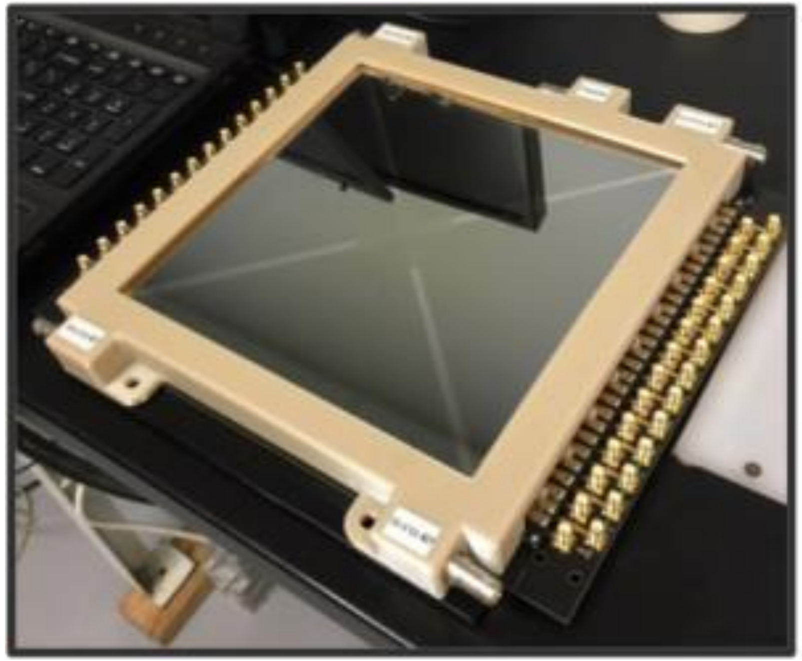
Two Modest Proposals for TOF-PET with LAPPD Readout

Bill Worstell
PicoRad Imaging, LLC
7/23/2019



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Requirement/Marching Orders:

Fwd: opportunities for funding by BRAIN Initiative

Inbox ×

stanimager .

to Simon, Jinyi, Michael, me, Stanislaw

Mon, Jul 22, 9:02 PM (13 hours ago)

Dear Gentlemen,

In view of the attached message below, the September 3 deadline seems to be potentially (one of) the last opportunity(ies) for a submission of the concept of fast high resolution detector based on LAPPDs to the Brain Initiative program. While we thought about slower process of implementation, Jinyi was right to suggest to go for the technique development and NOW.

If we could show in submission that we could be achieving "... *dramatically improved spatiotemporal resolution* " applicable " *to current human neuroimaging, preferable at mesoscale level* which emphasizes pushing the spatial resolution to very low levels (at the cost of lower sensitivities ....) "

Can we talk about 50 ps and 1 mm resolutions as potentially possible ? (at the expense of sensitivity ?)
Let us explore tomorrow during our call this unique and timely opportunity for LAPPD technology. Thank you.

Best regards.

Stan

PicoRad "LightSpeed" TOF-PET Detector Module Design For Time-of-Flight Positron Emission Tomography

Resolving individual Compton Scatter and Photocapture interactions' Space-time coordinates with precision

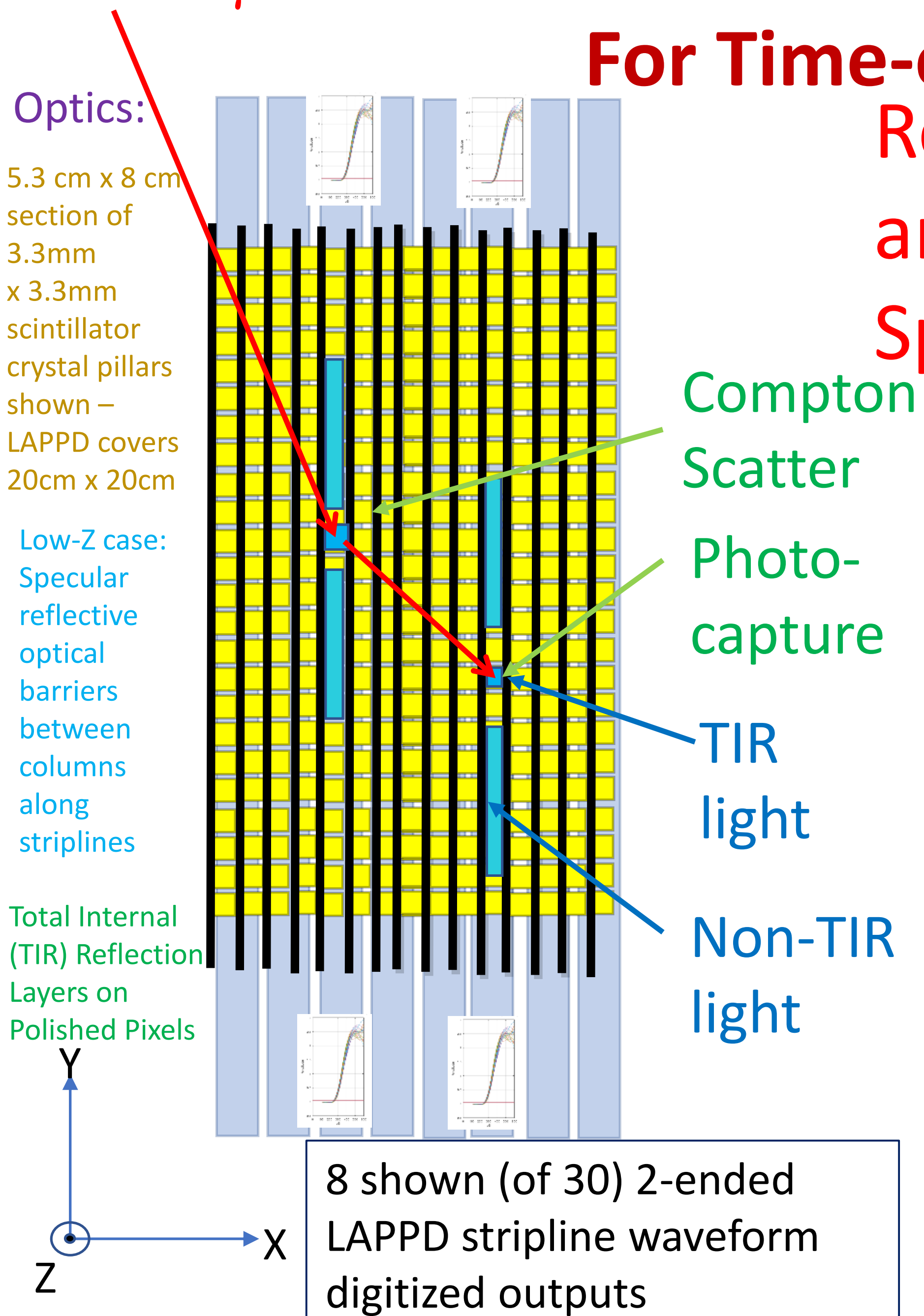
511 keV γ

Optics:

