Gamma-ray detectors for range and dose verification

Carlo Fiorini
Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano, Italy

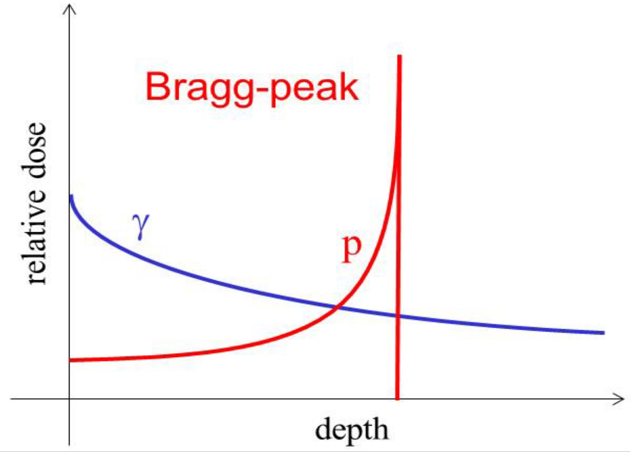
RadLab

OUTLINE

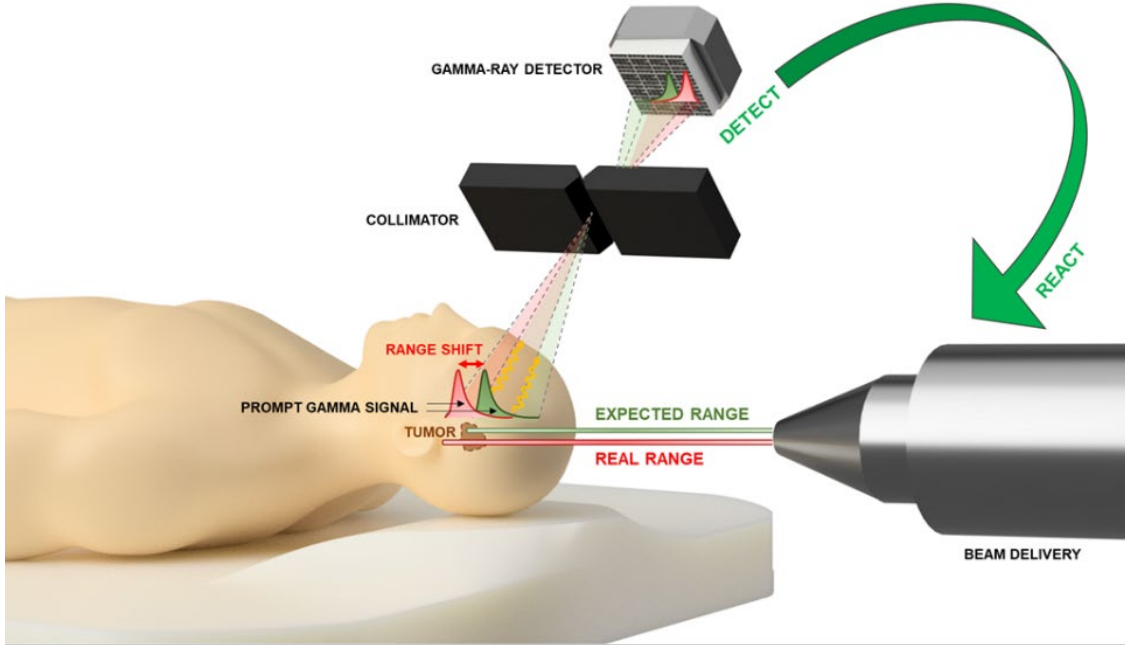
- **Range verification by prompt-gammas detection in C-ions radiotherapy**

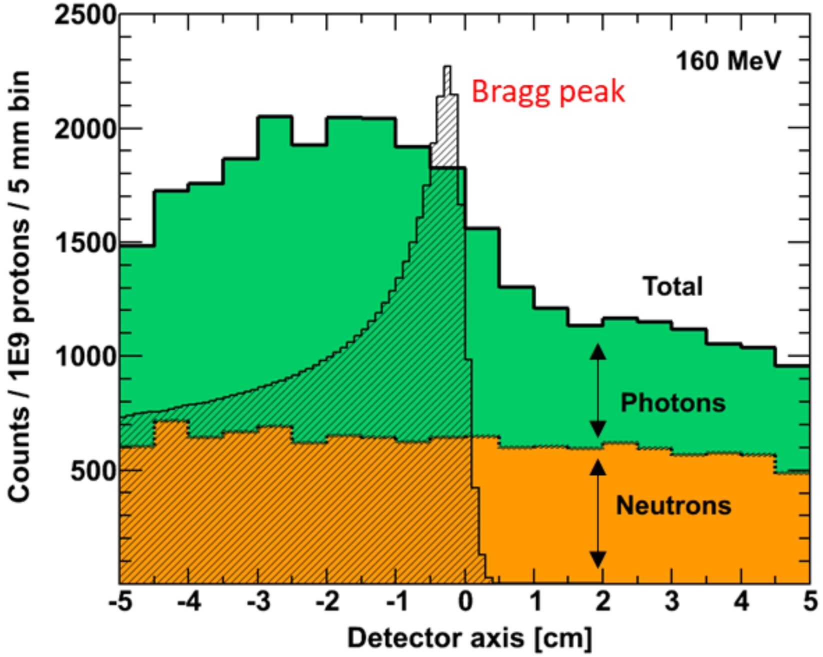
- **Dose measurements by gamma detection in BNCT (Boron Neutron Capture Therapy)**

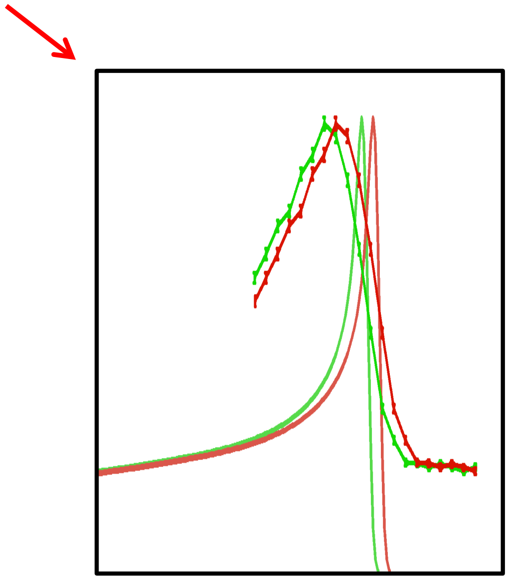
Prompt Gamma Imaging (PGI) for Range Verification in Hadrontherapy



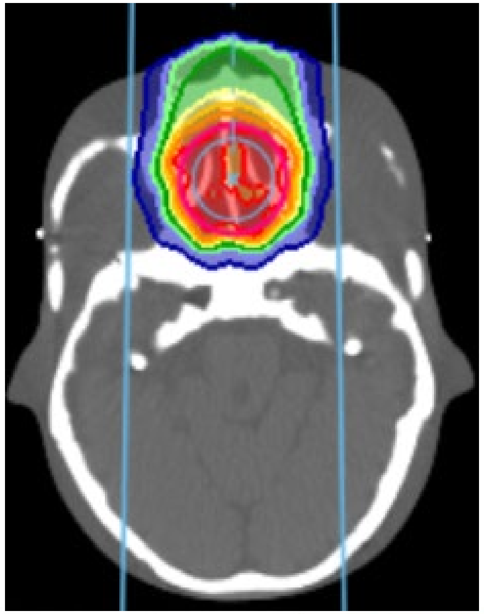
The measurement of the particle beam range in the target is very important: real range of proton beams in patients may contain uncertainties of up to 10-15 mm (uncertainties on tissue composition, density, organ motions, patient positioning, etc).

