DEVELOPMENT OF PROMPT-GAMMA DETECTORS BY THE CLARYS COLLABORATION

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MediNet Midterm meeting
Vinča Institute of Nuclear Sciences, Belgrade, 12-14 March, 2018

OUTLINE

1. Introduction: CLaRyS collaboration
2. Description of the two cameras
3. Description of components & experimental results
4. First hodoscope beam test with final acquisition system
5. Next steps and perspectives

Gamma detectors for ion beam therapy monitoring in France

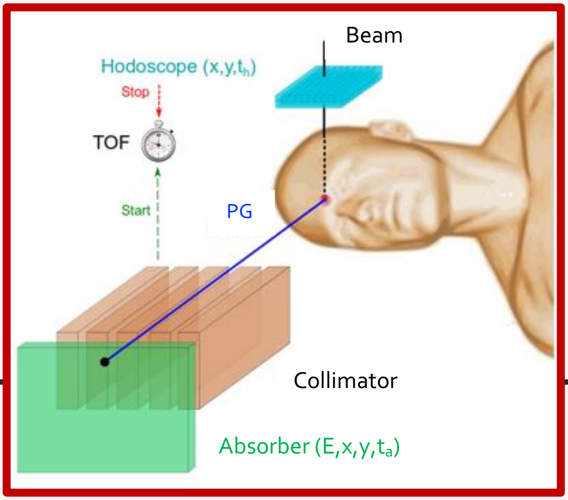
CLaRyS = Contrôle en Ligne de l'hadronthérapie par Rayonnements Secondaires – Online ion beam therapy monitoring by secondary radiation
Collaboration of 4 institutions -> IPNL (Lyon), LPSC (Grenoble), CPPM (Marseille), CREATIS (Lyon)

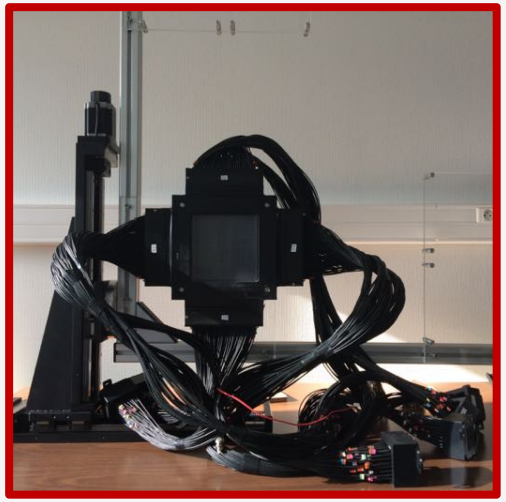
GOAL: development of gamma detection systems for time-of-flight prompt-gamma detection for ion beam therapy monitoring application.

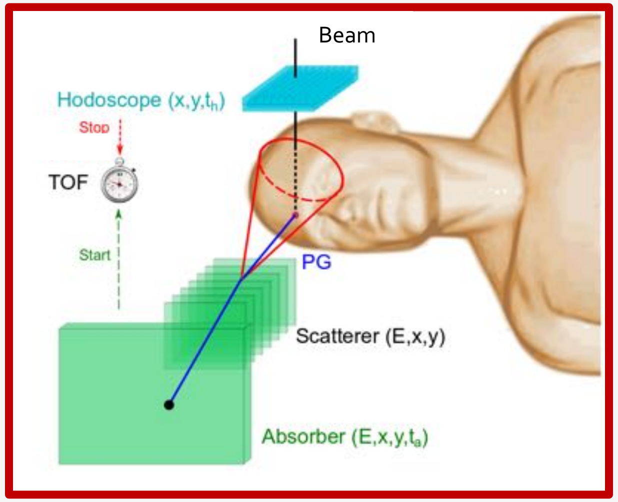
Development of two cameras:

- **Multi-slit collimated camera**
- **Compton camera**

A **beam tagging hodoscope** is also being developed for time-of-flight (TOF) measurements.

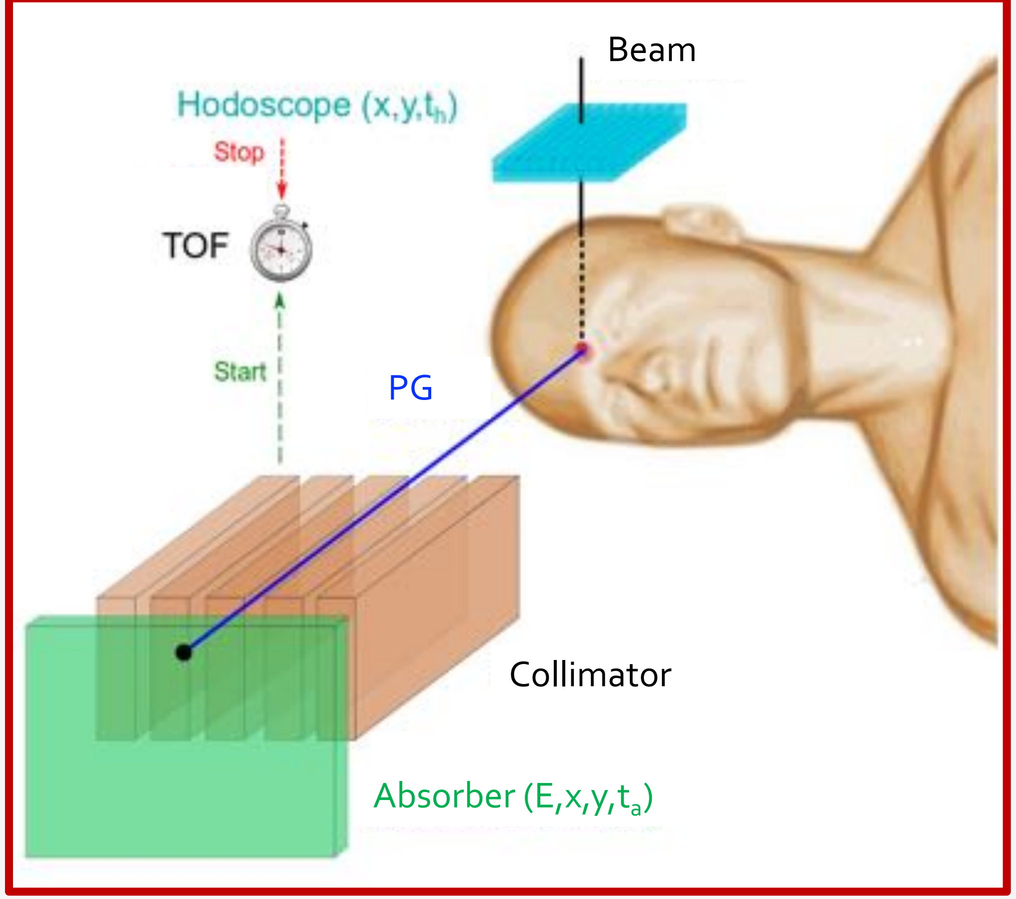






Multi-slit collimated camera (MSC)

MULTI-SLIT CAMERA (MSC)



Prototype design optimized by Monte Carlo simulations *[Pinto, PMB 2014]*

The γ-rays emitted towards the camera are selected by a multi-slit collimator and absorbed by scintillators

- Mono dimensional spatial distribution reconstruction
- Relatively simple and cheap detector
- Low transmission efficiency

- Application in ion range monitoring
  - Mono dimensional prompt gamma emission profile

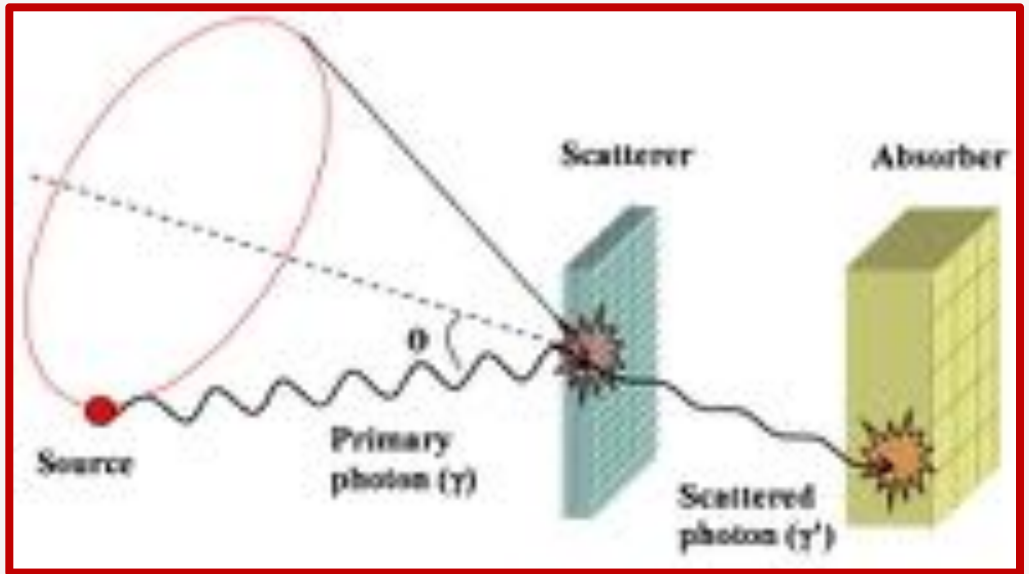
Components:

