Development of a high-resolution PET detector for small animal in-beam PET system

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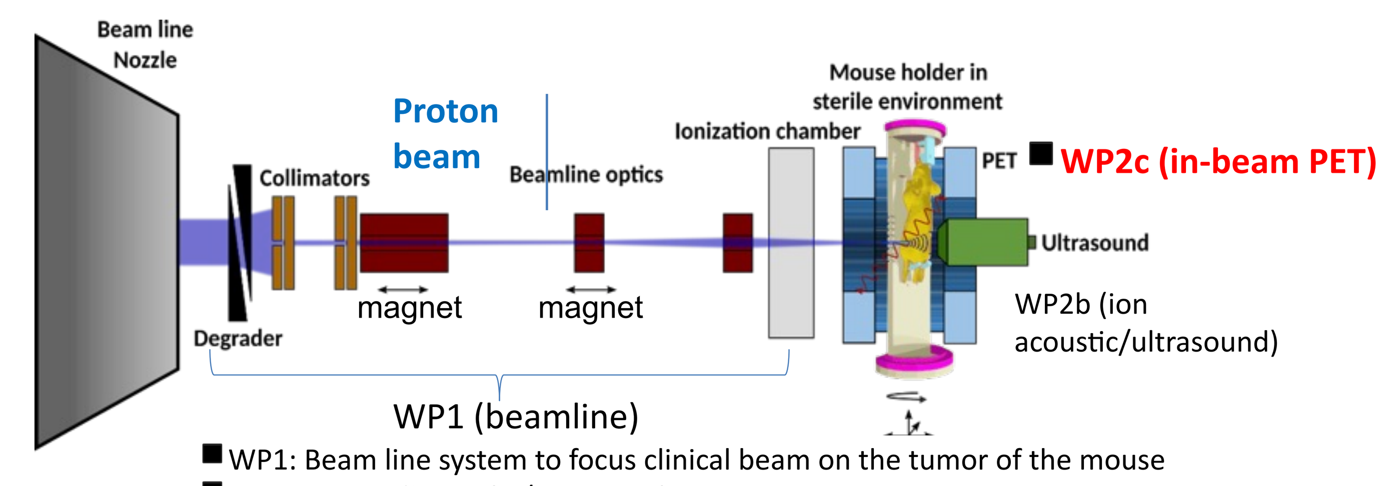
1. Introduction: SIRMIO project and high-resolution Small Animal in-beam PET system

Small animal proton Irradiator for Research in Molecular Image-guided radiation-Oncology: SIRMIO project [1] (www.lmu.de/sirmio)

The purpose of the SIRMIO project is to build a portable beam-line equipped with novel detector technologies for integration in clinical facilities. In-beam PET is used to image positron emitter distributions generated by interaction between the target and the proton beam



Novel technologies
- WP1: Beam line system to focus clinical beam on the tumor of the mouse
- WP2a: Ion radiography/tomography
- WP2b: Ion acoustics/ultrasound
- **WP2c: In-beam PET system for range verification of the proton beam**
- WP3: Adaptive treatment workflows & system integration/testing

Requirement and design

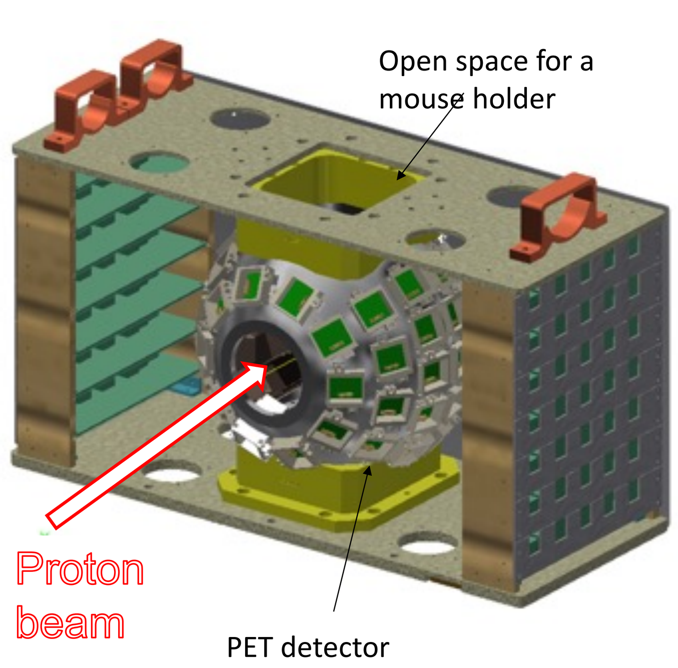
- Open space for beam directons,mouse holder and additional detectors (ionacoustic/US)
- High sensitivity for a few kBq positron emitters generated by the proton beam at typical treatment dose levels

