Characterization and test beam results of a LaBr$_3$ Compton telescope for treatment monitoring

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IRIS group: **I**mage **R**econstruction, **I**nstrumentation and **S**imulations in medical applications.

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

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International Conference on Translational Research in Radio-Oncology | Physics for Health in Europe.

Gabriela Llosá   ICTR-PHE 2016, Geneva 15-19 February 2016.   1
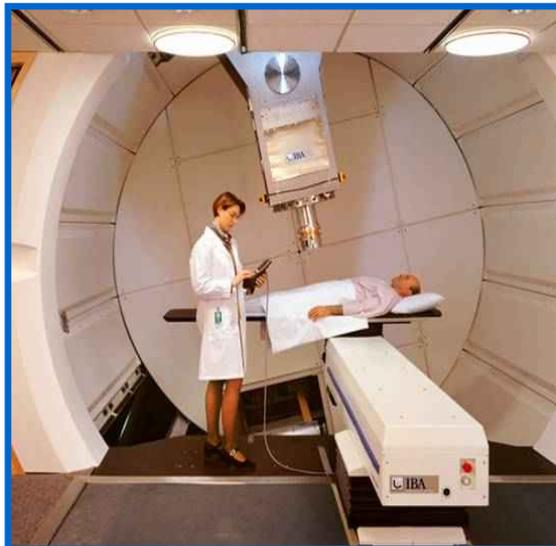
Hadron therapy

- Large benefit over conventional radiation therapies in some cases (ocular tumours, children, organs at risk, radioresistant tumours).

- Higher relative biological effectiveness (RBE) than photons.

- Precise delivery to tumour area => increase of cure rates and reduction of side and long term effects and secondary cancer.

photons **Protons**

70 Gy

20 Gy
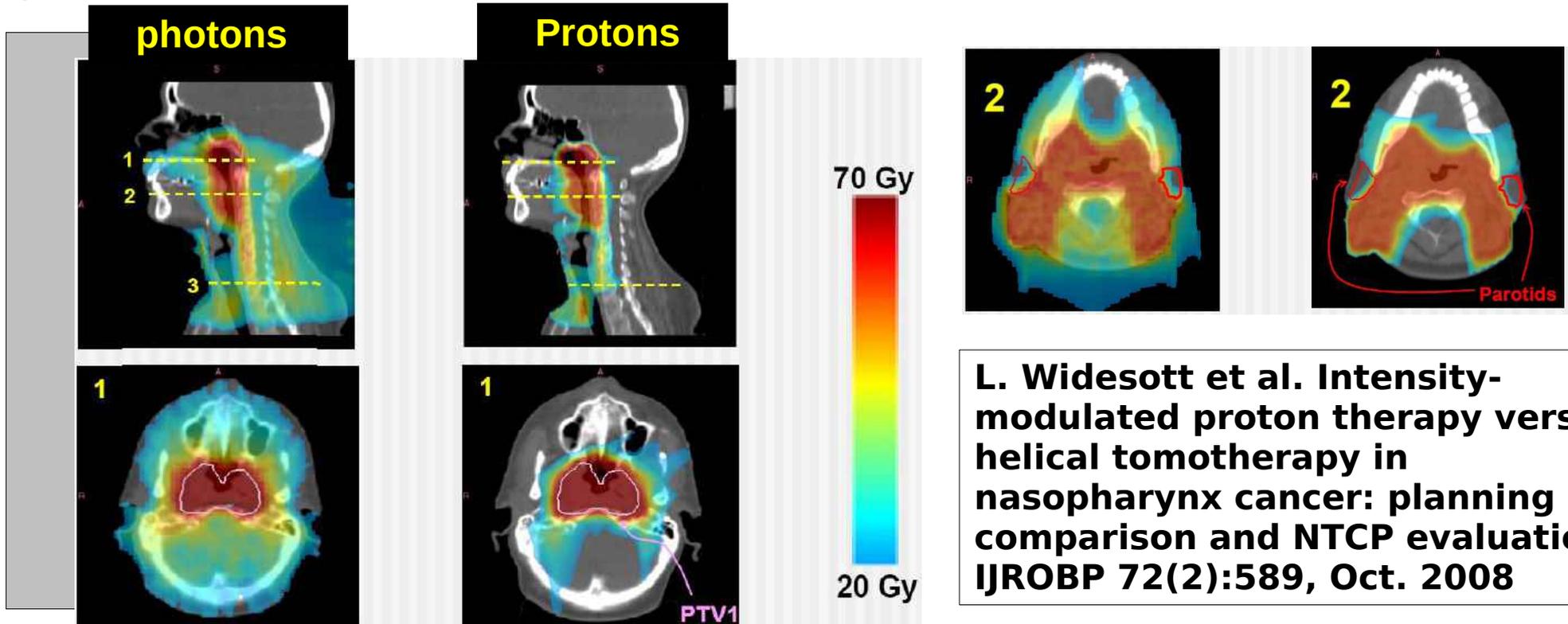
L. Widesott et al. Intensity-modulated proton therapy versus helical tomotherapy in nasopharynx cancer: planning comparison and NTCP evaluation. IJROBP 72(2):589, Oct. 2008

Dose monitoring in hadron therapy

- PROBLEM: the dose administered can not be directly measured (as done in conventional radiotherapy).

- Secondary particles emitted during treatment can be used for monitoring the dose delivery. Essential:

  - To verify dose delivery and correct for treatment deviations.

  - To reduce safety margins and better exploit hadron therapy.

- Positron Emission Tomography (PET) + MC currently employed. β+ emission is correlated with the dose.

Dose monitoring in hadron therapy

- Dose verification with PET:

  Comparison of dose planned and estimated from detected β+ activity.
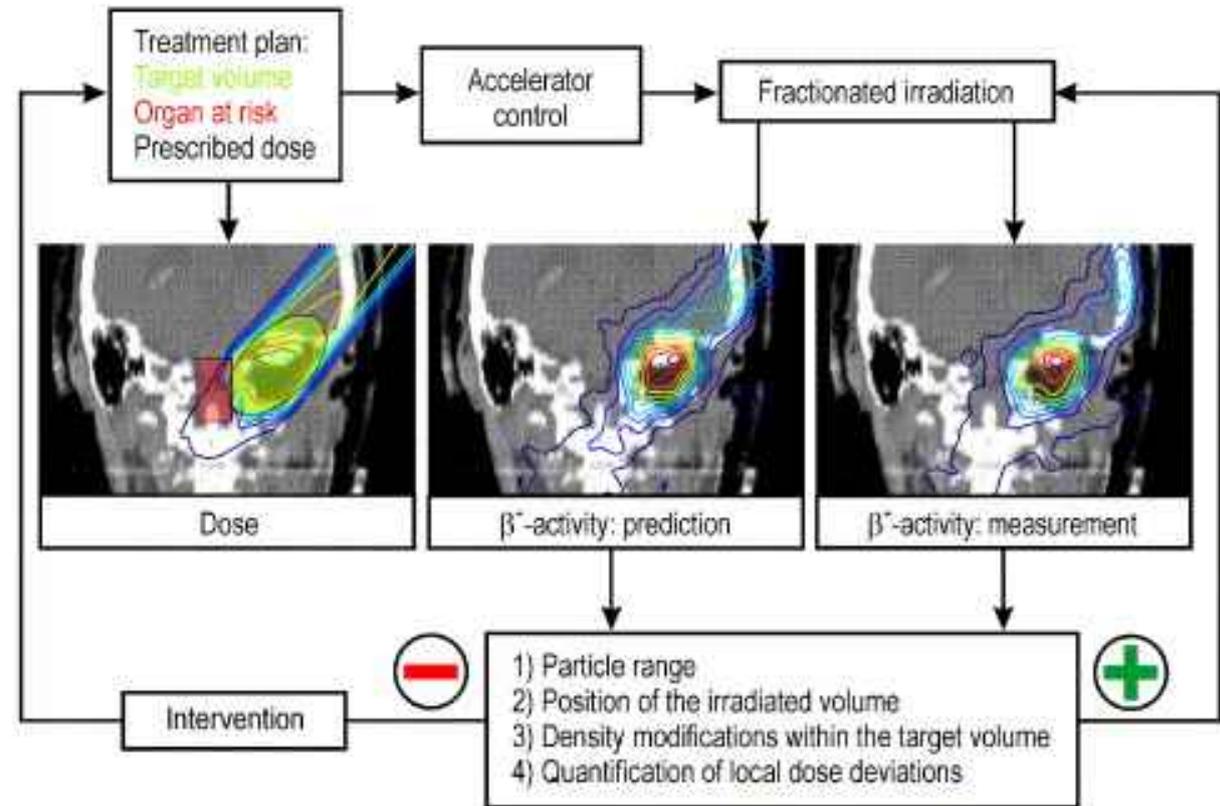
- PET Limitations:
  - Positron production does not follow irradiation immediately
  - Biological washout- activity carried away by metabolic processes
  - Low amount of β+ activity induced- low efficiency
  - Difficult online studies – partial ring
 - Photons produce significant background

ROOM FOR IMPROVEMENT

Dose monitoring in hadron therapy

- ALTERNATIVE: prompt gammas also emitted from nuclei excited during therapy and can be used for this purpose.

  - Emission correlated with dose.

  - Emission ~ns after irradiation.

  - ~ 7 times more particles/cGy than positrons.

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

Research on collimated and Compton cameras for gamma detection

Proton treatment plan   Emission of gammas
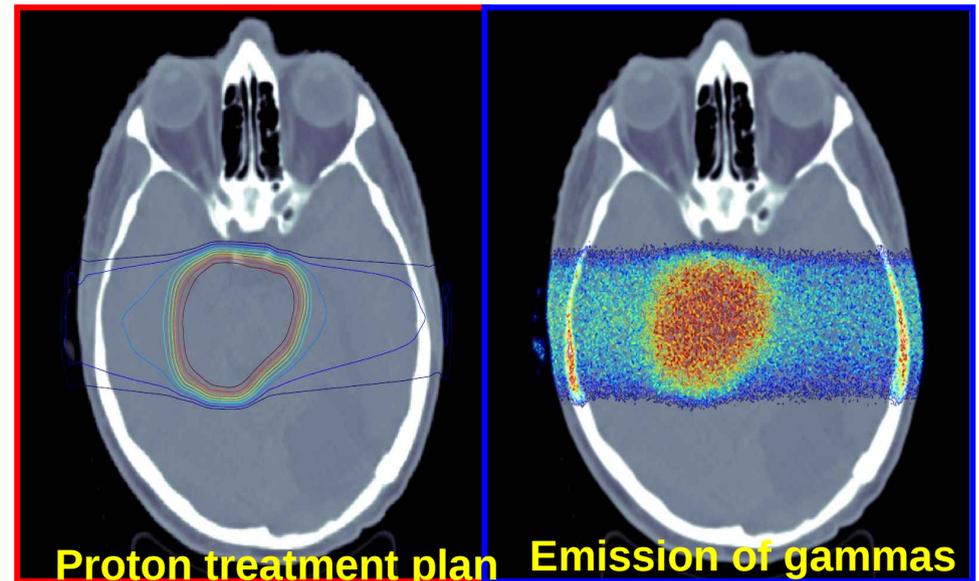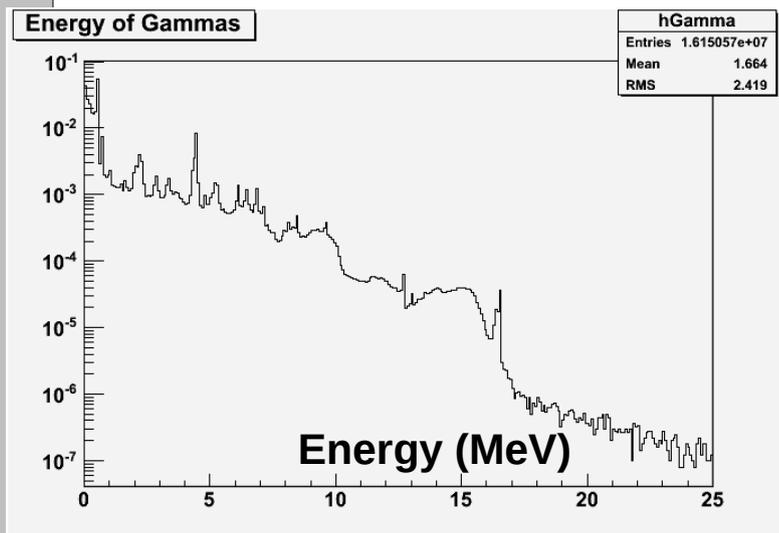
Compton camera configuration
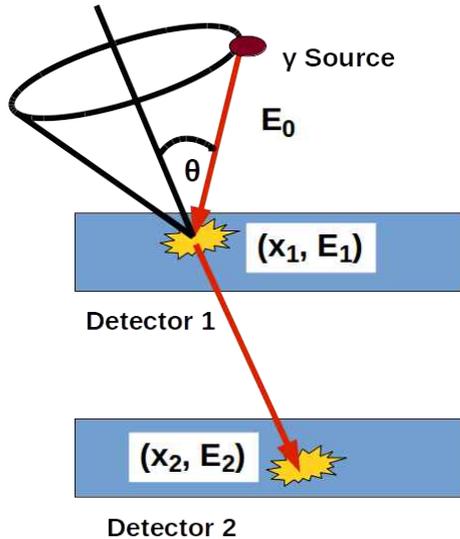
Scatterer + absorber: 2 interactions

