A Gamma-ray Detection Module for BNCT Dose Measurements

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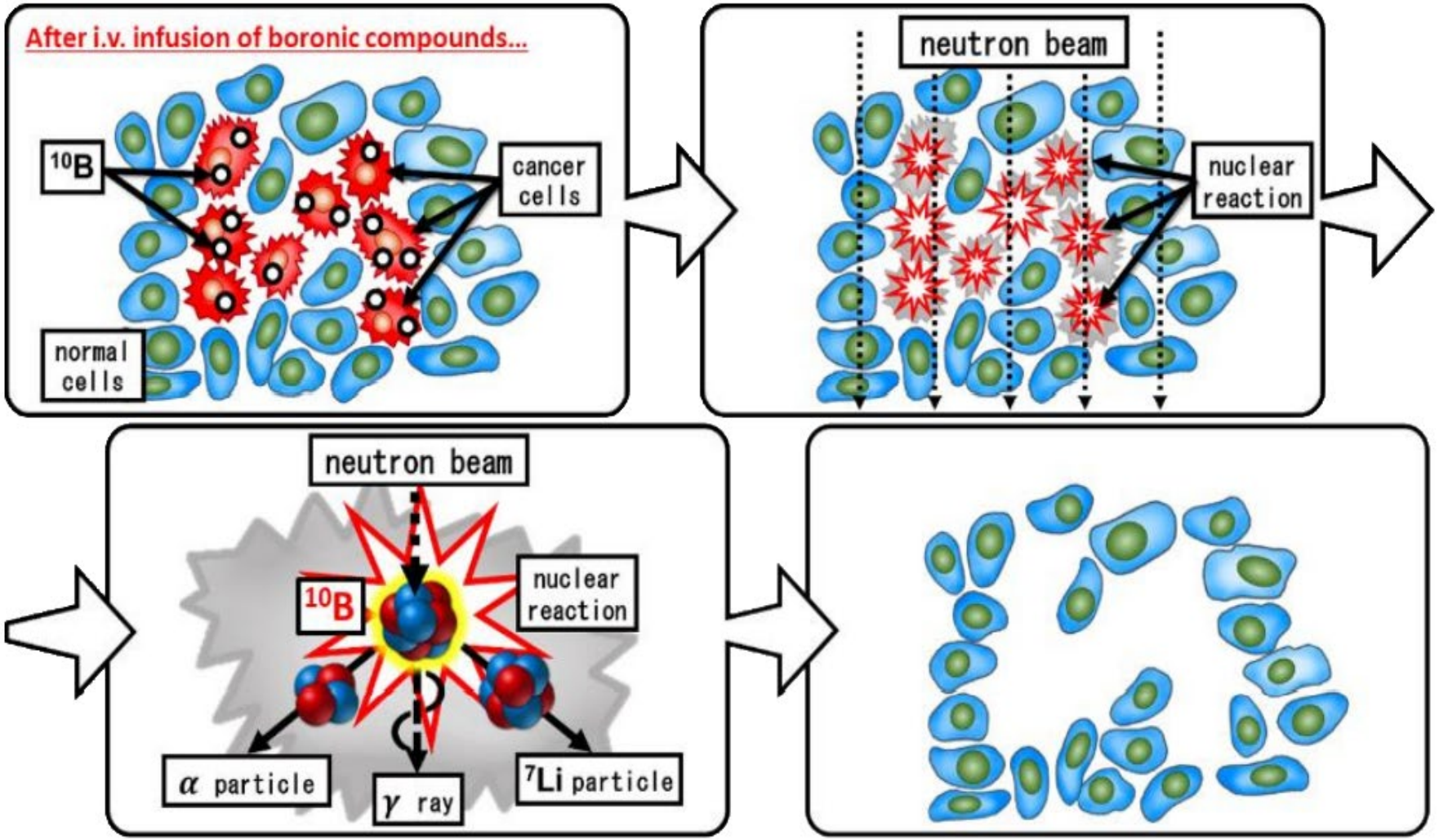
Outline

- Boron Neutron Capture Therapy and dose estimation (with γ-rays)
- The BENEDICTE detector and electronics
- Boron concentration measurements
- Preliminary tests of position sensitivity
- Future work

Boron Neutron Capture Therapy (BNCT)



- Boron compounds are selectively absorbed by cancer cells.
- Tissues are irradiated by a neutron beam.
- Neutron capture by ^{10}B generates high-LET secondary particles, destroying cancer cells and sparing normal cells.
- Research approach for recurrent and metastasized tumours.

Courtesy: S.Rossi (CNAO, Italy)

Accelerator-based neutron sources

p-Li reaction
Proton energy 2.5 MeV
Intensity 10-15 mA

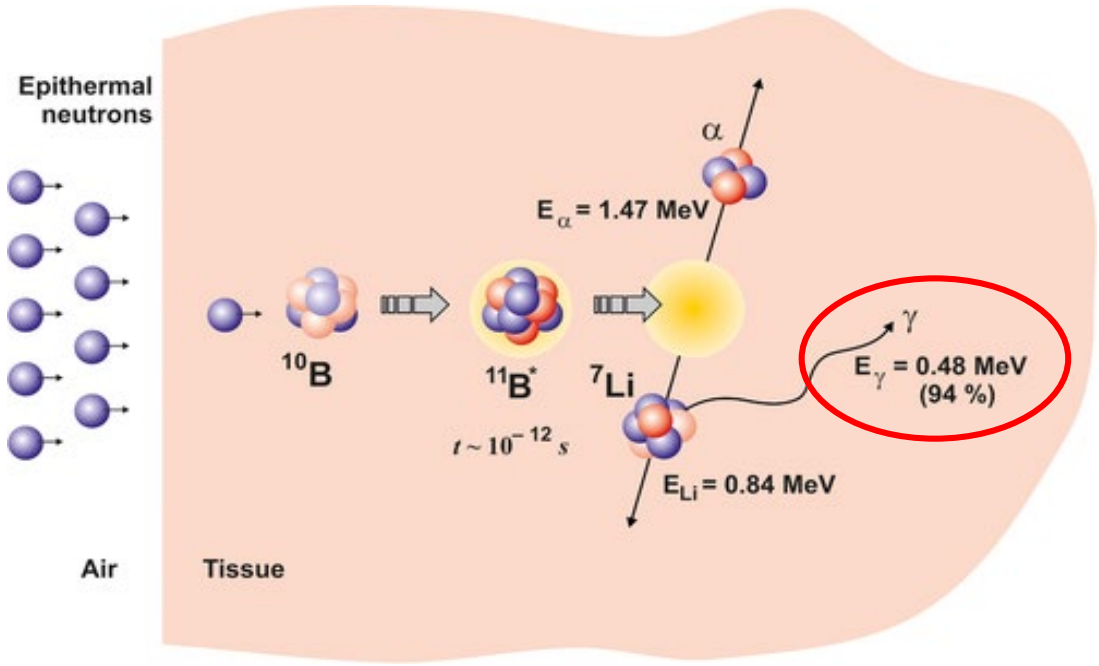
alpha beam™

tae

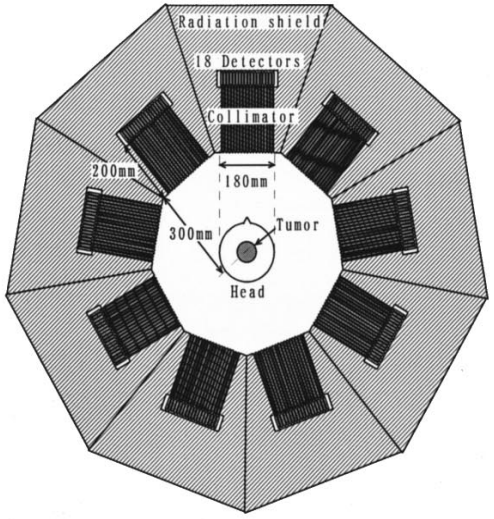
- BNCT previously based on nuclear reactors.
- Accelerator-based neutron sources available (Japan and Finland).
- Collaboration agreement between CNAO and TLS signed in 2020, installation >2023.

