



Development of Innovative PET Detectors at IRFU

V. Sharyy for the CaLIPSO group

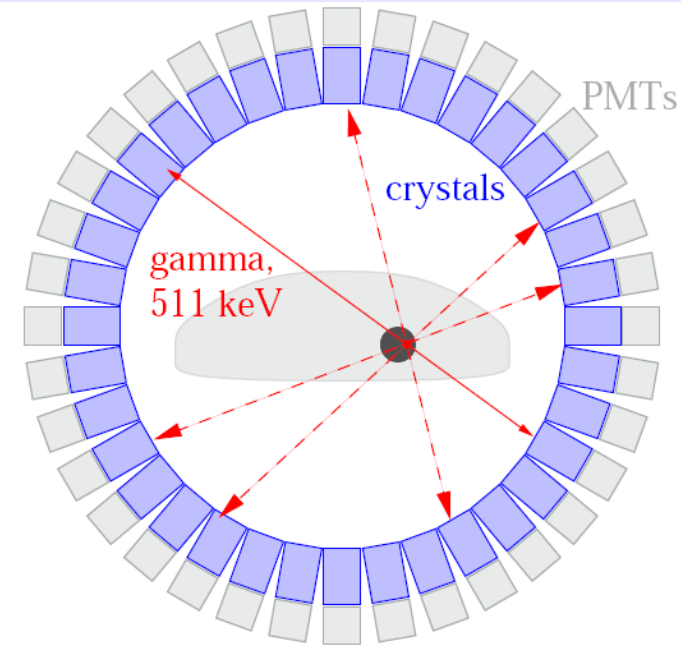
in collaboration with:

*Nuclear Physics Department TSUK,
SHFJ-CEA, LAL-CNRS, CSNSM-CNRS, IRAMIS-CEA*

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Positron Emission Tomography

- PET is a nuclear imaging technique used widely in oncology, cardiology and neuropsychiatry.
- Use radioactive tracer (e.g. ^{18}F -FDG, $\tau \sim 110$ min) emits positrons $\Rightarrow$ annihilation with an electrons $\Rightarrow$ two 511 back-to-back gamma.
 - Full body dose ~ 3 to 5 MBq/kg
- Main issues
 - Backgrounds: Compton scattering in the subject, random coincidence
 - Reconstruction: need corrections for scattering and attenuation
 - Contrast of the image directly correlated to the S/B and available statistics. Better spatial precision requires more statistics for an image.
- TOF techniques: using the difference in time between two photons $\Rightarrow$ improve S/B



Better image quality for the same dose requires:

- *Higher efficiency*
- *Better S/B*

– Simple estimation: $G = \frac{S/N_{TOF}}{S/N_{noTOF}} \sim \sqrt{\frac{D}{\delta x}} \sim \sqrt{\frac{D}{c/2 \delta t}}$



$D=30$ cm

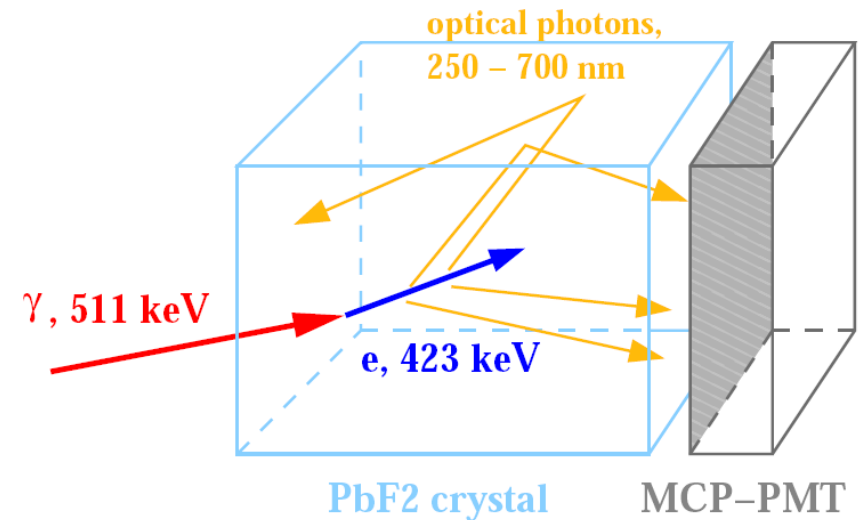
$\text{CRT}=350$ ps $\Rightarrow G \sim 1.9$

$\text{CRT}=150$ ps $\Rightarrow G \sim 2.9$

$\Rightarrow 8\times$ lower dose

Two Projects @ IRFU, CEA-Saclay

- **CaLIPSO**: development of the brain/animal size PET
 - High spatial resolution: $1 \times 1 \times 1 \text{ mm}^2$ (FWHM)
 - High resolution in time
 - Innovative liquid as a detection medium: TMBi(trimethylbismuth)
 - Dual read-out: ionization and light
- **PECHE**: development for TOF full-body size PET
 - High resolution in time
 - Crystals as a detection medium
- Common to both projects: use of the **Cherenkov** light for the extreme precision in time.



CaLIPSO project

TriMethyl Bismuth (TMBi), $\text{Bi}(\text{CH}_3)_3$

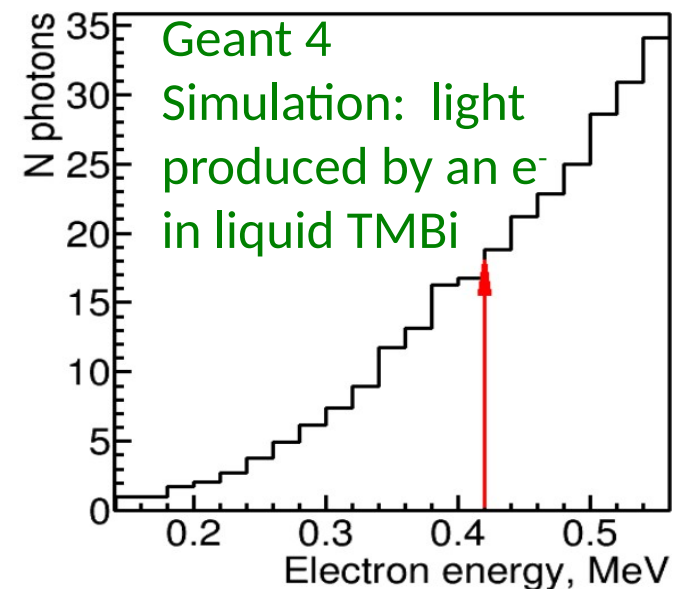
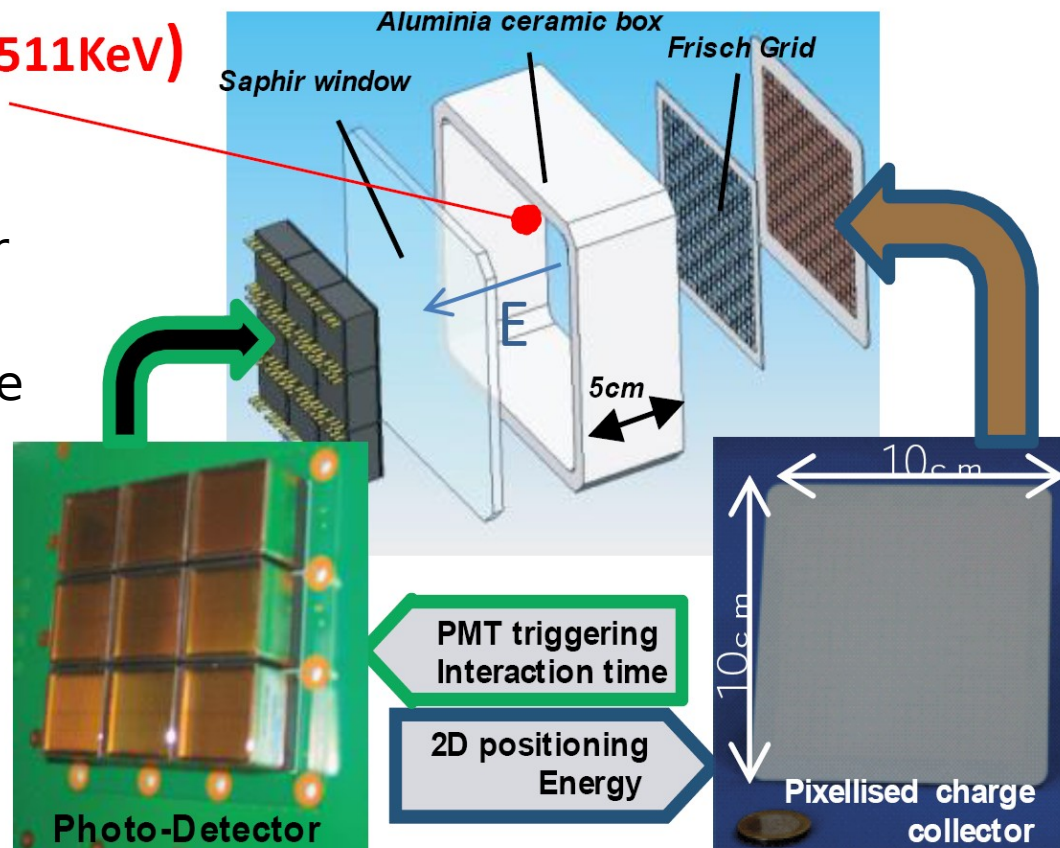
- Bi, Z = 83, highest Z non radioactive element.
- Photoelectric / (Photoelectric + Compton) ~ 47%
- Limpid ($\lambda > 400$ nm), dielectric, chemically stable
- Density 2.3 g/cm^3 , refraction index ~ 1.6

