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# XEMIS: Liquid Xenon Compton Camera for $3\gamma$ Imaging

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**Abstract.** An innovative liquid xenon Compton camera project, XEMIS (XENon Medical Imaging System) has been proposed by SUBATECH laboratory, for a new functional medical  $3\gamma$  imaging technique based on the detection in coincidence of 3  $\gamma$ -rays. The purpose of this  $3\gamma$  imaging modality is to obtain a 3D image using 100 times less activity than in current PET systems. The combination of a liquid xenon time projection chamber (LXe TPC) and a specific ( $\beta^+$ ,  $\gamma$ ) radionuclide emitter  $^{44}\text{Sc}$  is investigated in this concept. In order to provide an experimental demonstration for the use of a LXe Compton camera for  $3\gamma$  imaging, a succession of R&D programs, XEMIS1 and XEMIS2, have been carried out using innovative technologies. The first prototype XEMIS1 has been successfully validated showing very promising results for energy, spatial and angular resolutions with an ultra-low noise front-end electronics. The second phase dedicated to a 3D imaging of small animals, XEMIS2, is now under installation and qualification, while the characterizations of ionization signal using Monte Carlo simulation has shown preliminary good performances for energy measurement.

**Keywords:** Medical imaging ·  $3\gamma$  imaging · Compton camera  
Liquid xenon

## 1 Introduction

XEMIS is a *X*enon Medical Imaging System directed to the development of personalized medicine, which is based on the  $3\gamma$  imaging technique and a new liquid xenon Compton camera to realize a low activity medical imaging. This project contains three main phases: the first R&D prototype XEMIS1 has been successfully assessed with good experimental results proving the feasibility of the  $3\gamma$  imaging concept. The XEMIS2 which is designed for small animal imaging is now under installation and qualification. While for the future research, XEMIS3, a LXe clinical camera for total-body imaging will be investigated.

## 2 $3\gamma$ Imaging Technique

The  $3\gamma$  imaging is a new medical imaging modality proposed by our group, whose principle is to get a 3D location of the radioactive source by detecting simultaneously three gamma-rays [1]. A specific radionuclide that emits quasi-simultaneously a gamma ray and a positron is necessary in this technique. Our best candidate is  $^{44}\text{Sc}$ , produced by ARRONAX cyclotron while the related radio-pharmaceutical is under researched by Inserm and CHU of Nantes [2].

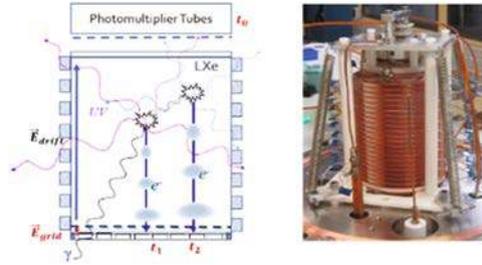
The position of the radionuclide is obtained by the intersection between the reconstructed line of response (LOR) and Compton cone. Where the LOR is given by the two back-to-back 511 keV gamma-rays resulting from the positron annihilation, and the Compton cone defined from the interaction of the third gamma-ray with a Compton telescope. The opening angle of the cone  $\theta$  is given by the Compton scattering kinematics, whereas the axis of the cone  $\Delta$  is determined by the first two interaction positions of the incoming photon inside the detector.

Thanks to the information given by the third gamma ray, the administered activity could be reduced a hundred-time compared to the standard PET. However, in order to get a high-quality image, all interaction vertexes should be detected with a good spatial and energy resolution, which is a big challenge for the experimental feasibility. For this purpose, a succession of R&D programs, XEMIS1 and XEMIS2, has been conducted whose recent status will be presented in the following sections.

## 3 XEMIS1: R&D Prototype

XEMIS1 a small dimension single-phase LXe TPC, designed for testing the possibility of using a LXe Compton telescope for  $3\gamma$  imaging. XEMIS1 camera consists a cylindrical TPC of 12 cm drift length full of LXe (Fig. 1).

