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Development of self-calibration techniques for γ -ray energy-tracking arrays

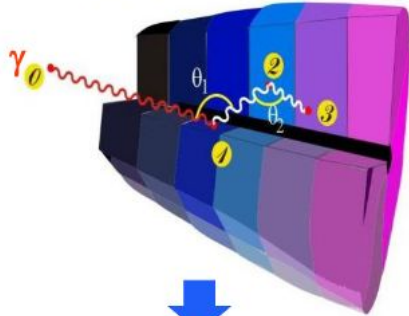
Sidong Chen¹, Michael Bentley¹, Stefanos Paschalis¹, Marina Petri¹,
Marc Labiche², Fraser Holloway³, and the **AGATA collaboration**

1. University of York, 2. STFC Daresbury Laboratory, 3. University of Liverpool

PSD13, 2023, Oxford

Gamma-ray tracking array

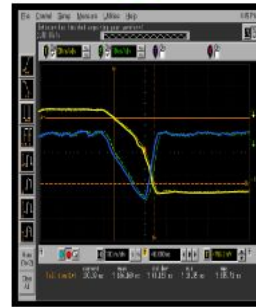
Highly segmented
HPGe detectors



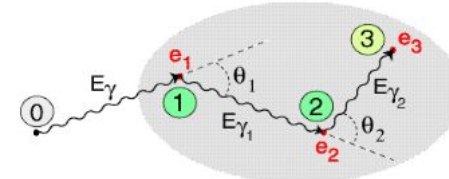
Digital electronics,
record signals

Identify (x, y, z, E, T)

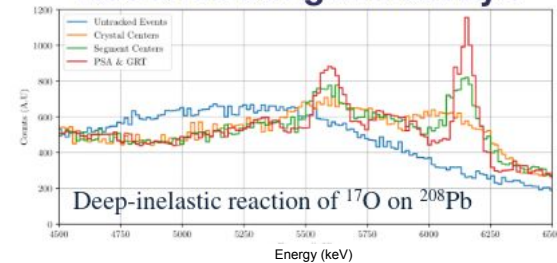
Pulse Shape Analysis



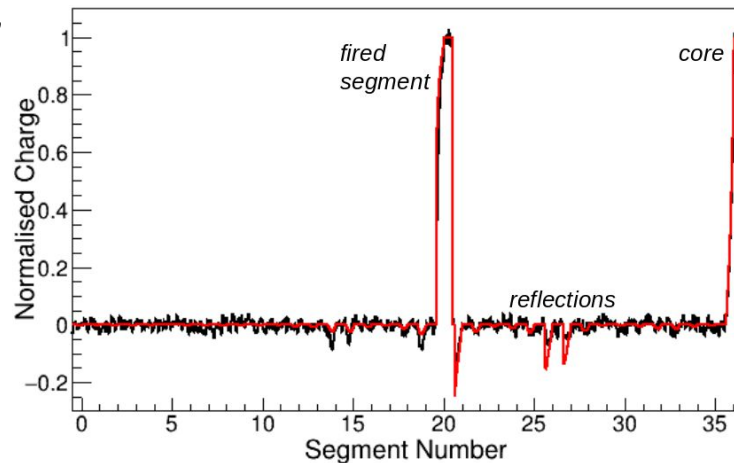
Track interactions



Reconstruct gamma rays

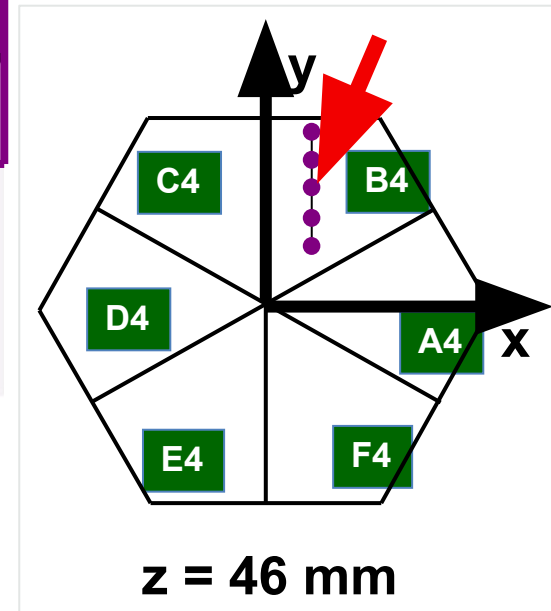
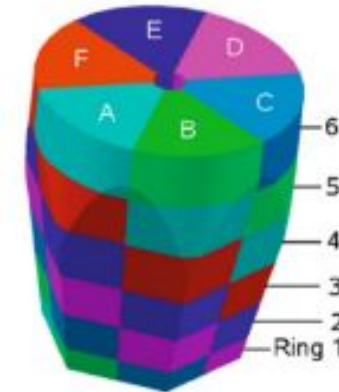
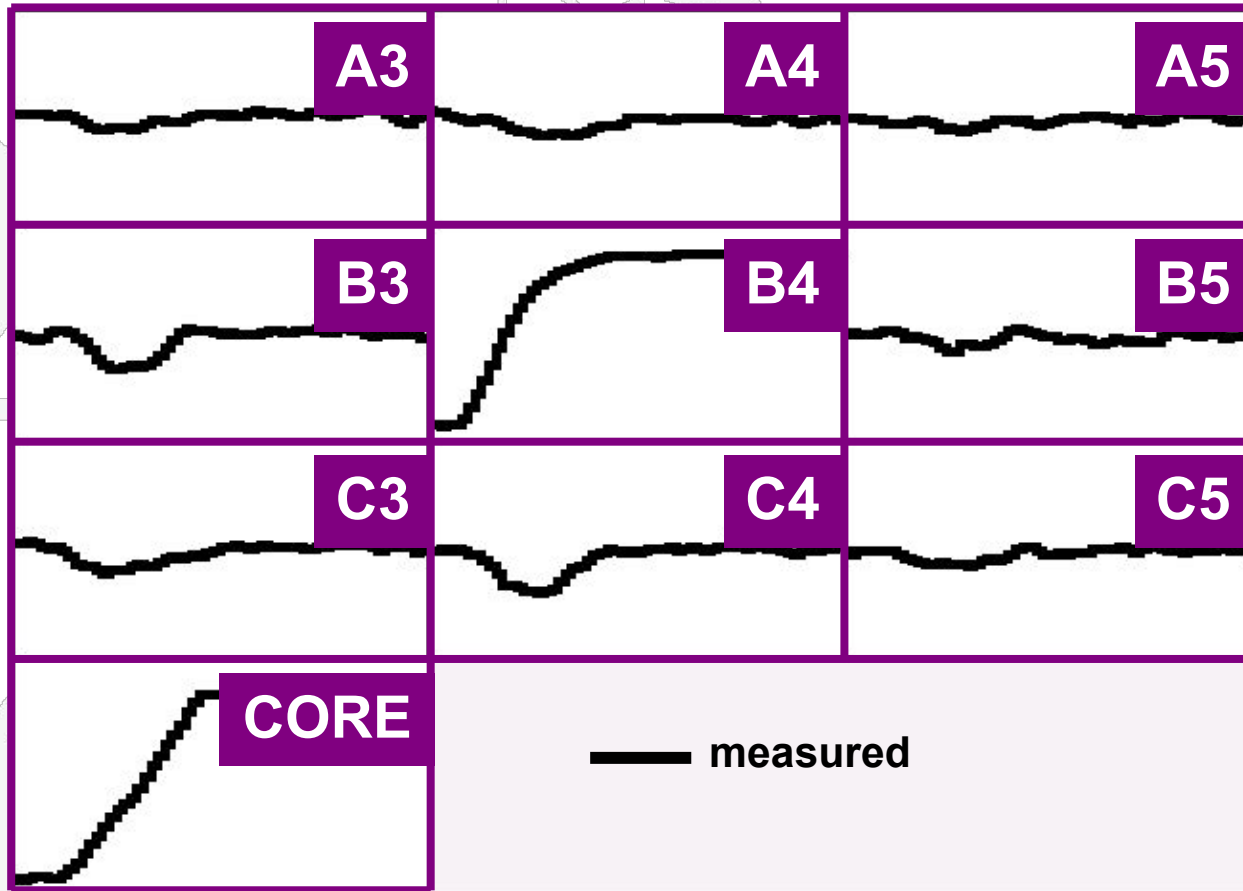


PSA:



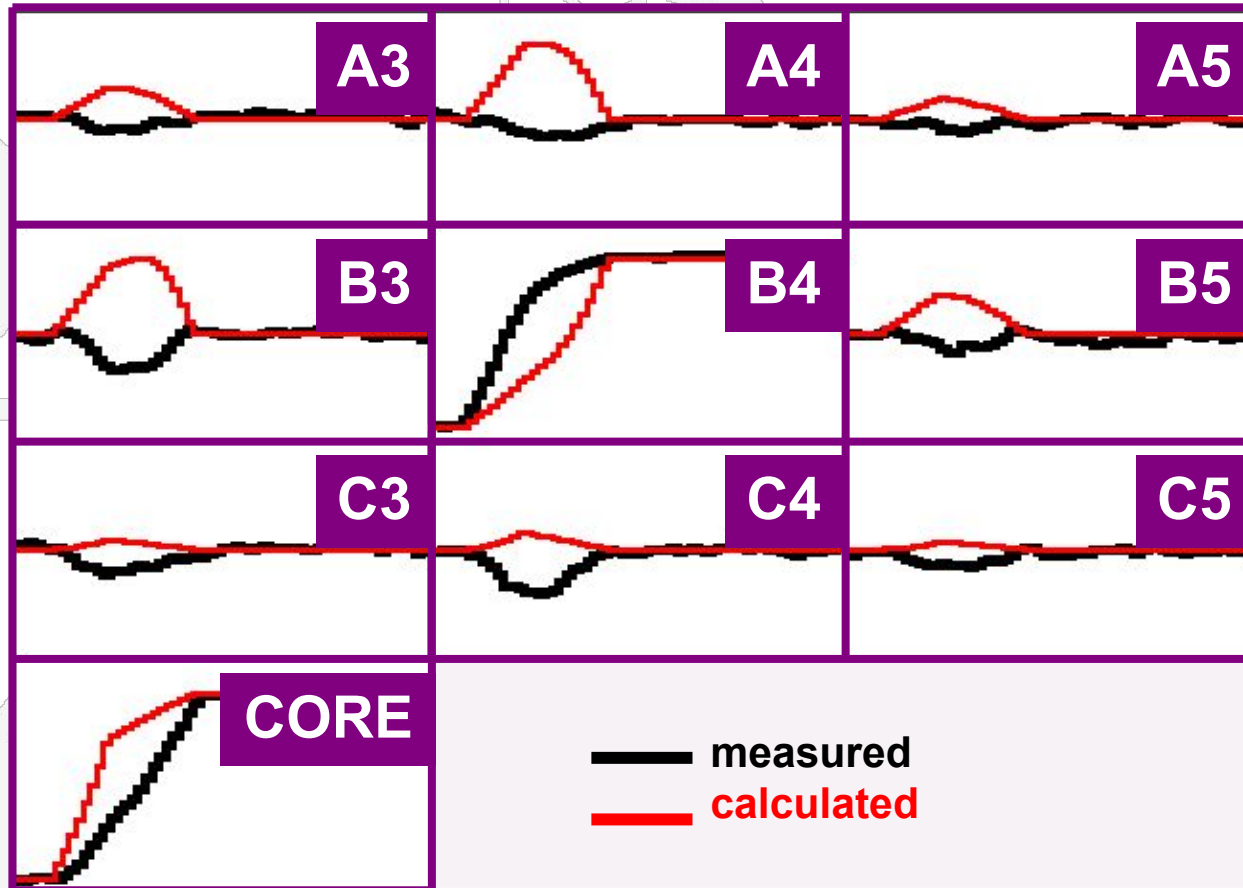
- Gamma-ray tracking array: highly segmented HPGe (36 segments)
- Pulse Shape Analysis (PSA)
=> interaction position
- PSA performed by comparing with **signal basis** for every detector

Pulse Shape Analysis concept



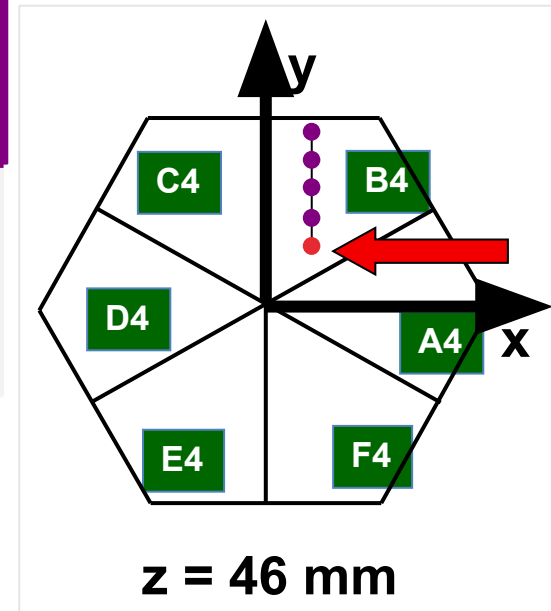
791 keV deposited in segment B4

Pulse Shape Analysis concept

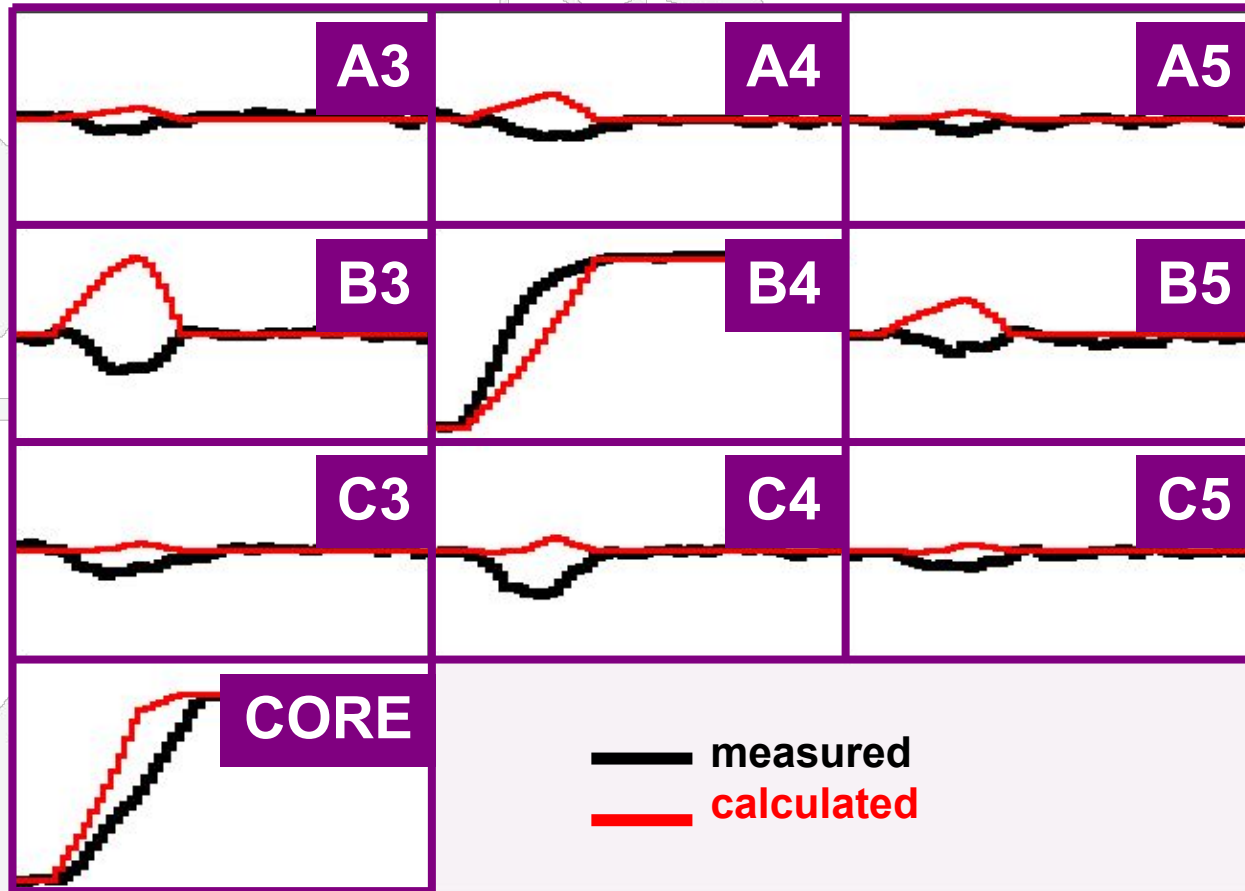


(10, 10, 46)

791 keV deposited in segment B4

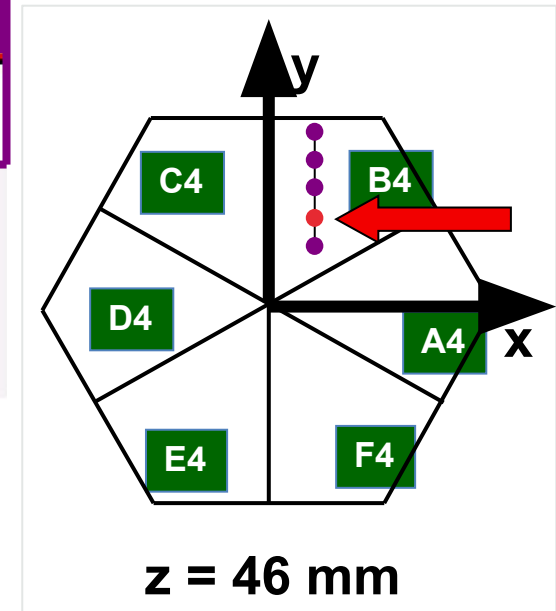


Pulse Shape Analysis concept

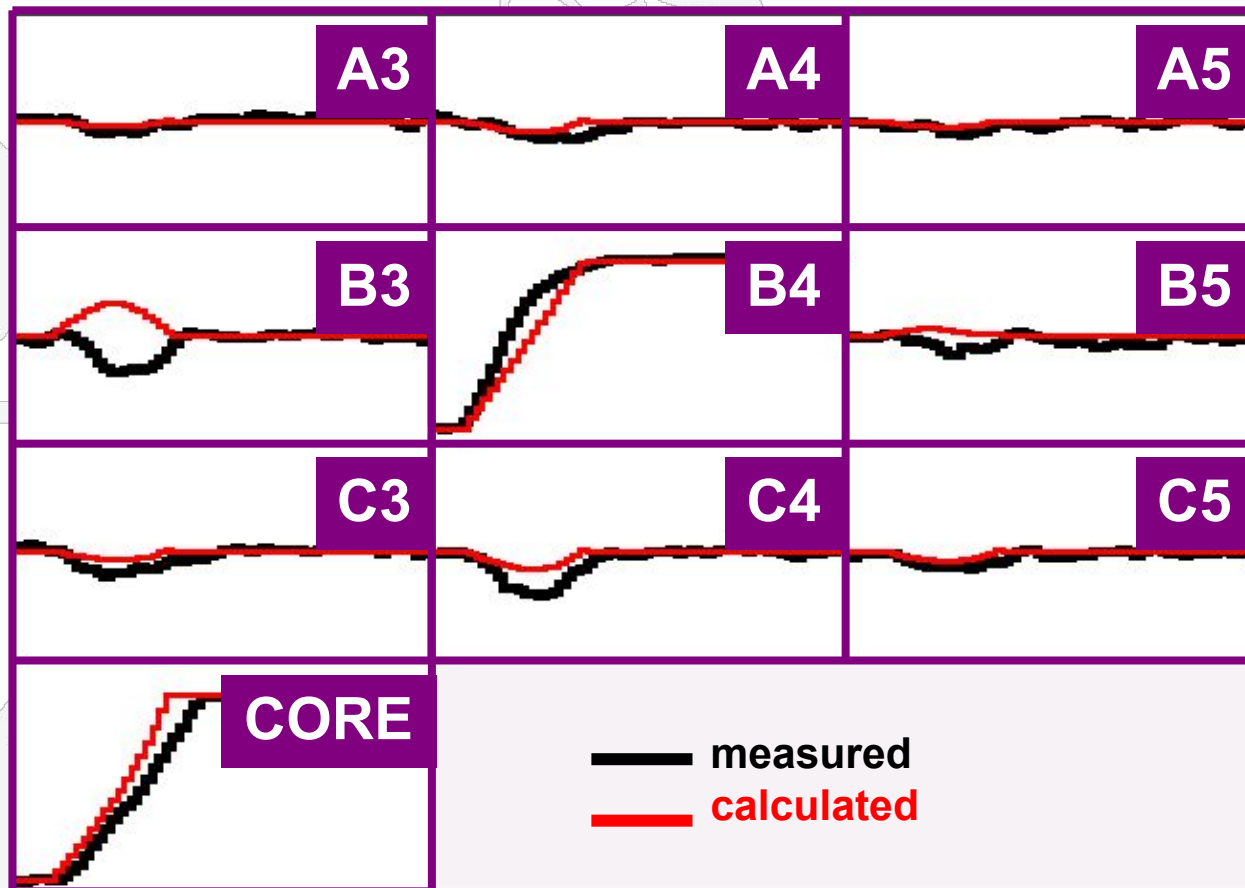


(10, 15, 46)

