PET Design: Simulation Studies using GEANT4 and GATE
- Status Report -

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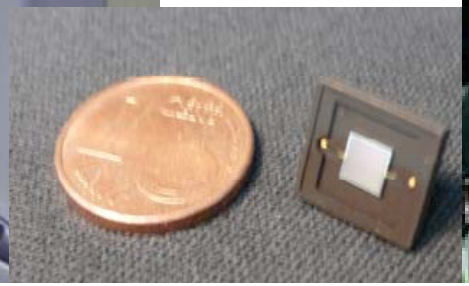
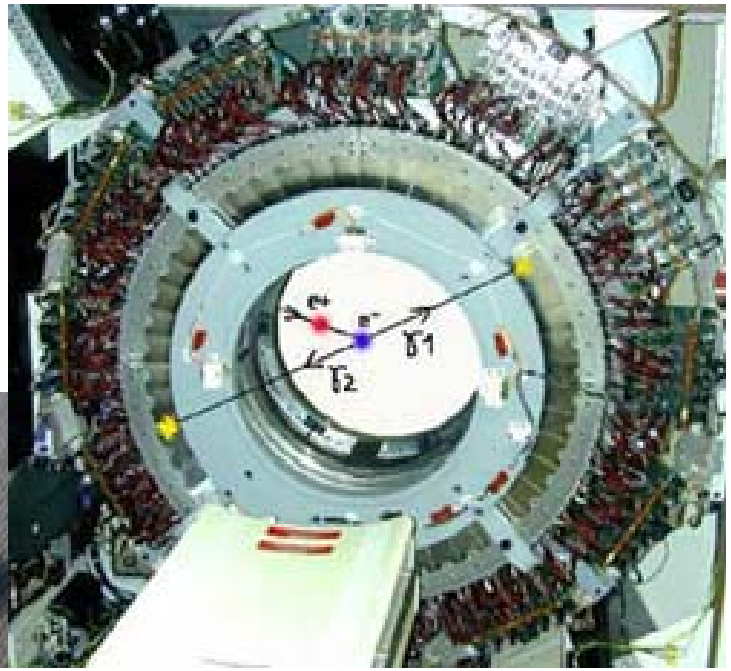
DESY

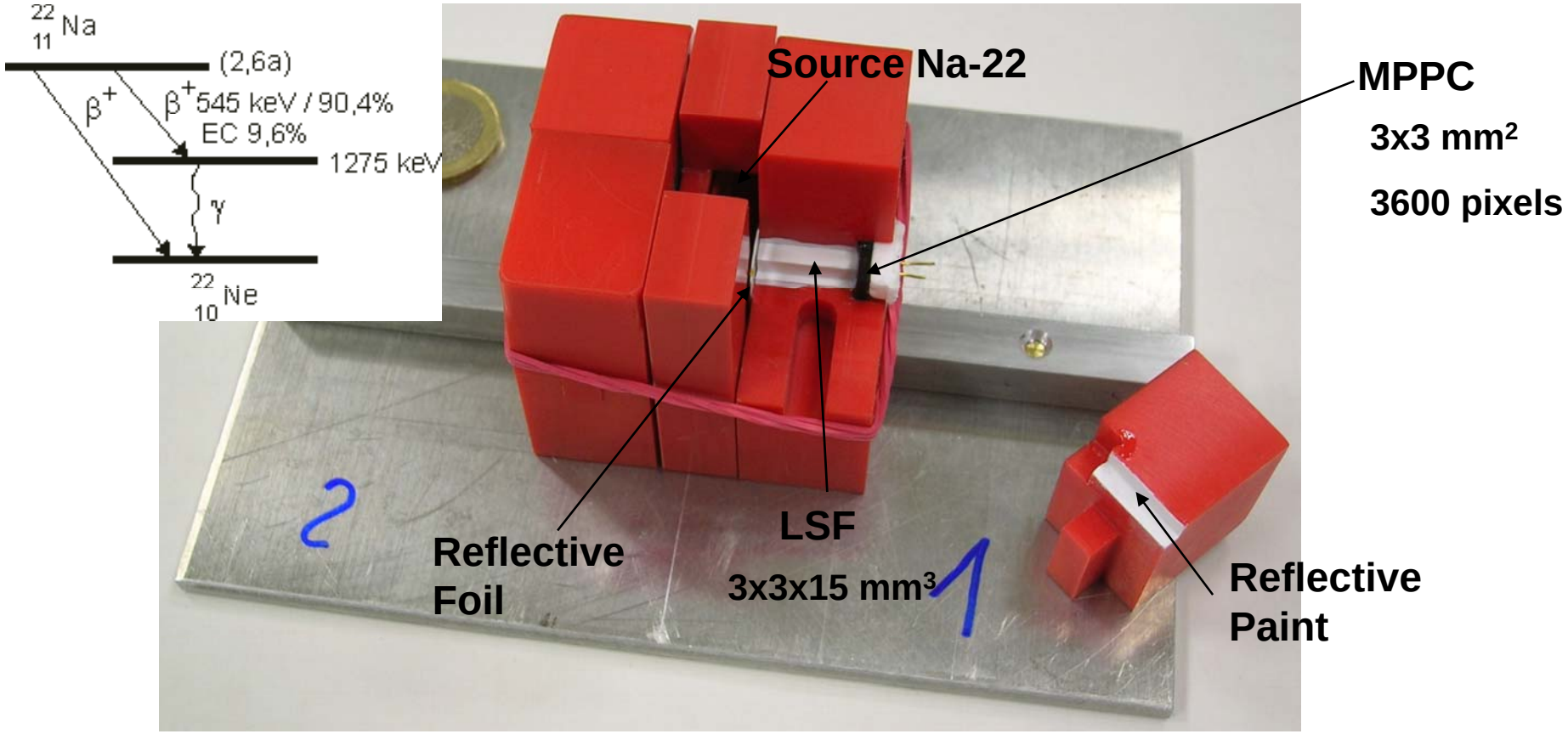




Outline

- Measurements
- Single crystal studies (GEANT4)
- PET scanner (GATE)

