Detector characterization and first coincidence tests of a Compton telescope based on $LaBr_3$ crystals and SiPMs

Gabriela Llosá[1], John Barrio[1], Jorge Cabello[1], Carlos Lacasta[1], Magdalena Rafecas[1], Carles Solaz[1], Vera Stankova[1], Stéphane Callier[2], Christophe de LaTaille[2], Ludovic Raux[2]

[1]Instituto de Física Corpuscular - IFIC (CSIC-UV), Valencia, Spain
[2] Laboratoire de l'Accélérateur Linéaire (LAL), Orsay, France

IRIS group `http://ific.uv.es/iris`

NDIP2011, Lyon, 4-8 July 2011

Dose monitoring in hadron therapy

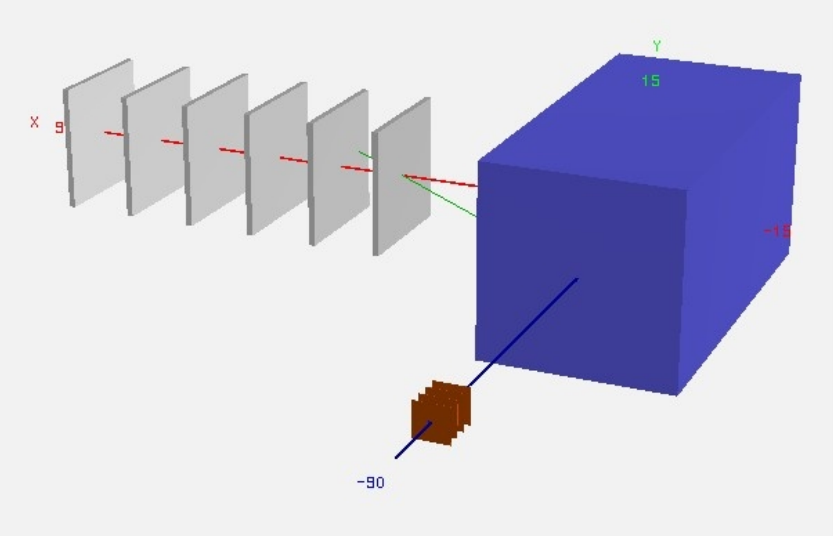
- Hadron therapy: charged particles-precise delivery of radiation dose (Bragg peak).
- ENVISION European project: dose monitoring in hadron therapy
- Secondary particles emitted after treatment can be used for monitoring the dose delivery:
  - In-beam PET + MC currently employed
  - Prompt gammas also emitted from nuclei excited during therapy and can be used for this purpose

Compton telescope

- A Compton telescope is a possible solution to determine the origin of the gamma-rays.

Requirements	Goals
• Excellent energy resolution • Very good spatial resolution • Very good timing resolution • High readout rate	• ≤ 4% @ 511 keV • ~ 2mm FWHM • ~ 1 ns FWHM

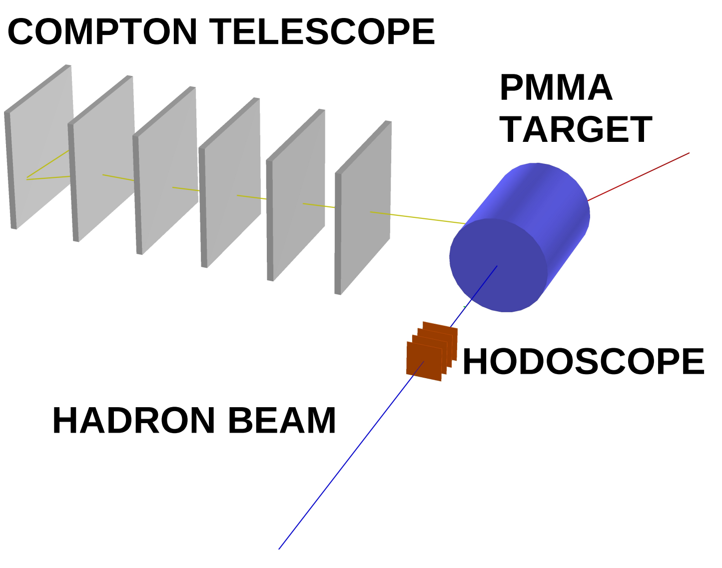
- Different configurations and materials being tested: silicon, CZT.



$LaBr_3$ Compton telescope

- Detector array composed of:
  - $LaBr_3$ continuous crystal:
    - high Compton probability,
    - high light yield=> good energy and timing resolution.
  - Silicon Photomultiplier arrays: compact, fast.

- Ongoing simulations to estimate the performance, optimize the geometry and develop image reconstruction algorithms.

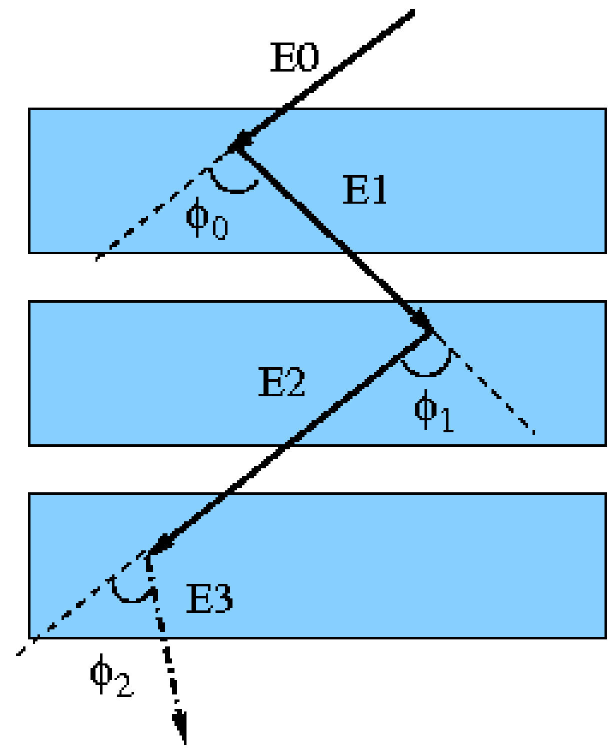


Compton telescope configuration

'Conventional' Compton camera (scatterer + absorber): 2 interactions → problems if the gamma-ray energy is unknown or if it can escape

Three Compton technique: 3 interactions in 3 detectors (+ correct ordering) → lower efficiency

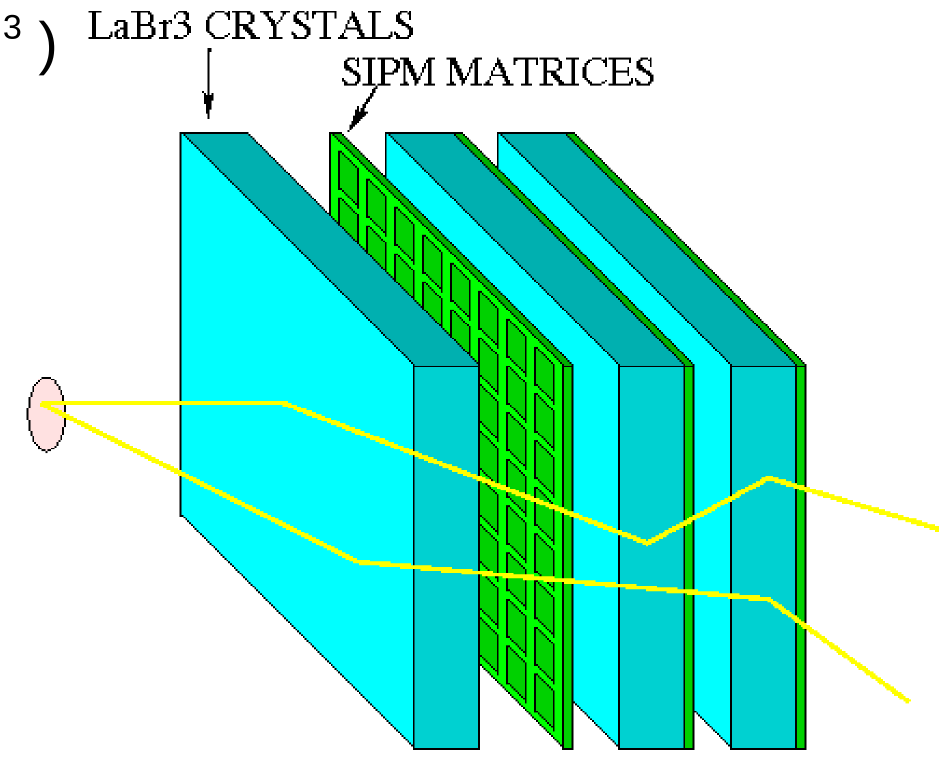
We are working on a method to estimate position and energy from 2 int (high efficiency) + the combination with 3 int (high resolution).



J. E. Gillam et al. A Compton Imaging Algorithm for On-line Monitoring in Hadron Therapy. Medical Imaging 2011: Physics of Medical Imaging (Proceedings Volume) Vol. 7961. Paper 796110. (2011), DOI:10.1117/12.877678.

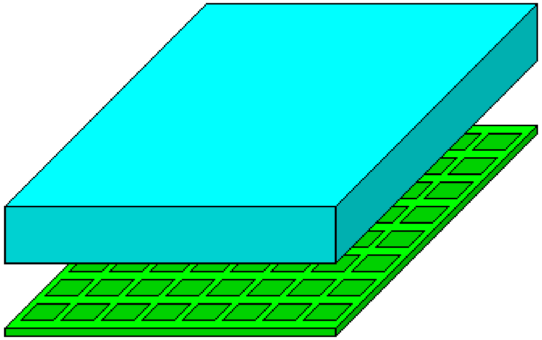
$LaBr_3$ prototype

- Development of a prototype with three layers of $LaBr_3$ crystals coupled to SiPM arrays:
- Detector characterization ($LaBr_3$ crystal 16 x 18 x 5 mm^3)
  - Energy resolution
  - Timing resolution
  - Position determination
- Coincidence tests: two detectors in time coincidence
- Development of larger detectors.

