# Development of a high resolution animal PET with continuous crystals and SiPMs

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

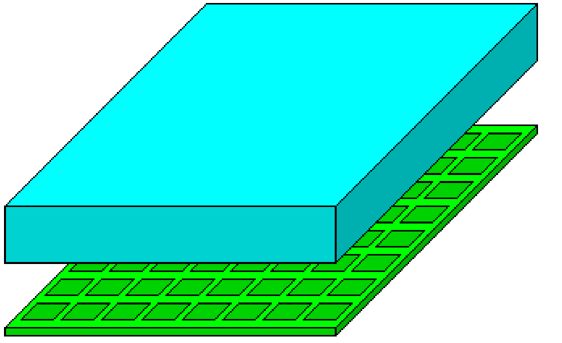
II Symposium on PET, Krakow 21-24 September 2014

# Outline

- First prototype
- Second prototype
- New geometries

# Goals

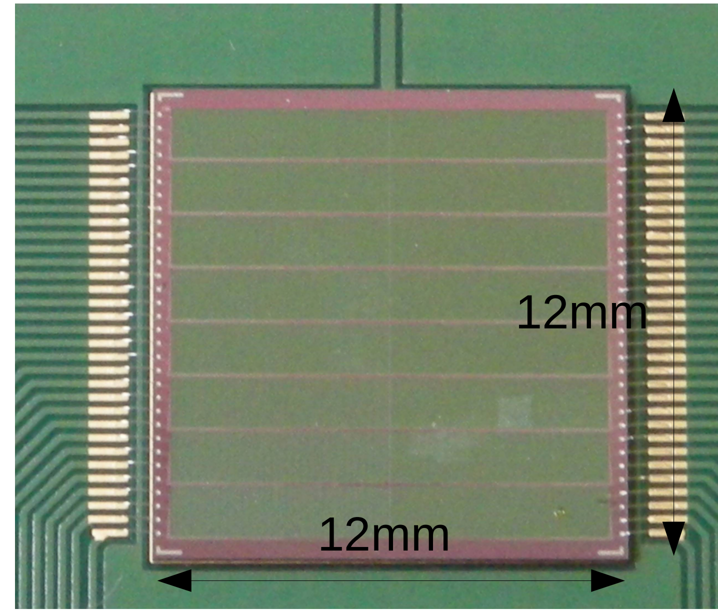
- Use of novel technologies (SiPMs) to evaluate performance improvements.
- Use of continuous crystals
  - Obtain excellent spatial resolution without loosing sensitivity
  - Instrumentation and software challenges.

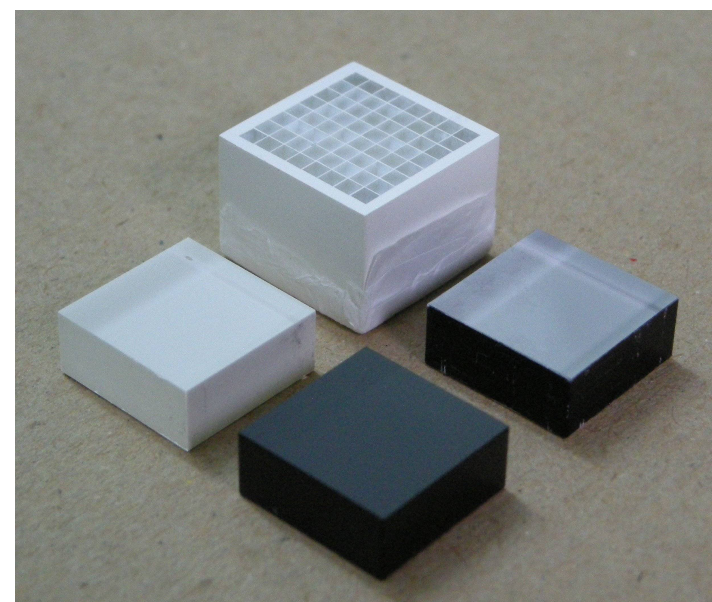


| Advantages | Challenges |
| --- | --- |
| • Higher efficiency than pixellated<br>• Very good spatial resolution<br>• Lower cost | • Large number of readout channels -> ASICs<br>• Position determination is an issue<br>• Timing resolution can be degraded |

# Detector components

- **Monolithic, 64-pixel SiPM matrices** from FBK-irst/ AdvanSiD
  - Elements of 1.5 x 1.4 mm$^2$ in a 1.5 x 1.5 mm$^2$ pitch.
  - 850 microcells of 50 μm x 50 μm size per pixel.
  - Readout on two sides.
- Different crystals tested. **Continuous, white painted LYSO crystals 12x12x5/10 mm$^3$** selected.

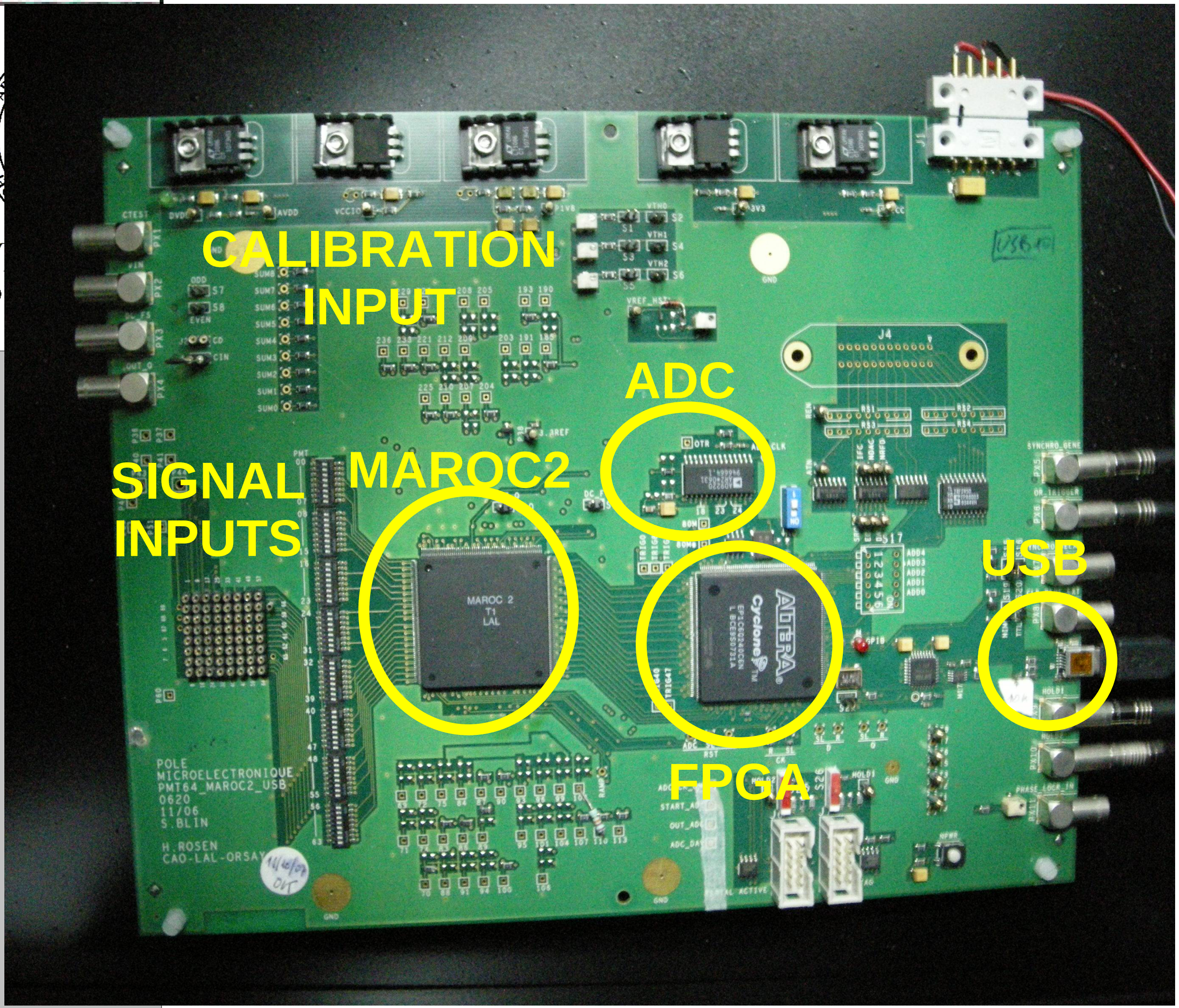


G. Llosá et al., *Characterization of a PET detector head based on continuous lyso crystals and monolithic, 64-pixel silicon photomultiplier matrices.*
PMB 2010, vol 55, p 7299-7315.

# Readout electronics

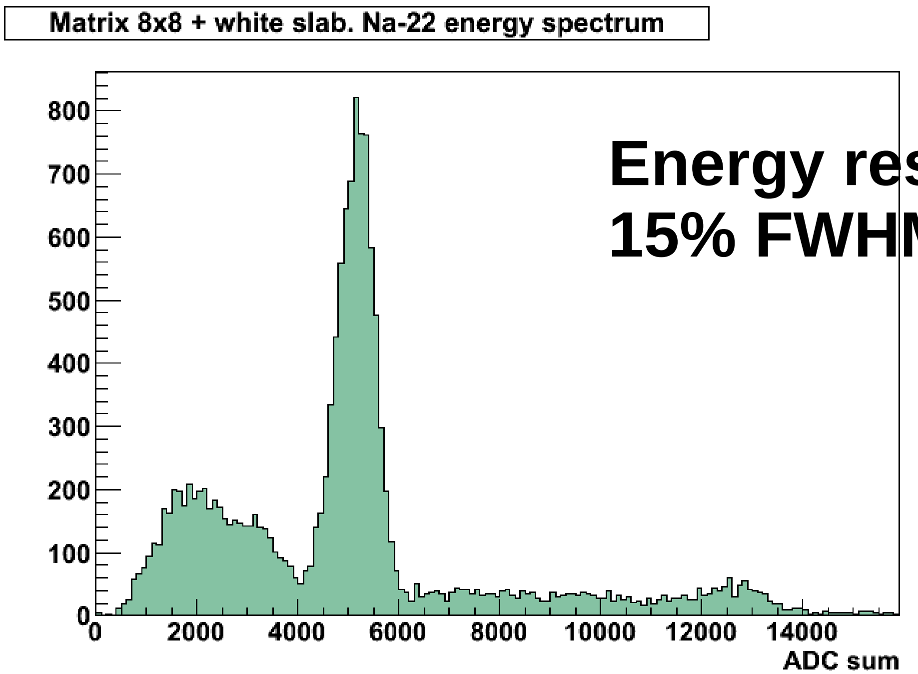
- MAROC2 ASIC from LAL, Orsay (France).



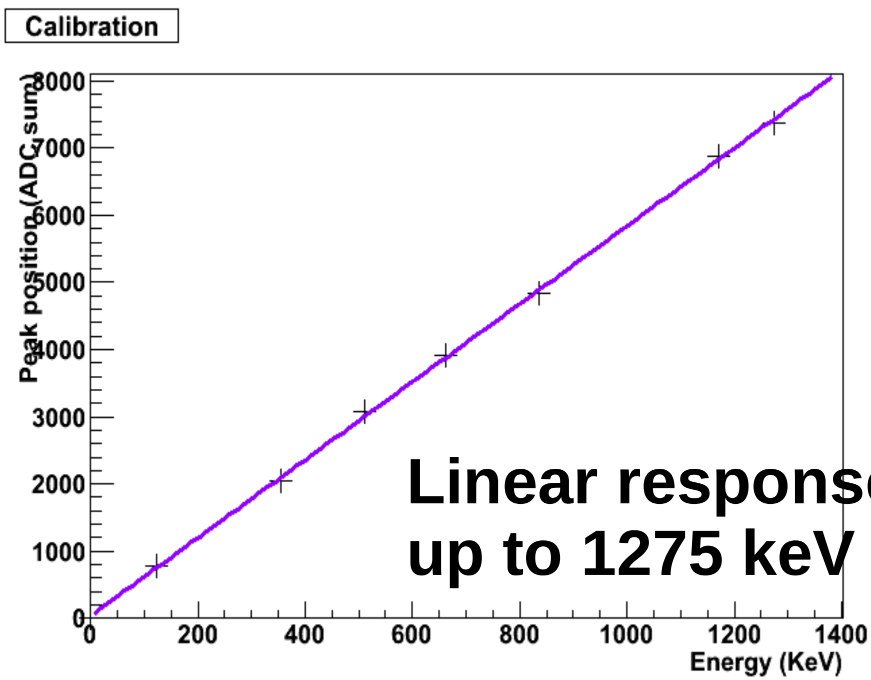

- 64 channels
- Variable gain (6 bits), low noise preamplifier
- Slow shaper (~20-150 ns, adjustable)
- Fast shaper (15 ns) + 3 discriminators =>Trigger signal.
- LabView software for DAQ

# Detector characterization - white slab

**Photodetector uniformity within 5%. No correction for gain variations.**




**Energy resolution: 15% FWHM at 511 keV**

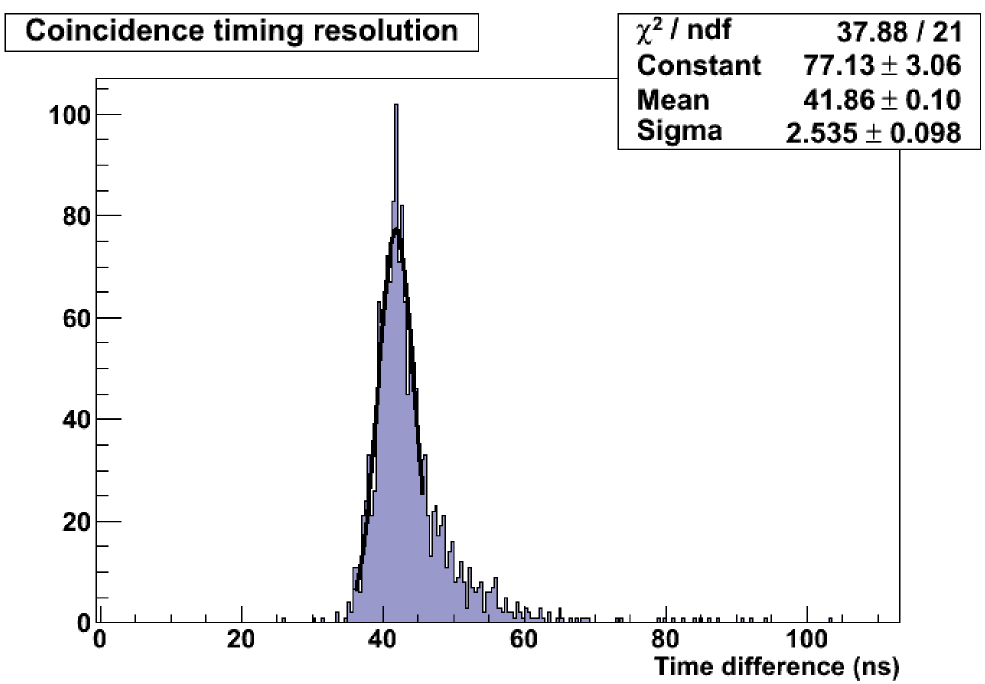



**Linear response up to 1275 keV**

# Detector characterization

Poor timing resolution: 6 ns FWHM.

- Low amount of light per pixel
- Trigger given by OR of all channels and common threshold.
- Only one discriminator- time walk
- Trigger shift increasing with channel number (up to 6%).