Problems if the photon energy is unknown or if it can escape (MeV)

$$cos\theta = 1 - m_0 c^2 \left(\frac{1}{E_0 - E_e} - \frac{1}{E_0} \right)$$
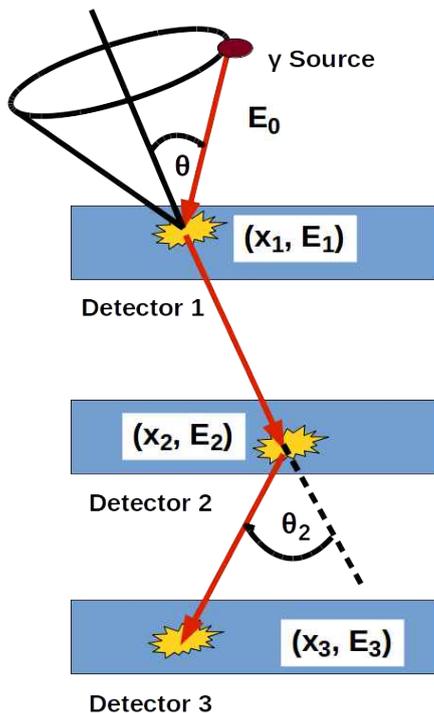
Multilayer: 3 interactions in 3 detectors (+ correct ordering):

- Energy determined

- lower efficiency

$$\cos(\theta) = 1 - \frac{E_1 m_e c^2}{E_0(E_0 - E_1)}$$

$$E_0 = E_1 + \frac{1}{2}\left(E_2 + \sqrt{E_2^2 + 4\frac{E_2 m_e c^2}{1 - \cos\theta_2}} \right)$$

Compton telescope prototype at IFIC

- (More than) three detector layers:

    - Continuous LaBr$_3$ crystals.

    - SiPM arrays.

- Combination of :

    - 2 int events (high efficiency) +

    - 3 int events (high resolution).

- Method to estimate both position and energy simultaneously from 2- interaction events for image reconstruction.

NO ABSORPTION REQUIRED

LaBr3 CRYSTALS
SIPM MATRICES
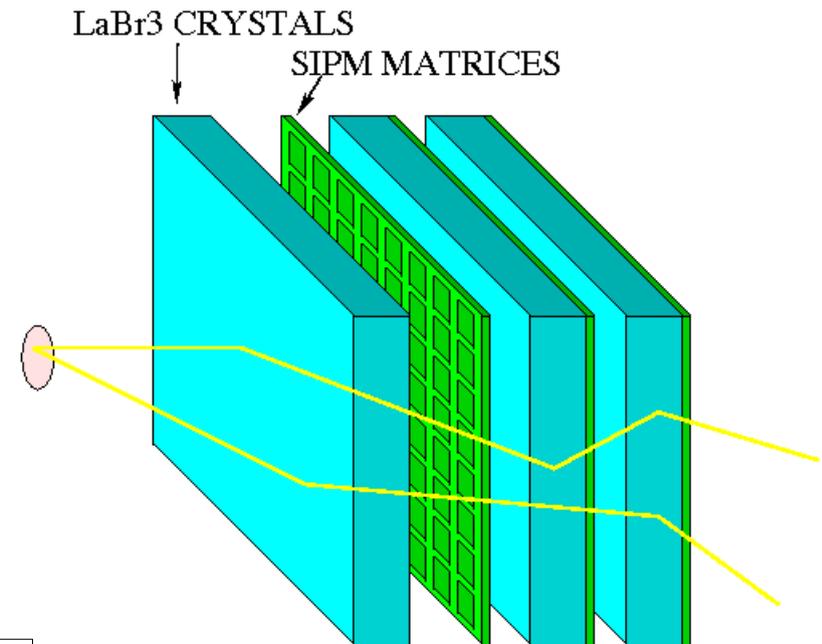
> **J. E. Gillam et al.**
> *A Compton Imaging Algorithm for On-line Monitoring in Hadron Therapy.*
> **Phys Med Im Vol. 7961. Paper 796110. (2011).**

Compton telescope prototype at IFIC

- LaBr$_3$ crystals coupled to SiPM arrays => simple assembly and operation.

LaBr$_3$ crystals	SiPM arrays
• High Compton probability • High light yield => good energy and timing resolution	• Compact • Fast
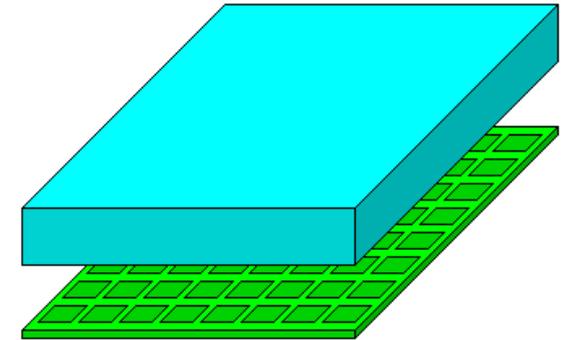
- Continuous crystal:

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

Three-layer prototype

Detectors 2 and 3

Detector 1

Crystals

- LaBr$_3$ crystals:

  - 27.2 x 26.8 x 5 mm^3.

  - 32.5 x 35 x 5 mm^3.

  - 32.5 x 35 x 10mm^3.

- Tests with a PMT+ MCA: Energy resolution **3.5% FWHM @ 511 keV**

Energy calibration

χ^2 / ndf	4.331e+04 / 3
p0	-114.8 ± 1.49e+04
p1	7.231 ± 53.49
p2	-0.001369 ± 0.03883
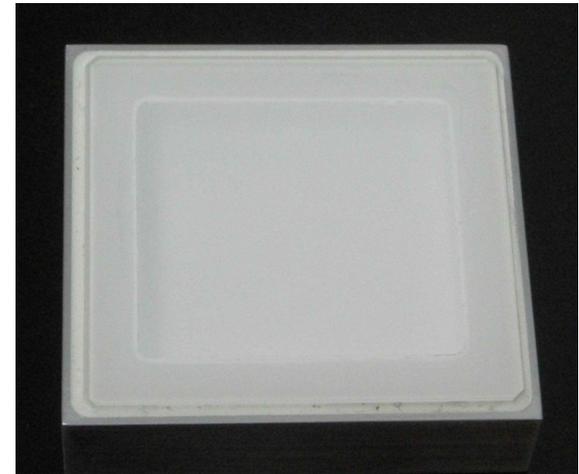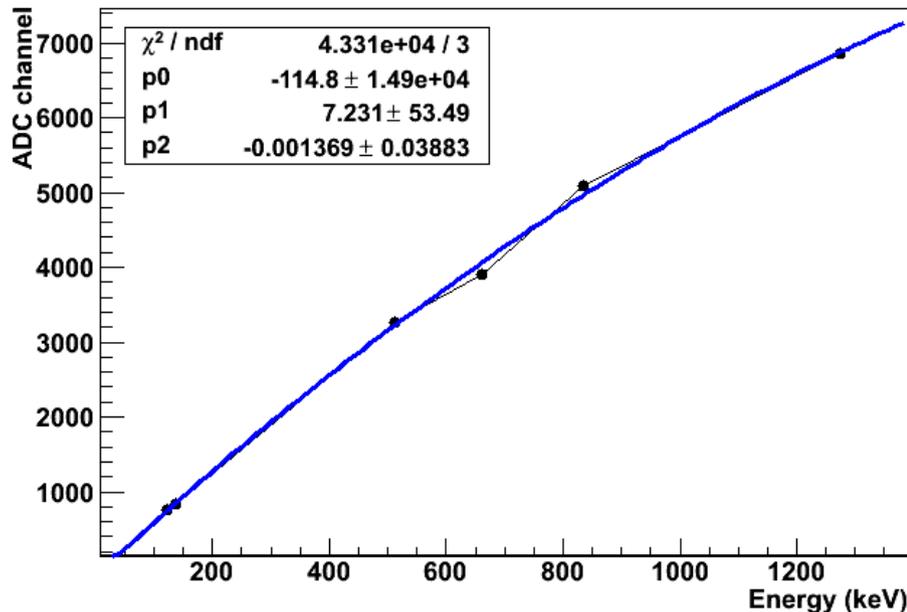
Resolution vs. Energy
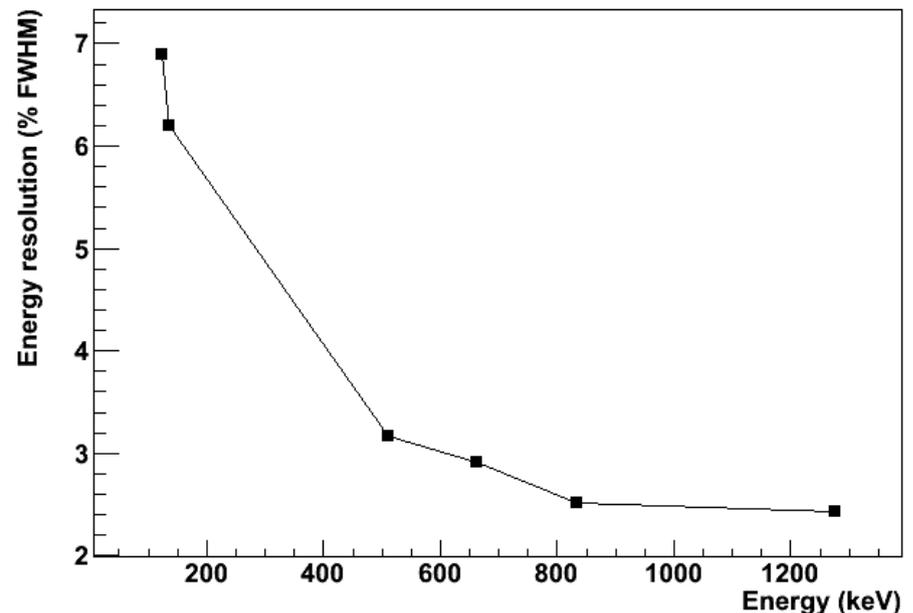
Detectors

