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

CERN KT Medical Application projects: Development of TOF-PET modules toward 10 ps time resolution

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14th September 2022

Principle of Heterostructures in TOF-PET [1]

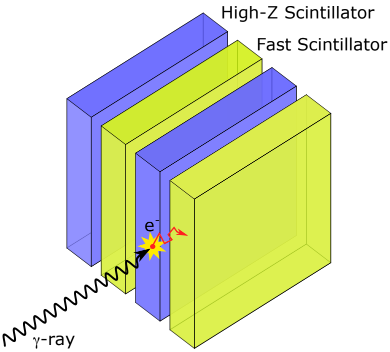
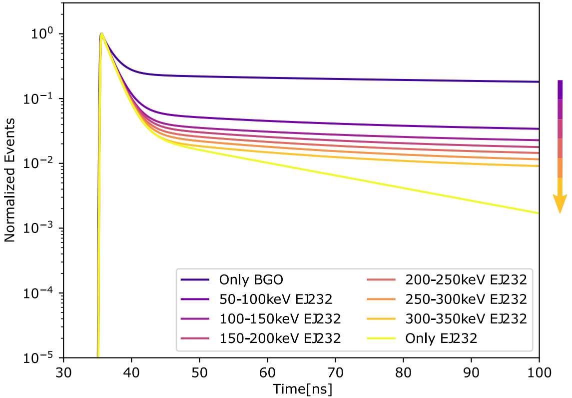


Figure: adapted from *F. Pagano et al, Phys. Med. Biol. 67 (2022)*

- Combination of two different materials with complementary properties
  → **BGO** and **EJ232** plastic scintillators in our preliminary studies
- 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

[1] R. Martinez Turtos et al 2019 Phys. Med. Biol. 64,
ERC Advanced Grant TICAL (grant agreement 338953, PI: P. Lecoq, CERN)

Energy Sharing



- The scintillation kinetics of heterostructures in first approximation can be modeled as

$$S(t)_H = E_P \cdot S(t)_P + (1 - E_P) \cdot S(t)_B$$

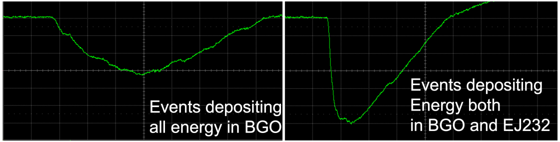
$S(t)_{H,P,B}$ = intrinsic scintillation function (sum of exponential) of heterostructure, plastic, BGO

E_P fraction of energy deposited in plastic (over 511 keV)

Selecting the events according to the amount of energy deposited in BGO and plastic
$\Longrightarrow$ The decay time gets faster as the amount of energy deposited in plastic increases

Classifying events based on energy sharing

The events selection is possible due to the different pulse shape of the BGO and EJ232



- LY BGO ≈ LY EJ232 = 8-10 ph/keV
- $\tau_{d,\mathrm{eff}}$ BGO = 130 ns **vs** $\tau_{d,\mathrm{eff}}$ EJ232 = 1.5 ns