- multi-slit collimator
- segmented absorber

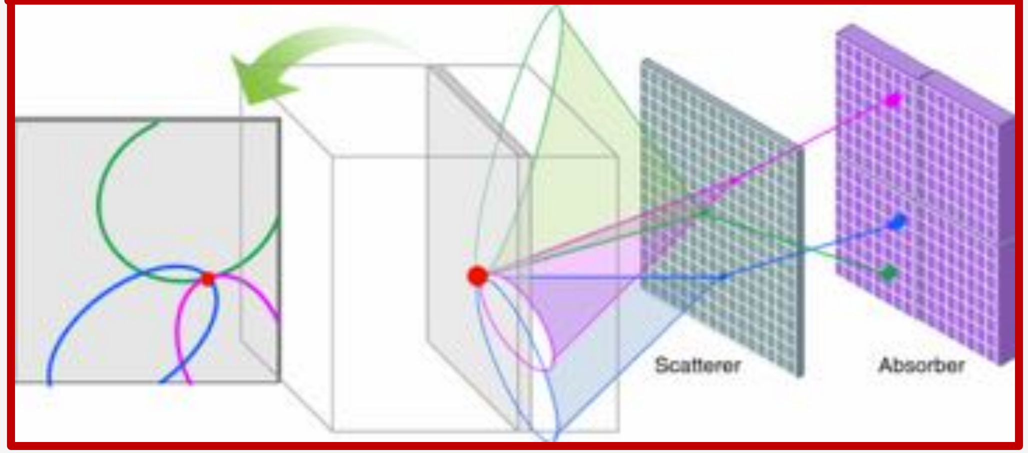
  +
- Beam tagging hodoscope (background rejection via TOF)

Compton camera: the principle

[Seo 2009]



[Kim 2013]



Two detector components:

- Scatterer – low Z position sensitive detector
  - maximize the probability of Compton scattering with respect to photoelectric absorption
  - reduce Doppler broadening effect
- Absorber – high Z segmented detector to maximize the probability of photoelectric absorption

→ Two positions and energy deposits

Compton scattering formula

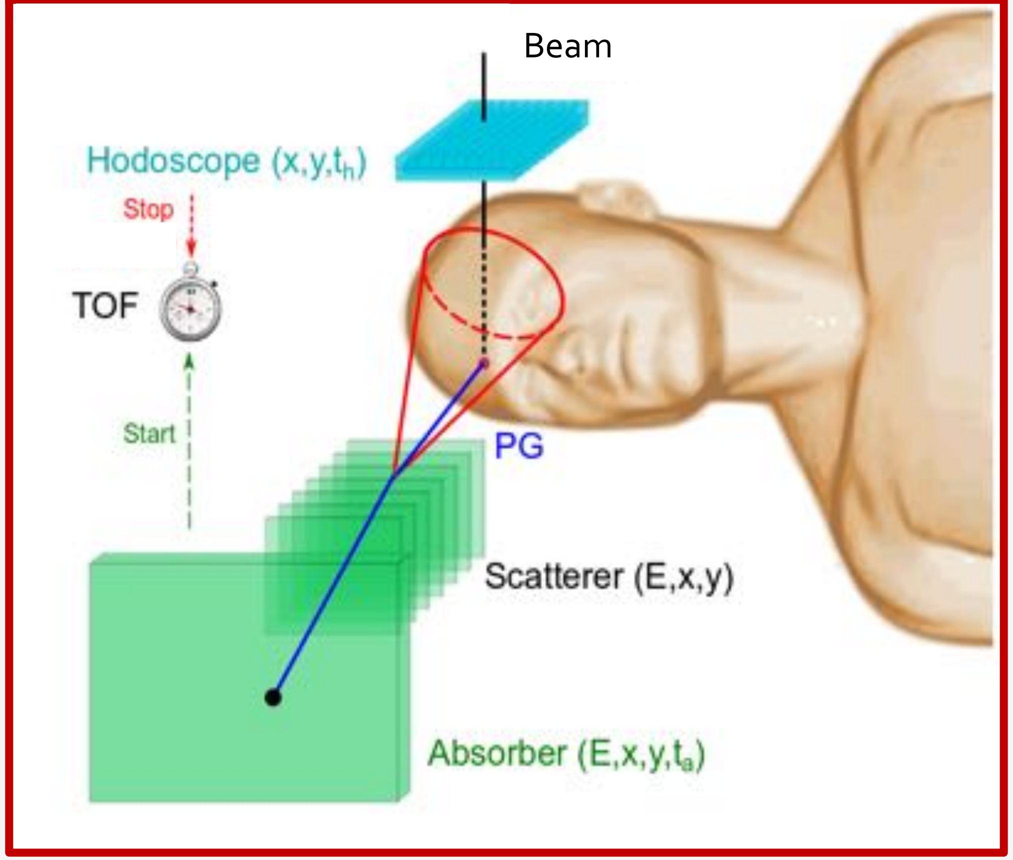
$$\cos\theta = 1 + m_e c^2 \left(\frac{1}{E_0} - \frac{1}{E_1}\right)$$

Reconstruction of a cone surface for each gamma event

Gamma emission vertex distribution reconstruction via cone interception

Compton camera (CC)

COMPTON CAMERA (CC)



Prototype design optimized by Monte Carlo simulations
[Roellinghoff, NIMA 2011]

Components:

- silicon scatterer stack
- segmented BGO absorber

+

- Beam tagging hodoscope – background rejection and beam positioning for simplified event reconstruction

Events:

- Time coincidences between scatterer and absorber energy deposits
  - TRUE GAMMA: coincidence by a single photon (Compton scattered)
  - BACKGROUND:
    - Coincidence of 2 different secondary particles
    - Coincidence induced by a single massive particle (n, e^-, …)

Events reconstruction:

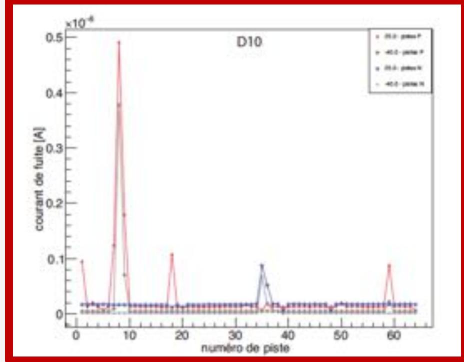
- Line-cone analytical algorithm
- LM-MLEM (List-Mode MLEM) algorithm developed by CREATIS group (Lyon)

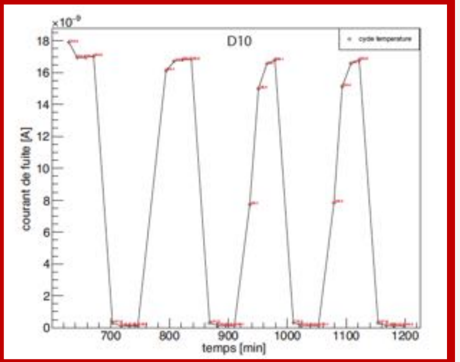
Detector components: scatterer/collimator

SCATTERER (for CC)

- 7 DSSD (Double-Sided Silicon Detectors) 96x96x2 mm^3 planes (10 planes were foreseen at the beginning, 3 are not suitable for the camera)
- 1.4 mm strip pitch
- 2 x 64 strips, XY position sensitive
- isolated box for thermal regulation
- custom electronic cards with new ASIC (developed by IPNL electronics group)

- Small prototype tested with radioactive sources
  - 14 keV FWHM energy resolution @ 122 keV (^{57}Co) at room temperature
  - ~20 ns FWHM time resolution P channels





- Final detectors characterized in terms of leakage currents
  - Tests performed with electronics card first prototype

COLLIMATOR (for MSC)

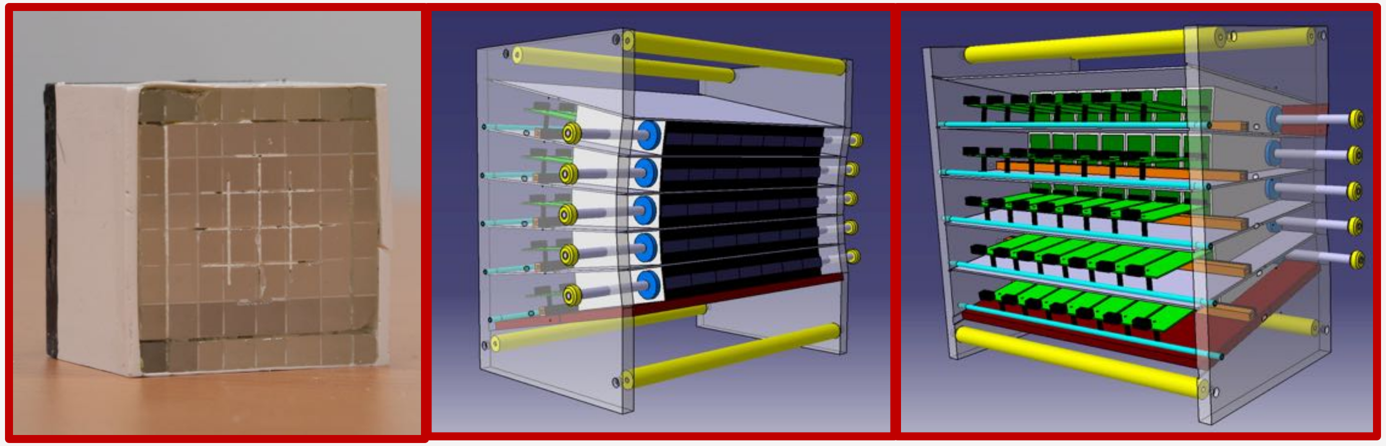
- tungsten, multi-slit
- optimized through simulation studies [Pinto PMB 2014]
- adjustable collimator and slit size

