XEMIS: The new Compton camera with liquid xenon

J. Donnard*
SUBATECH, UMR 6457, Ecole des Mines de Nantes, CNRS / IN2P3 / Université de Nantes, 4 rue Alfred Kastler BP 20722, 44307 Nantes cedex 3, France
E-mail: jerome.donnard@subatech.in2p3.fr

D. Chbib, W-T. Chen, J-P. Cussonneau, L. Gallego-Manzano, O. Lemaire , P. Le Ray, J. Masbou, A.F. Mohamad Hadi, E. Morteau, L. Scotto Lavina, J-S. Stutzmann, D.Thers
SUBATECH, UMR 6457, Ecole des Mines de Nantes, CNRS / IN2P3 / Université de Nantes, 4 rue Alfred Kastler BP 20722, 44307 Nantes cedex 3, France

T. Carlier, M. Cherel, F. Kraeber-Bodéré
CRCNA, UMR Inserm892 - CNRS 6299, Institut de Recherche en Santé de l'Université de Nantes, 8 quai Moncousu - BP 7072,1 44007 Nantes cedex 1

Subatech initiated the study of a new medical imaging concept in the environment of the Arronax cyclotron (Nantes, France). This innovative technique, called the 3 gammas imaging, aims at performing a direct 3D reconstruction of each decays of ^{44}Sc radionuclide with a resolution below the centimeter. This unique property should lead to a reduction of a few dozen times the injected activity compared to the activity required in the current PET scanners. This breakthrough in instrumentation technique is only possible by the use of a new detection medium and a new detection structure compared with conventional PET imaging technique. The good properties of ultrapure liquid xenon as detection medium (high atomic number, high density, high emission light and ionization yield) lead to the engineering of a sensitive monolithic and homogeneous volume of detection with an adaptable geometry. Thanks to an ultra-low noise front end electronics (around 100 electrons NEC) operating at liquid xenon temperature and a fast UV sensitive PMT, high spatial resolution and high energy resolution are achievable in 3D. This is particularly important for Compton imaging since all interactions in the medium have to be identified to derive the incoming gamma ray direction. A small prototype with an active area of 28x28 mm^2 is now in test at Subatech (Xemis1) and shows promising results with a 511 keV source (^{22}Na). All the cryogenic system is fully operational with a high purification rate and shows a very good stability. This paper reports on all these activities and introduce the next stage of the project: the development of Xemis2 a full preclinical camera prototype.

Calorimetry for High Energy Frontiers - CHEF 2013,
April 22-25, 2013
Paris, France

*Speaker.

1. Introduction

Subatech is developing the 3 γ imaging, a new concept of medical imaging which aims to perform direct 3D reconstruction of special radionuclides [1]. It is based on the use of a 3 γ emitter radionuclide, in particular the ^{44}Sc. This radionuclide emits a $\beta+$ (Emean = 632 keV, Emax = 1473 keV) decaying in 2 photons of 511 keV emitted back-to-back and in 99.9% of the disintegration and in quasi-coincidence a gamma ray (E=1.157 MeV). The two back-to-back 511 keV photons from the positron annihilation gives a line of response (LOR) and the arrival path of the third γ ray is reconstructed according to the Compton kinematics thanks to the following equation:

$$\cos(\theta) = 1 - m_e c^2 \frac{E_1}{E_0(E_0 - E_1)} \tag{1.1}$$

where θ is the scattering angle, $m_e c^2$ the mass of the electron (511 keV), E_0 is the energy deposited at the first hit (1157 keV) and E_1 is the energy deposited at the second hit. Since in dense medium the direction recoil of the scattered electron is generally not measurable, a revolution symmetry appears. This leads to the reconstruction of a cone of presence containing the incident γ ray and not a straight line. This reconstructed cone is determined by 3 parameters: the apex (3D position of the first hit), the aperture angle (θ determined by the energy deposited at the first hit) and the axis Δ (given by the vector between the first and the second hit). The 3D position of the radionuclide can be thus reconstructed by locating the intersection point between the LOR and the cone. The Fig. 1 shows the principle of the 3 γ imaging technique.