5.3 cm x 8 cm section of 3.3mm x 3.3mm scintillator crystal pillars shown – LAPPD covers 20cm x 20cm

Low-Z case: Specular reflective optical barriers between columns along striplines

Total Internal (TIR) Reflection Layers on Polished Pixels



8 shown (of 30) 2-ended LAPPD stripline waveform digitized outputs

δX: ~1mm FWHM

δY: ~1mm FWHM

δZ: ~2mm FWHM?

δT: <50pS FWHM REQUIRED

δE/E: <10%

X: From striplines position (centroid)

Y: From leading edge time difference

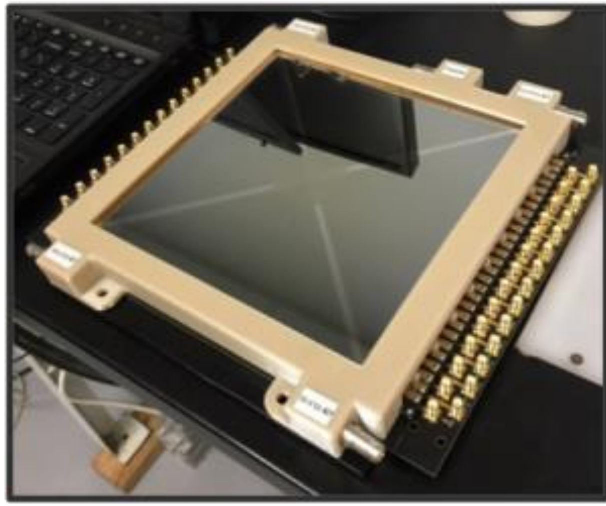
Z: From Non-TIR Y distribution of SPEs

T: From leading edges

E: From pulse amplitudes

Low-Noise Fast LAPPD Signals

Low Readout Channel Count/Cost



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Consistent with several Scintillator- or Cherenkov- (or mixed) TOF-PET Designs, with their associated Event Light Source Optics

- BGO (Cherenkov Fast, BGO Slow)
- LaBr (Cherenkov Fast, LaBr "Slow")
- BaF2(BaF2 Fast, BaF2 Slow)
- LYSO(Cherenkov Fast, LYSO "Slow")