Detector components: absorber

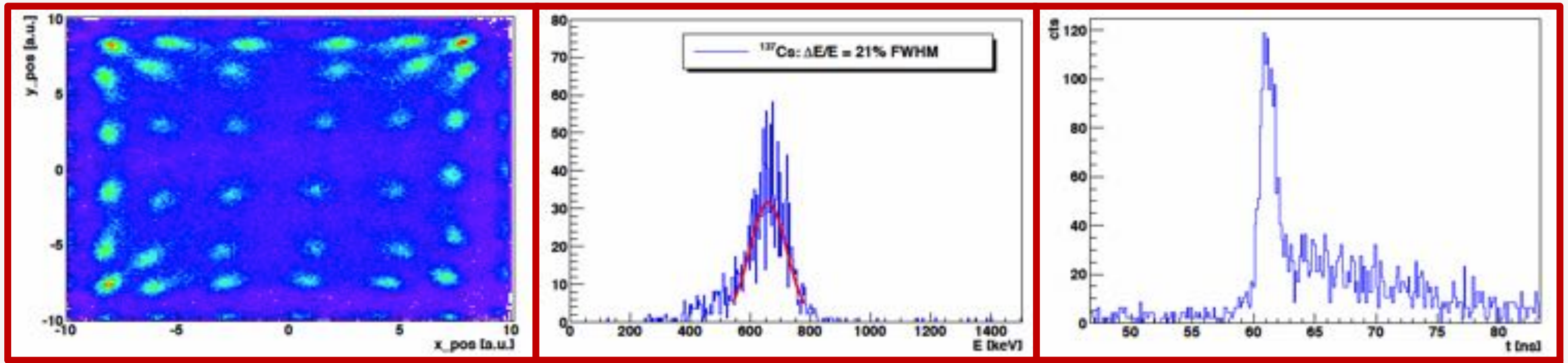
ABSORBER (common for the two cameras)

- modular structure – different geometrical possible setup
- ~30 BGO streaked blocks (~4 mm spatial resolution)
- 4 cylindrical PMs (Photo-Multipliers) for each block
- ASM front-end cards

- BGO blocks from a PET HR+ system by Siemens



- First characterization tests performed on original blocks @ GANIL and with radioactive sources



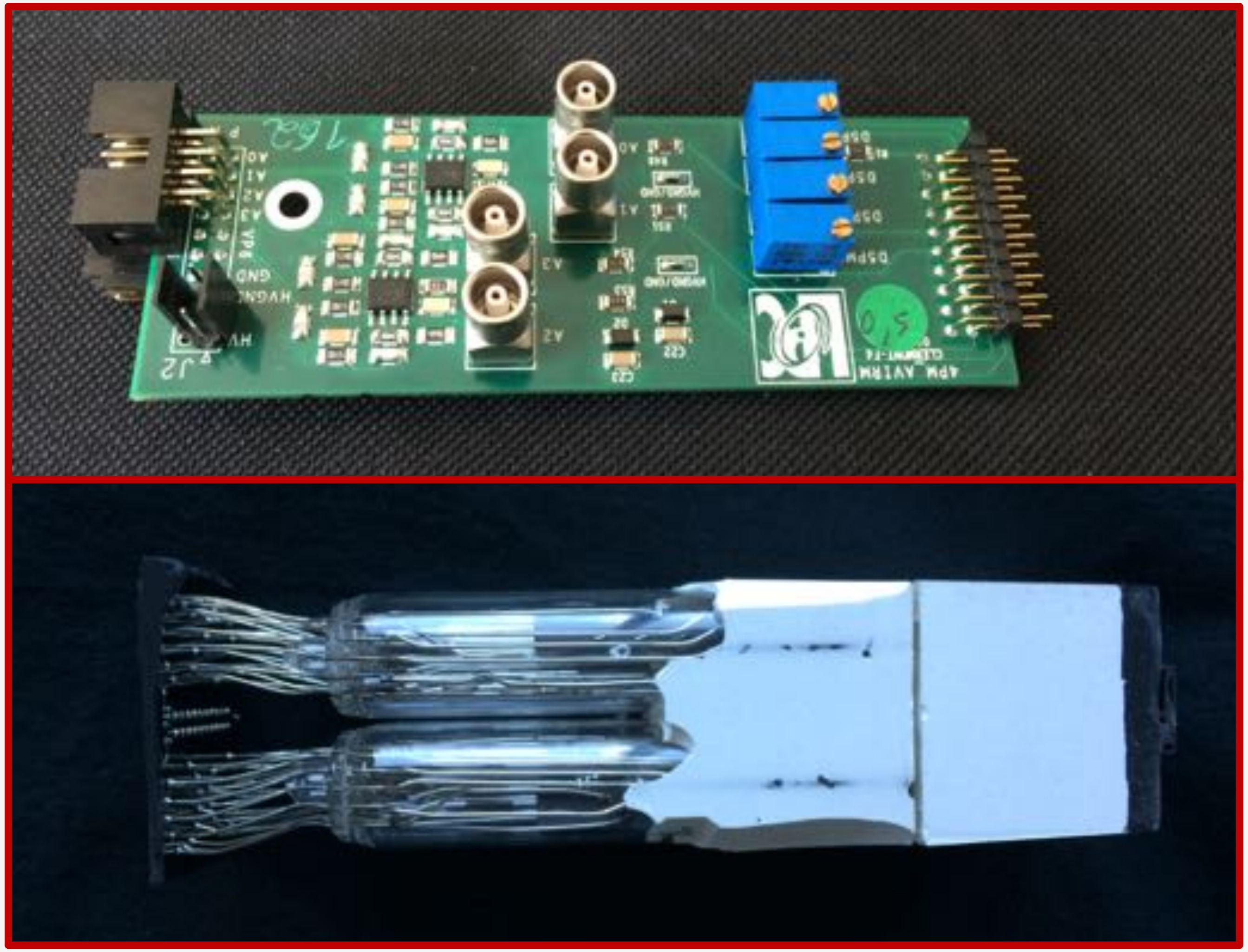
Energy resolution:
21 % FWHM
@ 667 keV (^{137}Cs)

Time resolution:
~2 ns FWHM
(PG measurement)

BGO blocks characterization

Characterization of energy, spatial and time response of each BGO block

- Based on gamma source irradiations:
  - ^{22}Na source: 511 keV + 1275 keV
  - ^{60}Co source: 1173 keV + 1332 keV



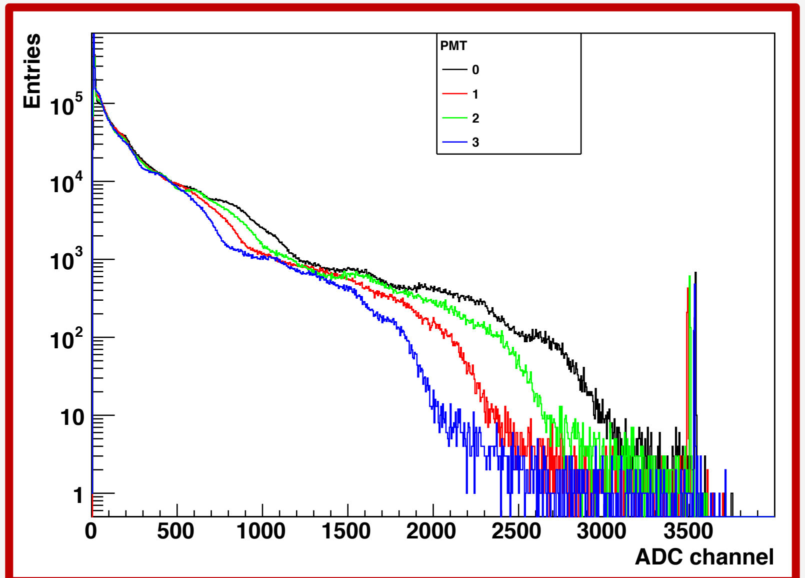
Let’s meet at my poster for further details!