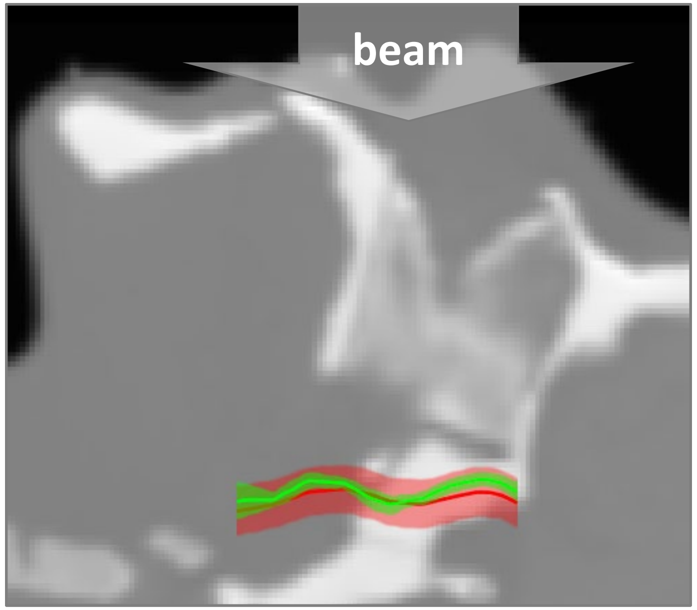


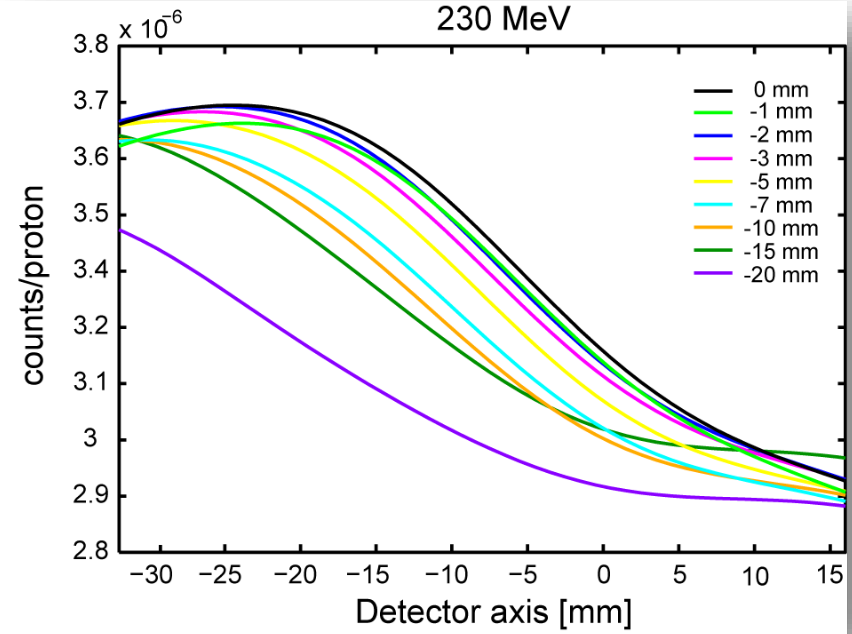




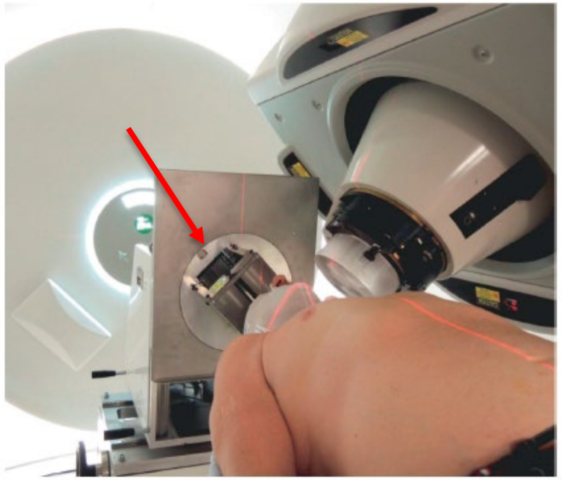
Range Verification with protons







Shift measurements



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

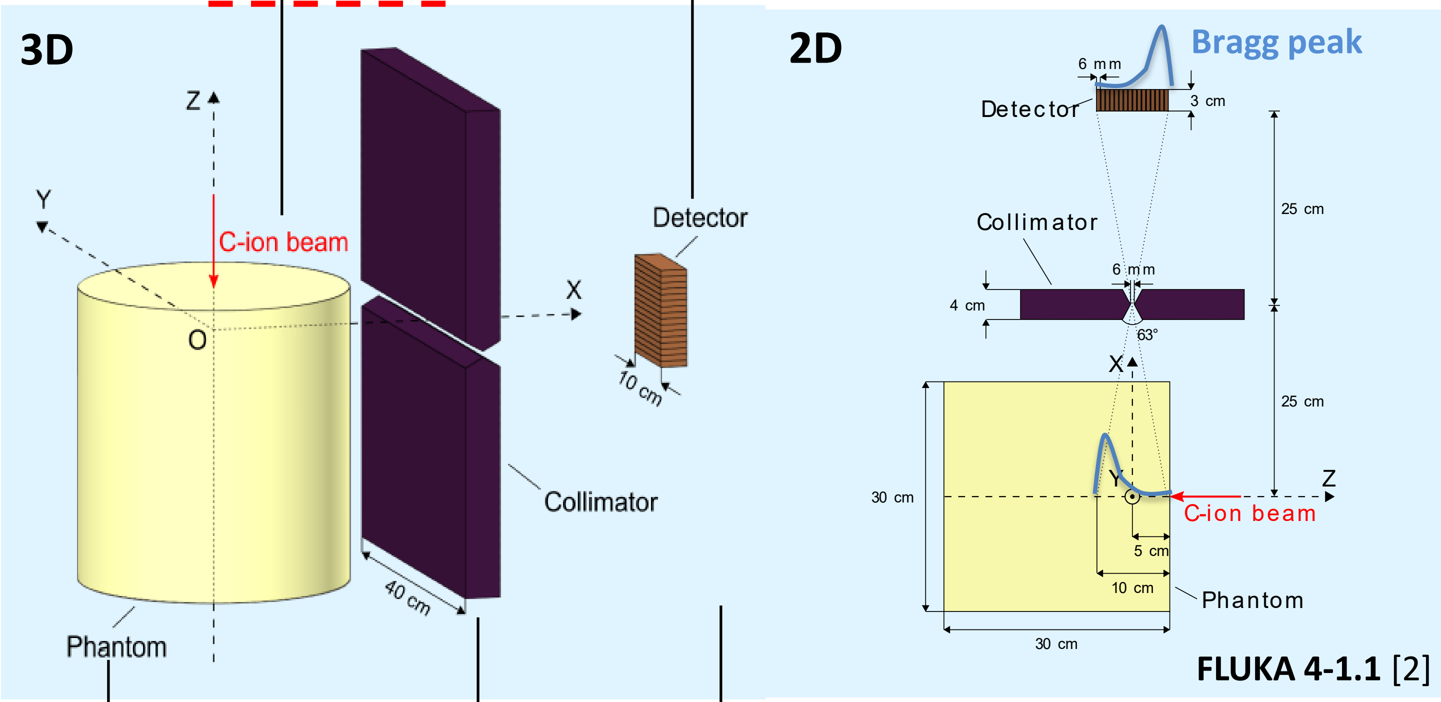
Clinical trial of PG camera for Proton irradiation

- 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)

$150\ \frac{MeV}{u}$ $Lu_{1.8}\ Y_{0.2}\ SiO_5$ (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.**

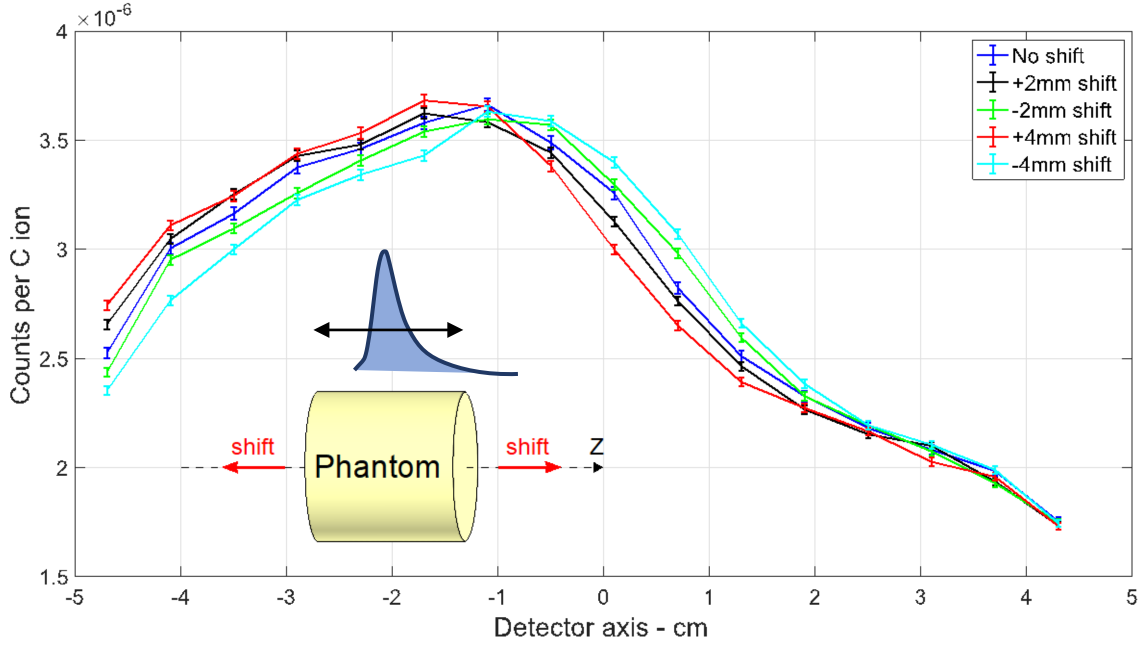
Energy interval: **3-7 MeV**

Reconstructed PGI profiles

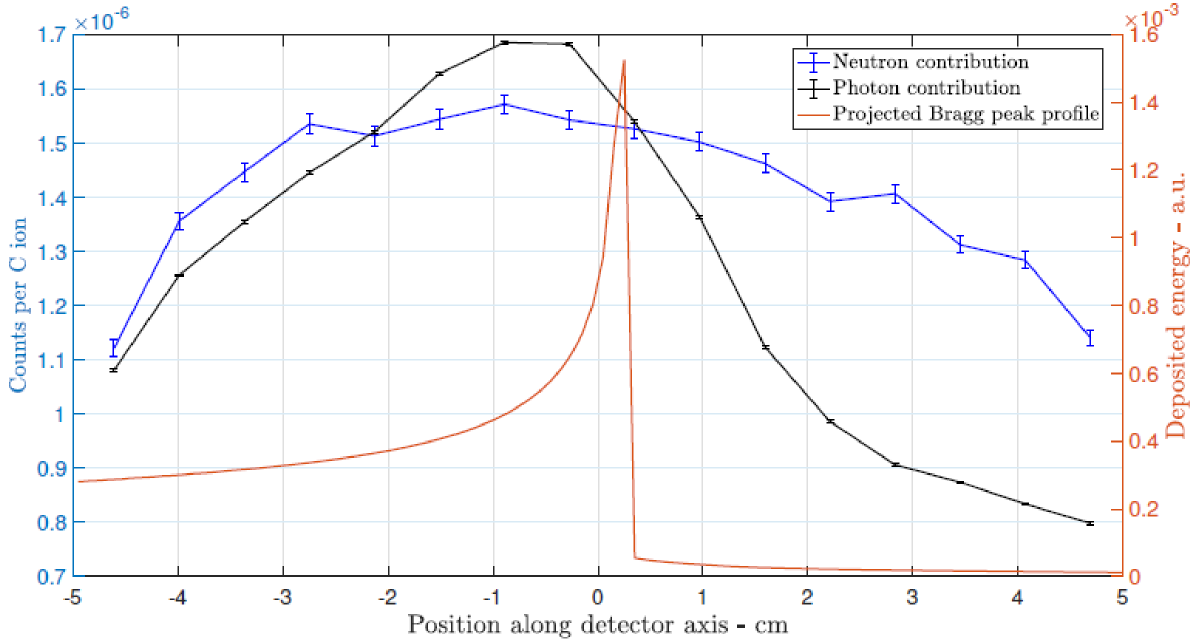
Particle range sensitivity determination by target longitudinal shifts

