Compton telescope prototype based on continuous $LaBr_3$-SiPM detectors

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

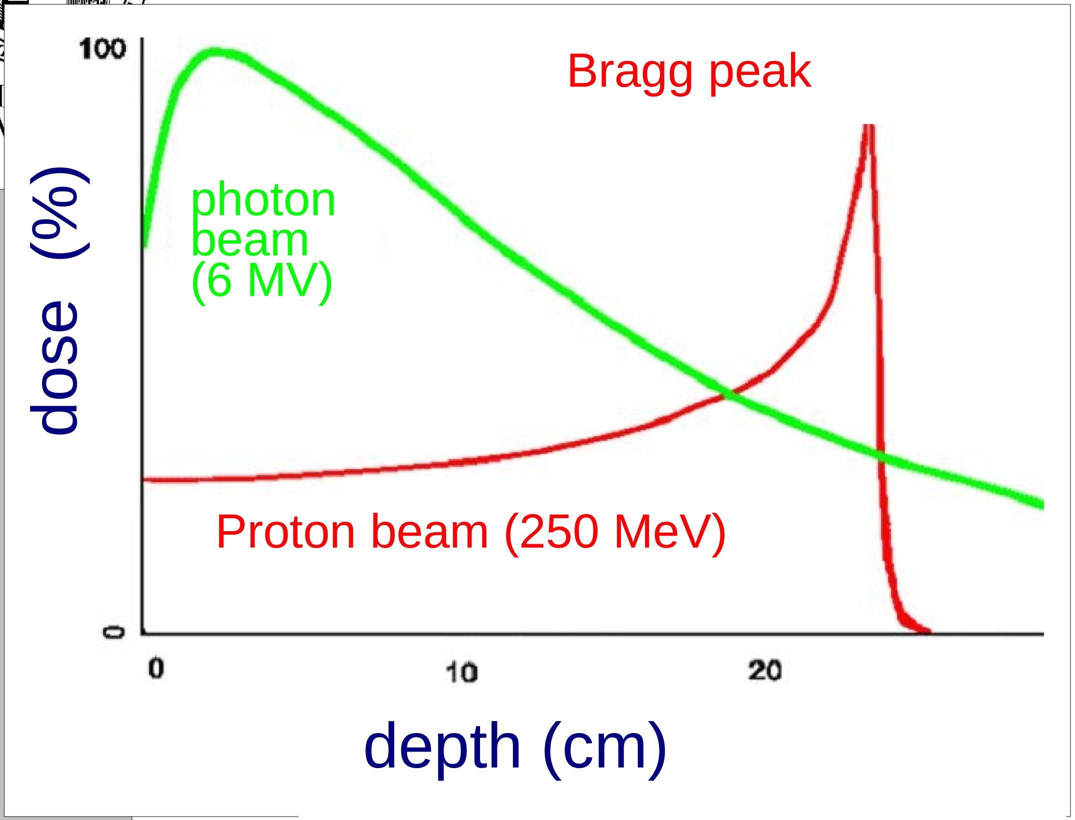
Frontier Detectors for Frontier Physics, 2012

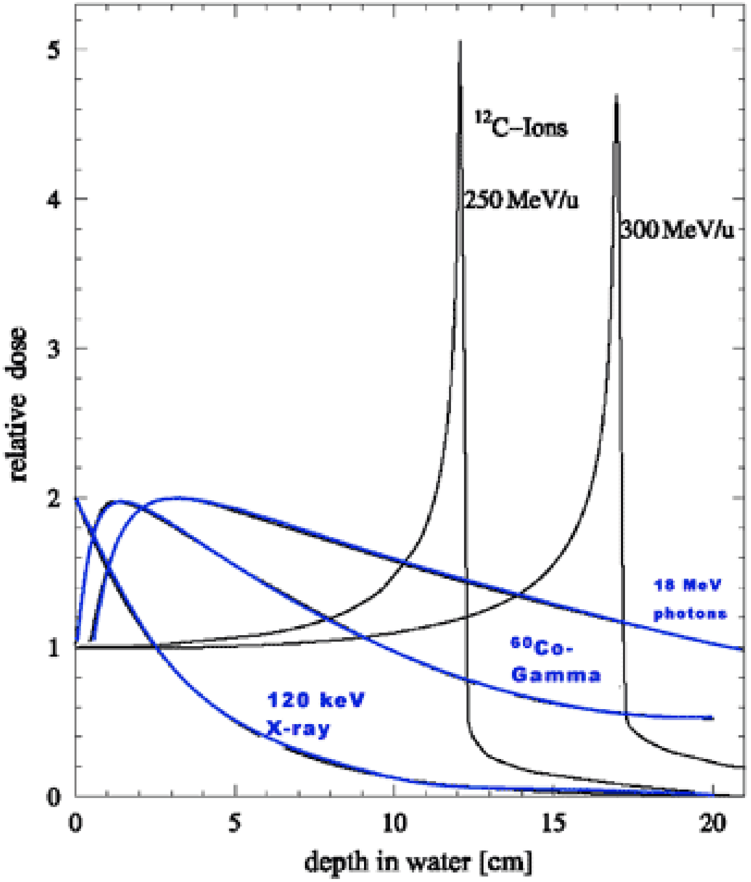
Outline

- Introduction: Compton detectors for dose monitoring in hadron therapy
- Detector characterization
- First prototype
- Larger detectors for the second prototype
- Conclusions

Dose monitoring in hadron therapy

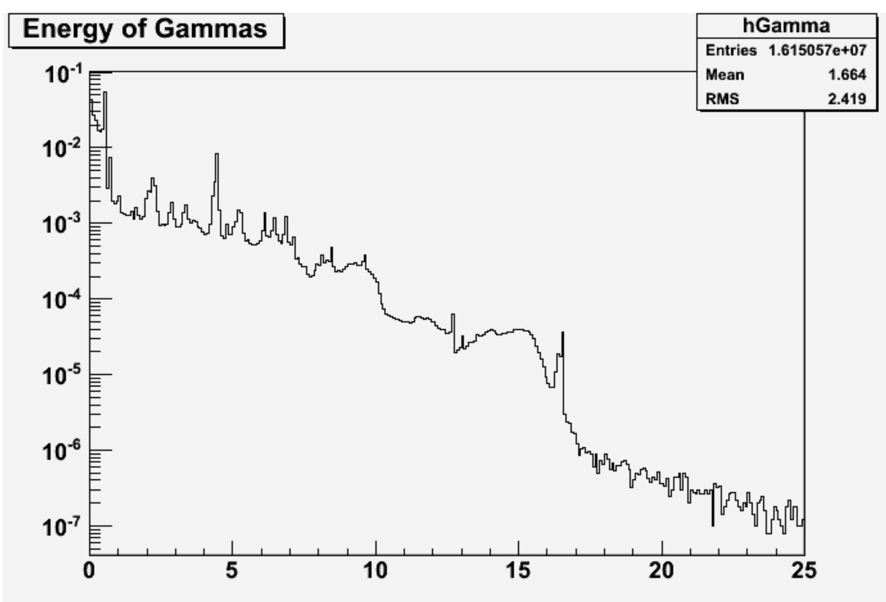
- Hadron therapy: charged particles-precise delivery of radiation dose (Bragg peak).





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. Emitted in a continuous energy spectrum with energies of MeVs.



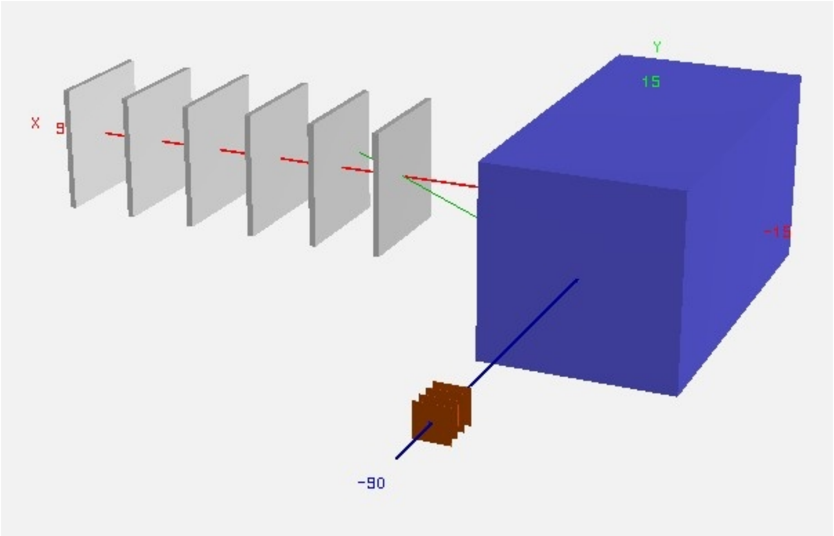
ENVISION European project (GA No 241851) coordinated by CERN

Compton telescope

- A Compton telescope is a possible solution for dose monitoring with prompt gammas.

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

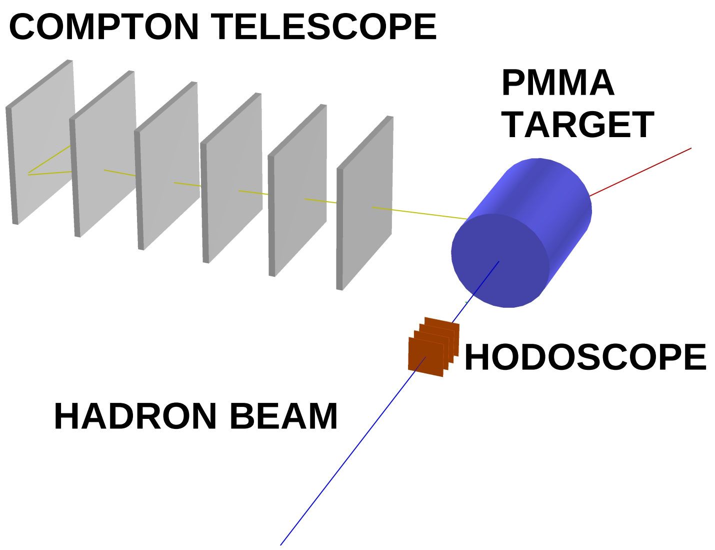
- Different configurations and materials being tested: silicon, CZT.



$LaBr_3$ Compton telescope

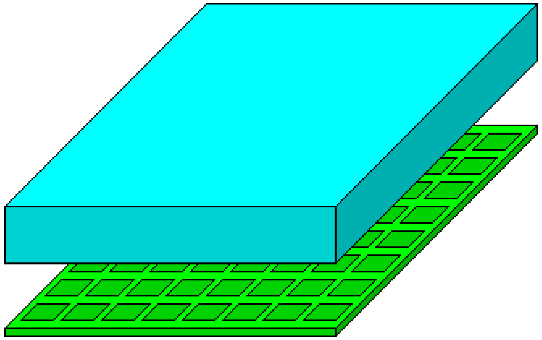
- Detector array composed of:
  - $LaBr_3$ continuous crystal:
    - high Compton probability,
    - high light yield=> good energy and timing resolution.
  - Silicon Photomultiplier arrays: compact, fast.

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



Continuous crystals

Advantages	Challenges
• Higher efficiency than pixellated crystals • Very good spatial resolution • Lower cost	• Large number of readout channels => ASICs • Position determination is complicated • Timing resolution can be degraded • High event rate

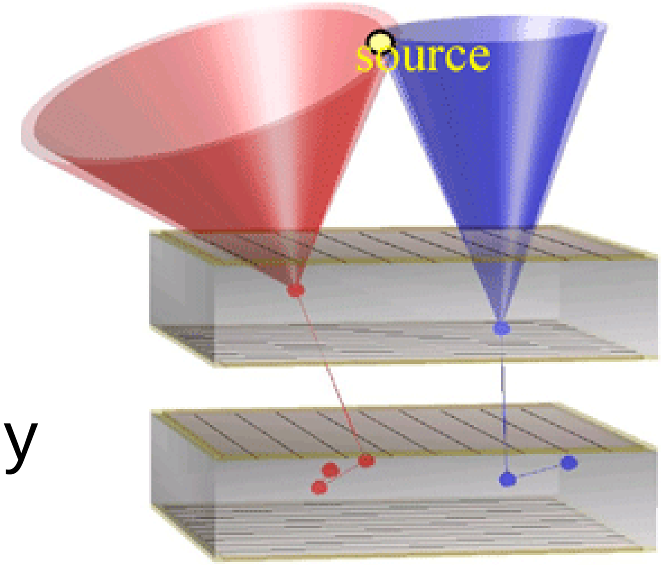


Detector configuration

'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)

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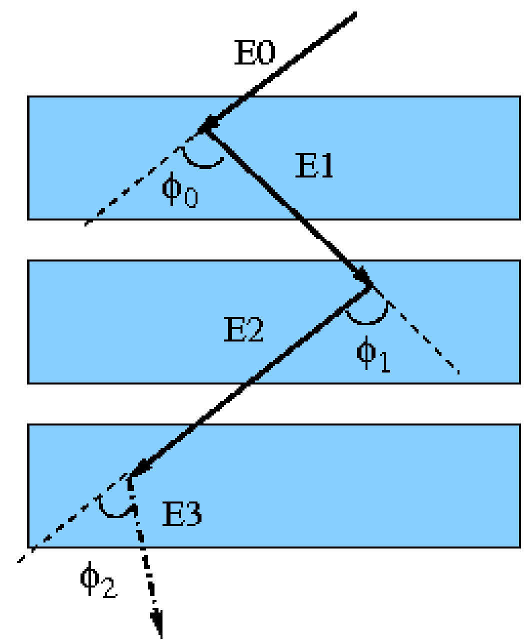
lower efficiency



Compton telescope configuration

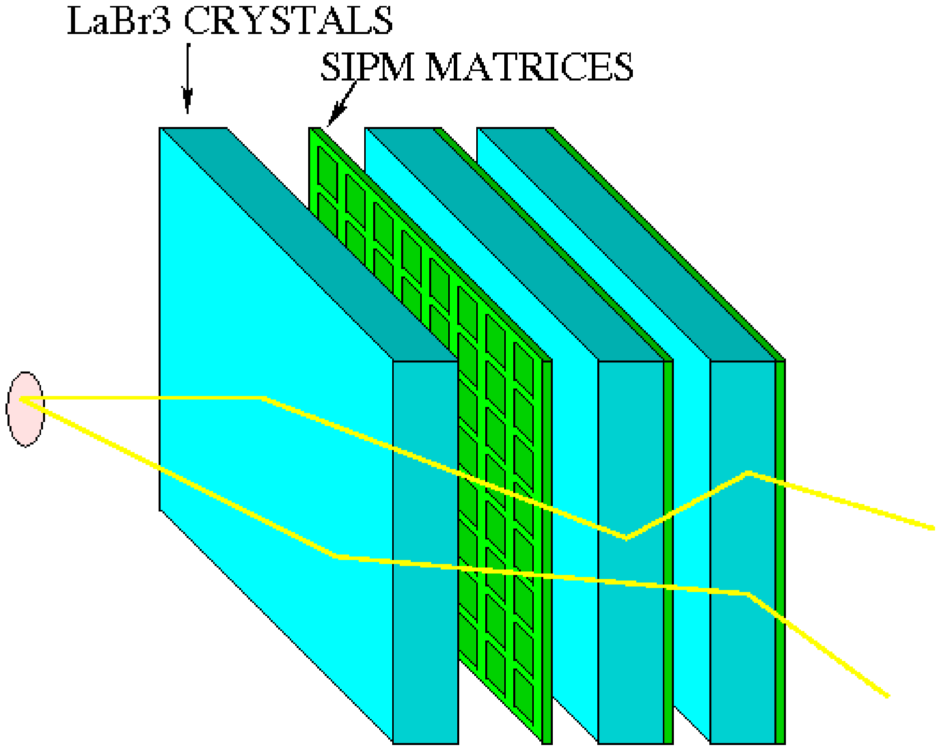
We are working on a method to estimate both position and energy from 2 int (high efficiency) + the combination with 3 int (high resolution).

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.

Compton telescope prototype

- **<u>Goal</u>:** prototype consisting of **3 detector layers** of continuous $LaBr_3$ crystals coupled to SiPM arrays.

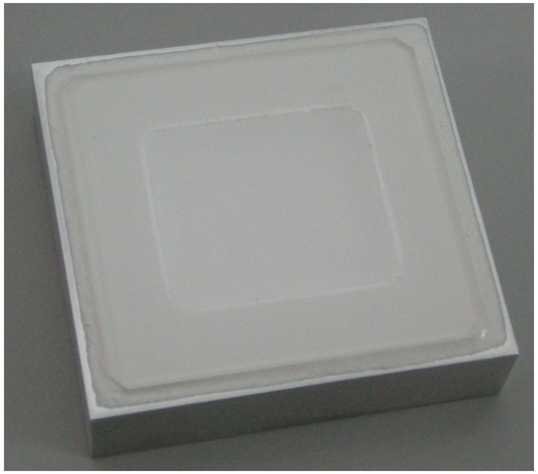
- High sensitivity
- No absorption required.
- 2-interaction and 3-interaction events are valid.
- Relatively simple assembly and operation.
- Low $/photon.



