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3γ MEDICAL IMAGING WITH A LIQUID XENON COMPTON CAMERA AND ^{44}Sc RADIONUCLIDE*

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The development of a liquid xenon Compton camera called XEMIS2 (XEnon Medical Imaging System) is a step forward to a new type of medical imaging based on the use of ^{44}Sc radionuclide emitting two annihilation γ rays and a third high energy γ ray simultaneously. The single phase TPC (Time Projection Chamber) under construction, containing nearly 200 kg of xenon, is designed to measure most of the Compton interactions in the active area with a sub-millimetre position resolution and a good energy resolution of 4% on 511 keV photopeak. The intersection of the Compton cone surface from the third γ ray with the line of response from the two annihilation γ rays allows to localize the radionuclide with a precision (FWHM) of about 1 cm along this line. The large field of view of such

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a liquid xenon camera combined with the 3γ imaging technique will provide a good quality image while keeping the injected activity at a very low level. XEMIS2 will be installed in the Nantes University Hospital in order to demonstrate its capability to image small animals injected with a low activity of only 20 kBq in 20 mn acquisition time. To achieve this goal, a precise measurement of the ionization signal is provided by a pixelized anode, shielded by a Frisch Grid and read out by a low noise front-end electronics. In addition, new cryogenic and purification subsystems have been tested, allowing safe recovery of xenon in liquid phase at flow rates of about 1 ton per hour.

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1. Introduction

A new functional medical imaging technique based on simultaneous detection of three γ rays is currently under development at SUBATECH laboratory. The basic principle of this 3γ imaging consists in combining a precise 3D localization of the radioactive decay of a (β^+,γ) emitter with a large Field Of View (FOV) camera resulting in a significant reduction of the administered dose to the patient for oncology diagnosis. This new imaging technique requires the use of a specific radionuclide, the ^{44}Sc [1] coupled to a Compton camera. Thanks to the kinematics of the Compton scattering process, this camera allows for reconstructing the origin of a primary photon on the surface of a cone. The position of the radionuclide is then obtained by the intersection between the Line Of Response (LOR) given by the two back-to-back 511 keV γ rays from the positron annihilation with an electron, and the cone from the measurement of the third γ ray in the Compton camera [2].

To exploit the advantages of the 3γ imaging technique, the Compton camera requires a high Compton scattering efficiency and a high spatial and energy resolutions [3–6]. A Liquid Xenon Time Projection Chamber (LXeTPC) represents a good option and has already proven to be a perfect candidate as a γ-ray detector in the energy range from several tens of keV to tens of MeV due to its ideal properties. For this reason, its use as radiation detection medium has increased in the recent years in numerous applications in particle physics, astrophysics and medical imaging [7]. Although our long-term project is to construct a large FOV camera for human body imaging, we have demonstrated the capacity of an LXeTPC to provide the necessary information for the 3γ imaging technique, in a first stage called XEMIS1. The second stage XEMIS2 is a camera dedicated to small animal imaging and is currently under construction. Progress on this two stages is reported in the following sections.

2. Performances of a liquid xenon TPC prototype (XEMIS1)

The XEMIS1 prototype consists of a single phase LXeTPC of $2.8 \times 2.8 \times 12(6)$ cm^3 active volume filled with liquid xenon. The VUV scintillation photons (178 nm) generated from the γ-ray interactions are detected by a Hamamatsu R7600-06 photomultiplier tube (PMT) specifically designed to work at liquid xenon temperature. The charge carriers produced in the ionization process are collected by an anode segmented in 64 pixels of size 3.125×3.125 mm^2. Individual pixels are connected to ultra-low noise front-end electronics IDeF-X HD-LXe [8] allowing to reach an electronic noise (Standard Deviation) of 90 e^-. To drift the electrons towards the anode, a homogeneous electric field up to 2.5 kV/cm is defined by copper field rings arranged around the TPC. A more complete description of the setup and the performance assessments using a ^{22}Na sealed source can be found in the previous publication [2]. Since then, several gap/grid configurations for the ionization signal readout have been tested in order to optimize the Frisch Grid efficiency and reduce the undesirable induced signal on neighbouring pixels. Furthermore, the mechanical frame has to maintain a constant space between the grid and the anode, and the electric field must reach several tens of kV/cm to ensure a 100% electron transparency of the mesh. Even though the optimization of the gap/grid structure is still ongoing, the electric field dependency of the average charge and the energy resolution on the 511 keV photopeak were measured and are shown in Fig. 1. These results were obtained with the following configuration: the LXeTPC 6 cm long in order to increase the scintillation light detection efficiency, the Frisch grid made up of a 100 LPI stainless steel woven mesh with wire diameters of 25 μm, the electric field ratio between induction gap and drift area set to 6 to achieve a 100% electron transparency and the gap size 0.5 mm. These results are consistent with previous measurements reported by other authors

