

Studies and optimization of ionization signal measurement for the 3-gamma imaging XEMIS2 liquid xenon Compton camera

Yajing Xing

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Yajing Xing. Studies and optimization of ionization signal measurement for the 3-gamma imaging XEMIS2 liquid xenon Compton camera. Nuclear Experiment [nucl-ex]. Ecole nationale supérieure Mines-Télécom Atlantique, 2021. English. NNT: 2021IMTA0249. tel-03373202

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THESE DE DOCTORAT DE

L'ECOLE NATIONALE SUPERIEURE MINE-TELECOM ATLANTIQUE BRETAGNE PAYS DE LA LOIRE - IMT ATLANTIQUE

ECOLE DOCTORALE N° 596 Matière Molécules et Matériaux Spécialité : Physique Subatomique et Instrumentation Nucléaire

Par Yajing XING

Studies and Optimization of Ionization Signal Measurement for the 3-gamma Imaging XEMIS2 Liquid Xenon Compton Camera

Thèse présentée et soutenue à Nantes, le 29 Juin 2021 Unité de recherche : Subatech (UMR 6457) Thèse N° : 2021IMTA0249

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To my parents.

Wherever you go, go with all your heart.

Confucius

Acknowledgements

At the end of the thesis work, I would like to thank all those who accompanied me on Ascientific and human adventures during these years.

First of all, I would like to express my deepest acknowledge to all defense committee members. Great thanks to Pol-Bernard Gossiaux for chairing my thesis. I am also sincerely thankful to the two rapporteurs of this thesis, Fabrice Retière and Étienne Testa, for the time you spent reviewing this manuscript and the valuable comments you provided me. Thank you again to Fabrice for taking the time to follow me during these years as a member of my thesis supervision committee. Profound thanks to Elena Aprile, Michela Marafini, Satoshi Mihara for doing me the honor of agreeing to be part of my thesis jury.

My heartiest thanks flow to Dominique Thers and Jean-Pierre Cussonneau, my supervisor and advisor, for these years spent supporting and guiding me towards this end of the thesis. The research exercises were as enriching as engaging but also full of discussions and disagreements. You offered me many constructive comments and suggestions with incomparable patience and gave me profound encouragement throughout the process. Your ambition and enthusiasm are contagious, which will continue to push me forward in my future career.

I would like to thank the entire XENON group at the Subatech laboratory for the work done together. The friendly team atmosphere and my lovely colleagues painted these years with brilliant colors, pleasant and unforgettable. The "magic hand" of Eric Morteau saved me countless times on electronics and experimental instruments, and I tried the first navigation in my life on his cherished wooden boat. Sara Diglio is always considerate and adorable, no matter at work or in life. The tiramisu she made is so delicious that no one can match it. A big thank you to Julien Masbou for his care and support during my two-year ATER teaching at the University of Nantes. A particular thought for my office colleagues: Chloé Therreau, Maxime Pierre and Yuwei Zhu. Your presence is a daily gift. How could I not express my great think to Jean-Sébastien Stutzmann, Patrick Le Ray, Jean-Luc Béney, Patrice Pichot, Olivier Lemaire, Stéphane Acounis, Stéphane Bouvier, Pascal Lautridou, Mariangela Settimo, Dingbang Cai, Claudia de Dominicis, Vincent Ceccini, Francisco Vasquez, Nicolas Beaupère, Clotilde Canot, Debora Giovagnoli, Lucia Gallego Manzano, Loïck Virone, Kevin Micheneau, and Joaquim Palacio, with whom I had the pleasure of working. All of you are never stingy with your expertise to share your experience and answer my numberless questions. I would also like to thank the doctoral students and other colleagues at Subatech, administrative staff, information services and the leadership team. Without you, I would not have had such a great time.

I sincerely thank all my colleagues and students of UFR science, who tolerated my imperfect French and gave me a precious experience, with special mention to Oliver Ravel, Magali Estienne, Saber Morsli and Saïd Hassini. Thank you very much.

My heartfelt appreciation also goes to all my Chinese friends: Li, Haohan, Lu, Danwen, Fengqi, Yuan, Xiao, Jing, Junle, Yifeng, and Dingbang, without whom this adventure would have been very dull. And special thanks to my intimate friend, Yuwei, who has always encouraged and supported me over the past years.

I owe a very substantial debt to my dear family for their adequate understanding, continuous support, and endless encouragement. I love you so much and forever.

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Introduction

Nuclear medicine has the ability to access, qualitatively and quantitatively, dynamic physiological processes within the patient through the detection of the traveling γ -rays generated from special radiopharmaceutical administered in the body for diagnostic purposes. It has brought considerable improvements in oncology diagnostics over the past decades. On the other hand, the challenge of personalized medicine to provide patients with more targeted and effective treatments has also led to advances in nuclear medicine detector technology, making it possible to reduce doses, speed up examinations, and increase sensitivity. On this basis, a significant reduction in dosage for vulnerable patients (e.g., children and pregnant women) has also become a priority in this area.

Our team proposed an innovative alternative XEnon Medical Imaging System (XEMIS) based on a liquid xenon Compton camera to realize low activity medical imaging. Liquid xenon (LXe), as an emerging monolithic radiation detection medium, has been widely used for particle physics and dark matter detection. It possesses many promising features, such as high stopping power, great sensibility, and simultaneous scintillation light and ionization charge production. Its efficient scalability affords the possibility to develop a total-body imaging detector. The Liquid Xenon Time Projection Chamber (LXeTPC) is suitable for building a Compton telescope for nuclear medical imaging applications. A pseudo-TOF PET performance could be achieved by applying the innovative 3-gamma imaging modality. This innovative nuclear imaging alternative aims to determine the 3D distribution of a specific (β +, γ) source through the coincident detection of triple photons with a Compton camera. The 3-gamma event is reconstructed from the two intersections of the line of response (LOR) (defined by detecting the two annihilation photons) with the Compton cone surface.

The small-scale prototype of the XEMIS project, XEMIS1, has been accomplished and showed promising results. A larger Compton camera XEMIS2 for small animal imaging is developed to demonstrate the advantage of LXe as a detection medium for 3-gamma imaging. **The first stage of XEMIS2 aims to obtain a high-quality image of small animals with only 20** **kBq activity for 20 minutes.** The XEMIS2 cryostat and the purification-cryogenic subsystem ReStoX have been installed in a small animal medical imaging center (CIMA) at Nantes University Hospital.

In **Chapter 1**, a brief overview of the present status of nuclear medicine from the physics and engineering perspectives is described. Then, two conventional scanner imaging techniques: the single photon emission tomography (SPECT) and the positron emission tomography (PET), are presented in detail, including the corresponding mechanisms and performances. In particular, the principle and the state-of-the-arts of PET scanner systems are performed. Afterward, the mechanism and technical requirement of the Compton imaging technique has been primarily discussed. Finally, the advantages of a new emerging and very promising medical application based on the use of a Compton telescope are presented. This so-called three-gammas imaging technique has been conceived and realized for the first time at the Subatech laboratory.

In **Chapter 2**, the main characteristics and advantages of LXe as a detection medium are first described. The state-of-the-art of LXe exploitation in nuclear medicine is reviewed at the same time. Then, the LXeTPC used in XEMIS2, from the operation principle to detector description, is presented. Finally, the safe and compact cryogenic infrastructure and high-capacity signals measurement system, specially developed for XEMIS2, are introduced.

The main work reported by this thesis begins with **Chapter 3**, where we have developed a new DAQ system dedicated to XEMIS2 to guarantee a continuous readout with negligible dead-time during 20 minutes. We first discuss the design criteria of the ionization signal measurement of a TPC dedicated to medical imaging focusing on the needed requirements and general architecture. A brief review of the charge collection structure, MIMELI, and the front-end electronic, IDeF-x HD-LXe, are presented. In the second part, the operation principle related to the newly developed signal extraction ASIC is described. Its performance has been preliminarily examined by the bench test with the prototype chip. The end of the chapter is devoted to the latest advancements of the DAQ development for XEMIS2.

To study the operational calibration and performance characteristics of the new data acquisition system designed for the XEMIS2, a complete prototype of the entire acquisition chain has been developed and integrated into the updated XEMIS1 detector with a new geometric configuration. The corresponding experimental results of the ionization signal measurement system are reported in **Chapter 4**. In the first part, an overview of the entire data acquisition process and the critical parameters from basic concepts are presented. Then, we focus on the calibration of those adjustable parameters related to the CFD performance and the threshold setting. It constitutes an essential step to operate the core ASIC chip, XTRACT. The measurement optimization dedicated to the concrete observed phenomena such as the threshold effect and fake triggers is discussed in the third section. An overall calibration performance is presented at the end of the chapter, including the charge and time response. Besides, the self-developed slow control system for automatic measurement is described.

Without the external coincidence triggers, the raw data contain all the over-threshold physics signals and electronic noise during the entire acquisition process. To complete the final interaction vertex reconstruction, a dedicated data processing development of XEMIS2 has been implemented, which is presented in **Chapter 5**. The physics data is taken from the updated XEMIS1 prototype using a ²²Na source under the same operating condition that will be applied to XEMIS2. The event topology displayed in TPC under experimental setup is first discussed. Then, a set of time corrections are performed to optimize the time measurement. The third part discusses the data filtering aiming at eliminating the noise present in the raw data and then reducing the storage volume for the following data analysis. Finally, the algorithm of the event reconstruction and selection is reported.

The potential detector performance of XEMIS2 is firstly estimated with the photoelectric peak calibration of 511 keV and 1.274 MeV γ -ray in the XEMIS1 prototype. **Chapter 6** reports the corresponding data analysis and experimental results. The first part is oriented to correct the potential effects resulting in the charge measurement distortion, thus reducing detector energy and spatial resolution. The space point reconstruction and energy resolution are also investigated in this work.

In the last chapter (**Chapter 7**), we propose an innovative Compton geometric calibration approach dedicated to small charge signal measurement. Thanks to a known source position, a geometric angle associated with the Compton scattering events could be calculated. By comparing with the Compton kinetic angle, the overall range energy calibration could be deduced. The actual situation is much more complicated concerning the Compton sequence separation and identification. The simulation studies and preliminary experimental results are reported in this part.

Nuclear Medicine and Compton Camera for Medical Applications

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This role of nuclear medicine in medical imaging is increasing considerably over the last decades. Its capability to provide accurate medico-biological information, makes it preferred to other imaging modalities like x-ray Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). Sensitive radiations measurements coupled to specific radiolabeled compounds allow obtaining high quality images even with a tiny amount of radioactive dose injected to

the patient. Furthermore, nuclear medicine covers a broad range of applications from different types of cancers to endocrine and neurological disorders up to prognosis potential of underlying diseases.

In this chapter I will first provide a brief overview of the present status on nuclear medicine from the physics and engineering perspectives. I will then discuss mechanisms and performances of two conventional scanner imaging techniques: Single Photon Emission Computed Tomography (SPECT) and the Positron Emission Tomography (PET). In particular, I will review the principle and the state-of-the-arts of PET scanner systems. Finally, I will focus on the advantages of a new emerging and very promising medical application based on the use of a Compton telescope. This so called three-gammas imaging technique has been conceived and realized for the first time at the Subatech laboratory.

1.1 Basic principles and technologies of nuclear medicine

Nuclear medicine involves the application of artificial radionuclides in a non-sealed state for diagnostic and treatment purposes. The gamma rays emitted by these radionuclides can be detected by external devices for diagnostic imaging purposes. The pattern permits obtaining in vivo the accumulation/distribution of the specific radionuclide administered in the body. SPECT and PET are both well-established nuclear medical imaging techniques used in clinical diagnosis and in research. The strength of nuclear medicine consists in its functional imaging modality i.e. in its ability to image dynamic physiological processes within the patient. It centers on revealing biochemical/physiological activities rather than detailed anatomic structure: this differentiates it from traditional anatomical imaging (MRI). As a result, nuclear medicine imaging plays a significant complementary role to others modalities, providing unique information for the diagnosis, treatment and prevention of serious diseases. The applications include many types of cancers, endocrine or neurological disorders and other abnormalities. Moreover, the modern hybrid methods combining SPECT/PET with CT/MRI allow doctors to access both structure and metabolic information of patients in a single exam.

Brief historical overview

The origins of nuclear medicine can be traced back to the discovery of X-rays in 1895 by Wilhelm Röentgen [1]. Then, followed by the discovery of radioactivity by Henri Becquerel in 1896 and of radium by Marie Curie in 1898, the prospects for radium sources and X-ray diagnosis were immediately recognized. These discoveries brought to the first body interior non invasive observation through shadow images resulted from the transmission and absorption of the radiation. In 1913, the principle of radiotracer was carried out by Georg de Hevesy [2] who was awarded with the Nobel Prize in 1943. However, the production of radioisotope for medical applications was not available until the invention of the cyclotron [3] and the development of nuclear reactor facilities at the end of the Second World War. A radioisotope, ¹³¹I, was first used for the treatment of thyroid cancer in the late 1930s. Its success made nuclear medicine recognized officially in 1946.

Early developments in imaging equipment appeared in 1950s. Major milestones included the production of the rectilinear scanner [4] in 1951 and the development of Anger/gamma camera in 1958 by Hal Anger [5], which allowed to obtain the radionuclides distribution images. Anger camera was considered as the forerunner of modern single-photon imaging systems. Nowadays, the vast majority of SPECT scanners are still based on this principle. Besides, the first clinical applications of positron emitters were carried out during the same period [6]. Another important development in nuclear medicine dates back to 1970s: it consists in the tomographic image reconstruction technique from multiple projections of emission counting [7, 8], that provide a full three-dimensional (3D) reconstruction.

1.1.1 Fundamental concepts

Nuclear medicine imaging is based on visualization by means of a specific radionuclide tracer injected into the patient's body. Depending on the actual organ or biological function we went to image, different radiotracers can be chosen. Once the labeled drug is administered to the patient, the tracer accumulates in specific organs or cellular receptors with a certain biological function. When the radionuclide decays, gamma rays or positrons with a specific energy are emitted. During the transport in tissue materials, a significant number of gamma rays can traverse the body without being attenuated or scattered. Those radiations that cross the body are revealed by an external gamma-ray detector. The image of the radioactive compound is then reconstructed by using specific reconstruction techniques: it offers important information to clinical diagnosis of various diseases. Besides, the "dynamic" image provides the evaluation of the organ functional activity for morphological research.

Lots of efforts have been made in the past century to improve the abilities of nuclear medicine imaging in order to realize personalized medicine. This can be achieved by working on the two following aspects of medical imaging: the injection of radiopharmaceuticals to the patient and the imaging of its distribution using external imaging cameras. I will discuss both of them in the next two subsections.

1.1.1.1 Radiopharmaceutical

The **radiopharmaceutical** is a radioactive compound (biomolecule or drug) that, for different target-organs, is produced by coupling the specific radio isotope to the pharmaceutical compound, forming the radio-tracer (e.g. Figure 1.1). It can be safely administered to humans for the purpose of diagnosis, therapy or research. For diagnostic imaging, the majority of radiopharmaceuticals are administered intravenously. Their bio-distribution is dominated by two major mechanisms: drug uptake and elimination. Both of them are affected by the dysfunction in body tissues, such as blood flow, capillary permeability and interaction with both intracellular and extracellular components.



Fig. 1.1 Chemical and tridimensional structure of 99m Tc-tetrofosmin (Color codes: yellow = 99m Tc; red = O; white = H; light blue = C; purple = P). Figure taken from [9].

Table 1.1 lists common radionuclides used in nuclear medicine. Certain physical characteristics are desirable for clinically useful radionuclides that keep the radiation dose to the patient as low as possible. Based on this fundamental requirement, the half-life of radionuclide decay has to be short enough to ensure that the radiation doses delivered to the patients are minimized. Therefore, the effective half-life is recommended to be just long enough to allow radiopharmaceutical preparation and the imaging completion. Furthermore, in order to detect the decay product of the radioisotope, the energy of the emitted gamma rays should result in an interval of 100-200 keV for SPECT and in a peak at 511 keV for PET. The energy range used in the former technique is to avoid the transparency of the collimator, which will be detailed later. Also, it is crucial that the radioisotope does not contain additional radiation that would result in an extra and unnecessary injected dose to the patient. Finally since the radionuclide needs to be labeled into some form of radiopharmaceutical, it is important that it can be produced in a chemical amenable form.

1.1.1.2 Radioisotope imaging equipment

To image the distribution of radionuclide administered to the patient, the external detection device must be capable of capturing and counting the gamma rays emitted from radiation decay.