Detector 1

Detectors 2 and 3

3 mm

18 mm

16 mm
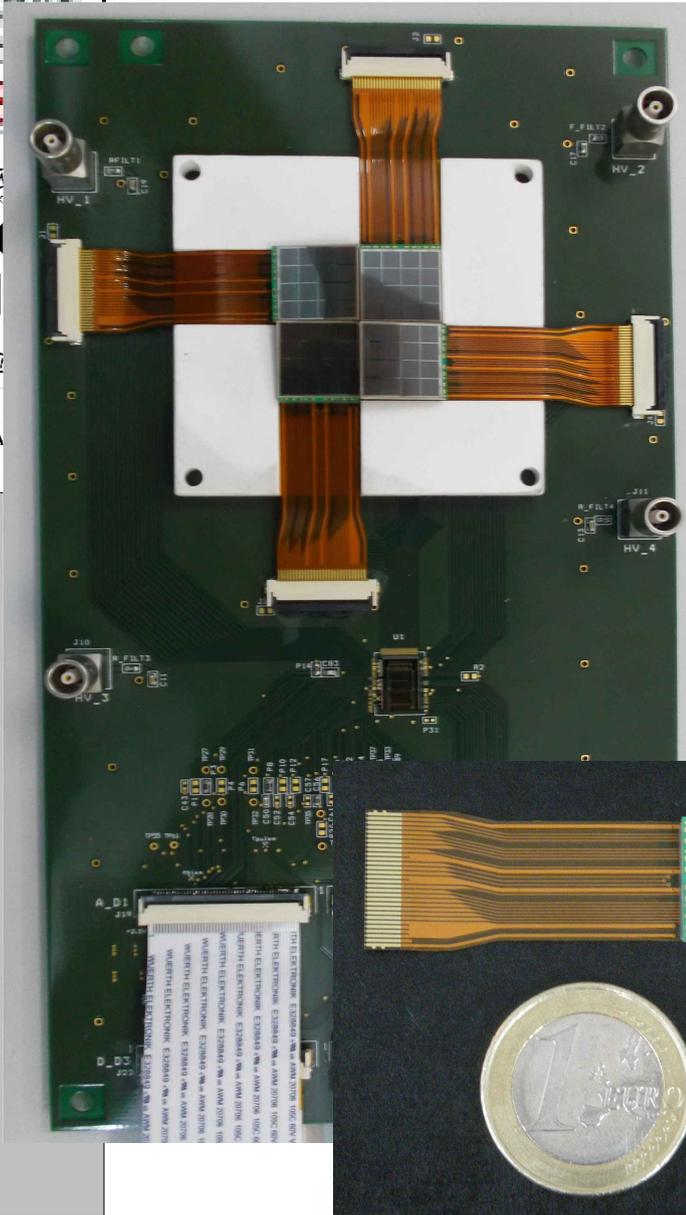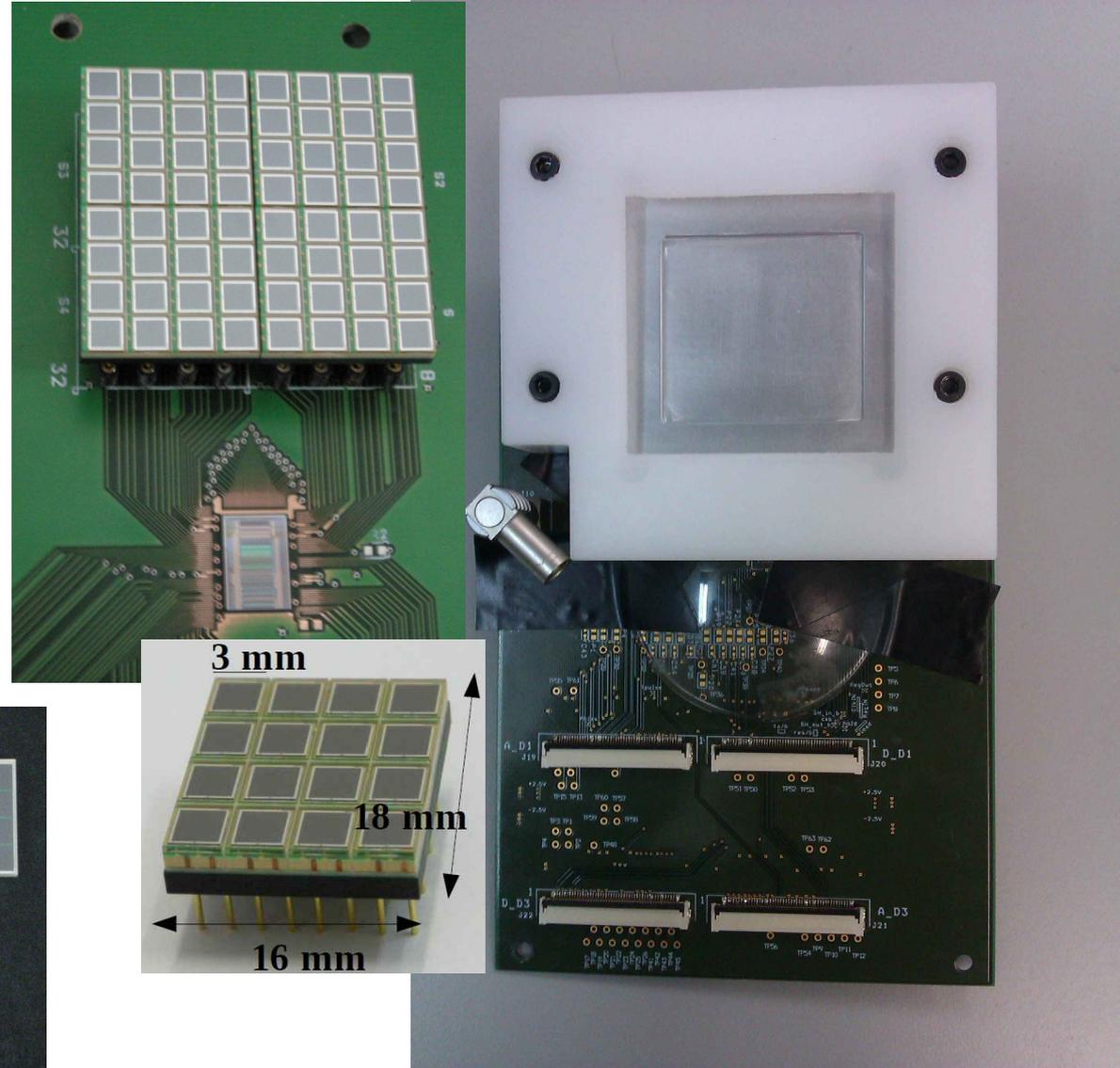
Temperature sensor attached to the board

Readout

- VATA64HDR16 ASIC from IDEAS – 64 channels.

- Connected to a DAQ system made at IFIC- Valencia.

- Compact and portable system.
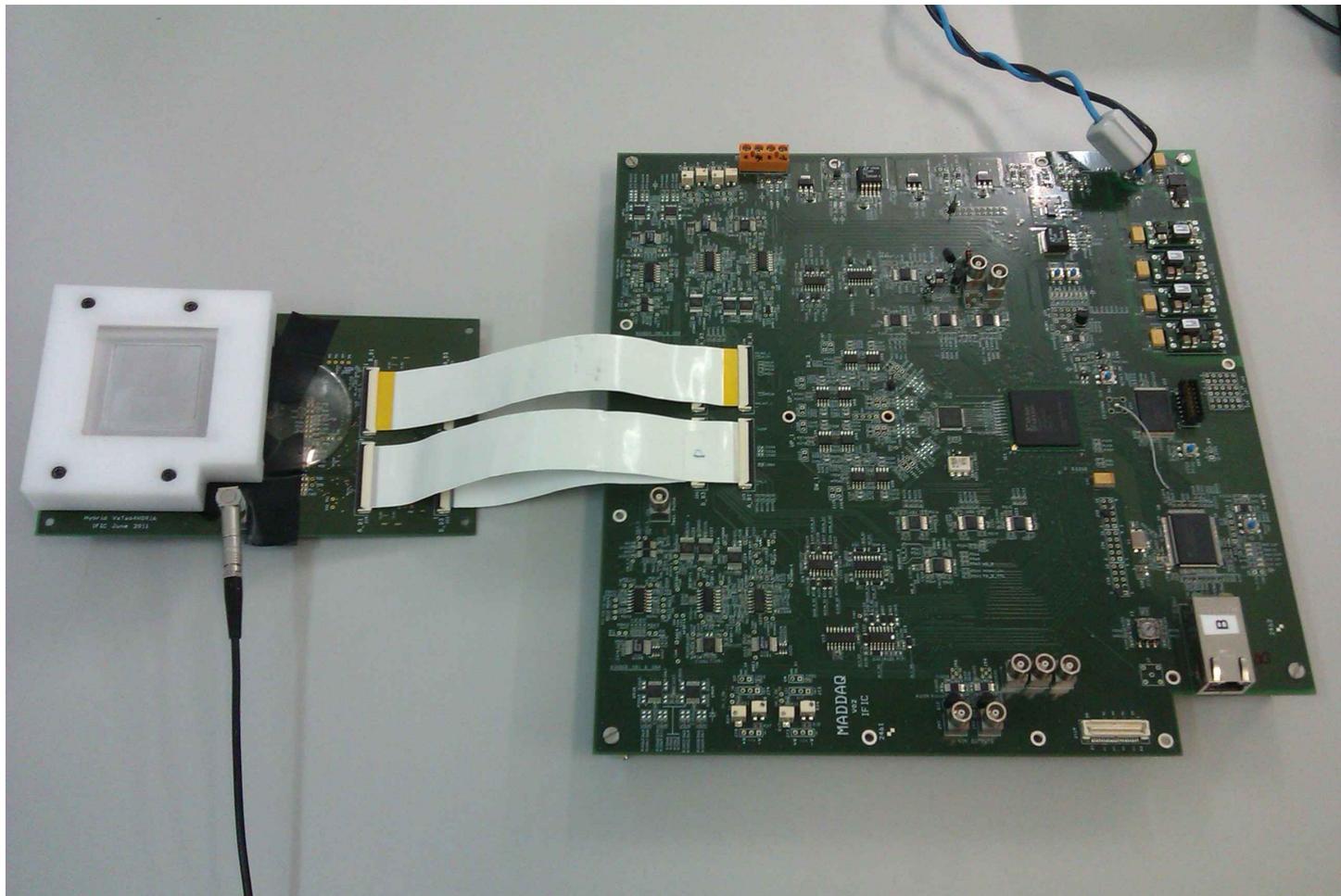
Coincidences board

- Coincidence board based on Xilinx Virtex® FPGA.