Detection Medium	LSO	CdTe	Liquid Xenon	TMBi
Attenuation length	95%(2.2cm)	95%(5cm)	95% (10cm)	85% (5cm)
Photo-electric ratio	30%	15%	21%	47%
τ	40 ns	Slow (ionization)	4 ns	~ ps (Cherenkov)
Energy resolution (FWHM)	15%	1%	5%	<10%
Interaction position accuracy	~1 - 0.2 cm	1 – 5 mm.	150 μm	150 μm
User friendly	Yes	Yes	No	Yes
TOF	Yes	No	Maybe	Yes

CaLIPSO Basic

- Double read-out
 - Light: coincidence and trigger for the ionization
 - Ionization: 2D coordinate with the pixel read-out, 3^d coordinate via the drift time
- Ionization:
 - modest yield ~ 10 pairs /keV
 - Energy resolution of about 10% FWHM
 - Slow drift: 1 cm/ μ s @ 10 kV/cm
 - Main issue is the ultra-purification of the liquid.
- Light: Cherenkov only
 - Low yield $\sim 20 - 40 \gamma$

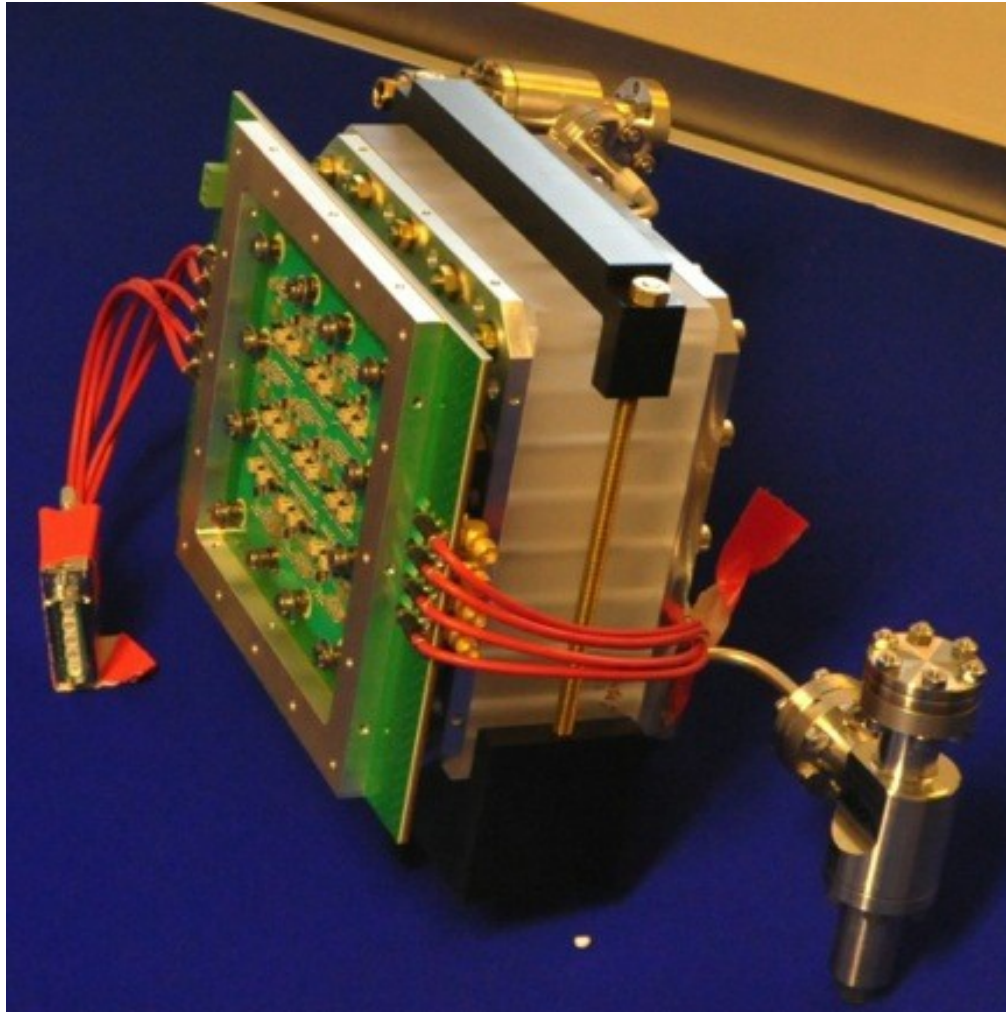
γ (511KeV)