BGO blocks characterization (i)

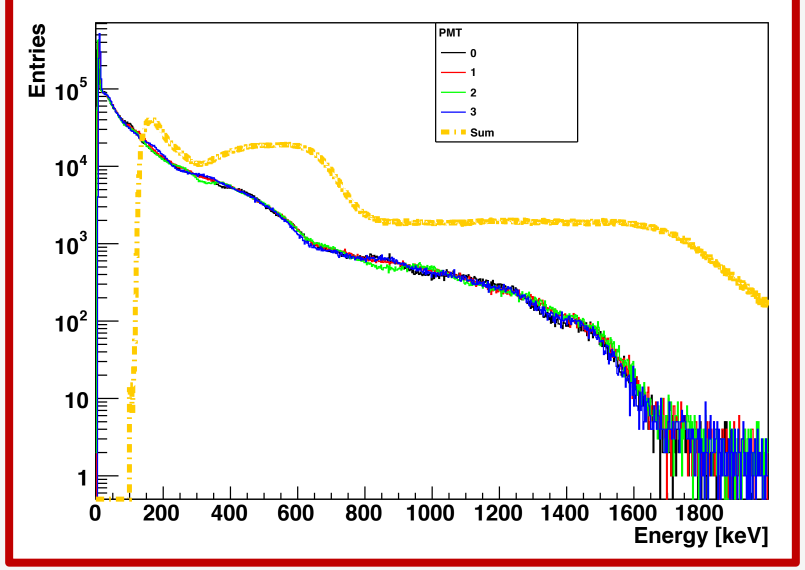
^{22}Na source homogeneous irradiation data

PM gain balance

Raw PM signal spectra



Balanced PM signal spectra



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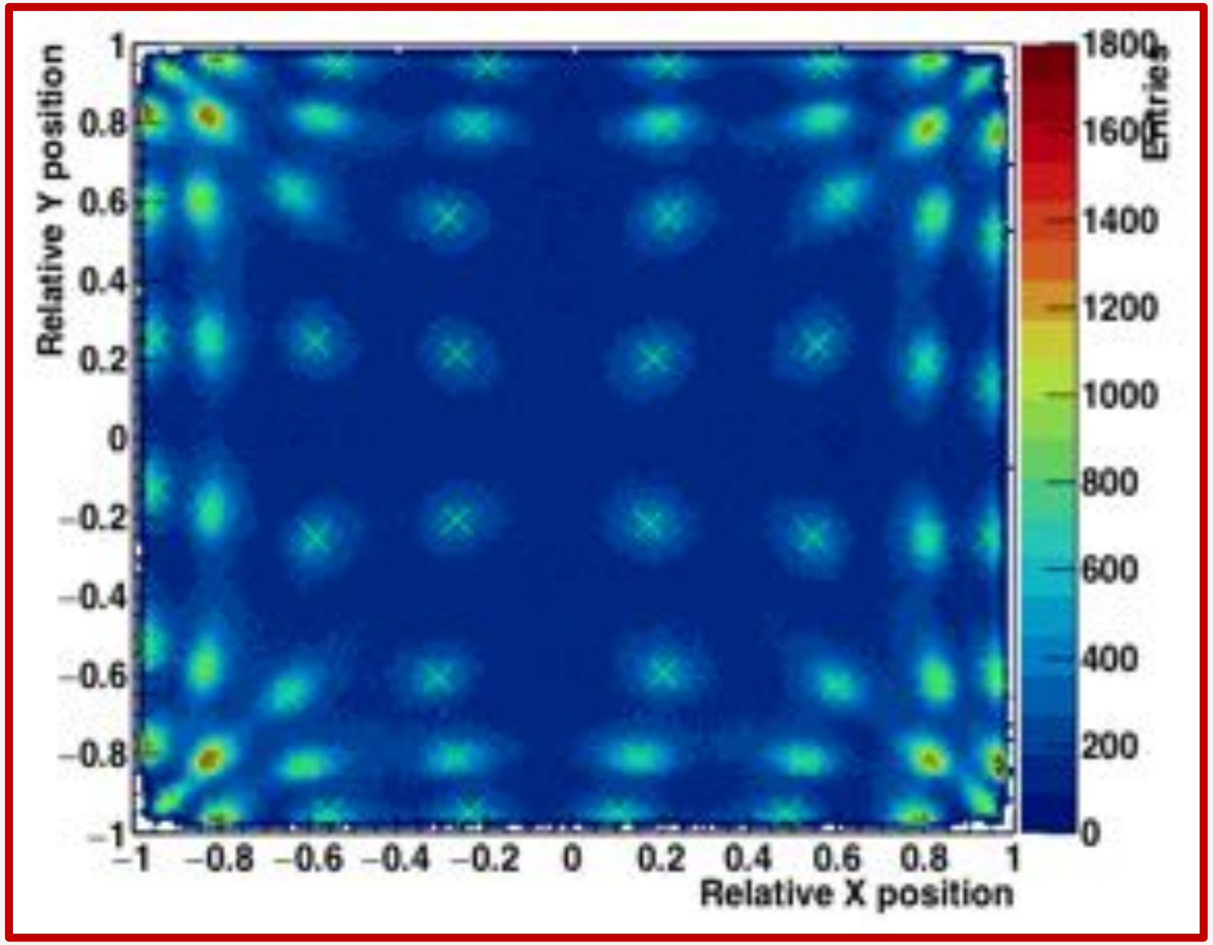
BGO blocks characterization (ii)

PM gain balance

Pseudo-pixel matrix reconstruction via automatic algorithm

^{60}Co source homogeneous irradiation data



Flood map with reconstructed pseudo-pixel matrix

Let’s meet at my poster for further details!

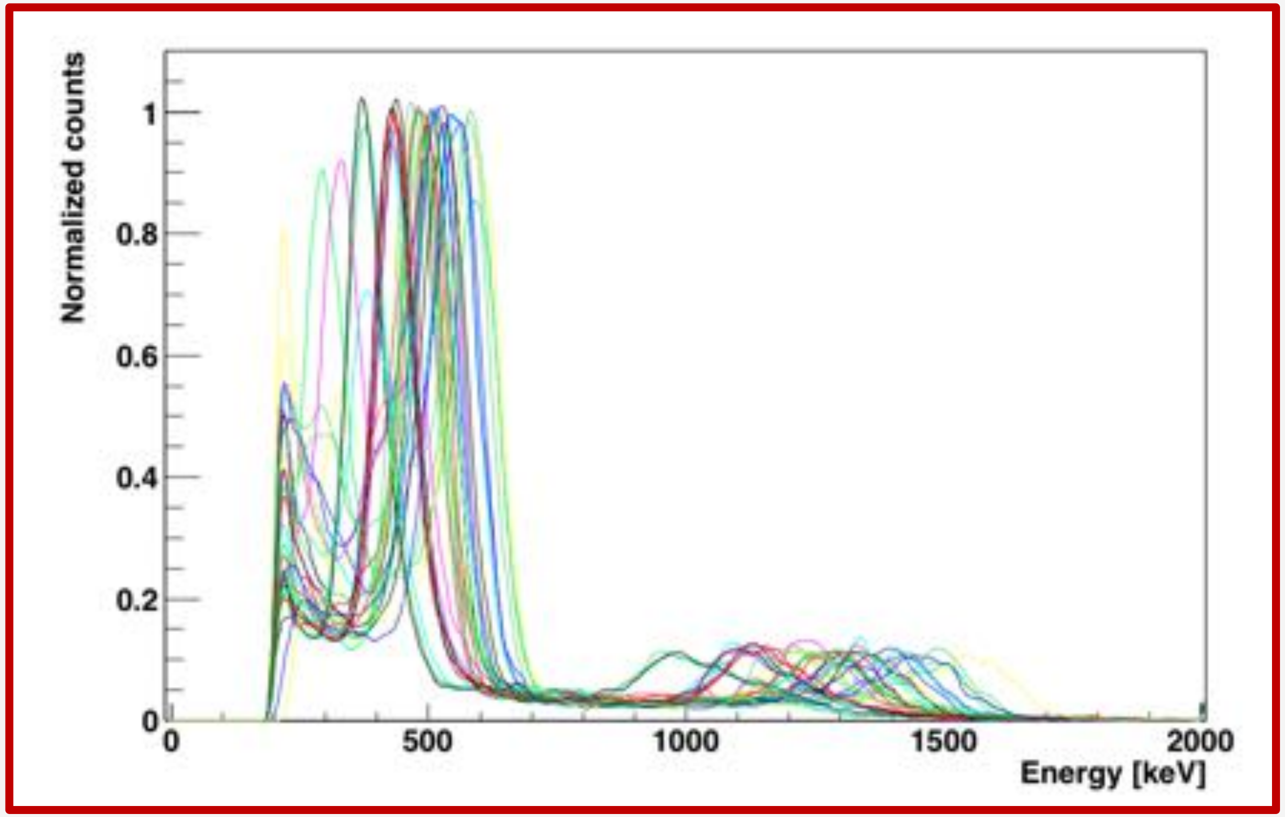
BGO blocks characterization (iii)

PM gain balance

Pseudo-pixel matrix reconstruction via automatic algorithm

Reconstructed events assignment to single pseudo-pixels

^{22}Na source homogeneous irradiation data



Energy spectrum pixel-by-pixel

Let's meet at my poster for further details!