Isotope	Half-life	Production	Mode*	Photon energy (keV)	Modality
${}^{11}C$ ${}^{13}N$ ${}^{15}O$ ${}^{18}F$	20.37 min 9.97 min 2.04 min 109.7 min	Linear accelerator /cyclotron	ß+	511	PET
$ 82Rb \frac{68}{Ga} Ga \frac{99m}{Tc} $	76.4 s 68 min 6.01 h	Radionuclide generator	IT	141 (89%)	SPECT
^{125}I ^{201}Tl	59.4 days 3.04 days	Nuclear reactor	EC EC	27 (14%); 31 (26%); 36 (7%) 68–82 (88%)	
^{111}In ^{123}I ^{67}Ca	2.81 days 13.2 h	Linear accelerator	EC EC	171 (90%); 245 (94%) 159 (83%)	
Ga	3.26 days	/cyclotron	EC	93 (39%); 185(21%); 300 (17%)	

Table 1.1 List of common radionuclides for imaging in nuclear medicine. Data taken from [9–12].

* Decay Mode: IT is isomeric transition, EC is electron capture, ß+ is the positive beta decay.

The majority of radioisotope imaging camera consists of a type of scintillation counter that is obtained by coupling a scintillating matter (scintillators) to a light sensor (photosensors). Furthermore, to determine the direction of incident gamma rays, there are two types of collimator, passive and electronic, which will be presented in the Section 1.1.2 and Section 1.1.3, respectively.

Scintillators Scintillators are materials that the ability is known as spontaneously emit optical light when excited by ionizing radiation. This property is known as radioluminescence. To detect gamma rays, scintillators convert the energy of incident photons to optical photons that can be detected by the coupled photodetector. This scintillation light is produced in two stages: firstly the incident photon creates an electron via either photoelectric effect or Compton scattering, and secondly the recoiling electron energy is converted into countable photons of optical light by excitation or ionization with the matter. Table 1.2 lists some properties of commercial or experimental scintillators used in medical imaging applications. Good scintillators are recommended to meet the following requirements on the physical parameters listed below :

- **High light yield** The light yield is defined as the number of scintillation light created per keV of deposited energy. Higher light yield implies higher light output which translates in an improvement of the detecting energy and time resolution.
- Good detection efficiency The detection efficiency is the ratio between converted and the total incident photons. Good detection efficiency indicates high photon absorption, that allows reducing detector volumes. The efficiency of a material can be expressed through the attenuation coefficient which largely depends on the material density and the atomic number.

S =: +: 11 = + = -	Density	Light Yield	Decay	Emission	Hardness	Hygro **	T **	D -f
Scintillator	(g/cm3)	(Ph/keV)	Time (ns)	peak (nm)	(Mho)	-scopic	Type	Ker
NaI:Tl *	3.67	38-55	230	415	2	Yes	Crystal	[13-16]
CsI:Na	4.51	38-44	630	420	2	Yes	Crystal	[14, 15]
CsI:Tl	4.51	52-65	1000	550	2	Slightly	Crystal	[13-15]
BGO	7.13	8-10	300	480	5	No	Crystal	[13-16]
LSO:Ce	7.4	30	40	420	5.8	No	Crystal	[13, 15, 16]
LYSO:Ce	7.15	30-33	50	420	5.8	No	Crystal	[14]
GSO(Ce)	6.7	8-10	30-60	430	5.7	No	Crystal	[13, 15, 16]
BaF2	4.88	4	0.8/600	220	3	Slightly	Crystal	[16]
LaBr3:Ce	5.2	63	25	380	3	Yes	Crystal	[13-16]
LuAP:Ce	8.34	12	18	365	8.5	No	Crystal	[13]
GAGG:Ce	6.63	40-60	50-150	520	8	No	Crystal	[17, 18]

 Table 1.2 Scintillators already used or in development for medical imaging.

* NaI:Tl is the most commonly used, being relatively malleable and inexpensive.

** The scintillating crystal is the most current used in commercialized medical imaging detectors owning to its electronic density. In view of material structure, scintillators could be divided into two big categories, organic and inorganic. Given that inorganic crystals can be segmented to small bits and be configurated to arrays, they are vastly used to provide position sensitivity. Only one notable disadvantage is that certain of them should be protected in airtight container from moisture due to their hygroscopicity.

- Short decay time and low afterglow Short duration of optical light emission after the radiation interaction implies large prompt signals and reduces the interval of time measurement. This improves the operation speed and time resolution of scintillation detectors.
- Well-matched radioluminescence spectrum To maximize the light yield, the peak emission wavelength of the scintillator should match the spectral quantum efficiency of the coupled photodetector.
- Good radiation hardness A malfunction of the system may be caused by high levels of ionizing radiation. It is thus crucial to choose resistant materials.
- Small temperature dependence Instabilities of the system may derive from the temperature fluctuations during the operations. It is thus important to minimize such temperature variations to ensure stable operation conditions.

Moreover, there are additional and less related to performance desired properties that scintillators for medical imaging application should meet, like production capability, low cost, and durability. Depending on each specific application and the corresponding requirements, different choices on the material could be made. I will discuss some of them in the following.

Photosensors for scintillation counting The Photosensors coupled to the scintillators convert the information carried by the scintillation light to countable electrical analogue signal. The process of optical photon detection is based on quantum mechanics and consists in absorbing the

Name	State	Mecanisme	QE (%)	Gain Typ.	Advantages	Limits
PMTs		discrete multiplication dynodes	~30	$\sim 10^6$	high gain, high speed low noise low dark current	concreller buller and
MCP-PMTs	Vacuum	discrete microchannel plate	~20	$\sim 10^{6}$	wide-bandwidth measurements (down to ps) low-light-level detection (photon counting level)	fragile, sensitive to all external influences
APDs	Silicon-based	avalanche photodiodes (APDs)	~80	~ 100	higher signal-to-noise ratio fast time response low dark current high sensitivity	strong dependence on temperature, device nonuniformity
solid solid		array of APDs operating in Geiger mode	~30	$\sim 10^6$	high internal gain high-speed response excellent time resolution wide spectral response range	the small cell size implies complex readout and electronics, relative high dark count rate

Table 1.3 Overview of most common photosensors used in nuclear medicine detectors.

QE is quantum efficiency, defined as conversion rate of photons to photoelectrons emitted from photochathode. Gain Typ. The gain of the PMTs is key to determining the amount of light detected and, subsequently, the energy of the incoming γ -ray. A higher gain means that a single photon can generate a larger number of electrons.

energy of the incident photon and convert it into free electron. The most common device used for gamma detector is the Photomultiplier Tube (PMT), whose schematic diagram is reported in Figure 1.2. Each PMT is composed of a photocathode and a series of multiple dynodes. The scintillation photons are converted to photoelectrons on the photocathode. Those free electrons emitted towards the dynodes are thus multiplied and induce a current or voltage pulse.



Fig. 1.2 Schematic diagram of the interior of a photomultiplier tube. Figure taken from [19]

Table 1.3 presents the characteristics of different photosensors commonly used in nuclear medical imaging. The desired information from the light signal could contain depending on the position of the detected signal, the starting-time of the event, the intensity in terms of a number of photons, and the wavelength [20]. The capacity of measuring the input light signal strongly depends on the charge generated at the output of the system. The following two aspects are of particular importance to ensure a good light signal detection: a high Quantum Efficiency (QE)

defined as conversion rate of photons to photoelectrons emitted from photochathode (the typical QE of a device is smaller than unity) and a high gain to measure single-photons. Besides, there are several important physical parameters that characterize the performances of photosensors. Below we provide a list of requirements on those parameters to achieve high spatial/energy/time resolutions:

- High stability Mean gain deviation for long term and gain shift against count rate change for short term.
- Good uniformity The collection efficiency and QE vary with the position on the photocathode from which the photoelectrons are emitted, and influences the spactial uniformity of a PMTs or SiPMs array.
- **Fast response time** The time response of reproduced waveform out from the anode depends on the rising time, electron transit time and transit time spread of device. A fast response time could provide a better time resolution, especially important for TOF-PET instrument (introduced in Section 1.2.2).
- Low dark count rate Extremely sensitive photosensors, ensuring a low dark count rate, are required to detect single photons. The low dark count rate is reduced by decreasing the system temperature.

1.1.2 Single-photon emission computed tomography (SPECT)

Emission tomography is an imaging by sections from information collected along the penetrating radiation related to the accumulation of activity at each point in the object from many directions. This technique allows to reconstruct the 3D distribution of the radioactive source through a tomographic reconstruction method like the Maximum-Likelihood Expectation-Maximization (MLEM) algorithm. Other than detecting the coordinates using the position sensitive photosensors described in the previous subsection, to determine the direction of ray, an additional information on the emitted gamma ray is needed to infer its direction. In PET, which will be discussed in Section 1.1.3, the direction of the gamma ray is directly determined by the detection of two back-to-back photons emitted from the annihilation of the positron. In SPECT, there is only one photon detected by the camera. Therefore, in addition to the scintillator and position sensitive photodetector, the use of a collimator is needed to identify the direction of the incoming gamma rays.

Almost all commercially available SPECT systems are based on the principle of the Anger camera [21], composed of a lead collimator, a scintillation crystal (commonly NaI:Tl), an array of PMTs and electronics, whose schematic is illustrated in Figure 1.3. The gamma-rays emitted from the body are restricted to access to the detector only when they travel through the holes. Once

the rays interact in the scintillator, the scintillation light detected by the coupled photodetector generates an electronic pulse proportional to the deposited energy. The output signal is then analyzed to determine the X and Y location. Besides, by comparing the intensity of the signal, the detector can select those γ -rays whose total deposited energy falls within the demanded window range. In order to obtain an optimal reconstruction, it is required that the detector is capable to take measure the emitted γ -rays in a full 360° or 180° depending on the diagnostic position. Thus, during SPECT imaging, the camera should be rotated around the patient with a slight angular increase (typically 3°-10°), in continuous motion or under the "step-and-shoot" mode.



Fig. 1.3 Schematic of major components of a gamma camera used in SPECT. Figure taken from [19].

Collimators

Collimators are typically made of lead or tungsten alloy, high atomic number materials, which have high absorption efficiency for γ -rays. It permits those γ -rays whose emission direction respects certain angles to the collimator holes. Depending on their geometry and the image formation process, we can distinguish two major groups of collimators: the pinhole collimator and the multichannel collimator. The former restricts photon paths essentially to the system's transverse planes; the latter allows photon paths to cross these planes. In addition, depending on the channel orientation, the second one could be further divided into three subgroups: parallel-hole (most commonly used), converging, and diverging. More detailed descriptions and illustrations can be found in *Ref.* [22].

Scintillator	Density (g/cm ³)	Effective Z	Decay time (ns)	Emission wavelength (nm)	Light yield (% of NaI)	Energy resolution at 140 keV (%)
NaI:Tl	3.67	50	230	420	100	9
CsI:Tl	4.5	54	800 (60%) 3400 (40%)	550	~150	11
CsI:Na	4.5	54	630	420	85	11
LaBr ₃ :Ce	5.29	46.9	17 (100%) (5% Ce)	360	~150	6
LaCl ₃ :Ce	3.9	47.3	20	350	~ 125	6
CZT*	5.78	49.1	n/a	n/a	n/a	4

Table 1.4 Scintillator candidates for SPECT [19].

* CTZ: $Cd_{(1-x)}Zn_x$ Te is a room temperature semiconductor. who has the advantages of being able to be segmented into small pixels to provide excellent spatial resolution, although the count rate is limited by slow charge transport compared with the much faster photon transport in scintillators.

Performances and limits

The quality of a gamma camera used for SPECT depends primarily on the collimator resolution and the detection crystal sensitivity. Collimators are used to determine the direction of the incident γ -rays whose knowledge may improve the spatial resolution. Meanwhile, the collimators cause a reduction of detection efficiency. The adequate choice of a collimator depends on the desired energy resolution for imaging purposes, on the sensitivity and on the spatial resolution. Comparing to PET imaging (which will be introduced in Section 1.1.3), not many scintillators choices for SPECT are on the market. The most widely-used is NaI:Tl coupled with an array of PMTs, which can provide an energy resolution of about 9%. In the recent decades, some new scintillator candidates for SPECT have been developed with improved performances (Table 1.4). Besides, development of noise-filtering in the spatial domains, the Fourier noise-filtering and the convolution method have been carried out with the purpose of increasing image resolutions. Furthermore, illustrated in Figure 1.4, the emerging SPECT/CT hybrid image perfectly combines both structure and metabolic information of patient in a single exam.

1.1.3 Positron emission tomography (PET)

PET is an alternative imaging technique using positron emitter as radiotracer. The positron emitted from the administered radiopharmaceutical has a maximum energy around MeV. Most of this energy is rapidly absorbed by the surrounding tissues generating ionization and excitation. After the thermalization the positron interacts with an electron. In the majority of the cases, the positron and the electron form a bonded state called positronium (para and ortho). The



Fig. 1.4 ^{99m}Tc-HMPAO-SPECT/CT—study in three projections axial (left), sagittal (middle) and coronal (right). Bottom panel presents CT scans. Corresponding SPECT sections are presented in middle row and fusion images (^{99m}Tc-HMPAO-SPECT/CT) are placed in upper row. ^{99m}Tc-HMPAO-SPECT/CT shows an accumulation of radiolabeled leucocytes in the vicinity of an implanted electrode (arrows). Figure taken from [23].

positronium (para) decays into two γ -rays of 511 keV each in nearly opposite directions. This phenomenon is known as annihilation. The two back-to-back γ -rays are then quasi-simultaneously detected by surrounded ring-like detectors. The position of the detected gamma rays is used to built a straight line that crosses the source, called Line Of Response (LOR). PET camera allows to map the distribution of radiopharmaceuticals by accumulating sufficient LORs. The basic technique of a PET camera is very similar to SPECT: scintillation crystals combined with photosensors. Owning to the annihilation coincidence detection who delivers an effect of collimator, in multi-slice PET system, there is no physical collimator request.

Annihilation coincidence detection

The principles of PET coincident annihilation detection is illustrated in Figure 1.5. Almost all commercial PET detectors consist of ring-like structures based on the same concept of scintillating detectors described earlier, composed of an array of coupled scintillating crystals and photosensors (PMTs or Silicon-based solid sensors) units. Whenever two signals fall into a certain coincident time window (typically 4-10 ns) with corresponding enegy close to 511 keV, both digitized signals are recorded as originating from the the same annihilation. A LOR is then reconstructed starting from these two gamma rays.



Fig. 1.5 Schematic of coincident annihilation detection method in PET. Figure taken from [24].

Performances and limits of PET imaging

The performances of PET imaging mainly depend on detection sensitivity and spatial resolution. The sensitivity is defined as the ratio between the rate of a true coincidence (true detected events) and the source activity (true emitted events). There is a trade-off between resolution and sensitivity. In conventional PET scanners, the sensitivity is normally smaller than one percent or even a few parts per thousand due to multiple factors (e.g. camera geometry, crystal detection efficiency, and photon scatter/attenuation in the body). The backgrounds resulting from false coincidence events (scatter and random events defined in the following) decrease the Signal Over Noise Ratio (SNR), therefore degrades the sensitivity. Besides, the limitation of sensitivity is also represented by the small field of view (FOV) which implies that lots of γ -rays may escape the detection. To solve this issue, most recently the total-body PET system has delivered a satisfactory solution, which will be introduced in the next section.

Another fundamental parameter to improve PET analysis is spatial resolution. However, two intrinsic factors related to the emission of the positron (positron range) and to the detection of the annihilation photons (non-collinearity) participate in the degradation of the spatial resolution and constitute its main physical limits.

 1^{st} intrinsic limitation to spatial resolution - positron range The measured LOR is distant from the true emission point due to the positron range. In particular, from the radiation emission position, positron travels a few millimeters in the patient's body before thermalizing and annihilating with the electron. This distance depends on the composition of the traveled tissues and the kinetic energy of the emitted positron from the β + decay. Table 1.5 presents positron energies and ranges for the common β + emitters used in PET imaging. It therefore generates an intrinsic factor that constrains the spatial resolution in PET.

	•].			
Isotope	E_{mean} (keV)	E_{max} (keV)	R_{mean} (mm)	R_{max} (mm)
^{18}F	252	635	0.660	2.633
^{11}C	390	970	1.266	4.456
^{13}N	480	1190	1.730	5.572
^{15}O	730	1720	2.965	9.132
^{68}Ga	844	1899	3.559	10.273
^{64}Cu	1280.6	2926	6.077	16.149
^{82}Rb	1551	3378	7.491	18.603

Table 1.5 Positron energies and ranges for the common β + emitters used in PET [25].

The parameters (R_{mean} and R_{max}) are the (mean/max) range values in water.

2^{nd} intrinsic limitation to spatial resolution - non-collinearity of the annihilation photons The spatial resolution of the image is intrinsically degradated by the non-collinearity of the annihilation photons. As it was previously explained, PET imaging reconstruction is

based on the measurement of a LOR (which is constructed based on the assumptions that the two annihilation photons belong to the same straight line that also cross the source). In reality, the two photons are not emitted exactly at 180° because of the residual momentum of the positron at the end of its path and the momentum of electrons on atomic layers. This acolinearity (illustrated in Figure 1.6) can be described by a Gaussian distribution with the standard deviation of about 0.25°, equivalent to a full width at half maximum (FWHM) of Fig. 1.6 Non-colinearity of 511-keV annihilation the order of 0.5° [26].



photons. Figure taken from [26].