- 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

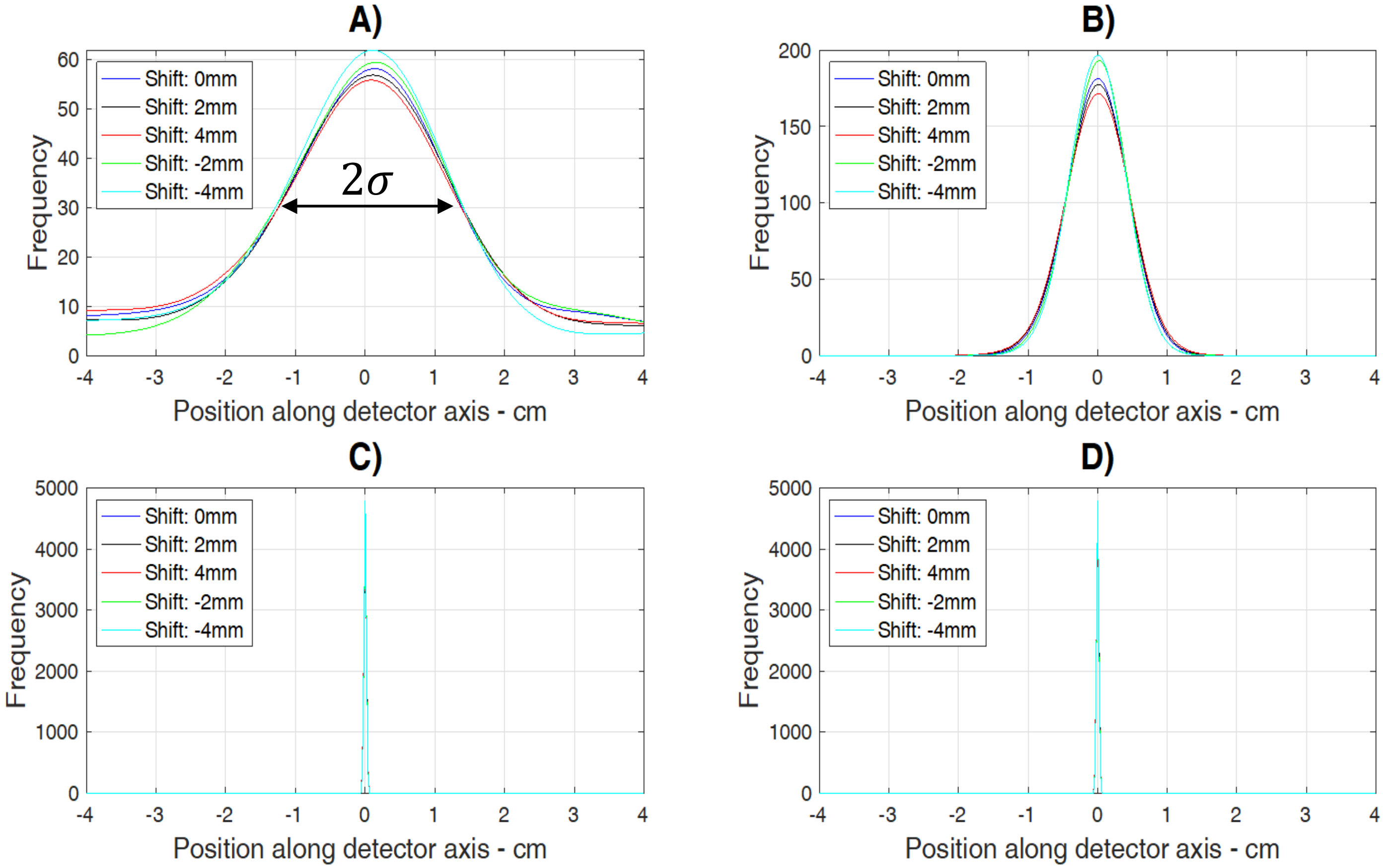


Prompt-gamma component over an almost **uniform neutron background**

Particle Range Precision Determination – Spot and Spill irradiations

Graphical representation of the **precision (2σ)** in retrieving the Bragg peak fall-off for **different phantom shifts** and **number of C-ions** : A) 10^6 , B) 10^7 , C) 10^8 , D) 10^{10}

irradiation **spot** (A) · irradiation **spill** (B, C) · upper bound (e.g. FLASH therapy) (D)

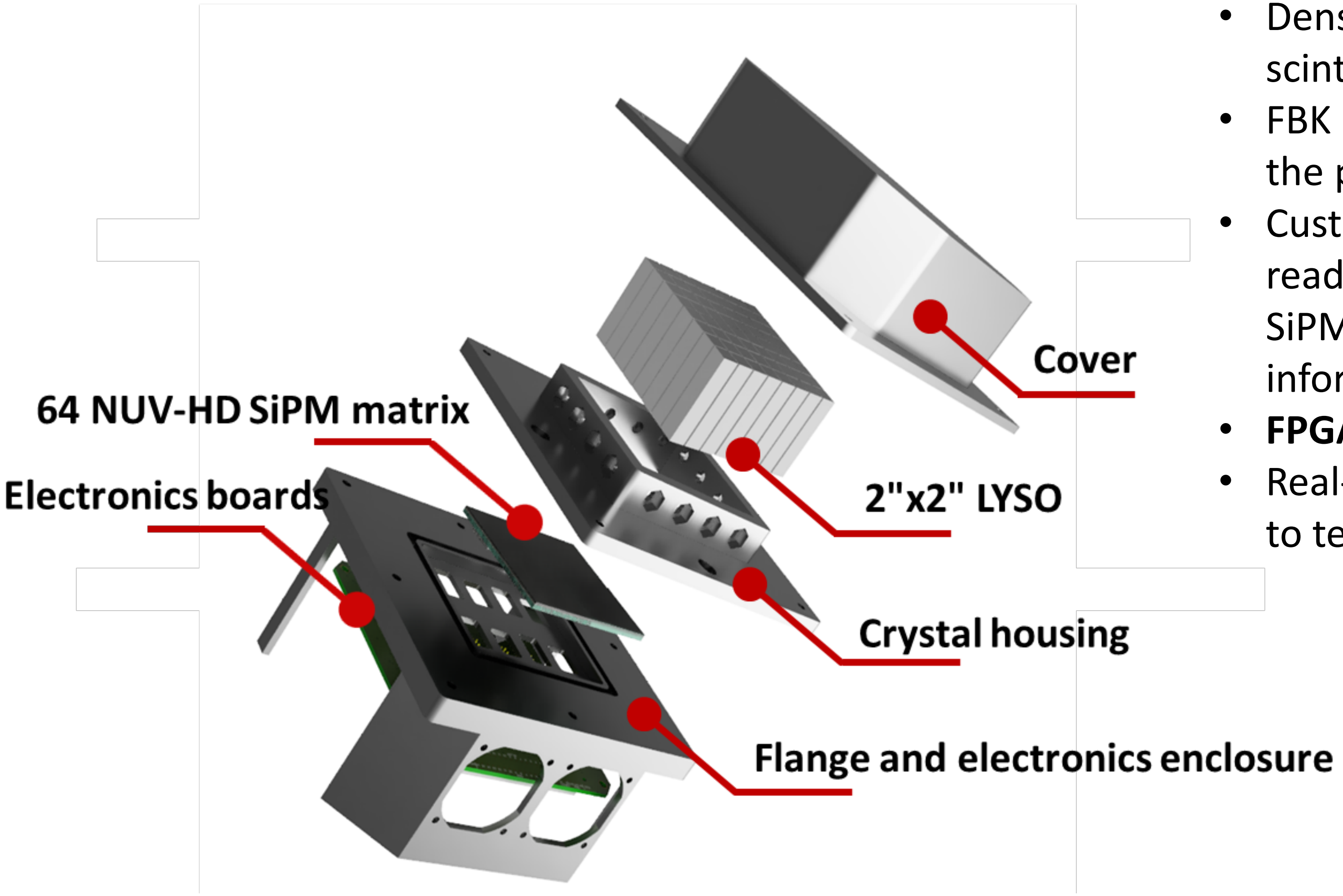


- **Spot irradiation** to the phantom for different number of incident carbon ions (10^6, 10^7, 10^8 and 10^{10}) → **~ 10 mm.**

- **spill irradiation**, namely **5x10^7 ions** → From ***range retrieval analysis***: **4.2 mm** precision.

