AS Thematic meeting:
Project summary

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Outline

- Summary of the accomplishments in AST 2019-2021
- Next steps
Project motivation

- Range verification in particle therapy
- TOF-PET imaging
- Imaging anatomical changes during particle-therapy treatment
- Non-destructive imaging of any material sample?
Background

Depth distribution of dosed secondary particles due to protons interaction in water

Proton range vs energy in water and PMMA

GATE/Geant4 simulation
QGSP_BIC_EMY physics list
Major outcomes

- TOF-PET development
- KE-PET simulated and performance
- Ti marker for range verification
- 3D-PG detection method

Other works
- AI for mapping detector activity to dose
- Flatness calibration of a beam monitor
PAG: initial tests

Setup

16 channels vs 16 channels of detector used for a beam test

Each channel:
SiPM 3x3 mm² + LYSO 3x3x20 mm³
Readout:
STiC ASIC evaluation kit
Target: PMMA 4cmx8cm face, 12.5 cm thickness (beam)
Beam: 130 MeV protons
PAG: initial tests

Coincidence counts
Predicted counts of 511 keV from coincidences match the simulated values.
Ratios of the PAG isotopes were measured.

Proton Beam

Counts normalized to peak (%)

Counts - experimental
Positron emitters simulated
Dose CGMH
Coincidences - simulated

Dose deposited

0 20 40 60 80 100 120
Depth (mm)

0 20 40 60 80 100 120
Counts

Experimental measurement

Entries 91
Mean 341.3
Std Dev 257.6

511 keV coincidences

time (s)
ASPET palm sized module development
Front end board 1

Front end board 2

Mother board

FEB1+FEB2 → Crystal+SiPM → Detector with mechanics

Assembly of palm-sized module (5cm x 10cm)

Status:
- Hardware, DAQ, software design, development and testing complete. ✓
- Successfully obtained an initial image with a radioactive source in the laboratory. ✓
- Simulation and reconstruction are ready. ✓
- Assembly, optimization and calibration in progress.
- Preparing for a test at the proton center.

Currently supports 1028 readout channels

PET framework for small animal testing

*Supports 8x512ch
ASPET palm sized modules x2
Test conditions

- Detector separation : 5.5 cm
- $T_{\text{box}} = 25^\circ\text{C}$
- $T_{\text{room}} = 23-24^\circ\text{C}$
- Na$^{22}$ activity = 3.194MBq (171201)

Gamma activity image reconstructed from the coincidence signals measured by the detector. The radioactive source is moved along the detector axis; a corresponding change in the image (yellow spot) is observed. Source shifts in 1.5 mm steps can be seen in the image to the right.

Geometry: Single or multiple pairs of coincident modules
- 1536 channels
- 2 modules
- Simulated on GATE
- D = 50 cm (distance between modules)

Goal is to develop at least 2 modules
- D = 15.48 cm
- 5.16 cm
- 6144 channels
- 12 modules

Brain PET / InBeam PET / animal PET
- 1024 channels
- 2 modules

Salient aspects of ASPET:
- Modular design allows us to scale the detector and configure in several geometries including full body PET
- Compact design suitable for applications with tight constraints such as proton therapy.
- Spatial and time resolution comparable to the state of the art TOF-PET systems.
- High data rate (25Mcps per module design limit)
- Ideal for in-vivo range verification, nuclear-medicine TOF-PET imaging, hypoxia measurement etc. Ultrafast timing capability.
- Radioactive source is a positron emitting isotope Na$^{22}$ which emits coincident gamma with 511 keV energy.
Gamma activity image reconstructed from the coincidence signals measured by the detector. The radioactive source is moved along the detector axis; a corresponding change in the image (yellow spot) is observed. Source shifts in 1.5 mm steps can be seen in the image to the right.

*Radioactive source is a positron emitting isotope $^{22}\text{Na}$ which emits coincident gamma with 511 keV energy.
ASPET palm sized modules x2

511 keV source  FOV: 10.24 cm x 5.12 cm

$^{22}$Na source in the center, D=5.5 cm
Axial position L-52mm
Line of response reconstruction

Gamma activity image reconstructed from the coincidence signals measured by the detector. The radioactive source is moved along the detector axis; a corresponding change in the image (yellow spot) is observed. Source shifts in 1.5 mm steps can be seen in the image to the right.