Motivation for this Design

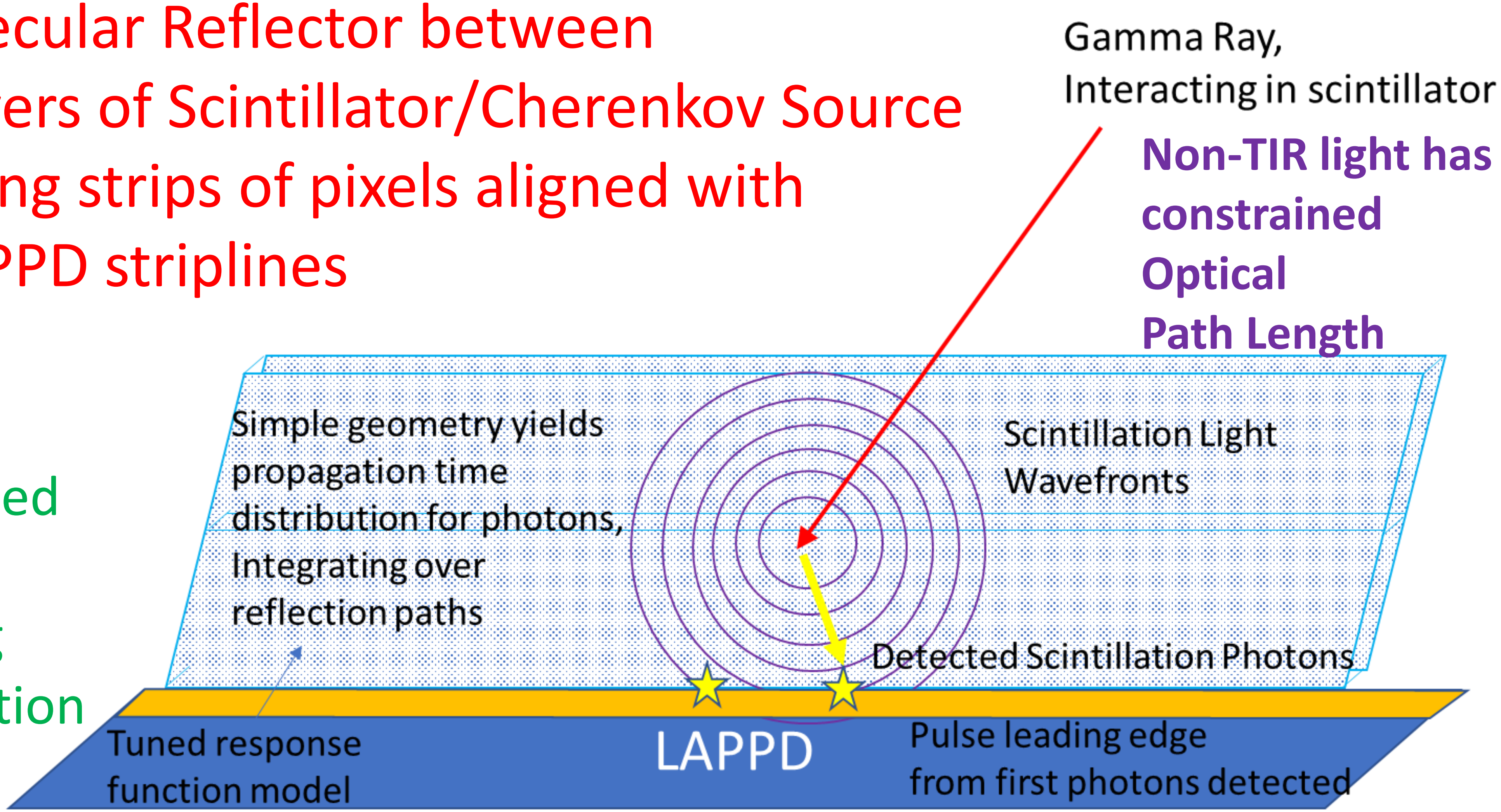
PicoRad Imaging

A Strong Claim/Conjecture from PicoRad Imaging: "50ps FWHM Time-of-Flight PET will require readout of a Cherenkov component with extremely high timing accuracy by a precision photosensor with high QE and good coupling optics, in addition to preservation of photon optical path length before detection (no path length ambiguity), for at least some detected Cerenkov photons"

Optics: Total Internally Light Encodes Interaction Coordinate in space-time with high accuracy

Specular Reflector between Layers of Scintillator/Cherenkov Source along strips of pixels aligned with LAPPD striplines

Total Internal Reflection (TIR) coating on polished pixels yields pattern encoding Depth-of-Interaction



Motivation: From a recent review

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5986096/#R139 -

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Semin Nucl Med. Author manuscript; available in PMC 2019 Jul 1.
Published in final edited form as:
Semin Nucl Med. 2018 Jul; 48(4): 311–331.
Published online 2018 Mar 12.
doi: 10.1053/j.semnuclmed.2018.02.006

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NIHMSID: NIHMS945850
PMID: 29852942

Innovations in instrumentation for positron emission tomography

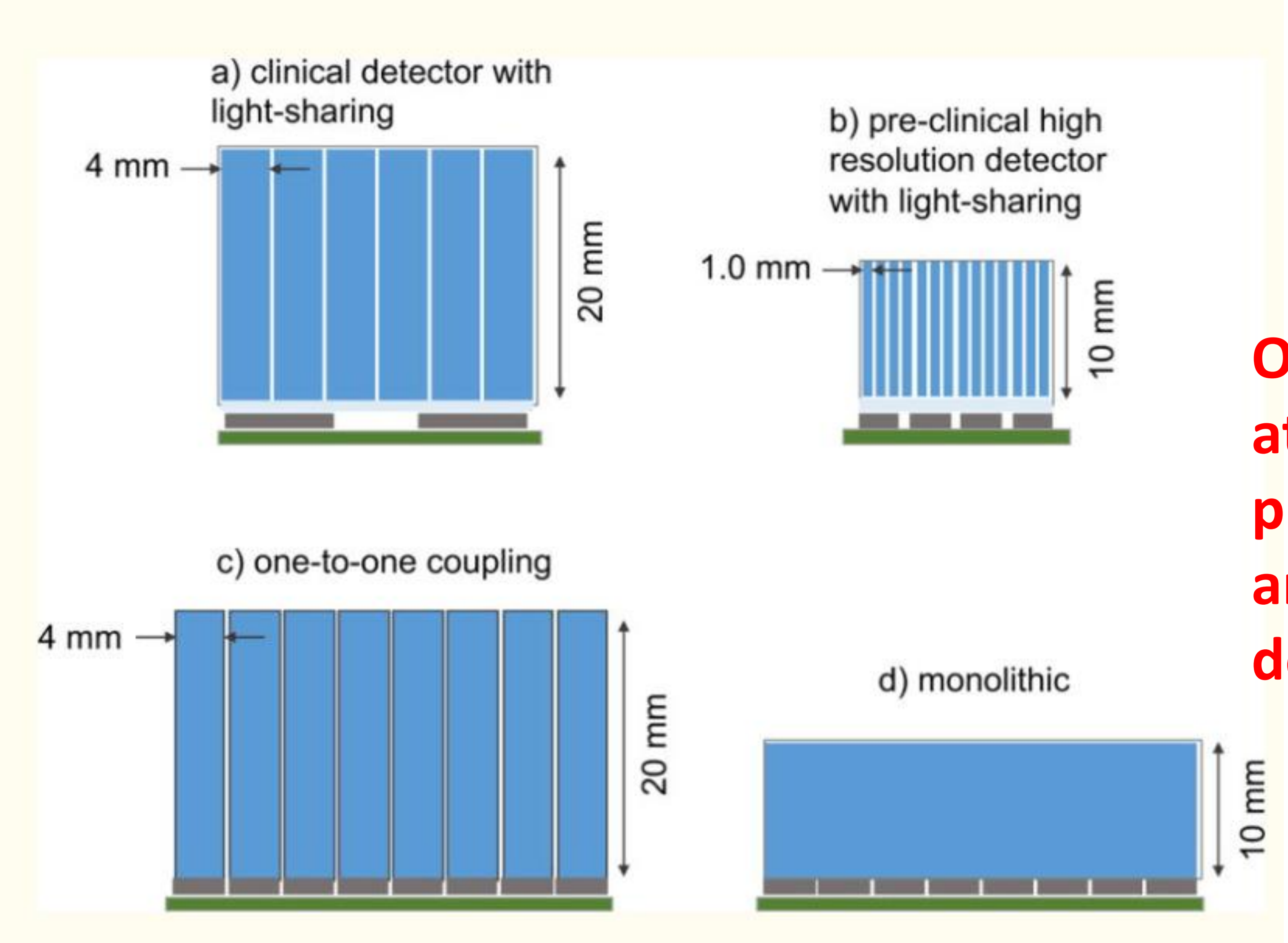
Eric Berg, Ph.D.[1] and Simon R. Cherry, Ph.D.[1,2]