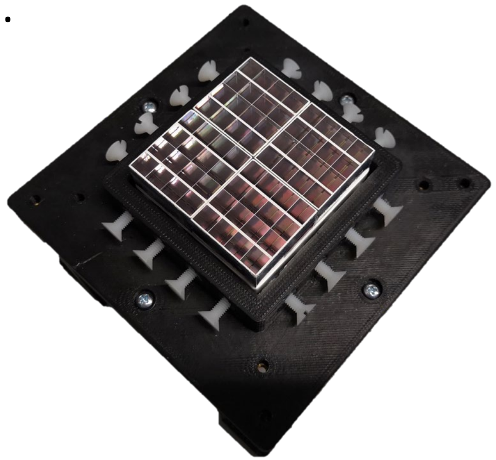
Toward the Development of a PGI System for CIRT

FIRST PROTOTYPE (64 channel)

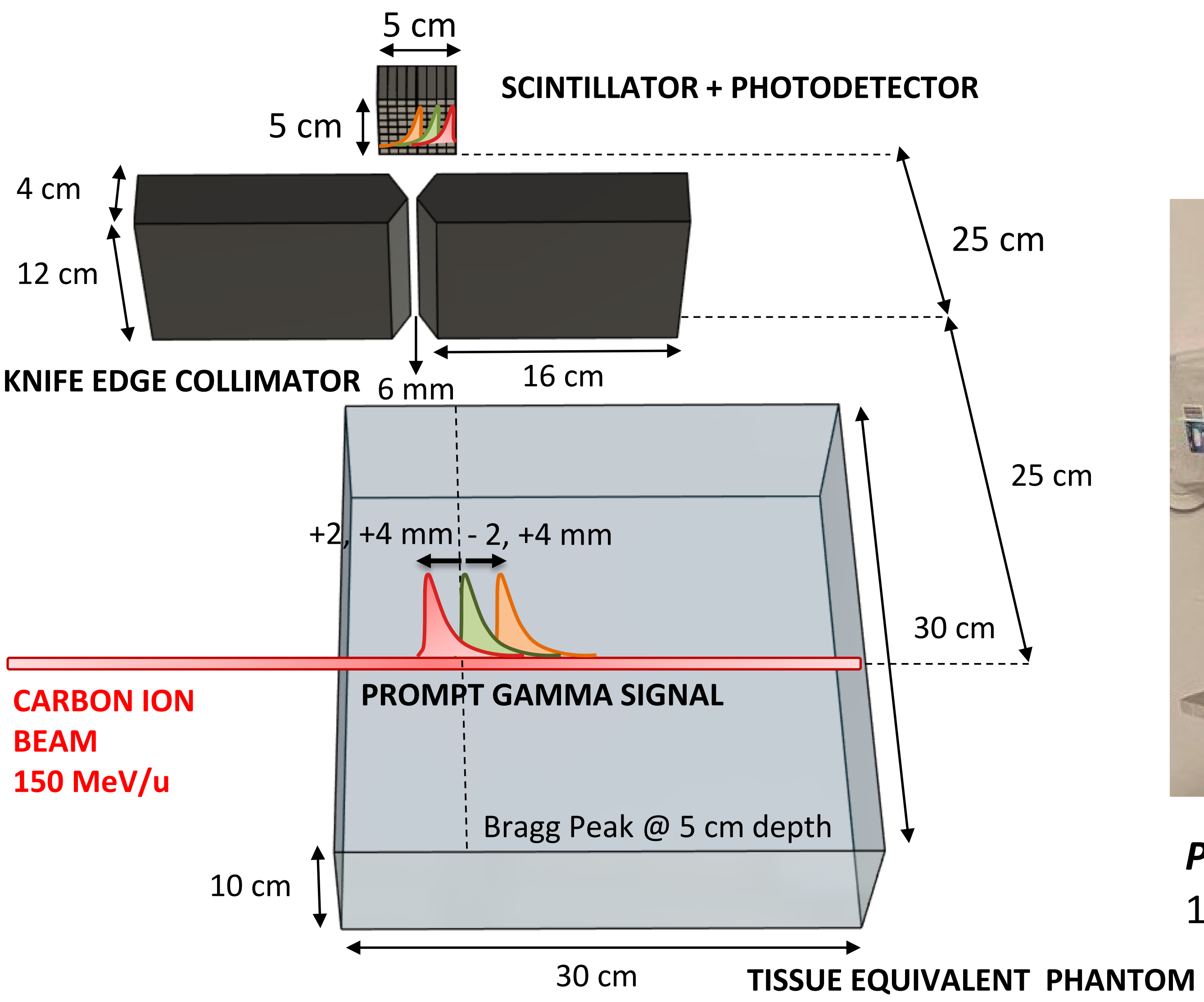


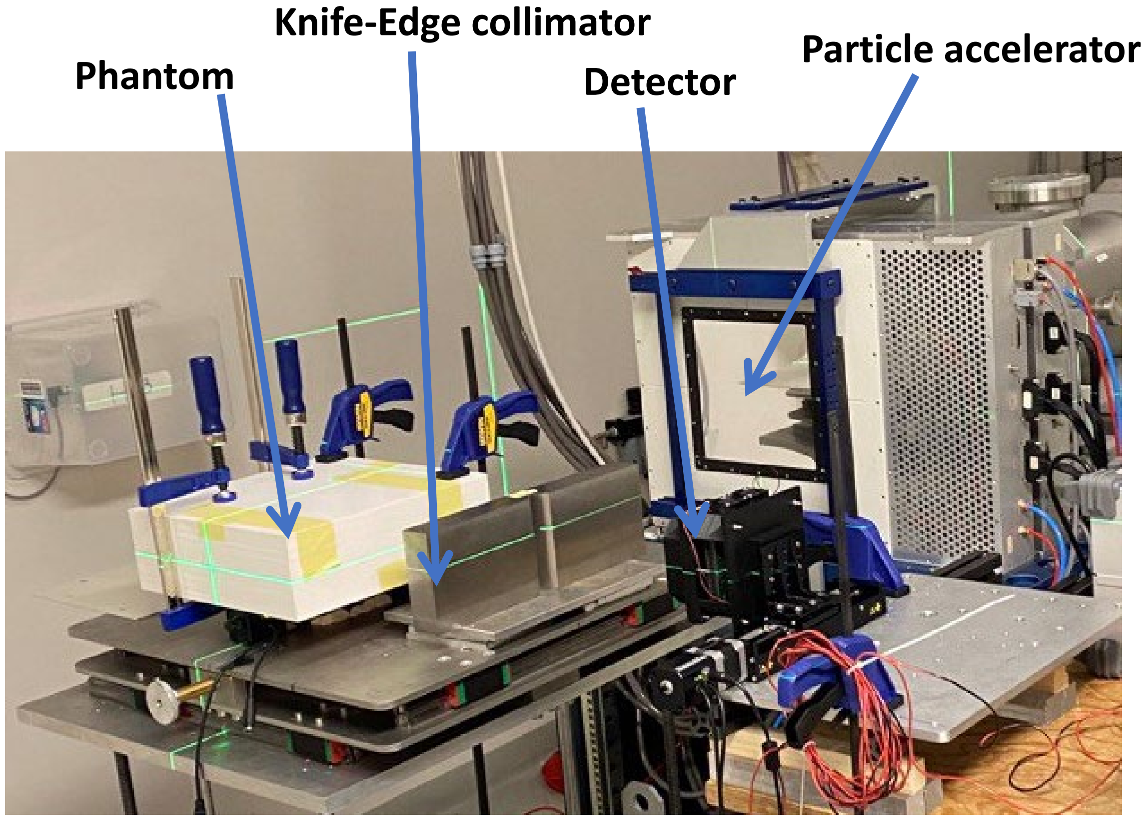
SYSTEM FEATURES

- Dense, fast, high light yield pixelated **LYSO** scintillator.
- FBK **NUV-HD SiPMs** suitable for **1:1 coupling** with the pixelated scintillator.
- Custom **16-ch GAMMA ASIC** that has the goal to read monolithically the current supplied by each SiPM and to provide in output the energy information of the gamma ray.
- **FPGA-based DAQ system**.
- Real-time **compensation of SiPM gain drifts** due to temperature variations.



