13TH VIENNA CONFERENCE ON INSTRUMENTATION

Study of a Cherenkov based TOF-PET module

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Contents

TOF-PET with Cherenkov light

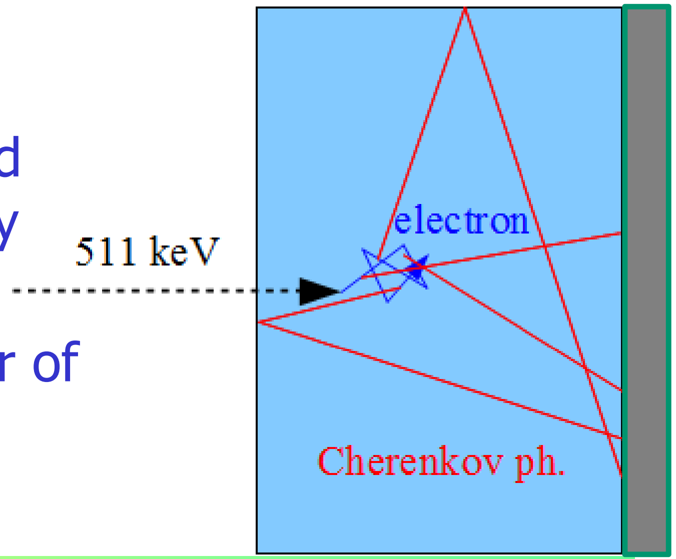
Time-of-Flight difference of annihilation gammas is used to improve the contrast of images obtained with PET:

- localization of source position on the line of response
- reduction of coincidence background
- improvement of S/N

Novel photon detectors – MCP-PMT and SiPM – have excellent timing resolution → TOF resolution limited by the scintillation process

Cherenkov light is promptly produced by a charged particle traveling through the medium with velocity higher than the speed of light c_0/n.

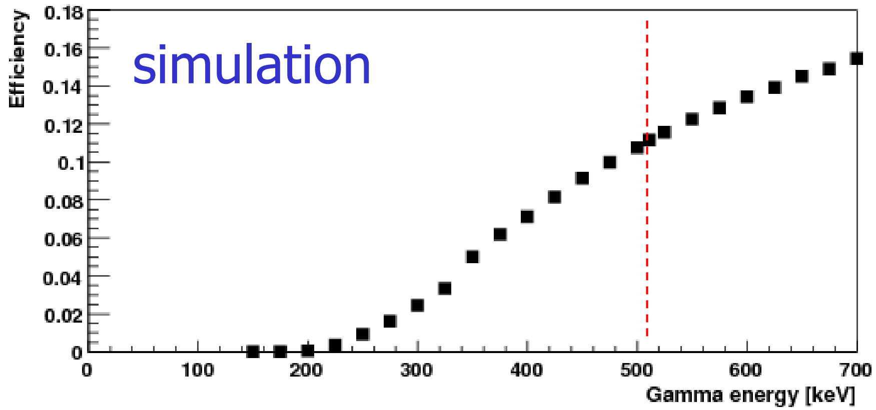
Disadvantage of Cherenkov light is a small number of Cherenkov photons produced per interaction → detection of single photons!



Intrinsic suppression of scattered events

Annihilation gammas scatter in patient or detector → unwanted background when scattered gamma is detected in coincidence

- Traditional PET
  - number of scintillation photons proportional to energy deposited
  - measurement of gamma energy → rejection of scattered (lower energy) events
- Cherenkov PET
  - at most a few photons detected → no energy information available
  - but: detection efficiency drops with gamma energy → intrinsic suppression



  - also: very high Z material, less Compton scattering in the radiator

Cherenkov radiator for gamma detection

Requirements for the Cherenkov radiator for annihilation gammas:

- High gamma stopping power
- High fraction of gamma interactions via photoeffect → electrons with maximal kinetic energy → more Cherenkov photons
- High enough refractive index (needs to be optimized)
- High transmission for visible and near UV Cherenkov photons
- Studied: PbF_2 and $PbWO_4$

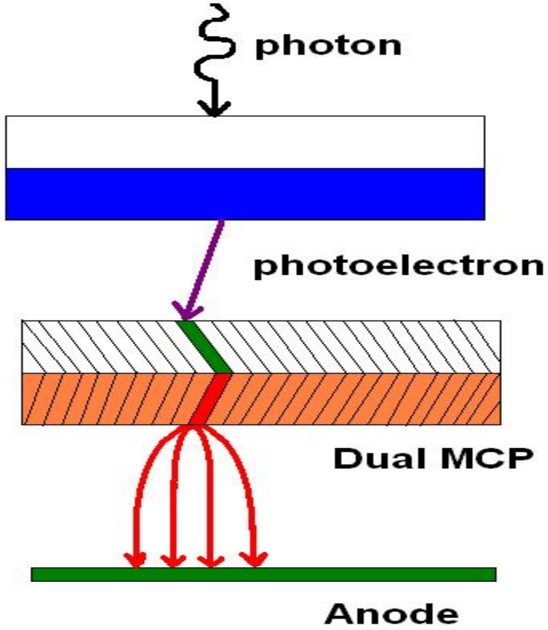
	ρ (g/cm^3)	n	Cherenkov threshold (v/c_0)	e^- Cherenkov threshold (keV)	Cutoff wavelength (nm)	Radiation length (cm)
PbF_2	7.77	1.82	0.55	101	250	0.93
PWO	8.28	2.2	0.45	63	350	0.89

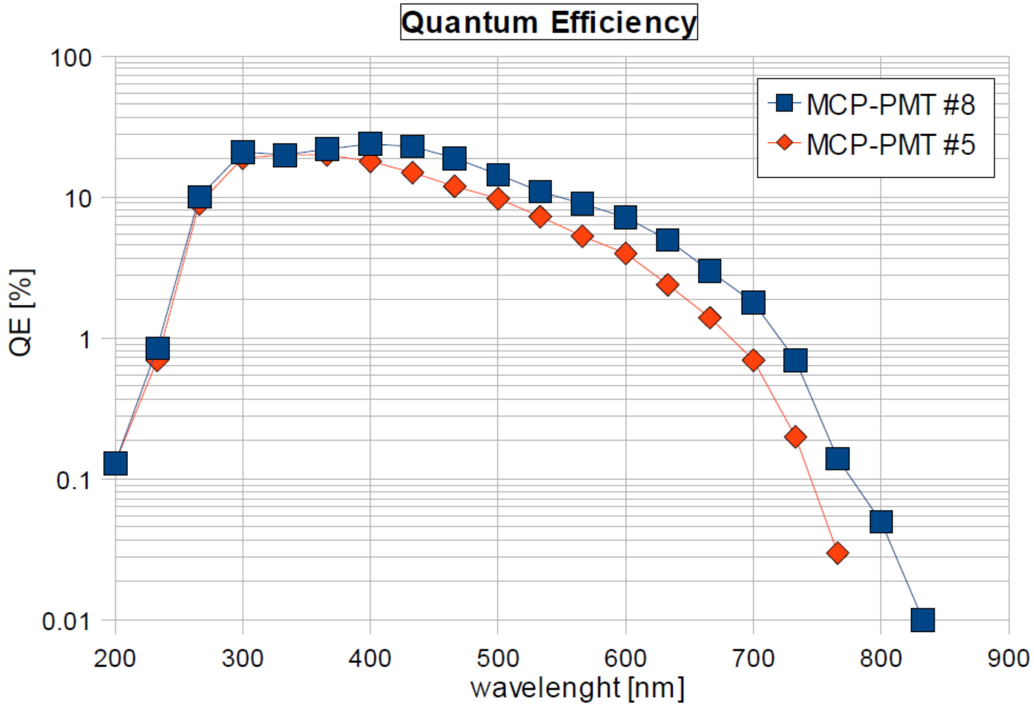
N.B. $PbWO_4$ is also a scintillator.