791 keV deposited in segment B4

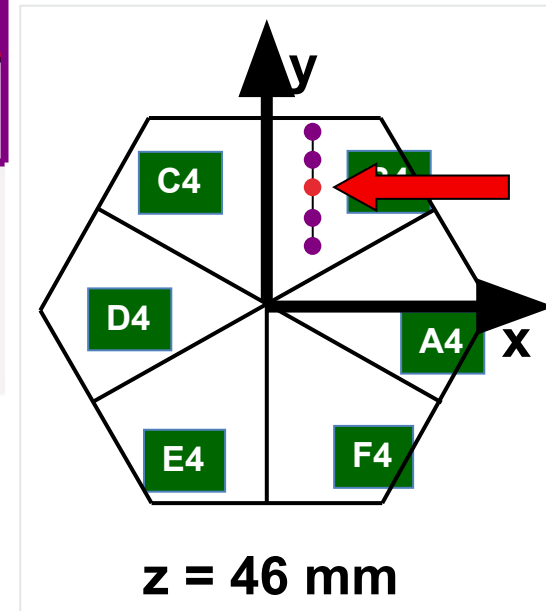


Pulse Shape Analysis concept

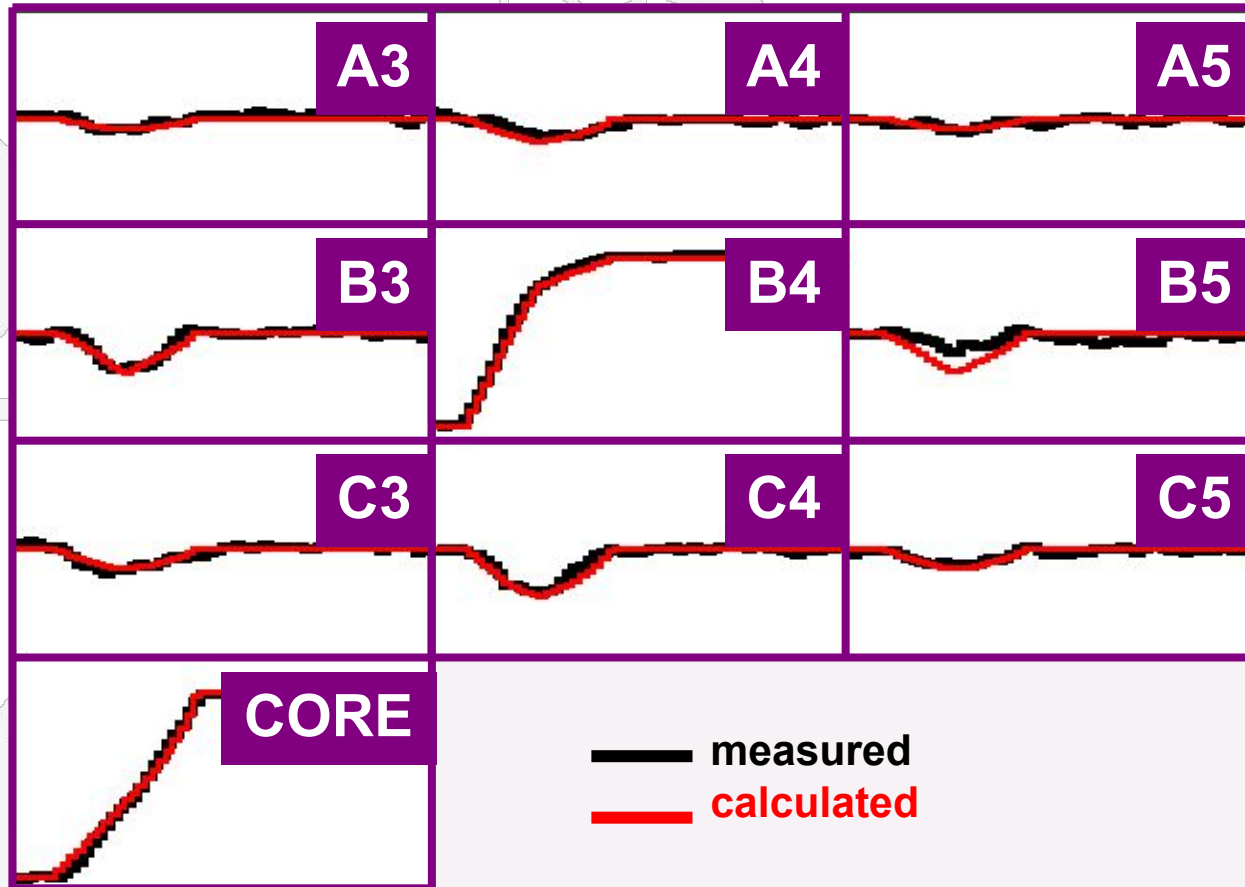


(10, 20, 46)

791 keV deposited in segment B4

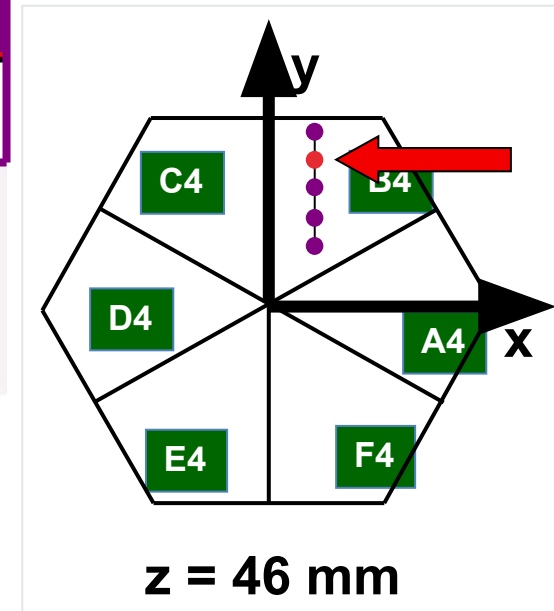


Pulse Shape Analysis concept

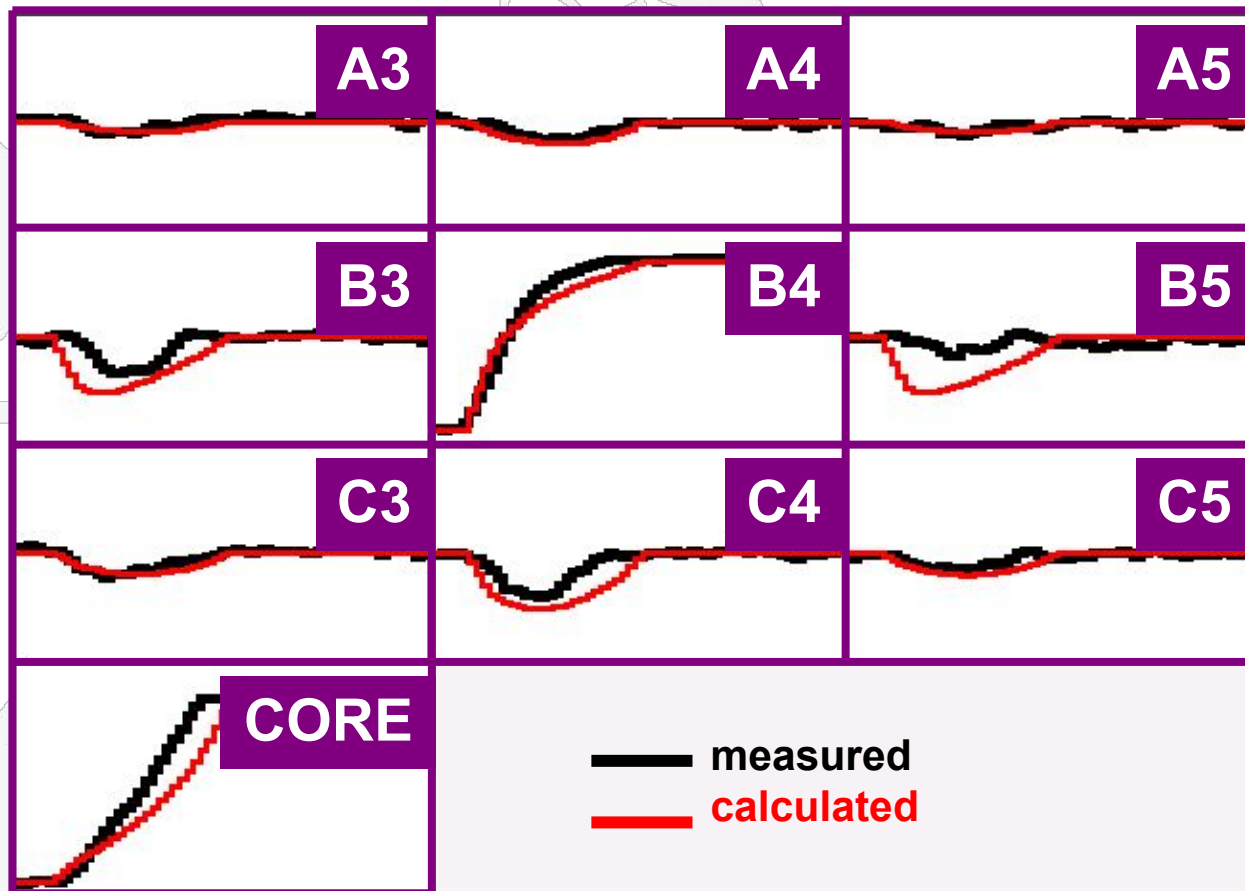


(10, 25, 46)

791 keV deposited in segment B4

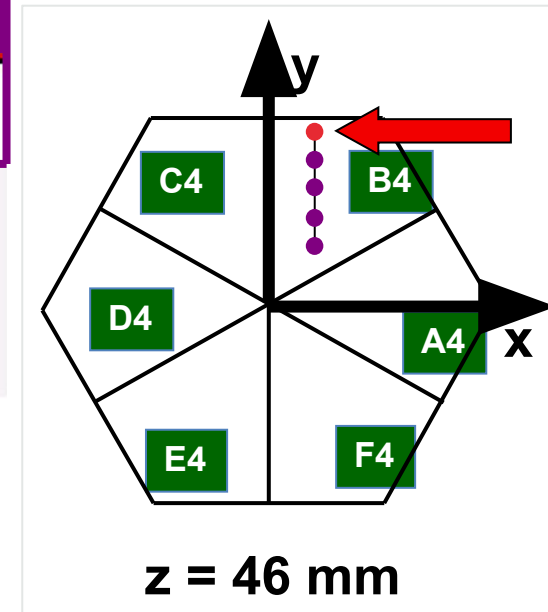


Pulse Shape Analysis concept

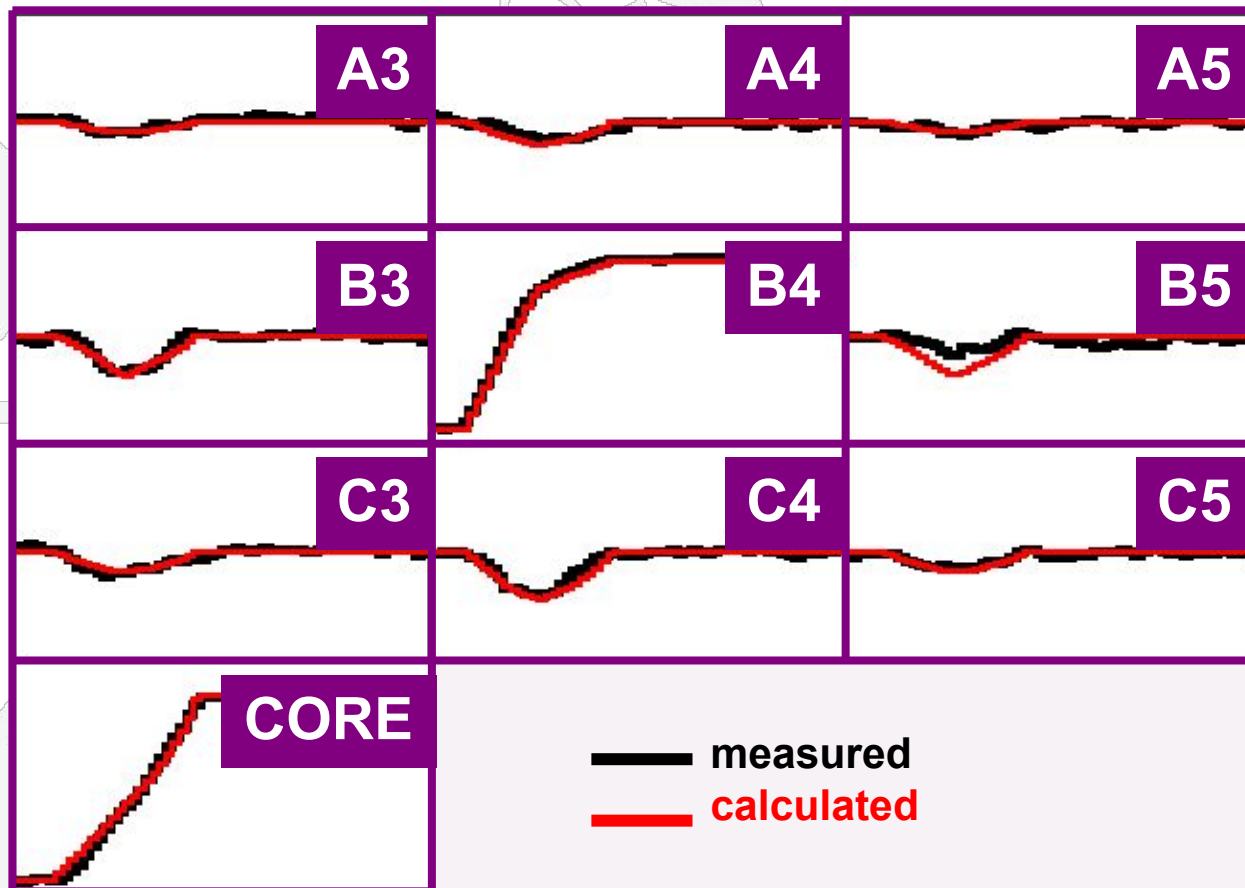


(10, 30, 46)

791 keV deposited in segment B4

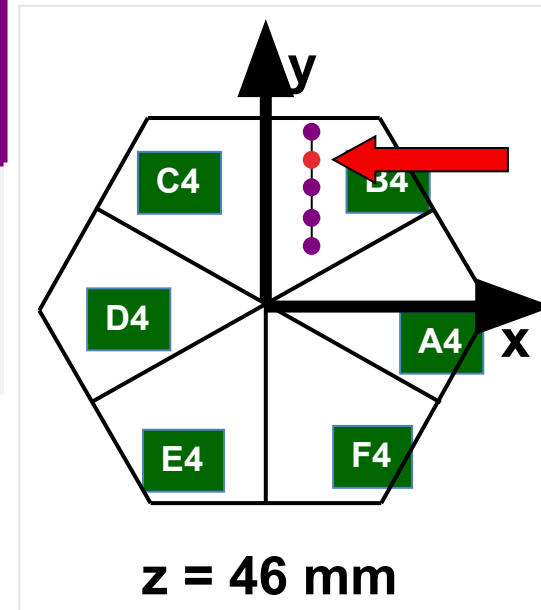


Pulse Shape Analysis concept



Result of
Grid Search
algorithm
(10, 25, 46)

791 keV deposited in segment B4



Current challenges

signal basis generation

Experimental (scanning)

- long acquisition times
- different conditions between scanning and experiment, e.g. noise, radiation damage
- mechanical alignment

Analytical (calculated)

- intrinsic space-charge density
- the electron/hole mobility
- crystal temperature and
- crystal orientation
- passivated and contact thickness
- shape of charge cloud

Self-calibration concept

- Generate signal basis in experimental way

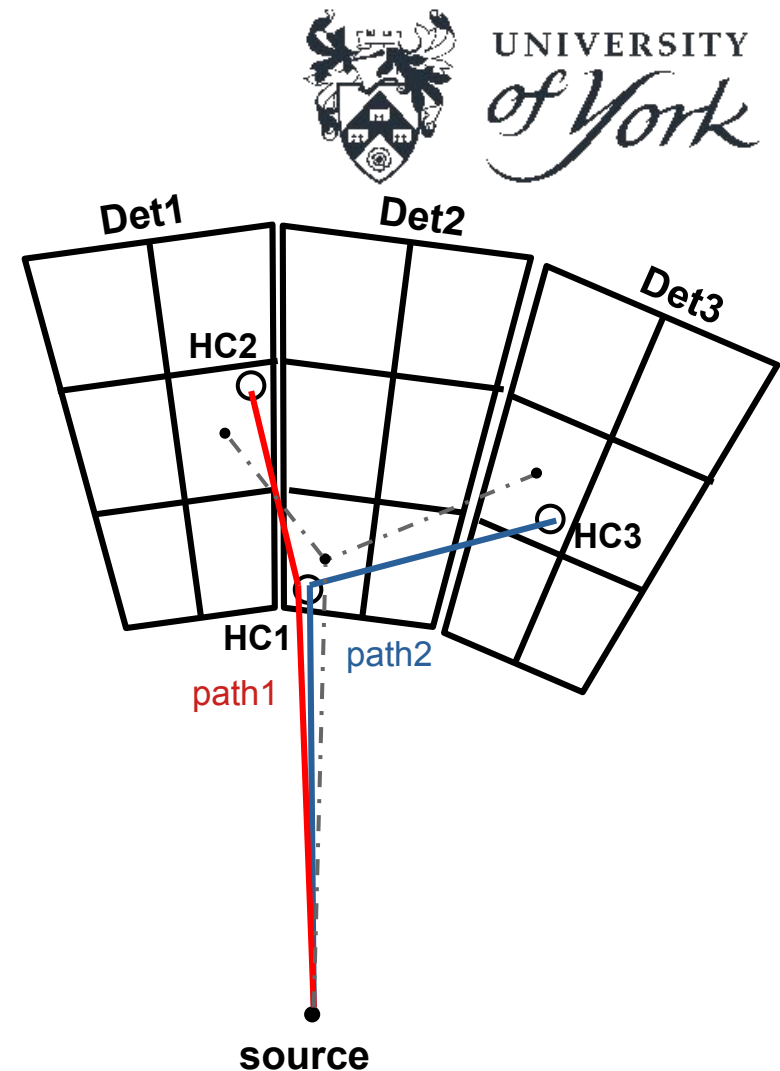
S. Heil, S. Paschalis, and M. Petri, Eur. Phys. J. A (2018) **54**: 172

