as a function of plastic thickness (keeping fixed BGO at 100 μm)
- The Photoelectric probability is compared to bulk BGO and LYSO

for $3\times3\times15\,\text{mm}^3$ pixels

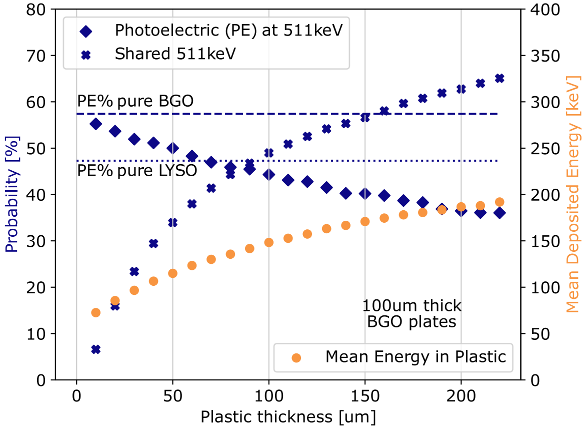
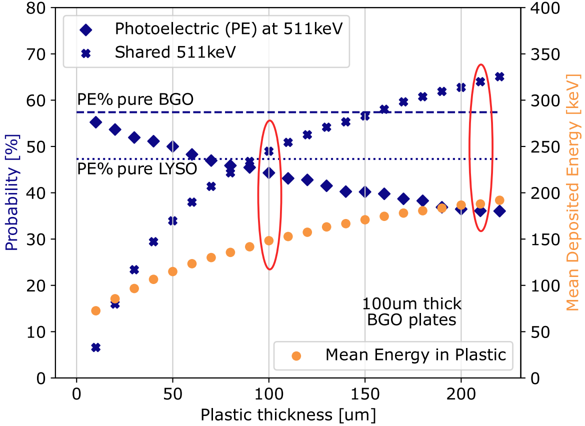


Figure: published in *F. Pagano et al (2022)*

Monte Carlo simulation on Energy Deposition

- **100 μm BGO and 100 μm plastic**
  - ➜ similar photoelectric probability to LYSO
  - ➜ almost 50% of photopeak events are shared
- **100 μm BGO and 200 μm plastic**
  - ➜ larger mean deposited energy in plastic
  - ➜ more shared photopeak events



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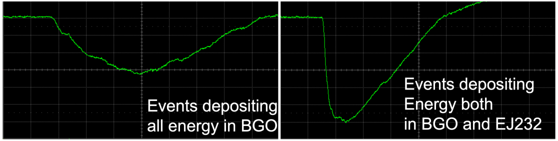
Events Classification based on Energy Sharing



➜ The different pulse shape of BGO and EJ232 enables events classification

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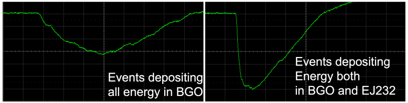

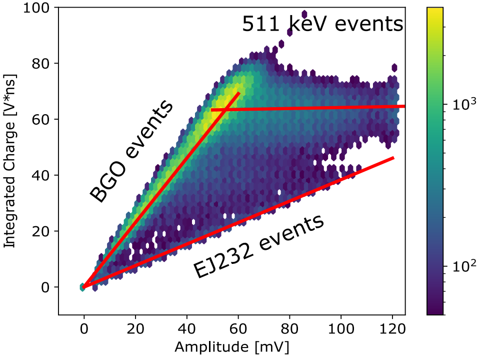

- → The different pulse shape of BGO and EJ232 enables events classification
- Correlation between integrated charge and amplitude to classify the events

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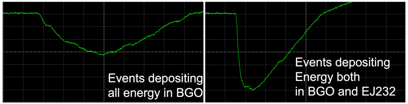

