Compton imaging for dose monitoring in boron neutron capture therapy

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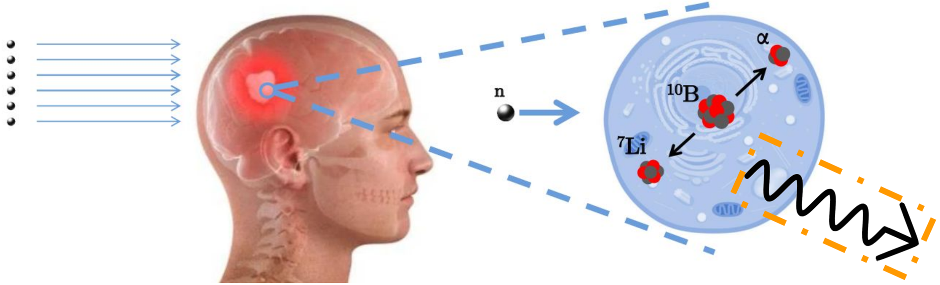
Outline

- Motivation: Boron neutron capture therapy
  - The State of the Art: Current dosimetry strategies and devices
- Our proposal for BNCT dose monitoring
  - Experimental Campaigns
    - Assessing feasibility and searching for main challenges
  - Tech Developments
- Conclusions

Boron Neutron Capture Therapy

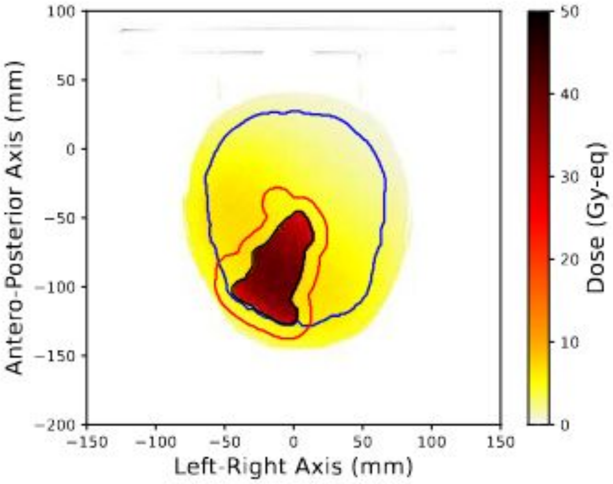


BNCT dosimetry is complicated:

$$D = w_B D_B + w_{n,th} D_{n,th} + w_{n,f} D_{n,f} + D_\gamma$$

^{10}BPA intravenous infusion / 20 ppm ^{10}B in blood

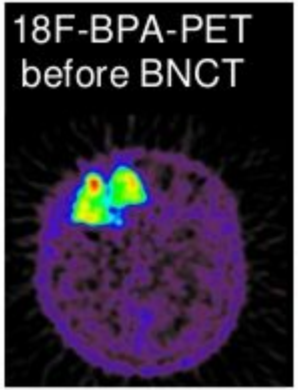
IAEA, Interactive Map of Accelerators, https://nucleus.iaea.org/sites/accelerators/Pages/Interactive-Map-of-Accelerators.aspx



Dosimetry in BNCT

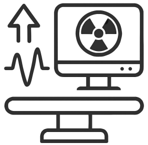
Current procedure

(1) Previous PET study of boron uptake with ^{18}F-BPA (up to 1 month before treatment)
(2) Boron concentration monitoring in blood during the treatment
(3) Extrapolation of dose based on (1) and (2)



Ideal objective

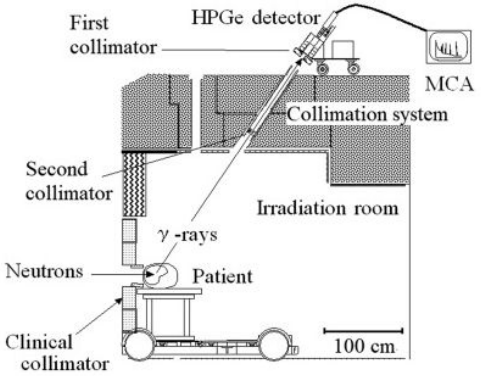
- Reliable and non-extrapolation-based dose determination
- High spatial resolution and real-time monitoring of the therapeutic dose
- Comprehensive detection of all BNCT dose components
- Compact, low-activation design that minimizes secondary radiation exposure



