Range verification in hadrontherapy: experience @POLIMI

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RadLab

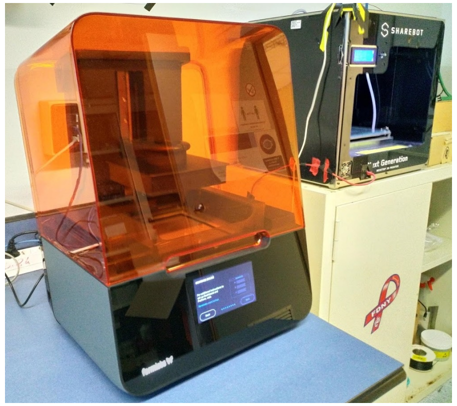
The RadLab Group @POLIMI

3 staff, 18 Ph.D. students and post-docs, 20 M.Sc. thesis students/year

Cadence workstations, Electronics assembly and test instrumentation, Wire bonding and Flip Chip, 3D printers, vacuum and climatic chambers, X/γ photon sources,…

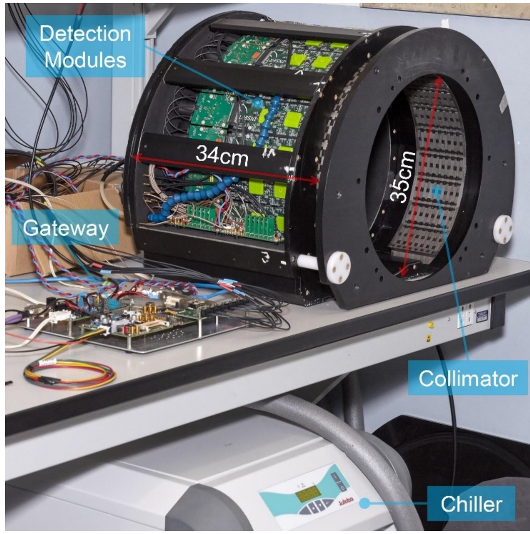
Wedge bonder

3D printer

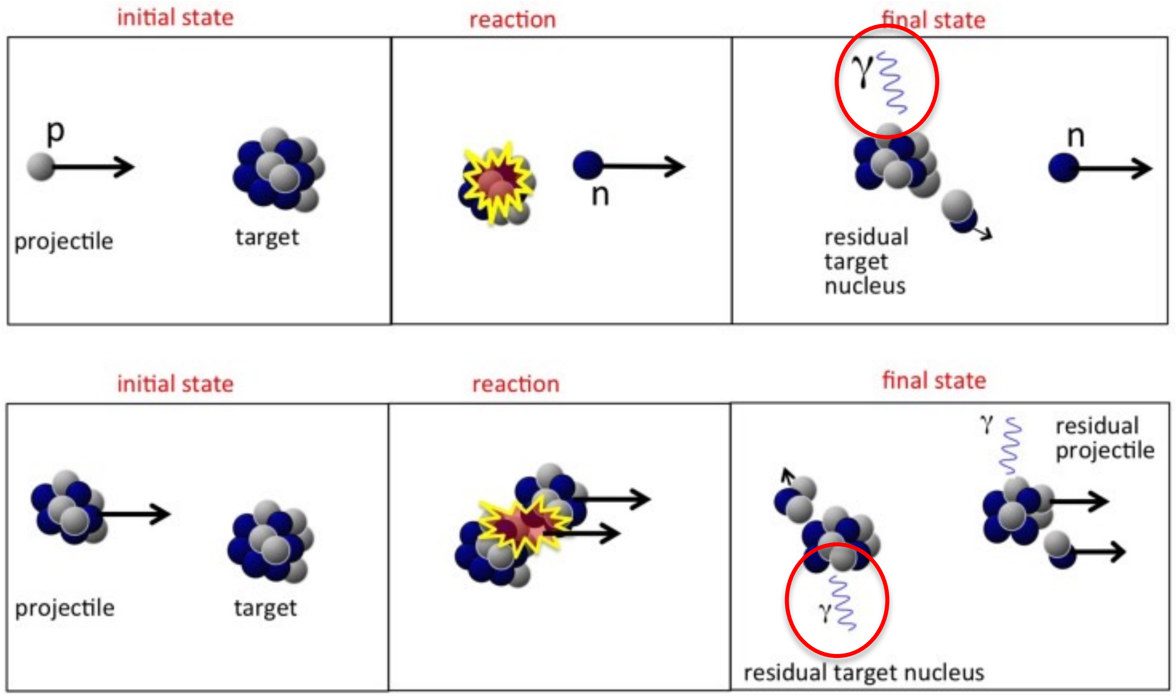


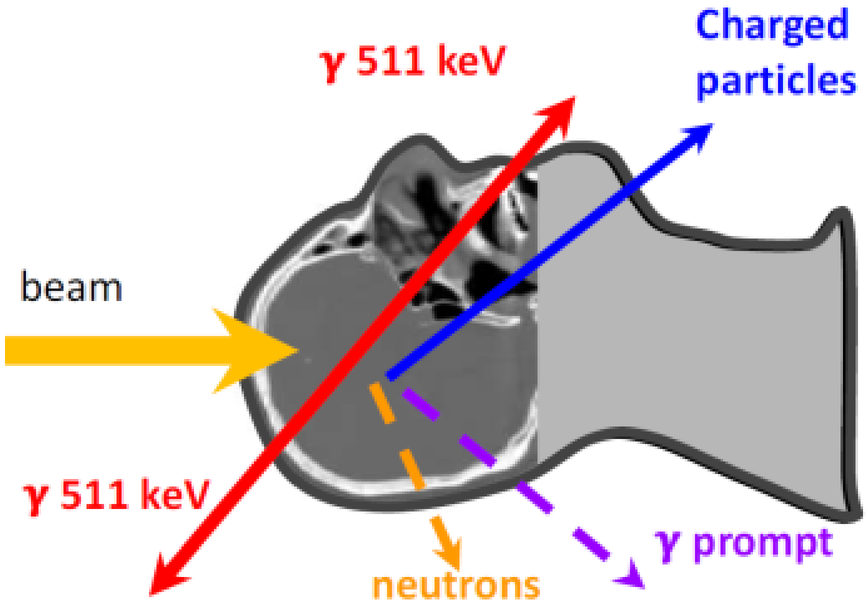
Flip-chip

Instrumentation



Principle: measurement of secondary radiation emitted upon irradiation of tissues with particles



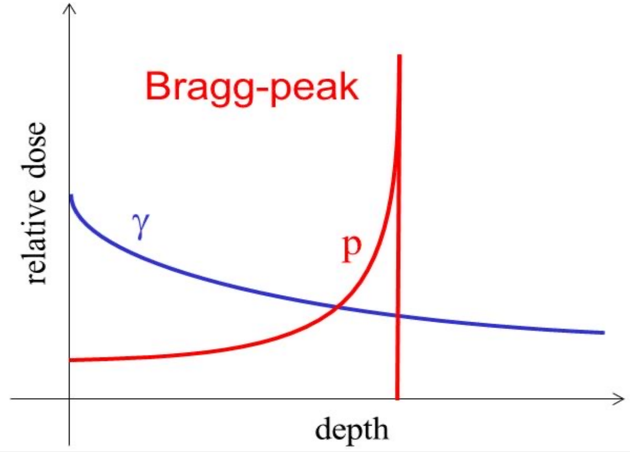


Our research @POLIMI:

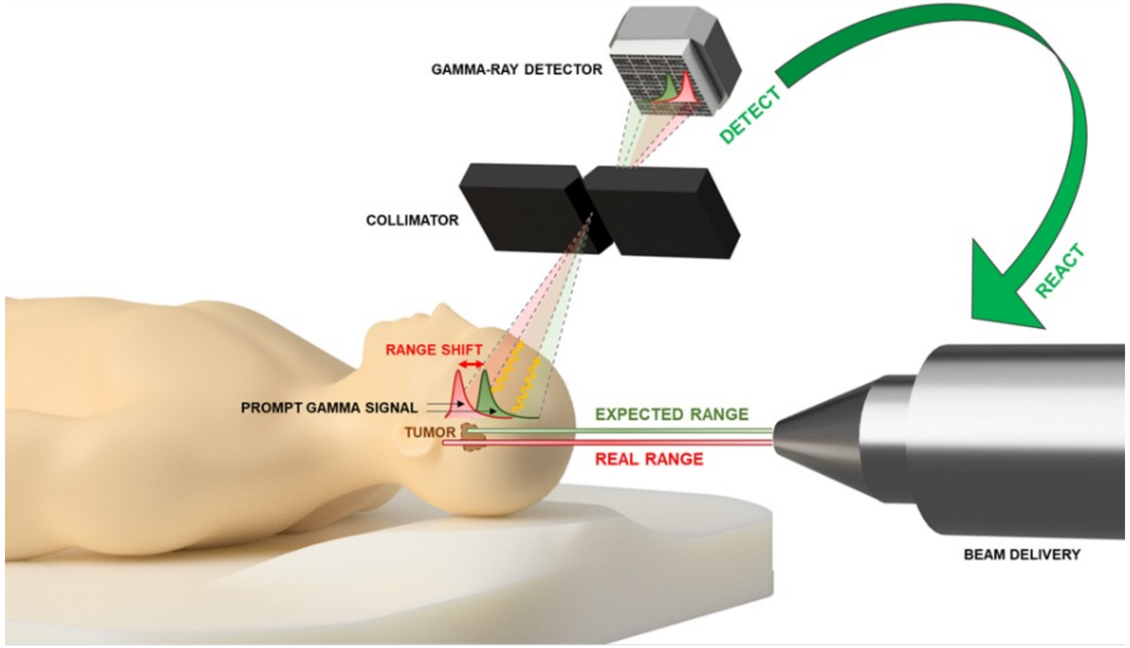
Range verification by prompt-gammas detection in hadrontherapy

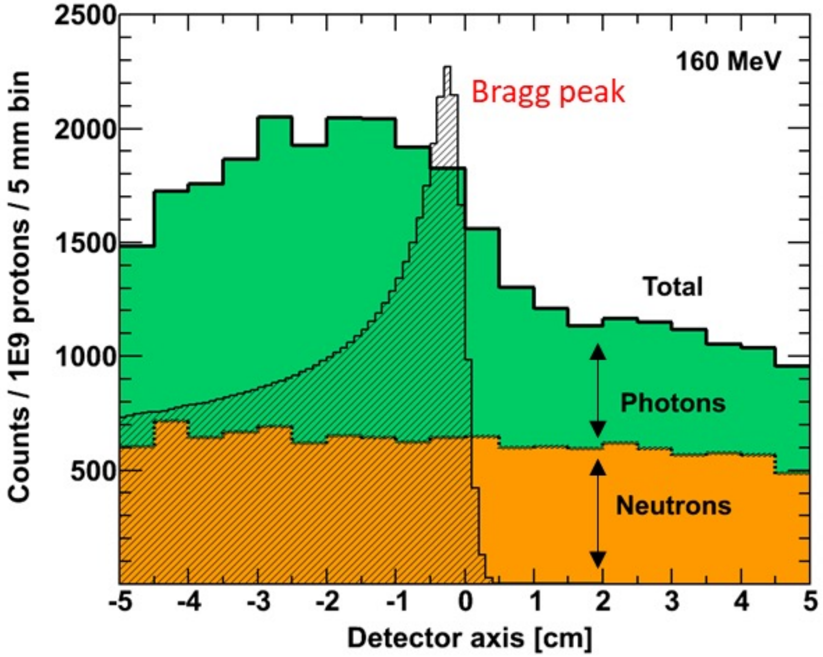
Dose measurements by gamma detection in BNCT (Boron Neutron Capture Therapy)

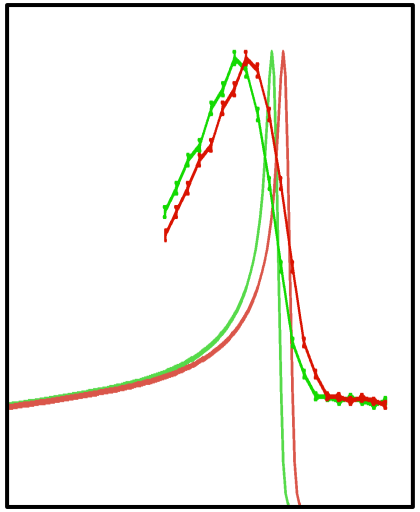
Range Verification in Hadrontherapy using Prompt Gamma Imaging



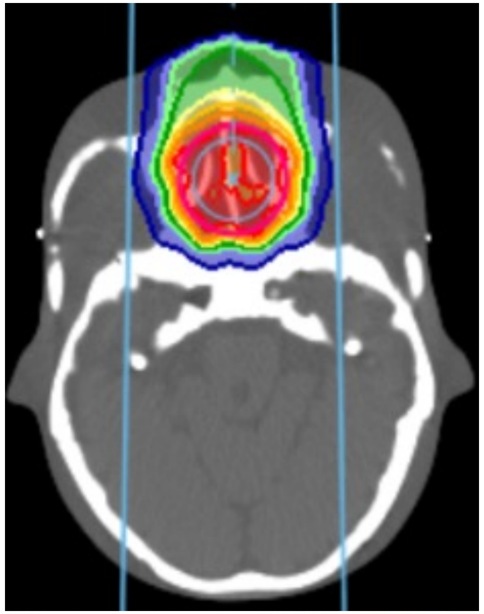
The measurement of the particle beam range in the target is very important: real range of proton beams in patients may contain uncertainties of up to 10-15 mm (uncertainties on tissue composition, density, organ motions, patient positioning, etc).