Courtesy: S.Rossi (CNAO, Italy)

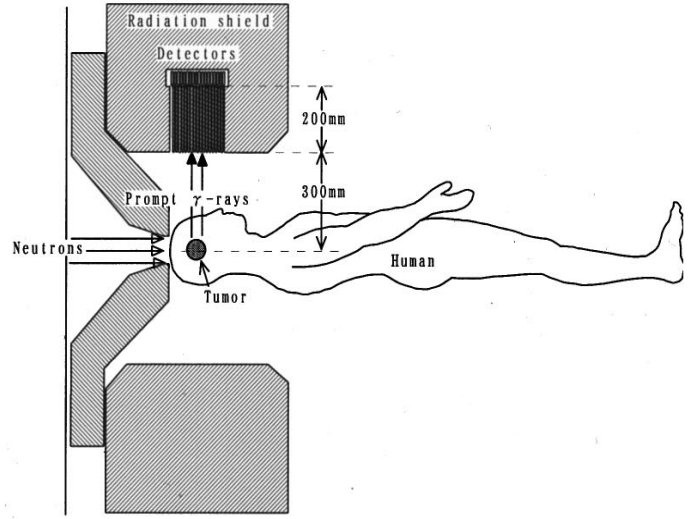
Dose measurement by Imaging boron-captures γ-ray emission



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



Frontal-view



Sidal-view

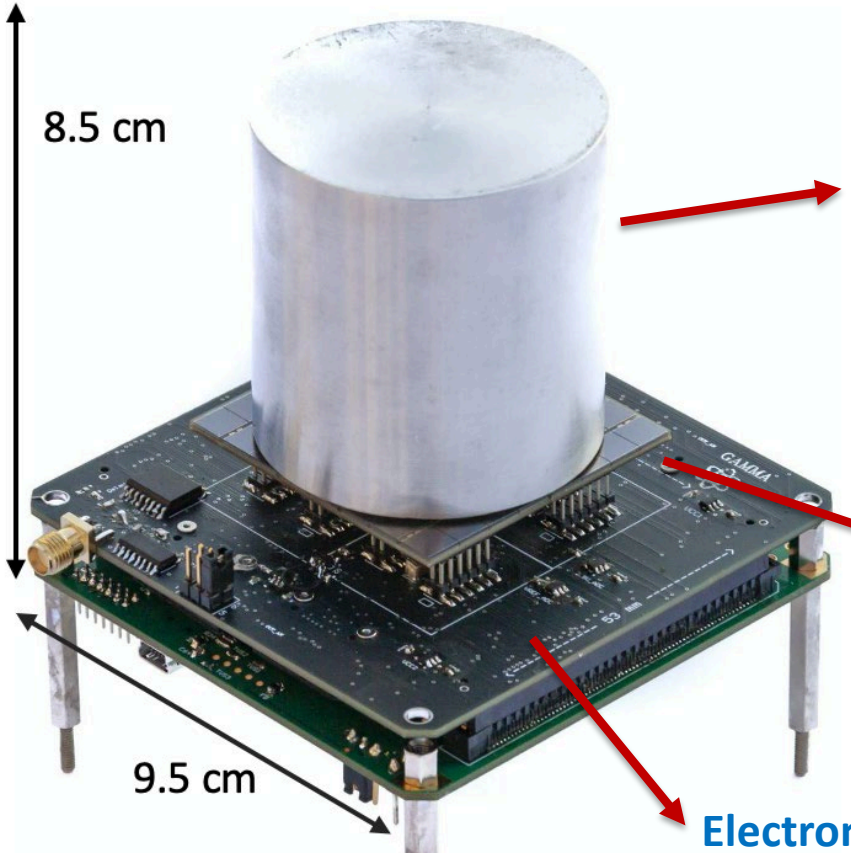
T. Kobayashi et al. Med Phys. 2000.

Main detector specifications:

- Good efficiency and energy resolution at 478keV (to separate it from 511keV annihilation photons)
- Spatial resolution: 5-10mm (limited by the collimator)
- Possibly, extended efficiency up to 2.2MeV (H-capture) for neutron flux estimation

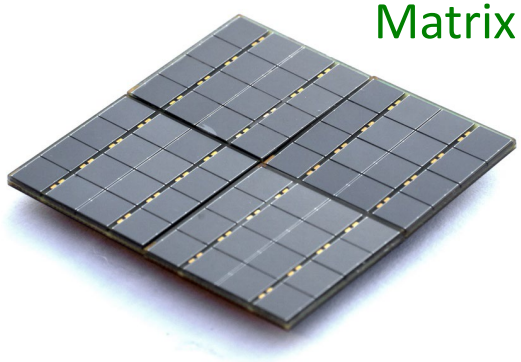
The BENEDICTE detector

BENEdiCTE (Boron Enhanced NEutron CapTurE) is a gamma-ray detection module, based on a **$LaBr_3$:Ce** scintillator crystal optically coupled with a matrix of 8x8 **Silicon Photomultipliers**. The SiPMs are read out by 4 custom 16-channels **GAMMA ASICs**.



Scintillator crystal	Light yield (ph/keV)	Wavelength of emission (nm)	Decay time (ns)	Energy resolution @662 keV
$LaBr_3$:Ce+Sr co-doped	73	385	25	< 3

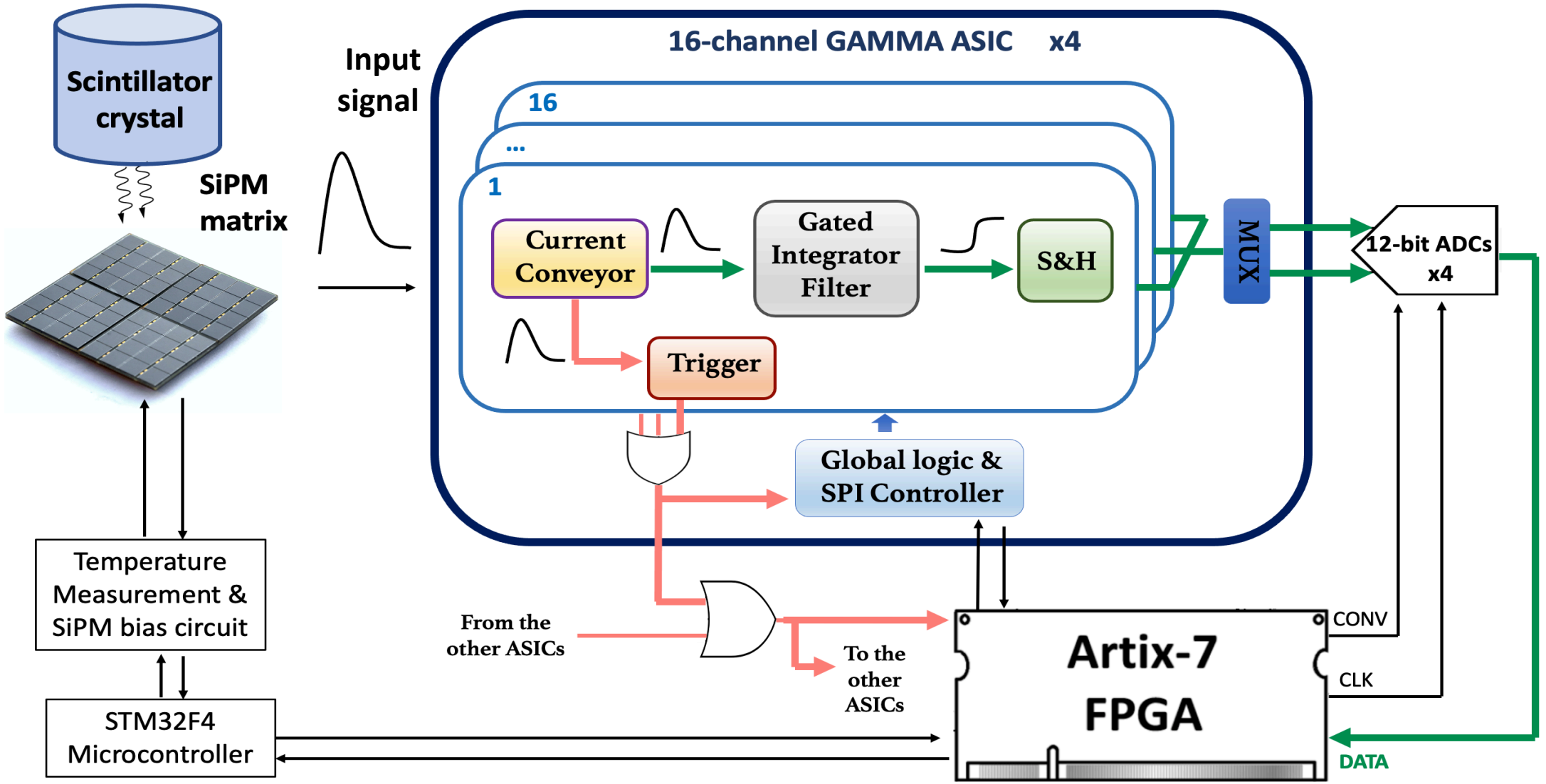
Matrix of **64 FBK NUV-HD SiPM**



- 6mmx6mm pixel size
- 30μmx30μm cell size
- > 50% PDE at 385 nm

Electronics (ASICs+FPGA)