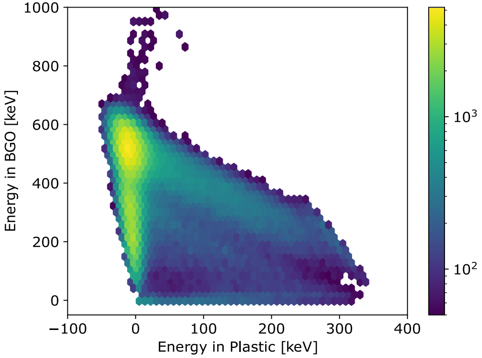

→ The different pulse shape of BGO and EJ232 enables events classification

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- Coordinate transformation to go from the (Amp, Charge) to the (BGO Energy, Plastic Energy) coordinate system

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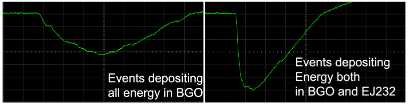

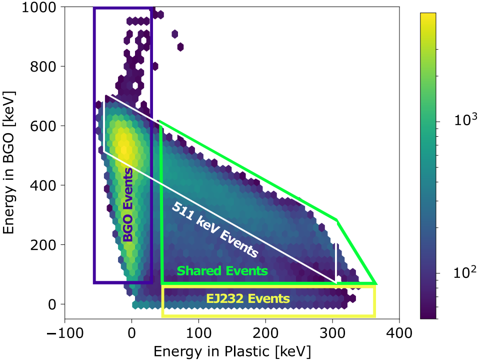

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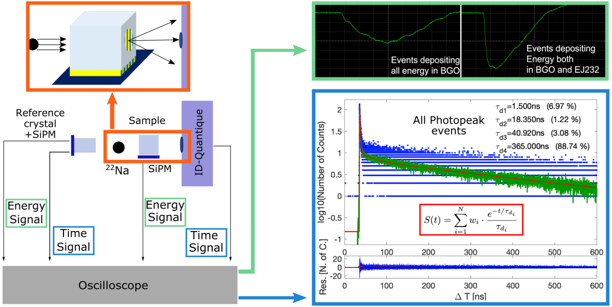
- Correlation between integrated charge and amplitude to classify the events
- Coordinate transformation to go from the (Amp, Charge) to the (BGO Energy, Plastic Energy) coordinate system
- **Photopeak events** $\rightarrow$ total reconstructed energy between [440,665] keV
  Shared photopeak events $\rightarrow$ photopeak events with at least 50 keV in EJ232

Impact of energy sharing on timing

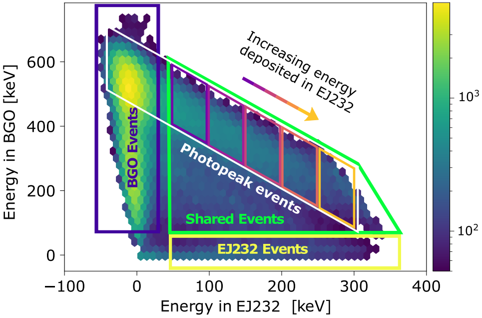
Time Correlated Single Photon Counting bench

- 3x3x3 mm^3 heterostructure with 200 µm thick plastic plates measured in Time Correlated Single Photon Counting (TCSPC) mode upon 511 keV irradiation[5]
- The experimental setup used allow to simultaneously record the TCSPC signal and the pulse shape event-by-event [6]



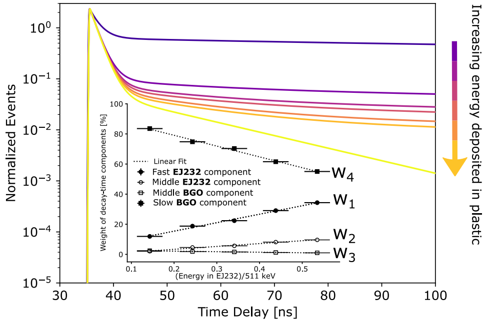
[5] F.Pagano et al, under review for IEEE TNS
[6] S. Gundacker et al 2016 Phys. Med. Biol. 61 2802

Modeling the Scintillation Kinetics



- The events were further classified according to the amount of energy deposited in EJ232

Modeling the Scintillation Kinetics



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- The scintillation time profile was analyzed for each class of events

