Simultaneous Gamma-Neutron Vision (GN-Vision) device:
Proof-of-concept of the neutron imaging capability & plans for the final device

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Outline

- Motivation
- The GN-Vision concept & development status
- Experimental characterization of the CLYC + SiPM
- Position sensitive neutron-gamma discrimination
- First proof-of-concept of neutron imaging
- Prospects

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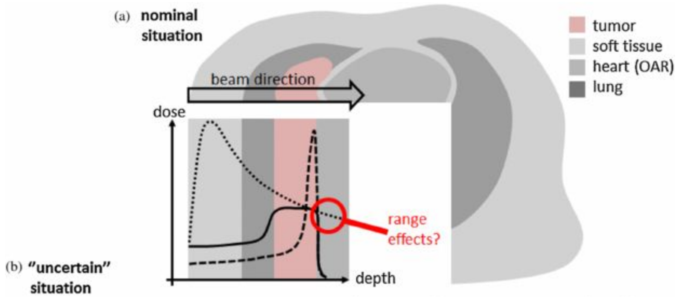
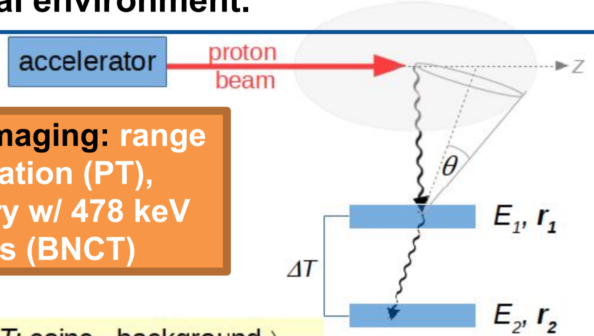
Motivation: hadron therapy

NEUTRON-GAMMA IMAGING IN HADRON THERAPY

- Gamma and neutron radiation can provide valuable information in treatments with hadron beams (**proton, ion, neutrons**).
- **Proton/Ion Therapy**: challenges associated to uncertainties in to **range of the primary hadron beam.**
- **PT & BNCT**: Significant fraction of the **secondary dose** that the patient receives is due to the **neutrons** produced/scattered during the treatment.
- **Very limited compact dual g-n imaging systems compatible to clinical environment.**



Proton/ion beam therapy

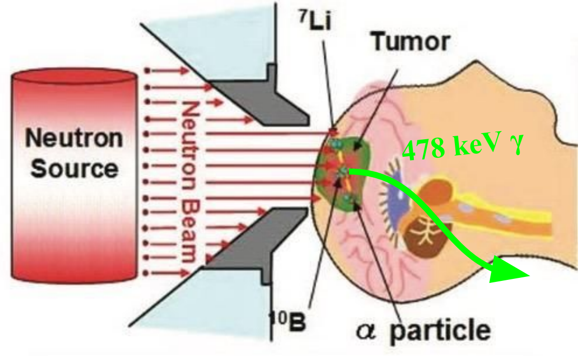


Gamma imaging: range verification (PT), dosimetry w/ 478 keV g-rays (BNCT)

ΔT: coinc., background ↘

$$E_1, \mathbf{r}_1, E_2, \mathbf{r}_2 \rightarrow \theta \rightarrow \frac{d^3N}{dx\,dy\,dz}$$

Neutron imaging: Dosimetry (PT), scattered neutron flux & neutron dosimetry (BNCT)



Boron Neutron Capture Therapy (BNCT)

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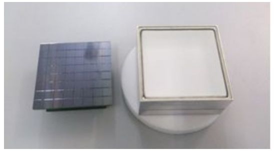
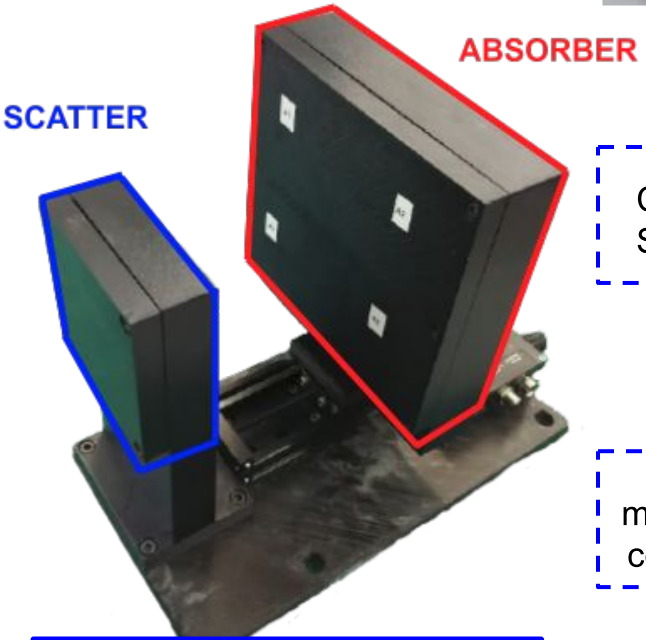
i-TED & the GN-Vision concept

i-TED:
Compton (g-ray) imaging



GN-Vision:
Simultaneous neutron & g-ray imaging

Pos. Sensitive detectors:
Monolithic crystals + SiPM

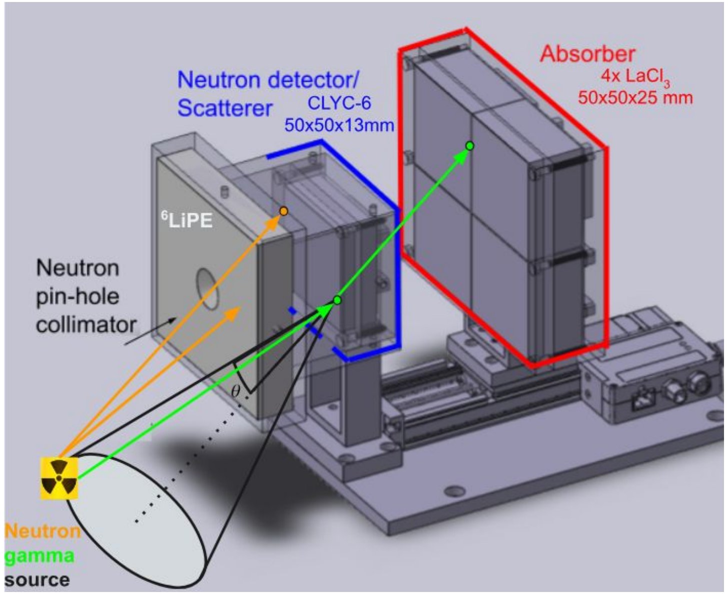


Compton Scatterer → Compton Scatterer & Neutron detector

$LaCl_3$ → CLYC-6

No mechanical collimation → Slow neutron collimator

^{6}LiPE



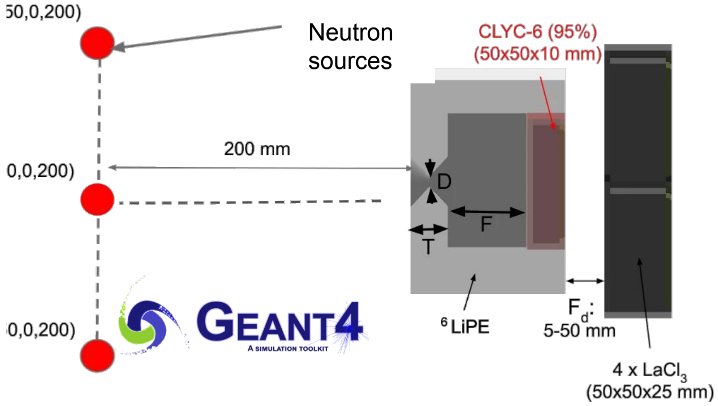
Gammas: Compton imaging (electronic collimation)

Patent: *ES2877772A1*

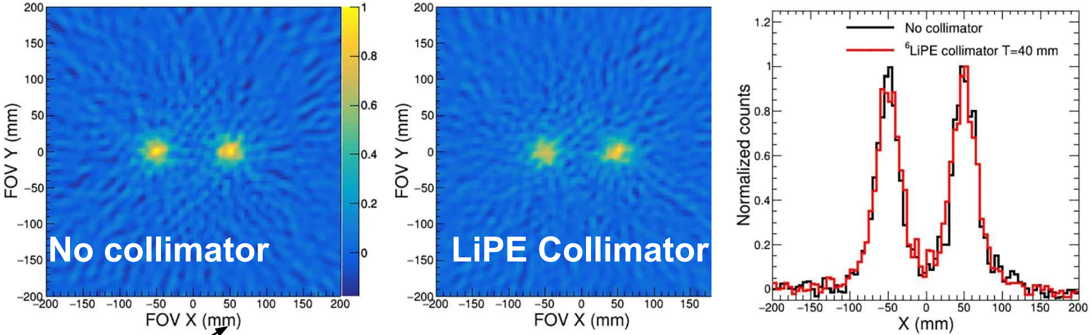
Gammas: Compton imaging (electronic collimation)
Slow neutrons (<100 eV): Mechanical collimation

MC-based design & validation

J. Lerendegui-Marco et al. EPJ-TI (2024)



Compton images of 500 keV g-ray source @ 20 cm



Optimization collimator parameters (D, T) vs En

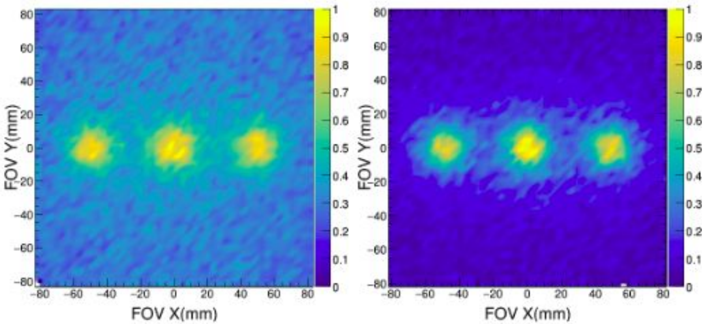
Neutron

Gamma

Collimator: No effect in g-ray imaging resolution

T = 10 mm

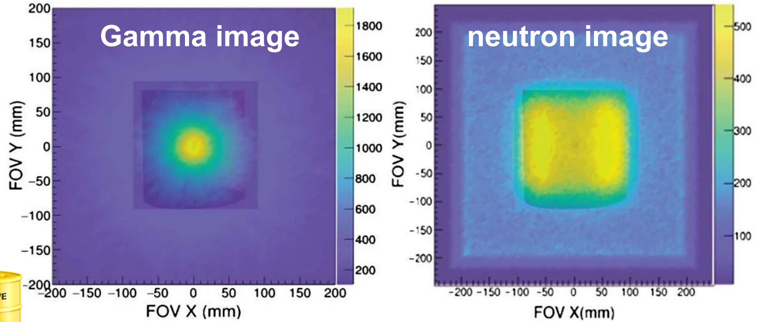
T = 20 mm



Neutron images: 1 eV sources @ 20 cm

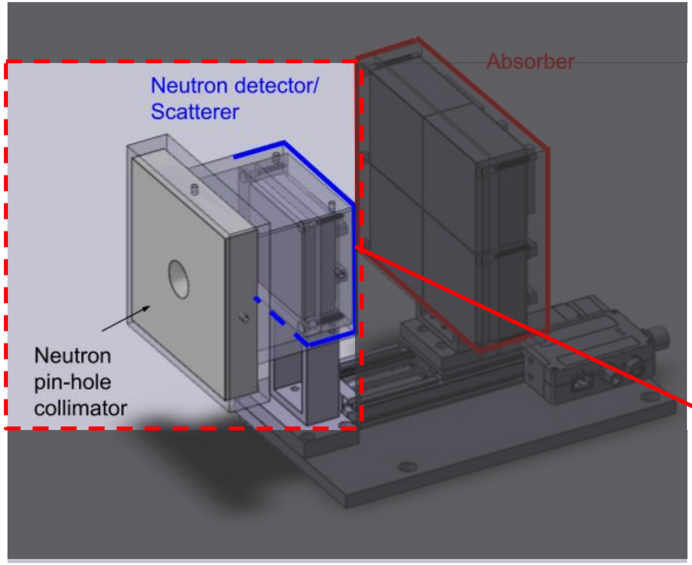
Thickness T:
Contrast / En

Diameter D:
Resolution / Eff



Realistic case: Cf-252 (SF) in 75 mm PE

GN-Vision: Experimental development



- **First detection layer:**
  - Monolithic block of **CLYC-6** ($50\times50\times13$ mm^3)
  - **Aim #1:** absorbing neutrons below 1 keV via ^{6}Li(n,a)
  - **Aim #2:** Compton scattering of γ-rays (Compton imaging)

- **Second detection layer:**
  - An array of four LaCl3 crystals $50\times50\times25$ mm (**i-TED**)
  - **Aim**: Absorber for Compton imaging.

- **Pinhole Collimator:** ^{6}LiPE

This talk:

- Characterization of the CLYC-6 + SiPM: Energy, neutron-gamma discrimination & position sensitivity
- First proof-of-concept experiment of neutron imaging

- On-going work & prospects for the final device

- **Position sensitive detectors:** Each crystal base is coupled to a 8x8 pixelated SiPM (SensL ArrayJ-60035-64P-PCB) **(i-TED)**

- **Compact electronics:** PETsys TOFPET2 ASIC **(LaCl3 / i-TED) + 4-channel readout AIT (CLYC-6 in GN-Vision)**

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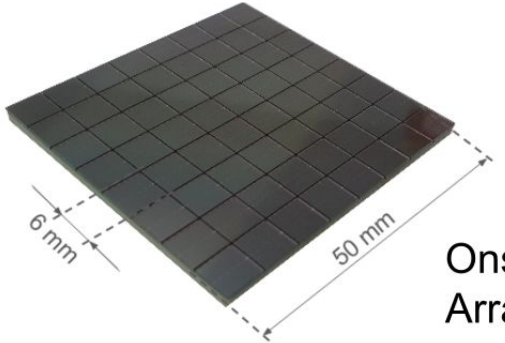
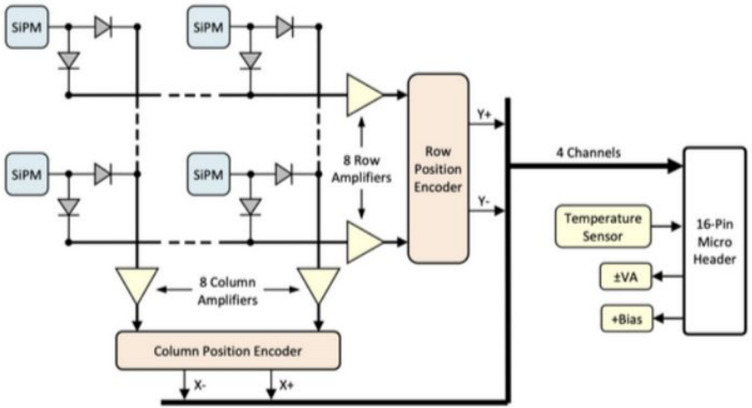
- Outlook

CLYC-6 + SiPM: Experimental setup

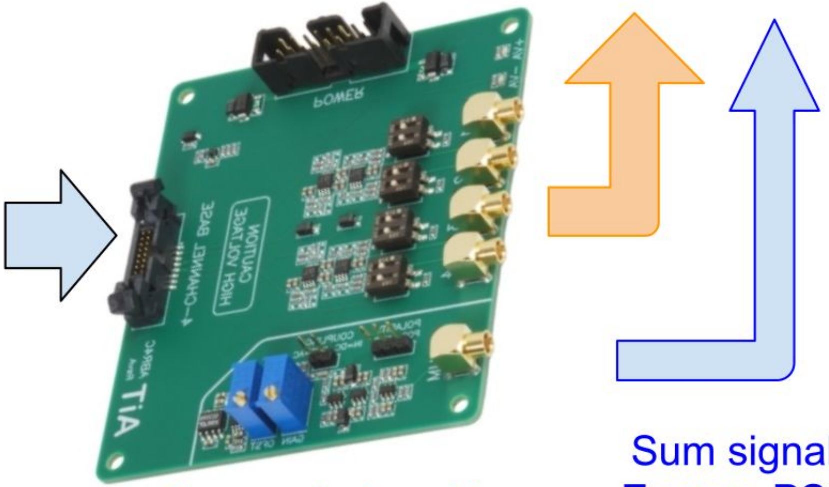


Onsemi
ArrayJ-60035-64P-PCB

CAEN DT5730
8 Channel 14 bit
500 MS/s Digitizer



AIT AB4T-ARRAY64P
4-Channel Active Base

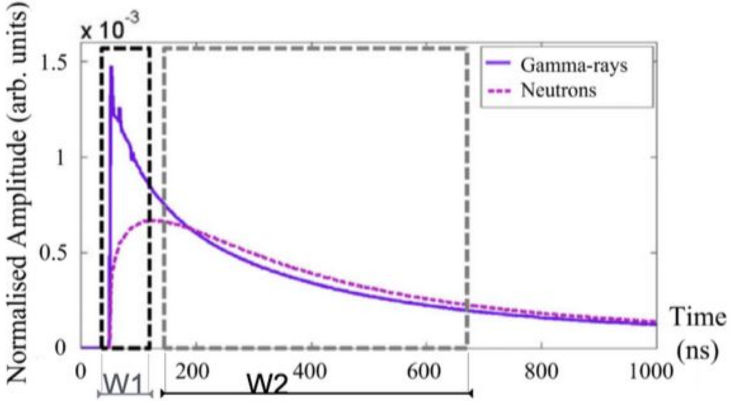


4- encoded position signals: X+,X-,Y+,Y-

Sum signal: Energy, PSD

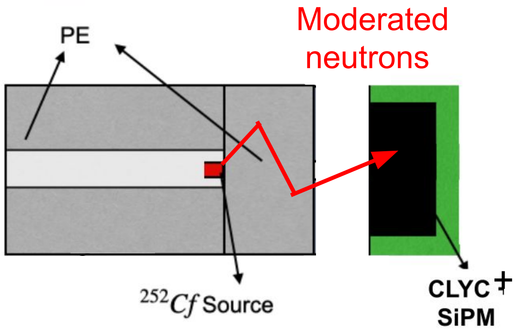
CLYC-6 + SiPM: Pulse shape discrimination

Neutron-gamma discrimination:
different pulse shapes



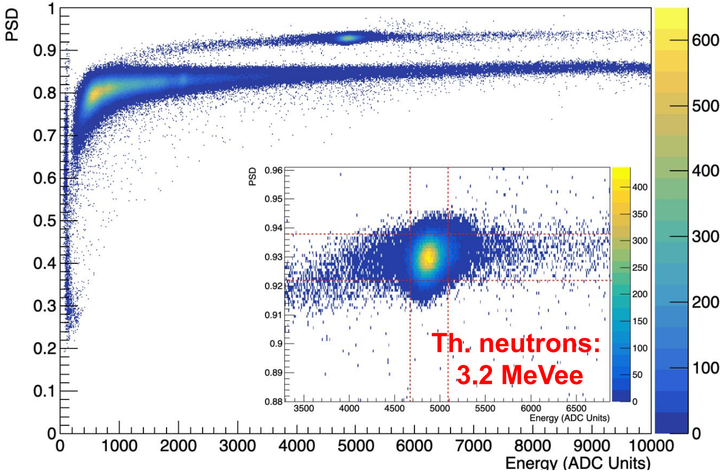
Q1: Integral W1 window
Q2: Integral W2 window