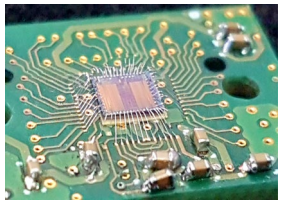
The BENEDICTE readout electronics

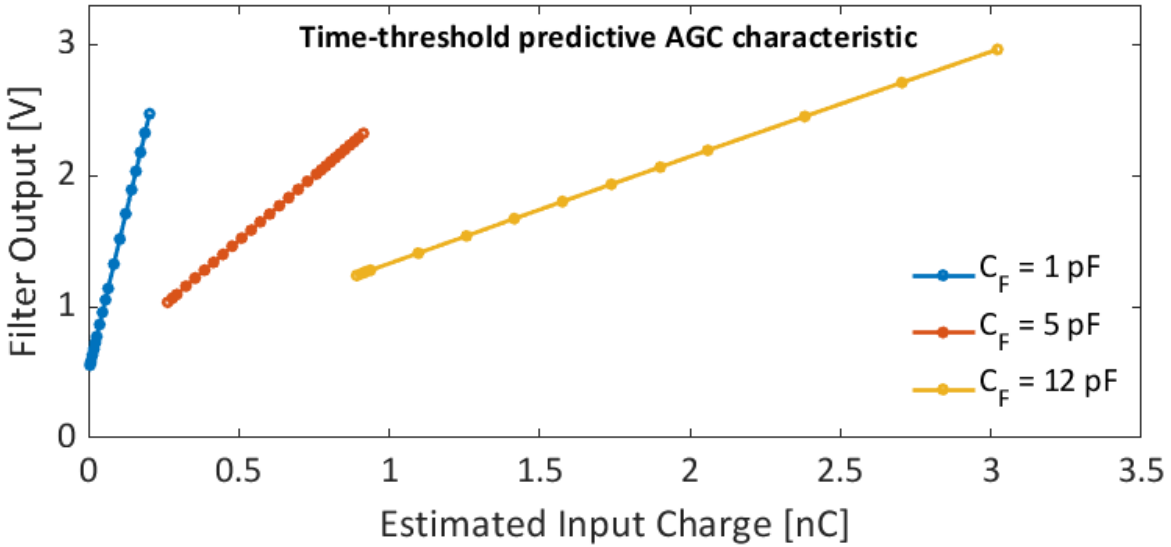


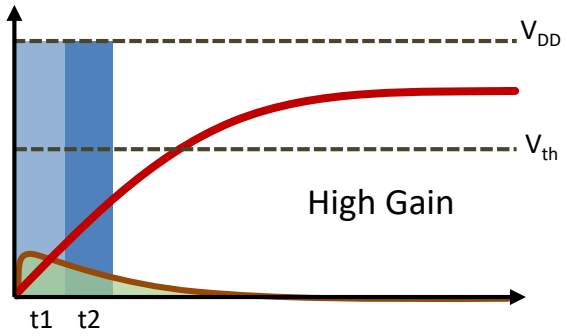
The GAMMA ASIC

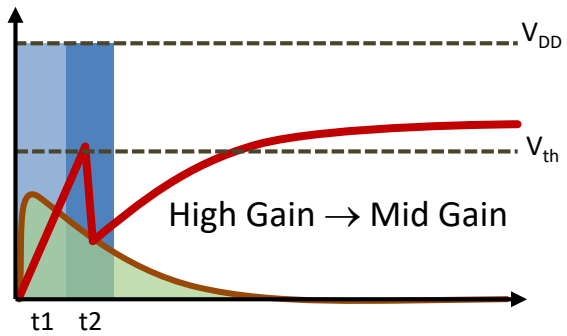
1. Compatible with large SiPMs (~tens fF); 2. Gain modulation allows for **84dB** Dynamic Range on each channel

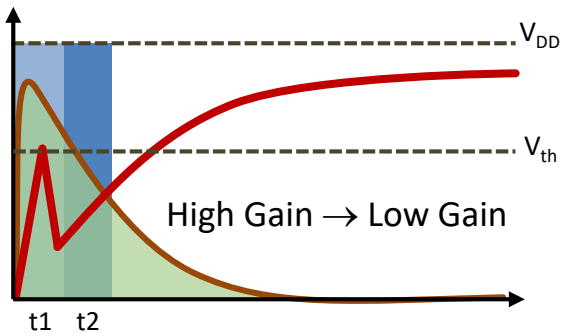
GAIN
AMPLITUDE
MODULATION
MULTICHANNEL
ASIC