Experimental Setup

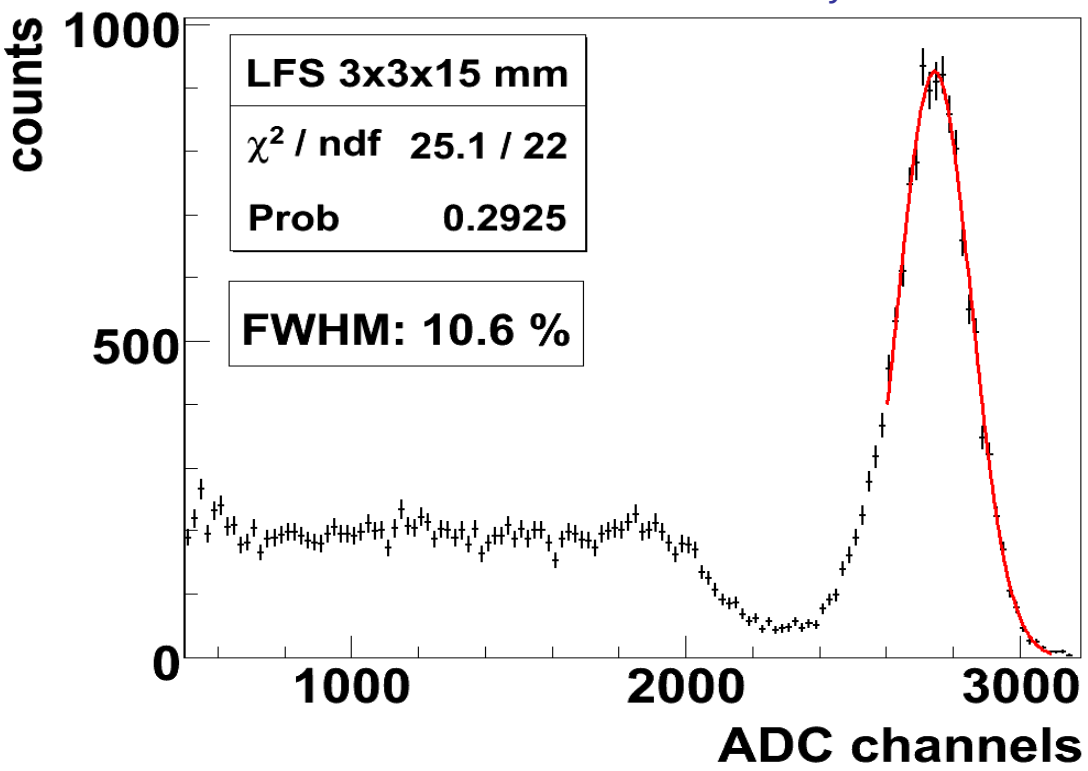


- MPPC and crystal well aligned, optical photons well contained, high reproducibility
- Reaching energy resolutions of 10-11 % FWHM (LSO and LSF)

Energy Resolution

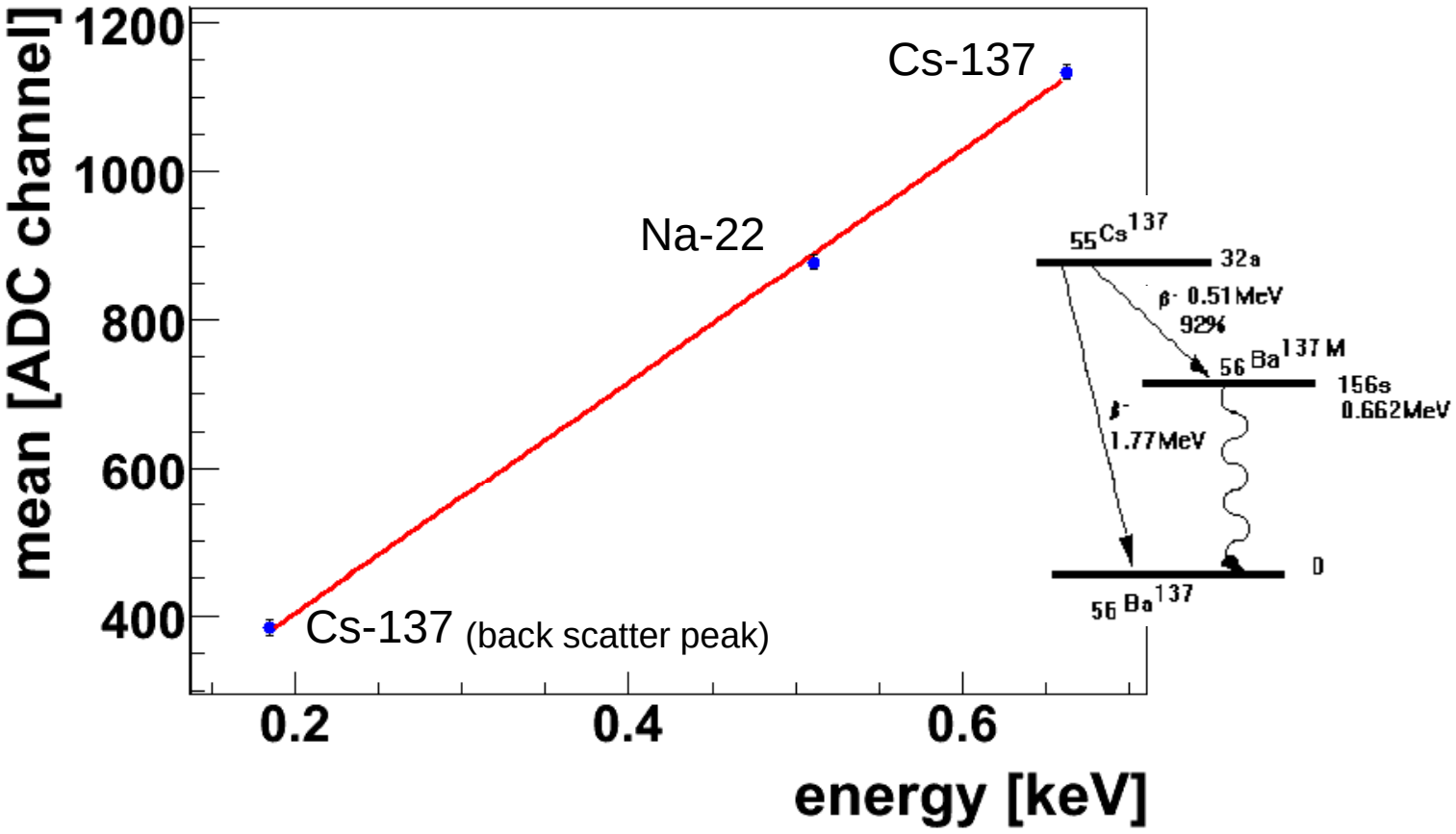
$$\left(\frac{\sigma(E)}{E}\right)^2 \approx \left(\frac{1}{\sqrt{N}}\right)^2 + (\Delta_{intr}(E))^2 + \left(\frac{\sigma_{noise}}{E}\right)^2$$

Poisson stat. (blue sensitivity) | 8% for LSO/LFS | negligible



- MPPC (3x3 mm, 3600 pixels) coupled to LFS (3x3x15 mm)
- Good separation between compton continuum and photo-electric peak.
- Mean at **2000 pixels**.
- Saturation not an issue: signal width ~120 ns, peak amplitude ~400 p.e.
- Linearity checked with different sources

Linearity



Linearity confirmed in the energy region of interest.

Simulation Studies

Single Crystal + MPPC

- Detailed studies to optimize single crystal dimensions
- **GEANT4** simulation
- Good description of the measurements in terms of energy resolution and photon yield.

PET System

- Design of a full PET system
- Spatial resolution (image reconstruction using FBP)
- Optimize crystal dimensions (DOI)
- **GATE** (GEANT4 Application for Tomographic Emission) toolkit based on GEANT4
- First results very promising.