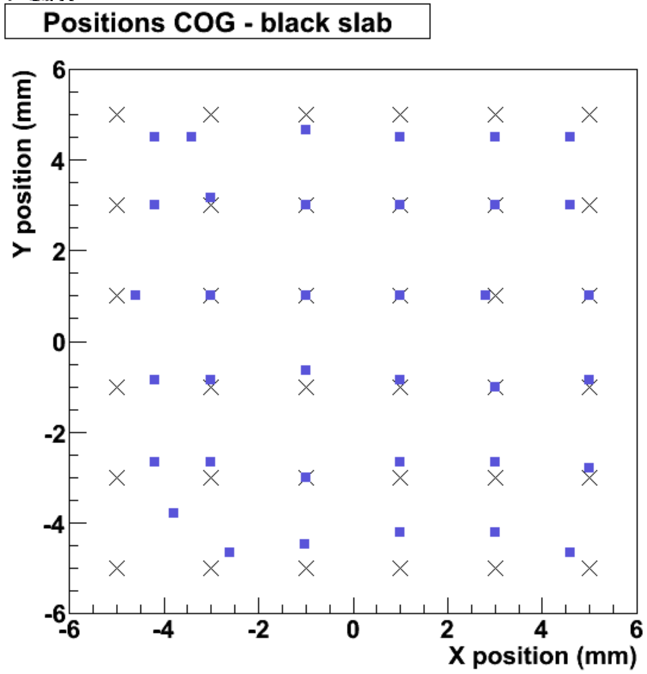



Triggering on the sum signal gives better results.

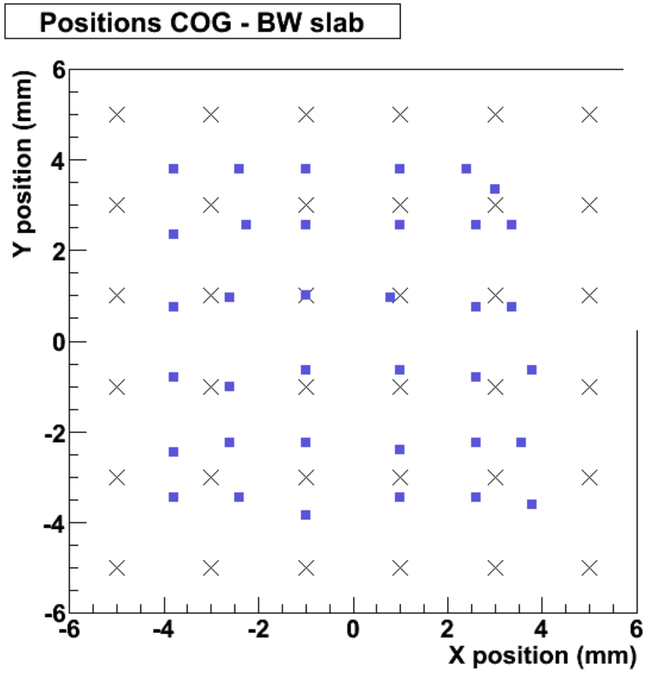
# Position determination

- Compression effects with COG

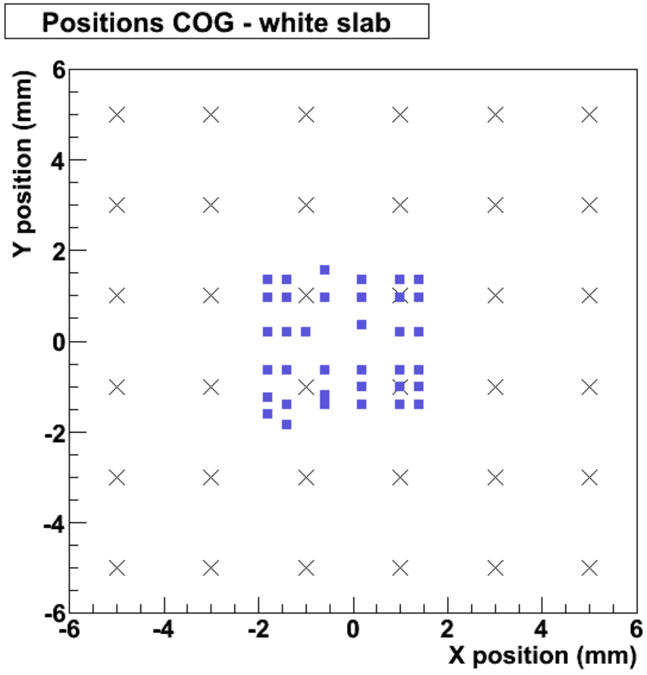
**Black crystal**




**Black and white crystal**



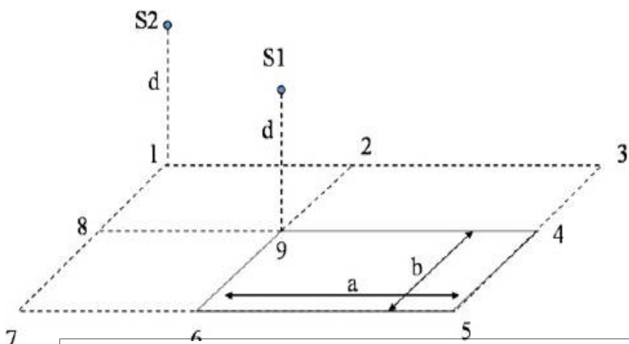

**White crystal**

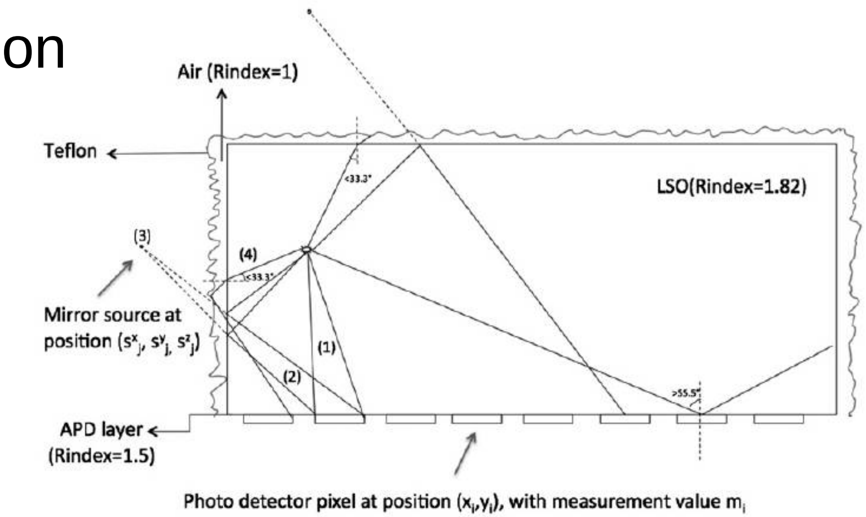


# Position determination

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

- Based on a model of the angle subtended by the interaction position with each photodetector element.
- **Provides x,y and DOI**
- **No calibration needed**




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*

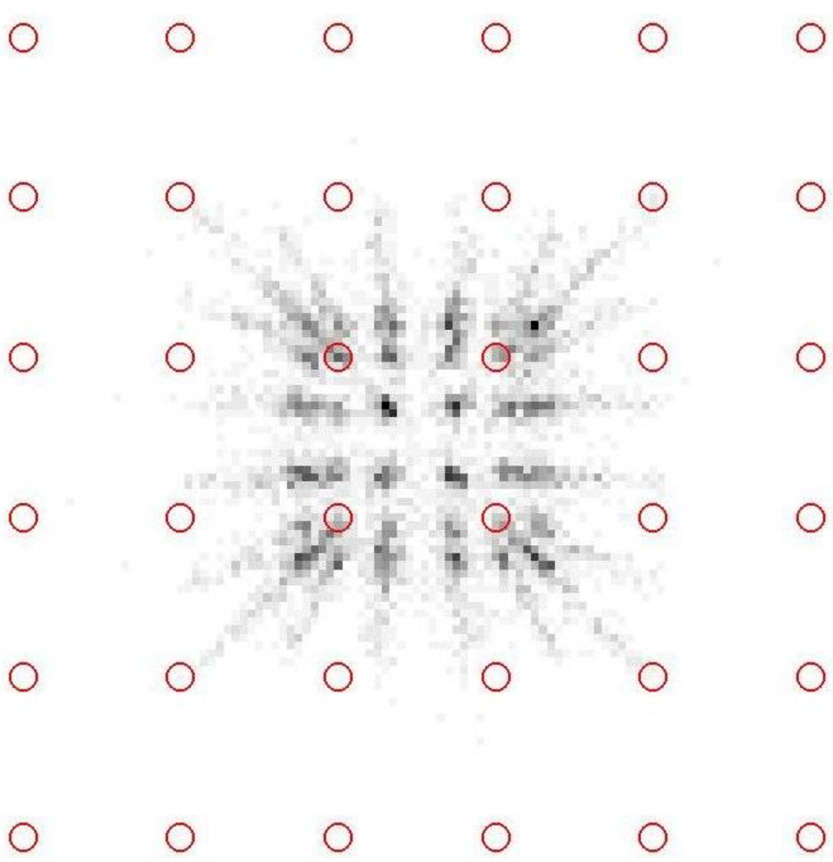
# photons in pixel *i* estimated by the model

Optimization method: **Least squares**

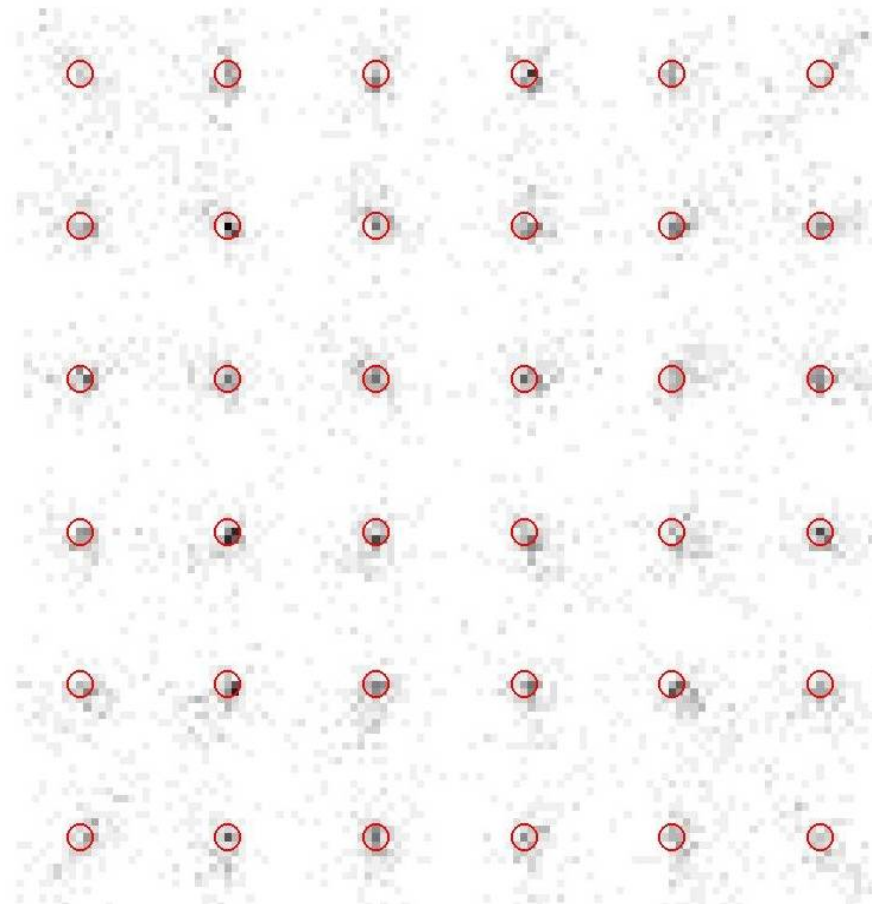
# Position determination

- Simulated data.

COG

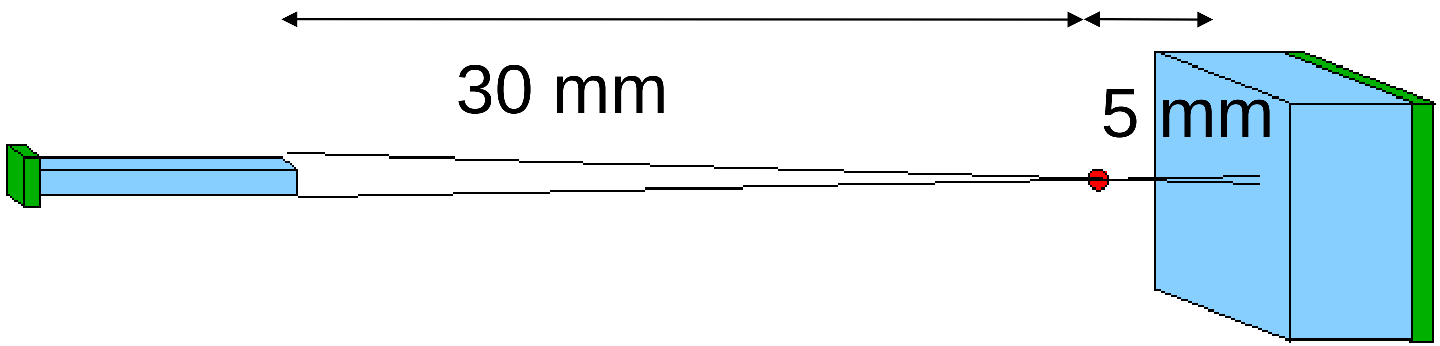


New method



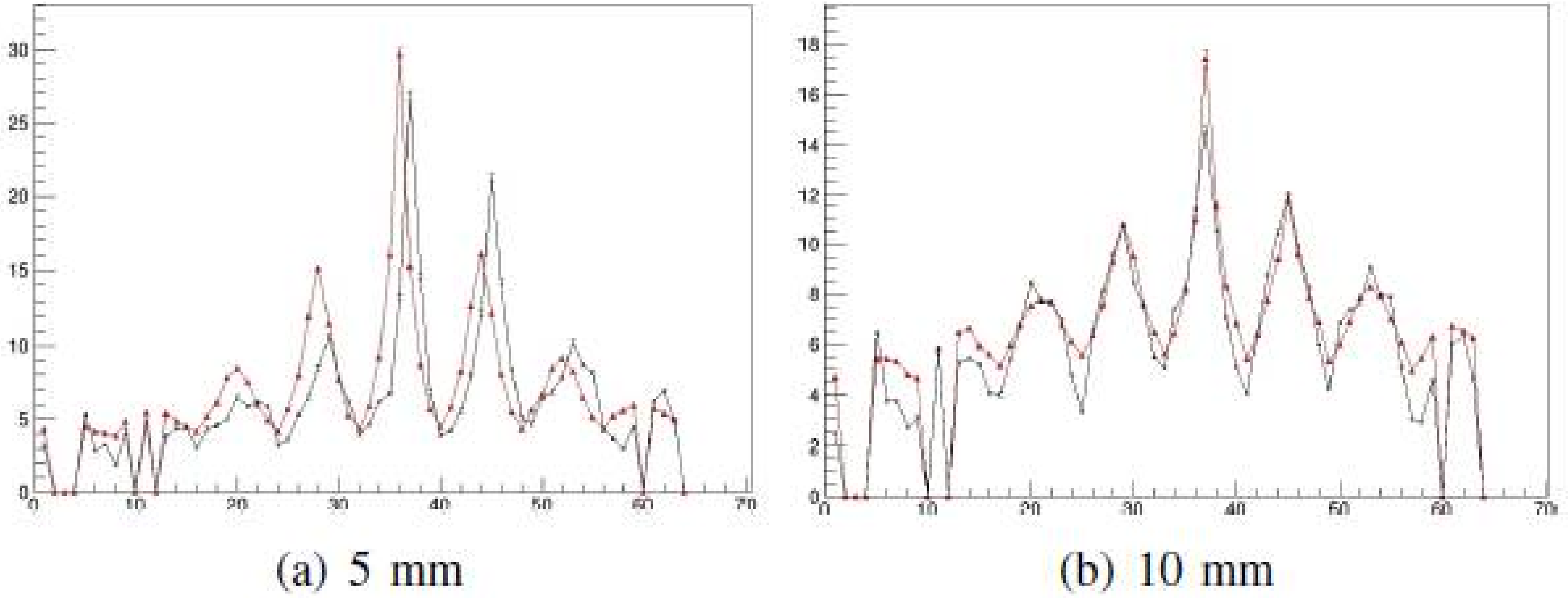
# Position determination

- Detector in coincidence with a 1mm x 1mm x 10mm crystal coupled to a 1 $mm^2$ MPPC.
- Na-22 source



# Positions simulated/measured

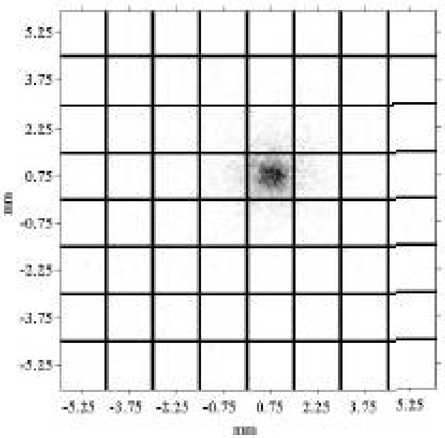
- Simulations with GATE.
- Optical photons included
- Comparison of light distribution in the crystal.