Dosimetry in BNCT

Main challenges to develop a BNCT dose monitor

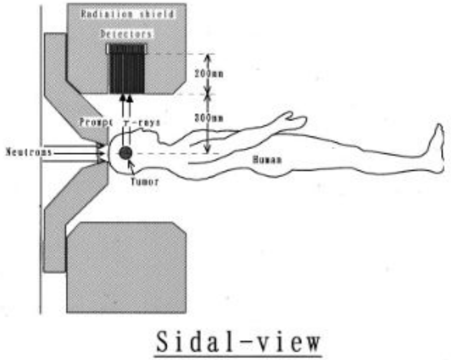
- High Count Rates
- Large Neutron and Gamma Backgrounds
- Resolution demands from clinicians
- Real-time analysis for monitoring



Y. Sakurai et al. *App. Radiat. Isot.* 2020
https://doi.org/10.1016/j.apradiso.2020.109256

Current proposals in the field:

Telescope monitors, SPECT, Compton Cameras



T. Kobayashi et al. *Med. Phys.* 2000
https://doi.org/10.1118/1.1288243

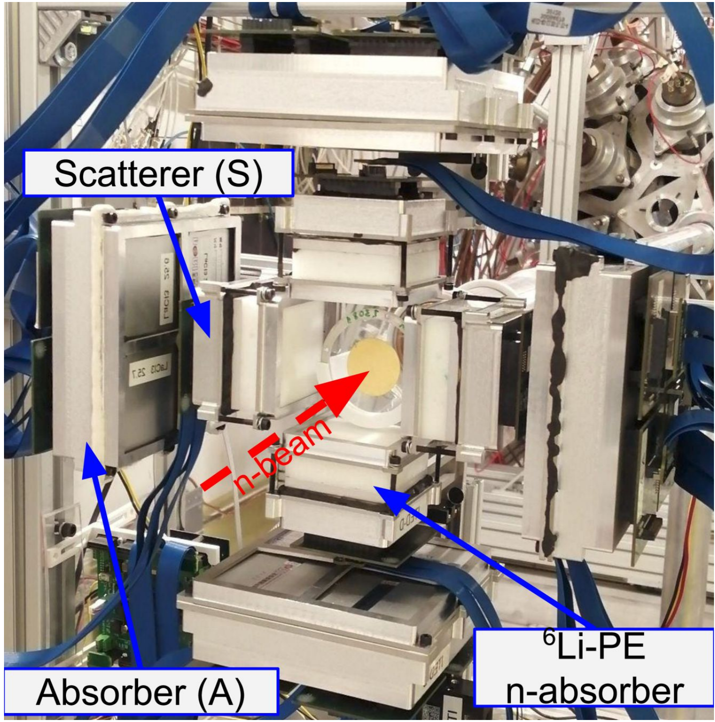
None commercial or for clinical use, all under development

iTED

ERC-CoG HYMNS Developments: from the i-TED Compton Imaging Array for nuclear astrophysics at n_TOF - CERN to ERC-PoC AMA for medical applications

$LaCl_3$ scintillators + SiPM (8x8 SensL) readout with PETsys electronics

- **Optimized** for **lowest neutron-induced** backgrounds (unique!)
- **Largest efficiency** (unique!) → Real Time Monitor
- **Large Field Of View** (1 scatter: 4 absorbers pyramidal configuration)
- **Optimized** for high-energy gamma rays and high count rates
- 1280 readout channels
- **AI**-aided **2D** and **3D** image-reconstruction algorithms



iTED: challenges towards BNCT

Original design has already many conforming features:

(high efficiency, low neutron sensitive crystals, large FOV, fast time response)

Experimental tests

→ Testing with the current device before developing the upgrades

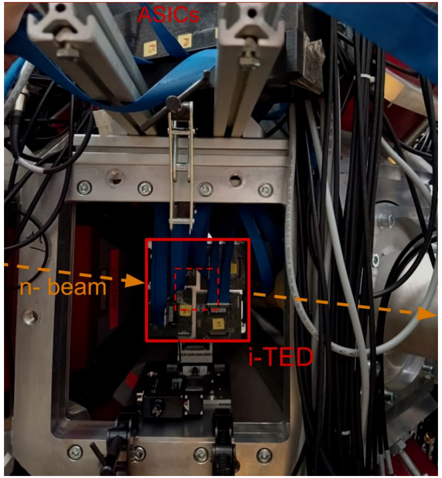
→ 1) Test viability in cleanest conditions

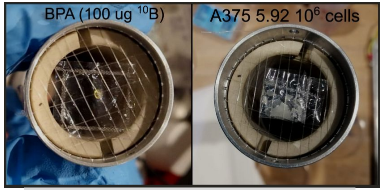
→ 2) Identifying major challenges and key points for development

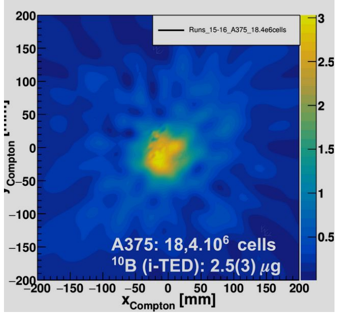
iTED for BNCT - Experiments at ILL

High intensity pencil beam at ILL
(FIPPS instrument, 10^8 n/cm^2/s, ∅1.5 cm)

Campaign 1 (2023): Assessing sensitivity under low background conditions



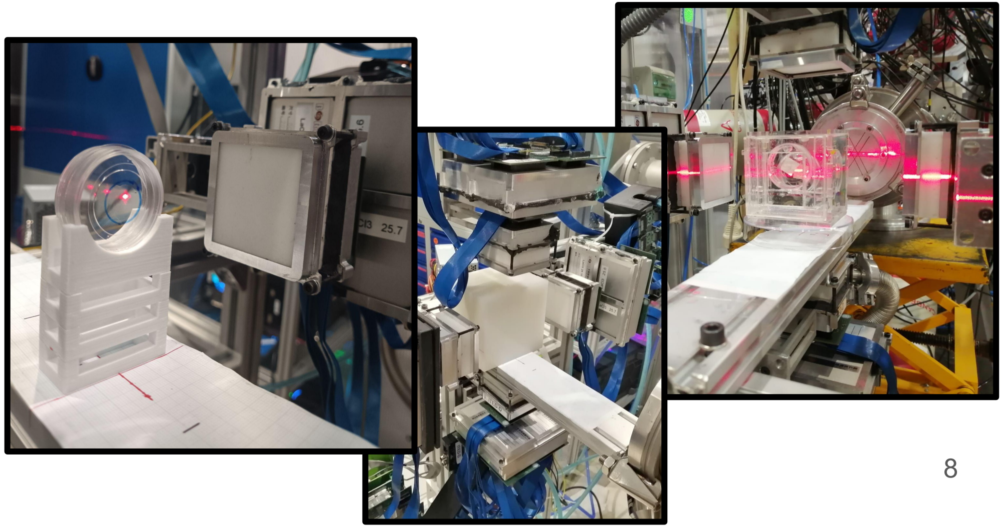




J. Lerendegui-Marco et al. First Pilot Tests of Compton Imaging and Boron Concentration Measurements in BNCT Using i-TED (2025)
https://doi.org/10.1016/j.apradiso.2025.112009

Campaign 2 (2024): Evaluating i-TED performance under stressful high-count rate conditions

Borated samples in phantoms of different materials and sizes (teflon,PMMA, HDPE, Water)



iTED for BNCT - Experiments at ILL

Campaign 2: Evaluating i-TED performance under stressful high-count rate conditions