LY = light yield

$\tau_{d,\mathrm{eff}}$ = effective decay time

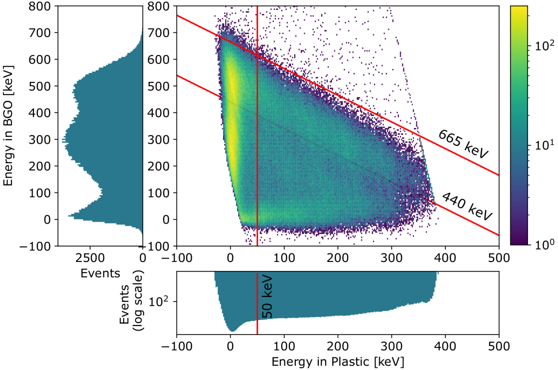


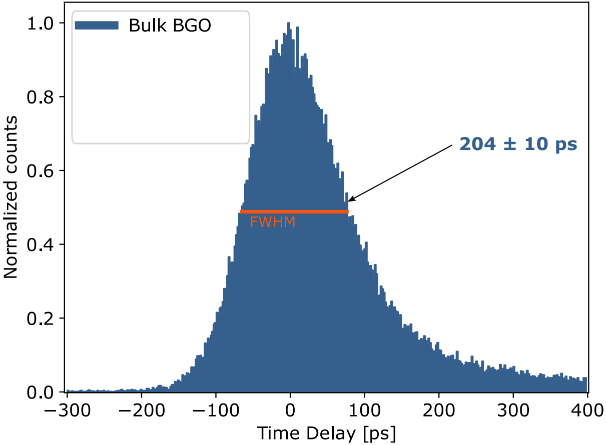
Figure: *F. Pagano et al, Phys. Med. Biol. 67 (2022)*

- **All 511 keV**: 440 keV $< En_{BGO} + En_{EJ232} <$ 665 keV
- **Shared 511 keV**: All 511 keV + $En_{EJ232} >$ 50 keV

Bulk BGO vs BGO & EJ232 heterostructure

Significant **improvement in CTR** (coincidence time resolution) when passing from bulk BGO $\Longrightarrow$ BGO&EJ232* heterostructure

* both $3 \times 3 \times 3\,mm^2$, heterostructures made up of alternating plates of $100\mu m$ thickness



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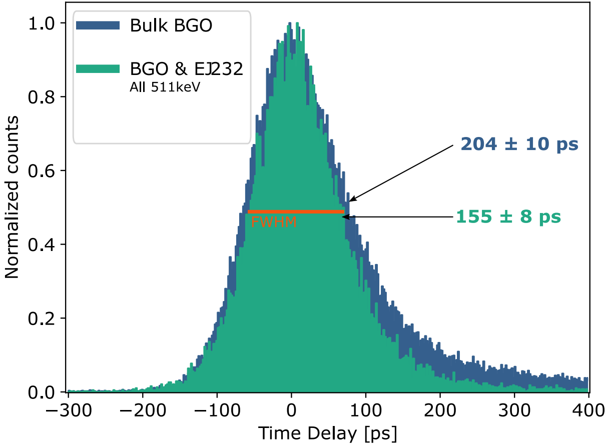

* both $3 \times 3 \times 3\,\text{mm}^2$, heterostructures made up of alternating plates of 100μm thickness

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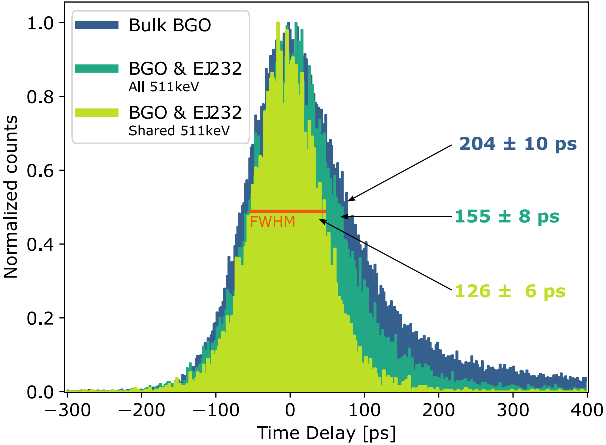

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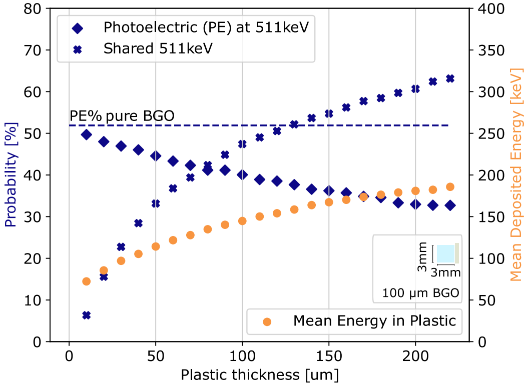
Compromise between timing and sensitivity