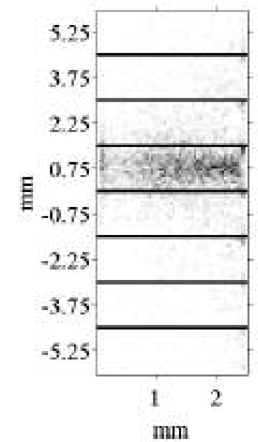

**A. Etxebeste et al. 2014 IEEE NSS MIC.**

# Positions simulated/measured

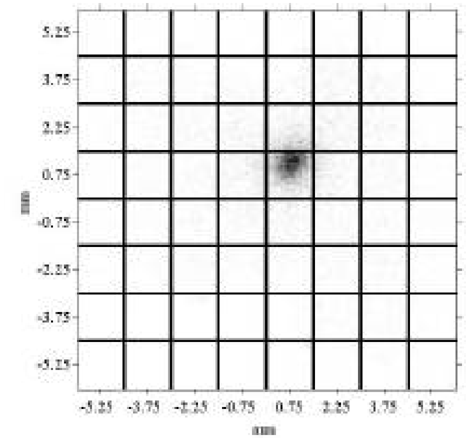
- Simulated data
- Real data



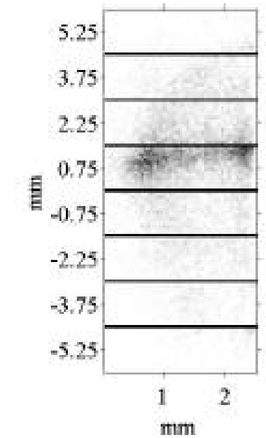

(a) XY simulated



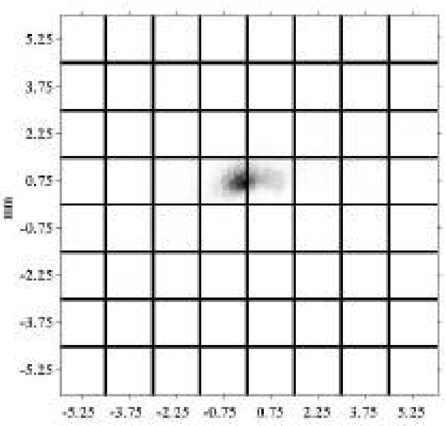

(b) DoI



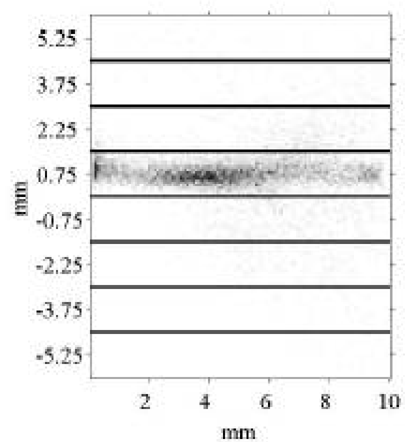

(a) XY experimental



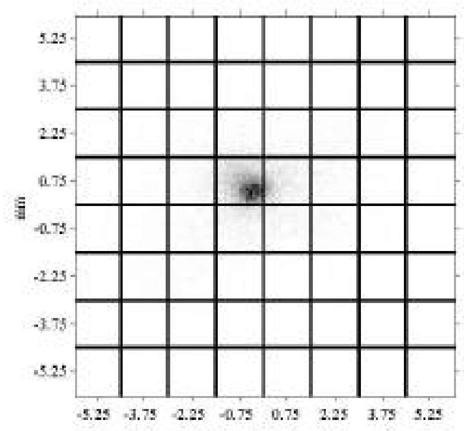

(b) DoI



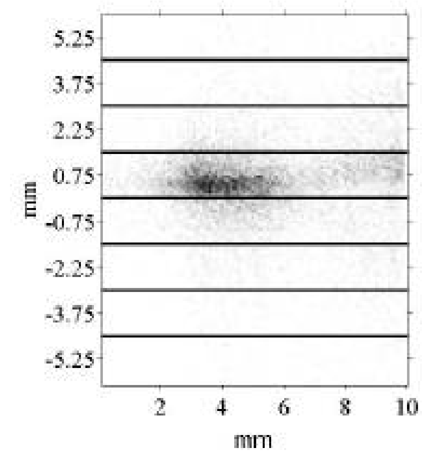

(c) XY simulated




(d) DoI




(c) XY experimental



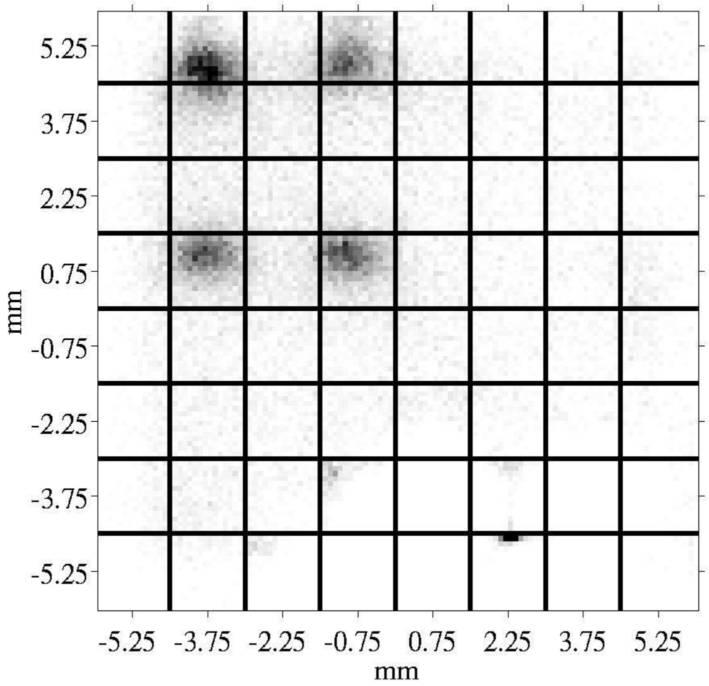

(d) DoI

Direction of photons

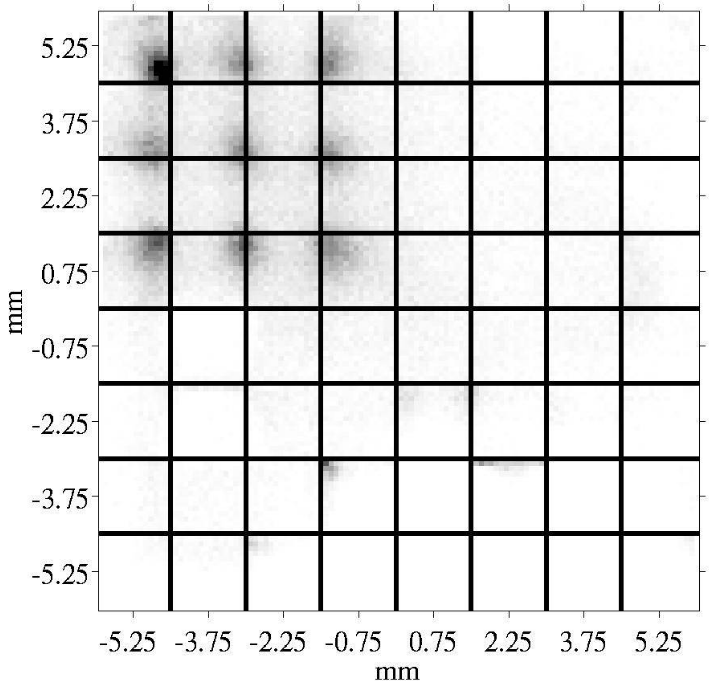
Direction of photons

# Position determination- Real data

5 mm thick crystal




10 mm thick crystal



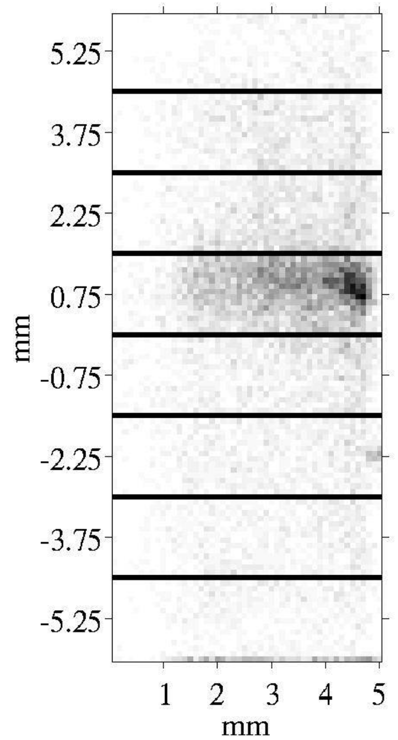

**FWHM: 0.69±0.08 mm**
**FWTM: 1.89±0.22 mm**

**FWHM: 0.73±0.11 mm**
**FWTM: 2.0±0.1 mm**

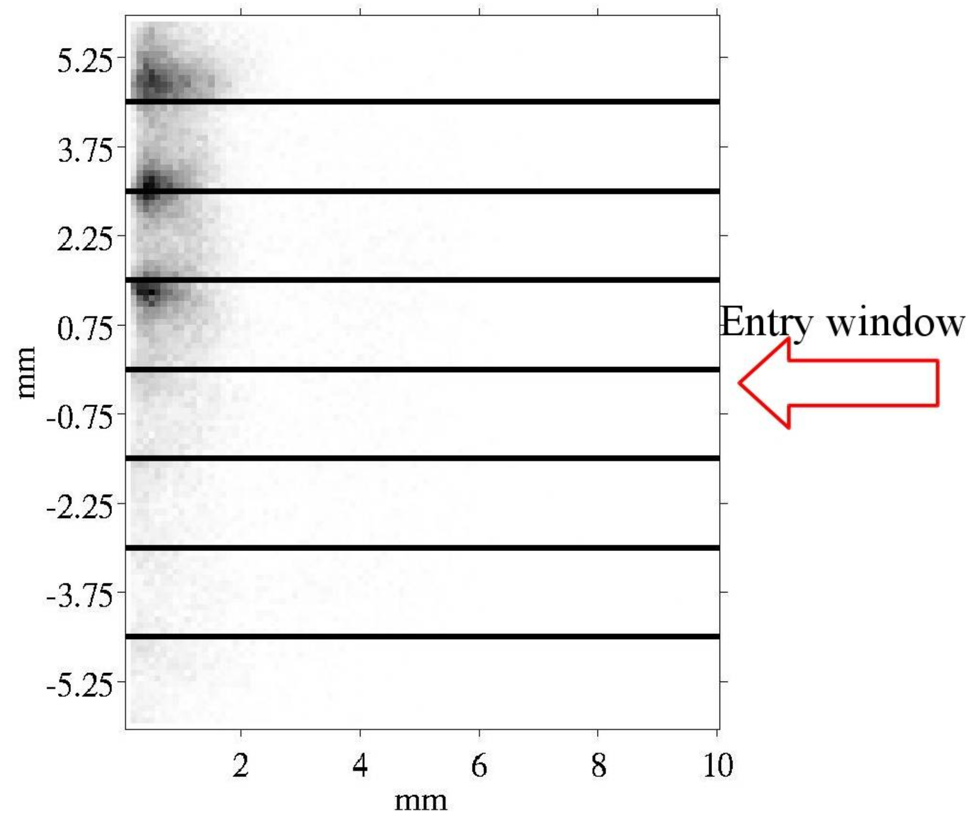
**J. Cabello et al. NIMA 2013, 718, p 148-50.**