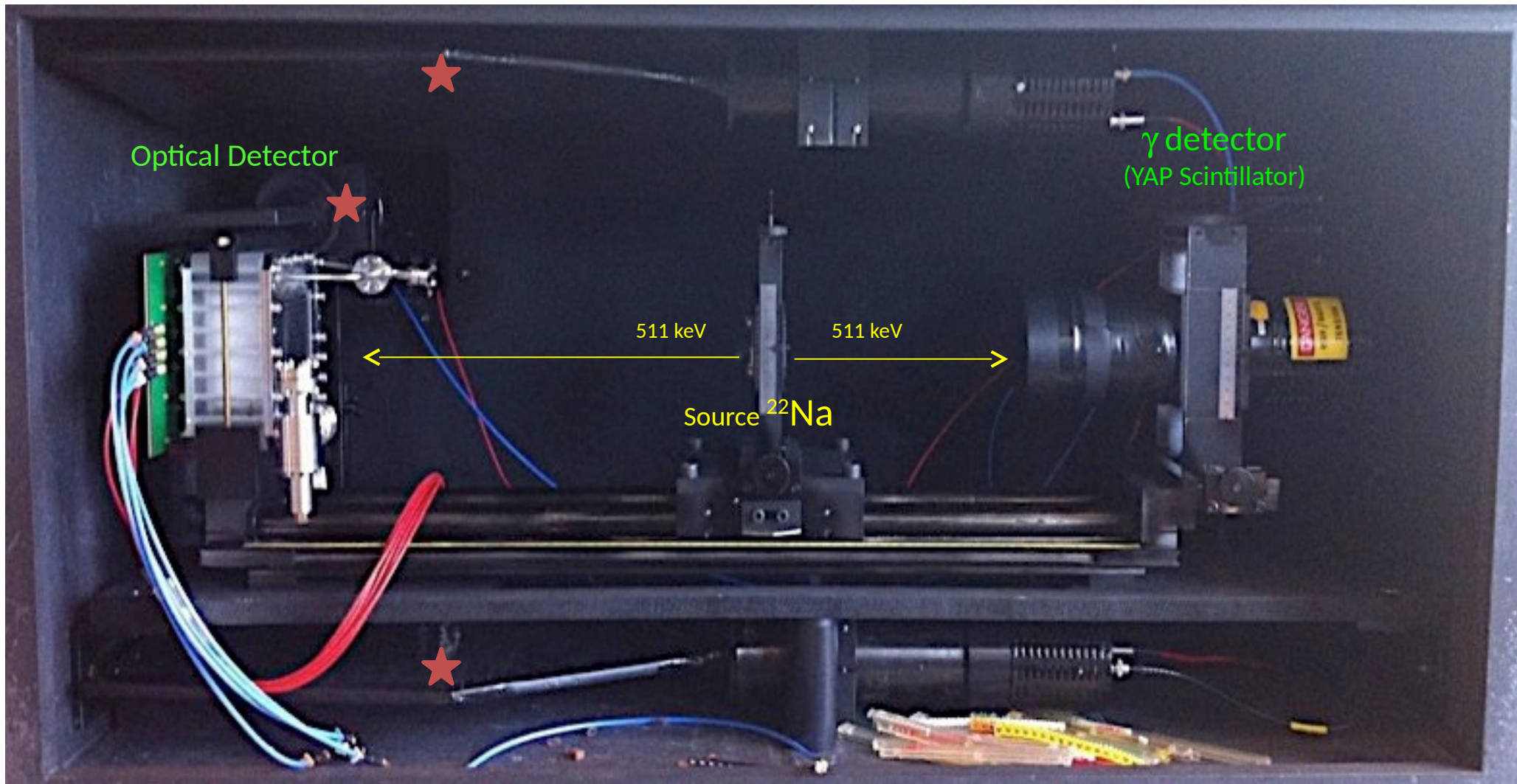
D. Yvon et al., "CaLIPSO: An novel detector concept for PET imaging", IEE E TNS, 61 (2014) 60

E. Ramos, et al. "Trimethyl Bismuth Optical Properties ...", in Nucl. Scien., IEEE Trans., vol.62, no.3, pp.1326-1335, 2015

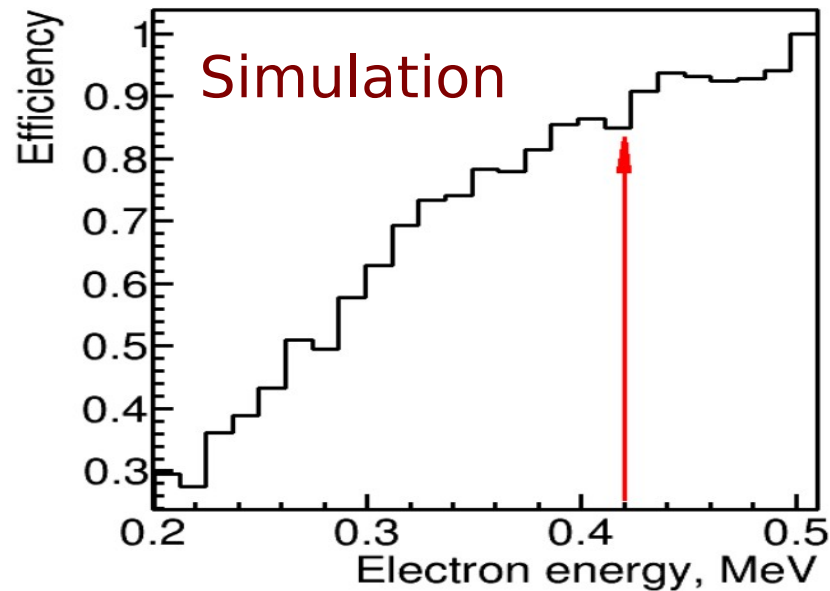
Optical Prototypes



Test Bench



Selected Results 2^d Prototype

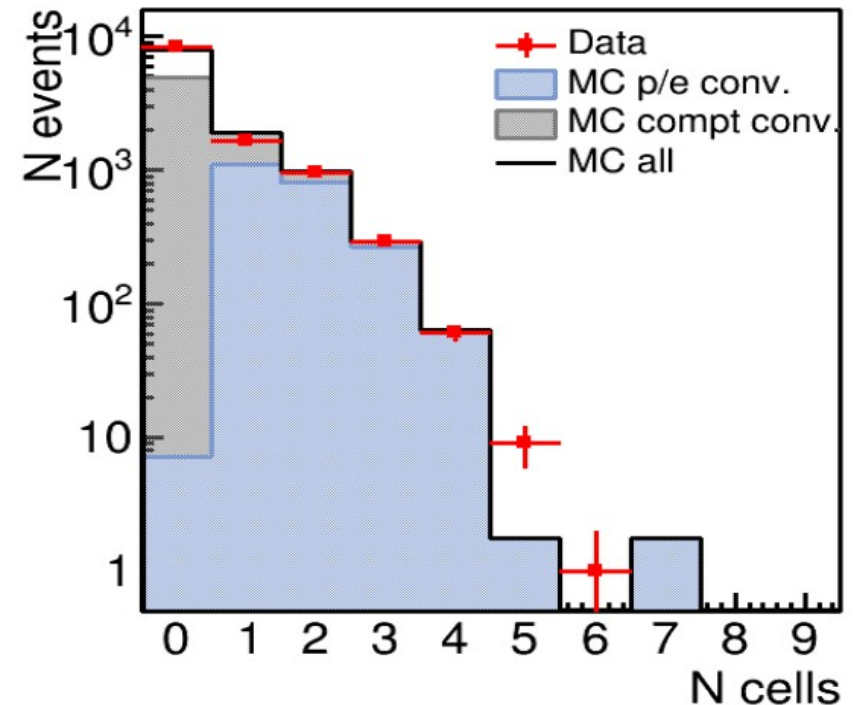
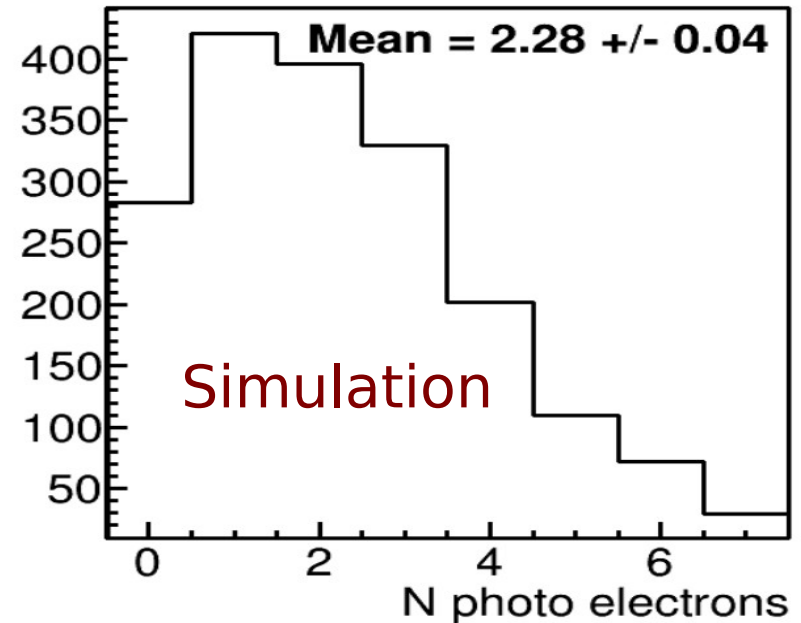