BGO blocks characterization (iv)

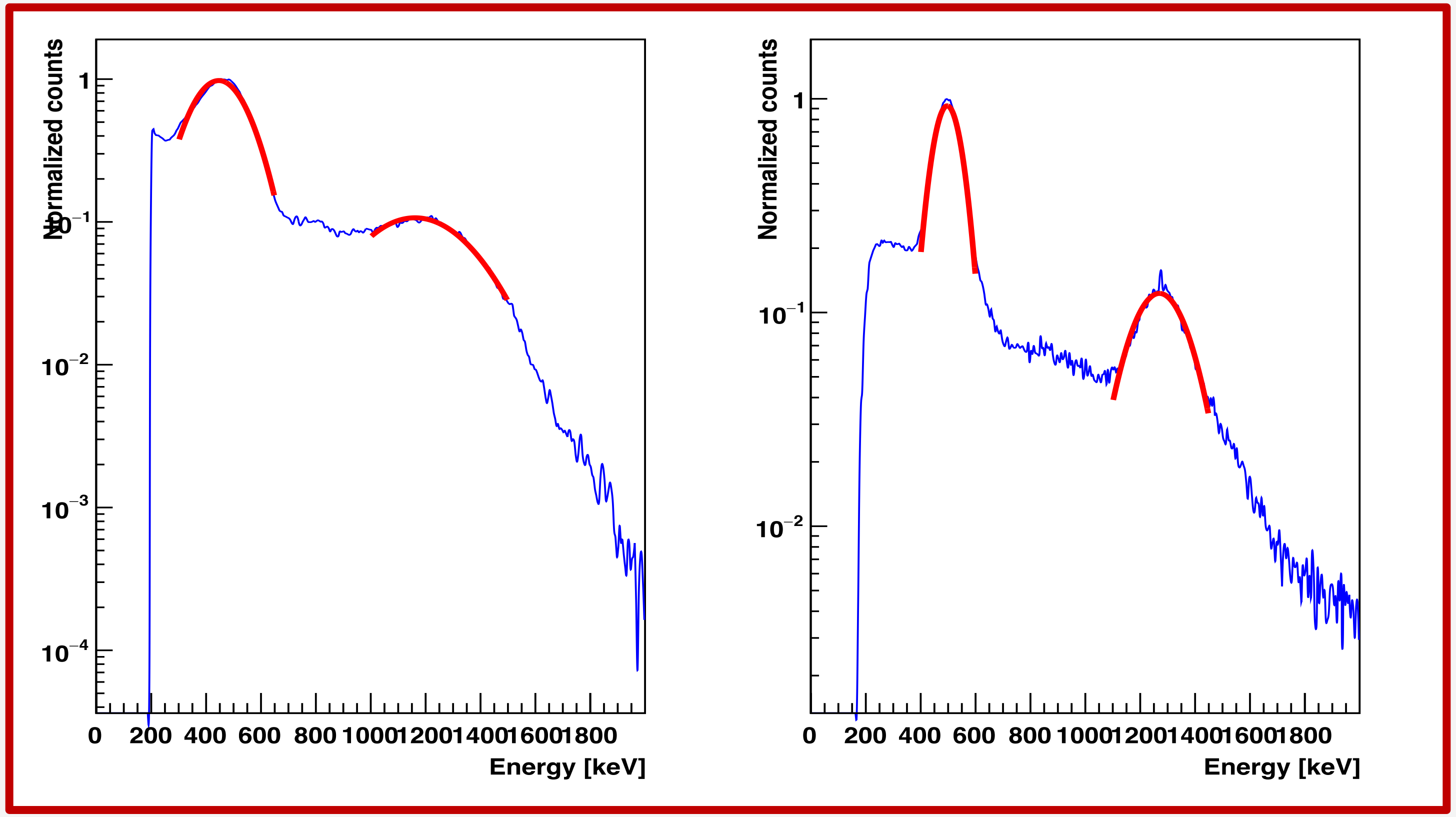
PM gain balance

Pseudo-pixel matrix reconstruction via automatic algorithm

Reconstructed events assignment to single pseudo-pixels

Pixel energy calibration

^{22}Na source homogeneous irradiation data



Block energy spectrum after PM balancing

Block energy spectrum after PM balancing and pixel calibration

Let's meet at my poster for further details!

BGO blocks characterization (v)

PM gain balance

Pseudo-pixel matrix reconstruction via automatic algorithm

Reconstructed events assignment to single pseudo-pixels

Pixel energy calibration

BGO BLOCK ENERGY RESOLUTION:

- Before pixel energy calibration
  - **511 keV : 46% FWHM**
  - **1275 keV: 39 % FWHM**
- After pixel energy calibration
  - **511 keV : 24 % FWHM**
  - **1275 keV: 19 % FWHM**

Let's meet at my poster for further details!

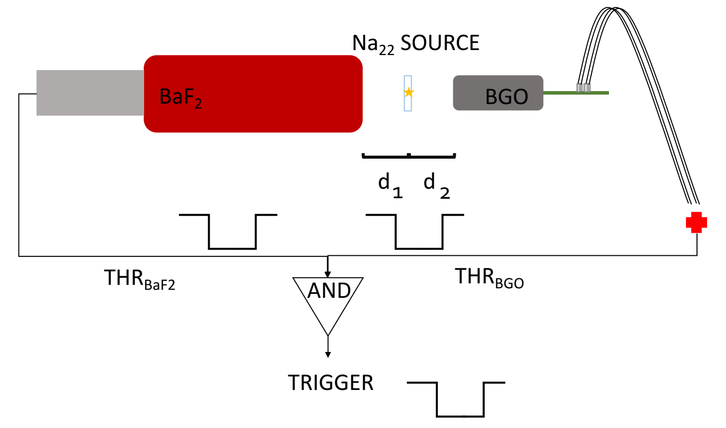
BGO blocks time resolution

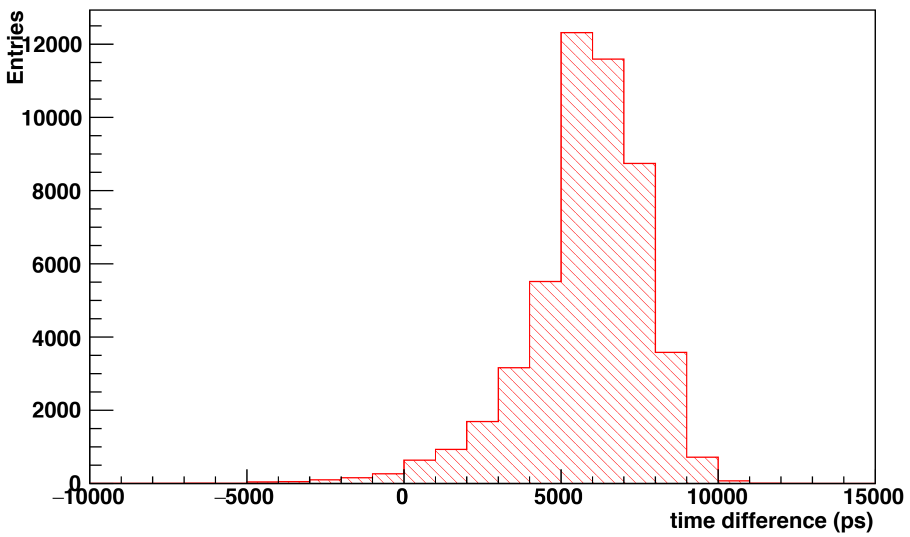
TIME RESPONSE CHARACTERIZATION

- BaF_2 as reference detector
- ^{22}Na coincidence irradiation
- 312 ps resolution acquisition system
- Timing signal analysis based on constant fraction discrimination
- BaF_2 - BaF_2 data set to define the BaF_2 resolution
- Time difference analysis to define the BGO time resolution

BGO BLOCK TIME RESOLUTION:

- **1.9 ns RMS**





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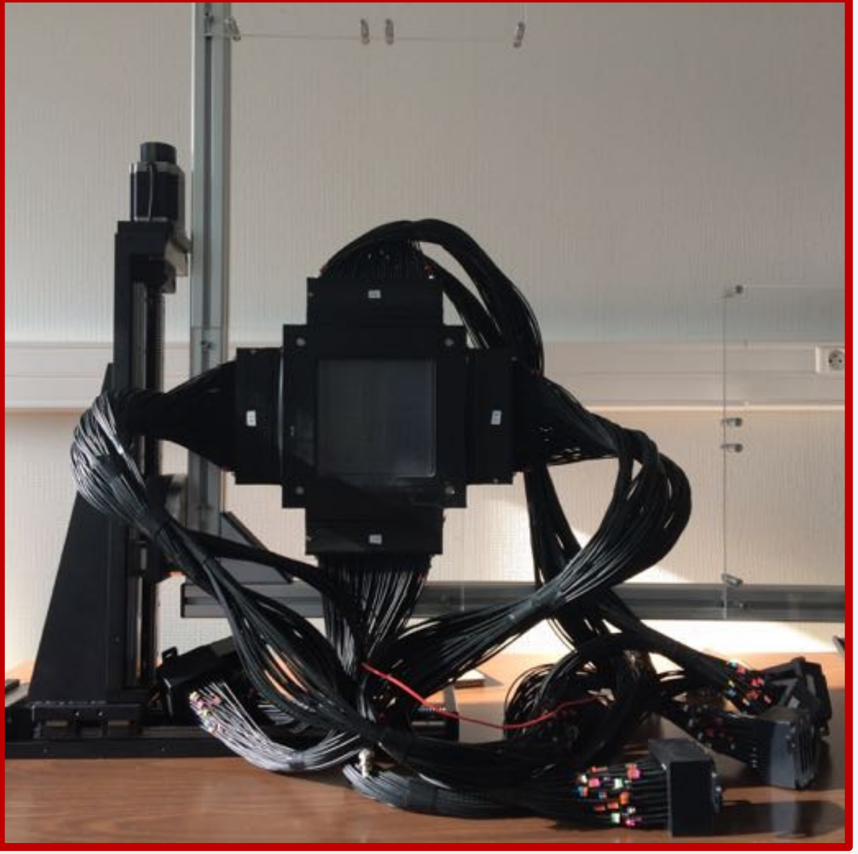
TOF and beam hodoscope