⇨ Spherical shape

- Sub-millimeter image resolution for range monitoring in small animal
- Uniform spatial image resolution

⇨ High resolution depth of interaction (DOI) PET detector

In-beam PET scanner



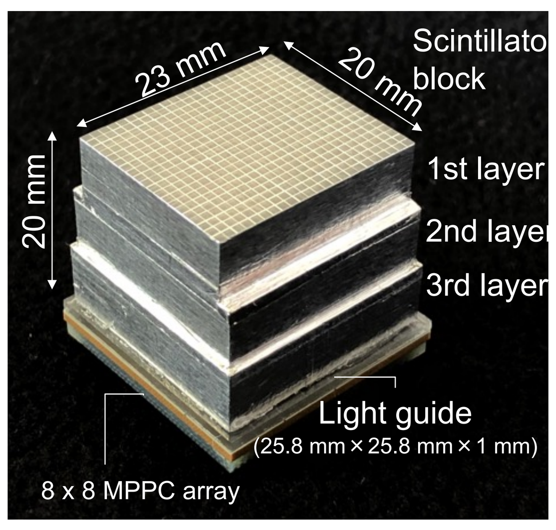
In this poster

- Introduction of the High-resolution DOI PET detector developed by us
- Two imaging performance studies:

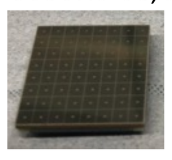
1. Imaging of point sources with the PET scanner designed for the SIRMIO project
2. Capability of our high-resolution PET detector for imaging of radioactive ion beams with in-beam PET system

2. Sub-millimeter resolution PET Detector

2-1 Detector components (collaboration with QST) [2]

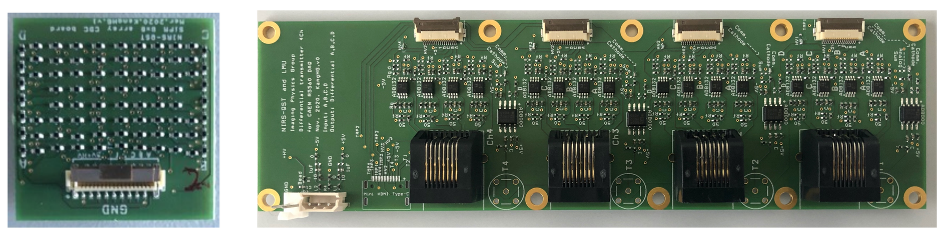


- Scintillator block: $Lu_{1.8}Y_{0.2}SiO_5$ (LYSO, EPIC/China)
  - Pixel size: 0.9 mm x 0.9 mm x 6.67 mm
  - 3 layer structure
  - 1st layer: 20 x 23 crystals 2nd layer: 23 x 23 crystals 3rd layer: 24 x 24 crystals
  - Reflector between scintillator pixels : $BaSO_4$
- Photo detector (SiPM)
  - Multi Pixel Photon Counter (MPPC, Hamamatsu photonics K.K, S14161-3050HS-08, Japan)
  - Array: 8 x 8 (64 signals)
  - Active area: 3 mm x 3 mm
  - Dimension: 25.8 mm x 25.8 mm
  - Optical coupling with RTV rubber (SE-420, shin-etsu, Japan)



- Readout circuit board

(a) Charge division circuit (CDC) (b) Amplifier circuit



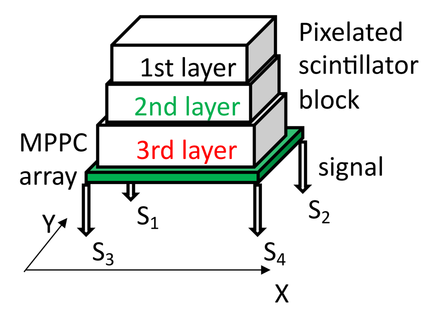
(a) CDC reduces 64 signals from the MPPC arrays to 4 single-ended readout signals.