Photon detector: MCP-PMT

Hamamatsu SL10 MCP-PMT
(prototypes for Belle II TOP counter → talk by K. Matsuoka):

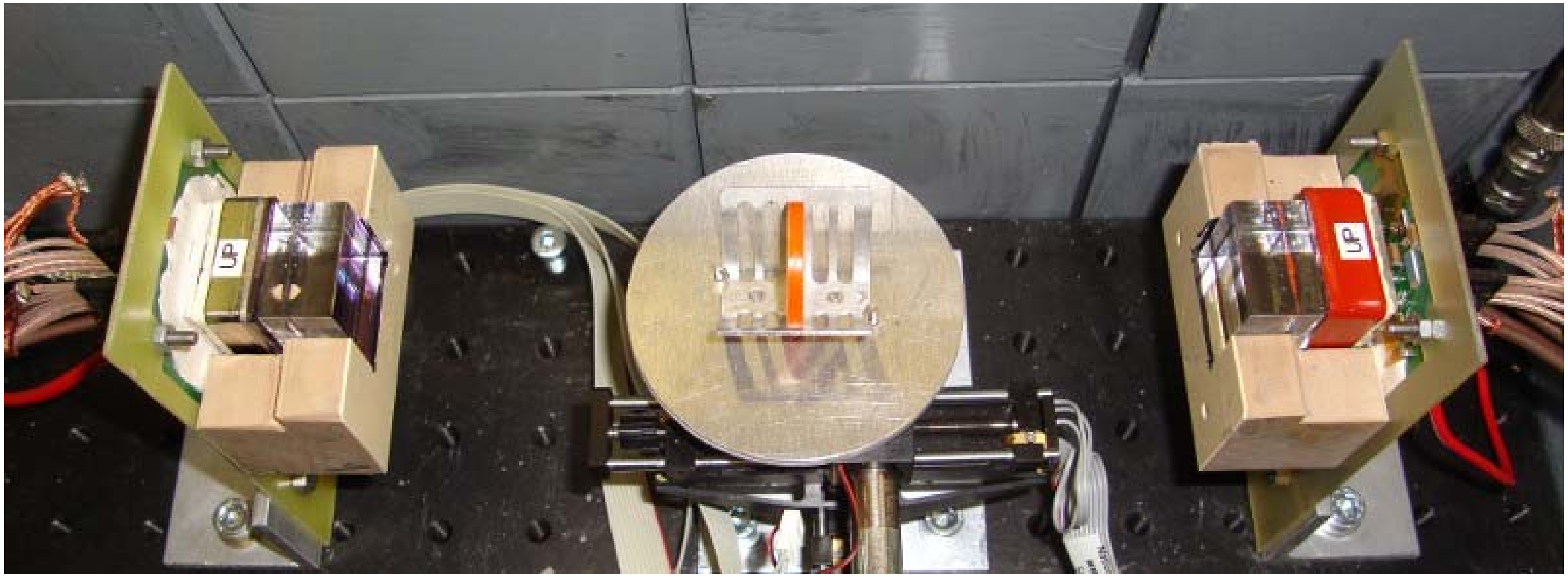
- multi-anode PMT with two MCP steps, 10 mm pores
- 16 (4x4) anode pads, pitch ~ 5.6 mm, gap ~ 0.3 mm
- box dimensions ~ 27.5 mm square
- excellent timing ~ 20ps for single photons
- multi-alkali photocathode
- 1.5 mm borosilicate window
- gain > 10^6





Experimental setup

Two detectors in a back-to-back configuration with 25x25x15 mm^3 crystals coupled to MCP-PMT with optical grease.

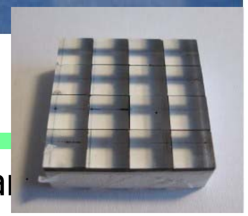


Cherenkov radiators:

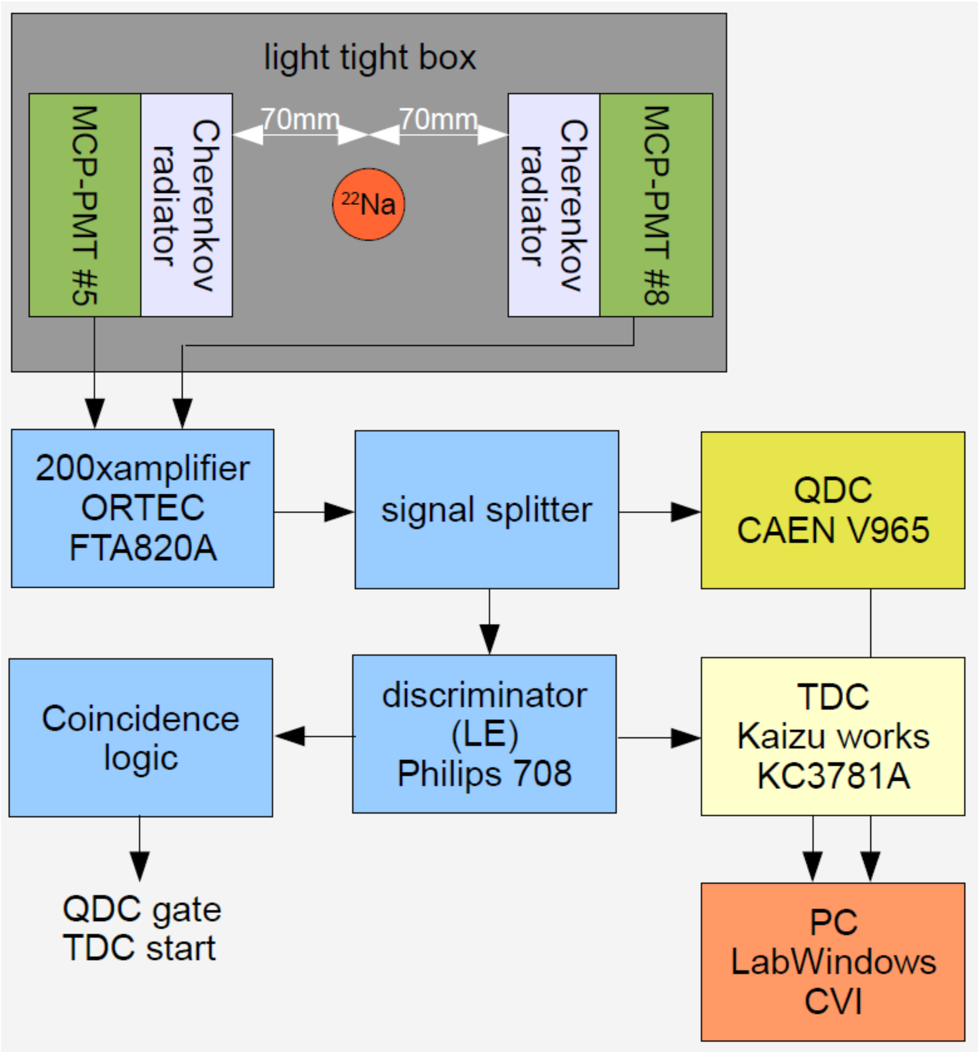
-monolithic: 25 x 25 x 5,15 mm^3 (PbF_2, $PbWO_4$)

