One module of a Compton camera for online beam range monitoring in proton therapy

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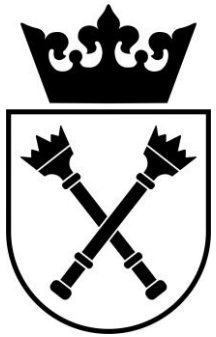

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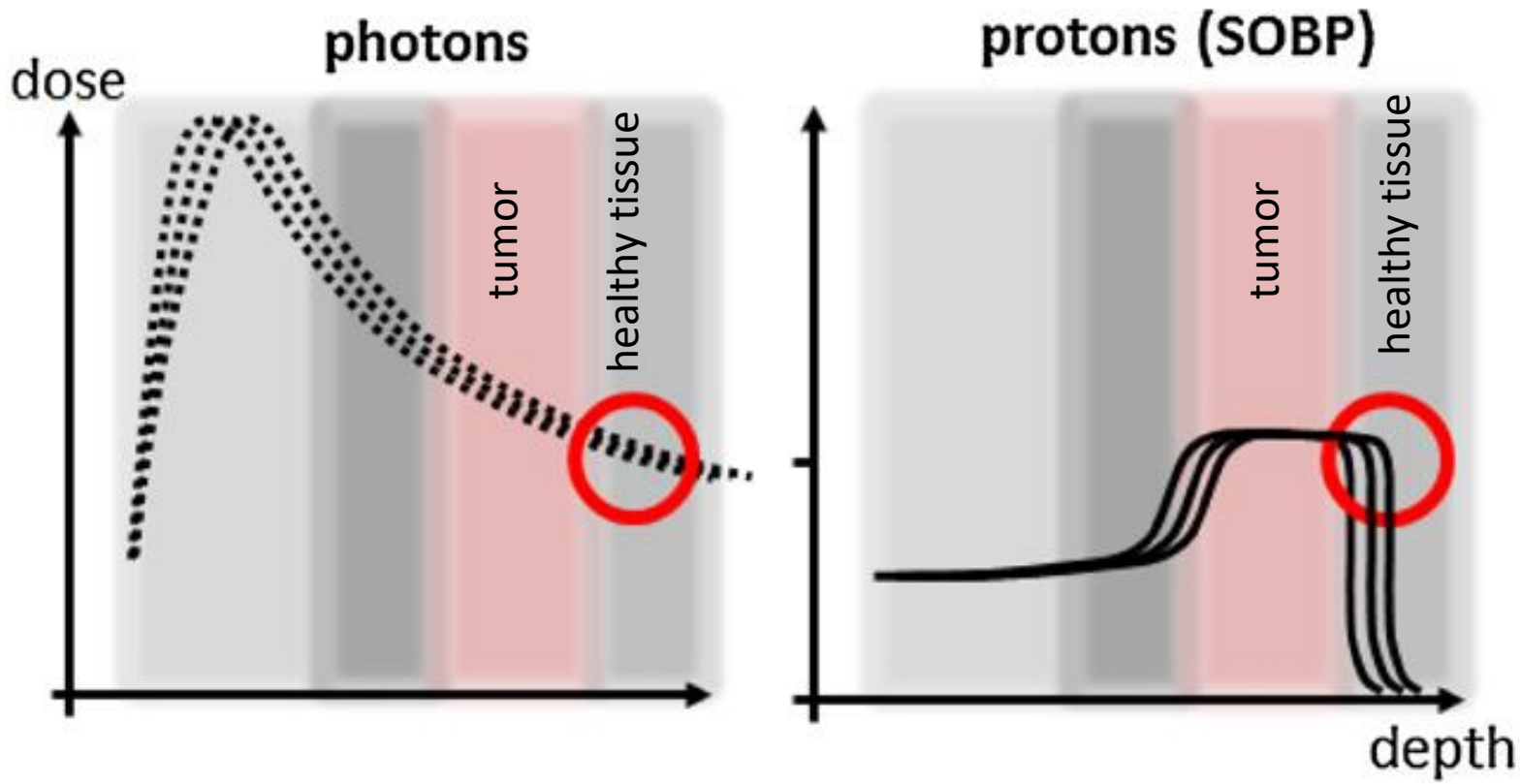
Plan of the talk

1. SiFi-CC project: overview and status
2. Testing the SiFi-CC detector prototype in the Coded Mask mode (*last year – testing the prototype components)
3. Towards the full-scale SiFi-CC detector measurements
4. Subproject: comparison of data acquisition systems (DAQ)

Proton therapy - introduction



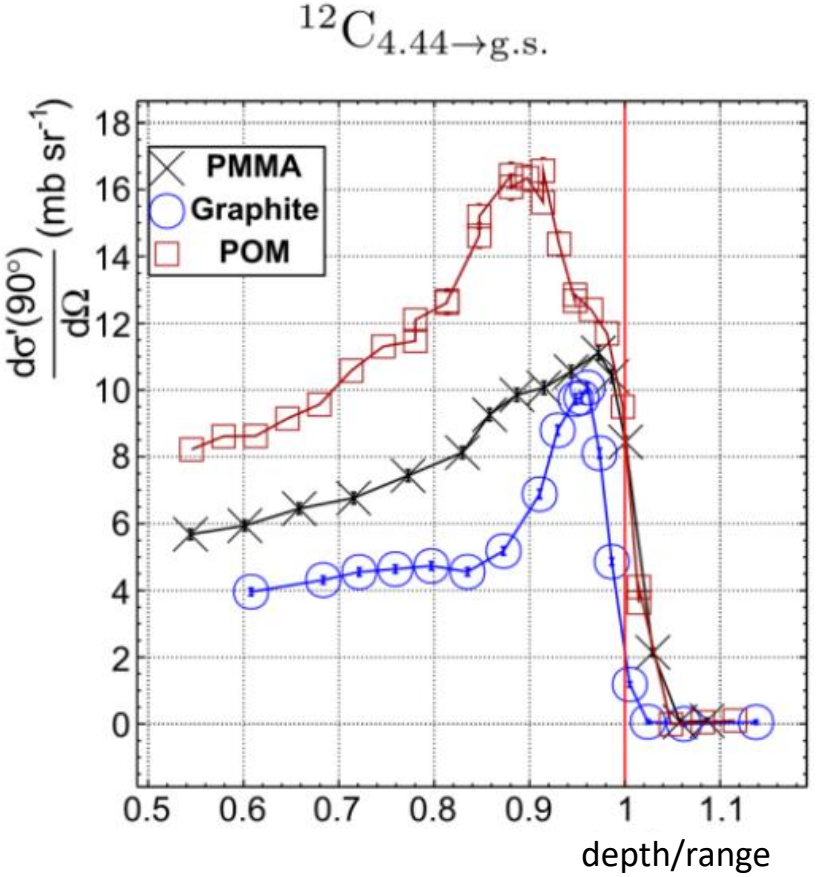
Uncertainty sources: patient positioning, anatomical changes, organ movement etc.

Consequences: safety margins, higher dose deposited in the surrounding healthy tissues

Image sources: https://www.ilcn.org/proton-beam-therapy-versus-photon-beam-therapy-the-debate-continues/
Antje-Christin Knopf and Antony Lomax 2013 *Phys. Med. Biol.* **58** R131

Proton beam range monitoring – prompt gammas

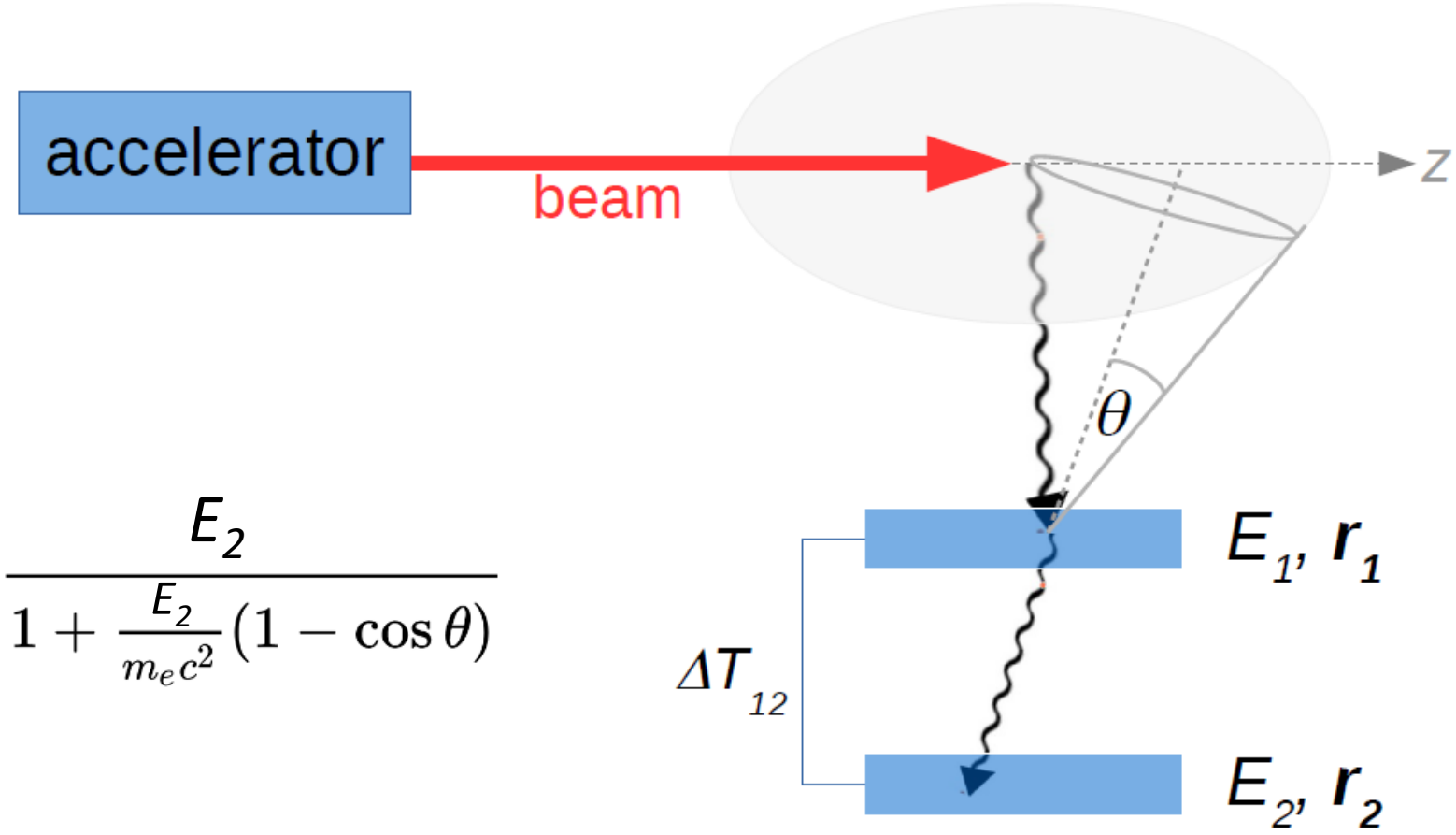
- Detection of gamma quanta of discrete energies, emitted in deexcitation of nuclei
- Emission occurs within short times (~fs-ps)
- Strong correlation between emitted prompt gamma spectrum and and the Bragg peak position[1]



[1]Min C H, Kim C H, Youn M Y and Kim J W 2006 Applied Physics Letters 89 183517
Image source: L. Kelleter *et al.* Spectroscopic study of prompt-gamma emission for range verification in proton therapy, Physica Medica 34 (2017) 7-17