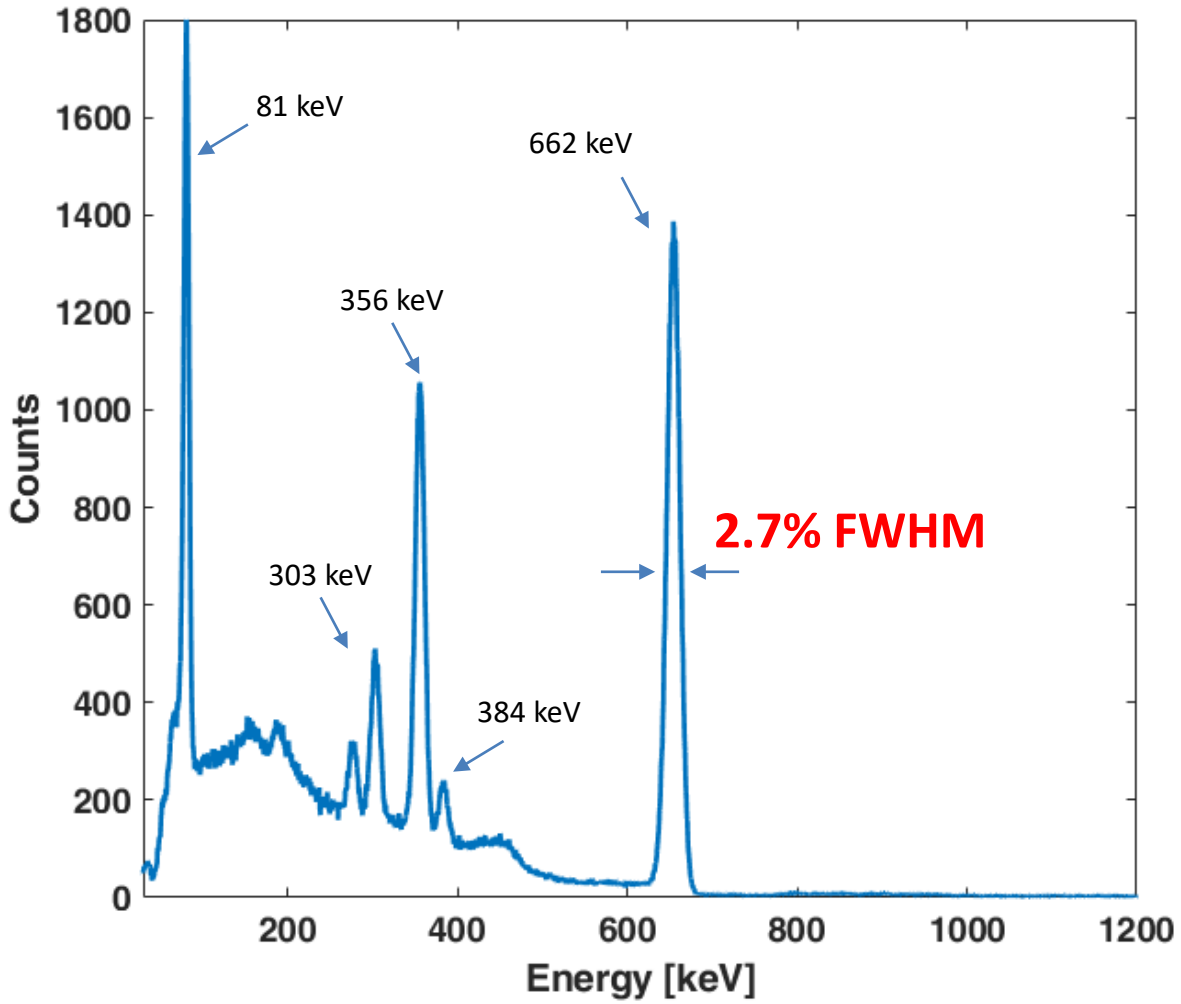




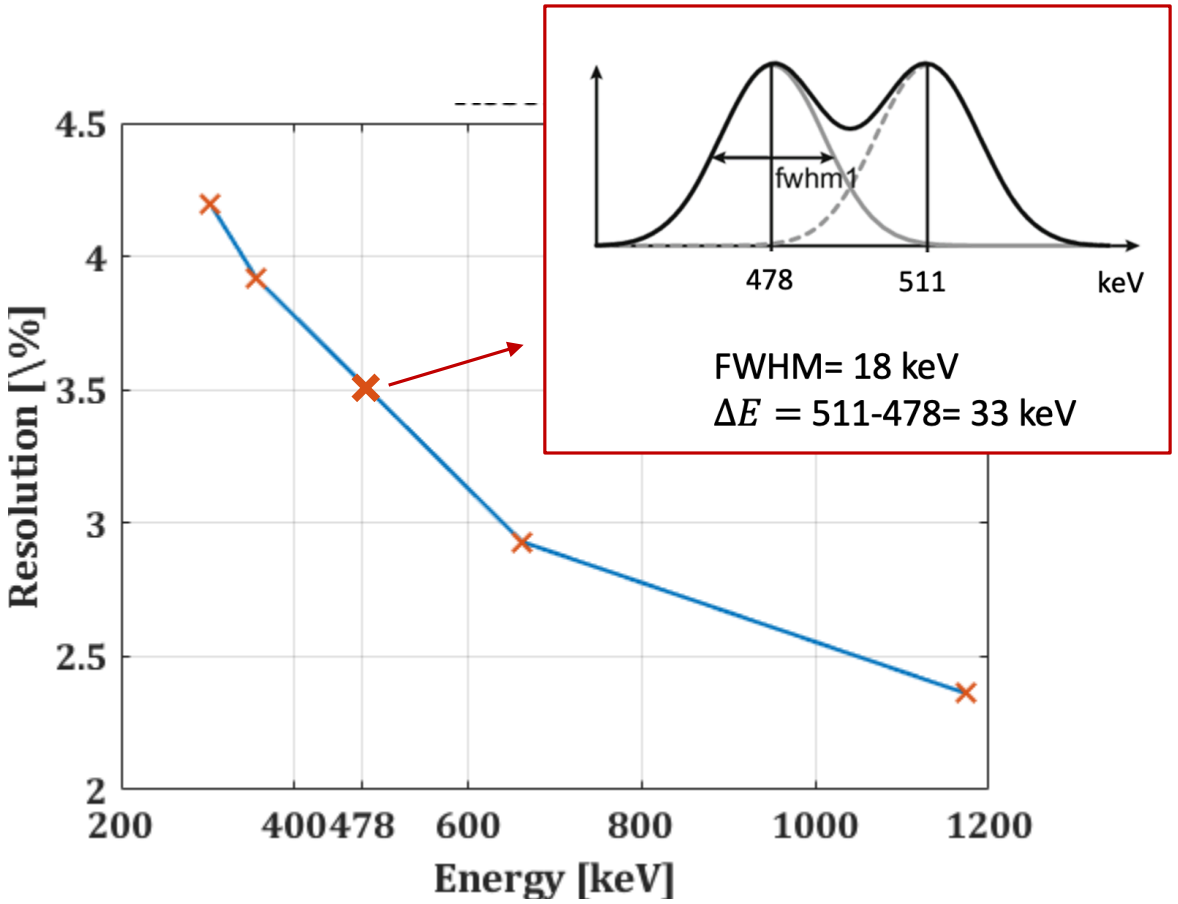


Input charge
Output voltage

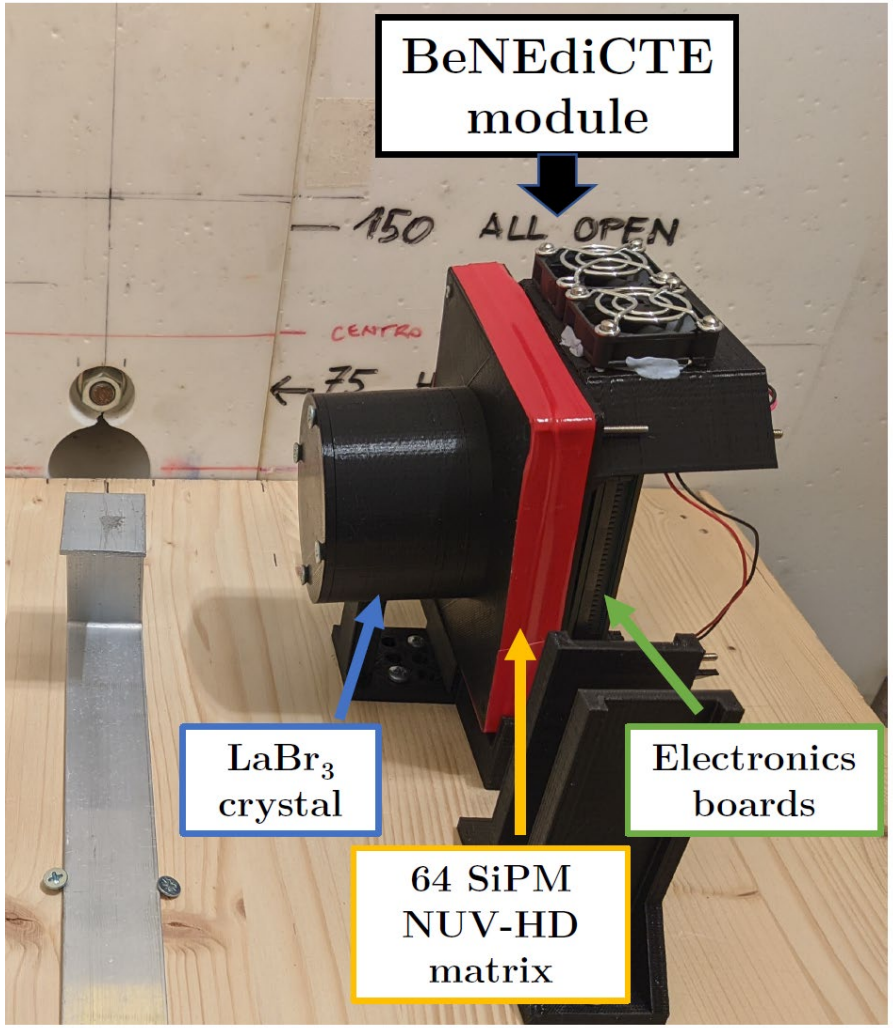
Energy resolution



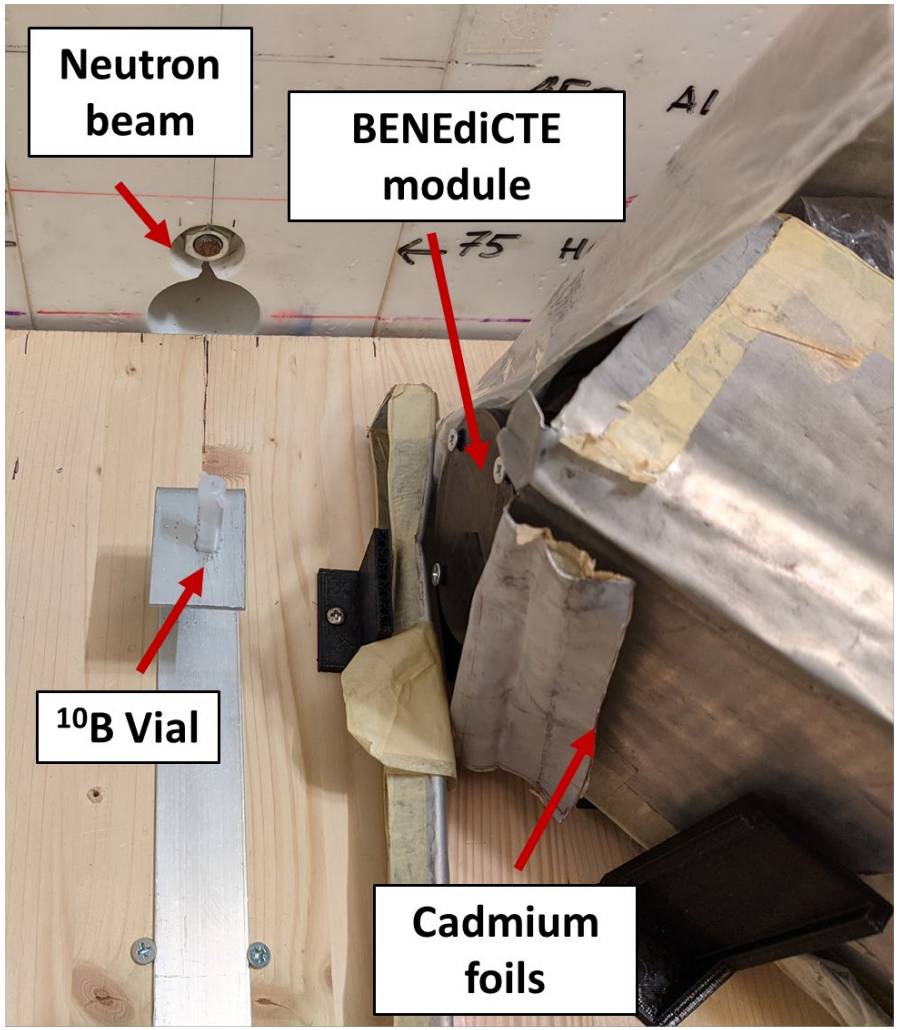
478keV vs. 511keV separation challenge:



Measurements at TRIGA MARK II nuclear reactor in Pavia (Italy)