Detection Efficiency on 511 keV (30 mm of TMBi): **34.5 %**

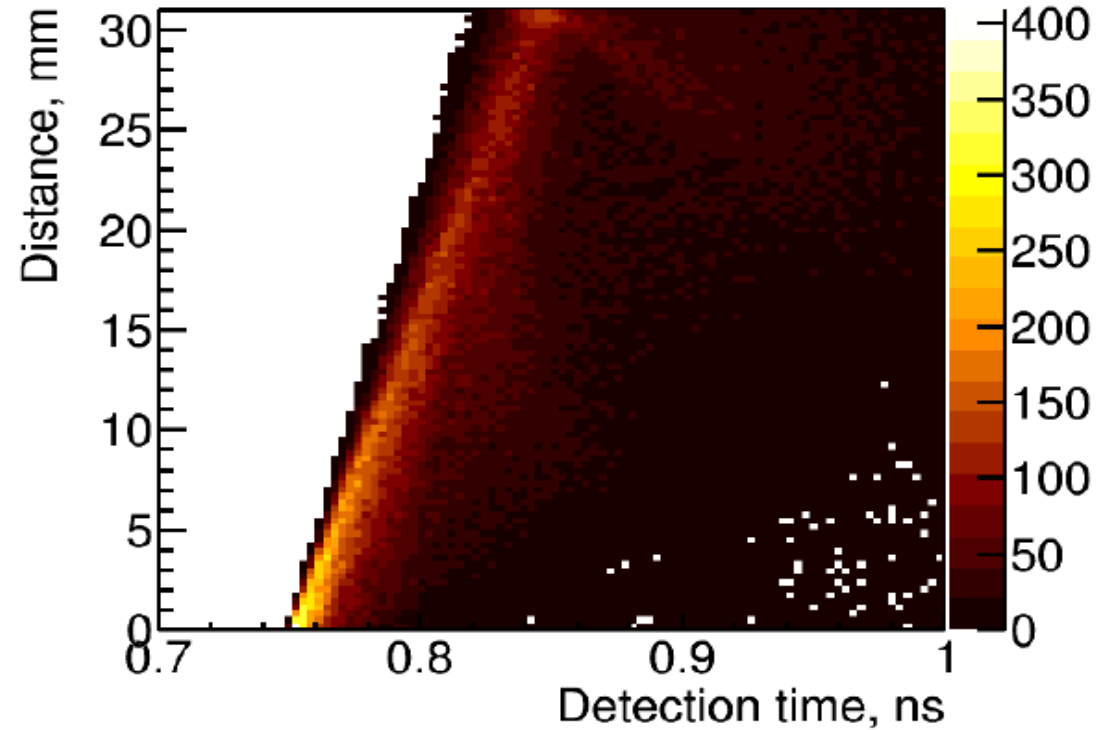
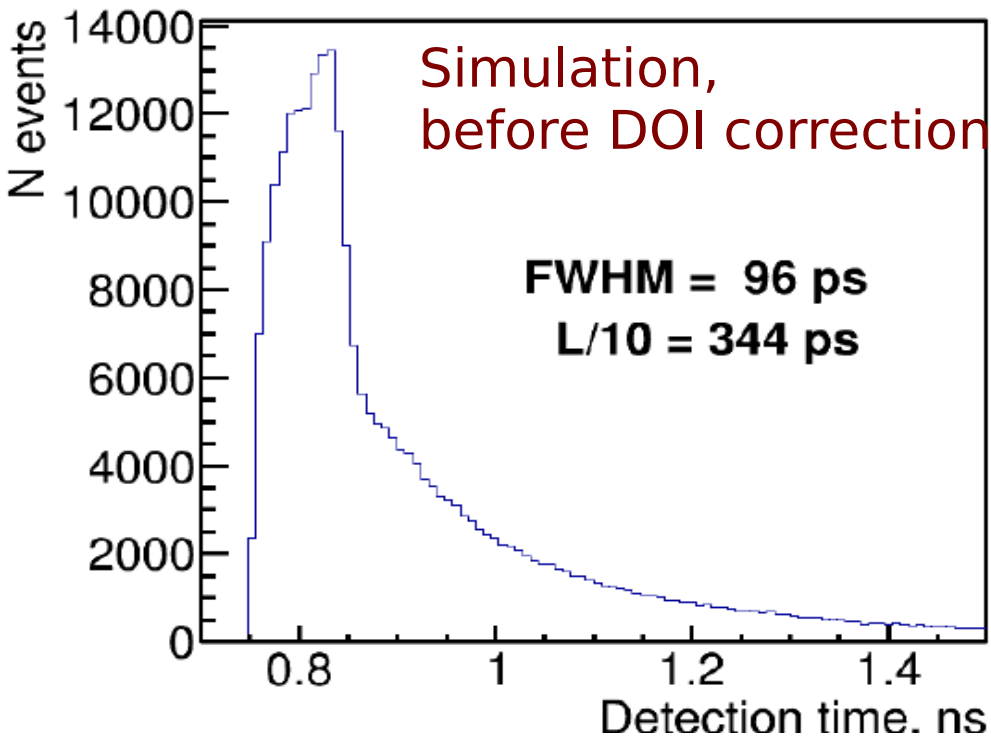
Expected if only Photoelectric: = 27%

→ **efficiency close to 100% on Photoelectric electrons + Compton**

Timing on 511 keV (including PMT):
 539 ± 25 ps (FWHM)

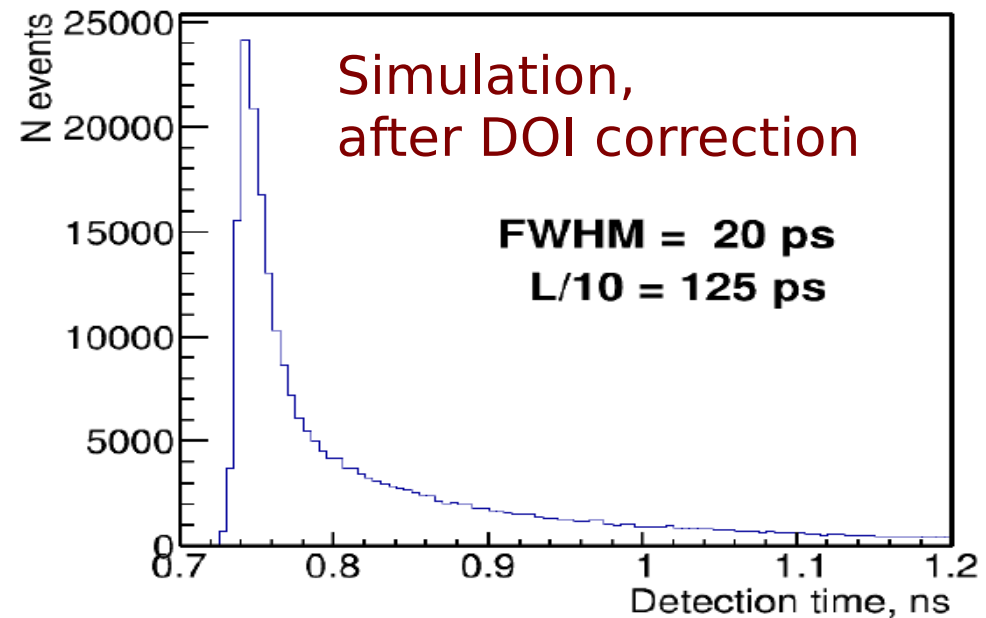


Discussion on the Timing Performances



Next Step (DO3): **Optimize Timing** with MCP-PMT + SAMPIC (flash ADC, 10 GSPS, time resolution < 5 ps)