- Coincidences between any two or three planes.
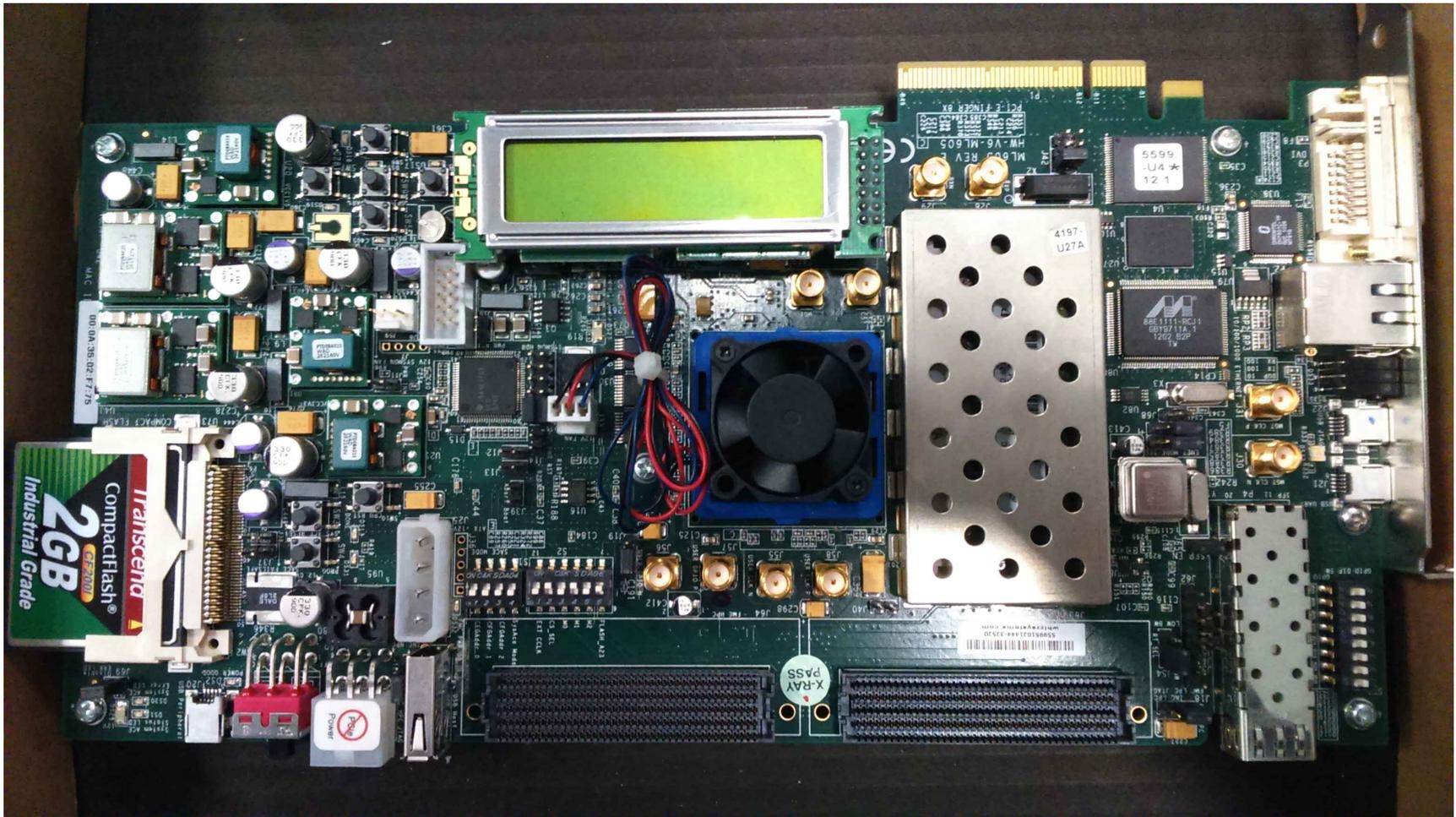
Prototype

- User-friendly DAQ software also developed at IFIC-Valencia.

Detector calibration

Detector 2

Fit to Calibrated Spectrum

hSpectrumCalib	
Entries	1024
Mean	429.2
RMS	319.5

Energy resolution: 7 % FWHM @ 511 keV

Position determination 5 mm

χ^2 / ndf = 3.141 / 7

Constant	83.29 ± 4.97
Mean	11.38 ± 0.03
Sigma	0.535 ± 0.030

Spatial resolution close to 1 mm FWHM with dedicated algorithm

1.25 mm FWHM

Hit Map[31]

Adjustment of individual bias through ASIC input DACs

PeakPos vs Temperature (21)

- 511 keV
- 1275 keV

Temperature calibration

Detector calibration

Detector 1

Co-57

Na-22

Co-60
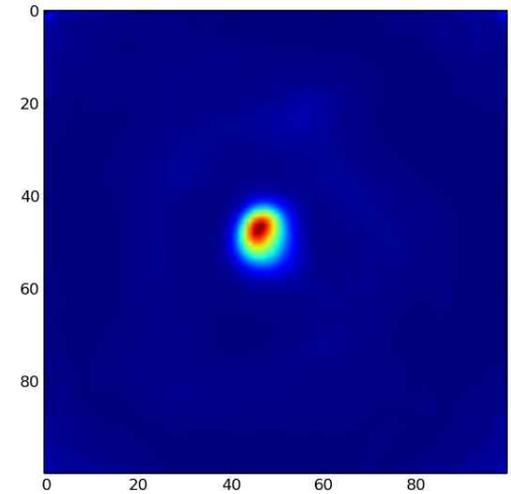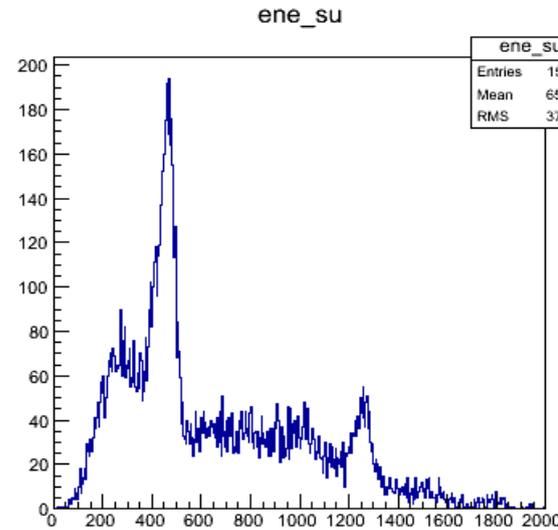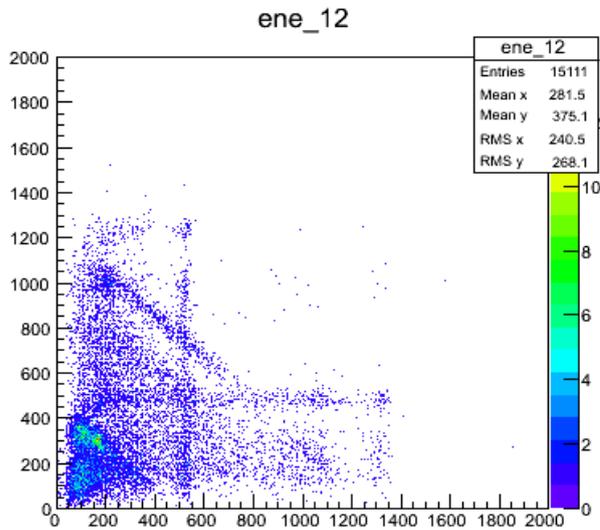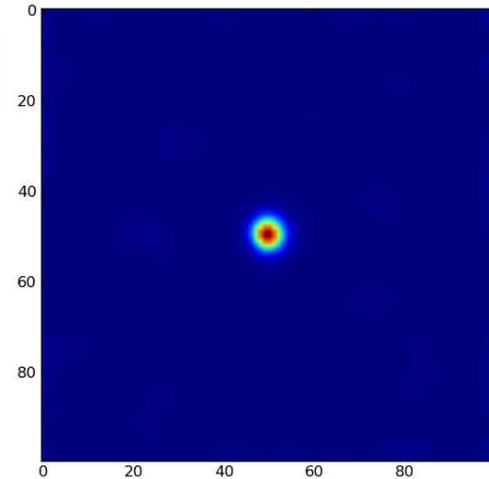
Detector calibration

Detector 1

Na-22 energy spectrum

χ^2 / ndf = 29.63 / 27	
Acalib	330.3 ± 5.7
posxcalib	515.3 ± 0.2
sigmacalib	13.32 ± 0.21

**Energy resolution:
6 % FWHM @ 511 keV**

Entries	4901
Mean	-3.936
RMS	5.753
χ^2 / ndf	5.463 / 12
Constant	120.6 ± 4.5
Mean	-5.419 ± 0.025
Sigma	0.5828 ± 0.0366

**Spatial resolution
close to 1 mm FWHM**

1.3 mm FWHM

Hit Map[11]

Better uniformity:
different bias per SiPM array +
adjustment of individual bias
through ASIC input DACs

PeakPos vs Temperature (11)
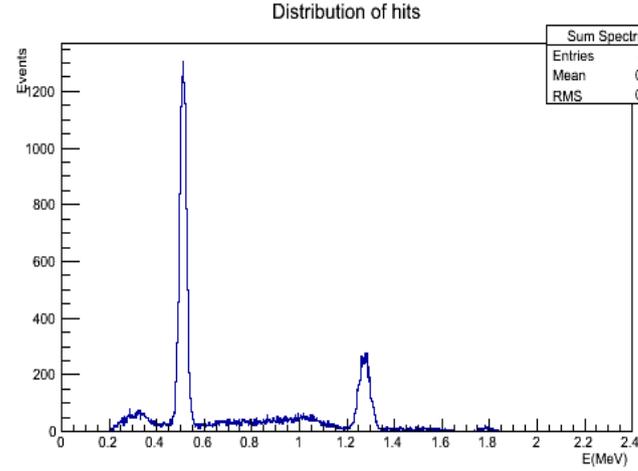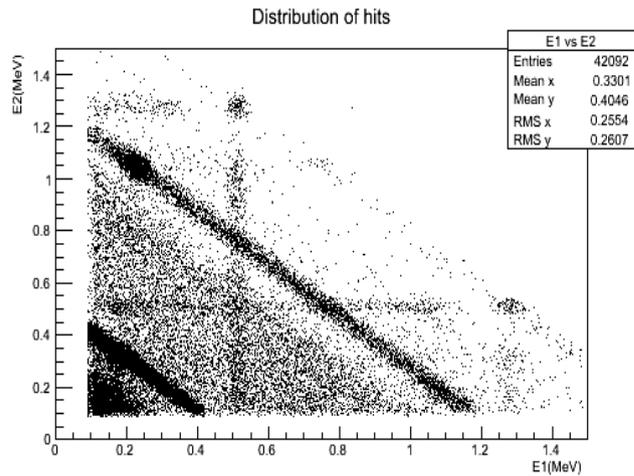
- 511 keV
- 1275 keV

**Temperature
calibration**
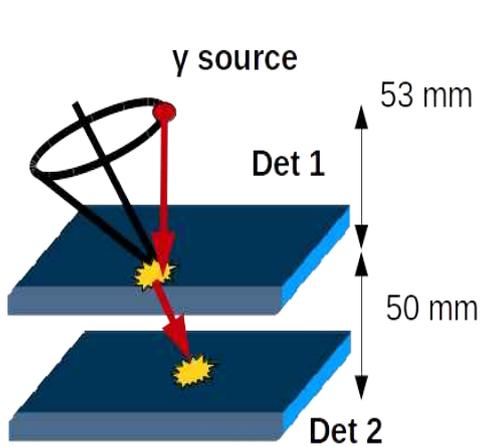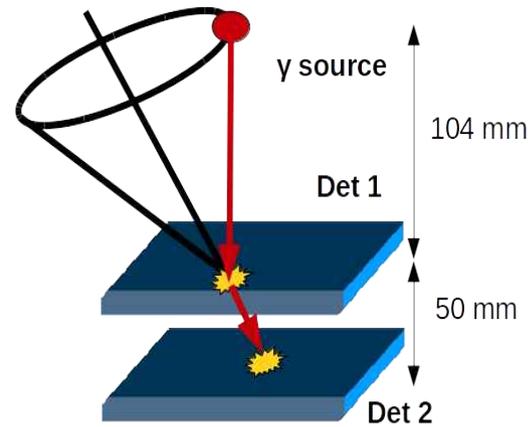
Results with two layers
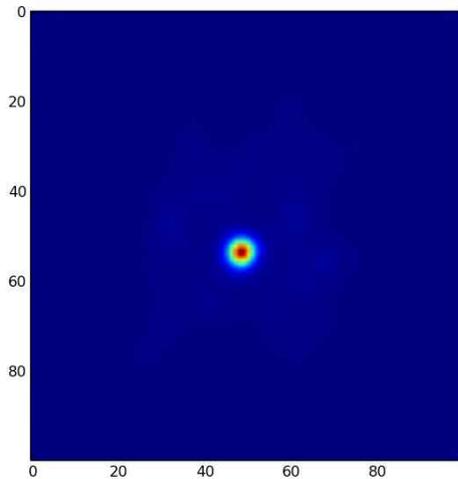
- Experimental data

