I. INTRODUCTION: THE AXIAL PET CONCEPT

The Axial PET (AX-PET) concept [1] proposes novel detection geometry for PET, based on the axial arrangement of LYSO crystals which are individually readout by Geiger-mode Avalanche Photo Diodes (G-APDs). The goal of this design is to provide a 3D reconstruction of the gamma interaction point with parallax-free resolution. For this purpose, the crystals are stacked in several radial layers, which are interleaved by arrays of Wavelength Shifter (WLS) strips, also individually readout by G-APDs [3] (see Fig. 1). Transaxial depth-of-interaction (DoI) information is thus obtained directly from the address of the hit crystal. The axial coordinate \(Z\) is retrieved from the WLS strips, which are placed below each crystal layer in the perpendicular direction (axial DoI). Hence, the AX-PET design allows for the decoupling of spatial resolution and sensitivity.

A two-module scanner prototype has been build following this concept. In this paper, we present the latest results obtained with this system after a test campaign at the company Advanced Accelerator Applications (Saint Genis, France). As a novelty, compared to the work presented in [2], the rotation of one module has been implemented, allowing the transaxial Field–of–View (FoV) to be substantially extended and thus larger phantoms to be imaged. Additionally, various reconstruction approaches have been developed and tested using measured data.

II. MATERIALS & METHODS

The AX-PET scanner prototype: The current system consists of two detector modules, each comprised by 6 crystal layers (8 crystals per layer, crystal size: \(3 \times 3 \times 100 \text{ mm}^3\)). The crystal layers are interleaved by arrays of 26 WLS strips each. Both LYSOs and WLSs are readout by G-APDs (also known as Silicon Photomultipliers, SiPMs) from Hamamatsu, marketed as Multi Pixel Photon Counters (MPPCs). The MPPCs for the LYSO are \(3 \times 3 \text{ mm}^2\) (divided into 3600 cells), while the MPPCs for the WLS strips are custom-made with active area of \(3.22 \times 1.19 \text{ mm}^2\) (782 cells). The crystals in one layer are axially staggered by 2 mm, and the crystal layers are staggered in the \(Y\) coordinate by half the crystal pitch (1.75 mm). This staggering among layers serves to optimize the photon interaction probability. The WLS strips are staggered by 5.4 mm in \(Y\), but there is no horizontal staggering between WLS strips of different layers.

The electronics chain of AX-PET consists at the front-end of fast amplifiers (Texas Instruments OPA843 for LYSO and OPA847 for WLS) which are fed with the MPPC signals via Kapton cables. The amplified signal has to pass a threshold to be readout. This threshold is set to 50 keV for LYSO crystals. The coincidences between two modules are formed when the sum of discriminated LYSO signals in both modules is within the range 400 keV and 600 keV. The energy resolution, and the transaxial and axial spatial detector resolution obtained from point-like measurements are 11.6\% (at 511 keV); \(\sigma_{XY} = 0.87 \text{ mm}\) and \(\sigma_{Z} = 0.64 \text{ mm}\), respectively.

Reconstruction of the \(Z\) coordinate: The reconstruction of the “axial DoI” (\(Z\) coordinate) relies on the absorption by the WLS strips of the scintillation light which escapes the crystal. The strips which are fired in the event contribute to the computation of the \(Z\) coordinate by a Centre–of–Gravity (CoG) method. In order to remove the contribution from the noise, a clustering algorithm is applied on all the WLS detected in the same layer of the LYSO crystal. (A cluster is defined as a group of adjacent WLS strips above the detection threshold. Only the WLS in the cluster are used to compute the reconstructed \(Z\) coordinate.) The amount of light detected by each strip guarantees the \(Z\) reconstruction capability down to an energy of at least 200 keV.

The AX-PET concept also allows the detection of multiple coincidences resulting from Compton interactions in the crystal matrix (Inter-Crystal Scatter). These coincidences could be used to enhance the system sensitivity providing that the Compton interaction sequence can be properly reconstructed. We are currently implementing various identification techniques, and simulations suggest that a large fraction of those scattering events can be fully recovered. The impact on the final image is still to be determined.