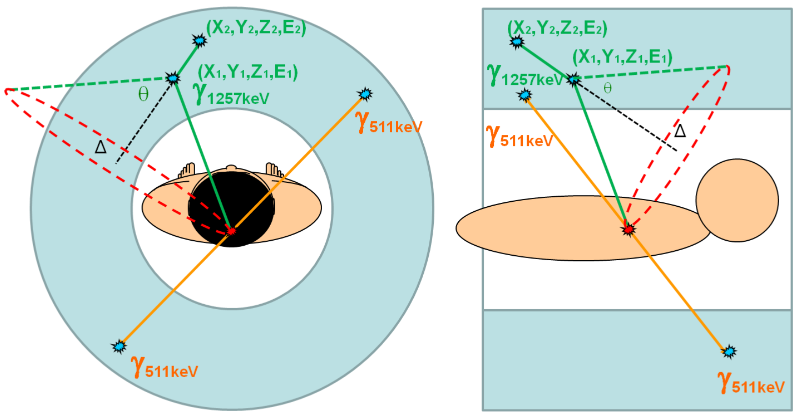

Figure 1: Pricniple of 3 γ imaging technique with a Compton camera

This device would benefit from a large acceptance and no dead area to have a high efficiency for both LOR and Compton reconstruction. The goal is thus to build a monolitic volume filled with a dense medium to have a high stopping power for γ ray. The use of liquid Xenon (LXe) to is then particularly relevant [2]. Firstly, LXe is a relative high Z (Z = 54) and dense medium (3g/cm^3) which is very useful to have a high stopping power for γ rays (~84% of 1.157 MeV gamma rays could be detected with a 12 cm length volume). Secondly, LXe has a high scintillation (~16000

UV photons/ MeV) and ionization yield (∼54400 electrons/ MeV) at a 2 kV/cm electric field and finally, the use LXe gives the advantage to have a monolithic and homogeneous active volume.

2. The instrument

XEMIS (XEnon Medical Imaging System) is an experiment developed to demonstrate the feasability to reconstruct the Compton sequence of a MeV $-\gamma$ ray interacting with the instrument. The system is composed of 5 different major parts: (1) the cold-head, (2) the purification loop, (3) the storage and recovering, (4) the rescue system and (5) the cryostat containing the instrument.

(1) A Pulse Tube Refrigerator (PTR) which is specially designed and optimized for xenon liquefaction [3] is selected to be the cold-head of XEMIS. It is used to provide stable cooling power up to 200W at 165K. An electrical heater up to 180W is assembled between the copper cold head and PTR in order to adjust the net-cooling power by compensating the extra cooling power from the PTR. All this liquefaction part is connected to the cryostat and is maintained at a distance of 2 meters for the purpose of reducing mechanical noise due to the vibration of the PTR.

(2) A recirculation system shown on Fig. 2 driven by an oil-free membrane pump is used to purify xenon continuously in order to reduce the electronegative contamination (O_2, CO_2, NO_2, etc.) from outgassing. These impurities have to be removed as much as possible because the ionizing electrons created by the interaction of γ rays can be captured by electronegative molecules instead of drifting to anode. Two rare-gas purifiers (SAES PS4-MT3-R/N getter) connected in parallel are used to purify the gaseous xenon. Since the getters can only purify gaseous xenon, the liquid xenon must be evaporated to gaseous state before entering purification loop. Therefore, a coaxial heat exchanger made of stainless steel is placed in order to recuperate the vapor heat during the circulation. This heat exchanger is designed to have 95% of efficiency up to 50 NL/min (4.92 g/s) [4].

(3) The storage and recovering system of the Xenon is made of classical commercial gas bottle B50. (4) A 4m^3 stainless steel tank is connected to the cryostat in case of recuperation in emergency.

(5) The instrument in the cryostat is composed of a Time Projection Chamber (TPC) immersed in a vessel filled with LXe. When a γ ray interacts inside the TPC, the energy deposit creates proportional scintillation (VUV photons of 178nm) and ionization signals. By applying an external low electric field (E_{drift}) tunable up to 2 kV/cm provided by 24 copper field rings, ionizing electrons will drift toward the anode with constant velocity and can then be collected. The active volume of the TPC is 28x28 mm^2 (X-Y plane) with 12 cm length (Z direction). The anode is placed on the bottom part of the TPC and is segmented into 64x64 square pixels with a size of 3.5x3.5 mm^2. This anode is connected to 2 ultra-low noise front-end readout electronics of 32 channels each based on the IDeF-X HD-LXe chip [5] which has around 100 electrons NEC at LXe temperature. A 670 lpi (line per inch) micromesh made of a 5 μm thick copper foil is placed 200 μm above the anode and is used as a Frisch grid. In this space, an electric field with a strength upper than 50 times the electric field present in the drift space must be applied to ensure a 100% electron transparency. A Hamamatsu R7600-06MOD-SSY99 photomultiplier tube (PMT), placed at the other side of the TPC, is used to detect VUV scintillation signals.