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Searching for bottlenecks and limitations

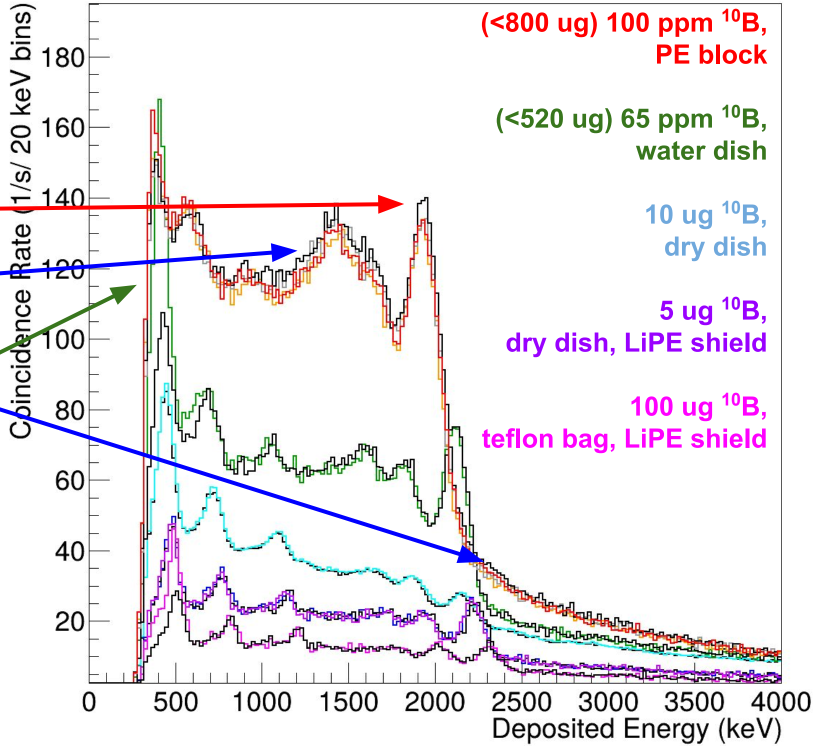
- Bckg → Dominated by neutron induced 2.2 MeV gamma rays (^1H captures)
- Signal detection → Low energy thresholds and angular discrimination
- High Count rates → Dead time losses and pileup + Also gain drift induced

Also good news

- Clear 478 keV sensitivity of 65 ppm ^{10}B concentration (typical tumor uptake) (when above threshold, water dish, green line in figure)

Addressing the challenges

- Lower count rates →Thinner crystals
- Lower energy threshold→Thinner Scatterer
- Large gamma background→Dedicated angular discrimination for improved signal rejection
- **<u>All: Use of pixelated detectors</u>**



i-TED for BNCT - Why Pixelation?

Our timing configuration goes:
Signal (charge) integration window: 320 ns

Event (pixel) integration window: 100 ns

In Monolithic crystals:

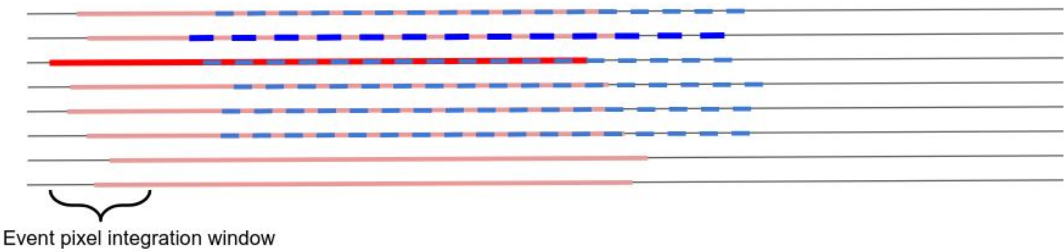
A large fraction of pixels are triggered (possibly all of them if E_{dep} is large)

In Pixelated crystals:

Only one pixel is triggered

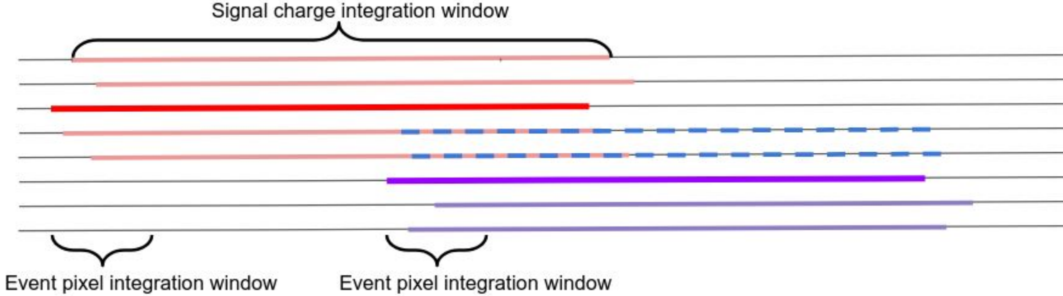
Under high count rate conditions:

Example 1:



The second event is not recovered, most of it is included in the previous event (almost full pile up)
Observed count rates are lower than real, events recovered are not valid events

Example 2:



The second event is partly recovered, and some is included in the previous event.
The system could be trapped in a chain of badly recognized events.

i-TED for BNCT - Pixelation

Pros and Cons of Pixelation to our goals

- Reduces pixel trigger rates → Allows higher count rates ✅
- Allows for better bad event rejection (e.g. multiple Compton interactions inside the same crystal) ✅
- Slightly improves time resolution 👌
- Reduces spatial resolution (weighting-based event position reconstruction cannot be used) but avoids dealing with decompression distortions ❗
- Lower energy resolution (smaller crystals) ❌
- Light concentration to a single pixel strongly reduces the dynamic range, forces gain reductions ❌

This is our main goal

We get a 10 % cleaner Compton event list with this

To be confirmed if this really helps in stressful conditions

Not a big deal of a worsening in our case with thinner crystals

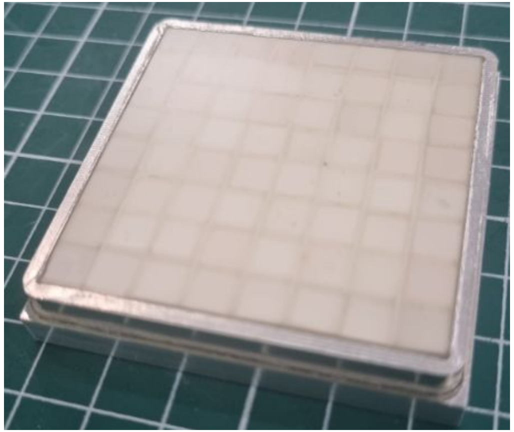
Not the largest loss of resolution, electronics contribution still dominates

Dealt with changes in the electronics configuration

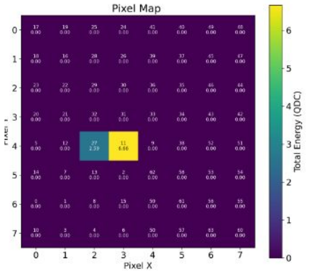
i-TED for BNCT - CLLBC Pixelated crystal

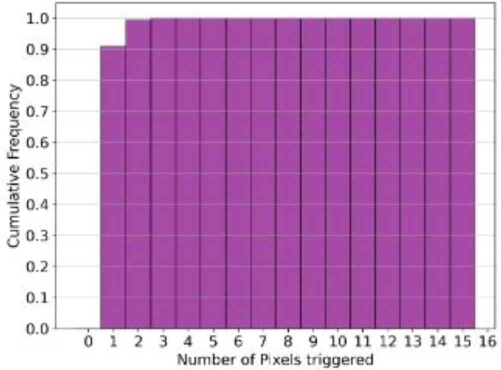
We have a **CLLBC** ($Cs_2LiLa(BrCl)_6:Ce$) pixelated crystal