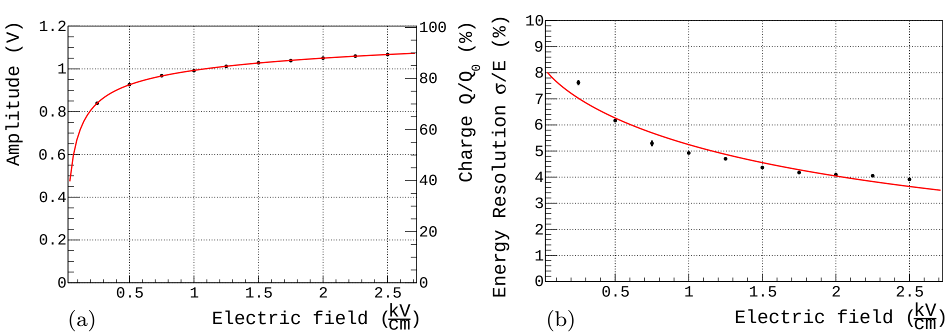
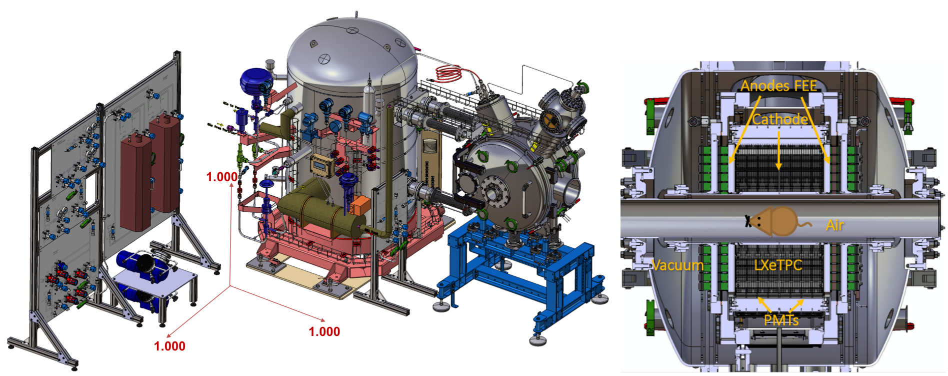


Fig. 1. (Colour on-line) Electric field dependence of the relative charge yield (a) and the energy resolution (b) on 511 keV photopeak in XEMIS1. The lines (red) correspond to the fit of our data with the parameterized Thomas *et al.* model [10].

in [9]. An energy resolution better than 4% has been reached for electric field larger than 2 kV/cm for photoelectric interactions: it is dominated by the statistical fluctuations of the charge production process in liquid xenon.

3. A liquid xenon camera for small animal imaging (XEMIS2)

A small animal imaging camera called XEMIS2, currently under construction, is intended to be used for preclinical researches at the Nantes University Hospital. In order to maximize the FOV and thus to increase the sensitivity, the design of the camera is based on a monolithic cylindrical detector that surrounds the animal. The objective is to realize a good quality image in 20 minutes of exposure by injecting only 20 kBq of ^{44}Sc to the small animal. An overview of the experimental set-up is presented in Fig. 2 (a), including the XEMIS2 cryostat, the cryogenic infrastructure used to store, liquefy and recuperate the xenon and the purification and recirculation systems. XEMIS2 consists of two back-to-back cylindrical LXeTPCs with a common cathode containing about 200 kg of liquid xenon in total. Figure 2 (b) illustrates the design of the active zone of XEMIS2 which is a cylinder of 7 cm inner radius, 19 cm outer radius and 2×12 cm drift length. The active volume will be completely surrounded by 380 PMTs to detect the VUV scintillation light at 178 nm wave length.



(a) (b)

Fig. 2. Overview of the XEMIS2 experimental set-up: XEMIS2 camera of 80 cm in external diameter, Recovery and Storage of Xenon (ReStoX) of 190 cm in height and purification system (a). Design of the XEMIS2 camera (b).

3.1. Readout electronic of ionization signal

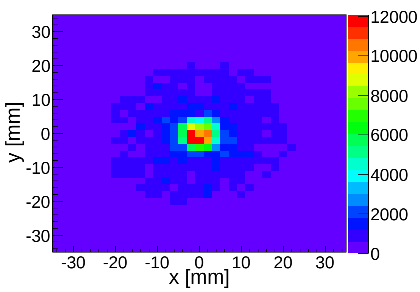
Each anode on both sides of the detector is segmented in 10^4 pixels, read out by the IDeF-X HD-LXe low noise electronics immersed in liquid xenon. A dedicated ASIC called XTRACT [11] has been developed to extract, on each pixel, the relevant information from the analog pulse generated by charge carriers moving in the induction gap. The channel connected to the pixel is self triggered with a very low threshold, just above the electronic noise ($3\sigma_{\mathrm{noise}}$), to maximize the detection efficiency. Meanwhile, the arrival time of the pulse is measured using a Constant Fraction Discriminator (CFD) method. The parameters of the delayed signal, which is internally generated to define the zero crossing point of the CFD, are thoroughly chosen to measure the pulse height. Due to the low threshold, the output data flow will be dominated by fake pulses randomly generated by noise fluctuations. This data flow will be of the order of 10^4 measured charge and time per pixel per second and will be further reduced in FPGA boards by removing low amplitude signals isolated in space and time.