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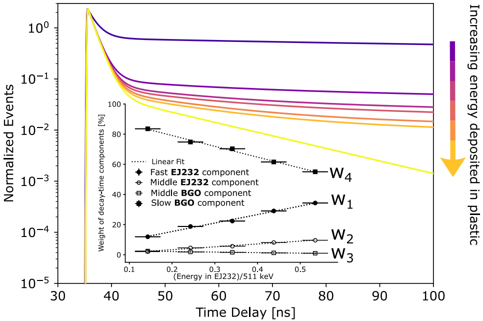
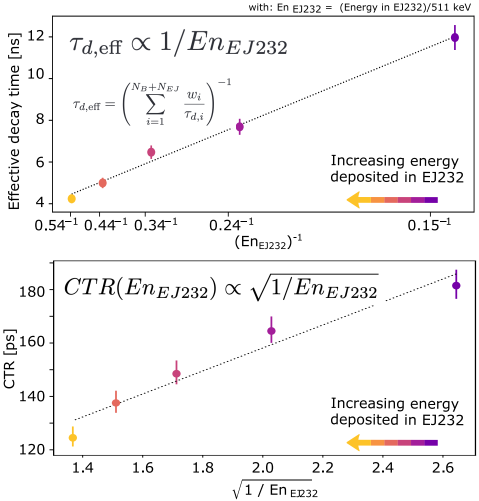


- The events were further classified according to the amount of energy deposited in EJ232
- The scintillation time profile was analyzed for each class of events

➜ Experimental proof that the scintillation kinetics of heterostructures is given by the **linear combination** of the scintillation kinetics of the constituent materials, **weighted by the energy deposited in each**

$$S_H(t) = S_{EJ}(t) \cdot w_{EJ} + S_{BGO}(t) \cdot w_{BGO}, \qquad \text{with} \quad S_x(t) = \sum_{i=1}^{N} \frac{e^{t-\tau_{d,i}}}{\tau_{d,i}} \cdot w_i$$

Timing vs Energy Deposited in Plastic



➜ Linear dependency between

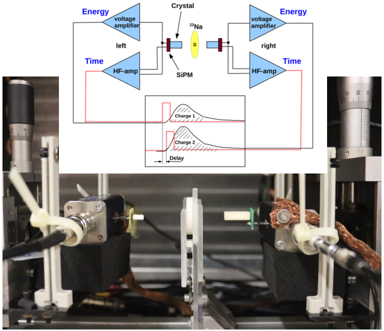
- **Effective decay time** ($\tau_{d,\mathrm{eff}}$) and the inverse of the **fraction of energy deposited in EJ232** (over the total 511 keV)
- **Coincidence time resolution** (CTR) and the square root of the inverse of the **fraction of energy deposited in EJ232** (over the total 511 keV)

CTR improvement from bulk BGO to BGO&EJ232 Heterostructures

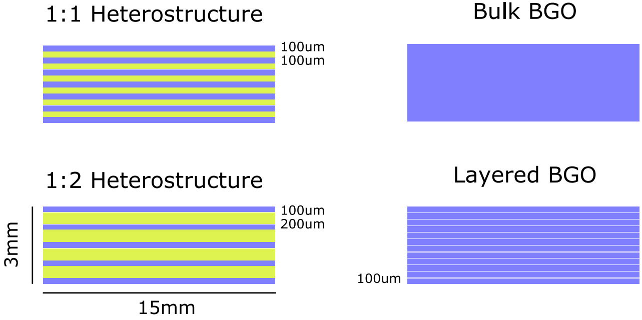
Coincidence Time Resolution

➜ Timing improvement of heterostructures compared to BGO via CTR measurements

High Frequency electronics[7,8]



Samples

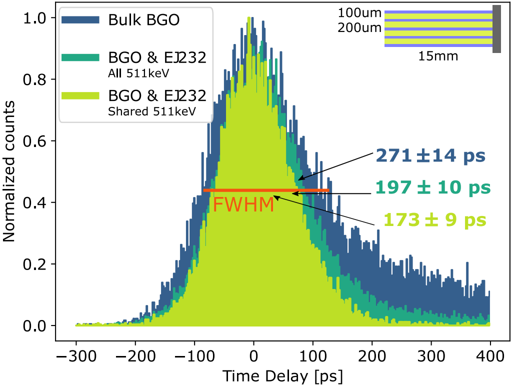


[7] J. Cates et al 2018 Phys. Med. Biol. 63
[8] S. Gundacker et al 2019 Phys. Med. Biol. 64