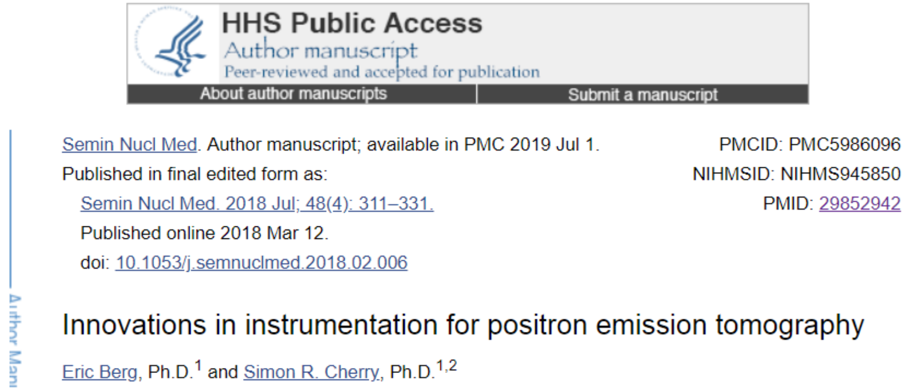
Further developments at the detector, electronics and systems levels strongly suggest timing resolution will continue to improve, probably to the 200–250 ps range in the relatively near term. Beyond that, a combination of the rate of scintillation light production and the response speed of the photodetector become limiting factors, however, major efforts are underway in research laboratories, that offer possible pathways to reaching 100 ps or even beyond in the future

Obtaining a precise estimate of the time-of-interaction in the detector thus relies on minimizing the variance in the detection times of the earliest photons. This includes generating and collecting as much scintillation light as possible, reducing the rise and decay times to increase the early photon flux, minimizing the spread in propagation times in the crystal, and preserving the timing properties of the detected photons after electrical conversion in the photodetector. Progress in these areas represents most of the significant developments in time-of-flight PET detector technology.

Motivation: From a recent review

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5986096/#R139 -





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Our Optics retains attributes of each of the pre-clinical (TIR-like) and monolithic (non-TIR-like) detector optics designs

In the high-Z BGO case, one omits specular reflectors and corrects for optical path lengths of a 2D Non-TIR detected photoelectron distribution

An interesting mixed (Cherenkov and Scintillator) light source optics design:

Phys Med Biol. Author manuscript; available in PMC 2017 Sep 21.
Published in final edited form as:
Phys Med Biol. 2016 Sep 21; 61(18): L38–L47.
Published online 2016 Sep 2. doi: 10.1088/0031-9155/61/18/L38
PMCID: PMC5056849
NIHMSID: NIHMS815116
PMID: 27589153

Bismuth germanate coupled to near ultraviolet silicon photomultipliers for time-of-flight PET

Sun Il Kwon,[1,3] Alberto Gola,[2] Alessandro Ferri,[2] Claudio Piemonte,[2] and Simon R. Cherry[1]

For BGO, the energy threshold for an energetic electron to emit Cerenkov photons is about 66 keV given the refractive index of 2.15. The estimated number of produced Cerenkov photons produced per photoelectric interaction is ~15.6 over a wavelength range of 320 nm to 800 nm

since the number of Cerenkov photons is far less than the number of scintillation photons, and they are more abundant in the UV and blue part of the spectrum, photosensors need to have high UV/blue sensitivity, fast temporal response, and very low noise in order to trigger on the faint Cerenkov signal.

Limitations of this design as tested:

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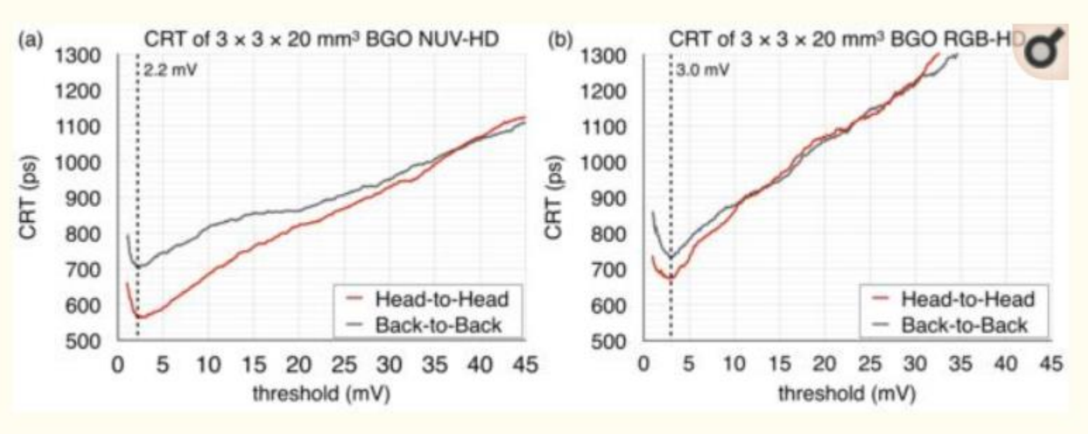
Promptly produced Cerenkov photons contribute to narrowing of the timing spectrum at lower thresholds, resulting in improvement in timing resolution. At higher thresholds, the signal from the Cerenkov photons is not sufficient to exceed the threshold and triggering is dominated by the scintillation photons.