Group interaction points from different gamma-rays into hit collections

Optimise coordinates of hit collection using the tracks that link their constituent points and Compton formula

Use Compton formula to order interaction points

Define tracks between interaction points that also link the hit collections with each other

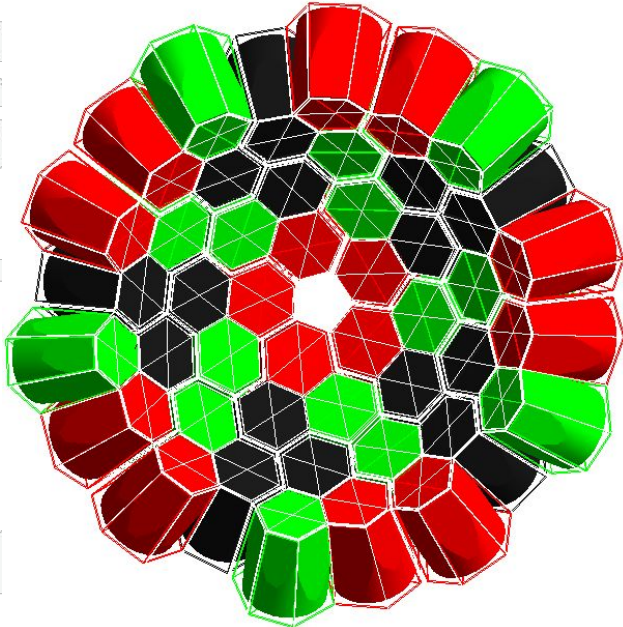


- Produce pulse shape basis for all detectors
- Strong gamma source illuminate the whole array
- Compton formula optimize scattering events

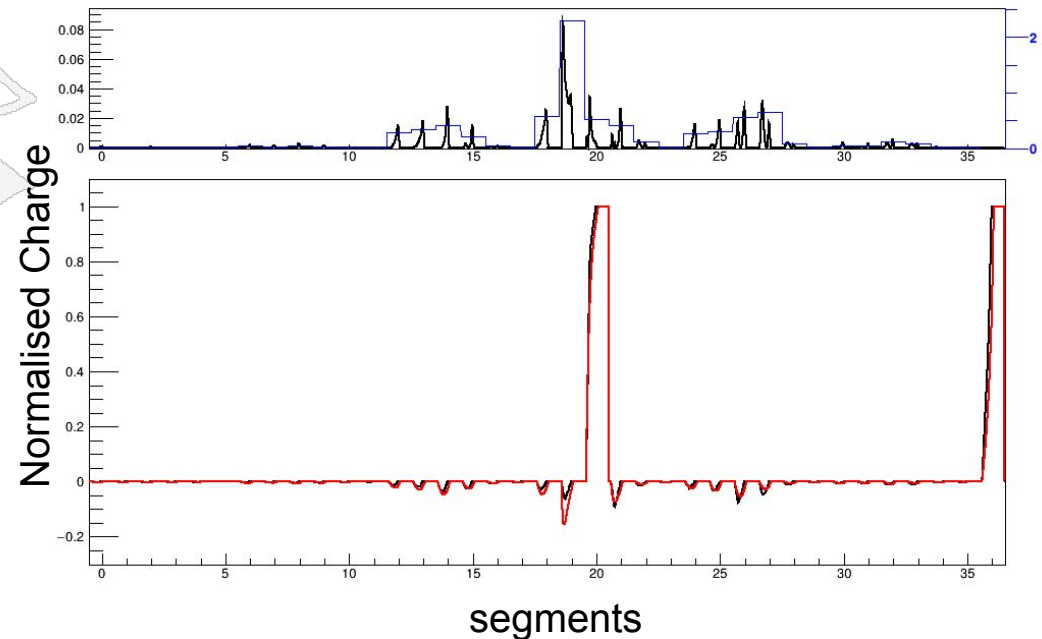
Simulation with Pulse Shape



Geant4 simulation:

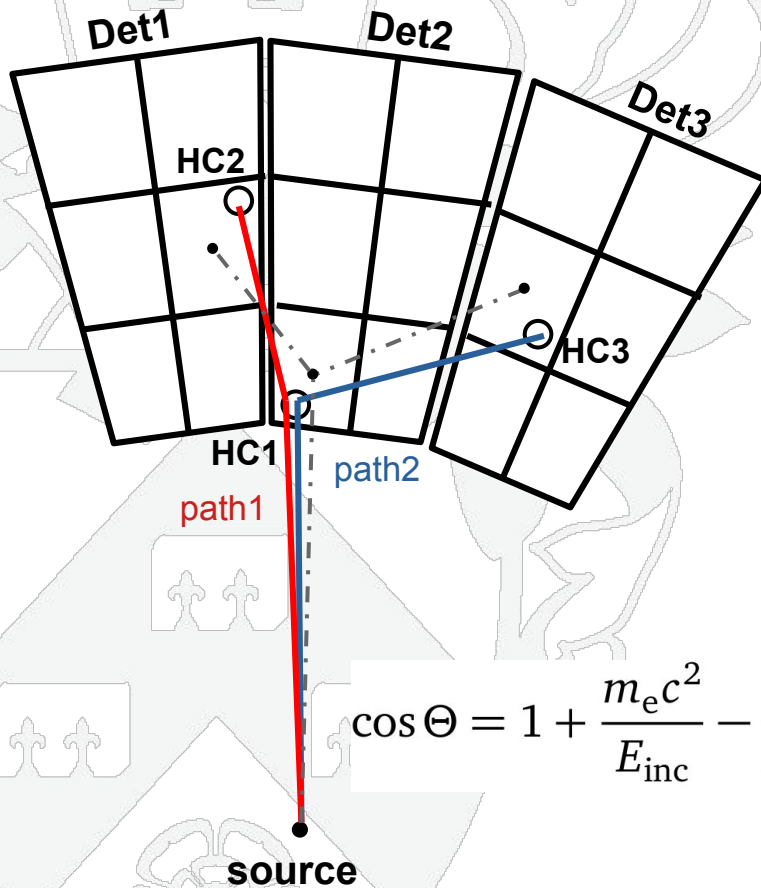


Group pulse shape:



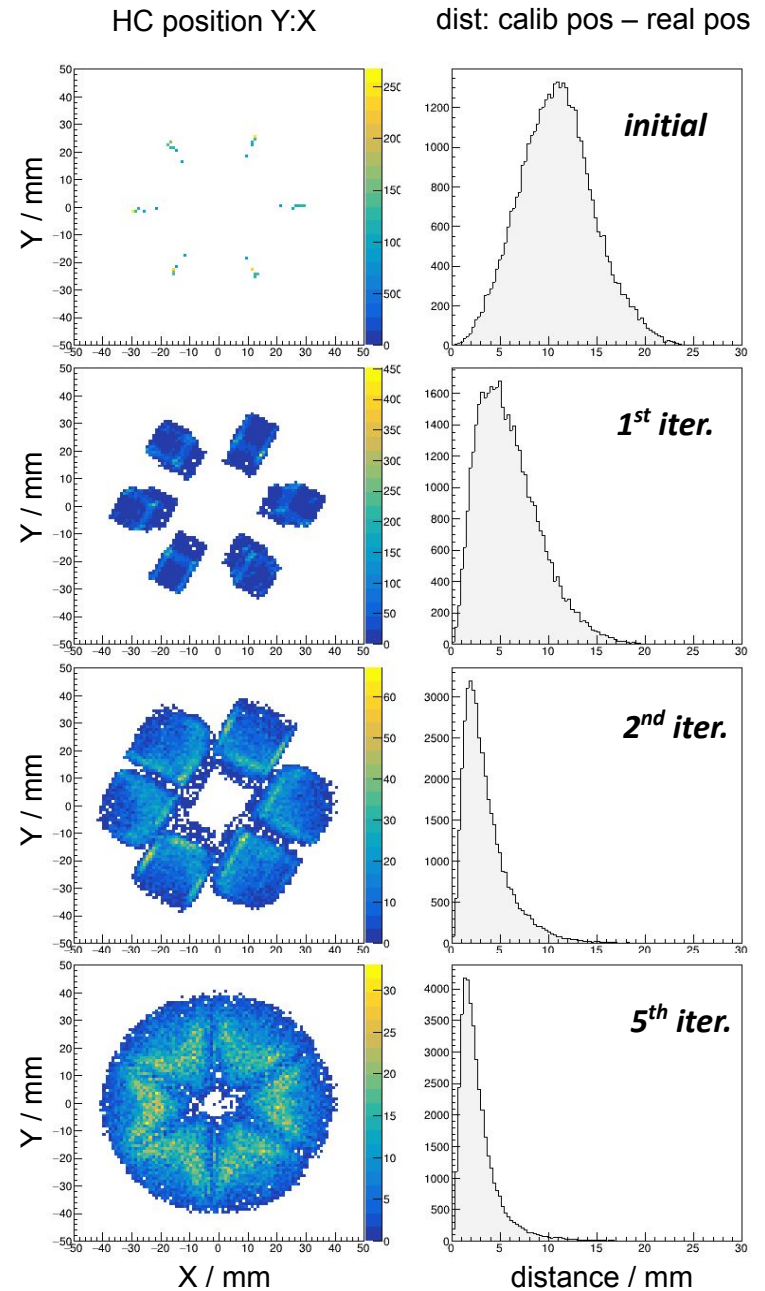
- Geant4 simulate AGATA-1Pi array, save Compton scattering events
- Pulse shape basis linear interpolation → simulation data
- Group pulse shape according to similarity

Simulation: Position optimization

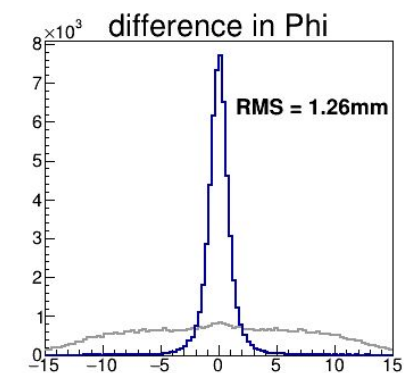
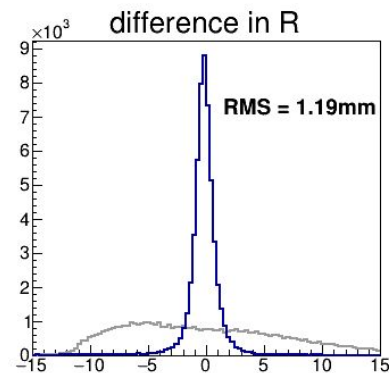
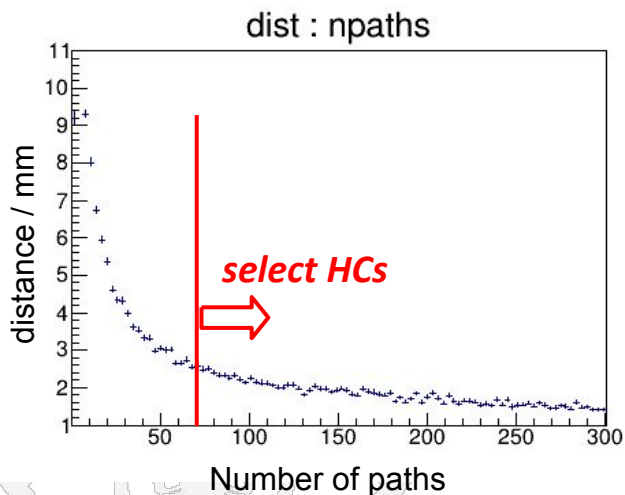
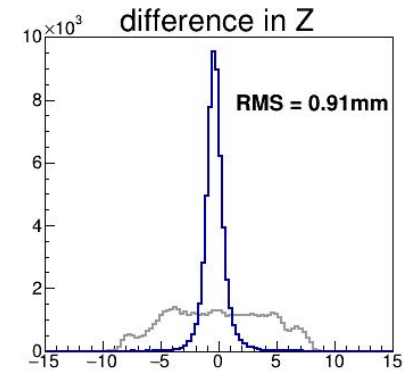
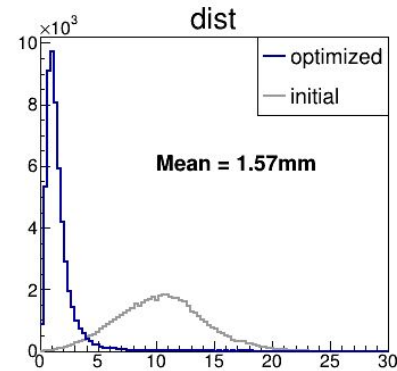
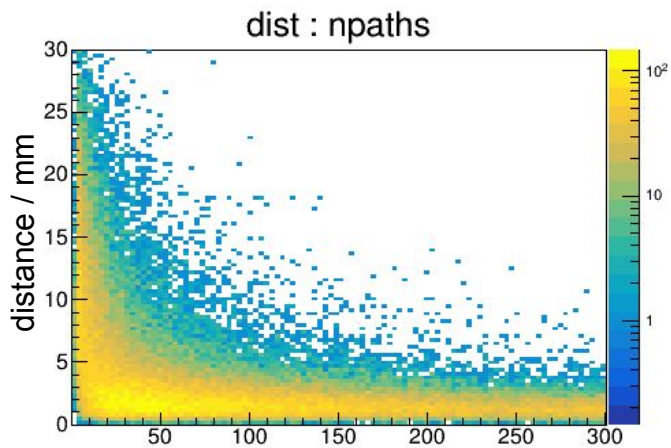


$$\cos \Theta = 1 + \frac{m_e c^2}{E_{\text{inc}}} - \frac{m_e c^2}{E_{\text{inc}} - E_{\text{dep}}}$$

Simulate 2MeV gamma 2e10 events



Simulation: Position fidelity



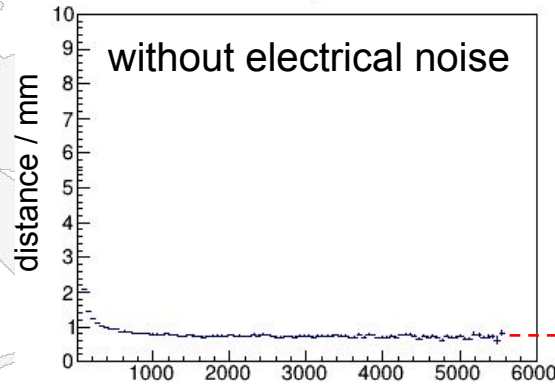
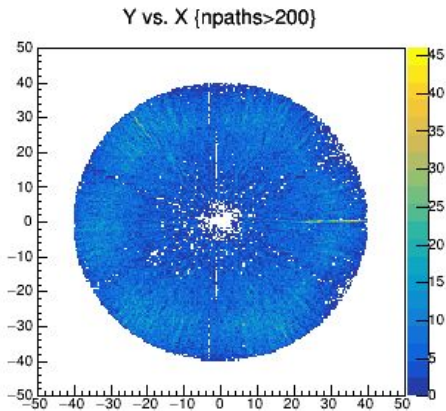
- Select HC linked with large number of paths
- Converged HC position reach ~1mm (RMS) fidelity
- Slightly worse resolution in phi direction

Simulate 2MeV gamma 2e10 events

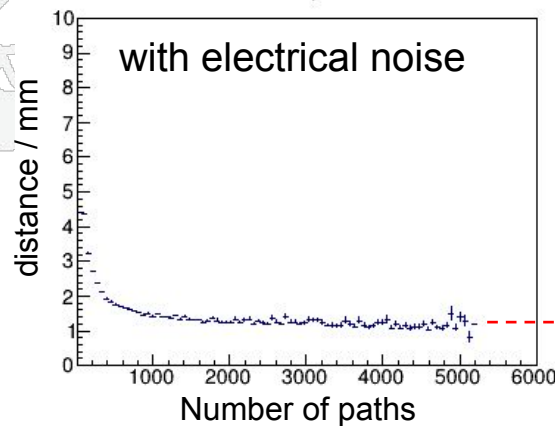
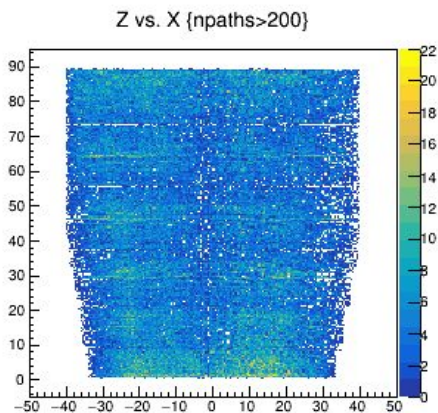
Simulation: Position fidelity

2MeV gamma $2e11$ events

Distance between self-calib
position and “real” position



Better than 1mm

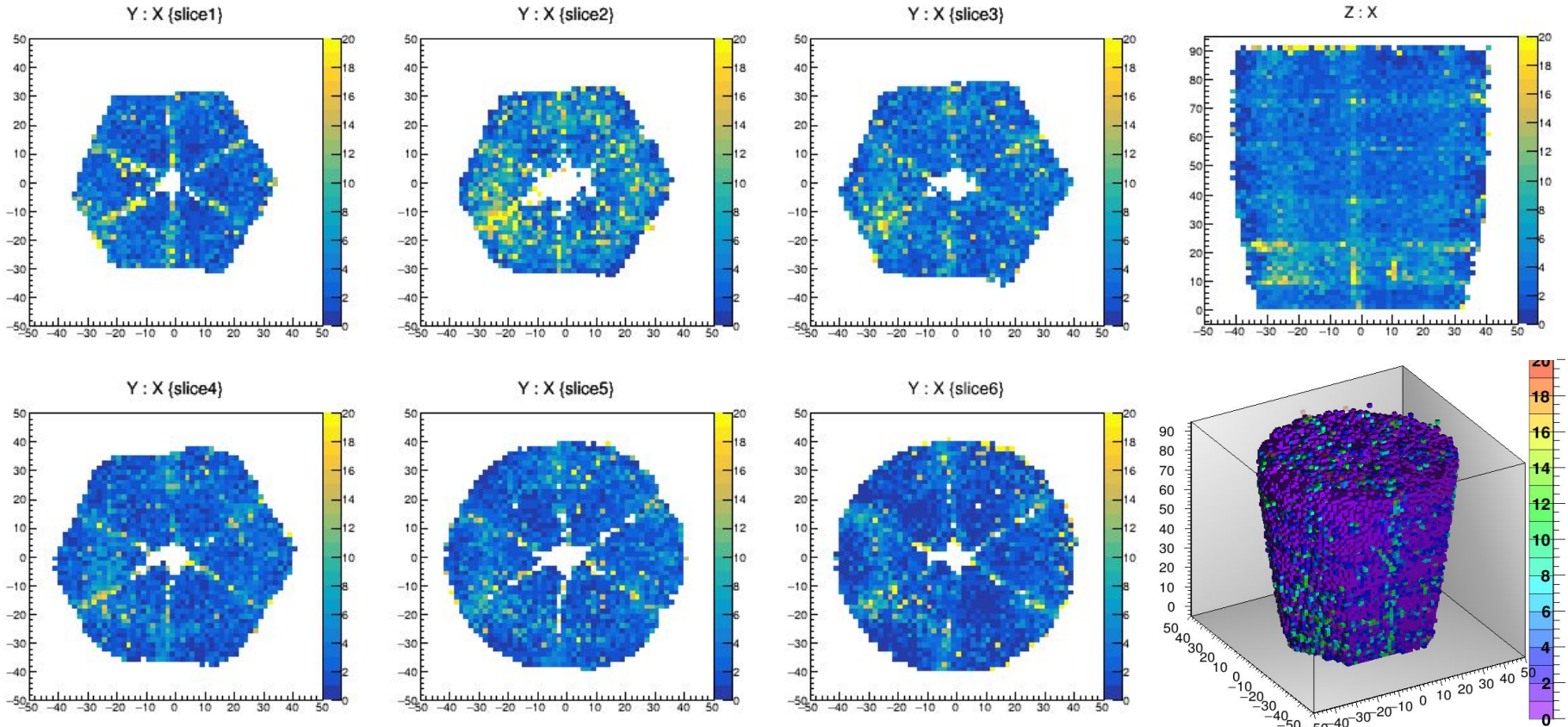


1-2 mm

Self-calibration basis (simulation)