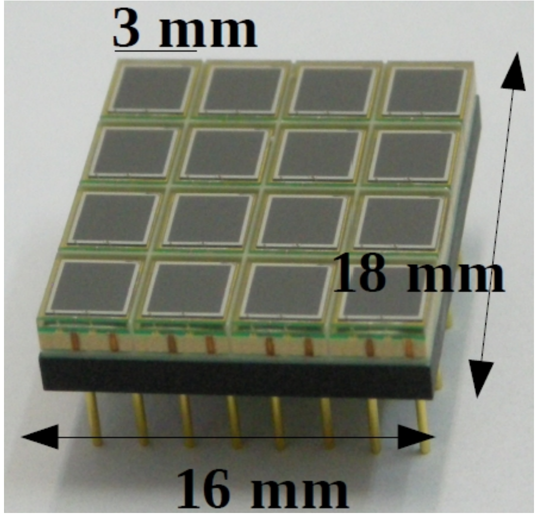
- First prototype developed with two layers:
  - $LaBr_3$ crystal 16 x 18 x 5 mm^3
  - LYSO crystal 16 x 18 x 5 mm^3

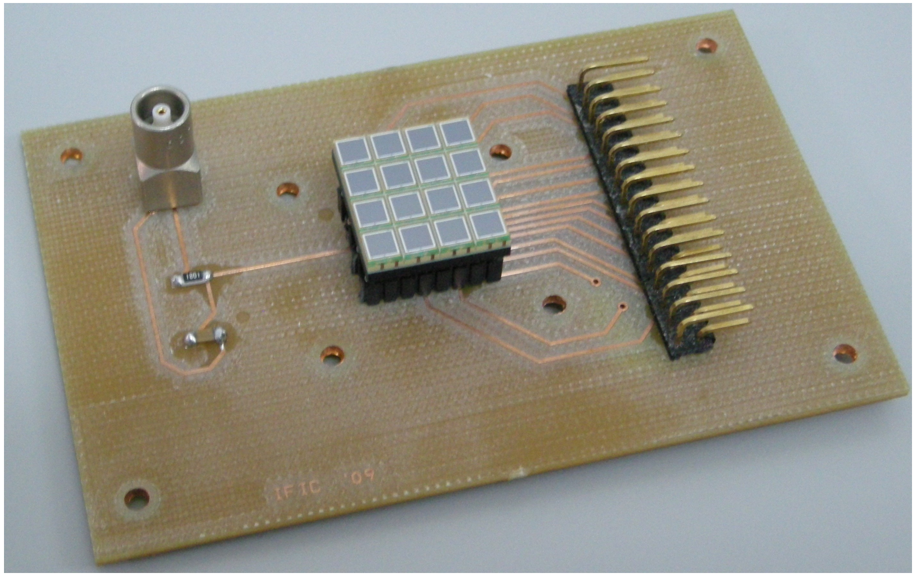
Detector characterization

First prototype components



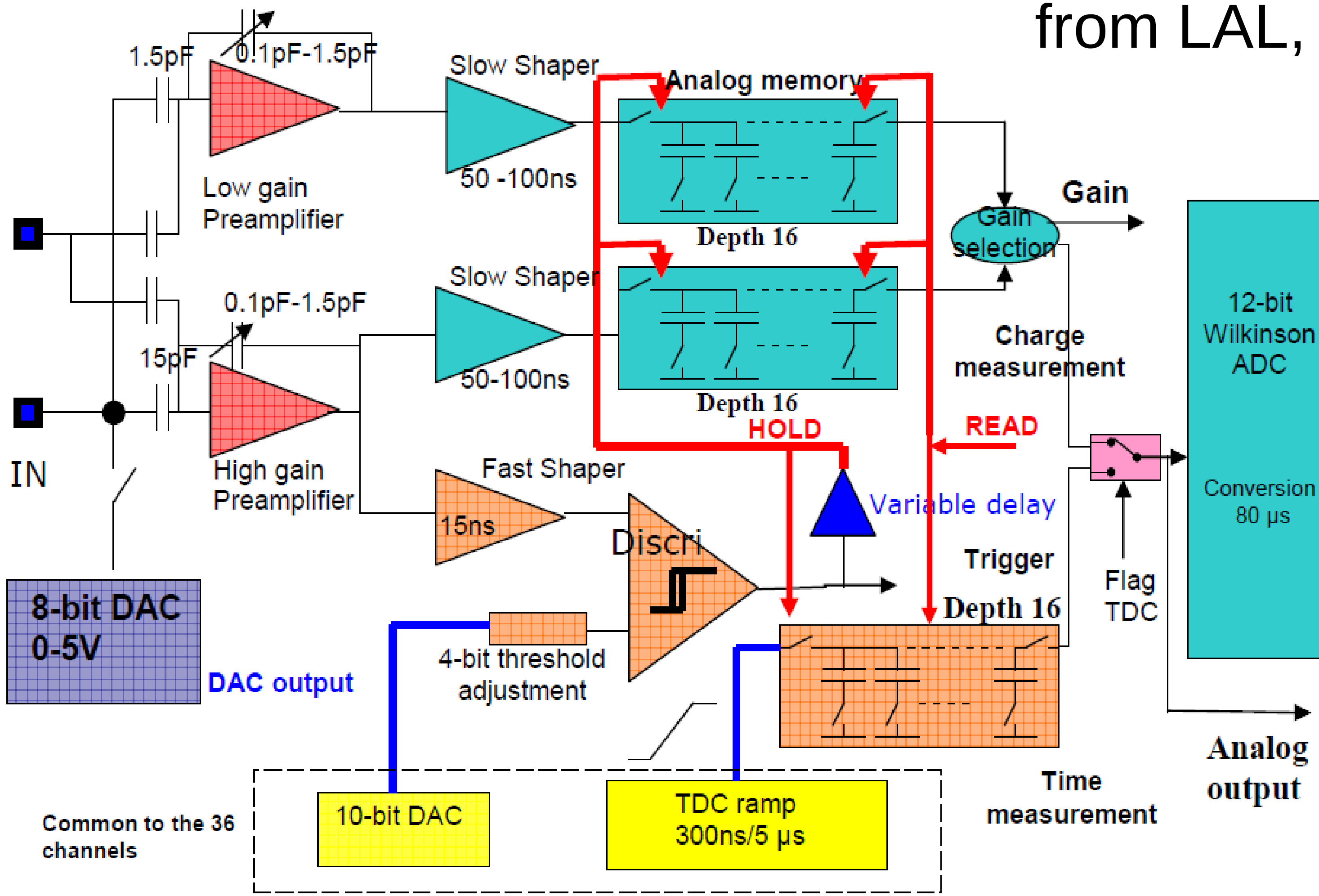
- $LaBr_3$ crystal (Saint Gobain), 16 mm x 18 mm x 5 mm
- Silicon photomultiplier (MG-APD) array:
  - MPPC from Hamamatsu
  - 16 pixels of 3 mm x 3 mm size
  - 50 µm microcell size
  - Pitch 4.05 mm x 4.5 mm





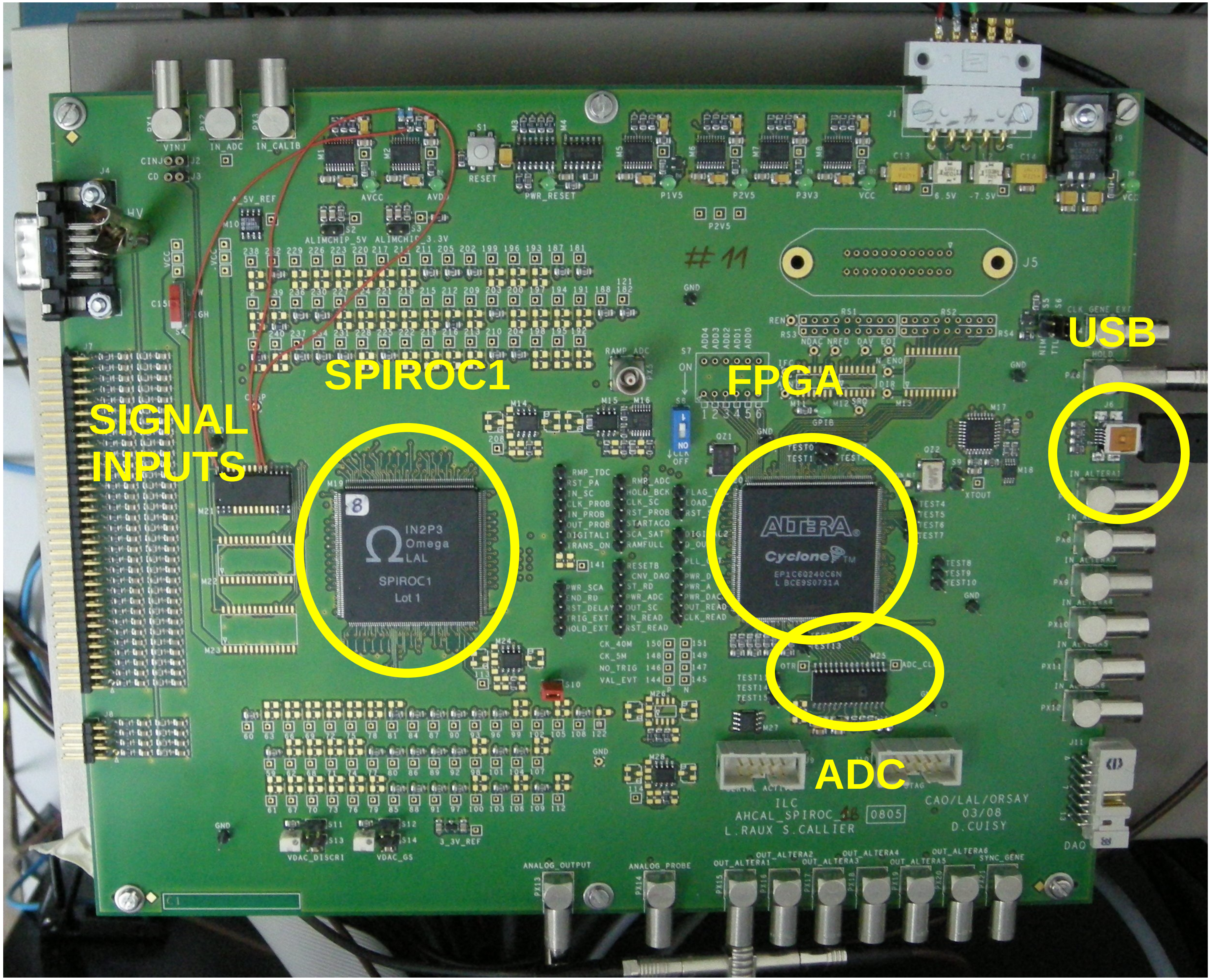
Readout electronics

SPIROC1 ASIC from LAL, Orsay



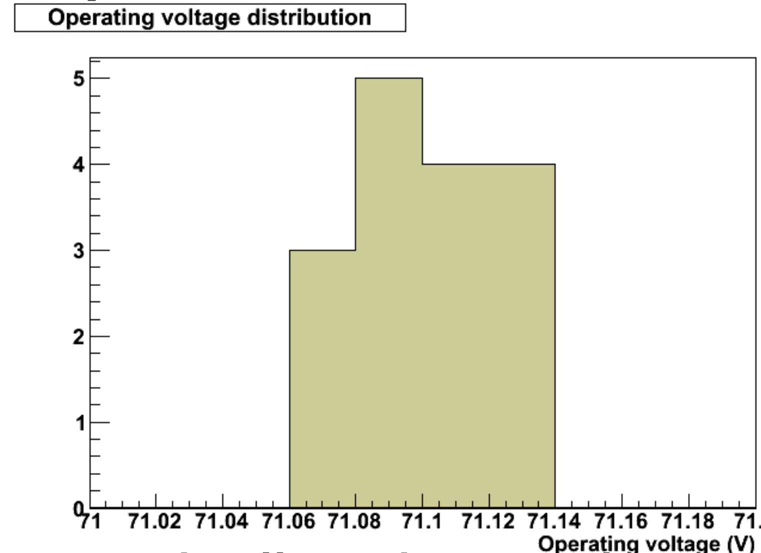
- 36 channels, **DACs for bias variations.**
- Selectable gain
- Slow shaper (~50-100 ns, adjustable)
- Fast shaper (15 ns) + discriminator =>Trigger signal.

Readout electronics

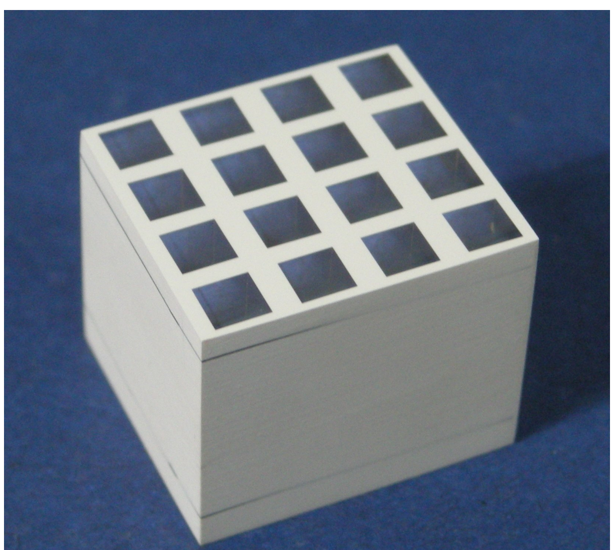


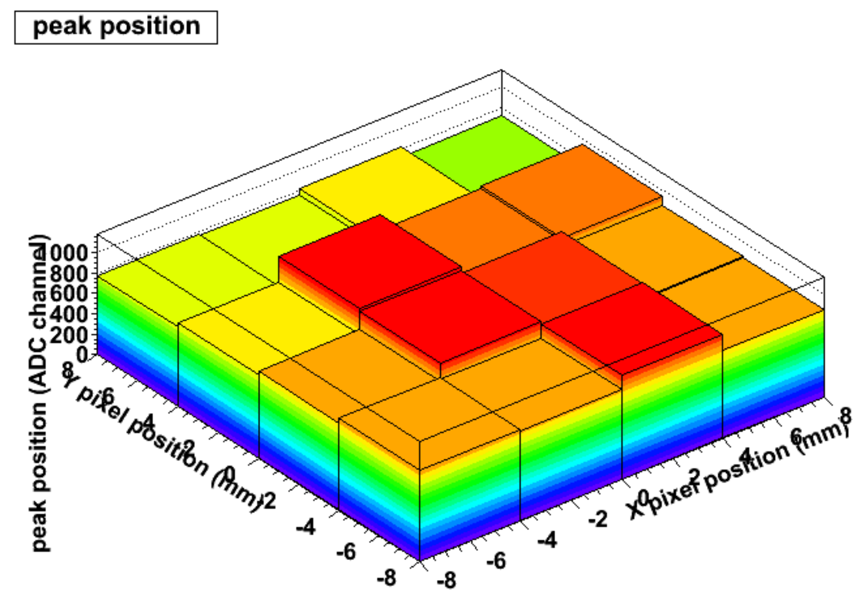
Photodetector uniformity

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.

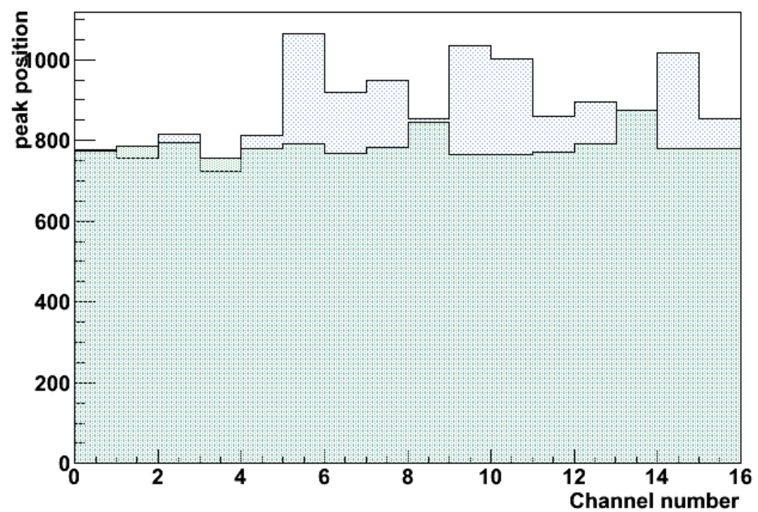




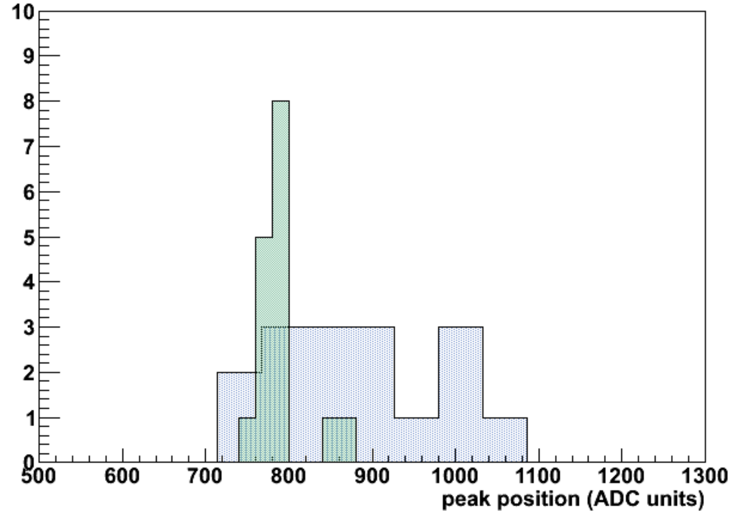
Photodetector uniformity

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

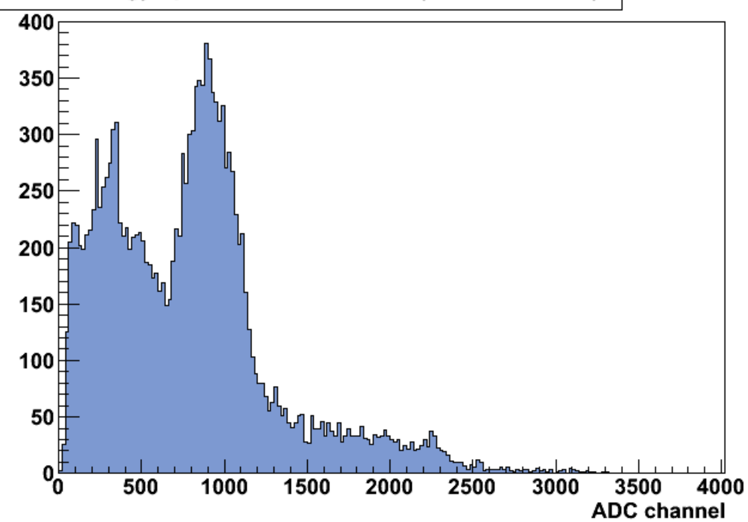
Peak position vs channel



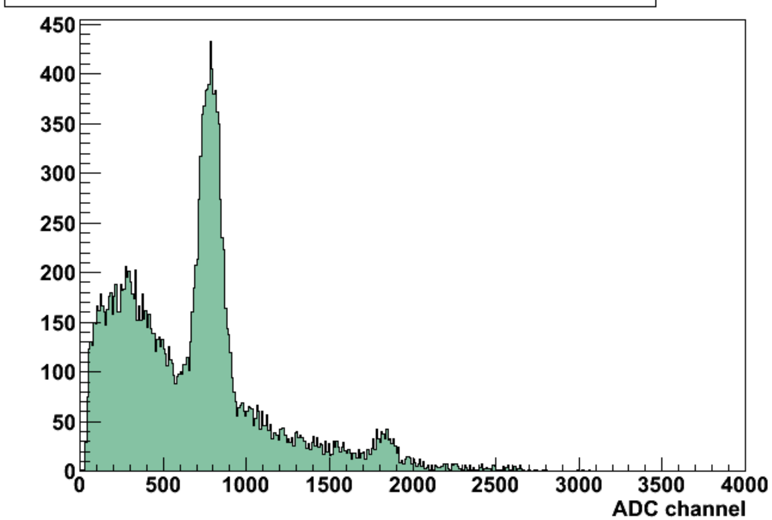
Peak position distribution



Na-22 energy spectrum all channels (no corrections)