- GATE simulations

Measurements in different configurations

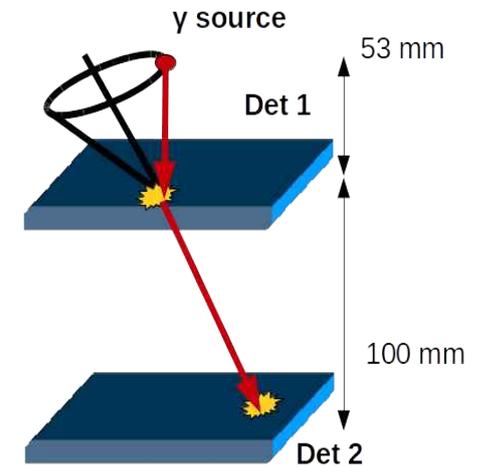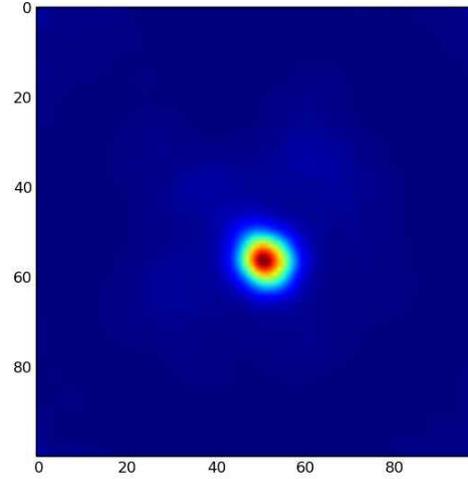- Spatial resolution depends on configuration.
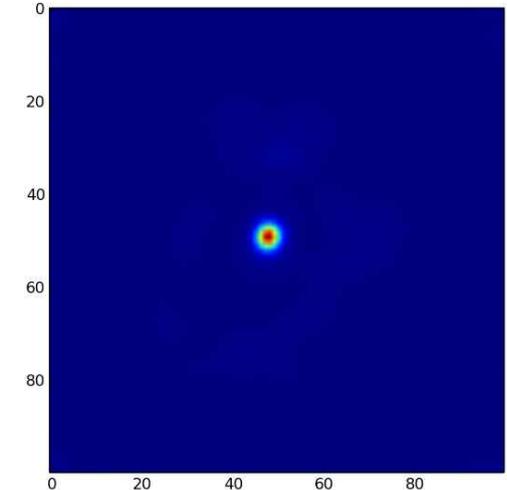
- Image reconstruction with ML-EM.

Results with two planes
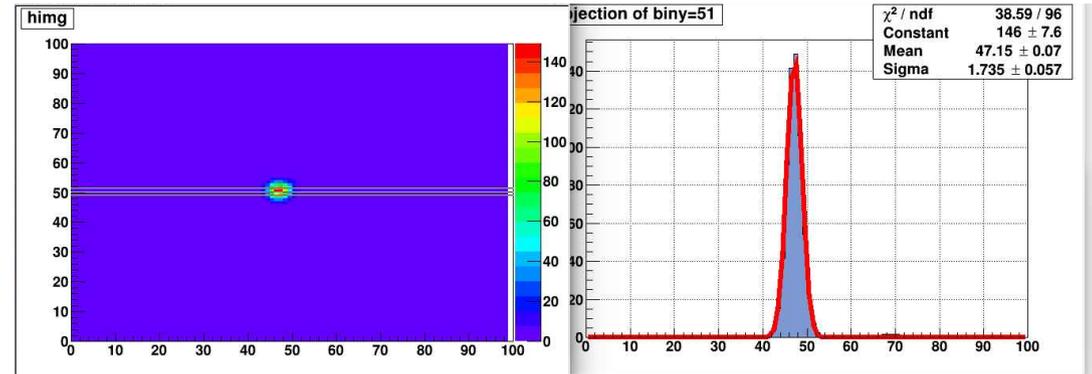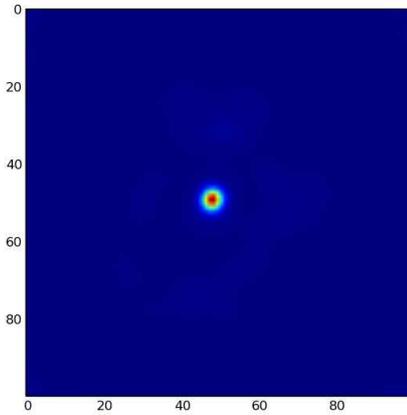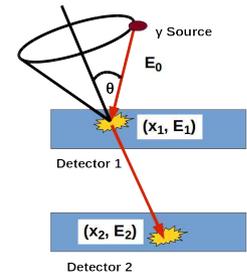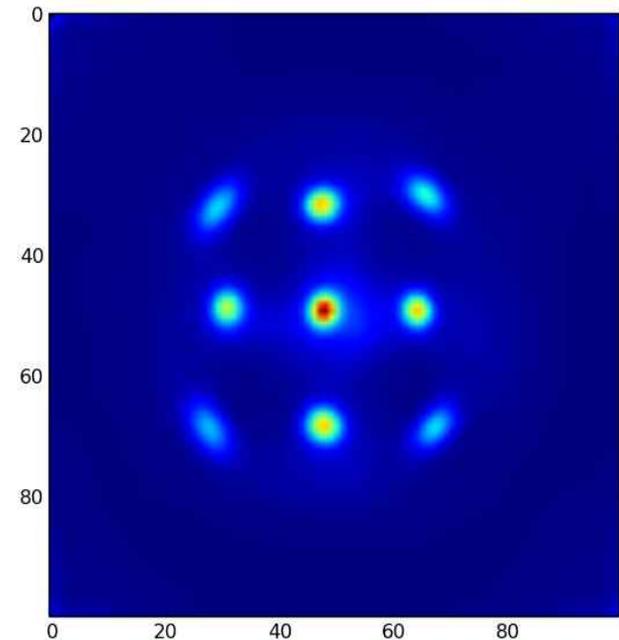
- Central position for config 3 (53 mm-100 mm).

- Selecting 1275 MeV peak

Gaussian fit to X profile through the maximum
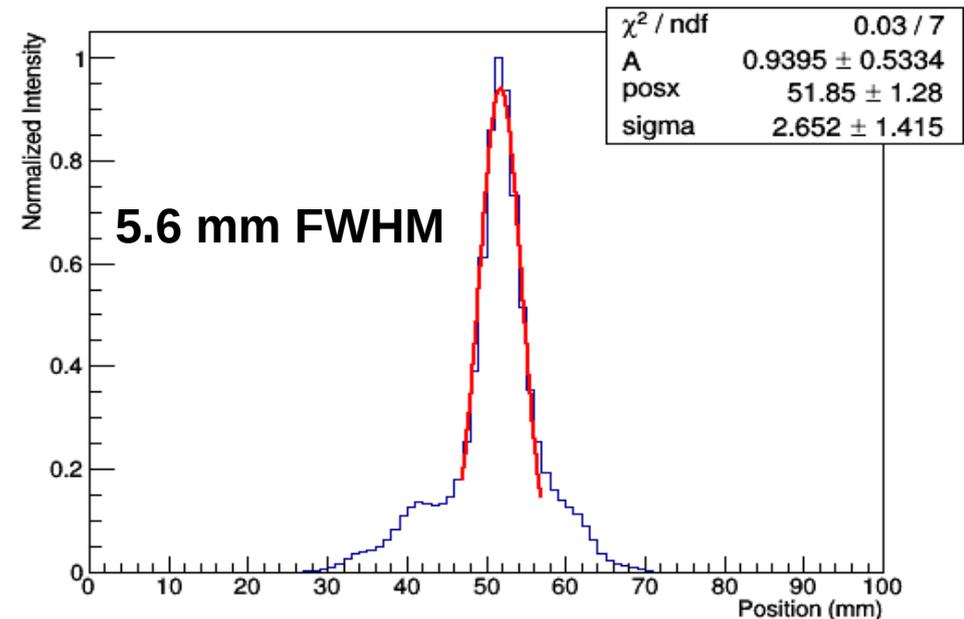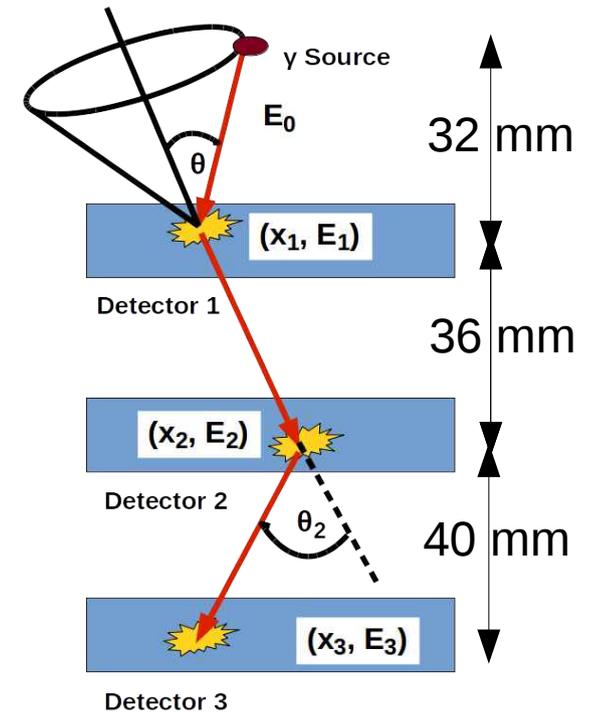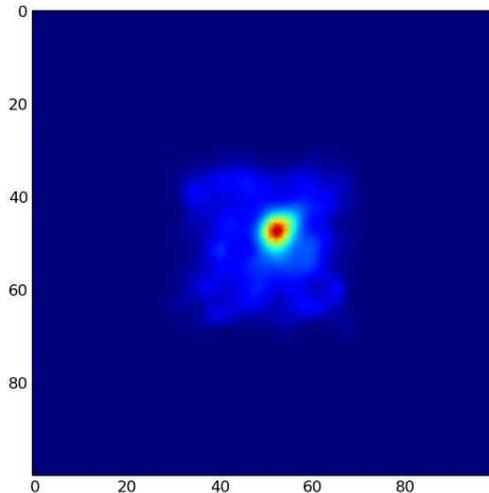
Spatial resolution 4 mm FWHM

• Source also placed in different positions, separated 20 mm.

• Image reconstructed at correct position.
• Points reconstructed separately.

Results with three planes

- 650 keV< Esum < 1350 keV.

Sum energy spectrum

5.6 mm FWHM

χ² / ndf	0.03 / 7
A	0.9395 ± 0.5334
posx	51.85 ± 1.28
sigma	2.652 ± 1.415
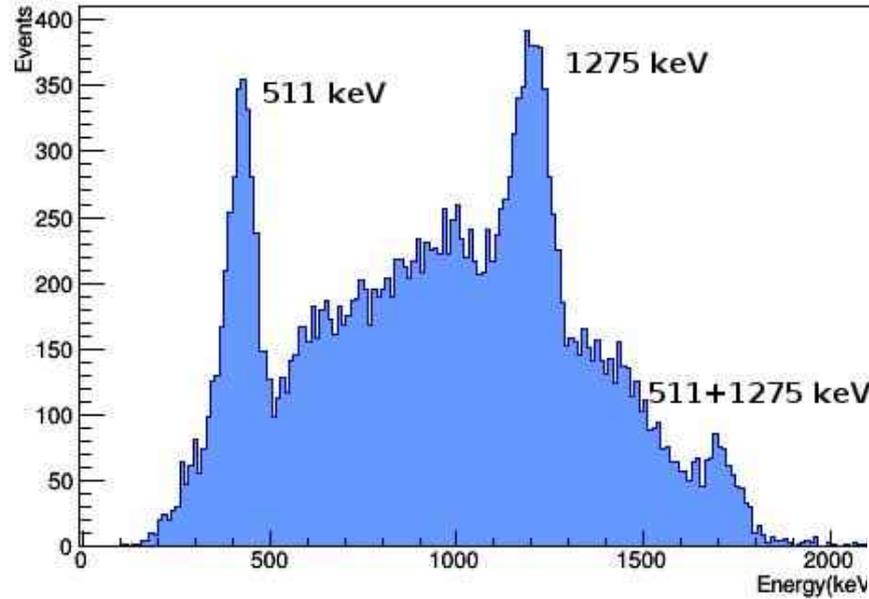
Tests in a proton beam

- Tests at KVI-CART, AGOR cyclotron (Groningen).