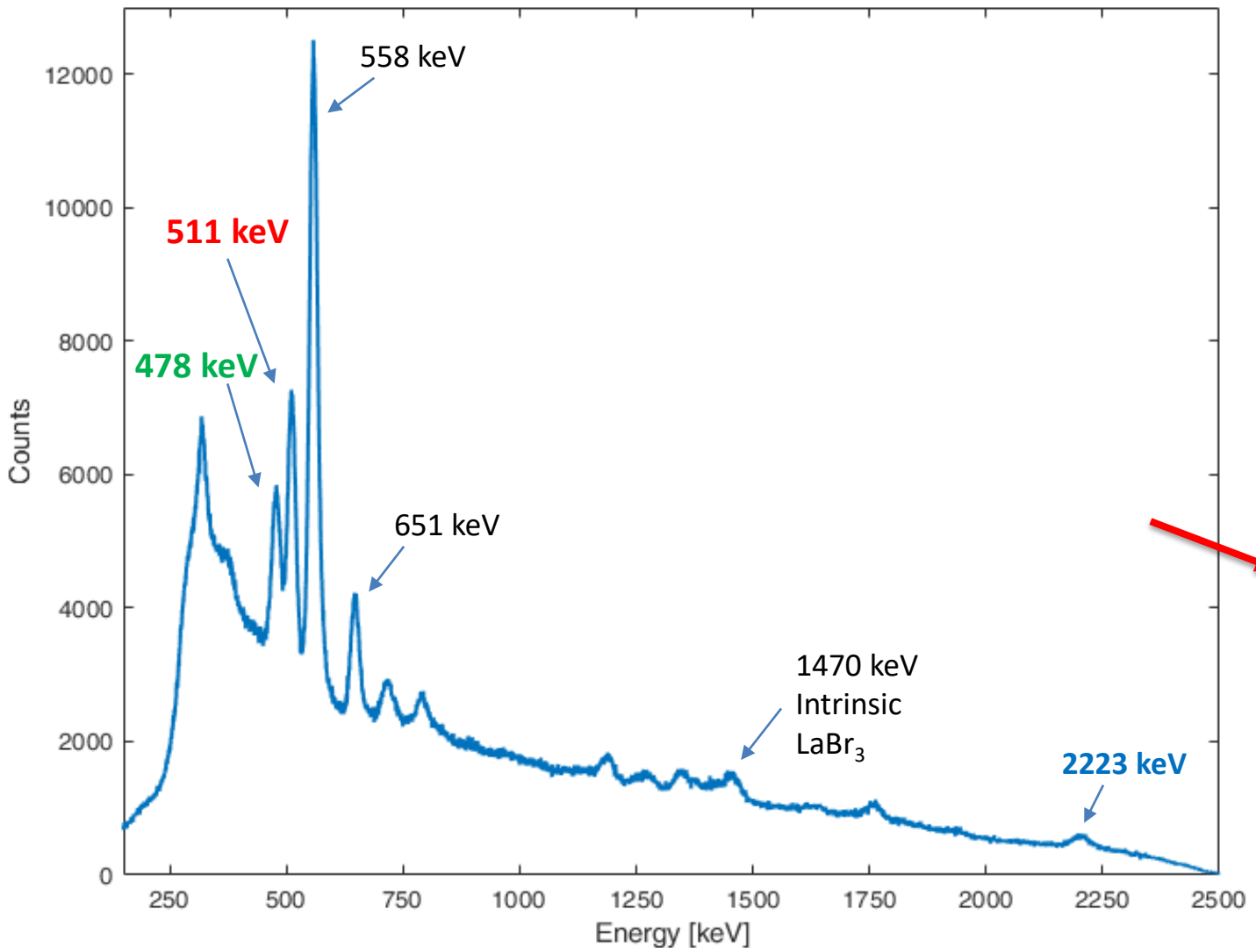


Unshielded



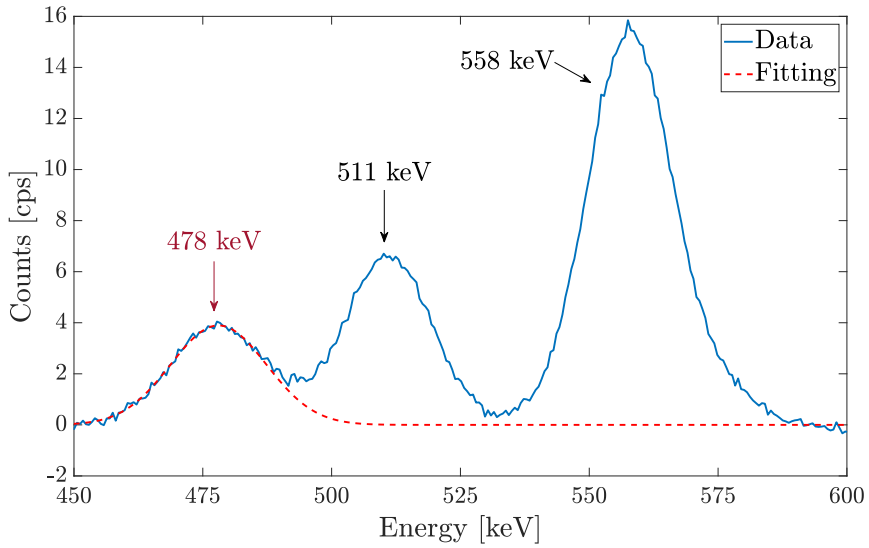
Shielded

Spectroscopy measurements

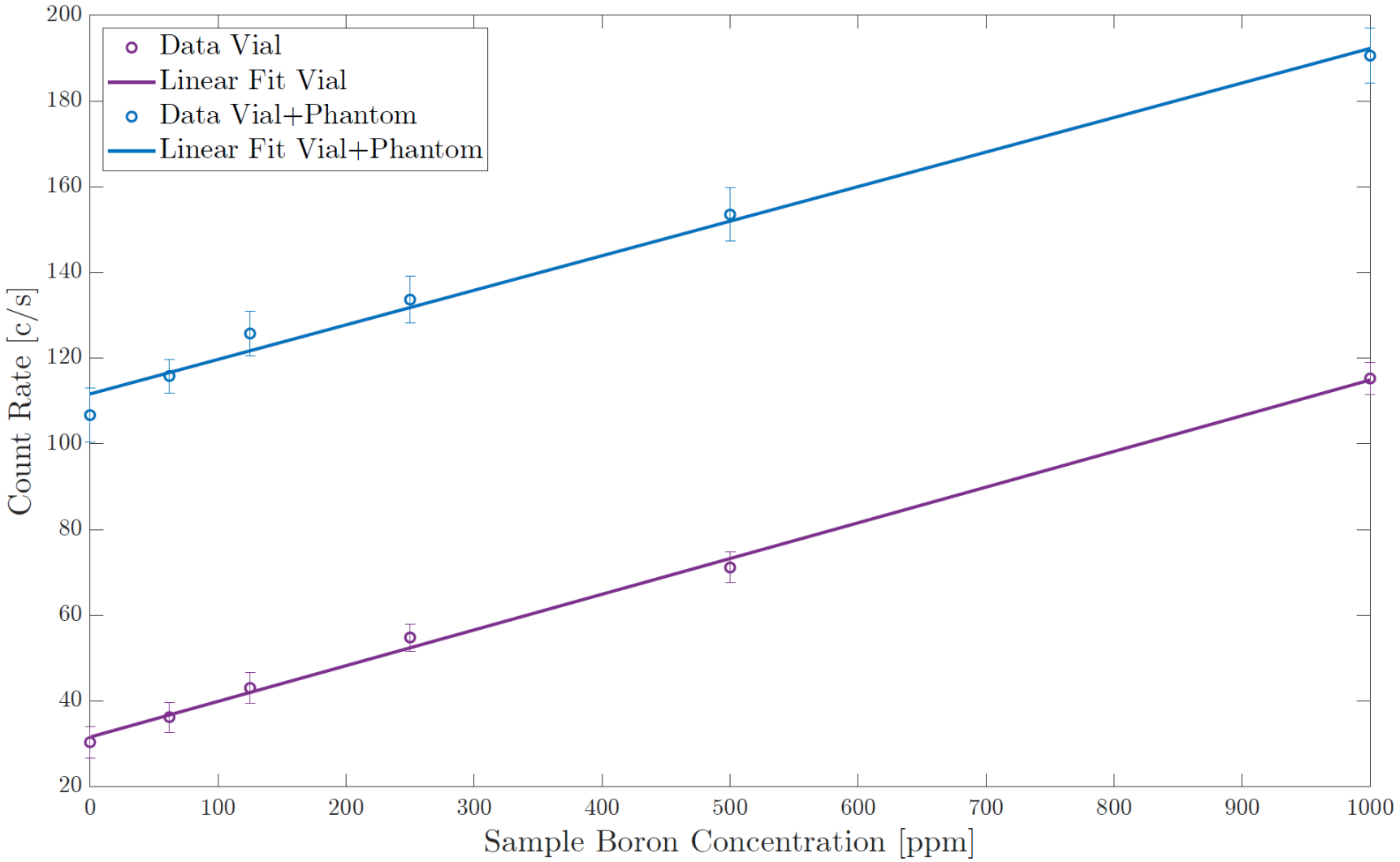


Peak's origin	Energy [keV]
Boron neutron capture	478
Annihilation photons	511
Cadmium neutron capture	558
Cadmium neutron capture	651
Hydrogen neutron capture*	2223