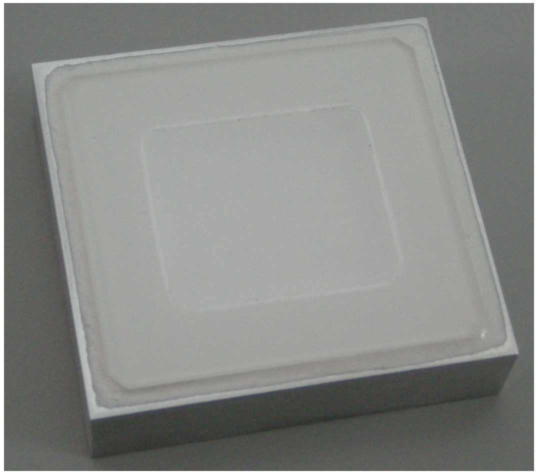


Continuous crystals

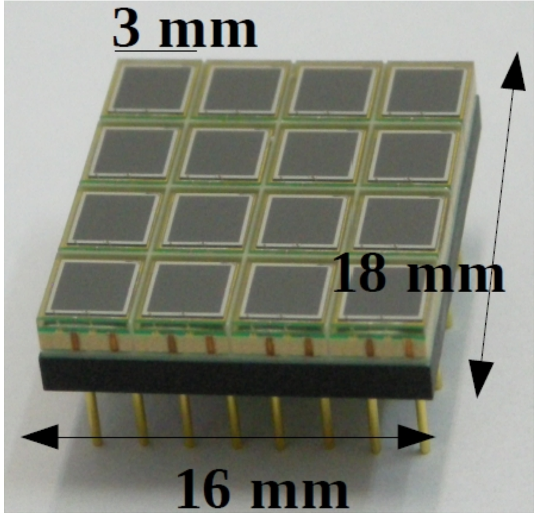
Advantages	Disadvantages
• Higher efficiency than pixellated crystals • Very good spatial resolution • Lower cost	• Large number of readout channels => ASICs • Position determination is complicated • Timing resolution is degraded

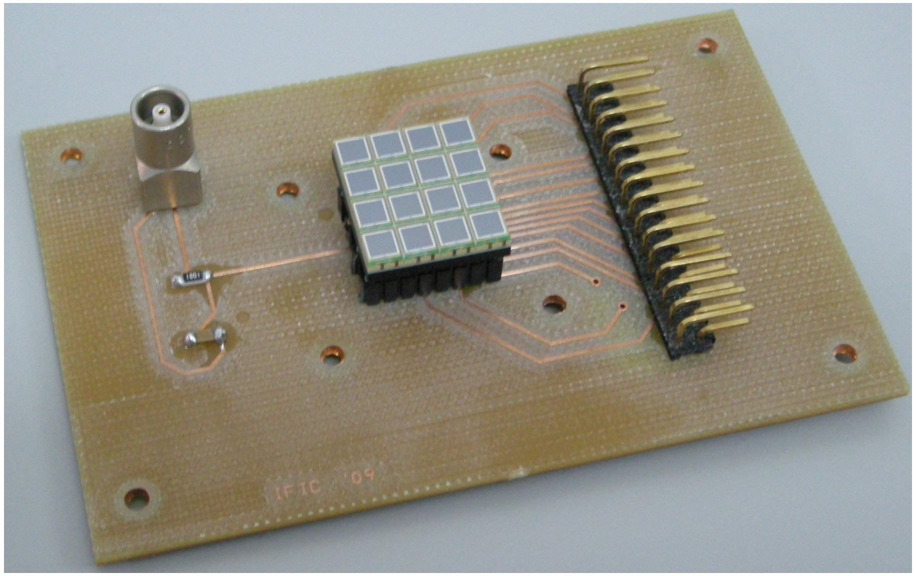


Detector components



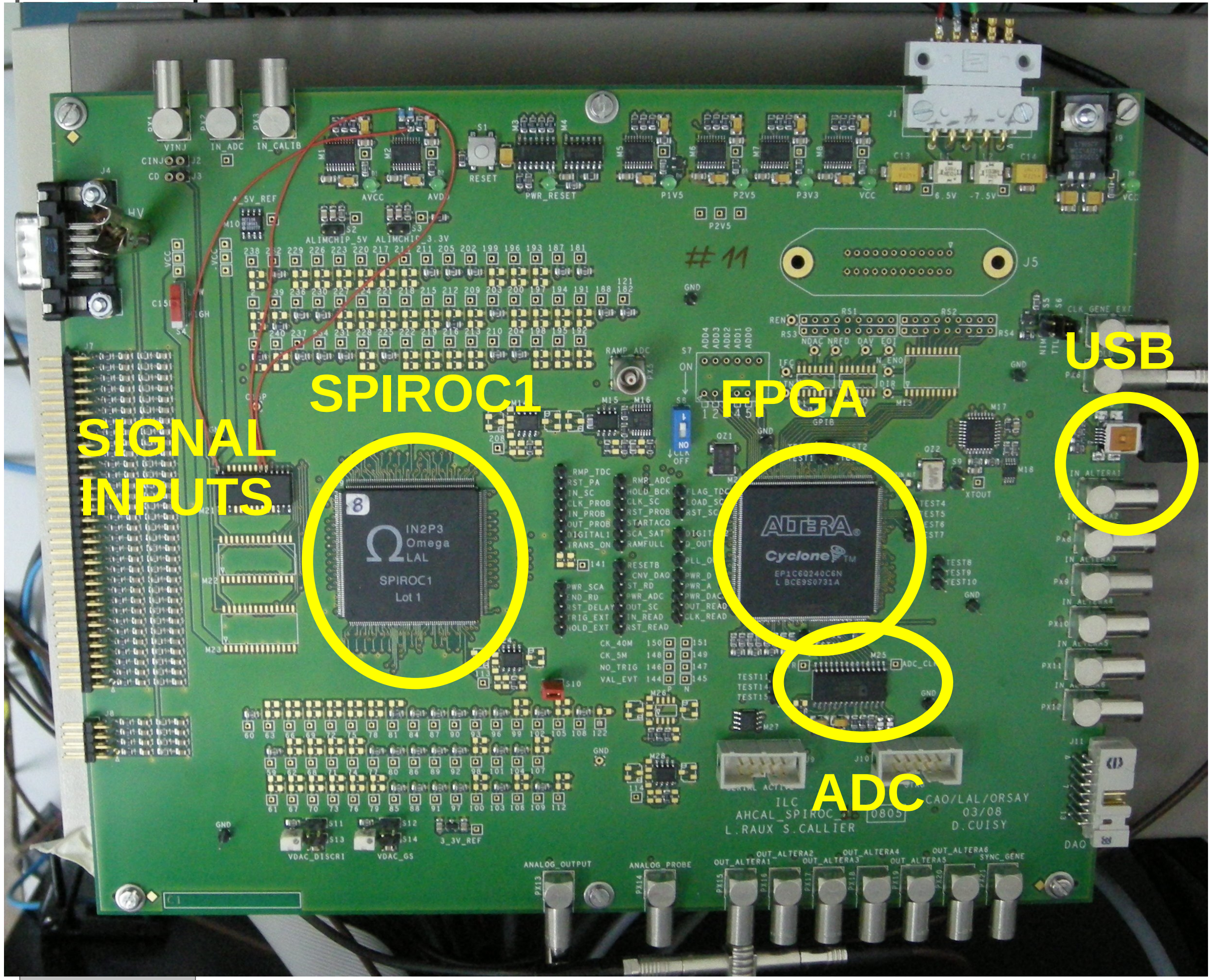
- $LaBr_3$ crystal (Saint Gobain), 16 mm x 18 mm x 5 mm
- Silicon photomultiplier (MG-APD) array:
  - MPPC from Hamamatsu
  - 16 pixels of 3 mm x 3 mm size
  - 50 µm microcell size
  - Pitch 4.05 mm x 4.5 mm





Readout electronics

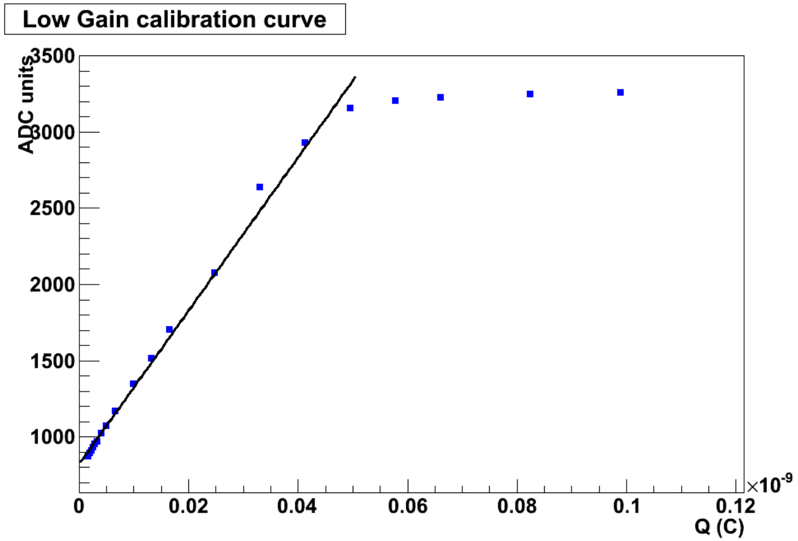
SPIROC1 ASIC form LAL, Orsay.



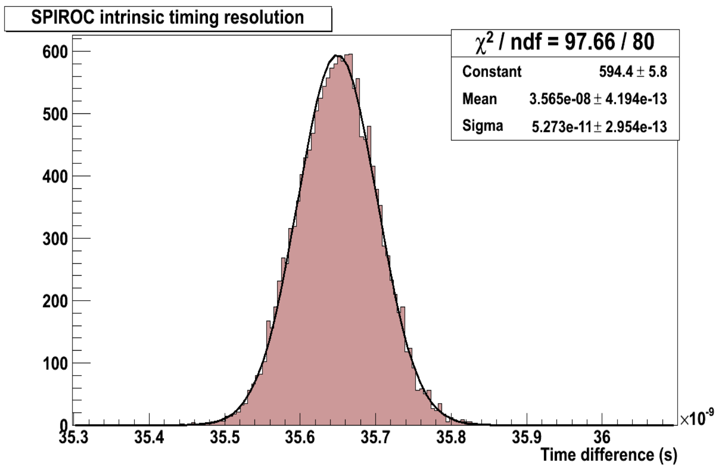
- SPIROC1
  - 36 channels (16 used)
  - Variable gain
  - Slow shaper (adjustable ~50-100 ns)
  - Fast shaper (15 ns) + discriminator =>Trigger signal.
- FPGA ALTERA Cyclone
- DACs for bias variations.
- LabView software for DAQ