One of the main parameters defining the performances of heterostructures is the volume ratio between the two materials

- The greater the fraction of volume occupied by the fast material, the higher
  - → the percentage of shared events
  - → the energy here deposited
  - ⇒ more fast photons produced

  ... and the lower the stopping power



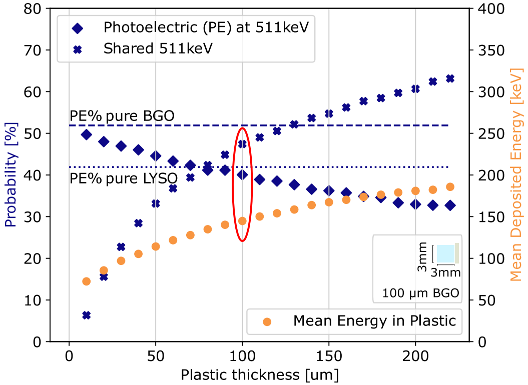
Monte Carlo simulations (Geant4) on energy deposition in heterostructures according to plastic thickness

Compromise between timing and sensitivity

One of the main parameters defining the performances of heterostructures is the volume ratio between the two materials

- Aim of heterostructures: improving time resolution without loosing in sensitivity
- **100μm thick BGO + 100μm thick plastic** has comparable sensitivity to LYSO, standard crystal used in TOF-PET scanner

⇒ We used this criterion to choose the optimal configuration

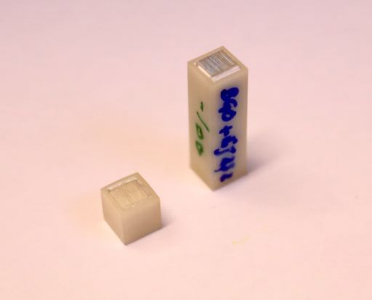


Monte Carlo simulations (Geant4) on energy deposition in heterostructures according to plastic thickness

Transition from short to long pixels

- Another way to increase sensitivity is to increase the pixel length
- Crystal length in PET scanner is 15-30 mm
- The longer the crystal, the greater the depth-of-interaction (DOI) uncertainty

$\Longrightarrow$ Worse timing



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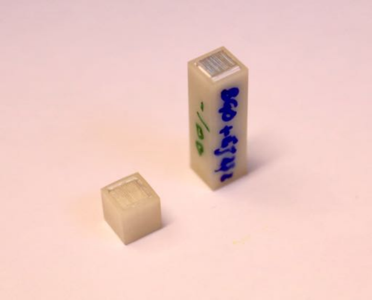


CTR [ps]	100 μm EJ232	
	$3\times3\times$**3** mm^3	$3\times3\times$**15** mm^3
All 511 keV	155 ± 8	239 ± 12
Shared 511keV	126 ± 6	214 ± 11

Short pixel performs about **80 ps better** than long one
$\longrightarrow$ due to different light transport

Impact of DOI on CTR

By irradiating collimated DOI, a correlation between CTR and DOI is observed

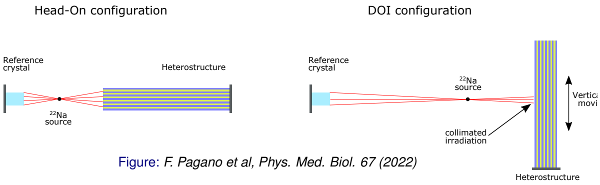
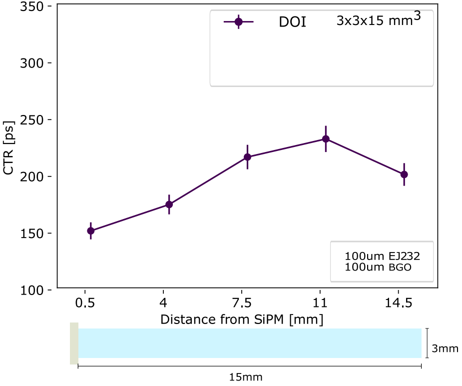


