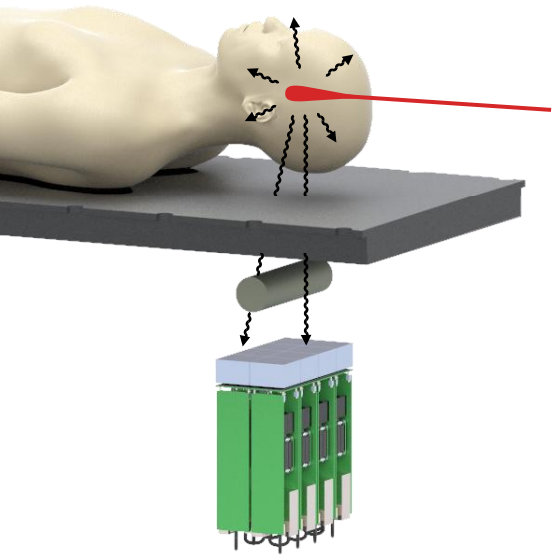
An Imaging and Spectroscopy Detector for High-Energy, High-Rate Gamma-Ray Measurements during Proton Therapy



Korbinian Urban,
Politecnico di Milano

M. Piroddi, C. Riboldi, A. Forgione, L. Santini, G. Borghi, M. Carminati, D. Bortot, D. Mazzucconi, and C. Fiorini

The 14th International Conference on Position Sensitive Detectors
Sept. 1st 2026

Content

1. **Motivation: Prompt-gamma-based range verification in proton therapy**
2. **REALPATH detector and readout design**
3. **Characterization and tests**

Content

1. **Motivation: Prompt-gamma-based range verification in proton therapy**
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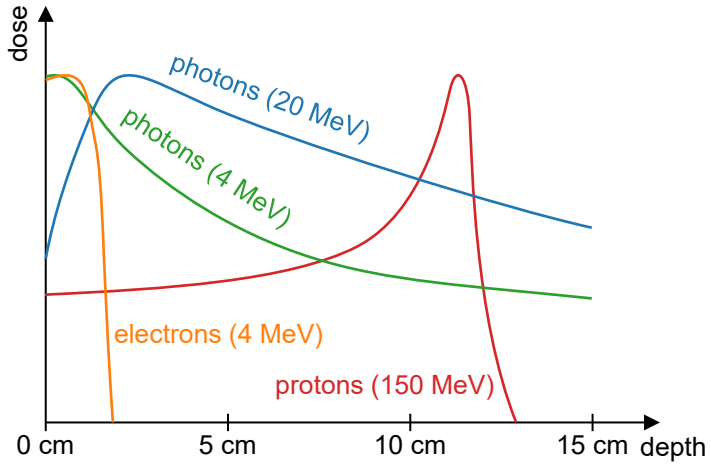
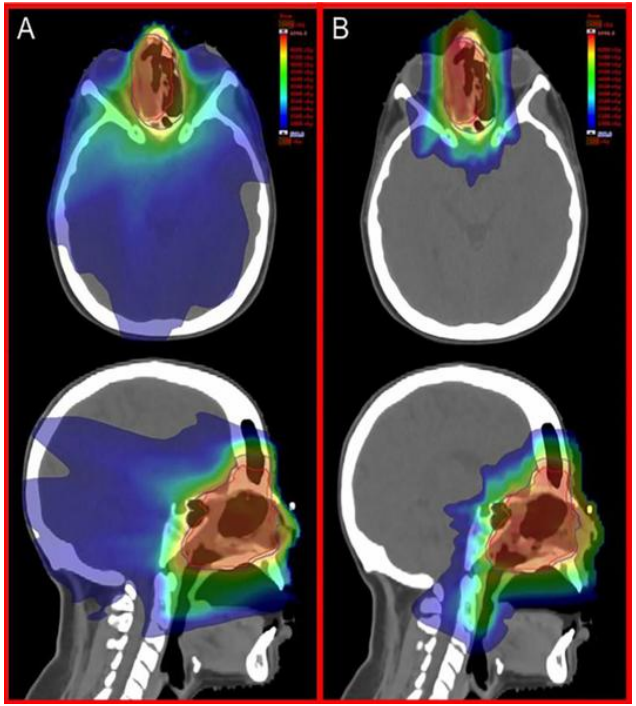
Radiotherapy overview

Moreno et. al. (2019) Oral Oncol.
DOI: 10.1016/j.oraloncology.2018.11.015

illustration of **depth-dose profiles**:



example treatment plans:



proton therapy advantageous:

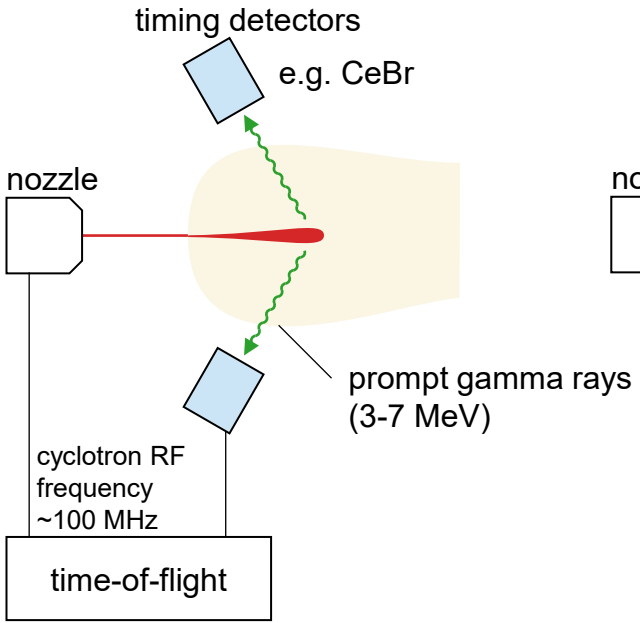
- less dose at entrance
- almost no dose behind tumour