Readout electronics

SPIROC1 response in low gain configuration: **linear up to ~40 pC**

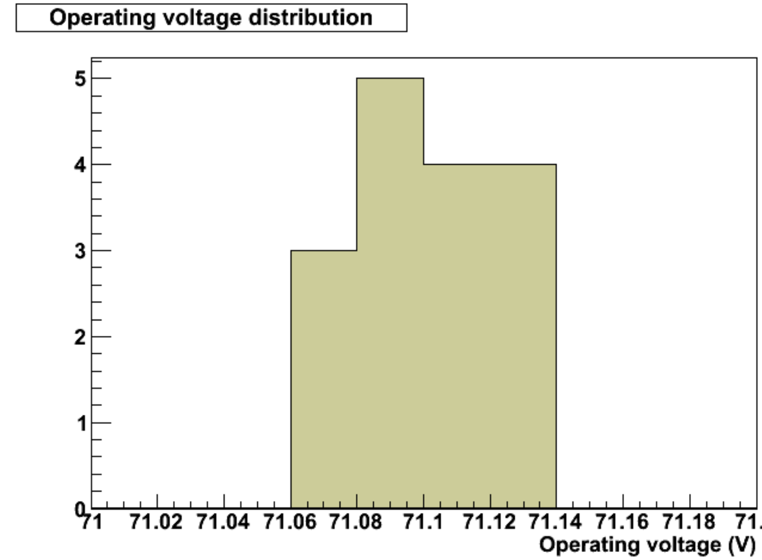


SPIROC1 intrinsic timing resolution: **125 ps FWHM**

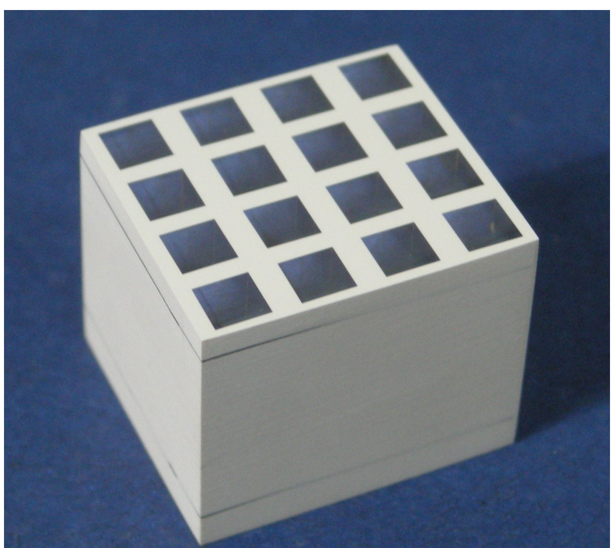


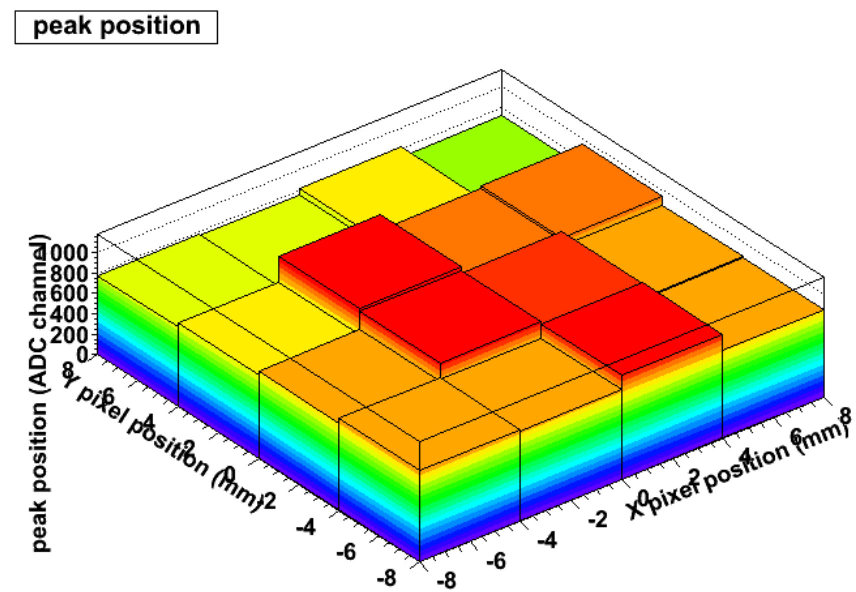
Response uniformity

MPPCs in the array have different operating voltage (71.08 to 71.12), but they are all biased at the same voltage (71.1 V).



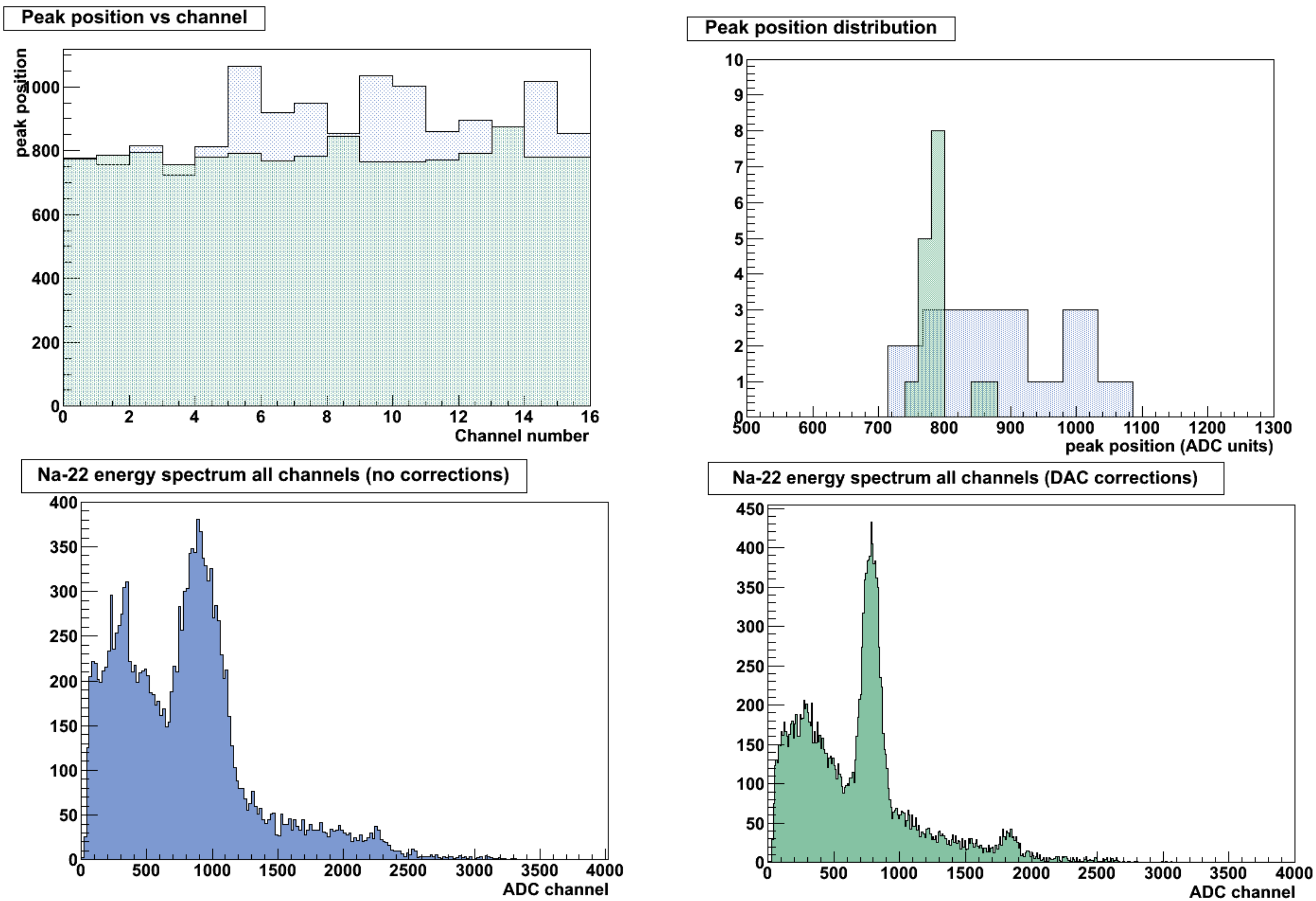
Response uniformity tested coupling a pixellated crystal array one-to-one to the MPPC array and taking data with a Na-22 source.





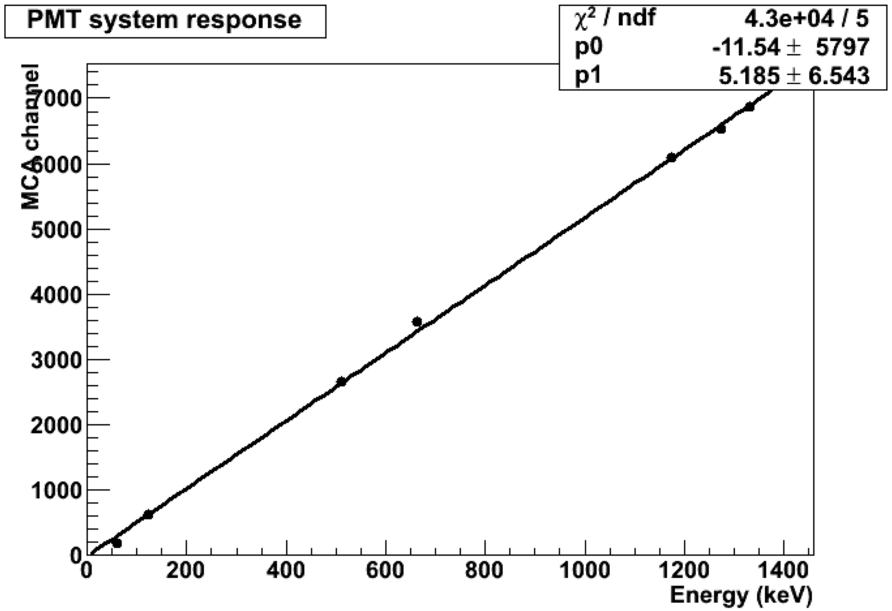
Photodetector uniformity

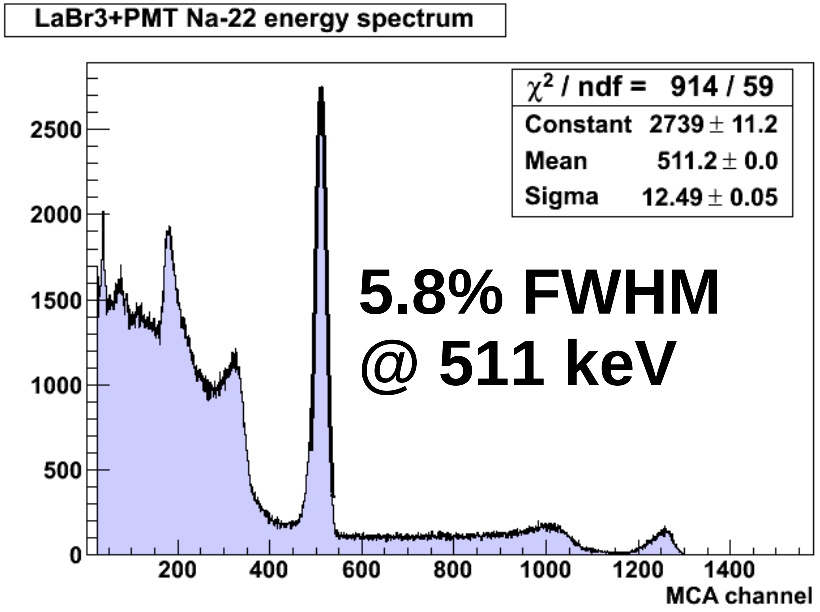
Small corrections to the bias voltage of each channel applied through input DACs: 4V, 256 steps, 20 mV/step.