Heterostructures vs BGO

CTR [ps][9]	bulk BGO	layered BGO	100 μm EJ232	200 μm EJ232
All 511 keV	271 ± 14	303 ± 15	239 ± 12	197 ± 10
Shared 511keV	//	//	214 ± 11	173 ± 9

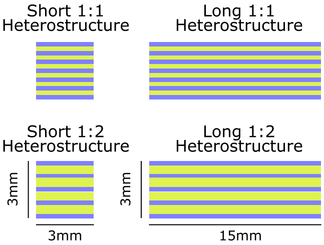
- ➜ The CTR gets worse passing from bulk to layered BGO
- ➜ It significantly improves when introducing EJ232



[9] F.Pagano et al 2022 Phys. Med. Bio. 67

Effect of Depth of Interaction (DOI) Uncertainty on Timing

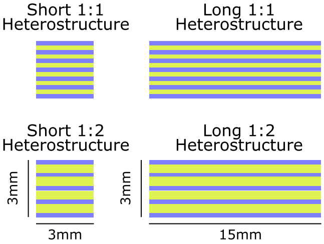
Short vs Long Heterostructures



CTR [ps]	100 μm EJ232		200 μm EJ232	
	short	long	short	long
All 511 keV	155 ± 8	239 ± 12	142 ± 7	197 ± 10
Shared 511keV	126 ± 6	214 ± 11	114 ± 6	173 ± 9

- ➜ Short pixels perform about **80 ps better** than long ones
- ➜ Light transport worsens with crystal length

Short vs Long Heterostructures



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- DOI measurements (collimated side irradiation measurements) to estimate CTR blurring due to **DOI uncertainty**

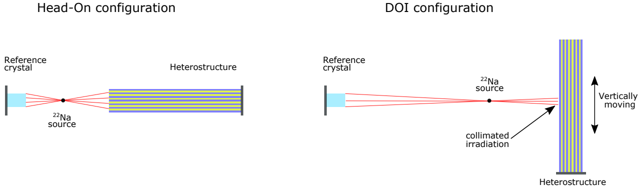


Figure: published in *F. Pagano et al (2022)*

Modeling DOI contribution

- DOI contribution modeled as difference between the shift of time delay peak (Δdt) and the time the γ-ray takes to go from the 1st to 5th DOI (t_γ)

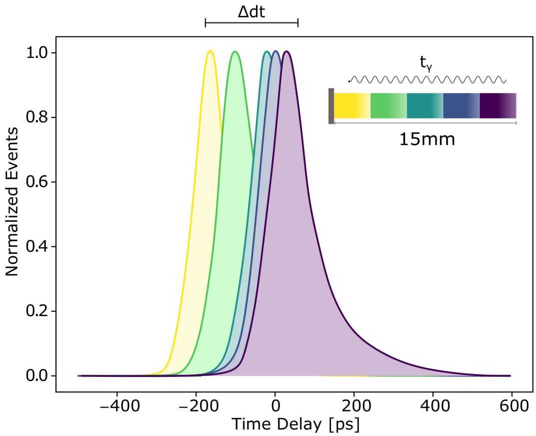


Figure: *F. Pagano et al, Phys. Med. Biol. 67 (2022)*

Modeling DOI contribution

- DOI contribution modeled as difference between the shift of time delay peak (Δdt) and the time the γ-ray takes to go from the 1st to 5th DOI (t_γ)
- Assuming the small pixel unaffected by DOI blurring, the DOI contribution was added quadratically to the measured CTR of the small pixel