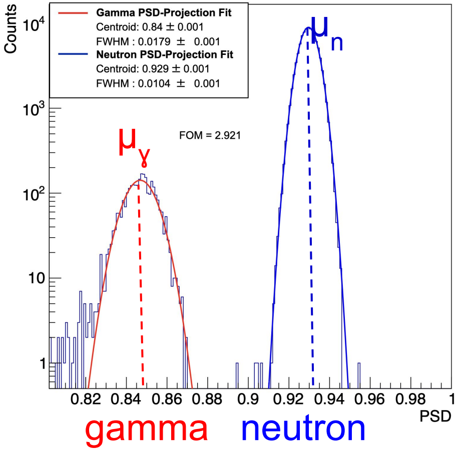
$$\text{PSD Ratio} = \frac{Q_2}{Q_1 + Q_2}$$



$$\text{FOM} = \frac{|\mu_n - \mu_\gamma|}{\text{FWHM}_\gamma + \text{FWHM}_n}$$

FOM CLYC6 + SiPM : 2.92





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J. Lerendegui-Marco et al., NIM-A arXiv:2410.12533

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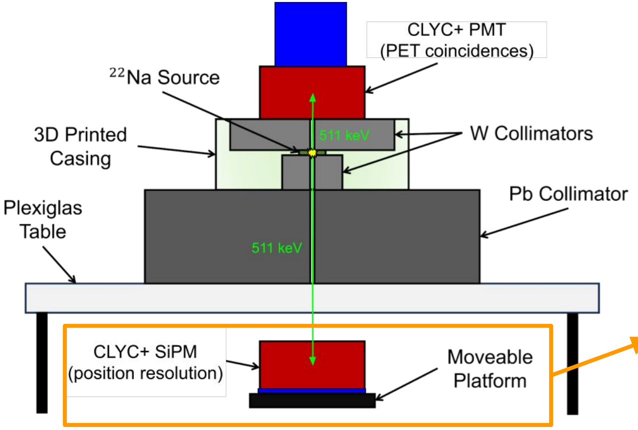
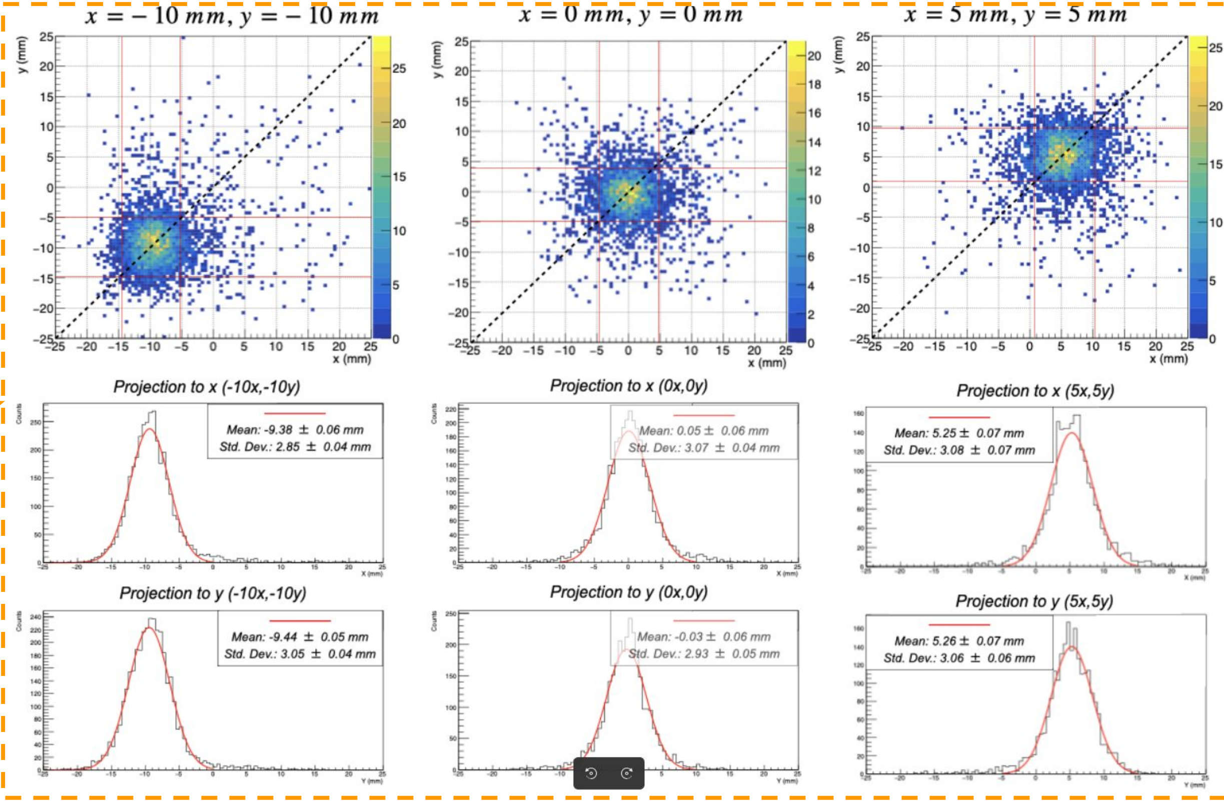
Position sensitivity: method

G-ray scanning table



2-fold collimation:

1) Mechanical
2) 2 x 511 keV in coincidence



G. Cisterna, Master's Thesis (U.Sevilla, IFIC)

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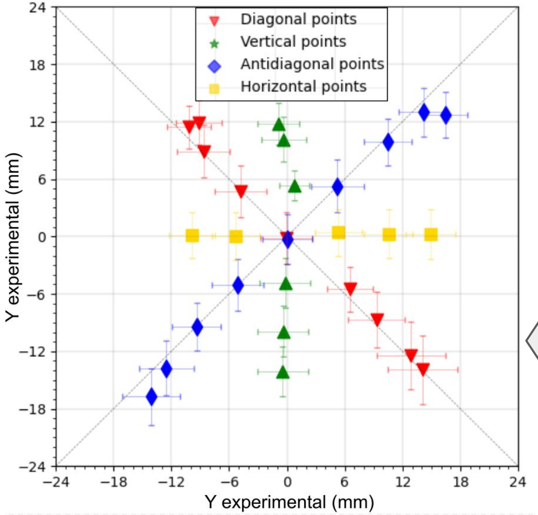
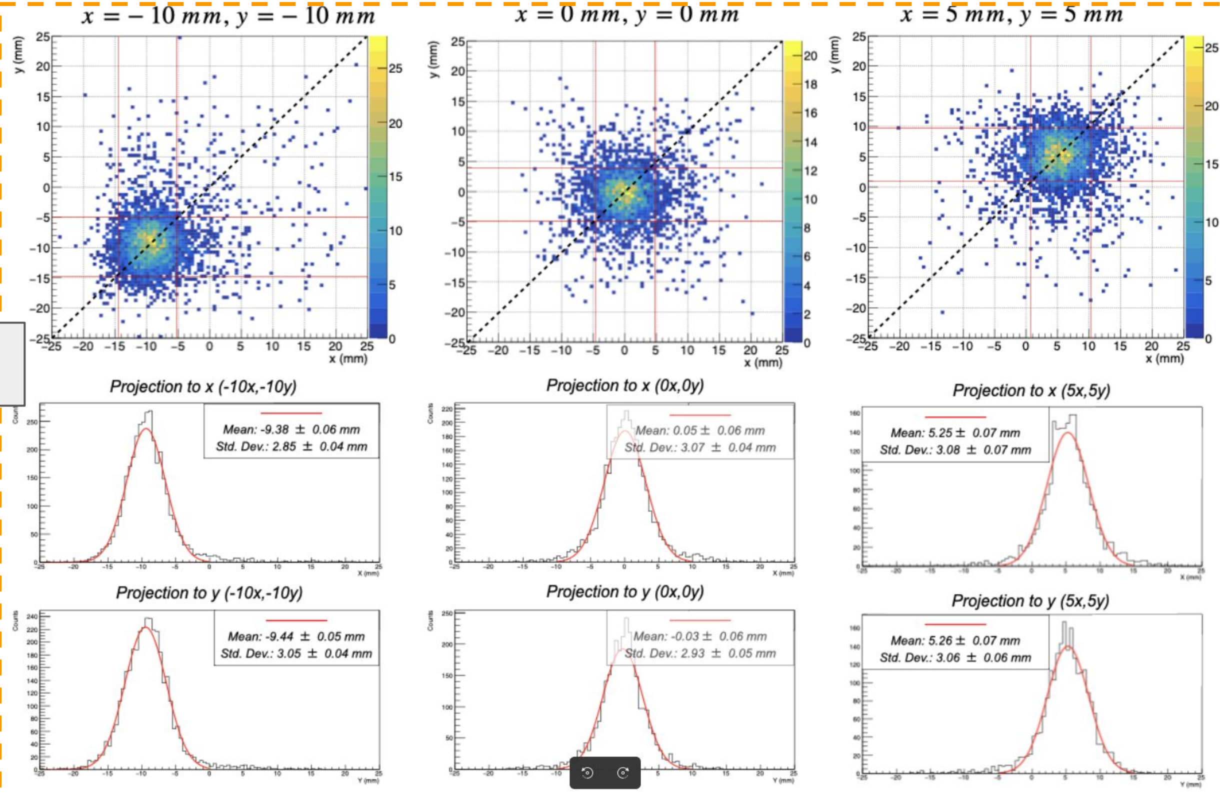
$$\mathbf{X\ column} = \frac{(X_+ - X_-)}{(X_+ + X_-)}, \qquad \mathbf{Y\ row} = \frac{(Y_+ - Y_-)}{(Y_+ + Y_-)}.$$

Position sensitivity: resolution & linearity





Best. Resol. (FWHM): 5 mm
sub pixel resolution!!

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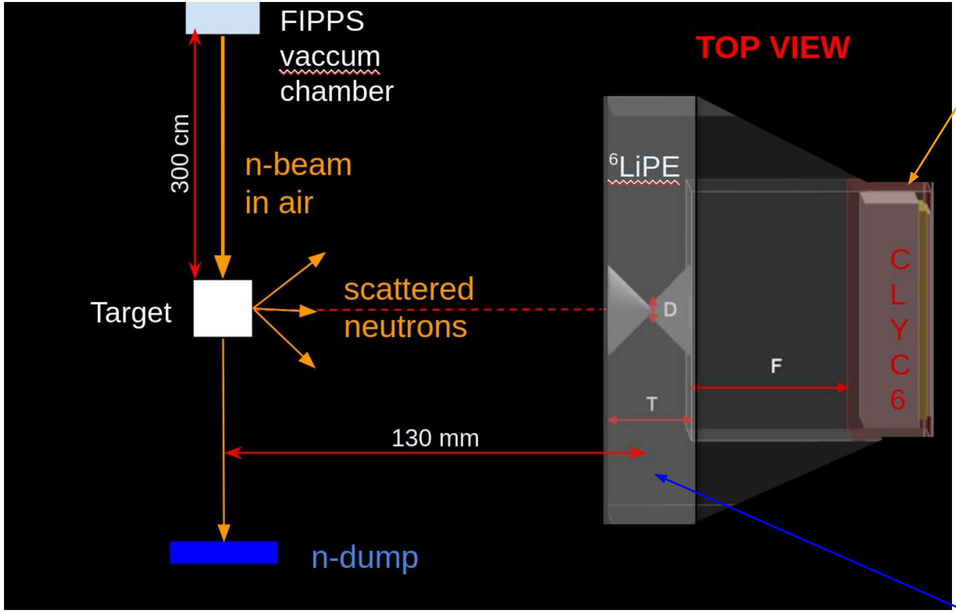
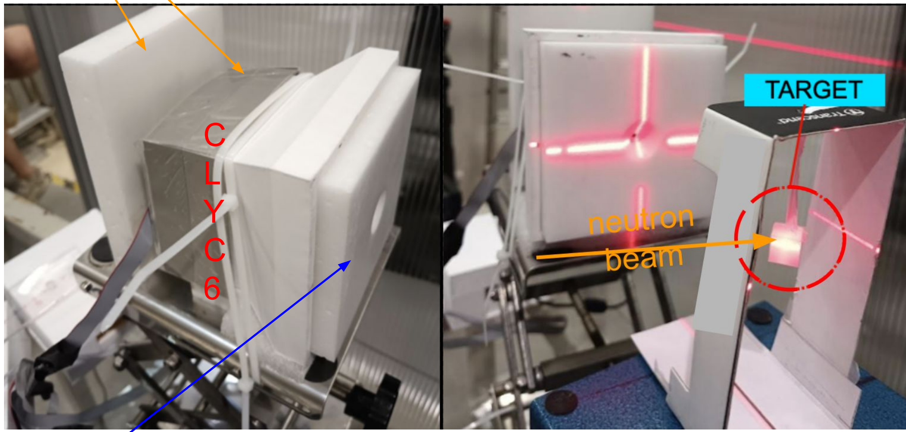
Experimental setup at ILL

Neutron beam at FIPPS experimental hall:

- Halo-free pencil beam of 1.5cm diameter.
- Thermal neutron flux: 10^8 n.cm^{-2}.s^{-1}

n-absorbing layers (bckg)





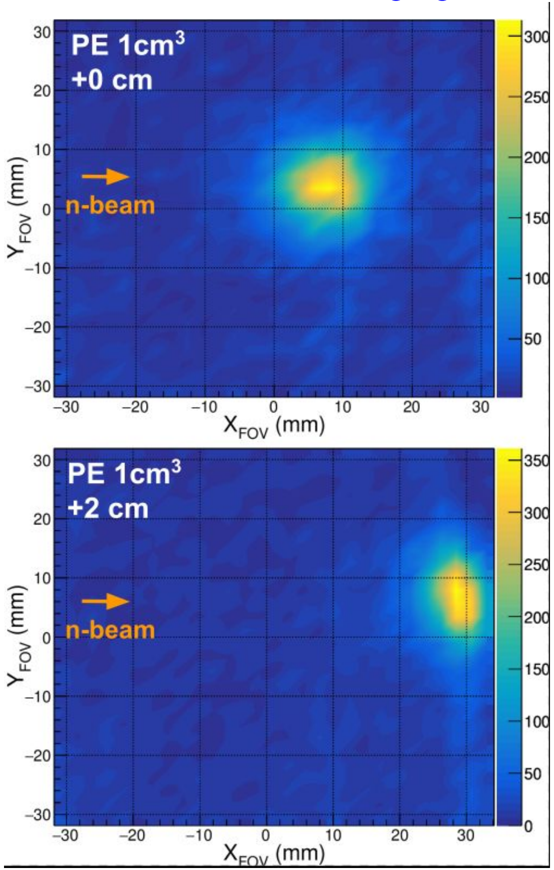
D = 2.5 mm
T= 20 mm
F = 40 mm

Neutron Pinhole collimator (6LiPE)

ILL Research proposal 3-17-75: :
Dual neutron-gamma imaging applied to Boron Neutron Capture Therapy

First neutron images

Imaging of 1cm3 PE cube



Shift: 21 mm
FWHM = 11 mm

n-Imaging capability. remarkable contrast (~15)

G. Cisterna, Master's Thesis (U.Sevilla, IFIC)

J. Lerendegui-Marco et al., NIM-A arXiv:2410.12533

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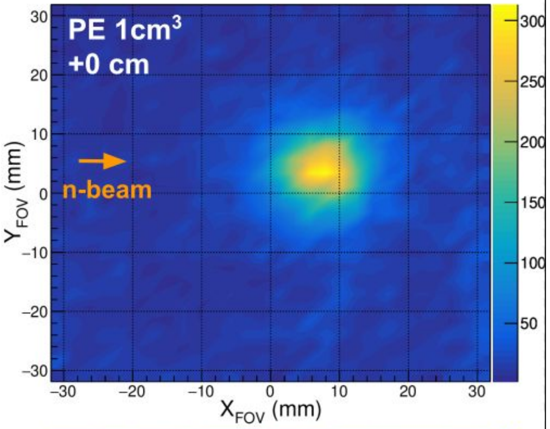
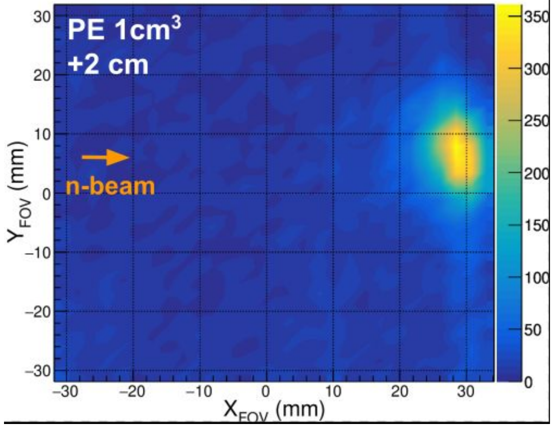
Imaging of 1cm3 PE cube

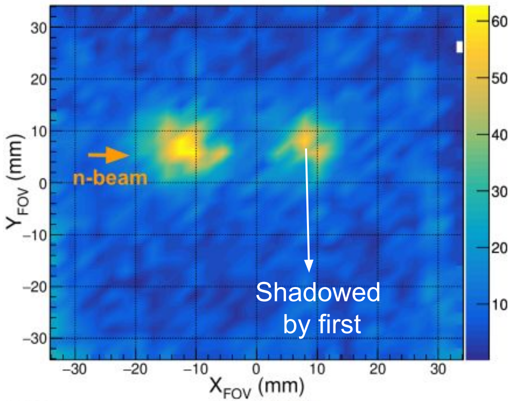




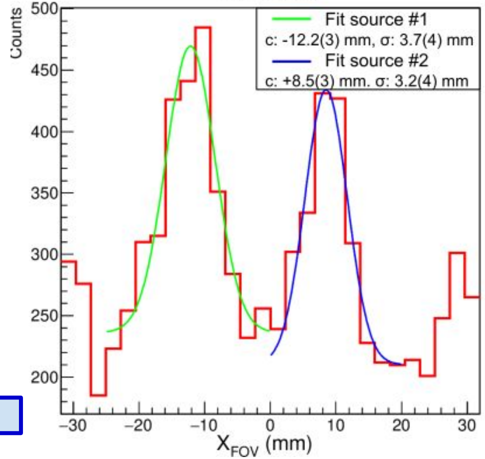
Shift: 21 mm
FWHM = 11 mm

n-Imaging capability. remarkable contrast (~15)

Resolution study:
Two 4-mm-side rubber at 2 cm



Resolution of ~8 mm or 4º (FWHM)



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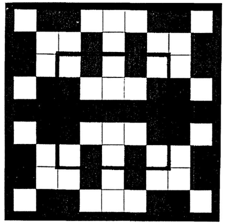
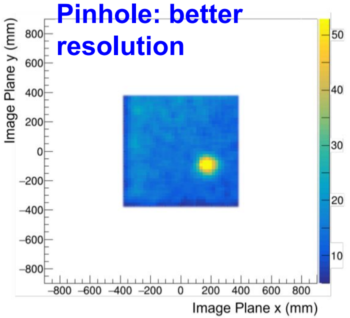
Prospects: collimator upgrade

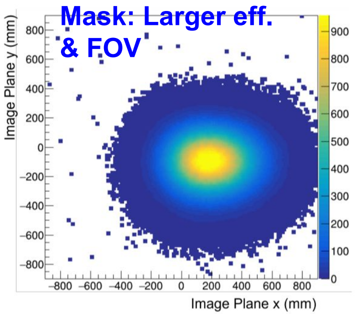
Recent MC study: Coded-aperture mask

- Methodology: Simulated response matrix for multiple positions + Unfolding
- Efficiency is enhanced in factor ~15 vs pinhole (with D = 5 mm)