Figure: *F. Pagano et al, Phys. Med. Biol. 67 (2022)*



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Two waves of photons reach the SiPM: **direct** and **reflected** and the time difference with which they reach the SiPM depends on the DOI

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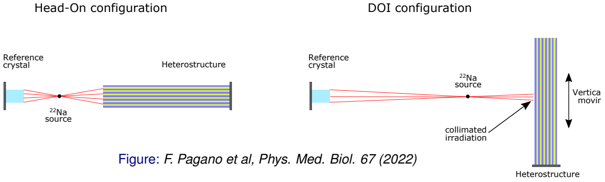

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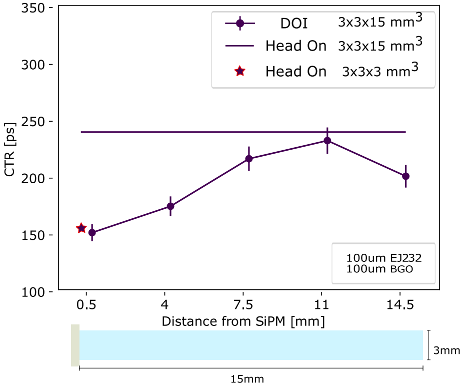

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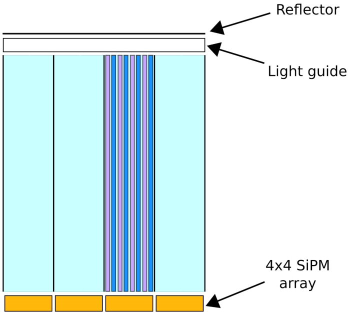
Two waves of photons reach the SiPM: **direct** and **reflected** and the time difference with which they reach the SiPM depends on the DOI

- The short pixel showed comparable CTR to the one at the DOI closest to the SiPM
- In the long pixel, all the DOI sum up and the CTR is worse than the one at single DOIs

TOF-PET module with DOI correction

- Correcting for DOI contribution by using light sharing method[2] can improve timing while keeping long crystal
- Feasibility study with 1 heterostructured pixel (LYSO + BC422 plastic scintillator) in bulk LYSO matrix[3]

	Layered LYSO* LYSO pol.	BC422 + LYSO
CTR_{NOcorr} [ps]	233 ± 3	346 ± 5
CTR_{corr} [ps]	200 ± 3	181 ± 3



* stack of LYSO plates for comparison

⇒ An improvement up to 160 ps was obtained

⇒ The module with BC422+LYSO heterostructure performs better than the one with layered LYSO

∗ Study carried out under previous KT project: *Development of new PET module*, See previous presentation by M. Pizzichemi