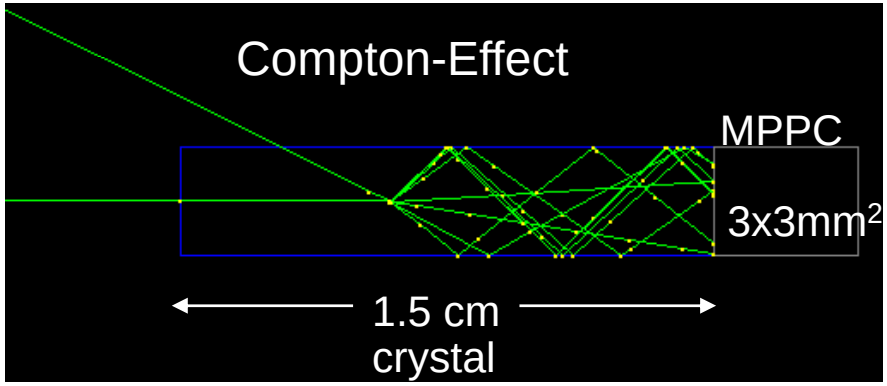
Single Crystal + MPPC GEANT4 Simulation

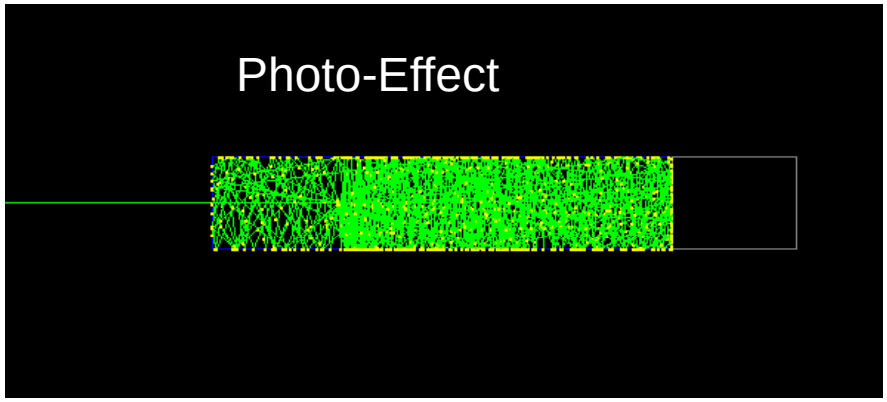
Important parameters:

- LSO/LSF: **scintillation yield** (23k), refraction index (1.82), **emission spectrum**, absorption length (50m)
- Optical grease BC-630 (10µm): refraction index (1.5)
- MPPC: **quantum efficiency**
- Teflon wrapping: **reflectivity** (0.98), **refraction index** (1.34)

Compare to measurements:

- number of pixels
- signal width
- signal shape

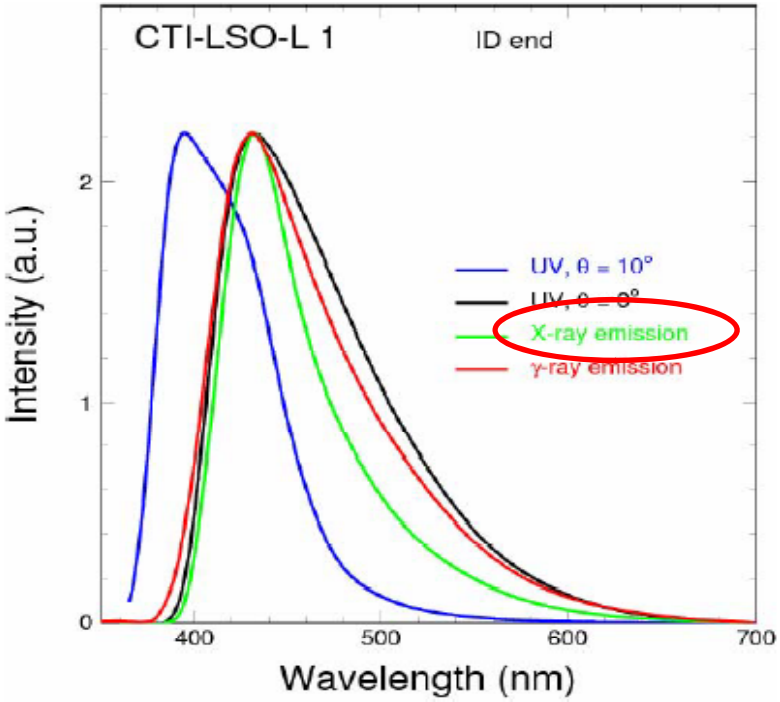


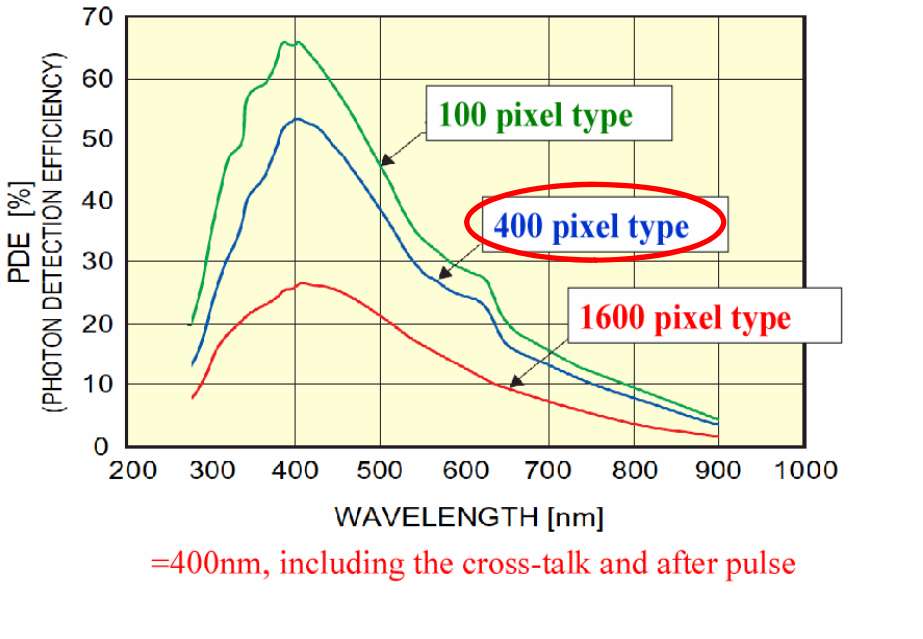


30 reflections:
P(absorbed)=45%
(98% reflectivity)

(LY: 100 photons/MeV)

Scintillation Yield and Photon Detection Efficiency





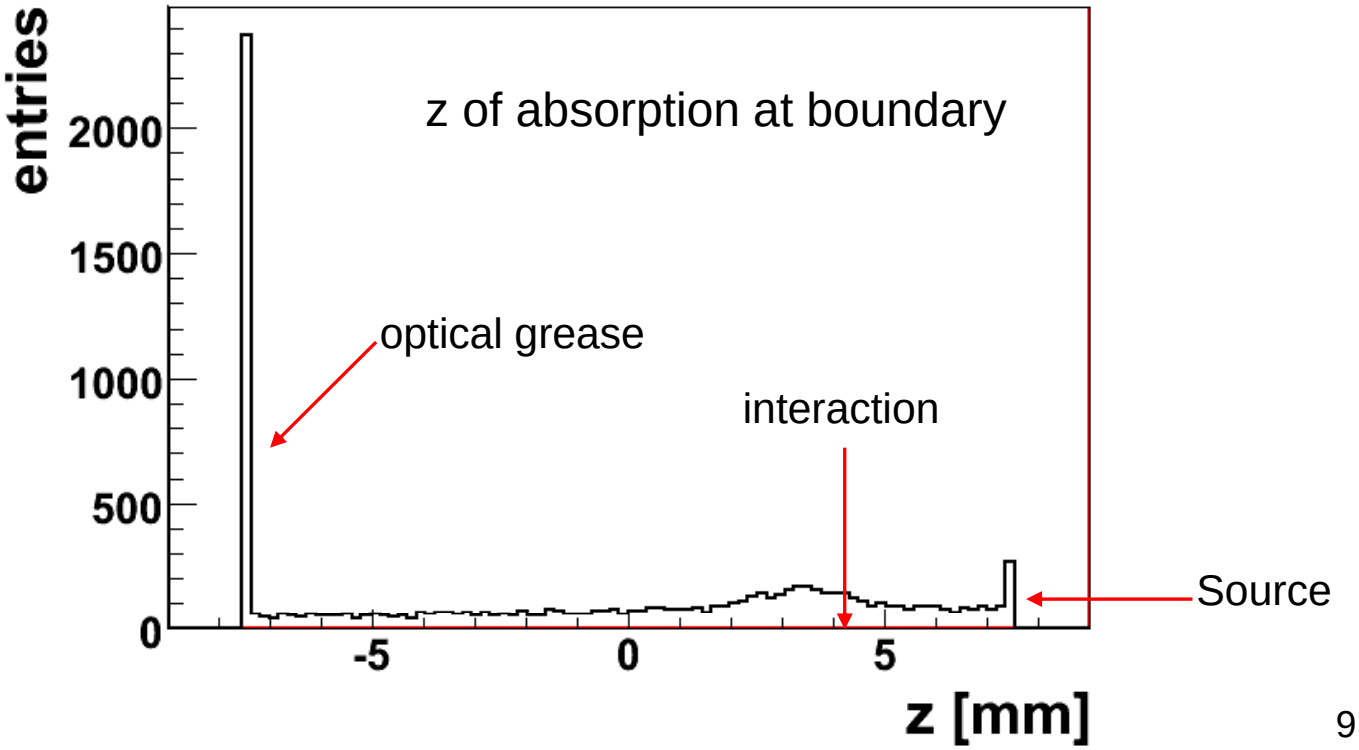
Incorporated published distributions.