As other liquid noble gases, both scintillation photons and ionization charges are emitted after the interaction of an ionizing particle with LXe. Therefore, at the top of the TPC, it equipped a 1" Hamamatsu photomultiplier tube (PMT) operating in LXe for detecting the VUV light (178 nm). It's used as a trigger of the signal acquisition to get the interaction time  $t_0$ . Under the homogeneous drift field generated by 23 copper field rings, the ionized electrons transport to the segmented anode by traversing the Frisch



**Fig. 1.** The schema of the principle of TPC (left) and a view of XEMIS1 TPC (right)

grid that forming the ionization signals represents the deposited energy and position of each interaction vertex. Aims to realize the accurate charges measurement with higher signal/noise ratio, an ultra-low noise (below  $100 e^-$  RMS) front-end electronic, IDeF-X operating at LXe temperature have been developed with collaboration.

The performance characterization of XEMIS1 is calibrated by the 511 keV gamma-ray emitted from a low activity  $^{22}\text{Na}$  source which is also a ( $\beta^+$ ,  $\gamma$ ) emitter. The experimental results have shown a 5% energy resolution and a timing resolution of  $44.3 \pm 3.0$  ns for 511 keV photoelectric events at 1 kV/cm, which is equivalent to a spatial resolution along the z-axis of roughly 100  $\mu\text{m}$ . In addition, a Compton cone measuring test has been done with XEMIS1. The resolution along the LOR is about 8 mm FWHM for 5 cm distant source [3]. This result is limited by the small active area of XEMIS1.

## 4 XEMIS2: Small Animal Imaging

XEMIS2 is a larger LXe Compton telescope for small animal imaging which is designed for quantifying the potential benefit of the  $3\gamma$  imaging technique in terms of injected dose. XEMIS2 camera is a monolithic liquid xenon with two back to back cylindrical TPC of 12 cm drift length, where a tube with 10 cm of diameter traverses using to put the little mice. It holds around 200 kg of liquid xenon, totally surrounding the small animal (see Fig. 2). The active volume of detector is covered by 64 Hamamatsu PMTs and two end segmented anodes with a total 20,000 pixels of  $3.125 \times 3.125 \text{ mm}^2$ , to detect both the VUV scintillation photons and ionization signals produced after interaction of ionizing radiation. A complete Monte Carlo simulation by Geant4 has been done in the first place. The simulation has been realized with a 20 kBq  $^{44}\text{Sc}$  source inside a cylinder full of water (simulating a mouse). Preliminary results shown a quite uniform event detection efficiency in all field of view (FOV). At present, XEMIS2 has been assembled in the laboratory, and prepared to install at the Nantes hospital.

**ReStoX Commissioning.** As the first LXe camera will be installed in a hospital, it should be compact and safe. For this purpose, a special cryogenic system named ReStoX (Recovery and Storage system of Xenon) has been built with the Air Liquid



**Fig. 2.** XEMIS2 camera with ReStoX

and SUBATECH collaboration. It could store 210 kg xenon from room temperature to liquid xenon temperature ( $\sim -100$  °C). In addition, the xenon cooling with liquid nitrogen is very powerful, up to 10 kW. The commissioning of ReStoX has been done in our laboratory. Results have shown that, for 200 kg LXe, without cooling source, the room temperature would be reached from LXe temperature in almost 1 year. And in case of extreme situation, a passive recovery with the gravity could be realized in almost 10 min.

**Ionization DAQ Chain.** For the low activity imaging, all the interaction signals need to be recorded without dead time during 20 min, that means  $\sim 10^4$  charges and time signals/pixel/s. In XEMIS2, there are more than 20000 electronic channels which is a big challenge for the data storage. The IDeF-X [4] and XTRACT [5] have been developed for the ionization DAQ, permitting reading out only the amplitude, time and address of pixel for each ionization waveform in order to control the data storage volume. Finally, there are only 80 process units connected to the 6 FPGA board to reduce the traverse number. There are still lots works to do before the operation of XEMIS2.

## 5 Conclusion

$3\gamma$  imaging would be a new medical modality thanks to LXe technology. The design and construction of XEMIS camera are quite challenging that involves lots of new technologies and innovations. At present, the second prototype XEMIS2 for small animal imaging is under qualification and it will be the first LXe camera installed in a hospital. The expected image quality is very promising with a quite uniform event detecting efficiency in all FOV. In addition, the LXe technology is scalable so that a design of large whole-body camera could be investigated in the future.

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