[2] M. Pizzichemi et al, 2016 Phys. Med. Biol. 61

[3] M. Pizzichemi et al, 2019 IEEE NSS/MIC conference

Towards TOF-PET module with Heterostructures

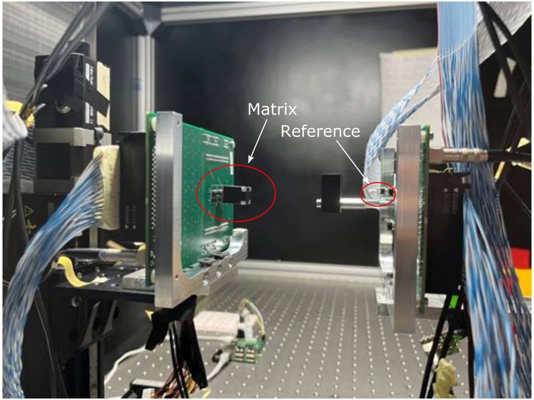


Figure: PET demonstrator developed in the frame of KT project

- The next step will be to measure a **4×4 matrix of heterostructured pixels**

Towards TOF-PET module with Heterostructures

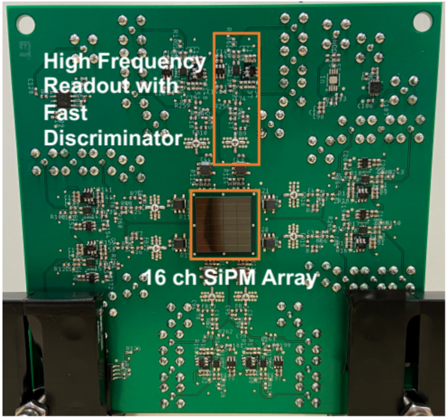


Figure: Developed by J. W. Cates from Lawrence Berkeley National Laboratory, Berkeley. See *J. W. Cates et al (2022) Sensor 22*

- The next step will be to measure a **4×4 matrix of heterostructured pixels**
- Work is ongoing to upgrade the PET demonstrator
  - $\rightarrow$ optimized **16 channels readout electronics for fast pulses** in collaboration with several groups [4]

$\ast$ Part of the PhD project of Giulia Terragni, PhD student at CERN Crystal Clear

[4] CERN/UB Barcelona, LBNL Berkeley, RWTH PMI Aachen

Image Reconstruction with GATE

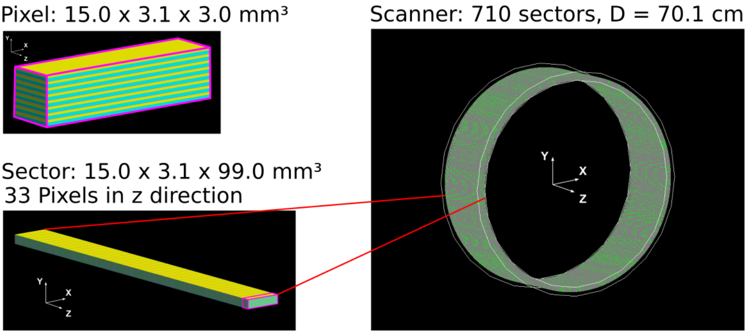


Figure: *P. Mohr et al 2022 IEEE Trans. Radiat. Plasma Med. Sci.*

- The effectiveness of heterostructures approach evaluated performing image reconstruction
- A new reconstruction framework based on GATE was developed to investigate this new detector designs

$\ast$ Master thesis project of Philipp Mohr, RWTH Aachen, Germany
now at University Medical Center Groningen, Netherlands

Image Reconstruction with GATE: First results

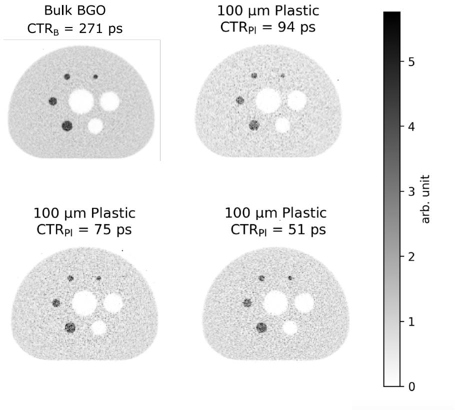


Figure: adapted from *P. Mohr et al 2022 IEEE Trans. Radiat. Plasma Med. Sci.*

- Visible improvement of the image quality (lower noise) with better CTR of plastic
- The image quality of bulk BGO resulted better then heterostructures because of better sensitivity

⇒ Faster and denser emitter than plastic scintillators must be used

∗ This work will be continued by Carsten Lowis, a PhD student at CERN Crystal Clear group

Nanomaterials replacing plastic scintillators

Benefiting from quantum confinement, nanomaterials can show ultra-fast emission

Scintillation decay of CsPbBr3 nanocrystals embedded in polysterene (10% filling factor) produced at CTU, Prague