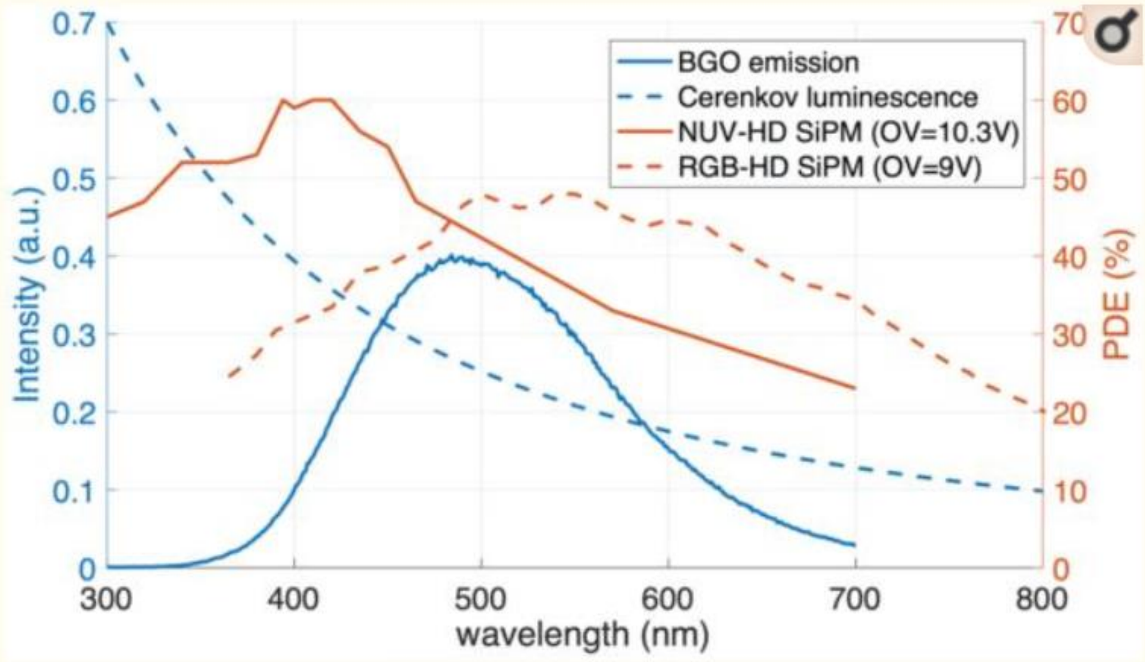


Figure 1

PDE of NUV-HD (red) and RGB-HD (dashed red) SiPMs, emission spectrum of BGO (blue) and spectrum of Cerenkov luminescence (dashed blue) as a function of wavelength. BGO data courtesy of Radiation Monitoring Devices Inc, Watertown, MA.

More sensitivity at shorter wavelengths and lower photosensor noise would both have been helpful

Another Vote for BGO

Phys Med Biol. 2017 Jun 7;62(11):4421-4439. doi: 10.1088/1361-6560/aa6a49. Epub 2017 Mar 30.

BGO as a hybrid scintillator / Cherenkov radiator for cost-effective time-of-flight PET.

Brunner SE[1], Schaart DR.

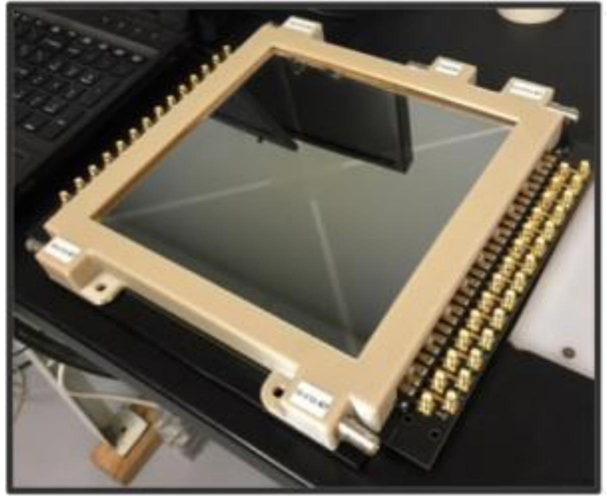
Author information

Abstract

Due to detector developments in the last decade, the time-of-flight (TOF) method is now commonly used to improve the quality of positron emission tomography (PET) images. Clinical TOF-PET systems based on L(Y)SO:Ce crystals and silicon photomultipliers (SiPMs) with coincidence resolving times (CRT) between 325 ps and 400 ps FWHM have recently been developed. Before the introduction of L(Y)SO:Ce, BGO was used in many PET systems. In addition to a lower price, BGO offers a superior attenuation coefficient and a higher photoelectric fraction than L(Y)SO:Ce. However, BGO is generally considered an inferior TOF-PET scintillator. In recent years, TOF-PET detectors based on the Cherenkov effect have been proposed. However, the low Cherenkov photon yield in the order of ~10 photons per event complicates energy discrimination-a severe disadvantage in clinical PET. The optical characteristics of BGO, in particular its high transparency down to 310 nm and its high refractive index of ~2.15, are expected to make it a good Cherenkov radiator. Here, we study the feasibility of combining event timing based on Cherenkov emission with energy discrimination based on scintillation in BGO, as a potential approach towards a cost-effective TOF-PET detector. Rise time measurements were performed using a time-correlated single photon counting (TCSPC) setup implemented on a digital photon counter (DPC) array, revealing a prompt luminescent component likely to be due to Cherenkov emission. Coincidence timing measurements were performed using BGO crystals with a cross-section of 3 mm × 3 mm and five different lengths between 3 mm and 20 mm, coupled to DPC arrays. Non-Gaussian coincidence spectra with a FWHM of 200 ps were obtained with the 27 mm^3 BGO cubes, while FWHM values as good as 330 ps were achieved with the 20 mm long crystals. The FWHM value was found to improve with decreasing temperature, while the FWTM value showed the opposite trend.

PMID: 28358722 DOI: 10.1088/1361-6560/aa6a49

Key Features of PicoRad Imaging Detector Optical Design with LAPPD Readout



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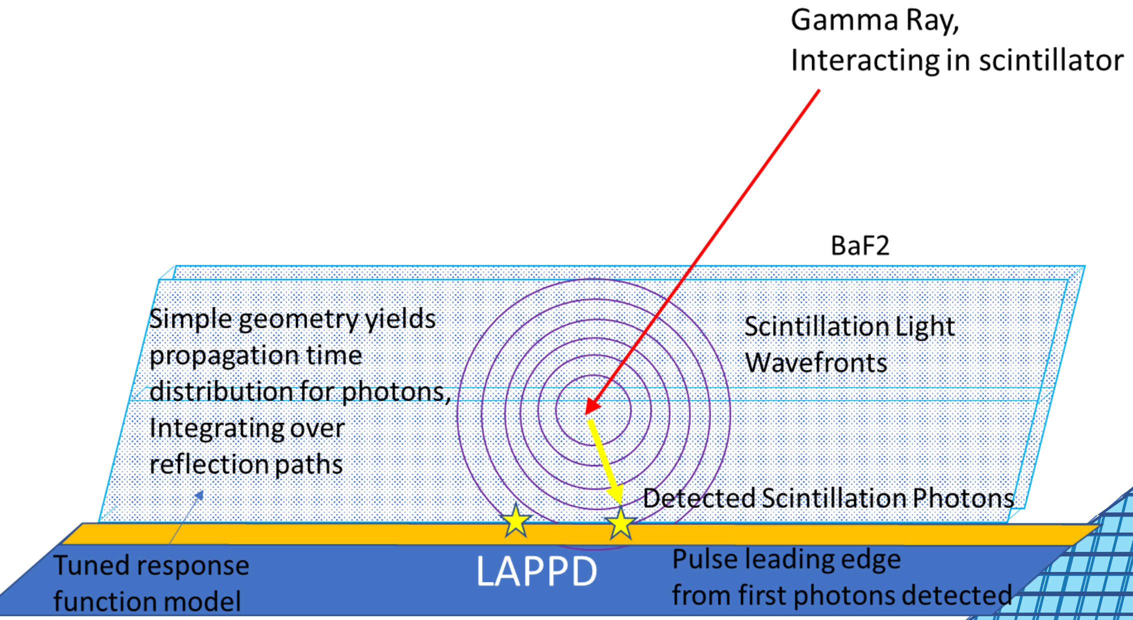
Allows precision measurement of all 4 interaction coordinates in space-time, which is necessary for Optical Path Length correction using leading edge photons, with an extremely low-noise precision photosensor available now.