3.2. ReStoX commissioning

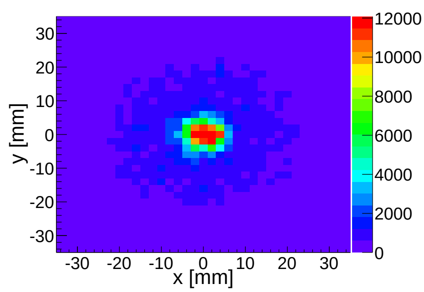
The LXe camera will be installed in a hospital, thus it should be compact and safe. For this purpose, a proper cryogenic system named ReStoX (Recovery and Storage system of Xenon) has been designed and built by the AIR LIQUIDE Advanced Technologies Division and SUBATECH laboratory. It can store up to 210 kg of xenon from room temperature to liquid xenon temperature ($-100°$C). In addition, cold xenon handling is very efficient thanks to the high cooling power of 10 kW provided by liquid nitrogen circulating in a specifically designed aluminium block located inside ReStoX tank. The commissioning of ReStoX has been carried out for 200 kg LXe in several stages of operation. Without cooling source, the room temperature would be reached from LXe temperature in almost 1 year. Moreover, in case of emergency, a fast passive recovery in liquid phase of xenon stock could be realized in less than 10 minutes with the help of the gravitational force.

3.3. Simulated performances of XEMIS2

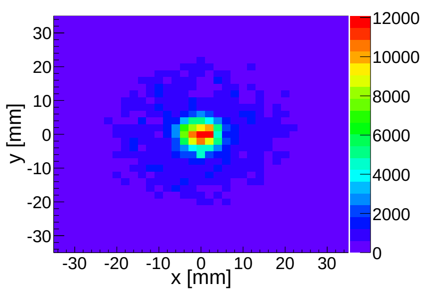
A full GATE/Geant4 Monte Carlo simulation [12] of the XEMIS2 camera was carried out to investigate the 3γ imaging performances. In a preliminary study, a cylindrical water phantom of 5 cm in diameter and 12 cm in length, uniformly filled with 20 kBq of ^{44}Sc was simulated for an acquisition time of 20 minutes. A hot sphere with a contrast of 15, size of 1 cm in diameter located in the center of the FOV, was added on top of the uniform distribution to assess the imaging capabilities of this technique even for very low injected activity. An original algorithm was developed to determine the 3D position of the emitter by intercepting the reconstructed Compton cone from the third γ ray with the reconstructed LOR from the two back-to-back 511 keV γ rays. Based on this algorithm, the sensitivity of the camera operating in 3γ mode was estimated to be 7% at the center of the FOV and is almost constant throughout the phantom. Moreover, the signal-to-noise ratio increases due to the precise localization of the radionuclide decay along the LOR of the order of 1 cm (FWHM), derived from simulation. The quite big sensitivity together with the 3D localization allow to seriously consider the possibility to obtain a good image quality at low activity. A Maximum Likelihood Expectation Maximization (MLEM) reconstruction algorithm was applied to the raw data consisting of points (*i.e.* 3D coordinates) resulting from the intersections of Compton cone surfaces with LORs. This iterative algorithm is assuming the Poisson distribution of the counting statistics and can be thought of as a deconvolution process of the phantom and detector effects. Indeed the simulated Point Spread Function (PSF) used for the deconvolution is assumed to be the same all over the FOV. The simulation results are presented in Fig. 3 and show that XEMIS2 is capable of imaging a hot sphere on top of a uniform background while recovering the true contrast. Thus, the main achievement of this 3γ technique using a Compton camera filled with liquid xenon consists in a good quality image that can be obtained even with a very low activity (20 kBq) compared to conventional small animal PET imaging.



(a)



(b)



(c)

Fig. 3. Reconstructed image of a hot sphere located at the center of a phantom uniformly filled with ^{44}Sc. Only central transverse slices are presented after 23 iterations of the MLEM algorithm: $z = -2$ mm (a), $z = 0$ (b), $z = 2$ mm (c). The voxel size is $(2 \times 2 \times 2)$ mm^3.

4. Conclusion

We reported on the advancement of the XEMIS project aiming to develop a new medical imaging technique taking advantage of the continuously improving LXe technology. XEMIS1 has already demonstrated the capability of an LXeTPC to reconstruct Compton cones thanks to the good energy and spacial resolutions. We measured the energy resolution with a 2D segmented anode and a small induction gap and we observed a clear improvement with increasing the electric field. A second prototype XEMIS2 for small animal imaging is currently under qualification: it will be the first LXe camera installed in a hospital for preclinical researches. The expected image quality is very promising with a quite uniform sensitivity throughout the FOV. In addition, by virtue of the fact that the LXe technology is easily scalable, the design of a large camera to image the full human body is foreseen in the near future.

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