-4x4 segmented: 22.5x22.5x7.5 mm^3 (PbF_2)

-black painted, Teflon wrapped, bare



Experimental setup: read-out



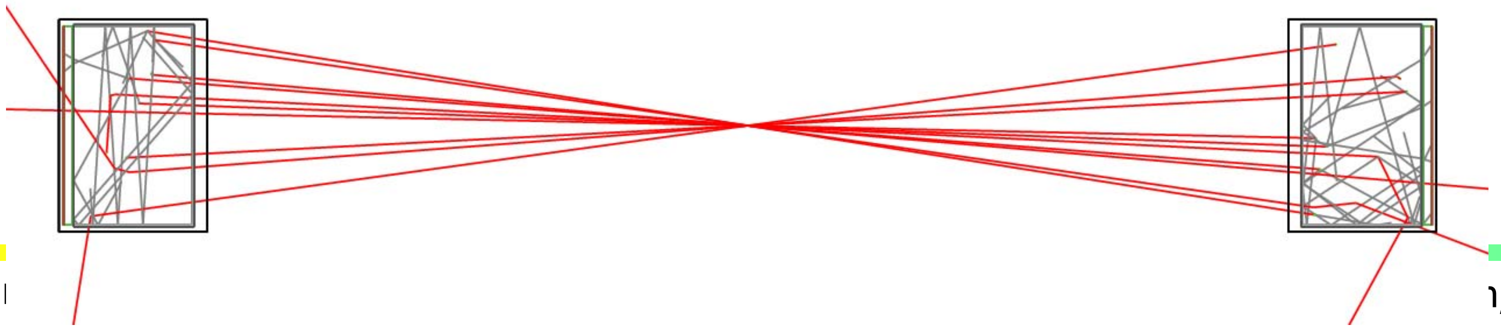
Readout:
- amplifier: ORTEC FTA820
- discriminator: Philips sc. 708LE
- TDC: Kaizu works KC3781A
- QDC: CAEN V965

- Time-walk correction applied in the analysis step

Simulation: GEANT4

Interactions in a single crystal and in a full back-to-back setup were simulated in GEANT4, taking into account:

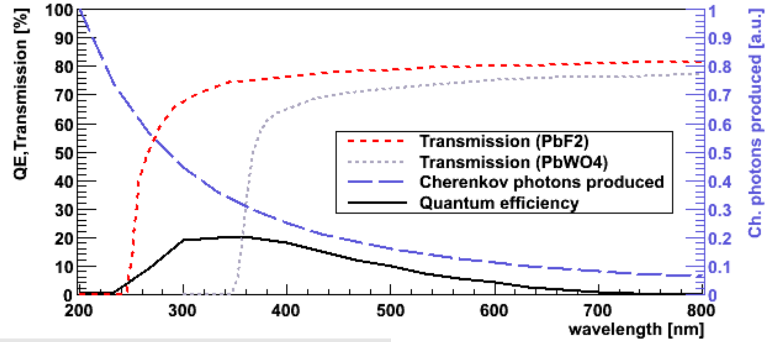
- gamma interactions with detector
- optical photons (Cherenkov and scintillation) produced between 250 nm – 800 nm (no scintillation assumed for PbF2)
- optical photon boundary processes (exit surface polished, other surfaces polished and wrapped in white reflector or black painted)
- photo-detector window coupled with optical grease (n=1.5)
- photo-detector QE (peak 24% @ 400nm)
- photo-detector intrinsic timing modeled according to the measured response function



Cherenkov photon production and detection

Simulation results for PbF_2 and $PbWO_4$ radiators

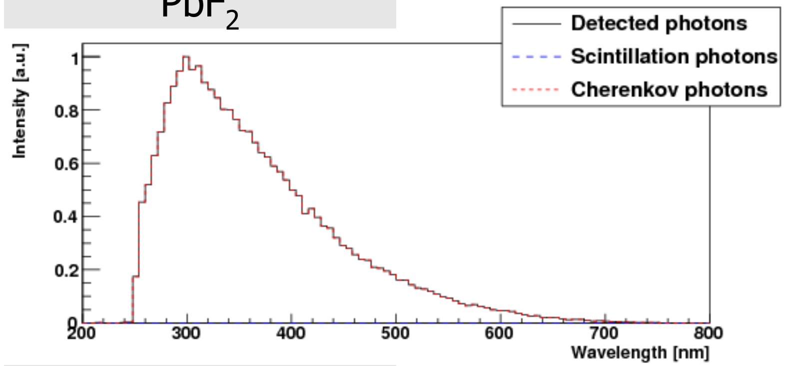
- $25 \times 25 \times 15\ mm^3$ crystal, black painted
- coupled to photo-detector with realistic PDE



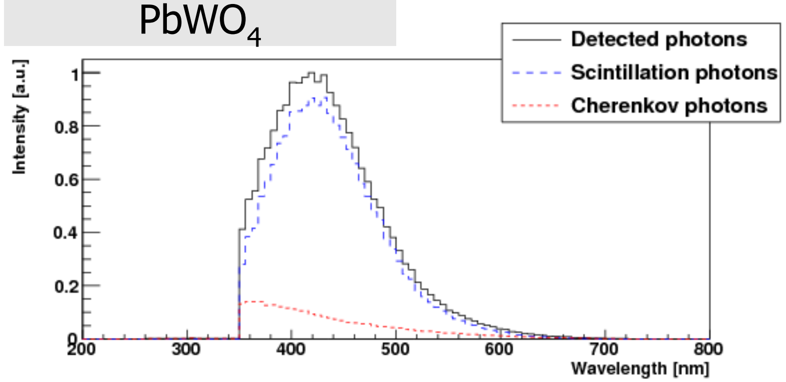
	PbF_2	$PbWO_4$
Gammas interacting	79.7%	80.1%
Electrons produced	1.53	1.57
Ch. photons produced *	15.1	22.2
Ch.photons reaching photodetector	2.11	1.27
Detected Ch. photons	0.14	0.07
Detected scint. photons	-	0.47

* in the 200 - 800 nm wavelength range

PbF_2



$PbWO_4$

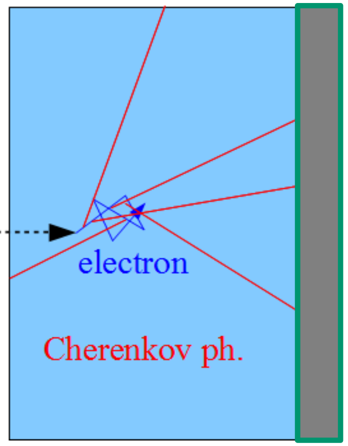


More Cherenkov photons produced in $PbWO_4$

More are detected in PbF_2 due to a better optical transmission (lower λ_{cutoff})