(b) Amplifier board amplifies and coverts the single-ended readout to differential signals.

- Digitizer R5560 (CAEN, Italy)

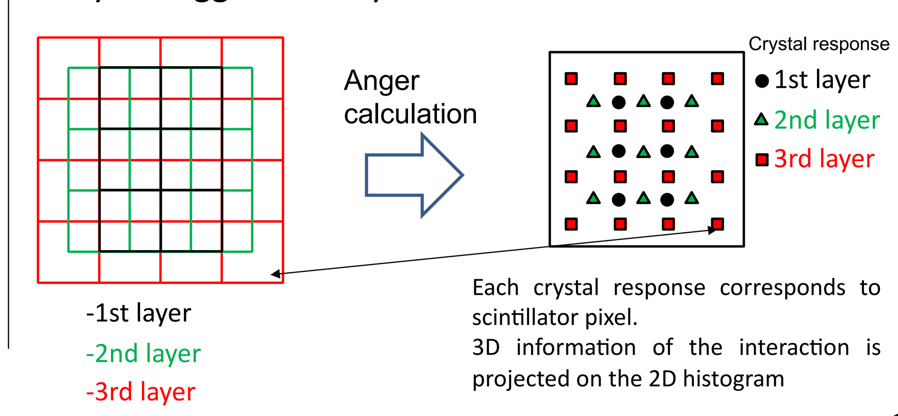
Input: Analog (differential signal ethernet cable, RJ45)
\# of channel: 128 channels (32 detectors)
sampling frequency: 125 MHz (default mode)
- FPGA is configurable to user's purpose
- Can operate as oscilloscope and in QDC mode
- External trigger is acceptable and can output logic signal.
- C++ libraries for data acquisition are provided by CAEN.
- Scalable with other CAEN digitizers.

2-2 Anger calculation



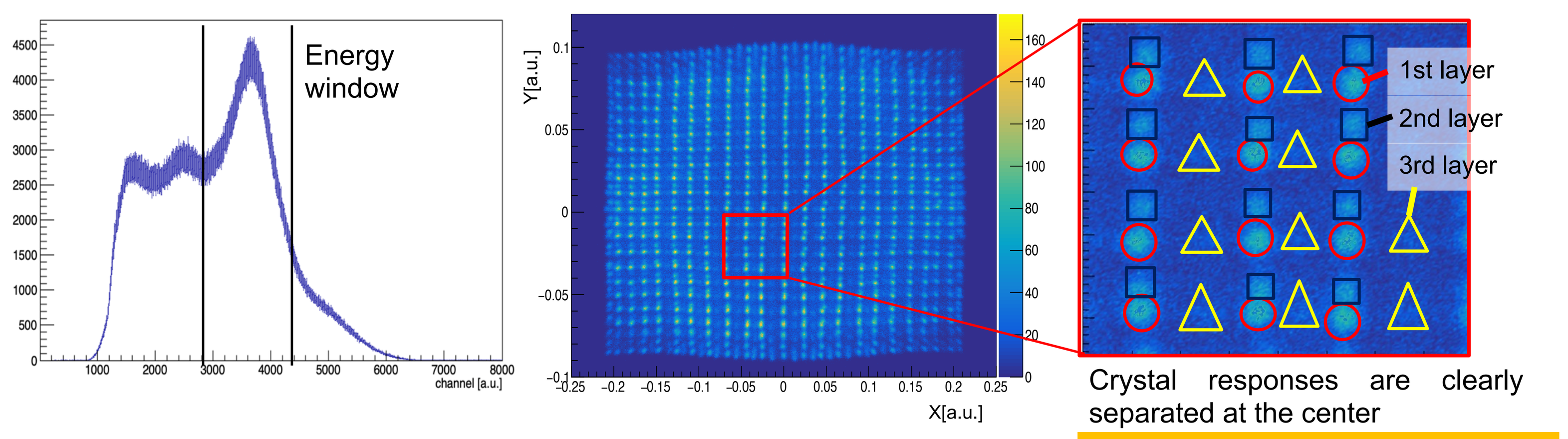
$$x = \frac{(s_2 + s_4) - (s_1 + s_3)}{\sum s_i}$$