Na-22 energy spectrum all channels (DAC corrections)



Energy resolution

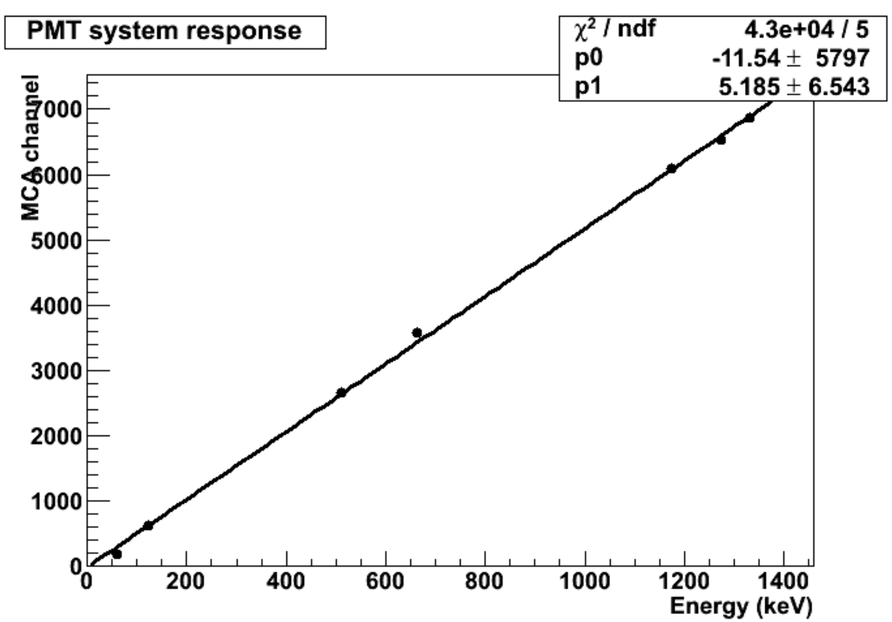
- Crystal specs from manufacturer

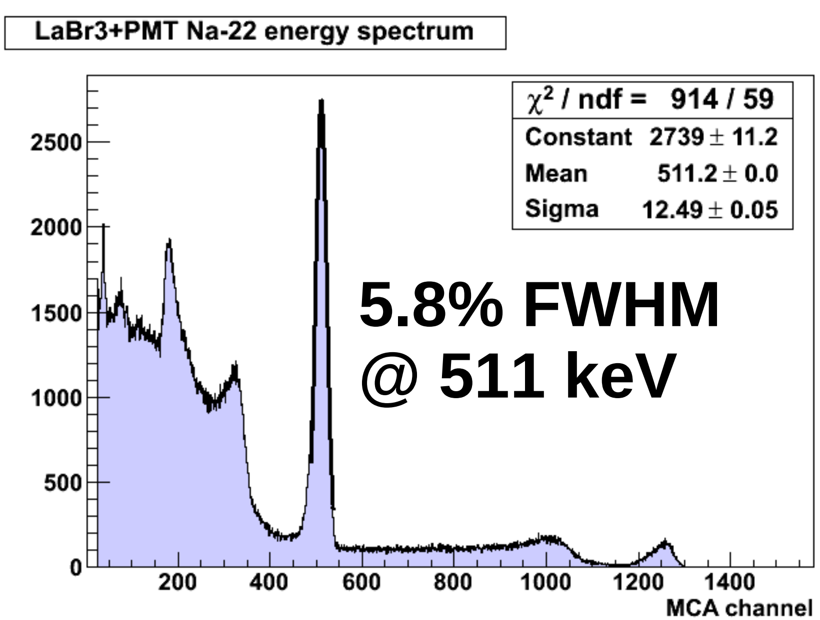
  energy resolution (with PMT Hamamatsu R4017):
  - 11.6% FWHM @ 60 keV (Am-241)
  - 6.3% FWHM @ 122 kev (Co-57, collimated source)

Expected ~ 4% FWHM @ 511 keV

Energy resolution

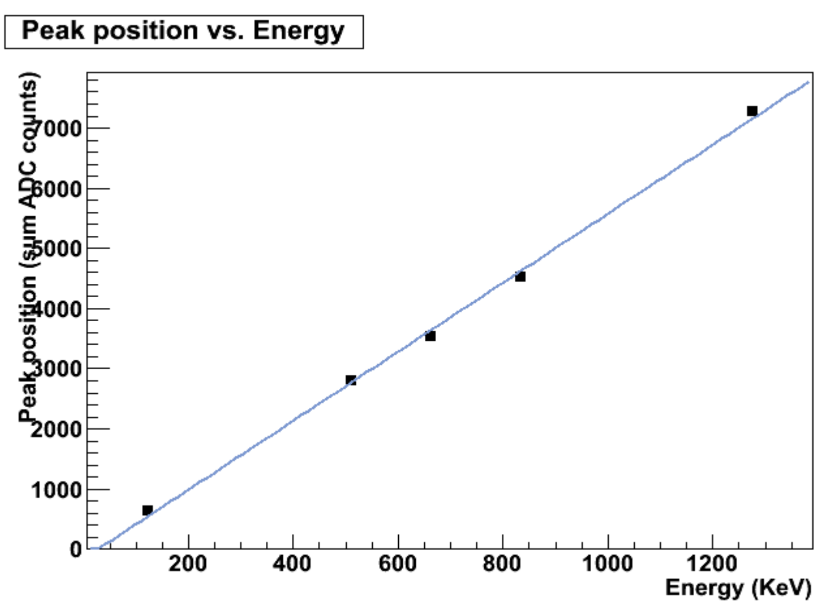
- Crystal tested with PMT (Hamamatsu R6236)+MCA:
  - ~10% FWHM @ 60 keV
  - 8.8% FWHM @ 122 keV
  - **5.8% FWHM @ 511 keV**
  - 4.25% FWHM@ 662 keV

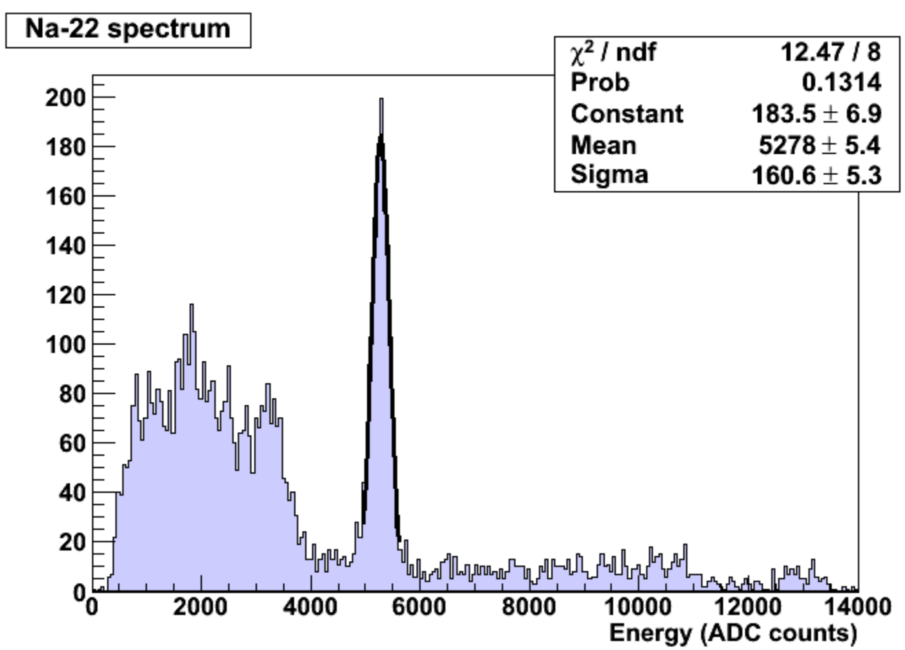




Energy resolution

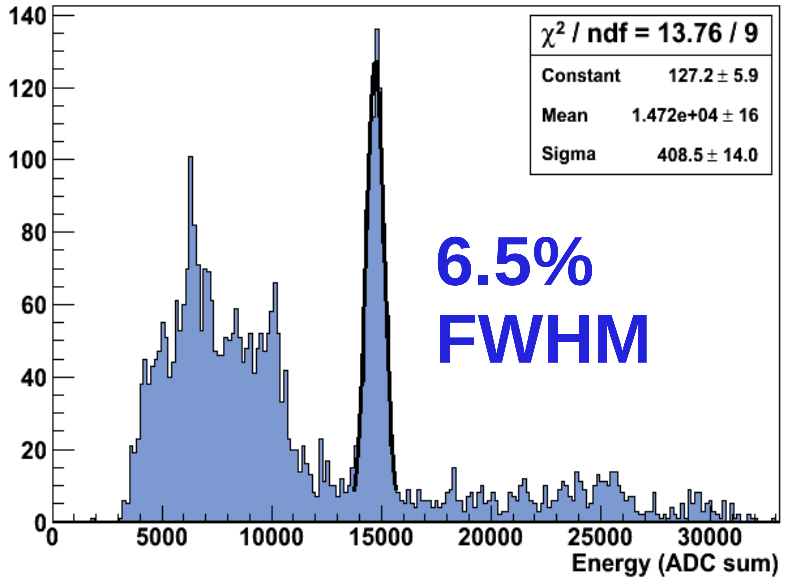
- Crystal coupled to MPPC array: **7% FWHM** @ 511 keV (at Vop + 1 V).
  - **without correcting** for response variations among pixels
  - MPPC array has a 50% loss of active area due to the gaps between the detector elements.



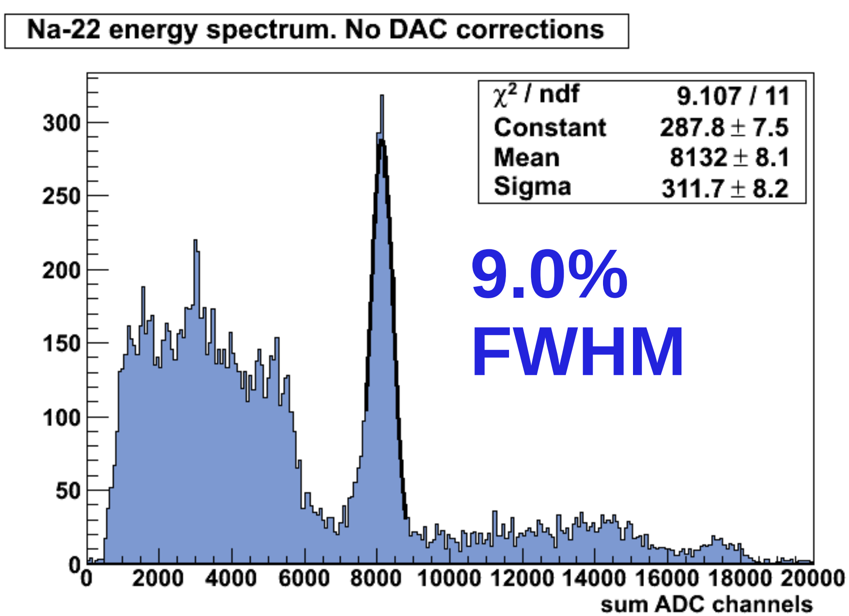


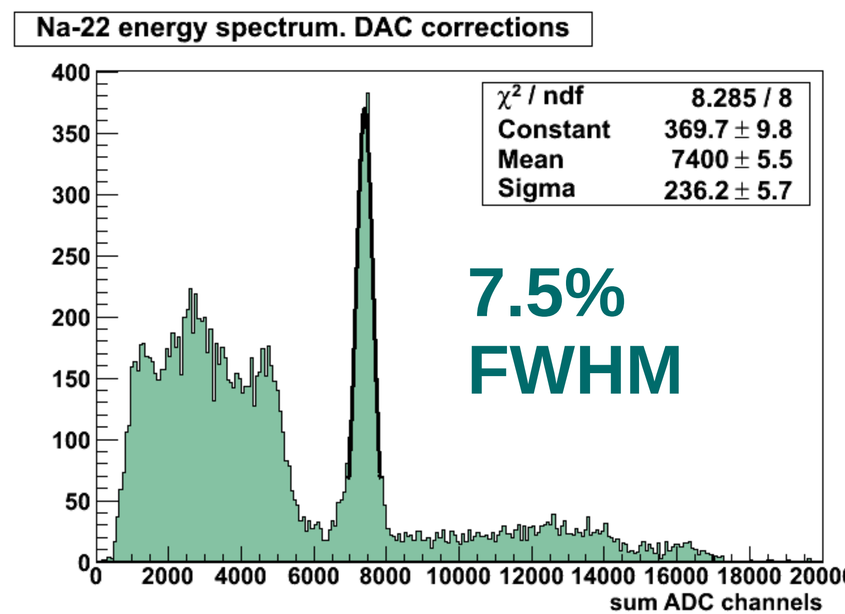
Energy resolution

- Energy resolution **6.5% FWHM** correcting offline for pixel variations (at Vop + 1 V).



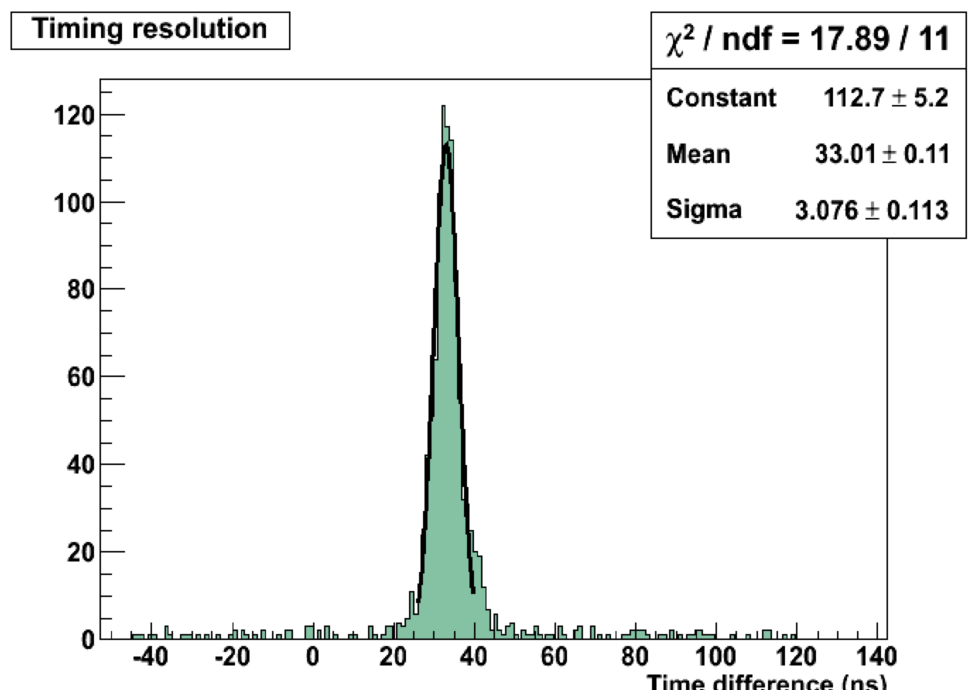
- $LaBr_3$ crystal with DACs (at Vop):





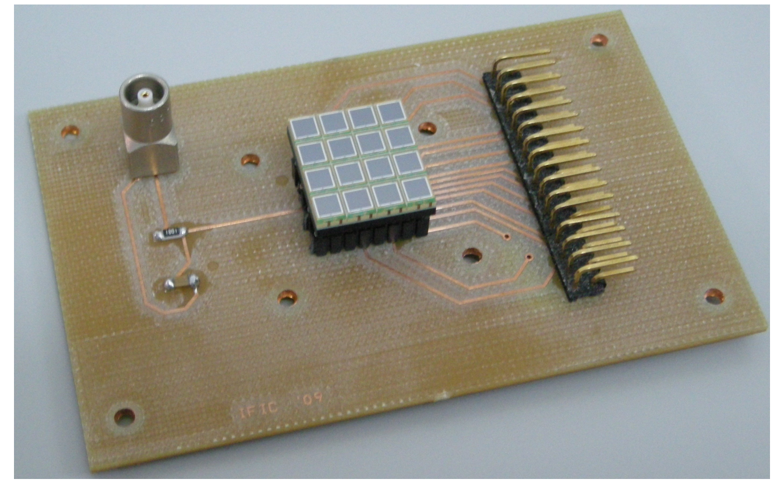
Coincidence timing resolution

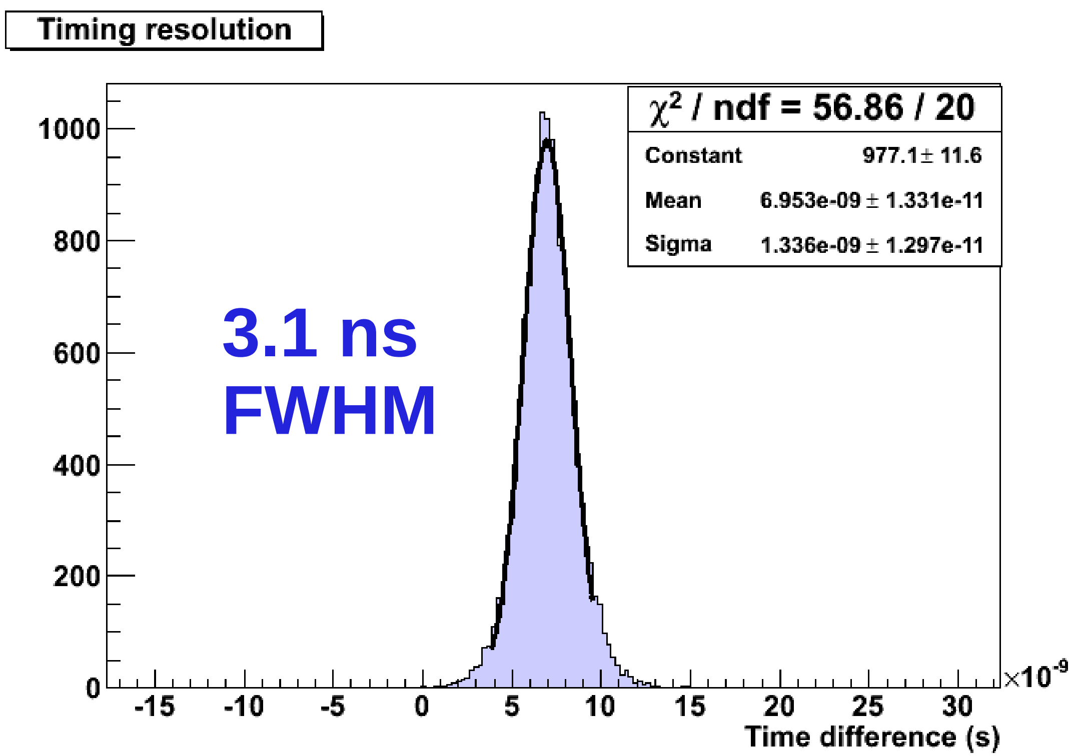
- Timing resolution 1 channel **~ 1 ns FWHM** (not optimized).
- Timing resolution $LaBr_3$ detector (16 channels) **7 ns FWHM.**
- The degradation comes from trigger differences among channels.