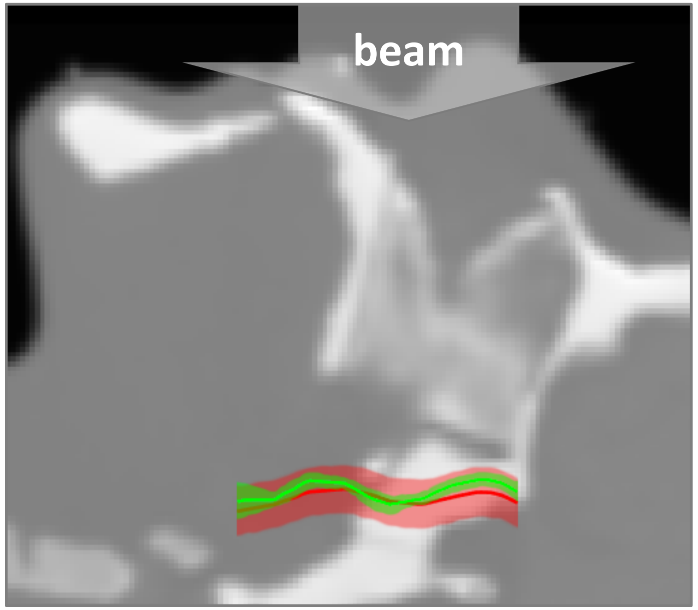




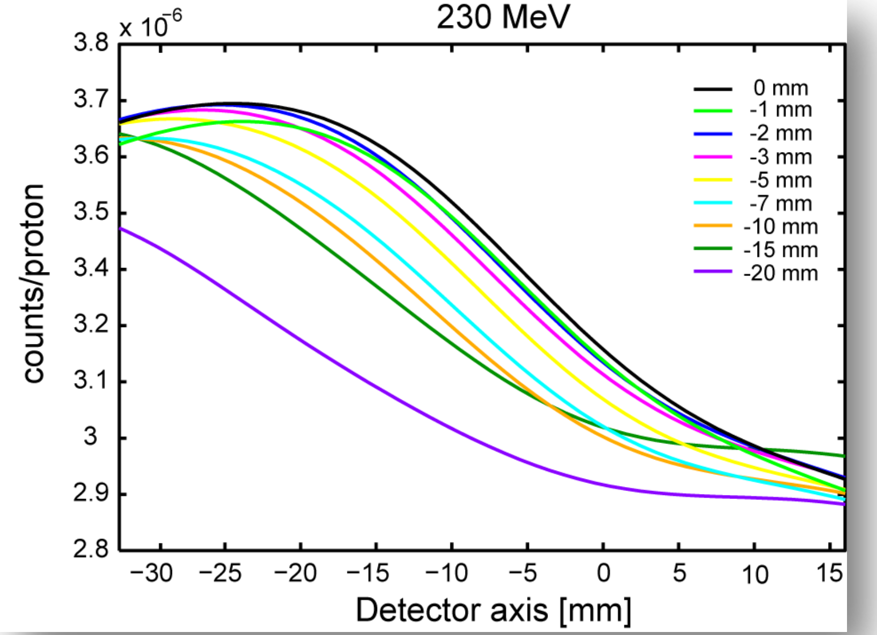


Range Verification with protons

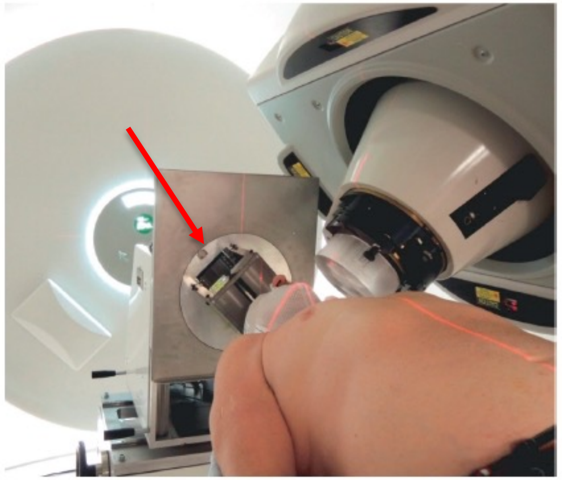




Planning uncertainty **> 5 mm**
(margin of 3.5% + 2 mm)
Measurement uncertainty (1.5σ)
≈ 2.0 mm



Shift measurements



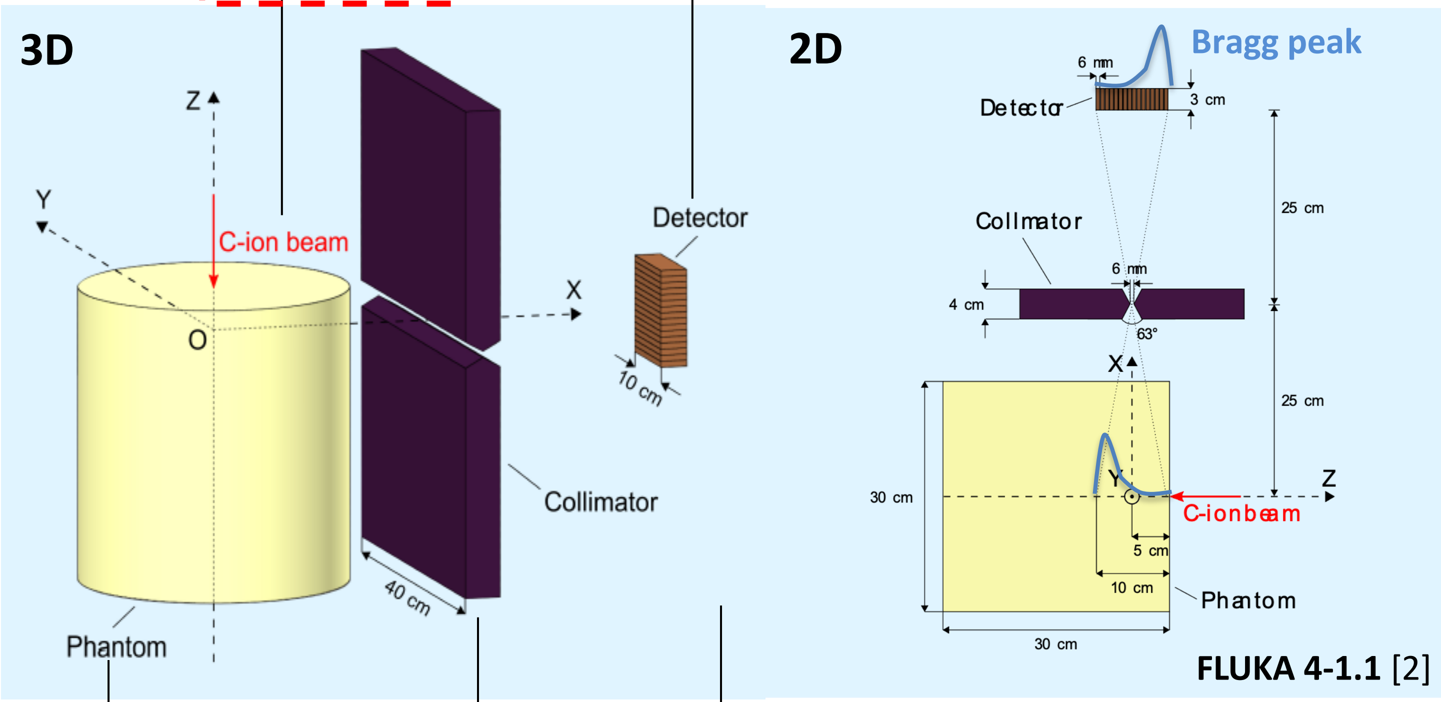
Clinical trial of PG camera for Proton irradiation

- C.Richter, et al., "First clinical application of a prompt gamma based in vivo proton range verification system", Radiother Oncol 2016;118:232–7.
- Y.Xie, et al., "Prompt gamma imaging for in vivo range verification of pencil beam scanning proton therapy", Int J Radiat Oncol Biol Phys 2017;99:210–8.

Feasibility Study for Range Verification with C-ions (MC study)

Considered beam energy range of **120÷400 MeV/u** for C-ions (CNAO)

$\boxed{150\ \frac{MeV}{u}}$ $Lu_{1.8}\ Y_{0.2}\ SiO_5$ (LYSO)



ICRP soft tissue | W - alloy | Air filled room

A.Missaglia, et al., **Prompt-gamma fall-off estimation with C-ion irradiation at clinical energies, using a knife-edge slit camera: a Monte Carlo Study,** Physica Medica 107, art. no. 102554, 2023.

Challenges for PGI with Carbon irradiation:

- Two orders of magnitude less carbon ions than protons used for irradiation (issue partially compensated by higher PG yield of carbon vs. proton)
- Secondary gammas reduces the range-end falloff
- Higher neutron background (vs. proton irradiation)

Scoring of the response of a **pixelated knife-edge slit camera** to the secondary particles emitted by a **ICRP soft tissue phantom.**