Energy resolution

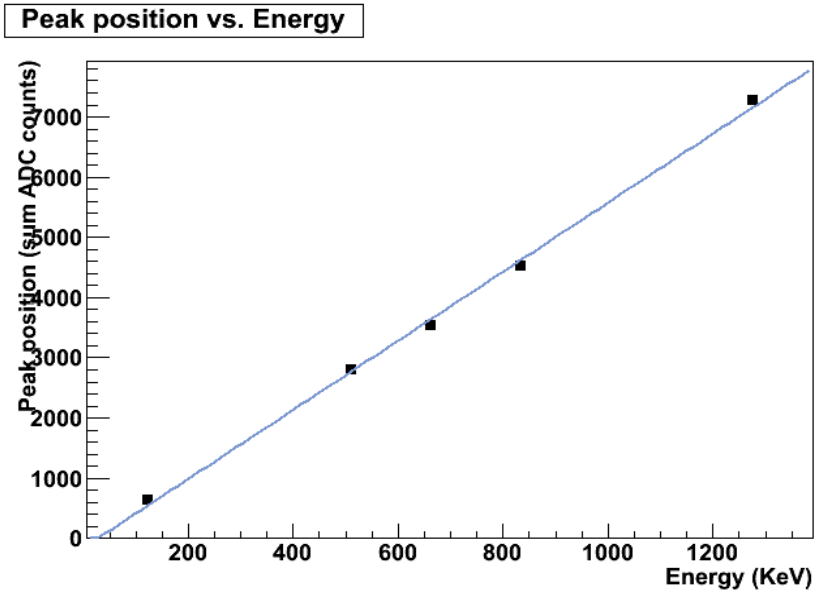
- Crystal specs energy resolution with PMT Hamamatsu R4017:
  - 11.6% FWHM @ 60 keV (Am-241)
  - 6.3% FWHM @ 122 kev (Co-57, collimated source)
  - Expected ~ 4% FWHM @ 511 keV
- Crystal tested with PMT (Hamamatsu R6236)+MCA:
  - ~10% FWHM @ 60 keV
  - 8.8% FWHM @ 122 keV
  - 5.8% FWHM @ 511 keV
  - 4.25% FWHM@ 662 keV

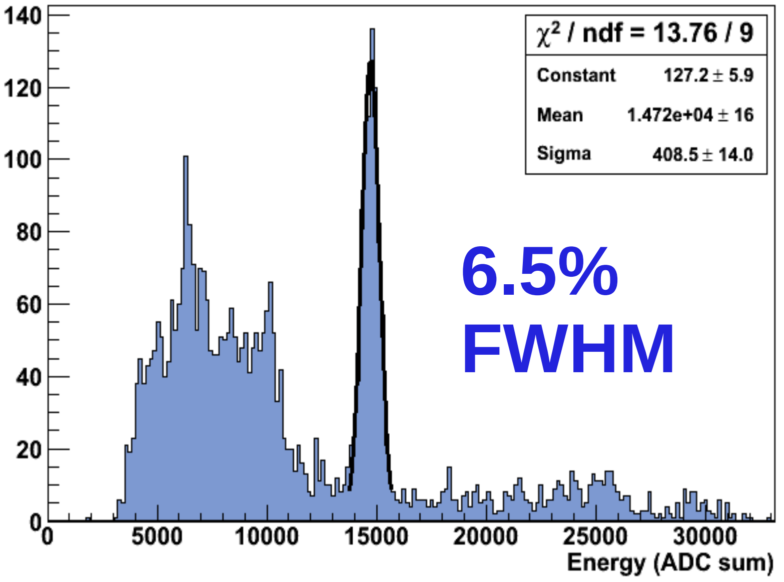




Energy resolution

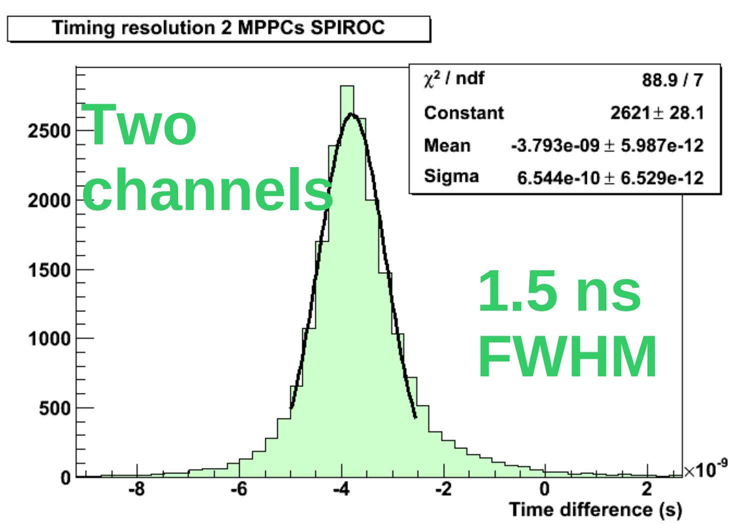
- Crystal coupled to MPPC array: 7% FWHM without correcting for variations among pixels (at Vop + 1.5 V).
- MPPC array has a 50% loss of active area due to the gaps between the photodetector elements.
- Energy resolution **6.5% FWHM** correcting offline for gain variations.

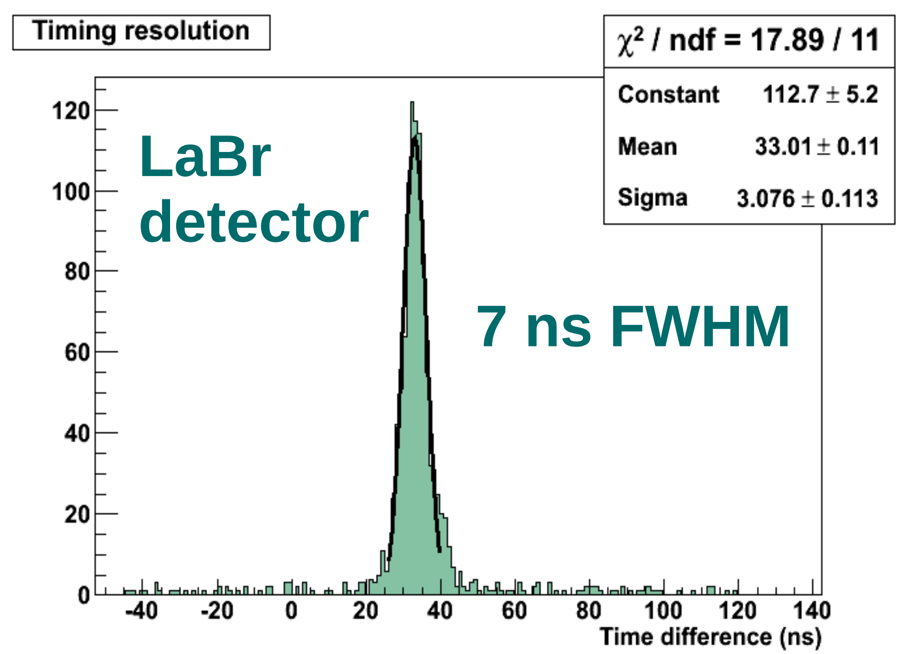




Timing resolution

- LYSO crystal 3x3x10 mm^3 coupled to two MPPCs on both sides and connected to two SPIROC1 channels of two different boards: **1.5 ns FWHM** (not optimized)
- LaBr$_3$ detector (16 channels) in coincidence with a 1 mm x 1mm x 10mm LYSO crystal coupled to one MPPC: **7 ns FWHM**
- The main degradation comes from the OR signal of all channels given by the ASIC