Timing resolution

- **Alternative trigger**: signals from all channels split on the PCB and part summed to a common output.



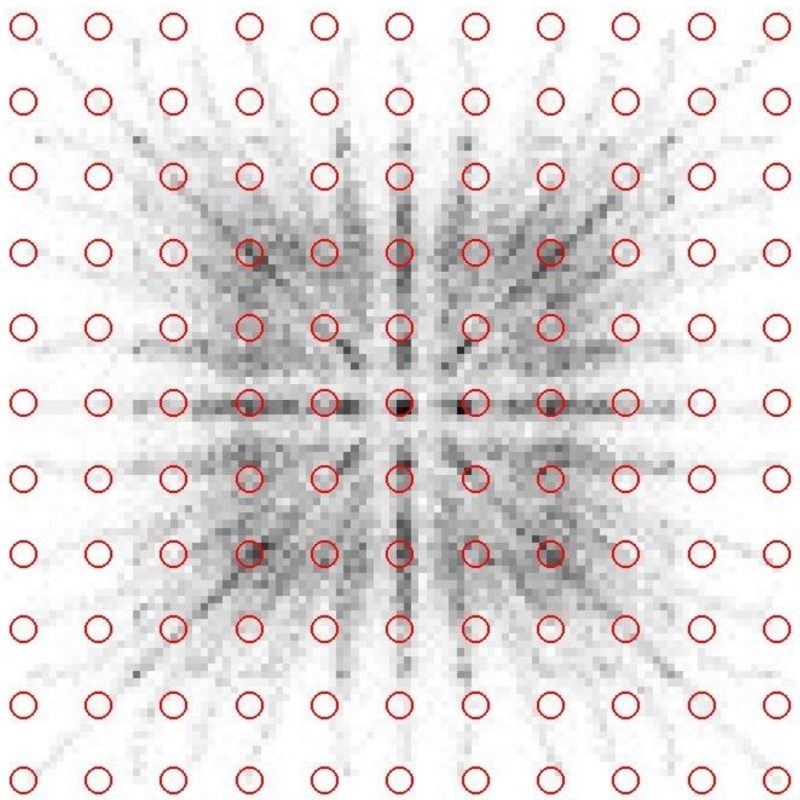


Significant improvement of the timing resolution

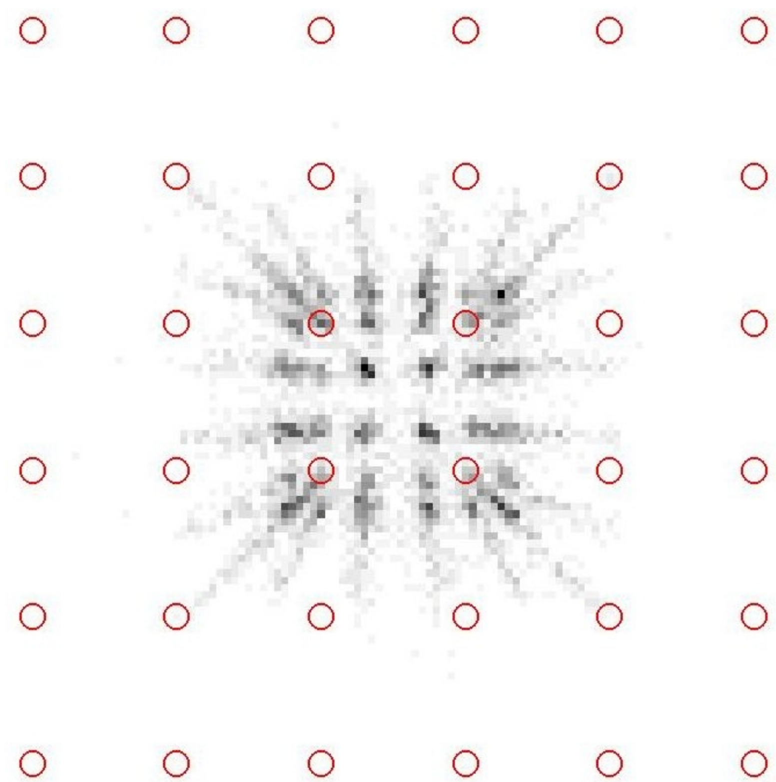
Position determination

- CoG (Anger) results in compression effects

BLACK CRYSTAL



WHITE CRYSTAL

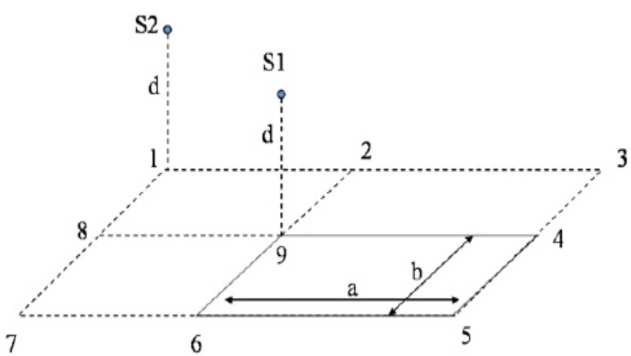


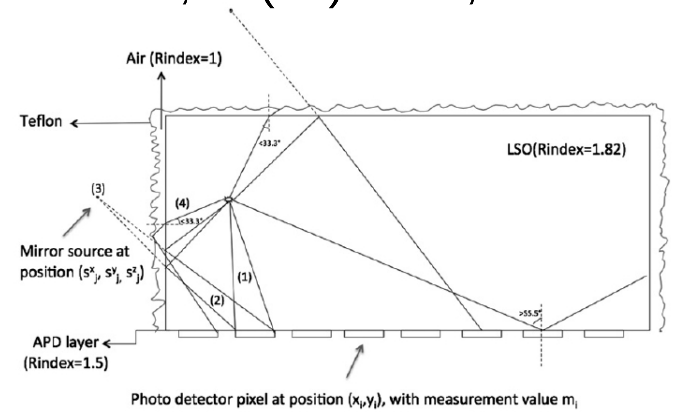
- Several methods are being considered by different groups: Maximum Likelihood, ANNs, other...

Position estimation

model 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

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

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

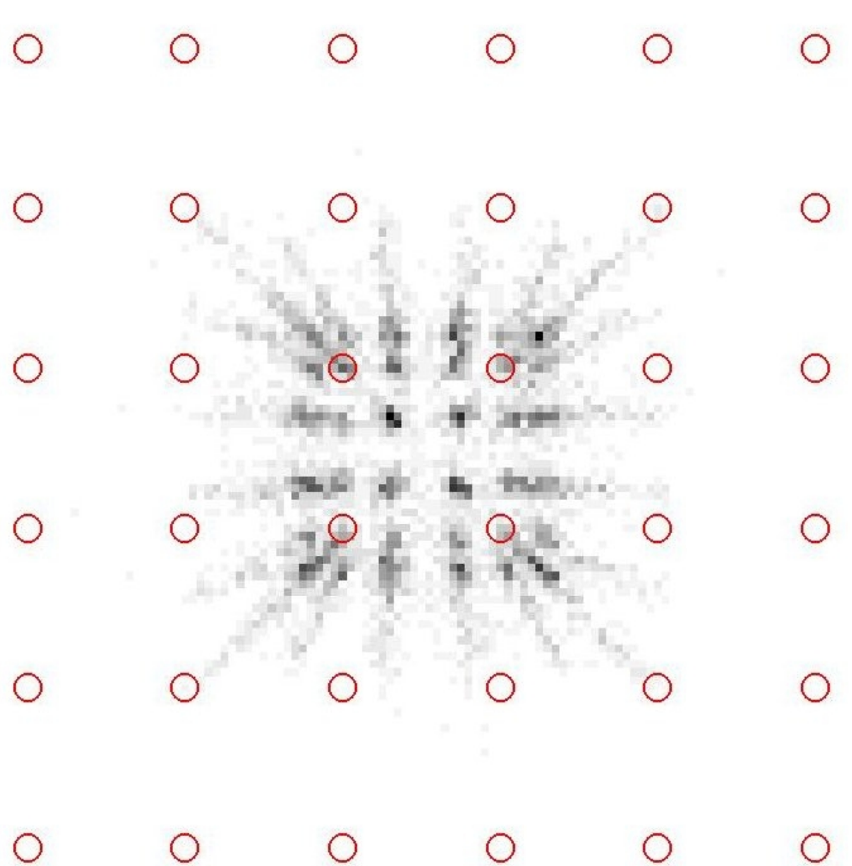
Optimization method:
Local minimization interior-reflective Newton

Position determination

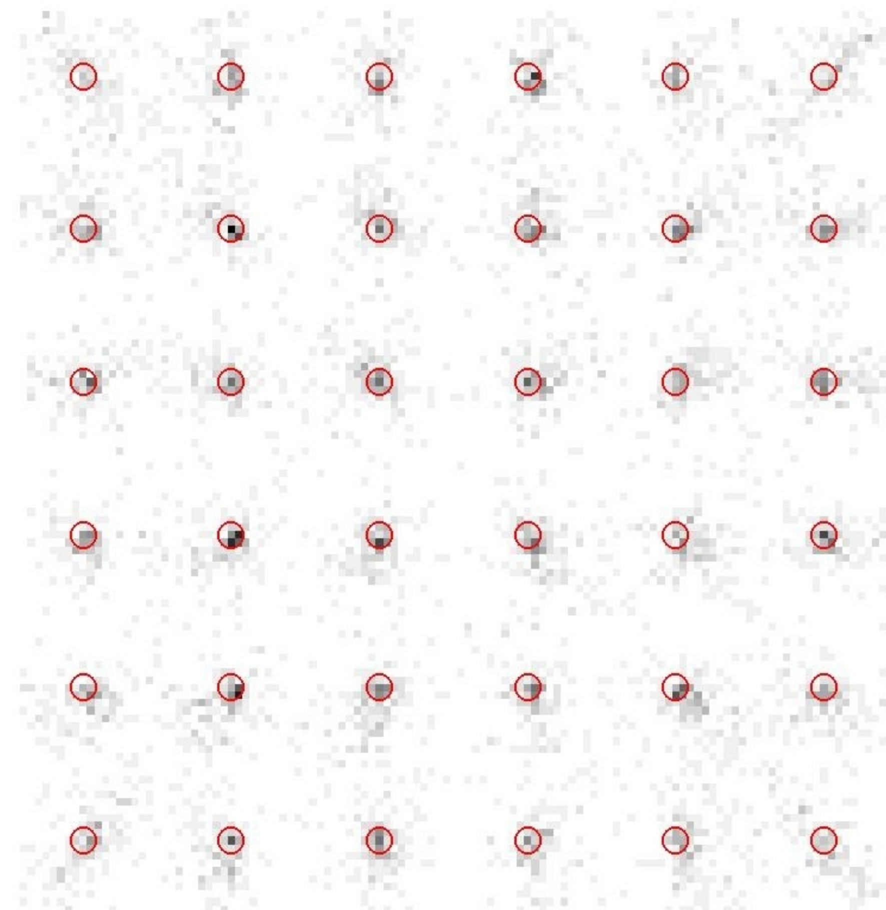
Advantages: **much less compression + DOI**