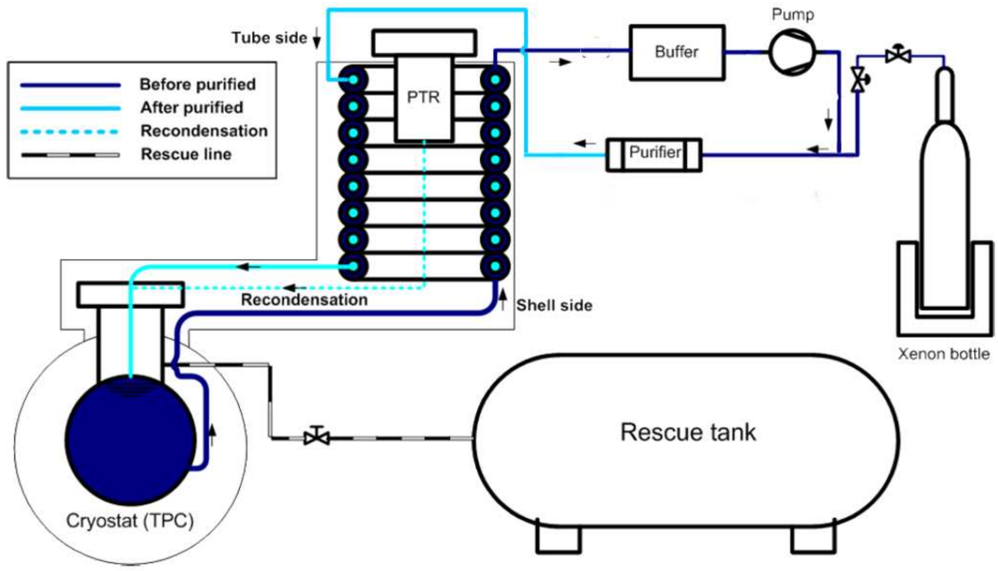

Figure 2: Xemis 1 gas circulation circulation containing the condensation and purification loop

3. Calibration

In order to check the validity of all parameters we developed a calibration setup at Subatech. It is based on a ^{22}Na source ($\beta+\gamma$ emitter $E_{mean} = 545\,\text{keV} E_{max} = 1257\,\text{keV}$ and $1274\,\text{keV}\gamma$ ray in 99.9% of disintegration) placed outside the TPC at 12.5 cm distance from the anode as shown in Fig. 3. This source can thus be used for 511 keV calibration by triggering in coincidence with a BaF_2 crystal placed behind the source and the xenon PMT. Waveforms of the 64 pixels electric signals and scintillation signals from PMT are recorded with a V1740 Caen DAQ system and a V1720 Caen DAQ system, respectively.

4. Results

In order to ensure a good Compton reconstruction, the TPC must have good features in terms of spatial resolution, energy resolution and electronegative impurity.

4.1 Spatial resolution

With the TPC, the X and Y positions are given by the relative signal present on each of the 64 pixels of the anode. This 64 pixels segmentation allows a spatial resolution below 500 μm in each X and Y direction [6]. The Z position is determined by measuring the time difference between the PMT signal and the collection time of electrons created by the Compton interaction. This time difference multiplied by the drift velocity gives the Z value. The drift velocity of the charge carriers is extracted from data by calculating the time difference between the beginning and the end of the TPC as presented in Fig. 4. To determine the Z resolution, a gaussian error function is adjusted on the first edge defined by the very begining of the sensitive medium. The resolution in

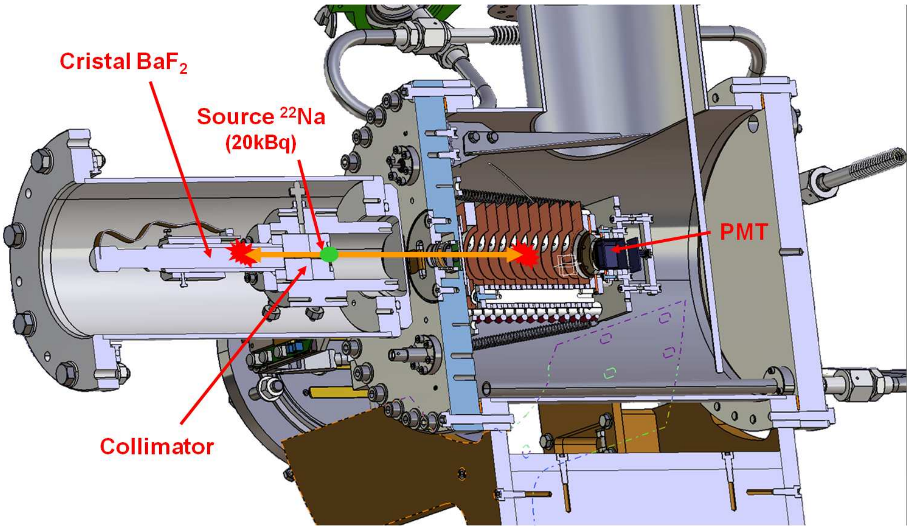

Figure 3: Xemis 1 equiped with the 511 keV calibration line triggered with a BaF_2 crystal and in coincidence with the xenon PMT

the Z-direction is given by the dispersion of the gaussian error function and is measured at 350 μm [7].