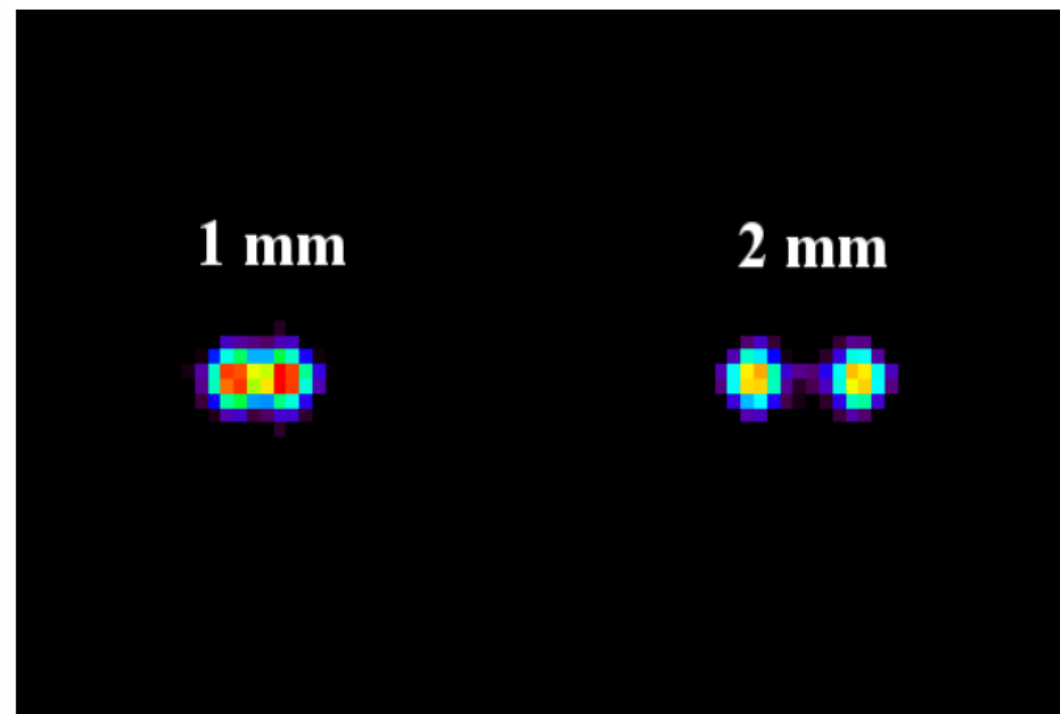
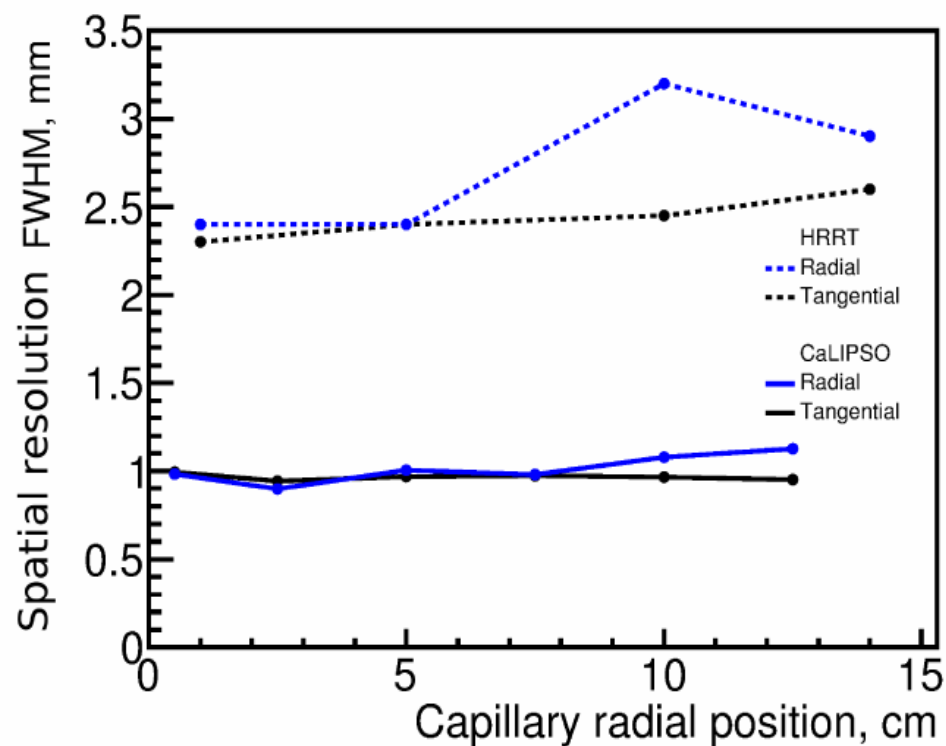
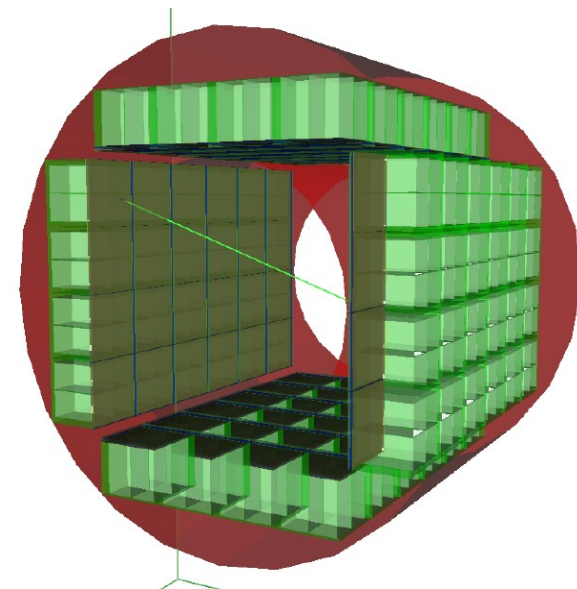
In parallel started the simulation and reconstruction of the full size PET scanner using the Geant4/GATE software (in collaboration with SHFJ-CEA)