- Capable of gamma and neutron discrimination
- 50x50x6 mm^3 array of 8x8 pixels (matching our 8x8 Onsemi SiPMs)
- Equipped with a **dedicated light-guide layer** to avoid light diffusion and pixel cross-talk



We tested at our lab and checked the **high quality pixel light isolation.**
Most **gamma** events trigger a single pixel (>90 %)
The remaining 10 % correspond to two-pixel events (Compton scattering followed by capture in adjacent pixels, cross-checked via simulations)
Tested also with **neutrons** (larger ~3.5 MeV signals), with only slight deterioration (~14 % of 2-pixel events)





i-TED-P for BNCT

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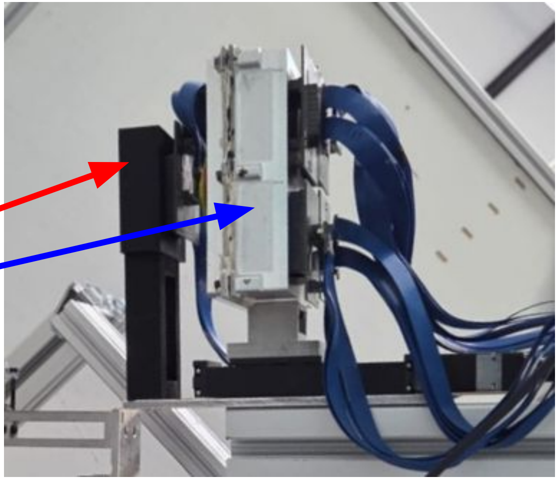
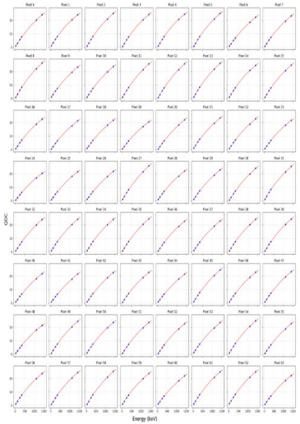
We have just commissioned the first i-TED module with a pixelated crystal

- Pixelated Scatterer: CLLBC crystal, 8x8 pixels (5.7x5.7x6 mm^3)
- Monolithic Absorbers: 4 thinner $LaCl_3$ crystals (50x50x15 mm^3)

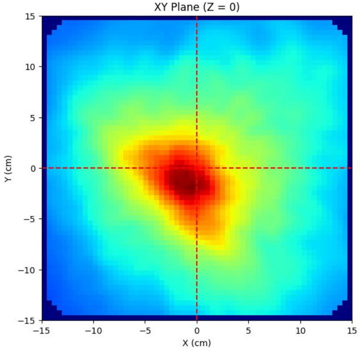


Full 64 pixel independent calibrations for the pixelated scatterer
\+ 4 aggregate calibrations for the 4 monolithic absorbers

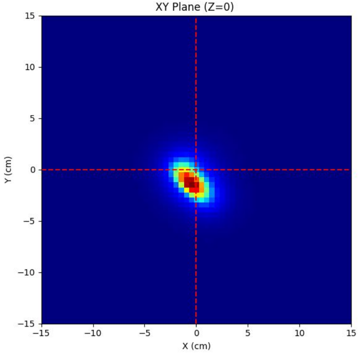


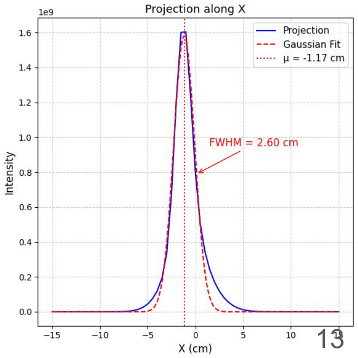
First 3D image reconstruction with a ^{22}Na point source