Prompt gamma imaging – Compton Camera

Compton camera – principle of operation

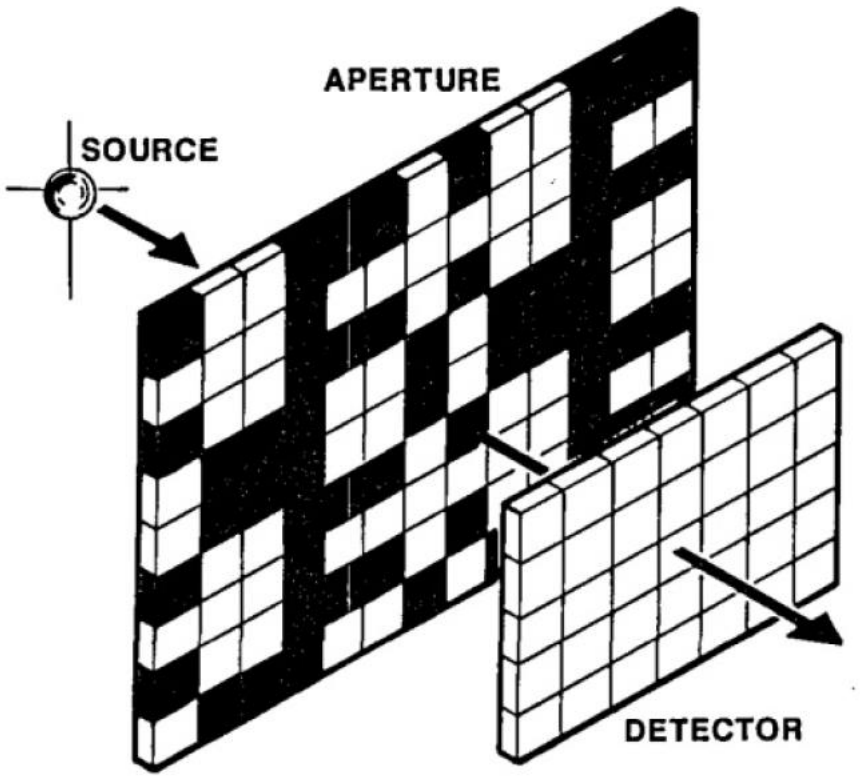


$$E_1+E_2 = \frac{E_2}{1+\frac{E_2}{m_e c^2}(1-\cos\theta)}$$

Source: A. Wrońska, *Prompt gamma imaging in proton therapy - status, challenges and developments,* Journal of Physics: Conference Series **1561** (2020) 012021

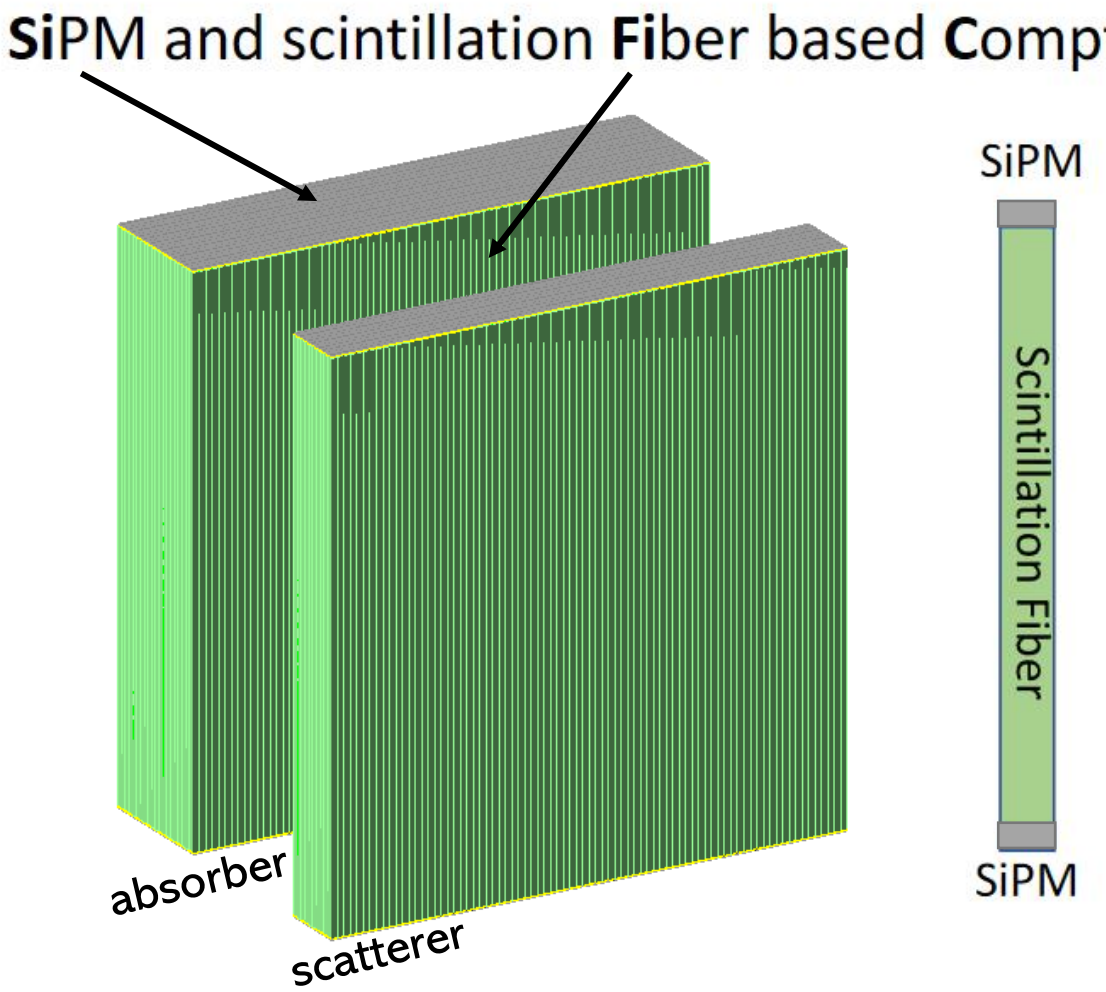
Prompt gamma imaging – Coded Mask

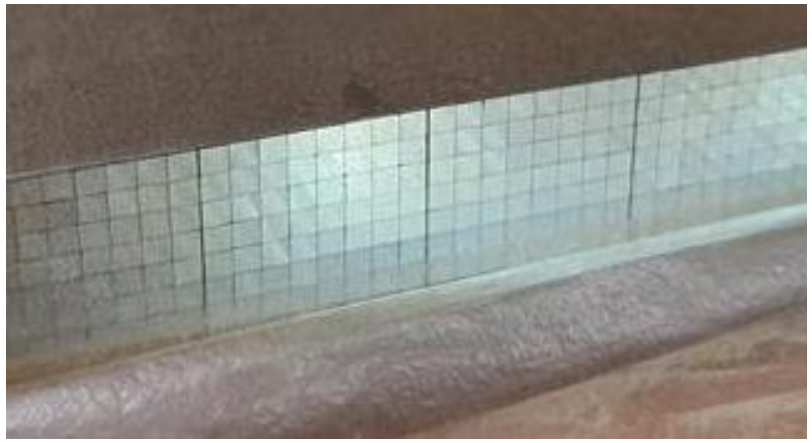
- An extension of the pinhole camera
- 50% pixels open, which enhances the statistics
- The mask casts a „shadow” on the detector plane
- Algorithm (e.g. MLEM) needed for image reconstruction



Source of image: S. R. Gottesman & E. E. Fenimore, Applied Optics 28 (1989)

SiFi-CC project – Compton camera





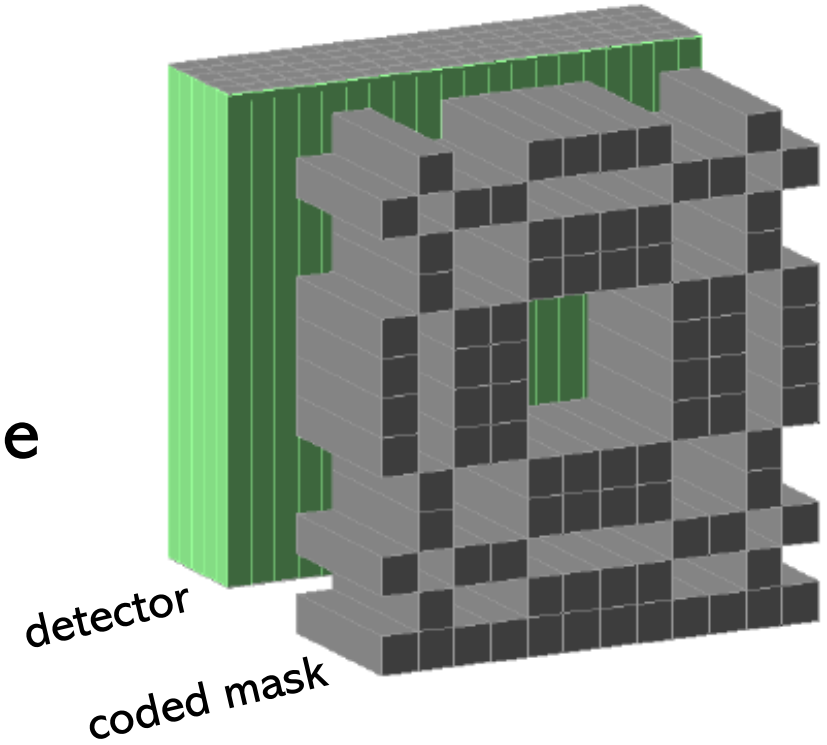
LYSO:Ce(Ca) fibers of size $1.94 \times 1.94 \times 100$ mm^3

- High detection efficiency (high Z and high density material)
- High rate capability (independent hits)
- High granularity (low pile-up ratio)
- Known hit position in 2 dimensions, 3rd coordinate reconstructed from charge ratio

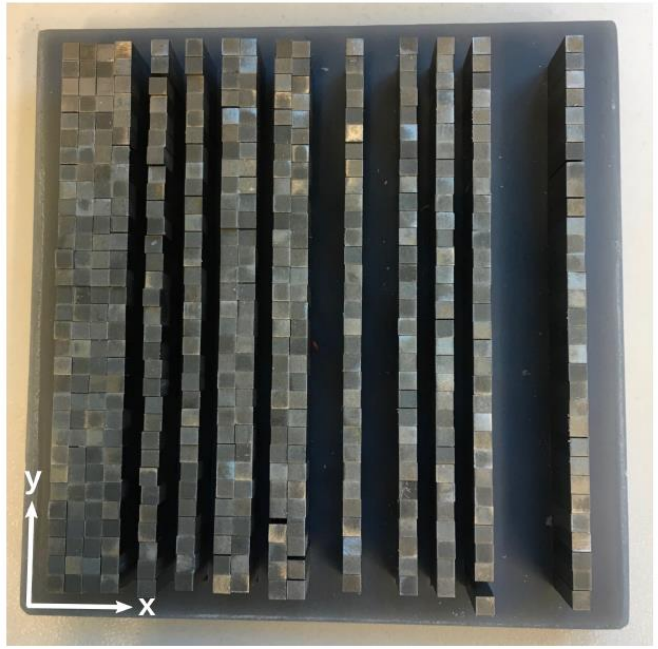
Source: J. Kasper, K. Rusiecka, R. Hetzel, M. K. Kozani, R. Lalik, A. Magiera, A. Stahl, A. Wrońska, Physica Medica 76, 317–325, DOI 10.1016/j.ejmp.2020.07.013 (2020).