Chi2 difference: self-calib pulse vs. real pulse

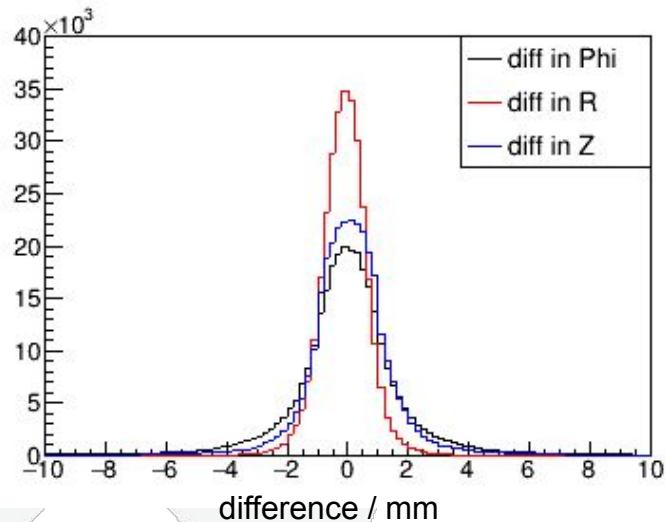


- Large Chi2 observed around segment boundary

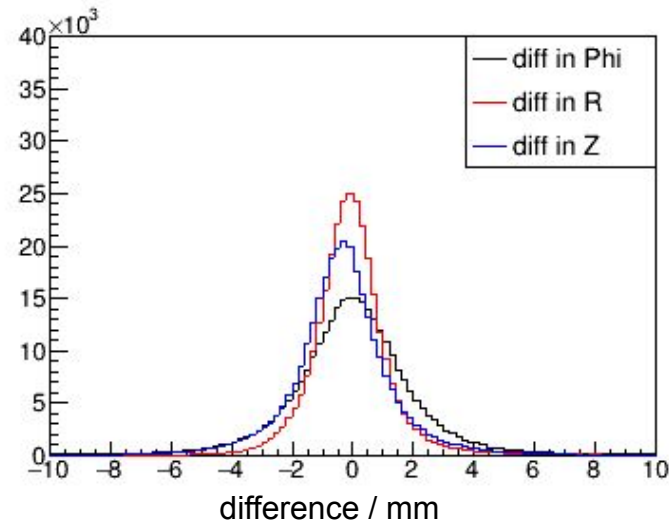
Simulate 2MeV gamma 2e10 events

PSA position resolution (simulation)

*Using the calculated
Basis on a 2mm grid*



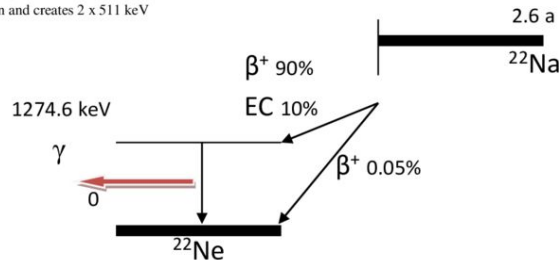
*Using the self-calibrated
basis*



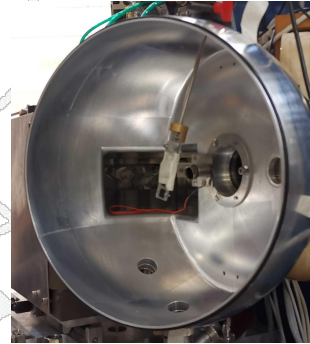
Experiment: source data

^{22}Na source, 130kBq

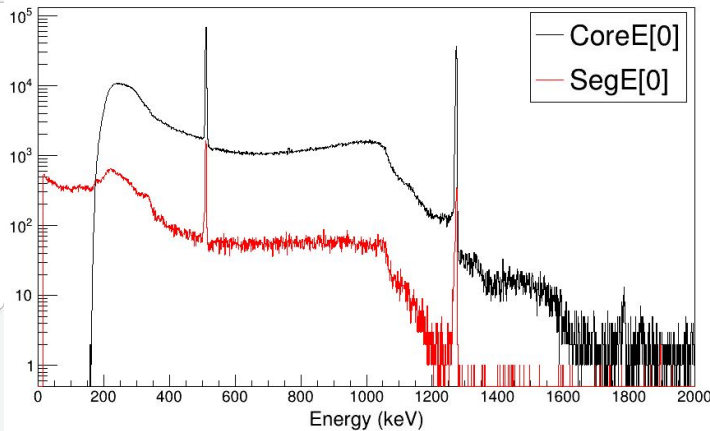
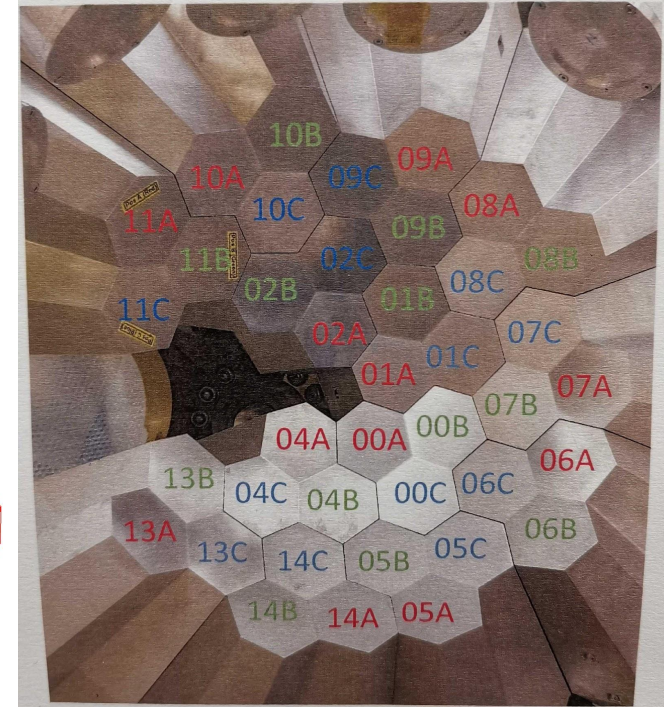
The positron (β^+ particle) then annihilates with an electron and creates 2 x 511 keV γ -rays



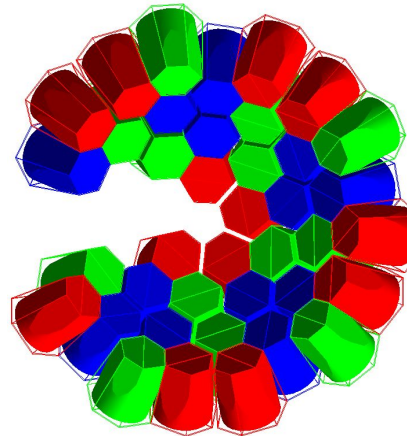
source at target position



○ 05A, 14A, 14B, 14C not included in the GTS



13 ATC at LNL

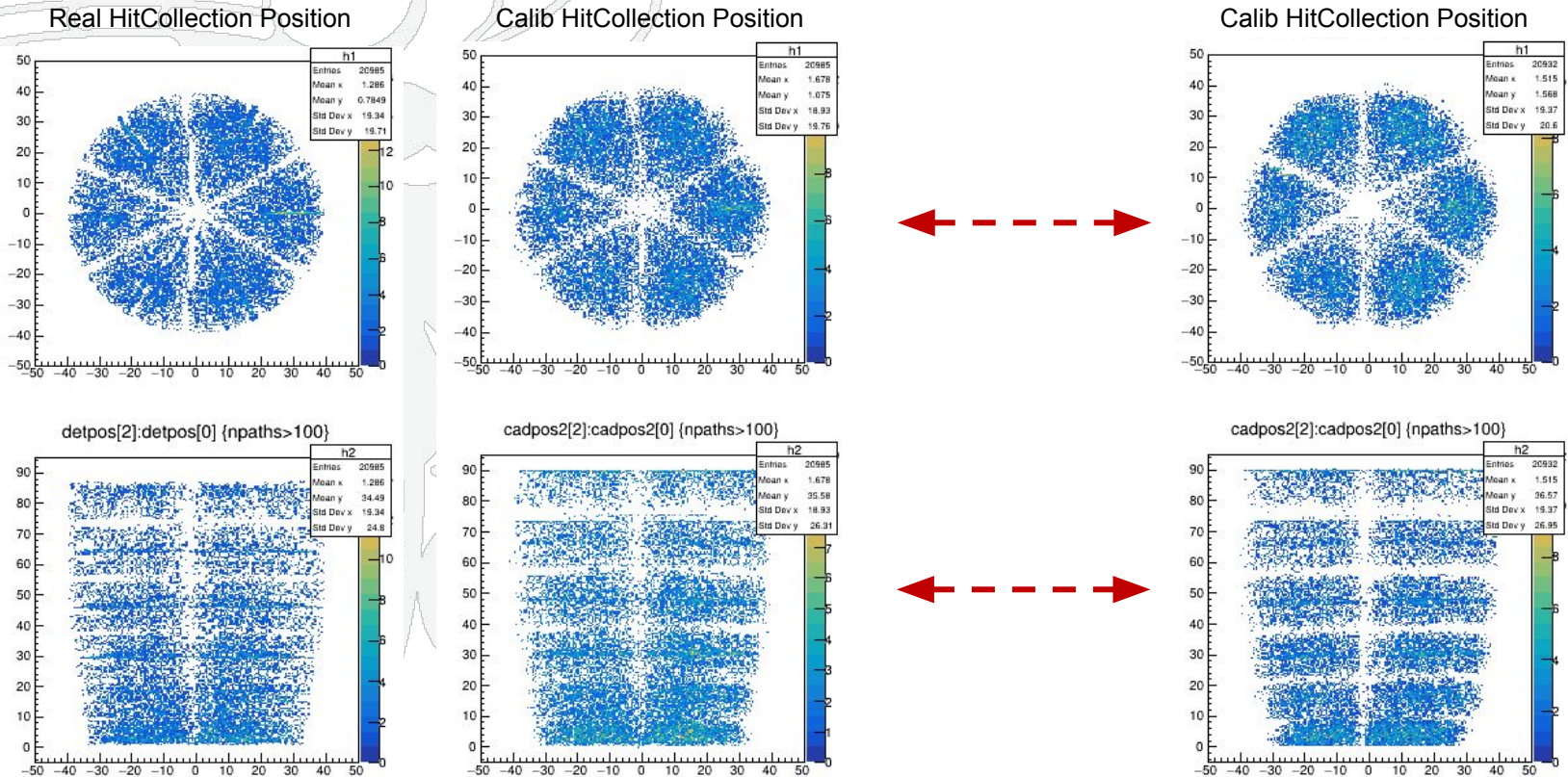


- ^{22}Na source at center of array
- Large signals, CoreE>200keV (small relative noise level)
- Compton scattering events (fold 2 trigger)

Self-calibration result

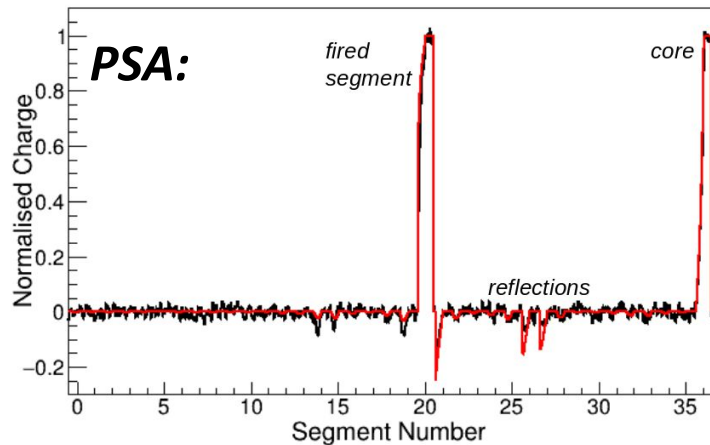
Simulation data (same size as source data)

source data

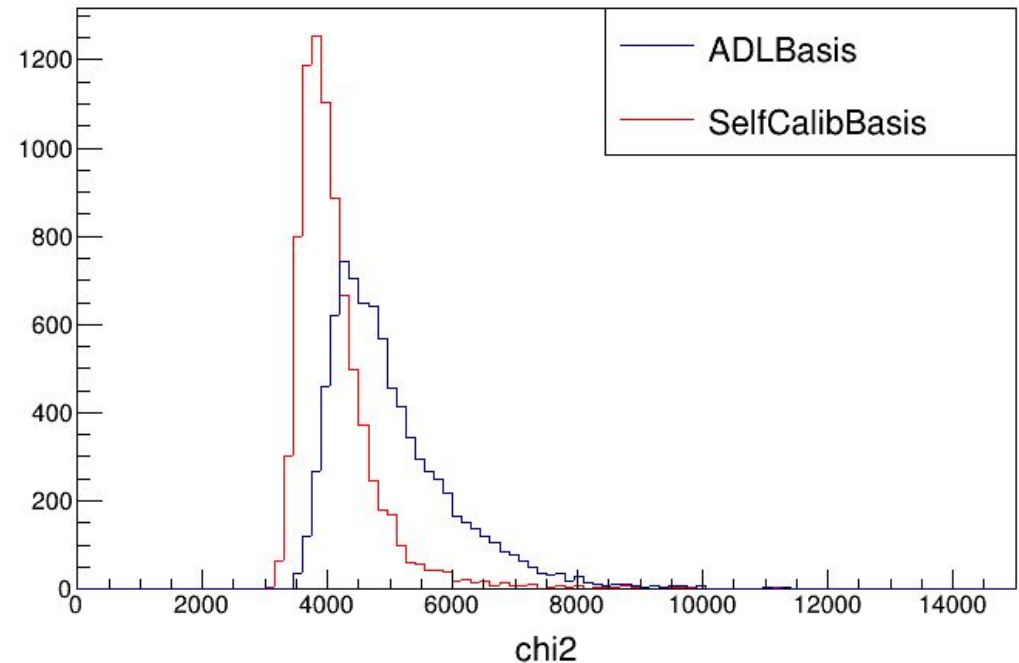


- Identify incoming gamma energy by OFTtracking
- consistent results between simulation and source calibration

Pulse Shape Analysis (PSA)



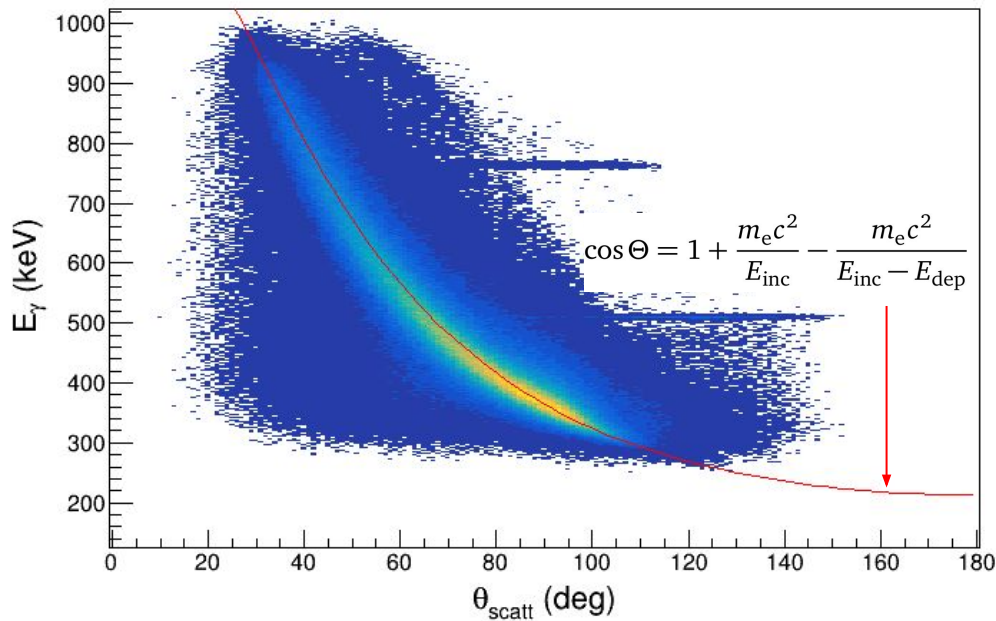
PSA Final Chi2



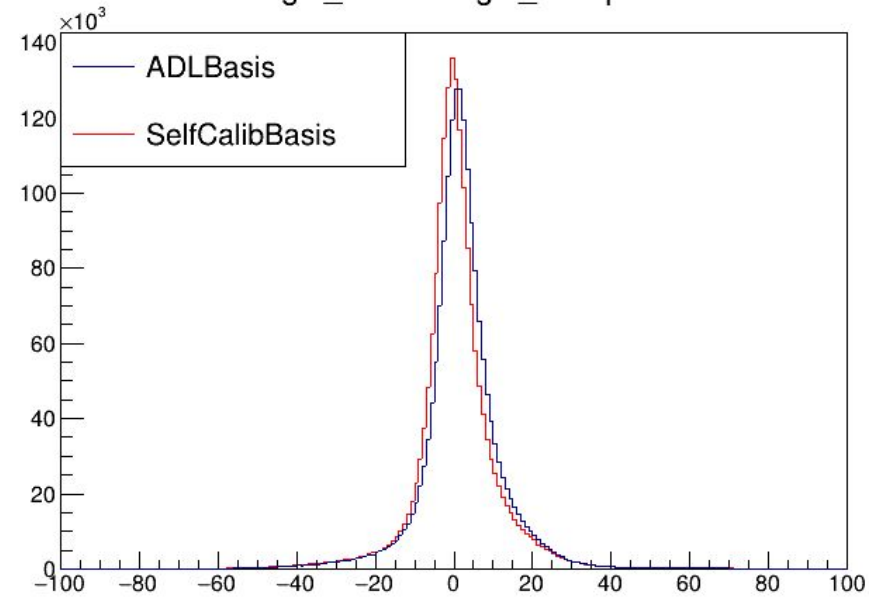
- ADL (AGATA Detector Library): theoretical calculated basis on 2 mm grid
- Chi2: the difference between experimental signal and the signal basis fitting
- The PSA final chi2 with self-calibration basis is smaller than that with ADL basis \Rightarrow self-calibration basis better describe experimental signal