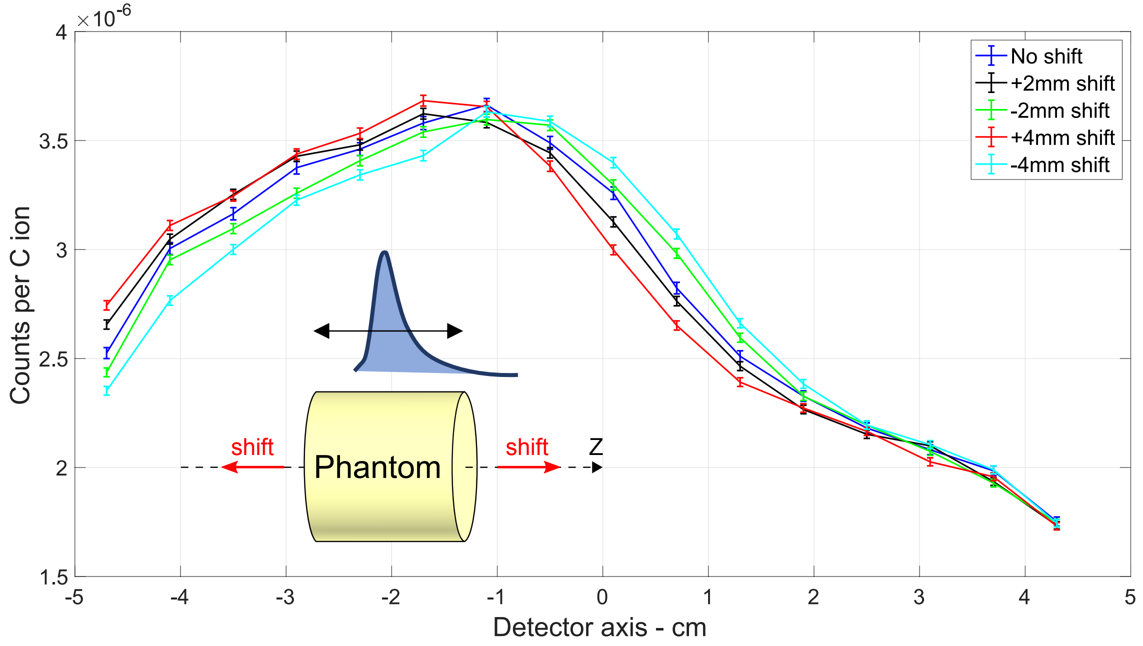
Energy interval: **3-7 MeV**

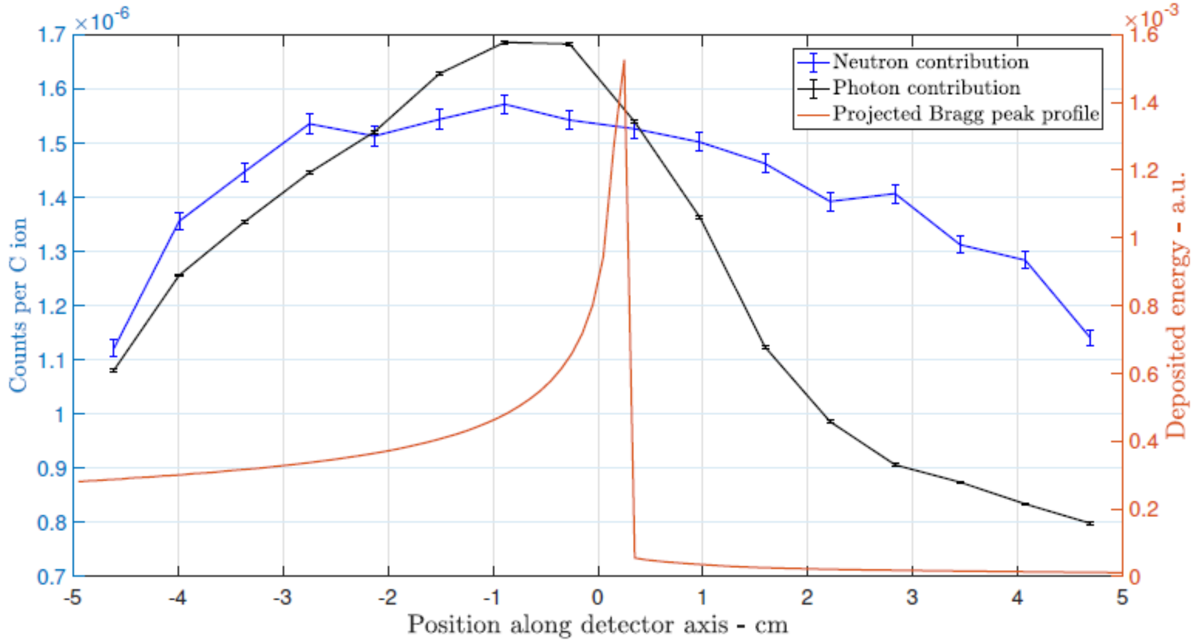
Reconstructed PGI profiles

Particle range sensitivity determination by target longitudinal shifts

➢ Spatial **correlation** between the **Bragg peak** and the **secondary gamma emission** in the high neutron background of CIRT.

Simulated primary particles for each shift of the phantom: **4x10^9 carbon ions**





Distinguishable PGI signal curves for different phantom shifts

Prompt-gamma component over an almost **uniform neutron background**

The challenge: range verification precision vs. signal statistics

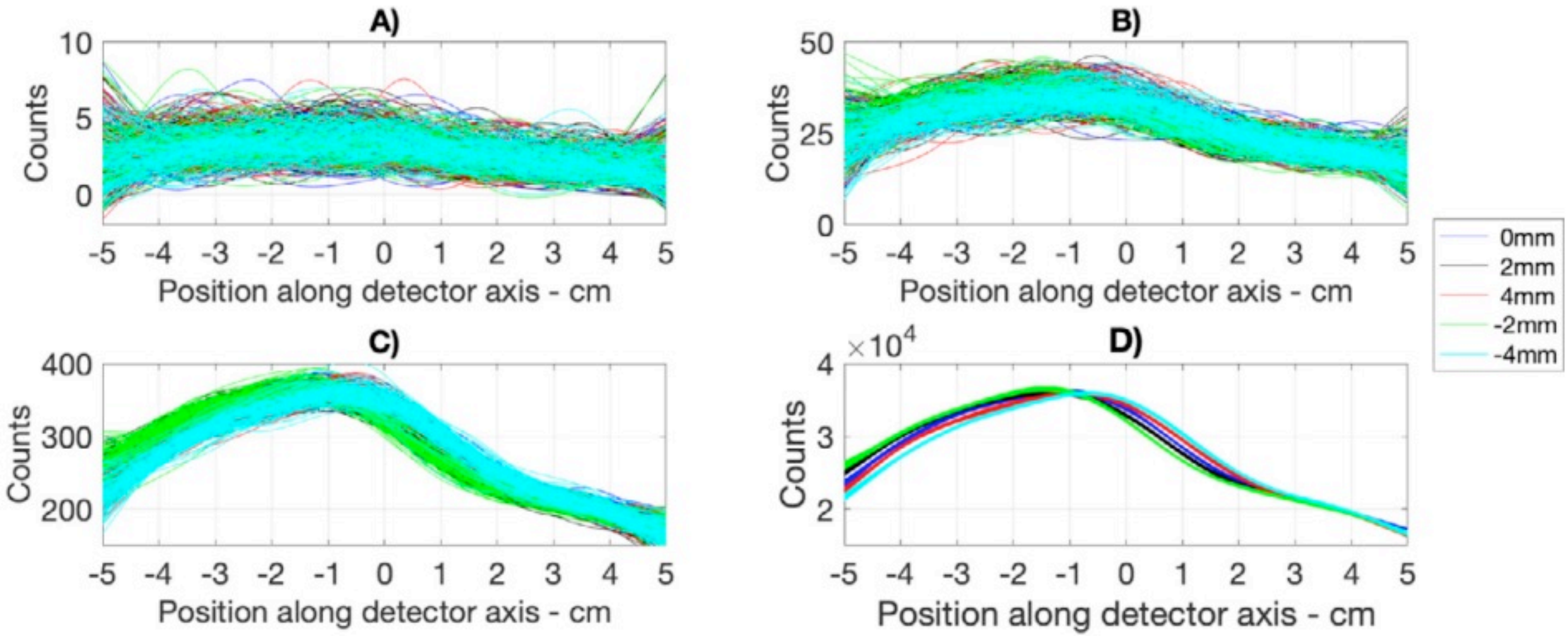
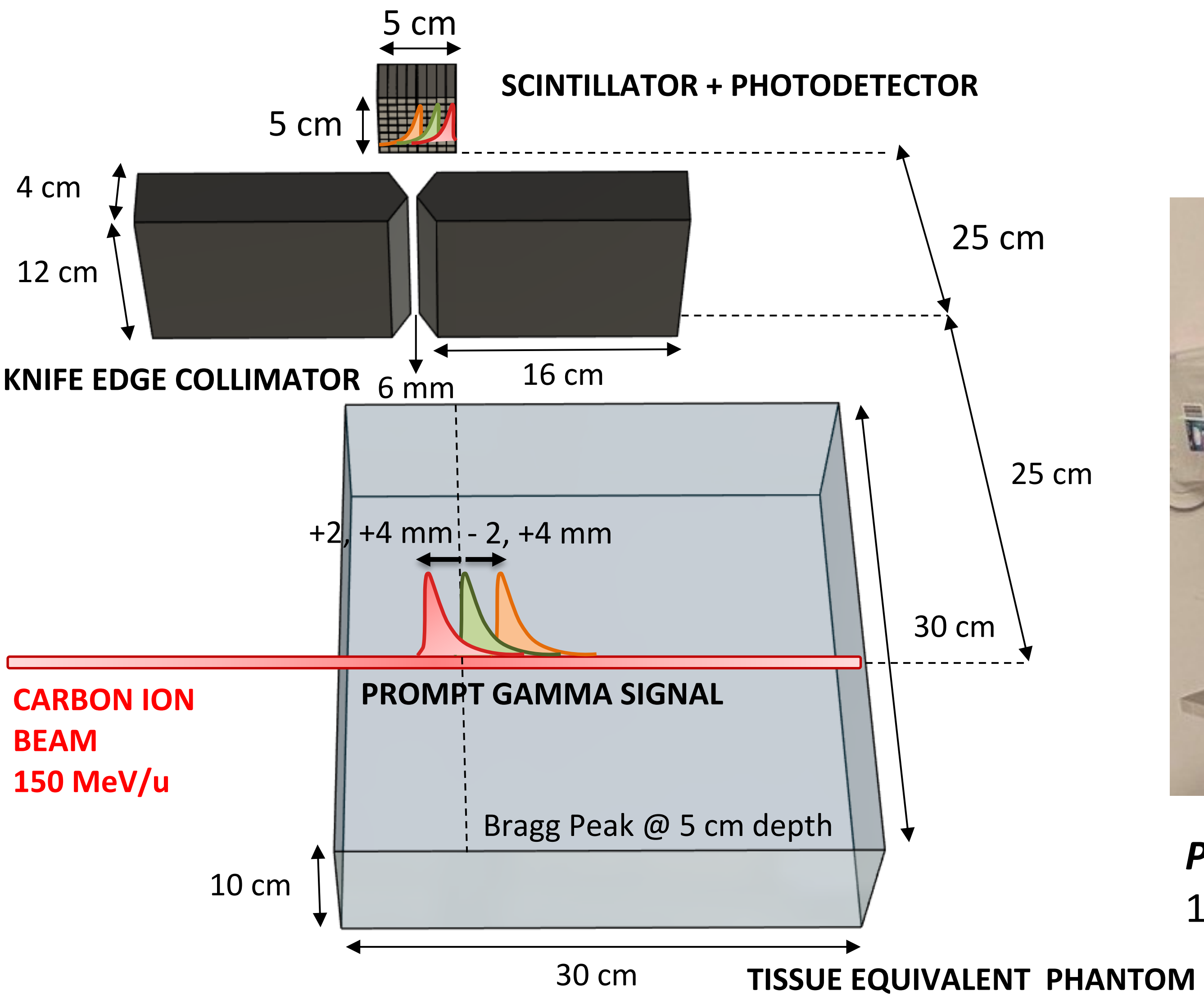
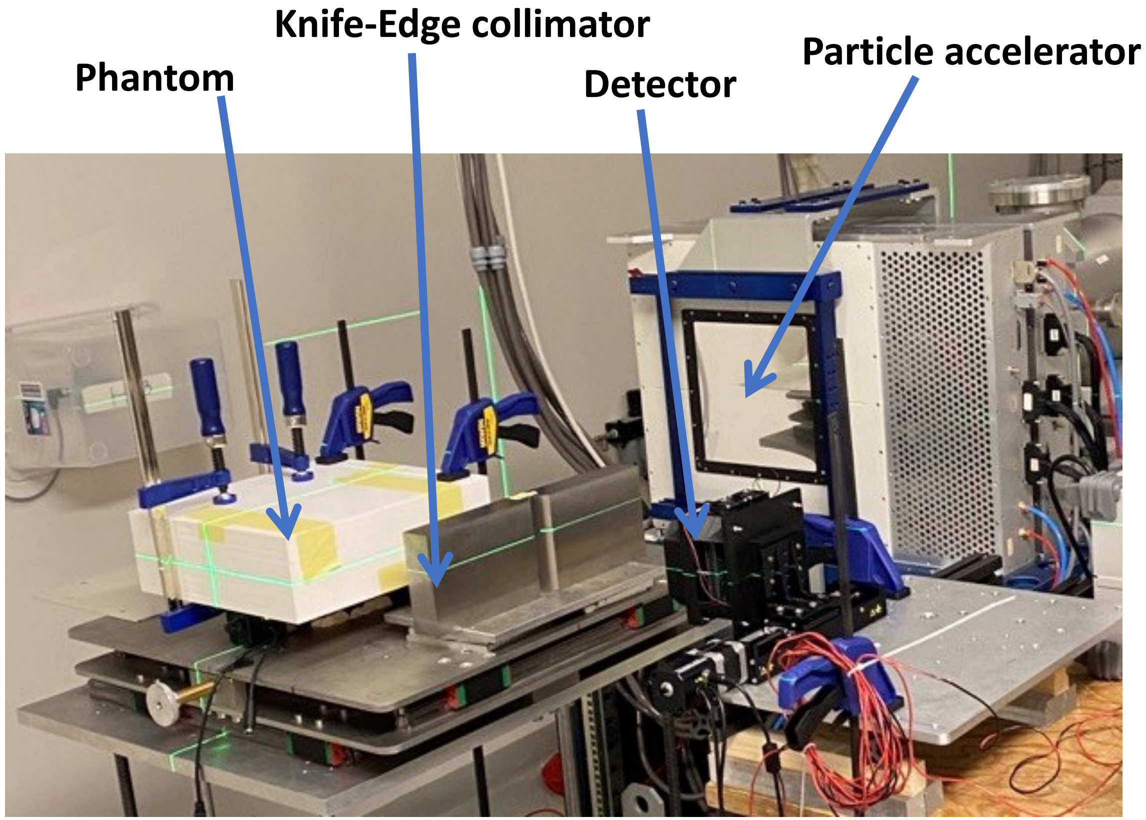


Fig. 4. Graphical representation of the generated noisy curves for different phantom shifts and numbers of C-ions: (A) 10^6, (B) 10^7, (C) 10^8, (D) 10^{10}.