Detection modality limitation - coincident events

Figure 1.7 illustrates the three typical events from coincidence detection: true, scatter and random coincidences. The true coincidence is the ideal case that two annihilation photons directly hit the surrounding camera with no scatter interactions in the patient's body. In this case. The measured LOR corresponds to the true path of a pair of γ -rays. On the contrary, the scatter coincidence is when either one or both photons generate one or more scattering interactions before reaching the scintillator. In this Compton case, at least one of the two paths has changed the direction and deviated from the line where the source is located, resulting in

a false coincidence event. The last category of coincident events is the one on which the two signals belong to two different random events that are close in time and are thus associated to one single event.



Fig. 1.7 Illustrations of a) true, b) scatter, and c) random coincidence. Figure taken from [24].

Those two latter false events cannot be distinguished from the true events. This leads to the presence of an irreducible background in image reconstruction, that reduces the image contrast and resolution. Note that refining the time coincidence windows and improving energy resolution could naturally enhance the situation and remove more effectively those overlap events and Compton scattering. The drawback of this solution is a worse sensitivity and efficiency. Therefore, a compromise between the spatial resolution and sensitivity, corresponding to image quality and administered dose, need to be found.

1.2 Advances in PET imaging

During the last decades the healthcare interest in personalized (or precision) medicine has sensitively increased. This attention has brought improvements in diagnostic technology that can provide patients with more targeted and effective treatments. All this led to an advancement of nuclear medicine modalities which translates into an even more precise quantitative accuracy and molecular sensitivity. On this basis, drastically reducing the administered dose to vulnerable patients (such as children and pregnant woman) has become a priority in the field.

Nowadays PET imaging provides the best reachable sensitivity and quantitative accuracy. For what concerns personalized medicine, advances in PET imaging devices can be divided into three categories, based on different approaches: the total-body PET (TB-PET), the time-of-flight PET (TOF-PET) and the depth-of-interaction PET (DOI-PET). The TB-PET imaging dramatically reduces the exam time with the same dose of the other two modalities by increasing the field of view. This modality is highly developed in US. Another approach more explored in EU is the TOF-PET, which aims at reducing the length of LOR with the best time resolution targeted to 10 ps. The third method tries to reduce the Parallax effects through a depth of

interaction on the whole FOV. All those three approaches proved the capacity to reach a significant improvement of the camera sensitivity in terms of higher resolution image and faster exam. Besides, in an effort to reach an extremely good performance, the hybrid detector which combines two or all the above mentioned methods represent a forefront topic in this research domain.

1.2.1 Total-body PET

Motivation In nuclear medicine imaging, the radio-tracer administrated to the patient travels through the area being examined and may give off radiation not just in the organ of interest but in entire body. As mentioned in Section 1.1.3, the current commercial PET device is a kind of ring-like scintillation crystal camera. The typical axial FOV is smaller than 25cm. With this small FOV, a whole body image is possible only through a step by step scanning of the different body parts. This operation implies that the exam will take longer than a total-body PET with a larger FOV. Besides, a non-negligible limit in detection efficiency comes from the thin FOV: roughly 85%-90% of the body will be placed outside the FOV. Furthermore, the amount of administered activity in-vivo is a limit in conventional PET, which implies that collected data may suffer of low counting statistics. The basic principle of total-body PET (TB-PET) is to drastically increase the sensitivity through the ultimate FOV designed to cover the entire body (illustrated in Figure 1.8).



Fig. 1.8 Whole-body PET (A) vs. total-body PET (B). Figure taken from [27].

Impact A major advance of the total-body PET is the capacity to simultaneously register dynamic data from the entire body all at once. This provides an opportunity to diagnose the disease with a short half-life pharmaceutical. Besides, studies summarized in *Ref.* [28] reported that, compared to the whole-body imaging with current PET scanners, the effective sensitivity of a 2 m long TB-PET possesses an overall more than 40-fold gain and the signal-to-noise ratio is increased by more than 6 times. Such increase in statistics thanks to a larger FOV can reduce the imaging time at less than 40 times while keeping the same image quality. This means that a

whole-body scan could be completed in several seconds instead of ten to twenty minutes. The TB-PET fulfills the request of personalized medicine providing more possibilities of diagnostic test per person. Moreover, thanks to TB-PET, the patients can also choose whether to improve the image quality or to reduce the administered activity. This adds the possibility of doing pharmacokinetics.

State-of-the-art The idea of TB-PET dates back to 1990s. This option has been studied by several research teams, but the first completed TB-PET scanner has been accomplished only recently by the EXPLORER consortium. The last development of this EXPLORER TB-PET/CT scanner is reported in *Ref.* [29]: it has a 194-cm axial FOV, 68.6-cm trans-axial FOV and 78.6-cm inner diameter. This TB-PET detector consists of 8 LYSO-SiPM based units. Its time and energy resolutions (FWHM) are respectively 430 ps and 11.7%. This detector allowed to obtain a whole-body scanning image in only 1 s for the first time.

1.2.2 Time-of-flight PET

Basic principle As mentioned above, in PET system, the detection of two back-to-back photons is used to build a virtual line of coincidence events. Conventional PET images are reconstructed assuming that the unknown position of the radionuclide decay distributes uniformly along the LOR inside the reconstructed FOV. In fact, the emission point could be better localized with the additional measurement of the time difference between the arrival time of the two photons (Δt). This information allows to calculate the source deviation Δx from the center of LOR following the mathematical formula

$$\Delta x = \frac{d_2 - d_1}{2} = \frac{c \times t_2 - c \times t_1}{2} = c \times \frac{\Delta t}{2}$$
(1.1)

where c is the velocity of light, t_1 and t_2 are respectively the arrival time of two annihilation photons traveling a distance of d_1 and d_2 . This technique, illustrated in Figure 1.9, is known as time-of-flight (TOF). The time performance limitation of current scanners implies a non-perfect extrapolation of the Δx position. Therefore, in TOF-PET systems, an important parameter to evaluate the camera performance is the coincidence time resolution (CTR), that leads to an uncertainty in the position. The probability distribution could be thus reduced to a Gaussian function centered on the true position.

Impact Incorporating the TOF information into the PET image reconstruction process allows for a significant SNR image improvement with respect to the conventional PET system. This can be quantified by the following formula:



Fig. 1.9 Basic principle of time-of-flight PET. Figure taken from [30].

$$\frac{SNR_{TOF-PET}}{SNR_{nonTOF-PET}} = \sqrt{\frac{2D}{c \times CTR}}$$
(1.2)

where D is the diameter of the FOV. The significant increase of SNR is beneficial to improve the image quality, for dose reduction or enhancement of throughput.

Technical challenges To achieve good performances, this technique needs an extreme time precision meaning big technical challenges. For a scintillator-based detector, the technical requests for high CTR could be generally summarized in as tree parts:

- Scintillator It has been mentioned in Section 1.1.1.2 that among the desired characteristics needed for an good scintillator in γ -ray detector there are the high stopping power and the high light output. Beyond that, another factor dominantly affecting the timing performance is the scintillation decay time. Ideally, to get the best detectors' CTR, the decay time of scintillators should be as short as possible to ensure a quick response and the material should be dense enough to detect all incoming photons. Additionally a high light yield to produce big detectable signals is requested.
- **Photodetector** Light produced from scintillator must be detected/counted by a matching photodetector. Apart from an excellent QE and high gain, photosensor used in TOF-PET should have a fast time response and high time resolution.
- Electronic In PET, a huge number of front-end readout channels is necessary to acquire light signal from position sensible photosensors. A high time resolution electronic circuit should have low noise and high count rate to eliminate the signal interference. Besides, based on the commercial operation, low power consumption, greater extensibility and compactness, and reasonable cost should also be considered.
State-of-the-art The idea of TOF measurements is an old principle which could be traced back to 1969 [31]. It was not possible to built it before early 80s, due to the technical limits. Due to the limited light output of the scintillator, these systems cannot compete with BGO-based nonToF-PET systems that provide higher spatial resolution and sensitivity. The availability of lutetium-based fast scintillators in the 90s has led to a new development and research in this field. A first prototype of LSO PET scanner presented by Siemens in 2005, using PMTs and nonTOF-PET image reconstruction, showed a measurable gain in SNR even with a poor time resolution of 1.2 ns [32]. Very soon, in 2006, Philips presented the first commercial TOF-PET/CT, Gemini TF, that achieved a 585 ps (FWHM) time resolution using LYSO as scintillators still coupled with PMTs [33]. Then, the other two major PET vendors, General Electric and Siemens, have commercialized their TOF-PET/CT scanners around 2010 with similar system timing performances in the range of 520–550 ps [34, 35]. Since then, most of commercial TOF-PET systems are based on the instrumentation of LSO/LYSO and PMTs, and showed a better system time resolution around 400 ps.

Meanwhile, the need for high time resolution pushed the development of corresponding photosensors and faster electronics. The recent development of SiPM-based TOF-PET system made a further improvement of TOF performances. In 2014, the first SiPM TOF-PET was commercialized by Philips: a time resolution of 345 ps has been measured [36]. Another system developed by General Electric in 2017, Discovery MI PET/CT, presented a timing performance of 375 ps [37]. Recently, Philips announced that they have achieved 310 ps in system timing resolution [38].

Since 2017, *P. Lecoq* has proposed to push the limits in TOF to 10 ps corresponding only an uncertainty of 1.5 mm along the LOR in a whole body scanner [39]. Presently, the novel research of Cherenkov-based detectors emerged in last years. Latest publication from a research group of CEA reported a CTR of 280 ps using PbF2 coupled with MCP-PMTs [40]. Another group from Japan, who studied also with the combination of PbF2 and MCP-PMTs, published at the same time their measurement of a CTR of 46.9 ps FWHM, corresponding to a spatial resolution of 7.0 mm [41].

1.2.3 Depth-of-interaction encoding PET

Parallax effect In an effort to increase the detector sensitivity, the use of thick scintillators was imposed on PET systems. This choice resulted in an effective increase of the interaction probability of γ -rays traversing the crystals. While, as illustrated in Figure 1.10, the thickness also increases the uncertainty in the measurement of the interaction depth, DOI, the actual interaction position inside the scintillator. In traditional PET scanners, DOI is assumed to be

located on the surface (or central part) of the scintillator or as a constant calculated from the attenuation coefficient.





We call parallax effect, the error introduced by the difference between the reconstructed line (dashed line) and the true LOR (solid line). This discrepancy is due to the absence of the DOI information, which can cause a degradation of the annihilation point spatial resolution during the image reconstruction.

Impacts The parallax effect results thus in a trade-off between the detector sensitivity and spatial resolution. To be noticed that this impact is not uniform in all the FOV and depends considerably on the geometry of PET scanners. Firstly, as an example of standard ring geometry scanners in Figure 1.11a, we show how the parallax effect has almost no impact on radiation events at the center of the FOV: this is due to the fact that all incident photons are perpendicular with respect to the face of the detector. DOI information in this case is therefore not necessary. On the contrary, for radial off-center sources, an enhanced spatial resolution is present along radial axis and becomes poorer at the border of FOV. Moreover, in long axial FOV (Figure 1.11b)) and polygonal PET scanners(Figure 1.11c), the parallax effect is present even in the center of the FOV results from those LOR that have a certain angles with respect to the detector face. In short, parallax errors greatly limit the system spatial resolution for all types of PET camera.

State-of-the-art A first accurate DOI measurement has been carried out in 1987 [43] with the aim of properly measure the true LOR and estimate the effective parallax error correction in the PET system. The basic concept behind this approach is quite straightforward: attempting to realize "pixelize/grade" long scintillator crystals and corresponding photosensors in the depth direction. This is motivated by the request of a depth-encoding, most effective and low cost method. This idea allows PET systems to have the capability to primarily restore the spatial resolution, (peculiarly for border FOV sources in PET scanner configuration), and at the same



Fig. 1.11 Parallax effect (a) in ring geometry PET system, (b) in long axial FOV PET systems and (c) polygonal PET system, where shadows represent all accessible LORs. Figure taken from [42].

time, to enhance the detection efficiency through the reconstruction of a considerable fraction of Compton scattering events in the crystals.

Thanks to this specific capacity, many different DOI-encoding techniques have been developed for high-performance PET scanners, and in particular, they have been widely implemented on TOF-PET systems seeking for better CTR performances. For example, through a DOI measurement based on the improved *phoswich with pulse-shape discrimination schemes* module, in 2013, researchers from the University of Pennsylvania reported a TOF-PET performance with a CTR smaller than 200 ps [44]. In 2014, based on *double side readout methods*, S. Seifer *et al.* measured a CTR of DOI TOF-PET in a range of 121-183 ps with various sizes/layers of scintillator crystal matrices [45]. Most recently, in early 2019, 157 ps FWHM CTR has been measured in a TOF-PET with DOI measurement based on *a light sharing and recirculation mechanism* [46].

1.3 Emerging medical imaging with Compton camera

A rising development of Compton camera, in recent decades, shown a promising capacity of γ -ray imaging in a wide energy range and without any need of collimators. The use of Compton telescope has been largely exploited in the research domain of astronomy and particle physics where lots of detectors have been developed such as COMPTEL [47], MEGA [48], SPEIR [49], and LXeGRIT [50]. On the other hand, recent research in medical diagnosis application showed that Compton camera has promising capacity in SPECT imaging [51–54]. In this section, the investigation of Compton camera is introduced focusing on others emerging medical imaging modalities based on multi-tracer, range monitoring in hadrontherapy, and the novel modality 3-gamma imaging.

1.3.1 Compton medical imager

1.3.1.1 Imaging principle

As mentioned earlier, the detection efficiency of SPECT devices is largely limited by the lead collimator through which the detector determines the incident direction of γ -rays. Compton imager is an alternative approach that provides an electronically collimated radiation detection based on the kinematics of Compton scattering. The concept of Compton γ camera for clinical diagnosis can be dated back to 1974, proposed by Todd *et al.* [55]. Figure 1.12 illustrates a schematic diagram of the imaging principle of a conventional Compton camera. There are two position-sensitive detectors in a elementary Compton imager to identify the scattering events, in which the incident γ -ray undergoes a Compton-scattering in the first detector (thin scatterer) then deposite all its energy through a photoelectric absorption in the last detector (thick absorber). The deposited energies E_i and interaction positions \vec{x}_i of two successive quasi-coincident interactions in both detectors are recorded. Assuming that scattered gamma ray loses all its energy in the absorber, the scattered angle θ can be calculated from the Compton formula

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_1} - \frac{1}{E_1 + E_2}\right) \tag{1.3}$$

where $m_e c^2$ is the mass energy of an electron, E_1 the kinetic energy of the recoiled electron ejected from Compton scattering in the scatterer, and E_2 the deposited energy from photoelectric absorption in the absorber. The line connecting the two interaction points of the emitted gammas $\overline{x_1x_2}$ and the measured angle θ are used to built the axis Δ and the opening angle of a Compton cone. The radioisotope is located on the surface of this cone. The position of the γ -ray emitter could be then localized by integrating multiple reverse batch conical surfaces. For an extended source reconstruction, it is still necessary to use sophisticated reconstruction algorithms e.g. MLEM.

1.3.1.2 Technical requirements

Apart from the detection efficiency, an imaging system designed to operate under clinical conditions should possess a comparable spatial resolution with commercial imaging devices, and a spatial precision of the order of a few millimeters. For the development of Compton cameras, the reconstruction precision of the Compton cone is affected by the spatial and energy resolutions that are limited by the inherent performance of detectors. The degradation factors include, for each sequent interaction of a Compton scattering event, the uncertainties on the position and energy in the camera (scatterer and absorber). An additional limitation comes



Fig. 1.12 Schematic showing a conventional Compton camera setup and cones defined from the measurements. Figure adapted from [56].

from consideration is the Doppler broadening which degrades the achievable angular resolution, especially at low gamma ray energies.

Position resolution The position resolution of the devices directly impacts the uncertainty and tilt of the cone axis Δ , which connect the two interaction vertices in the scatterer and in the absorber. For common Compton camera based on crystal scintillator arrays, the true position of each interaction in one elementary crystal will be recorded and reconstructed from its barycenter. This method implicitly introduces an error on the position measurement whose precision will be mainly determined by the size of the segmentation. For monolithic devices, similar position measurement errors are mainly introduced by pixel size. Therefore, minimizing the size of the crystal or the pixel while preserving a good signal noise ratio (SNR) is a critical factor to successfully reduce the degradation of the reconstructed position.