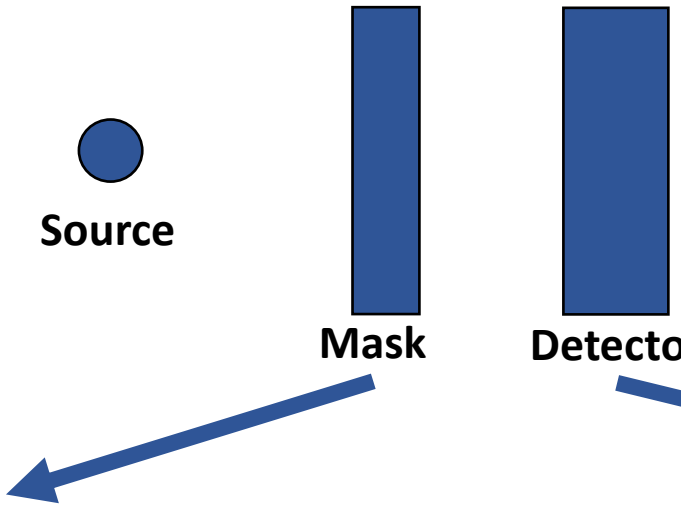
SiFi-CC project – coded mask

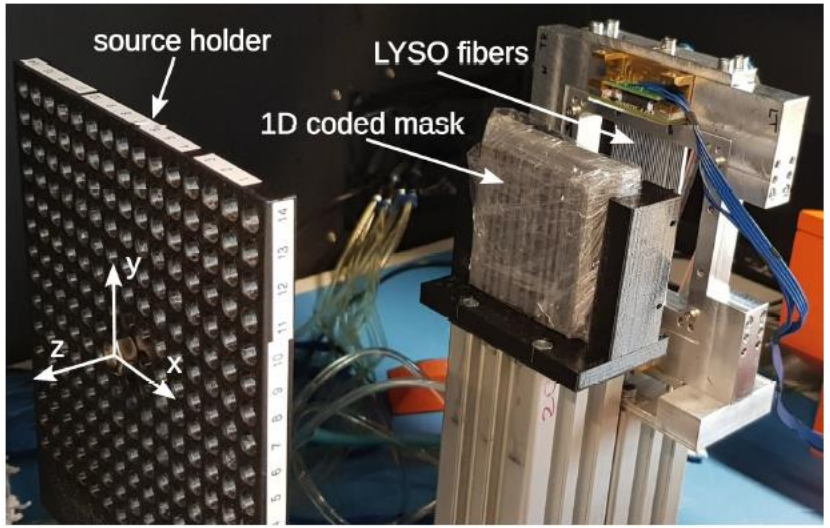
- Alternative imaging modality that requires only one detector module
- 2 versions of Coded Mask: 1D and 2D
- The 1D mask - image reconstruction along one axis, 2D mask - reconstruction on a plane
- Mask pattern and the setup dimensions optimized via Monte Carlo simulations

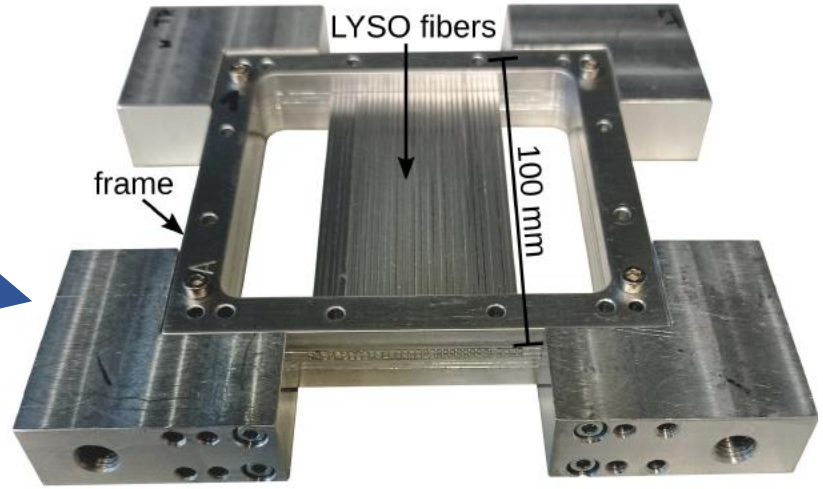


Coded Mask – 1D

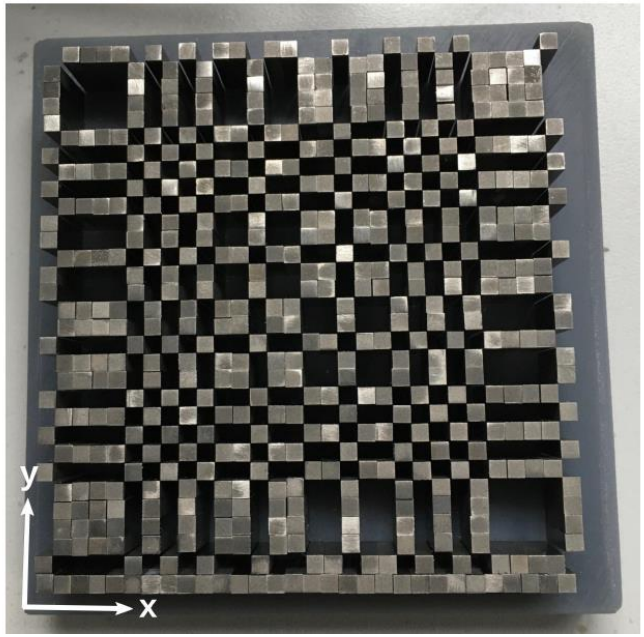


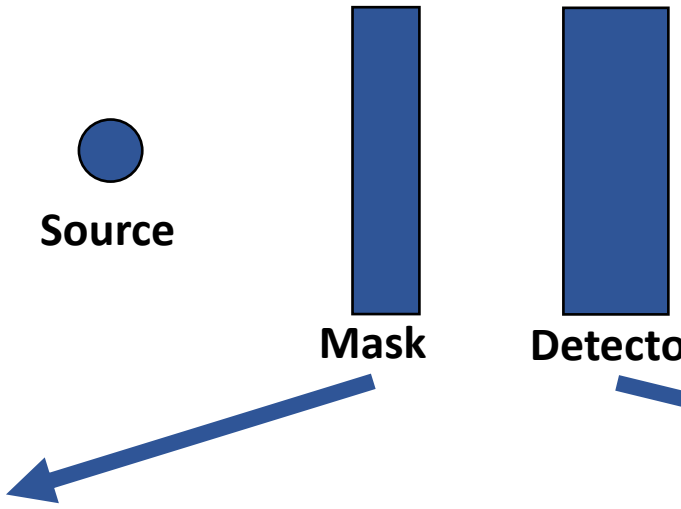


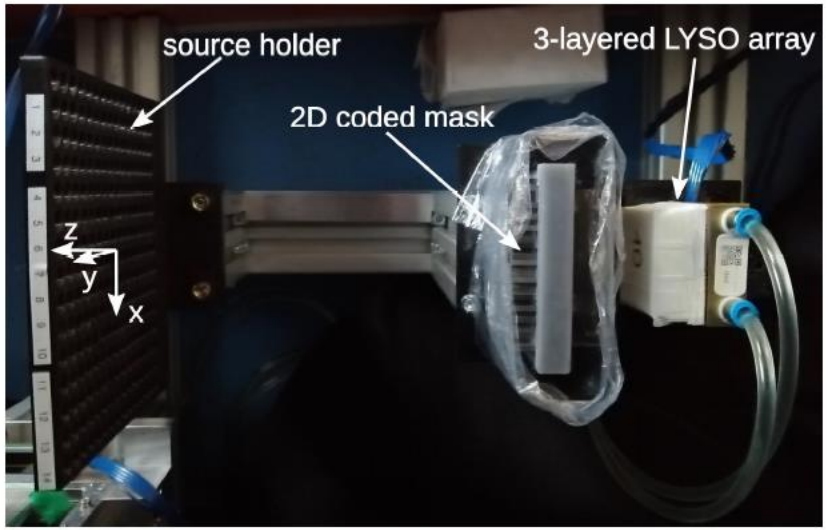


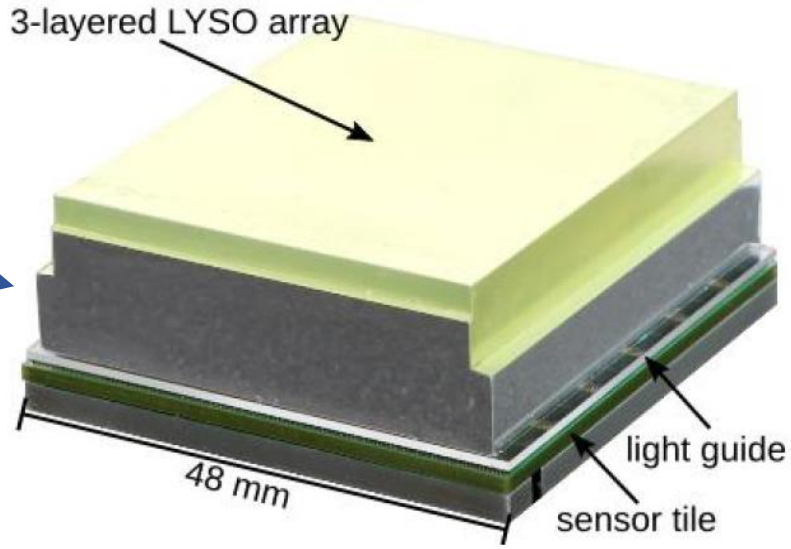


Coded Mask – 2D









Readout: Philips Digital SiPMs, operated by Hyperion III platform[1]

[1]https://hyperion-his.com

Performed measurements

- Imaging measurement: source in several positions + mask + detector
- Calibration measurement with the source
- Background measurement (LYSO activity)

Analysis chain

1. Preprocessing, 10 ns coincidence window
2. 1D setup:
    1. Fiber identification
    2. Energy and y-position calibration in 1D setup
3. 2D setup:
    1. Needle identification
    2. Energy calibration in 2D setup
4. Implementation of MLEM algorithm for image reconstruction
5. Efficiency and background corrections

Reconstruction algorithm

Maximum Likelihood Expectation-Maximization (MLEM) algorithm:

$$\mathbf{f}^{[k]} = \frac{\mathbf{f}^{[k-1]}}{\mathbf{S}} \left(\mathbf{H}^T \cdot \frac{\mathbf{I}}{\mathbf{H} \cdot \mathbf{f}^{[k-1]}} \right), \text{ for } k = 1, 2, \ldots$$

I - vector of measured data

f[k] - the image estimate after k-th iteration (f[0]=1)