*potentially useful to estimate neutron flux

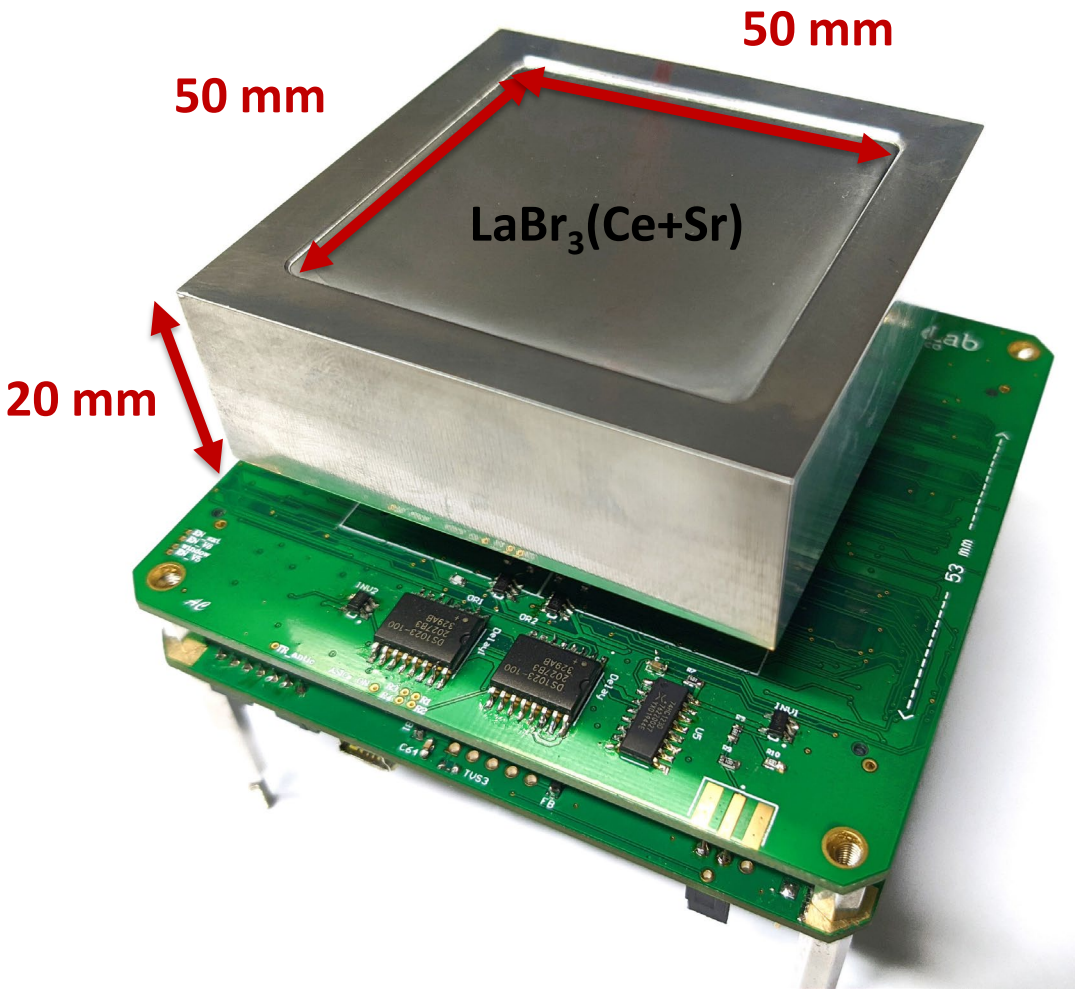


Measurements with ^{10}B at different concentrations

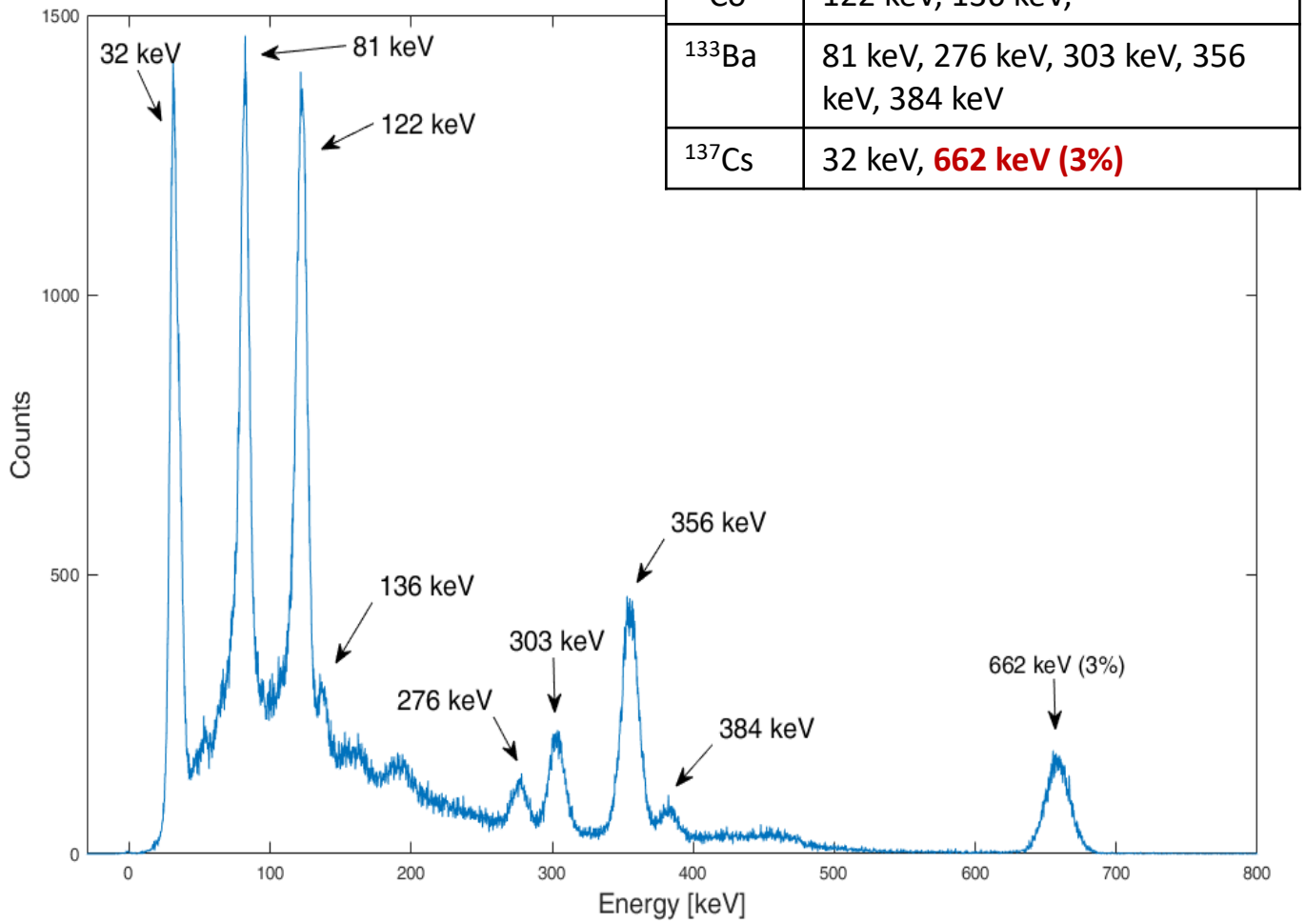


- 1×10^5 n/cm^2/s neutron flux (vs. 10^9 n/cm^2/s expected with clinical flux).
- 15min. measurement.
- Measurements with vial alone and vial inside a water phantom show similar results.
- Minimum Boron concentration of 62ppm measured.
- Events in the 478 keV region detected during the 0 ppm measurement. Topic under investigation.

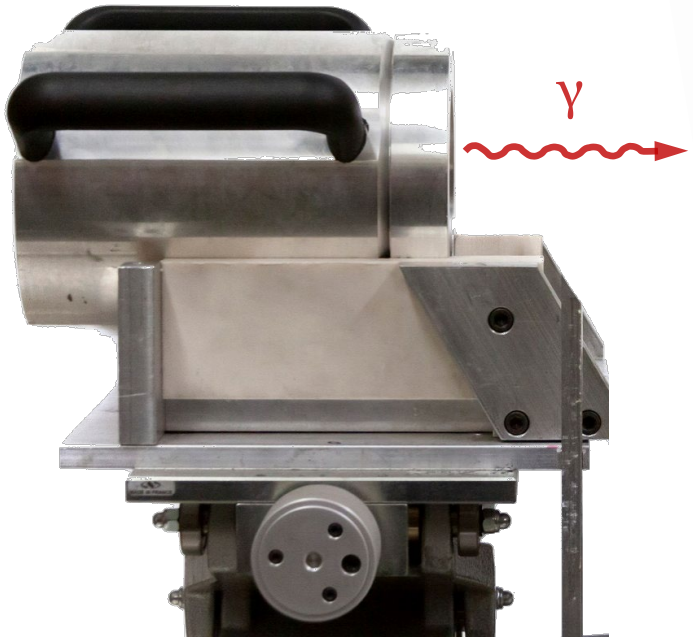
BeNEdiCTE module for imaging (square $LaBr_3$ 50x50x20 mm^3)