- Proton beam, 150 MeV, ~ 10^8 prot/sec.

- Graphite and PMMA targets.

Tests in a proton beam

- Data with two layers in coincidence.
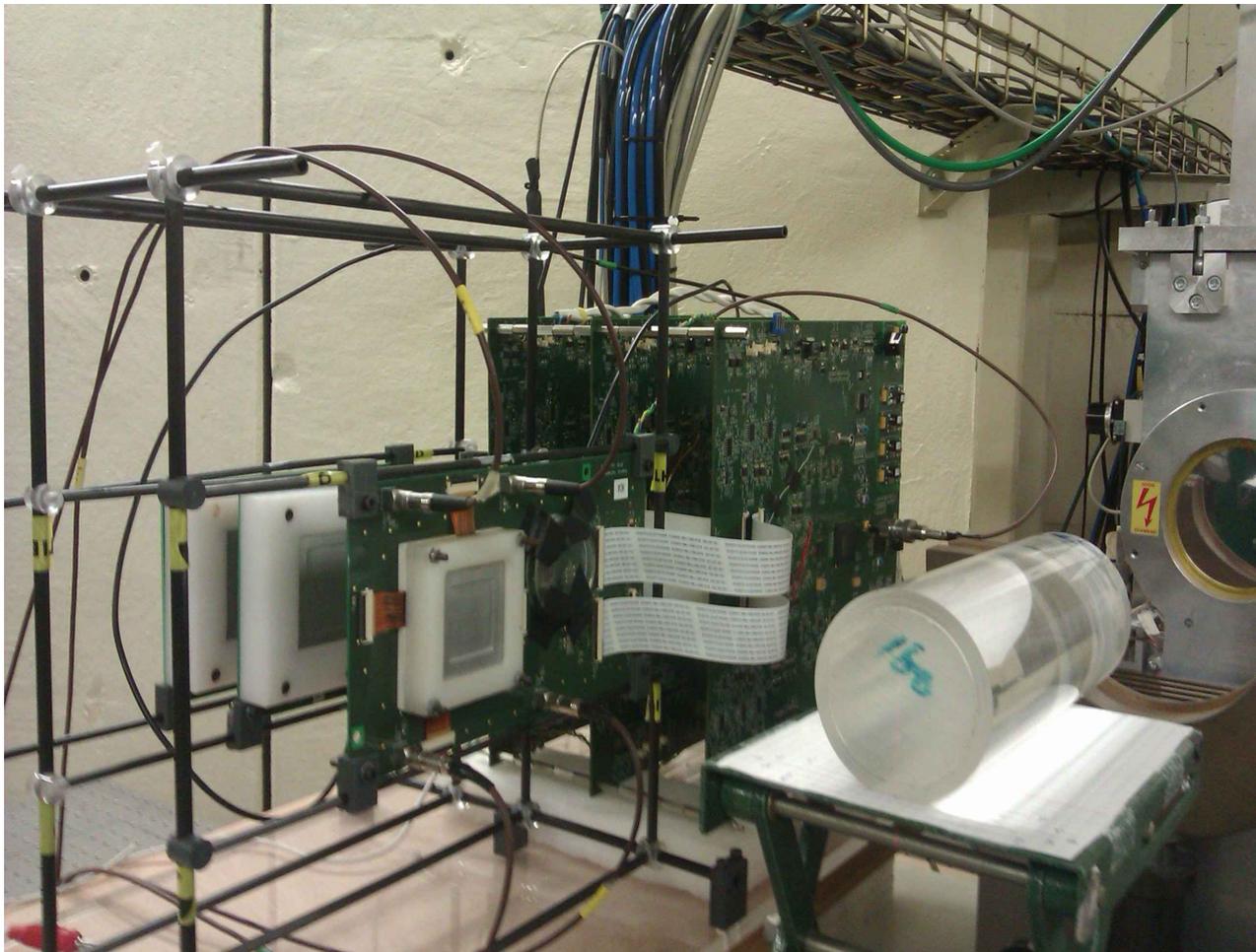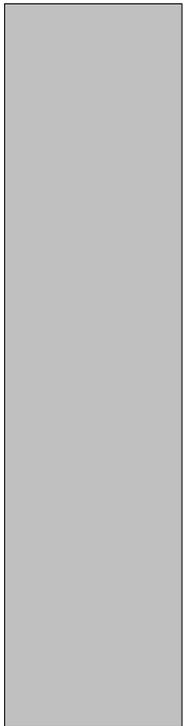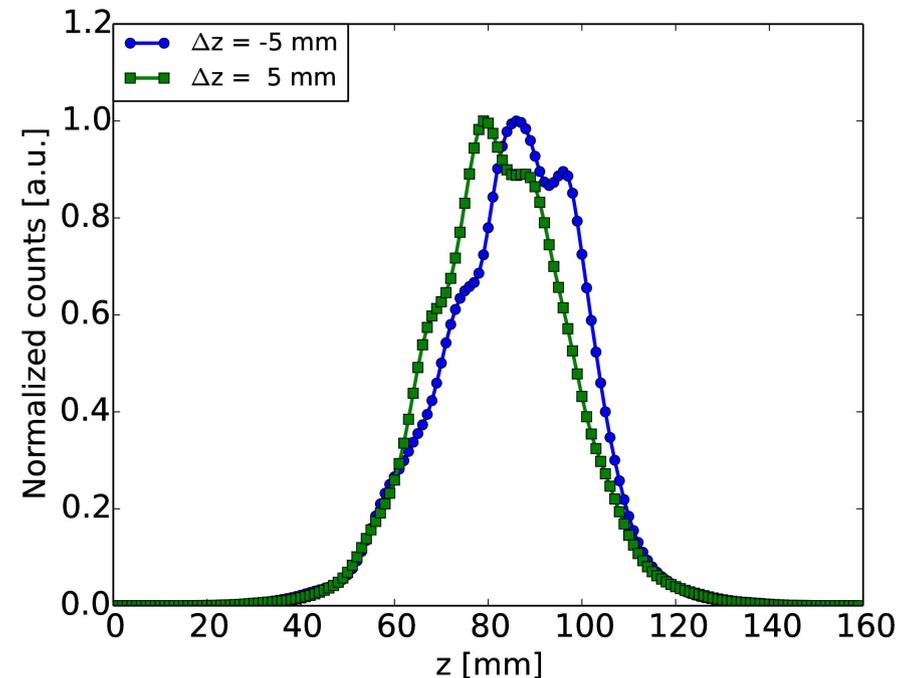
- PMMA target shifted to simulate Bragg peak variations.

- Shift observed in the Bragg peak position.

P. Solevi et al.
Submitted to Phys. Med. Biol.

Tests with high energy gammas

- Tests at HZDR 3MV Tandetron (Dresden).

- Gammas 4.439 MeV. $^{15}N(p,\alpha\gamma)^{12}C$ reaction.

- Low gamma emission rate.
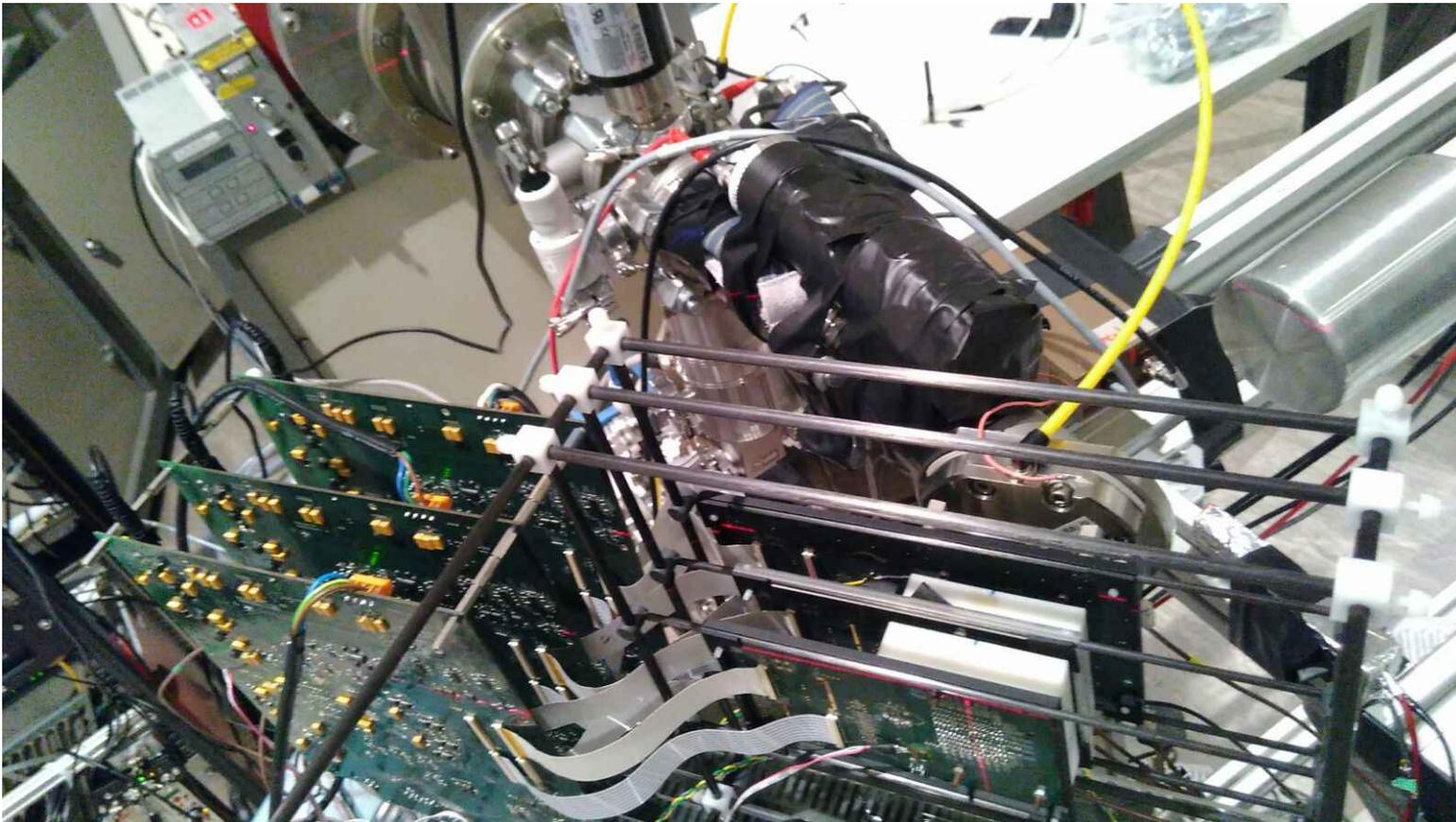
Tests with high energy gammas

- Coincidences with 2/3 layers. Too low rate for three layers.

- Telescope placed in three positions wrt target (-10,0,+10) mm.

- Results with layers 1-3 (source 43 mm, distance 55 mm).