Angular resolution The angular resolution σ_{θ} of a Compton imager is affected by the limited energy resolution σ_{θ_E} of detector and by the Doppler Broadening Effect $\sigma_{\theta_{DB}}$, especially at low gamma ray energies. the resolution of the aperture angle of the Compton cone can be thus expressed by the following equation:

$$\sigma_{\theta}^2 = \sigma_{\theta_E}^2 + \sigma_{\theta_{DB}}^2 \tag{1.4}$$

The uncertainty on the angle depending on the energy resolution could be directly derived from the kinematics of Compton scattering. Assuming that the total deposited energy is equal to the energy of incoming gammas, Equation 1.3 could be rewritten as

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_0 - E_2} - \frac{1}{E_0}\right)$$
(1.5)

where $E_0 = E_1 + E_2$ is the energy of incoming γ -rays emitted from the radiation decay. Assuming that there is no inner scattering before photons enter into the camera, E_0 is then a constant, already known as the initial energy emitted from the radiation decay. The uncertainty on the Compton angle introduced by the energy resolution could be therefore calculated by applying the error propagation to Equation 1.5, resulting in

$$\sigma_{\theta_E} = \left| \frac{1}{\sin \theta} \frac{m_e c^2}{(E_0 - E_e)^2} \right| \sigma_{E_e} \tag{1.6}$$

where σ_{E_e} is the energy resolution in the scatterer. It's worth noting that, even though the absorber energy resolution does not appear explicitly in the equation, a good enough precision of energy measurement in the absorber is necessary for Compton scattering event selection.

1.3.2 Multi-tracer imaging

Motivation Driven by the potential advantages shown for clinical diagnosis applications, multi-tracer imaging attracted more attention over the last years. This imaging modality provides the opportunity to simultaneously observe dual or multiple complex molecular and metabolic phenotypes. For example, Lehtiö *et al* reported in 2003 the great interest of observing hypoxia (important factor for tumor treatment) with the blood flow to improve the detection precision [57].

Background In the context of modern medical diagnosis, SPECT and PET have been introduced at the beginning of this chapter as two mainstream nuclear medicine imaging modalities. Studied reported in *Ref.* [58] have shown the benefit of multi-tracer SPECT in differential diagnosis of parkinsonism. Multi-tracer PET has also been studied specifically in the context of the longitudinal progression of sporadic Parkinson's and in autosomal dominant Alzheimer's diseases [59, 60]. Each of them has its specific measurement range/method and provide individual information in molecular diagnostics.

Development direction A single device that simultaneously observes different radiopharmaceuticals used for PET and SPECT would potentially improve the measurements by performing one signal scanner. However, such a combined detector cannot be easily realized for the reason explained in the following. For example, PET is dedicated to positron radiation measurements using electrically collimated LOR from the information of two annihilating γ -rays. Besides, the thickness of scintillators is also well adapted for the photoelectric absorption of 511 keV γ -ray. Under the same conditions, the single-gamma emitting isotopes used in SPECT can not be easily used in PET systems: the incoming direction could not be determined without physical collimator; the thick scintillators are not adapted for low-energy photons in the range of 100-300 keV. This effect introduces an additional degradation in the position measurement.

State-of-the-art of Compton cameras Compared to PET and SPECT systems, Compton camera showed a promising potential for application in multi-tracer imaging thanks to the wide energy band ranging from 100 keV to 1 MeV and to the electronically collimated detection mechanism. The investigation of Compton camera coupled to multi-tracer imaging system could be traced back to the beginning of the 21st century. A Compton camera for the above mentioned applications has been developed and documented by the Japanese research team of Kanayama in 2005 [61]. However, insufficient position and angular resolutions of Compton scattering detectors represent the most difficult obstacle to overcome for successive developments until recently. A recent advancement in the field is represented by the Si/CdTe-based Compton camera that succeed in simultaneously injecting ^{99m}Tc-DMSA and ¹⁸F-FDG (two common radiopharmaceuticals respectively used in SPECT and PET) in a human body. This procedure demonstrated for the first time the clinical operating feasibility of using a PET and a SPECT radiopharmaceutical in a unique detector [62]. Besides, the novel exploitation of Compton-PET hybrid imagers has also advanced in this imaging research field. Figure 1.13 schematically illustrates the composition and functional principle of the GAGG-SiPM based pixel Compton-PET scanner developed by Shimazoe Kenji et al. This device operates in PET and Compton mode using two radiopharmaceuticals, ¹¹¹InCl₃ and ¹⁸F-FDG, at the same time. The result represent a novel alternative approach in medical imaging and related fields [63].



Fig. 1.13 Conceptual schematic of a Compton-PET hybrid imager consisting of thin and thick energy-resolving detectors. Figure taken from [63].

1.3.3 Hadrontherapy real-time treatment monitoring

Background Hadrontherapy is an emerging tumor treatment consisting in delivering charged particle beams, protons or carbon, into the tumor region abiding by the bio-mathematical model calculation and dose prescription consideration. According to a study conducted at the end of 2019, more than 200 000 patients are already treated with hadrontherapy in more than 100 already operational worldwide clinical facilities (statistic from PTCOG Stats, Available: *www.ptcog.ch*). The original proposal on hadrontherapy can be dated back to 1946 [64]. The critically effective aspect of this innovative technology is the fact that the ions have an almost straight tracking in matter and a maximum of energy deposited at the end of their range, in a sharply defined peak, called the Bragg peak region [65]. This property ensures a high precision of dose deposition within the tumor volume while effectively protecting the surrounding health tissues. Additionally, current studies indicate that carbon ions own a higher relative biological effectiveness (RBE) in the tumor region comparing with photon beams, providing a more effective treatment in normal and radio-resistant tumors [66, 67].

Motivation An accurate ion-range monitoring of the order of few millimeters becomes mandatory for the full exploitation of hadrontherapy clinical benefits and future developments. The surveillance of the delivered radiation dose on the Bragg peak region is a critical issue to ensure the quality of hadrontherapy. A too sharp deposition of the dose can be a double-edged sword because of its high impact on other parameters. For instance, any small change in patient position or morphology might cause a dose localization mismatch that could damage the healthy tissues instead of killing tumor cells. Therefore, the sharp deposition of dose and the density distribution on ion-range in vivo requires a dose monitoring, ideally in real time in three dimensions, to guarantee the Bragg peak location within the tumor volume.

Different approaches In the last decade, the worldwide increasing applications of hadrontherapy facilities has greatly boosted the development of different imaging instruments dedicated to on-and off-line ion-beam monitoring, which was reviewed in *Ref.* [68]. Almost all those techniques are oriented at secondary radiation detection since the treatment ion beams are stopped within the body. The secondary particles used to monitoring the range, described in Knopf *et al* [69], are originated from nuclear reactions of the primary projectiles with patient tissue. There are two kinds of ways to detect γ -rays: either we can detect the two coincident γ -rays from the production of positron emission isotopes or prompt γ -rays from the excitation of the target nuclei generated from the proton bombardment [70]. **In-beam PET monitoring** The in-beam PET monitoring in hadrontherapy, proposed by Parodi *et al* in *Ref.* [71], is the most widely explored technique that has been used to date to ensure high quality of PET images though the deposited dose range verification [72, 73]. It consists in generating the image of the vertex distribution of the γ -rays annihilation following the decay of positron emitters that are created during the fragmentation of target nuclei or of the projectiles themselves (main sources of activities in the hadrontherapy) [70]. This monitoring modality has already achieved clinical application online [74, 75], providing the capacity of 3D verification of the treatment dose delivery. However, differently from conventional PET scanners, the coverage angle of in-beam PET monitoring systems is limited by the presence of the gantry. Due to the low number of generated positron isotopes and their various half-lives, a longer data acquisition time is required to obtain a good image. This approach is thus feasible only to provide post-therapy information on the location of the dose deposition [76]. Additionally, the energy-dependence of the positron range, the location and activity uncertainties caused by metabolic processes and blood flow, and the time lag between the beam treatment and PET scanning contribute to the partial mismatching image with respect to the real distribution of the nuclear reaction.

Prompt gamma monitoring Another way to achieve the in-beam range monitoring is to measure the prompt gamma originated form various interaction mechanisms including the relaxation of generated nuclei in inelastic nuclear reactions of the primary beam ions. The large correlation between the prompt gamma distribution and the dose falloff region has been reported in Ref. [70]. This emission of the gamma ray after the nuclear reactions of hadron ions with atomic nuclei of tissue is almost instantaneous: it mainly occurs within a few ps following the passage of the projectiles. The distributions of secondary particles in proton and carbon-ion therapy has been studied and reported in Ref. [77]. The development of real-time range verification could avoid the influence of metabolism and biological washout through gamma monitoring. Also, the conventional imaging systems in nuclear medicine (PET, SPECT, etc.) are optimized to operate at energies below 1 MeV while the energy range of prompt gammas vary from roughly 100 keV up to 10 MeV. The measurement of energetic prompt gamma rays, as a consequence, has exceeded the capabilities of existing traditional medical systems. Different types of range assessment camera systems based on the prompt gammas detection have been reviewed in Ref. [78], including mechanically and electronically collimated gamma imaging modalities.

State-of-the-art of Compton cameras Figure 1.14 illustrates the basic principle of Compton cameras for in-beam therapy range monitoring. Compton imaging as an electronically collimated gamma detection technique does not need any passive collimator. It has therefore the potential



Fig. 1.14 Illustration of the basic principle of the Compton camera for in-beam therapy range monitoring. Figure taken from [86].

advantage of a higher efficiency and larger angular acceptance to incoming prompt gammas, as well as 3D imaging, compared to the conventional SPECT systems. Furthermore, using γ -ray tracking based on the Compton kinetic formula allows to identify and reject a great part of the background [76]. The sources of noise for such a system have been analyzed in detail by Ortega et al in Ref. [79]. Due to its potentially promising advantageous, the adaptation of the Compton imaging to ion-range hadrontherapy monitoring drawn wildly attentions worldwide. Specific studies by several research groups can be found in Ref. [80-83]. Many different detector geometries and materials are being investigated for the construction of a Compton telescope, including scintillator detectors, silicon detectors, CZT, and gas chambers [84]. The envisaged approaches consist of traditional two-layer (scatter and absorber) Compton cameras, threelayers or multi-layers Compton cameras requiring more than two interactions in detectors and monolithic devices. For example, the current research reported in Ref. [85] is based on two layers with silicon detectors as scatter and BGO scintillator material for absorber detector design. Different Compton telescope with three layers of LaBr3 crystals coupled to SiPMs are also under investigation and have already shown promising results for further developments [84, 86, 87]. Apart from the approach of prompt gamma measurements, a Si/CdTe based Compton Camera aiming of in vivo real-time monitoring was recently reported in Ref. [88], specifically dedicated to the γ -rays annihilation detection.

1.3.4 3-gamma imaging: a novel modality

The 3-gamma imaging technique is an emerging nuclear medicine modality aiming for determining directly the 3D distribution of specific $\beta^+\gamma$ coincidence emitters through the coincident detection of triple photons. This idea was first proposed and compared with TOF-PET by Liang *et al* [89, 90] in 1988 as c-TPCIT, angular constrained triple photon coincidence imaging technique. However, due to the technical limits and accessible clinical $\beta^+\gamma$ isotopes, it was shelved for more than a decade and re-proposed more recently in *Ref.* [91]. In 2004, Thers *et al* launched the project XEMIS at the SUBATECH laboratory that introduced the name of "3-gamma imaging" for the first time and the idea to realize a clinical application with a concrete instrument. This R&D project is undergoing, more details can be found in *Ref.* [92] and additional ones will be provided in this thesis.

Basic principle The imaging principle of 3-gamma modality is illustrated in Figure 1.15. The annihilation of a positron generates a pair of back-to-back photons whose position is used to build a LOR, similarly to what it is done in conventional PET. The third quasi-coincident single photon is detected via the electronic collimation e.g. using the Compton telescope. The 3-photon event is reconstructed from the two intersections of the LOR (defined through the detection of the two annihilation photons) with the Compton cone surface. In most cases there is only one between those two intersection points which is well located within the interested region of FOV. Considering the uncertainties resulted from the measurements, the localization



Fig. 1.15 Illustration of basic principle of 3-gamma imaging modality.

of an emitter can be obtained from one single radiation decay, which is very similar to the TOF-PET modality, following a Gaussian distribution. The unique difference between those two methods is that the deviation of such an uncertainty is resulted from the energy and angular resolution of the Compton telescope rather than from the precision of the TOF information. **Therefore, the 3-gamma imaging modality could be also considered as a pseudo-TOF PET approach.**

 $\beta^+\gamma$ coincidence emitters $\beta^+\gamma$ coincident emitters are indispensable to realize the 3-gamma medical imaging. Isotopes emit a positron and an additional single-photon simultaneously e.g. via the following decay process ${}^{44}_{21}Sc \rightarrow {}^{44}_{20}Ca^* + e^+ + \nu_e \rightarrow {}^{44}_{20}Ca + e^+ + \nu_e + \gamma$ (decay scheme shown in Figure 1.16). Several physic characteristics of the exemplary $\beta^+\gamma$ isotopes investigated in 3-gamma imaging are listed in Table 1.6. A more complete list of candidates has been recently reported in the paper overview [93].



Fig. 1.16 The decay scheme of isotope $\frac{44}{21}Sc$. Figure taken from National Nuclear Data Center [94].

Table 1.6 Selected physical characteristics of the exemplary $\beta^+\gamma$ isotopes used for both PET imaging and 3-gamma imaging. Data have been adapted from National Nuclear Data Center [94].

Isotope	Half-life	$E_{\beta^+}^{Max}$ (keV)	I_{β^+} (%)	E_{γ} (keV)	Excited nuclei lifetime	Application	
^{44}Sc	3.97 h	2495.5	98.97	1157	2.61 ps	aliniaal imaging	
^{89}Zr	$4.161\ m$	1325.6	6.06	1507.4	$coincident^{\star}$	chinical imaging	
^{22}Na	2.6018 y	1568.7	99.94	1274.5	$(5.9 \pm 0.6) \ ps \ [95]$	experiment source	
^{14}O	$70.606\ s$	2830.2	99.34	2312.6	$67.8 \ fs$	hadron therapy	
^{10}C	$19.290\ s$	2929.6	98.53	718.4	$0.8 \pm 0.2 \ ns$ [96]	monitoring	

* no published data found

Advantages As described before, in order to localize the β + γ emitter, we intersect the LOR (built from the pair of photons) with a hollow Compton cone (from the third single photon). Nevertheless, due to the uncertainties on the position, the line-of-response will rather be reconstructed as a cylinder. The length of the cylinder segments intersected by the hollow

cone is about 1 cm for intersections at right angles. Compared to TOF-PET performances, the localization of the emitter is significantly improved [90]. This offers a potentially better spatial resolution or, alternatively, the same quality image with less injected radioactivity (hence reducing the dose to the patient). This method also reduces the exposure time that has the advantage of diminishing the number of consultations in hospitals per day.

State-of-the-art In the last decade, accompanied by the appearance of limits in conventional medical imaging modalities, lots of attentions has been attracted to this emerging technique presenting a booming advancement. Apart from XEMIS camera based on a liquid xenon TPC (introduced in detail in the next Chapter), several others types of devices were being developed by different groups worldwide. A German group proposed a prototype ' γ -PET' consisting of 4 Compton camera modules based on a double-sided silicon strip detector (DSSSD) as scatter and LaBr3 as absorber whose simulation results are reported in Ref. [97]. Another pixelated-CdTe based Compton-PET scanner, named Voxel Imaging PET, was studied and simulated by a Spanish team: it shows a position resolution of about 5 mm, which is much better than what one can expect from a TOF PET scanner based on fast crystal detectors" described in Ref. [98]. Besides, a current publication [99] announced a feasibility study of the positronium and $\beta^+\gamma$ coincidence imaging by using super time resolution with the J-PET tomography, which is a cylindrically shaped PET detector made of multi-layers plastic scintillators. The most recently result came from the WGI (Whole gamma imaging) scanner, developed by a Japan research team. They achieved an experimental comparison of the spatial resolution in the PET, Compton imaging and 3-gamma modes through the first small animal demonstration using the isotope of ^{89}Zr [100]. Moreover, they compared also the performance of full-ring and limited-angle Compton imaging in Ref. [101].

1.4 Conclusions Chapter 1

Nuclear medicine has the ability to access, qualitatively and quantitatively, dynamic physiological processes within the patient through the detection of the traveling γ -rays generated from special radiopharmaceutical administered in the body for diagnostic purposes. In the first section of this chapter, a brief introduction about nuclear medicine has been given including the basic principle and its essential elements, radiopharmaceuticals and detection devices. Besides, the SPECT and PET system, as two proven modalities, have been investigated more in detail from the principle to device techniques. However, both of these techniques have their proper limitations. In the SPECT system, the dominant restriction comes from its passive collimation that largely limits the detection efficiency. In PET, the uncertainties on the detection represent an intrinsic

limit. Specifically, they are caused by the positron range and the non-collinearity of annihilation photons. Besides, different coincident events and parallax effect may reduce the efficiency and resolution of PET systems. In light of what was described above, a pivotal-compromise between the detectors' sensitivity and spatial resolution represents a common issue for both techniques.