$$CTR_{HeadOn,15mm} = \sqrt{CTR^2_{3mm} + (\Delta dt - t_\gamma)^2}$$

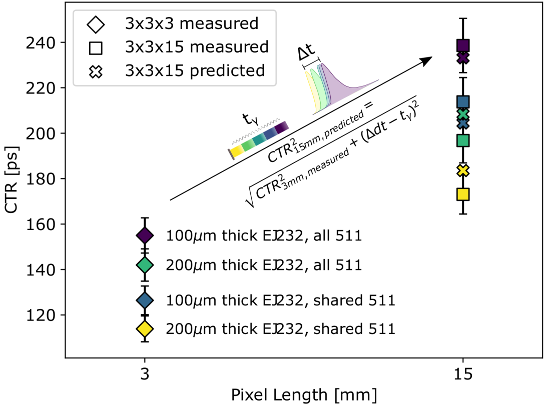


Figure: *F. Pagano et al, Phys. Med. Biol. 67 (2022)*

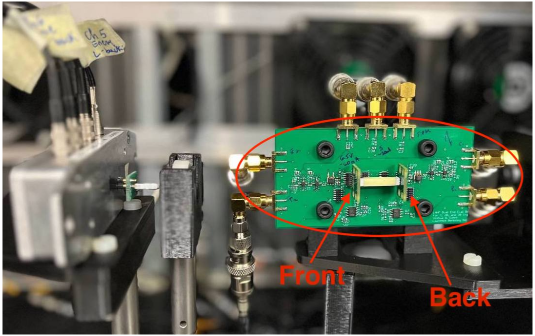
How to compensate for DOI effect?

Double-sided Readout

- Double-sided readout[10] (DSR) allows to:
  - increase the light collection
  - compensate for DOI uncertainty by averaging the timestamps of back and front SiPM

$$CTR = t_{ref} - \frac{t_{back} + t_{front}}{2}$$

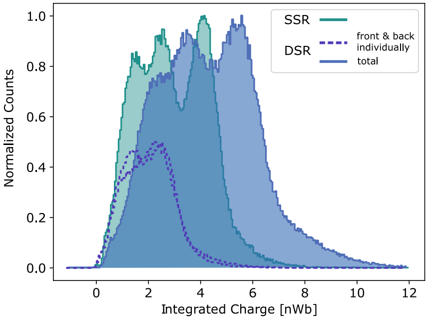
→ Improve timing!



Measurements performed on a $3\times3\times20\,\text{mm}^3$ heterostructure with both BGO and EJ232 plates 250 μm thick, purchased from CPI crystal

[10] HF circuit designed at Lawrence Berkeley National Laboratory

Single vs Double-sided Readout



- Based on the increased light output we expect at least a CTR improvement of **15%**

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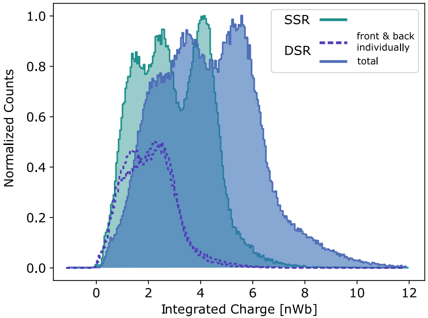
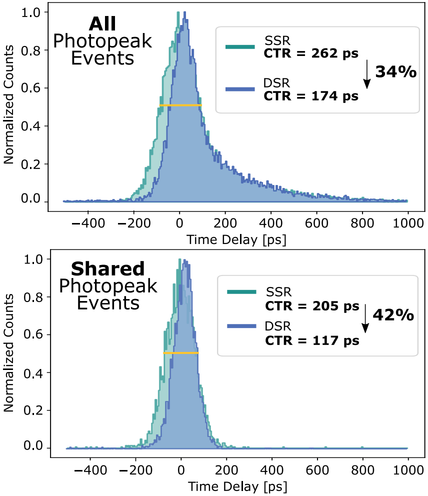


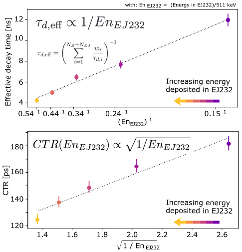


- Based on the increased light output we expect at least a CTR improvement of **15%**
- The measured improvement is greater
  - ➜ Averaging the timestamp of back and front SiPM compensates for DOI effect*

* Other CTR estimators were tested without further improvement. This topic will be presented in detail at IEEE MIC&NSS 2023