- For ion beam therapy monitoring, secondary particle background has to be handled and possibly subtracted
- Time Of Flight technique can be employed -> demonstrated possibility to reduce the background level and improve the SNR (Signal to Noise Ratio) – Testa 2010
- Fast beam tagging detector needed -> hodoscope under development

SCINTILLATING FIBER HODOSCOPE

- 128x2 scintillating fibers for 2D information
- 1 mm^2 squared fibers BCF 12 (Saint Gobain) , 140 mm long
- 2-sided read-out through 1 m optical fibers (one per channel)
- 8 Hamamatsu PM, 64 channels each (8x8 matrix)
- 512 channels in total
- Optical fibers connection in order to have the two sides of the same fiber on the same PM – uniform response
- Custom electronics cards
- Remotely controlled moving table as mechanical support, 2 axes

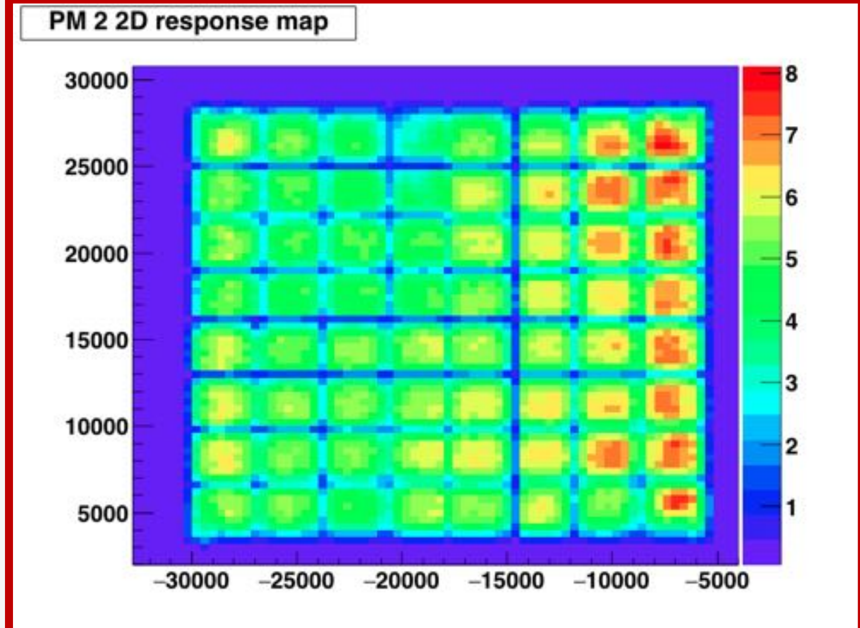


- Beam tests 2010-2014
  - 1 ns FWHM time resolution
  - ~90% efficiency
  - Rate 10^7 Hz per PM

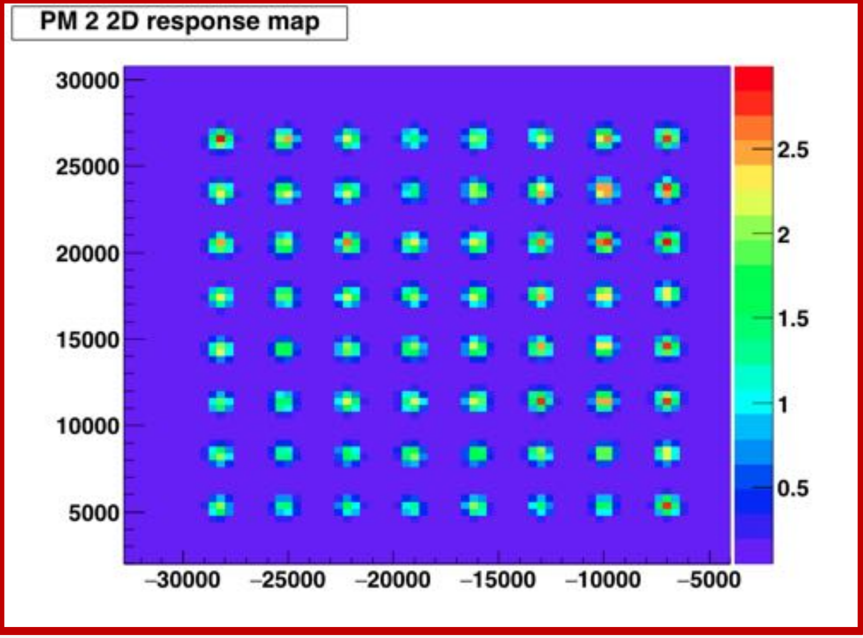
Hodoscope characterization (i)

- 8 Hamamatsu PM characterized with blue LED and moving table (November 2015 – May 2016)
  - Single pixel study for response uniformity characterization (2D response maps)
  - Study with fiber masks for cross talk characterization
- Complete system study for preliminary characterization with beta source (Stage M1 summer 2016) + simulation coding
- Characterization and verification of small hodoscope prototype (32 x 32 fibers)
- Test on beam of small prototype foreseen for April 2018
- Test on beam of final system foreseen before June 2018

Without mask



With mask



RESULTS
- PM response inhomogeneity factor 2-3
- New characterization on beam needed

Hodoscope characterization (ii)

- 8 Hamamatsu PM characterized with blue LED and moving table (November 2015 – May 2016)
  - Single pixel study for response uniformity characterization (2D response maps)
  - Study with fiber masks for cross talk characterization
- Complete system study for preliminary characterization with beta source (Stage M1 summer 2016) + simulation coding
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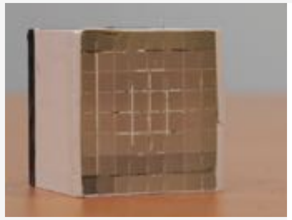
RESULTS

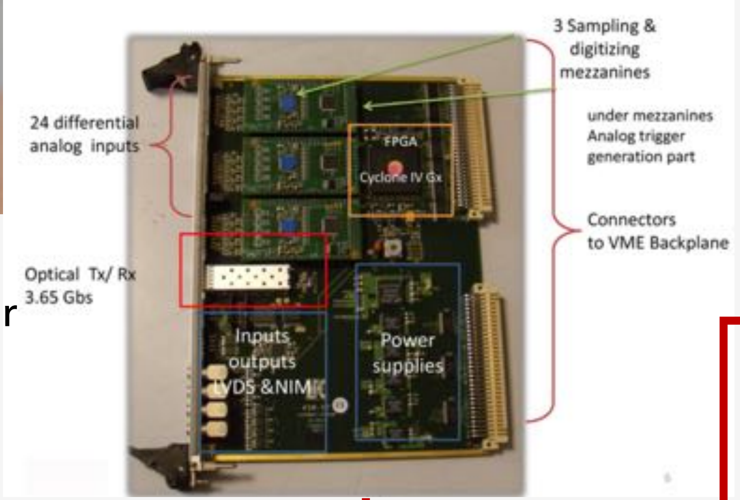
- PM response inhomogeneity factor 2-3
- New characterization on beam needed
- Cross-talk effect negligible in final detector configuration (with fiber mask)
  - **Signal detected on neighboring pixel always < 1%**