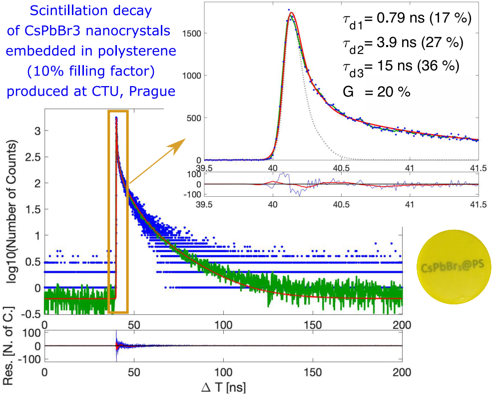


Figure: *K. Děcká, et al, Jour. Mat. C (2022)*

However, they generally have low stopping power

→ Preventing from using them as stand-alone detector

⇒ **Good candidate for heterostructures!**

- Work within Crystal Clear to develop and improve various nanomaterials [5]

→ Difficult to characterize their time resolution with standard techniques (511 keV γ-ray in coincidence)

⇒ We developed an experimental setup to measure **time resolution under pulsed X-ray**

[5] CERN, CTU, FZU, Cranfield, Ghent, ILM, UNIMIB

Experimental setup to better guide the R&D on nanomaterial [6]

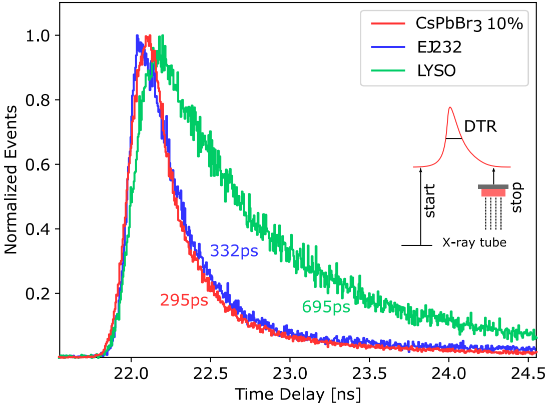


Figure: *K. Děcká, et al, Jour. Mat. C (2022)*

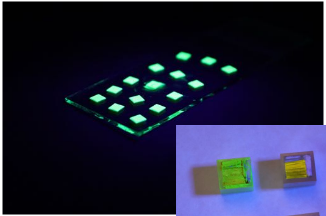
- The **sample** is coupled to a SiPM and excited with soft (0-40 keV) pulsed X-Ray
- The **time delay** between **SiPM output** and the **external trigger** of the laser triggering X-ray is measured
- Detector time resolution (DTR) $\Rightarrow$ FWHM of the time delay peak

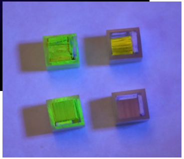
By measuring time resolution upon X-ray irradiation, we can predict it at higher energies and guide their development
$$CTR \propto 1/\sqrt{Energy}$$

[6] F. Pagano et al, under review in Frontiers in Physics

Preliminary test of heterostructure with $CsPbBr_3$

Preliminary tests with heterostructures with nanomaterials replacing plastic within the Crystal Clear Collaboration[7]





⟸ Stack of BGO or GAGG plates with a layer of $CsPbBr_3$ nanoscintillator deposited on top, produced at CTU, Prague [8]

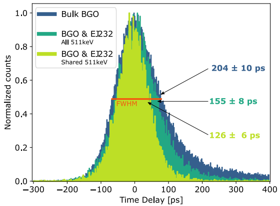
- The strong self-absorption of these materials prevented from observing energy sharing

- Joint work within the CCC to make these materials suitable for this application

[7] CERN, CTU, FZU, Cranfield, Ghent, ILM, UNIMIB

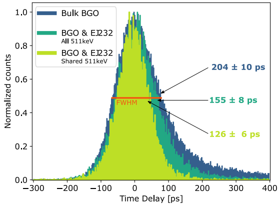
[8] K. Děcká, J. Král, E. Mihóková, V. Čuba