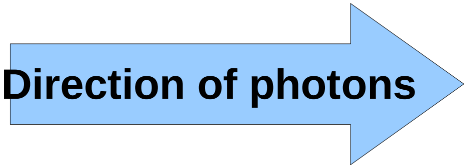
# Position determination - Real data

5 mm thick crystal




10 mm thick crystal

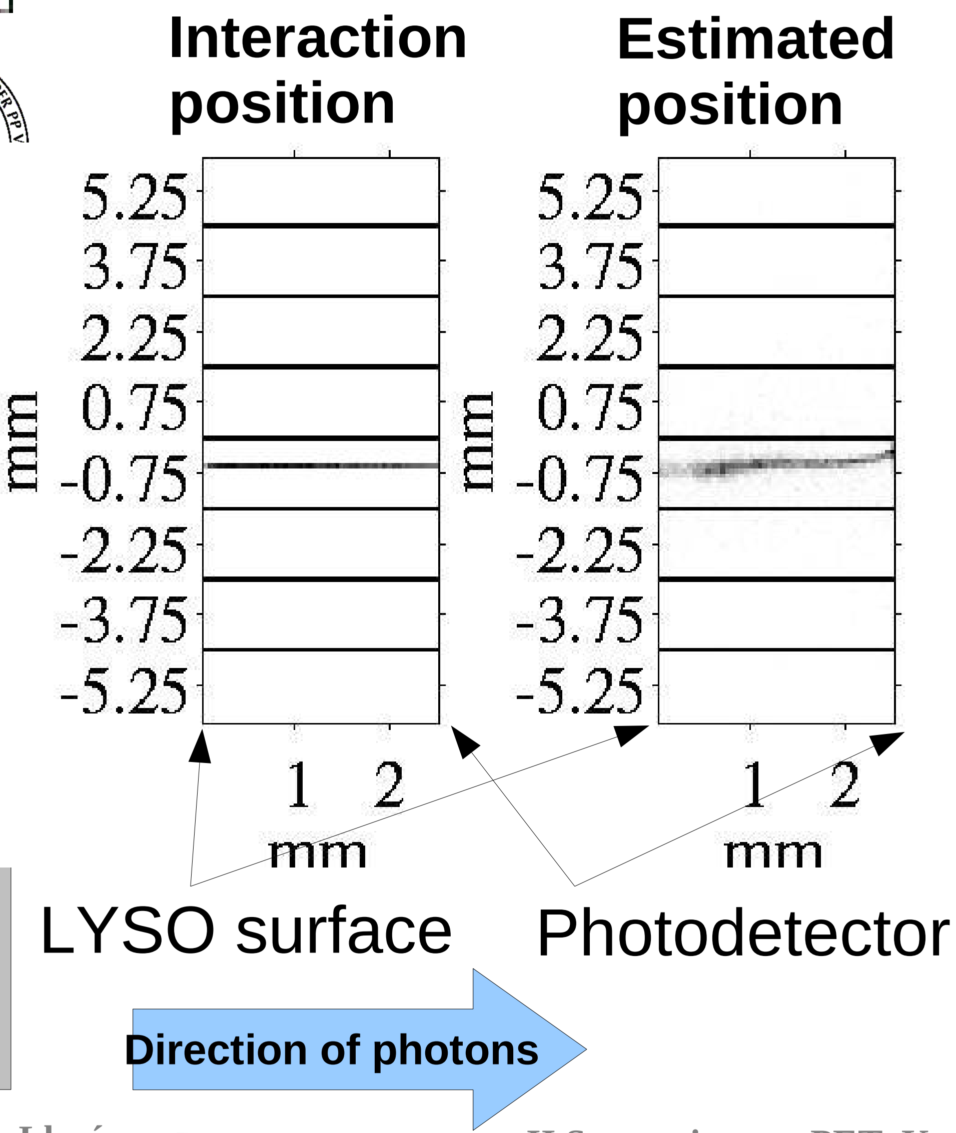


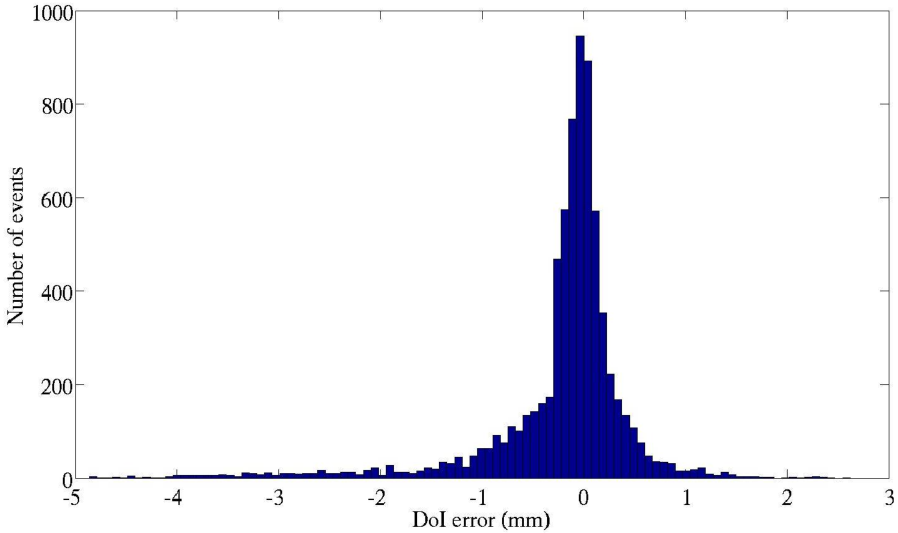

**J. Cabello et al. NIMA 2013, 718, p 148-50.**

# Position determination: simulation results

- DOI determination, 5 mm thick crystal

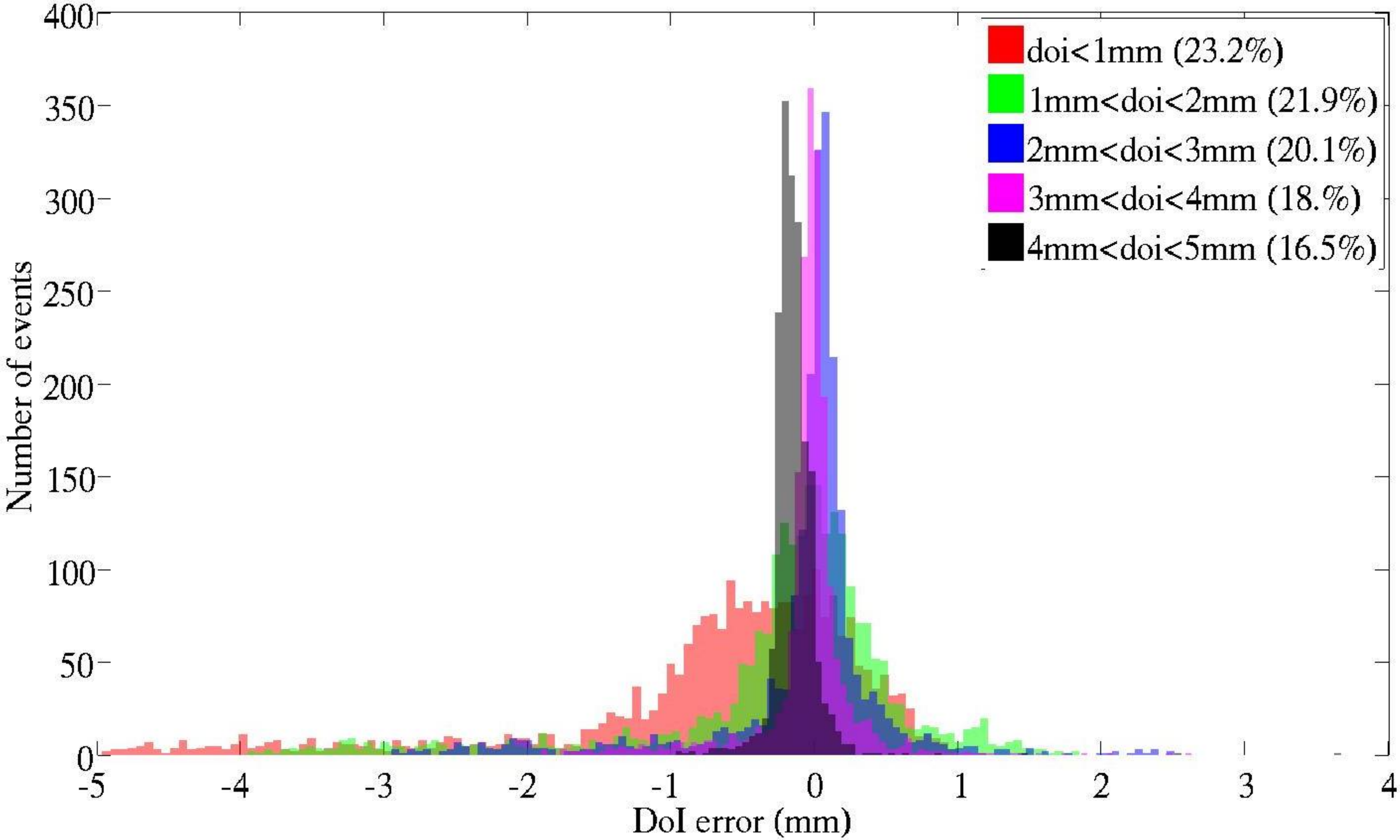



**DoI error (simulations):**
**0.5 mm FWHM**
**1.1 mm FWTM**



# Position determination: simulation results

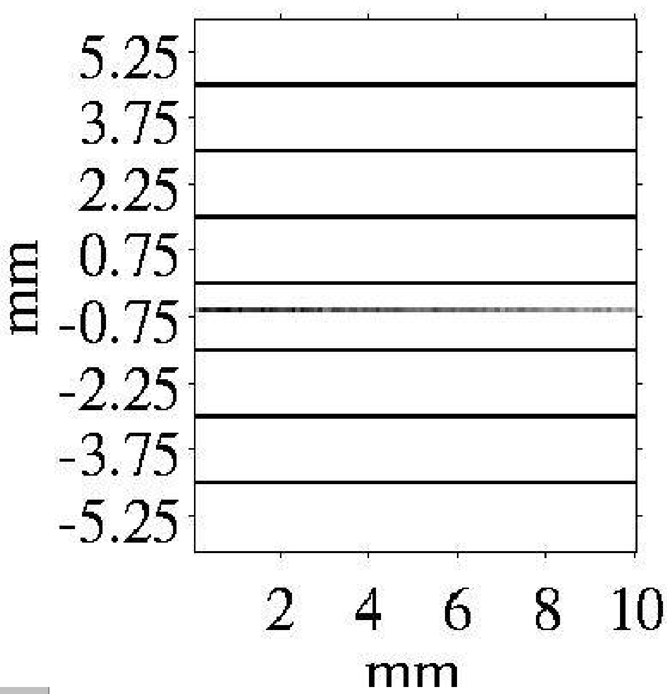
- DOI determination, 5 mm thick crystal



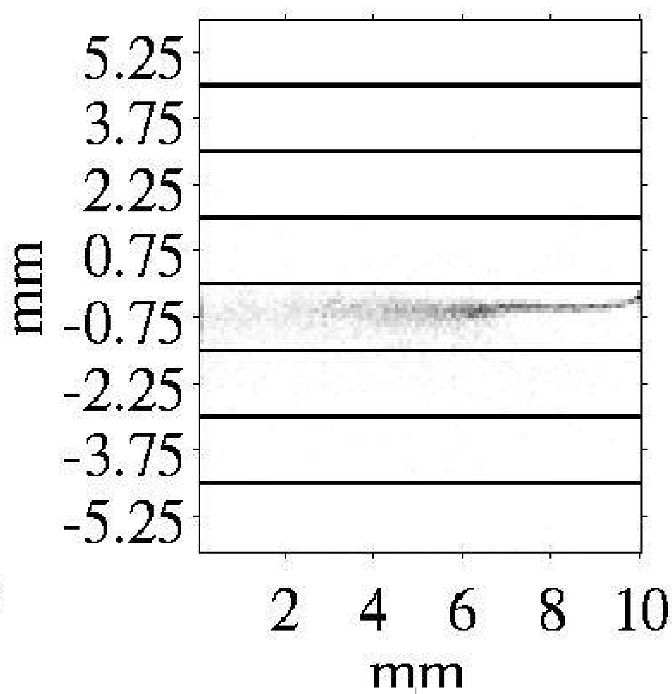
# Position determination: simulation results

- DOI determination, 10 mm thick crystal

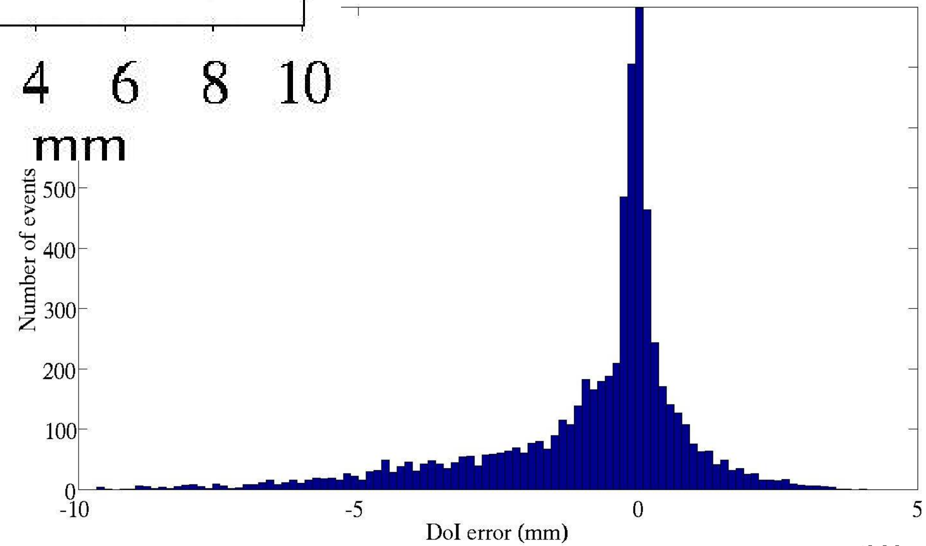
**Interaction position**




**Estimated position**



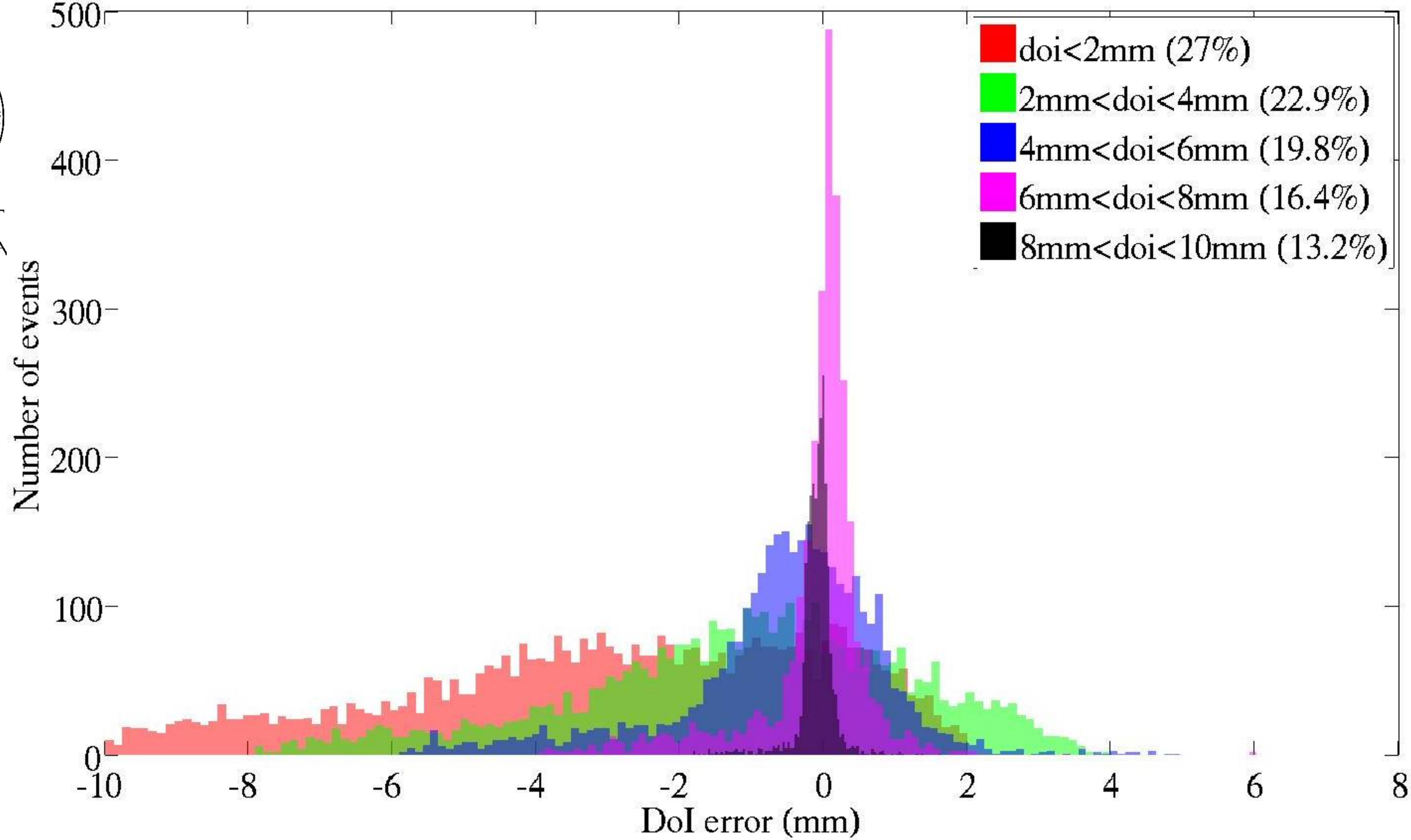

**DoI error (simulations):**
**0.5 mm FWHM**
**1.7 mm FWTM**




**Direction of photons**

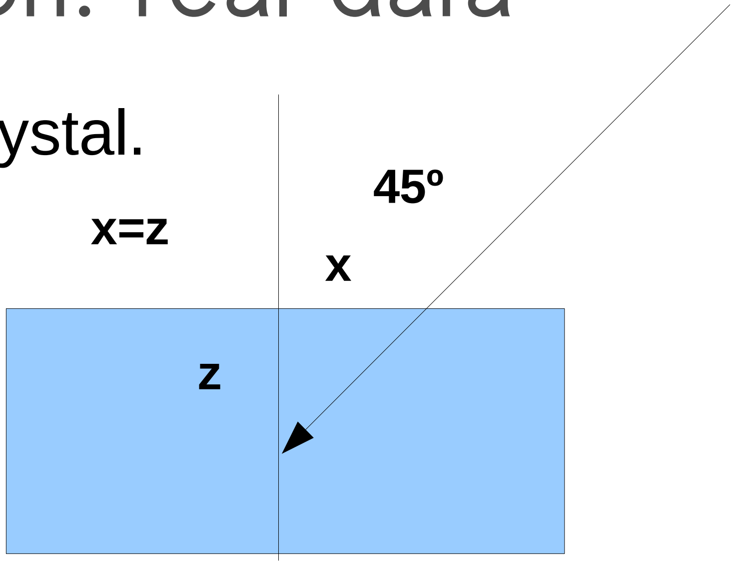
# Position determination:simulation results