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

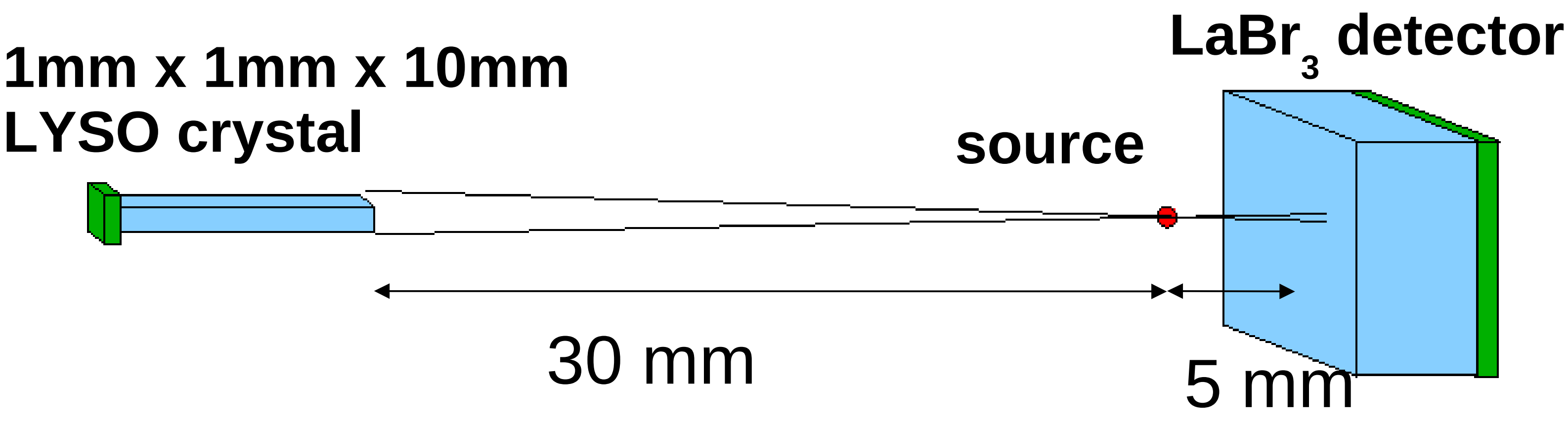
COG

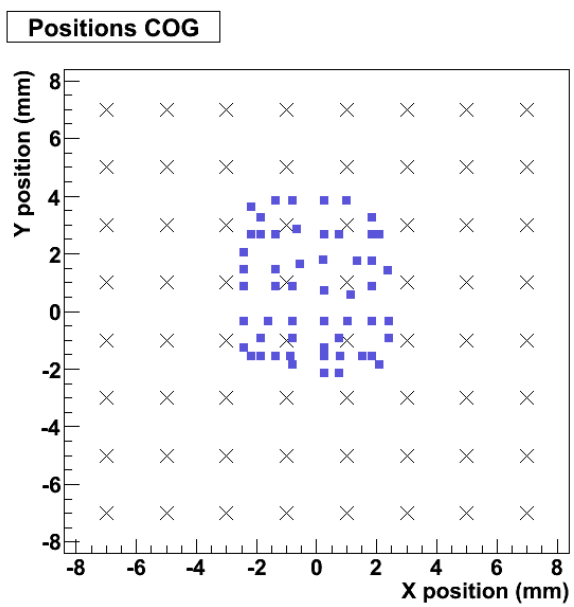


New method



Position determination

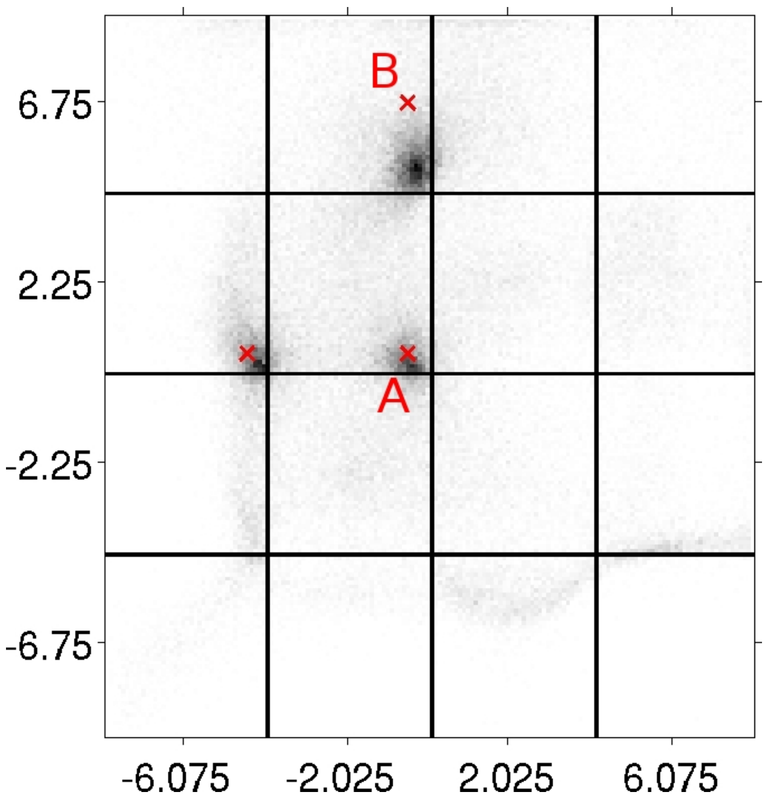




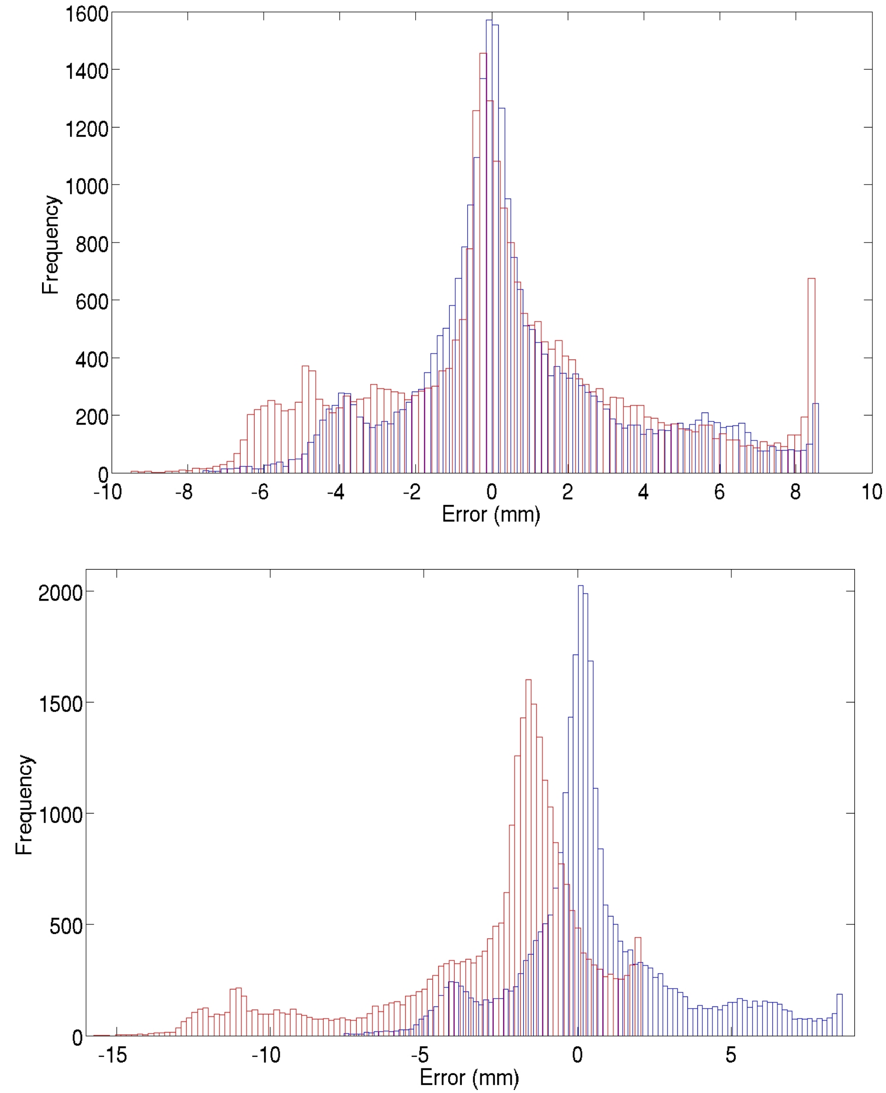
With CoG strong compression due to the highly reflective crystal wrapping.

Position determination

The red crosses represent
the real positions



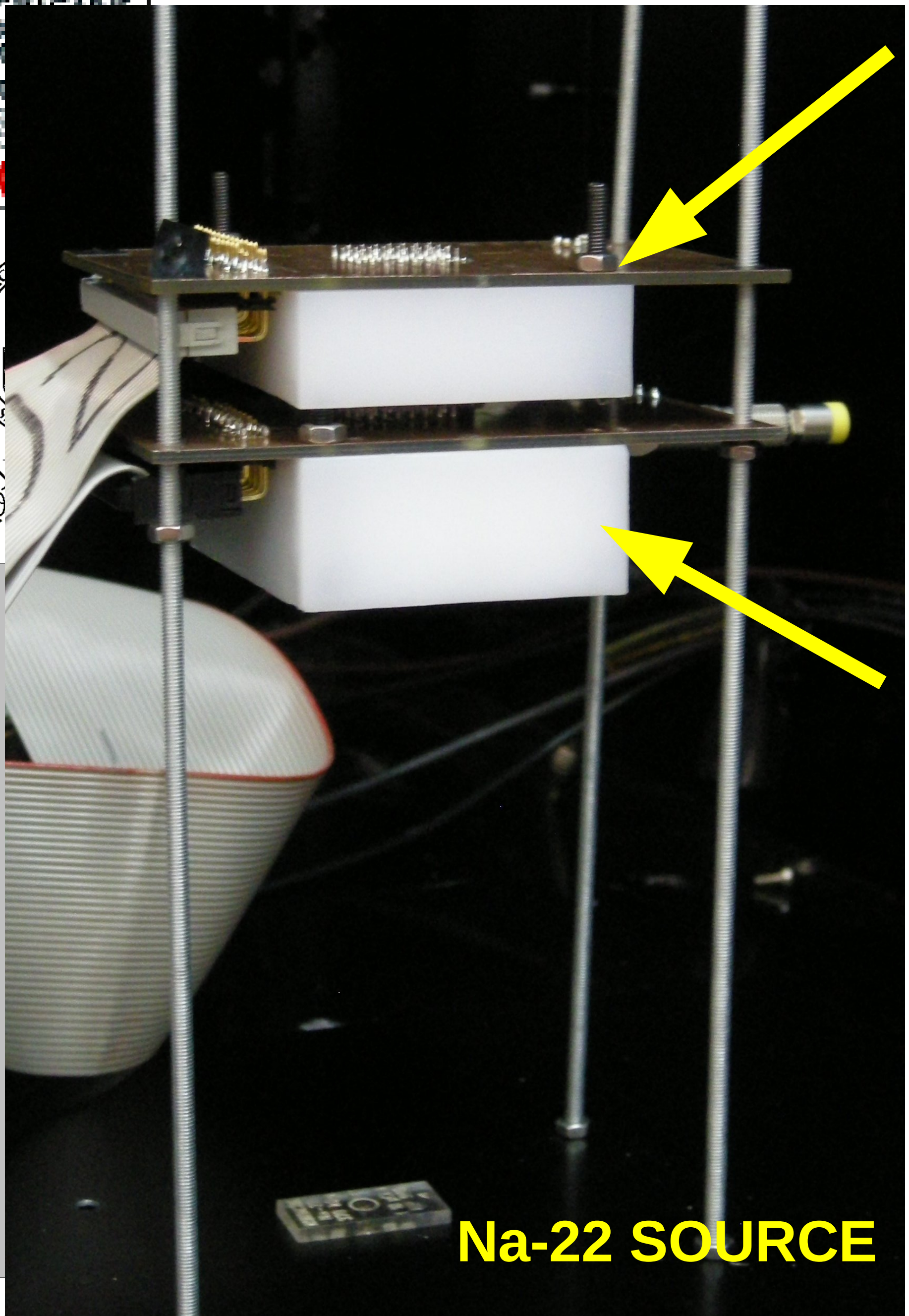
	Bias (mm)	FWHM (mm)
Centre	0.2	**1.1**
Edge	1.5	**1.4**



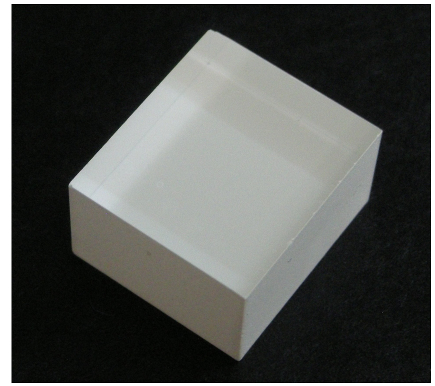
Histogram of estimated positions in X and Y of points A and B

First prototype

First CC prototype with LaBr3 crystals

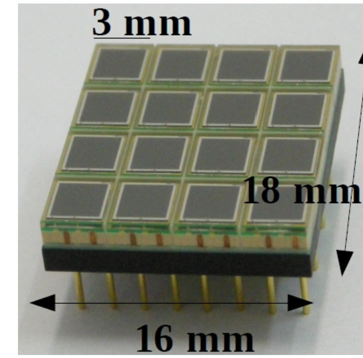


SECOND DETECTOR



LYSO crystal, $16x18x5mm^3$

+

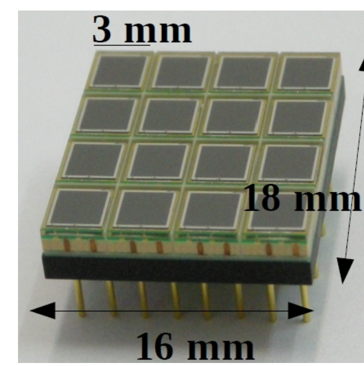


SiPM (MPPC) array

FIRST DETECTOR

$LaBr_3$ crystal, $16x18x5mm^3$

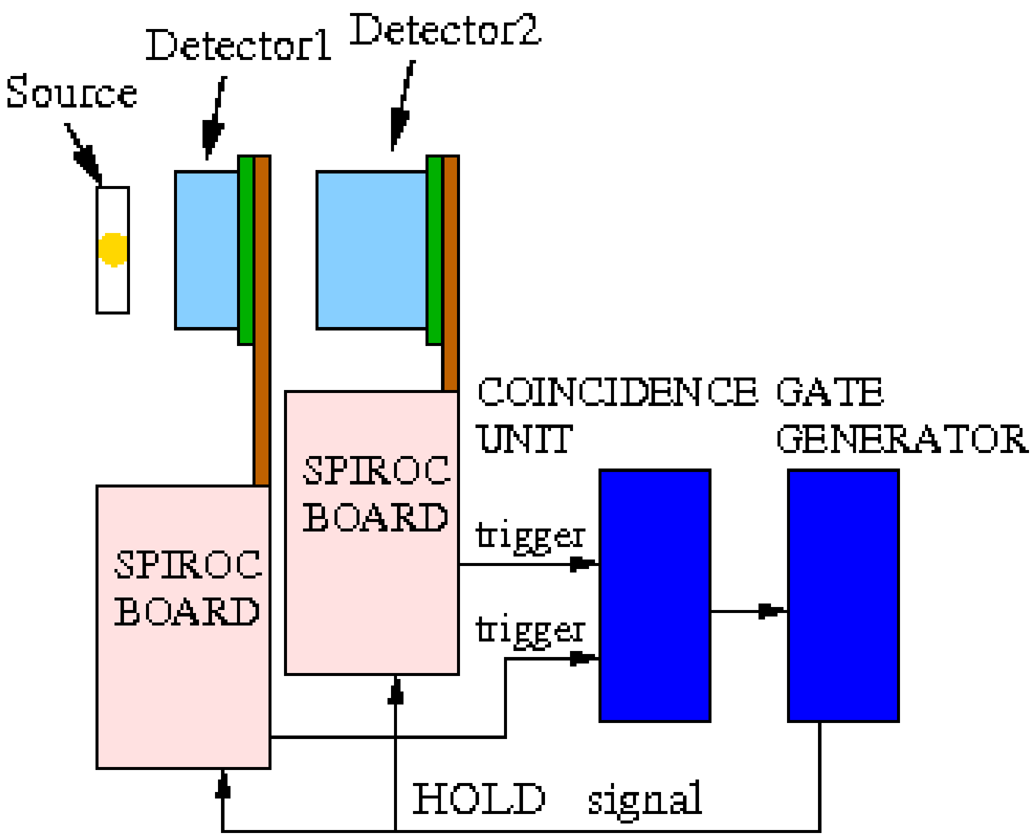
+



SiPM (MPPC) array

Prototype operation

- Readout with two SPIROC1 boards
- Each detector connected to one board
- NIM modules to do coincidence and generate trigger

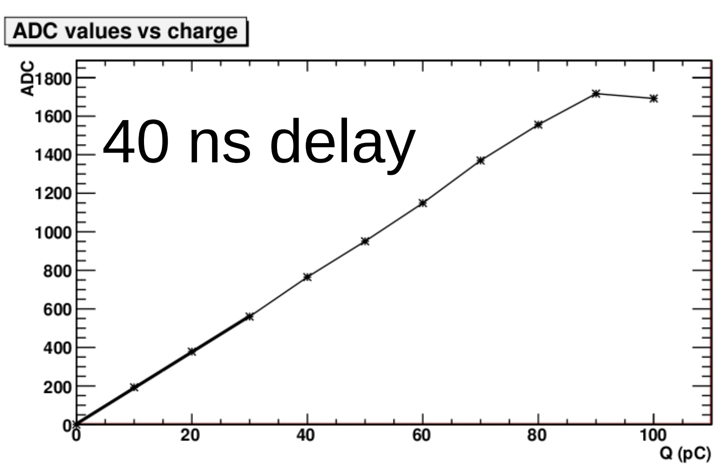


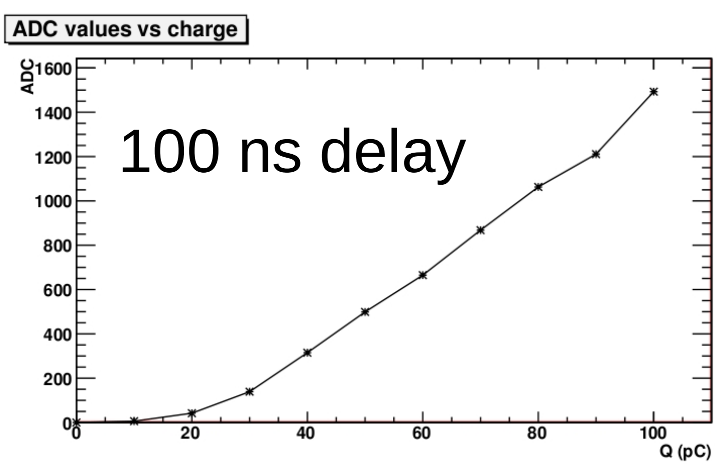
GOAL: test position determination and imaging capabilities.

Prototype performance not optimized

Prototype performance

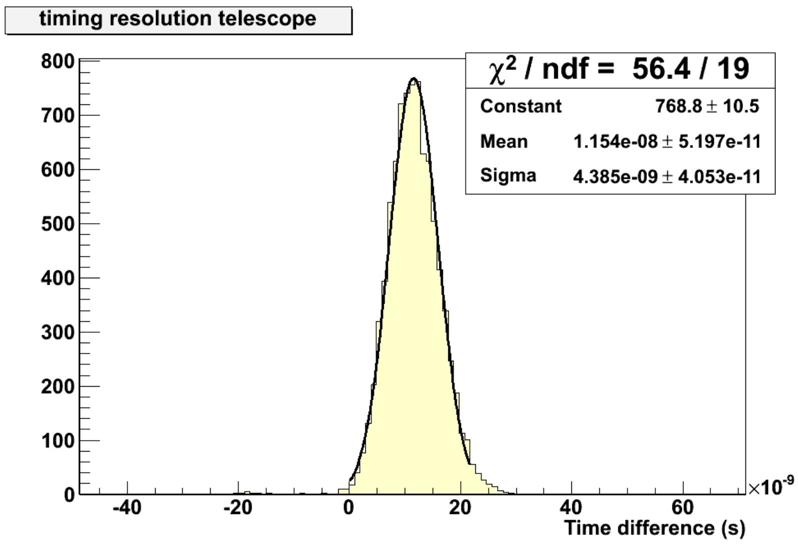
- Coincidence data taken with a Na-22 source of 620 kBq activity and 0.25 mm diameter (10 cm from 1st det, 3 pos).
- High rate of random events due to radioactive Lu background and low activity source.
- Variable coincidence window, up to 100 ns. No DAC corrections applied.
- Trigger from SPIROC boards: ~ 10 ns FWHM timing resolution.
- Deviation from linearity when we do coincidences due to HOLD delay .



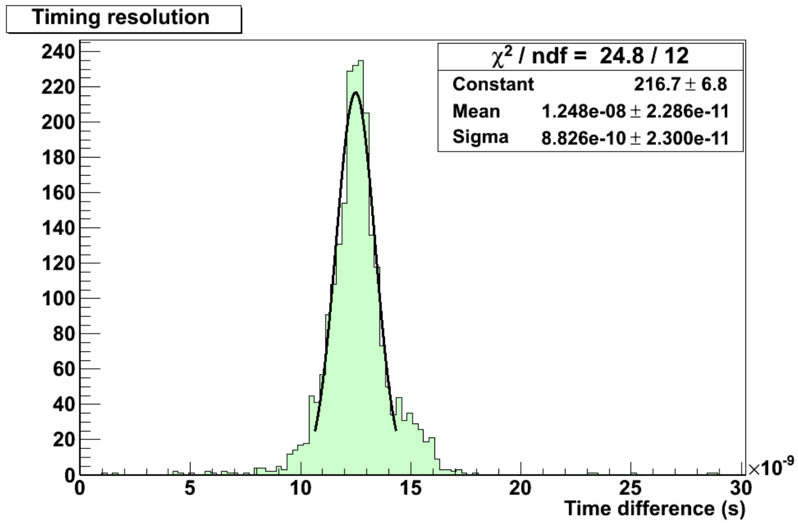


Coincidence tests - Timing

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

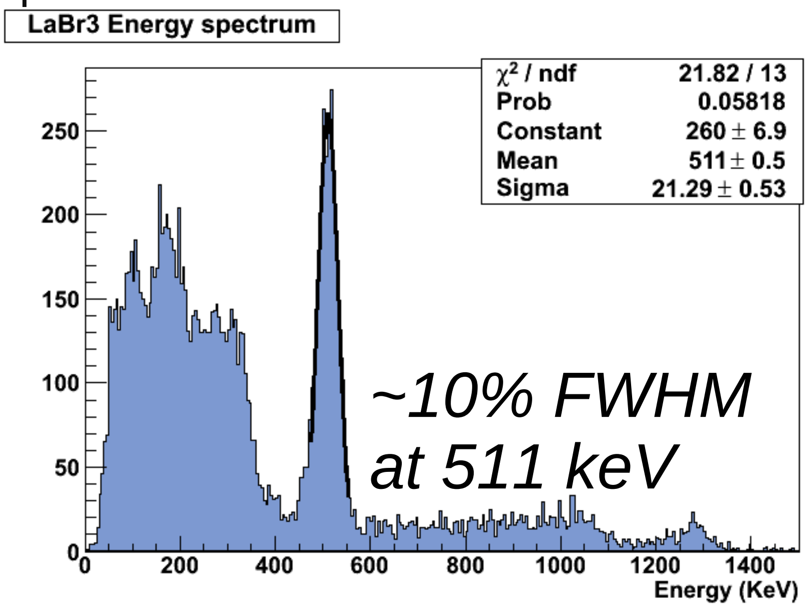


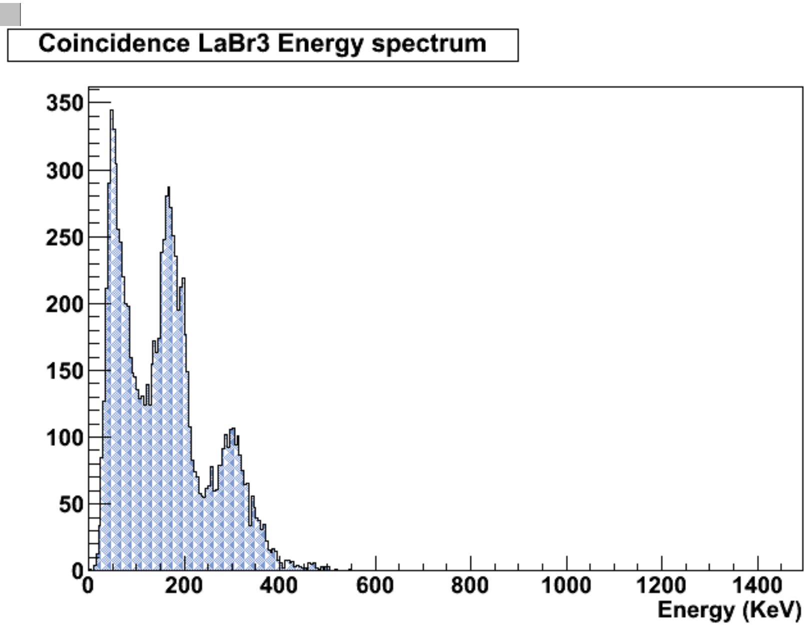
From the sum of all signals for each detector **~ 2 ns FWHM.**