Geometry: Single or multiple pairs of coincident modules

1536 channels 2 modules
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Brain PET InBeam PET /animal PET
1024 channels 2 modules

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Components used to assemble the module

Small-animal enclosure, $D=11.5\text{cm}$

Module placed inside the small-animal frame
Figure: Left: Schematic representation of the 512 channel TOF-PET module with the self-sufficient mechanics and cooling. Each module is connected to the motherboard through a USB C type connection that supplies the requisite power, enables the controls and transmits the data. Right: A schematic representation of a small animal PET system, alternatively useful to test on a small animal for range verification.
Prompt gamma imaging
Can we predict the range shifts?

Knife-edge collimator + PET module

Cylindrical PMMA phantom
H=110.4 mm, \( \phi = 200 \) mm

Proton beam

Tungsten collimator

Detector

\[ \alpha = 53.12^\circ \]

102.4 mm

110.4 mm

190 mm

190 mm

40 mm

Compact palm size PET modules
32 columns, 8 rows
3x3x20 mm\(^3\) LYSO crystals
3x3 mm\(^2\) SiPMs
Knife-edge collimator + PET module

90 MeV protons (2E9)

8 cm vs 4 cm collimator

Shifts predicted by the detector

Residual of the deviation from the detected and expected shift

We can predict range-shifts within ±1 mm

GATE/Geant4 simulation

We can predict range-shifts within ±1 mm

8 cm vs 4 cm collimator

Shifts predicted by the detector

Residual of the deviation from the detected and expected shift

GATE/Geant4 simulation
Fiducial marker

Protons on Ti target

Experimental measurement

The increasing gamma counts at beam energy with a given R80 (80% BraggPeak) position match with the Ti marker position.

Schematic setup of an energy scan of protons (70-90MeV) irradiated on Ti+water

984 keV gamma counts at different proton energies marked by the R80 position (mm). The position of Ti target is indicated by the brown region.
Position detection of PG

Schematic of module design
Position detection of PG
Simulated beam scan

40 MeV protons (2E9)
range 14.9 mm

Detector:
8 sectors, 3 modules each
sector-sector 2.5mm spacing

Module: 7cm
(radial)x4cm(theta)x10cm(axial)
LYSO
Two 7cmx4 cmx30 cm
collimators BGO,
2.5mm collimator gap (5.6mm resolution FWHM)

Target: 8cm x8cm x15 cm
water

GATE/Geant4 simulation
NEXT STEPS
Next steps

• Software integration
  • Realtime reconstruction, AI for direct mapping

• Optimization, final mechanical drawings, backup mechanics

• Lab and beam tests

• Publications to summarize our results
Next steps

- 2 PET modules to be assembled: targeted December
- +2 PET modules between March-May
- Assembly, calibration, optimization: November onwards
- Year 2022: laboratory tests + Beam tests PET
  - getting the results for industrial collaboration
- Prompt Gamma, subject to time/resources:
  - parallel investigations with CGU/NTU collaborators
  - Beam tests for gamma production cross sections - Summer 2021
Proton beam:
single position

Energy: 90MeV
Target: PMMA/Water
Range shifts: moving target
tumor site

EPID

Couch

Gantry position 1

Gantry position 2

Gantry position 3

Gantry position 4

Photon beam: multiple positions

Energy: 1-10MeV
Target: PMMA/Water
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Updates

• PET modules assembly complete:
  • Left: 256 channels, 50%, 4 chips diagonal arrangement
  • Right: 512 channels, 100%, 8 chips fill

• Two sets of read out boards (1024 ch) will be ready by 2021 end
Time difference (single channel)

Test pulse

Single chip PLL locking against a test pulse

Time difference of consecutive events is plotted below

Tcc bin = 1.6 ns
delta time coarse

Tfine bin = 50 ns
Time difference
Coincidences across two single channels from opposite boards against a reference test pulse.

Ch63 STIC1

Ch63 STIC2

Experimental measurement

COINCIDENCE

Test pulse

133 ps FWHM
COINCIDENCE

Gamma source - single channel pair

Coincidences vs VBias

Experimental measurement

\[ T_{box}=25^{\circ}C, \quad T_{room}=23-24^{\circ}C \]

- right0 G1S3 ch33
- left1 G3S1 ch30
Energy spectra

16 channel spectra of **time over threshold**

**LYSO BG spectrum**

- $^{176}$Lu$_{71} \rightarrow ^{176}$Hf$_{72}$ ($\beta$ decay)
- followed by $\gamma$ emission
- $202\text{ keV}, 307\text{ keV}$

**Na$^{22}$ spectrum**

- $511\text{ keV}, 1274\text{ keV}$
NOTE: Displays the topology of the channels - can be a static image with an indicator to show which chips are active.