$$y = \frac{(s_1 + s_2) - (s_3 + s_4)}{\sum s_i}$$



Each crystal response corresponds to scintillator pixel.
3D information of the interaction is projected on the 2D histogram

2-3 detector response (Na-22 source)



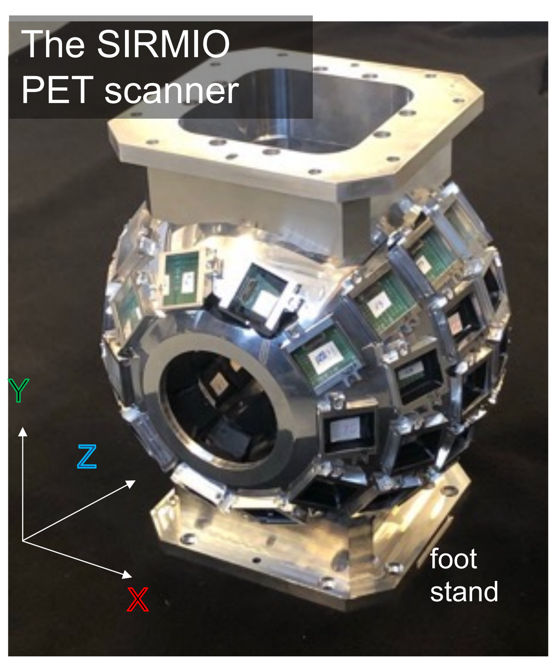
Crystal responses are clearly separated at the center

0.9 mm pixel resolution & 6.67 mm depth resolution

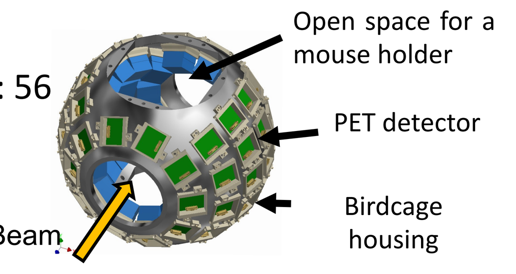
3. Imaging Experiment with the high-resolution PET detector

Image was reconstructed with the MEGAlib software which is Geant4 based simulation and reconstruction toolkit originally developed for Compton cameras [3]. Reconstruction of PET image has been implemented.

3-1 SIRMIO PET scanner (point source measurement)

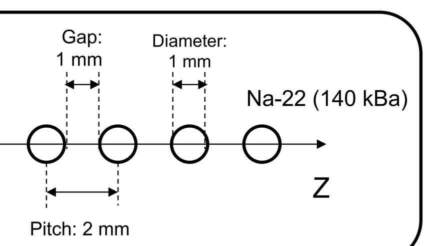


Geometry
- Inner radius: 72 mm
- Number of detectors: 56
- Number of rings: 6
- coverage: 44%