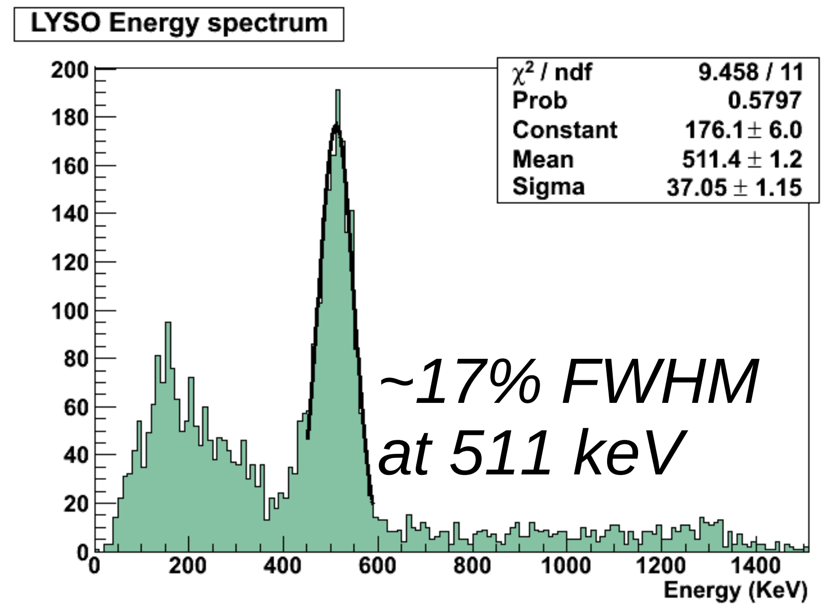
Results

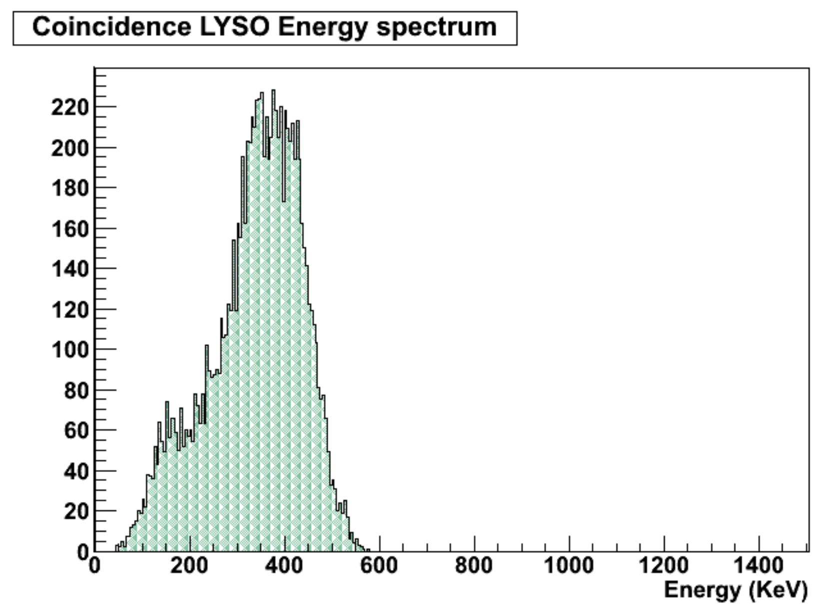
Det 1 ($LaBr_3$)





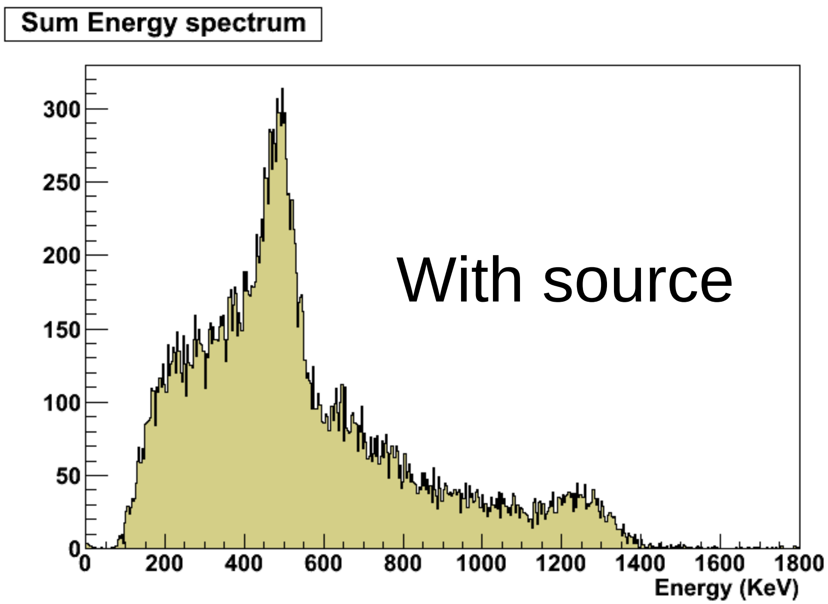
Det 2 (LYSO)

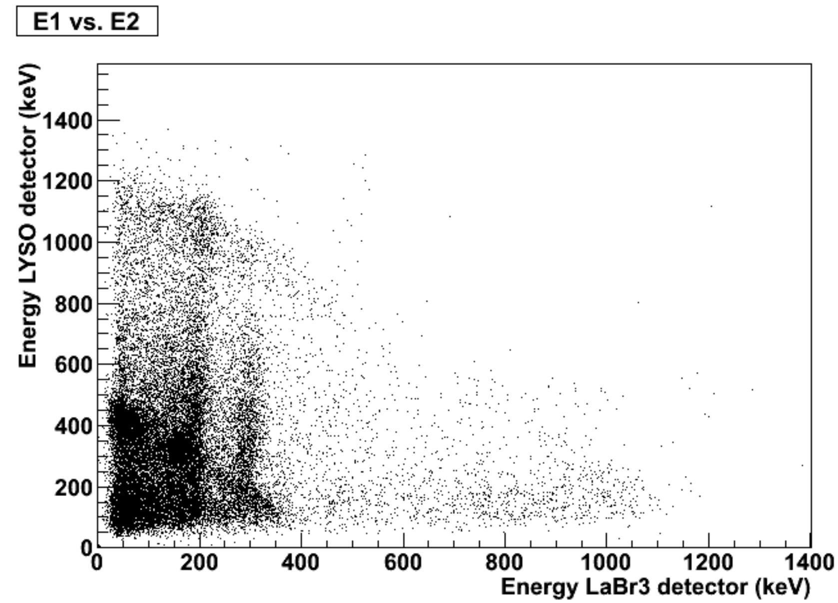


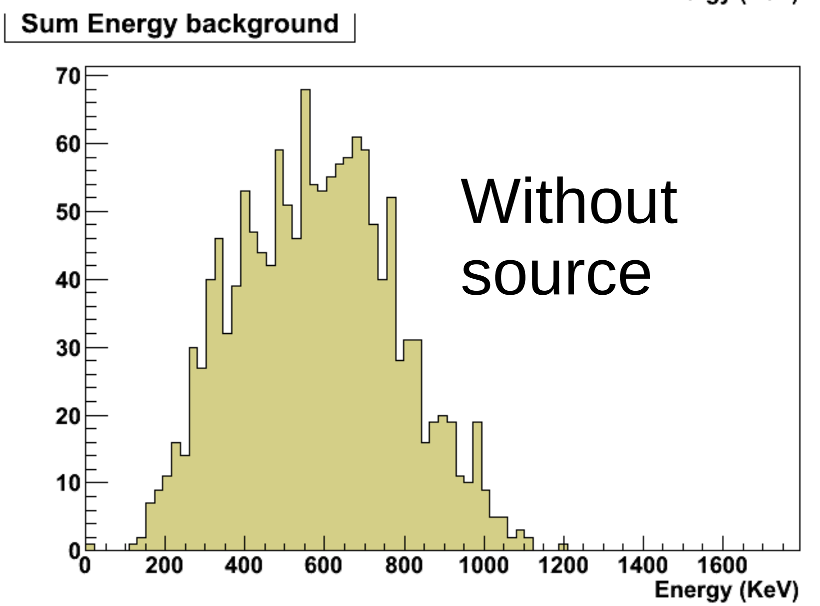


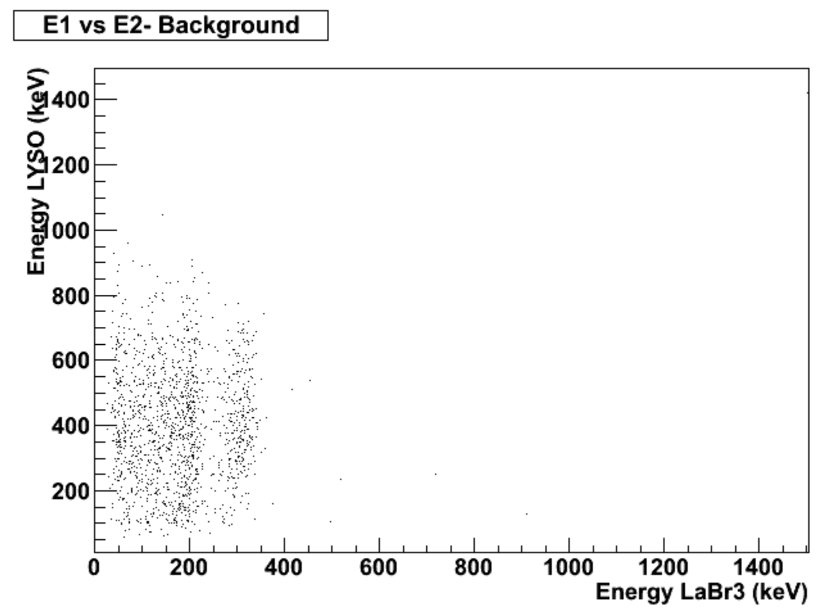
Results

Data in coincidence



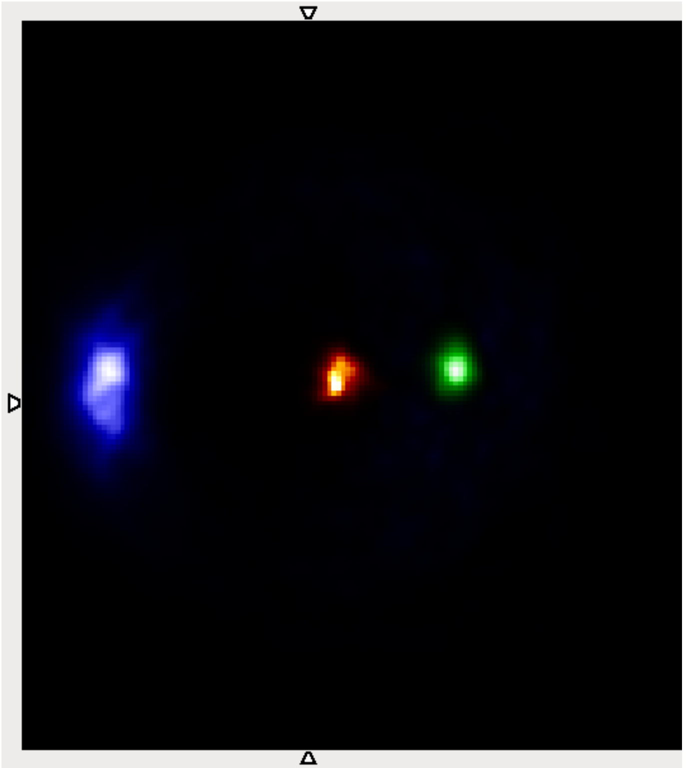






Still... successful!

- Successful imaging of the Na-22 source with Compton-SOPL[1].
- Source placed at 3 positions:
  - ~10 cm from first detector
  - ~ 5 cm between positions



[1]J. Gillam, et al., IEEE Nucl. Sci. Conf. R. (2011) p4206-10

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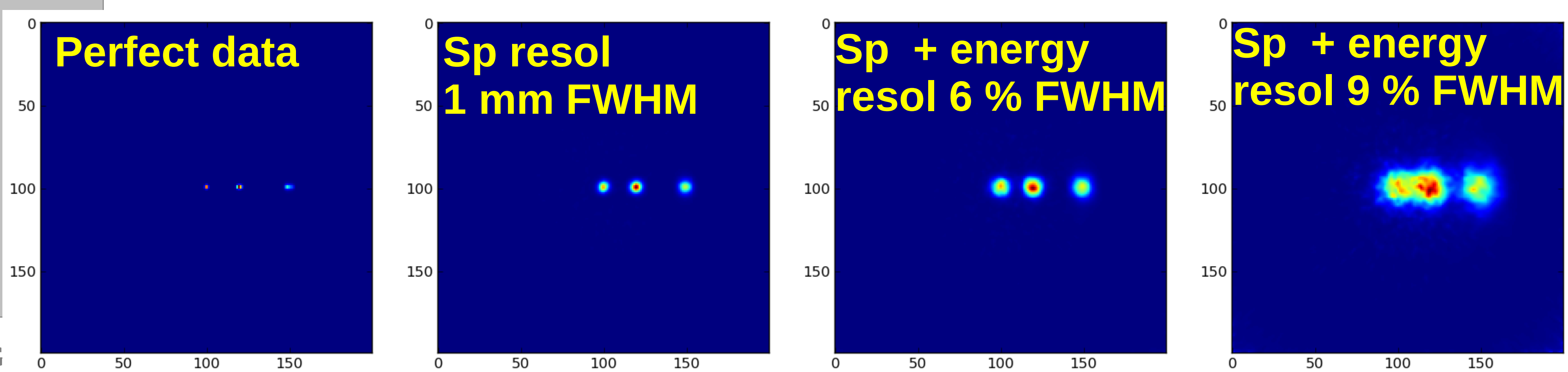
Next run (before summer)

Performance degradation factors identified

- Improvement of electronics performance
- Improvement of energy resolution:
  - Improvement of HOLD precision
  - DAC adjustment of voltage level for each channel
- Improvement of timing resolution using alternative trigger or board with improved ASIC performance.