Experimental results: Back-to-back time resolution

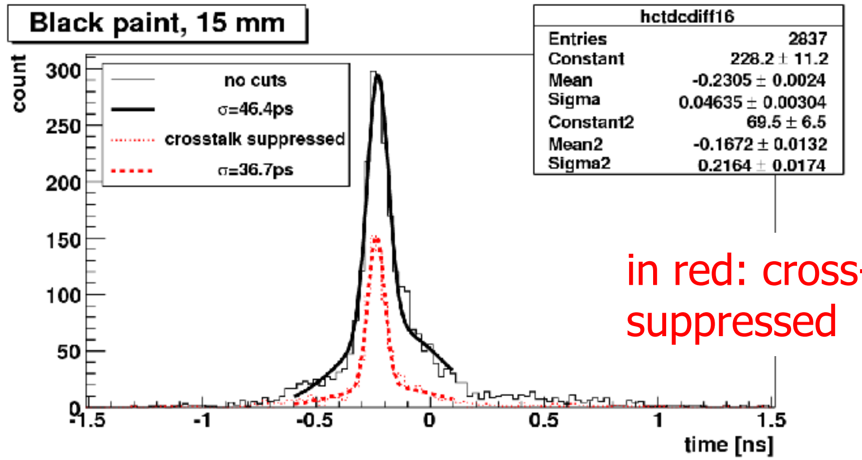
Best timing resolution: black painted PbF_2 crystals (Cherenkov light hitting the walls is absorbed - delayed Cherenkov photons suppressed → improved timing, reduced efficiency)



Data taken with :

- 15 mm long crystal:

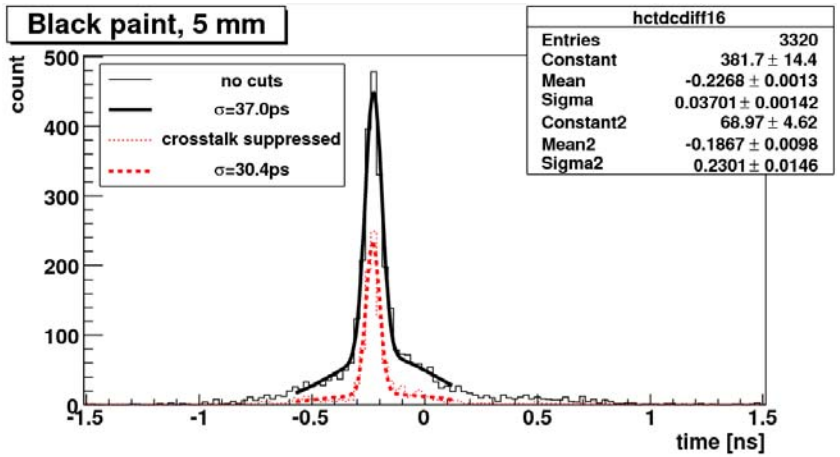
→ FWHM ~ 95 ps



in red: cross-talk suppressed

- 5 mm long crystal:

→ FWHM ~ 70 ps



→ NIM A654(2011)532–538

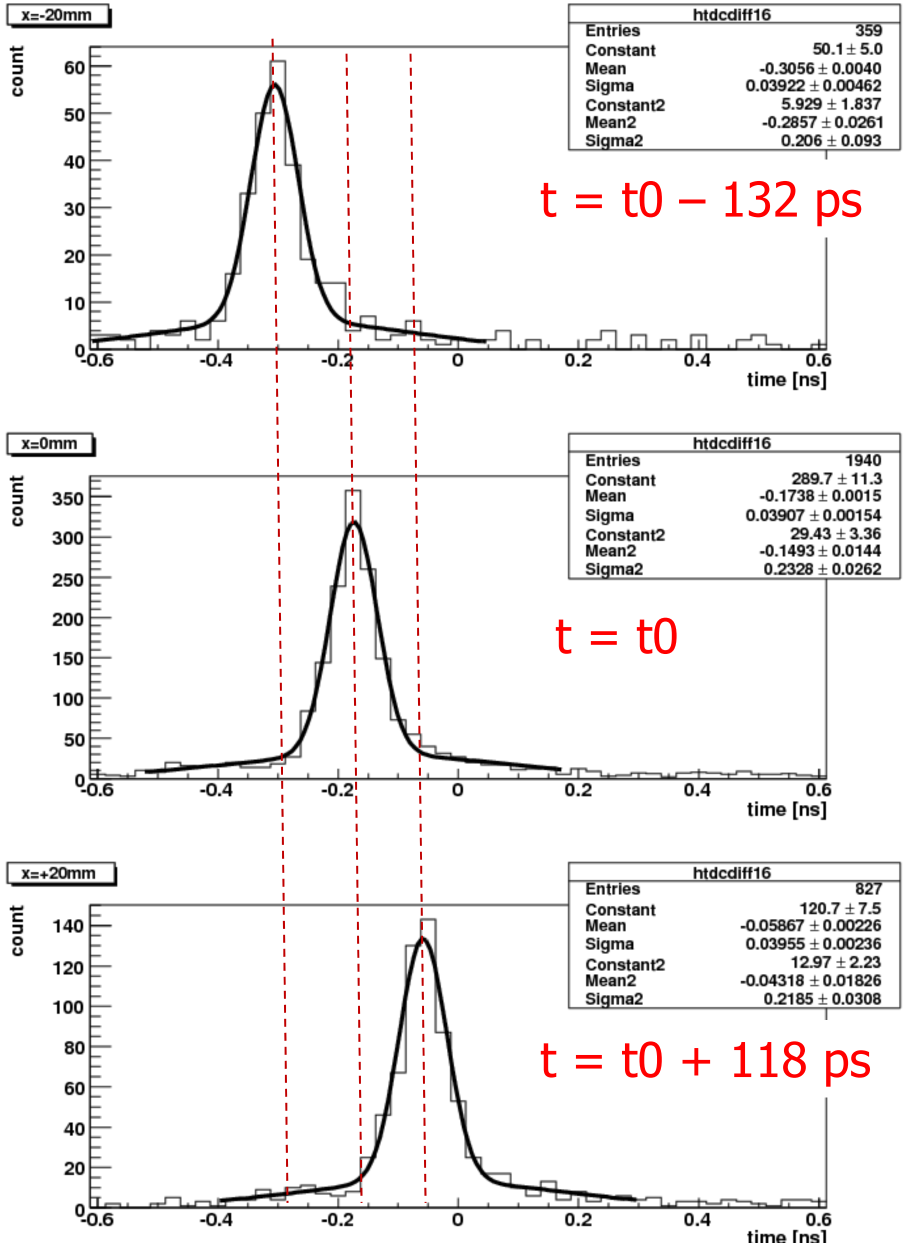
Point source position

Data taken at three different point source positions spaced by 20 mm:

- average time shift 125 ps
- timing resolution ~ 40 ps rms,
  ~ 95 ps FWHM
- position resolution ~ 6 mm rms,
  ~ 14 mm FWHM

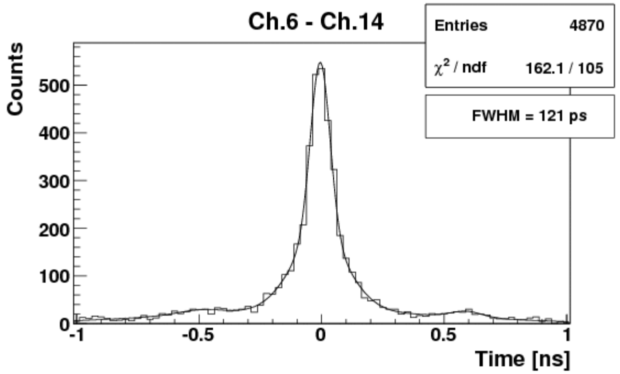
Black painted 15 mm PbF_2 crystals.