A Single Event

Number of photons produced : 10940
Absorbed in the crystal : 9
Absorbed at boundary : 9013
Detected : 1911
Leakage (optical grease) : 7

Crystal length: 1.5 cm

Reflectivity (Teflon): 90 %



Efficiency

Interaction in crystal?

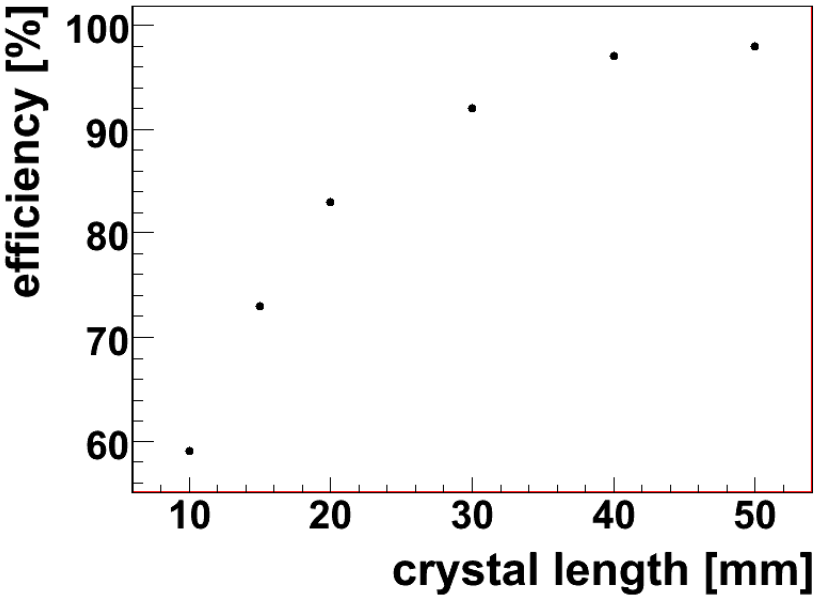
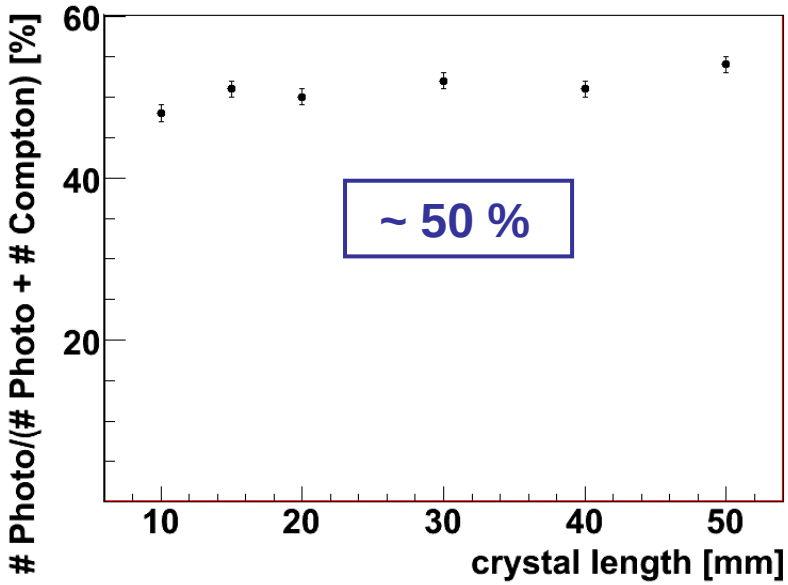
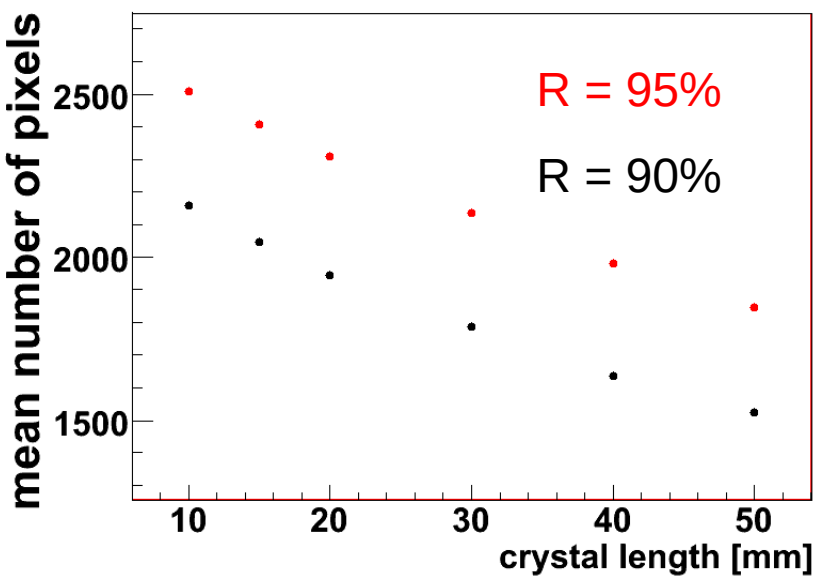


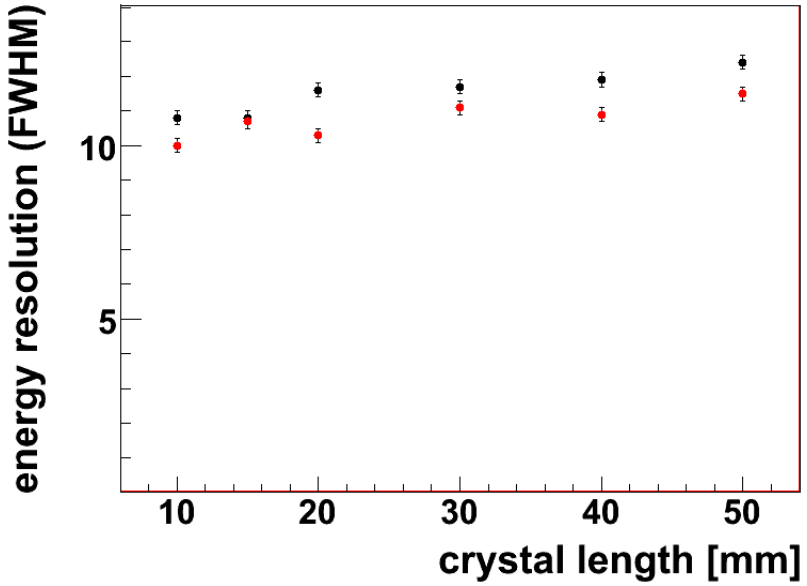
Photo- or Compton-Effect?