Knife Edge Slit Camera Setup Configuration at CNAO



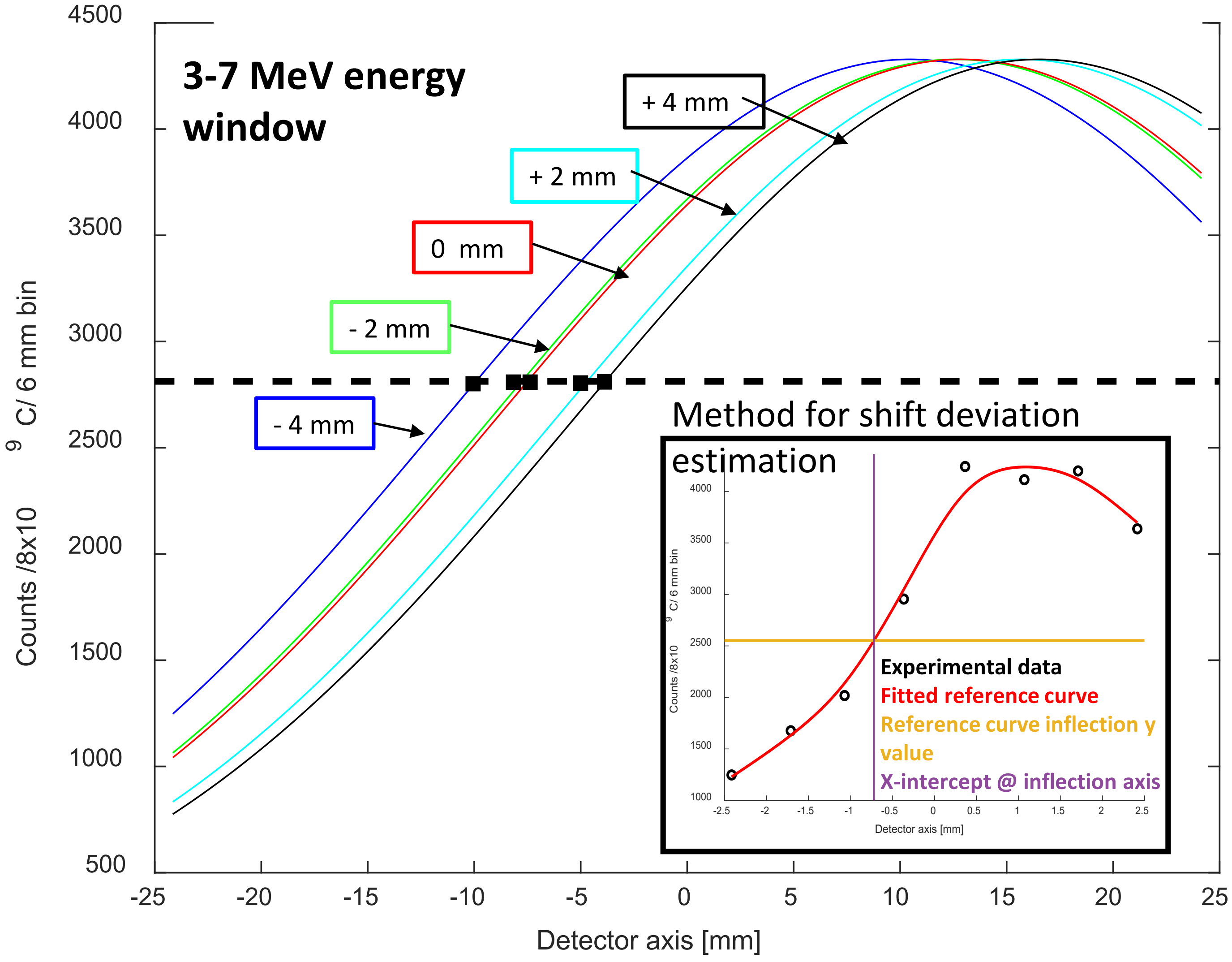


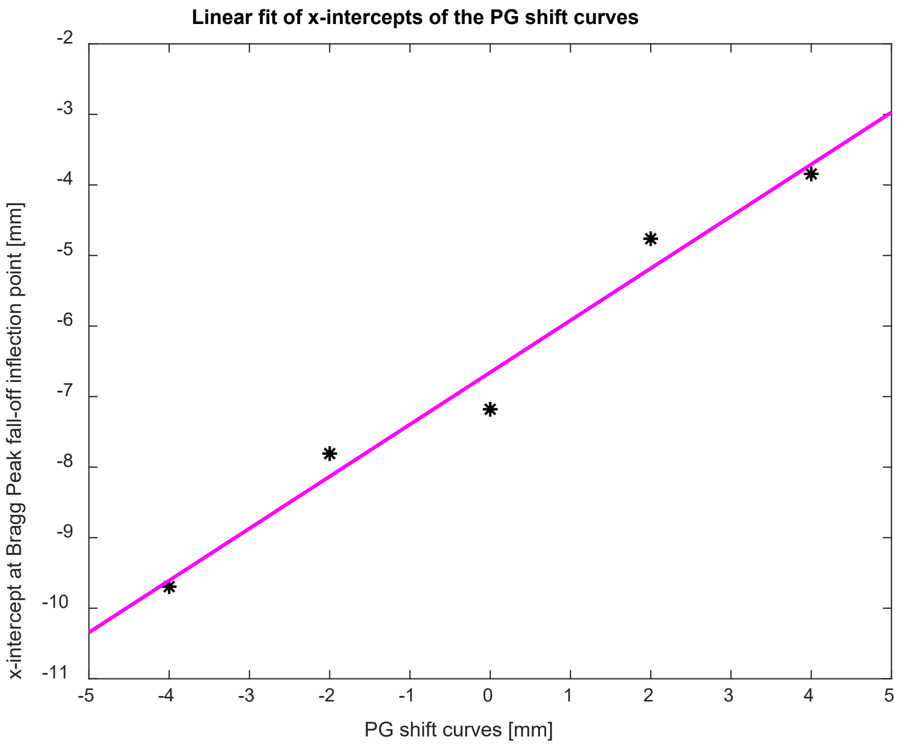
Particle beam structure:

100 spills of $8x10^7$ carbon ions = **$8x10^9$ carbon ions**

Analysis of Experimental Data: Curve Shifts (preliminary)

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



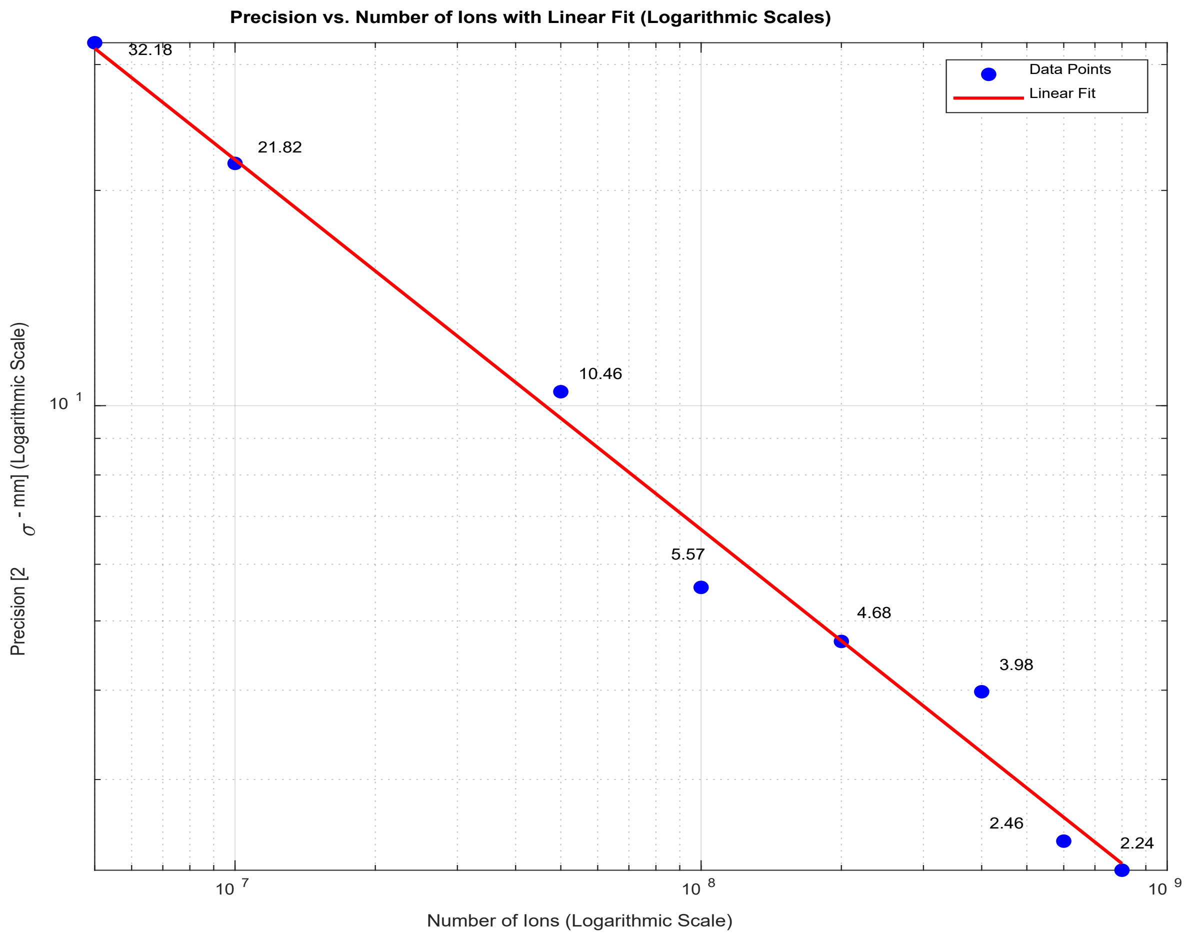


Mean deviation from the expected shift positions: ~**0.24mm**

Range retrieval precision vs. number of Carbon ions (preliminary)

Linear interpolation of the double logarithmic data log(precision) VS log(Number of carbon ions).