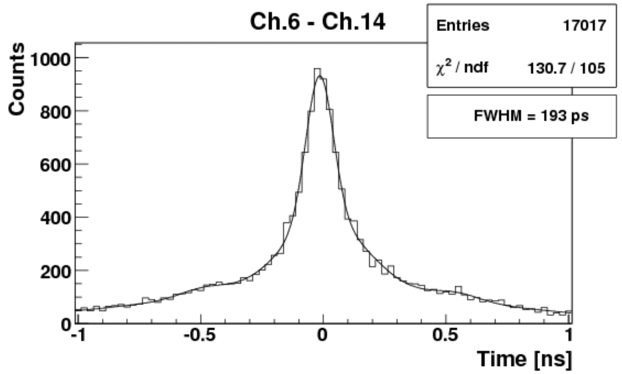
→ NIM A654(2011)532–538

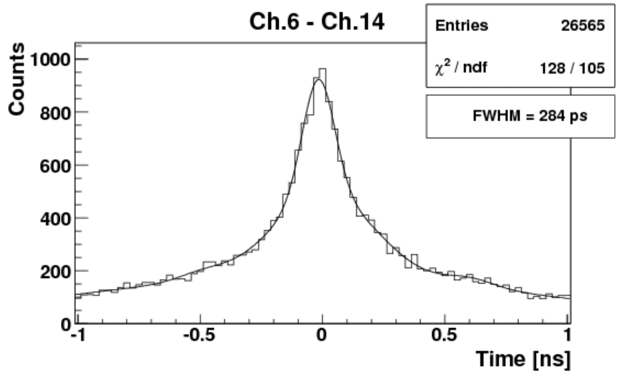


Time resolution, PbF_2

TOF resolution for different radiator surfaces (15 mm thick PbF_2):
black painted: **121 ps** FWHM, bare: **193 ps** FWHM, Teflon wrapped: **284 ps** FWHM







Indirect photons (bare and Teflon wrapped crystals): adds a very wide component, FWHM increases faster than sigma of the peak

→ FWHM probably not the right quantity to compare

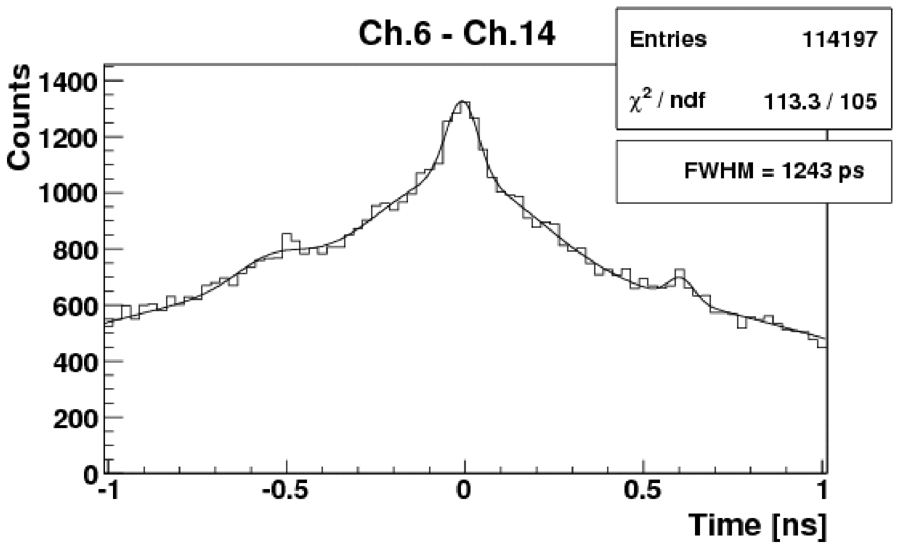
→ has to be checked on reconstructed images

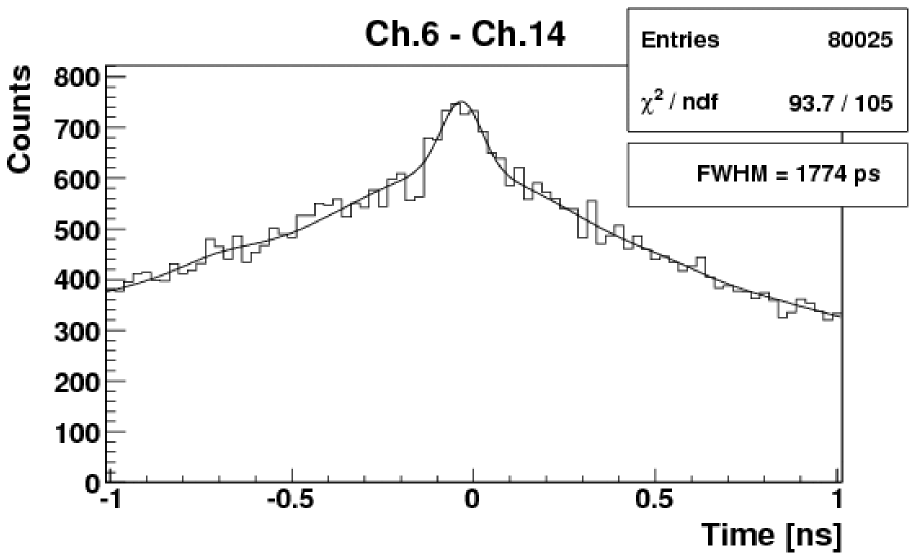
N.B. Somewhat worse timing performance than in the original set-up; now we have more channels, and not a perfect calibration.