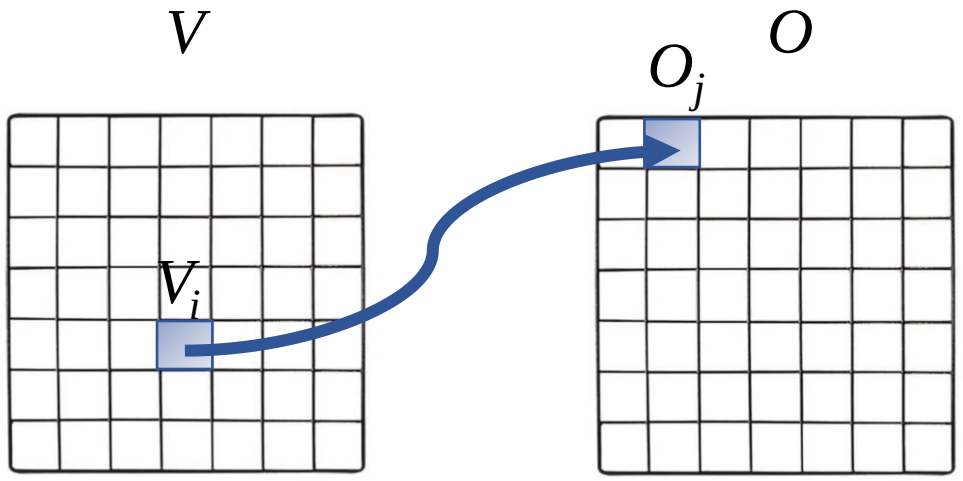
S - normalization term

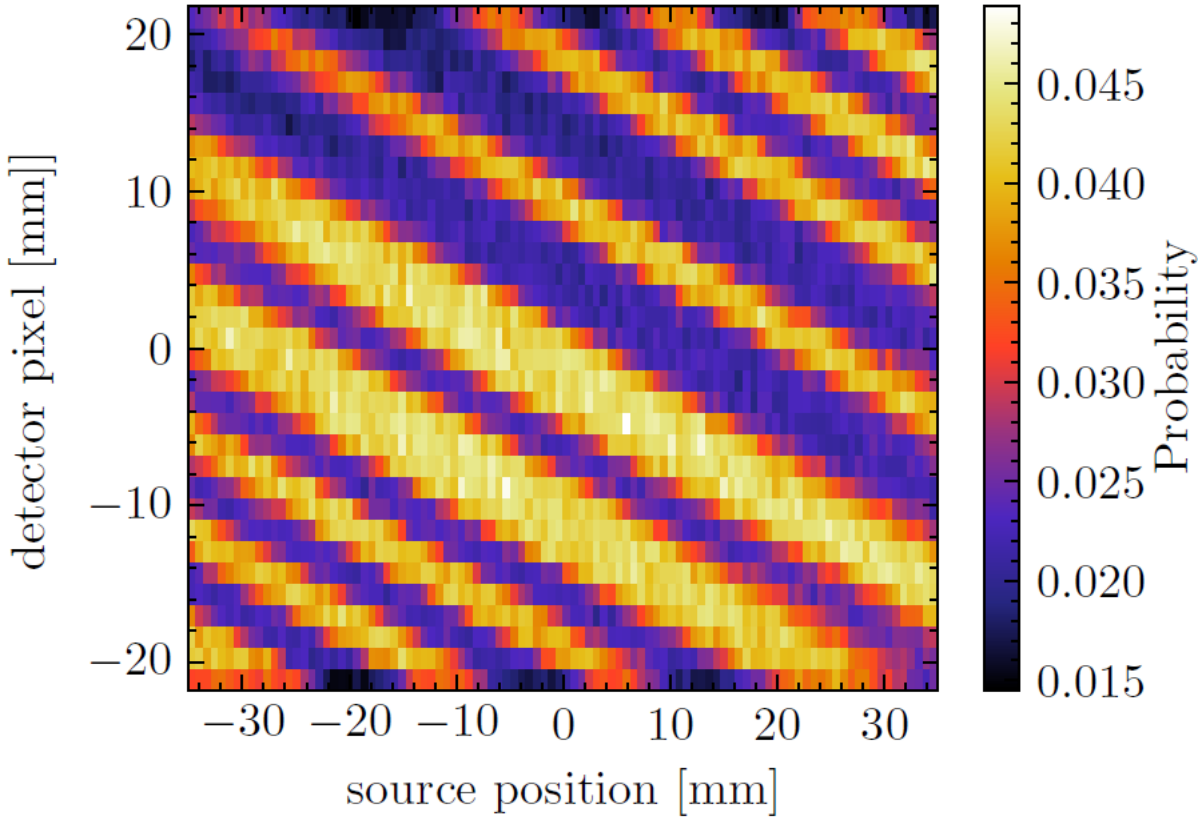
H - system matrix

System matrix for the 1D mask

An element of the system matrix is a probability that a particle originated from j-th voxel of the source plane V will be detected in the i-th voxel of the detector O

