DESCRIPTION AND VALIDATION OF A FULL MODEL OF AX-PET BASED ON GEANT4 AND GATE

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The AX-PET novel design consists of layers of axially oriented crystals, individually readout, interleaved by Wavelength shifter (WLS) strips arrays (see Fig. 1). AX-PET decouples sensitivity and spatial resolution, and avoids the parallax error inherent to radial geometries. Its non-conventional features pose several challenges from the data processing and event selection point of view as well as for reconstruction. The WLS based detection principle has to be properly studied, since it affects not only the spatial resolution, but the sensitivity of the device (i.e. signal dependence on the energy) and the random events rejection (e.g. multiple WLS clusters on the same layer). The large fraction of Inter-Crystal Scattering (ICS) events need to be identified and pre-processed to be included in the reconstruction and this requires a deep understanding of the Compton kinematics within our detector. Thus there is a special need of dedicated simulations in order to estimate, understand and optimize its performance.

**Fig. 1**: Schematic drawing of the AX-PET module. LYSO crystals are axially oriented and staggered in order to minimize gaps. Below each LYSO layer an array of WLS strips is placed, (left). The light escaping the LYSO crystal is partially collected by a cluster of WLS strips and by weighting the signal detected by each strip, the z coordinate of the interaction point can be reconstructed (right).

AX-PET modeling and simulation description

The modeling and simulation of AX-PET is a non trivial matter because of the non-conventional design of the device. We decided to employ the GATE simulation package since it offers several advantages in terms of time management of the events, easy modeling of the detector response and of source distributions. But to overcome the less flexible geometrical modeling of the scanner we had to perform some major modifications to the source code.

At first the WLS strips behavior has to be included in the MC simulation to provide a realistic axial resolution and a good event selection. In order to keep computation time reasonable, the optical photon transport in the crystal and in the WLS strips geometry is not performed directly by GATE, but modeled and parameterized independently. We first run a dedicated Geant4 simulation to **tune the optical material properties** on data acquired in a small laboratory setup, consisting of 2 LYSO crystals and 2 orthogonal WLS strips. In this measurement, an electron collimated beam was employed rather than gamma beam to better control the interaction point. A bunch of electrons of average energy $E=200$ keV hit the crystal at different axial positions and the light detected on each strip is recorded as a function of the electron beam interaction point (see Fig. 2).

**Fig. 2**: Comparison between data and simulations of the number of photoelectrons collected on the 2 WLS strips as a function of the axial interaction point of the electron beam.

Based on previous results, an AX-PET larger scale Geant4 simulation is employed to **extrapolate the parameterization of the signal on the WLS strips**. The amount of detected light on each strip is recorded and modeled as a function of the...
gamma interaction point within the LYSO crystal and the deposited energy. The WLS parameterization is implemented into GATE, where the signal distribution of the WLS strips is computed hit by hit, and a dedicated digitizer module computes the centre of gravity associated to a given Single (i.e., the result of the pulse integration over the reference sensitive volume). In the ROOT output file, the detected light in each fired strip is stored as well as the associated z coordinate. The results for an AX-PET module homogeneously illuminated by 511 keV gamma were validated against measurements. From measurements, by selecting data events at 511 keV with only one LYSO crystal hit, the average number of fired WLS strips was found to be ~3, while the total number of photoelectrons detected by the WLSs is ~90 pe. The simulation exhibits a good agreement with measurements (see Fig. 3), however small differences are observed probably due to the lack of noise modeling and detector response in the strips.

**Fig 3:** Number of WLS strips fired when 511 keV energy is deposited in one LYSO crystal (left) and total number of photoelectrons over the fired strips (right) as computed from simulations. The black dots in the left figure represent the measurement result.

The high granularity of AX-PET, enhanced by good spatial and energy resolutions, yields a large number of Inter-Crystal Scatter (ICS) interactions that can be tracked and reconstructed to further enhance the sensitivity of the device. *Simulations can be used as a training platform to test identification criteria and reconstruction algorithms of ICS events.* For this purpose, it’s important to achieve a good agreement data/simulations in terms of crystal energy and occupancy. One AX-PET module, illuminated by a collimated 511 keV gamma beam, was simulated and the results were compared to data acquired in the same configuration, exhibiting an excellent agreement (see Fig. 4).

**Fig 4:** All LYSO crystals energy spectrum with $R_{511\text{ keV}}=12\%$ (left) and multiplicity of hit LYSO crystals (right). Both plots are obtained when requiring that the energy sum in the 48 crystals is 511 keV.

The AX-PET GATE simulation is now being validated with respect to measurements with two modules in coincidence. ICS identification algorithms have been also tested on synthetic data providing promising results in terms of identification rate.

**Conclusions**

The unique features of AX-PET require dedicated MC simulations and its non conventional design makes its modeling rather challenging. We decided to employ the GATE package to simulate AX-PET, because of its many advantages in terms of time management and detector/source modeling. In order to keep computation times reasonable, the optical photon transport in the WLS/LYSO geometry is independently simulated and modeled and eventually parameterized in the GATE simulation, in a dedicated digitizer module. The simulation was then validated against experimental data with respect to WLS strips behavior, LYSO energy spectra and crystal occupancy. An excellent agreement with data was achieved. AX-PET simulations are extensively employed to test and optimize image reconstruction software and, at the same time, train ICS identification and reconstruction algorithms. The corresponding results will be shown in the forthcoming paper.