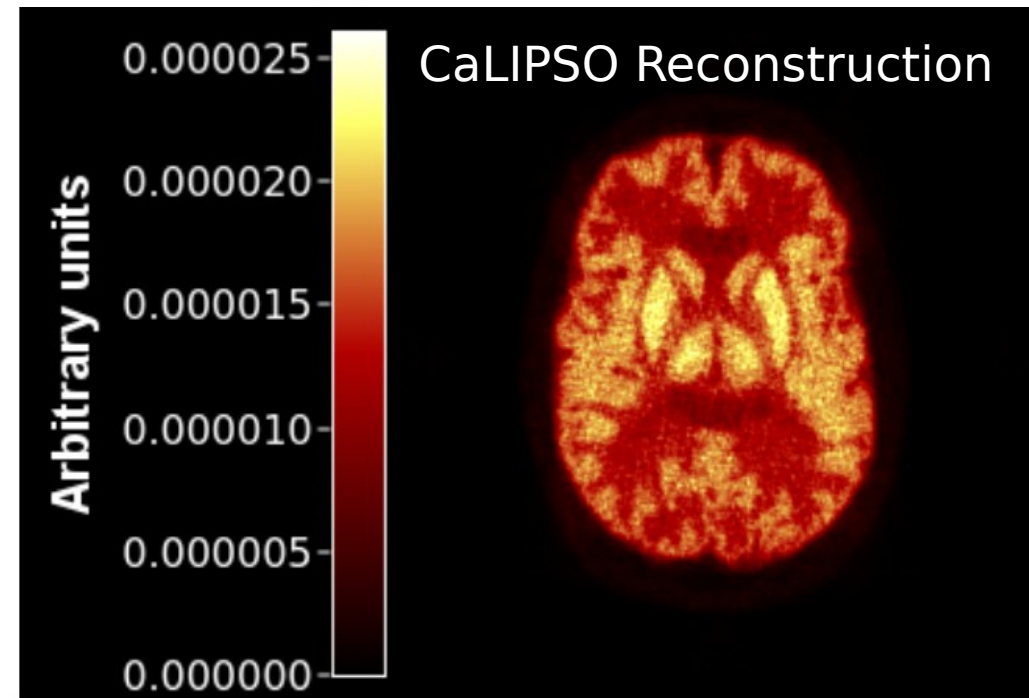
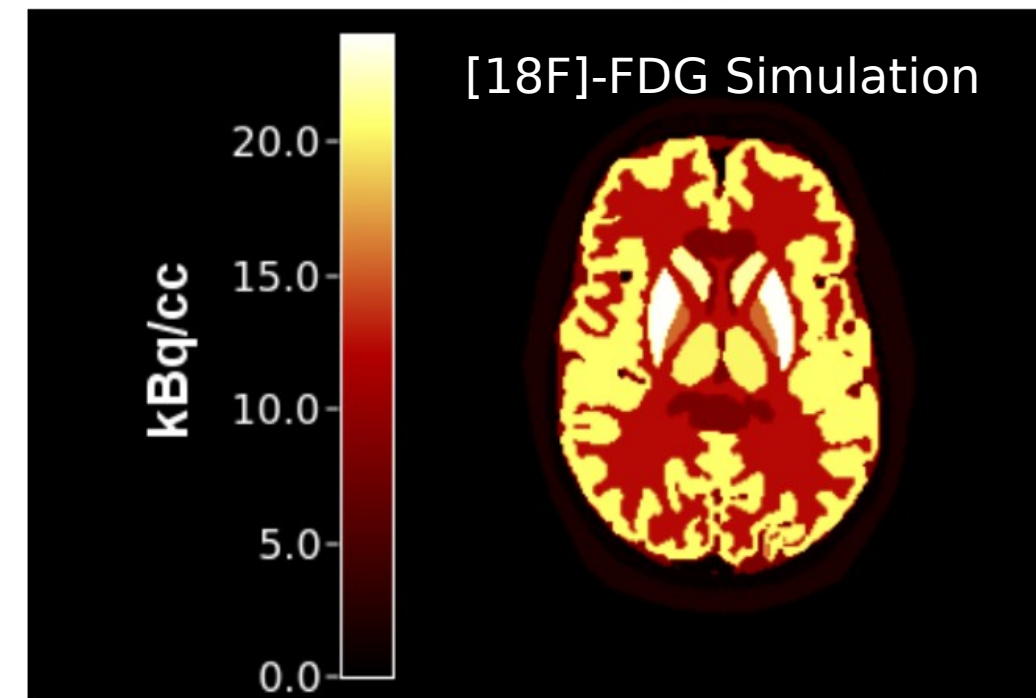
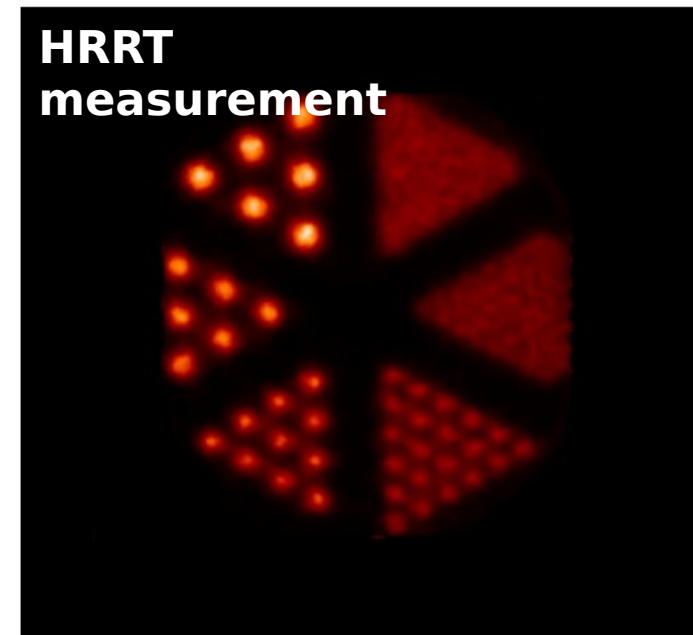
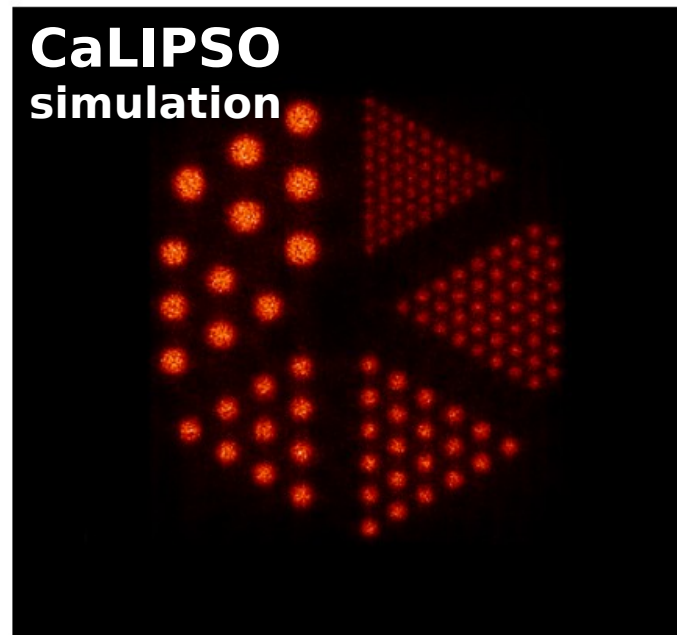
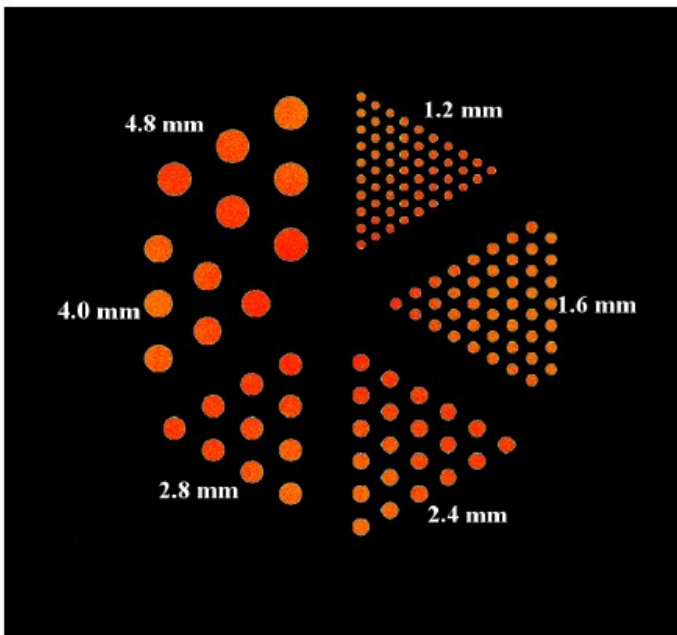
Performance in Reconstruction

In parallel started the simulation and reconstruction of the full size PET scanner in collaboration with SHFJ-CEA, using the Geant4/GATE software for the simulation and CASTOR for the reconstruction.