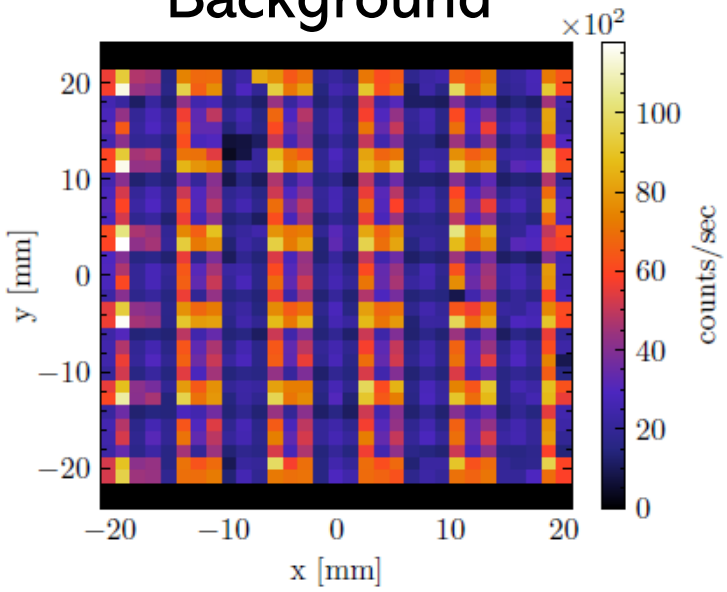
$$\mathbf{H}_{ij} = p(V_i|O_j)$$



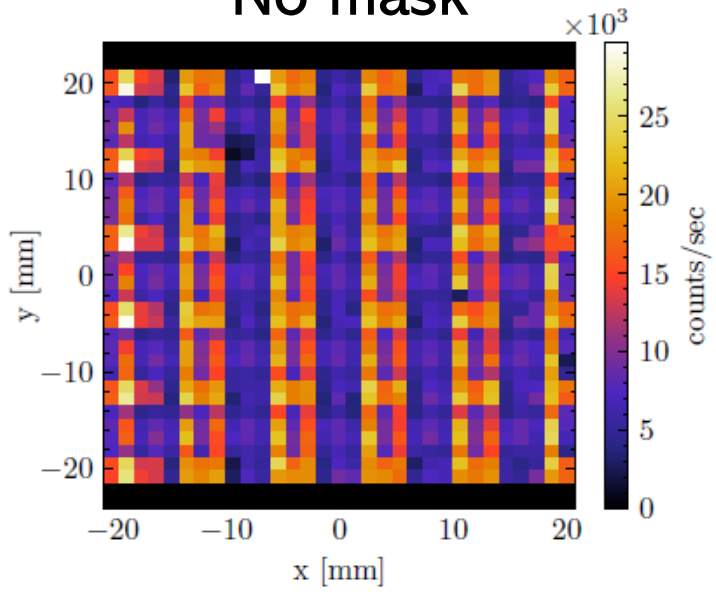


Preprocessing components

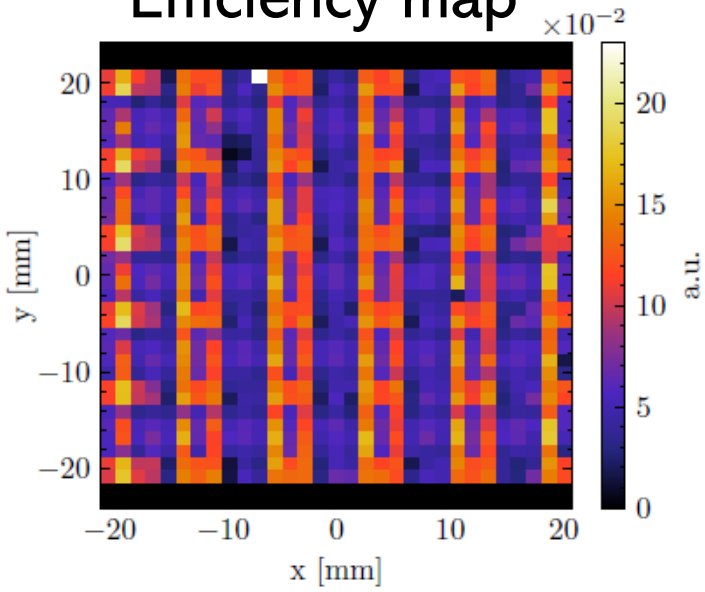
Background



No mask



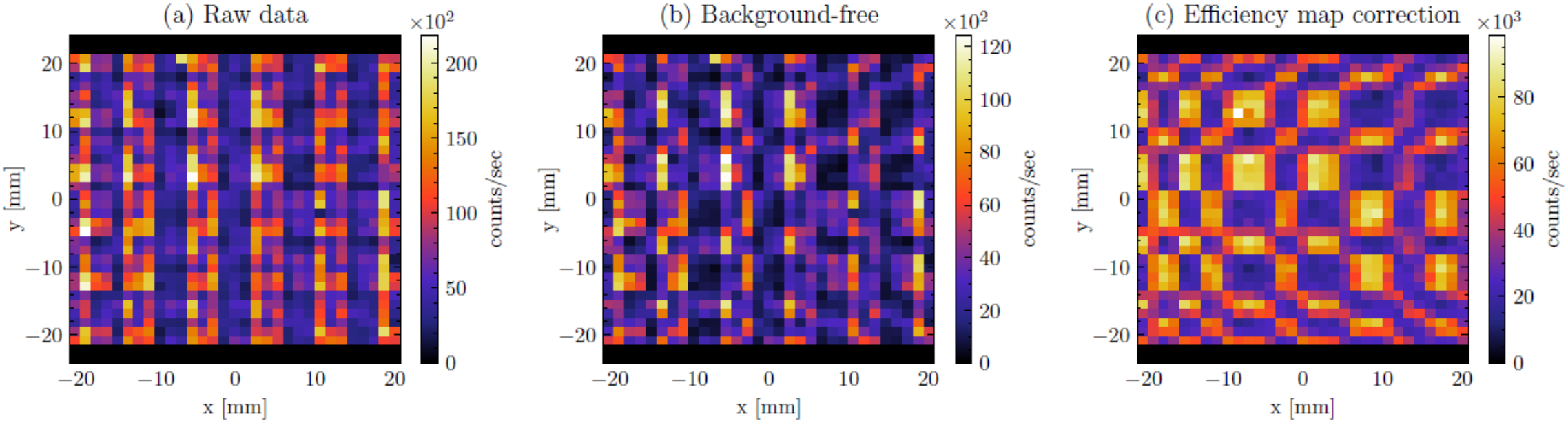
Efficiency map



Preprocessing steps applied to data

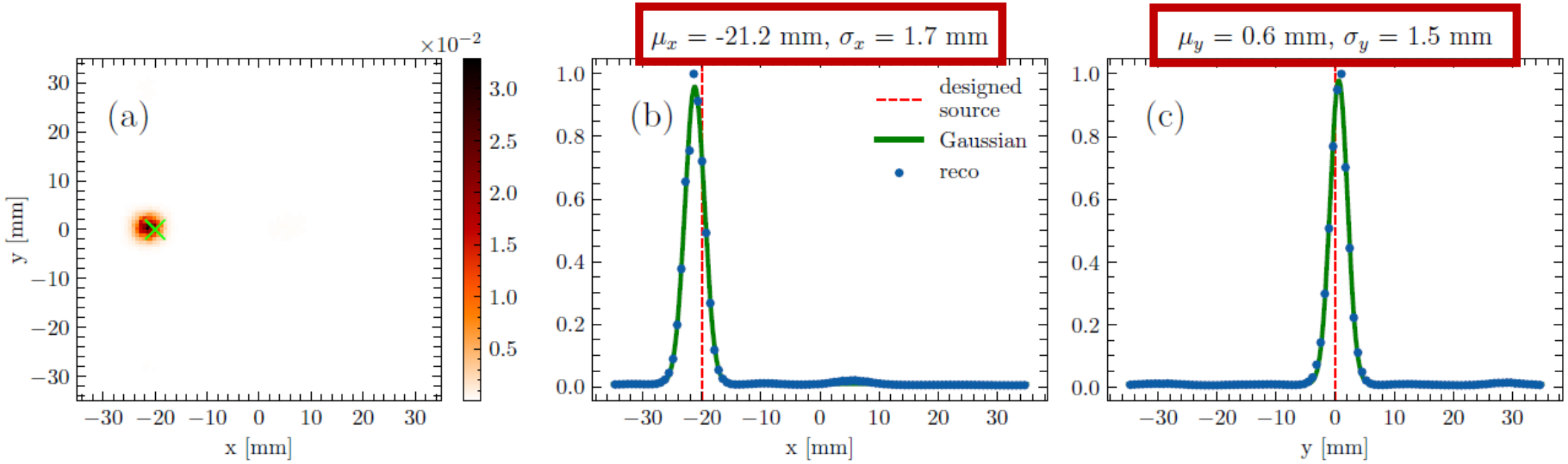
background subtraction

efficiency correction



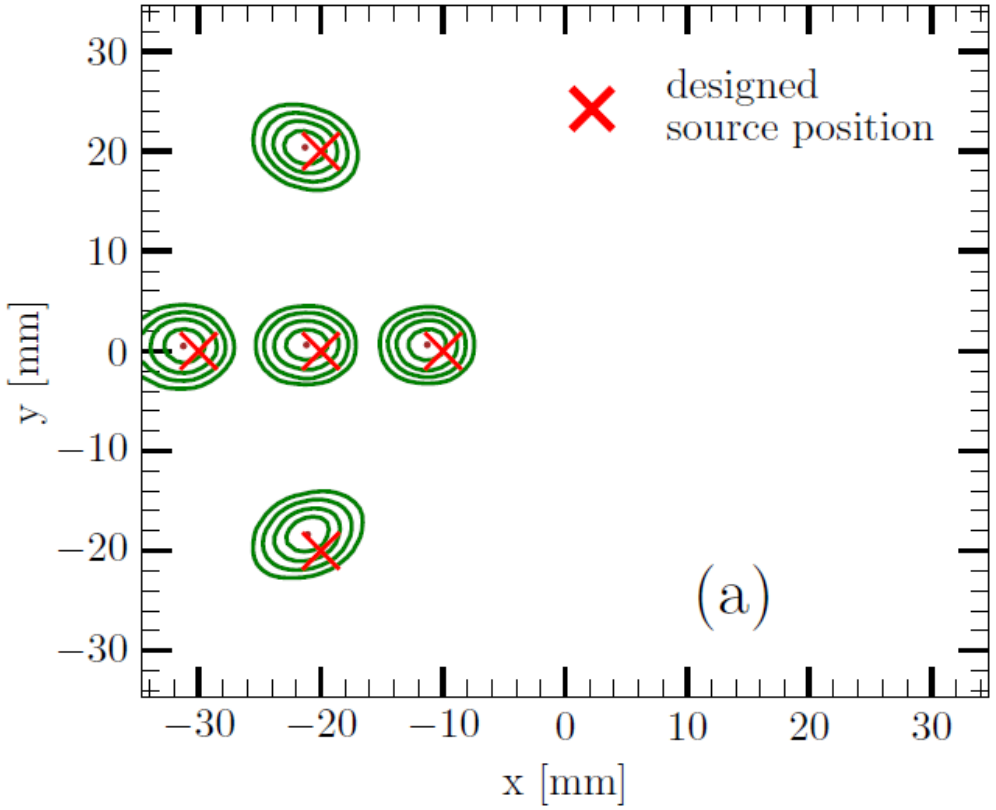
An example 2D reconstruction

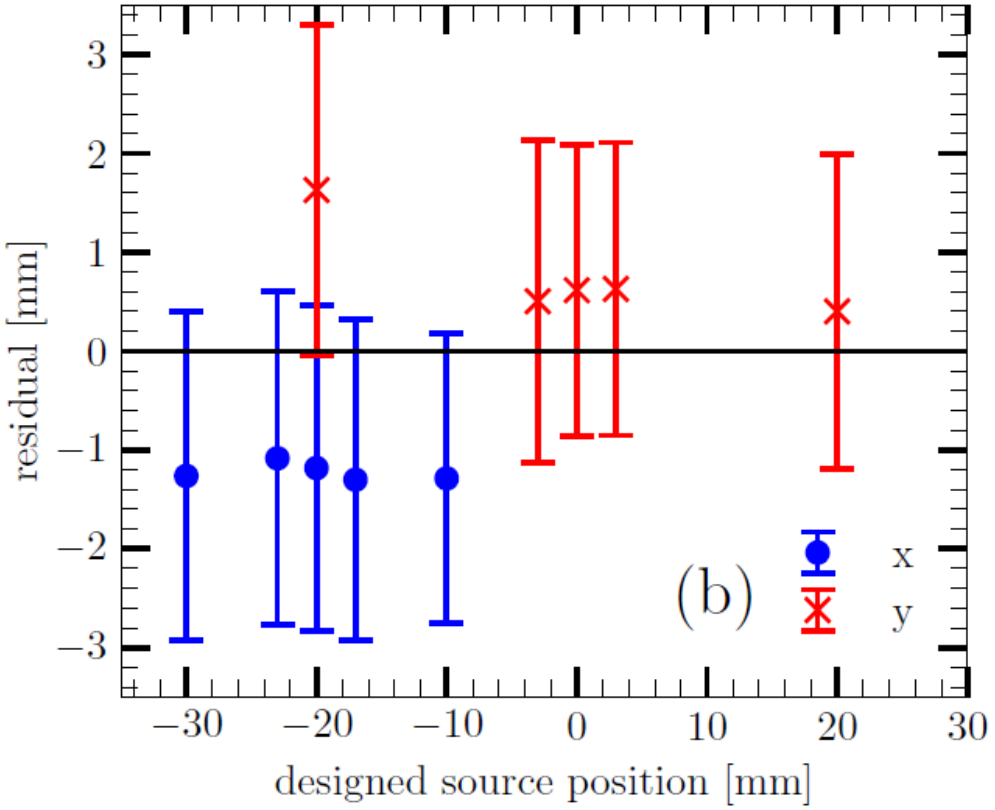
Evaluation of reconstruction performance: comparing reconstructed peak position and the designed position, calculating mean and sigma of the fitted Gaussian



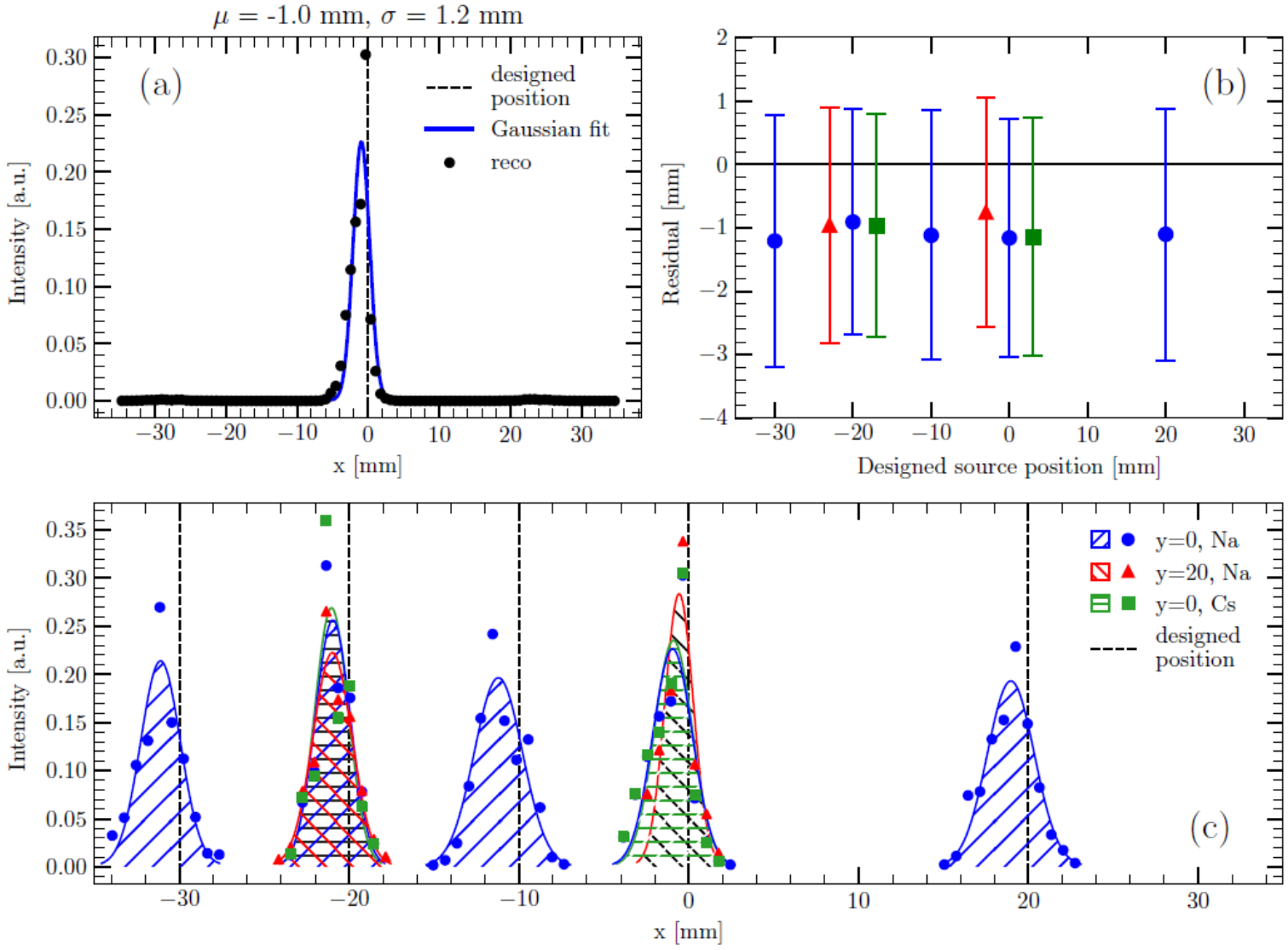
Results of the reconstruction: clear, distinct peak, no artifacts, low background

Results of 2D image reconstruction





Results of 1D reconstruction



Coded Mask measurements - summary

- Near-field coded mask imaging is feasible with gamma sources
- Reconstruction with both 1D and 2D approach, clear peak without artifacts is always visible
- The article summarising these results has been submitted to PMB and will soon be available on ArXiv
- Small-scale prototype is too small to reconstruct continuous sources
- Simulation of the full-scale detector showed promising results so we proceeded to build it and test it in clinical conditions

Full scale detector module - experiment

Fibers (7x55)