Compton Scattering Angle

Scattering angle vs. Scattering Energy

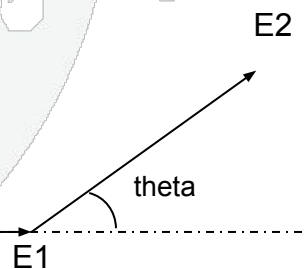


Angle_PSA - Angle_Compton



$E1 + E2 = 1274\text{keV}$

1274keV



- Compton scattering of 1274keV gamma
- Interaction position from PSA with ADL basis and SelfCalib basis
- Comparing scattering angle from PSA and the Compton angle from energy deposit

Summary

- Self-calibration is tested with AGATA simulation data with pulse shape yielding reasonable results
- Influences of statistics, noise levels are studied
- Experimental data is taken with ^{22}Na source at LNL, self-calibration with experimental data give results consistent with simulation data
- PSA with self-calibration basis and original basis are compared, yielding some improvements with self-calibration basis

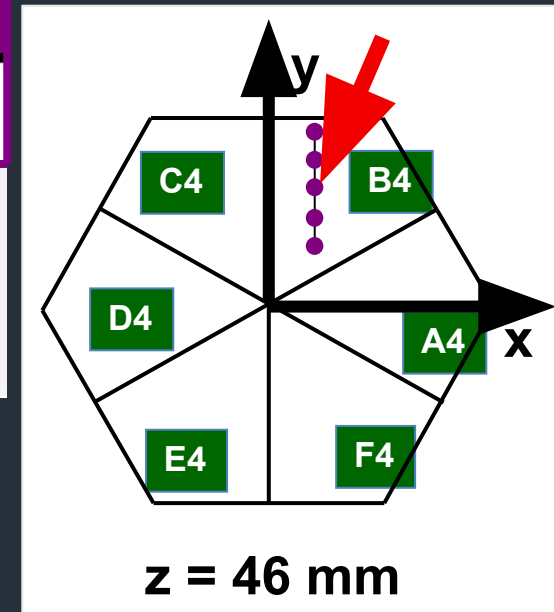
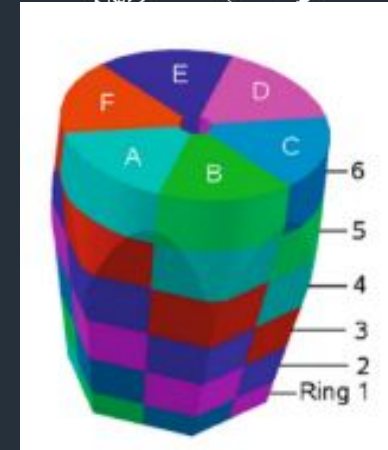
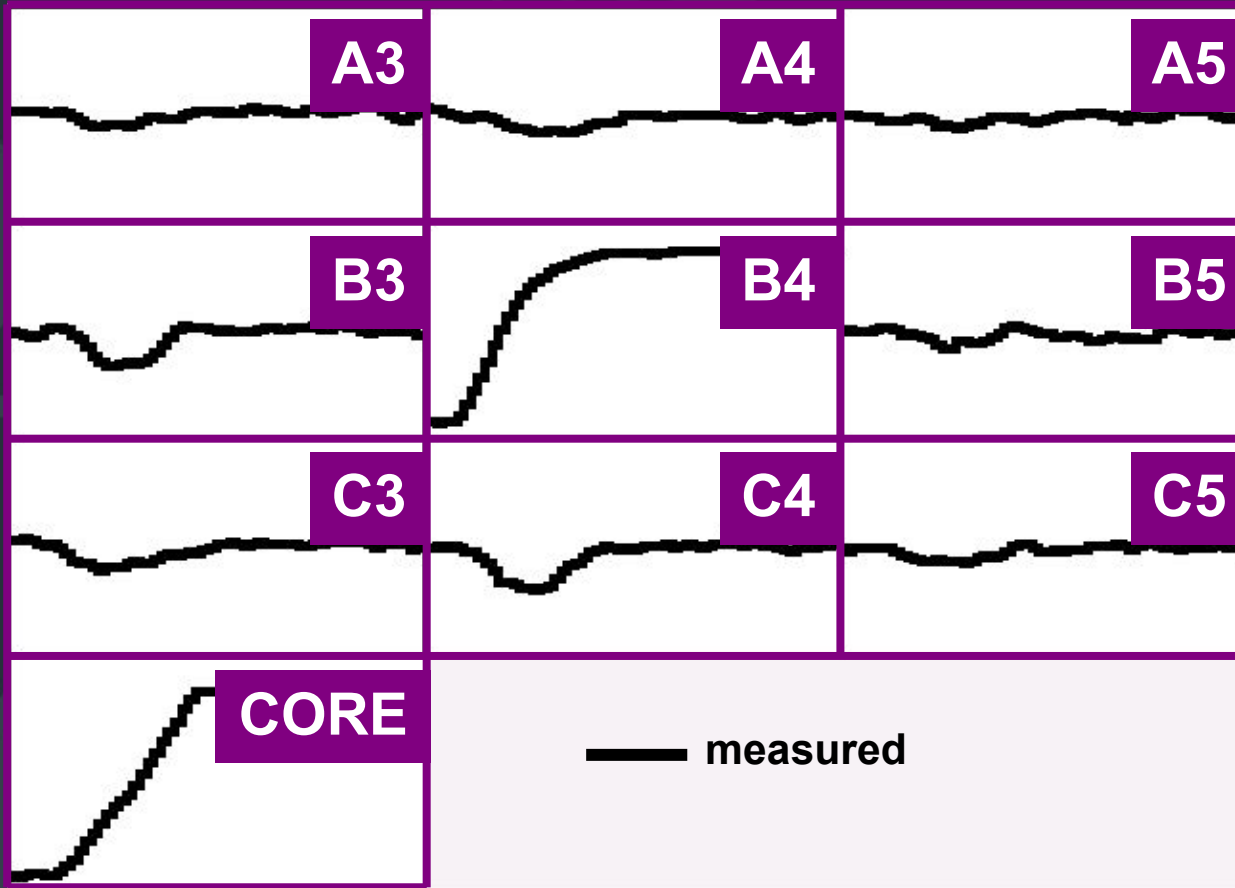
Thank you for your attention



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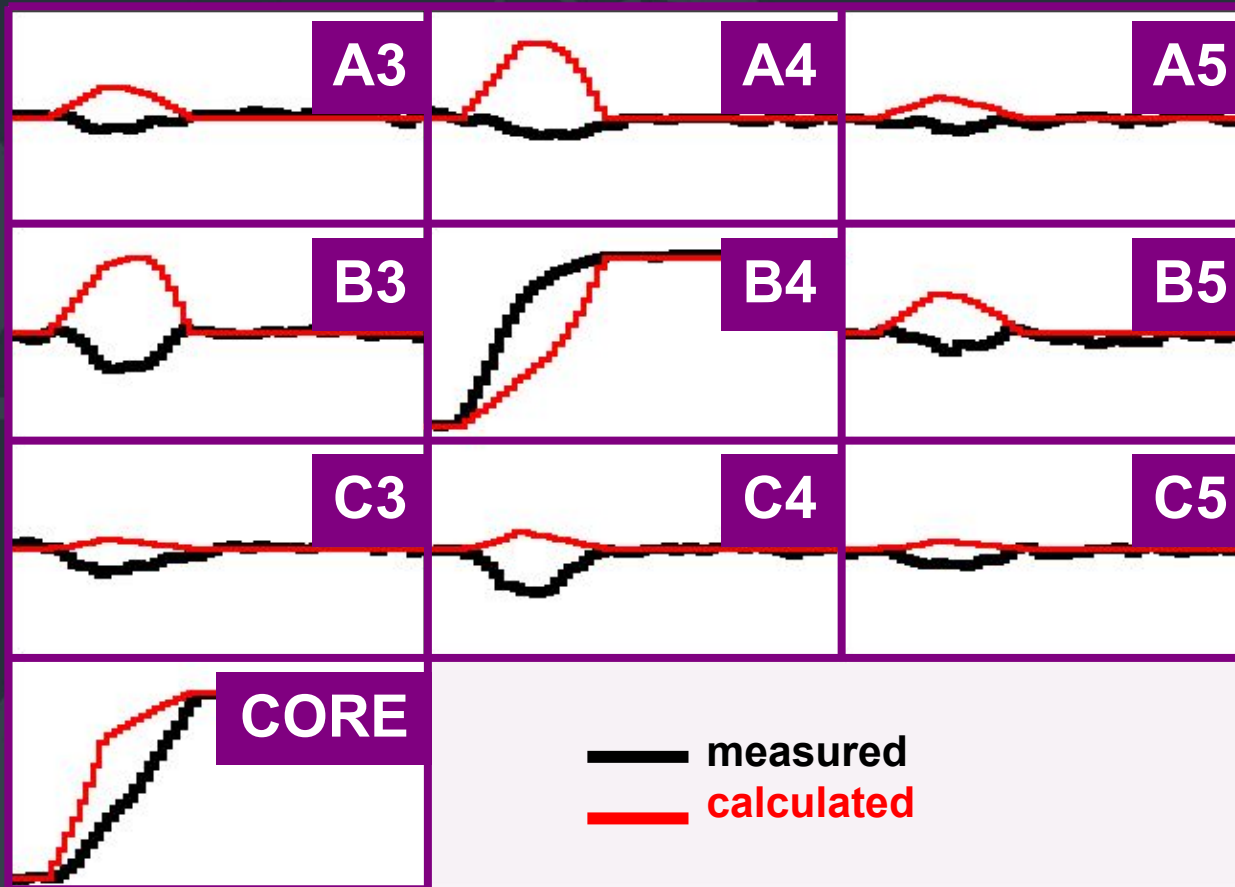
Backup

Pulse Shape Analysis concept



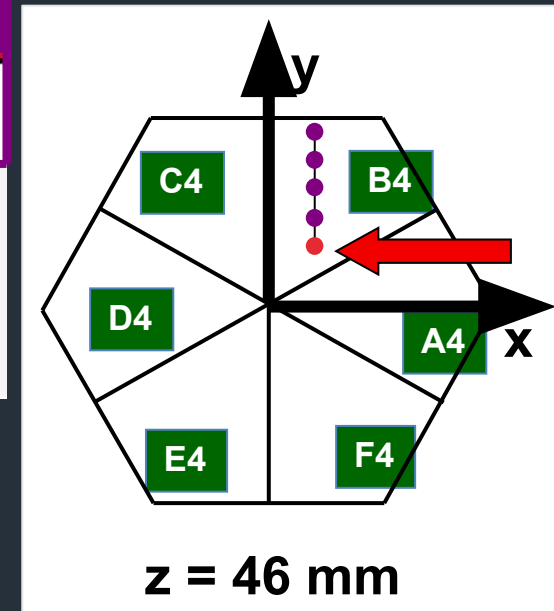
791 keV deposited in segment B4

Pulse Shape Analysis concept

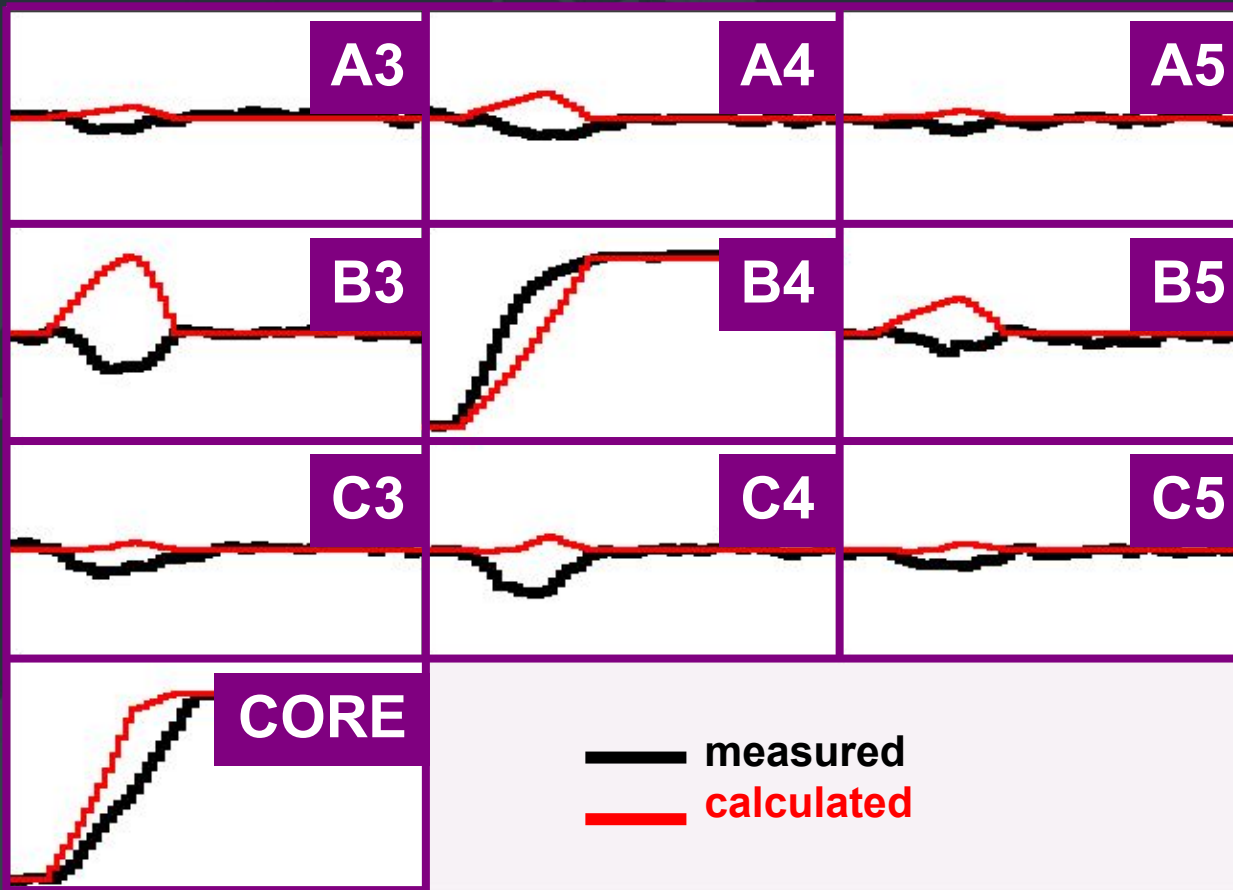


(10, 10, 46)

791 keV deposited in segment B4

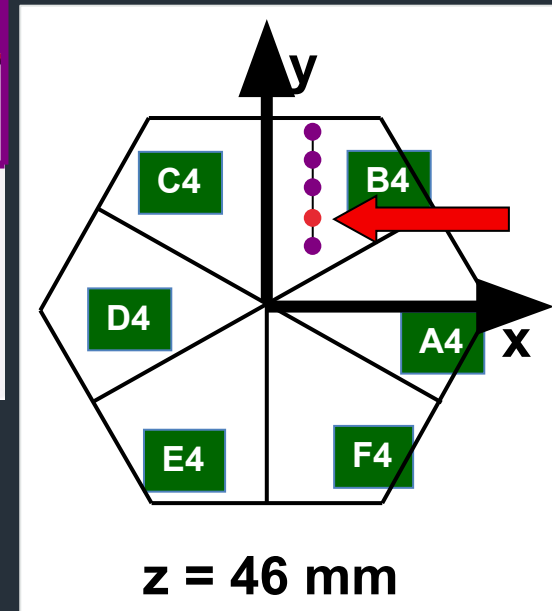


Pulse Shape Analysis concept

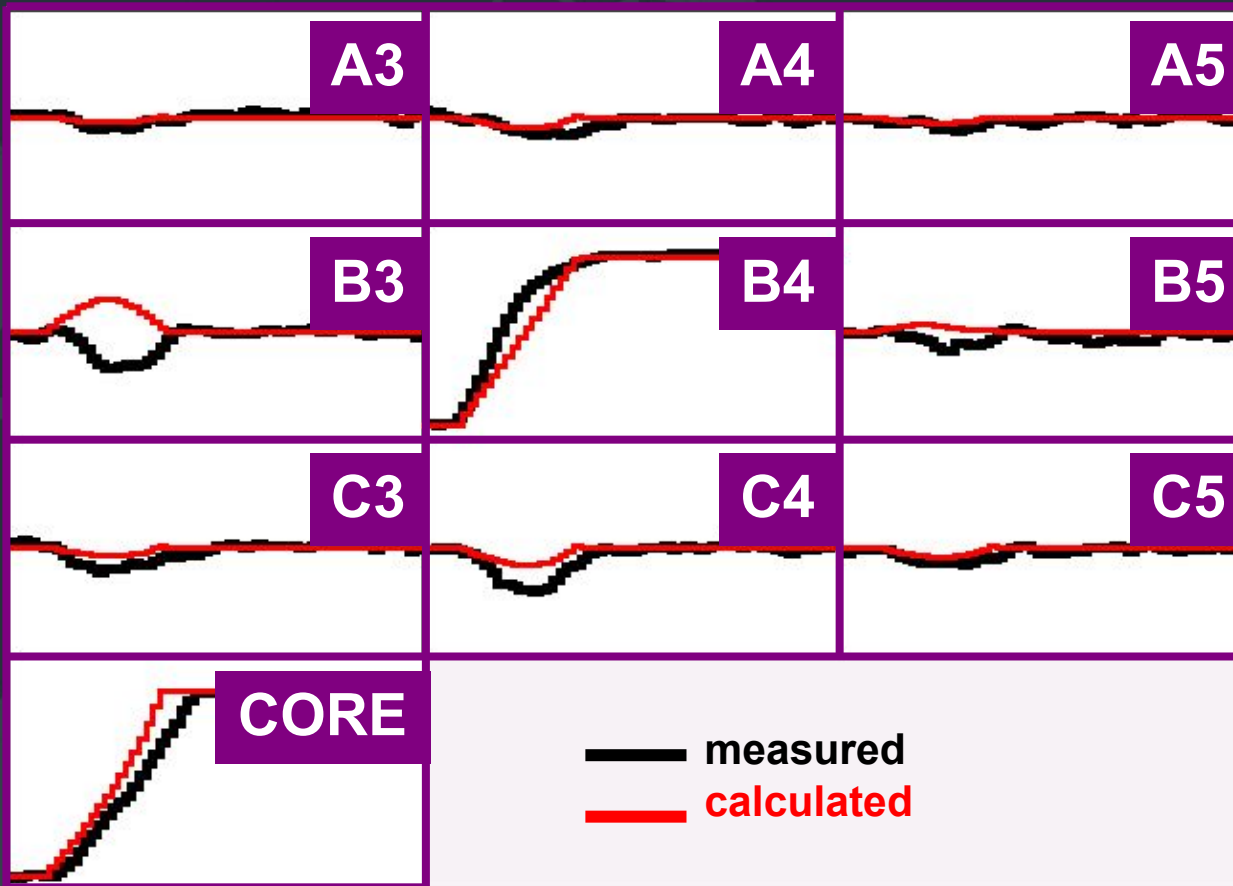


(10, 15, 46)