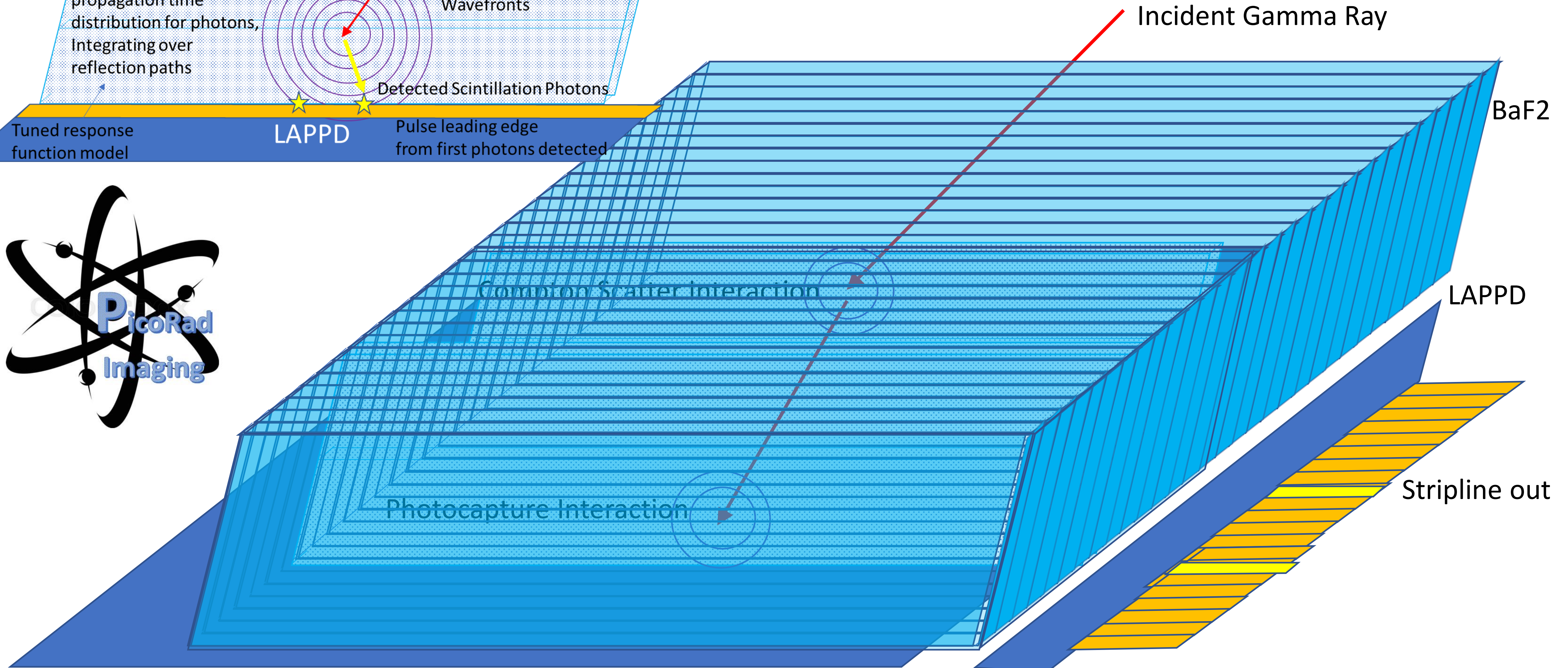
Provides paths for future performance improvement:

- Improving optical coupling to LAPPD through integrated detector design with Cerenkov/scintillator source internal to a modified LAPPD
- Improving LAPPD Quantum Efficiency (photocathode) and intrinsic timing resolution per single photoelectron (smaller pore MCPs with narrower pulses) and higher-bandwidth waveform digitizers