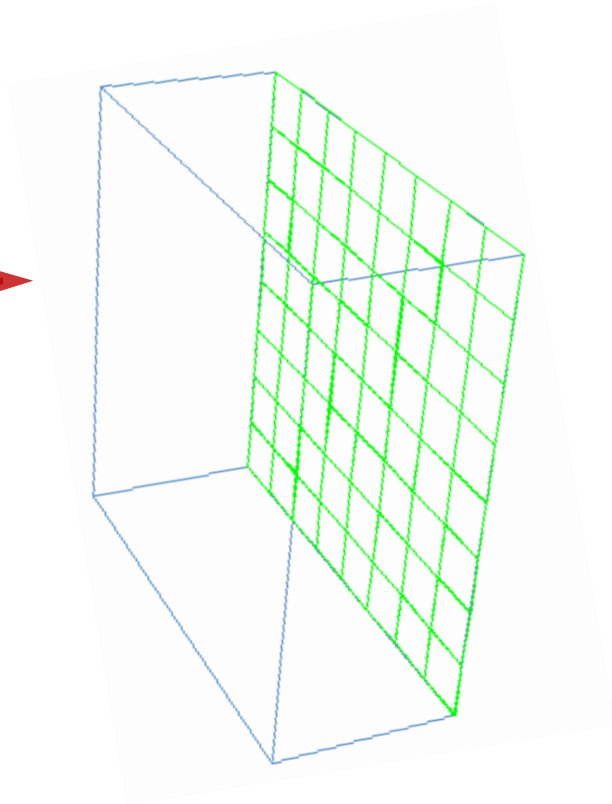
Source	Peaks energy
^{57}Co	122 keV, 136 keV,
^{133}Ba	81 keV, 276 keV, 303 keV, 356 keV, 384 keV
^{137}Cs	32 keV, **662 keV (3%)**



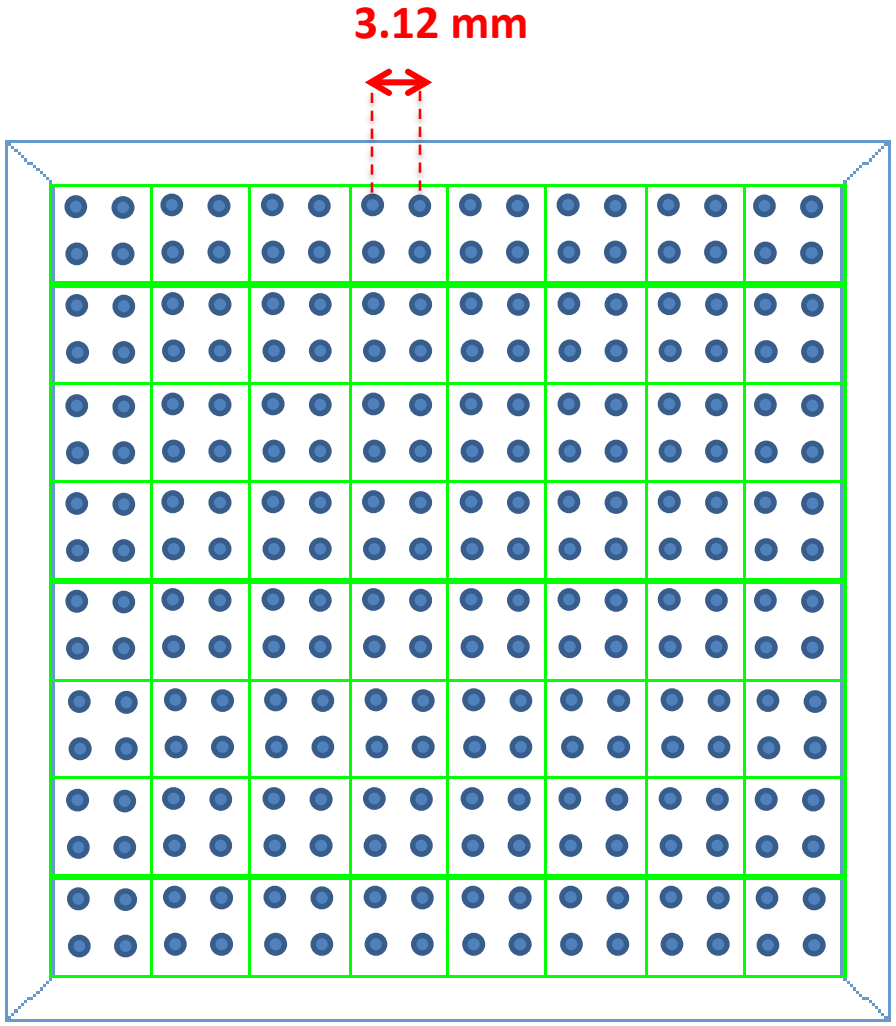
Position sensitivity test with scanned ^{137}Cs source (662keV)



Collimated ^{137}Cs
Photon Beam (**1 mm**)



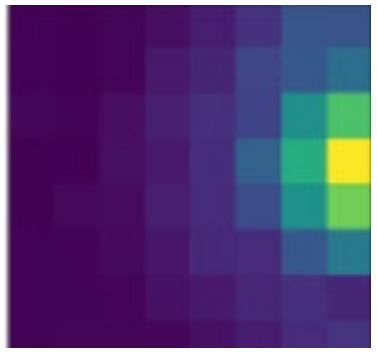
Benedicte detector



256 points

Position reconstruction by Convolutional Neural Network (CNN)

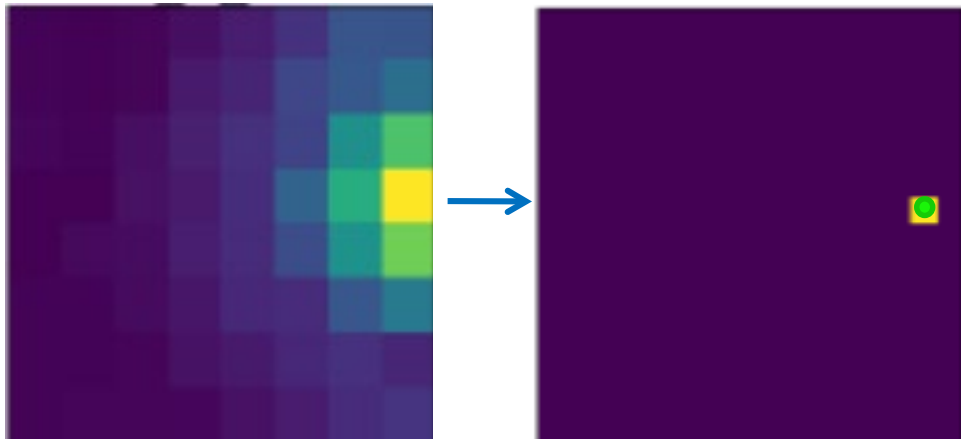
INPUT:
[8x8 SiPM signals]



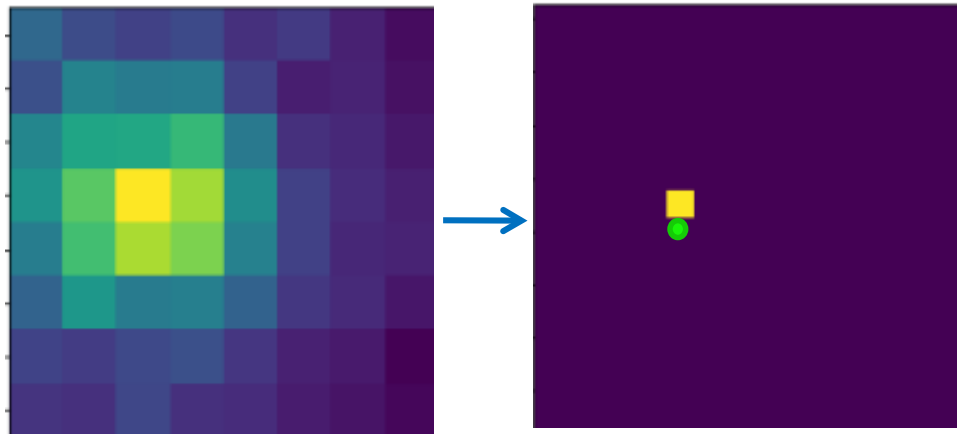
C N N

OUTPUT:
[Predicted Position]

TRUE PREDICTION



FALSE PREDICTION



Results: Confusion Matrix (X coordinate)