The precision is proportional to $N_{ions}^{-1/2} = \frac{1}{\sqrt{N_{ions}}}$

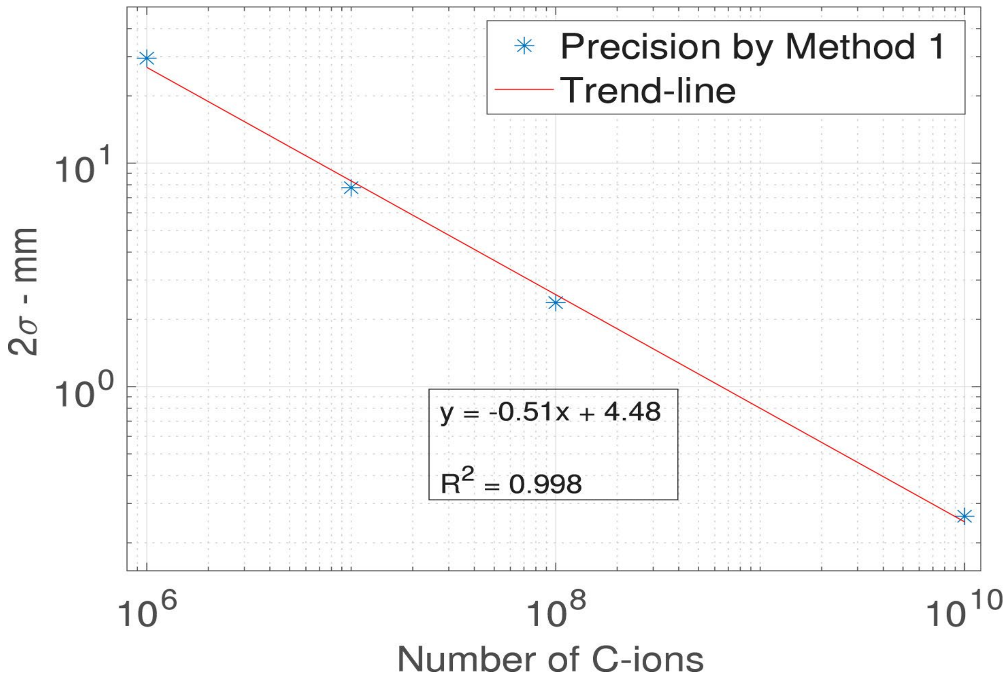


Estimated Slope (m): -0.5172

Residual Sum of Squares (RSS): 2.9724

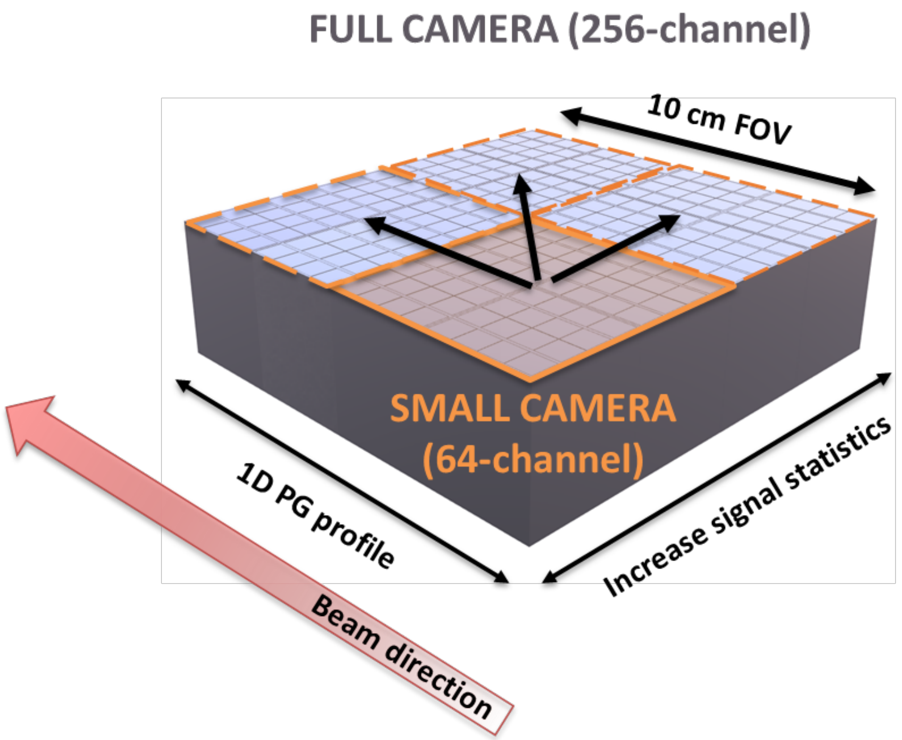
R-squared (R^2): 0.9964

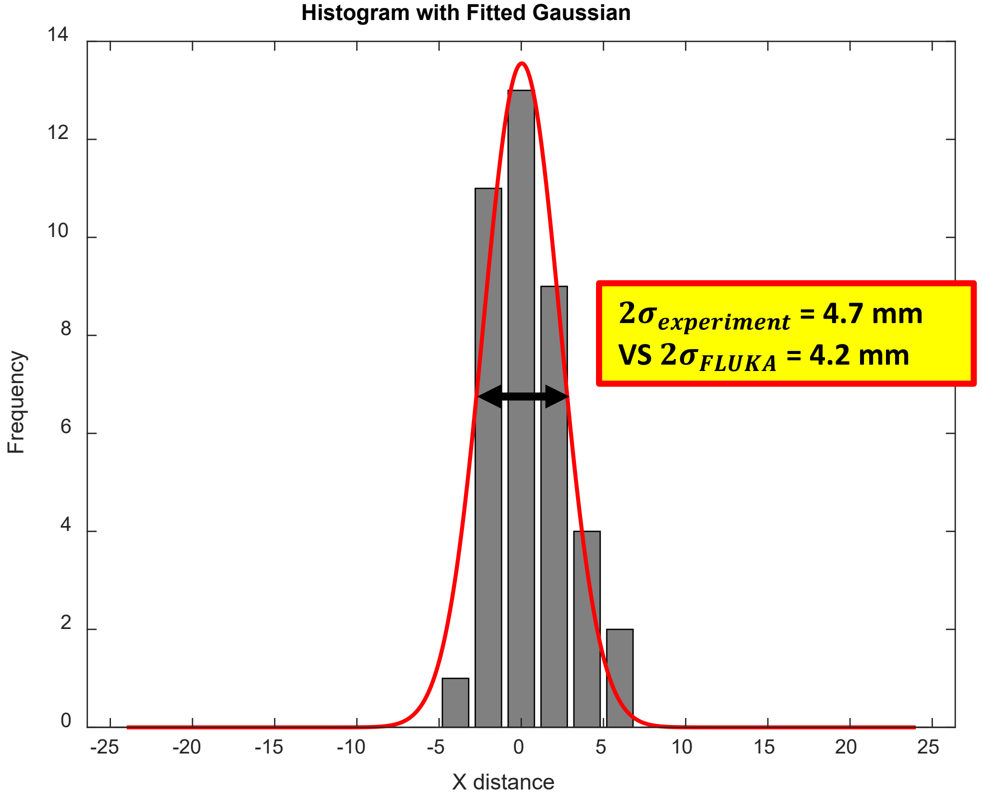
FLUKA SIMULATIONS



Measured vs. simulated precision (preliminary)

$$N_{C-ions} = 2x10^8$$

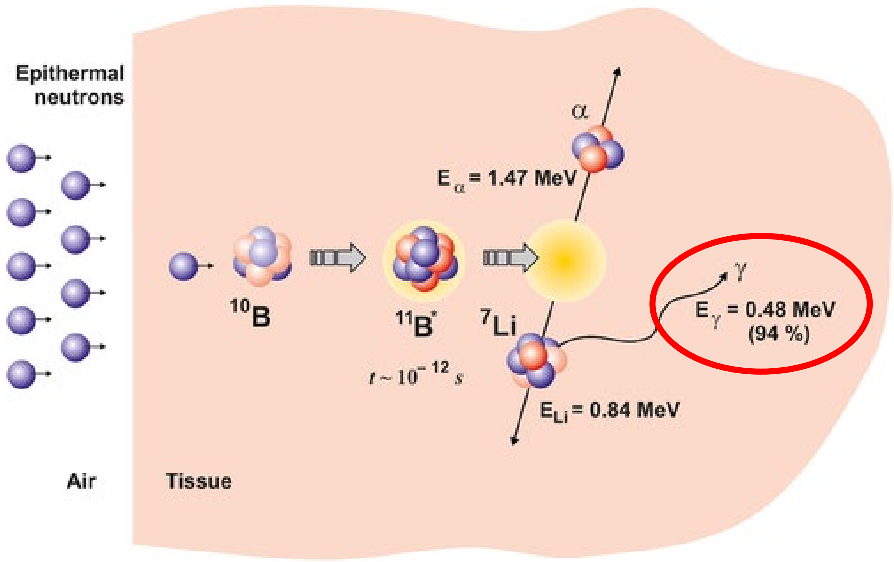




In order to achieve the desired statistics as for the 256 channel camera, we assume to multiply x4 the number of carbon ions of the measurement corresponding to a spill:
4 x **$5x10^7$ ions = $2x10^8$ ions**

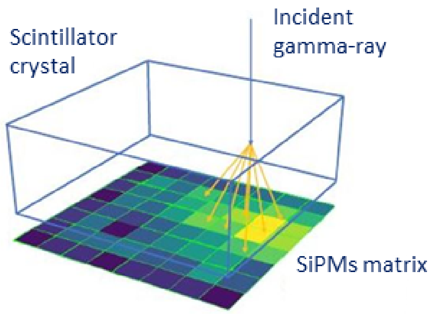
Plot of the histogram of distances between the reference and noisy curve peaks distances between their x value at the y inflection of the reference curve

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

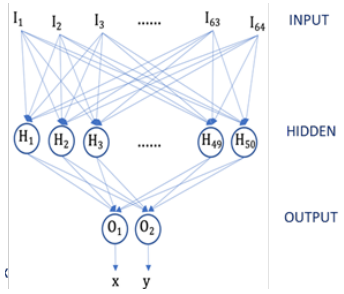


Detection of emitted **478keV gamma photons** may let to estimate ^{10}B neutron captures and support therapeutic outcome (personalized dosimetry).