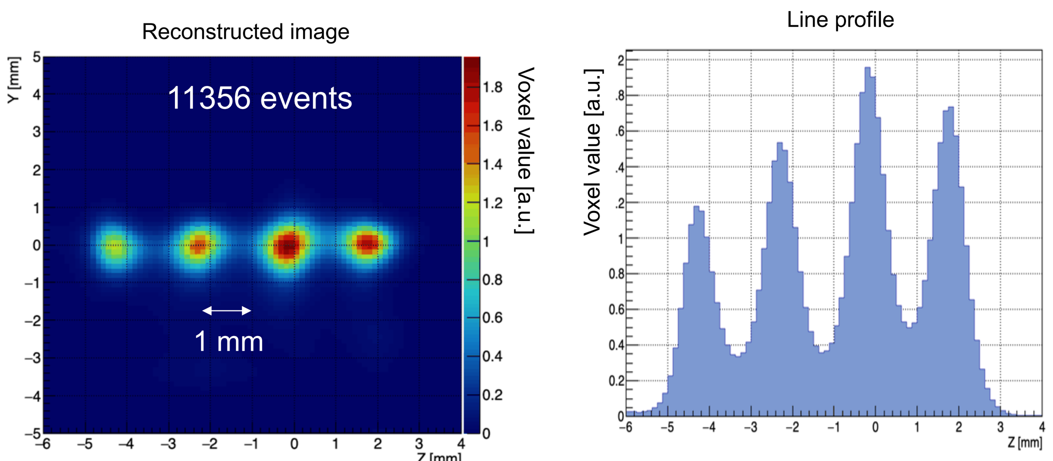


Na-22 source setup

A Na-22 point source with a diameter of 1 mm was placed 2 mm pitch along Z with a moving stage and measured for 2 minutes. Data of each point was merged and used for reconstruction.



Imaging result



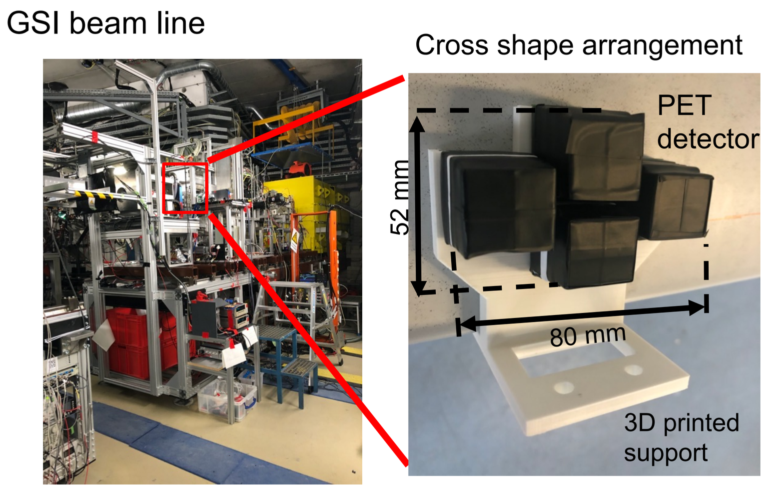
Outlook
- 1 mm imaging resolution is achieved.

3-2 Radioactive Carbon Ion Beam Imaging

"Biomedical Application of Radioactive Beams" (BARB) project at GSI Darmstadt [4] (www.gsi.de/BARB)

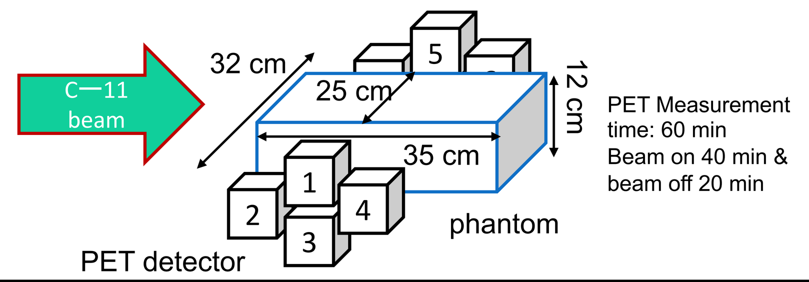
Goal of the BARB project is to exploit GSI's capability of generating radioactive ion (RI) beams to demonstrate their image guidance advances in small animal studies with a novel imaging system.