Mura rank 5

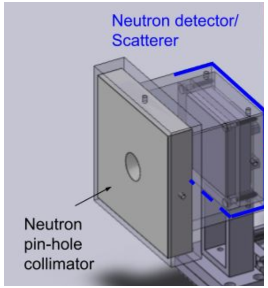


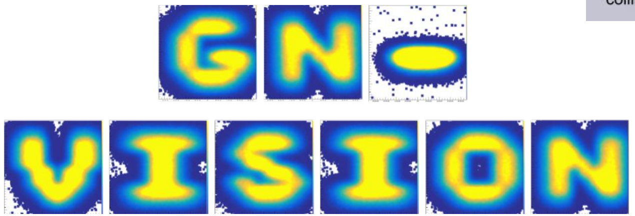




First design: pin-hole

- Limited efficiency
- 95% ^{6}Li enrichment



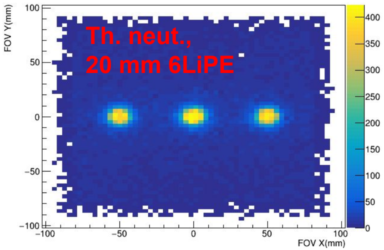


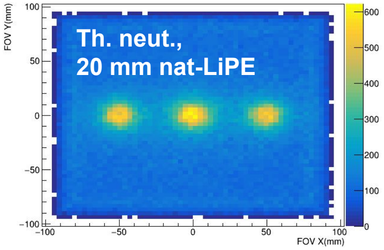
Recent MC study: ^{6}Li enrichment in the collimator

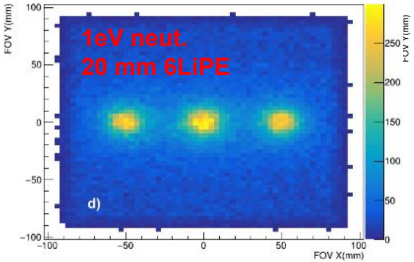
- Natural LiPE is sufficient to image thermal neutrons
- Imaging epithermal neutrons → ^{6}Li enriched for a good contrast

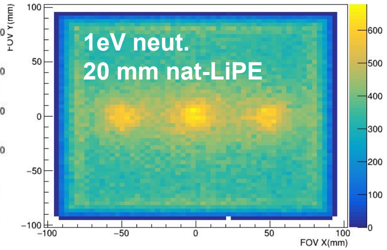
A. Sanchis-Moltó, Bachelor's Thesis (U.València, IFIC)

J. Hallam, Master's Thesis (U. Surrey, IFIC)









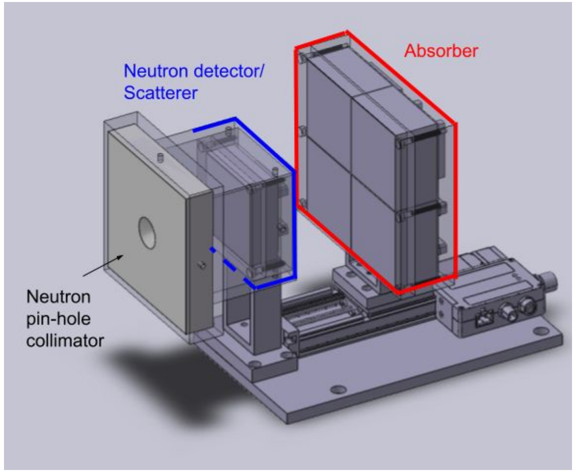
Prospects: dual neutron-gamma image

Short-term plans: integration of neutron-gamma imaging

Option A: Integrate CLYC-based neutron module in PETsys

CLYC-6 + Multiplexed readout (AIT 4 channel active base)

4x LaCl3 + single SiPM (64) readout (PETSys)



Option B: Replace CLYC by CLLBC & read all crystals in PETsys

CLLBC

4x LaCl3

Single SiPM (64) readout (PETSys)

CLLBC: monolithic & pixelated

- **Goal:** Events in the 1st plane (CLYC-6) & 2nd plane (LaCl3) in coincidence→Compton imaging
- Digitalize CLYC-6 + SiPM output signals (AIT 4ch active base) in PETSys

- **Goal**: Read all crystals with PETSys to enable coincidences→Compton imaging
- CLYC-6 not possible single-SiPM readout: low photon yield & **slow decay constant**
- **CLLBC**: 2x higher yield, 4-5 x faster decay → Expected to work with single-SiPM readout (PETSys)
- **Pixelated CLLBC:** even higher photon yield / SiPM

Summary

GN-Vision: Dual gamma-ray & neutron imaging device of interest for medical and nuclear applications

Dual GN imaging concept was developed and optimized on the basis of **MC-simulations**

Patent: *ES2877772A1* | *J. Lerendegui-Marco et al. EPJ-TI (2024)*

This contribution: First experimental milestones in the development of **GN-Vision**

Performance of the CLYC6 + SiPM: E, PSD

Energy resolution: 8.9% (vs 6% with PMT)
Neutron-Gamma PSD FOM: 2.92

Characterization of the position sensitivity

G-ray scanning table: Position sensitivity
Resolution ~5mm (FWHM) & linearity (central 30 mm)
Pos. sensitive n-g discrimination: 1st neutron patterns

First POC experiments of neutron imaging

Experiment with thermal neutrons at ILL
First neutron images of scattered neutrons in targets
Image resolution ~ 8 mm (4º) (FWHM)

Prospects: optimized collimator ,integration neutron-gamma imaging & upcoming test clinical beams

Gamma-Neutron Vision aimed at improved cancer treatments in Hadron Therapy (Grant No. 101113330)

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First experimental results of a dual neutron-gamma imaging system for hadrontherapy and nuclear inspections

BACK-UP

Motivation: nuclear security

NEUTRON-GAMMA IMAGING IN NUCLEAR SECURITY

- **Nuclear security inspections** of reactor spent-fuel control and Non-proliferation inspections
- **Unmanned inspections** in nuclear accidents
- Materials are many time covered or hidden with neutron moderators → thermal neutrons spectrum
- **Limitations of existing:** Large scintillation arrays:, sensitive only to fast neutrons & not portable.
- **Interest in compact hand-held dual N-G imagers.**

Angular-resolution and material-characterization measurements for a dual-particle imaging system with mixed-oxide fuel

CrossMark

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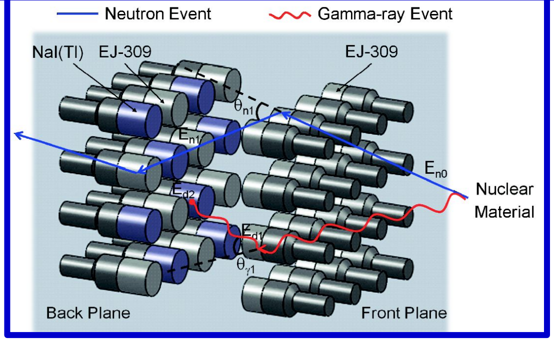

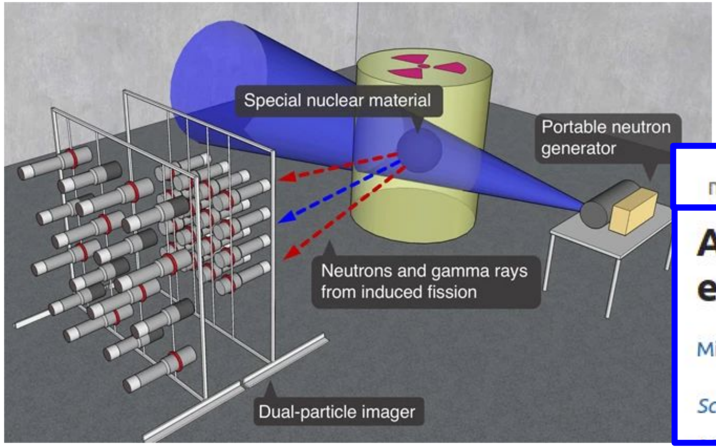

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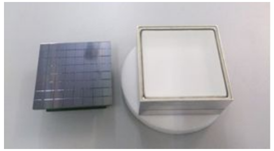
Active neutron and gamma-ray imaging of highly enriched uranium for treaty verification

Michael C. Hamel, J. Kyle Polack, Marc L. Ruch, Matthew J. Marcath, Shaun D. Clarke & Sara A. Pozzi

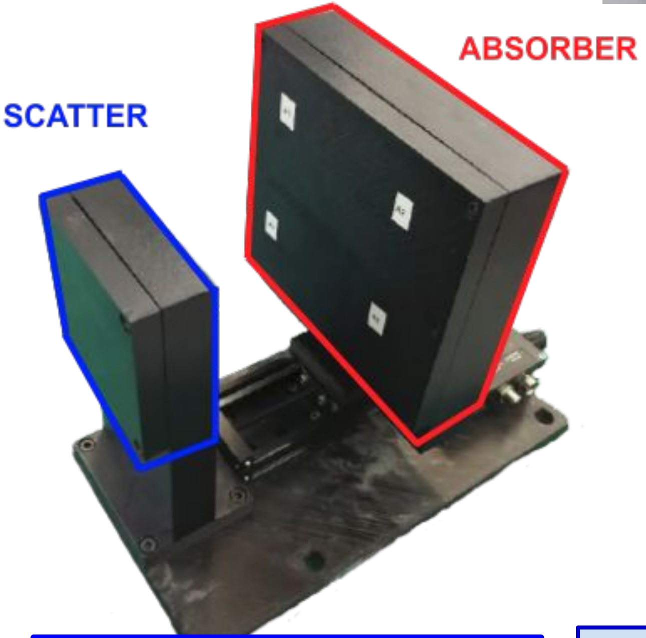
Scientific Reports 7, Article number: 7997 (2017) | Cite this article

i-TED & the GN-Vision concept

i-TED:
Compton (g-ray) imaging



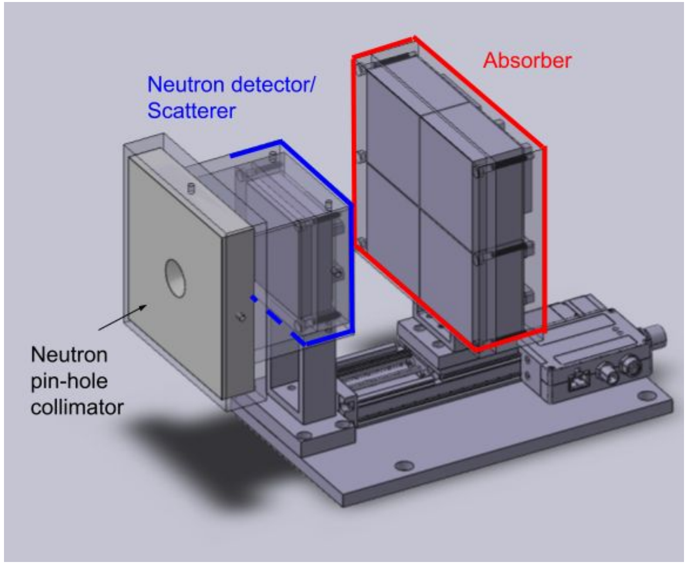
Pos. Sensitive detectors:
Monolithic crystals + SiPM



Gammas: Compton imaging (electronic collimation)

[1] C. Domingo-Pardo et al., Nucl. Phys. A 851, 78-86 (2016), doi: 10.1016/j.nima.2016.04.002
[2] V. Babiano et al., Eur. Phys. J. A 57, 197 (2021),doi:10.1140/epja/s10050-021-00507-7
[4] J. Balibrea-Correa et al., Eur. Phys. J. Plus 137, 1258 (2022), doi:10.1140/epjp/s13360-022-03414-y

GN-Vision: Experimental development



- **First detection layer:**
  - Monolithic block of **CLYC-6** ($50\times50\times13$ mm^3)
  - **Aim #1:** absorbing neutrons below 1 keV via ^{6}Li(n,a)
  - **Aim #2:** Compton scattering of γ-rays (Compton imaging)

- **Second detection layer:**
  - An array of four LaCl3 crystals $50\times50\times25$ mm (**i-TED**)
  - **Aim**: Absorber for Compton imaging.

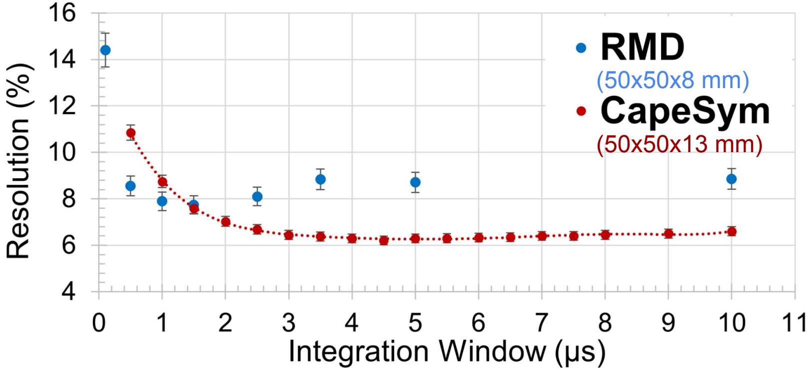
- **Pinhole Collimator:** ^{6}LiPE

- **Position sensitive detectors:** Each crystal base is coupled to a 8x8 pixelated SiPM (SensL ArrayJ-60035-64P-PCB) **(i-TED)**

- **Compact electronics:** PETsys TOFPET2 ASIC **(LaCl3 / i-TED) + 4-channel readout AIT (CLYC-6 in GN-Vision)**

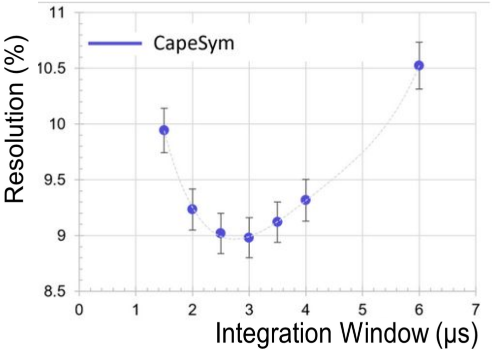
CLYC-6 + PMT / SiPM: E-resolution

CLYC + PMT

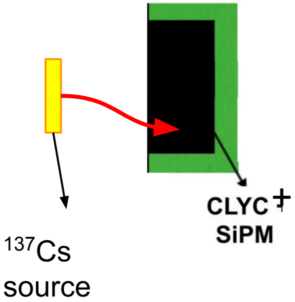


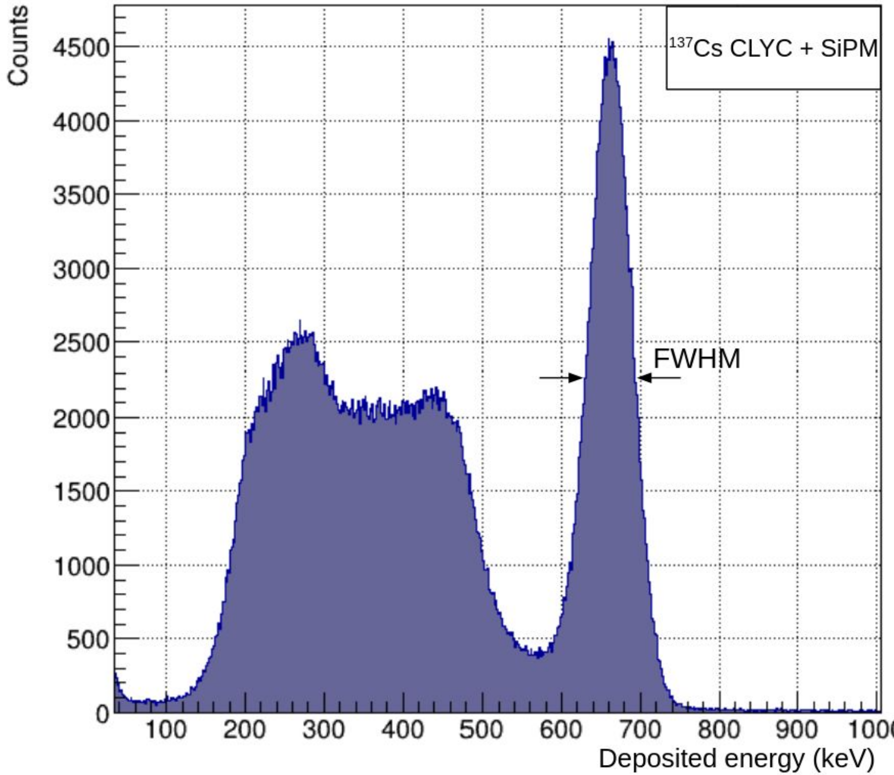
Best Resol. (PMT): 6.1%
Best Resol. (SiPM): 8.9% → 5.9% (Spec. Amp)

CLYC + SiPM



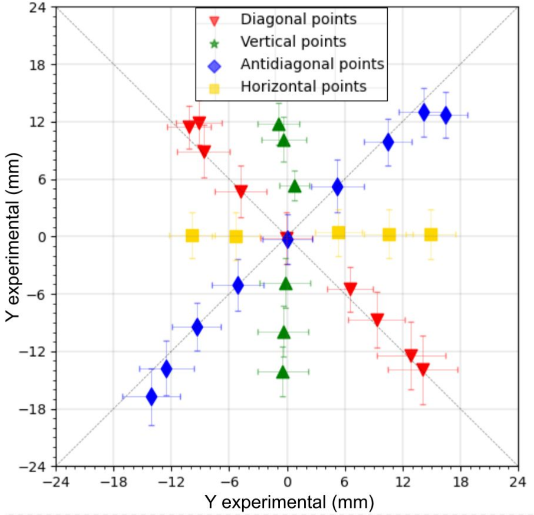
662 keV g-rays



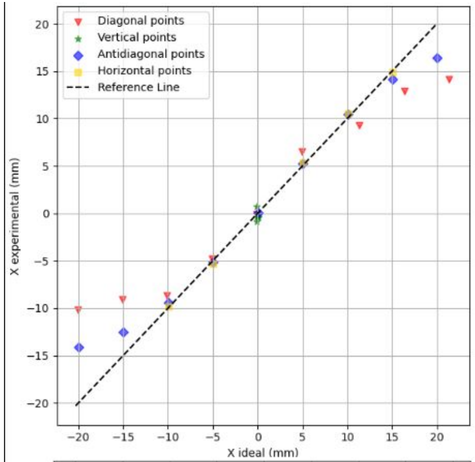


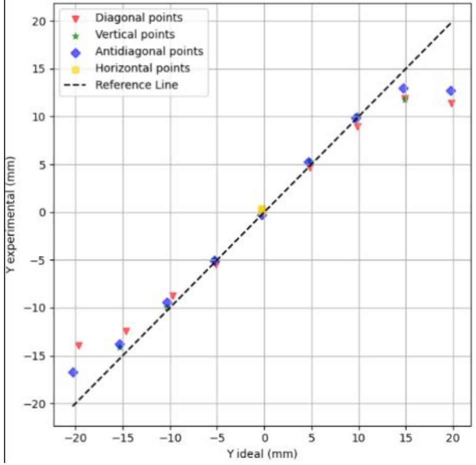
J. Hallam, Master's Thesis (U. Surrey, IFIC)

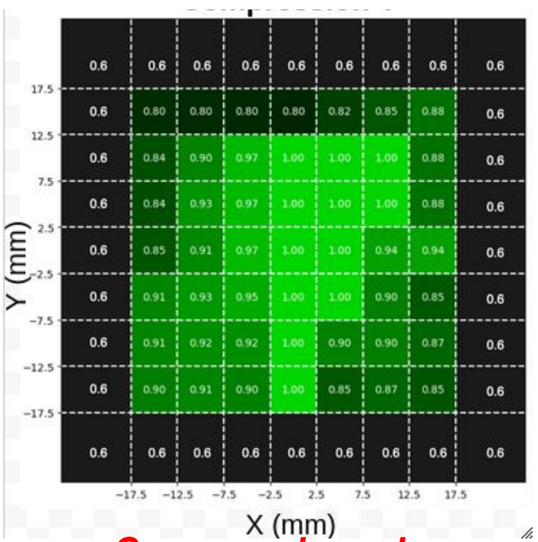
Position sensitivity: resolution & linearity



Best. Resol. (FWHM): 5 mm
sub pixel resolution!!