→ **5 cm > total length > 3 cm**

Energy Resolution

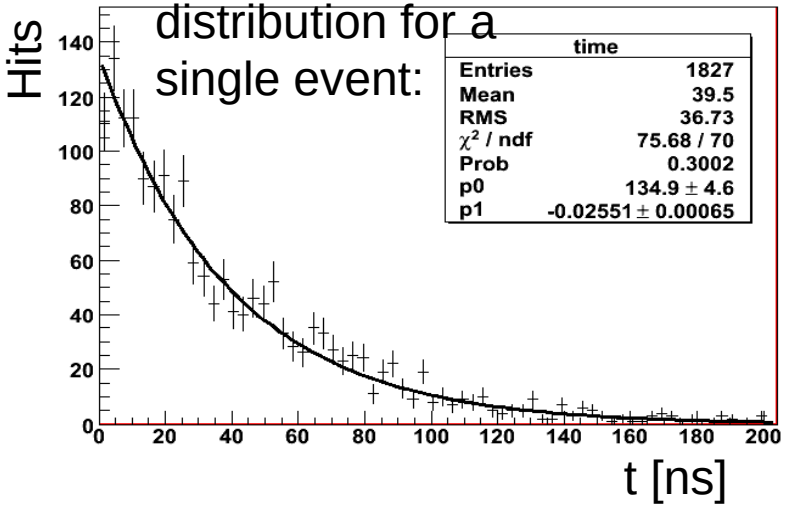


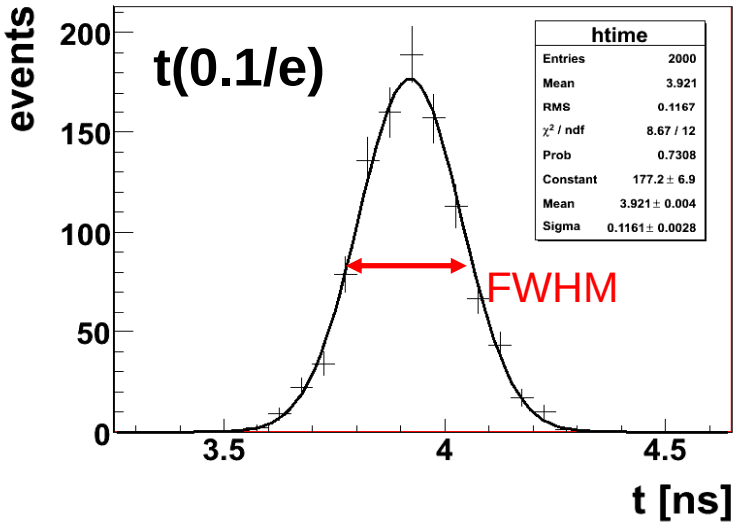


- Energy resolution is slightly decreasing for longer crystals due to absorption in the Teflon wrapping.
- The larger the reflectivity the smaller the effect.

Time Resolution

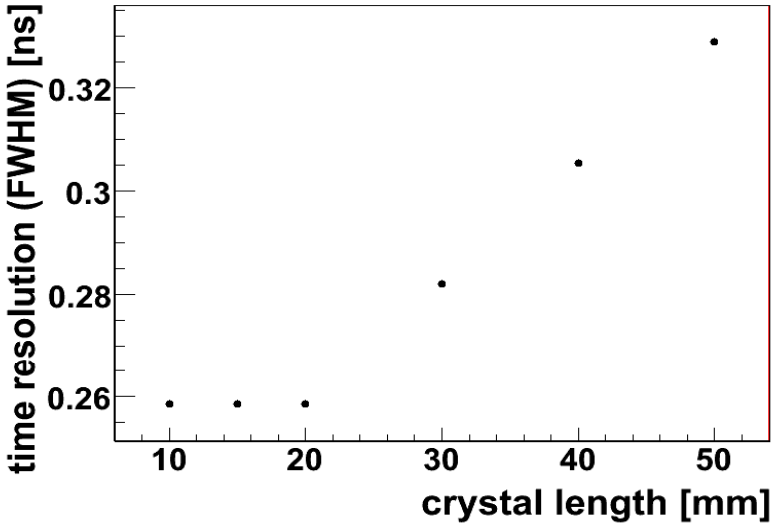
Hit-time distribution for a single event:



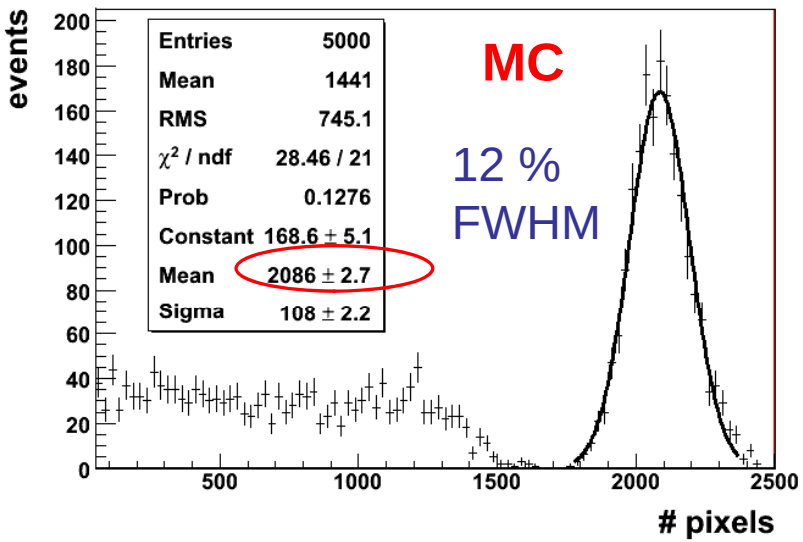


Triggering at low threshold, i.e. the very first photons which arrive:

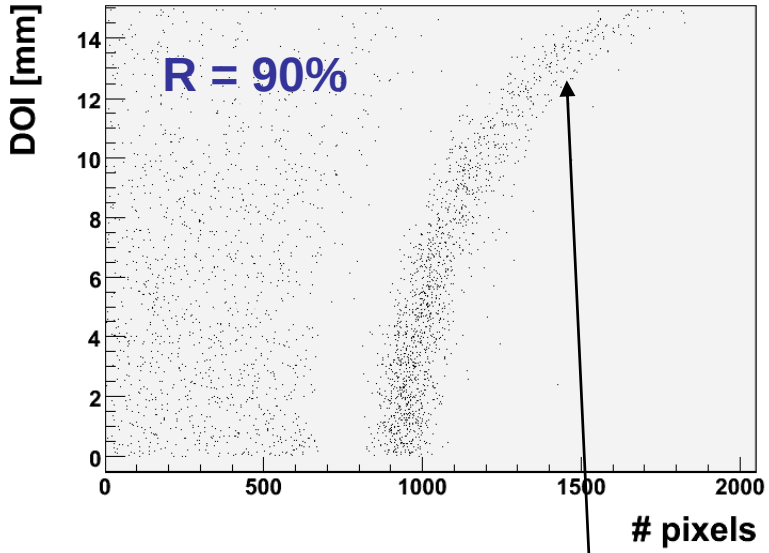
Crystal length has only a small influence on the timing.

