Full modeling of AX-PET, a new PET device with axially oriented crystals, based on Geant4 and GATE

P. Solevi*, J. F. Oliver, J. Gillam and M. Rafecas
IFIC (University of Valencia/CSIC)

On behalf of the AX-PET collaboration**

Abstract: AX-PET is a novel PET detector based on long axially arranged crystals and orthogonal Wavelength shifter (WLS) strips, both individually readout by Geiger-mode Avalanche Photo Diodes (G-APD, also known as SiPM or MPPC) [1,4]. Its design was conceived in order to reduce the parallax error and simultaneously improve spatial resolution and sensitivity. The sensitivity can be further enhanced by adding additional crystal layers as well as by including Inter-Crystal Scatter (ICS) events, identified and processed post-acquisition. Its unique features require dedicated Monte Carlo (MC) simulations and its non-conventional design makes modeling rather challenging. We developed an AX-PET model based on Geant4 and GATE packages. Simulations were extensively validated against experimental data obtained from both small scale laboratory and full module setups. The first simulations aimed at developing an analytical model of the WLS behavior which was afterwards coupled to GATE. Full AX-PET acquisitions were used to test the GATE simulations. The agreement between data and simulations was very good. AX-PET simulations are employed to test and optimize image reconstruction software and, at the same time, train ICS identification and reconstruction algorithms.

1. The AX-PET concept

- The crystals are axially arranged on different layers and provide the transverse coordinates x, y
- Layers of wavelength shifter strips interleaved between the crystals yield the axial coordinate z
- Full 3D-reconstruction of the interaction point of the impinging 511 keV gammas
- SiPMs individually readout both LYSO and WLS (combined PET/MRI is possible)
- Potential to identify and reconstruct Compton events (ICS) increasing the system sensitivity
- Spatial resolution independent on the depth of interaction
- Uncorrelated sensitivity and spatial resolution within the detector.

2. The AX-PET status

Two AX-PET modules set in coincidence, with dedicated front-end electronics, were widely tested:
- with NaI point-source at CERN
- with various radioisotopes filled with "F at the Institute of Pharmaceutical Sciences (ETH, Switzerland) and at the Advanced Accelerator Application company (AAA, France).

The resolution achieved ranges between 1.7 and 1.9 mm FWHM in the three dimensions.

3. GATE and Geant4 simulation

GATE was used to simulate AX-PET. In order to include the unique WLS strip behaviour, modelled by using a Geant4 dedicated and validated Monte Carlo simulation, the GATE source code was modified [2,3]. The WLS model is implemented at high level:

\[ N_{LYSO} = N_{WLS} \times (1 - e^{-\gamma}) \]

\( n \) is the Hit counter in the LYSO and \( j \) the WLS index.

A dedicated digitizer module computes the Centre of Gravity (CoG) of the WLS associated to each Single and the information of each strip is stored in the output ROOT file to allow post-acquisition processing of the events.

The simulation includes:
- Time resolution 1.8 ns
- Energy blurring 11.7%
- LYSO intrinsic radioactivity [5].

4. Single Module validation

At first the simulation was addresssed to validate the LYSO occupancy, energy and multiplicity. For this purpose, one AX-PET module is illuminated by a collimated 511 keV gamma beam and the results are compared to data.

The energy spectrum shows an excellent agreement both in photo-peak and Compton region, as well as for the LYSO intrinsic radioactivity.

5. Coincidence sorter and Count rate

To select coincidences, a dedicated sorter unit was developed to model the AX-PET trigger logic. The coincidences are formed by using:
- 20 ns coincidence window
- Energy sum per module at the photo-peak
- Deadline is linearly dependent on the number of active channels (WLS+LYSO) ~200 ns

A mini-Derenzo phantom (19.5 mm diameter, 15 mm height) was homogenously filled by "F and measured at different activities.

The rate of coincidences from the sorter is compared to that measured (without deadline).

6. WLS model validation

A point-like (~0.5 mm) NaI source is placed in between the 2 modules and acquired in coincidence. The rate was ~3 kHz for both data and simulations (the source activity is 635 kBq).

- the mean number of fired strip forming a cluster is 3,
- the total number of ADC counts detected per cluster by the WLSs is 370±115 and 400±91 for data and simulation respectively.

Differences between data and simulation may arise from the lack of modeling of noise and MPPC response in the simulation.

7. Axial resolution

For the same setup, the z resolution was estimated. The intersection of LOR (Line Of Response) with the middle planes (X=0), where the source is located, determines the 2-d geometrical reconstruction of the source, from which the axial coordinate resolution is estimated.

Data and simulation provide respectively \( \sigma_{\text{axial}} = 0.65 \text{ mm} \) and \( \sigma_{\text{axial}} = 0.49 \text{ mm} \).

8. Conclusion and Outlook

The unique features of AX-PET require dedicated MC simulations and its non-conventional design makes its modeling challenging. GATE was modified in order to include the WLS response and an ad-hoc sorter was developed to mimic the AX-PET trigger logic.

The validation of the simulation with different acquired data sets demonstrated excellent agreenement with data, with respect to:
- LYSO energy and multiplicity in single module acquisition
- Count rate performance (no deadline included)
- WLS cluster morphology i.e. number of strips and ADC counts
- Z resolution from the CoG computation.

Better modeling of the deadtime in the sorter is currently under development, in order to support the planning of next measurements campaigns and the reconstruction of images. Simulations are also used to train and test ICS identification and reconstruction algorithms employing different algorithms, providing a correct reconstruction rate ranging between 60% and 75% [8,7].

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