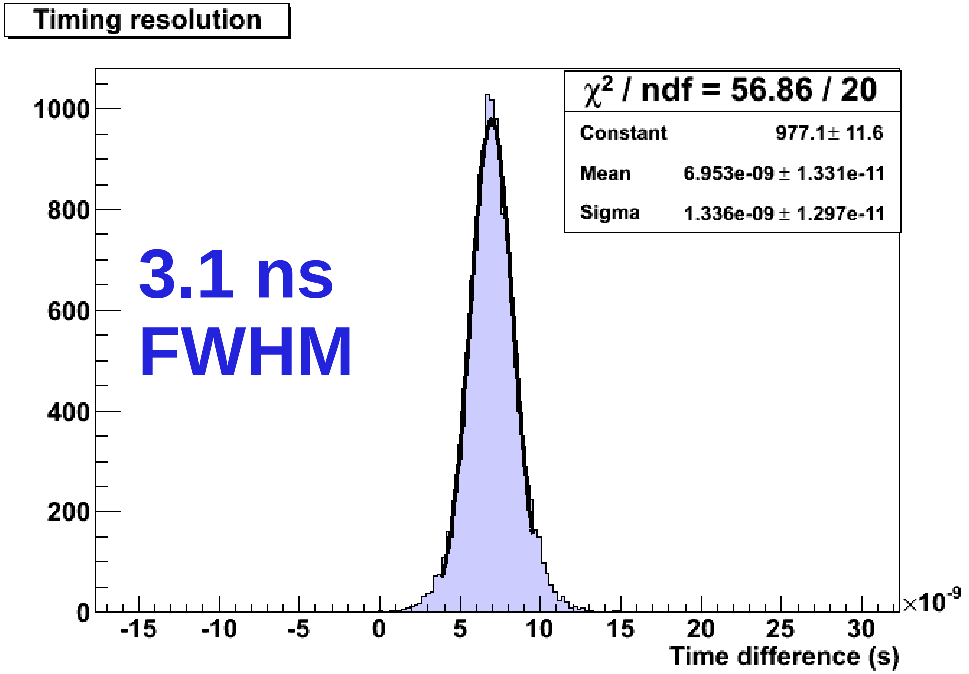




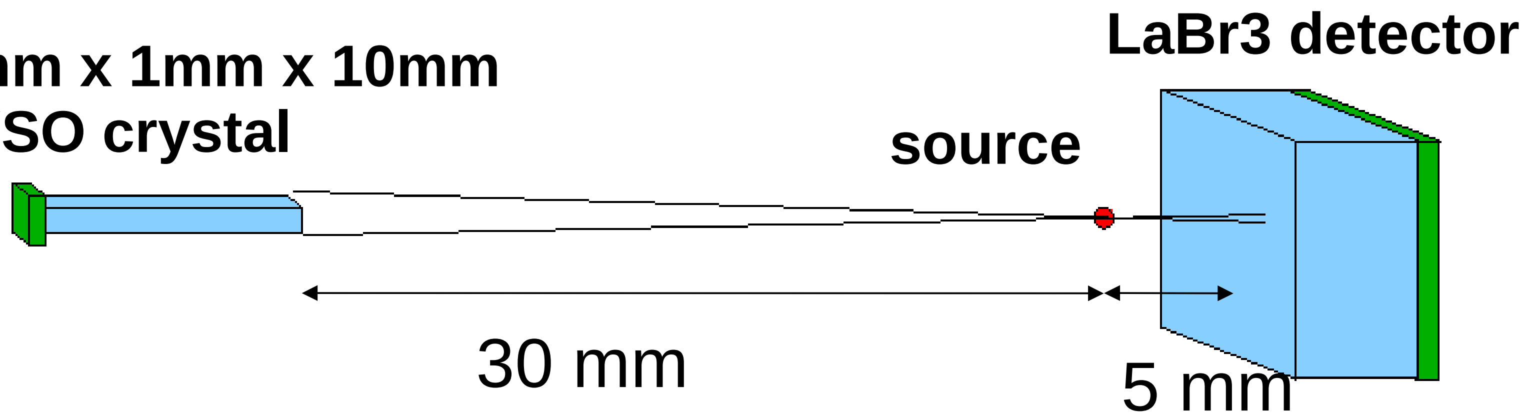
Timing resolution

- Alternative trigger: signals from all channels split on the PCB and summed to a common output.
- $LaBr_3$ detector in coincidence with the 1mm x 1mm x 10mm LYSO crystal : **3.1 ns FWHM**

Significant improvement of the timing resolution

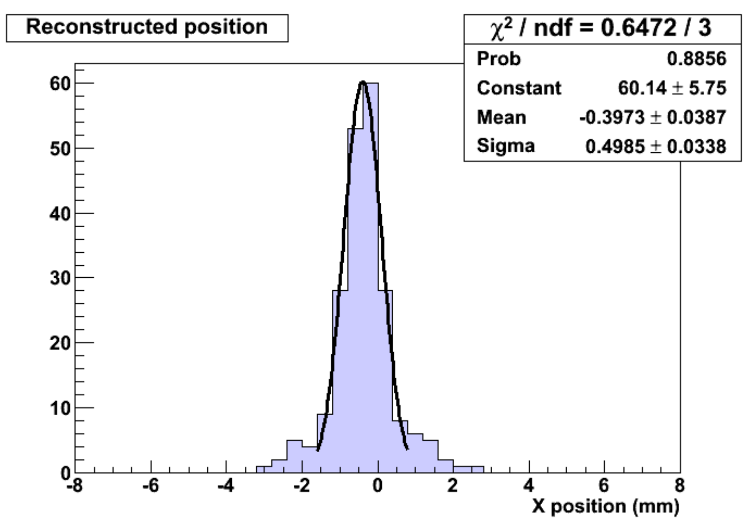


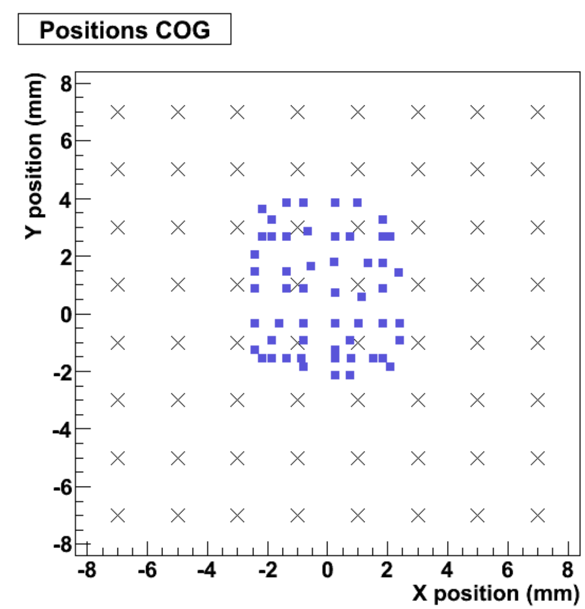
Position determination



- Different methods tested. Spatial resolution with center-of-gravity: **1.2 mm FWHM.**

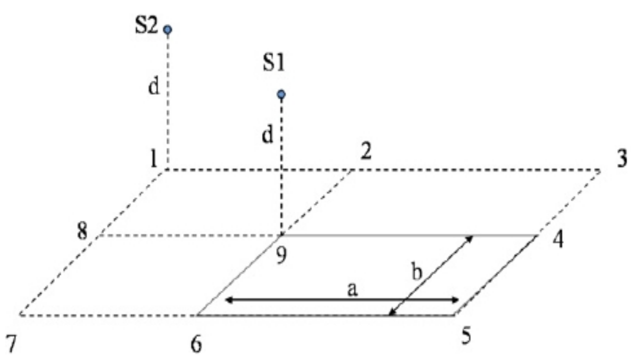
- Compression due to the highly reflective crystal wrapping.



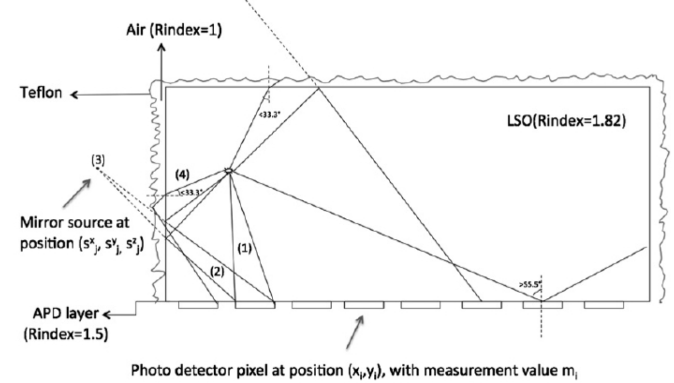


Position estimation

Algorithm based on the angle subtended by the interaction point (x,y,z) with each pixel



Li, Z. et al. *Nonlinear least-squares modeling of 3D interaction position in a monolithic scintillator block*. Phys. Med. Biol., 55(21):6515, 2010.



Reflections modeled as mirror sources

Model

$$\text{photonNum}_i = C_{\text{est}} + f(x - x_i, y - y_i, z) + \sum_j f\left(s_j^x - x_i, s_j^y - y_i, s_j^z\right)$$

Reflections

$$f = A_0 \times \Omega .$$

$$\Omega = \mathrm{d}x \times \mathrm{d}y \times \frac{z}{((x - x_i)^2 + (y - y_i)^2 + z^2)^{3/2}}$$

Approximated angle model

$$(\hat{x}, \hat{y}, \hat{z}, A_0, C_{\text{est}}) = \underset{(\hat{x}, \hat{y}, \hat{z}, A_0, C_{\text{est}})}{\arg\min} \sum_{i=1}^{i=64} (m_i - \text{photonNum}_i)^2 .$$

Parameters to estimate

photons measured in pixel *i*

photons in pixel *i* estimated by the model

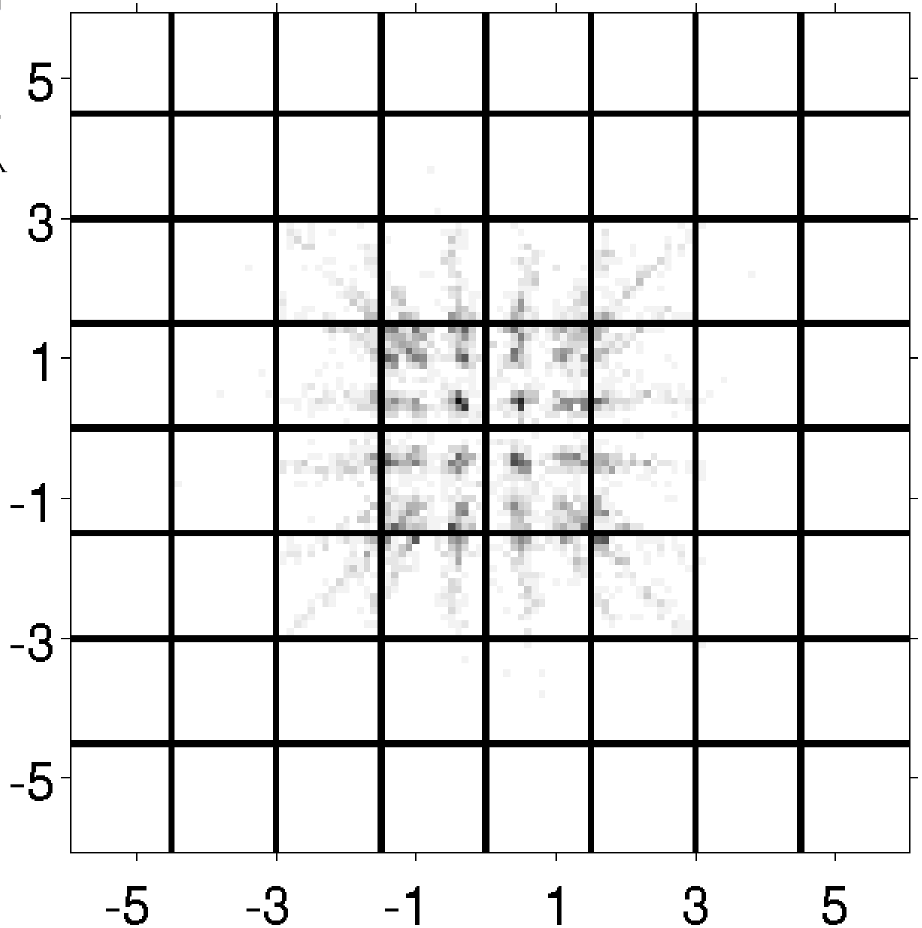
Optimization method:
Local minimization interior-reflective Newton