but: sensitive to range uncertainties

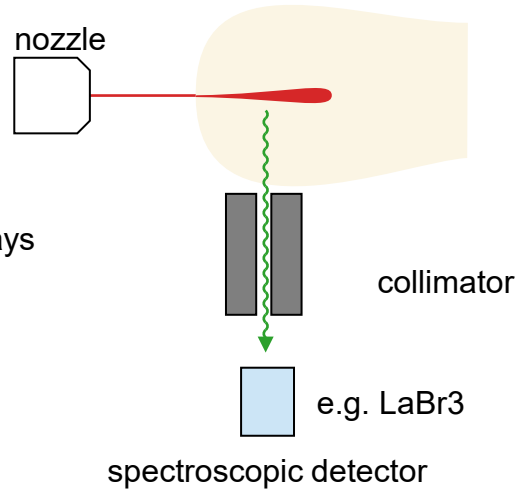
→ range verification

Prompt gamma rays for in-situ range verification

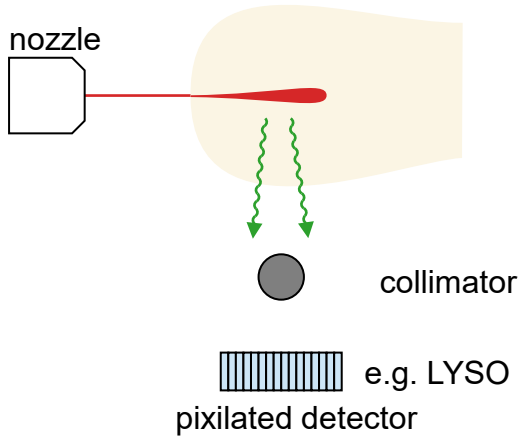
Prompt-Gamma Timing PGT



Prompt-Gamma Spectroscopy PGS

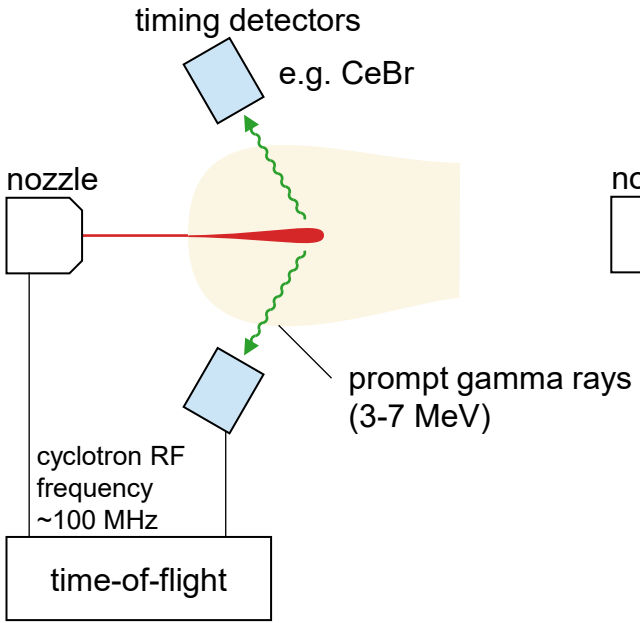


Prompt-Gamma Imaging PGI

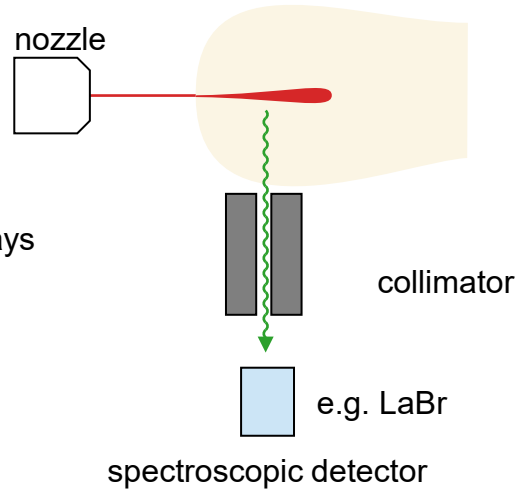


Prompt gamma rays for in-situ range verification

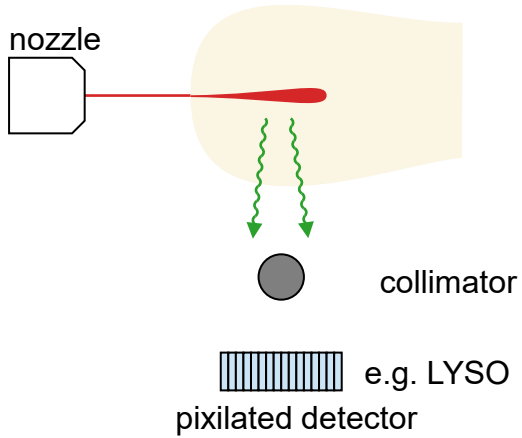
Prompt-Gamma Timing PGT



Prompt-Gamma Spectroscopy PGS



Prompt-Gamma Imaging PGI



Prompt gamma rays for in-sit tion

Prompt-Gamma Timing PGT

timing detectors

e.g. CeBr

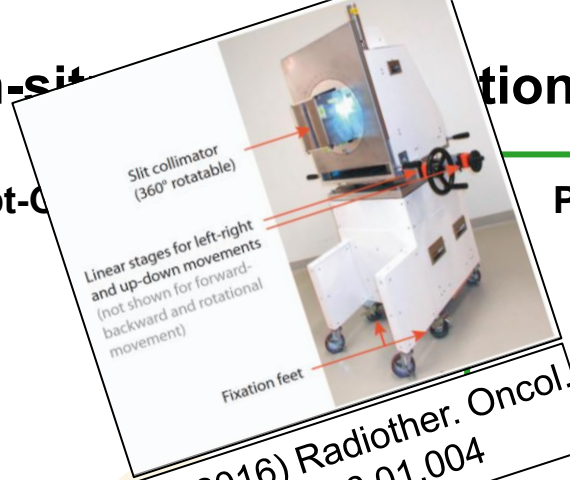
nozzle

prompt gamma rays
(3-7 MeV)

cyclotron RF
frequency
~100 MHz

time-of-flight

Prompt-C



e.g. Richter et al (2016) Radiother. Oncol.
DOI: 10.1016/j.radonc.2016.01.004

nozzle

collimator

e.g. LaBr

spectroscopic detector

Prompt-Gamma Imaging PGI

nozzle

collimator

e.g. LYSO

pixilated detector

Prompt gamma rays for in-sit tion

Prompt-Gamma Timing PGT

timing detectors

e.g. CeBr

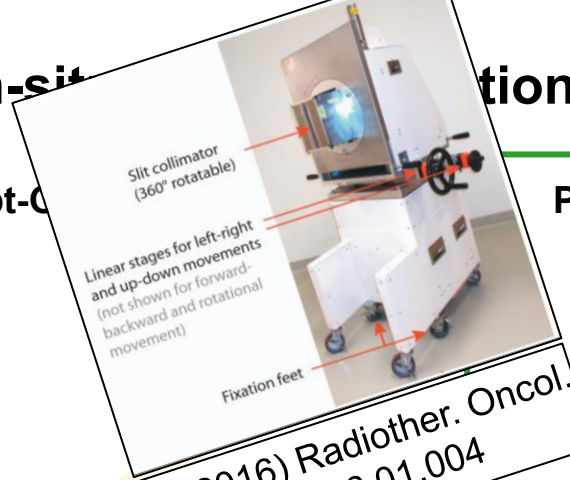
nozzle

prompt gamma rays (3-7 MeV)

cyclotron RF frequency ~100 MHz

time-of-flight

Prompt-G



e.g. Richter et al (2016) Radiother. Oncol. DOI: 10.1016/j.radonc.2016.01.004

nozzle

collimator

e.g. LaBr

spectroscopic dete

Prompt-Gamma Imaging PGI

nozzle

collimator

e.g. LYSO

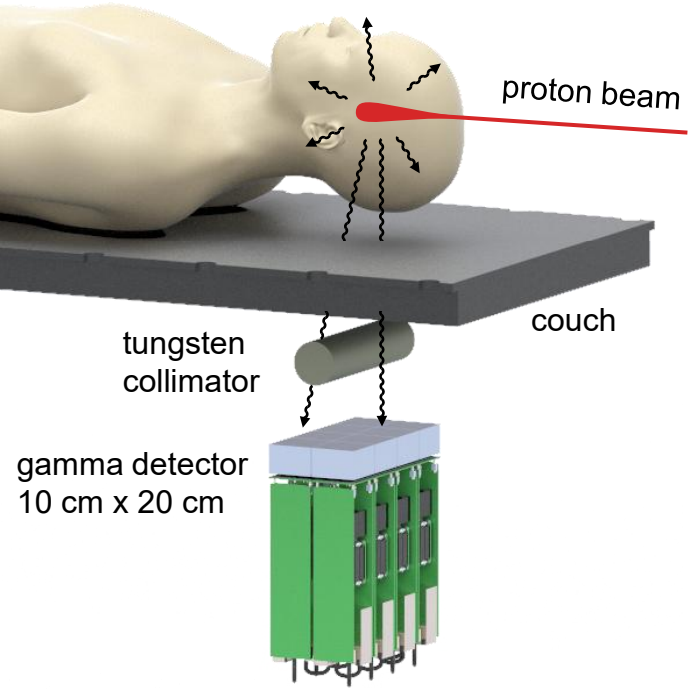
pixilated detector

REALPATH: new powerful and easy-to-use PGI camera for clinical application

Content

1. **Motivation: Prompt-gamma-based range verification in proton therapy**
2. **REALPATH detector and readout design**
3. **Characterization and tests**