Through the full exploitation of the limits mentioned above, three mainstream types of next generation PET are being currently developed aiming at a personalized (or precision) medicine. In the second section, a literature review from the concept to the state-of-the-art has been presented. The total-body PET scanner achieved a drastic sensitivity increase through the ultimate field of view covering the entire body. The first completed total-body PET scanner has been recently accomplished by EXPLORER: it performed a whole-body scanning image in 1 s. Ultra coincident time resolution searched in TOF-PET technique has brought the spatial resolution to sub-centimeter level in the last research. The development of depth-of-interaction encoding PET modality has the possibility to solve the trade-off between the detectors' sensitivity and spatial resolution caused from the parallax effect existed in the conventional PET systems.

A rising development of Compton camera, in recent decades, showed a promising capacity of γ -ray imaging in a wide energy band and without any need of collimators. This technique can probably become an alternative to SPECT imaging. In the third section, the mechanism and technical requirement of Compton imaging technique have been primarily discussed. Successively, we focused on the potential advantages of Compton telescope in nuclear medicine. It brought novel modalities on multi-tracer imaging, range verification in hadrontherapy, and 3-gamma imaging. Multi-tracer imaging provides the opportunity to simultaneously observe dual or multiple complex molecular and metabolic phenotype. Real time range verification allows to fully exploit the hadrontherapy treatment. Besides, based on the combination of Compton telescope and special $\beta^+\gamma$ coincidence emitted isotopes, a novel 3-gamma imaging modality has attracted lots of attention as it constitutes a strong advancement in the field.



XEMIS2: Liquid Xenon Compton Camera for 3-gamma Imaging

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XEMIS (XEnon Medical Imaging System) project is directed to personalized medicine, based on an innovative liquid xenon Compton camera to realize a low activity medical imaging. Liquid xenon (LXe), as an emerging monolithic radiation detection medium, has been widely used for particle physics and dark matter detection. It possesses many advantageous features, such as high stopping power, outstanding sensibility, and simultaneous scintillation light and ionization charge production. The liquid xenon time projection chamber (LXeTPC) is a suitable candidate to build a Compton telescope for nuclear medical imaging applications. It operates primarily with ionization signals combining the scintillation triggering information, allowing for three-dimensional (3D) position reconstruction, energy measurement, and multi-hit sequence identification. Meanwhile, a "TOF-like" PET performance could be achieved by applying the innovative 3-gamma imaging modality, measuring with good precision the intersection of LOR and Compton cone to obtain a direct 3D location of the radiotracer. Moreover, its efficient scalability affords the capacity for developing a total-body imaging detector.

In this chapter, we would like to introduce an innovative Compton camera for small animal imaging, XEMIS2, based on LXeTPC technique. It is developed in the SUBATECH laboratory to demonstrate the advantage of LXe as a detection medium for 3-gamma imaging. XEMIS2 is a monolithic single-phase detector with a large axial field of view, handling up to nearly 200 kg of ultra-high-purity liquid xenon. The first stage aims to obtain a small animal image with an ultra-low activity of 20 kBq in 20 minutes while preserving the image quality in oncology diagnosis. The main characteristics and advantages of LXe as a detection medium are described in Section 2.1. The state-of-the-art of LXe exploitation in nuclear medicine is reviewed at the same time. Section 2.2 is devoted to describing the LXeTPC used in XEMIS2 from the operation principle to detector description. The safe and compact cryogenic infrastructure and high-capacity signals measurement system, specially developed for XEMIS2, are introduced in Section 2.3.

2.1 Choice of liquid xenon as radiation detection medium

Liquid xenon (LXe) is not a commonly used radiation detection medium in nuclear medicine imaging. The large majority of devices in use today are based on crystal scintillators presented in the first chapter. However, the excellent properties of LXe for γ -ray detection have been widely exploited for both position-sensitive detectors and calorimeters in the domain of particle physics and astrophysics [102]. LXe also showed a growing attraction in medical imaging applications since 1972, when it was firstly used for SPECT [103]. This section will first give a brief introduction to LXe primary physical properties and signal generation. A discussion on the potential and advantage of integrating LXe into nuclear medicine from current studies will then be presented.

2.1.1 Main physical properties and advantages

A fundamental characteristic of LXe, which is common to all liquid noble gases, is the simultaneous production of charge carriers and scintillating photons following the ionization radiation.

	Physic properties of liquid xenon	Values	Ref
	Atomic number Z	54	[104]
υ Ο	Average atomic weight A	131.293	[104]
asi	Density at −109 °C (g·cm ⁻³)	2.95	[104]
В	Boiling point (°C) *	-108.09	[104]
	Melting point (°C) *	-111.74	[104]
	Radiation length X_0 (cm)	2.77	[105]
ц	Ionization potential in liquid phase I (eV)	9.28	[106]
atic	Average ionization energy W-value (eV)	15.6 ± 0.3	[107]
niz	Electron mobility μ_{el} (cm ² V ⁻¹ s ⁻¹)	2000 ± 200	[108, 109]
Io	Electron saturation velocity v_s (cm s ⁻¹)*	$2.6 \times 10^5 \pm 10\%$	[108, 109]
	Transverse diffusion coefficient D_T (cm ² s ⁻¹)**	50 - 80	[110]
	Longitudinal diffusion coefficient D_L (cm ² s ⁻¹)	$0.1 D_T$	[110]
	W_{ph} in liquid for relativistic e^- (eV) e^- *	21.6	[102]
ц	Peak emission wavelength (nm)	178	[102, 111]
ttio	Refractive index (at 178 nm)	[1.6,1.72]	[112, 113]
illa	Fast decay time (singlet state $ au$ s) (ns) *	2.2	[102, 111]
zint	Slow decay time (triplet state $ au$ s) (ns) *	27	[102, 111]
Š	Recombination time ($ au$ r) (ns) *	45	[102, 111]

Table 2.1 Main properties of liquid xenon as radiation detector medium

* at 1 bar

* at an electric field of 3–10 kV/cm

** at an electric field of 1-10 kV/cm

* for detectors without electric field

This advantage provides LXe detectors with four types of signals readout possibilities: ionization mode, scintillation mode, sum mode, and time projection chamber (TPC) mode. Detectors based on the first two modes are only respectively sensitive to either ionization or scintillation processes. In contrast, the sum and TPC modes use both radiation-responses to obtain a better energy resolution and/or a 3D interaction localization. Among all these types of detection modes, the most interesting one for us is the one based on the use of a TPC. It is an excellent candidate for the Compton telescope that will be described in the next section. Table 2.1 summarizes the principal physical characteristics of liquid xenon as a radiation detector medium that can be summarized as follows:

- high stopping power LXe shows a similar *high density* and *significant atomic number* as the conventional crystal scintillator used in a gamma camera, NaI:Tl (see Table 1.4). Those properties afford LXe a critical capacity to stop the incoming radiation, which is necessary for obtaining a detector with high detection efficiency.
- fast scintillation decay time and high scintillation yield Compared to other scintillators already in use or in development for nuclear medicine (listed in Table 1.2), LXe is a competitive in terms of light yield and decay time. That fact makes it particularly attractive for the scintillation detector, especially for TOF-PET development.

- excellent ionization proprieties Among liquid noble gases suitable for radiation detection, LXe provides the best ionization yields, the highest electron mobility, and lowest diffusion.
- monolithic detection with a uniform response Owing to the liquid form, LXe has the advantageous capacity to create large scalable monolithic detectors where a large field of view with high sensitivity and negligible dead zones could be considered feasible.
- cryogenics required Compared to other conventional crystalline radiation detection medium LXe has the disadvantage of being in its liquid form only in a temperature range between 165 K and 161 K at the pressure of 1 bar. This might be problematic in medical applications especially for safety reasons. Despite this problem, all the above mentioned advantages make the LXe still an excellent candidate. Furthermore, highly effective cryogenics systems have become accessible in recent years due to the explosive growth of large-scale LXe-based projects in diverse physics research domains, e.g., XENON [114], EXO [115], PandaX [116].

2.1.2 Interaction of ionizing radiation

Given that the radiation used in nuclear medicine consists of γ -rays with an energy spanning from ~100 keV up to 10 MeV (the upper limit is used in medical imaging or hadrontherapy monitoring), in the following, we will study their interactions and that of the electrons with LXe in this energy range.

Photon interactions in matter

There are four principal interactions between photons and matter: photoelectric effect, Compton scattering, Rayleigh effect, and pair production. The probability of each interaction has a strong dependency on the atomic number Z of material and the energy of the incident photon E_{γ} . The cross-section of different interaction modes of photons with LXe is presented in Figure 2.1, while Figure 2.2 shows their relative contribution in the energy range of interest from 10 keV to 10 MeV.

• **Photoelectric effect** - In this process, the total incident energy is absorbed and transferred to a bound electron. If the incoming photon energy is greater than the binding energy, the electron is thrown out of its orbit with a kinetic energy equal to the difference, causing ionization of the inner shells of atoms (*K* and *L*). The ionized atom then returns to the ground state from the excited state accompanied by an emission of characteristic X-rays or Auger electrons (largely predominant up to 90%). The probability of having a



Fig. 2.1 Calculated cross-sections of different modes of interaction of photons with xenon. Data taken from [117].



Fig. 2.2 Relative contribution of the different interaction modes of photons with xenon. Data taken from [117].

photoelectric interaction increases as the energy decreases. In LXe, as shown in Figure 2.2, the photoelectric effect dominates other interaction processes at low photon energies range. The drops observed around 5 keV and 30 keV are the absorption edges of the atomic shells presented in Table 2.2. For incident photons with energy over 35 keV, there is a high possibility of emitting a fluorescence X-ray of about 30 keV (*K*-shell) during the photoelectric process. In contrast, the Auger electron ejection is almost negligible.

Table 2.2 Ionization energy of the electronic layers of xenon atom

Atomic shell	M_1	L_3	L_2	L_1	K
Energy (keV)	1.149	4.782	5.104	5.453	34.56

- Compton scattering The Compton effect is an inelastic diffusion between the incident photon and a bound electron, that produces a recoil electron and a scattered photon. This process typically takes place at higher photon energies than the photoelectric effect. The direction in which the scattered photon and the electron are emitted depends on the initial energy of the incident photon. The possibility to have a Compton scattering becomes significant for an energy value from several hundred keV to a few MeV, with a maximum at around one MeV: this value corresponds to the energy of the third γ -ray used in XEMIS2. Compton scatter events are of main interest in XEMIS2. A more detailed study will be presented in Chapter 7 dealing with Compton geometric angular calibration.
- **Rayleigh scattering** It is also called coherent scattering or Thomson scattering. This effect mainly appears at low photon energy via their interaction with atoms as a whole (coherent scattering). The transfer of energy from the photon to the atom could be considered negligible. The scattered photon deviates from its precedent trajectory without energy loss. Compared to Photoelectric or Compton effects, the possibility to have a Rayleigh scattering in LXe is minimal, even at a low-energy regime. For this reason we consider that it could be neglected.
- **Pair production** It corresponds to the conversion (materialization) of a photon into an electron-positron pair from the energy of the incident photon in the nuclear or electron field. This effect is only possible if the incident photon has energy above 1.022 MeV, twice the mass energy of an electron at rest, to satisfy the conditions of conservation of energy. In LXe, it becomes predominant starting from energy around 10 MeV, which is outside the above mentioned energy range of interest.

Electrons interactions in matter

Incident photons with an energy lower than 10 MeV, mainly produces a photoelectric effect or/and Compton scattering when interacting with liquid xenon, resulting in ejecting recoil electrons. Unlike photons, charged particles interact in matter by the Coulomb force and lose their energy progressively through continuous elastic/inelastic collisions before being stopped. There are several mechanisms of interaction of electrons with matter:

- Elastic collisions with atom will just deflect the electron from its incident direction without degrade its energy. In contrast to heavy charged particles, electrons and positrons are more likely to undergo multiple scattering by atom due to their low mass.
- **Inelastic scattering with the atomic electrons** will result in either excitation or ionization of the atoms of the medium depending on the transferred energy in each collision. This process can generate a secondary electronic cloud along the track, accompanied by

scintillation light in liquid xenon. Ionization and scintillation can be measured during this process.

• **Bremsstrahlung** or **braking radiation**, is the electromagnetic radiation produced by the deceleration of the incident electron interacting with the Coulomb field of nuclei. Figure 2.3 shown the stopping power of electrons with respect to electrons energy.



Fig. 2.3 Stopping power of electrons in xenon. Data taken from [118].

• Cherenkov radiation [119] is the electromagnetic radiation emitted when an electron passes through at a speed greater than the phase velocity of light in that medium. This mechanism won't be discussed since it is irrelevant in this thesis, except when the medical imaging applications using Cerenkov radiation in liquid xenon will be mentioned.

Additionally, electrons and positrons suffer from larger deviations from the electron path than heavy charged particles, resulting in erratic trajectories.

2.1.3 Ionization and scintillation signals generation

Once the incident photon interacts with LXe, one or more recoil electrons will be emitted in most cases as a consequence of photoelectric or Compton effect. The primary electrons then lose their energy mainly through ionization and atomic excitation. This part of energy deposited by recoil electron could generate ionization and scintillation signals in LXe (illustrated in Figure 2.4). Both signals are produced simultaneously and could be used alone or in combination for the detection of the radiation particles.

Ionization properties

In liquid xenon, the deposited energy E by the incident ionizing particle is ultimately expended in the production of a number of electron-ion pairs N_i , excited atoms N_{ex} , and free electrons



Fig. 2.4 Illustration of signals generation in liquid xenon

with kinetic energy lower than that of the first excited level, known as sub-excitation electrons. The deposited energy E can be expressed by the Platzman equation [120] in noble gases:

$$E = N_{ex}E_{ex} + N_iE_i + N_i\epsilon \tag{2.1}$$

in which E_{ex} is the average energy needed to produce atomic excitation, E_i corresponds to the average energy expenditure to create an electron-ion pair, and ϵ represents the kinetic energy of the sub-excitation electrons.

Given that LXe is a non-crystalline semiconductor, the gap between the valence band and the conduction band defines a minimum energy necessary to ionize an electron out of its atom, i.e. ionization potential I (given in Table 2.1). While the average energy W to create an electron-ion pair can be defined as:

$$W = \frac{E}{N_i} \tag{2.2}$$

Combining the above two equations, we could obtain:

$$W = E_i + E_{ex} \frac{N_{ex}}{N_i} + \epsilon$$
(2.3)

Except for very low energies, W in liquid xenon is a value almost constant of $15.6 \pm 0.3 \, eV$ [107]. According to the Equation 2.2, a high ionization yield around 64000 pairs/MeV in LXe could be calculated. E, the energy deposited by the incident particle, in turn, could be deduced by measuring N_i by collecting the produced electrons. This principle is used in time projection chambers to measure the energy of the incident particle.

Scintillation mechanism

Liquid xenon is also a promising scintillator. As shown in autoreffig:scintillationmechanism, the scintillation photons are produced simultaneously with the charge carrier generation during the ionizing radiation. Both ion and exciton generated from the ionizing particle passage can combine with the surrounding xenon atoms and eventually create the excimer Xe₂^{*}. The excited dimer Xe₂^{*} will decrease towards its ground state after a few nanoseconds by emitting a scintillation photon

$$Xe_2^* \to 2Xe + h\nu \tag{2.4}$$

There are two energy levels of the excited xenon dimer: singlet and triplet, with respective relaxation times of about 2.2 ns and 27 ns [121]. The excimer lifetime relies on neither the formation process nor the state of xenon (liquid or solid). The singlet/triplet production ratio is not constant, it depends on the linear energy transfer (LET) [122]. The formation of an excited dimer Xe_2^* can be summarized as follows.

 <u>Combination of excited atom and another xenon atom.</u> In this process, the excited atom combines directly with the surrounding xenon atoms producing an excited dimer.

$$Xe^* + Xe + Xe \to Xe_2^* + Xe \tag{2.5}$$

<u>Recombination of ionized atom and liberated electron</u>. The ionized atom will firstly combine with another xenon atom forming an ionized dimer Xe₂⁺, then recombine with a nearby liberated electron produced by ionization. This process produces again an excited dimer, which will decay by emitting the same scintillation signal as before, but will take more time than the first one. The scintillation recombination component represents a non-exponential form with a decay time of 45 ns [121].

$$Xe^{+} + Xe + Xe \rightarrow Xe_{2}^{+} + Xe$$

$$Xe_{2}^{+} + e^{-} \rightarrow Xe^{**} + Xe$$

$$Xe^{**} \rightarrow Xe^{*} + heat$$

$$Xe^{*} + Xe + Xe \rightarrow Xe_{2}^{*} + Xe$$
(2.6)

The excimer produced from both formation processes generates the identical scintillation light through de-excitation, whose typical wavelength is 178 nm [123] transparent in liquid xenon, which allows it to be measured as a scintillation signal.