Compression edges: Pin-cushion effect

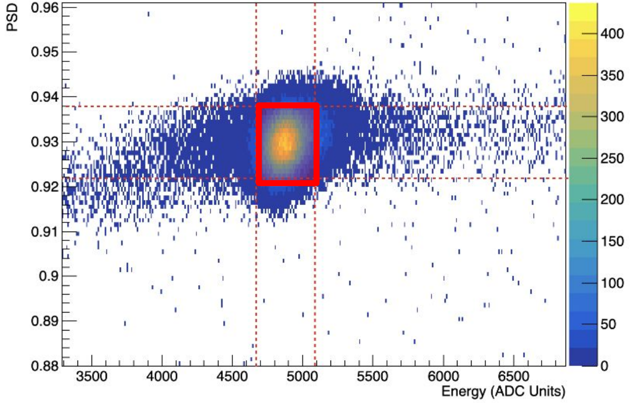
Up to ∓15 mm, the linearity is good.
Linearity >0.85 for the central area

G. Cisterna, Master's Thesis (U.Sevilla, IFIC)

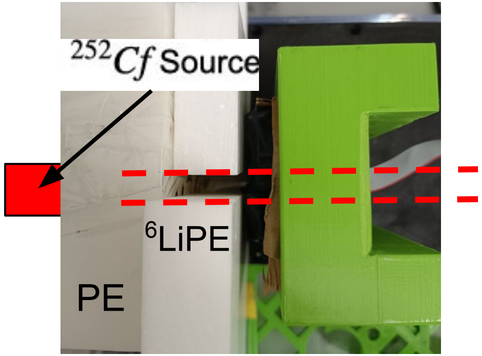
J. Lerendegui-Marco et al., NIM-A arXiv:2410.12533

Position sensitivity: Neutron patterns

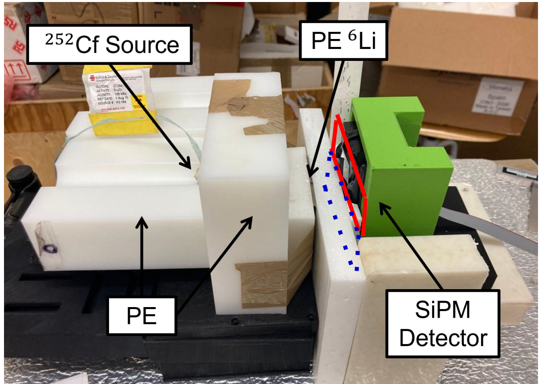
Moderated ^{252}Cf source:
Selection of slow neutrons



^{6}LiPE with a 5-mm-width slit



^{6}LiPE shielding ½ of the CLYC6



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Position sensitivity: Neutron patterns

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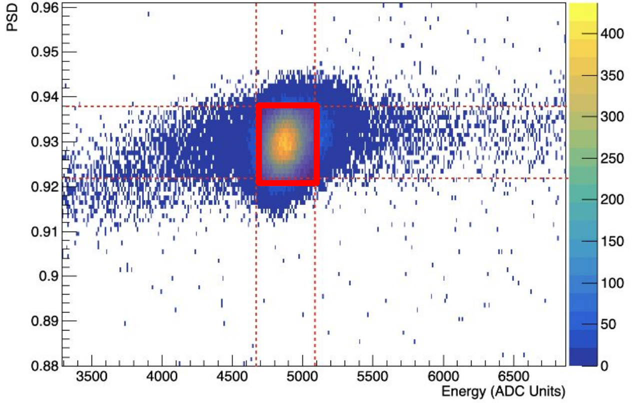
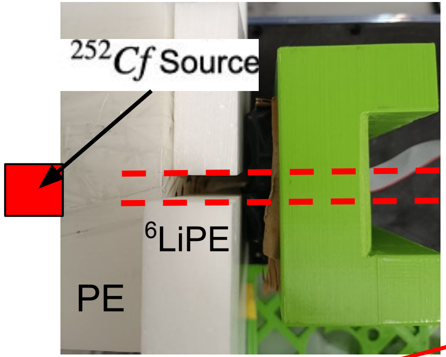
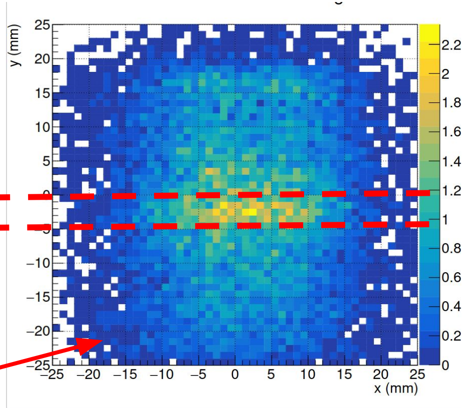


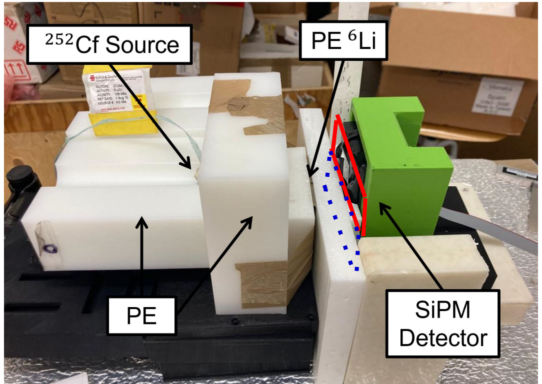
^{6}LiPE with a 5-mm-width slit

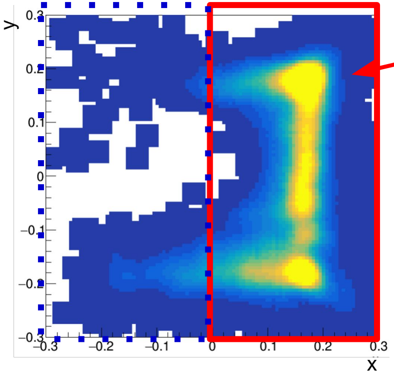




Reconstructed patterns of neutron hits

^{6}LiPE shielding ½ of the CLYC6





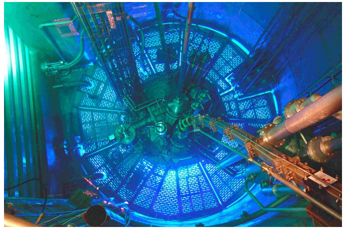
Able to perform **position-sensitive neutron detection** with CLYC6 + SiPM!
First step towards **neutron imaging**

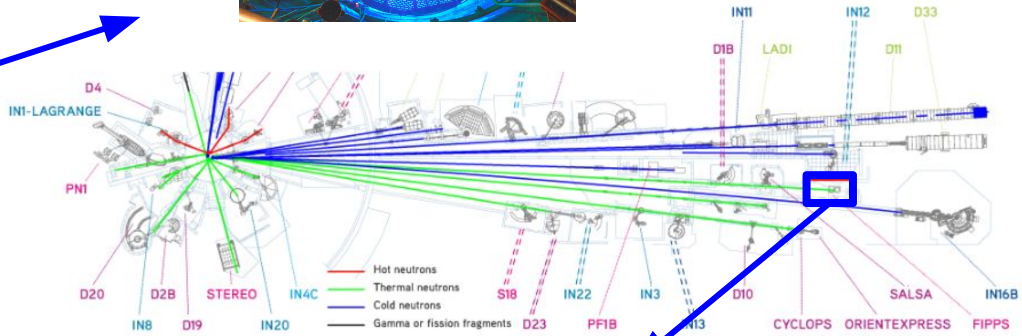
J. Hallam, Master's Thesis (U. Surrey, IFIC)

G. Cisterna, Master's Thesis (U.Sevilla, IFIC)

J. Lerendegui-Marco et al., NIM-A arXiv:2410.12533

Experimental setup at ILL

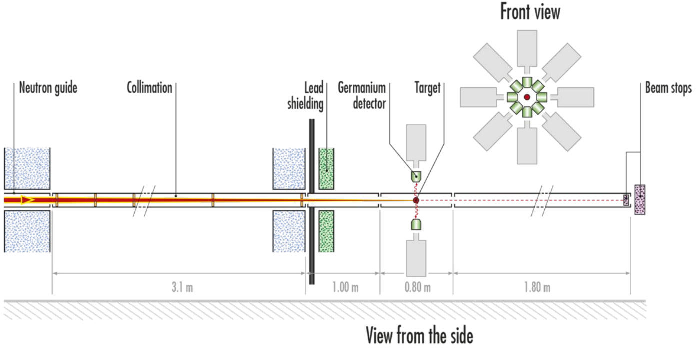




Neutron beam at FIPPS experimental hall:

- Halo-free pencil beam of 1.5cm diameter.
- Thermal neutron flux at the target position is of 10^8 n.cm^{-2}.s^{-1}

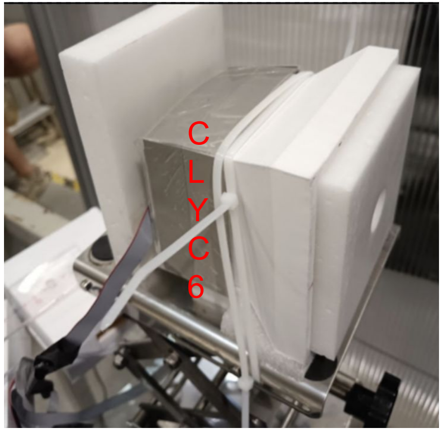
ILL Research proposal 3-17-75: :
Dual neutron-gamma imaging applied to Boron Neutron Capture Therapy

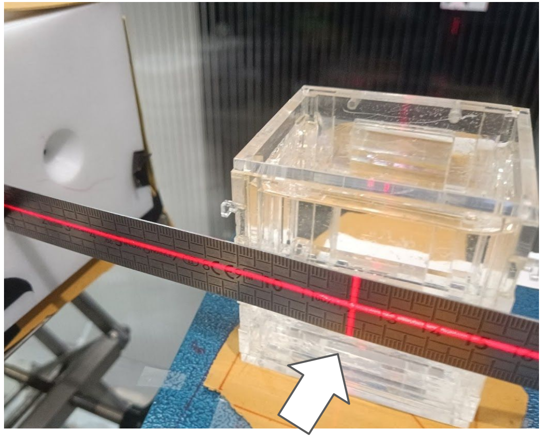


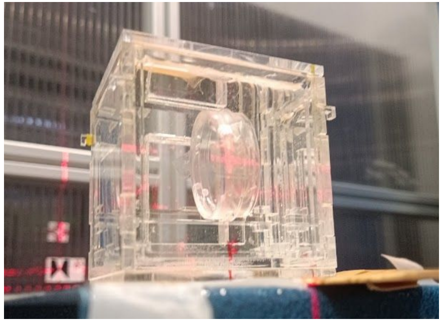
Prospects: First pilot experiments BNCT

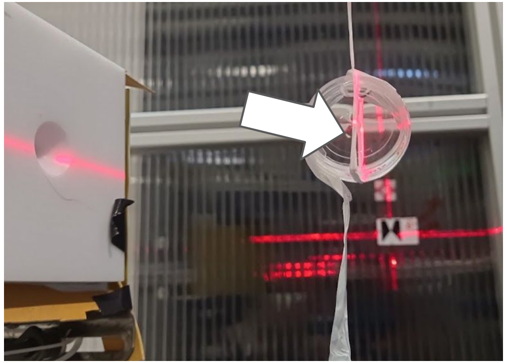
Short-term plans: analysis of the first pilot experiments neutron imaging in BNCT

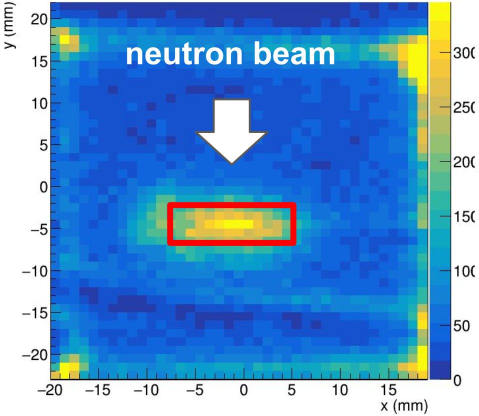
ILL Research proposal 3-17-75:
Dual neutron-gamma imaging applied to Boron Neutron Capture Therapy







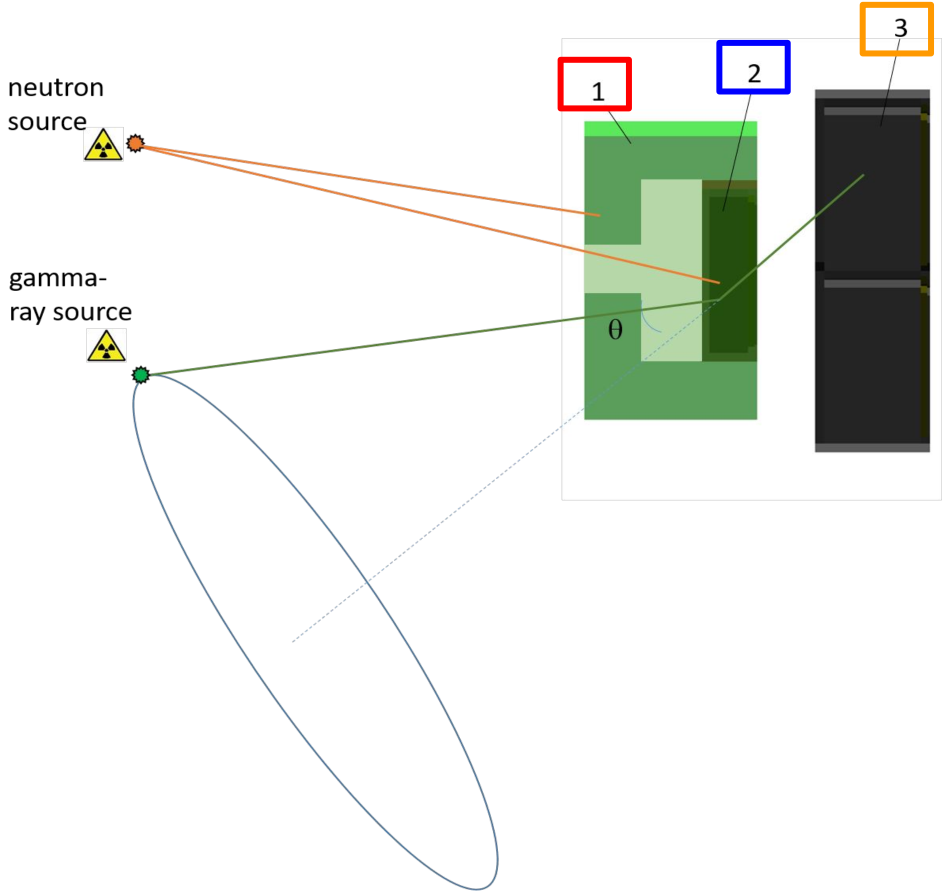




More realistic phantoms
- ^{10}B + water discs
- Water phantom
- Water phantom + disc with ^{10}B

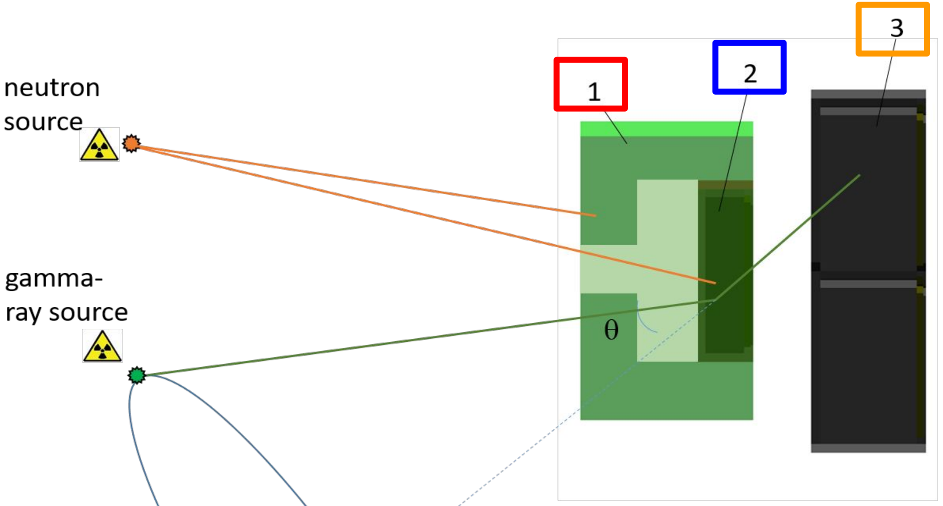
Gamma-image same phantoms: i-TED

The GN-Vision concept



- **<u>GN Vision working principle</u>**:
    - Compact device that can detect and **image both g-rays and slow (<100 eV) neutrons**
    - Detector based on two PS detection planes, labelled **(2)** and **(3)**.
    - These two planes allow applying the **Compton Technique: imaging of γ-rays** with energies of between 100 keV and several MeV.
    - The first detection plane **(2)** is able to detect neutrons of energies <1 keV and allows discriminating them from γ-rays,
    - A passive neutron collimation system **(1)** attached to the first detection plane allows to carry out **neutron vision as in pin-hole cameras** for γ-rays. It does not affect g-rays.

The GN-Vision concept



DEVICE FOR SIMULTANEOUS DETECTION, IDENTIFICATION, QUANTIFICATION AND/OR LOCATION OF GAMMA RADIATION AND NEUTRON SOURCES

OBJECT OF THE INVENTION

The object of the invention is a portable device for simultaneous detection, quantification, identification and spatial location or visualisation of both neutron emission sources and of gamma radiation sources, suitable for use, for example, in inspections relating to nuclear safety, port safety, nuclear threats and accidents, medical physics and other applications.