1.94x1.94x100 mm

Taiwan Applied Crystals

Stacks wrapped in Al foil

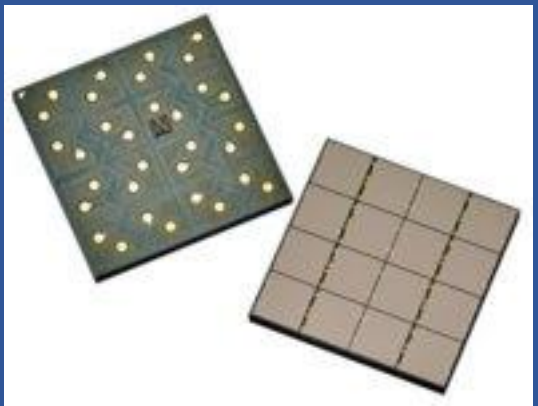
SiPMs

AFBR-S4N44P164M

Broadcom

4 x 4 array

16 x 16 mm²



FULL SCALE DETECTOR

DAQ – TOFPET2

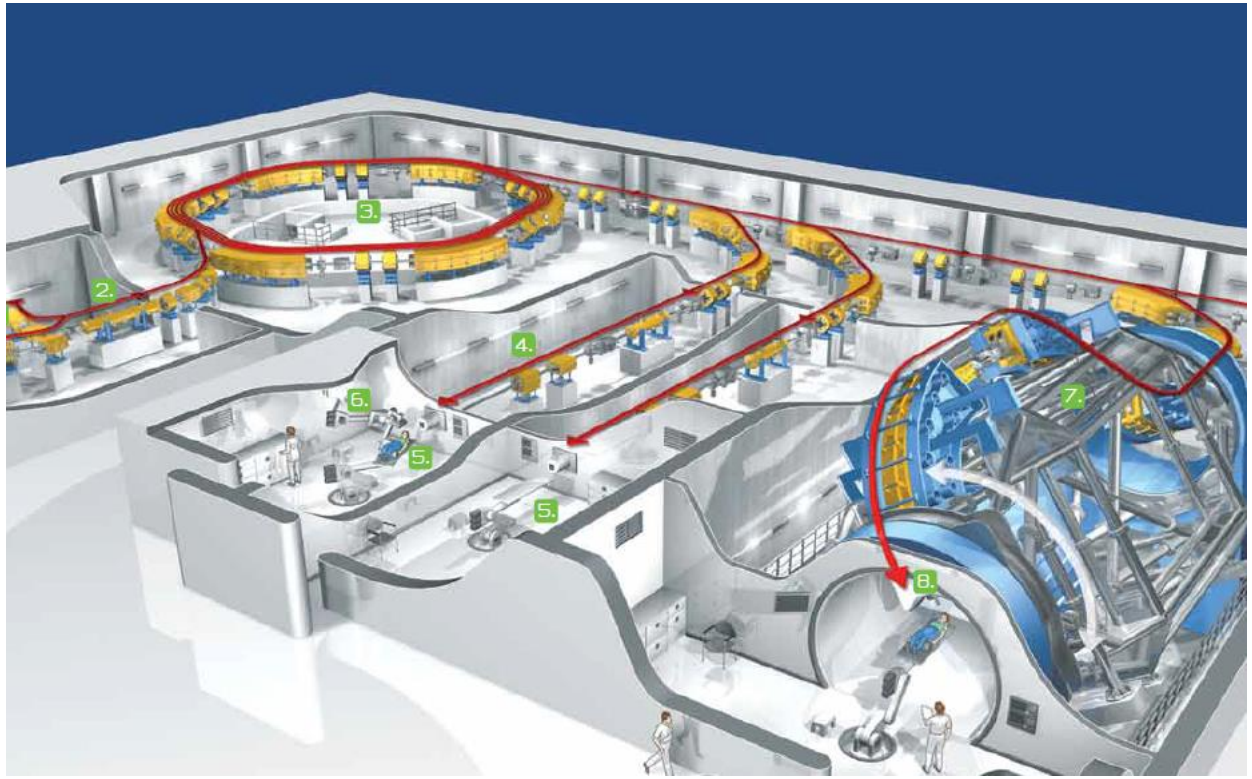
Dead time per channel

Coded Mask

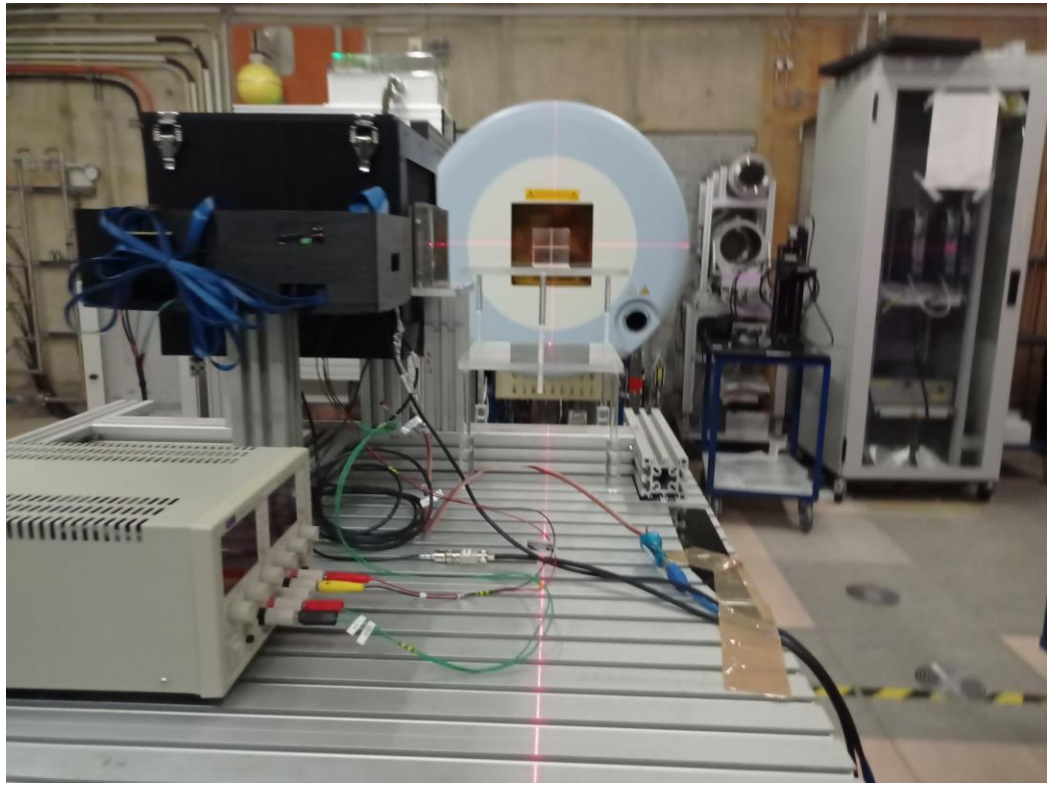
2 variants: 1D or 2D

image reconstruction

Measurements in clinical conditions



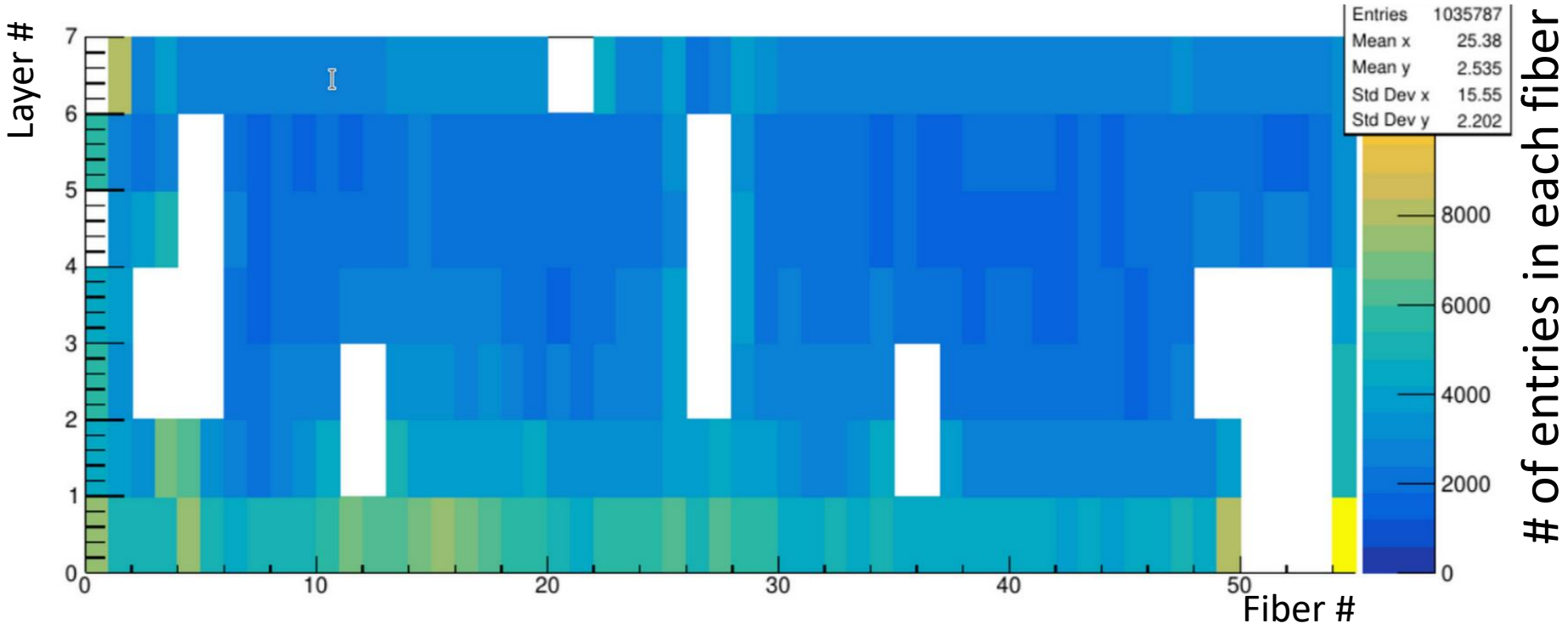
Heidelberg Ion Beam Therapy Center



Full-scale detector in the coded mask mode in the experimental hall

Source of left image: https://www.dkfz.de/en/medphys/ion_beam_therapy/index.html

Example hitmap – input for image reconstruction algorithm



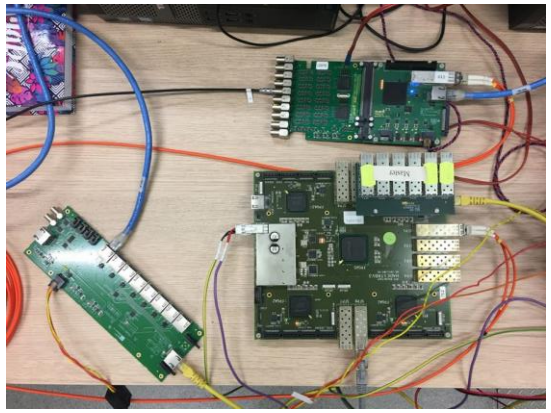
Such maps are an input to the MLEM algorithm – to be processed

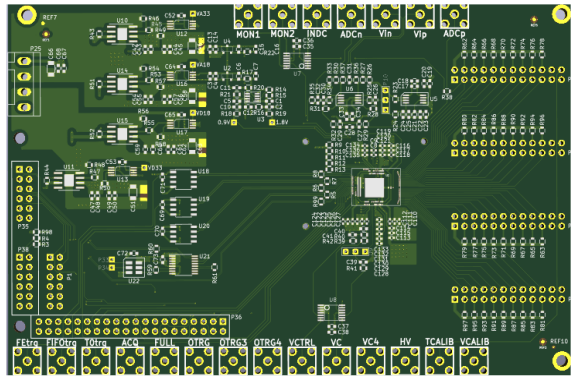
DAQ tests

Test readout with **Desktop Digitizer** DT5742 – 16 channels only (not scalable)