BP



LM-MLEM





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i-TED for BNCT - 3D imaging

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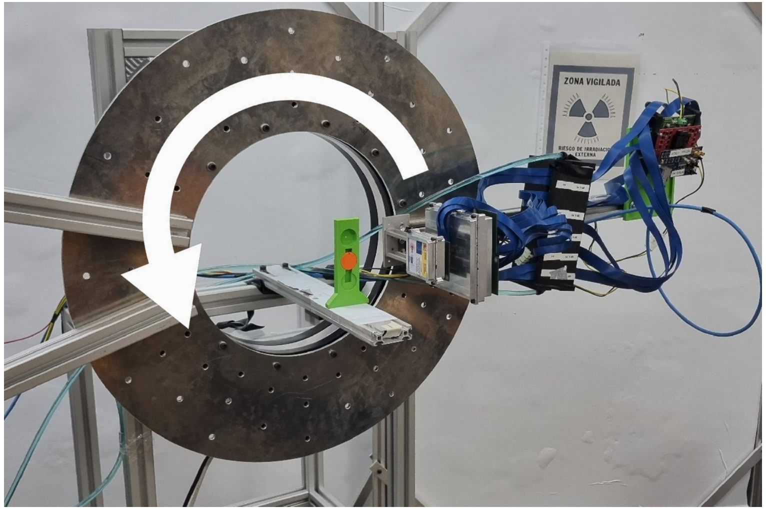
Experimental validation of the 3D reconstruction algorithms using a Rotatory Gantry

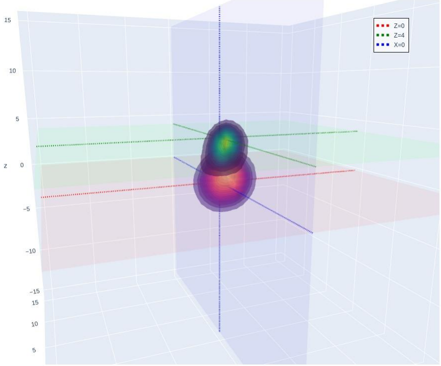
List mode MLEM

Infrastructure for 3D reconstructing up to few million coincidence events in a single processing batch (**CPU and GPU parallelized**)

Capable of handling 50k coincidence events in 3.2 s (WS with **Nvidia RTX 4080**)

(50kHz is the expected maximum manageable coincidence rate during treatments with our current PETsys-based electronic readout)





B. Gameiro *et al.* Towards Real Time Compton Imaging in Demanding Conditions (2024) https://doi.org/10.1007/978-3-031-90203-1_47
P. Torres-Sánchez *et al.* The potential of the i-TED Compton camera array for real-time boron imaging and determination during treatments in Boron Neutron Capture Therapy (2025) https://doi.org/10.1016/j.apradiso.2024.111649
S. Valladares-Sánchez. Master thesis: Detector Developments Towards Real-Time Dose Monitoring Via Compton Imaging In Radiotherapy (2025)

Prospects - Next steps

Next Week!

New experiment (LENA reactor, Pavia, IT)
Testing and validating recent upgrades, including:

- the new i-TED module (pixelated scatterer and thinner absorbers)
- fast 3D GPU-based reconstruction algorithms (LM-MLEM)

Near future

Challenging measurements in a clinical-grade BNCT neutron source (HF-ADNF Birmingham, UK)

Conclusions

- **BNCT** requires a reliable in-beam dose monitoring system to ensure safety and efficacy in clinical applications.
- **Compton imaging** presents a promising approach for real-time dose monitoring in BNCT environments.

- A design based on the **iTED** concept already demonstrates strong potential for this purpose.
- Ongoing developments are addressing the specific challenges posed by BNCT.

    - **Experimental campaigns** have been conducted to systematically identify and characterize these challenges.
    - We are currently exploring **pixelation** of our crystals as a means to reduce the extremely high count rates and associated distortive effects.
    - Further hardware (thinner crystals, materials) and software **upgrades** to the monitoring system are underway to enhance its precision, speed, and clinical compatibility.

Thank you for your attention!

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