Position determination

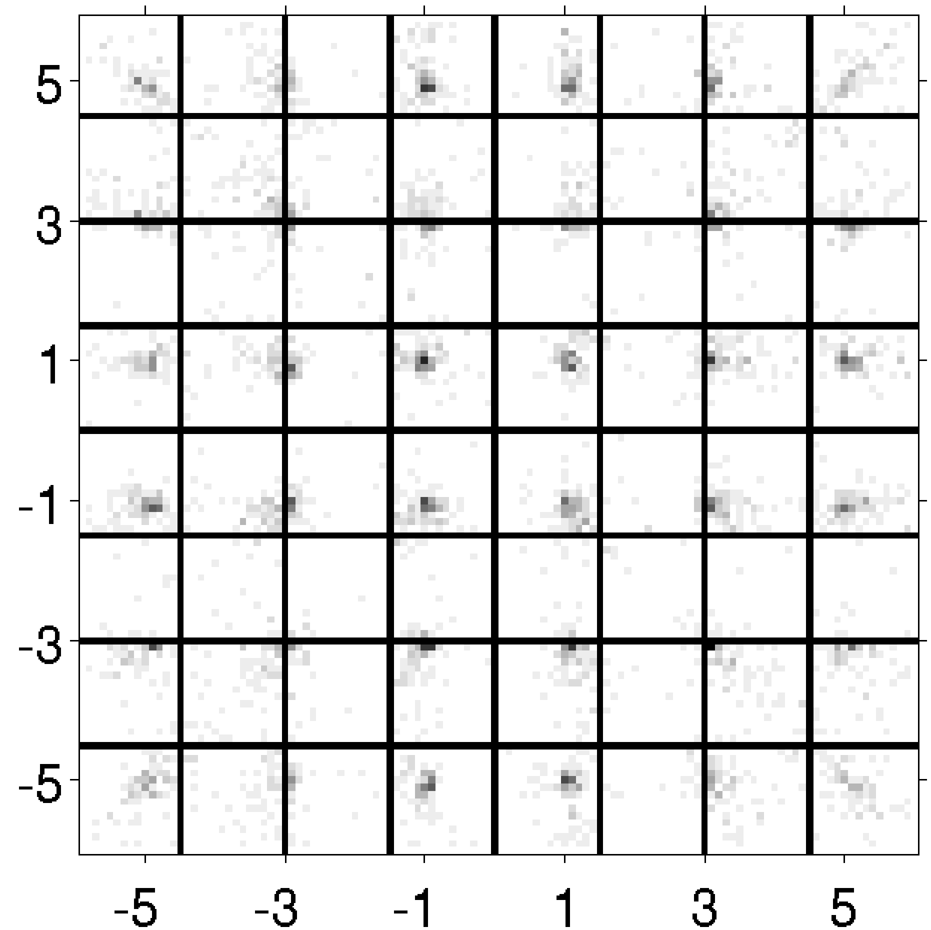
Advantages: **much less compression + DOI**

Reconstructed distribution of simulated data (LYSO crystal) at 2 mm steps

COG

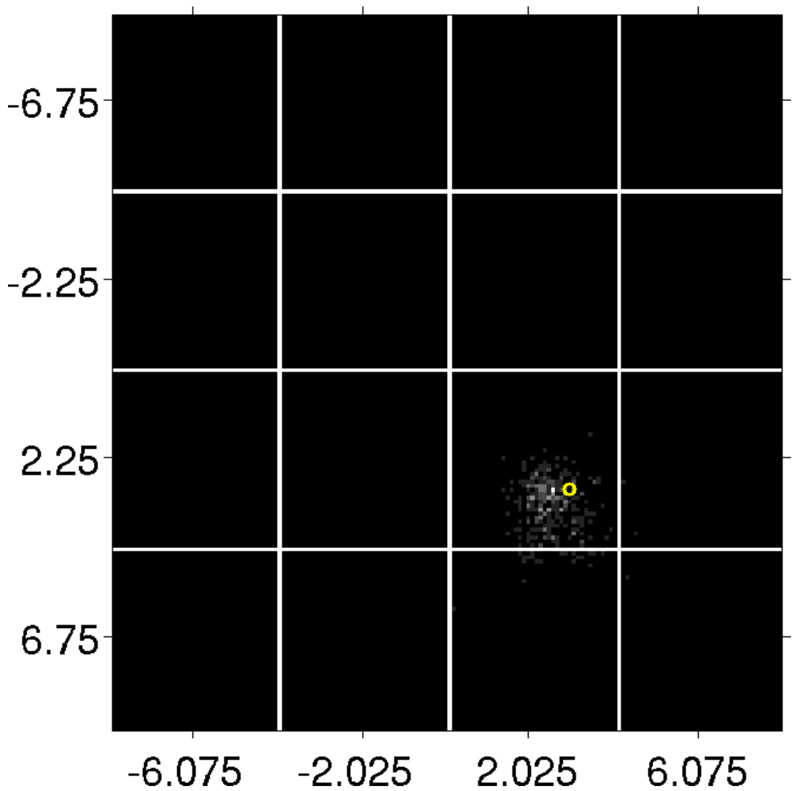


New method

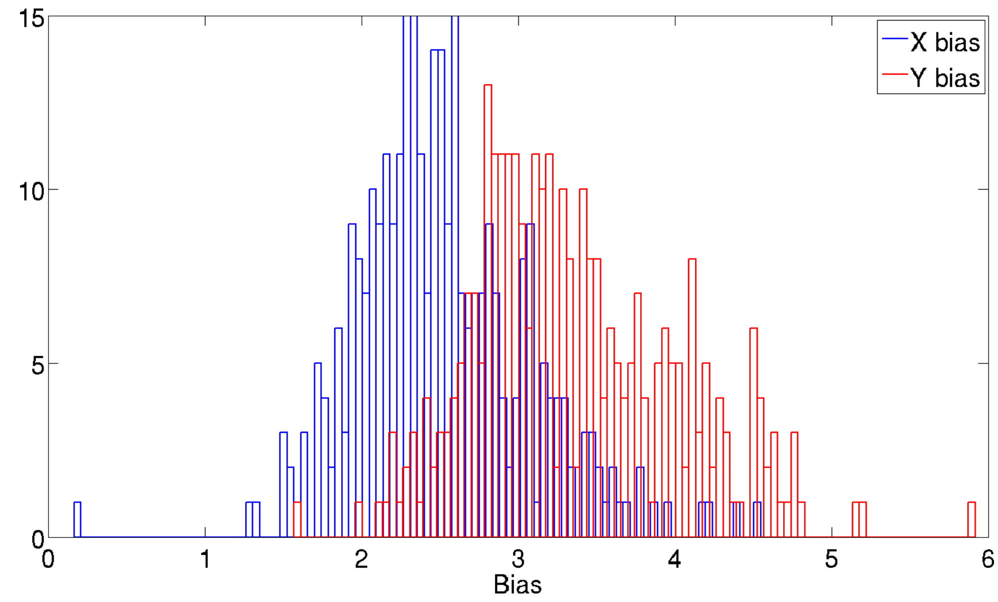


Position determination

- Simulated results



The yellow circle represents the real position

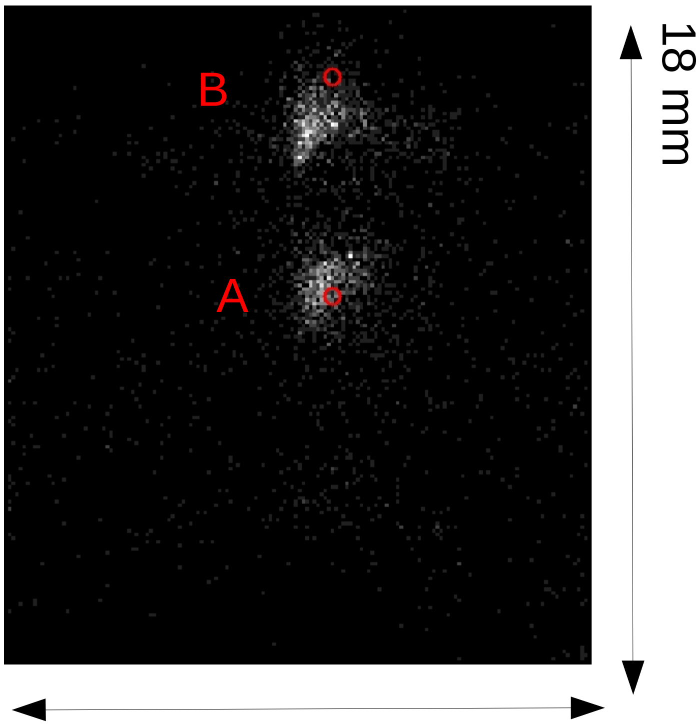


Histogram of estimated positions in X and Y of point A

	Bias	FWHM
X	0.6 mm	1 mm
Y	0.1 mm	1 mm

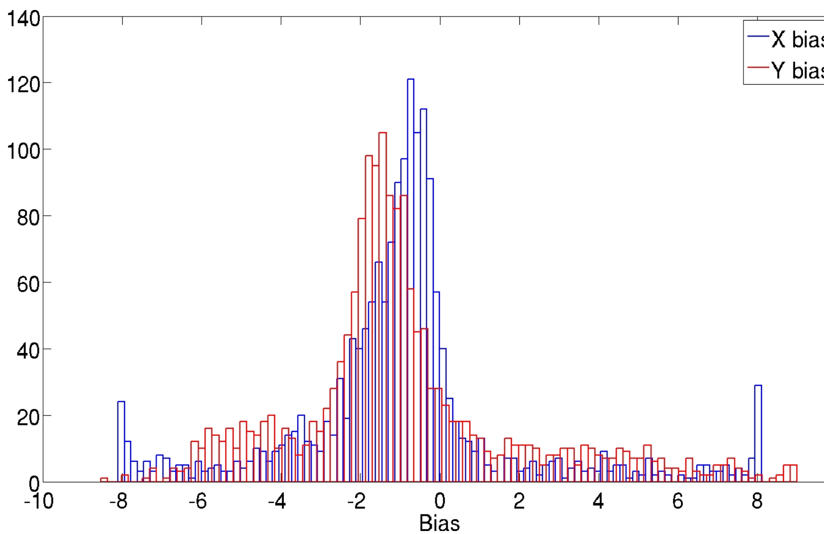
Position determination

- Experimental results:



16.2 mm

The red circles represent the real positions

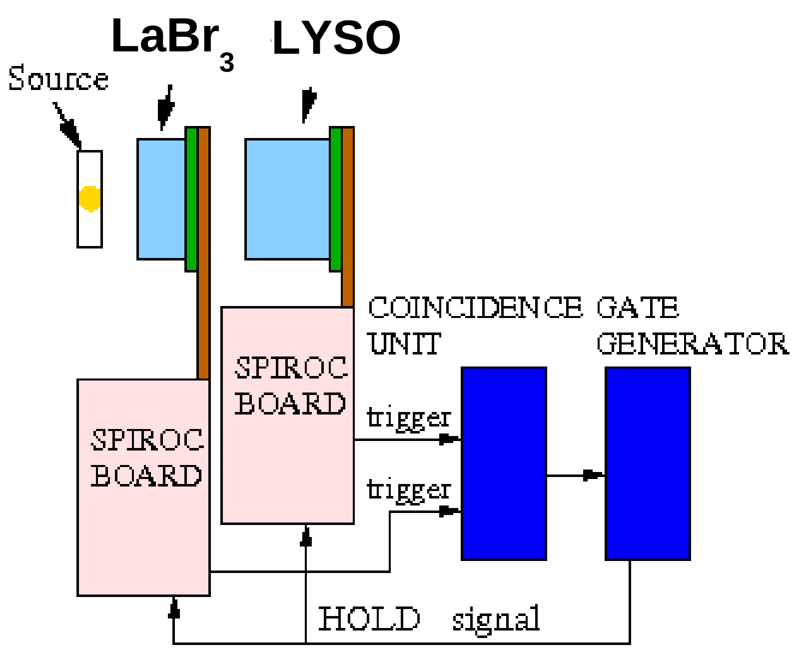


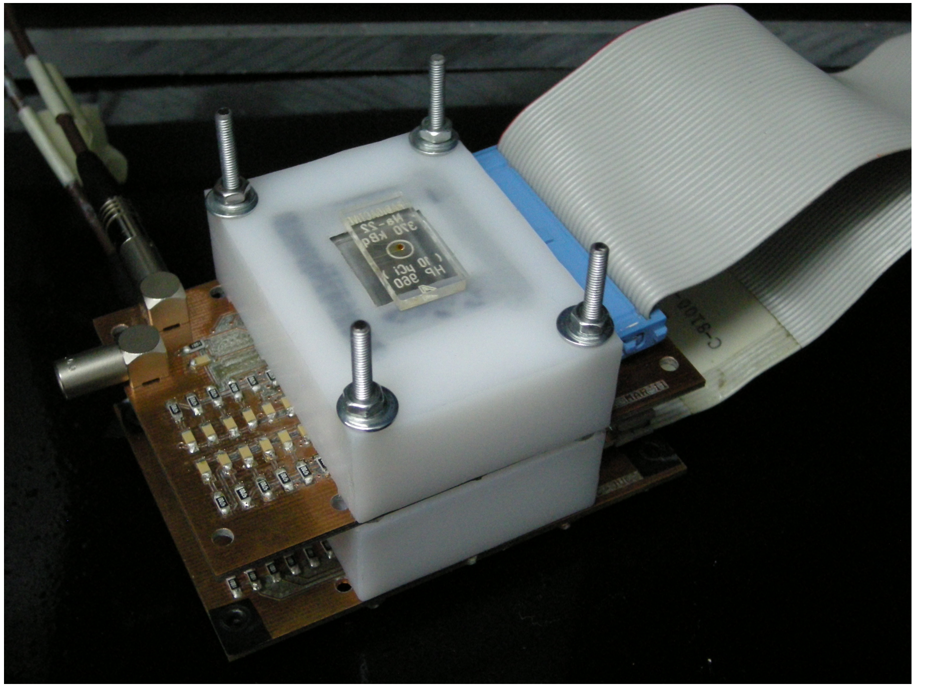
Histogram of estimated positions in X and Y of point A

	Bias	FWHM
Centre	0.4 mm	1.5 mm
Edge	1.1 mm	1.2 mm

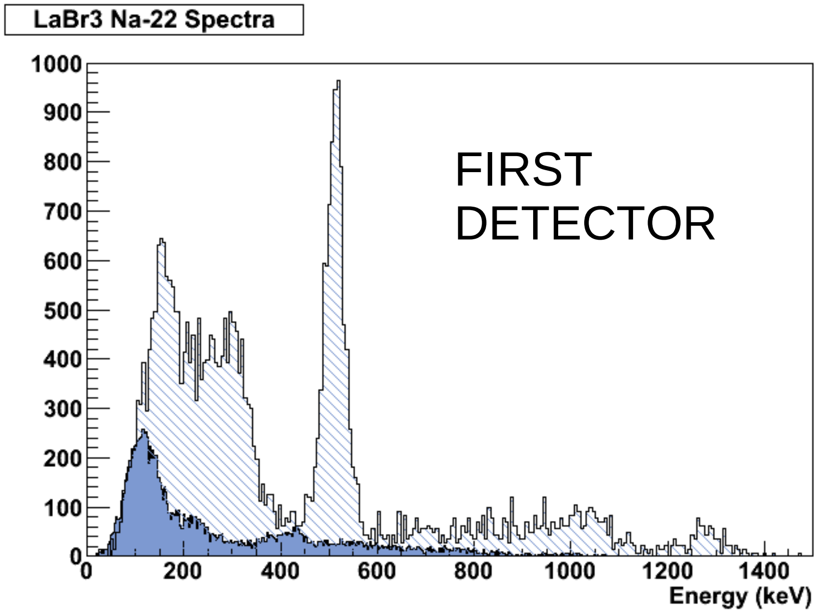
Coincidence tests: setup

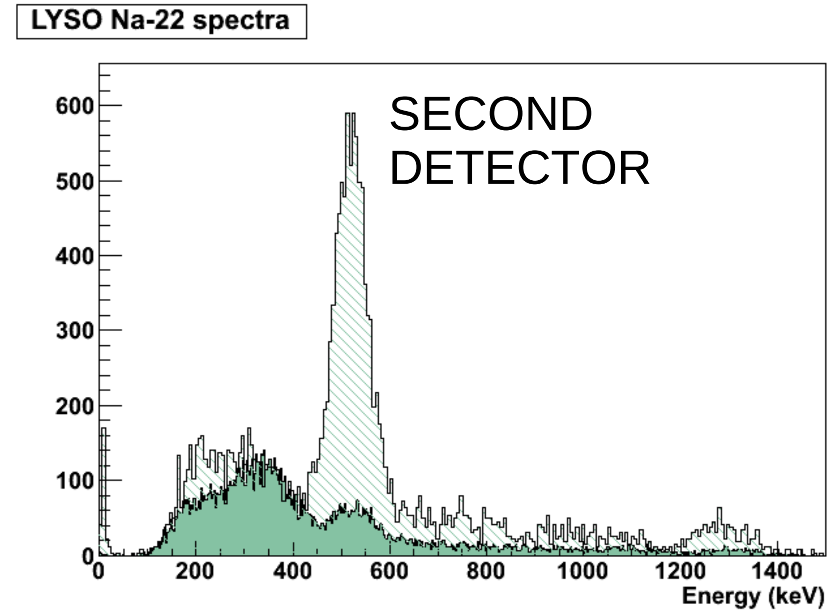
- Two detectors in time coincidence: $LaBr_3$ 16 x 18 x 5mm + LYSO 12x12x5mm
- Two DAQ boards operated simultaneously. DAQ software modified.
- Data acquired with Na-22 (511 keV and 1275 keV) and Cs-137 (662 keV).