Time resolution, $PbWO_4$

TOF resolution for $PbWO_4$ (black painted):

- time distributions dominated by scintillation background, with a small Cherenkov peak
- 5 mm thick: **1.2 ns** FWHM, 15 mm thick: **1.7 ns** FWHM

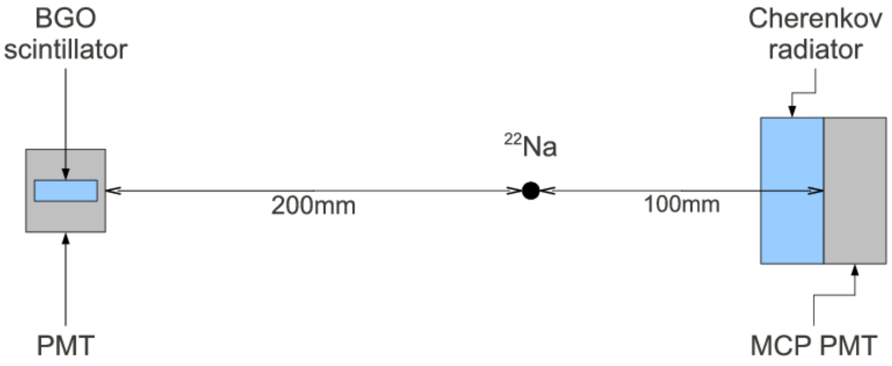


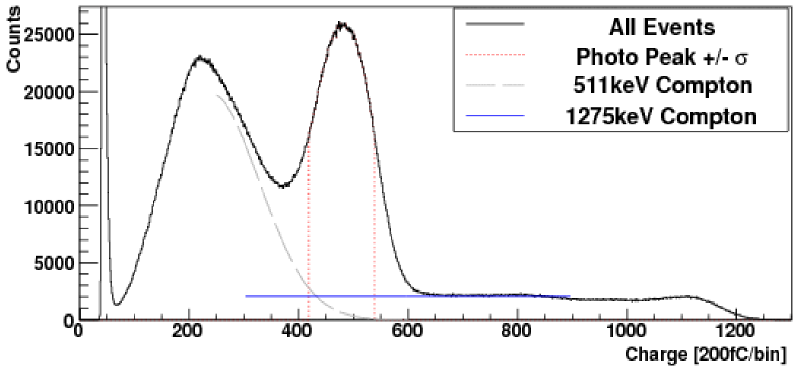


+ smaller number of Cherenkov photons
→ $PbWO_4$ does not look like a competitive Cherenkov detector for annihilation gammas

Detection efficiency

Triggered photons: on one side of the ^{22}Na source use a scintillation detector with energy measurement





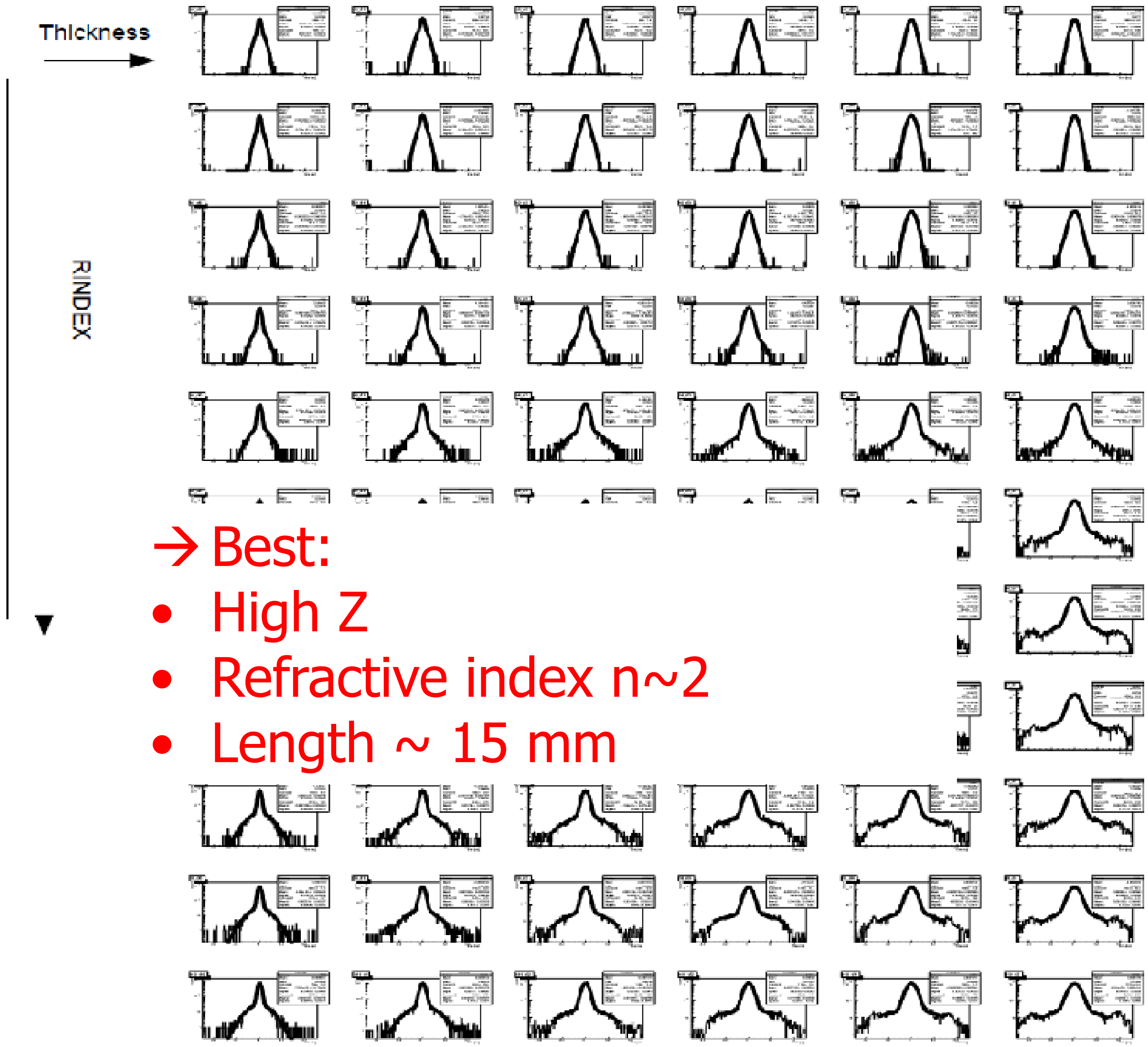
Detection efficiency =

$$\frac{\text{\# events detected on Cherenkov detector with a 511 keV trigger}}{\text{\# events with 511 keV trigger}}$$

Corrected for events due to Compton scattering of 1275 kev gammas from ^{22}Na source

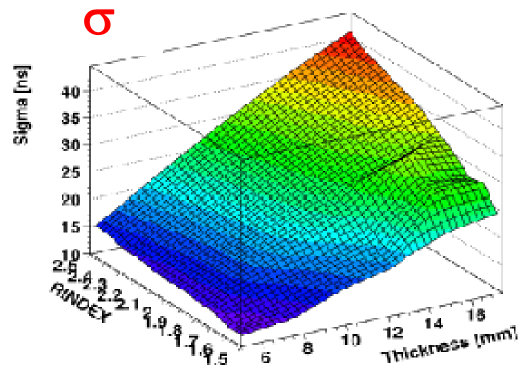
→ Results: from **4.3%** (5 mm thick, black painted PbF_2) up to **18%** (15 mm thick, Teflon wrapped PbF_2)

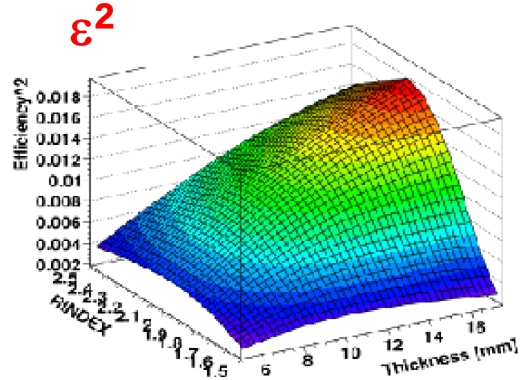
Simulation: search for optimum radiator parameters