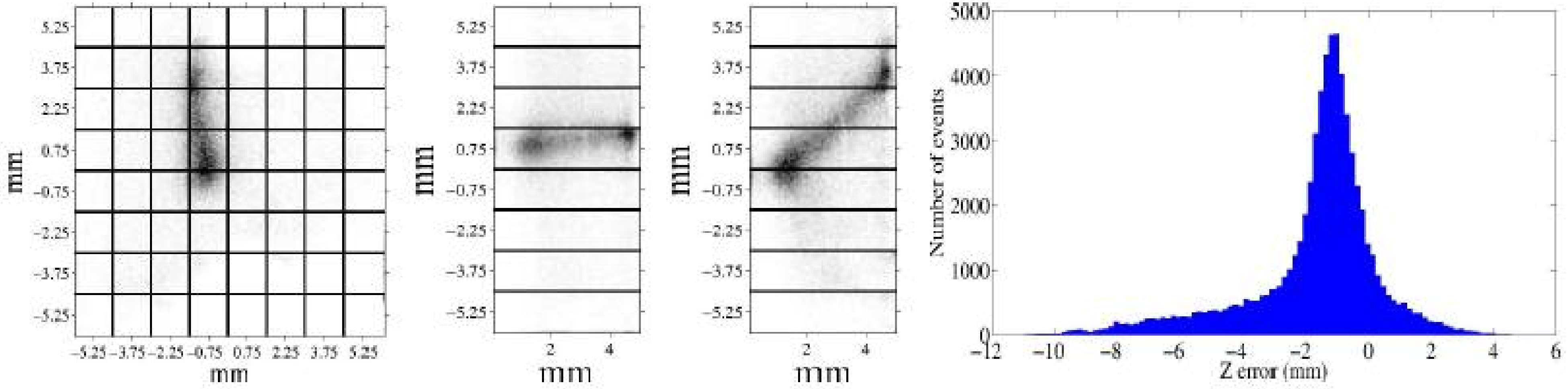
- DOI determination, 10 mm thick crystal.



# Position determination: real data

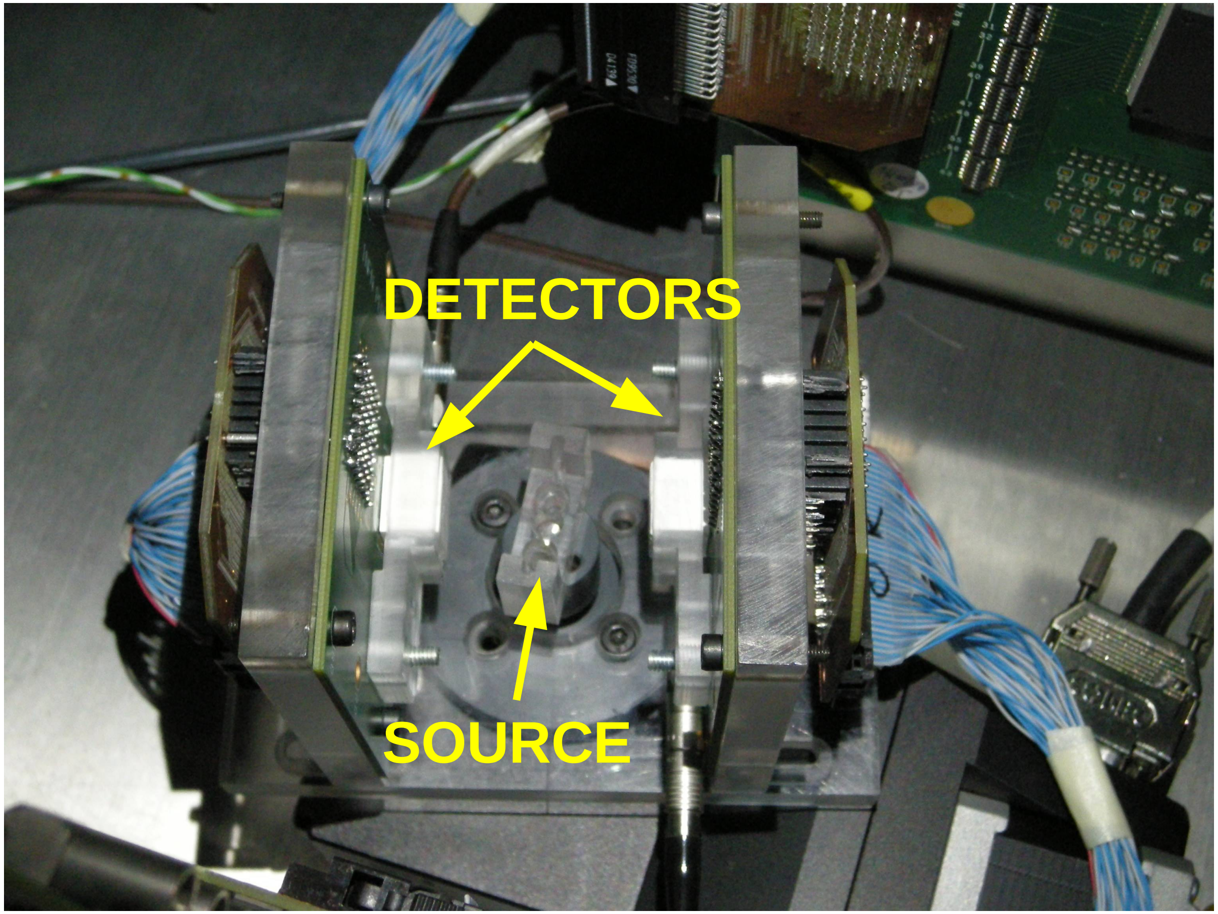
- DOI determination, 5 mm crystal.




Experimental x-z error, 1.8 mm FWHM

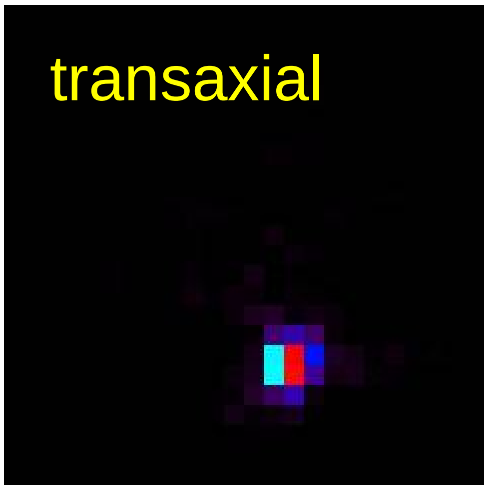
# Detectors tested in prototype

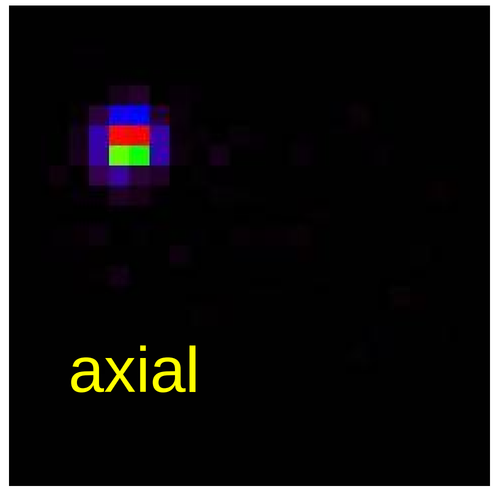



- Readout with two MAROC2 boards + NIM modules
- Data  taken at 6 different positions from 0º to 150º
- Na-22 sources in different positions

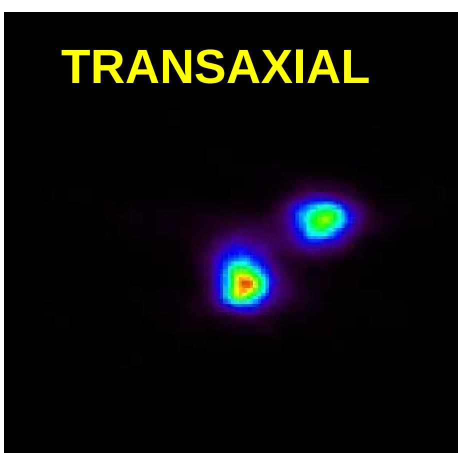
# Image reconstruction with ML-EM

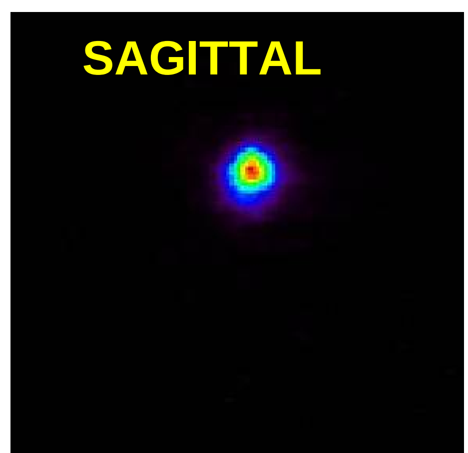
Adapted to continuous crystals.

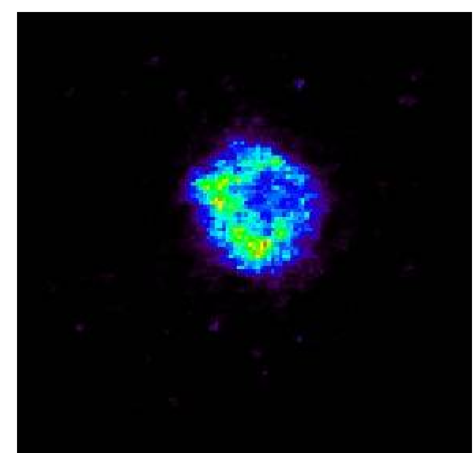



| | (x/y) |
|---|---|
| Transax FWHM (mm) | 0.71/0.68 |
| Transax FWTM (mm) | 1.9/1.7 |
| Ax FWHM (mm) | 0.8/0.9 |
| Ax FWTM (mm) | 2.2/1.8 |

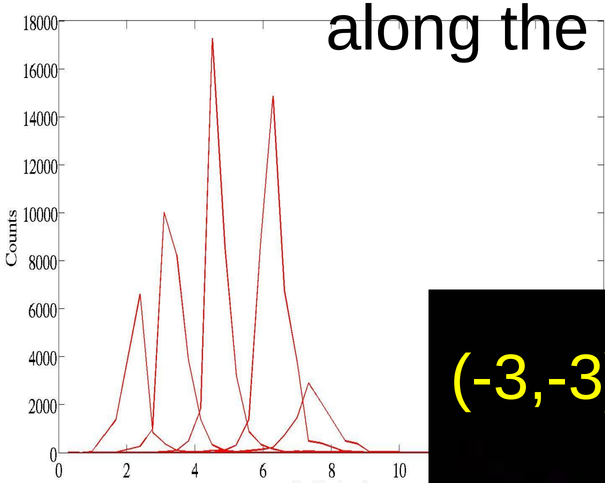


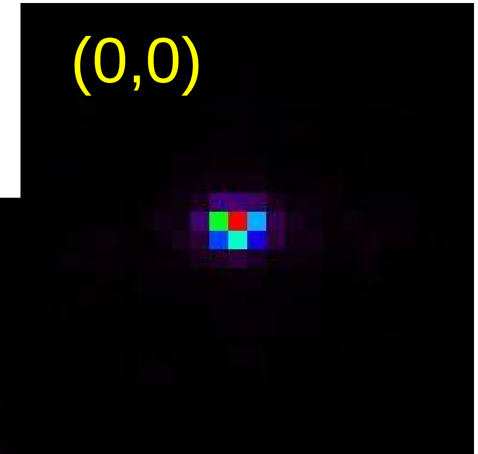



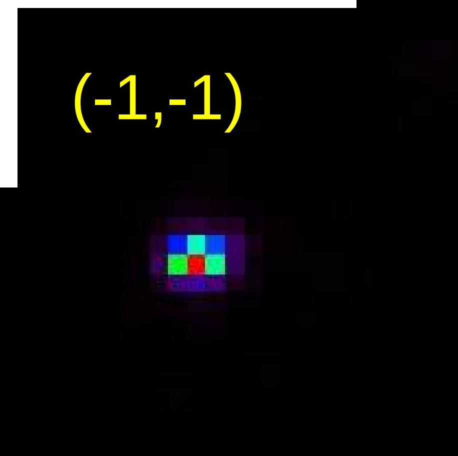



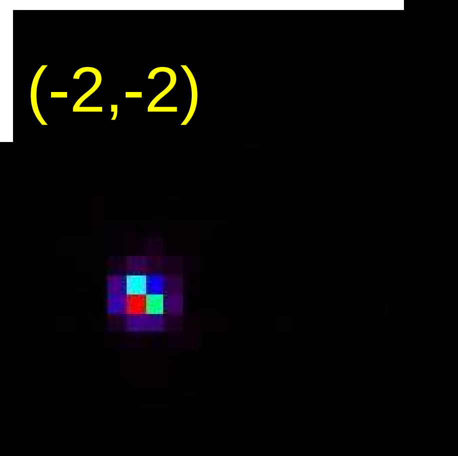
# Image reconstruction with ML-EM

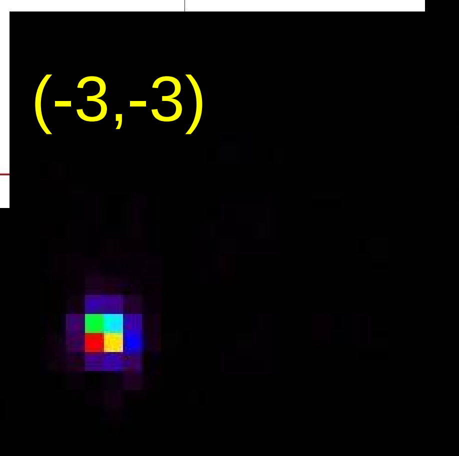
- 5 mm thick crystal.
- Source at different positions along the diagonal of FOV.