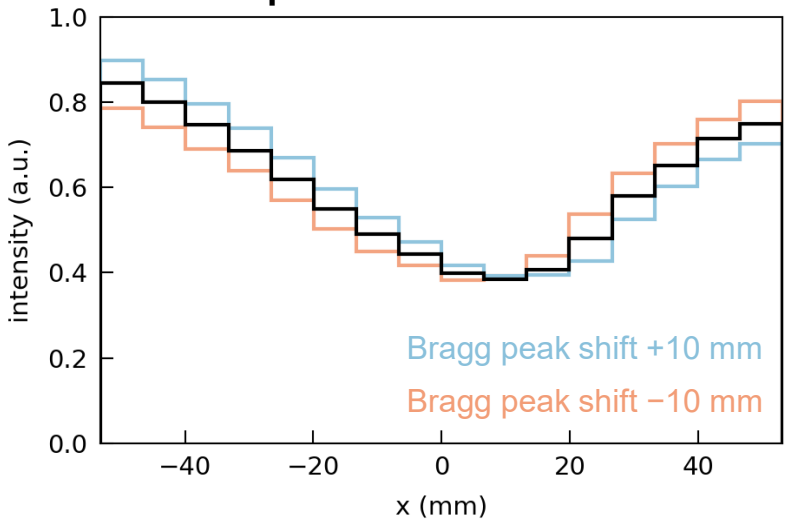
REALPATH camera setup



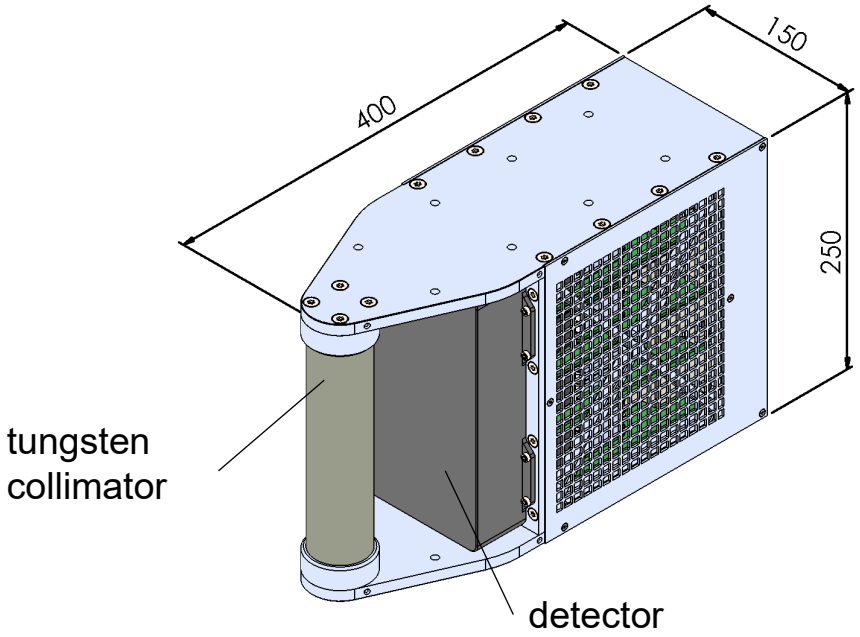
mechanically collimated gamma camera with
inverted collimator

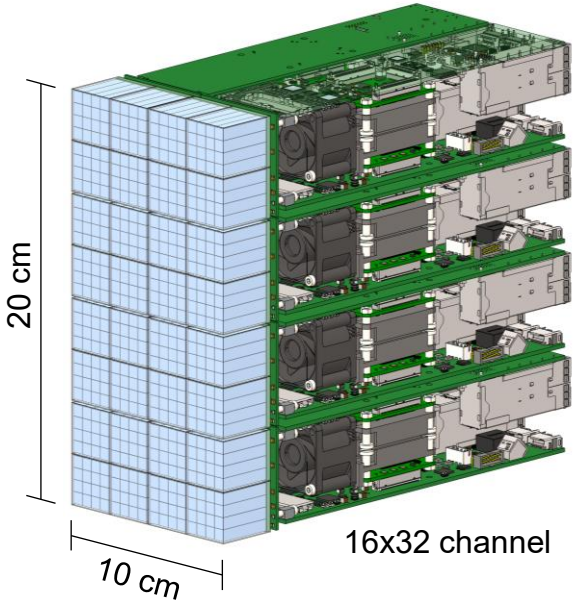
- tungsten bar casts shadow on detector
- moving Bragg peak → moving shadow

detected profile



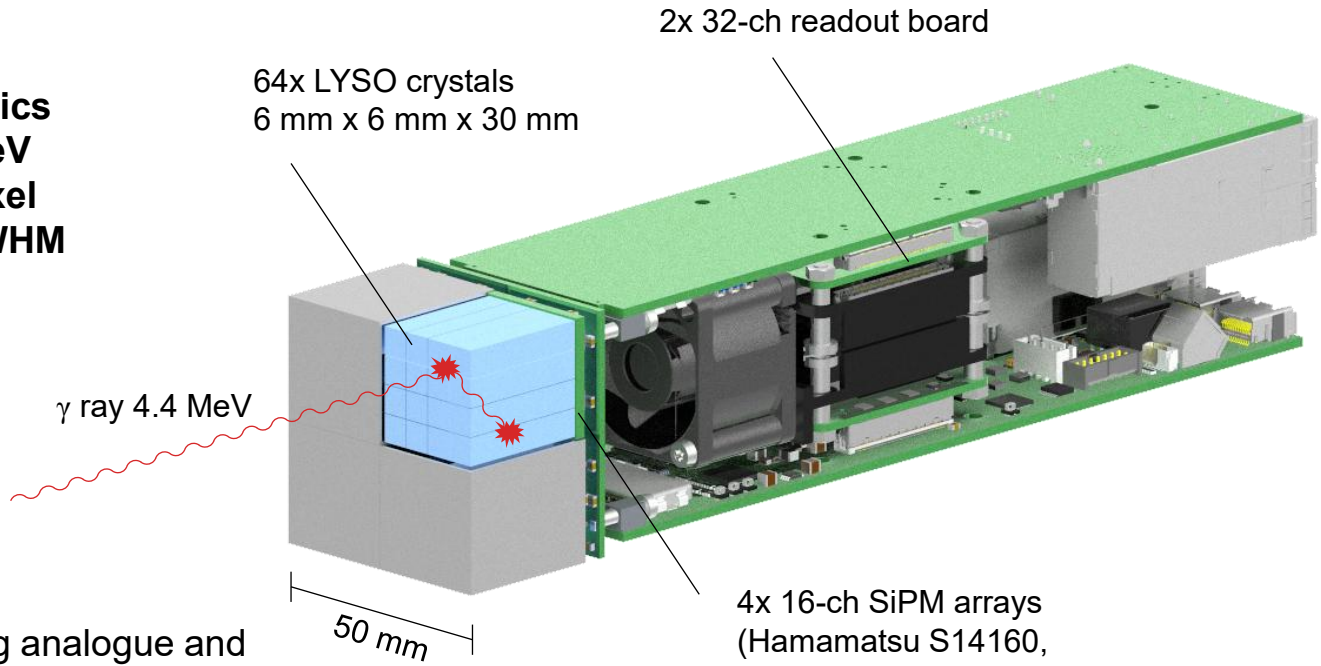
REALPATH camera design





Modular detector and readout platform (64 channel)