Patent: *ES2877772A1*

J. Lerendegui-Marco et al. EPJ-TI (2024)

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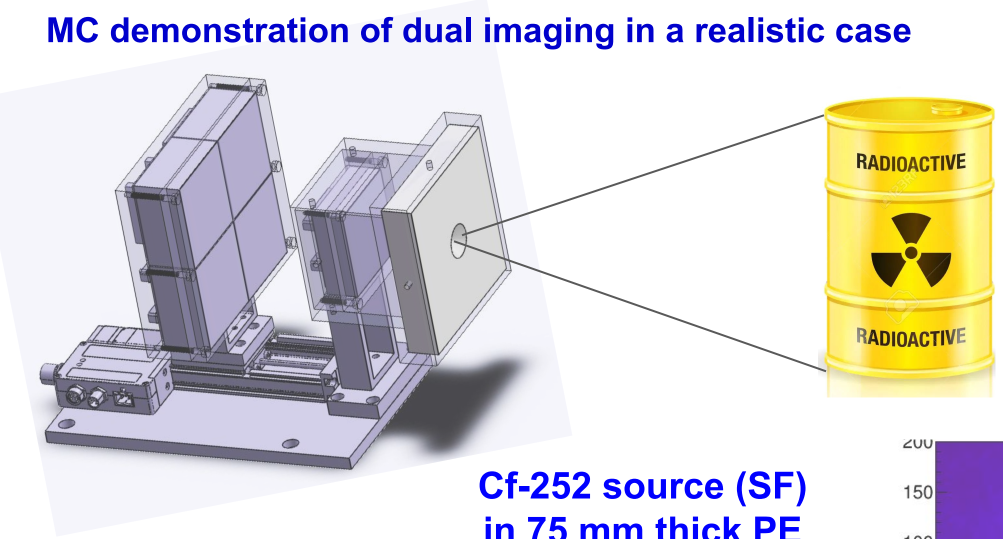
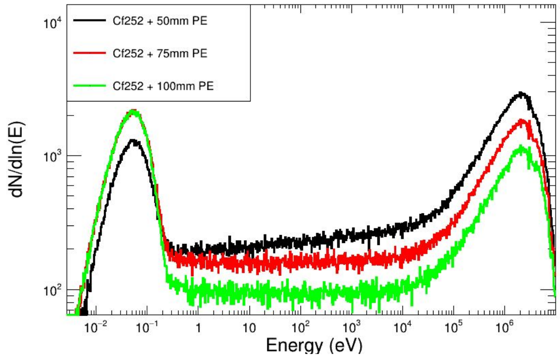
MC-based design: dual imaging

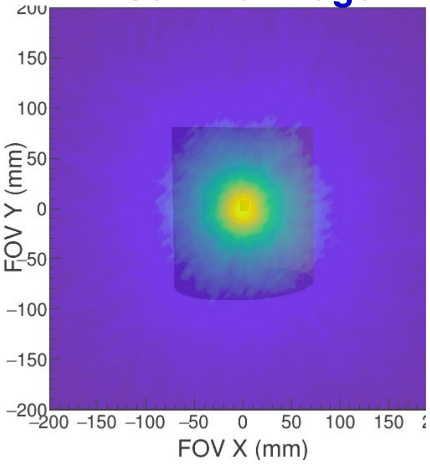
MC demonstration of dual imaging in a realistic case



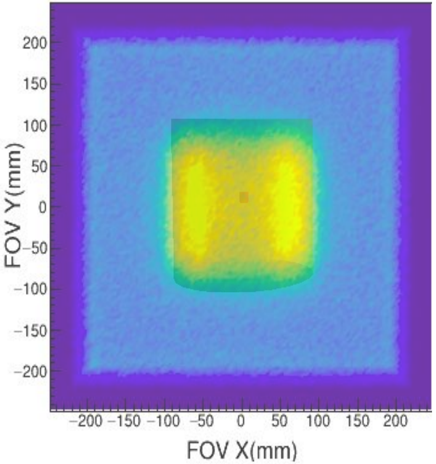


Cf-252 source (SF) in 75 mm thick PE container

Gamma image



Neutron image



RESEARCH ARTICLE — Open Access

Simultaneous Gamma-Neutron Vision device: a portable and versatile tool for nuclear inspections

Jorge Lerendegui-Marco[1*], Víctor Babiano-Suárez[1], Javier Balibrea-Correa[1], Luis Caballero[1], David Calvo[1], Ion Ladarescu[1] and César Domingo-Pardo[1]

J. Lerendegui-Marco et al. EPJ-TI (2024)

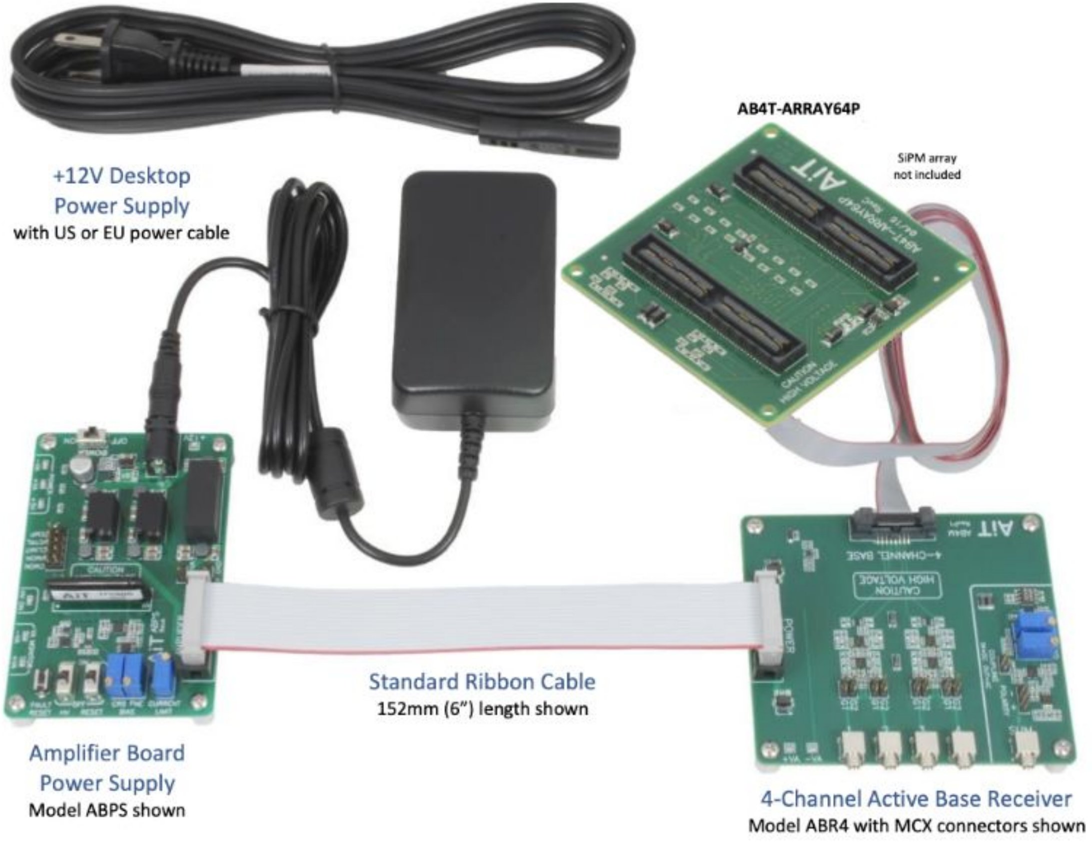
Multiplexed readout

i-TED to GN-Vision:

1) simply replacing the PSD of the LaCl3 scatterer with CLYC, while keeping the SiPMs connected to the ASICs and the PETSys TOFPET2 readout electronics (64 individual SiPMs are read out)

2) significant issues arise due to the inherent disparities between CLYC and LaCl3. CLYC exhibits a significantly lower light yield of 20,000 photons per MeV compared to the 50,000 photons per MeV characteristic of LaCl3. Additionally, the signal width of CLYC, approximately 4-5 μs, is much greater and more diffuse than that of LaCl3, which is around 300 ns. Consequently, the light yield per nanosecond in CLYC is approximately 40 times smaller, leading to substantial SNR challenges when using CLYC with pixelated SiPMs.
3) As a consequence, we failed to read out of individual pixel signals both with anoscilloscope or with PETSys.
4) Solution: Multiplexing method → 64 SiPMs → 4 position-encoded signals

Multiplexed readout

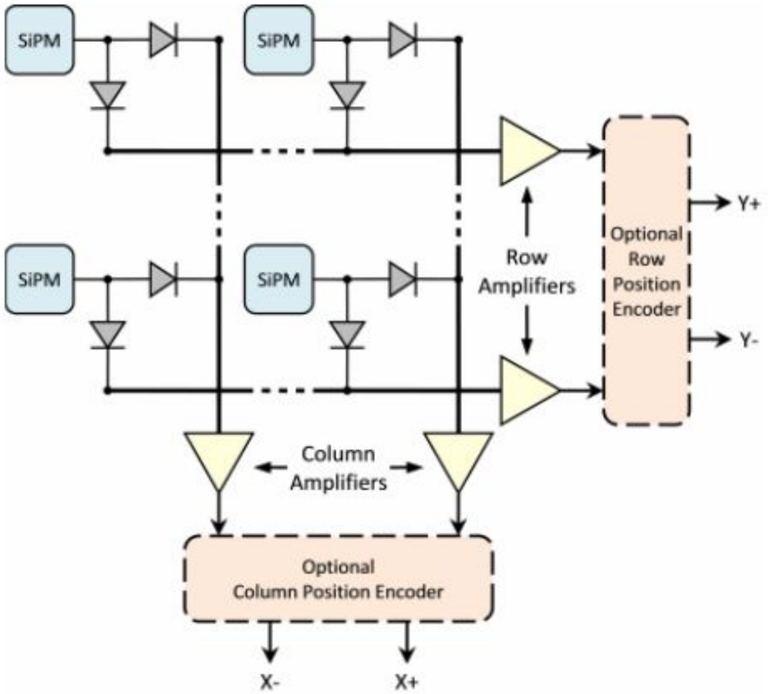


Multiplexed readout

Row & Column Readout with Optional 4-Channel Encoder

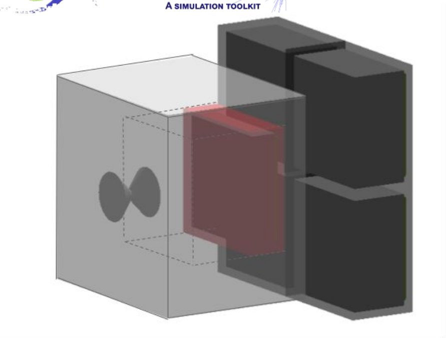
- SiPM current is divided equally into one row and one column
- Each row and column has a separate transimpedance amplifier
- Optional 4-channel encoder further multiplexes the rows and columns into two X and two Y signals
- Often referred to as "symmetric charge division"

(Diodes oriented for positive SiPM signals)

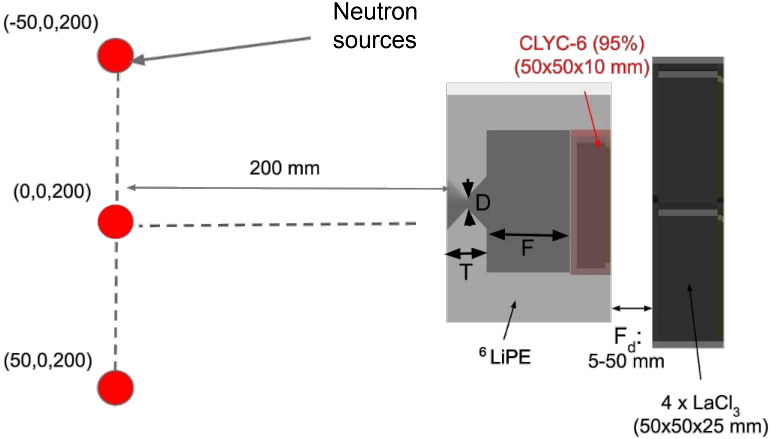


MC-based design: neutron imaging

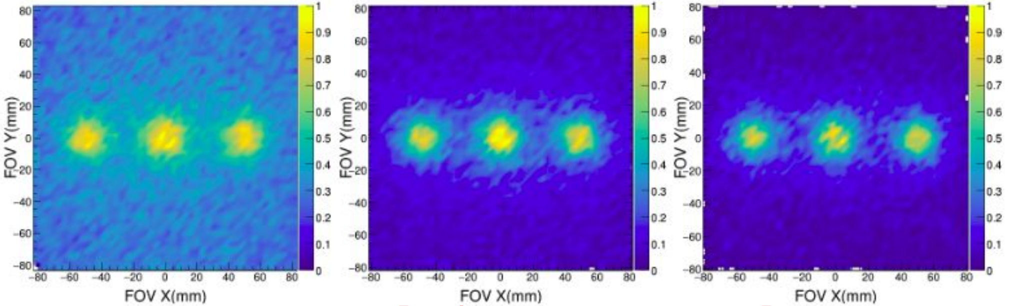
GEANT4 A SIMULATION TOOLKIT

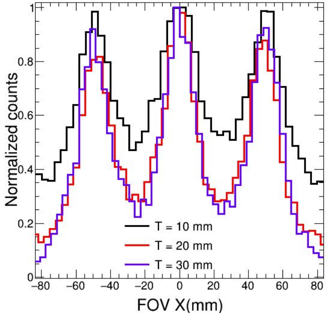


T = 10, 20, 30, 40 mm.
D = 1, 2.5, 5 mm
En = 25 meV, 1, 10, 100 eV



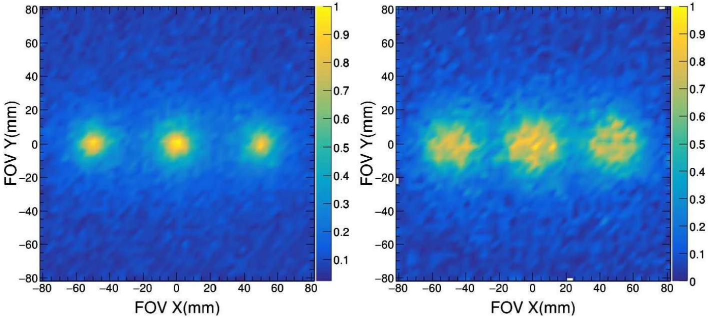
T = 10 mm **T = 20 mm** **T = 30 mm**

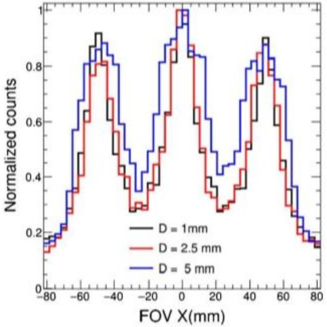




Images for 1 eV neutrons

D = 1 mm **D = 5 mm**





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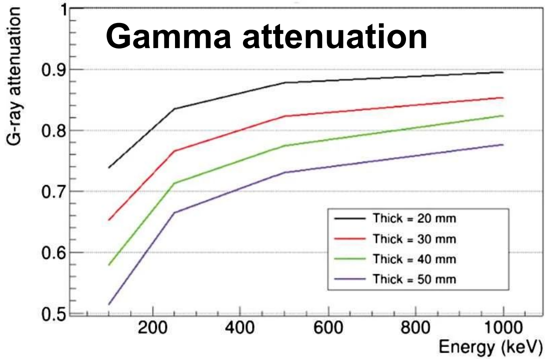
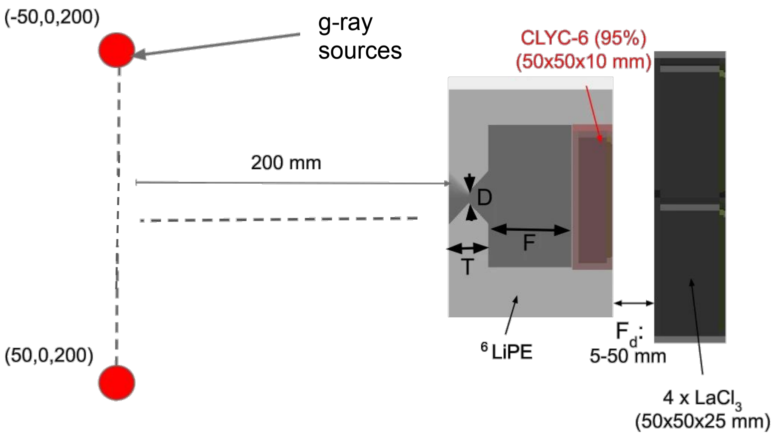
Thickness T: Contrast / En
Diameter D: Resolution / Eff

J. Lerendegui-Marco et al. EPJ-TI (2024)

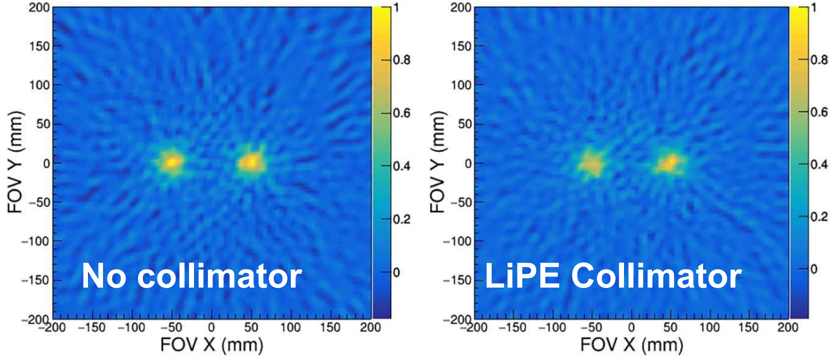
MC-based design: g-ray imaging

Dual gamma-neutron imaging?



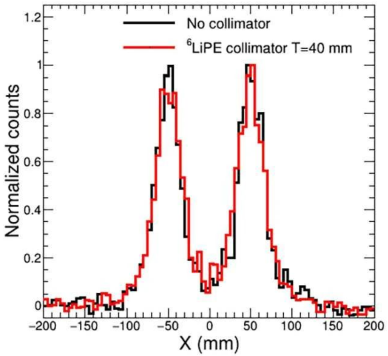


Compton images of 500 keV g-ray source



Impact of neutron collimator:

- Loss in g-ray imaging efficiency
- No effect in the g-ray imaging resolution



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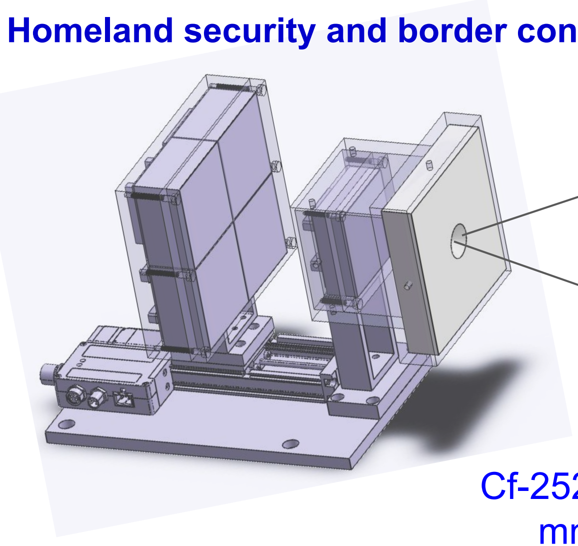
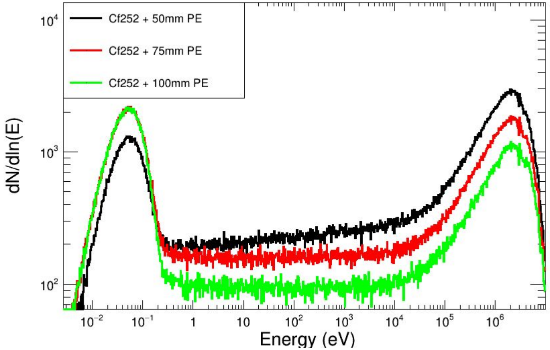
J. Lerendegui-Marco et al. EPJ-TI (2024)

GN-Vision: nuclear inspection

Homeland security and border control of radioactive materials





Cf-252 source in 75 mm thick PE container

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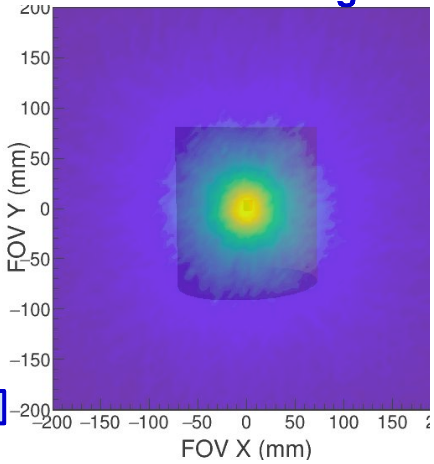
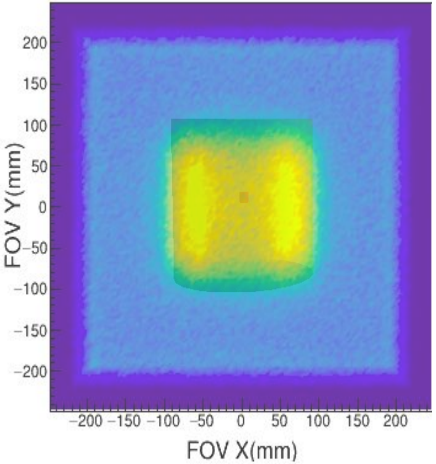
J. Lerendegui-Marco et al. EPJ-TI (2024)