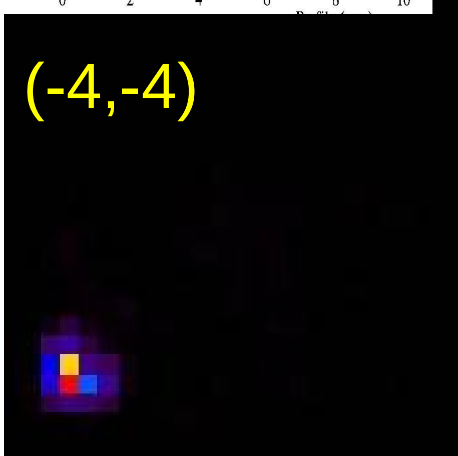



Average:
**0.77±0.08 mm FWHM**

| Nominal | Reconst | X FWHM (mm) | Y FWHM (mm) | Av FWHM (mm) |
|---|---|---|---|---|
| [0,0] | [-0.25,-0.25] | 0.93 | 0.66 | 0.78 |
| [-1,1] | [-1.25,-0.75] | 1.04 | 0.7 | 0.87 |
| [-2,2] | [-2.25,1.75] | 0.72 | 0.67 | 0.7 |
| [-3,3] | [-3.75,2.75] | 0.8 | 0.71 | 0.76 |
| [-4,4] | [-4.25,3.75] | 0.67 | 0.79 | 0.73 |

**G. Llosá et al.**
**NIM A 2013, 702, p 3-5.**

# Second prototype

# Prototype performance improvement

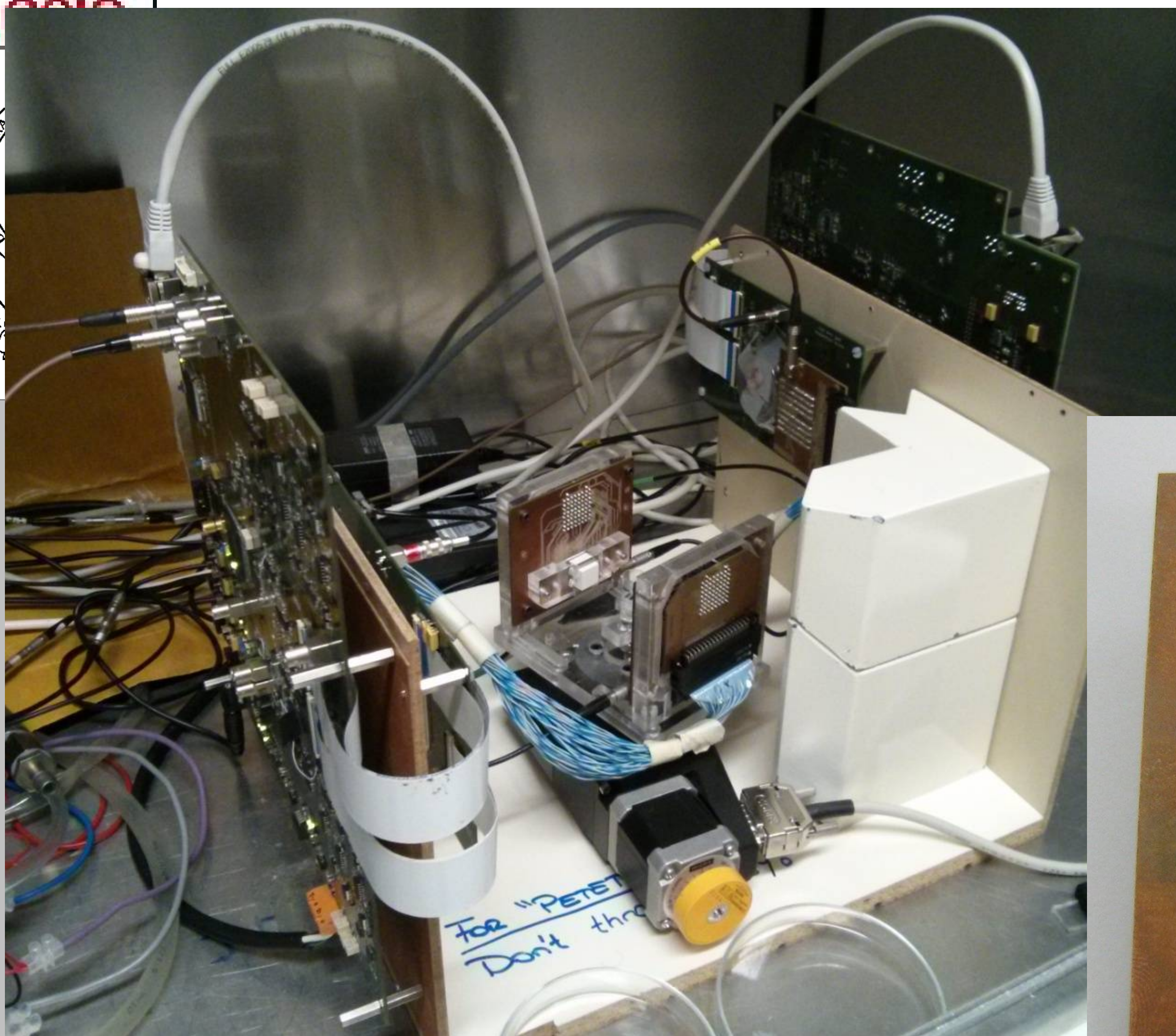
- ✔ Custom made electronics board to replace NIM modules for coincidence.
- ✔ Use of a new DAQ system.
- ✔ Improvement of timing resolution.
- ✗ Improvement of detector alignment.

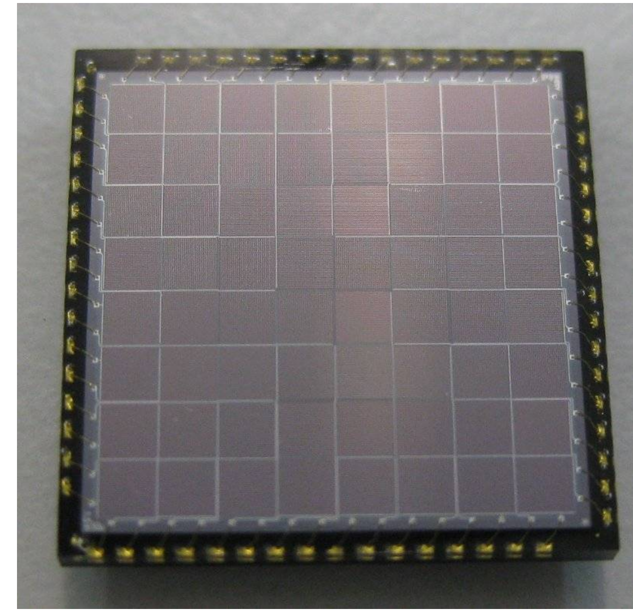
# Second prototype

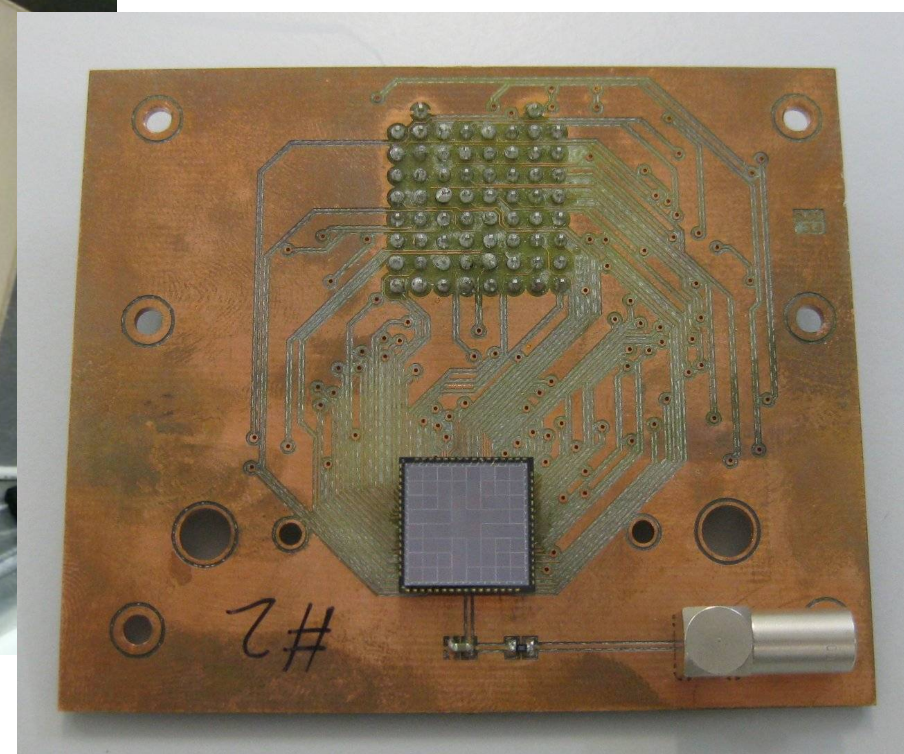
- New electronics needed for full ring

| | PETETE v1 | PETETE v2 |
|---|---|---|
| • New photodetectors | FBK SiPM 1.4 mm x 1.5 mm | AdvanSiD RGB-SiPM 1.45 mm x 1.45mm |
| • New electronics | MAROC2 | VATA64HDR16 |
| • New Data Acquisiton System | LabView program based on Windows USB output | MADDAQ+VMEDAQ based on Linux Ethernet output |

# Second prototype

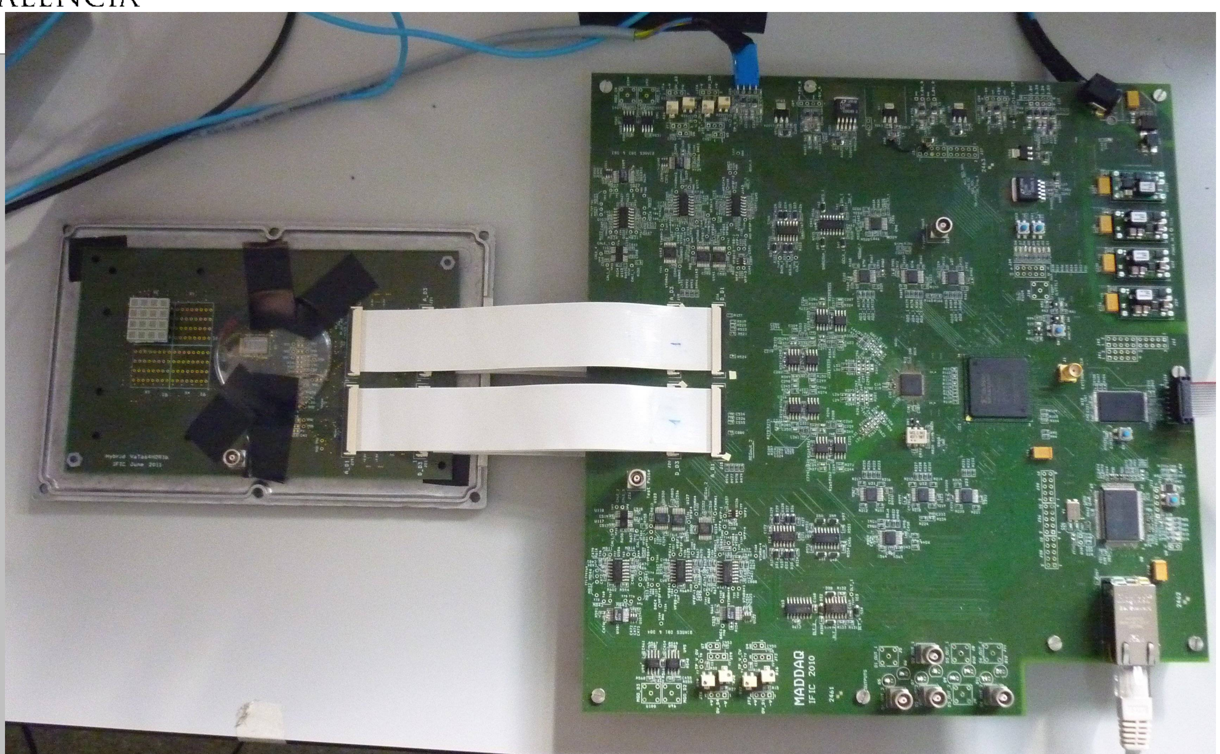






# New DAQ system

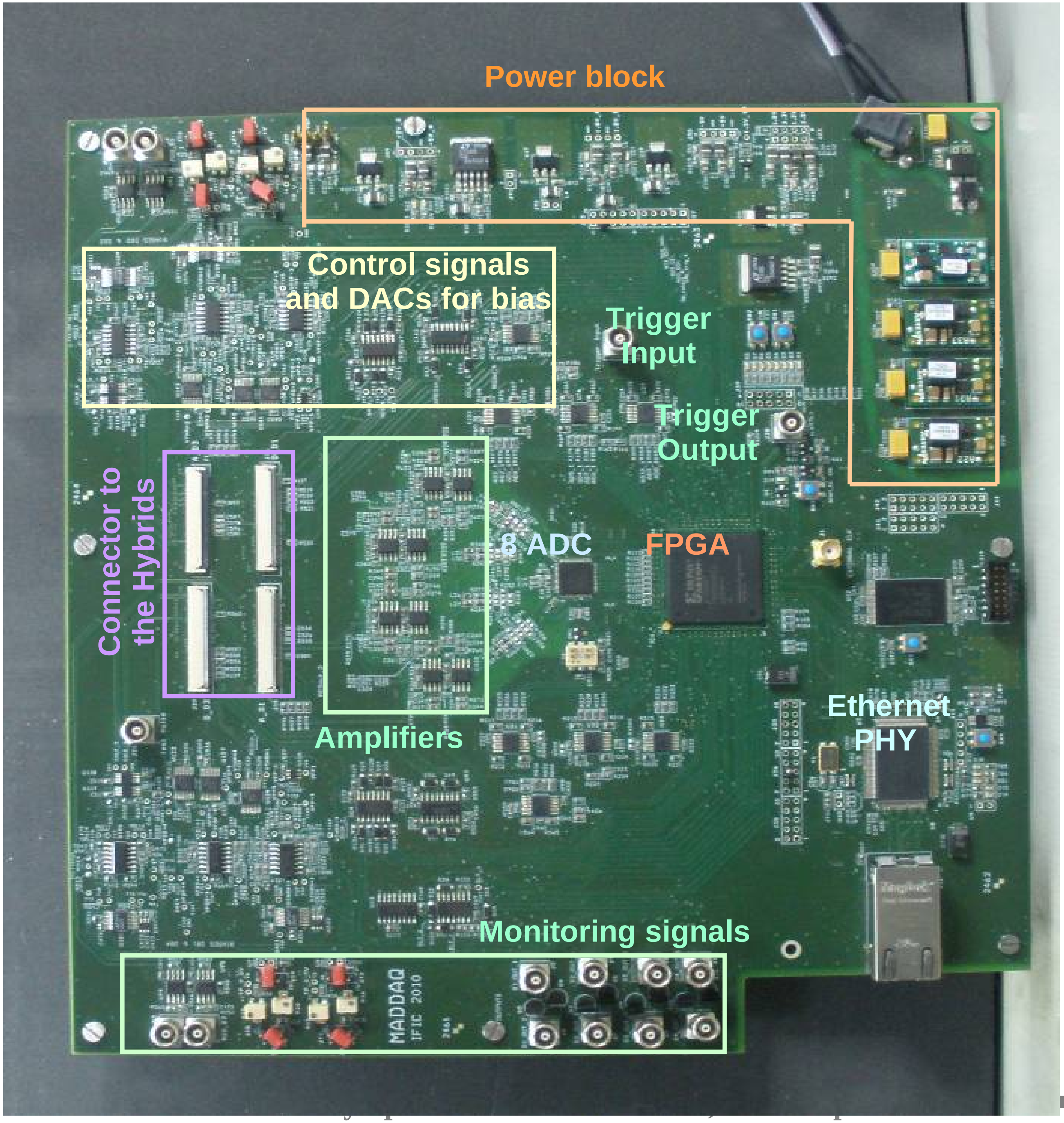
- Custom-made DAQ system.
- Employing VATA64HDR16 ASIC from IDEAS.
- Modular and flexible design.
- Easily adaptable to different types of detectors.