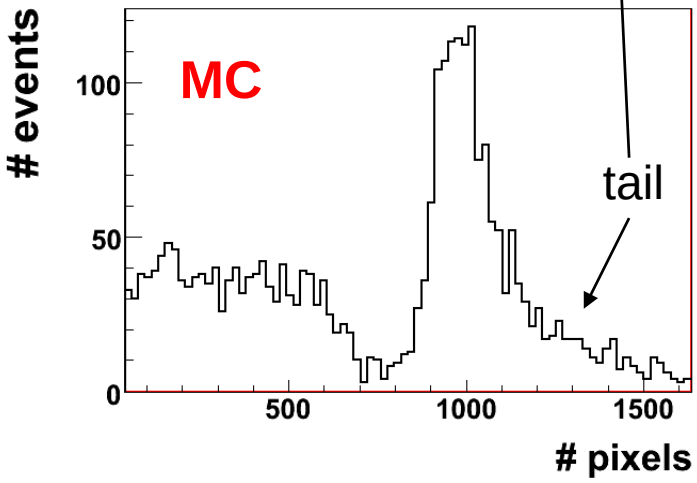


Measurements vs. Simulation



Reasonable agreement with data (parameters see prev. page).

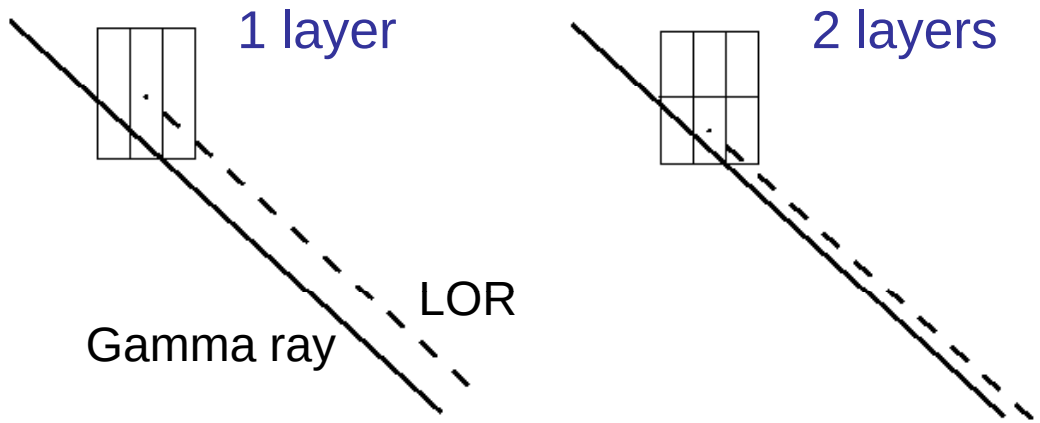




Tuning of the **reflectivity**: No tail in data. Reflectivity >> 95 % + # pixels

Crystal Length and DOI

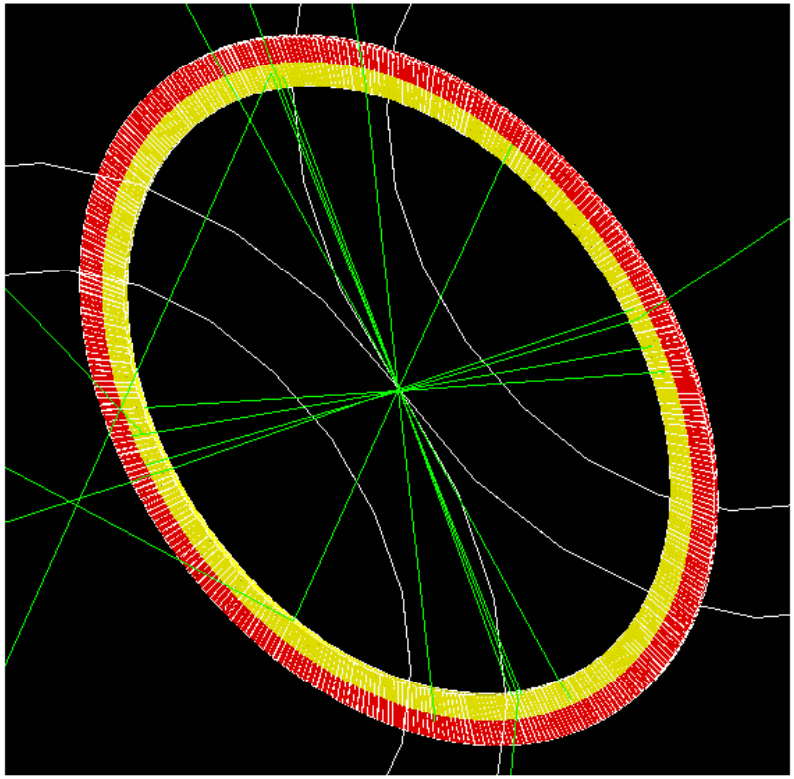
Depth of interaction (DOI) information improves resolution considerably.



Simulation of a full PET scanner

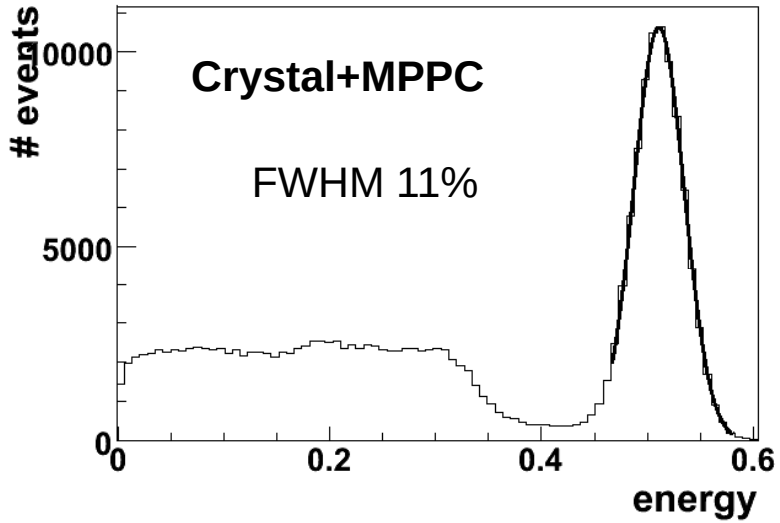
PET System - GATE

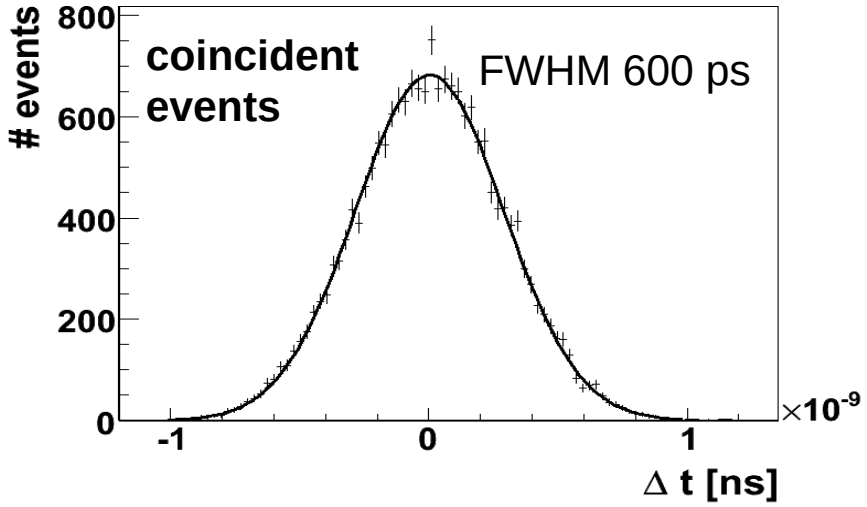
- Simulation of a full PET system to optimize camera design (high granularity, DOI, TOF).
- Image reconstruction using Filtered Back Projection (STIR)
- Determination of spatial resolution in compliance with NEMA NU 2-2007 standard*.
- Dead material, movement, noise, dead time, dose, phantom, scan time, efficiency
- Simulation of a simple PET system: 2x387 crystals (LSO, 3x3x15 mm^3)