Need to resolve reconstruction issues related to the huge amount of the detection elements.



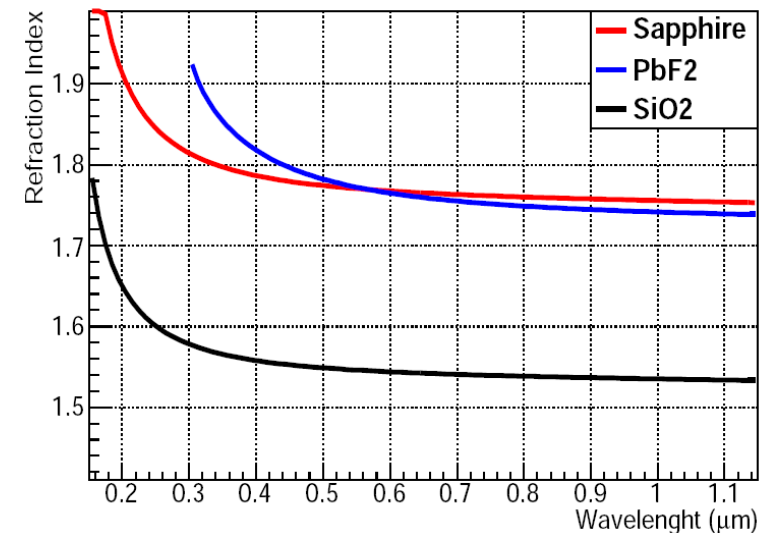
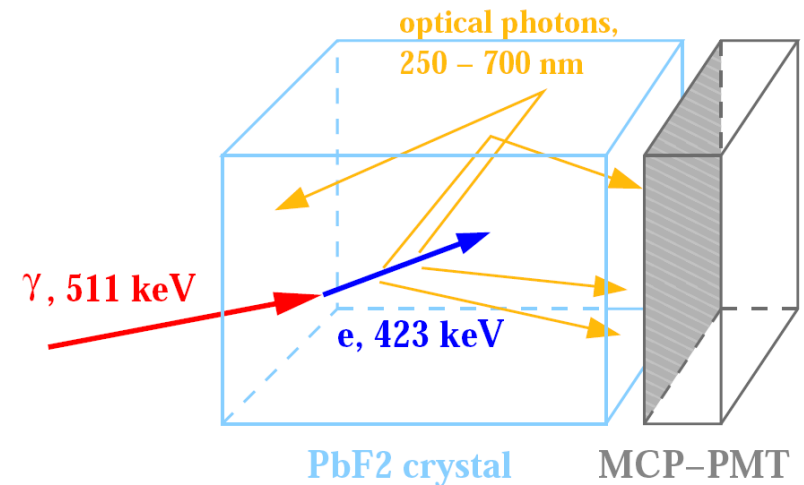
Reconstructed Images



PECHE project

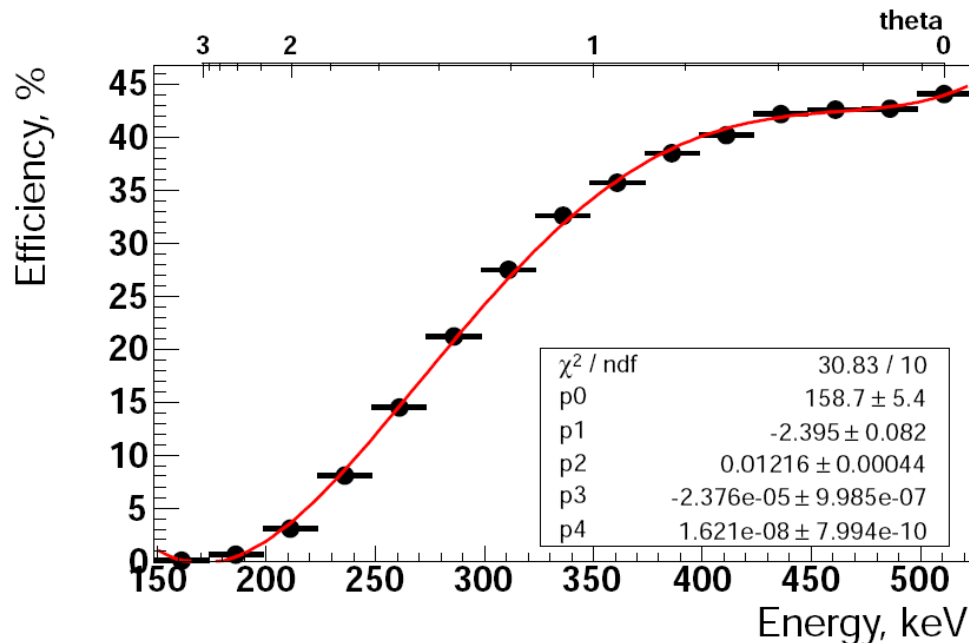
paten

- Goal of the project: improve PET image contrast by using detectors with excellent TOF resolution and high efficiency.
- Idea: use PbF_2 crystal + MCP-PMT
- Similar to
 - Korpar et al. TIPP 2011 1531-1536 (2012).
- Idea is to improve efficiency at least by a factor of four by improving the optical interface:
 - MCP-PMT with Sapphire Window
 - Use of the molecular bonding to glue MCP-PMT with the crystal (no optical grease)
- Idea is patented by CEA:
 - D. Yvon, CEA, French Patent 136103, November 12, 2013
- In collaboration with Nuclear Physics Department of the Taras Shevchenko University of Kyiv