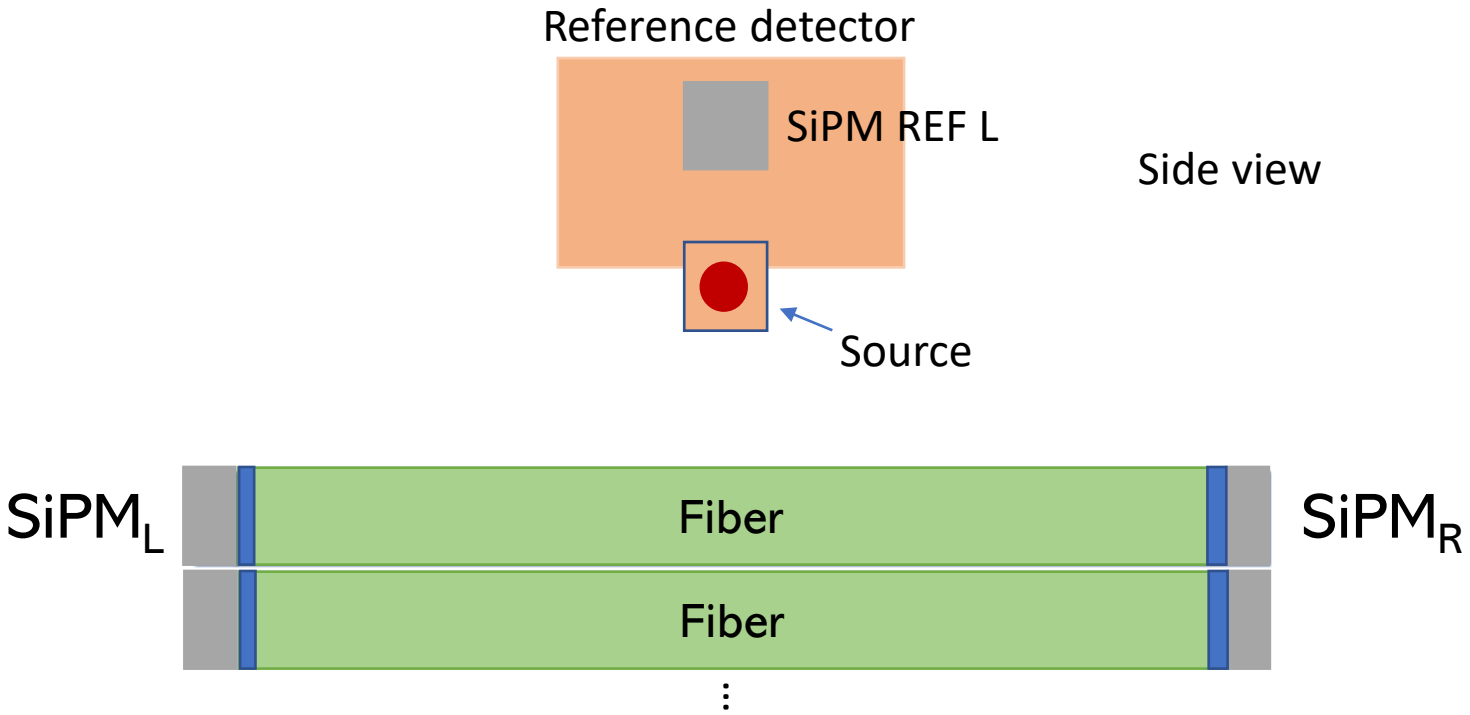
Scalable options examined:

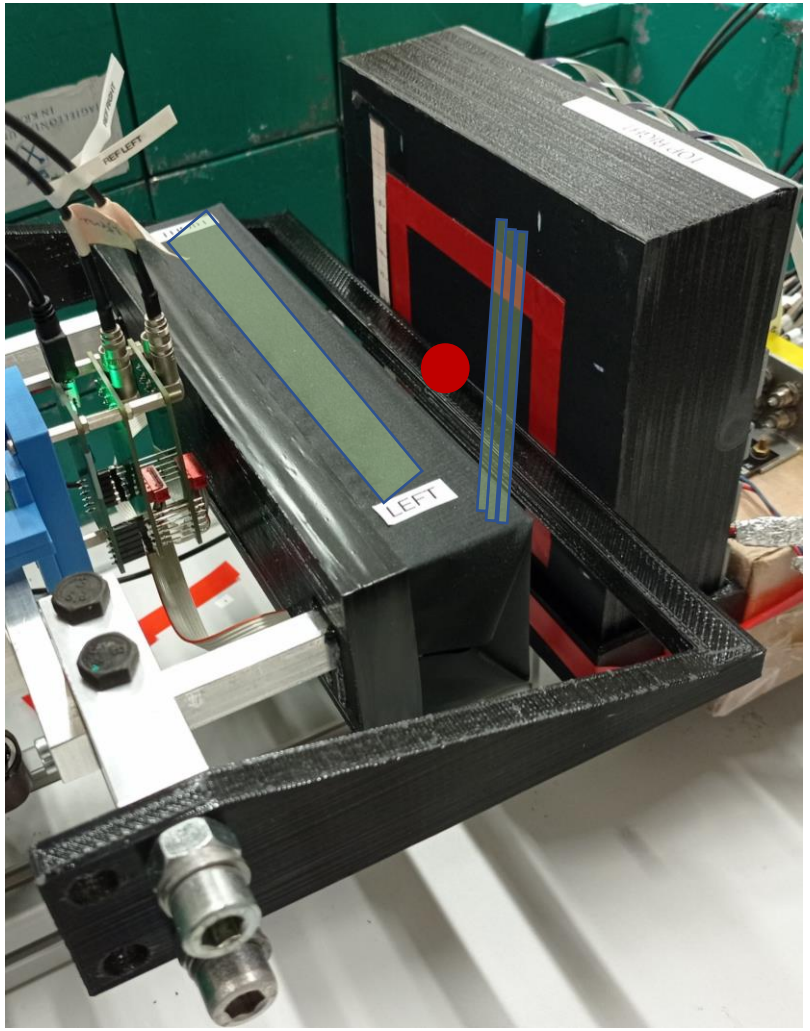
CAEN A5202/Citiroc	TwinPeaks+TRB	TOFPET2 by PETSYS	KLauS6





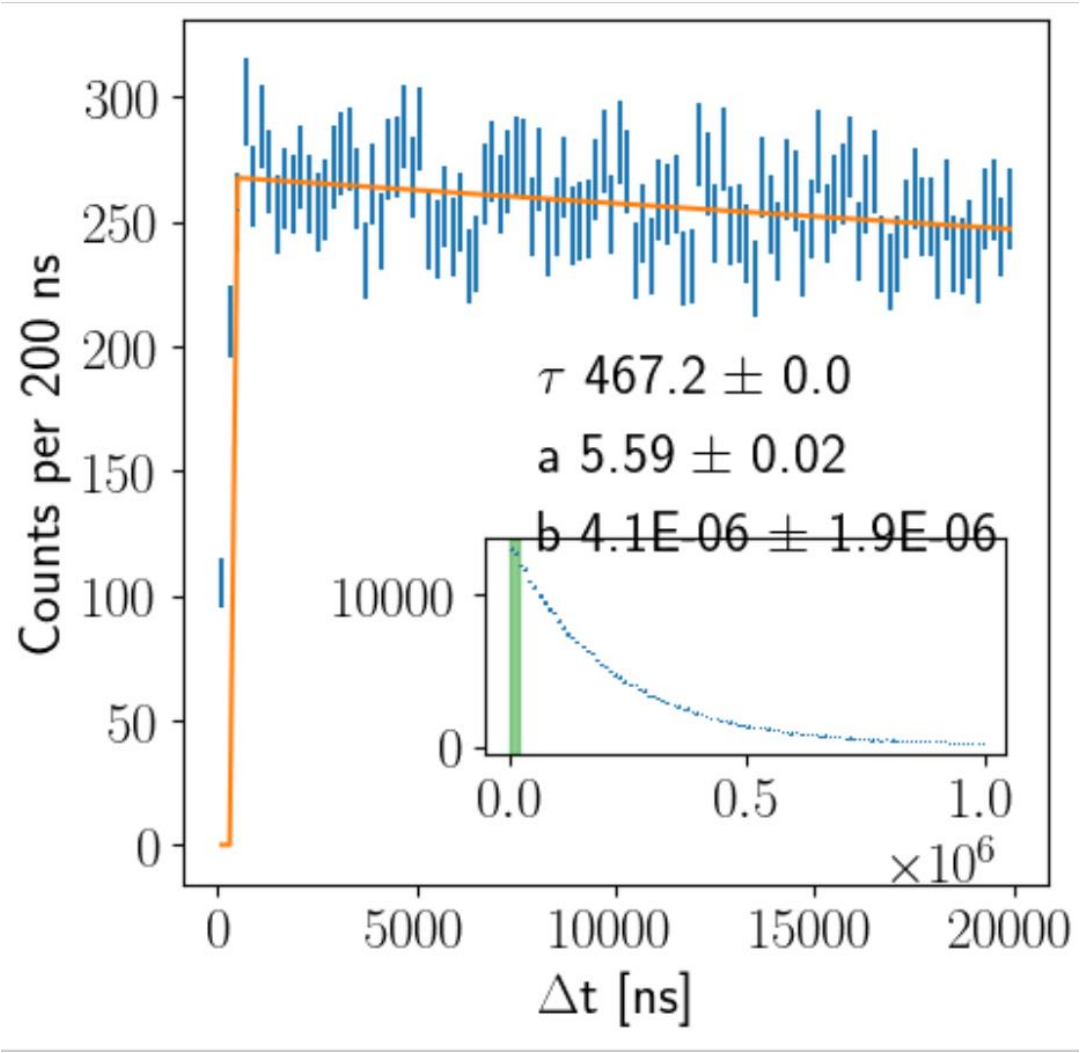
DAQ comparison – test setup





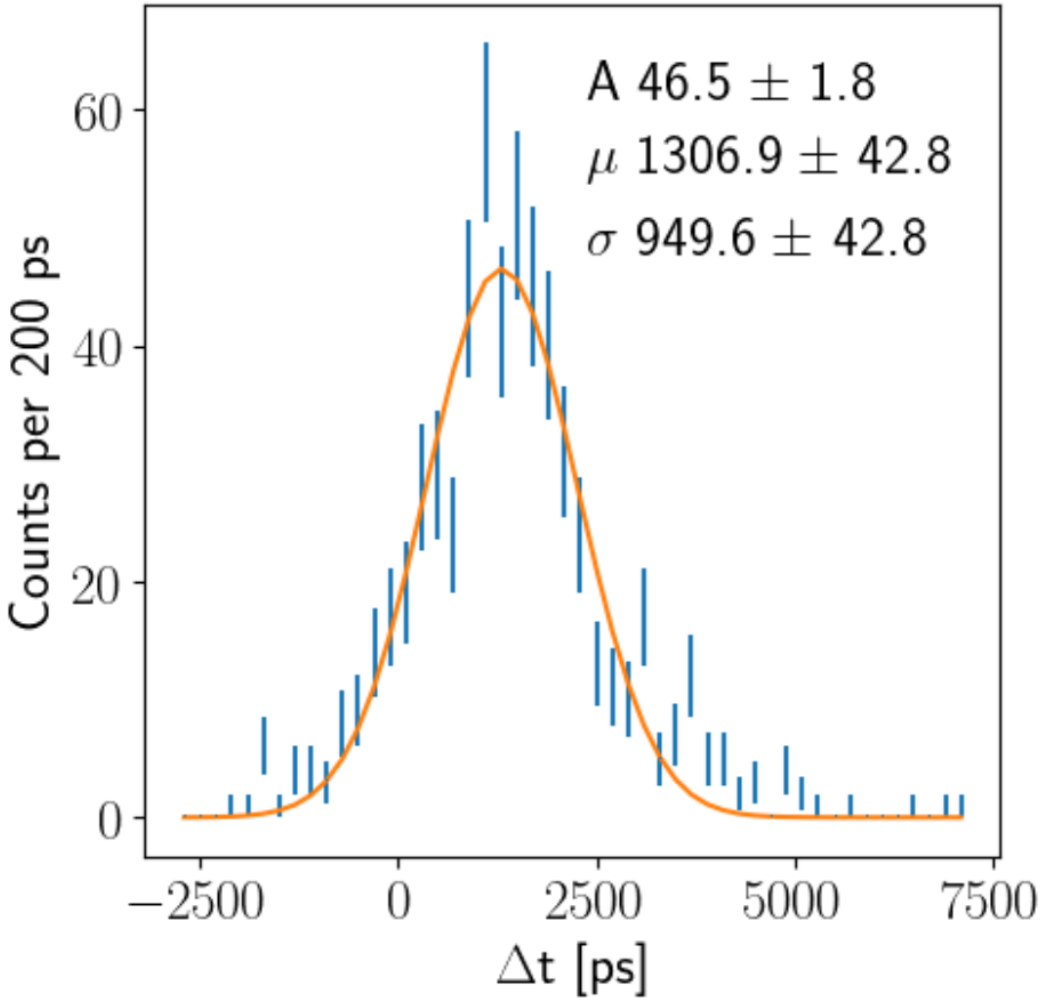
DAQ comparison – dead time

We observe **time interval** between subsequent events in one channel (TOFPET2), to assess the **dead time**