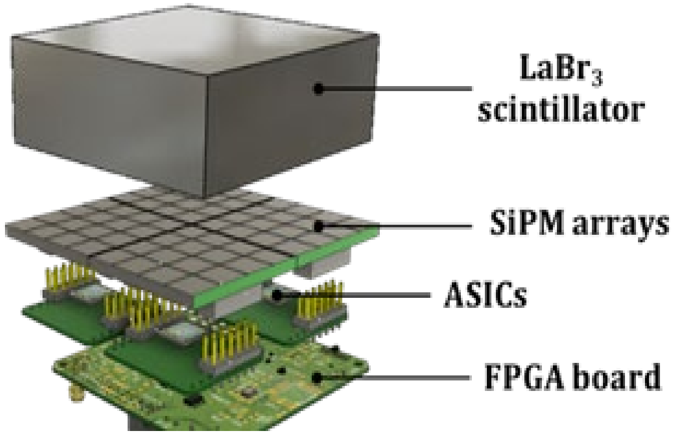
Goal: Development of a SPECT (Single Photon Emission Thomography) system) for BNCT

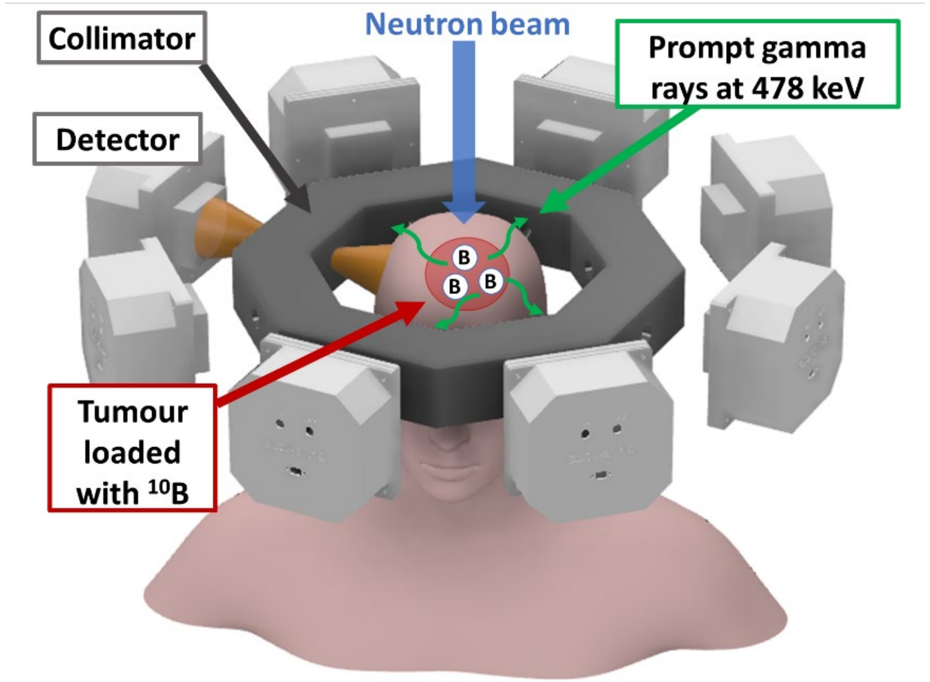


Scintillator/SiPMs-based gamma-ray detector



Neural-Network for event reconstruction

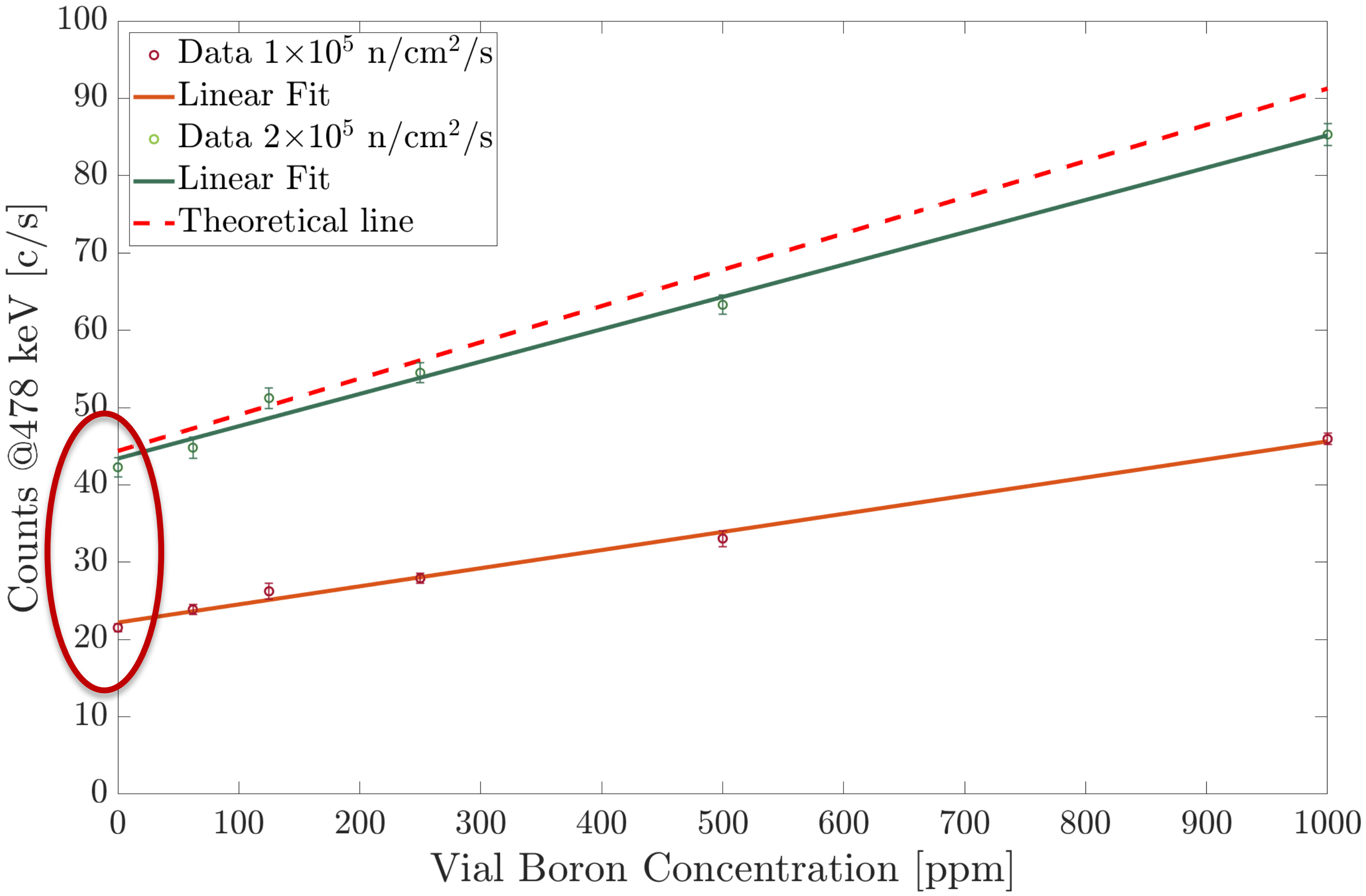




Linearity Measurements

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)



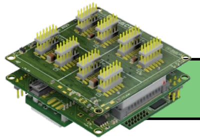
✓ Good **linear correlation** between the boron concentration and the detected events at 478 keV.

✗ Events at **478 keV** detected during the 0ppm measurement

Shielding study

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

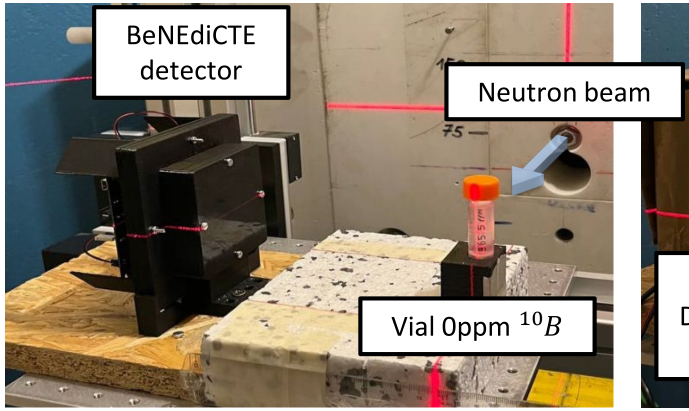
→ **Cd housing** to shield thermal neutrons.