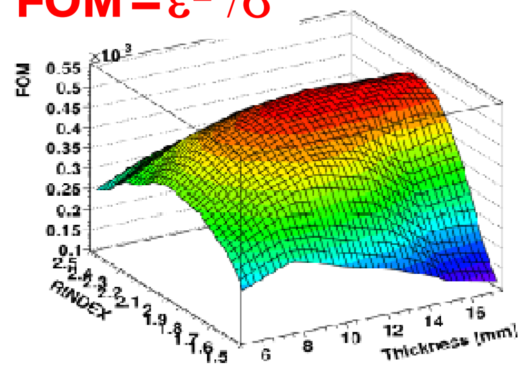
→ Best:

- High Z
- Refractive index n~2
- Length ~ 15 mm





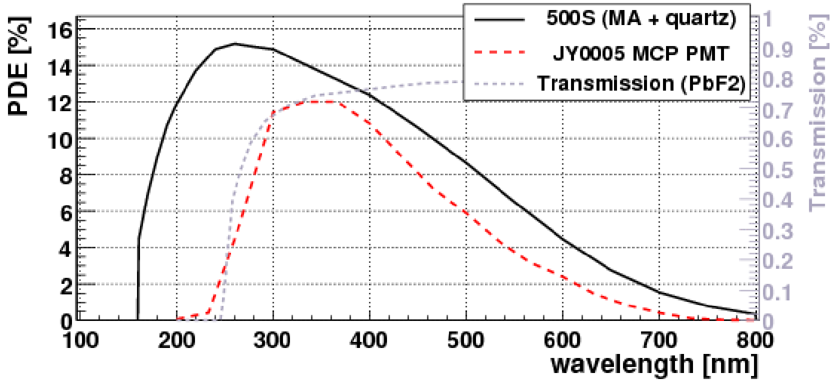
FOM = ε^2/σ



Efficiency improvements, MC estimates

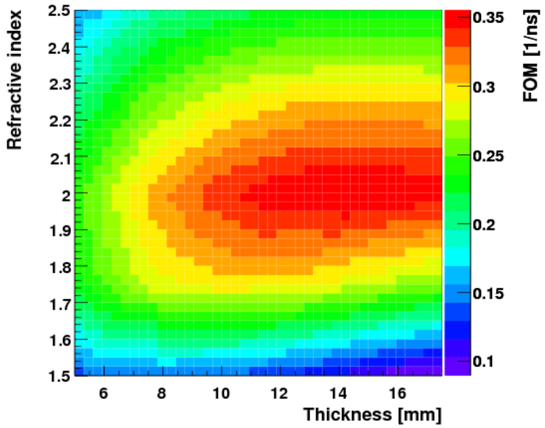
- **Photodetector**:
  - improved photon detection efficiency
    - photocathode with better QE
    - window, transparent to lower λ (quartz → 160 nm)
  - example: Hamamatsu 500S photocathode

  → **1.4x** detection efficiency (2x in FOM=ε^2/σ)



- **Transport of photons** from radiator to photo-detector:
  - optimal optical coupling of the radiator to the photon detector (at present radiator refractive index n=1.8, optical grease n=1.5, PMT window n=1.5) → ~**1.4x** efficiency (2x FOM)

- **Radiator optimization** with a hypothetical, PbF_2-like crystal (using 500S photocathode):
  - With an optimized refractive index, thickness (n=2.0, d~14mm) → **1.5x** efficiency (3x FOM)
  - Improved optical transmission (λ_{cutoff} = 160 nm) → **2.4x** efficiency (6x FOM)

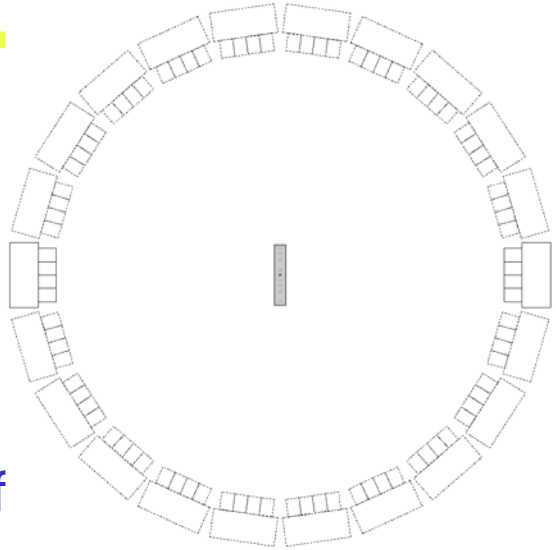


→ poster by S. Kurosawa et al, on $Gd_3Ga_5O_{12}$

Reconstruction

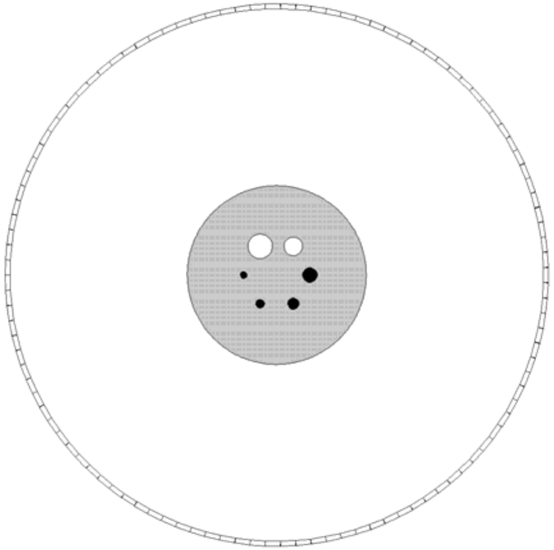
Cherenkov PET tested experimentally

- data equivalent to one PET ring obtained with only two detectors
- source rotated in discrete steps
- data collected at each step for the same amount of time
- D = 185 mm, H = 22.5 mm



Full body PET scanner simulated

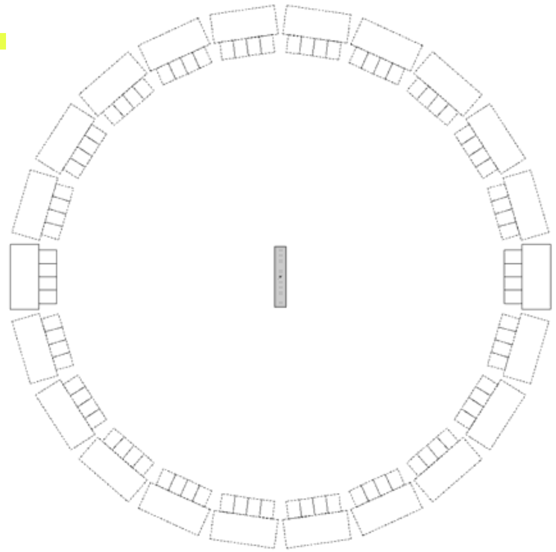
- D = 800 mm, 15 rings (H = 340 mm)
- phantom with d = 270 mm, 4 hot spheres (d: 10 - 22 mm) and 2 cold spheres (d = 28, 37mm)