Acquisition system

- 8 hodoscope DAQ cards – 1 PM each



- ASM cards for the absorber
- TRIGGER

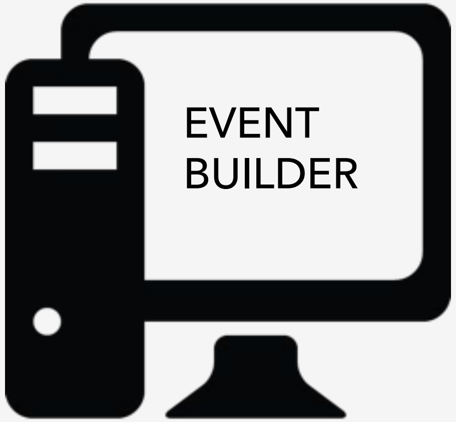


- 7 custom ASIC cards for scatterer detectors

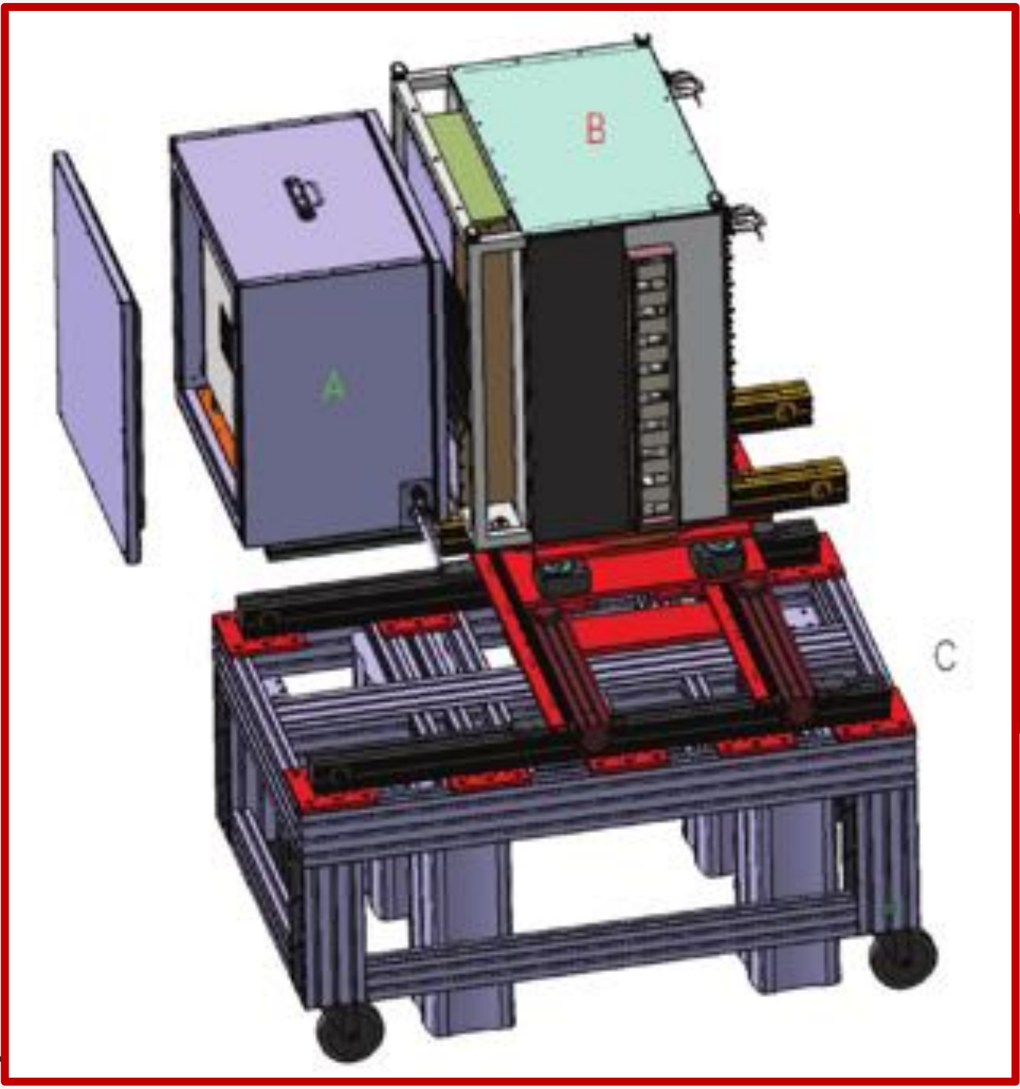
THOR

- Clock

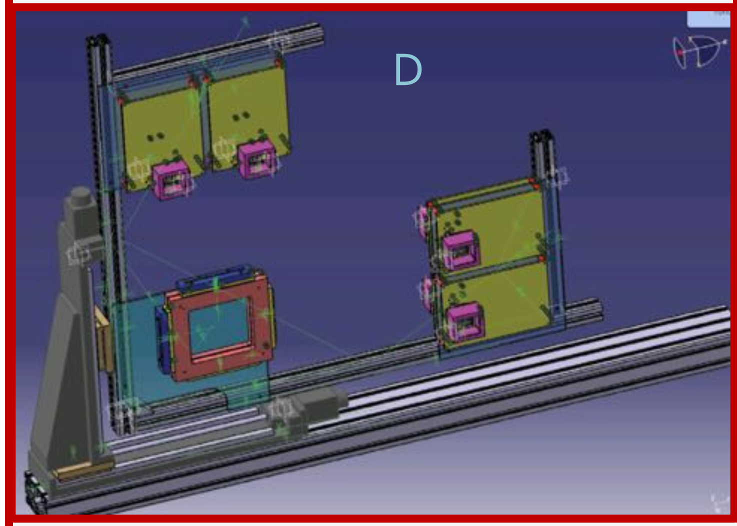
- AMC40 (µ-TCA standard)

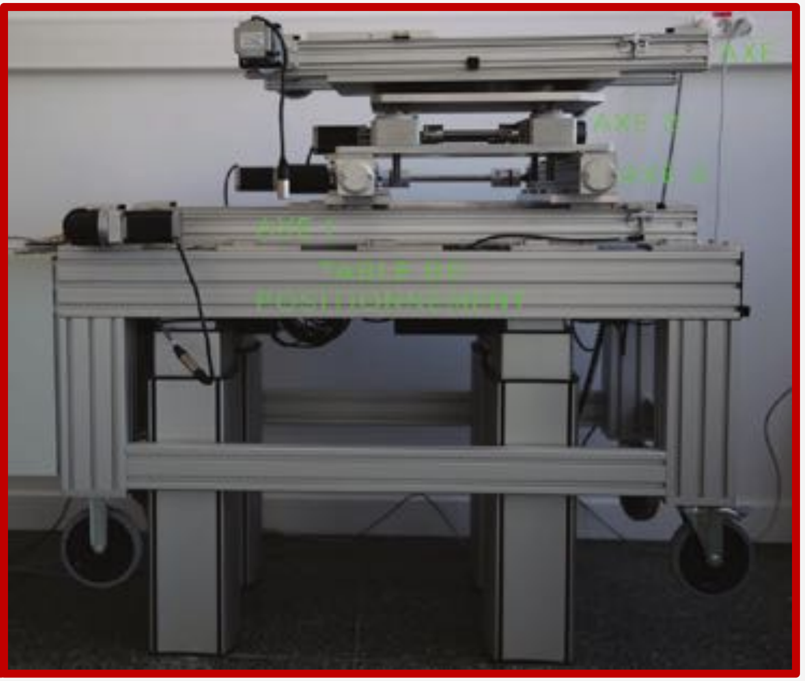


Mechanical support



- A : thermal box with Silicon detectors / collimator
- B : Absorber
- C : Positioning table
- D : Hodoscope table





- 2 movement axes
- Electronics cards support integrated

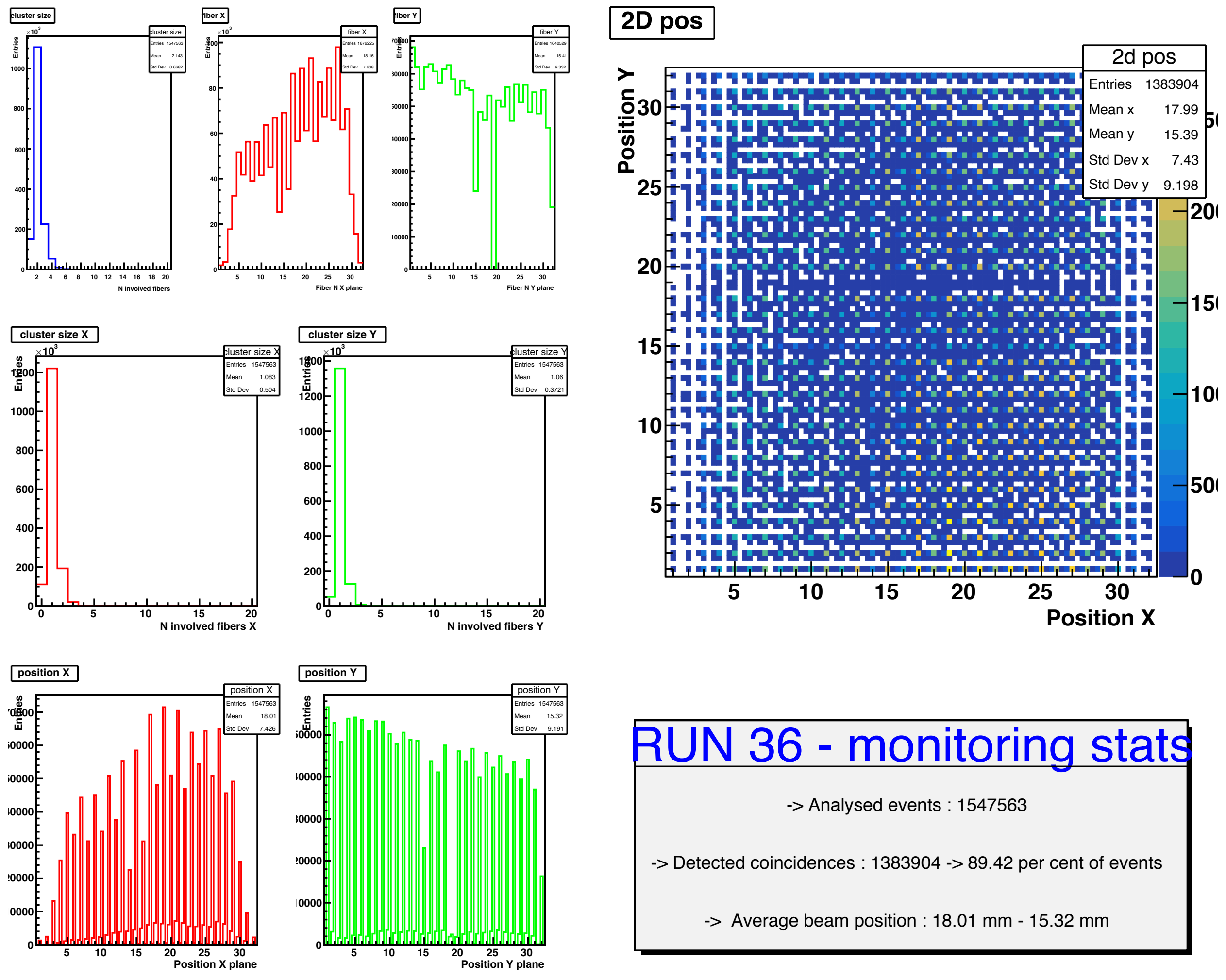
- 4 movement axes
  - 3 D overall movement
  - 2 section distance regulation
- Height range from 60 to 150 cm
- Wheels for portability