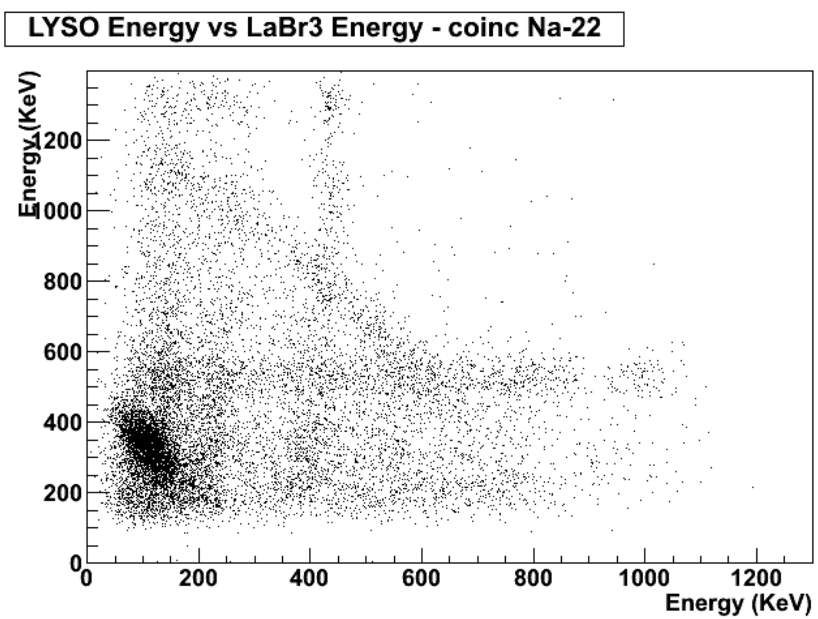


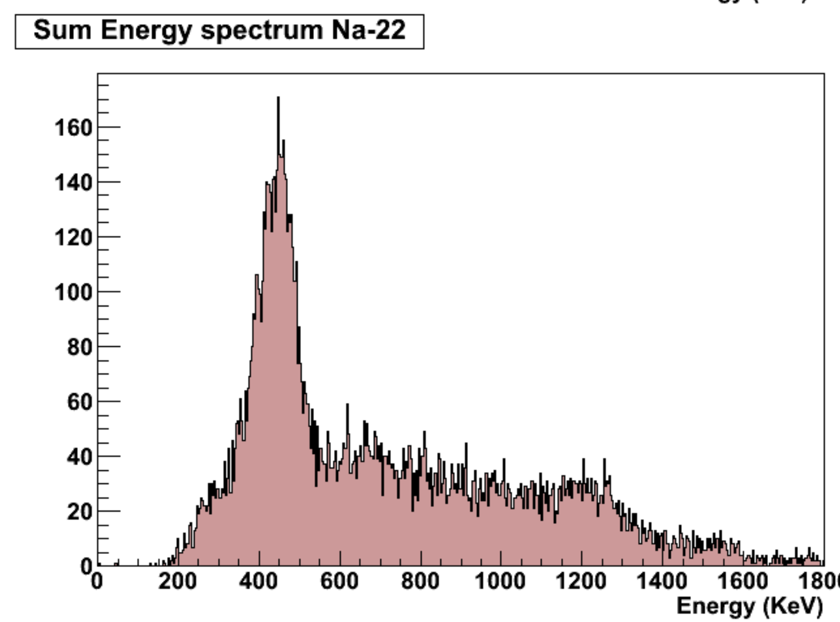


Coincidence tests: ^{22}Na



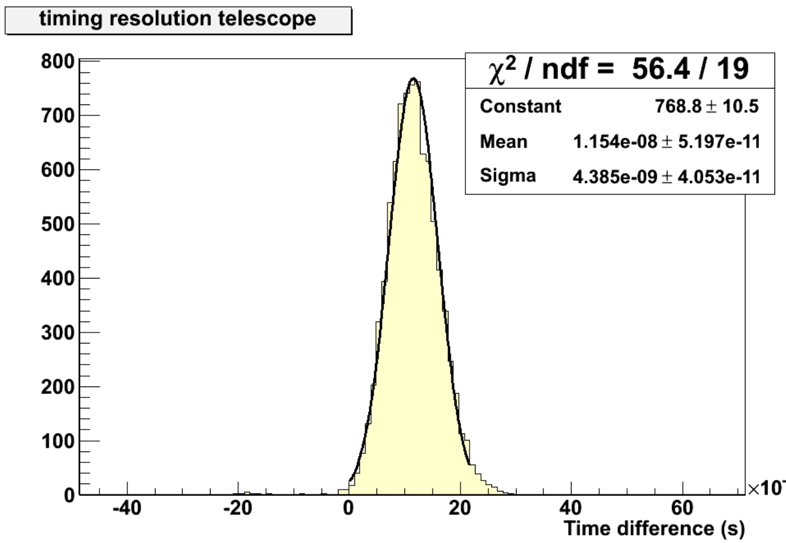




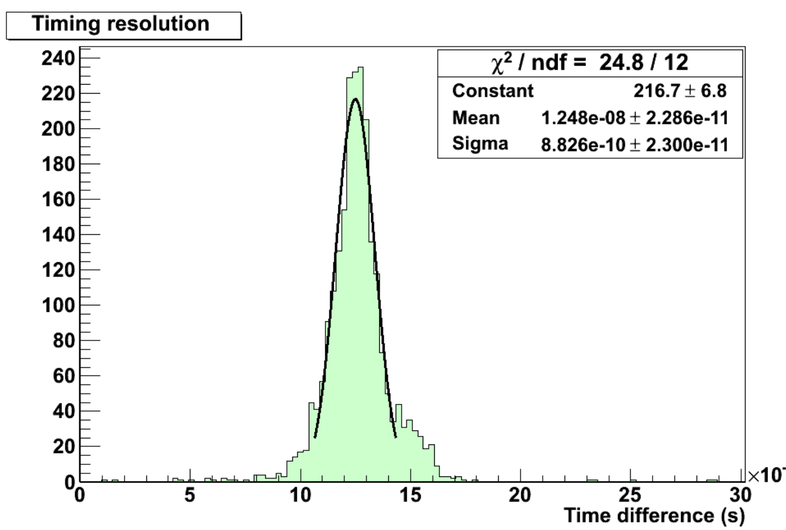


Coincidence tests - Timing

Timing resolution: 10 ns FWHM with trigger signal from 2 SPIROC boards

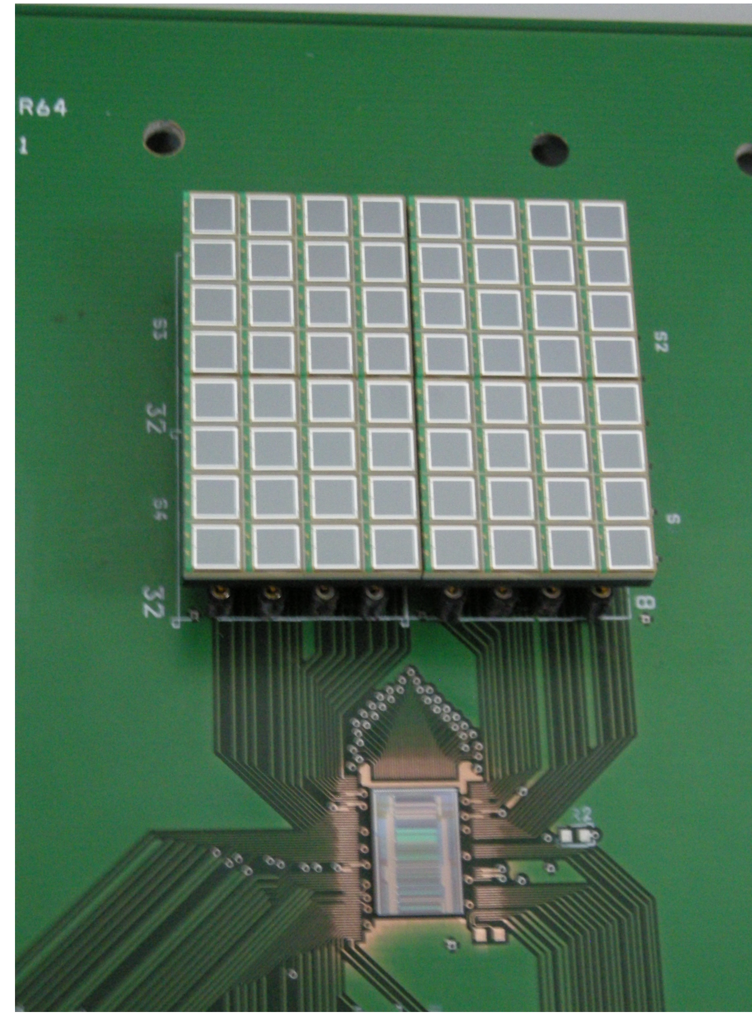


From the sum of all signals for each detector **~ 2 ns FWHM.**



Development of larger detectors

- $LaBr_3$ crystals 32mm x 36mm x 5/10mm
- Each one coupled to four MPPC arrays
- VATA64HDR16, Gamma Medica – IDEAS 64 channels
- DAQ system developed by our group.

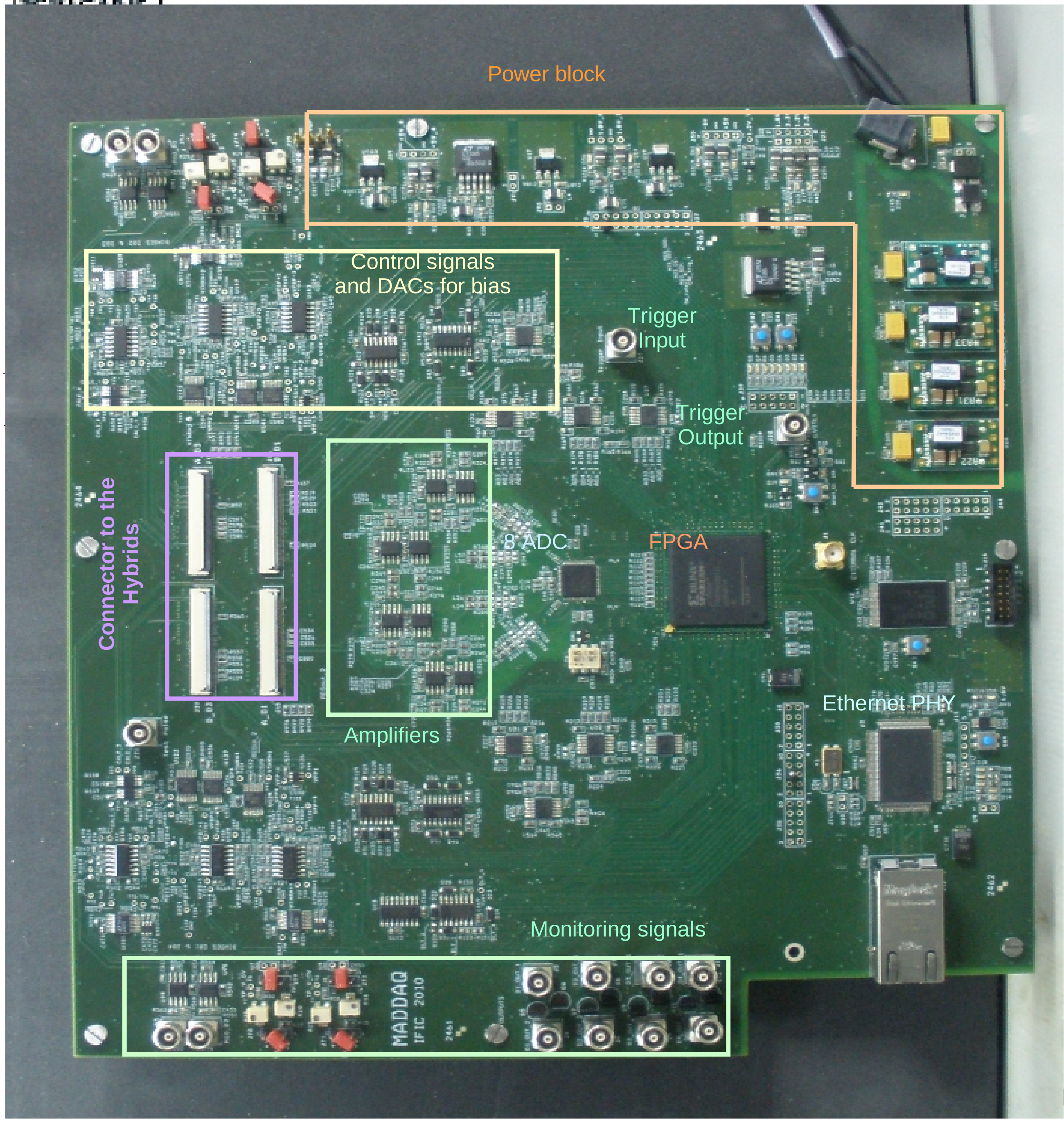


Acknowledgment

- This work was supported in part by the European Commissions 7th Framework Programme through a Marie Curie European Reintegration Grant (ASPID). Grant Agreement num 239362).
- This work was supported in part by the ENVISION project, that is co-funded by the European Commission under FP7 Grant Agreement num 241851
- This work was supported in part through a Research project of the Spanish Ministry of Science and Innovation (FPA2010-14891).

Thank you! Questions?

DAQ system



Modular and flexible design

FPGA Xilinx

Fast data transfer: Ethernet (up to 1 Gbps)

Time stamp with 1 ns resolution

Several boards can work in time coincidence

Coincidence tests: ^{137}Cs