- FPGA Xilinx.
- Fast data transfer: Ethernet (up to 1 Gbps)
- Time stamp with 1 ns resolution.
- Several boards can work in time coincidence.

**V. Stankova et al. 2012 IEEE NSS Conf Record N14-107.**

# DAQ system

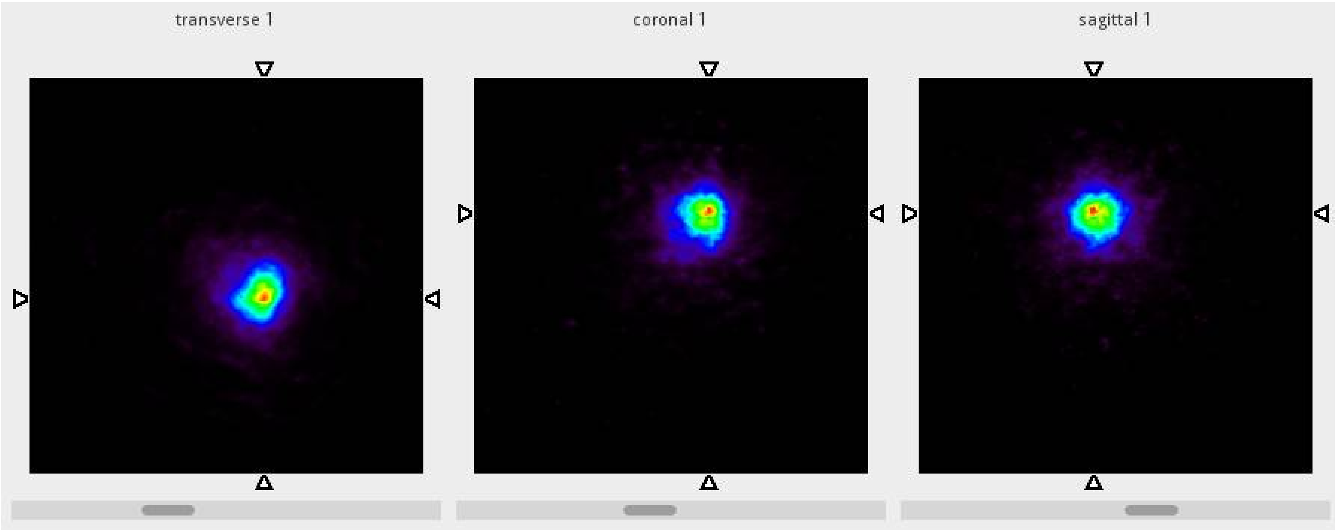

Power block
Control signals
and DACs for bias
Trigger
Input
Trigger
Output
Connector to
the Hybrids
Amplifiers
8 ADC
FPGA
Ethernet
PHY
Monitoring signals
MADDAQ
IFIC 2010

# Second prototype

**PRELIMINARY !!**

- 4 ns coincidence timing resolution

Reconstructed Point like source (0.5 mm radius)



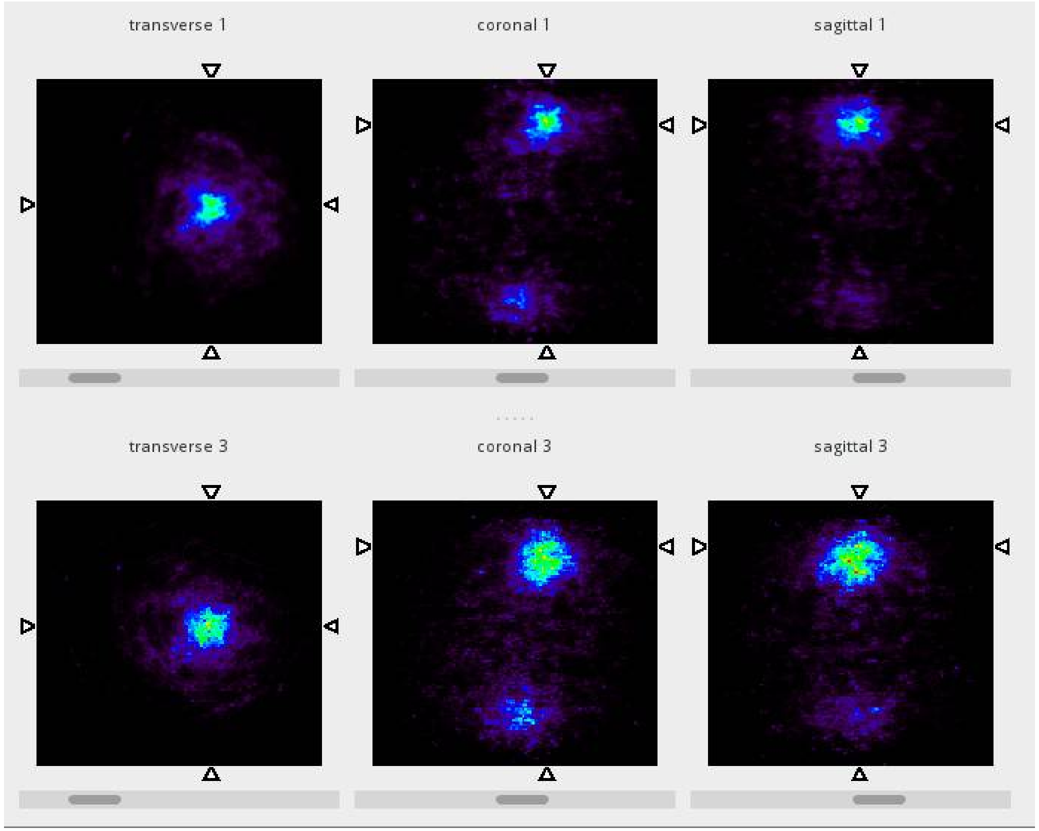

FWHM around 1.0 ±0.1 mm. 9 iterations

# Second prototype

**PRELIMINARY !!**

- Two point sources with different activity

d=8.7mm
FWHM =1.2mm




d=7.3mm
FWHM =1.5mm

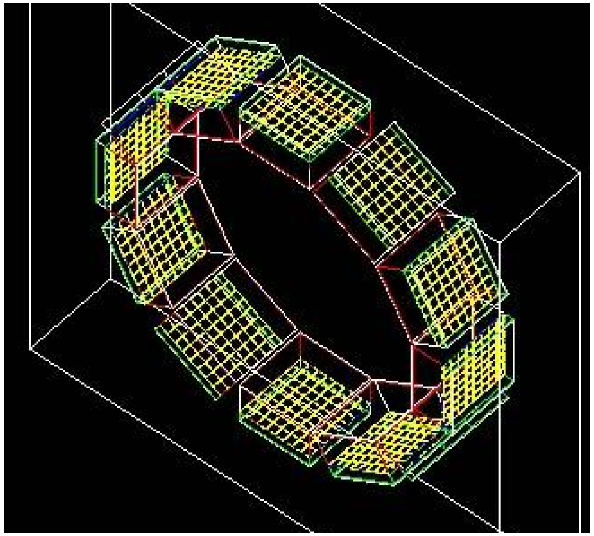
d=distance between reconstructed sources

- Tests with FDG ongoing

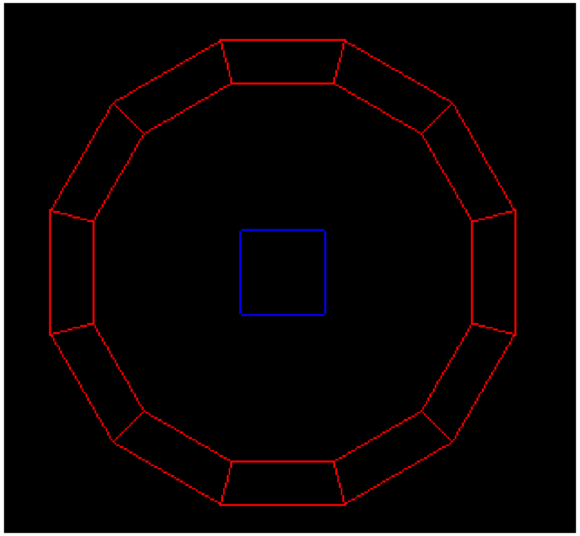
# New geometries

# Prototype performance improvement

- Full ring simulations with GATE:
  - Study effect of DOI corrections.
  - Use of tapered crystals to minimize the gaps.



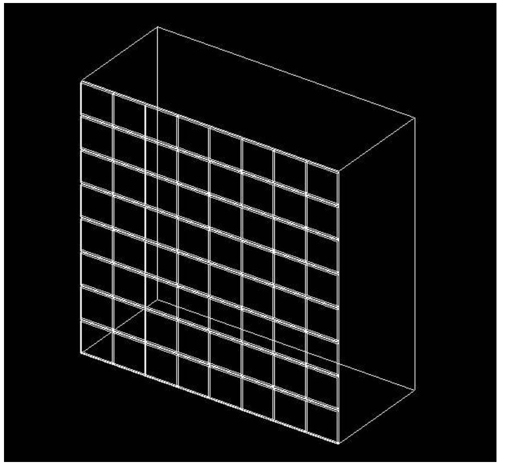
Continuous squared crystals
with optical properties



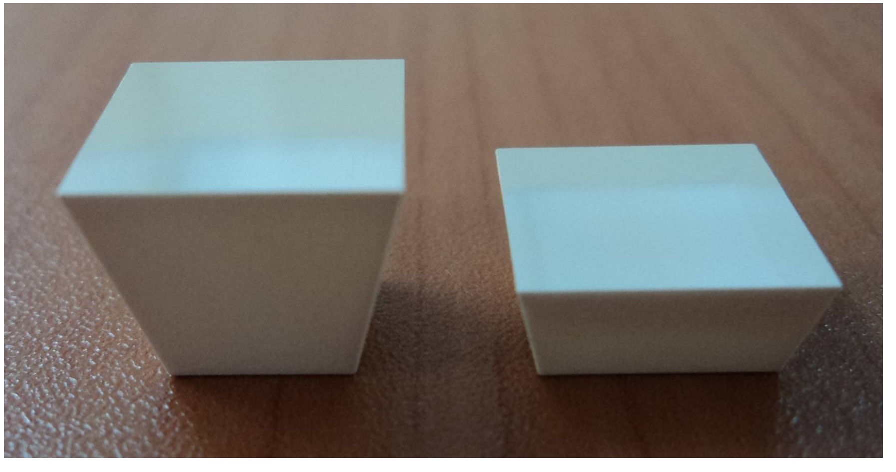
Tapered crystals

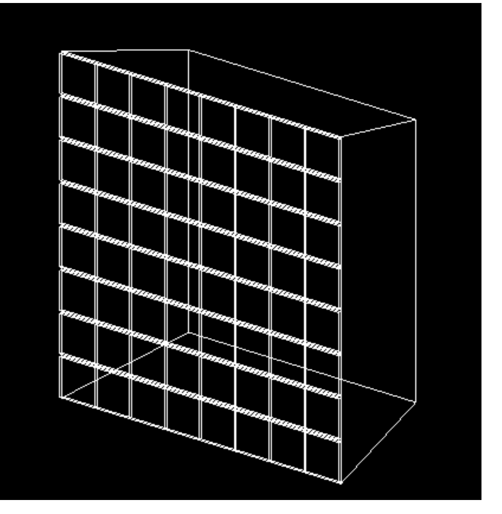
# Prototype performance improvement

- Detector simulations with GEANT4 to estimate the performance with different configurations and geometries
  - Including transport of optical photons.
  - Square and tapered crystals.
  - Simulations compared to real data.



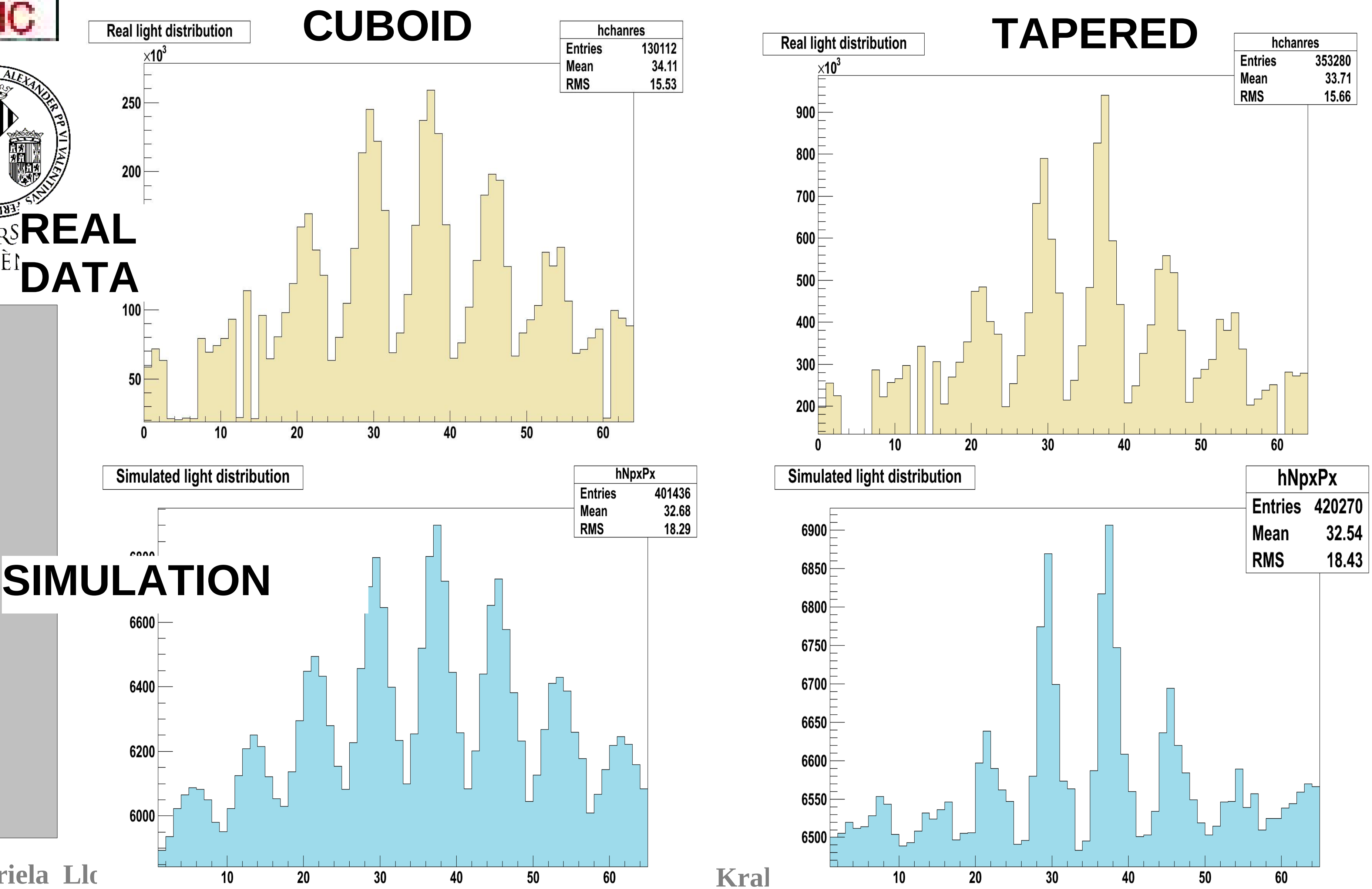
**J. Barrio et al.**
**2012 IEEE MIC**
**conf record**