First hodoscope beam test

Beam test at the Centre Antoine Lacassagne (CAL) in Nice

- Small hodoscope prototype (32x32 fibers)
- 4 Hamamatsu PMs
- 1 single read-out card
- **Final acquisition system (AMC40)**
- No need for card synchronization

- Low intensity large size beam
  - 2-3 hodoscope fibers per event on average
  - hodoscope surface totally irradiated



RESULTS:

- Still some acquisition issues to be debugged (ongoing)
- Acquisition software to be optimized (ongoing)
- New beam tests planned for spring 2018

Next steps and perspectives

- Detector complete characterization with final electronics card
  - ASM cards ready, firmware to be debugged
  - Hodoscope cards ready, firmware to be tested with the final acquisition
  - Scatterer cards ready, firmware to be developed
  - μ–TCA acquisition firmware to be coded for detector specific application (CPPM PhD thesis)
  - μ–TCA acquisition system to be tested
- Camera components synchronization
- Test on beam

TIMELINE

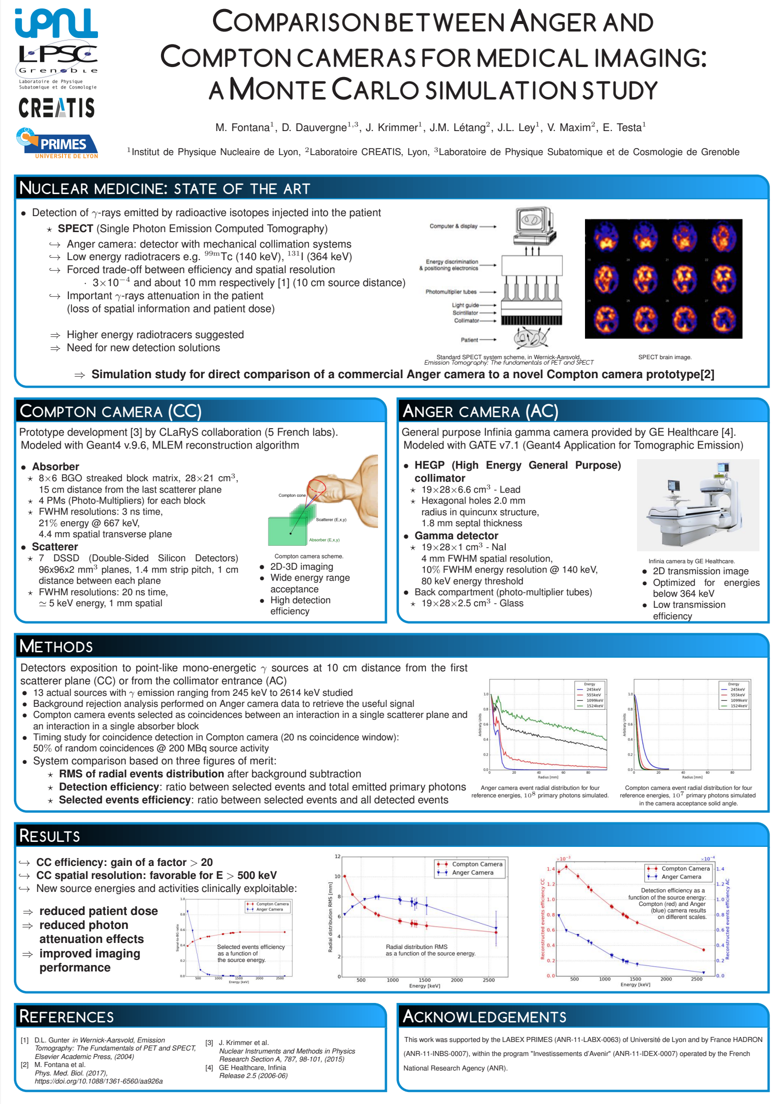
- Before June 2018
  - End of debugging of hodoscope firmware and μ–TCA acquisition
  - Hodoscope test with synchronized cards
  - Beginning of scatterer firmware coding
- September 2018
  - End of tests on BGO blocks and hodoscope
  - Test on beam with a preliminary collimated camera configuration
- Half 2019
  - Beam test preliminary Compton camera configuration

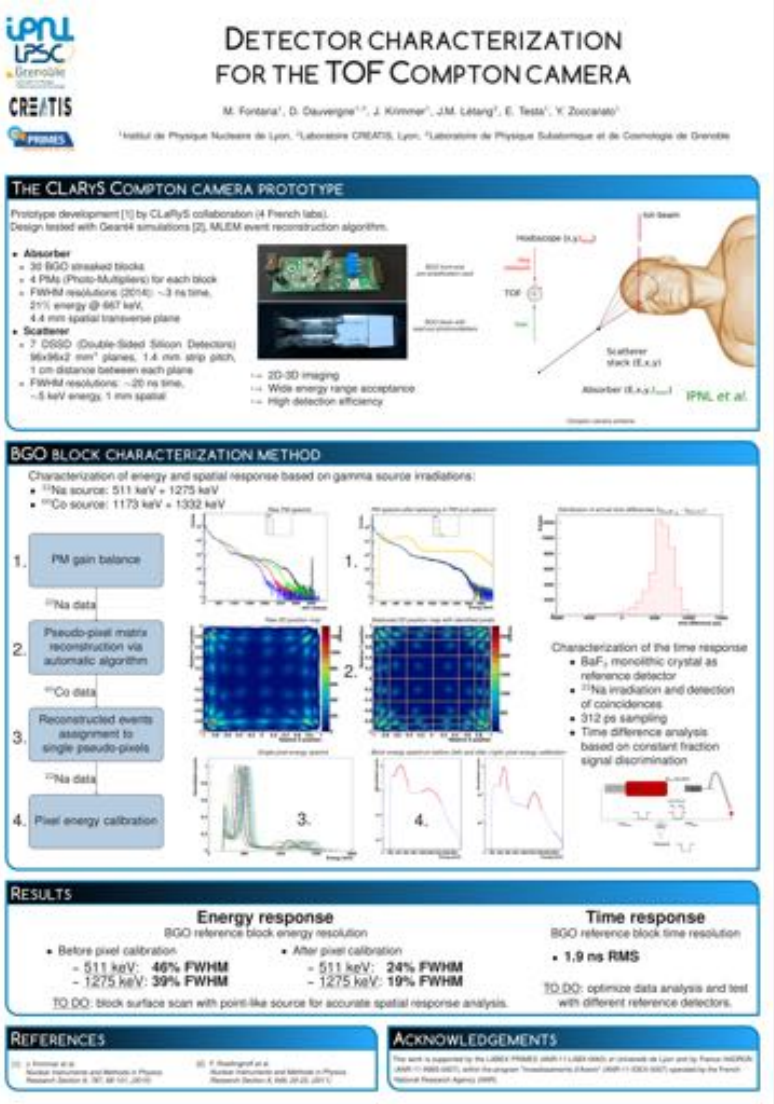
- ...

Acknowledgements

CLaRyS Collaboration
L. Balleyguier, E. Bechetoille, D. Bon, A. Bongrand, J.-P. Cachemiche, C. Caplan, L. Caponetto, B. Carlus, X. Chen, M. Dahoumane, D. Dauvergne, D. Delaunay, R. Della Negra, F. Doizon, N. Freud, M.L. Gallin-Martel, L. Gallin-Martel, N. Giraud, J. Krimmer, D. Lambert, J.M. Létang, M. Magne, F. Martin, H. Mathez, V. Maxim, G. Montarou, J.-L. Montorio, C. Morel, F. Mounier, M. Rodo-Bordera, E. Testa, W. Tromeur, Y. Zoccarato

LabEx PRIMES
This work was supported by the LABEX PRIMES (ANR-11-LABX-0063) of Universite de Lyon and by France HADRON (ANR-11-INBS-0007), within the program "Investissements d'Avenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR).





Thanks for your attention