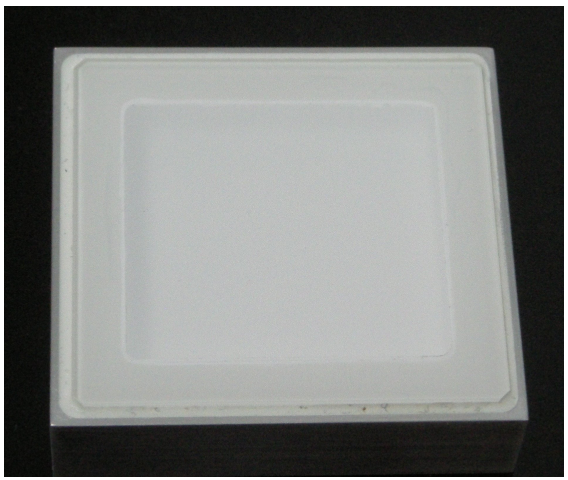
Simulation results:

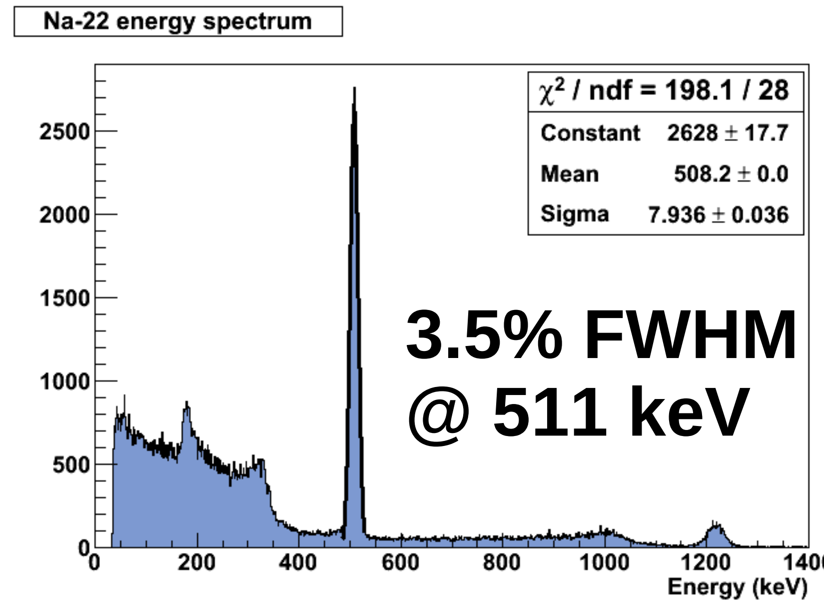


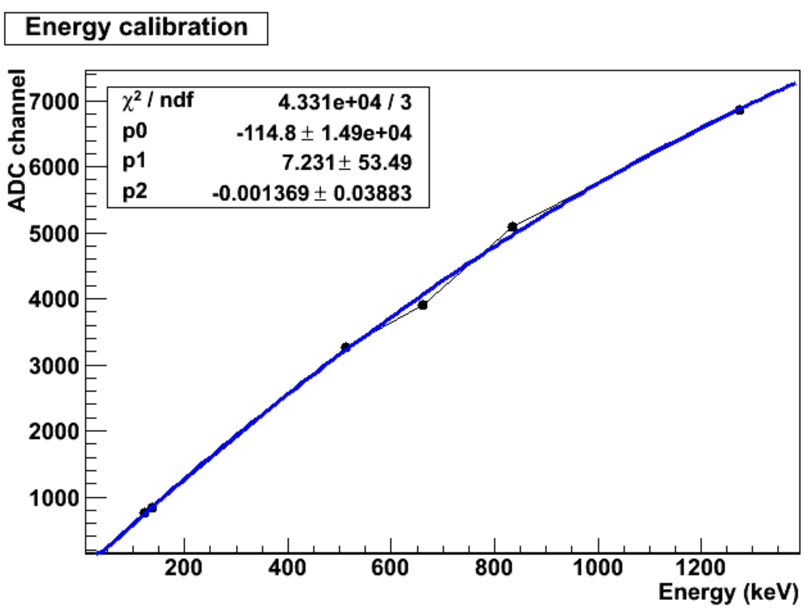
Development of larger detectors for the second prototype

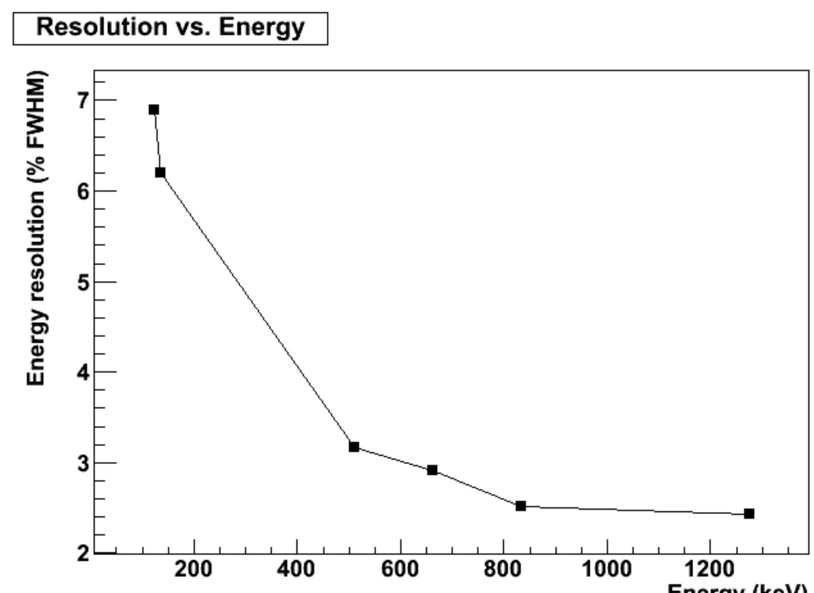
Development of larger detectors

- $LaBr_3$ crystals 32x36x 5/10mm^3.
- Tests with a PMT+ MCA



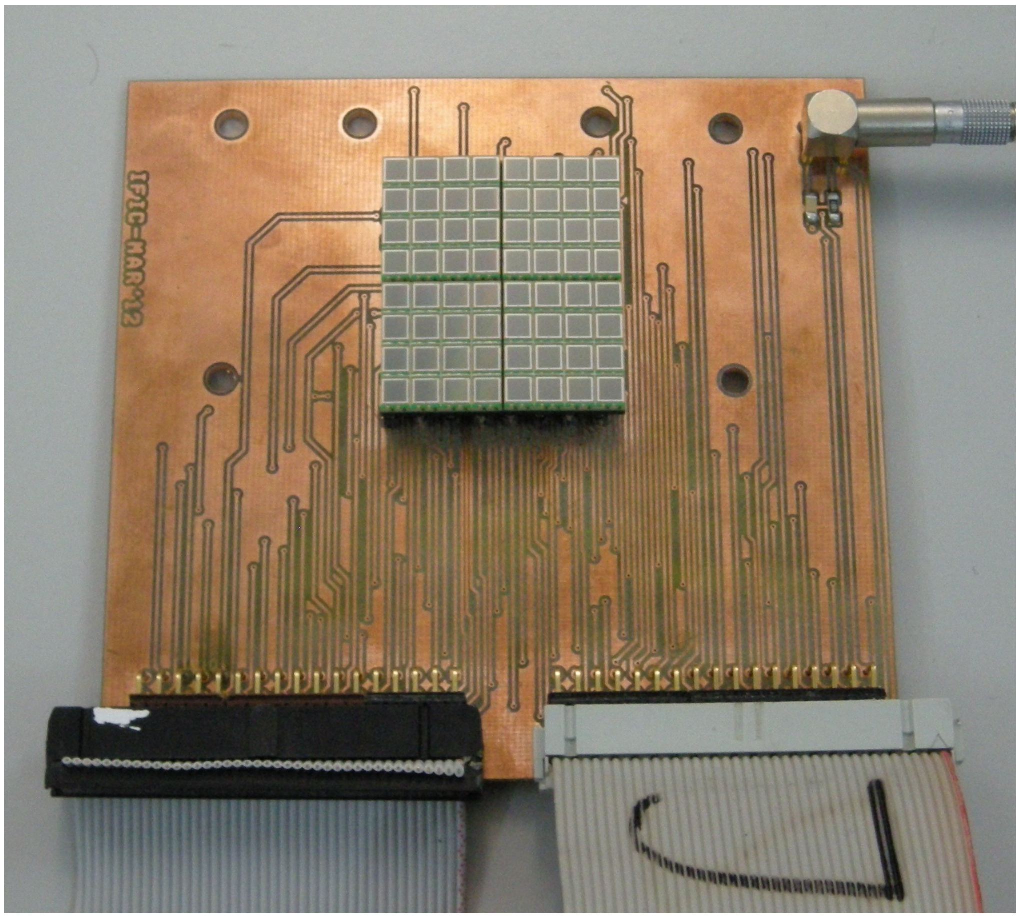






Large crystal readout

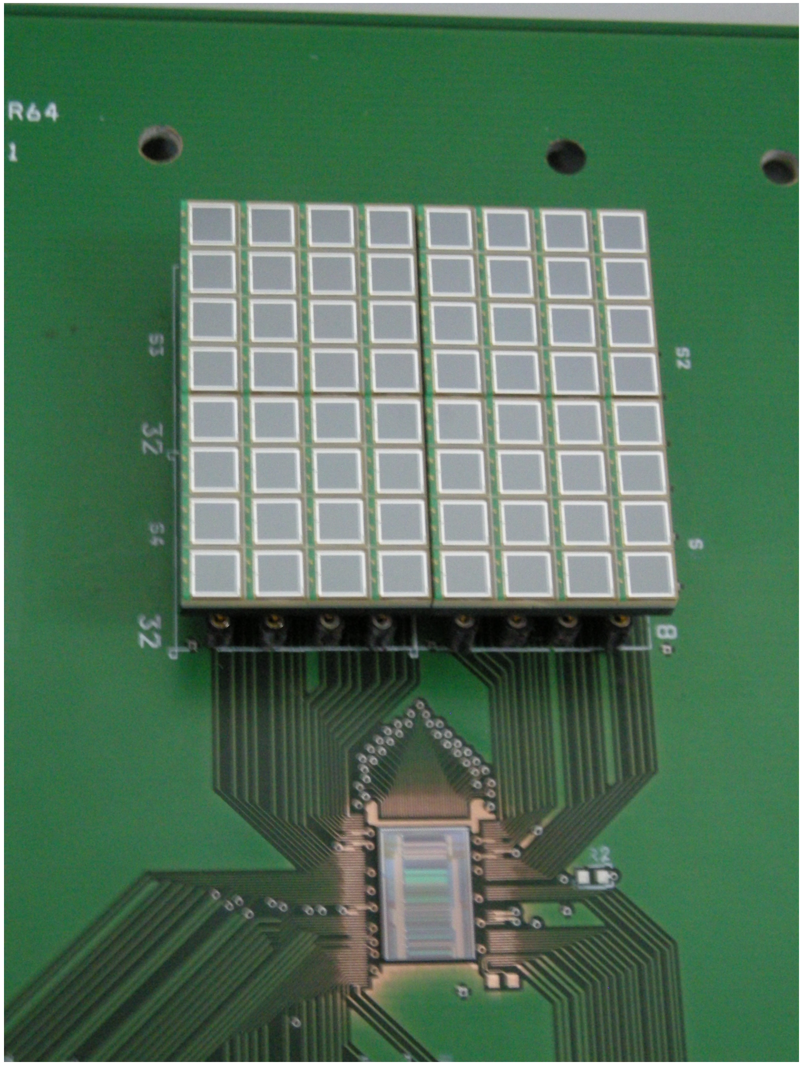
- Each crystal coupled to four MPPC arrays
- Tests with two readout systems

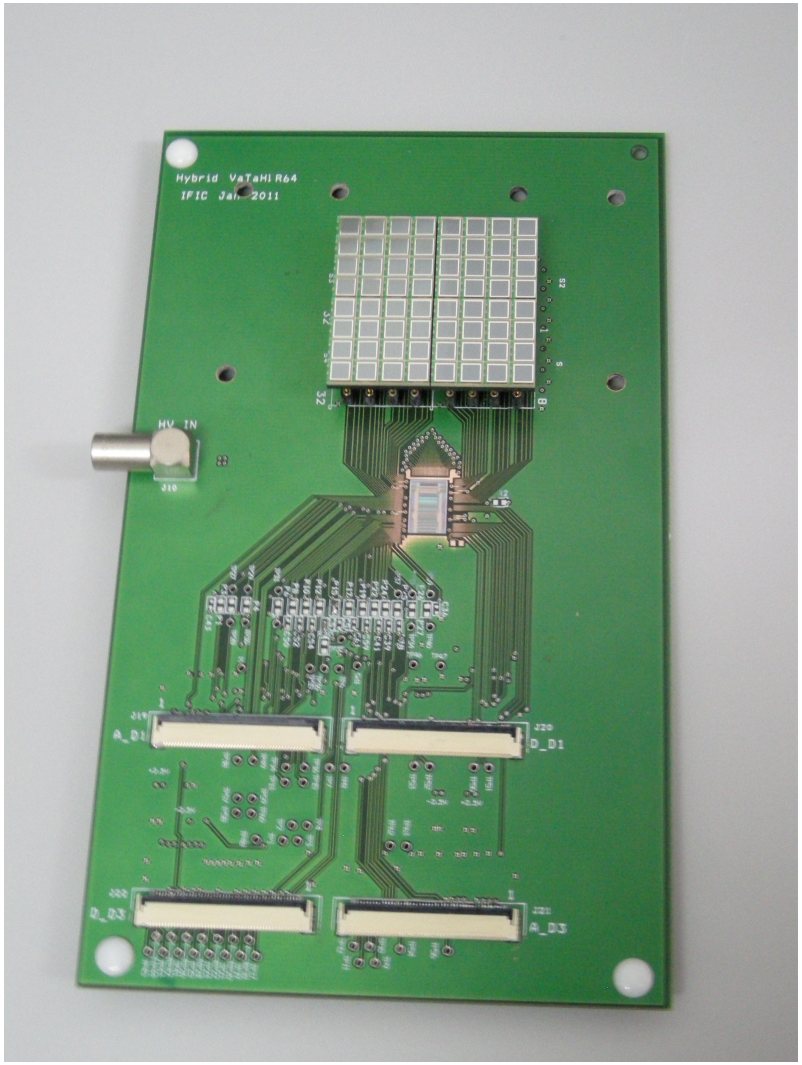


- Readout with two SPIROC / EASIROC ASICs.
- ASIC performance improvement carried out at LAL
- Tests with PCB connected to two SPIROC1 boards

Large crystal readout

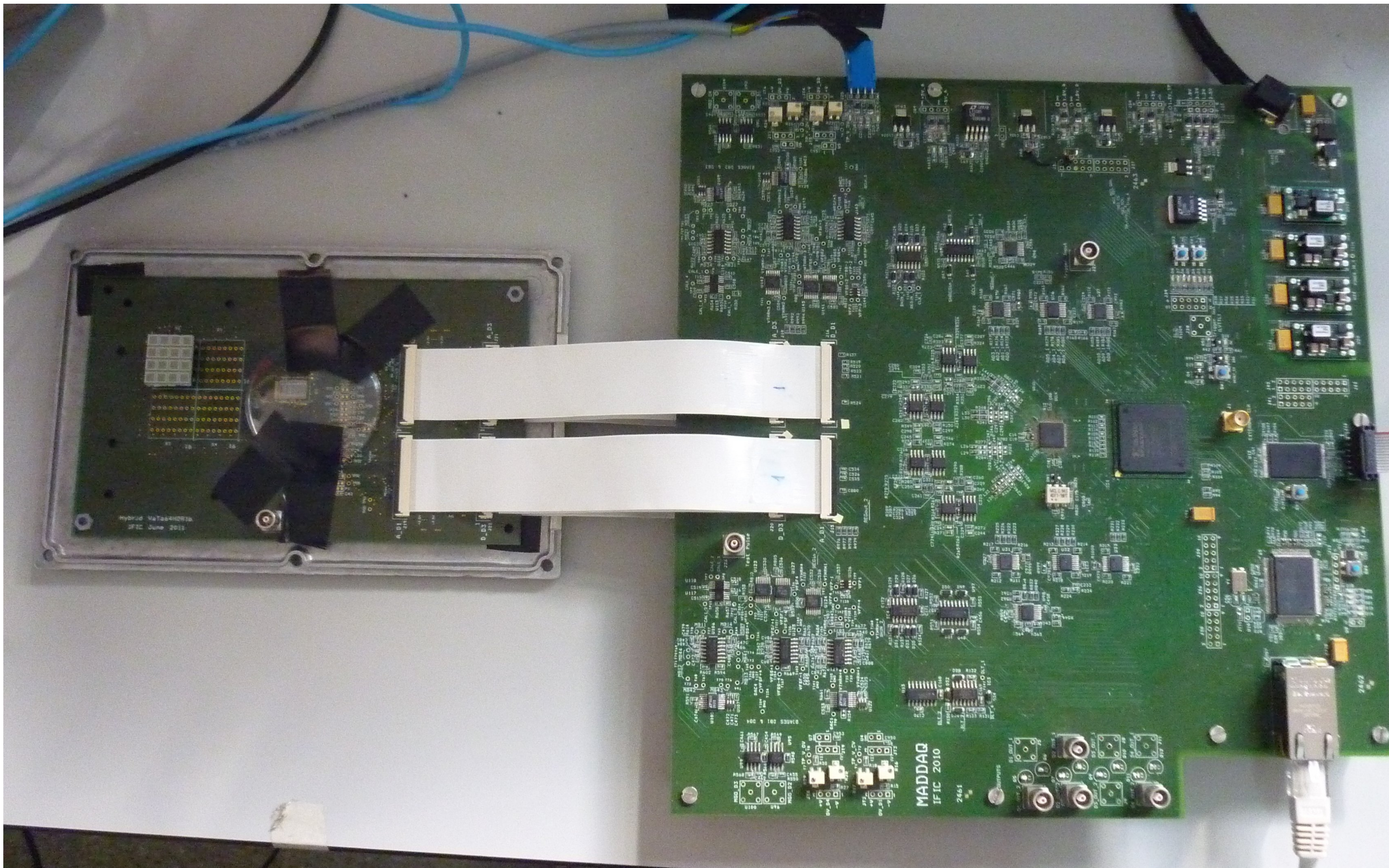
- VATA64HDR16 ASIC from IDEAS



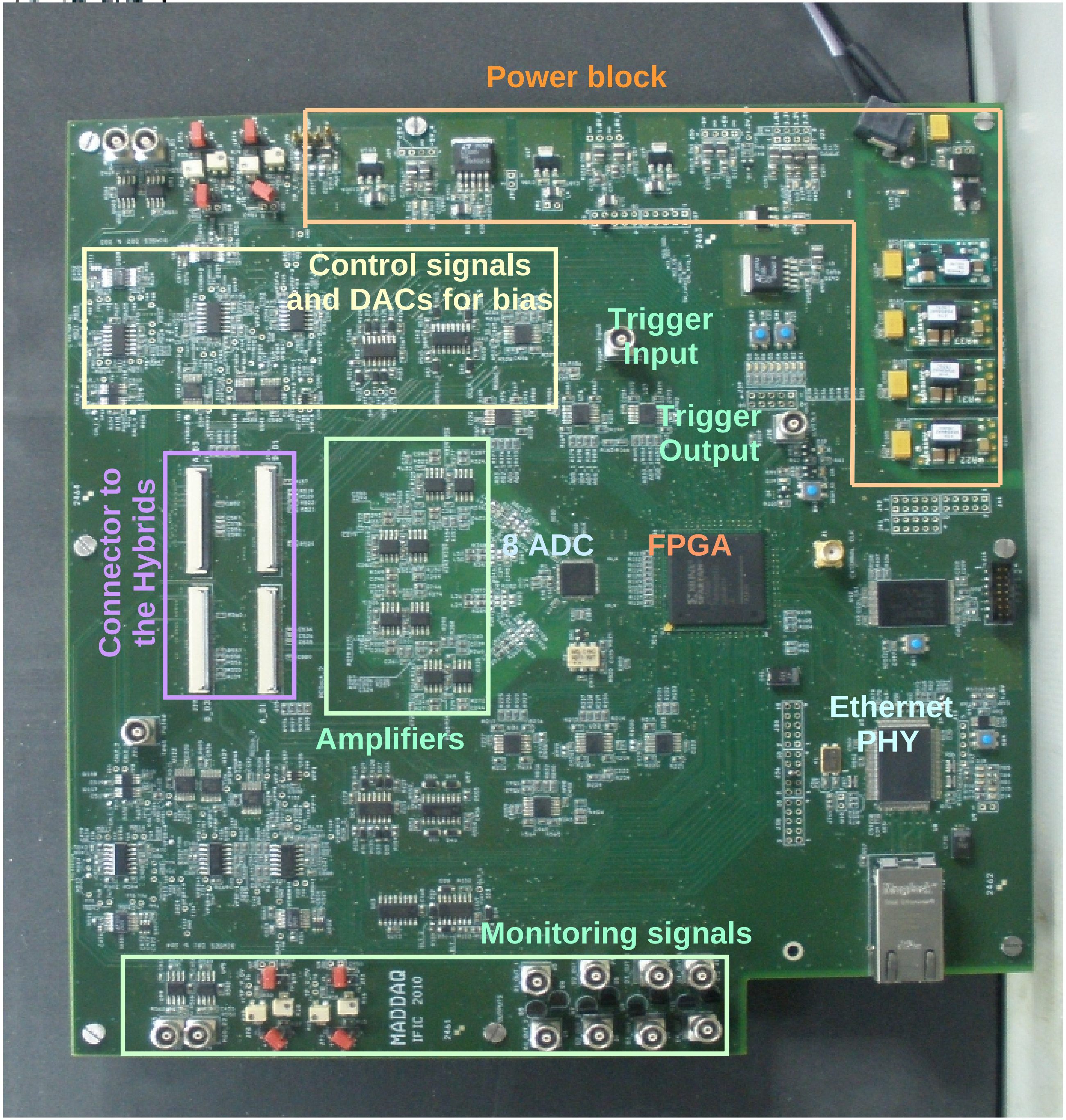


Large crystal readout

- Connected to a DAQ system developed in Valencia



DAQ system



Modular and flexible design

FPGA Xilinx

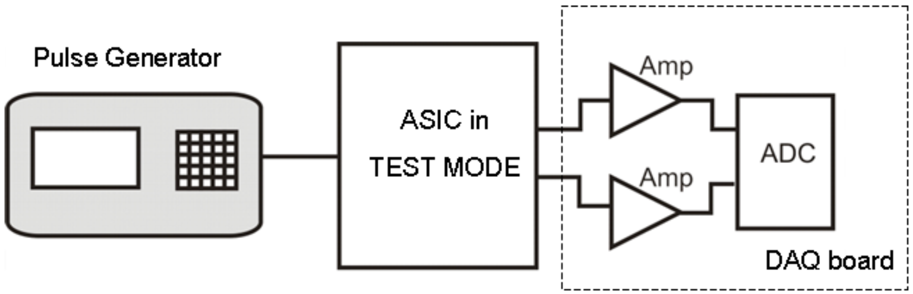
Fast data transfer: Ethernet (up to 1 Gbps)