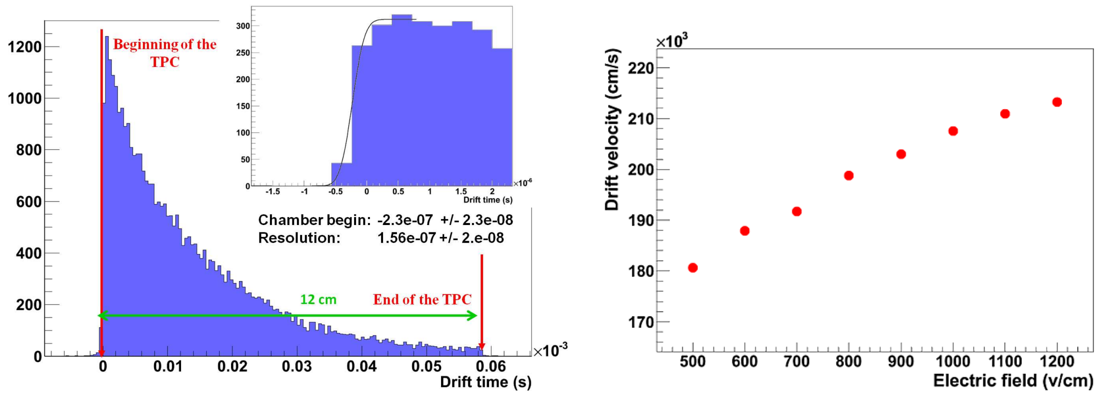

Figure 4: (*left*)Depth interaction profile for photoelectric 511 keV events. The begining and the end of the TPC are determined by edges on left and right. A gaussian error function is adjusted on the first edge defined by the very begining of the sensitive medium to determine the Z resolution. (*right*)Drift veolicity of electrons in LXe as a function of the drift electric field.

4.2 Xenon purity

As described precedently, electronegative impurities in xenon capture drifting electrons. This absorption law is described by an exponential model $S(z) = S(0)e^{-\frac{z}{\lambda}}$ where $S(z)$ is the signal amplitude at the z altitude and λ is the attenuation length. All the amplitudes measured are then corrected accordingly to their altitude. This effect is clearly visible on Fig. 5 $(left)$ where the amplitude of the collected signal produced by a 511 keV is exponentially dependent on the depth of interaction. Absorption length above 1m have been measured.

4.3 Energy resolution

The energy deposited at the interaction point is determined by measuring the amplitude of the produced signal on the anode. The Fig. 5 (*right*) shows energy resolution at 511 keV for photoelectric events as a function of the dirft electric field. Energy resolution on the ionisation signal of 5% can be obtained with a drift field of $1.2kV/$cm. The curve shows the adjustment of data with the Thomas model [8] [7] which describes the electrons insteraction in dense liquid with 511 keV energy input. Data obtained with XEMIS shows a good agreement with the model.