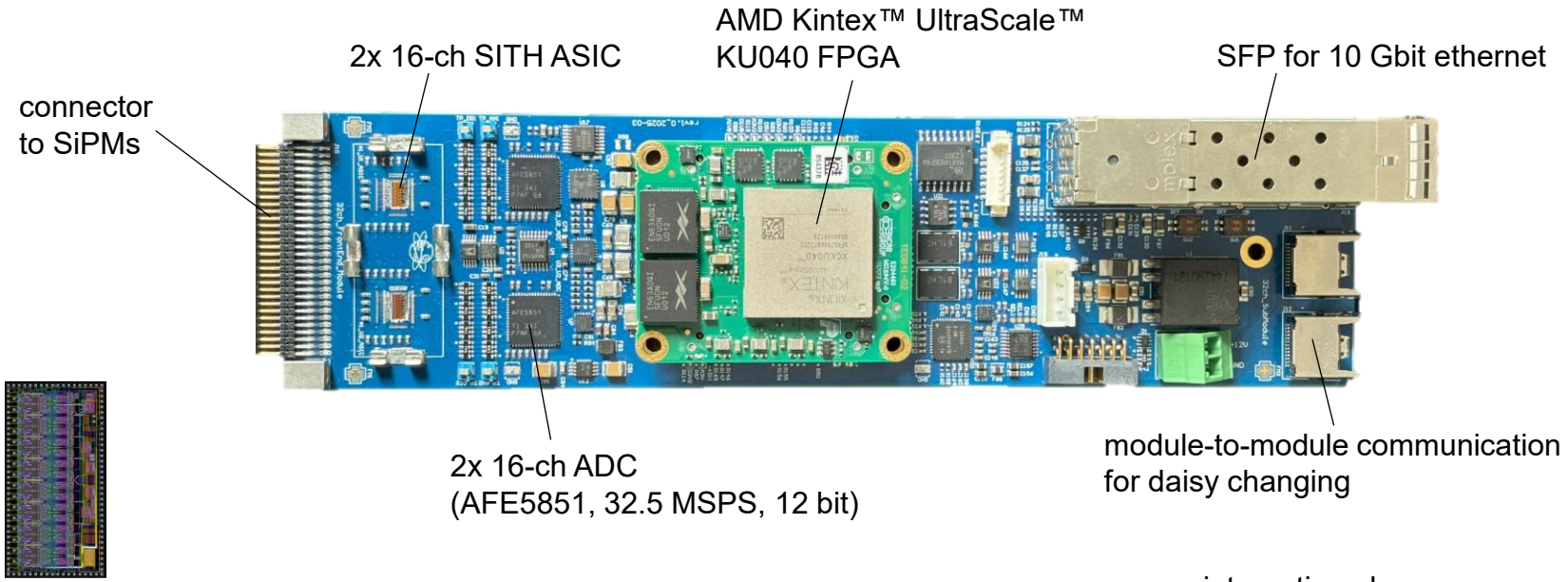
target channel characteristics
- energy range: **up to 10 MeV**
- count rate: **1 Mcps per pixel**
- time resolution: **250 ps FWHM**



features
- ✓ compact module including analogue and digital processing
- ✓ flexible arrangement with daisy-chained readout

32-channel readout board

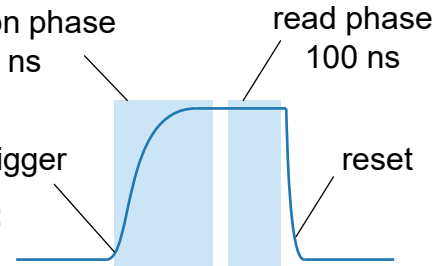
Riboldi et al (2025) J. Instrum.
DOI: 10.1088/1748-0221/20/09/p09037
D'Adda et al (2024) IEEE Trans. Nucl. Sci
DOI: 10.1109/tns.2024.3439598



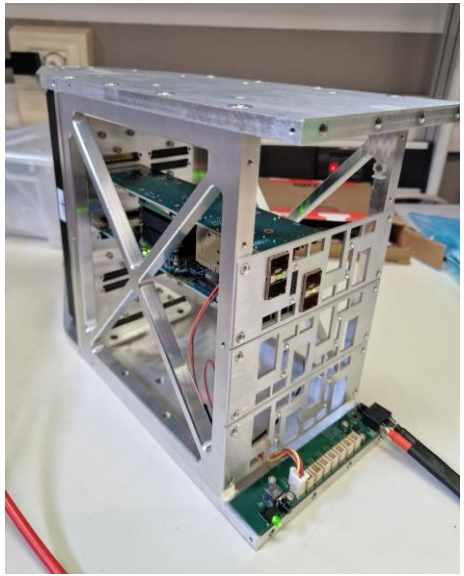
16-ch SITH ASIC: **S**pectroscopy **I**maging **T**iming **H**adrontherapy

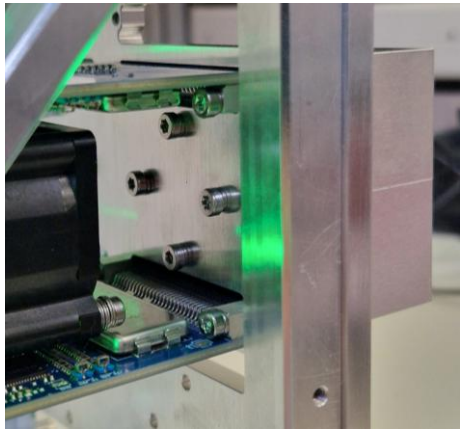
+ measure **energy** and **time-of-arrival** of each event
+ **large dynamic range** (up to 5 nC)
+ fast due to **low input impedance** (~10 Ohm)
+ **…**

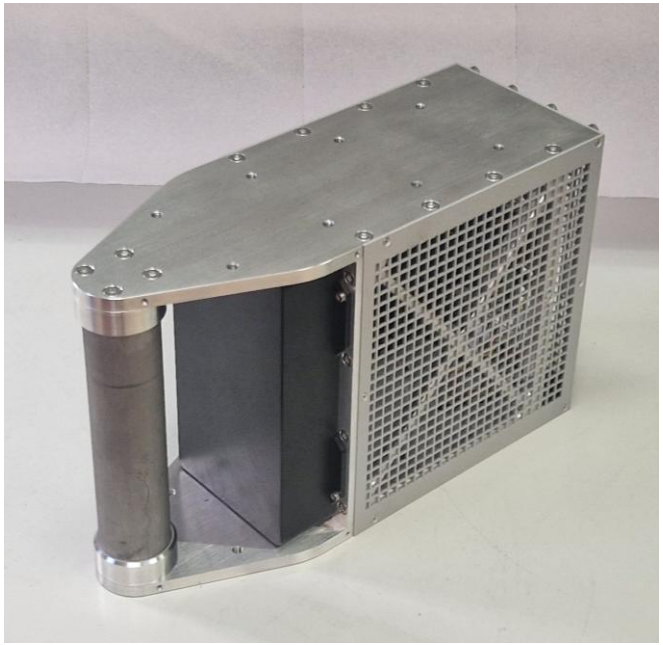
SITH ASIC output waveform:



Pictures







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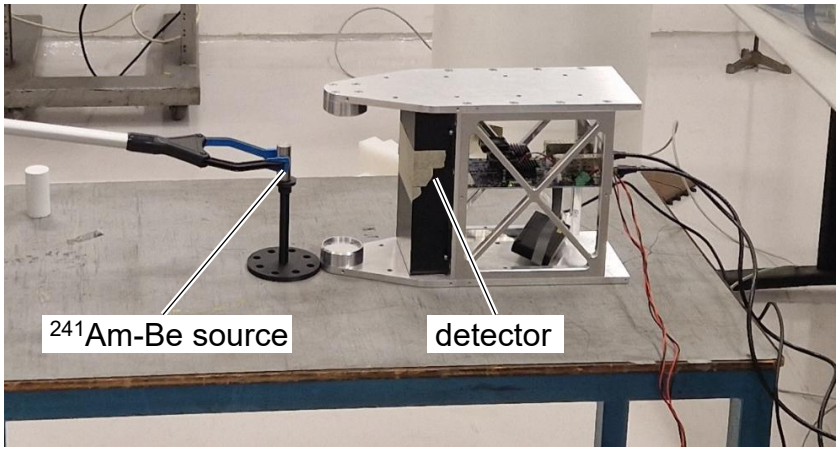
Energy calibration with ^{22}Na and ^{241}Am-Be



two calibration sources:

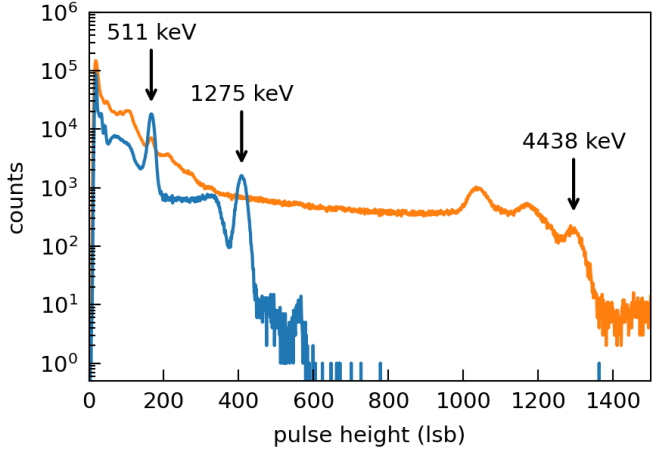
- ^{22}Na (511 keV and 1275 keV)
- ^{241}Am-Be (4438 keV)

$$^{9}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + n + \gamma$$

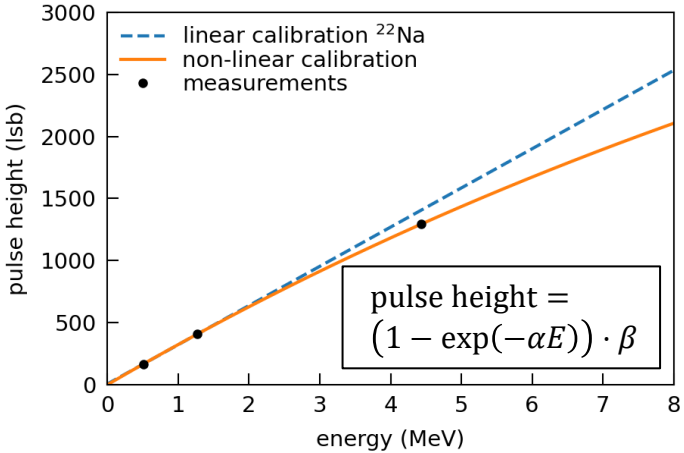
→ SiPM saturation effect causes non-linearity at high energies

non-linearity effect: ~8.8% lost at 4.4 MeV

measured spectra



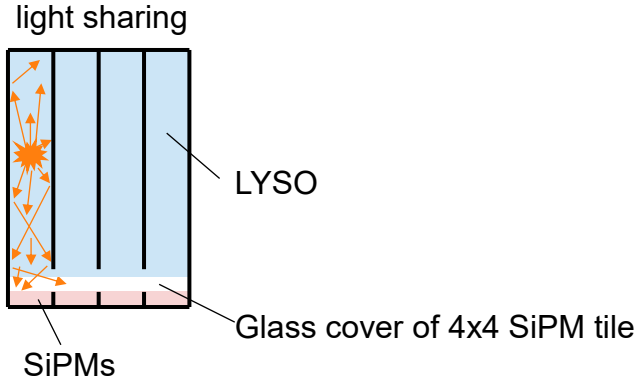
calibration



Spectrum reconstruction

two effects mitigate the spectral response due to pixelated design:

1. **light sharing:** leak of scintillation light to neighbouring channels



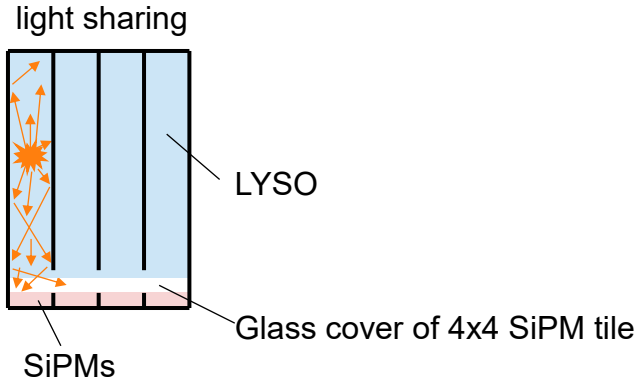
Spectrum reconstruction

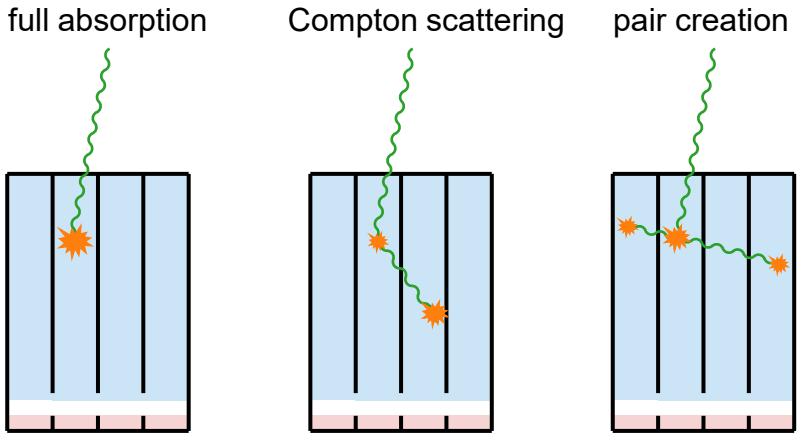
two effects mitigate the spectral response due to pixelated design:

1. **light sharing:** leak of scintillation light to neighbouring channels

2. **physical interactions**: energy deposition in more than one channel due to
   - Compton scattering events
   - positron annihilation of pair creation events

approach: use time coincidence for identification and correction

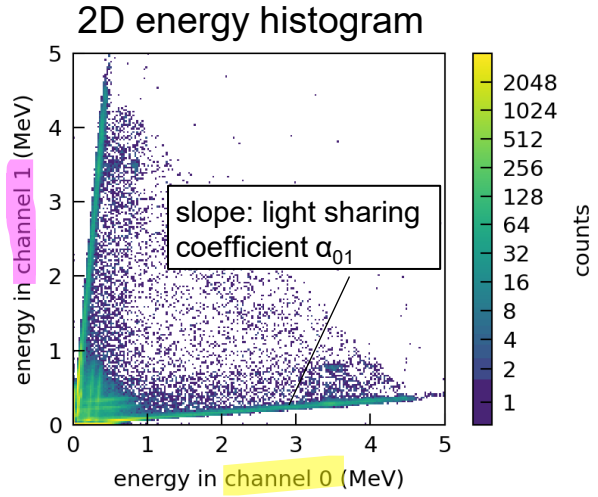




Light sharing correction

pixelmap

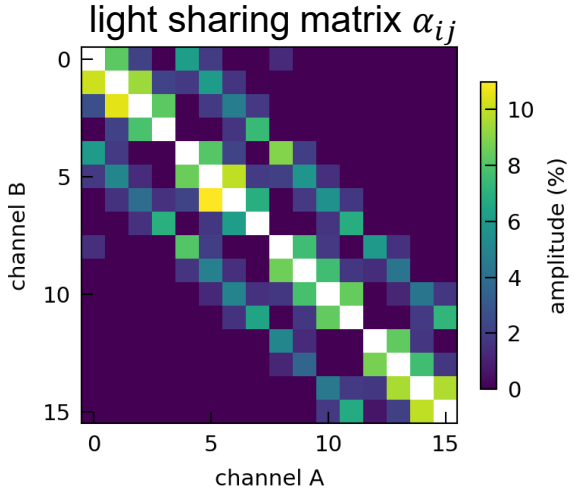
3	7	11	15
2	6	10	14
1	5	9	13
0	4	8	12



- characterized by light sharing coefficient of each pixel combination α_{ij}

$$E_{\text{measured } j} = \alpha_{ij} \cdot E_{\text{true } i}$$

- light sharing coefficients α_{ij} determined by measurement
  - ✓ α_{ij} up to 11%
  - ✓ α_{ij} shows physical neighbors