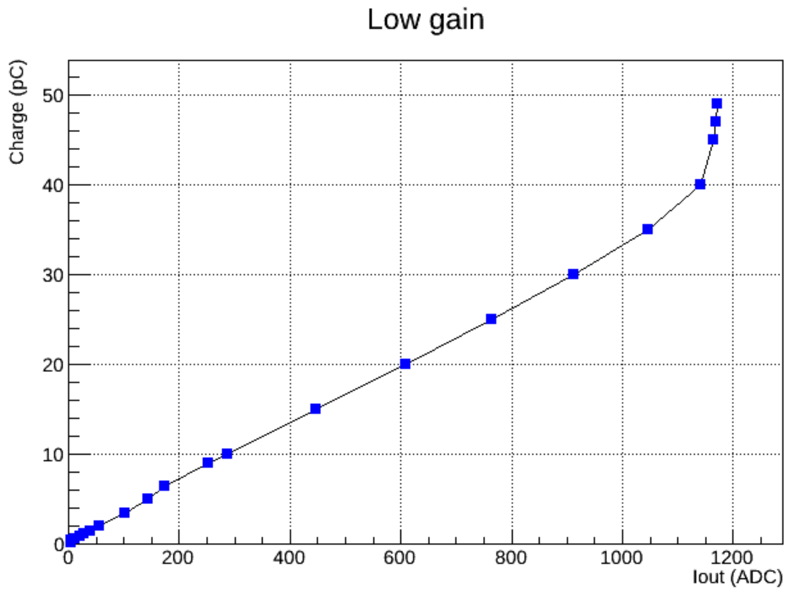
Time stamp with 1 ns resolution

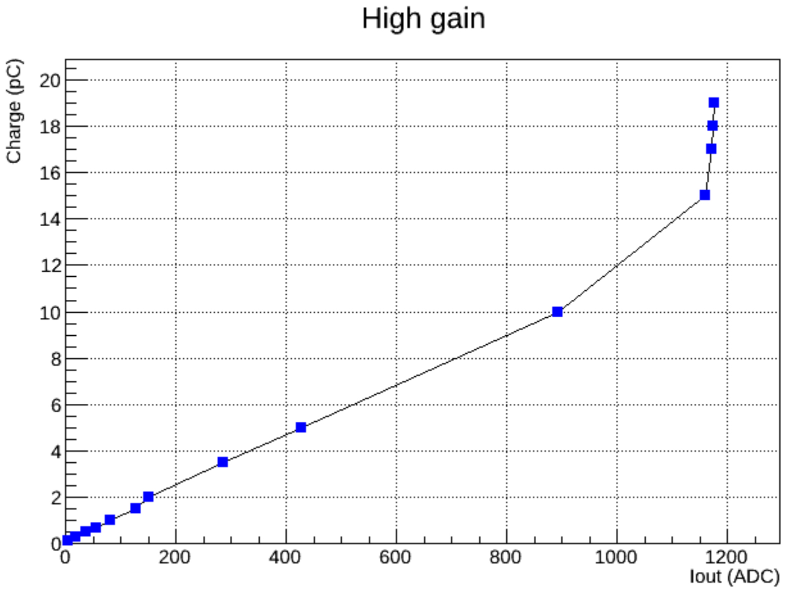
Several boards can work in time coincidence

First results

- Calibration with pulse generator: linear response up to ~30-35 pC in low gain.

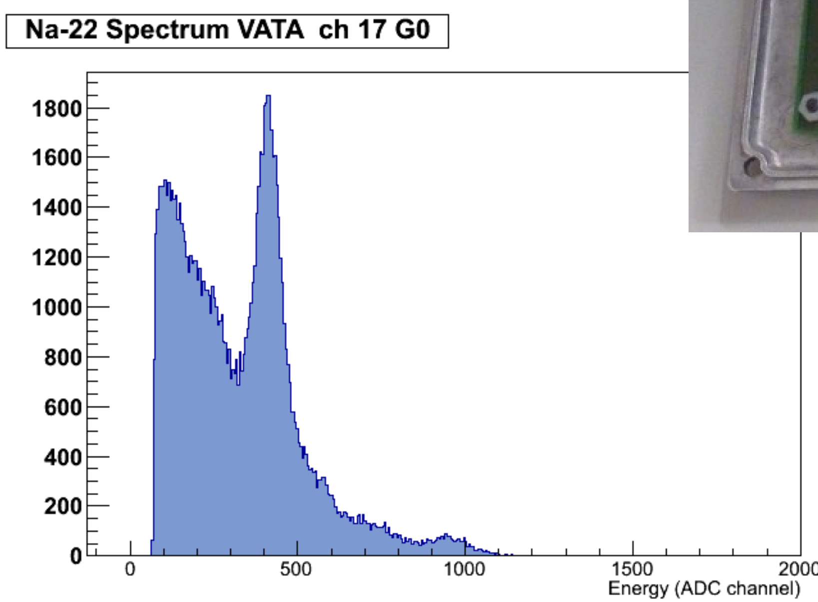






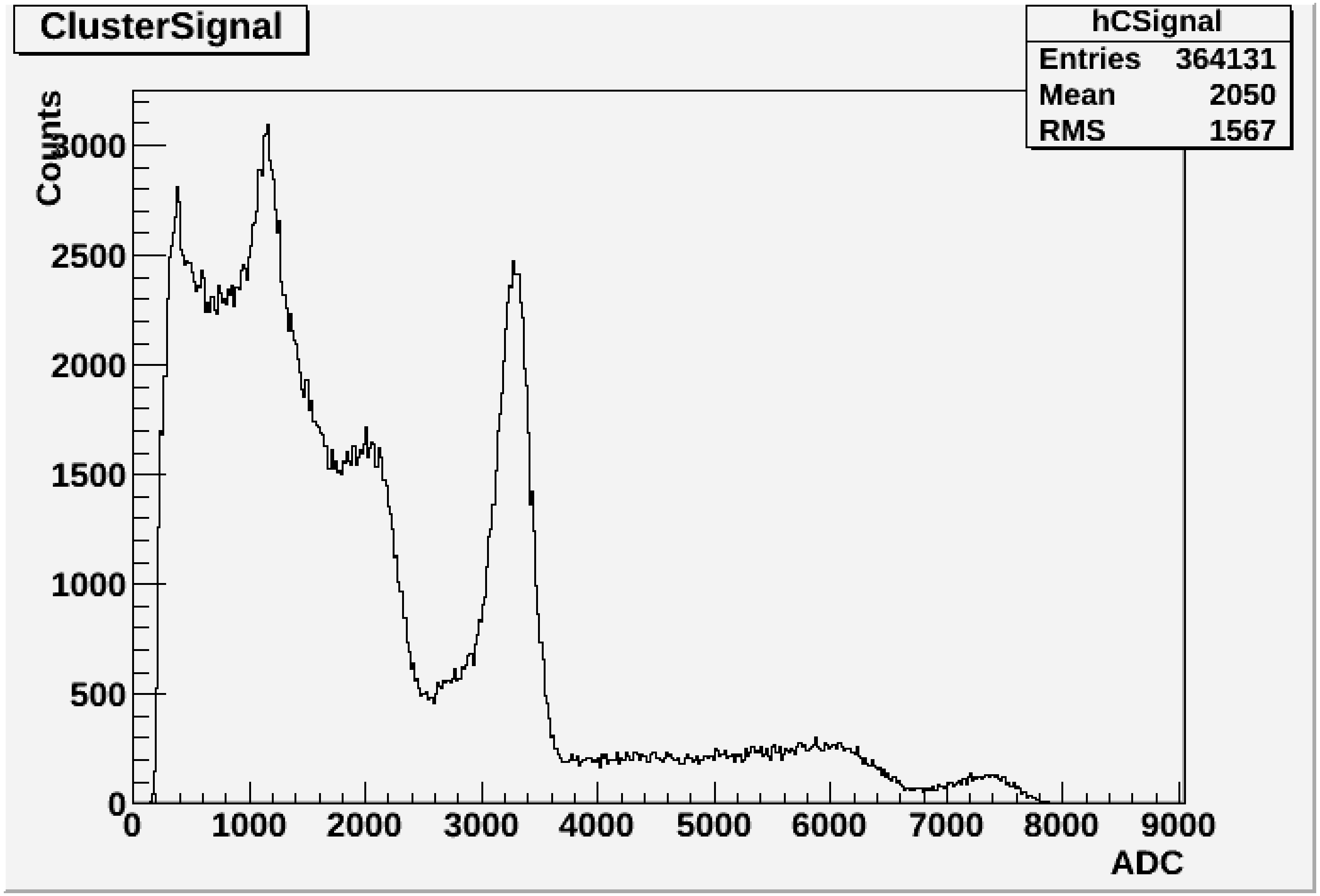
First results

- First tests with MPPCs and scintillator crystals successfully working. Na-22 spectra acquired.



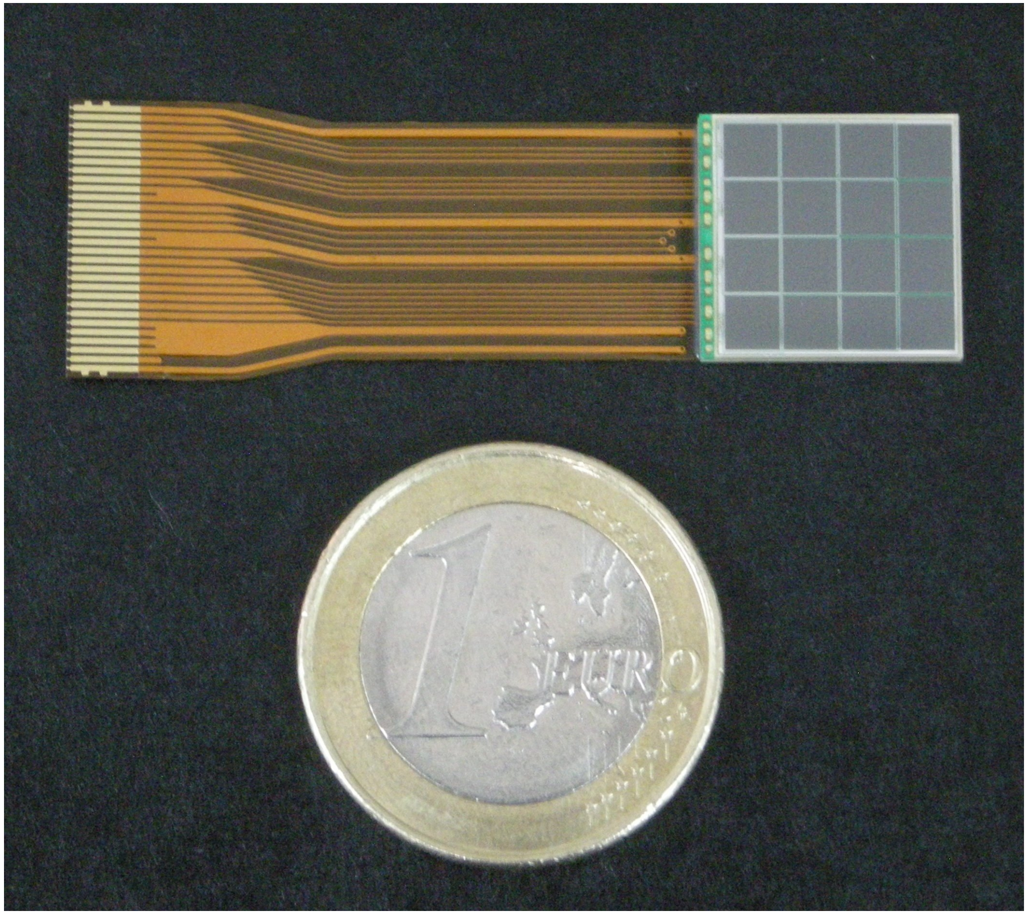
First Results

- Na-22 spectrum with a continuous $LaBr_3$ crystal coupled to an MPPC array with 16 elements (low gain).



New MPPC arrays

- Much less dead area. Better energy resolution.
- Smaller detector: 27.2 x 28.6 mm^2 with four arrays.



Conclusions

- First Compton telescope prototype with continuous $LaBr_3$ crystals and SiPMs developed.
- Images of Na-22 point sources in different positions successfully reconstructed.
- Performance degradation factors identified. On the way to be solved.
- Prototype optimization ongoing for performance estimation run.
- Development of larger detectors for the second prototype on the way.
- Two readout systems being evaluated for this application.

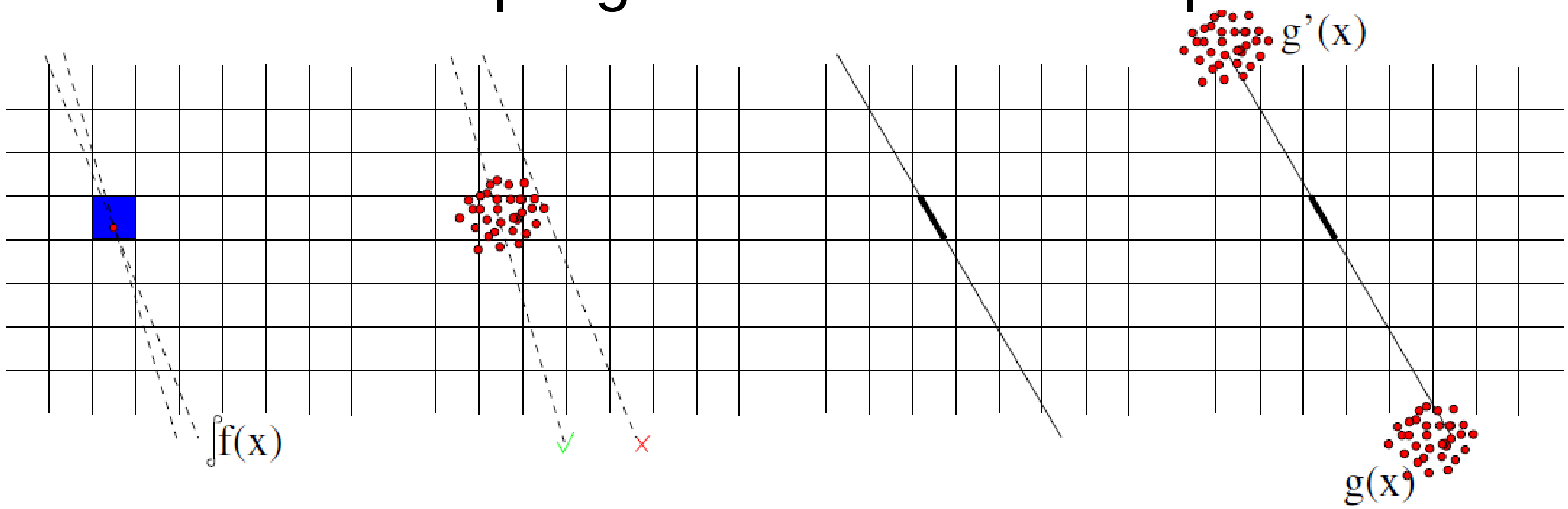
Acknowledgment

- 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 Economy and competitivity (FPA2010-14891).
- Several group members are supported through the Juan de la Cierva (CSIC), JAE-DOC (CSIC) and Atracció de Talent (UV) programs.

Thank you! Questions?

Image reconstruction with SOPL

- Random Sampling in Measurement Space



Monte-Carlo Calculation

•Highly accurate physics models.
•Computation time scales like statistics (assuming set cuts/steps etc.).
•Monte-Carlo approaches decouple computational effort from model accuracy.

SOPL: A Hybrid approach to system matrix calculation:

•Ray-ensemble (Fast-analytic).
•MC sampling of PDF (Fast-simulation).
•Requires extension for Compton image reconstruction