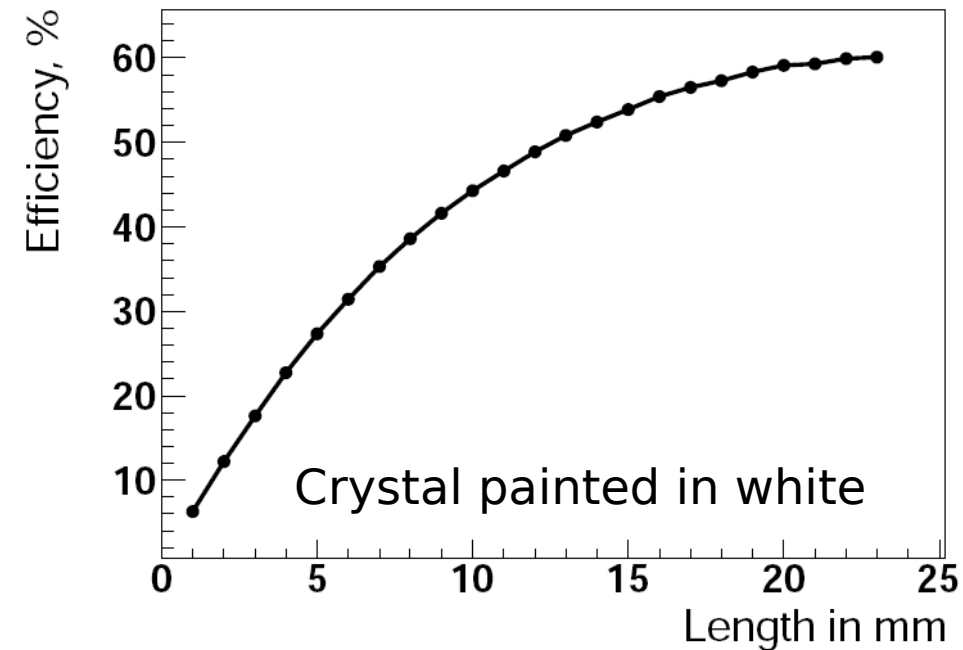
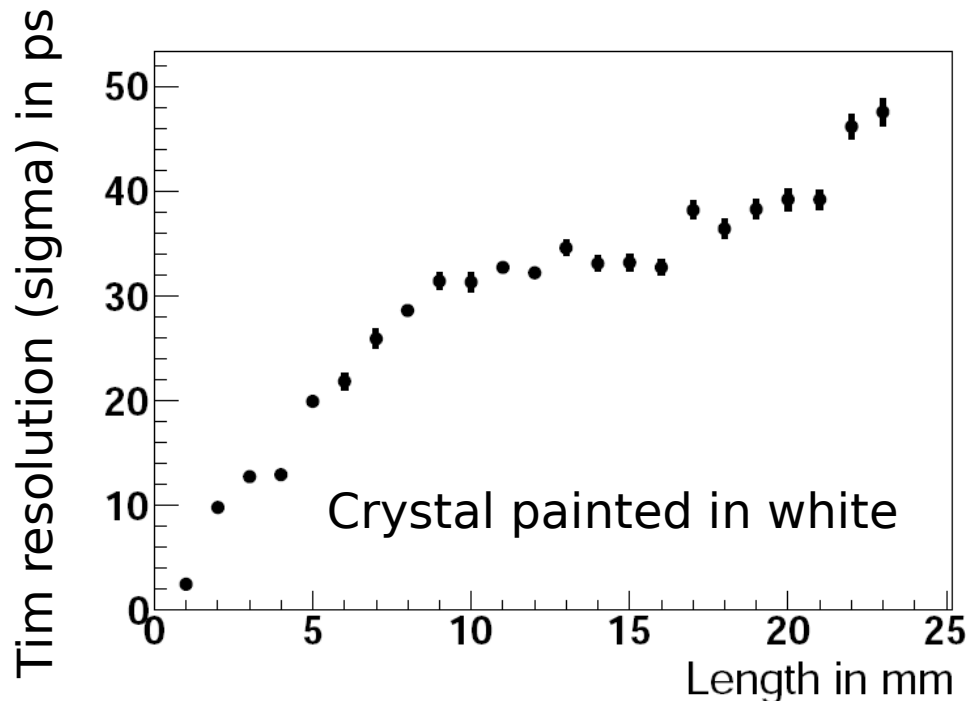
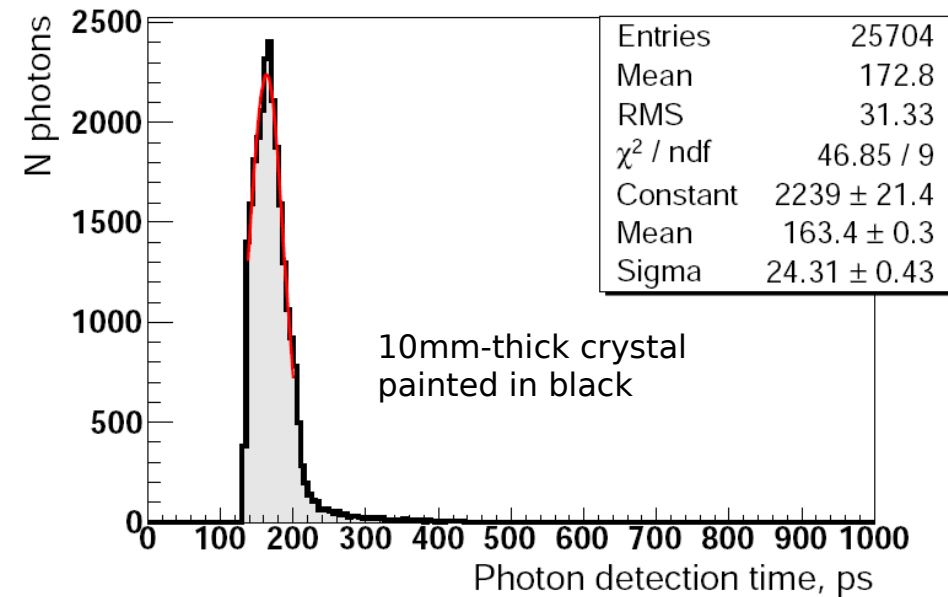
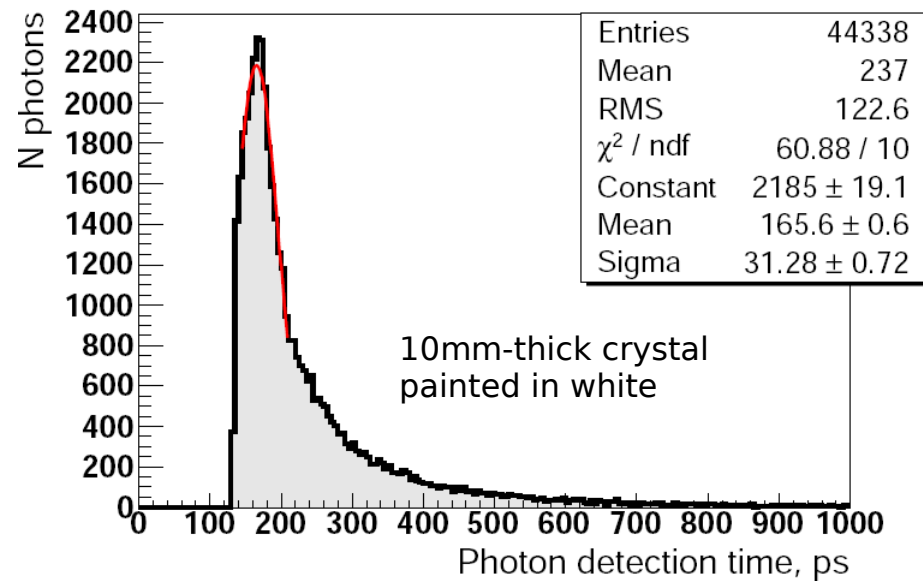


Why PbF₂?

	Plastic Scintillators	BaF ₂	LaBr ₃	PbF ₂
Density, g/cm^3	~ 1	4.88	5.3	7.77
Photoelectric fraction	$10^{-3}\%$	22%	15%	46%
Attenuation length (511 keV)	$\sim 10\text{cm}$	22 mm	21 mm	9 mm
Light Yield, MeV^{-1}	~ 10000	1800	63 000	~ 60
Scintillation decay time	(2 ÷ 4) nsec	0.8 nsec	25 nsec	$\sim 1\text{ps}$



Geant4 Simulation : efficiency versus timing



PETHE developments

- We are starting to work on the hardware:
 - Test of the Sapphire MCP-PMT
 - Molecular bonding development
 - Use SAMPIC flash ADC (10 GSPS, time resolution < 5 ps)
 - Tests using Na²² source
- In parallel we started development of the simulation and reconstruction of the full size PET scanner using the Geant4/GATE software.
 - See Marharyta's presentation

Conclusion

- We demonstrated the possibility of the efficient detection of the photoelectric conversion from 511 keV gamma in the TMBi liquid via the Cherenkov light.
- Started the work to obtain a high time precision
- In parallel we work on the ionization detection where the first signals are obtained.
- Use the same approach (Cherenkov light detection) for the crystal. Start the hardware work.
- For both approaches:
simulate the full size scanner using Geant4/GATE and develop the appropriate reconstruction in collaboration with SHFJ-CEA

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