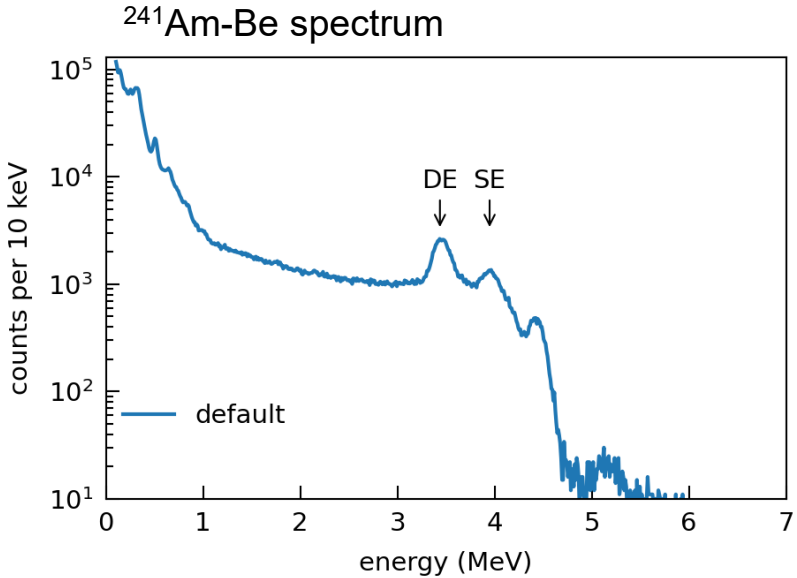


Event reconstruction

example event

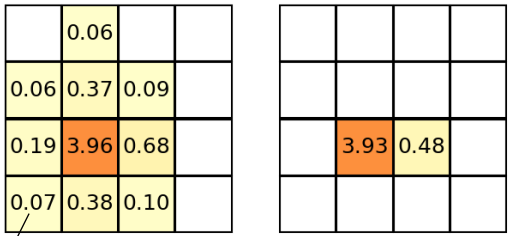
	0.06		
0.06	0.37	0.09	
0.19	3.96	0.68	
0.07	0.38	0.10	

energy
in MeV

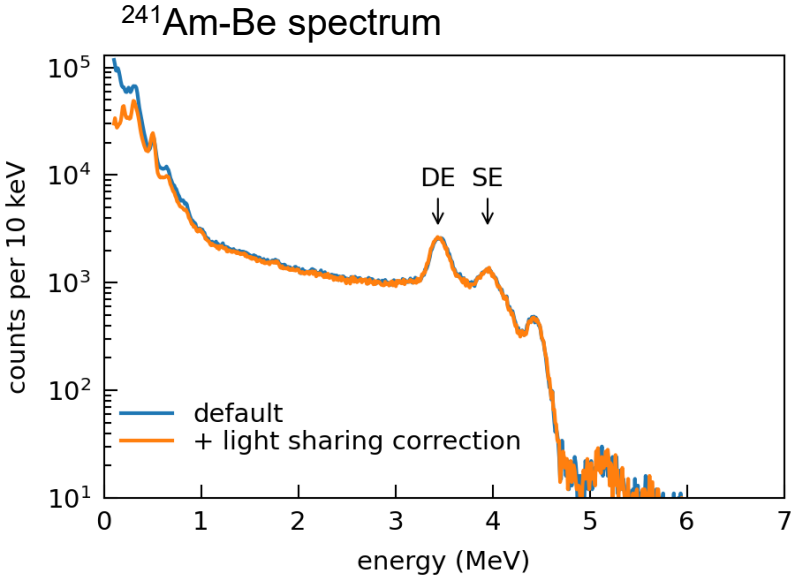


Event reconstruction

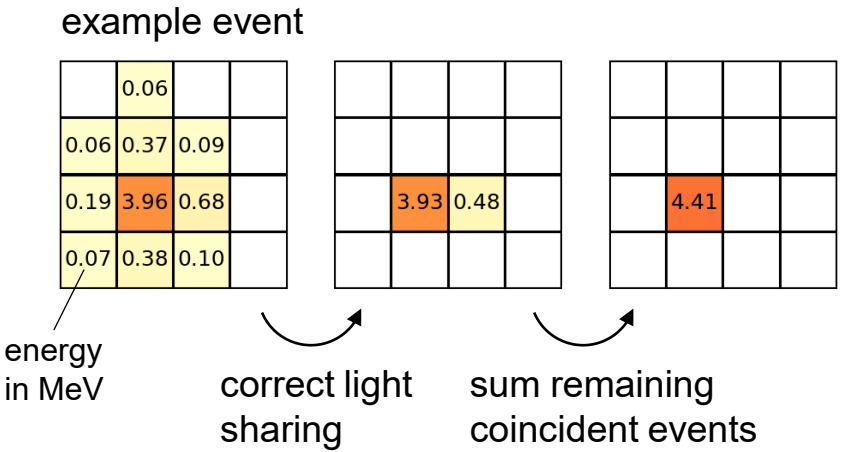
example event

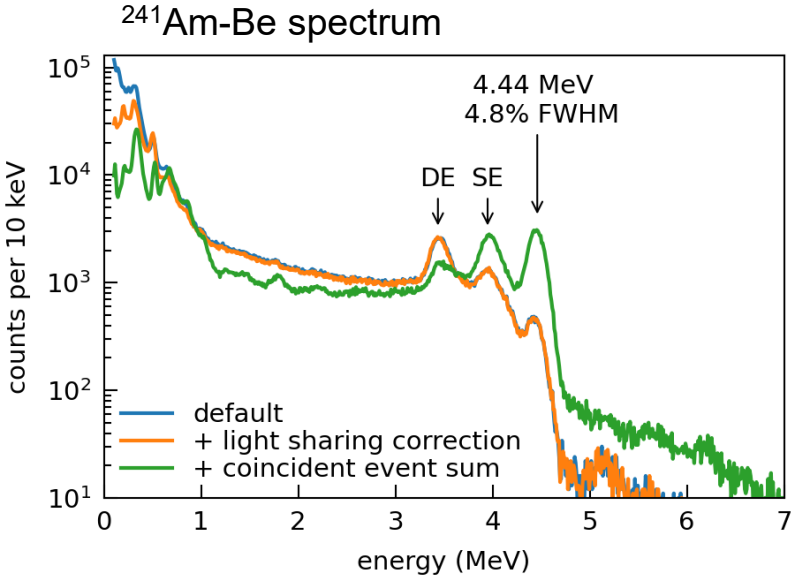


$$E_{\text{true } i} = \alpha_{ij}^{-1} \cdot E_{\text{measured } j}$$



Event reconstruction





- ✓ coincident event sum recovers full energy peak
- ✓ 5% FWHM at 4.4 MeV

High rate test: ^{137}Cs

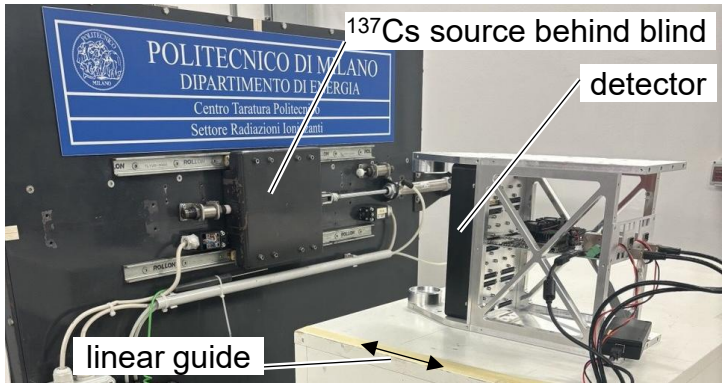
- scan rate by varying distance:
  up to 2 Mcps input rate **per pixel**