Knife Edge Slit Camera Setup Configuration at CNAO



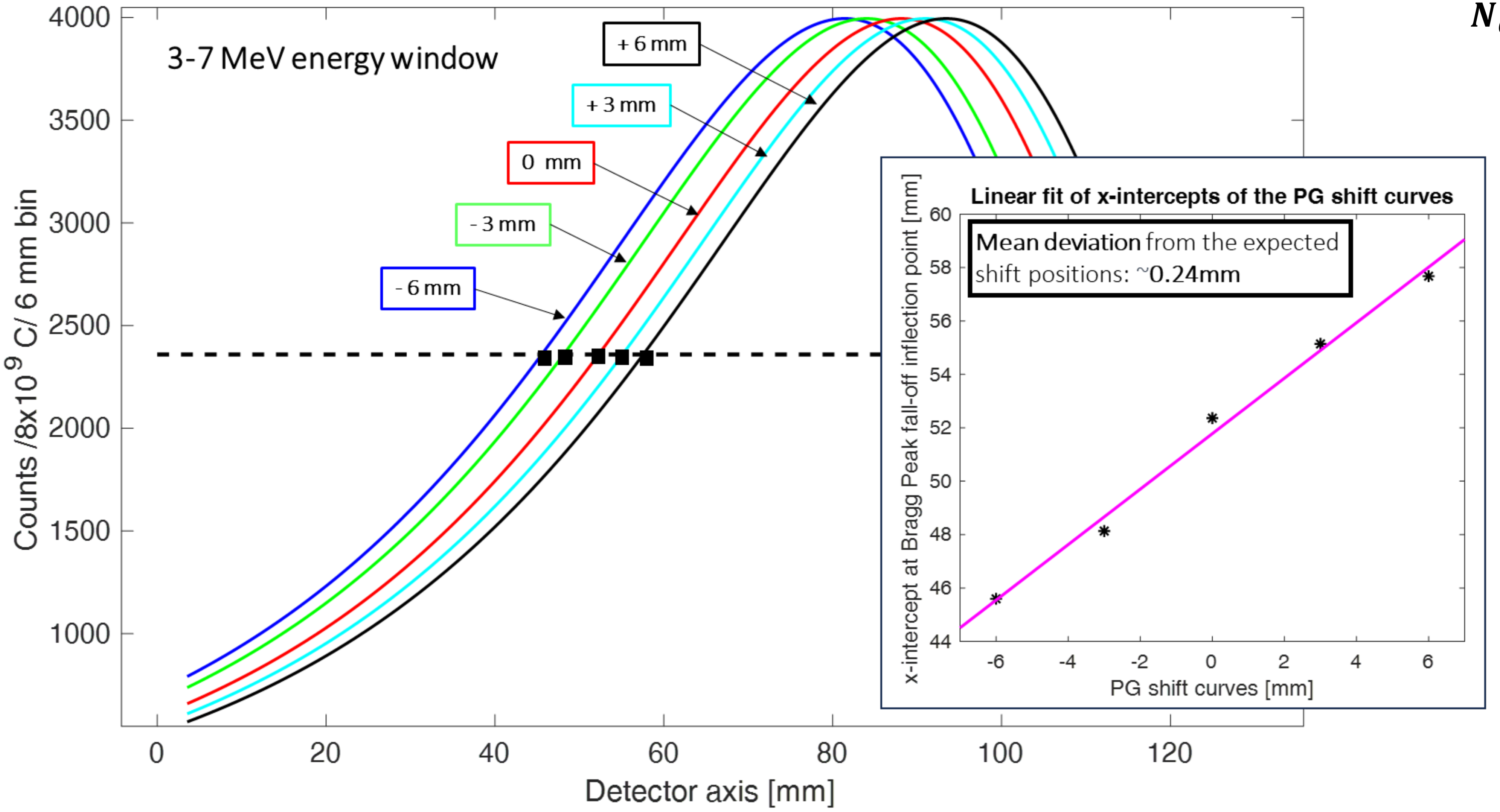


Particle beam structure:

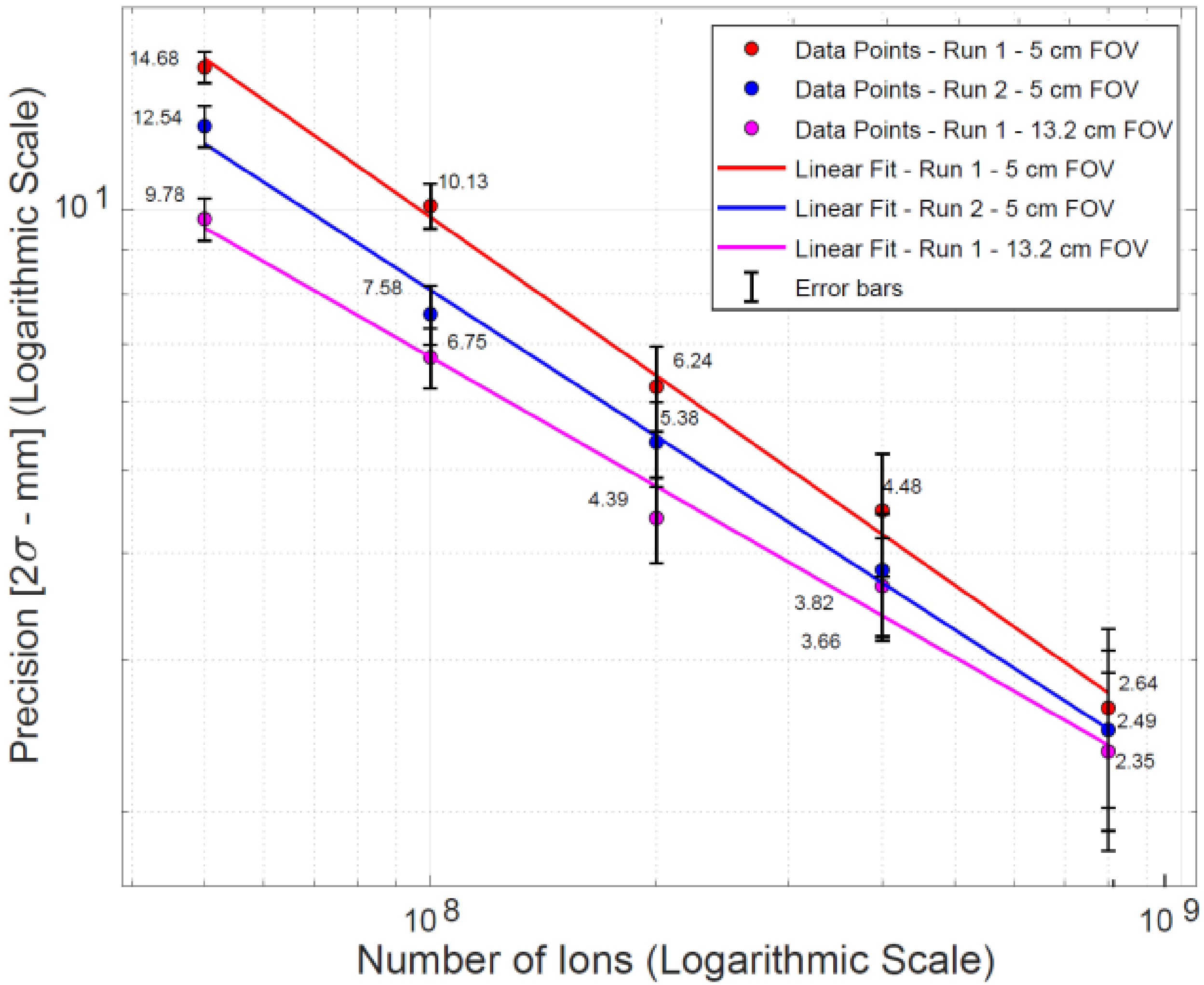
100 spills of $8\text{x}10^7$ carbon ions = $\mathbf{8x10^9}$ **carbon ions**

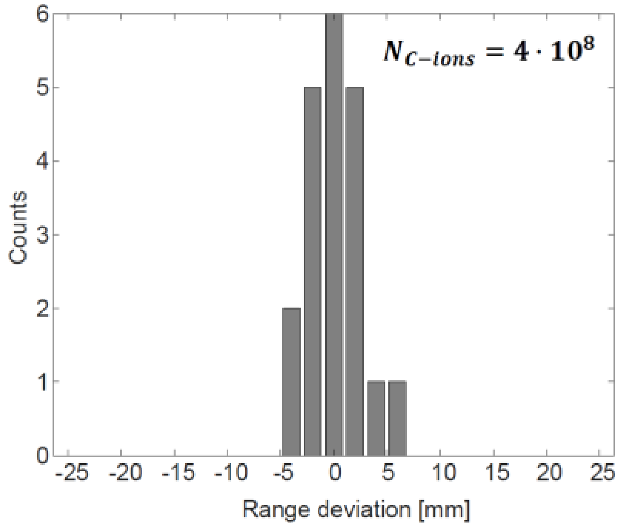
Analysis of Experimental Data: Curve Shifts

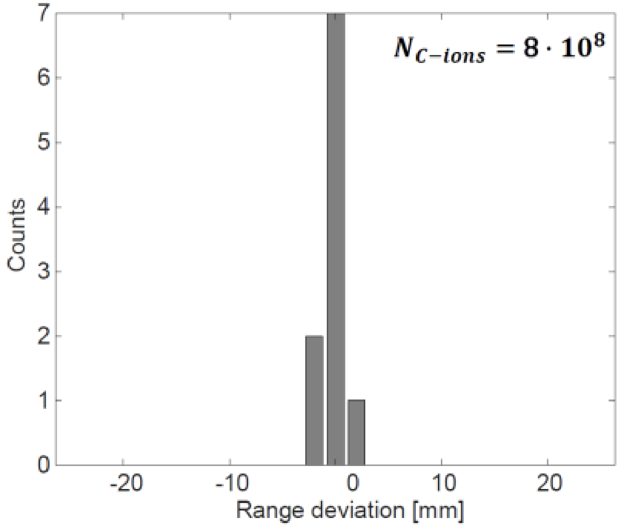
$N_{C-ions} = 8x10^9$



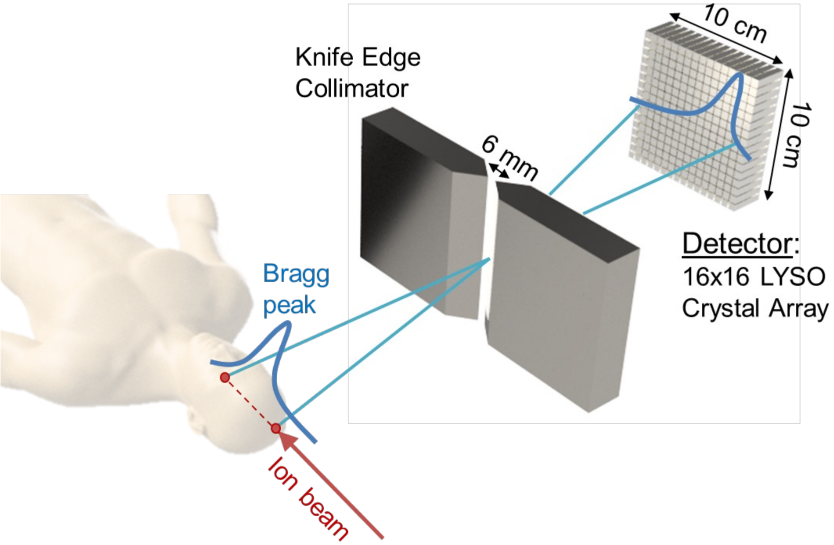
Precision in Range Verification vs. Signal Statistics