Conclusion and Outlook



Improved timing performances compared to bulk BGO

Conclusion and Outlook



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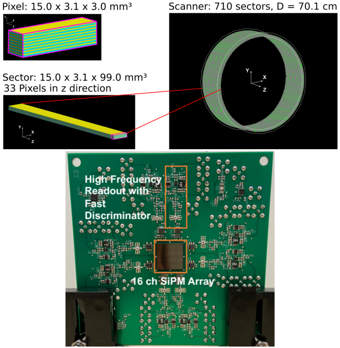
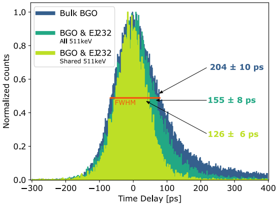


First steps toward heterostructures-based system

Conclusion and Outlook



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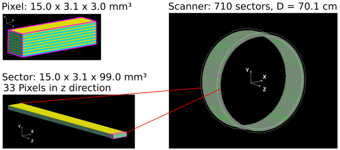
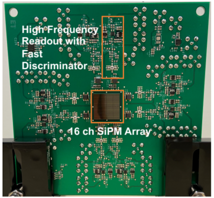




First steps toward heterostructures-based system

First steps toward new generation of heterostructures with nanoscintillators

Thank you for your attention and I welcome any questions!

Acknowledgment

This work was carried out in the frame of the Crystal Clear Collaboration, based on the concept initiated in the framework of the ERC Advanced Grant TICAL (grant agreement No 338953, PI: P. Lecoq, CERN) funded by the European Research Council. It received support from the CERN Budget for Knowledge Transfer to Medical Applications

Backup Slides – Coincidence Time Resolution (CTR) Bench

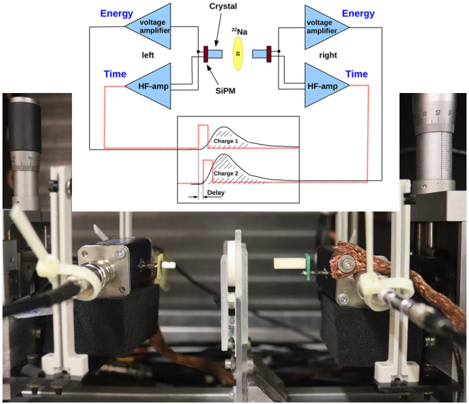


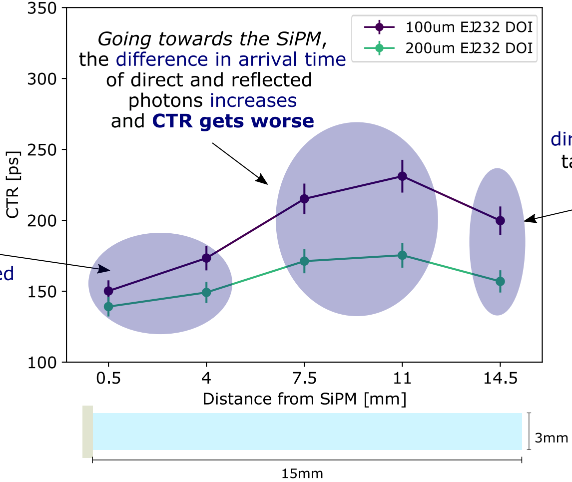
Figure: Schematic representation of the setup from[6]

- Heterostructure in coincidence with a reference crystal (LSO:Ce:0.4%Ca)
- SiPMs NUV-HD technology
  - FBK 3 × 3 mm for the reference
  - Broadcom 3.7 × 3.7 mm for heterostructure
- Optimized custom made electronics readout[9]:
  - High Frequency electronics for the time signal
  - Analog amplifier for energy signal

[9]Stefan Gundacker et al 2019 Phys. Med. Biol. 64

Backup Slides – DOI explanation

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