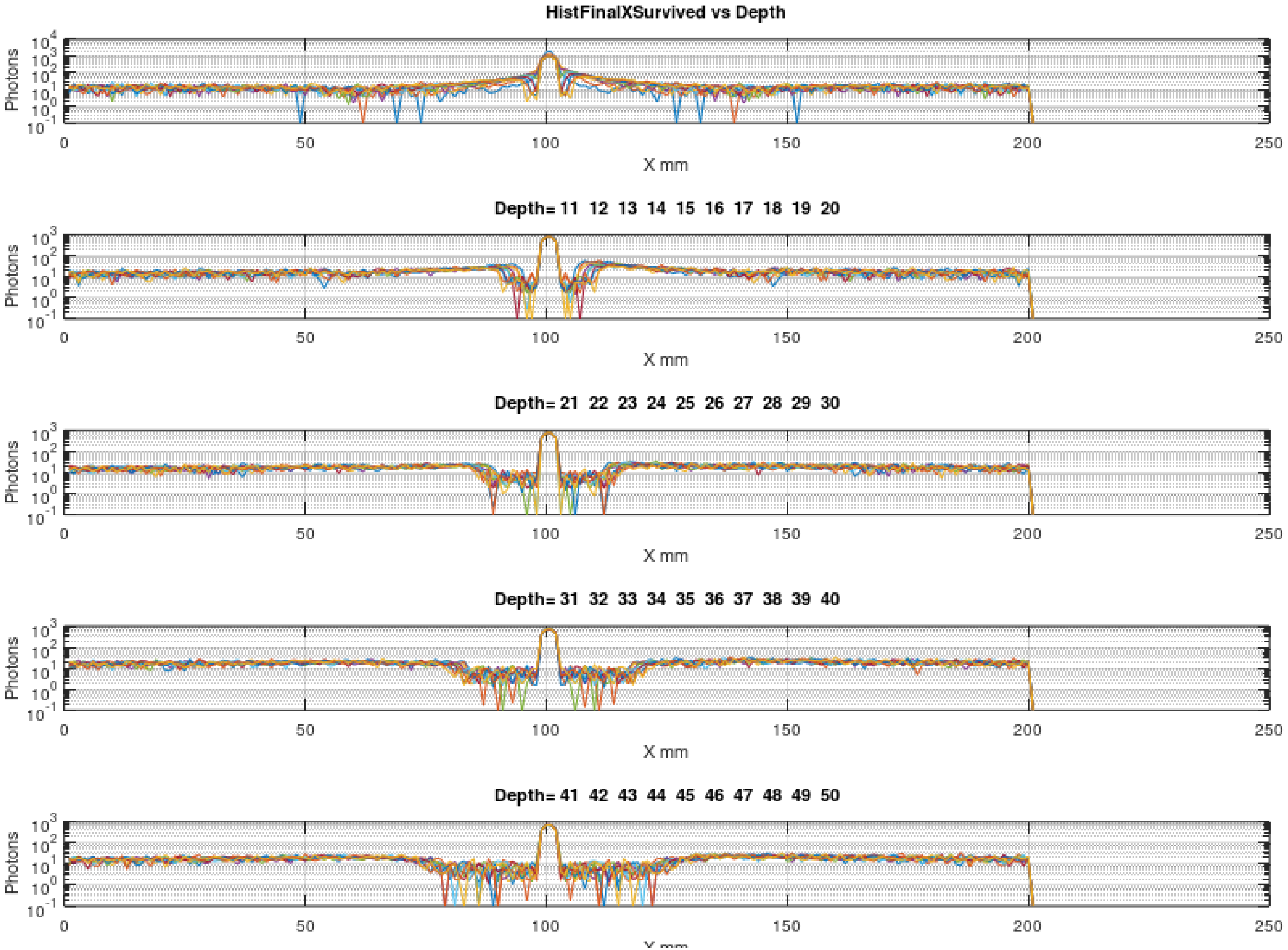
Individually resolved gamma ray
Interaction coordinates, energy, time

Separated determination of interaction coordinates in lower-Z (LaBr2, BaF2) detectors





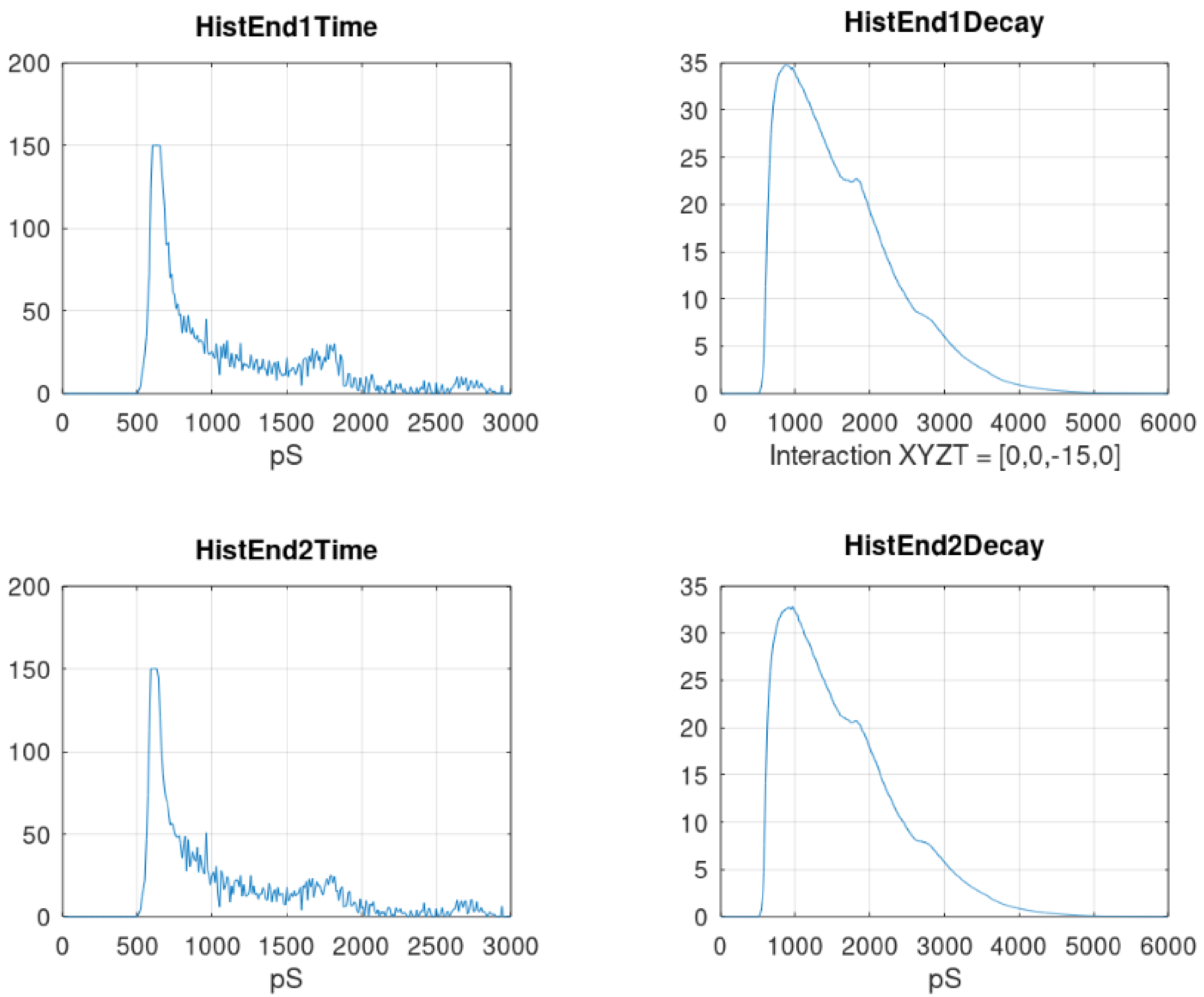
Separated determination of interaction coordinates in lower-Z (LaBr2, BaF2) detectors including Depth-of-Interaction from spatial pattern of slow SPEs