X-axis Test Average Accuracy	65%

Including adjacent pixels	90%

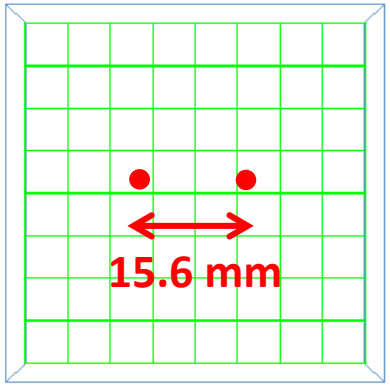
TRUE CLASS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	74,48%	19,79%	9,62%	2,09%	0,75%	0,38%	0,39%	0,11%	0,14%	0,15%	0,05%	0,10%	0,09%	0,10%	0,05%	0,16%
2	20,37%	66,24%	19,49%	4,95%	1,33%	0,78%	0,36%	0,17%	0,17%	0,10%	0,05%	0,09%	0,09%	0,05%	0,08%	0,12%
3	2,30%	10,91%	56,71%	15,95%	3,18%	1,01%	0,48%	0,12%	0,29%	0,22%	0,05%	0,01%	0,06%	0,13%	0,08%	0,16%
4	0,71%	1,51%	10,27%	60,28%	12,49%	3,25%	1,14%	0,36%	0,53%	0,25%	0,05%	0,13%	0,14%	0,06%	0,09%	0,14%
5	0,25%	0,46%	1,69%	10,31%	65,59%	15,15%	2,94%	1,01%	0,67%	0,45%	0,13%	0,19%	0,07%	0,10%	0,14%	0,28%
6	0,10%	0,15%	0,38%	3,09%	11,96%	63,97%	13,05%	2,54%	1,37%	0,74%	0,34%	0,21%	0,13%	0,13%	0,11%	0,06%
7	0,13%	0,07%	0,32%	1,10%	2,48%	10,01%	65,45%	13,94%	3,44%	1,45%	0,55%	0,27%	0,18%	0,16%	0,17%	0,06%
8	0,05%	0,06%	0,18%	0,73%	0,90%	2,70%	11,31%	66,11%	13,54%	3,52%	1,10%	0,66%	0,28%	0,16%	0,18%	0,10%
9	0,28%	0,09%	0,19%	0,41%	0,43%	1,20%	2,61%	11,25%	64,83%	14,58%	2,89%	1,37%	0,44%	0,28%	0,17%	0,12%
10	0,50%	0,11%	0,18%	0,33%	0,21%	0,46%	0,78%	2,31%	10,82%	62,34%	12,19%	3,26%	0,81%	0,36%	0,23%	0,14%
11	0,20%	0,02%	0,22%	0,18%	0,16%	0,41%	0,59%	0,96%	1,99%	11,25%	65,44%	13,58%	2,58%	0,81%	0,26%	0,14%
12	0,10%	0,09%	0,22%	0,23%	0,13%	0,19%	0,27%	0,42%	0,72%	2,97%	12,09%	62,90%	12,01%	1,88%	0,79%	0,20%
13	0,10%	0,15%	0,23%	0,09%	0,10%	0,16%	0,17%	0,26%	0,55%	1,04%	3,07%	11,09%	63,30%	10,04%	1,75%	0,62%
14	0,20%	0,13%	0,10%	0,07%	0,10%	0,18%	0,17%	0,20%	0,38%	0,47%	0,96%	3,41%	14,35%	67,36%	10,68%	2,56%
15	0,15%	0,06%	0,14%	0,12%	0,08%	0,10%	0,17%	0,06%	0,34%	0,32%	0,63%	1,57%	3,61%	13,48%	60,95%	20,23%
16	0,08%	0,17%	0,07%	0,08%	0,10%	0,04%	0,11%	0,17%	0,24%	0,16%	0,42%	1,16%	1,86%	4,90%	24,30%	74,93%

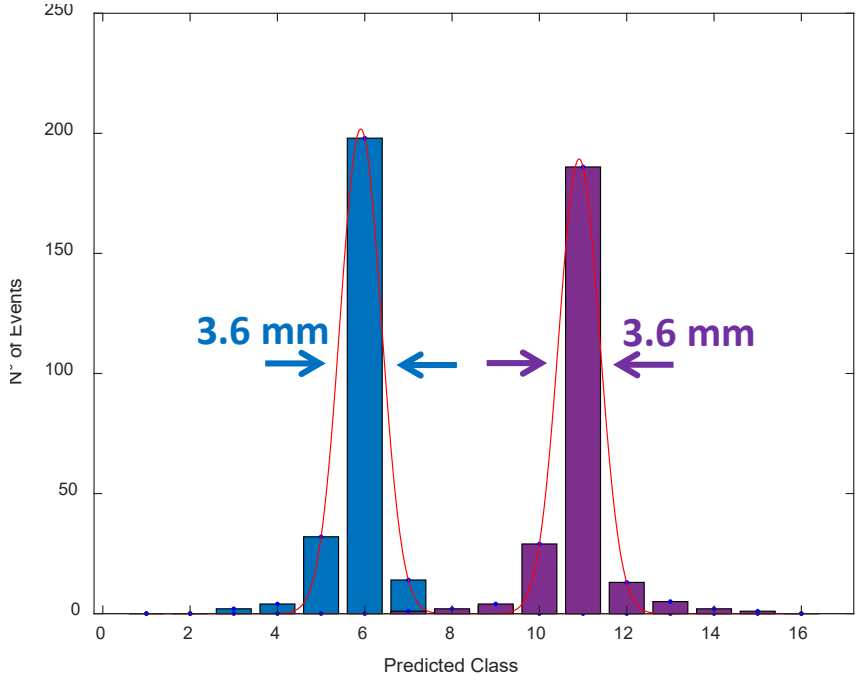
PREDICTED CLASS

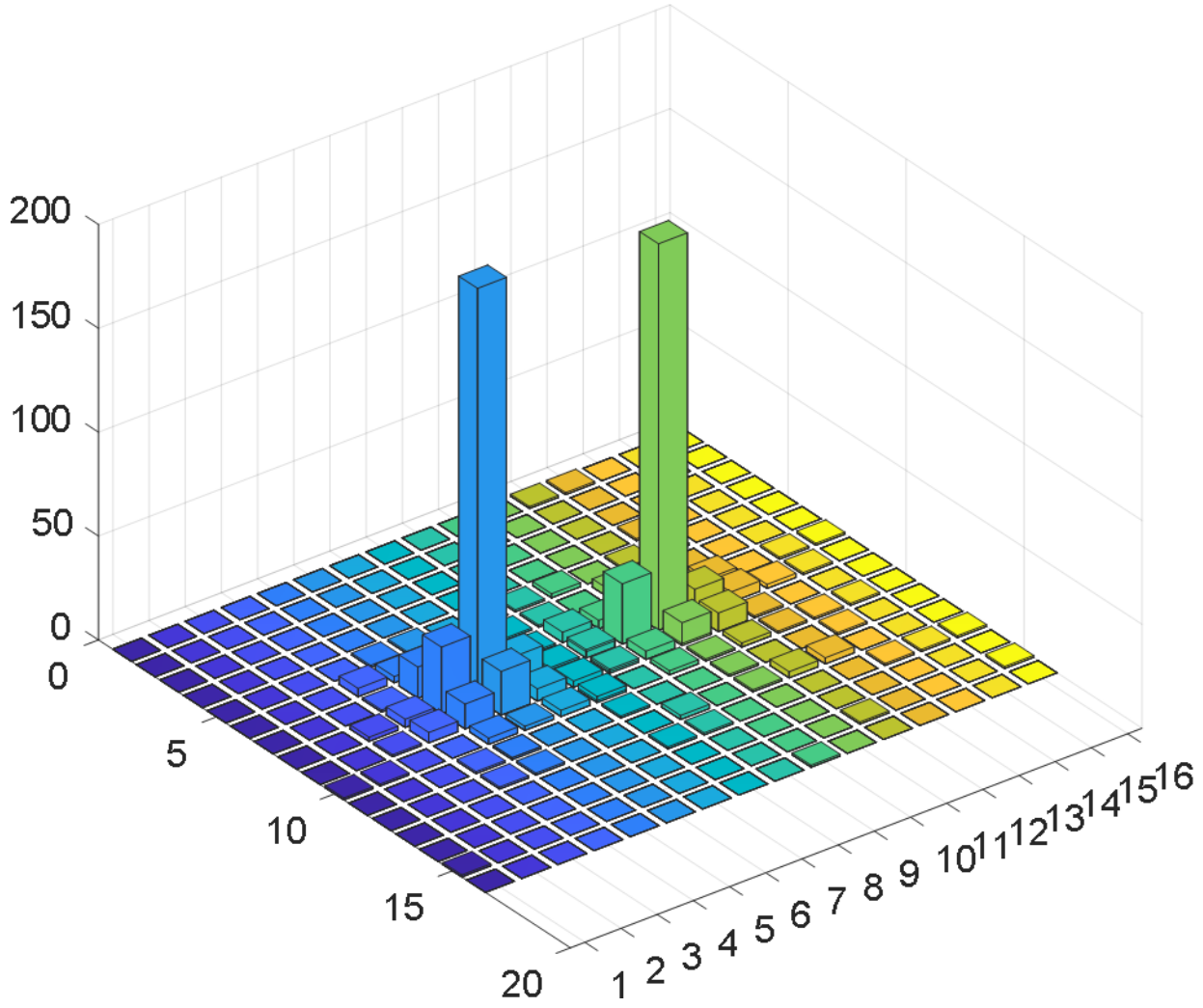
74,48%	94,85%
66,24%	96,94%
56,71%	86,47%
60,28%	86,54%
65,59%	90,04%
63,97%	89,12%
65,45%	89,80%
66,11%	91,30%
64,83%	89,18%
62,34%	88,17%
65,44%	89,71%
62,90%	87,57%
63,30%	89,67%
67,36%	90,87%
60,95%	95,93%
74,93%	95,15%

Similar result for Y coordinate

Results: two irradiated points reconstruction







Future work

- Collimator development and imaging tests on ^{10}B samples
- Study of detector shielding
- Detector development for NCEPT (Neutron Capture Enhanced Particle Therapy) with ANSTO (Australia). (A.Chacon, et al., Scientific Reports volume 12, 5863, 2022.)
- Embedding ML reconstruction in hardware accellerator: towards analog Neural Network in ASIC (submitted to IEEE NSS-MIC 2022).

Thank you
for your attention!