Tomographic imaging: In the current gantry, one module is fixed, while both the rotation of the phantoms (placed over a rotating table) and the rotation of one module are possible. While the first motion ensures tomographical imaging, the latter allows the transaxial FoV to be enlarged. In this work, the rotatable module was first placed in front of the fixed module at 150 mm (face-to-face), and then rotated by 20\(°\) (oblique). The sources were rotated in 20\(°\) steps over 180\(°\) (face-to-face configuration) and over 360\(°\) (oblique configuration). The two rotation movements are equivalent to a virtual 4-head system with modules at \(-20°; 0°; 20°, \text{ and } 180°\).

To reconstruct the data, we have developed four approaches...
which take into account the particular nature of AX–PET data (the identification index (ID) of the hit crystal is a discrete number, whereas the Z coordinate can take any value along the crystal length forming a continuous axial detection domain). The first approach is based on analytical techniques [4]; however, to fully exploit the particular characteristics of AX–PET, we have also implemented statistical iterative methods: The current AX–PET Image Reconstruction Software (AIRS) combines MLEM with a system response matrix (SRM) computed off-line. The SRM is based on a multi-ray approach, and takes into account not only geometry but also crystal penetration and attenuation in the neighbouring crystals. A drawback of off-line calculation of the SRM is the computational cost and the fact that the SRM is attached to a particular system configuration. As an alternative, we have also developed the Simulated One-Pass List-Mode (SOPL) reconstruction algorithm which calculates the SRM elements on the fly and also preserves the continuous nature of the Z coordinate [5]. Finally, to avoid binning in Z but still using the off-line computed SRM, we are also exploring how to reconstruct data using the crystal ID and the signals of the strips [6].

These algorithms and the new configuration are being tested using real data from 22-Na point-like sources, as well as various extended phantoms filled with FDG. To assess the resolution capability of the scanner, sets of thin 3-cm long capillaries (1.4 mm inner diameter) placed at various spatial orientations were employed. Additionally, two custom-made resolution phantoms with drilled rods of various diameters were also imaged. For image quality studies, the NEMA NU4 Micro-PET Image Quality Mouse Phantom (QRM Quality Assurance in Radiology and Medicine GmbH, Germany) was also employed. Various acquisition protocols were tested, and the resulting data sets were processed in order to select those coincidence events characterized by only one LYSO hit per module and one WLS strip cluster for each hit crystal (golden events).

III. RESULTS & DISCUSSION

In Fig. 2 two views of the reconstructed NEMA-NU4 phantom using AIRS are presented. In the transaxial slice, all rods can be identified, although partial volume effects affect the representation of the smallest one (1 mm diameter). In the coronal slice, the cold rod as well as one of the active rods are clearly visible. Concerning the resolution phantoms (not shown here), count losses at certain oblique steps gave rise to artifacts which affected some sectors of the phantom. Still, the region containing 2.6-mm rods could be reconstructed adequately. These count loss problems, related to the prototype front-end electronics and DAQ system, have been recently solved, and tests using point sources showed an improved performance of the system, in terms of count rates.

Concerning the reconstruction codes, the AIRS approach is providing the best image quality at present, but at the cost of long computing times to calculate the SRM. On the other hand, SOPL is a very promising, flexible alternative which can be easily adapted to any change in the AX–PET configuration. In spite of the complex geometry and the crystal gaps, an analytical reconstruction has been recently applied to real data [4] and is currently under optimization. Preliminary data reconstructed using the fourth approach (no Z binning but discrete SRM) provided smoother images (axial slices) but at the cost of degrading the axial resolution. Alternative ways to improve this technique are currently under development.

IV. CONCLUSION

The new measurements carried out with extended phantoms have confirmed the imaging capabilities of AX–PET for a larger transaxial FoV, even though data were affected by irregular count losses. Recent advancements in the DAQ system have provided significant improvements which are expected to enhance image quality. This should be confirmed in the next measurement campaigns, planned for the upcoming months. The 3D image reconstruction codes have been successfully tested and improvements in terms of SRM modelling and computing time are under development.

The obtained results support the Axial PET concept as a succesfull design to tune the spatial resolution and sensitivity. Both properties could be optimized at the same time by adding more crystal layers or modules, and by reducing the crystal and strip sizes. Although not part of this report, it is still worth mentioning that the AX–PET concept is compatible with the integration within a MR system.

REFERENCES