LaBr2 and BaF2 simulations using a virtual (simulated) 200 Gigasample/second Waveform digitizer convolved with LAPPD single photoelectron output pulse shape

Simple Parametric Optical Model (No Cherenkov) incorporates:

- Scintillator properties (isotropic)
  - Index + TIR coating Index
  - Temporally resolved light yield
    - Intrinsic Rise Time
    - Fast and Slow Decay Times
  - Reflections and reflection loss
  - Photon propagation Delays
- Photosensor properties
  - Transit time spread per SPE
  - SPE pulse shape
  - Stripline readout delays
  - Digitization (Sampling)



Lessons from the Cartoon Optical Model

- High initial γ/ps rate of LaBr2 made it predicted as best for timing
- LAPPD pulse shape had big impact on timing (-> smaller pore MCPs)
- Fluctuations in waveforms at 100 GS/s were due to intrinsic temporal fluctuations at the source in addition to variations in photon path length, where the interaction position errors were negligible
- For high-index LaBr2, LYSO and BGO signal propagation is faster for electrical signals in the strip-lines than for optical signals in the scintillator.
- For lower-index BaF2 it is the opposite, optical signals outrace electrical signal along striplines.
- Lower bounds on timing resolution with variable assumptions on optics but known parameters for light emission and LAPPD signal + QE

No design could meet ~50psec FWHM coincidence time resolution spec -> Cherenkov signal required

Pressing need for better Optical and Radiation Transport Modeling, and for Component and Subsystem-level Measurement and Test

GATE is one option, UC Davis has access to many others as well

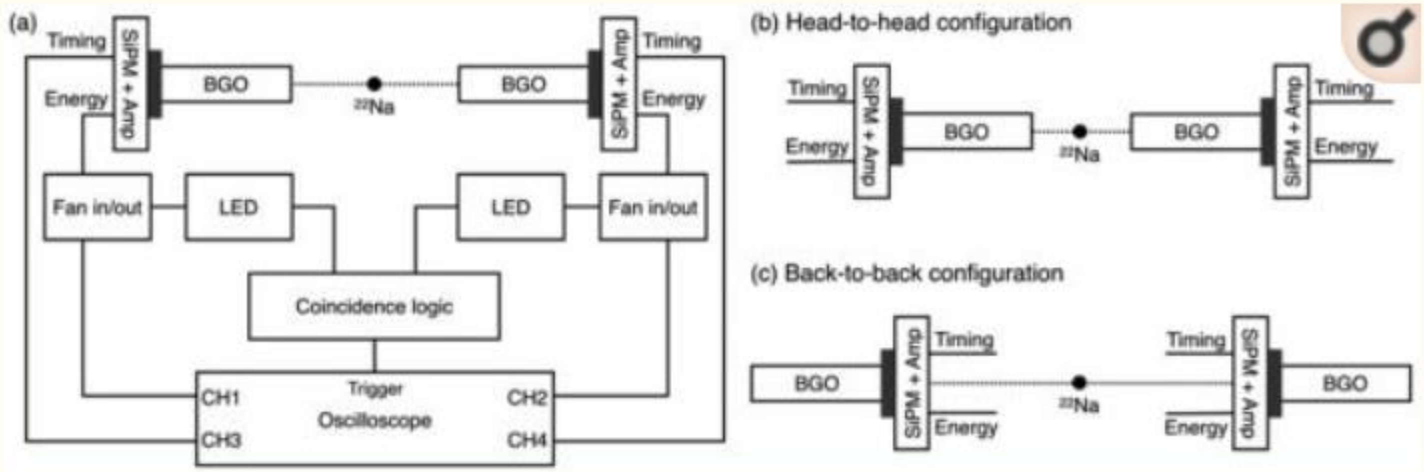


Figure 2

Experimental setup for coincidence events (a). To examine the influence of Cerenkov photons, coincidence events were measured using head-to-head (b) and back-to-back (c) configurations.

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Bismuth germanate coupled to near ultraviolet silicon photomultipliers for time-of-flight PET

Sun Il Kwon,[1,3] Alberto Gola,[2] Alessandro Ferri,[2] Claudio Piemonte,[2] and Simon R. Cherry[1]

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5056849/

Scintillator Advantages and Disadvantages

	LaBr2	BaF2	BGO	LYSO
+ Advantages	Extremely Fast Very Bright Short Waveform	Lower Cost Very Fast Fast/Slow decays	Lower Cost Very high index Very high Z Fairly bright	“Standard” Bright Fast Signal Short Waveform High Z
-Disadvantages	High Cost Hygroscopic Low Z	Low Z Low Index UV Fast signal	No fast signal other than Cherenkov	High Cost Less Novel

High-Cost,
High-Performance
Option

Low-Cost
Higher Sensitivity?

Low-Cost
Lower Sensitivity?

Well-suited to potential low-cost EXPLORER-scale deployment

Diverging system application requirements drive diverging device/product designs

- UCDavis/Incom BRAIN RO1
  - Insist on Time Resolution Spec
  - Loosen Sensitivity Spec
  - -> BGO (LaBr2 backup?)
- PicoRad/UCDavis SBIR
  - Insist on Sensitivity Spec
  - Push Time Resolution hard
  - -> BaF2 (BGO backup?)

Scope of Work

- UCDavis – System
- UCDavis – Optics
- Incom - LAPPD

Scope of Work

- PicoRad – System
- UCDavis – Optics
- Incom - LAPPD

Testing migrates from Incom (PicoRad) -> UC Davis over Phase I -> Phase II