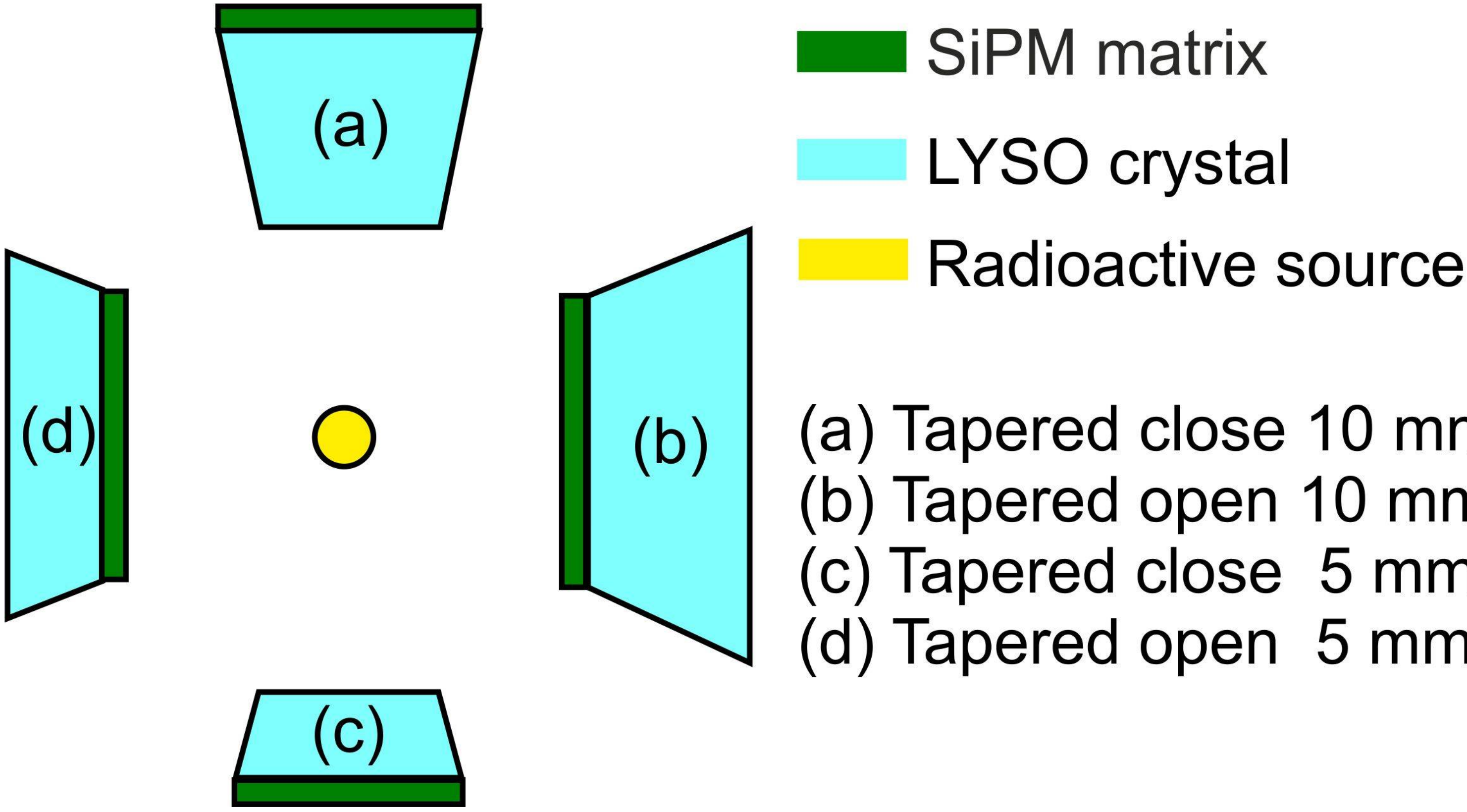


# Performance improvement

Light distribution in the photodetector



# Position determination



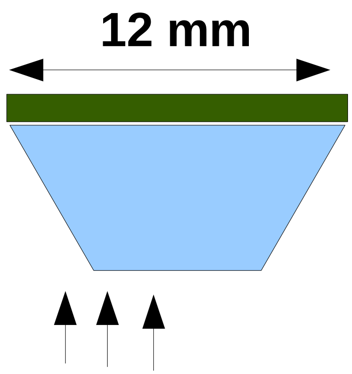

(a) Tapered close 10 mm
(b) Tapered open 10 mm
(c) Tapered close 5 mm
(d) Tapered open 5 mm

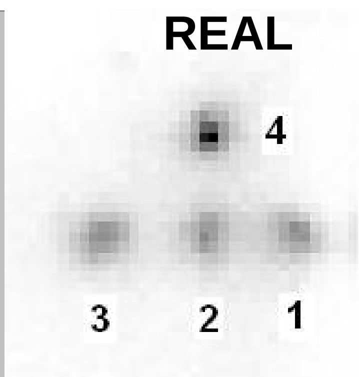
**J. Barrio et al.**
**2013 IEEE MIC**
**conf record**

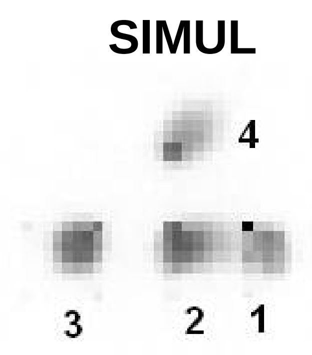
# Position determination

**PRELIMINARY !!**

- Tapered close 5 mm

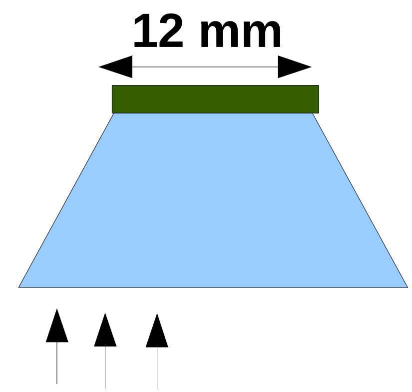


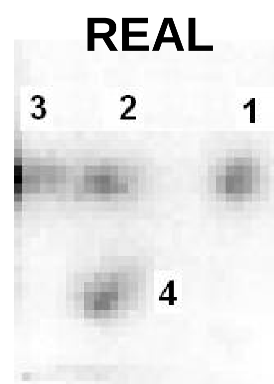



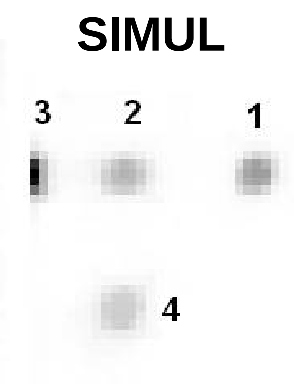




| point | Real | simulated |
|---|---|---|
| 1 | 1.07 | 1.02 |
| 2 | 1.02 | 1.05 |
| 3 | 0.71 | 1.23 |
| 4 | 0.95 | 0.77 |

- Tapered open 5 mm




| point | Real | simulated |
|---|---|---|
| 1 | 1.00 | 0.88 |
| 2 | 0.89 | 0.98 |
| 3 | 0.78 | 1.03 |
| 4 | 0.61 | 1.12 |

# Conclusions and future work

- A first prototype of a PET scanner with continuous LYSO crystals and SiPMs developed.
  - Position determination (including DOI) and image reconstruction algorithms adapted and working successfully.
  - Images of point-like sources reconstructed with FWHM better than 1 mm.
- Second prototype with improved performance recently assembled.
  - First tests ongoing. Needs optimization.
  - Imaging of Derenzo-like phantoms initiated.
- Development of a full ring underway.
- Alternative geometries are being tested.

# Acknowledgment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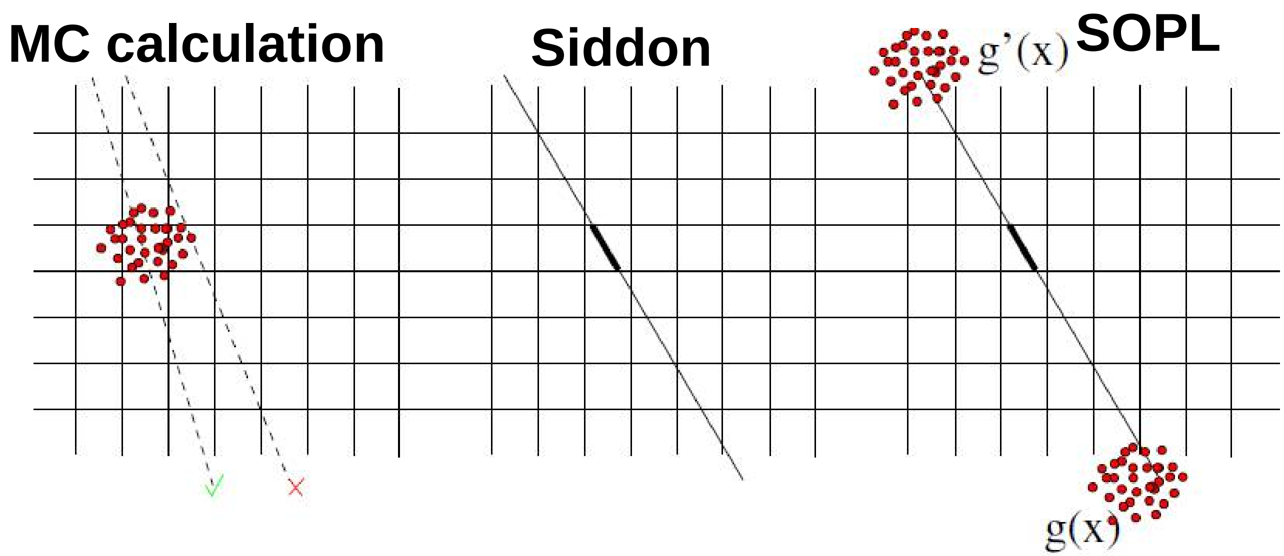
Thank you! Questions?

# Image reconstruction with SOPL

SOPL Simulated one-pass list mode.



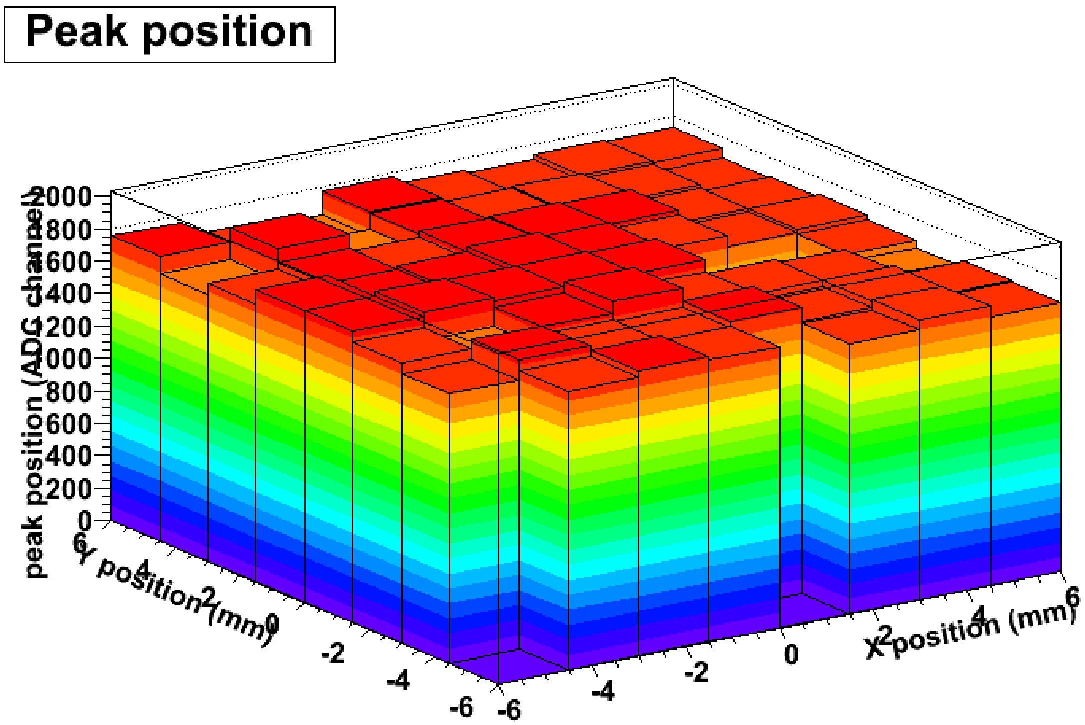

- Random Sampling in Measurement Space

SOPL: A Hybrid approach to system matrix calculation:

- MC sampling of PDF (Fast-simulation).
- On-the-fly calculation of matrix elements
- List-mode data

# Detector characterization

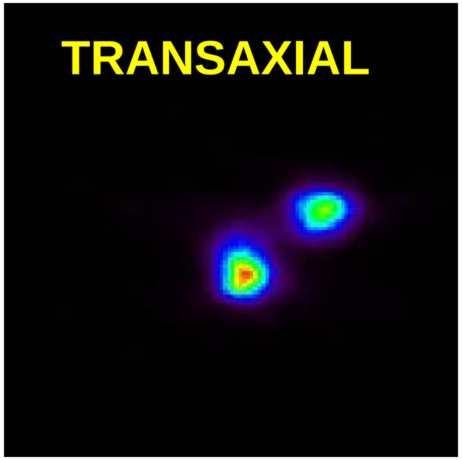
- Uniformity with pixellated crystal array coupled to SiPM matrix one-to-one
- Na-22 photopeak positions within 5%.
- No corrections applied

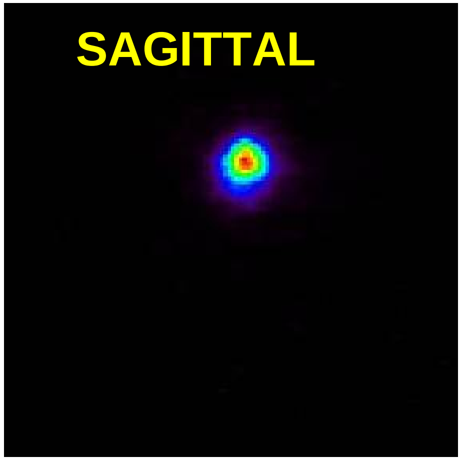


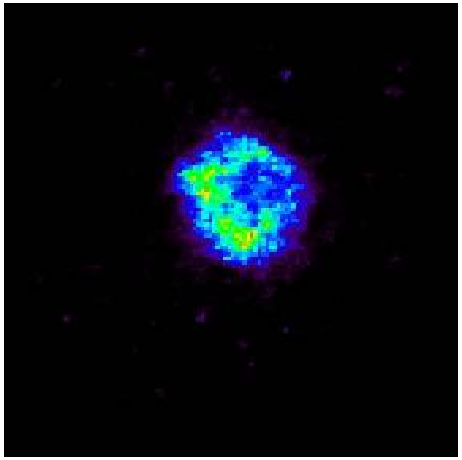
# Image reconstruction with ML-EM/SOPL

SOPL adapted to continuous crystals:

- On-the-fly calculation of system matrix elements.
- MC sampling of PDF.
- List-mode data.



J. Gillam et al.
*An Efficient Method of Reconstruction for AXPET Data: Simulated One–Pass List–Mode.*
11th International Meeting on Fully Three-Dimensional Image Reconstruction in Radiology and Nuclear Medicine, 2011, p 310--313