Gamma image

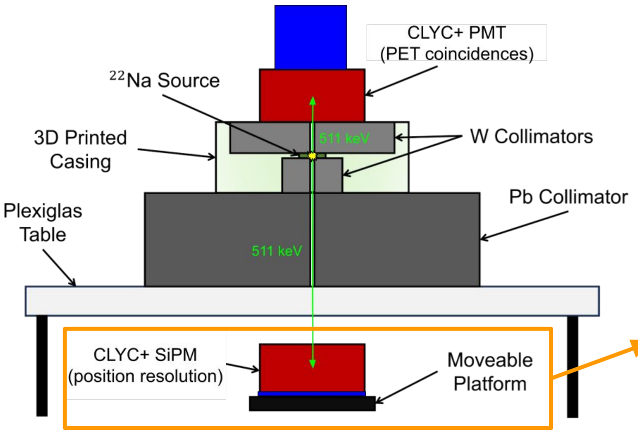


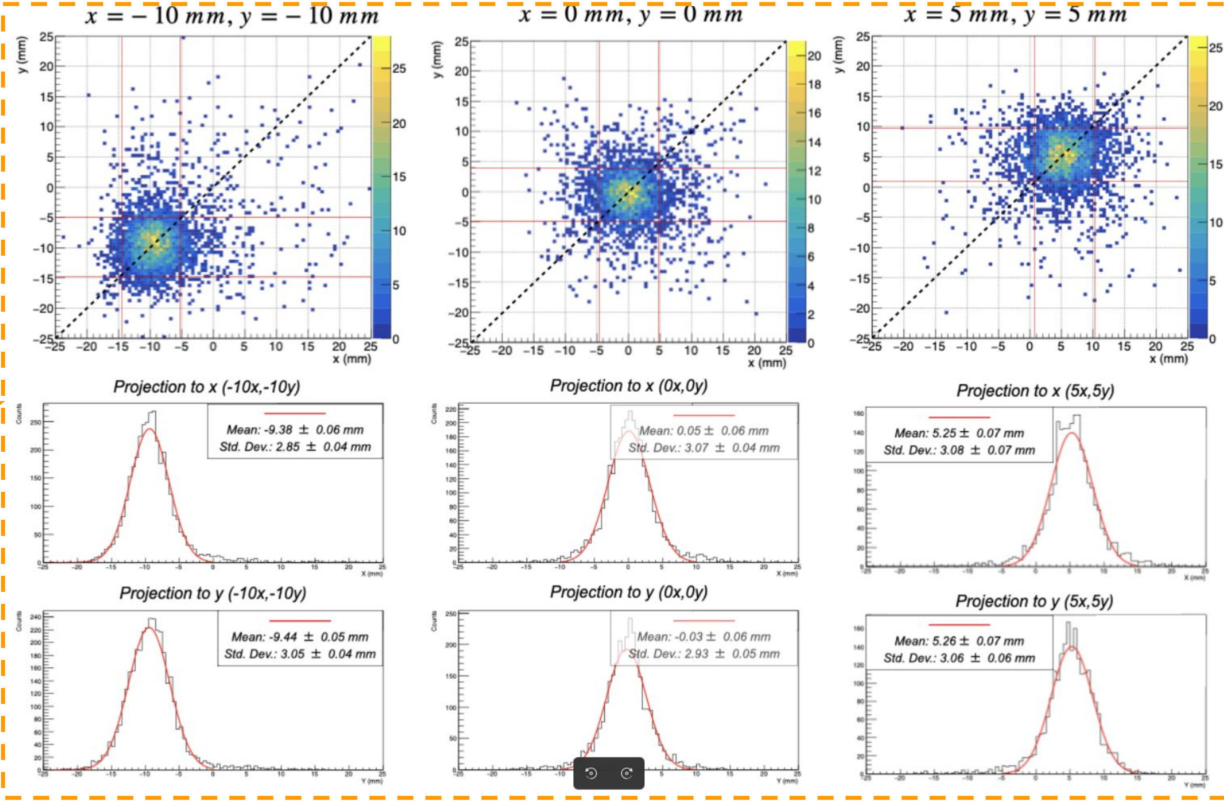
Neutron image



Position sensitivity: method

G-ray scanning table





2-fold collimation:

1) Mechanical
2) 2 x 511 keV in coincidence

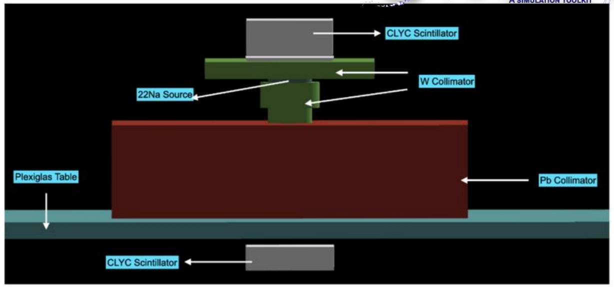
Width of the reconstructed positions: **contribution of the non-ideal collimation?**

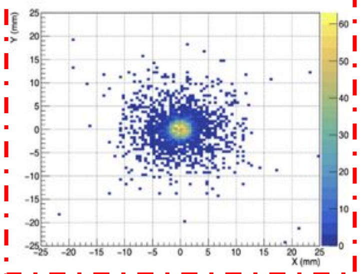
Examples of reconstructed positions from the 4 pos-encoded signals X+,X-,Y+,Y-

$$\mathbf{X\ column} = \frac{(X_+ - X_-)}{(X_+ + X_-)}, \qquad \mathbf{Y\ row} = \frac{(Y_+ - Y_-)}{(Y_+ + Y_-)}.$$

Position sensitivity: spatial resolution

GEANT4
A SIMULATION TOOLKIT

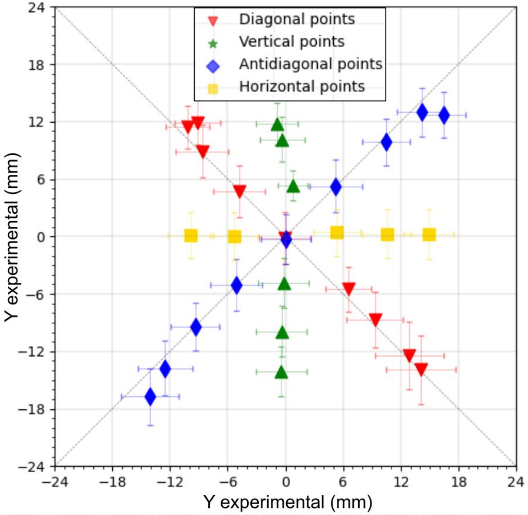


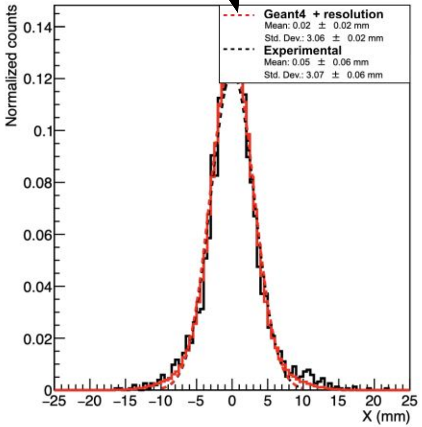


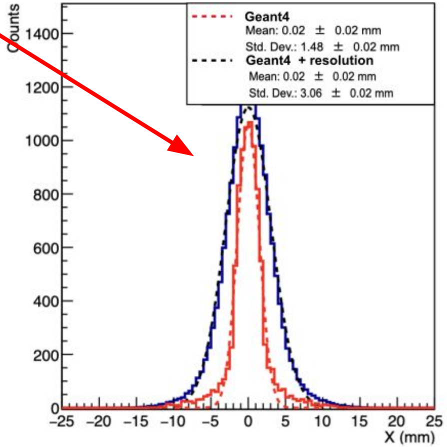
MC

Exp. $f(\sigma_{\mathrm{MEASURED}}, \mu) = g(\sigma_{\mathrm{SETUP}}, \mu) \circledast \mathcal{N}(\sigma_{\mathrm{CLYC}}, \mu)$

Our aim: Position resolution







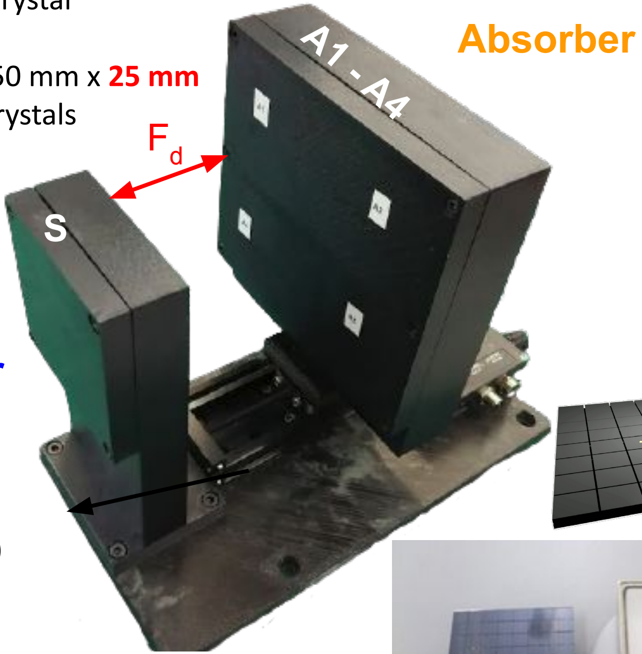
Best. Resol. (FWHM): 5 mm
sub pixel resolution!!

G. Cisterna, Master's Thesis (U.Sevilla, IFIC)

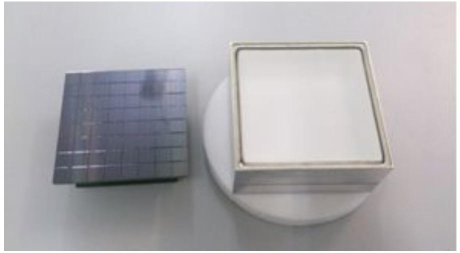
The starting point: i-TED

i-TED: Compton Cameras

- 1 Scatterer: 50 x 50 mm x **15 mm**
  $LaCl_3$ monolithic crystal
- 4 **Absorbers** 50 x 50 mm x **25 mm**
  $LaCl_3$ monolithic crystals



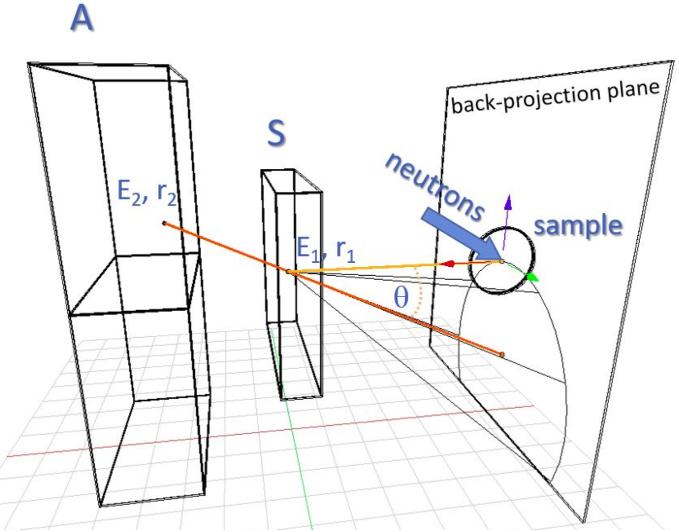
Dynamic Electronic Collimation:
micropositioning stage
(M-683 from PI-miCos)
→ Adjustable F_d



Read-out: 8x8 SensL Pixelated SiPM

Electronics: PETSys acquisition system

Compton imaging



$$\boxed{\theta = arcos\left(1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1+E_2}\right)\right)}$$

$$\boxed{\Delta\theta = \frac{E_1+E_2}{sen\,\theta}\left(\frac{1}{E_1^2}\left(\frac{\Delta E_1}{E_1}\right)^2 + 2\,sen^2\theta\left(\frac{\Delta r}{r}\right)^2\right)^{1/2}}$$

The starting point: i-TED


Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

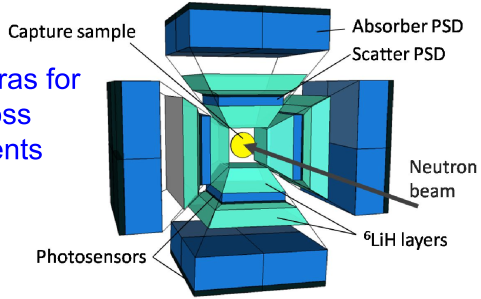
i-TED: A novel concept for high-sensitivity (n,γ) cross-section measurements

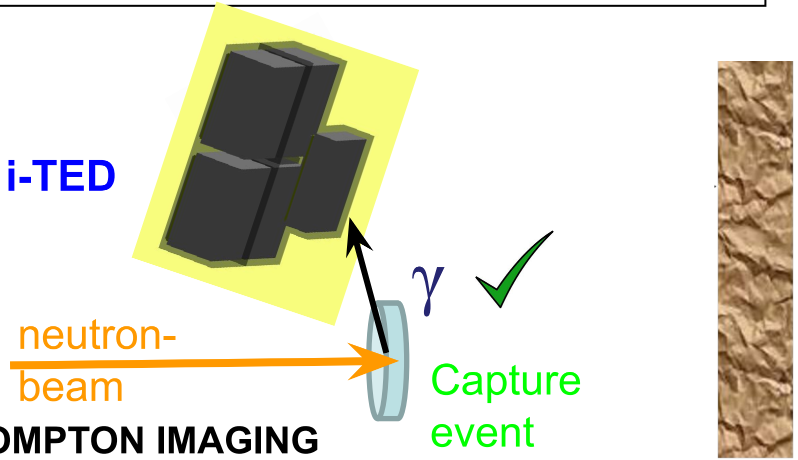
C. Domingo-Pardo

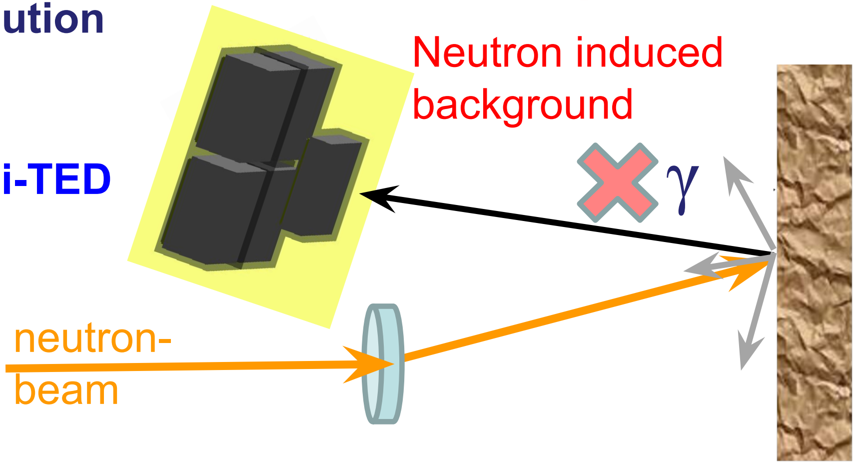
Instituto de Física Corpuscular, CSIC-University of Valencia, Spain

HYMNS nucleosynthesis & MS evolution

i-TED: An array of 4 compton cameras for neutron capture cross section measurements







COMPTON IMAGING TECHNIQUE

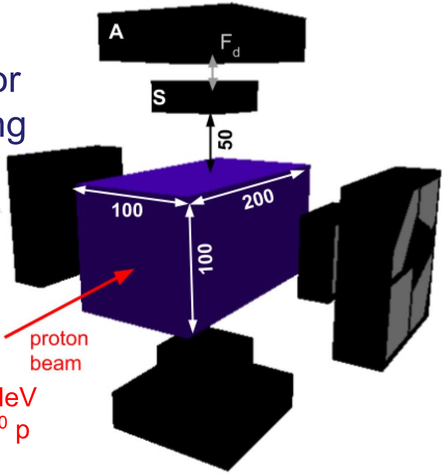
$$\theta = \arccos\left(1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1+E_2}\right)\right)$$

IDEA: Exploit the Compton Imaging technique to reduce the extrinsic neutron background and enhance the detection sensititivity

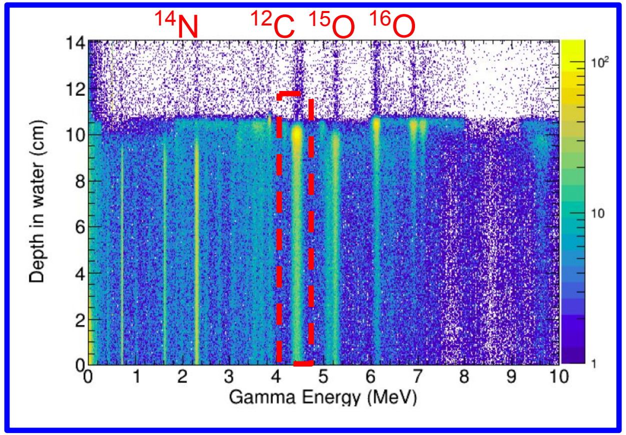
i-TED: proton range verification via PG imaging

MC:
4-iTEDs for
PG imaging

GEANT4

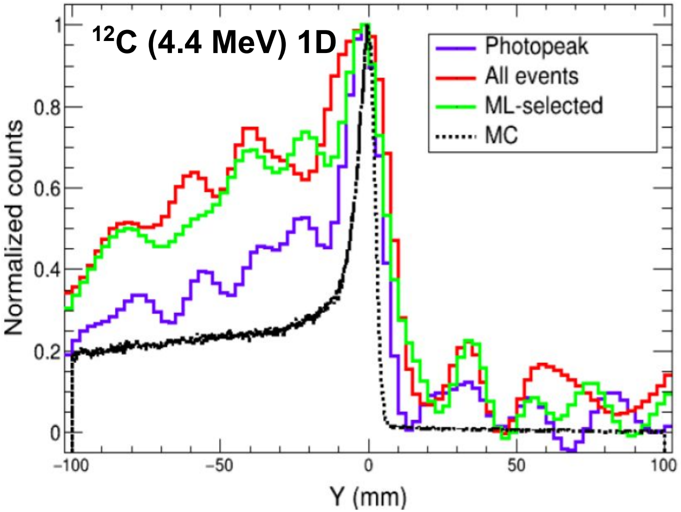


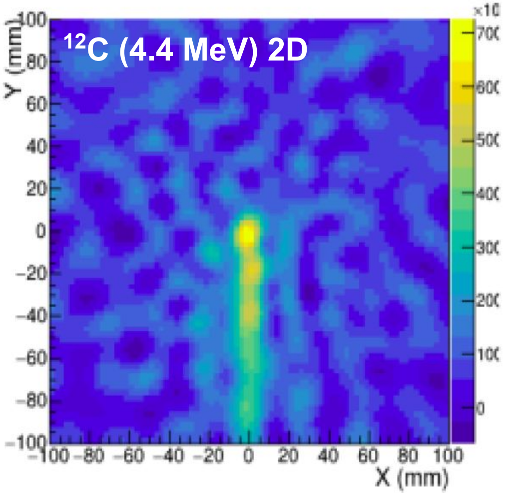
120 MeV
$2x10^{10}$ p



1D Projection: MC vs reconstructed

Reconstructed 2D Compton image



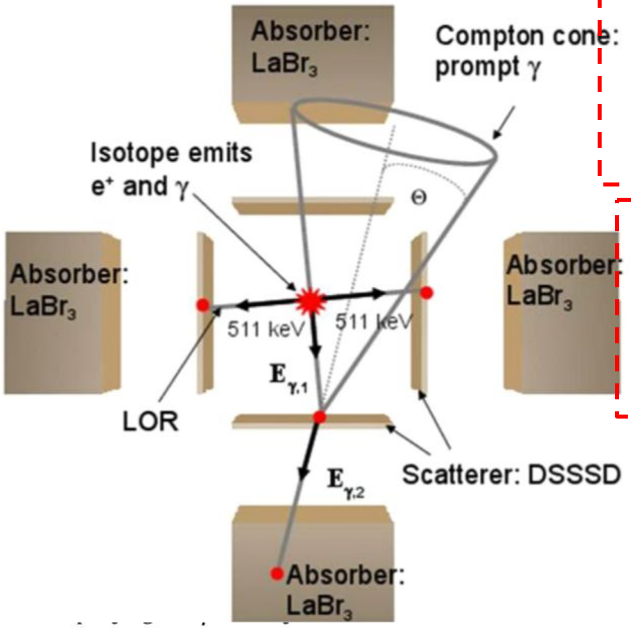


- Suitable for imaging in the gamma-ray energy range around 4 MeV
- Good E- and spatial resolution
- State-of-the art Compton algorithms + ML-aided event selection