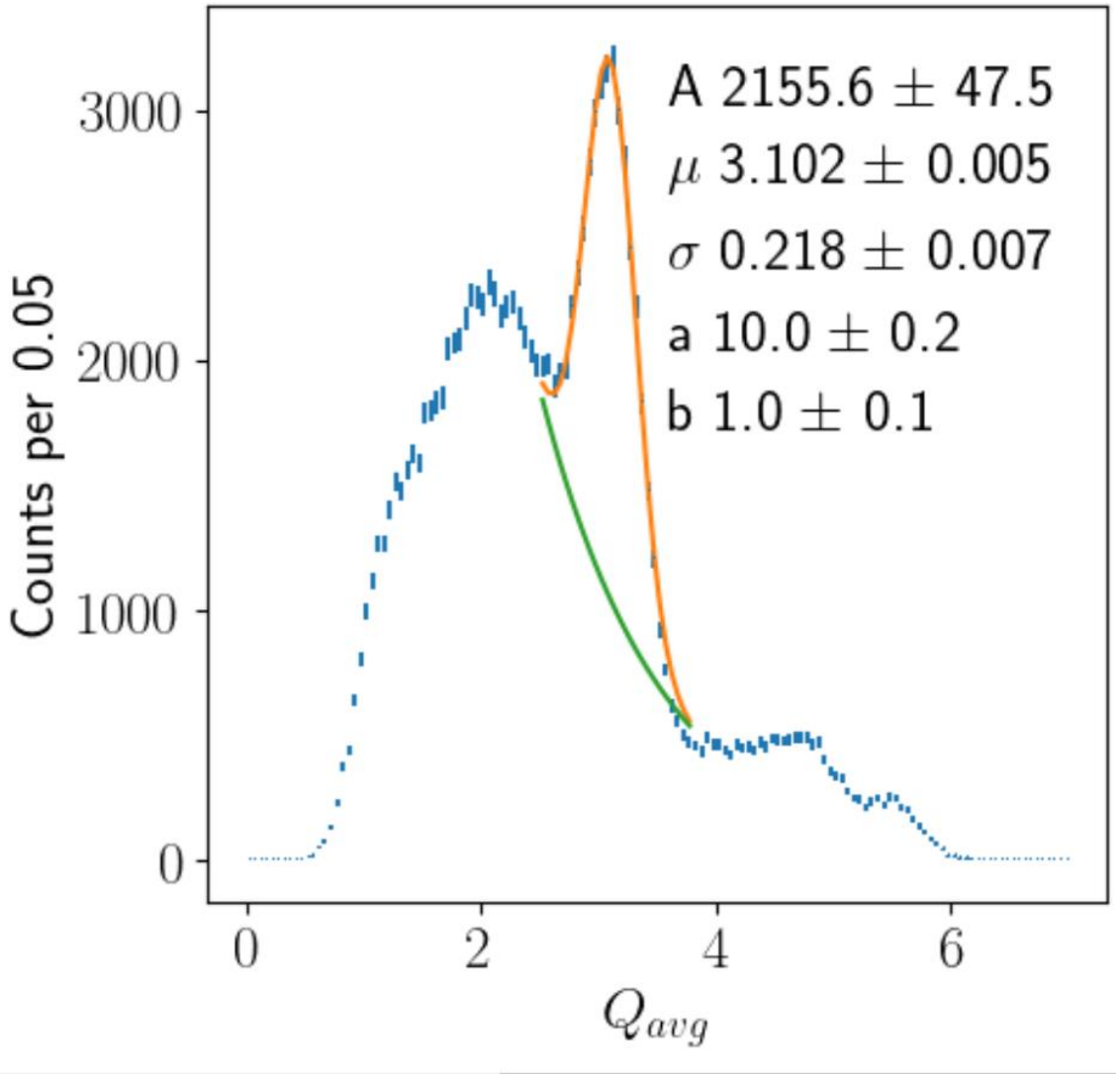
DAQ comparison – time resolution

We observe **arrival time difference** between two channels on opposite ends of the fiber (TOFPET2) to measure **time resolution** (sigma)



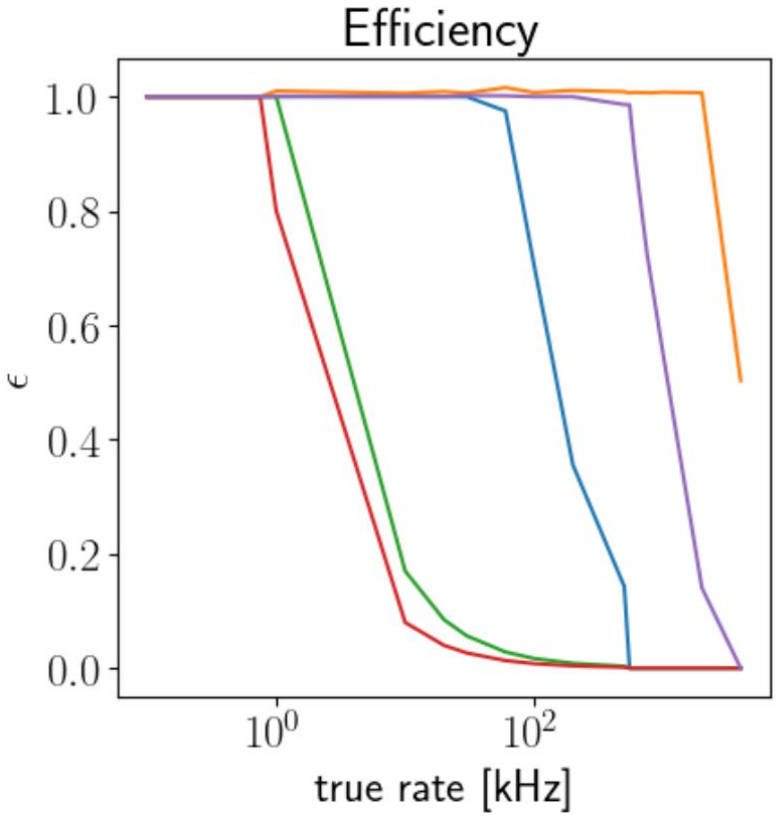
DAQ comparison – energy resolution

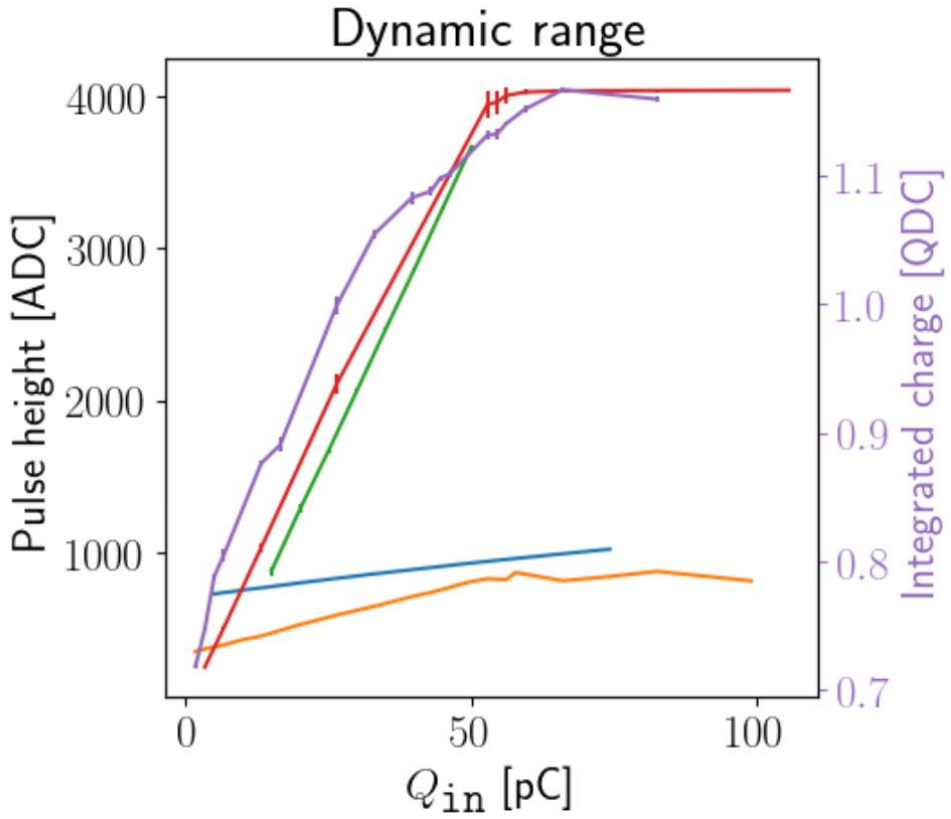
We observe Na-22 spectrum from a single LYSO crystal to assess the **energy resolution**, which is defined as sigma of the fitted 511 keV peak (TOFPET2)

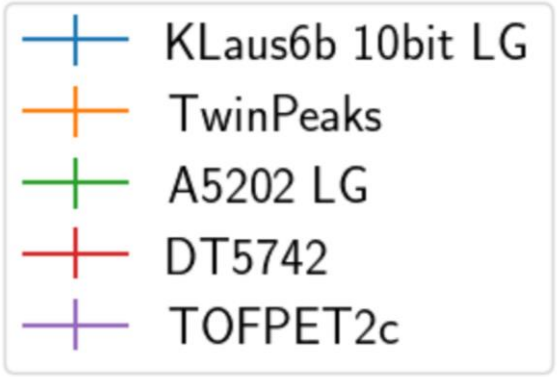


DAQ comparison - parameters

Dynamic range and **efficiency** (all systems) – injecting a simulated SiPM pulse (of variable frequency or amplitude) to the DAQs







DAQ comparison – preliminary results

System	Deadtime [ns]	Time difference, σ [ns]	Energy resolution [%]
DT5742	181†	1.152(0.001)	8.55(0.04)
TwinPeaks	870(9)	10.5(0.3)	11.1(1.3)
A5202	37082(0)	3.04(0.21)	9.39(0.30)
KLaus6b	100(?)	0.084(0.001)	15.7(0.1)
TOFPET2c	467.2(0.0)	0.79(0.02)	7.81(0.16)

Summary

- Feasibility of near-field CM technique for gamma sources has been proved with a small-scale detector module
- Preliminary results for the full scale module indicate that the detector is operational in clinical conditions. Detailed analysis in progress
- Comparative study of DAQ systems has been performed, the article on that topic will be available on arXiv by the end of the month

Thank you for your attention!

Project's website: bragg.if.uj.edu.pl/gccbwiki

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