VERY PRELIMINARY RESULTS
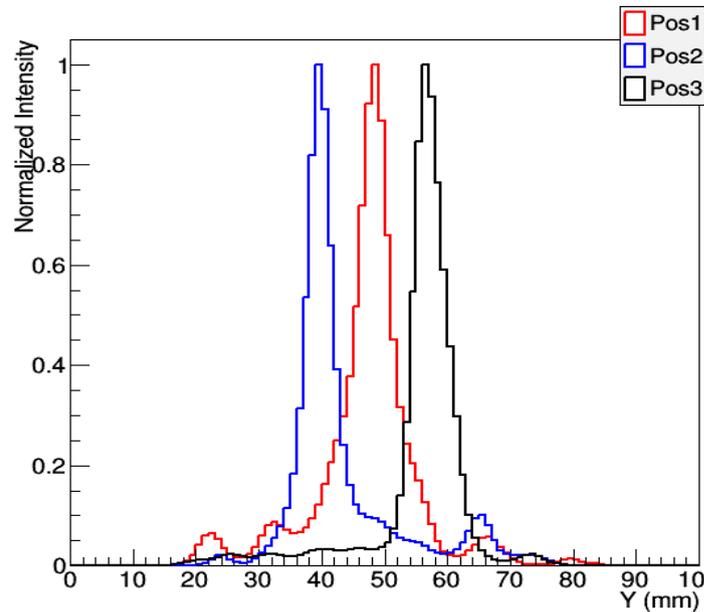
Summary and conclusions

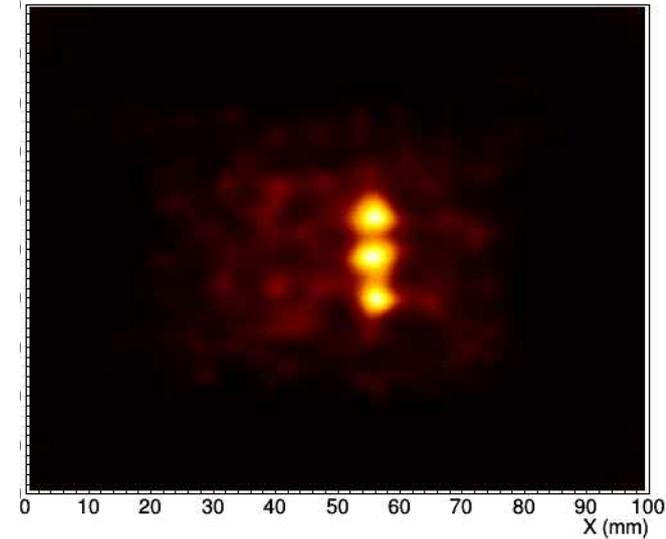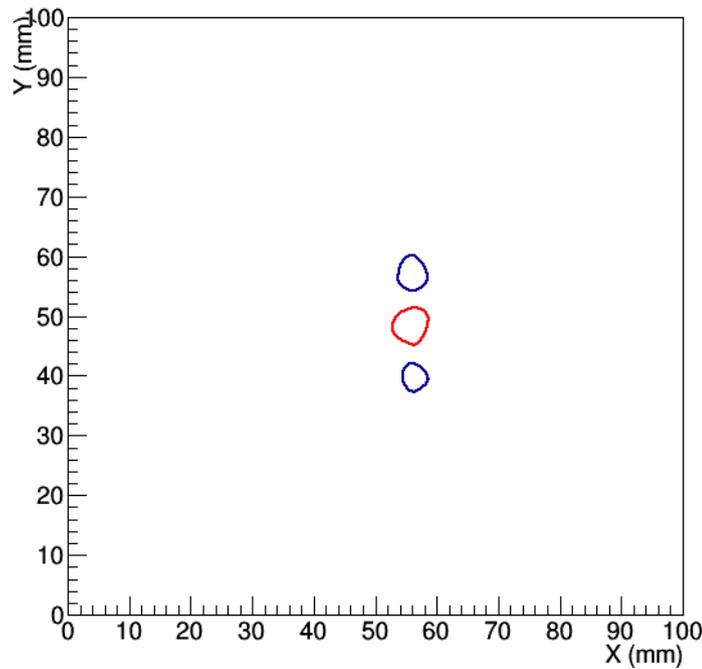- Three-layer Compton prototype based on continuous LaBr$_3$ crystals and SiPMs constructed at IFIC-Valencia.

- Promising results obtained in lab tests with two and three layers.

- First tests in accelerator facilities carried out.

- Ongoing: data analysis, combination of 2 and 3-layer events, prototype performance improvement and full characterization.

Further results @ PTCOG 2016

Acknowledgements

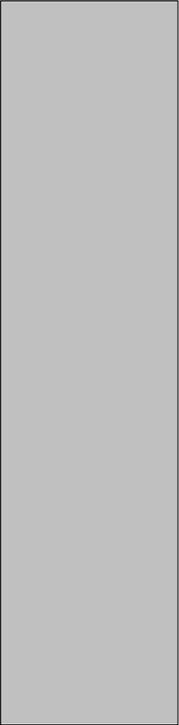- This work was supported in part by the European Commission-FP7 through ENVISION project (g.a. num 241851) and IA ENSAR (RII3-CT-2010-262010).

- This work was supported in part through the Spanish Ministerio de Economía y competitividad/Plan Nacional de I+D+i (FPA2014-53599-R).

- Group members are supported through Ramón y Cajal, Atracció de Talent (UV) and Generalitat Valenciana contracts.

Thank you! Questions?

Hadron therapy

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

- Reduce the dose to healthy tissue.
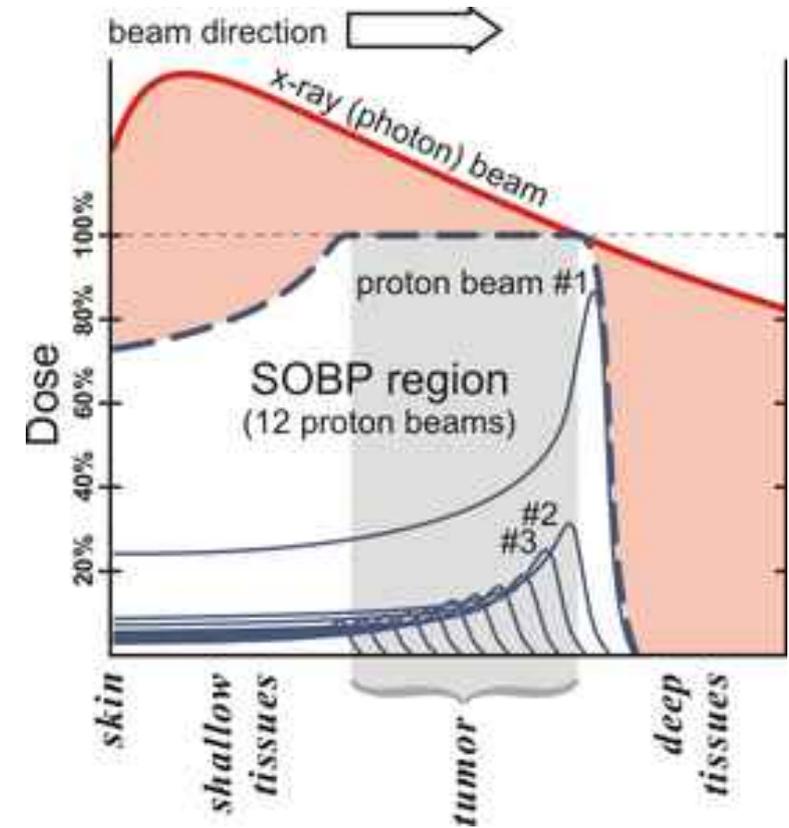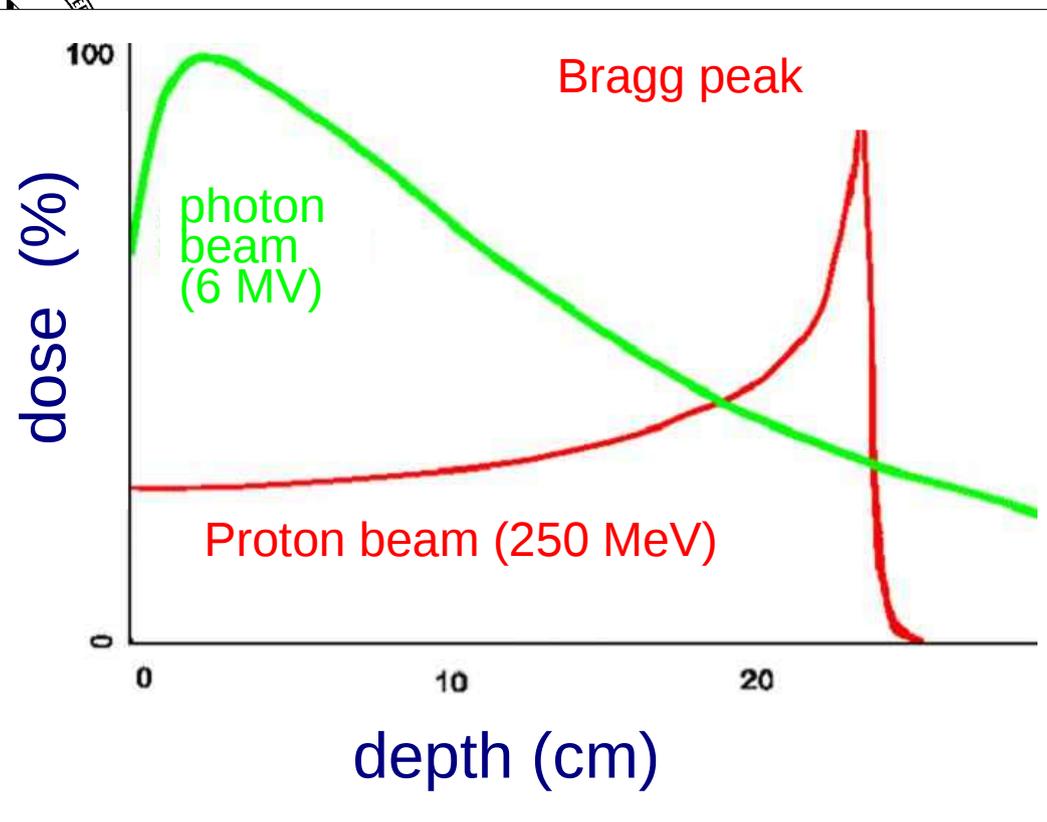
- Increasing number of HT centers in the world

Hadron therapy

- Gaining increasing importance -> growing number of centers in Europe and in the world.

Hadron therapy centers in the world
(from http://ptcog.web.psi.ch/ptcentres.html)
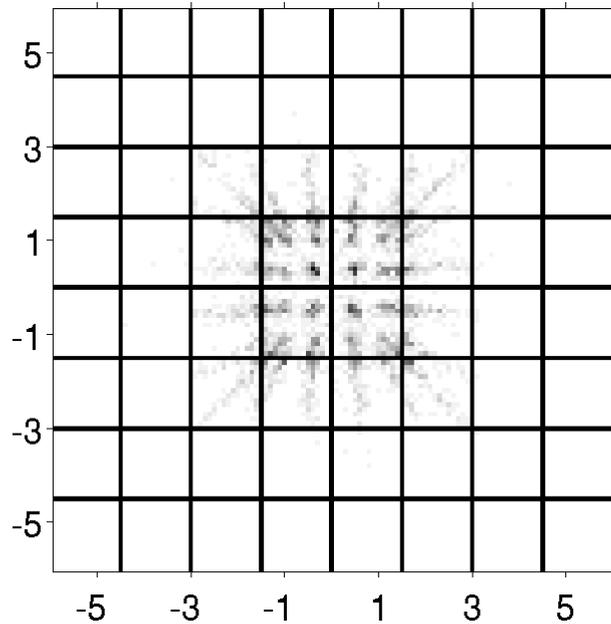
Position determination