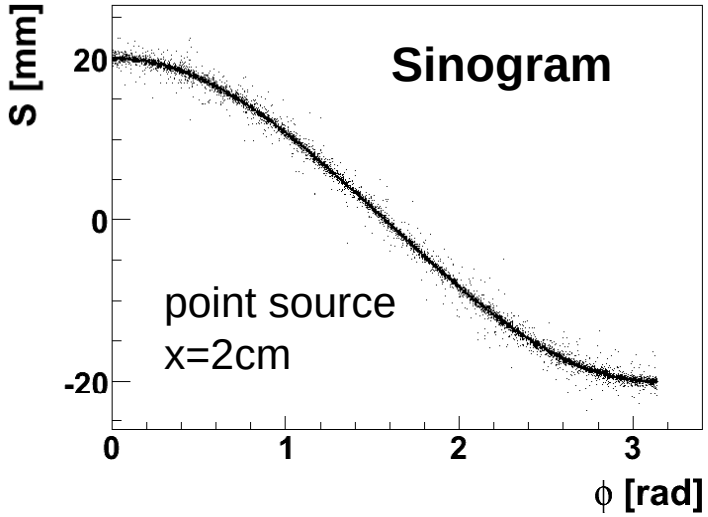
* National Electrical Manufacturers Association

PET System – First Results





Tune energy and time resolution of single crystal+MPPC element according to measurements.



next steps: granularity, FBP (STIR)

Conclusions and Outlook

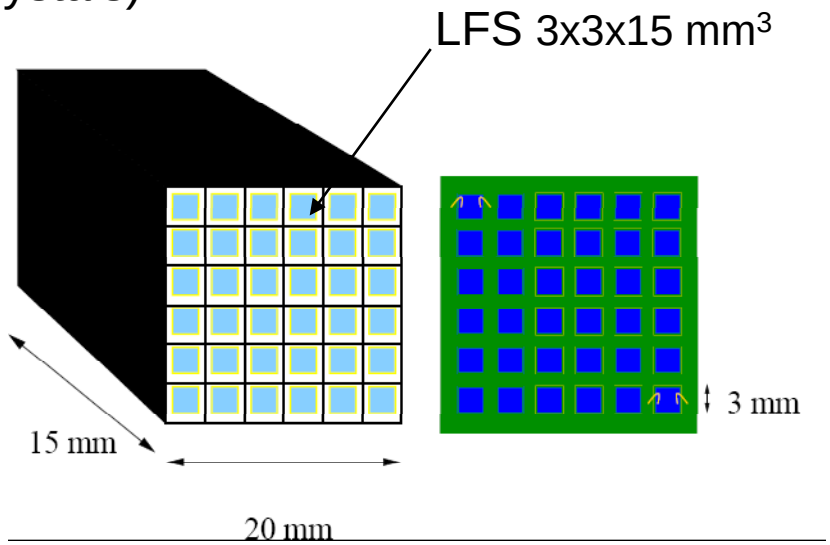
- Simulation: Tools are ready. More detailed studies follow. Emphasis on simulation of full PET scanner.
- Build and test prototype.

BACKUP FOILS

Design Criteria

Camera design (matrix of crystals, each crystal read out individually by an MPPC) guided by the following criteria:

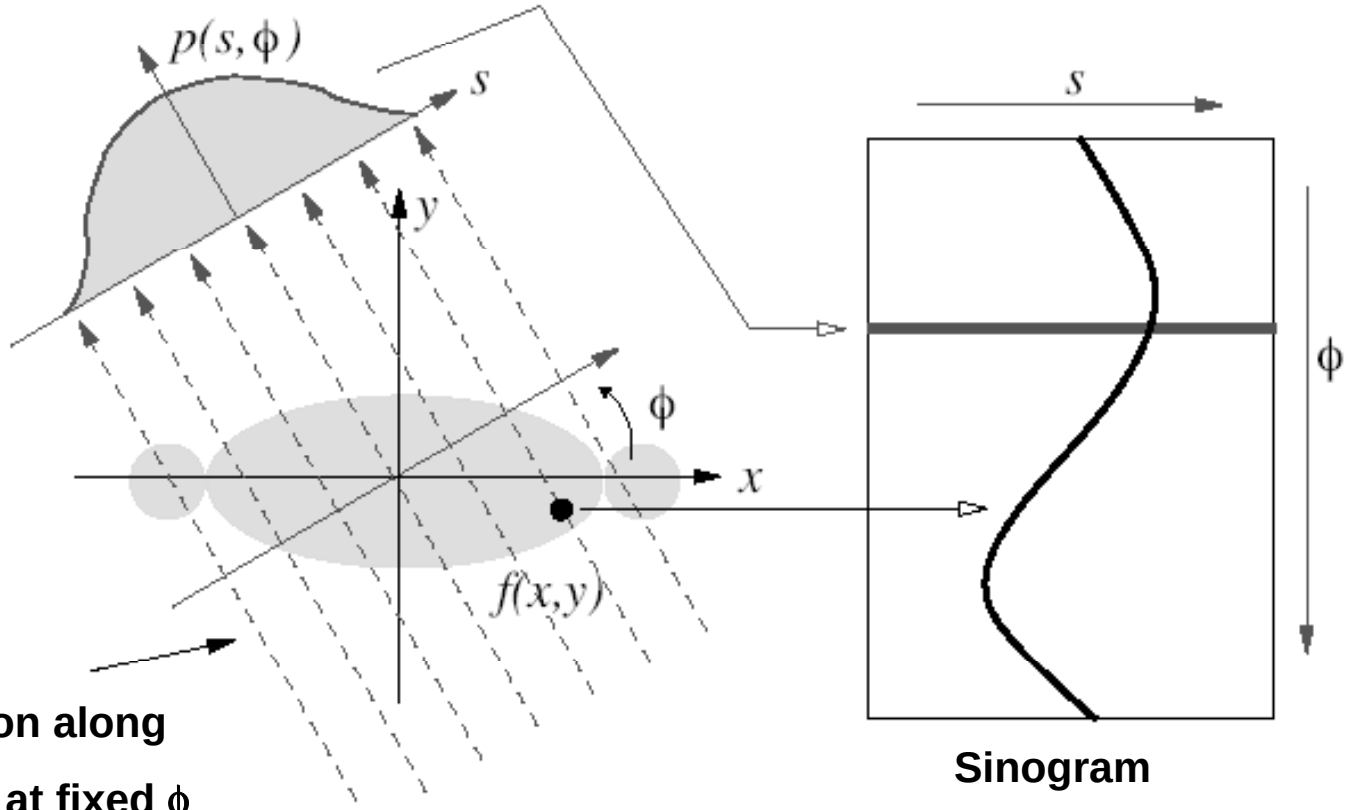
- spatial resolution (DOI: two layers of crystals)
- time resolution
- efficiency
- exposure to radiation, scan-time
- costs