Correlation between scintillation and ionization signals

The intensity of ionization and scintillation production following the ionization radiation in liquid xenon is deeply dependent upon the applied electric field because of the electron-ion recombination process (see next section). As shown in Figure 2.5, more electrons escape recombination as the electric field increases, generating a more substantial charge carrier. Meanwhile, the fraction of scintillation light created from the ionization-recombination decreases. The dependence of the electric field allows to favor either scintillation or ionization signal following the indented application. No matter how the electric field changes, the total production of two signals remains constant and relies only on the energy deposited by the incident particle. This anti-correlation between the signals provides the potential to improve the energy resolution by combining the two of them [124].



Fig. 2.5 Light and charge yields as a function of drift field for 662 keV γ rays from ¹³⁷Cs. Figure taken from [124].

2.1.4 Liquid xenon in nuclear medicine: state-of-the-art

The emerging application of liquid xenon in nuclear medicine has proliferated in recent decades. Diverse types of liquid xenon based SPECT/PET scanners have been proposed, e.g., ionization chambers, scintillation calorimeters, and time projection chambers (TPCs). Table 2.3 provides a schematic overview of the liquid xenon exploitation in nuclear medicine. Several devices based on a single signal (light or charge) type will be introduced in this subsection, while a more detailed presentation on the TPC based Compton camera, relying on both signals, will be presented in the next section.

Imaging Modality	Detector Technology	Phase	Read-out Mode	Project/ Laboratory	Country	Ref
SPECT	$\frac{\text{Multiwire ionization chamber}}{\Gamma^1 + 1}$	Single	Ionization	Lawrence	USA	[125]
PET	Multiwire/Mini-strip plate ionization chamber	Single	Ionization & Scintillation	PETYA/ LIP-Coimbra	Portugal	[126]
DOI-PET	Segmented scintillation elementary module	Single	Scintillation	PET/ LPSC	France	[127]
TOF DET	LXe based PET + PMT	Single	Scintillation	Collaboration	Japon USA	[128]
101-111	LXe based PET + SiPM	Single	Scintillation & Cerenkov	PETALO/ LIP-Coimbra	Portugal	[129]
Compton-PET		Single	Ionization & Scintillation	Collaboration	Japon USA	[130]
	Time projection chamber			XEMIS/ SUBATECH	France	[131]
				Micro-PET/ TRIUMF	Canada	[132]

Table 2.3 Exploitation of liquid xenon in nuclear medicine

Multiwire Ionization Chamber for SPECT/PET

The history of using liquid xenon as a detection medium in nuclear medicine could be dated to the early 1970. A small multiwire ionization chamber filled with liquid xenon was proposed for the first time as a gamma camera for SPECT by the researchers of the Lawrence Berkeley Laboratory [125]. Instead of using the fast scintillation light, this ionization calorimeter measured the charge carriers generated from the interacting gamma-ray. The liberated electrons are transported in pure liquid xenon under a strong electric field of 10^6 V/cm, then attracted to the nearest wires avalanching to produce the needed electrical signals. Even though the signal was read out with low-noise electronics, the signal-to-noise ratio has been limited by the low electron amplification in the liquid xenon. In obtaining sufficient amplification, another trial of a dual-phase gas/liquid system was then proposed. This time, the limitation of the gain was mainly due to the large number of ultraviolet photons emitted by xenon during the avalanche development process, which caused the emission of secondary electrons from the surface, resulting in uncontrollable discharge. As the first attempt to use liquid xenon in nuclear medicine, it opened up a new exploration domain.

In the late 1990s, a LIP-Coimbra group led by A.J.P.L. Policarpo developed a liquid xenon PET scanner, named PETYA, targeted to realize the time-of-flight measurement. The fast scintillation light was detected by photomultipliers as the trigger signal, while both deposited energy and interaction vertex was provided by the ionization signal measured by the multiwire ionization chamber. A coincidence time resolution of 1.5 ns was obtained and published in [126].

Besides, the multiwire ionization chamber provides a depth of interaction, thus enabling parallaxfree detection. Ultimately, small ionization signal measurement and electrons drift time were two dominating impact factors that limited the energy resolution and maximum counting rate, respectively.

Monolithic scintillation calorimeter for TOF-PET

Liquid xenon is a promising scintillator for time-of-flight techniques, whose scintillation decay time (except the recombination light) could be comparable to plastic scintillators. The prospects of liquid xenon scintillator for TOF-PET were first presented in the work of L. Lavoie in 1976 [133]. He summarized the scintillation physics of liquid xenon, especially its high scintillation yield and fast responses, and pointed out the potential of applying time-of-flight techniques on the liquid xenon based PET devices. However, the development of liquid xenon scintillation TOF-PET was shelved because the exploration of new crystal scintillators attracted most of the attention.



Fig. 2.6 (a) Arrangements of 32 PMTs. (b) Cross-sectional view of a prototype model. (c) Cross-sectional view of liquid xenon scintillation TOF-PET scanner seen from the front. Figures taken from [128].

In the late 1990s, a liquid xenon scintillation prototype was constructed and tested to explore the potential of liquid xenon for TOF-PET experimentally by T. Doke *et al.* [111, 134]. It consisted of a homogeneous scintillation calorimeter with a number of photomultipliers immersed in liquid xenon to measure the fast scintillation light produced by the interaction of a gamma-ray with the target. In each proposed module, an arrangement of 32 1" PMTs covered the sensitive volume except the entrance window. The experimental results presented in the last article [128] showed that the liquid xenon scintillation signal could be used for TOF-PET with performances even better than those reachable by commercially available crystal scintillators. Furthermore, on this basis, they proposed a full-size LXe scintillation TOF-PET scanner, whose drawing is shown in Figure 2.6.

Based on the same monolithic continuous ring, a new liquid xenon TOF-PET concept named PETALO (Positron Emission TOF Apparatus based on Liquid xenOn) was proposed by a Portuguese research team in recent years. They attempted to demonstrate that using liquid xenon scintillator and novel techniques, SiPMs and fast electronics, could significantly improve the TOF measurement. Instead of surrounding the sensitive volume completely, the SiPMs would be instrumented only in the entry/exit face or both, depending upon the intended application. Other detector faces are covered with absorber materials to avoid reflections and spatial aberrations. The transversal section of the ring is depicted in Figure 2.7. The latest Monte Carlo studies published in [129] indicate a promising intrinsic time resolution of around 70 ps using scintillation light, and 30-50 ps with Cherenkov light. A prototype is under construction to prove those predictions experimentally.



Fig. 2.7 Scheme of the transversal section of the ring showing the LOR of the 511 keV Figure taken from [129].

Segmented scintillation module for DOI-PET

Other than using the monolithic continuous liquid xenon medium, the group's members of a French laboratory, the LPSC, proposed a parallax error free LXe μ PET- using segmented detection modules and light guide techniques to realize the DOI measurement. Figure 2.8 illustrates the camera geometry and the structure of an elementary module. The emitted scintillation light is reflected by the MgF_2 -covered aluminum UV light guides and then read out by two end-side position sensitive PMTs. The module prototype simulation and experimental results were published in [135]. An average time resolution of 700 ps (550 ps with energy selection) was obtained, which could not provide a TOF measurement but it's good enough to reduce the random coincidence rate. Besides, it demonstrated that the DOI measurement could effectively eliminate the sensitivity of detector to any parallax effect. The latest experimental results showed a good spatial resolution of about 1-2 mm RMS in each axis [127].

LXe module

PMT2

UV light



(a) Camera geometry (b) Elementary module (z along the axial direction) Fig. 2.8 Scheme of the LXe μ PET camera. Figures taken from [135].

Time projection chamber for Compton-PET

As listed in Table 2.3, different Compton PETs based on liquid xenon TPCs have been proposed worldwide. Apart from the XEMIS project developed for 3-gamma imaging and discussed in this thesis, the primary purpose of this type of detector is to use Compton reconstruction to reduce image results from inner and outer scattering events, thus improving the PET system performance. A schematic comparison between two detection principles based on a single monolithic detector or a double scatter telescope, is shown in Figure 2.9a. The single detector principle is employed in both XEMIS [92] and micro-PET [136]: it will be detailed in the next section. The double scatter telescope proposed in [130] consists of two parts: a thin TPC layer used as a scatterer and a thick one as an absorber, separated by a large vacuum volume, whose elementary module is shown in Figure 2.9b. This design favors the photon to be scattering in the first layer and fully absorbed in the second detector. The double scatter telescope design might result in a much better angular accuracy due to the considerable scattering sequence distance. Whereas, the additional diffusion occurring in the material of the two detectors wall needs to be considered. The main advantage of the monolithic detector is the higher detection efficiency compared to the double scatter detector.



(a) Principle of operation.(b) Elementary moduleFig. 2.9 Scheme of the Compton PET constructed by double scatter telescope. Figures taken from [130].

2.2 Time projection chamber used in XEMIS2

The simultaneous generation of ionization and scintillation signals following ionizing radiation is the essential and exclusive characteristic of noble gases as detection media, independently of their phase. Either of the two signals has been employed for energy measurements in liquid xenon calorimeters. It has been shown that, under a high electric field, the ionization signal usually provides a better energy resolution than the scintillation one because in this latter case only a low fraction of emitted photons can be measured. Nevertheless, thanks to its fast decay, the scintillation signal can be used as a trigger signal due to its fast decay. A time projection chamber (TPC), the technology used in XEMIS2, is an excellent example primarily operated with ionization signals combining the scintillation triggering information. It allows threedimensional (3D) localization, energy measurement, and particle identification. Besides, it is also a promising candidate for Compton imaging. In this section, an overview of the TPC used in XEMIS2 will be explicitly presented from the operating principles, technical development, and detector description.

2.2.1 Principle of detection

The construction concept of a TPC was first proposed by C. Rubbia in 1977 for a large-scale liquid argon detector dedicated to low background rare events particle physics experiments [137]. Shortly after, in 1979, E. Gatti *et al.* [138] developed a non-destructive electrode system of this type of liquid argon TPC for ionization imaging. The TPC concept and technique were then successfully developed using the liquid xenon as detection medium, addressing several most fundamental and intriguing questions in physics research, like the direct detection of dark matter and the neutrinoless double-beta decay measurement. The most concerning employment for our XEMIS project is the TPC-based Compton telescope, which was proposed for the first time in 1996 by E. Aprile *et al.* [139] in the Liquid Xenon Gamma-Ray Imaging Telescope (LXe-GRIT) research program for MeV energy astrophysics. The conceptual operation of LXeGRIT for Compton imaging is illustrated in Figure 2.10. It has a similar design to the TPC used in XEMIS2, except for the readout electrode. The multiwire structures used in LXeGRIT allow the drifting electrons to pass from one sensing wires plane to another with one coordinate determined at each plane. While in XEMIS2, we use a single-readout plane with a two-dimensional array of independent pixels, each read with an individual preamplifier.

Fundamental structure and operation concept A typical liquid xenon TPC is composed of a monolithic sensitive volume with a uniform drift electric field defined by a cathode, a series of field shaping rings, and a segmented anode two-dimensional (2D) charge readout. A shielding



Fig. 2.10 Conceptual operation of the LXeGRIT detector for Compton imaging. Figure taken from [140].

grid is frequently placed in front of the anode, aiming to eliminate the dependence of the induced signal to the Z-position of the interaction. While an ionizing particle interacts with liquid xenon in the active zone, the fast scintillation light is detected by the UV sensitive PMTs quasi-instantaneously, measuring the time of the interaction. The free ionized charge carriers from ionizing radiation are then drifted toward the anode under the homogeneous electric field. Once the drifting electrons start to cross the shielding grid and move toward the anode, the electric signals will be induced on the segmented readout system. The ionization signal formed on the pixelated anode provides two coordinates on the (X, Y) plane, perpendicular to the drift electric field. The Z coordinate along the drift field direction can be inferred from the electron drift time, the delay time between the ionization signal and the scintillation signal. The 3D interaction position reconstruction can be consequently obtained. Besides, the total collected charges, which are proportional to the deposited energy in the detector, enable energy determination.

Advantages and limits Both good spatial and energy resolution are reachable thanks to the unique physics properties of liquid xenon as detection medium. Moreover, the development of a self-triggering device can also be considered. However, limited to the long electrons drift time, varying from microseconds to milliseconds, which mainly depends on the chamber dimension and intensity of the electric field, the TPC is typically used for low counting rate applications.

Multiple Compton scattering The incoming gamma-ray direction can be reconstructed with Compton kinematics from the energy and position information of each interaction. This requires

a detector with accurate 3D localization, precise energy measurement, and multi-interactions separation ability. For achieving those requirements, all other proposed detector approaches are based on the multi-layers position-sensitive elements. However, multiple interactions might occur, in the same layer or out of the sensitive region, resulting in detection efficiency restriction. Liquid xenon TPC affords a monolithic 3D homogeneous position-sensitive detection volume, in which interactions can be determined in any location, maximizing the detection efficiency of multi-scattering events. Another important limitation of Compton imaging, to be considered for Compton imaging, especially for gamma-rays with energy below few MeV, is ambiguity due to the unknown temporal order of the Compton scattering sequence, which will be discussed in Chapter 7.

XEMIS2 TPC for 3-gamma imaging A scheme of XEMIS2 camera for small animal imaging with 3-gamma modality is illustrated in Figure 2.11.



Fig. 2.11 Scheme of XEMIS2 camera for small animal imaging with 3-gamma modality.

The XEMIS2 detector is composed of two identical liquid xenon cylindrical TPCs sharing a common central cathode. The active zone is covered by PMTs and two end-sides equipped with segmented anodes, detecting the scintillation light and ionized charges, respectively. A detailed detector description will be given later. The capacity of all interactions identification in a liquid xenon TPC (with a specific separation limit depending on the detector performance) allows XEMIS2 to record both Compton multi-scattering event and photoelectric single-scattering event. With these information, the LOR and Compton cone can be reconstructed simultaneously in the same detector.

2.2.2 Processes affecting charge carriers collection

As explained in previous section, ionization signals in a TPC allow both position and energy measurement of particle interactions. The optimization of charge carriers collection and readout, therefore, becomes a crucial point for detector performance. Many physics and device related mechanisms play a role in this optimization process among which the electron-ion recombination, the transport of electrons (drift and diffusion), the electrons attachment by impurities, and electronic signal generation. This subsection focuses on the increase of charge collection efficiency based on the xenon purity, electric field, and readout electronics optimizations. Additional prerequisite impact factors, such as the cryogenic system, material selection, and design detail, will not be considered here. In the following, a brief review of the ionization process from electron generation to electronic signal formation will be firstly presented.

Ionization process from electron generation to electronic signal formation

As mentioned in the precedent section, when a ionizing particle has interacted in the detector, the deposited energy E_0 generates a certain amount of electron-ion pairs N_0 through ionization, following the relation of $N_0 = E_0/W$, where W is the average energy needed to create an electron-ion pair. If all those electrons could be collected ultimately, the deposited energy would be directly calculated from the electronic signal waveform amplitude owing to the well-known W-value. However, the final measurable electron number is intensively affected by the following processes before being collected by the anode.

- Electron-ion recombination As soon as electron-ion pairs are created, a portion of the created electrons recombines with ions immediately before drifting to the anode. The recombination is the main reason of charge loss, whose fraction depends on the local density of electron-ion pairs and the applied electric field.
- Electron drift The electrons that escape from recombination then drift towards the anode, traversing the liquid xenon under the electric field. Since the drift time is measured from the delay time between the arrival ionization signal and the fast scintillation light, the known drift velocity allows determining the Z coordinate of the interaction along the drift axis. Thus, it is necessary to have an accurate knowledge of the drift velocity, whose dependence on the applied electric field will be discussed later.
- Electron diffusion The electron cloud resulting from the collision of electrons with atoms and molecules, spreads in liquid xenon during the transport, along the transverse and longitudinal planes simultaneously. The diffusion process expands the electron cloud size from an initial almost punctual to a gaussian distribution when they arrive at the anode, leading to a certain number of fired pixels.

- Electron attachment by impurities Like all noble gases, the xenon atom surrounded by a full outer electron shell that prevents electron capture during free-electron propagation. However, the drift electrons might be attached by the contaminants molecules inside liquid xenon, especially electronegative impurities like oxygen. This phenomenon results in a reduction of collected charge number on the anode, which is dependent on the drift distance: longer the distance, greater the degradation.
- **Signal waveform** Electron movement produces an induced current in the anode during the drifting in the electric field volume. The duration and amplitude of the current induced by an electron cloud will vary with the drift time. For the same deposited energy, the signal waveform and amplitude depend on the Z position of the interaction. Therefore, to eliminate this dependence as much as possible, a Frisch grid is placed just above the anode to shield it from the movement of ions between the cathode and grid. In this way, all induced current starts from the moment that electrons arrive at the grid and ends when all electrons are collected on the anode, for any electron cloud position in the drift volume, to realize the signal waveform uniformity.