Summary & Conclusion

Approaching a full understanding of heterostructures



Analytical model to describe scintillation kinetics and CTR

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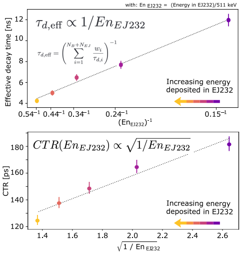

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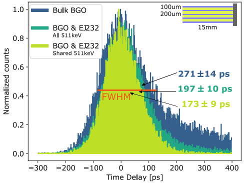

Improved timing performances compared to bulk BGO

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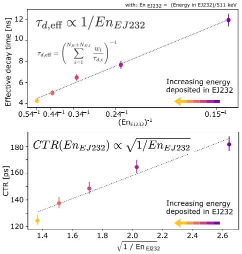

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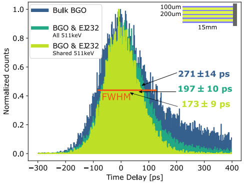

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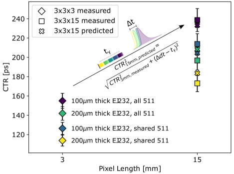

Analytical model to describe PTS due to DOI blurring

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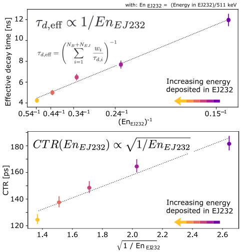

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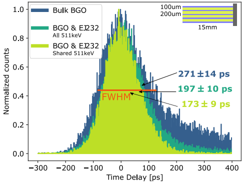

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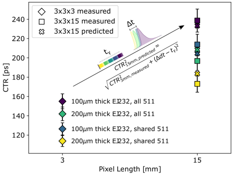

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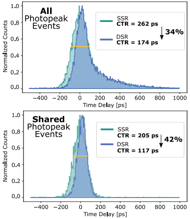
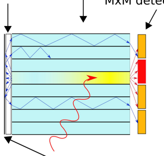


DSR significantly improved the CTR

➜ averaging back and front SiPM, up to 42 %

Outlook

Matrix of Heterostructure with HF readout



- DSR gives an insight on its performances of when using light sharing method [10] to extract and correct for DOI

➜ Measurements start soon!

[10] M. Pizzichemi et al 2019 Phys. Med. Biol. 64

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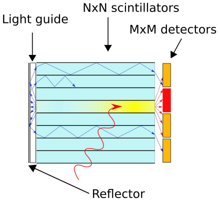

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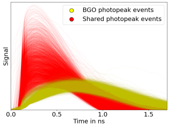
New Techniques for Events Classification



- Amp&Ch are not both available in many multi-channel readout system
- Coordinates transformation not applicable at system level

➜ Machine Learning algorithms applied to different features are being investigated

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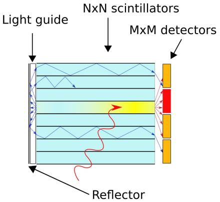

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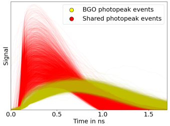

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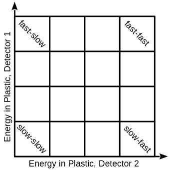
Multi-Kernel Approach for Image Reconstruction



- Depending on how the energy is distributed between the two materials, a different CTR distribution will result [11]

➜ It can be exploited in imaging reconstruction using a multi-kernel approach[12]

[10] M. Pizzichemi et al 2019 Phys. Med. Biol. 64
[11] N. Kratochwil et al 2021 Phys.Med.Biol. 65
[12] P. Mohr et al 2022 IEEE TRPMS

New Radiation Detector Technologies for Time-of-Flight PET: Heterostructured Scintillators