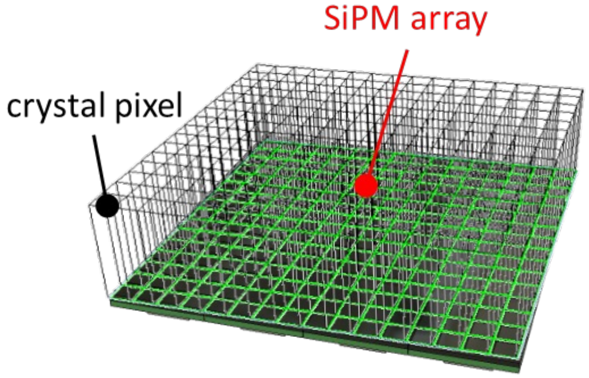


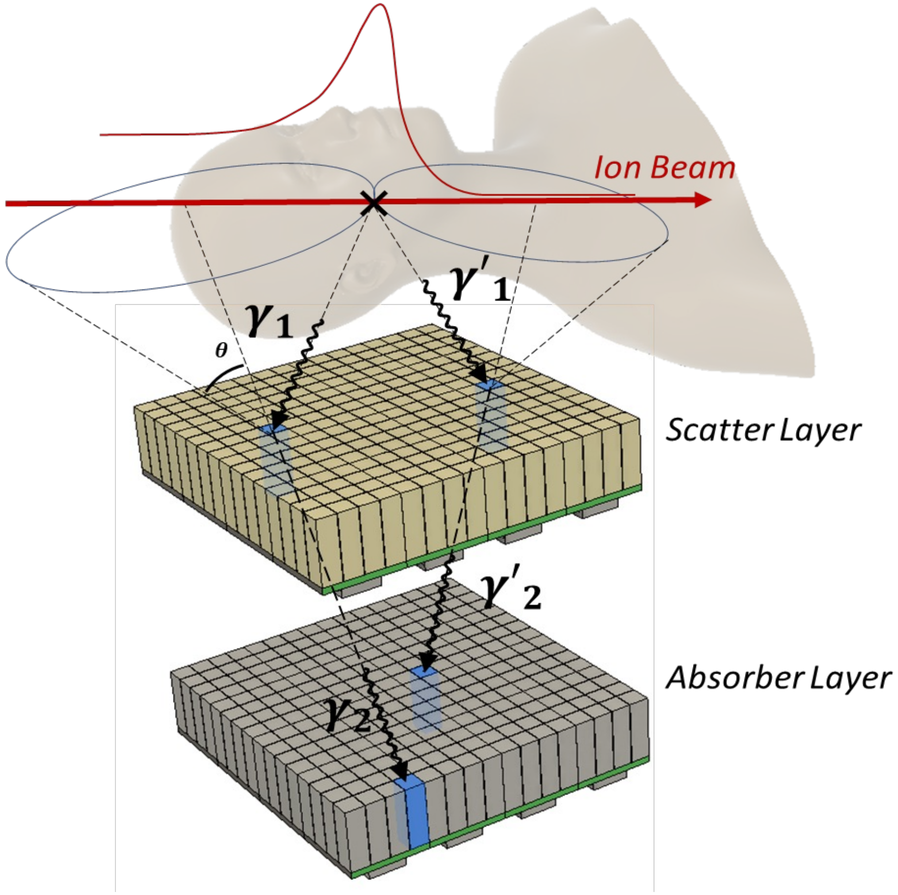




Detectors and electronics development for PGI

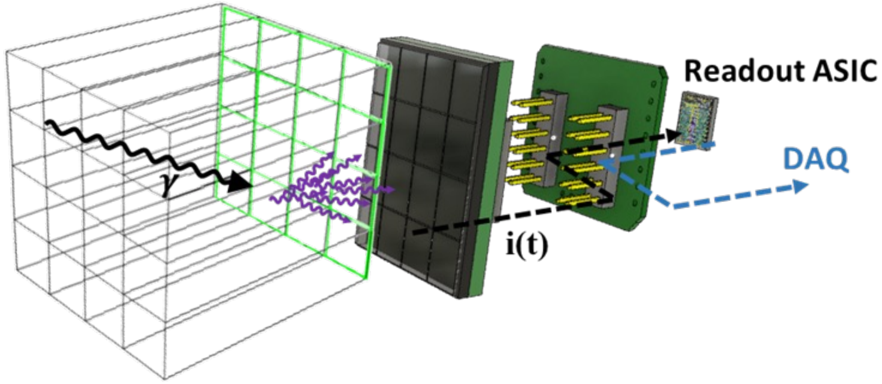




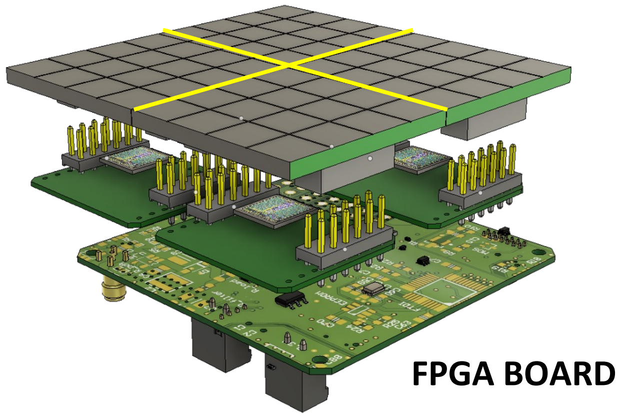


Compton – Camera
(collimator-less)

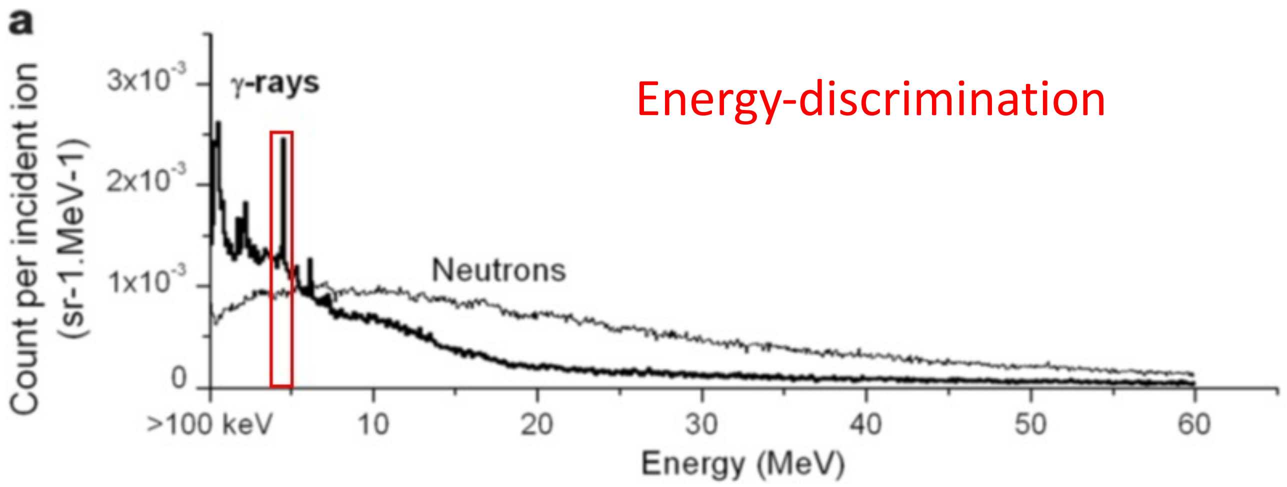
16–SIPM/ASIC UNIT:



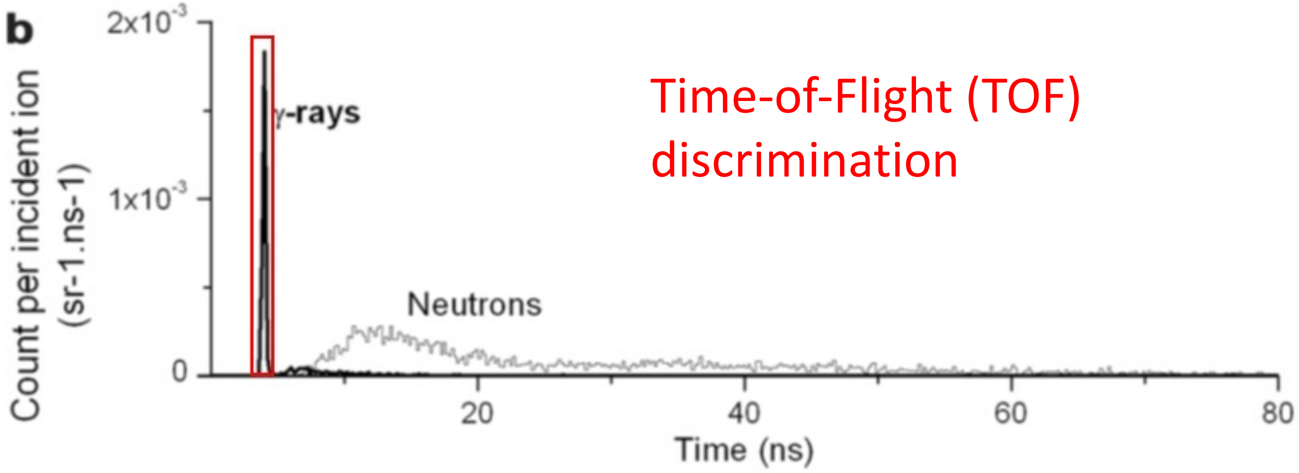
64–SIPM UNIT:



Gamma-Neutron discrimination

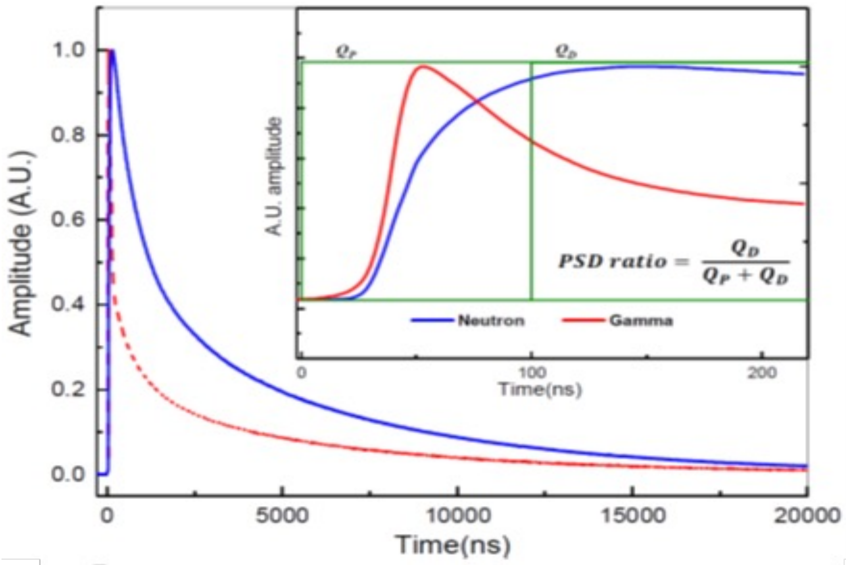


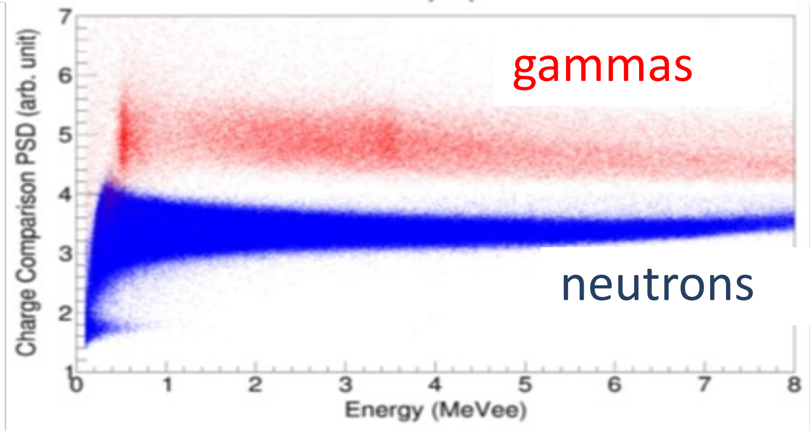
Energy-discrimination



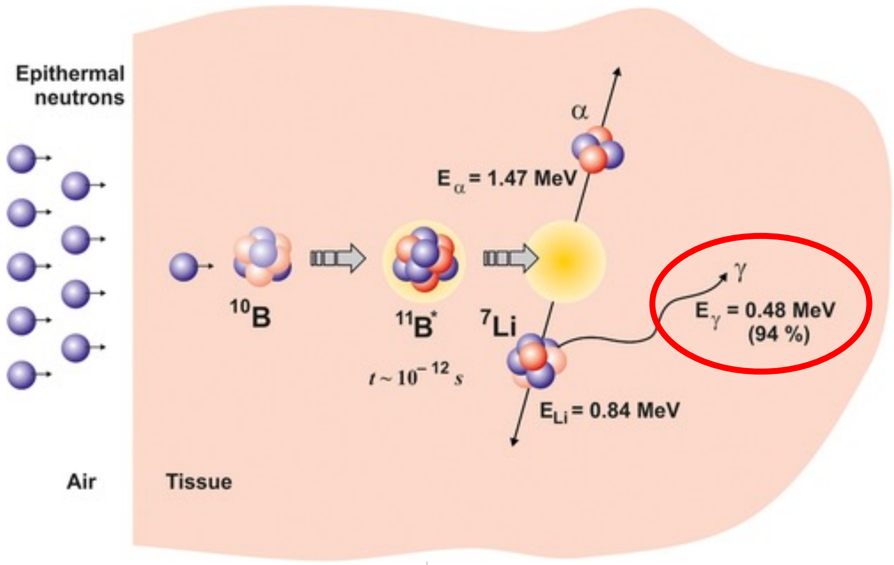
Time-of-Flight (TOF) discrimination

Pulse-shape-discrimination (PSD)



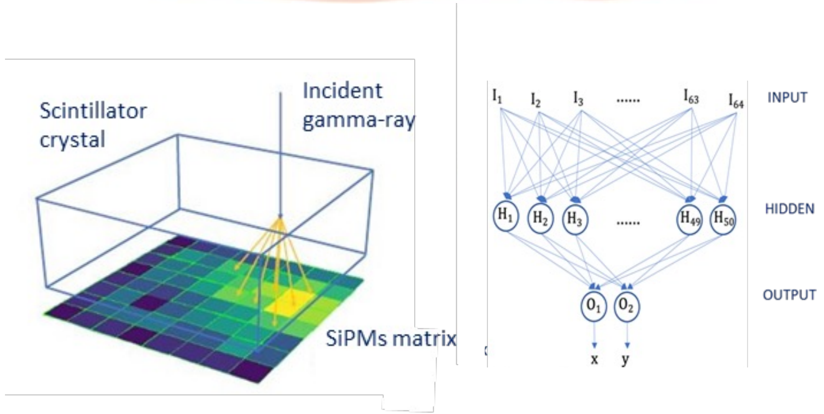


Gamma-ray detectors for BNCT (Boron Neutron Capture Therapy)



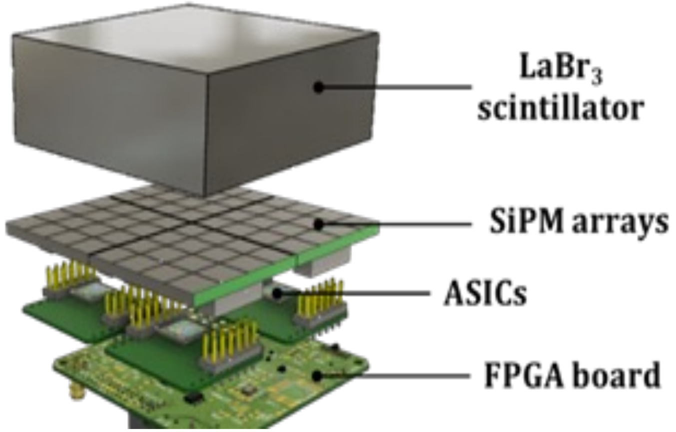
Detection of emitted **478keV gamma photons** may let to estimate ^{10}B neutron captures and support therapeutic outcome (personalized dosimetry).

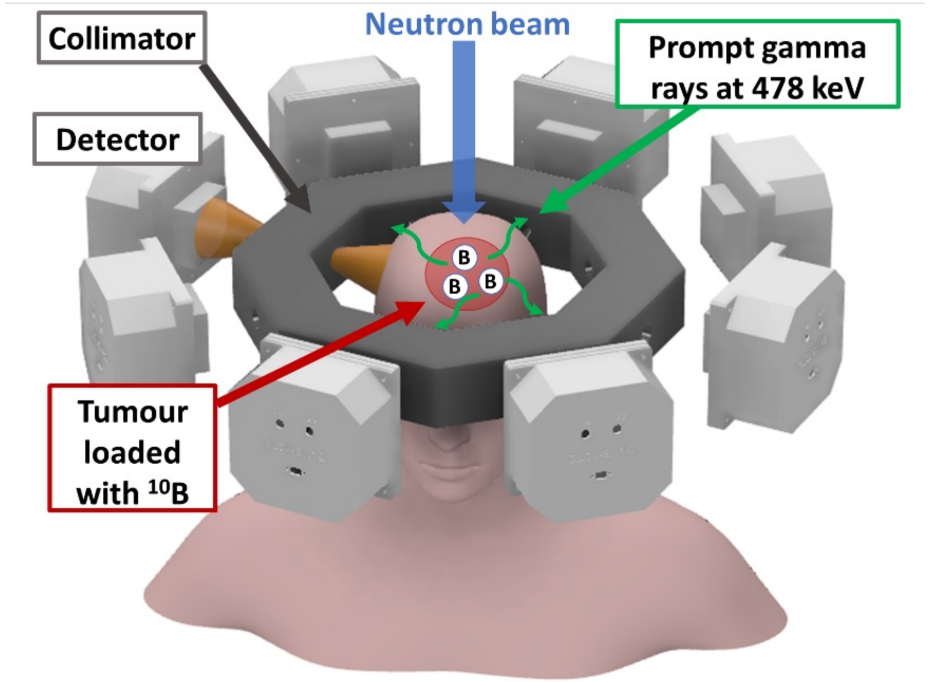
Goal: Development of a SPECT (Single Photon Emission Thomography) system) for BNCT



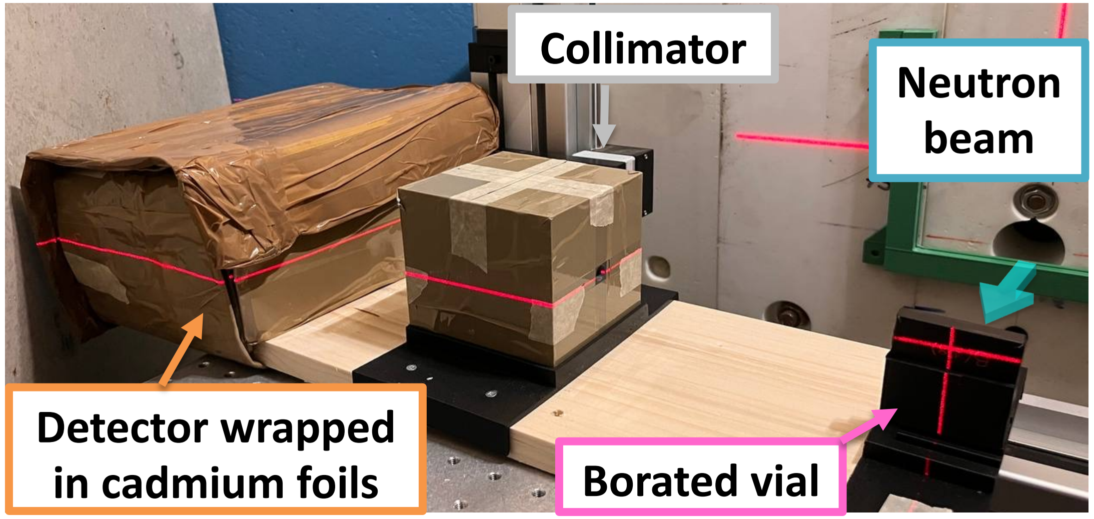
Scintillator/SiPMs-based gamma-ray detector

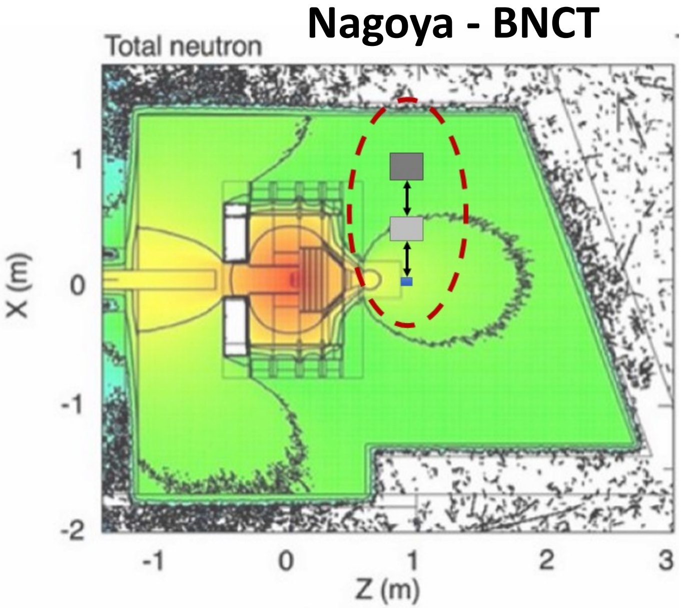
Neural-Network for event reconstruction

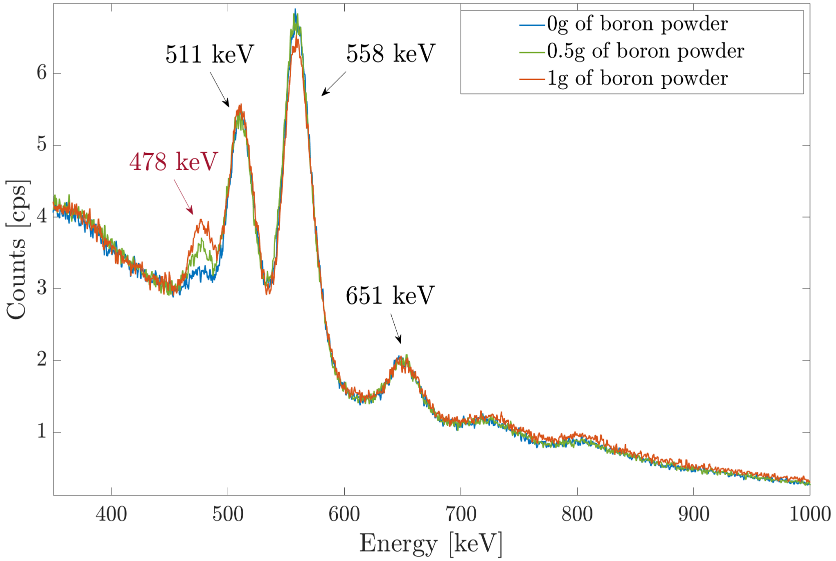




Experiments at nuclear reactor in Pavia (towards BNCT facilities..)