setting



Geometry and target

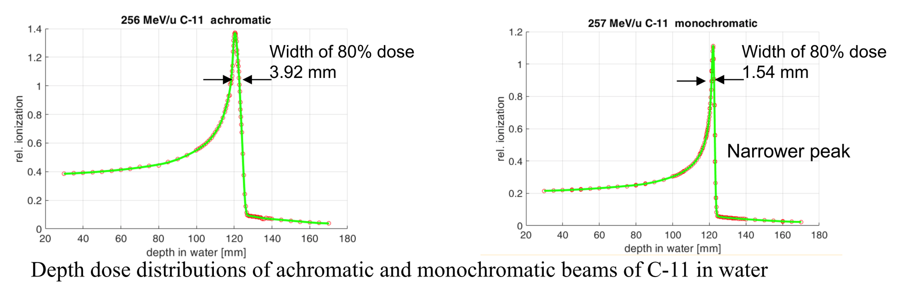
Phantom: PMMA (25 cm x 12 cm x 35 cm)
Phantom position was set so that Bragg peak was at the center of the PET FOV



Beam properties

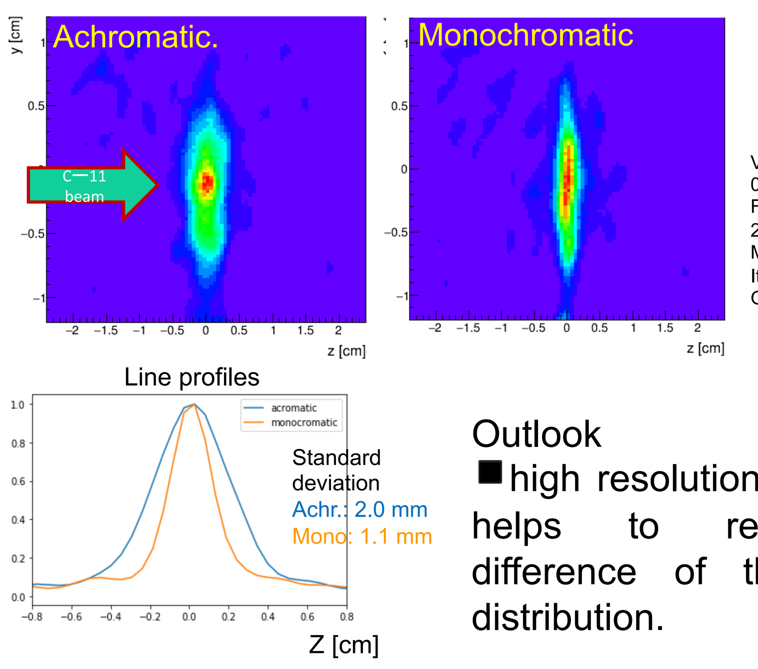
Ion: C-11, Intensity: ~10^7 particles/s

- Achromatic beam
  - Energy: 256 MeV/u
  - Momentum spread: 11.8 MeV/c/u
- Monochromatic beam
  - Energy: 257 MeV/u
  - Momentum spread: 2 MeV/c/u



Depth dose distributions of achromatic and monochromatic beams of C-11 in water

Imaging result



Voxel size: 0.5 mm x 0.5 mm x 0.5mm
Field of view: 2.4 cm(X) x 2.4 cm(Y) x 4.8 cm(Z)
Method: MLEM
Iteration: 8
Geometrical sensitivity correction

Outlook
- high resolution PET detector helps to resolve small difference of the RI beam distribution.

4. Conclusion & future work

- The SIRMIO PET scanner shows 1 mm image resolution.
- Our PET detector is useful for imaging the RI beam and resolving a few mm distribution difference.
- An experiment for imaging proton beams with the SIRMIO is planned in September 2022.
- Simulation study of the RI beams is ongoing for the BARB project in preparation of small animal experiments.

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References:
[1] K. Parodi, et al. Towards a novel small animal proton irradiation platform: the SIRMIO project; Acta Oncologica; *(2019), 58, 1470-1475*, [2] 2021, Kang et al., BPEX, vol 7, no. 3, pp. 035018, [3] G. Lovatti et al.,2020 IEEE NSS/MIC, M-08-275, [4] *Durante M and Parodi K (2020) Radioactive Beams in Particle Therapy: Past, Present, and Future. Front. Phys. 8:326.*