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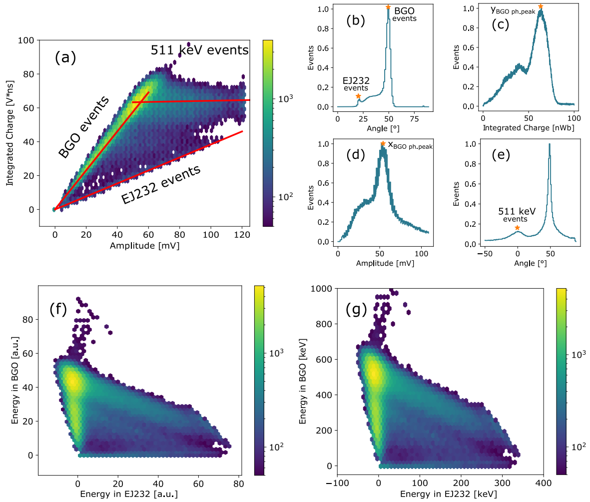
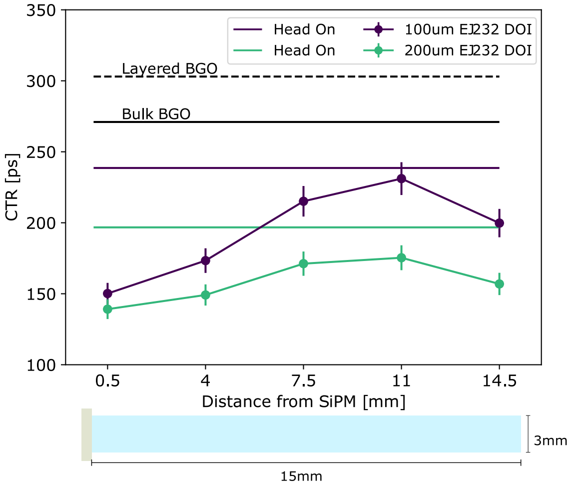
Backup Slides – Events Selection

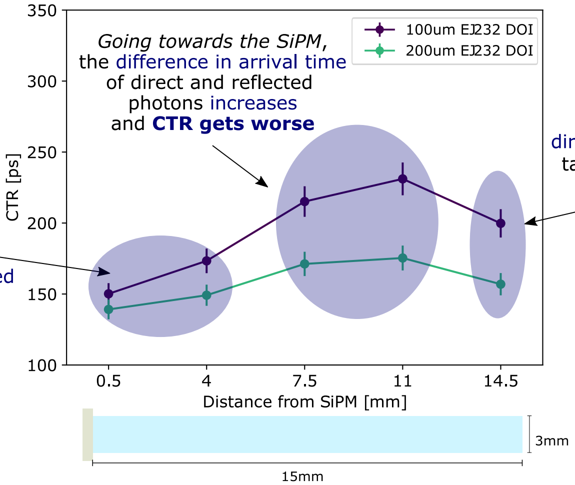


Backup Slides – DOI results



Backup Slides – DOI results

Close to the SiPM,
difference in arrival times
in maximum, but because of
significant attenuation
only direct photons are detected
and **CTR improves**



Far from SiPM,
direct and reflected photons
take about the same time
to reach the SiPM

Backup Slides – Bulk vs Layered vs Heterostructure: Role of DOI

Comparison of the time delay peak shift between heterostructures, bulk and layered BGO

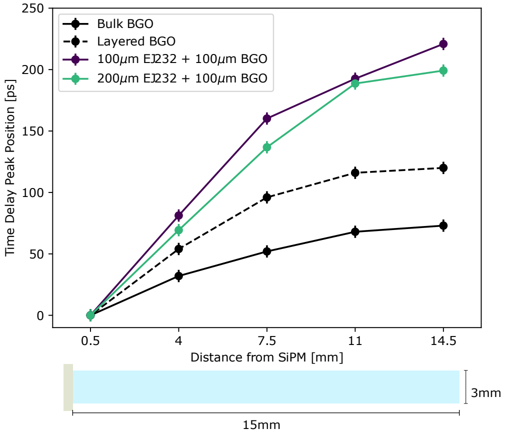


Figure: *F. Pagano et al, Phys. Med. Biol. 67 (2022)*

- In layered BGO the shift is almost double the one in bulk BGO
- reflected in CTR degradation

	bulk BGO	layered BGO	100 μm EJ232	200 μm EJ232
CTR [ps]	271 ± 14	303 ± 15	239 ± 12	197 ± 10

→ CTR of long heterostructures is highly dominated by poor light transport