→ **Few mm accuracy**

[1] Tomitani et al., DOI: 10.1088/0031-9155/47/12/309 (2002)

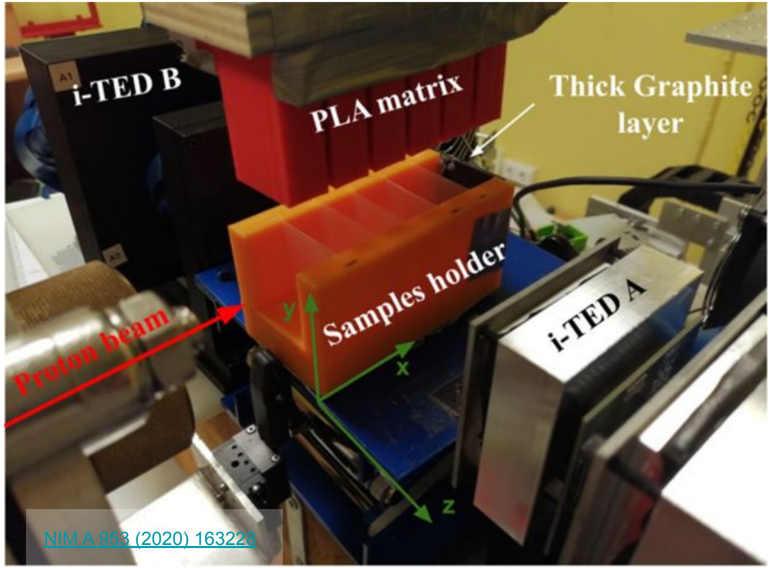
Hybrid Compton/PET systems for hadron-therapy



Proposed by K. Parodi in 2016
NIM A 809 (2016) 113–119

G. Llosa & M. Rafecas
Eur. Phys. J. Plus **138**, 214 (2023)

First experimental realization by J. Balibrea et al. in 2020
Eur. Phys. J. Plus **137**, 1258 (2022)

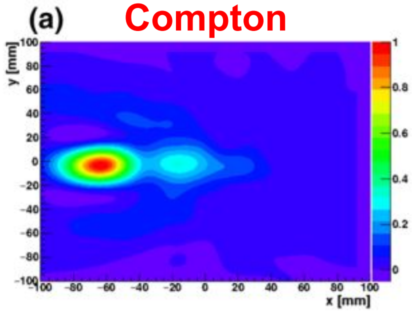


NIM A 953 (2020) 163228

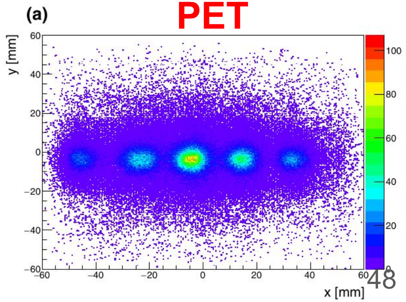
Although it is likely that such hybrid detection schemes will imply some compromises in the individual performances of prompt gamma or PET imaging in comparison to the dedicated systems discussed in the previous sessions, it is expected that their complementary information could largely overcome this drawback and open new perspectives of in vivo ion beam treatment verification. In fact, whereas prompt gamma imaging is expected to be the most promising approach for quasi real-time in vivo control of the beam range, PET is still a very attractive imaging modality owing to its intrinsic tomographic and functional character. For example, two groups have already reported changes of

Two i-TED Compton Cameras, p @ 18 MeV (CNA)

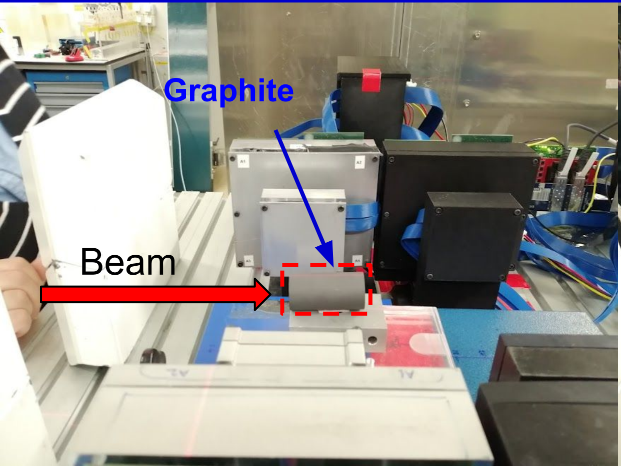
Compton

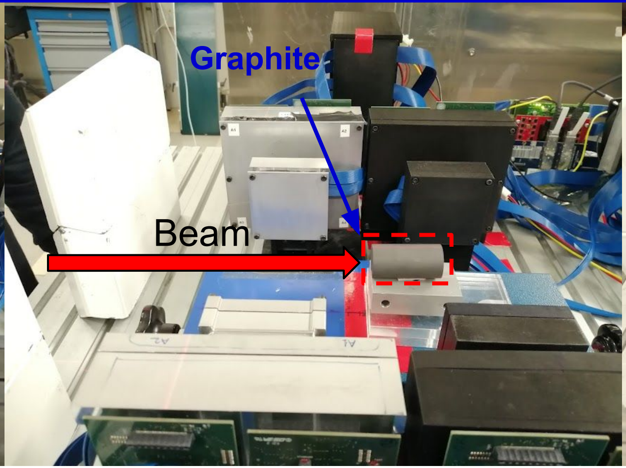


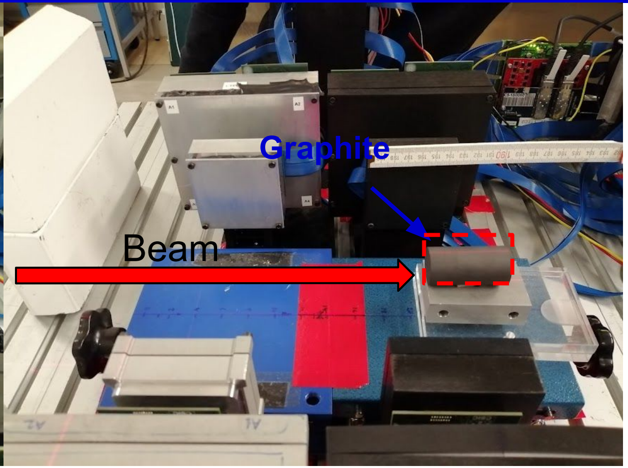
PET



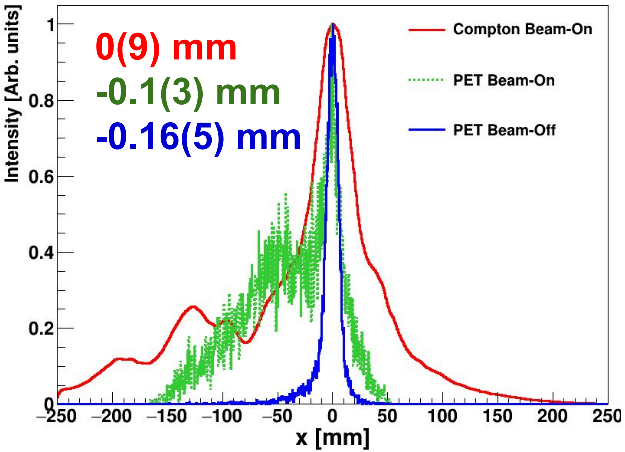
Compton vs PET Beam-on/off @ 55 MeV

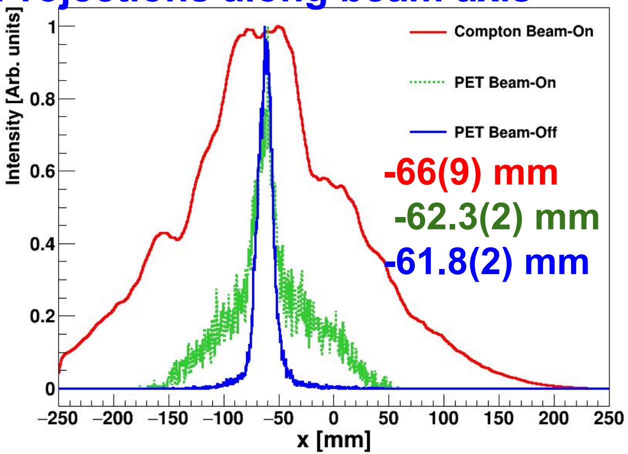


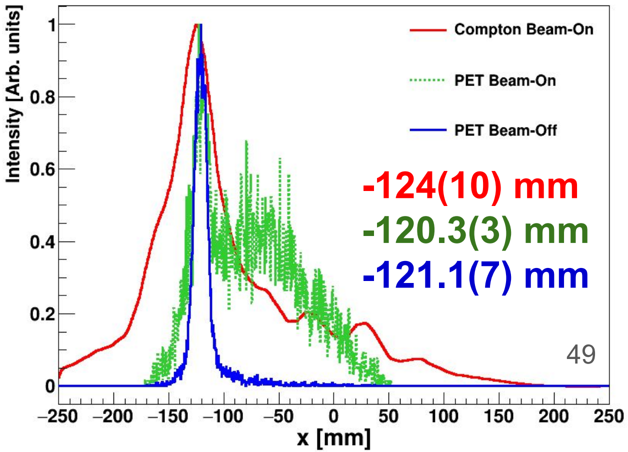




Projections along beam axis



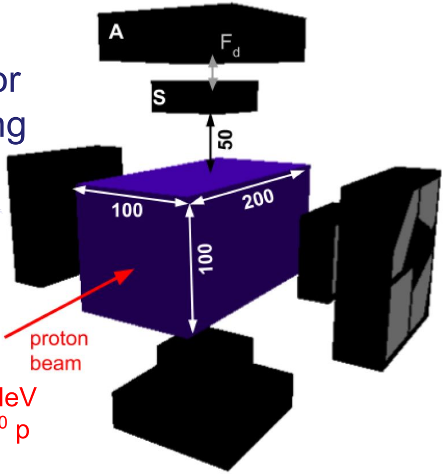




i-TED: proton range verification via PG imaging

MC:
4-iTEDs for
PG imaging

GEANT4



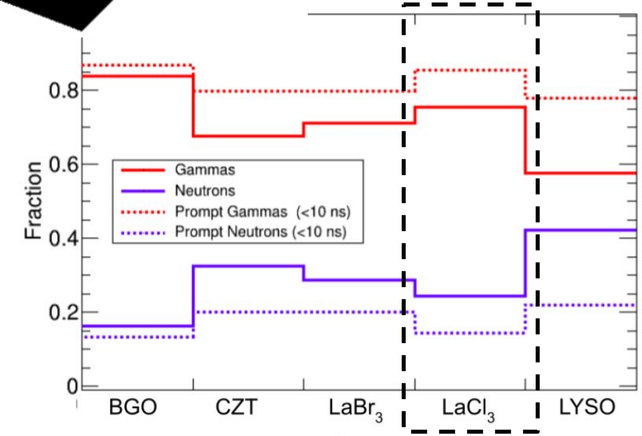
120 MeV
2×10^{10} p

- High detection efficiency, high CR-capability, Fast imaging algorithms → **Real time**
- Low sensitivity to n-induced backgrounds → **Improved S/B-ratio**
- Compact & lightweight → **Compatible with clinical environment**

Efficiency per incident proton

	Focal distance (mm)		
Energy selection	5	15	30
All PG (1-7 MeV)	2.6×10^{-4}	2.1×10^{-4}	1.6×10^{-4}
4 main PGs	4.3×10^{-5}	3.5×10^{-5}	2.6×10^{-5}
^{12}C (4.3-4.6 MeV)	1.5×10^{-5}	1.2×10^{-5}	8.8×10^{-6}

Fraction Neutron induced counts



Algorithm	Time (s)
BP	<5
SOE	14
AA (CPU Single-thread)	1821
AA (CPU Multithreading-8)	260
AA (GPU)	15

Computing time for an image (20k events)

Talk of **Javier Balibrea** (Tuesday, 14:40, JANÁK HALL) on the first experimental tests

Position reconstruction in i-TED

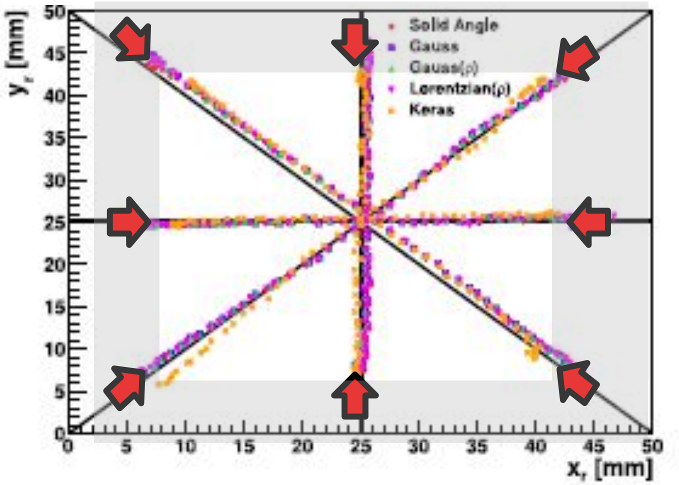
Challenge with thick crystals: ***Pin-cushion effect***
Large Compression in the output image

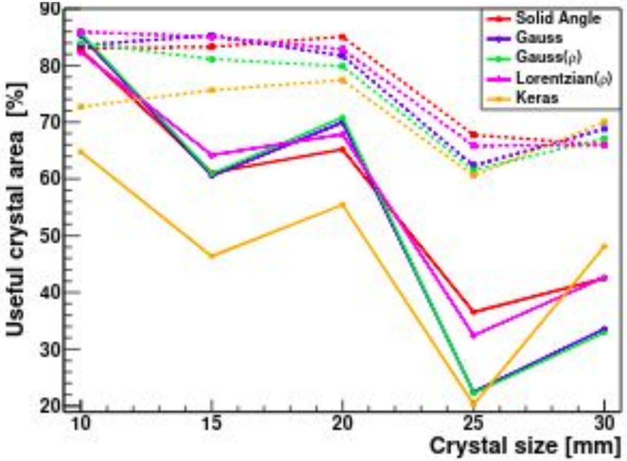
Solution: Machine Learning algorithm (Support Vector Machine).

Idea: Position reconstructed (x_r,y_r) fitted to the "known" real positions (x,y).

Useful crystal area: 30-40%
AFTER SVM: 70%

15 mm thickness





Nuclear Inst. and Methods in Physics Research, A

Machine Learning aided 3D-position reconstruction in large $LaCl_3$ crystals

J. Balibrea-Correa*, J. Lerendegui-Marco, V. Babiano-Suárez, L. Caballero, D. Calvo, I. Ladarescu, P. Olleros-Rodríguez[1], C. Domingo-Pardo
Instituto de Física Corpuscular, CSIC-University of Valencia, Spain

MC design: SBR and Efficiencies

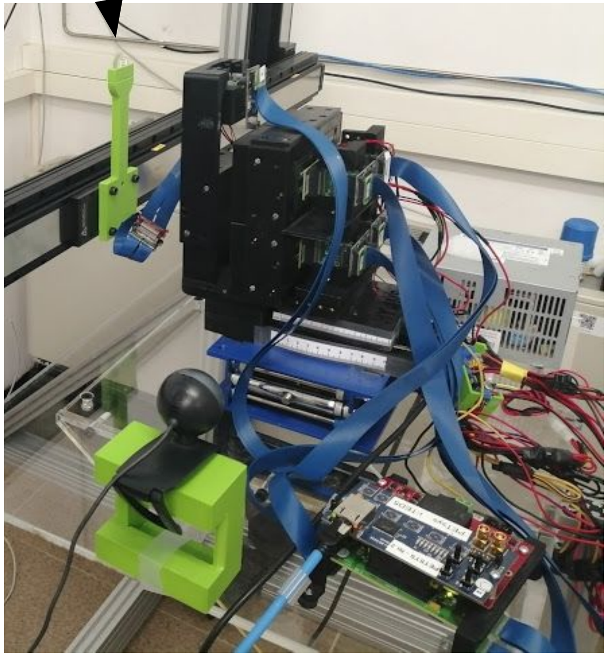
En (eV)	T = 10 mm	T = 20 mm	T = 40 mm
0.025	14.73	18.95	46.16
1	2.23	5.86	14.05
10	1.41	2.31	7.56
100	1.21	1.31	2.42

Pin-hole diameter D (mm)	Efficiency	Resolution (mm)
1	3.1×10^{-5}	17.4
2.5	4.0×10^{-5}	18.9
5	6.0×10^{-5}	24.1

Energy (MeV)	Focal distance (mm)		
	5	15	30
0.5	1.72×10^{-2}	1.31×10^{-2}	8.43×10^{-3}
1.0	2.18×10^{-2}	1.80×10^{-2}	1.36×10^{-2}
2.0	2.10×10^{-2}	1.74×10^{-2}	1.35×10^{-2}
5.0	2.79×10^{-2}	2.33×10^{-2}	1.84×10^{-2}

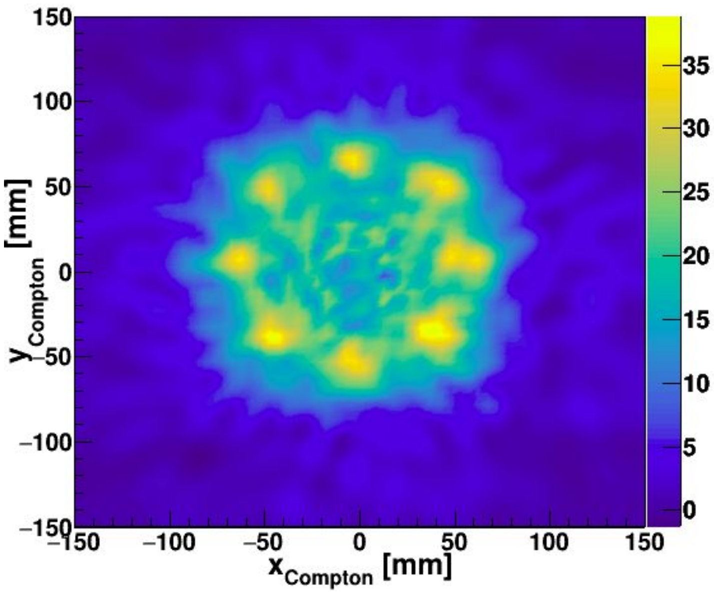
Status of the development: g-ray imaging

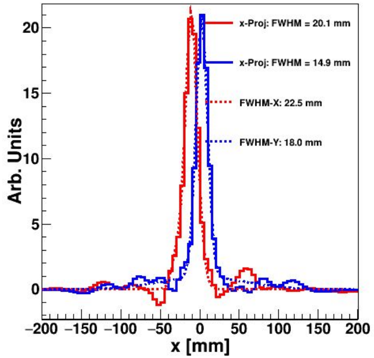
XY-gantry @ IFIC lab



Experimental Compton images:

^{22}Na Source @ 8 positions on a plane at 100 mm





Spatial Resolution ~ 15-20 mm @ 100 mm

The gamma imaging capability with high resolution algorithms is fully experimentally demonstrated, after the technical developments of the **i-TED detector** + studies for application to range verification

Neutron interaction CLYC: energy ranges

Thermal neutrons: Li-6(n,a)

Li-6 enrichment maximum: 95% (literature)
Li-6(n,a): 940 b @ 25 meV

Literature: CLYC6

Fast neutrons:

Depleted Li (i.e. enrichment in Li-7 >99%) (literature)
Dominant reactions: Cl-35(n,a), Cl-35(n,p):
100-300 mb (@ MeV)

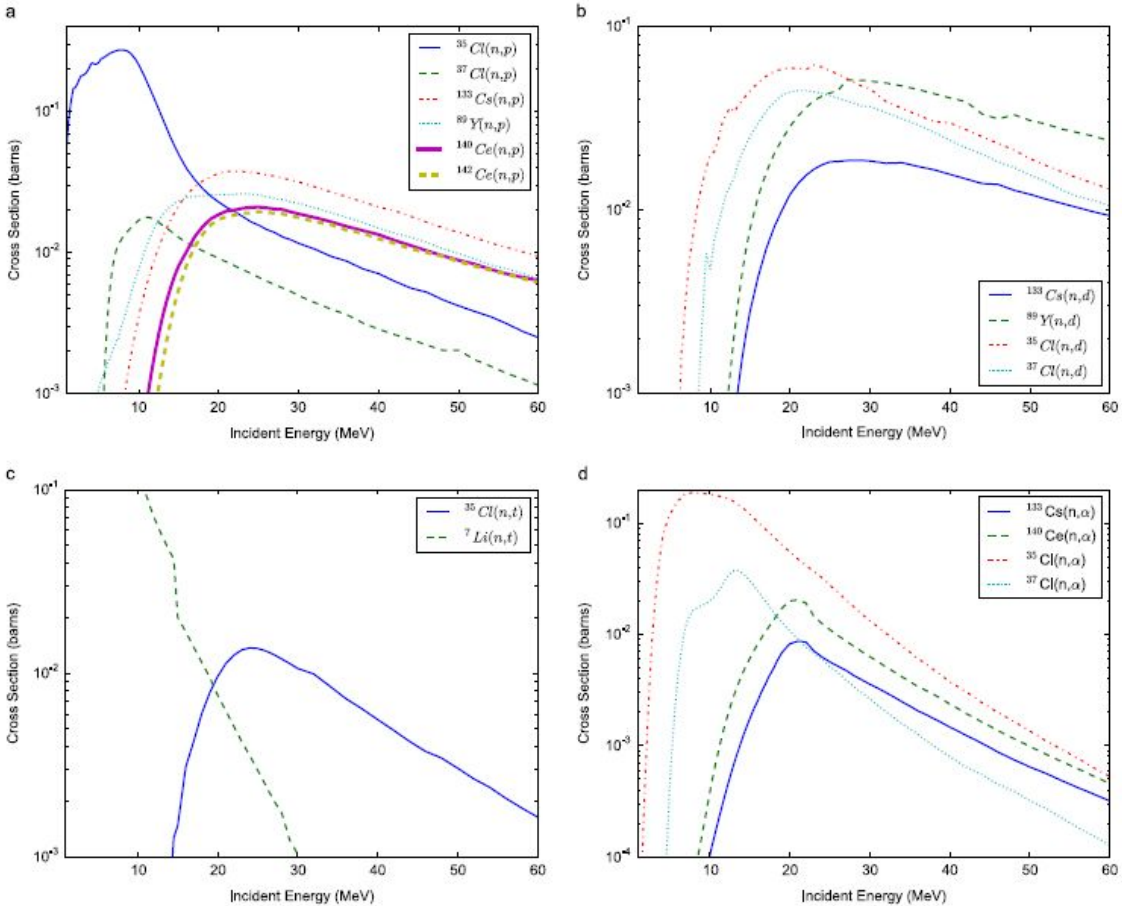
Literature: CLYC7

The sensitivity to thermal neutrons is given by the well known reaction $^{6}Li+n={}^{3}H+\alpha$ which has a cross-section of 940 barns [9–12]. The emitted tritium (^{3}H) and the α particles deposit approximately 3.2 MeVee (MeV electron equivalent). The sensitivity of CLYC to fast neutrons, instead, was found to be given by the reactions on ^{35}Cl ($^{35}Cl+n={}^{35}S+p$ and $^{35}Cl+n={}^{32}P+\alpha$), which have cross-sections of the order of 100–300 mb [13–16,22–24]. In addition, the energy of the outgoing proton and α particle scales linearly with the kinetic energy of the incident fast neutron [13,15,24]. Therefore, the energy of the incident neutron can be directly deduced from the pulse generated by the detector. This unique capability makes CLYC a very promising scintillator for both γ and neutron spectrocopy in base research and application.

Since the capability of CLYC to detect thermal neutrons is provided by ^{6}Li, the selection of ^{6}Li or ^{7}Li enrichment allows to control the sensitivity of a CLYC scintillator to thermal neutrons. In particular, an enrichment in ^{6}Li (CLYC-6) increases the sensitivity to thermal neutrons while an enrichment in ^{7}Li (CLYC-7) suppresses the sensitivity to thermal neutrons allowing a better detection of fast neutrons.

Nuclear Instruments and Methods in Physics Research A 810 (2016)132–139

Neutron interaction: fast neutron channels



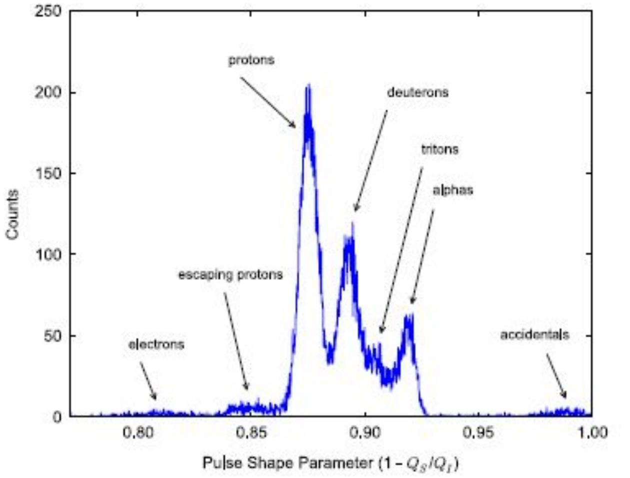
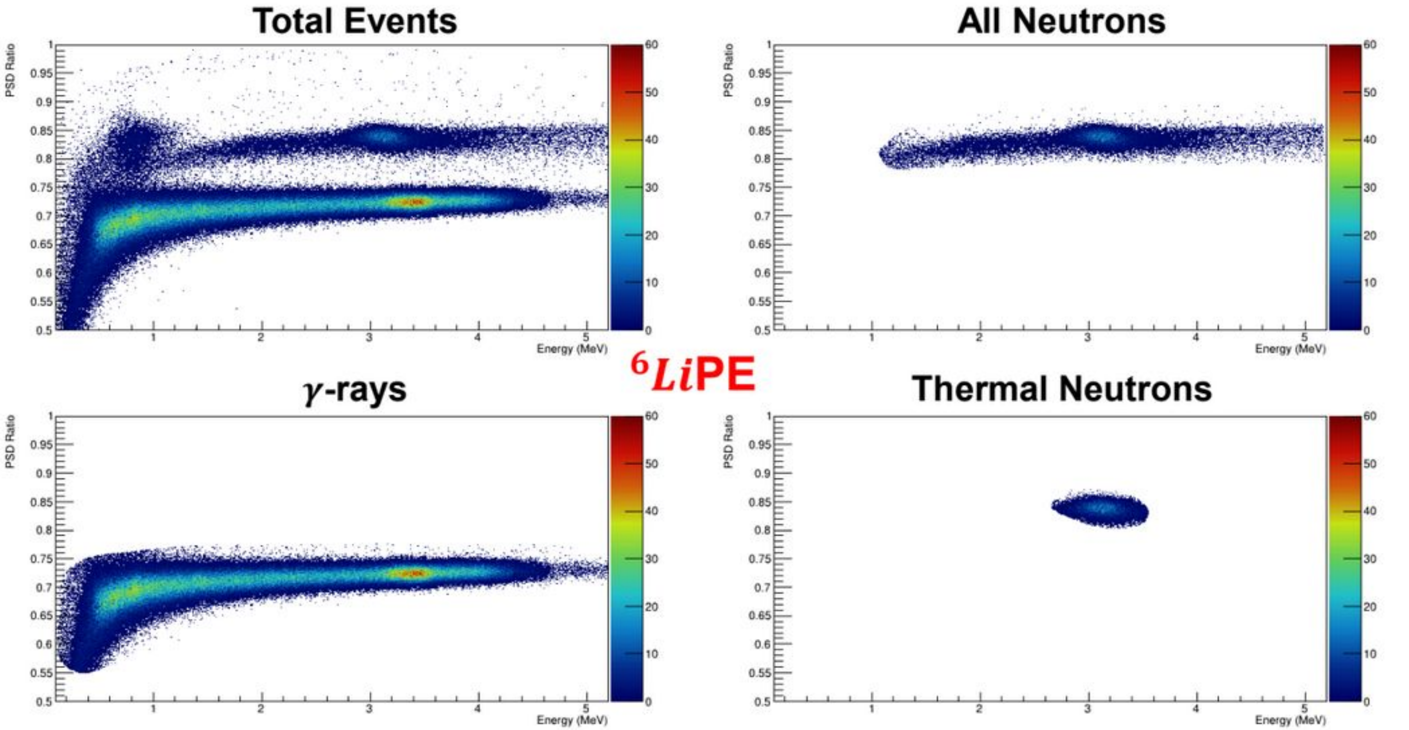


Fig. 10. The 1-*d* histogram of the pulse shape for the 25.4 mm × 25.4 mm × 25.4 mm CLYC-7 scintillation detector irradiated by a 60.5 MeV neutron beam at the Crocker Nuclear Laboratory. This plot is annotated to indicate the reaction channels and accidental events observed.

PSD for fast neutrons

Nuclear Instruments and Methods in Physics Research A 803 (2015) 47–54

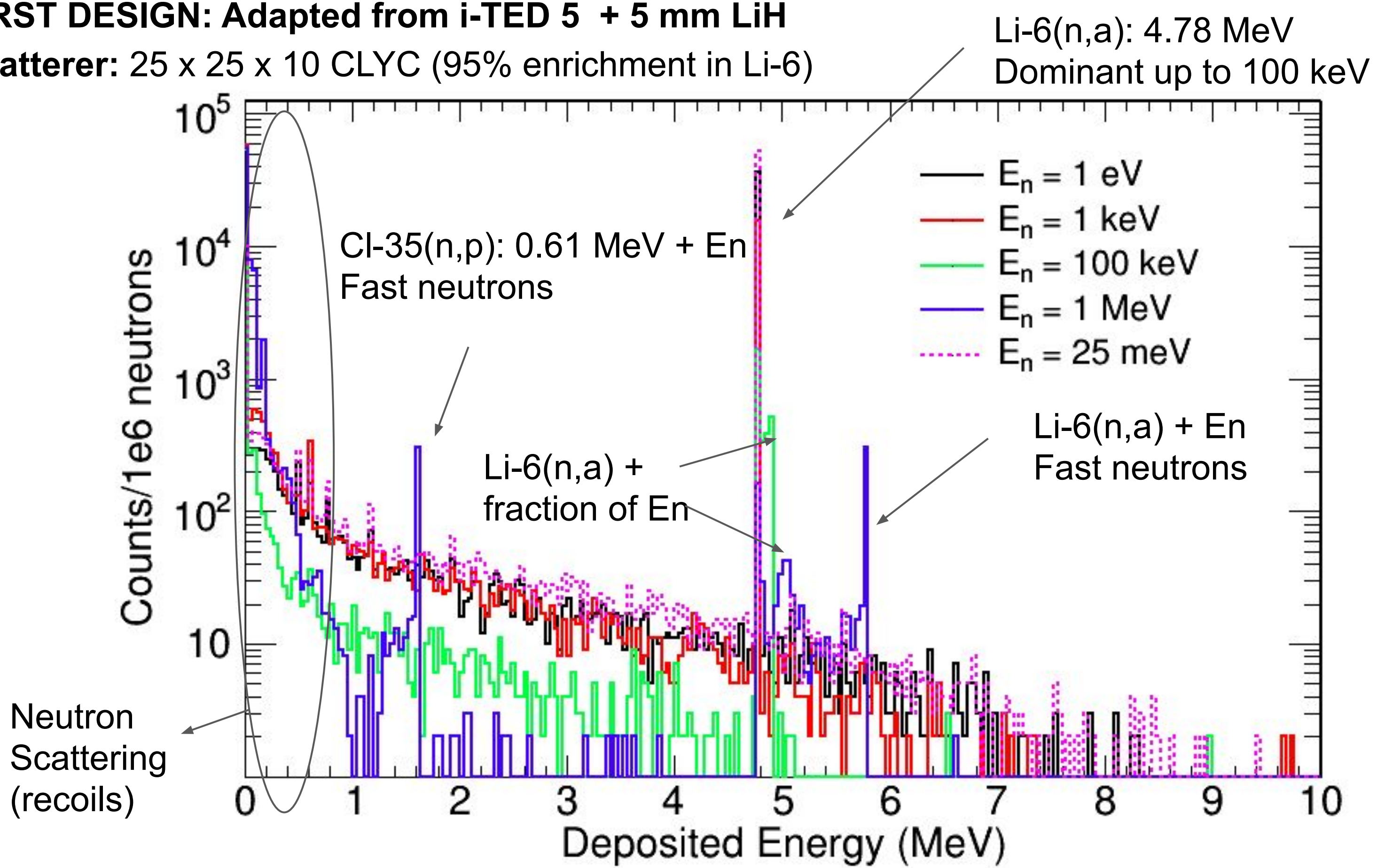
PSD: fast vs slow neutron



Results: Deposited energy spectra CLYC

FIRST DESIGN: Adapted from i-TED 5 + 5 mm LiH

Scatterer: 25 x 25 x 10 CLYC (95% enrichment in Li-6)



Eff (4.78 MeV Peak)

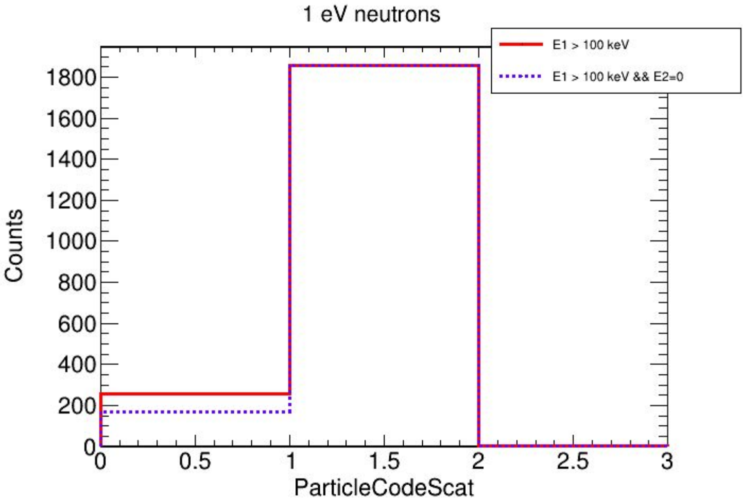
25 meV:
1 eV:
1 keV:
100 keV:
1 MeV:
10 MeV:

Particle Tagging @ Scatterer

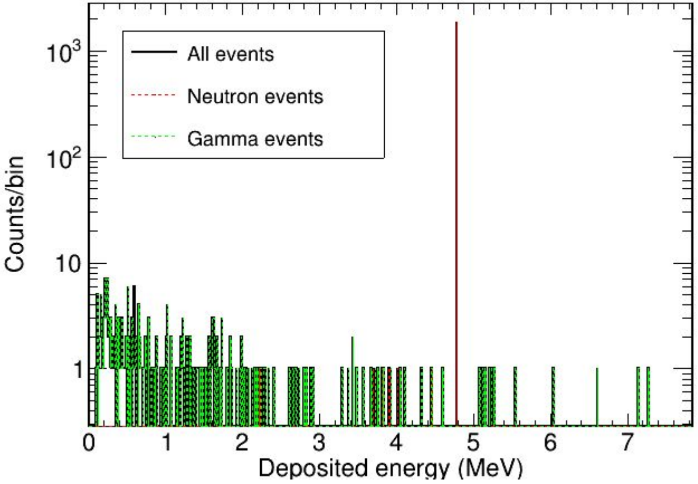
CLYC Detection based on the different signal shape depending on the particle which deposits energy

- **Tagged events by particle depositing energy→ each has a different quenching.**
  - Electron/positron → gamma rays→ **ParticleCode = 0**
  - Alpha/Triton → thermal neutrons Li6(n,a)→ **ParticleCode = 1**
  - Proton → Fast neutrons (n,p) reactions→ **ParticleCode = 2**

```
*............................................................
*Br    5 :ParticleCodeScat : ParticleCode/I
*Entries :       92 : Total  Size=          970
*Baskets :        1 : Basket Size=        32000
*............................................................
```



(n,g) contribution small and reduced if anticoincidence with absorber



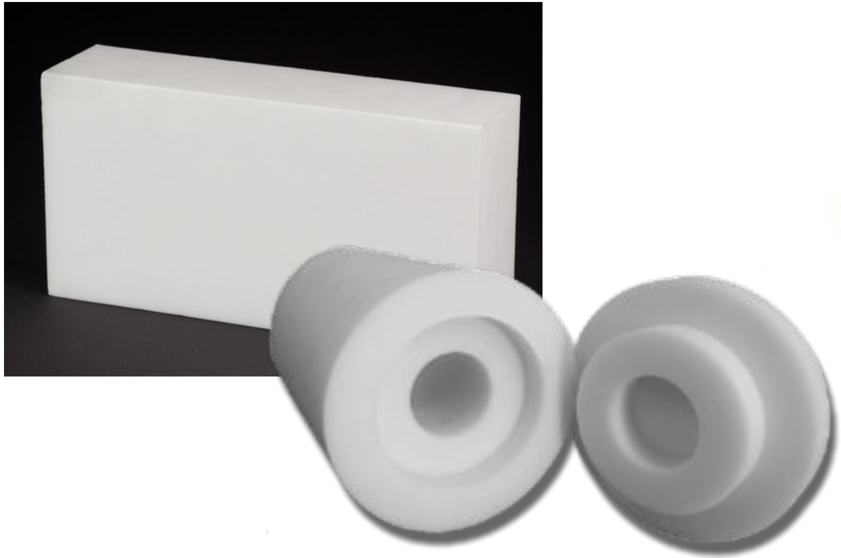
Perfect identification of alpha + triton peak and gamma events→ (n,g) reactions

Neutron collimator material: Li-PE

- LiH
  - Difficult to mechanize
  - Hygroscopic
  - Expensive

- Other possibility: Lithium Polyethylene
  - Comercially available:

https://johncaunt.com/products/lithium-polyethylene/



COMPOSITION DATA	JC215
Hydrogen atom density / cm3:	5.44×10^{22}
Hydrogen weight percent:	8.59%
Lithium atom density / cm3:	6.96×10^{21}
Lithium natural isotope distribution:	92.6 % ^{7}Li and 7.4 % ^{6}Li
Weight percent of all isotopes of lithium:	7.56%
Total Density:	1.06g/cm^3 (66.2 lbs./ft^3)

FEATURES AT A GLANCE

- Useful for shielding detectors in neutron fields as the thermal neutron poison utilised does not emit capture gamma
- High hydrogen content with 7.5% lithium
- Shields using enriched lithium 6
- Pre-cast shapes and sizes on request
- Other lithium concentrations on request