✓stable resolution:

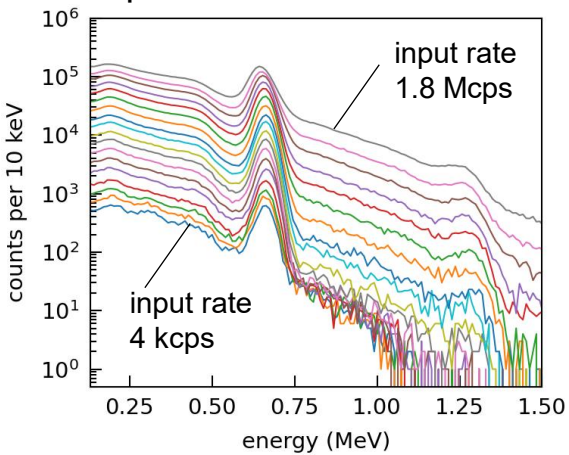
up to >100 kcps per pixel: 8.5% FWHM @ 662 keV
at 2 Mcps input count rate: 12% FWHM @ 662 keV

✓dead time per event: 417 ns

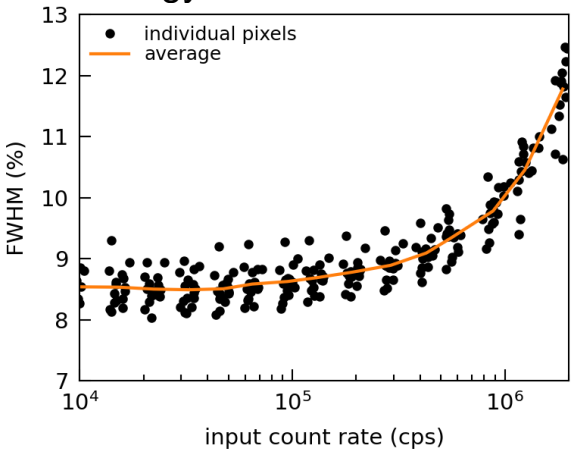
test stand at department of energy of Politecnico di Milano:



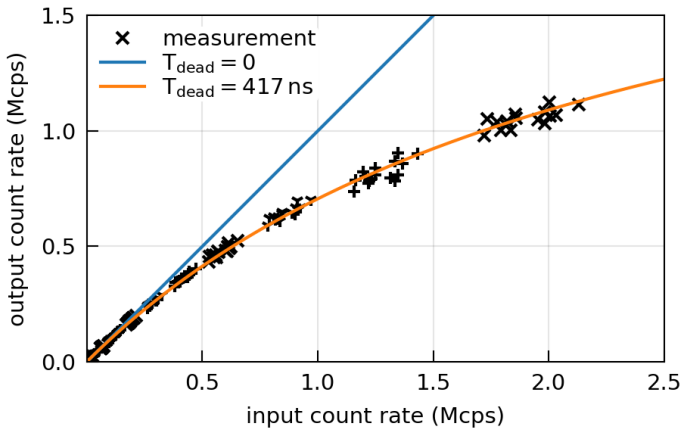
spectra



energy resolution

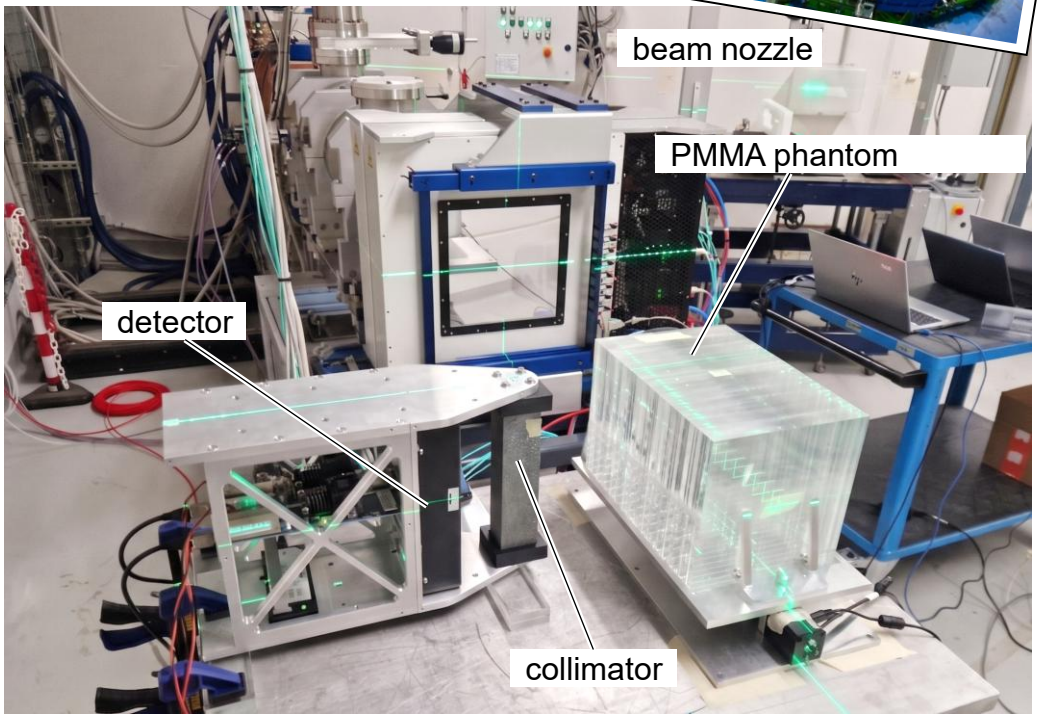


dead time



Tests at CNAO

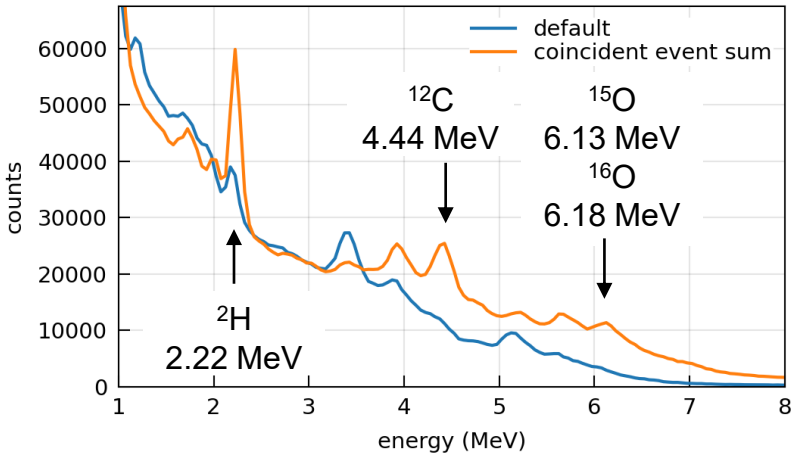
Centro Nazionale di Adroterapia Oncologica, Pavia, Italy