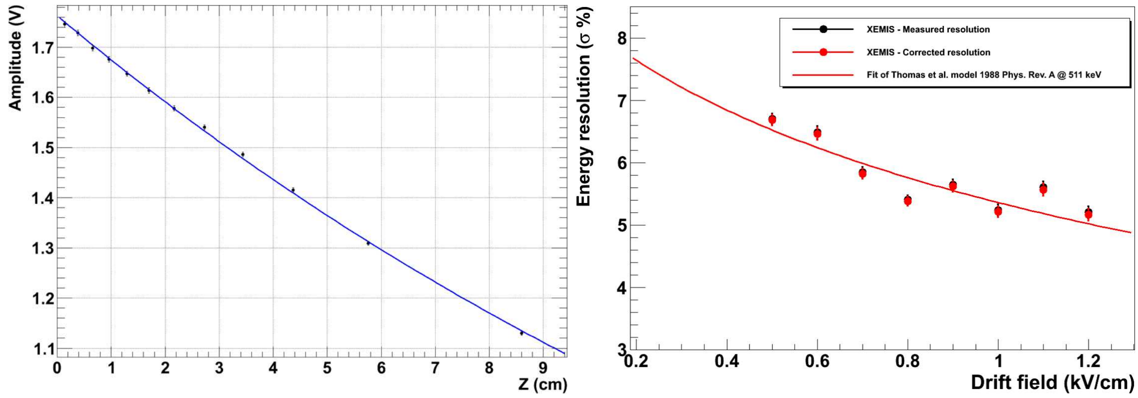

Figure 5: (*left*511 keV photoelectic peak measurment of the xenon as a function of the depth of interaction fitted by an exponential law. The slope parameter of the exponential law is used to measure the purity and gives the drifting length of the electrons) (*right*Energy Resolution measured at 511 keV with the calibration line as a function of the drift electric field. The line represents the Thomas model fitting at 511 keV energy input.)

5. Xemis2

A first work has been initiated with the open GATE collaboration [9] [10] to implement the Xenon as a medium in GATE in order to be able to quantify and share the benefit of this new imaging technique. XEMIS2, presented in Fig. 6, is a new geometry able to achieve a full 3 γ imaging with liquid Xenon. The aim of this new instrumental development is to detect both the $\beta+$ disintegration and the third γ ray with only one device. This geometry is a hollow cylinder of 24 cm length designed containing two different readout planes on the top and the bottom part of the cylinder. Each plane is equipped with a thin micromesh Frisch Grid and contains an anode segmented in pixel of $3.175x3.175\,\mathrm{mm}^2$. The anode will be connected to 200 Front-End electronics readout cards of 64 channels each. There will be a total amount of 25000 electronic channels. This new geometry will hold around 180kg of LXe. A new concept of REcovery and STOrage system for Xenon (ReStoX) is developed by Subatech and AirLiquide [11], which is designed to be able to store xenon at a temperature between -108°C (liquid phase) and 20°C. XEMIS2 will be equipped with a small ReStoX system to ensure a rapid filling and recovering of the Xenon. The inner radius of the camera is 7 cm and the outer radius is 19 cm giving a depth volume of 12 cm for an orthogonal incident γ ray. The UV-light produced by the interaction of γ rays is collected by an assembly of 192 Hamamatsu PMT. By a particular trigger system on the scintillation light, it is possible to read only pixels that are susceptible to contain information in order to reduce the flow of data and to be able to follow the rate.

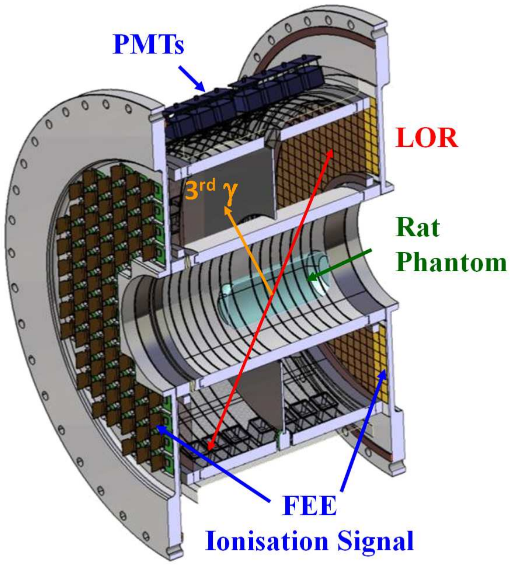

Figure 6: XEMIS 2 device devoted to the small animal 3 γ imaging

Acknowledgments

This work is supported by the E.U. and the region Pays de la Loire in France.

References

[1] C.Grignon et al. *NIM*, A571:142–145, 2007.

[2] E. Aprile and T. Doke. *Rev.Mod.Phys.*, 82:2053–2097, 2010.

[3] T. Haruyama et al. *Cryocoolers*, 13:689–694, 2004.

[4] W.T. Chen et al. *ICEC ICEC24-ICMC2012 Proceeding*, 2012.

[5] O. Lemaire et al. *IEEE NSS/MIC Conference*, pages 858–861, 2012.

[6] A.F. Mohamad Hadi et al. *IEEE NSS/MIC Conference*, pages 2667–2670, 2012.

[7] T. Oger et al. *NIM*, A695:125–128, 2012.

[8] D.A. Imel J. Thomas and S. Biller. *Phys.rev.A.*, 38(11):5793–5800, 1988.

[9] OpenGATE collaboration: http://www.opengatecollaboration.org/.

[10] G. Santin et al. *IEEE Trans.Nucl.Sci.*, NS-50:1516–1521, 2003.

[11] P. Briend et al. *ICEC ICEC24-ICMC2012 Proceeding (16P-P01-01)*, 2012.