Impact of electric field

In a TPC, the impact of the applied electric field on charge carriers collection can be summarized into two aspects: **uniformity** and **intensity**. First of all, the nonuniform field can cause the local variation in the electron drift velocity, resulting in a distortion of the track pattern. Distortions could be amplified if a component of the field becomes parallel to the readout plane. Therefore, for the correct operation of the TPC, it is essential to ensure the electric field uniformity in the drift region. This can be obtained by using a surrounding field-shaping system located outside of the drift volume. Besides, the high intensity of the electric field in drift volume can optimize the electron collection for two significant reasons: (i) decreasing the rate of ionelectron recombination will improve the signal-to-noise ratio and ameliorate the intrinsic energy resolution resulting from the liquid xenon; (ii) increasing the electron drift velocity will lead to a shorter drift time.

i. Electron-ion recombination High charge yield provides the detector with a better signalto-noise ratio, improving the sensibility and resolution. The phenomenon of electron-ion recombination was mentioned above in the correlation between scintillation and ionization signals, indicating the strong dependence of charge and light yields on the electric field. Numerous theoretical and experimental studies have been done to interpret and reproduce this recombination process in liquid noble gases. The three most used traditional models are the germinate recombination [141], the columnar [142], and the Thomas and Imel box ones [143].



Fig. 2.12 Predictions based on NEST for the light and charge yields of electronic recoil events when the primary particle interacting with liquid xenon is a gamma-ray or a beta particle (a pure electron or a delta ray). Figure taken from [146].

The germinate recombination model is based on the Coulomb interaction between the charge carriers and the initial ions. On account of the previous concept, the Columnar recombination approach completes the dependency with the possibility that free electrons may recombine evenly with other positive ions along the particle ionization path. More realistic assumptions were considered in the Thomas-Imel box recombination model, where a more detailed description could be found in [144]. In recent years, an updated simulation model that incorporates a semi-empirical physic model, named Noble Element Simulation Technique (NEST) [145], provides a more realistic estimation of scintillation light and ionization charge yields from recoiling particles in liquid xenon in a wide range of energies. Figure 2.12 shows the predictions based on NEST for the light and charge yields of electronic recoil events when the primary particle interacting with liquid xenon is a gamma-ray or a beta particle (a pure electron or a delta ray).

In liquid xenon, yields depend on the type of incident particle, its kinetic energy and the electric field. For a given particle with a specific energy, like in the case of nuclear medicine for which we choose the incident particle as well as its energy, the electric field becomes the determinant factor for charge and light yields. A higher electric field decreases recombination, raising the charge yield so that a better signal-noise-ratio could be reached. However, in liquid xenon, applying a high voltage to create an intense electric field may lead to spurious non-physical electron and light emission near the electrode, whose signals will perturb the physics signals. Thus, to optimize the charge yields without signals perturbation, it is important to choose the appropriate electric field intensity based also on the detector dimensions. In XEMIS2,

a high electric field of 2 kV/cm is defined all along the 12 cm long drift area of each TPC, corresponding to a high voltage of 25 kV applied to the cathode in order to optimize the charge yield and detector resolution.

ii. Electron drift velocity In a TPC, the electron drift velocity v_{drift} allows to calculate the Z position along the drift direction, according to the formula:

$$Z = v_{drift} \times t_{drift} \tag{2.7}$$

where t_{drift} is the electron drift time. For a correct estimation of the z position it is thus needed to measure the drift velocity accurately. The electron mobility depends not only on the applied electric field in the active volume but also on the density of the xenon, relying on the pressure and temperature of the system. Since the operating conditions of XEMIS2 are very stable pressure of 1.2 bar and temperature of 165 K, hence the density of liquid xenon is almost constant as well as the electron mobility around 2200 cm² V⁻¹s⁻¹ [147]. Besides, the electron drift velocity can be increased by contaminations such as carbon hydroxides [102], but this is not the case in XEMIS2. Here, the variation of electron drift velocity is simplified to a single variable problem, which only depends on the applied electric field. Figure 2.13 shows the electron drift velocity in liquid (163 K) and solid (157 K) xenon as a function of the electric field strength, with respect to that in solid xenon.



Fig. 2.13 Electron drift velocity in liquid (163 K) and solid (157 K) xenon as a function of the electric field strength. Figure taken from [108].

In liquid xenon (same as in the solid-state) the thermal equilibrium between the electrons and the medium can be established at low-field intensity. In this region, the electron mobility μ_L is almost constant, and the electron drift velocity v_{drift} behaves quasi-linearly with the electric field *E* like:

$$v_{drift} = \mu_L \times E \tag{2.8}$$
However, the thermal equilibrium could not be maintained as the field strength increases. Above a few kV/cm, the dependence of the electron mobility on the applied electric field disappears progressively. The electron drift velocity is no longer linear with the field and tends to saturate. This behavior is still not completely explained, although several theoretical descriptions [148, 149] and experimental complements [150, 151] have been addressed. The electron drift velocity in liquid xenon under 2 kV/cm has been experimentally measured in XEMIS1, and it is about 2.3 mm/ μ s [152]. Since the mobility of holes and positive ions in liquid xenon is about 10⁻⁵ times lower than that of electrons [153, 154], the effect is negligible in the context of low activity used in the XEMIS2 experiment.

iii. Electron diffusion The electron cloud resulting from the collision of electrons with atoms and molecules spreads out during the transport. According to the kinetic theory, the spread along any axis of an initial point-like electron cloud can be described by a Gaussian distribution with a standard deviation equivalent to the diffusion of charge carriers. Therefore, the diffusion along any one axis x can be described according to

$$\sigma_x = \sqrt{2 D_x t_{drift}} \tag{2.9}$$

where D_x is the diffusion coefficient along the x axis expressed in cm²s⁻¹ and t_{drift} is the electron drift time. The spread of the electron cloud depends on the electrons collection time, which is related to the travelled distance by the electron through the LXe (d_{drift}) and the electron drift velocity (v_{drift}). Therefore, it can be expressed in terms of the distance according to

$$\sigma = \sqrt{2 D_x \frac{d_{drift}}{v_{drift}}} \tag{2.10}$$

Figure 2.14 shows that the electron transverse (D_T) and longitudinal (D_L) diffusion coefficients for liquid xenon reduce with the increase of the electric field.

iv. Electrons attachment by impurities Due to electronegative impurities present in liquid xenon, such as oxygen or water, the initial number of ionized electrons after recombination N_0 reduces into $N_e(t_{drift})$ electrons collected on the anode after a drift distance d_{drift} , which can be expressed by the following equation:

$$N_e(t_{drift}) = N_0 e^{-\lambda \, d_{drift}} \tag{2.11}$$



Fig. 2.14 Transverse (D_T) and longitudinal (D_L) diffusion coefficients for liquid xenon as a function of the electric field. Figure taken from [102].

where λ is the electron attenuation length of the detector, which can be represented by the product of electron lifetime τ_e and electron drift velocity v_{drift} , directly related to the total attachment rate inside liquid xenon, as follows:

$$\lambda = v_{drift} \cdot \tau_e = \frac{v_{drift}}{\sum_i k_i [N_i]}$$
(2.12)

where $[N_i]$ is the molar concentration of a given impurity, and k_i is the attachment rate constant of such contaminant. The electron-attachment rate constants of impurities are measured and described, under different electric fields, in *Ref.* [155]. The total attachment rate of a detector is commonly estimated by equivalent impurity concentration of oxygen, $k.[O_2]_{eq}$, which is measured in parts per billion (ppb). The phenomenon of electron attenuation could be greatly eliminated by reducing the impurity concentration through a purification system. A purification system is implemented in XEMIS2 to render xenon ultra-pure during the recirculation loop.

Besides according to the Equation 2.11, the electrons reduction during propagation depends also on the electron drift velocity, i.e., on the electron drift field where the experimental results are showed in Figure 2.15. As we can see, the experimental results indicate that the electron attachment rate is reduced with the increase of the applied electric field. The attenuation length can be experimentally measured, allowing estimating the purity level of the liquid xenon inside



Fig. 2.15 Attachment rate constant of electrons in LXe as a function of the applied electric field for three different contaminant. Figure taken from [156].

the detector. Moreover, to get the correct initial electron number, a collected charge correction as a function of the drift distance should be done during data analysis.

Effect of Frisch grid

A Frisch grid is conventionally a metallic mesh placed above the segmented anode, with the aim of obtaining a readable ionization signal whose amplitude is proportional to the number of collected electrons and independent of the interaction position along the drift direction. As explained previously, the operating principle is to shield the electrons drift motion in the electric field before electrons arriving at the grid so that no signal is induced in the anode in ideal conditions. Therefore, undesirable variations of the induced signal with respect to the distance of the interaction to the anode can be eliminated.

However, the charge induction shielding might not be perfect, in reality, due to numerous parameters such as the mesh geometry, material, and manufacturing technique. For the selection of the grid material, the coefficient of thermal expansion should be similar to that of other structures constituting the detector, otherwise, during the immersion and removal of TPC in liquid xenon, the grid deformation caused by the contraction and expansion effects could increase electronic noise or even destroy the electronic components. The Frisch grid inefficiency might affect the waveform of the anode signal, directly resulting in an impact on energy resolution.

After studies in XEMIS1, 500 LPI copper micro-mesh was selected as a Frisch grid in XEMIS2. Besides, to attain electron transparency close to 100%, a strong electric field should be applied in the gap, at least a factor 5 to 10 times higher to the value of the electric drift field depending on the type of Frisch grid.

2.2.3 Detector description

The XEMIS2 Compton camera is currently under construction. The detector is based on the single-phase liquid xenon TPC technique, whose transverse and longitudinal cutout views are illustrated in Figure 2.16. The detector was designed as a monolithic and high-sensitivity cylindrical camera containing around 200 kg of LXe, whose geometrical acceptance for small animals is always superior to 50% (up to 75% at the center) within the whole field of view (FOV).



Fig. 2.16 Design of the XEMIS2 camera (TPC is inside the cryostat), where (a) presents a longitudinal section and (b) shows a transverse cut view.

XEMIS2 TPC The active region of XEMIS2 consists of two identical cylindrical TPCs sharing a common central cathode. The whole detector is traversed from the center by a hollow tube used for small-animal holding during the imaging. Each TPC is of 7 cm of inner radius, 19 cm of outer radius, and 12 cm of drift length. The schematic diagram of an upper half TPC, i.e., one-quarter of the active zone, is illustrated in Figure 2.17. For VUV scintillation light detection, in a first phase of the project the active volume is peripherally equipped with 64 PMTs, while for future researches, an entire lateral surface cover with 380 PMTs will be realized and installed. Two segmented anodes are placed in both end-sides of the TPC, symmetric to the cathode, with pixel size of $3.1 \times 3.1 \text{ mm}^2$. A micro-mesh is located at $120 \mu m$ above the anode serving as a Frisch grid. The charges produced by ionizing radiations are drifted under the electric field and then collected by the anode. A more detailed description of light and charge collection systems is given in the following section.



Fig. 2.17 Simplified geometry of XEMIS2. Only half of the right TPC with respect to the cathode is represented.

2.2.3.1 Light detection system

Although XEMIS2 is not intended to operate as a scintillation calorimeter, the light collection has been optimized as much as possible without affecting the ionization signal collection. Compared with the crystal scintillator based PET system, in the liquid xenon based XEMIS2 camera, there is a big difference in light detection. In the traditional crystal detectors, the scintillation photons are reflected and oriented towards a readout PMT. In contrast, due to the monolithic design of XEMIS2, the emission and propagation of VUV scintillation light generated in the XEMIS2 detector are isotropic in 4π . Therefore, to ensure that the produced light can be collected, the active zone is covered by a set of PMTs, entirely immersed in the liquid xenon during the detector operations.

PMTs In a first phase of the project, XEMIS2 will be equipped with 64 PMTs to detect scintillation light for a source activity of 20 kBq. These photodetectors are the VUV-sensitive Hamamatsu R7600-06 MOD-ASSY PMTs (Figure 2.19), developed especially for working at liquid xenon temperature. The active area of this PMT consists of a bi-alkaline photocathode of 18 x 18 mm², behind a quartz window of 24 x 24 mm², so the dead zone of the PMT at each

side is about 8.8 mm. The PMT displays an excellent UV photon sensitivity, whose quantum efficiency is about 30% at 175 nm. The gain of PMT can reach about 10⁶ under a high voltage alimentation of 750 V.



Fig. 2.18 Mechanical support for the 380 PMTs



Fig. 2.19 Hamamatsu PMTs used in XEMIS2

Mounting bracket A stainless-steel support (Figure 2.18) is utilized for PMTs assembly, placed in the peripheral region at around 31 mm from the active zone. As many as 380 PMTs can be mounted to realize a full coverage of the active zone, which will be accomplished in future phase of the project to handle a bigger activity up to 200 kBq. The separation structures add a distance of 3 mm between each PMT position, resulting in a little additional dead zone between two PMTs, with a total dead distance of about 20.6 mm.

Shielding grid A shielding copper mesh is set at 7 mm in front of the PMTs surface; in other words, 15 mm outside the electric field rings, to protect PMTs from the impact of the high voltage applied to the field rings and cathode. The pitch size is 6.3 mm, providing optical transparency of 89%.

Conclusion In XEMIS2, the scintillation light is mainly employed as a trigger signal for initial interaction time t_0 measurement, providing the z-position. The PMTs all around the active region allow for light collection and measurement. However, due to the strong electric field of 2 kV/cm used to collect charge carriers, for more than 100 keV gamma-ray used in nuclear medicine, the scintillation yield reduced to less than 50% with respect to zero electric field applied. Other factors used for electrons collection also affect the light collection efficiency, such as the field rings placed around the active zone hindering the light propagation to PMTs through reflection and diffusion. As the number of measured photoelectrons is small, the scintillation signal cannot be used for spectroscopy to optimize the energy resolution by combining it to the charge measurement. Nevertheless, light detection has another important application that

consists in a pre-localization of the interaction position which permits to reduce the occupancy rate.

2.2.3.2 Optimized charge collection system

The charge collection system installed in XEMIS2 TPC includes a central shared cathode, two symmetric segmented anodes with micromeshes above, and a series of field shaping rings. The associated data acquisition electronics for ionization signal measurement is described in the next section.

Cathode The cathode used in XEMIS2 is an annular electrode made of stainless steel with an inner radius of 76.5 mm, an outer radius of 203.5 mm, and a thickness of 2 mm. The frontal view of the cathode with the stainless steel field shaping rings is shown in Figure 2.20. The central hole allows the aluminum tube traversing, in which the small animal is held during the imaging process. Eliminating the cross-influence of scintillation detection between two back-to-back TPCs, the cathode is entirely opaque for the UV photons and placed in the middle of the detector as a separation plane. A high voltage of 25 kV will be applied at the cathode during the standard operating conditions to realize a 2 kV/cm drift electric field.



Fig. 2.20 Front view of the cathode with the stainless steel field shaping rings.

Field rings In XEMIS2, the electric field uniformity in the drift volume is ensured by two sets of field-shaping rings located respectively on the inner and the outer sides of each TPC, between the anode and the cathode. The internal one is a set of micro copper electrodes, each of 2 mm wide and 0.35 mm thick, printed directly in a Kapon insulation layer, patched on the wall of the hollow middle tube. A partial zoom view is illustrated in Figure 2.17, where every two copper electrodes keep a constant gap of 1 mm. The external set comprises 21 stainless-steel field rings immersed in the liquid xenon for shaping a uniform electric field, whose potential is driven from the cathode to the first field ring through a resistive divider chain. The last resistor of the divider chain is connected to the ground via a 500 M Ω resistor, whereas the first one is connected to the high-voltage electrode. After a detailed simulation study, the gap of those field rings above the PMT has been expanded from 5 mm to 10 mm to optimize the light collection, while the electric field uniform should not be perturbed.

Charge collecting electrode In XEMIS2, two identical electrodes are placed opposite to the central cathode at the end-side of each TPC to collect the drifting electrons. Based on the MIMELI (MIcro-MEsh for dense Liquid Ionization chamber) technique, each charge collecting electrode includes a segmented anode and a micro-mesh as a Frisch grid.

• Segmented anode - The anode is composed of more than 10,000 pixels of $3.1 \text{mm} \times 3.1 \text{ mm}$, equipped with micro-pillars of 130 μ m. It is a four-layer ceramic circuit made of ROGERS RO4350B, where the pixels, the strips between pixels, and the pillars are made of copper. The presence of the tracks as well as the micro-pads can be observed in Figure 2.21a. On the back of the anode, using 60-point connectors allow the front-end electronics to be connected (Figure 2.21b). The golden color of the circuit comes from the passivation Ni-Au layer deposited at the surface of copper.