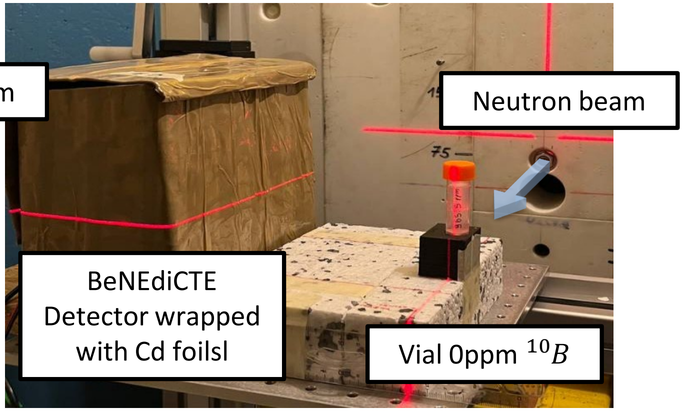


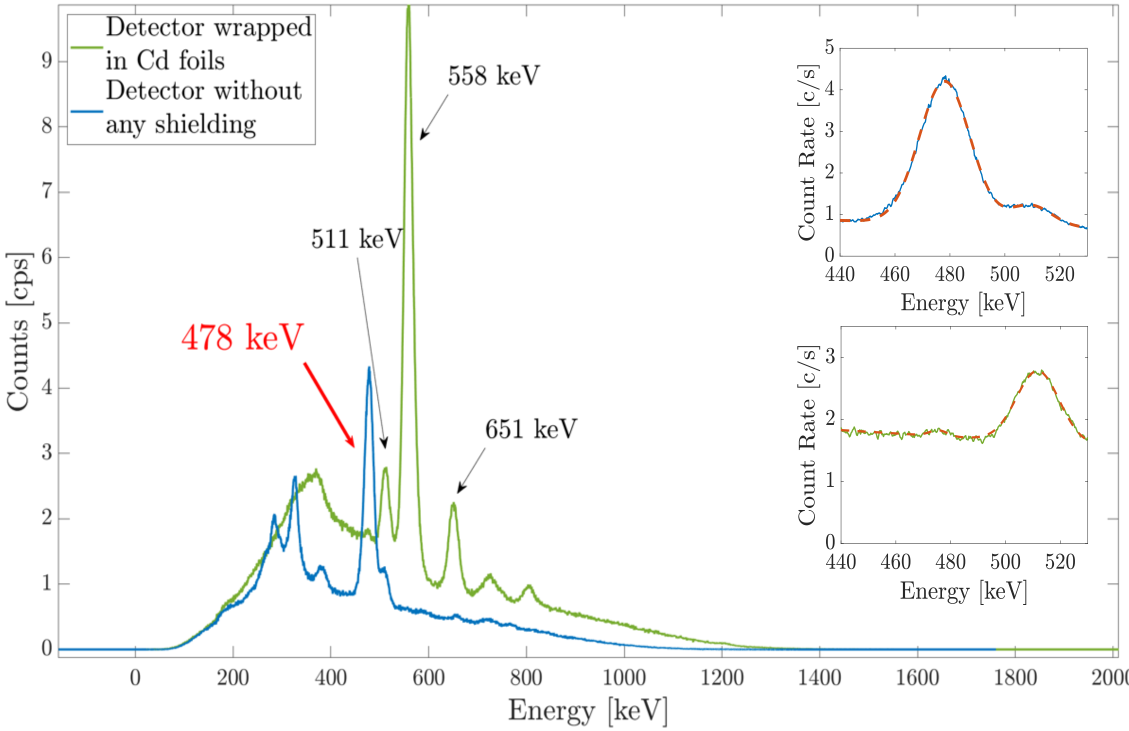
Flame Retardant (FR4) substrate

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

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







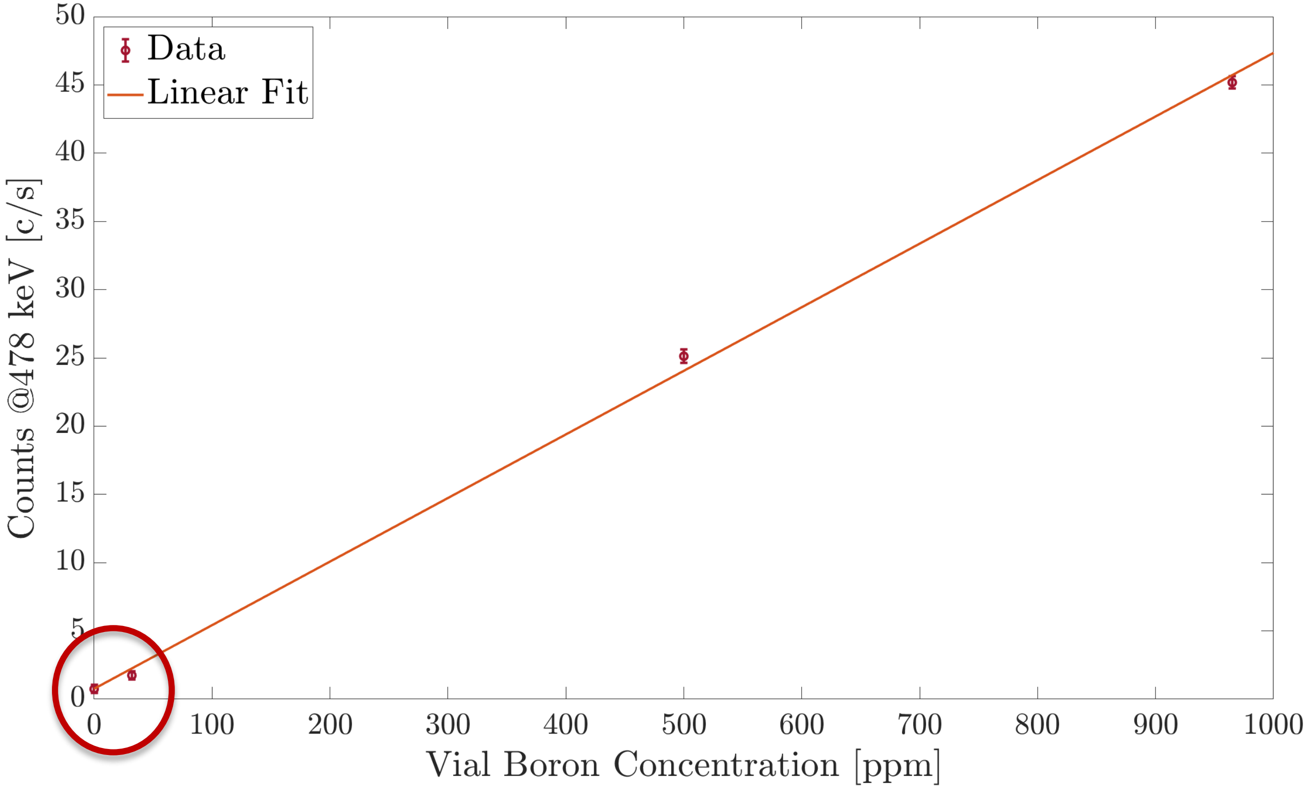
✔ Almost **complete reduction of the boron peak coming from the electronics.**

✘ 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.

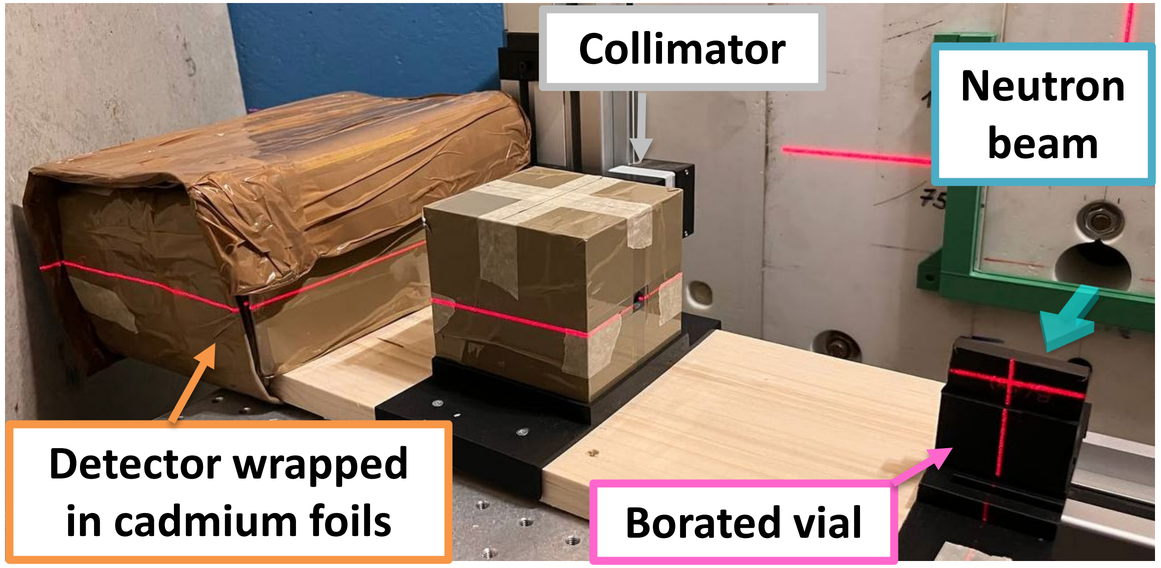


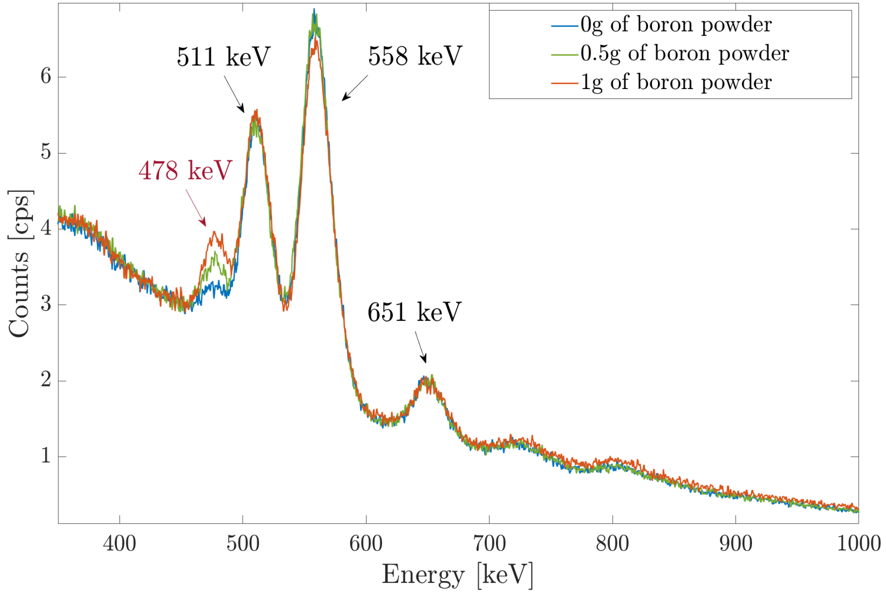
- Good **linear correlation** between the boron concentration and the detected events at 478 keV.
- Almost zero events at **478 keV** detected during the 0 ppm measurement.

Spectroscopy/Imaging Measurements at TRIGA MARK II nuclear reactor

Experimental setup at nuclear reactor of Pavia:

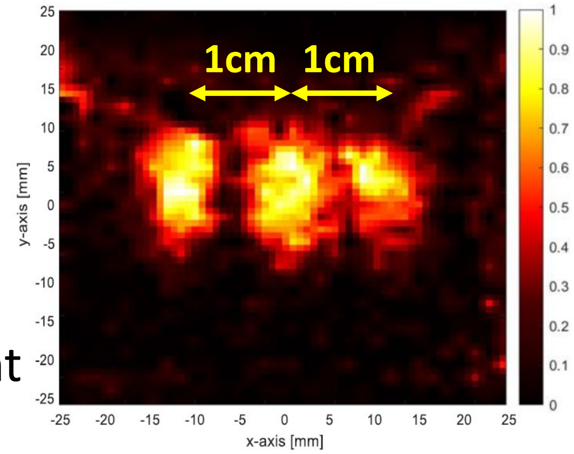
- Neutron flux of $2x10^6$ n/cm^2/s
- Sample 4x0.3x1.6 cm^3 filled with boron powder
- 40 cm distance between the sample and the detector
- **Pinhole collimator**





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