791 keV deposited in segment B4

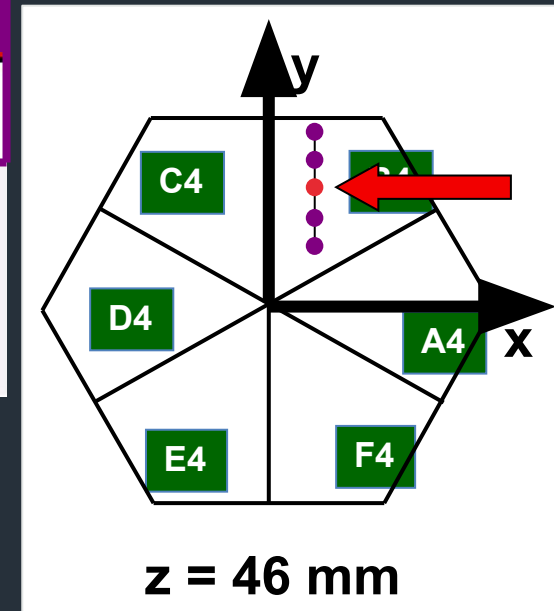


Pulse Shape Analysis concept

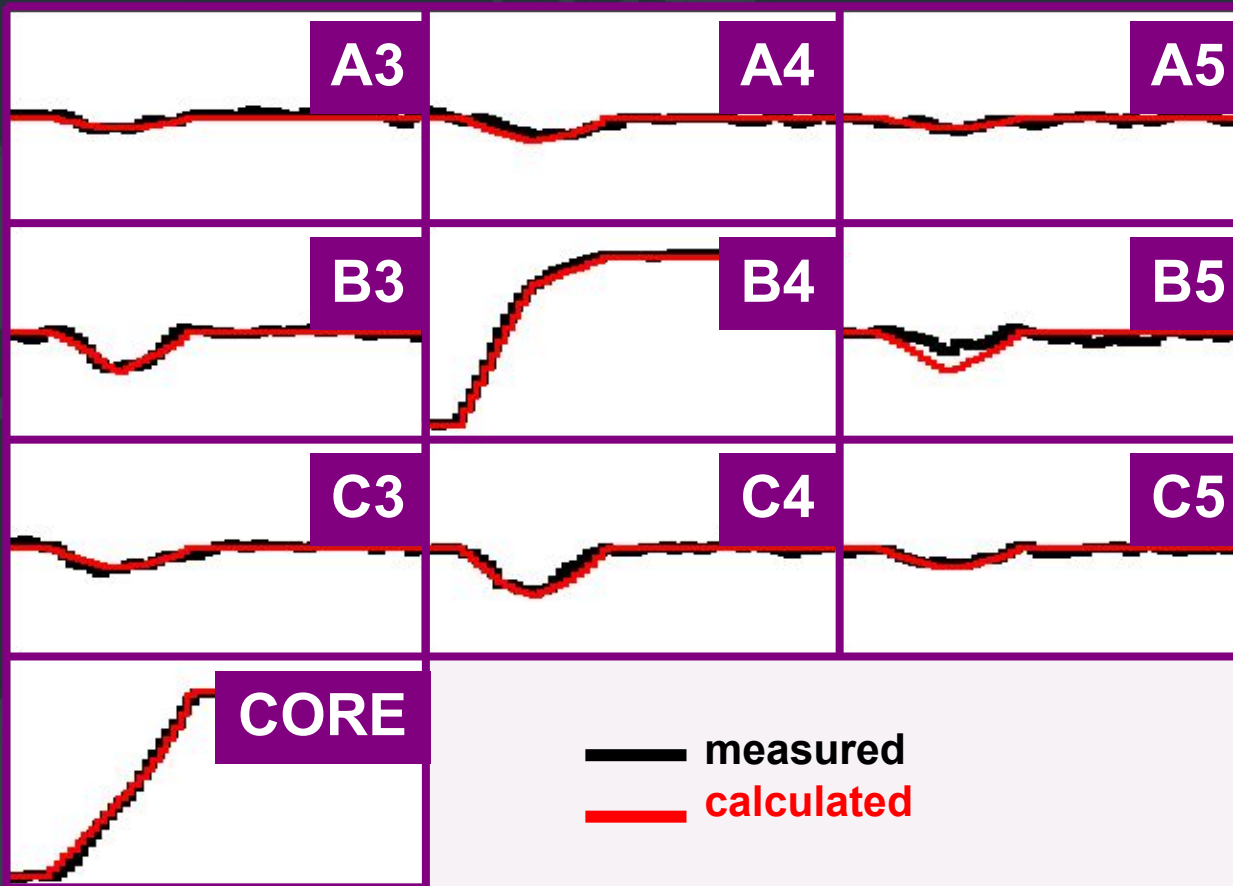


(10, 20, 46)

791 keV deposited in segment B4

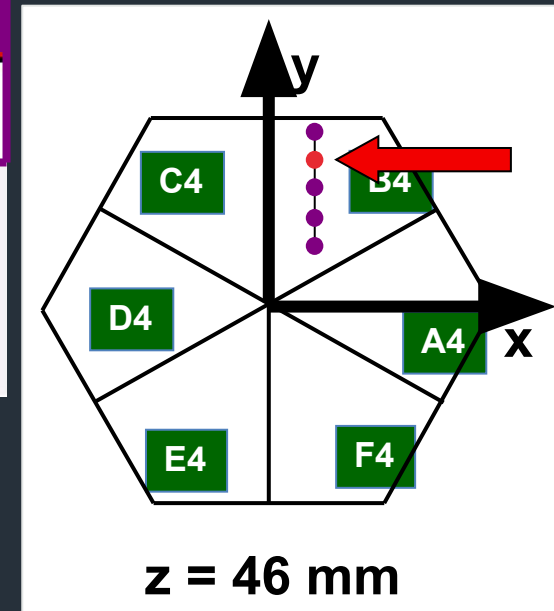


Pulse Shape Analysis concept

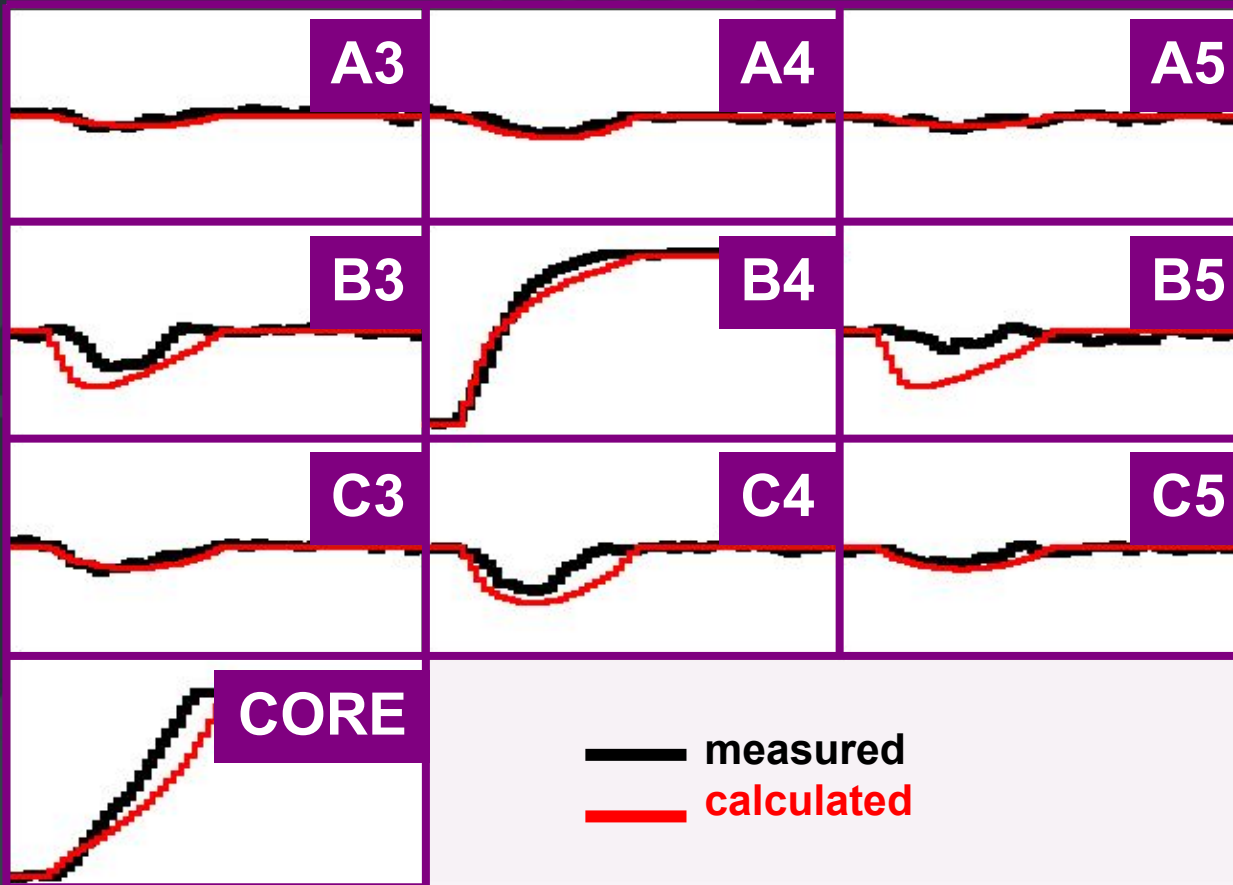


(10, 25, 46)

791 keV deposited in segment B4

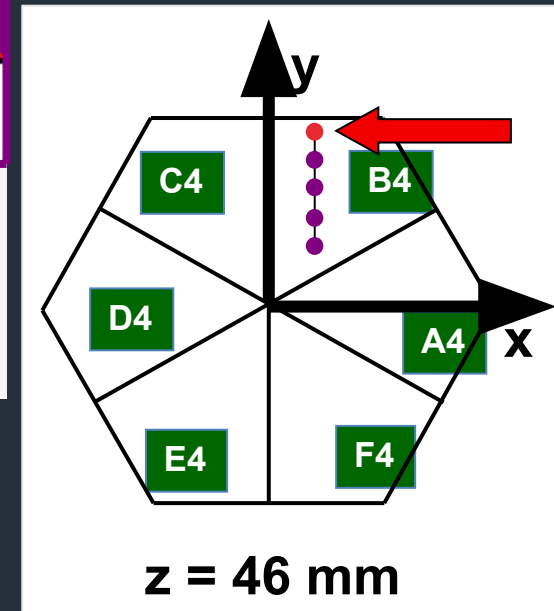


Pulse Shape Analysis concept

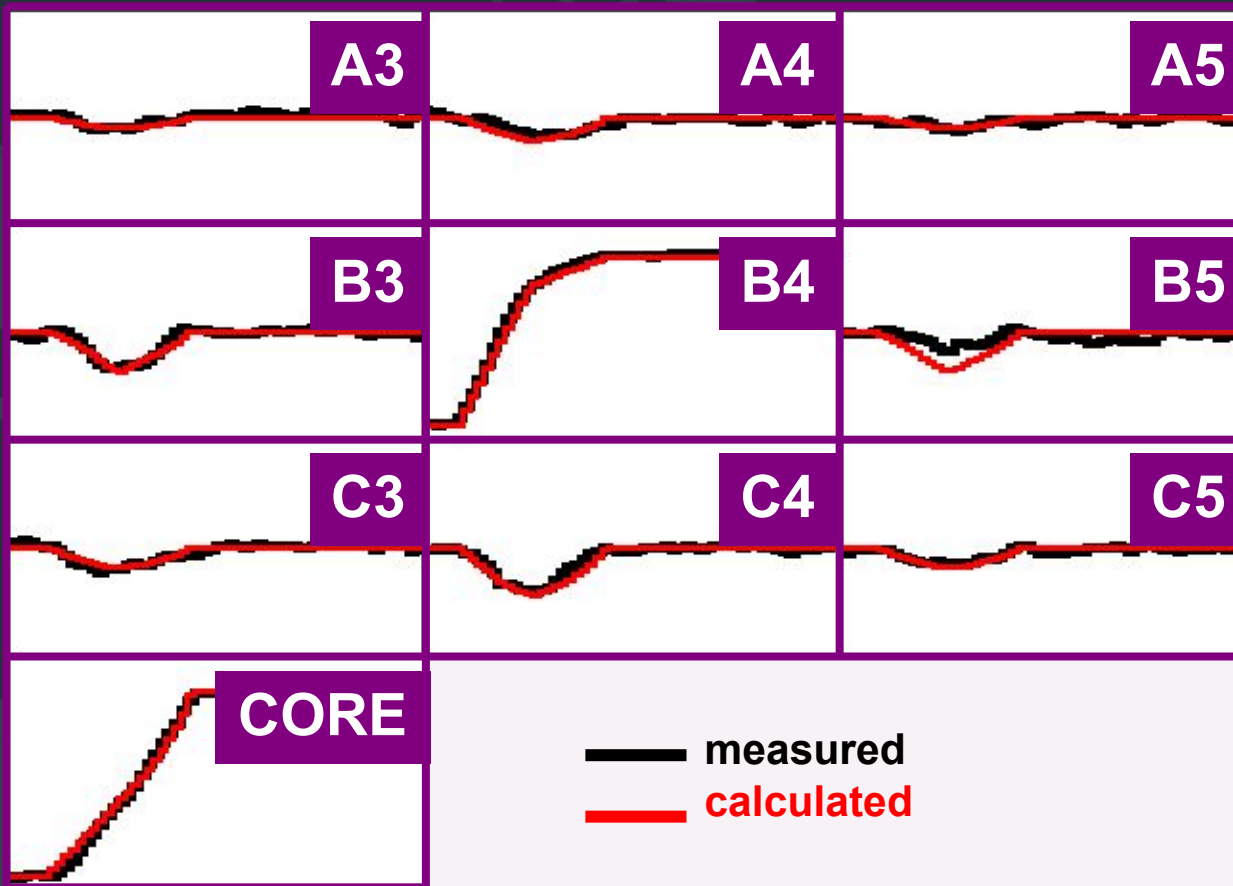


(10, 30, 46)

791 keV deposited in segment B4

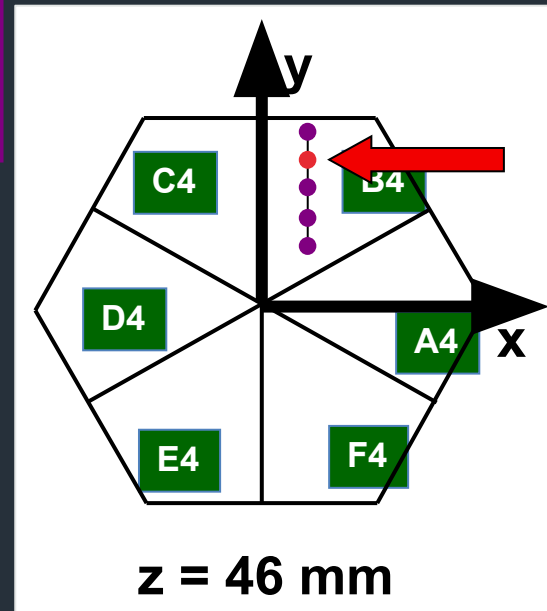


Pulse Shape Analysis concept



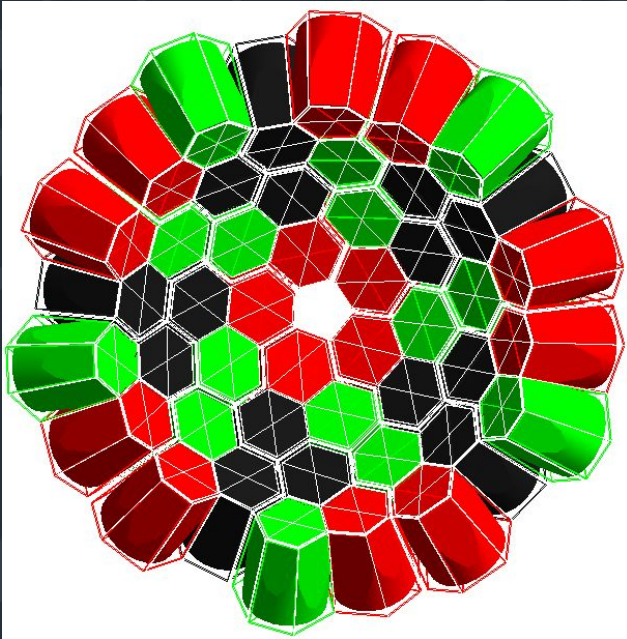
791 keV deposited in segment B4

Result of
Grid Search
algorithm
(10, 25, 46)

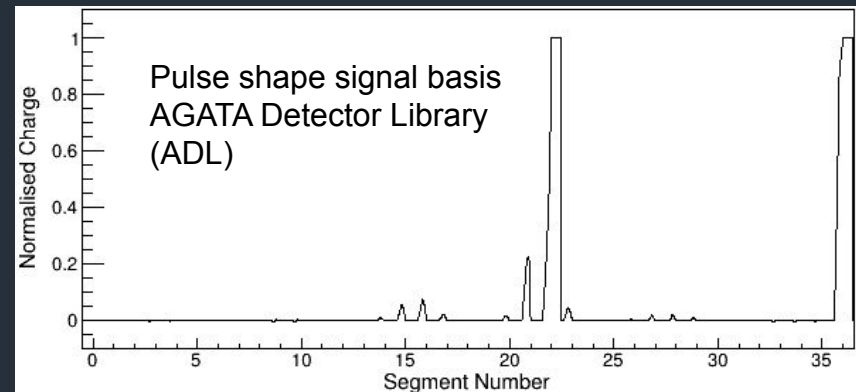
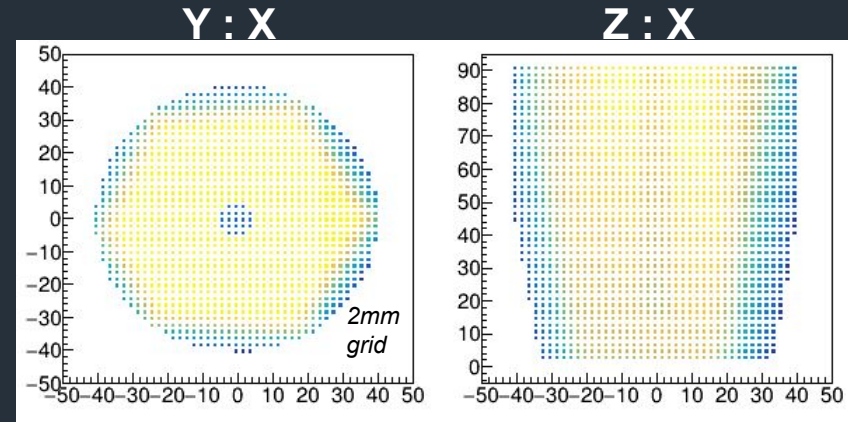


Simulation with Pulse Shape

Geant4:

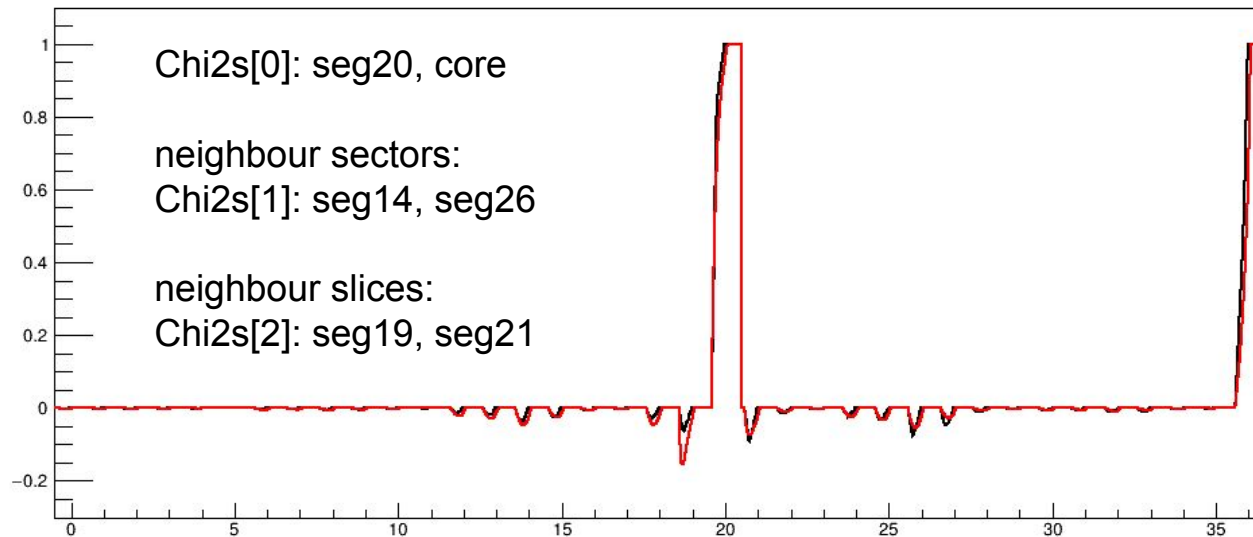
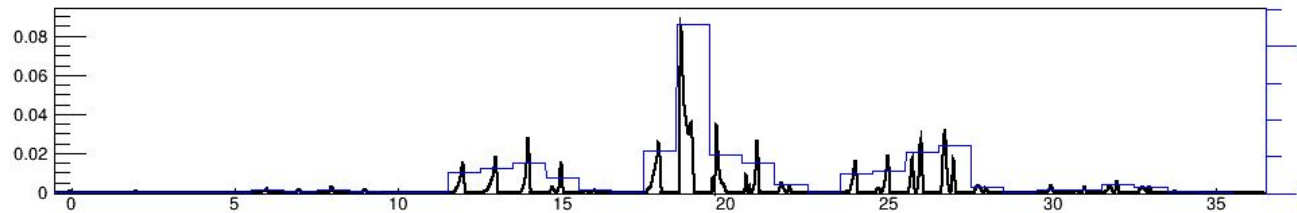


Signal Basis:



- AGATA-1Pi array: 45 detectors
- Geant4: Compton events information
- Linear interpolation ADL pulse shape basis

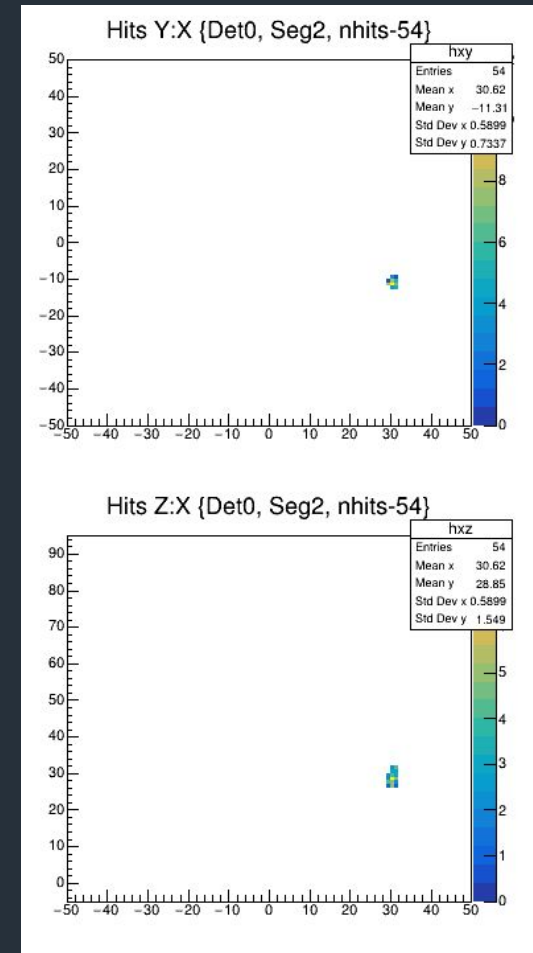
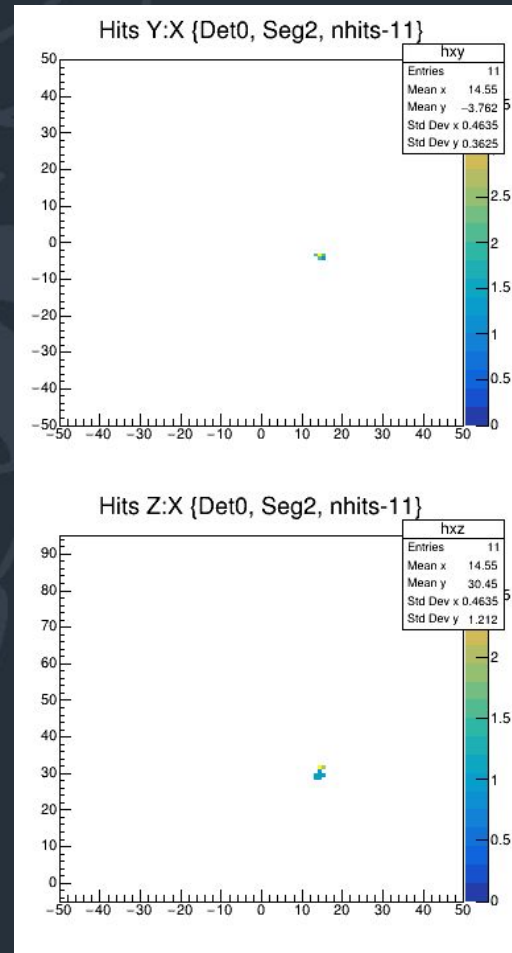
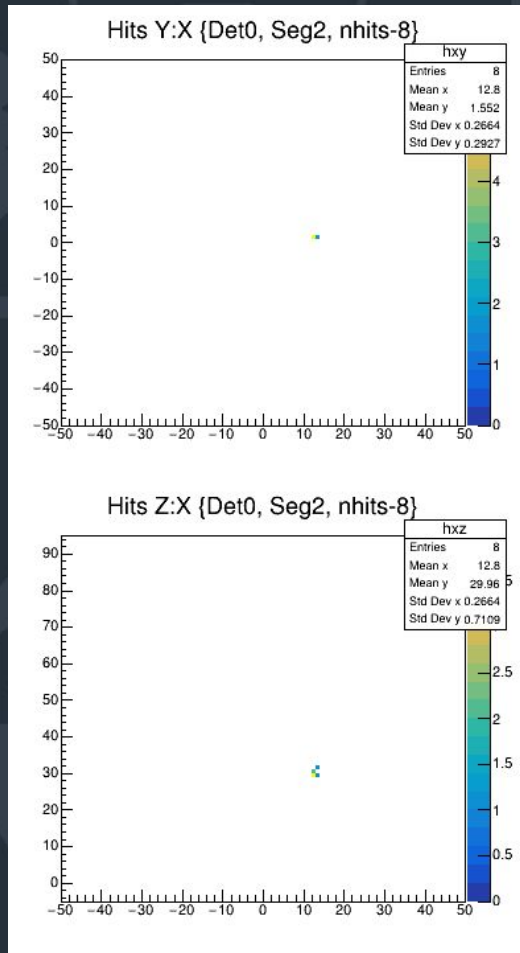
Group Pulse Shape



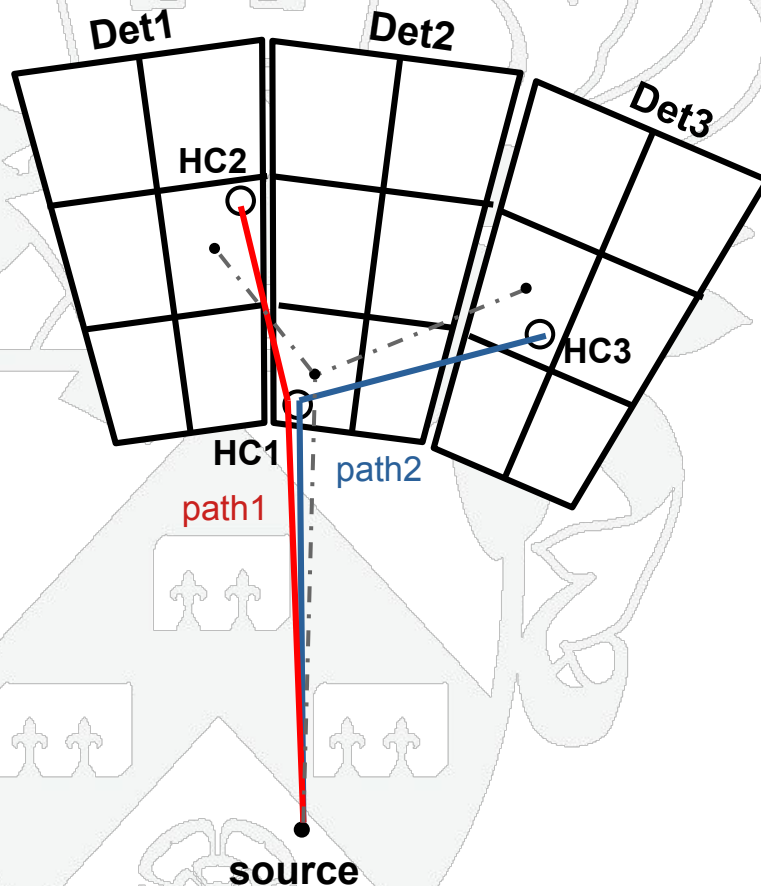
```
seg = 20
nhits1 = 1 : 1571.00
nhits2 = 1 : 1590.26
nfired = 36
Eng1 = 1571
Eng2 = 1590.26
chi2 = 7.29173
dist = 9.98804
rdifphi = 7.03852
diffr = 5.51792
diffz = 4.50787

PhiRZ1 = -165.32 29.76 31.31
PhiRZ2 = -177.72 35.28 26.80
difphi = 12.4017 degree
```

Group Pulse Shape



Position optimization

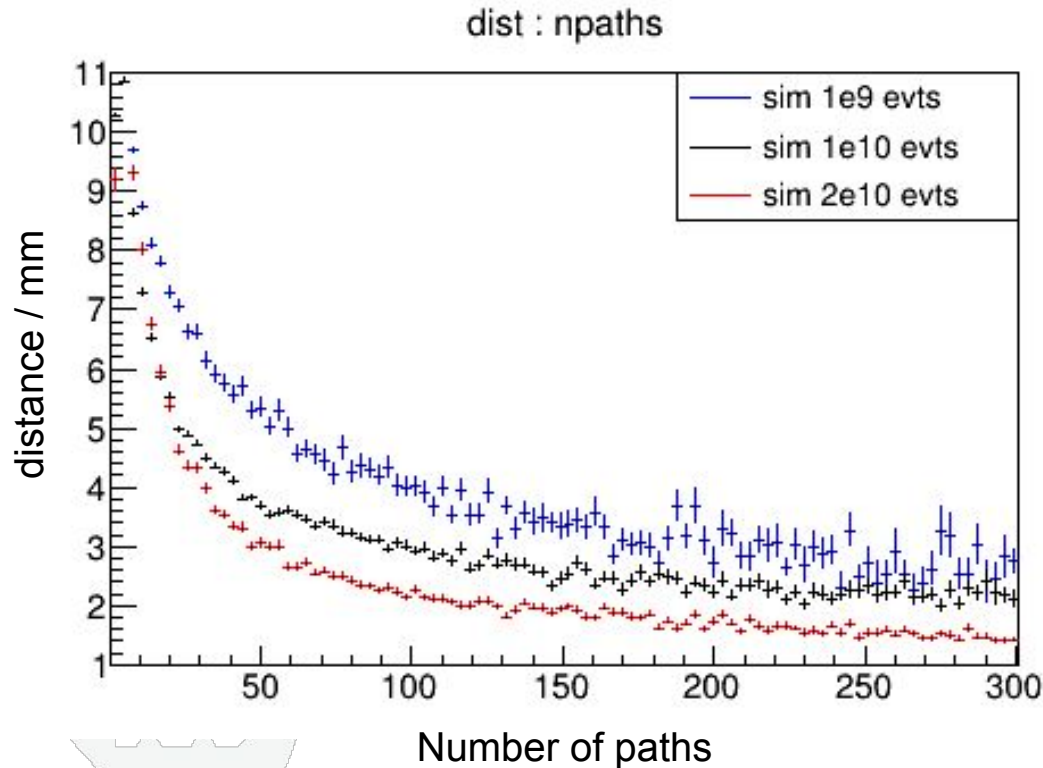


- Initial HC position: segment center
- Compton scattering angle:

$$\cos \Theta = 1 + \frac{m_e c^2}{E_{\text{inc}}} - \frac{m_e c^2}{E_{\text{inc}} - E_{\text{dep}}}$$

- Scattering angle from path Θ'
- Optimize HC position
→ reduce angle difference
- Loop HCs and iteration

Position resolution



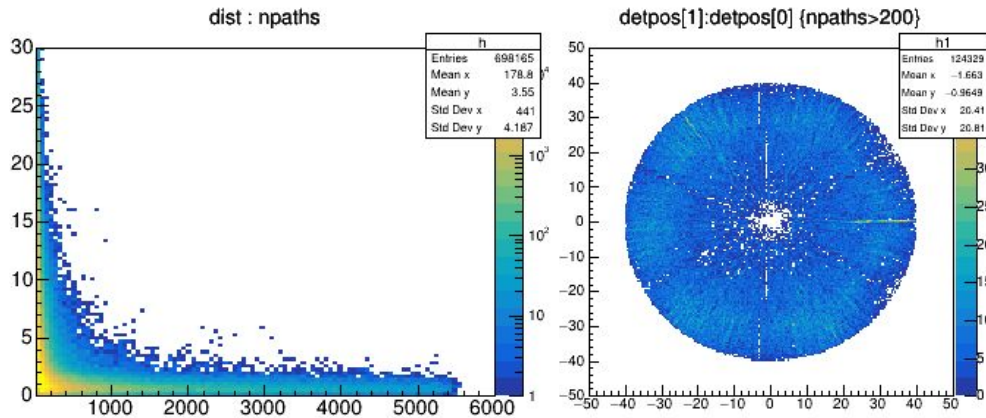
- Simulation data size influence to position resolution

Simulation: Position resolution

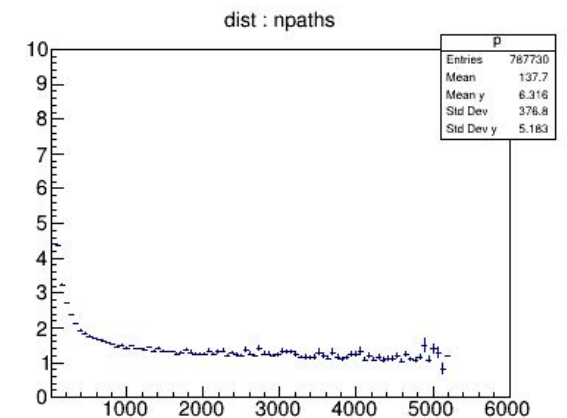
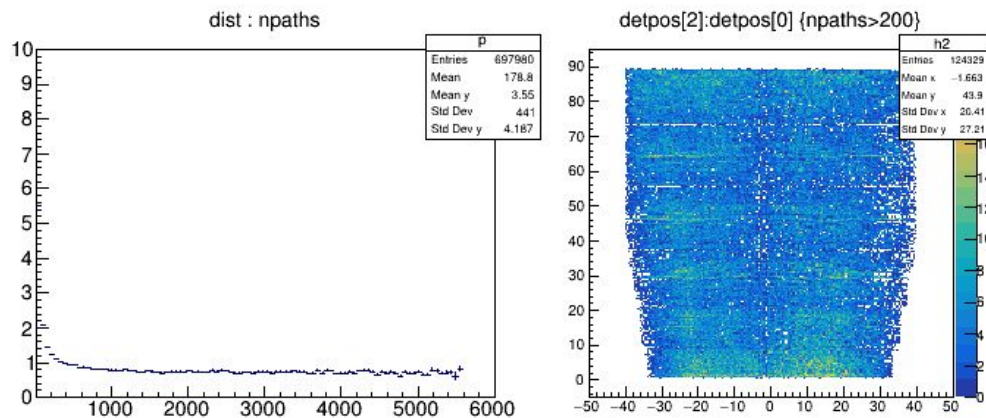
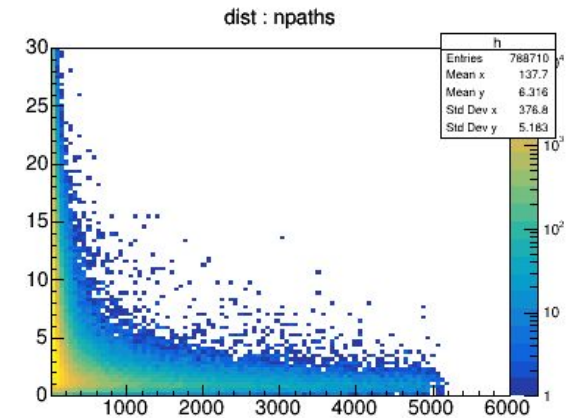


Simulate 2MeV gamma 1e11 events

without noise



with noise



Gamma source

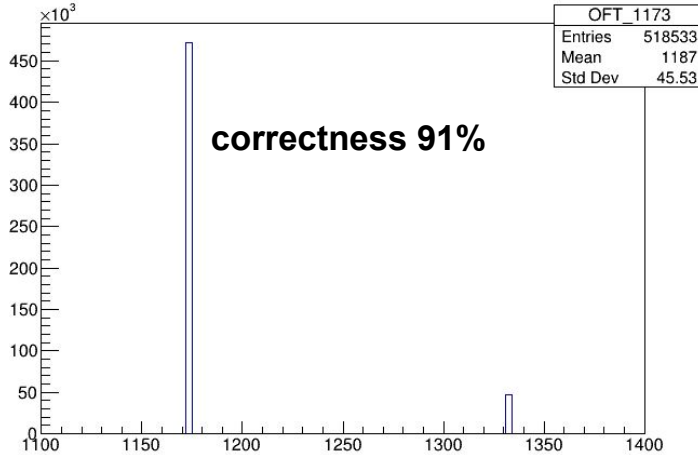
Identify incoming energy according to figure of merit from OFT



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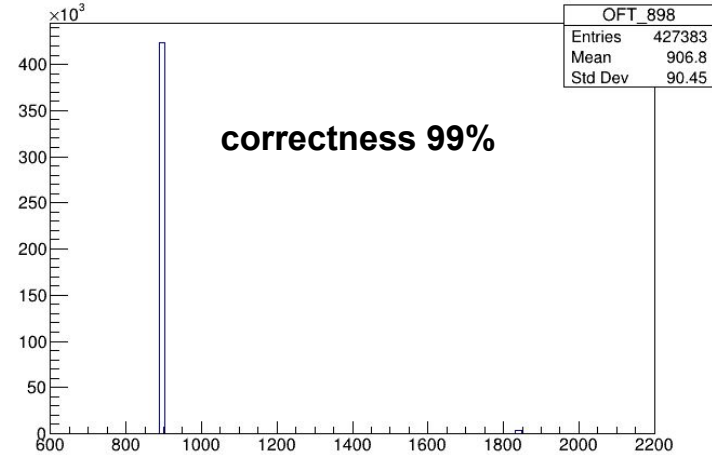
⁶⁰Co source