setup

- 158 MeV proton beam
- homogeneous PMMA phantom
- four out of 32 pixel rows operated

spectrum

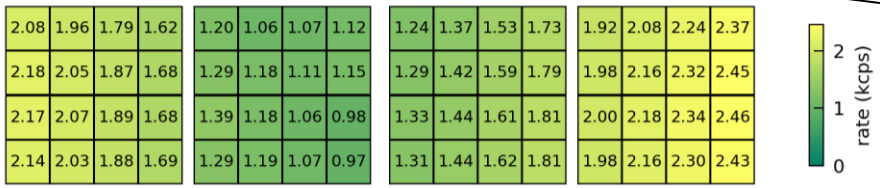


✓ event reconstruction improves spectrum quality

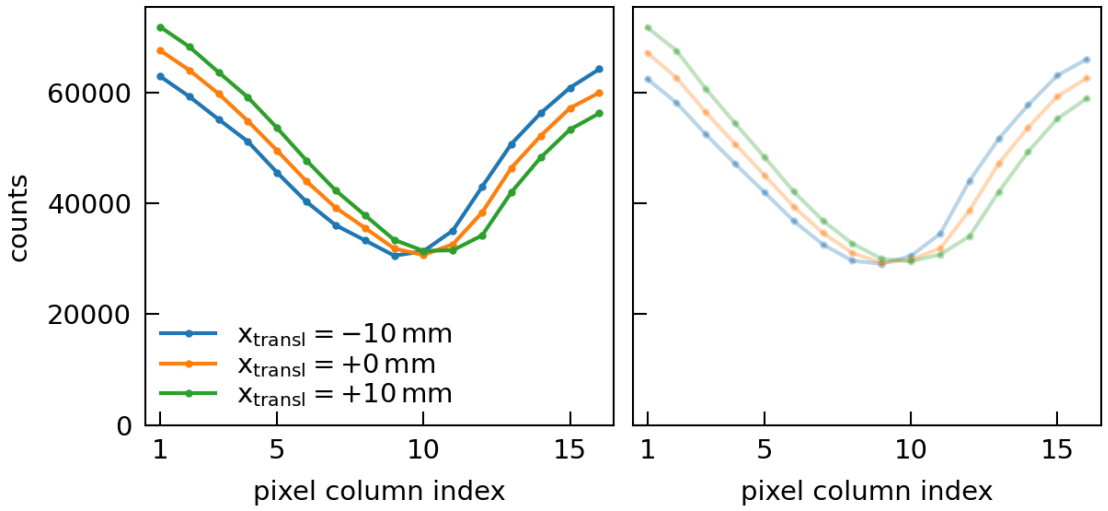
Tests at CNAO

measured “image”

energy window: 1.5 MeV to 7 MeV

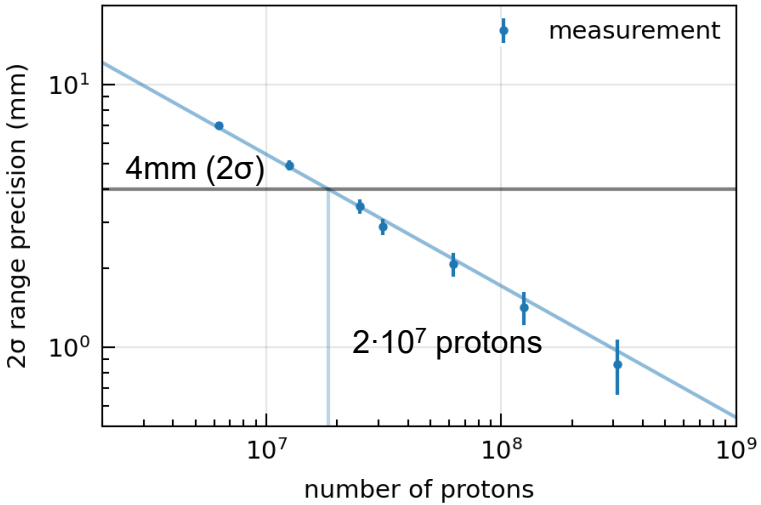


measured profiles



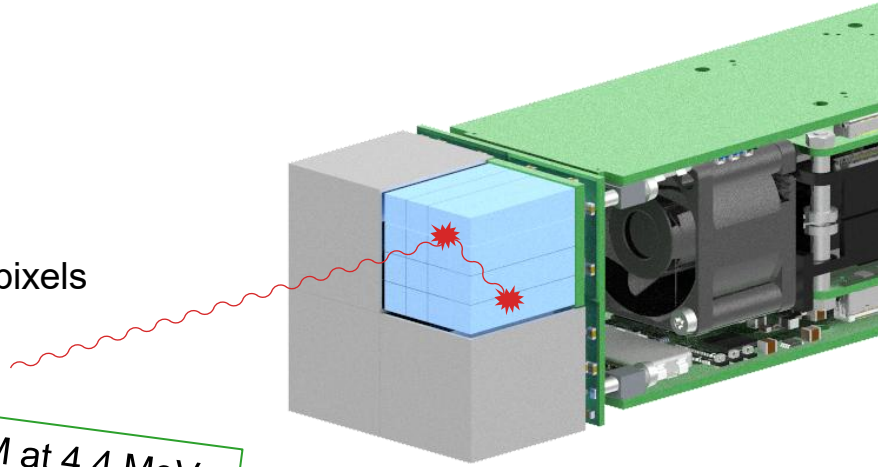
simulated profile

statistical precision of range measurement



- ✓ good agreement between measurement and simulation
- ✓ excellent statistical range precision: **4 mm (2σ) with $2{\cdot}10^7$ protons** (scaled to full detector)

Conclusions



REALPATH prompt gamma camera

- range verification in proton therapy
- new modular detector and readout platform with 64 pixels

experimental characterization

resolution 5% FWHM at 4.4 MeV

- ✓ spectroscopic performance improved by event reconstruction
- ✓ high-rate performance with low dead time

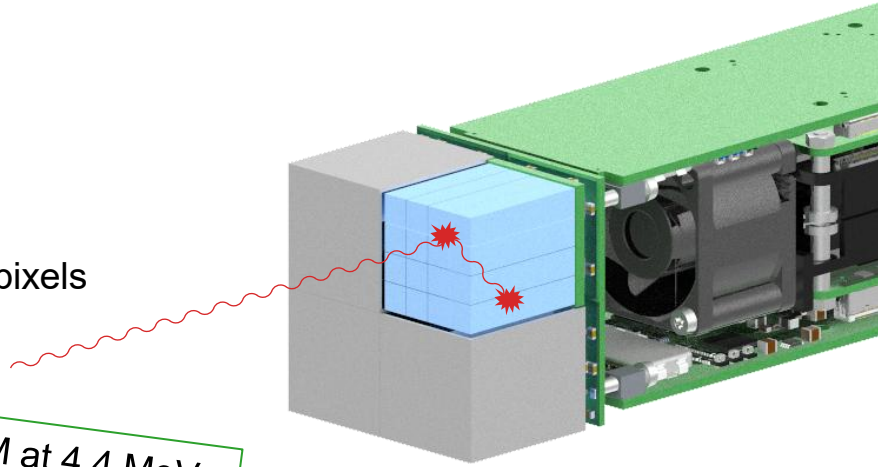
up to 1 Mcps per pixel

- ✓ successful tests of prompt gamma imaging at CNAO proton therapy center

outlook

- experimental tests at **cyclotron accelerator** and with **FLASH** therapy mode
- explore combination with **timing** (PGT) and **spectroscopy** (PGS) information
- test application also during **Carbon ion** therapy

Conclusions



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Thank you for your attention!