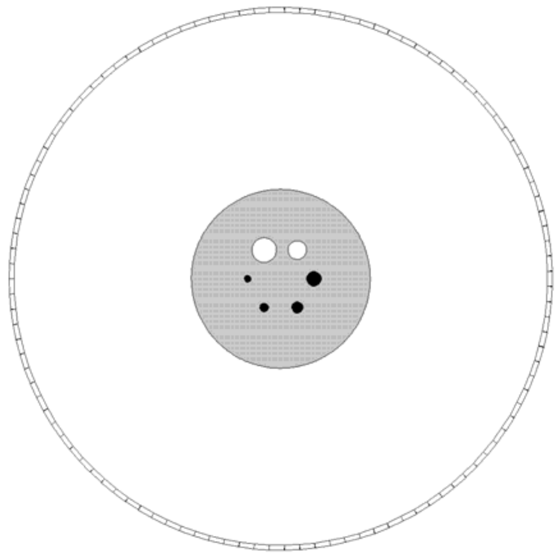


Reconstruction

Reconstruction algorithms:

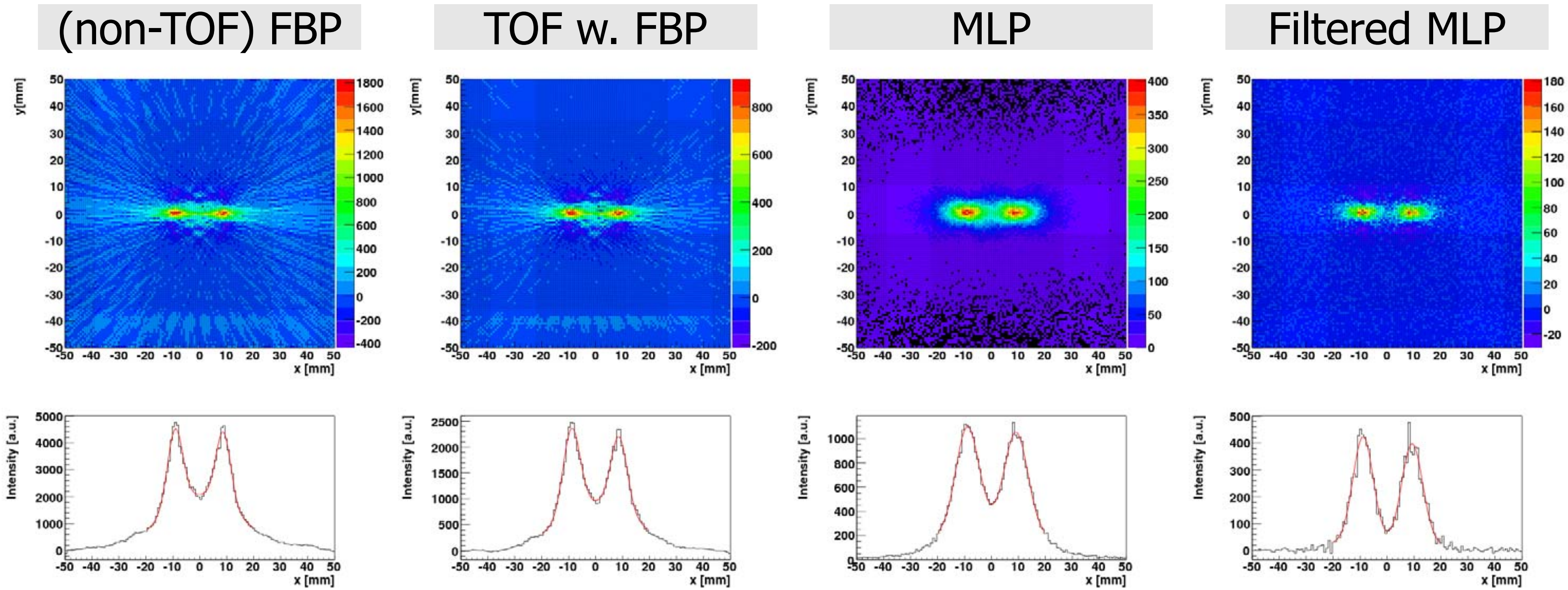
- **Filtered backprojection (FBP):** basic non-TOF algorithm
- **TOF weighted FBP:** pixels along LOR incremented with TOF response defined weight
- **Most likely position (MLP):** point of decay on LOR calculated from TOF information
- **Filtered MLP:** MLP image deconvoluted for TOF response





Reconstruction - experiment

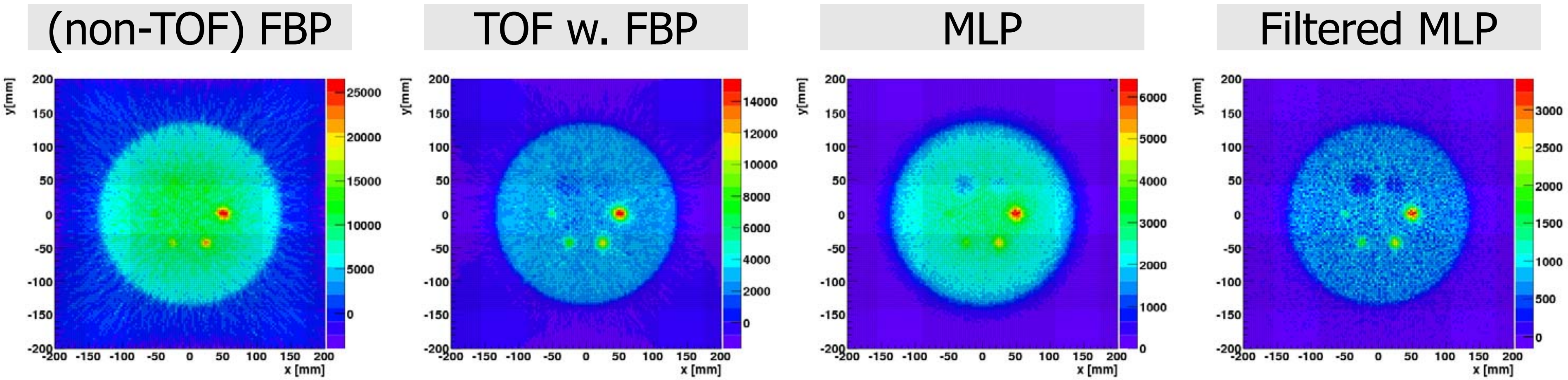
- ^{22}Na point sources at +10 mm and -10 mm
- 4x4 segmented, black painted PbF_2 radiators



→ Simple, very fast Most-likely-point (MLP) method (~histograming of points) already gives a reasonable picture

Reconstruction - simulation

- Hot spheres activity concentration: 3x phantom background
- Statistics equivalent to 163 s of PET examination
- 4x4 segmented, Teflon wrapped PbF_2 radiators
- 20 mm thick axial slices



First tries, have to understand how the possible improvements in the detection efficiency will influence the performance.

- Black painted (better TOF resolution) → better contrast,
- Teflon wrapped (higher statistics) → better contrast-to-noise ratio