- Main problem of continuous crystals

- New method applied based on direct light distribution + reflections

Li, Z. et al.
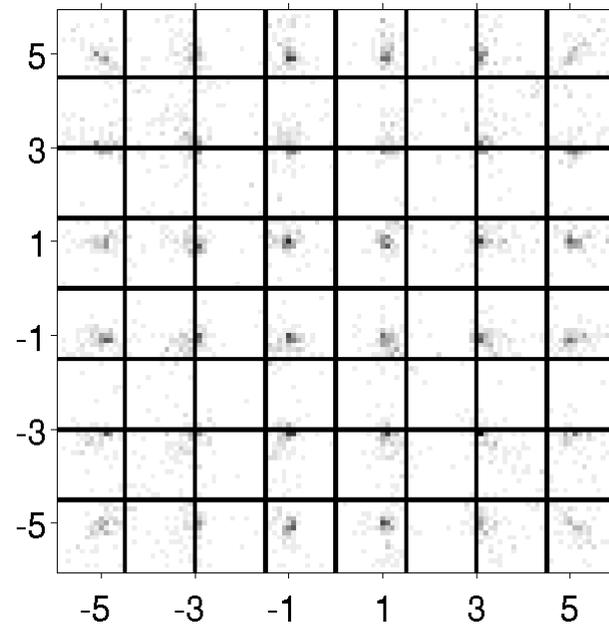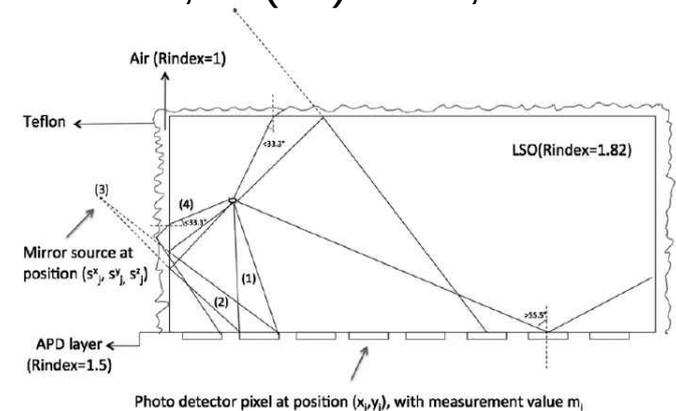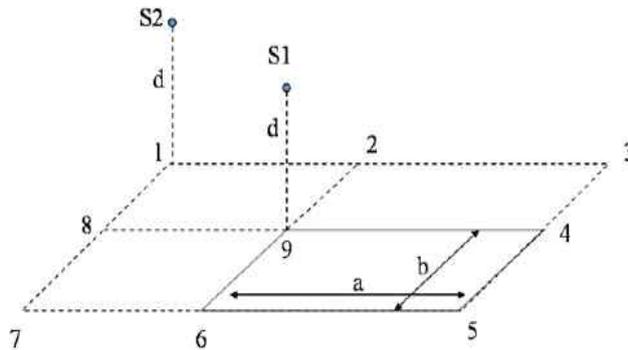Phys. Med. Biol.,
55(21):6515, 2010.

COG

New method

Position determination

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

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

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

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

Reflections

Approximated angle model

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

Optimization method:
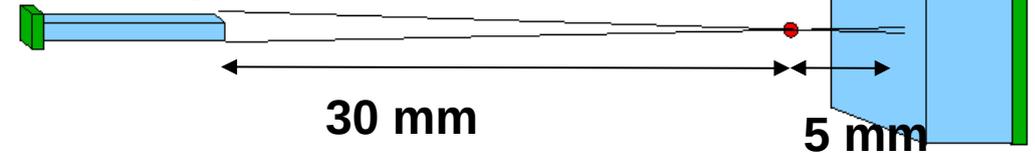**Local minimization interior-reflective Newton**

Position determination

Preliminary resolution:

- 5 mm crystal: 1.0±0.3 mm FWHM

- 10 mm crystal: 1.44±0.09 mm FWHM
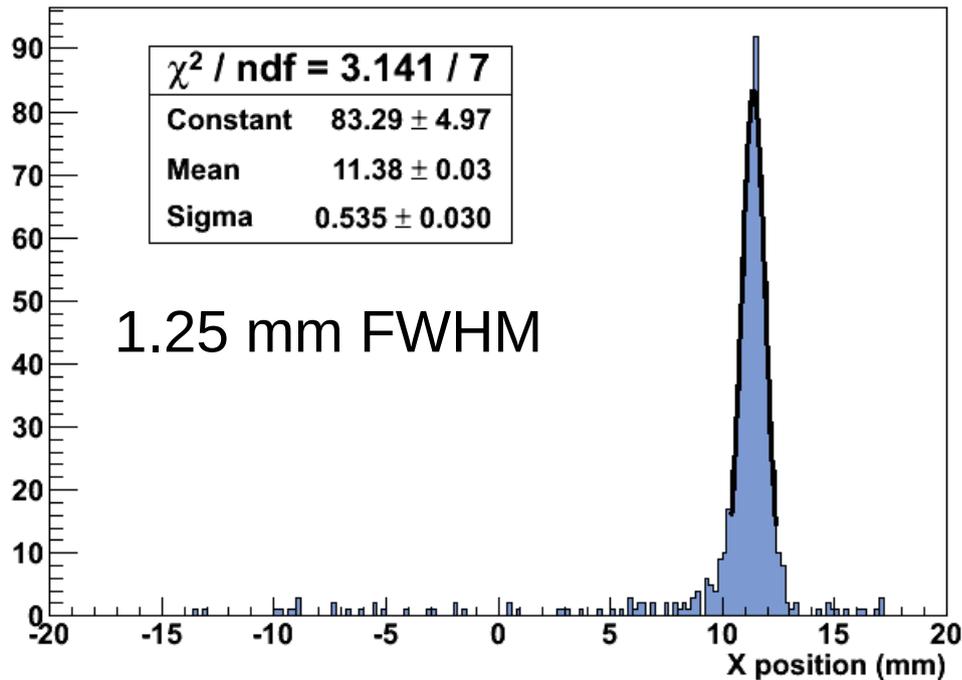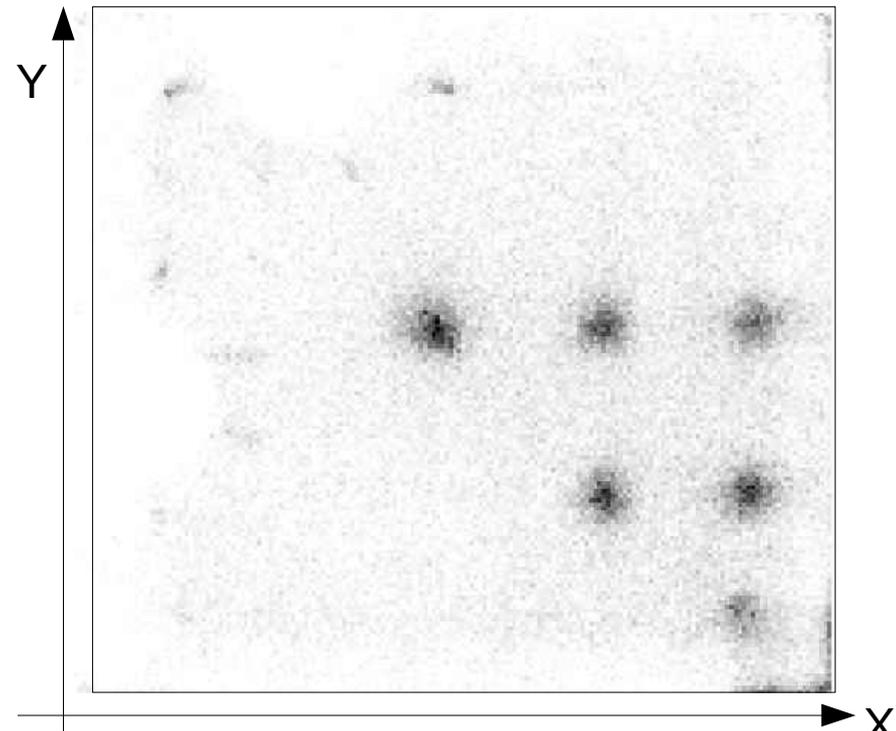
1mm x 1mm x 10mm LYSO crystal

LaBr$_3$ detector

Na-22 source

30 mm

5 mm

Positions in the 10 mm thick crystal

Position determination 5 mm

χ^2 / ndf = 3.141 / 7

Constant	83.29 ± 4.97
Mean	11.38 ± 0.03
Sigma	0.535 ± 0.030

1.25 mm FWHM

X position (mm)

Y

X

DAQ system
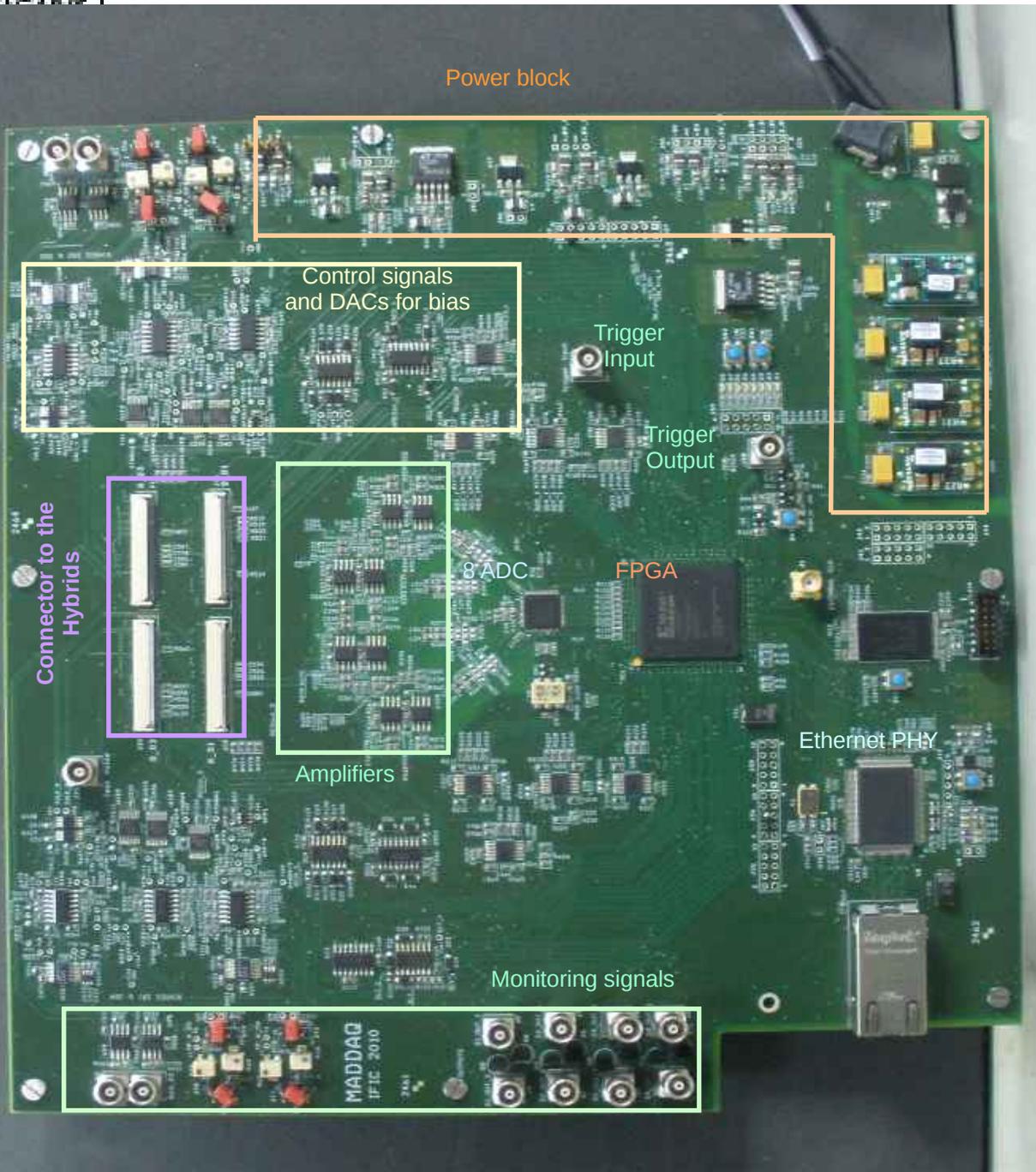
Modular and flexible design

FPGA Xilinx

Fast data transfer: Ethernet (up to 1 Gbps)

Time stamp with 1 ns resolution

Several boards can work in time coincidence

Ongoing work

- New photodetectors.

  - TSV, 8x8 pixels.

  - Better uniformity.

  - Better PDE

- Improvement of timing resolution.

28.5 mm