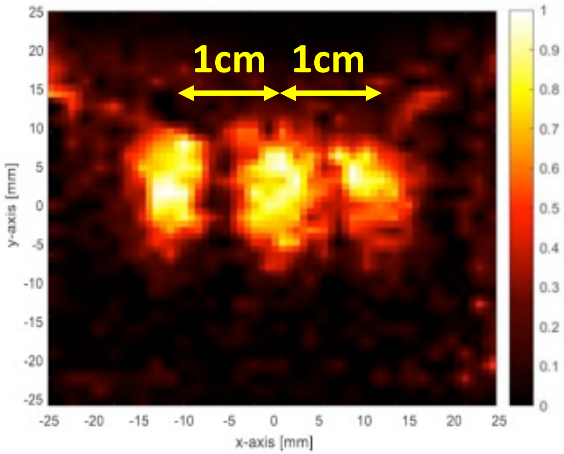






Spectroscopic Results

Identification of the BNCT photopeak at 478 keV and linear response at different boron quantities



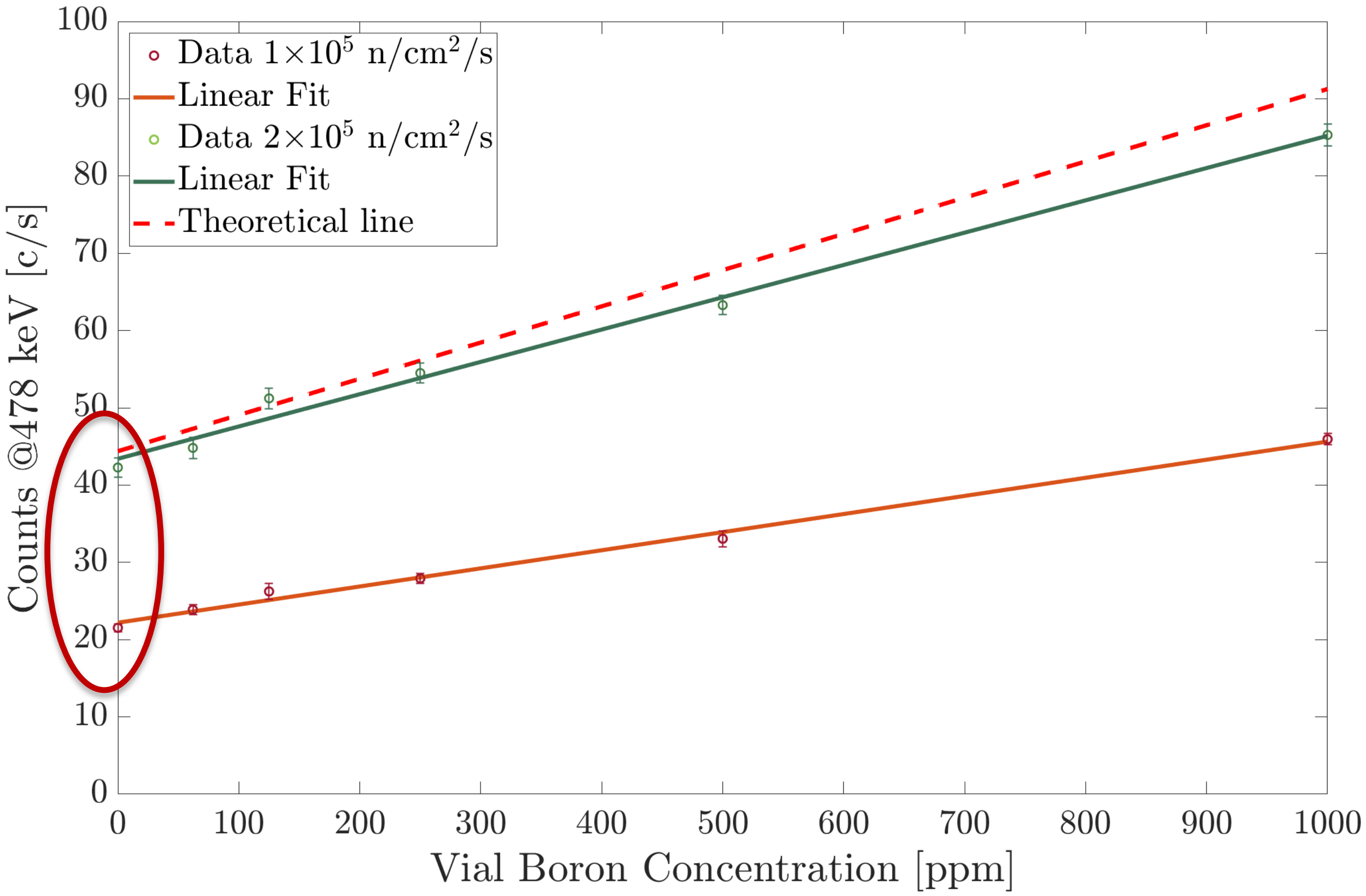
Imaging Results

The ANN algorithm is able to track shifts of 1 cm of the borated sample

Linearity Measurements

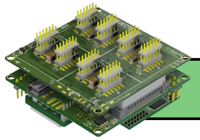
Measurements performed at the **TRIGA Mark II** reactor of Pavia University (Italy).

Six vials at different concentrations taken at different reactor power (4 kW and 8 kW)



- ✓ Good **linear correlation** between the boron concentration and the detected events at 478 keV.
- ✗ Events at **478 keV** detected during the 0ppm measurement

Shielding study



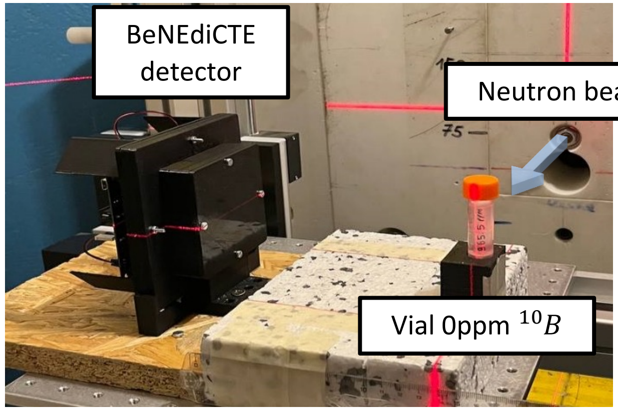
Flame Retardant (FR4) substrate

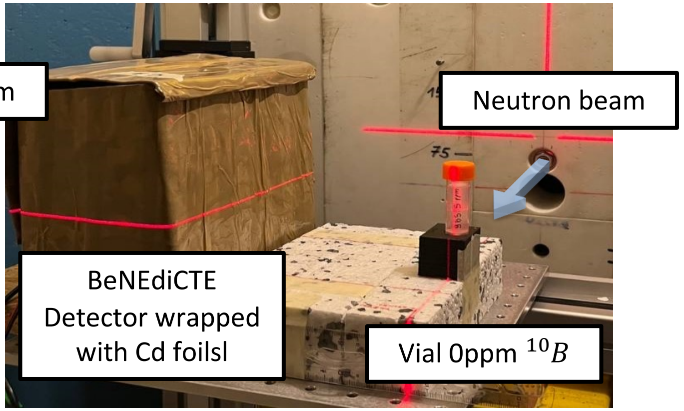
Epoxy resin 40%	"E"-grade glass fiber 60%

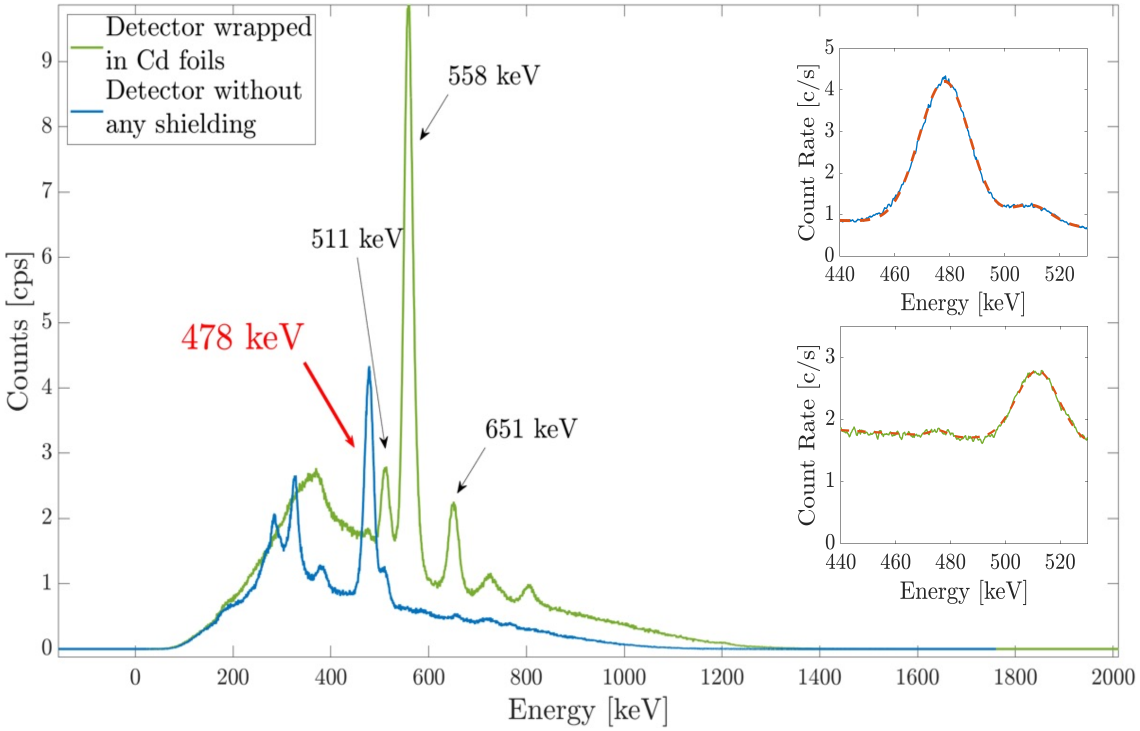
$0.2 - 0.3\ \%\ {}^{10}B$ **by weight**

FLUKA simulations showed a high 478 keV contribution given by the **presence of boron in the electronics.**

Cd housing to shield thermal neutrons.







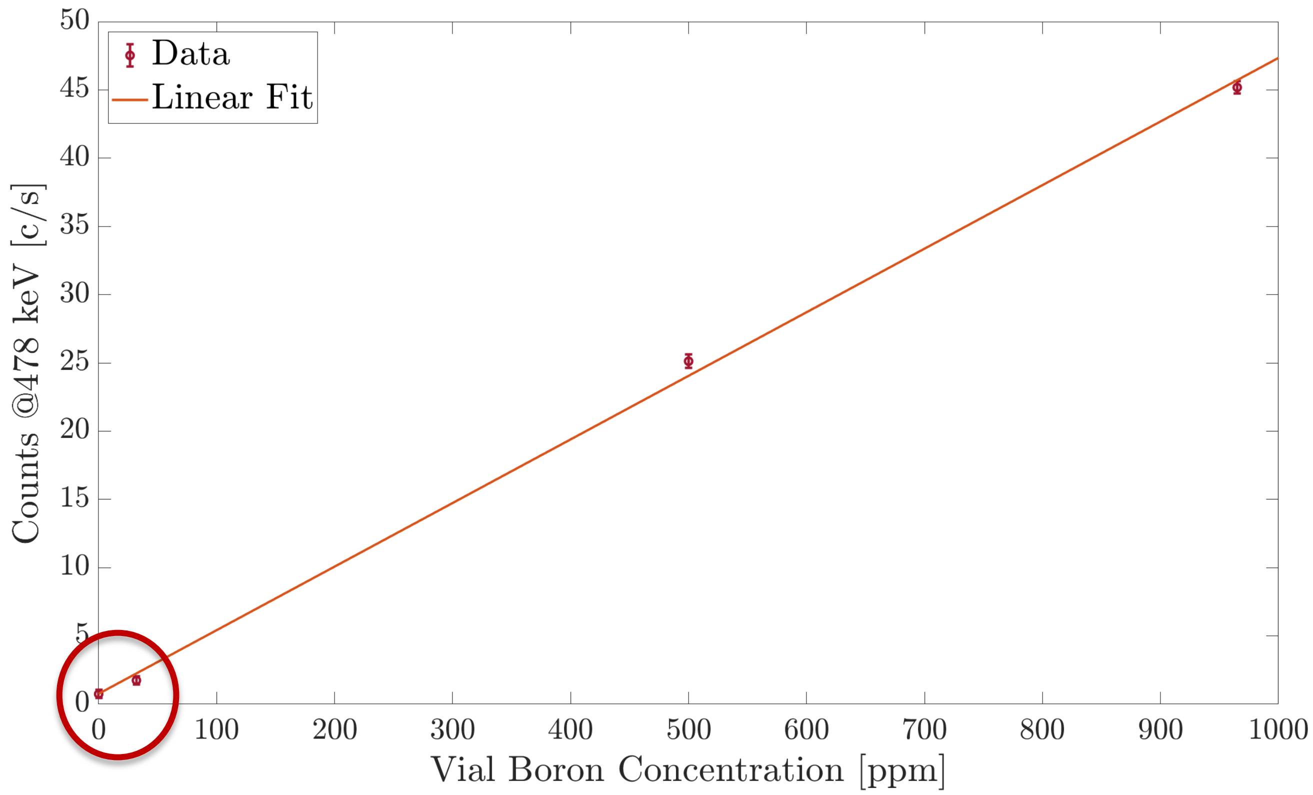
Almost **complete reduction of the boron peak coming from the electronics.**

Background radiation enhancement.