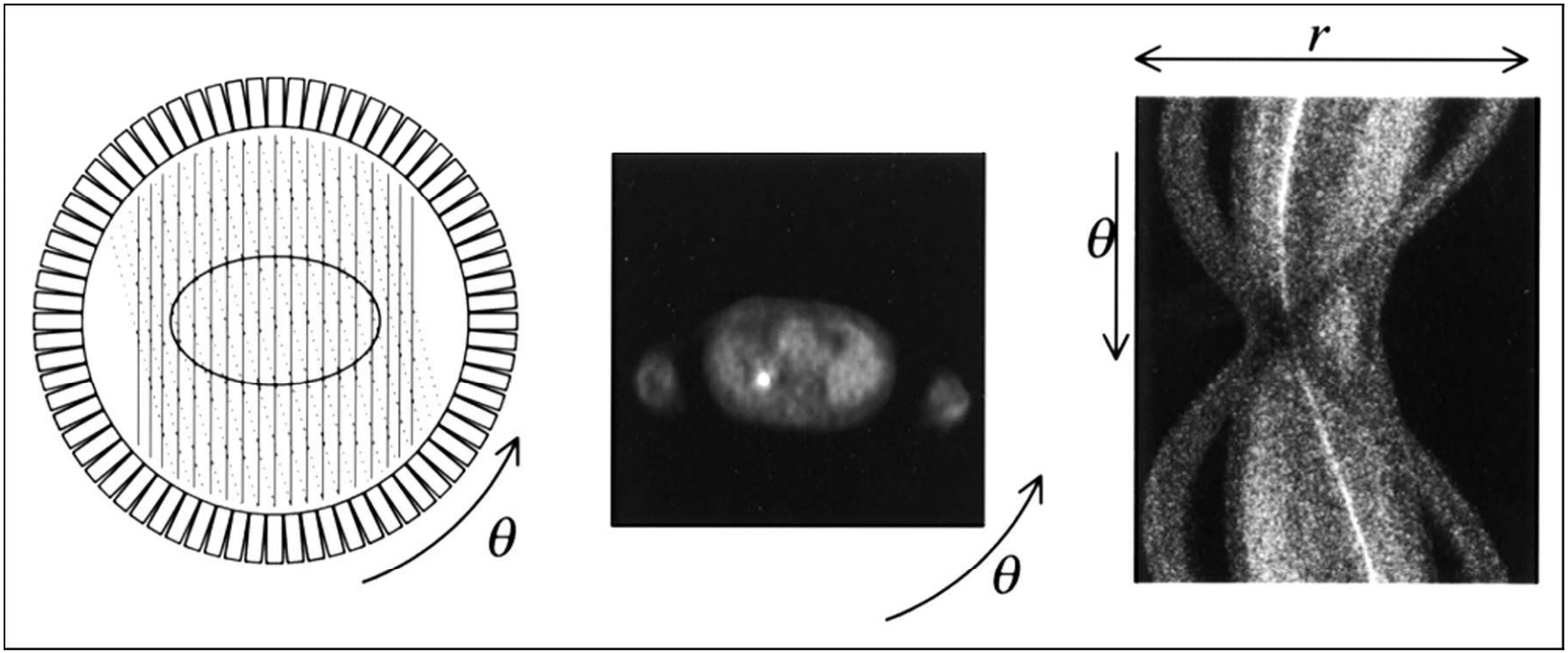
Prototype:

- Two matrices of 6x6 crystal double-layers
- Study uniformity of channels, multi-channel r/o, calibration
- Image reconstruction of a point source

Sinogram


p(s, ϕ)
s
y
ϕ
x
f(x,y)
s
ϕ
Integration along
all LORs at fixed ϕ
Sinogram

Sinogram - Example



Each point in the sinogram corresponds to a LOR.

Filtered Back Projection

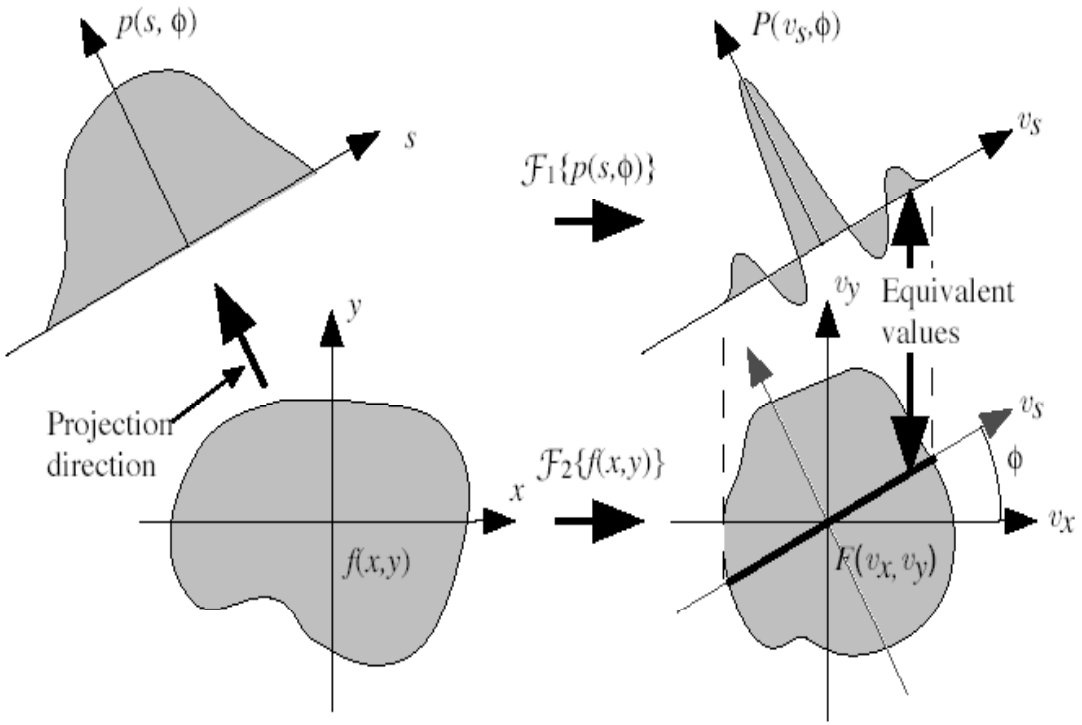
(**Analytic 2D image reconstruction**)

Imaging system: **p = Hf + n**

p: observation, **H**: system model, **f**: image, **n**: error

(Radon transform closely related to Fourier transform.)

Solution: unfolding, inverse problem ill-posed, regularization



2D central-section theorem:

The Fourier transform of a 1D projection is equivalent to a section at the same angle through the center of the 2D Fourier transform of the object.

Ramp-filter:

$$p^F(s,\phi) = \mathcal{F}_1^{-1}\left\{|\upsilon_s|\,\mathcal{F}_1\{p(s,\phi)\}\right\}$$

A Commercial Example

GEMINI TF PET/CT (Philips)

- diameter of 90 cm, axial field of view of 18 cm
- 4 x 4 x 22 mm^3 LYSO (lutetium-yttrium oxyorthosilicate) crystals
- coincidence timing resolution: **585 ps**
- resolution near the center: **4.8 mm** (FWHM)
- single high-quality image: **1-2 min**
- whole-body scan: **10-30 min** (depending on patient size)
- available for $1.85M