Simulate 1173keV

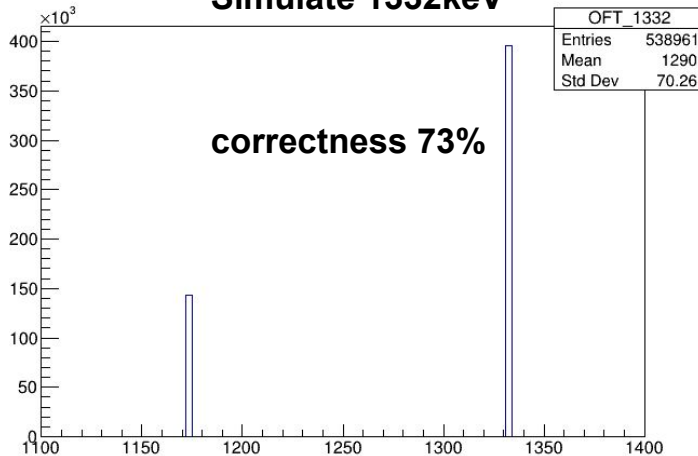


⁸⁸Y source

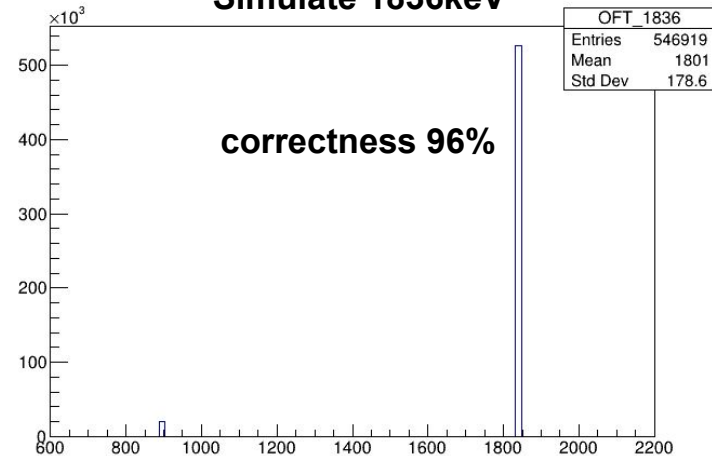
Simulate 898keV



Simulate 1332keV



Simulate 1836keV



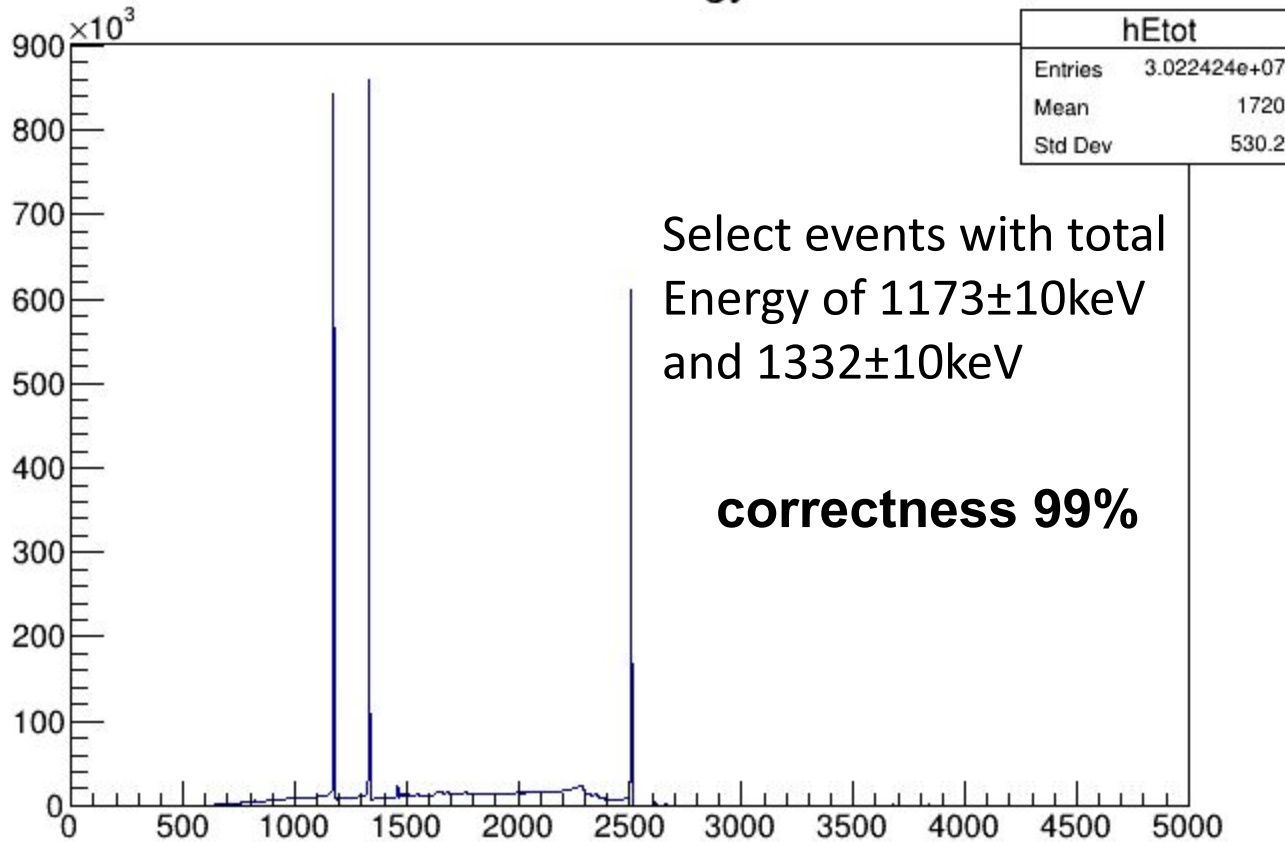
^{60}Co source

Identify incoming energy according to total energy deposit in array



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total Energy



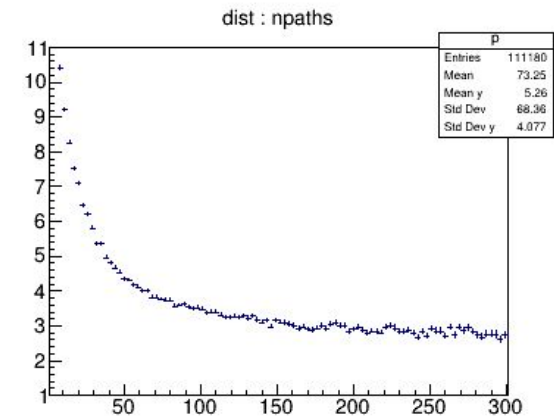
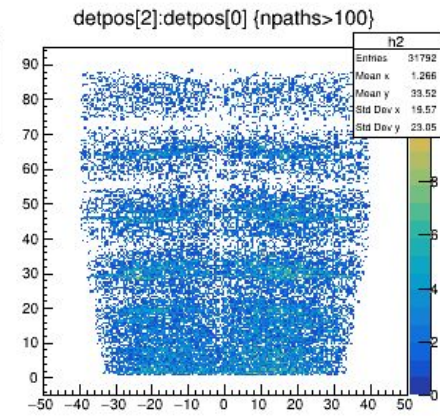
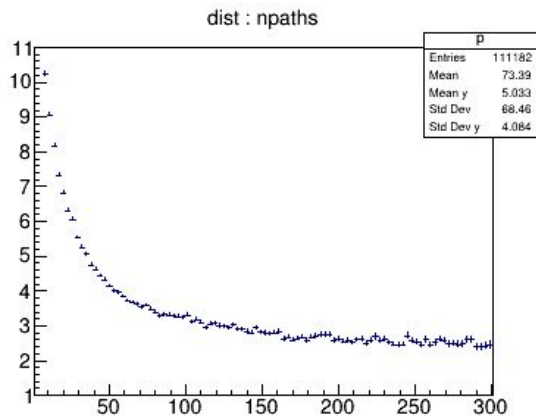
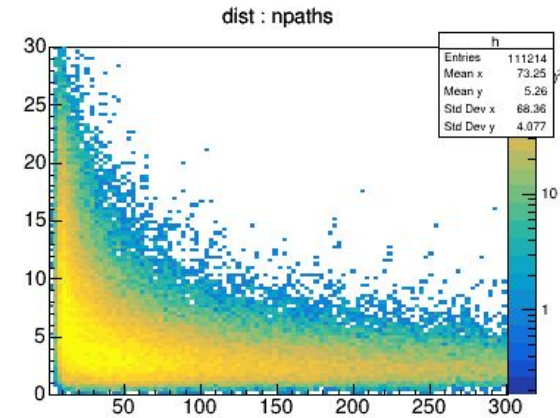
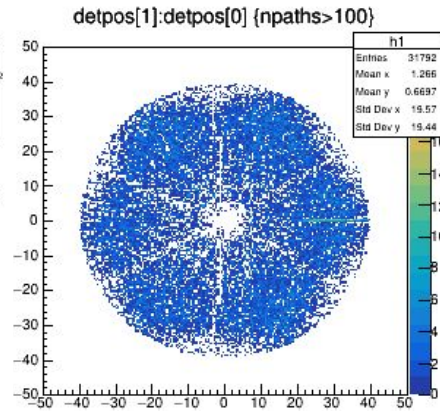
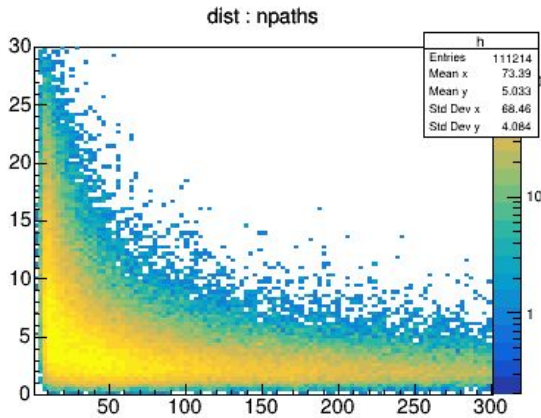
^{60}Co source



Simulate ^{60}Co source $2e10$ evts (energy gate $\pm 10\text{keV}$, $\sim 2e8$ good evts)

accurate source position

10mm mistake

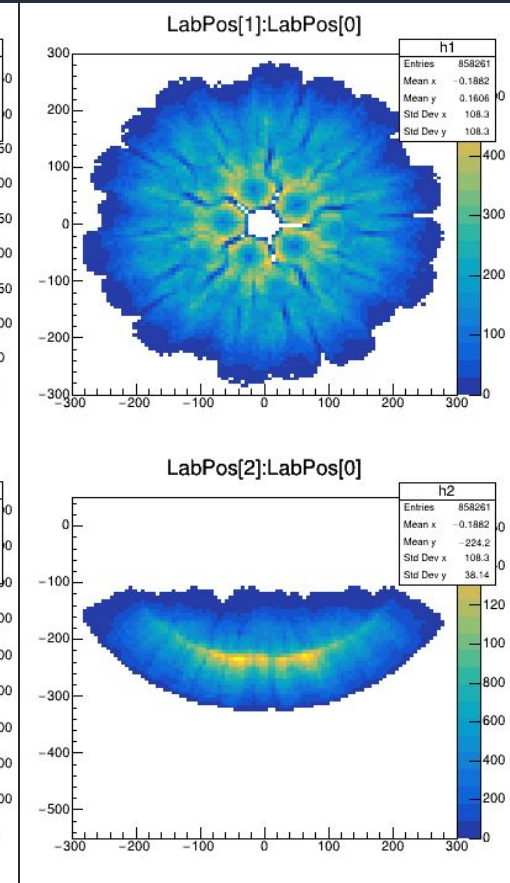
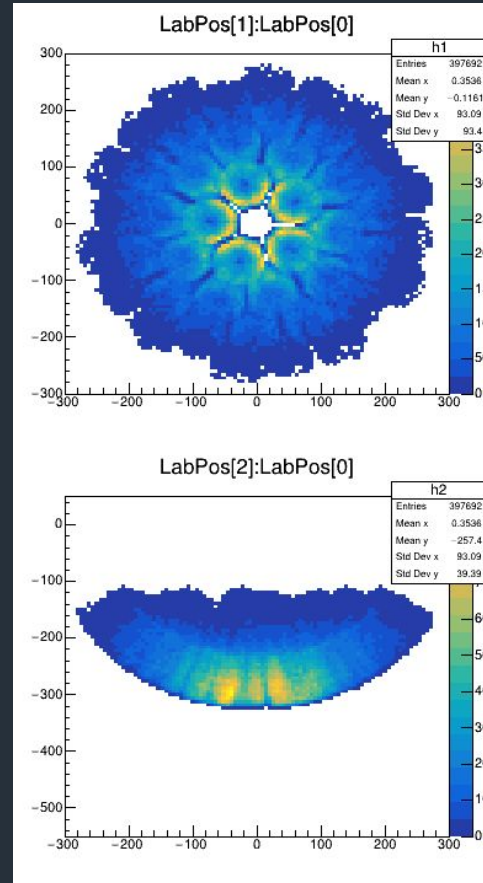
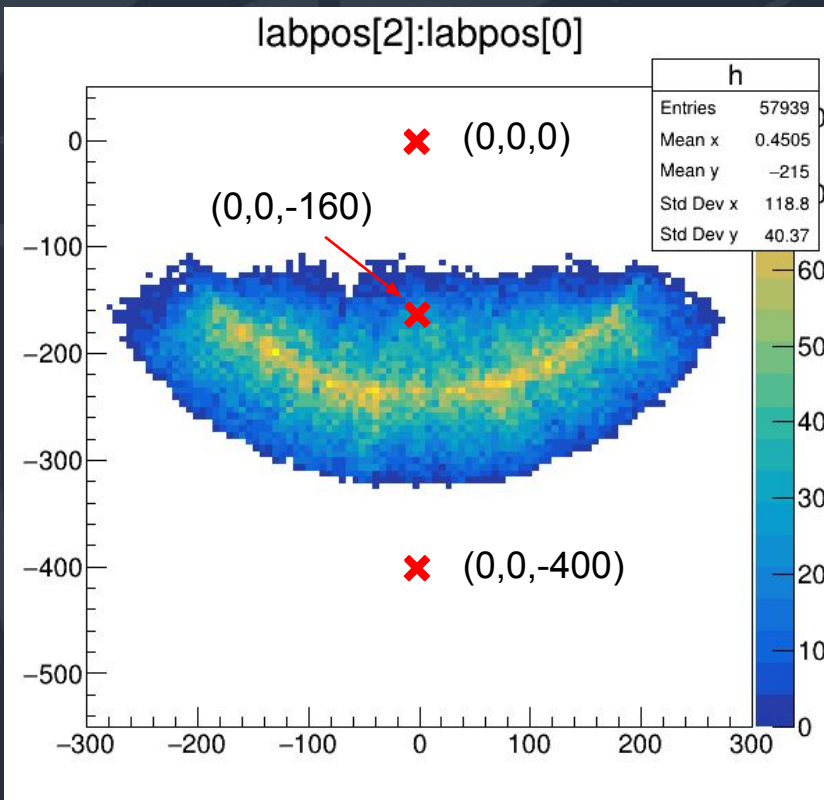


Source position

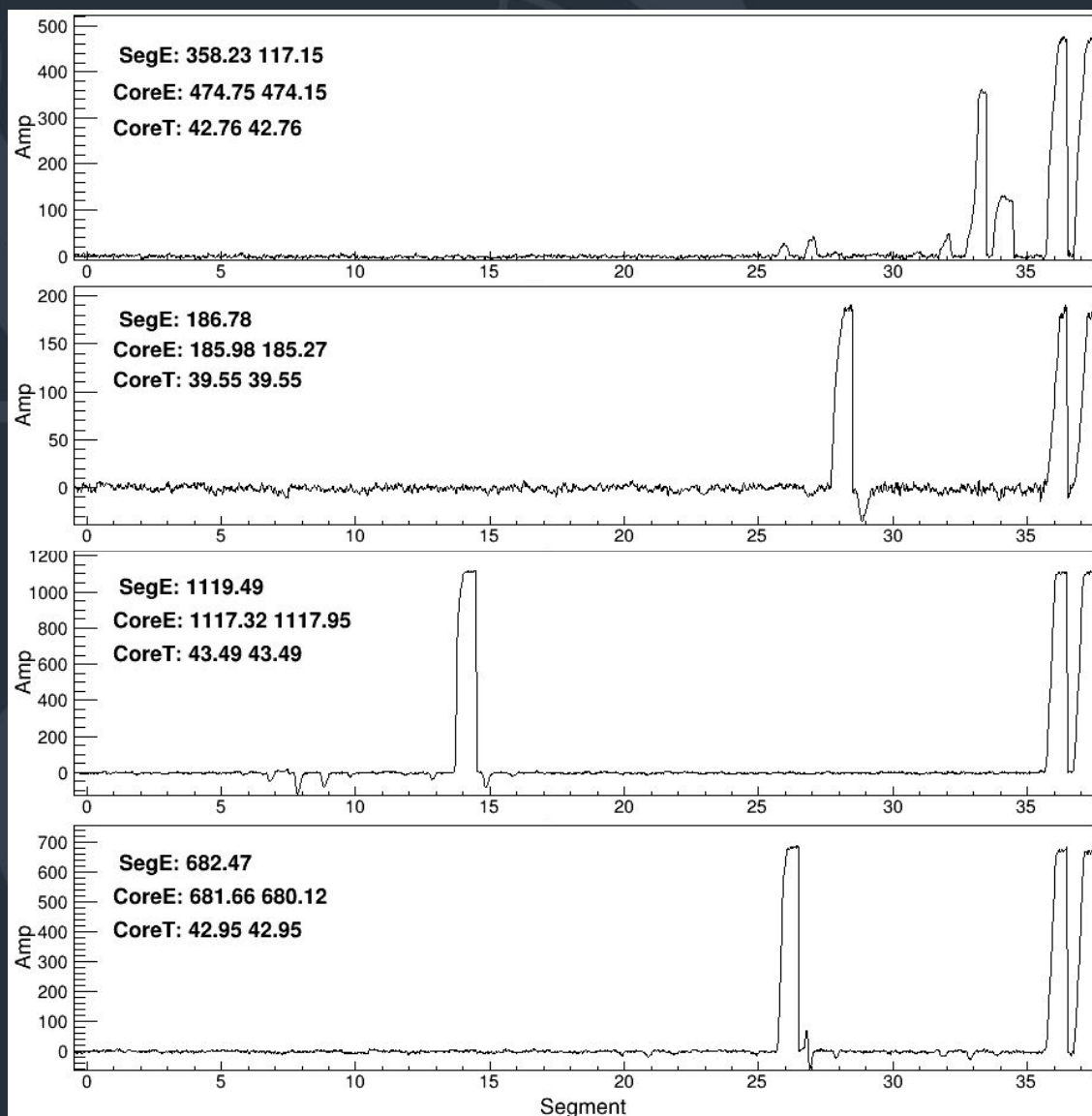


Source at
(0,0,-400)

Source at
(0,0,-160)



Calibration data



✗ multi segments hit

✗ small signal

✗ small Compton signal

○ accepted