New Linearity Measurements

Measurements performed at the **TRIGA Mark II** reactor of Pavia University (Italy).

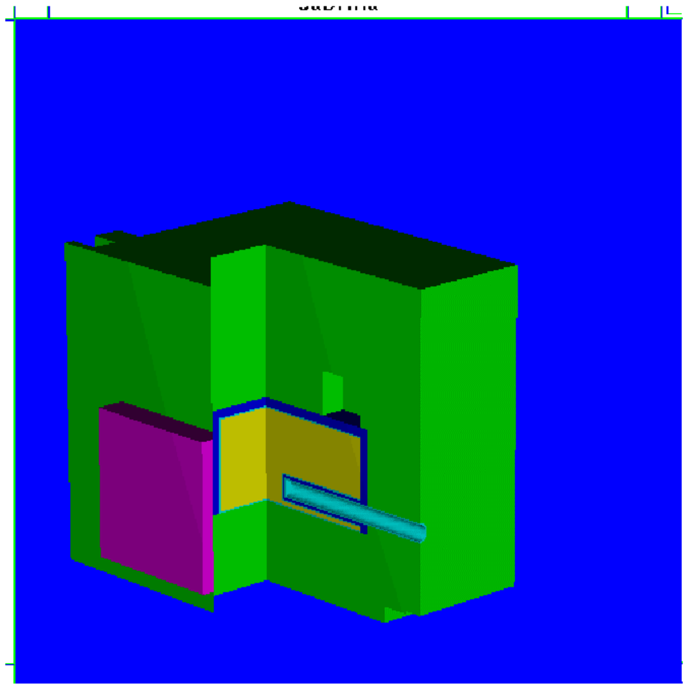
4 vials at **different concentrations** (0 ppm, 32 ppm, 500 ppm, 1000 ppm) and
Neutron flux of 10^5 n/cm^2/s.

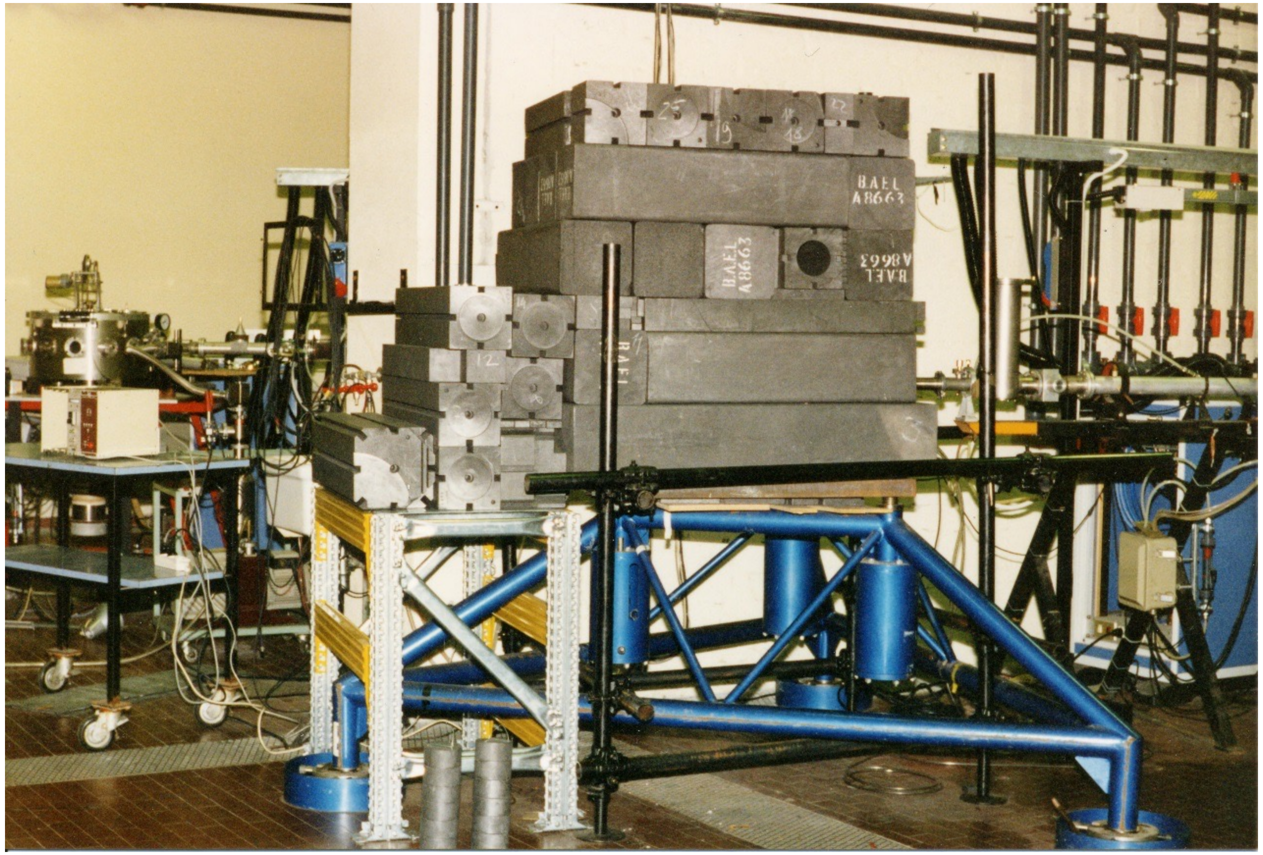


- Good **linear correlation** between the boron concentration and the detected events at 478 keV.
- Almost zero events at **478 keV** detected during the 0 ppm measurement.

New challenge: in BNCT facilities, walls are covered by **borate** compounds!

Accelerator-based neutron source for BNCT



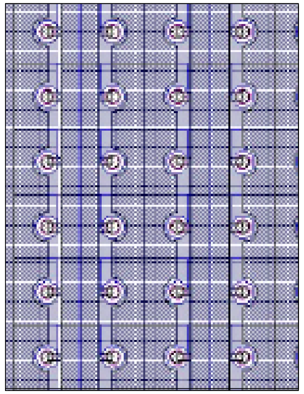


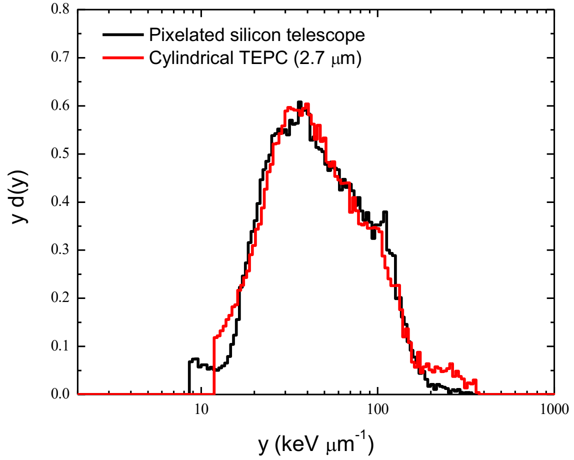
Experimental facility @LNL

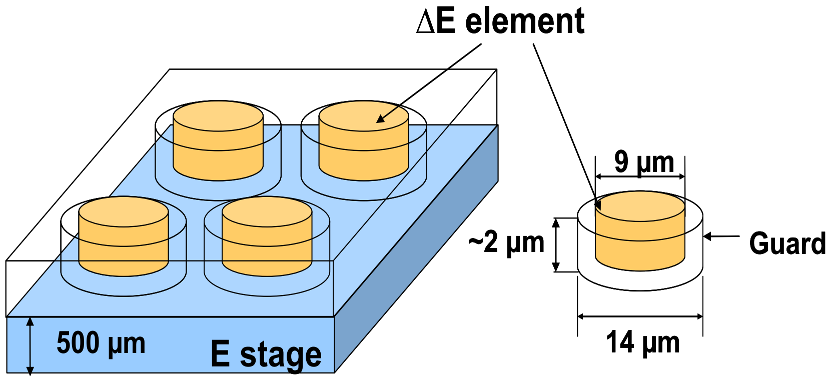
Courtesy: S.Agosteo (POLIMI)

Segmented silicon telescope

- segmented silicon telescope:
  - ✓ constituted by a matrix of cylindrical ΔE elements (about 2 μm in thickness) and a single residual-energy E stage (500 μm in thickness);
  - ✓ the nominal diameter of the ΔE elements is about 9 μm and the width of the pitch separating the elements is about 41 μm.
  - ✓ more than 7000 pixels are connected in parallel to give an effective sensitive area of about 0.5 mm^2.
  - ✓ minimum detectable energy is limited to about 20 keV by the electronic noise.
  - ✓ the ΔE stage acts as a microdosimeter and the E stage plays a fundamental role for assessing the full energy of the recoil-protons, thus allowing to perform a LET-dependent correction for tissue-equivalence.





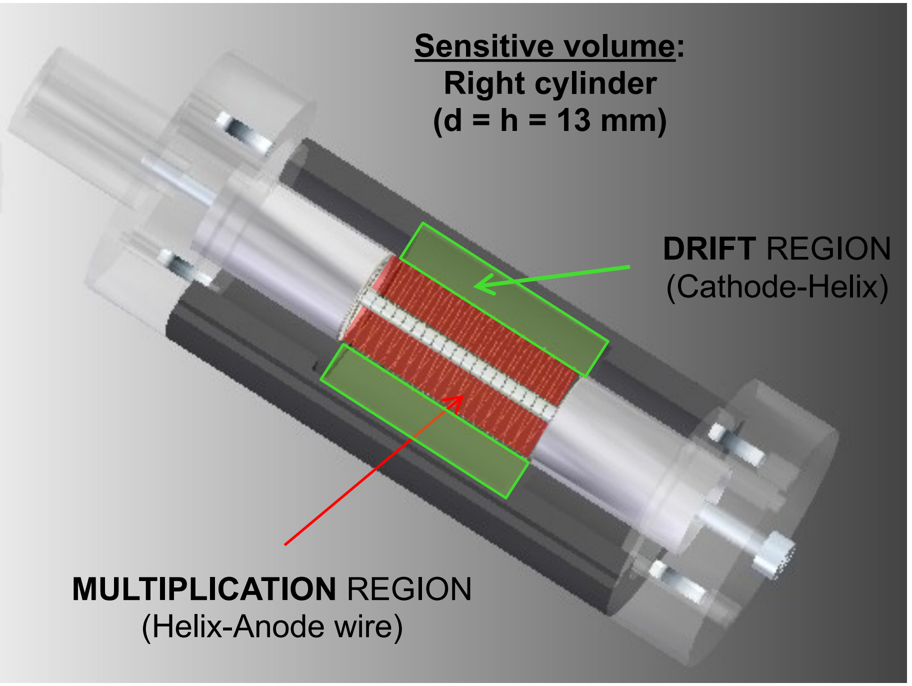


Courtesy: S.Agosteo (POLIMI)

Avalanche confinement TEPC

Microdosimetry ⇄ Track-nanodosimetry

Feasibility of extending the TEPC performances down to the nanometric domain (down to 25 nm)



3 electrodes independently biased
(Anode, Helix, Cathode)
$V_{anode} > V_{helix} > V_{cathode}$

HELIX = electronic avalanche confinement

Courtesy: S.Agosteo (POLIMI)

Acknowledgments

- The RADLAB team at POLIMI
- S.Agosteo, D.Mazzucconi, G.Baroni (Politecnico di Milano)
- S.Altieri, N.Protti (Università di Pavia and INFN)
- M.Pullia, M.Donetti, M.Ciocca, S.Rossi (CNAO)
- G.Iaselli, G.Pugliese (Politecnico di Bari and INFN)

Fundings

- PGI: IBA, TERAPET, new project REALPATH (FISA 2022)
- BNCT: PRIN-PNRR, INFN