(a) Frontal view



(b) Bottom view

Fig. 2.21 The segmented anode employed in XEMIS2. The small squares at the center of the front view anode represent the pixels, whereas, in the bottom part, the connectors of front-end electronics are ready to bond.

• Frisch grid - A 500LPI copper micro-mesh of 5 μ m thick is placed above the segmented anode at a distance of approximately 125 μ m (gap obtained with the 130 μ m pillars welded) and applied a voltage of 300 V under at operation condition, serving as the Frisch grid. Its purpose is of obtaining a readable ionization signal whose amplitude is proportional to the number of collected electrons and independent of the interaction position along the drift direction. To maintain the flatness and the distance with the anode, the micro-mesh is stretched and fixed on a stainless-steel frame for generating a uniform electric field, as shown in Figure 2.22.



Fig. 2.22 The stainless-steel frame of the Frisch grid used in XEMIS2.

Conclusion Ionization signal provides information about the deposited energy and the position of each interaction vertex. The accurate measurement of charge carriers plays a fundamental role in Compton imaging, enabling the possibility of Compton scattering sequence discrimination and reconstruction. The collection of charge carriers is optimized in XEMIS2. A strong drift electric field of 2 kV/cm is applied uniformly in the active volume via the field-shaping rings. Drifting electrons are directly collected on the segmented anode in our single-phase LXe-TPC, without a gaseous phase electroluminescence amplification. Using a copper micro-mesh placed between two electrodes of the TPC allows the anode to shield the drifting motion of electrons, serving as a Frisch grid. The MIMELI technique has optimized the induced current signal on the charge collecting electrode via the minimization of Frisch grid inefficiency. Besides, an ultra-low noise high capacity signal readout system has been developed, which will be discussed in the next section. Compared with the highly expensive PMT/SiPM, the direct ionization signal measurement also has a tremendous economic advantage for medical imaging applications.

2.3 Compact and safe cryogenic facility

One complexity of the whole detector is due to the use of liquid xenon. The operation condition of liquid xenon is 168 K at 1.2 bar abs with a range of 6.7 K under this pressure. Like all liquid noble gas detectors, the cryogenic facility is indispensable to control the stable detection medium for proper operations. Moreover, since XEMIS2 was conceived to be installed at CIMA (Nantes Hotel Dieu hospital) for preclinical research, its cryogenic infrastructure has to comply with the criteria of a medical imaging facility. Compactness and safety are two crucial characteristics that should be considered additionally. As shown in Figure 2.23, the XEMIS2 cryogenic facility consists of three sub-systems: the TPC container (Cryostat), the Recovery and Storage of Xenon (ReStoX), and the purification system. This section gives an overview of the cryogenic facility of XEMIS2 from description to performance.



Fig. 2.23 Overview of the XEMIS2 cryogenics facility. From left to right: XEMIS2 cryostat, ReStoX and purification system.

2.3.1 System description

Detector Cryostat To maintain the low temperature of liquid during the whole data acquisition period, the XEMIS2 detector is enclosed in a double-layer cylindrical cryostat made of stainless steel. The inner vessel filled with liquid xenon, possessed a diameter of 60 cm and a length of 5.4 cm. It allows the TPC to be entirely immersed during operations in about 200 kg of liquid xenon. The external envelope served as a safety vacuum enclosure to maintain thermal insulation, its dimension is 80 cm in diameter, 87.5 cm in length, and 5 mm in thickness. A vacuum level of 10⁻⁶ bar between two walls is continuously maintained under normal operating conditions, minimizing the heat transfer into the TPC resulting from the different temperatures between the liquid xenon and outer circumstance. To reduce the radiative heat transfer on the low-temperature part of the cryostat, the inner vessel is covered by multiple layers of aluminized Mylar foil (MLI). The reduction of heat load economizes in return the required cooling power.

Besides, a *specific inner central tube* is designed for small-animal holding. XEMIS2 is dedicated to in-vivo imaging of the small animal. A hollow aluminum tube measuring 100 mm in diameter and 2.5 mm in thickness is built, placed at the center of the camera to hold the small animal during the exam. The whole tube is wrapped in vacuum insulation of 7.5 cm thick separated from the stainless-steel inner vessel. This design aims to maintain the animal at room temperature while insulating the internal cold of the cryostat.

ReStoX The ReStoX cryogenic sub-system of XEMIS2 is connected to the cryostat through two pipes providing fast recovery and safe storage of liquid xenon. It is designed as a double-vessel cylinder tank to store and control liquid xenon (172 K at 1.5 bar abs). The inner vessel

is served as a xenon holder, with 20 cm of diameter and 1 m length, capable of holding 280 L xenon in all states. The external container works as a safety vacuum enclosure to maintain thermal insulation possessing a volume of 300 L. Both vessels are made of stainless steel, each with a thickness of 2 cm and whose total weight is up to 440 kg. The vacuum layer between them is filled with perlite insulation of 25 cm thick. Besides, there are two heat exchangers (E1 & E2) equipped on top of the inner vessel. E1 is a massive aluminum condenser powered by a continuous circulation of liquid nitrogen, served as a cooling system. The requisite cooling power is regulated by the mass flow of liquid nitrogen, whose nominal temperature is 170 K. E2 is a coaxial tube set for inlet/outlet xenon enthalpy saving.



Fig. 2.24 Scheme of ReStoX

Purification System As mentioned in the previous section, liquid xenon purity has a critical impact factor on detector performances. The electronegative impurities, such as N2 or O2, could capture the drifting electrons before arriving at the anode, decreasing the detector signal to noise ratio. Furthermore, traces of moisture inside the detector, as the main cause, could absorb the UV scintillation light. Therefore, a high liquid purity level is required to eliminate the impurities impact on both ionization and scintillation signals detection. In XEMIS2, the xenon is continuously circulated through a closed-loop purification system connected with the cryostat and ReStoX. It comprises two parallel purification branches, each consisting of a rare-gas getter and an oil-free membrane pump. The high-temperature SAES MonoTorr Phase II getter (PS4-MT3-R/N) [157] used in XEMIS2 is based on zirconium functioning only in the gas state. So, the xenon is continuously evaporated, purified, and condensed in the circulation loop. The pressure loss throughout the whole circulation is supplied by the pump installed in series, whose maximum circulation rate is 50 NL/min, to maintain the constant pressure. The purification process continues even during the storage for filling up the detector cryostat at any moment with ultra-pure liquid xenon (< 1 ppb O_2).

2.3.2 Commissioning: operations and performances

As mentioned above, the whole XEMIS2 camera was designed to be installed at the CIMA for pre-clinical researches. The primary concern is the security of the use of liquid xenon in an hospital environment. A complete commissioning has been carried on to demonstrate the system security under extreme conditions (except for force majeure conditions such as earthquakes). A

set of tests has been done, including the ones on the mechanical and cryogenic parts. Limited by the section length, the experiments concerning thermal losses and system warm-up are not addressed in the following.

1. *Leak tests* Due to safety concerns, leak tests (Figure 2.25) were done before other manipulations to ensure the detector cryostat tightness under vacuum and pressure (2.4 bar abs) conditions. Pfeiffer Vacuum HLT 260 QualyTest helium leak detector was used in tests to detect and locate small leaks, where an inside mass spectrometer detects the leak rate. In vacuum mode, the part to be tested was connected to the helium leak detector, while the outer surface was sprayed with a localized stream of helium tracer gas. For pressurized components, the test was done in sniffer mode. For both internal and external enclosures of the cryostat, the leakage rate was measured to be below $4.6 \ 10^{-7}$ mbar.l/s, which is lower than the threshold of 10^{-6} mbar.l/s, showing a satisfactory airtightness.



Fig. 2.25 Photograph of the XEMIS2 leak test performed in the Subatech laboratory.

2. Evacuation After testing the tightness of the container, the inner and outer containers were evacuated in sequence. The vacuum of the inner vessel can reduce the contamination of xenon with air during the following injection. The external vacuum enclosure creates thermal insulation to decrease the heat transfer into the detector, thus, reducing the required cooling power. Because of the large volume of the entire system, two primary vacuum pumps were first used to evacuate the container to reduce the pressure to 10^{-2} bar. The pressure was then reduced to 10^{-6} mbar owing to two turbo-pumps parallel to the primary pump. During the regular operation, only one primary pump and one turbo-pump connected to the external enclosure run continuously to maintain the vacuum level.

3. Pre-cooling and filling Once the vacuum level was achieved, we needed to fill the cryostat with liquid xenon from ReStoX. Two systems were directly connected through two stainless-steel

pipes where an Ultra High Vacuum (UHV) manual valve controls the exchange between inner vessels. Xenon injected automatically into the internal container when the valve was opened. Nevertheless, to ensure the cryostat pressure always below the security value of 2 bars, the continuous filling process could not be carried out until the whole system was entirely cooled. A precooling process needed to be achieved by continuously injecting the cooled gas xenon to cool down the entire stainless steel well. A pressure balance of 1.5 bar established about twenty minutes after the open of the valve. The temperature of the whole cryostat then reduced progressively from bottom to top during the injection. The ending point of pre-cooling arrived when a non-negligible mass of xenon was transferred from ReStoX to the cryostat, signifying the start of the fulling process. The evolution of temperature and ReStoX mass is represented in Figure 2.26. The whole procedure took about 30 h, divided into 21 h for pre-cooling and 8 h for liquid xenon filling. The final steady-state, normal operation condition, was attained when the cryostat pressure was reduced to 1.2 bars, whereas that of ReStoX remained at 1.5 bars. The above procedures are illustrated in Figure 2.27.



(a) Thermocouples posionning(b) Temperatures evolutionFig. 2.26 Evolution of temperature and ReStoX mass during pre-cooling and filling regimes.

4. *Recovery* The recovery step is a critical security procedure needed in case of specific issues that might require an urgent recuperation of the liquid xenon. Considering that the camera will operate in the hospital, to ensure safety under any extreme conditions (except for force majeure conditions such as earthquakes), XEMIS2 has been conceived as a passive gravity assisted rehabilitation system. The experimental results have been published by our cryogenic expert L. VIRONE in [158]. The setup takes advantage of the pressure difference and the height gap to realize the passive recovery of liquid xenon from the cryostat to ReStoX. More specifically, we only need to disconnect the pumps, by-passing the purification loop, so that a pressure balance is reestablished between ReStoX and the cryostat, pushing liquid xenon into the recovery tank.



(a) Pre-cooling and Liquefaction(b)Fig. 2.27 Diagram of the facility in different regimes.

(b) Normal regime

Under emergency circumstances, e.g., power outage, all active systems are stopped accidentally, which exposes XEMIS2 to a dangerous situation. Meanwhile, the pumps strike in the purification loop results in an automatic recovery within 10 minutes at a mass flow rate close to 1 ton. h^{-1} , with no need for human intervention.

Conclusion This commissioning demonstrates the high efficiency performance of the whole cryogenic system of XEMIS2, especially the safety characteristic. At present, the whole cryogenic facility has been verified and installed in the manipulating room of CIMA (Figure 2.28).



Fig. 2.28 General view of the XEMIS2 installed at CIMA (Nantes Hotel Dieu hospital): front) XEMIS2 cryostat and behind) Recovery and Storage of Xenon (ReStoX).

2.4 Conclusions Chapter 2

In this chapter, we introduced an innovative Compton camera for small animal imaging, XEMIS2. It is part of the XEMIS project, which is devoted to developing the LXeTPC-based Compton telescope to realize ultra-low activity medical imaging by using the 3-gamma imaging technique. This R&D project consists of three main phases: the prototype XEMIS1 that has been realized and completed; the XEMIS2 that is the subject of what presented in this thesis; and a total-body imaging/hadrontherapy-monitoring camera XEMIS-HD, which is currently under investigation.

In the first part of this chapter, the main physical properties and ionizing radiation characteristics of liquid xenon as a detection medium have been discussed. The advantages of the liquid xenon as a detection medium (its high density, large atomic number, etc.) have been presented. The importance of the possibility to simultaneously measure the scintillation and ionization signals has been underlined. The xenon fast light response makes it also attractive for timing applications. Moreover, the liquid phase renders it suitable for building scalable monolithic detectors with a uniform high-sensitivity response and negligible dead zone. Given its excellent radiation response, the emerging application of liquid xenon in nuclear medicine has proliferated in recent decades.

In the second section, we first discussed the basic operation principle of a time projection chamber (TPC). It operates primarily with ionization signals combining them with the scintillation triggering information, it provides a three-dimensional (3D) position reconstruction, energy measurement, and multi-hit sequence identification. The liquid xenon time projection chamber (LXeTPC) is a suitable candidate to build a Compton telescope for nuclear medical imaging applications. Precisely, a "TOF-like" PET performance could be achieved by applying the innovative 3-gamma imaging modality, measuring with good precision the intersection of the LOR and the Compton cone to realize a direct 3D location of the radiotracer. The processes that need to be accounted for when conceiving a LXeTPC have been discussed in Section 2.2.

XEMIS2 camera has been presented in Section 2.2.3: it consists of two identical cylindrical TPCs sharing a common central cathode, traversed in the center by a hollow tube used for small-animal holding during the imaging. 64 PMTs are installed in the peripheral region of the TPC and are used for VUV scintillation light detection. The ionized charges produced after ionizing radiation are drifted under the electric field. Two segmented anodes are placed in both end-sides of the TPC for charge collection. They are equipped with a Frisch grid made of copper micro-mesh. The charge collection electrode uses the MIMELI technique to optimize the induced signal. Besides, since XEMIS2 was conceived for preclinical research, developing a safe and compact cryogenic facility, the Recovery and Storage of Xenon (ReStoX), has been accomplished, detailed in Section 2.3.

Specific Electronics Development for High-Performance Data Acquisition

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Dedicated to low-activity small-animal imaging, the XEMIS2 Compton camera is developed to demonstrate the advantage of liquid xenon as a detection medium for 3-gamma imaging. The first phase of XEMIS2 consists in obtaining a small animal image in 20 minutes via the injection of a source whose activity is of 20 kBq. As explained in Chapter 2, the effective-ness of LXeTPC allows the feasibility of the Compton imaging, i.e., the Compton sequence

reconstruction. The required information about the deposited energy and 3D position of each interaction needs to be precisely extracted from the ionization signal generated in the detector via the readout electronics. For the sake of continuous readout with negligible dead-time during 20 minutes, a specific high-performance data acquisition system (DAQ) was developed and tested during this thesis.

The purpose of this chapter is to provide an explicit description of the new DAQ electronics chain. We will first discuss the design criteria of the signal measurement of a TPC dedicated to medical imaging focusing on the needed requirements and general architecture. A brief review of the charge collection structure, MIMELI, and the front-end electronic, IDeF-x HD-LXe, will also be given in this part. In the second part, the operation principle related to the new-developed signal extraction ASIC (Application-Specific Integrated Circui) will be presented. Its performance was preliminarily examined by the bench test with the prototype chip. A complete prototype of the entire acquisition chain was also built and integrated into the XEMIS1 detector for a complete performance test. The experimental results of the DAQ calibration and optimization will be shown in the next chapter. The end of the chapter is devoted to the latest advancements of the DAQ development for XEMIS2.

3.1 Small animal imaging oriented specifications

Concerning the precise charge measurement, an innovative segmented readout structure geometry, MIMELI, has been proposed. Additionally, an ultra-low noise front-end electronic named IDeF-X HD-LXe has been adapted for the LXe operation condition and successfully tested in the XEMIS1 prototype. An electronic noise of the order of 85 ± 5 electrons [159], under an electric field of 1 kV/cm, has been achieved thanks to the dedicated electronic devices. In XEMIS2, to achieve expected image quality with low-activity, extending the same/better performance from 64 pixels to more than 20,000 pixels under a higher electric field of 2 kV/cm has several technical hurdles to overcome. Besides, several critical issues should be considered in the ionization signal measurement system like energy and position resolutions optimization, event efficiency maximization, and high-frequency signals readout with processable data flow due to low threshold triggering. Moreover, a considerable quantity of data caused by the ultra-low threshold and self-triggering circuit needs to be managed.

3.1.1 Brief overview of ionization signal readout in XEMIS

In the section, we will give an introduction to the MIMELI technique and IDeF-X front-end electronics, which are particularly strategic for the development of the XEMIS2 project. The

prototype has been tested in XEMIS1 whose experimental results will be reviewed at the end of the section.

3.1.1.1 Innovative charge collection structure: MIMELI

The segmented anode implemented in the ionization chamber for interaction position determination results in a charge sharing effect. It is hard to amplify the charge signal in liquid xenon. The presence of a strong electric field gradient over a small part of their trajectories hardly generates parasitic phenomena such as electroluminescence or direct multiplication by an avalanche. The accuracy of the measurement of low induced current, therefore, influences both position and energy resolutions of the detector.

The innovative MIMELI (Micronesh-Mish for closed liquid ionization chambers) technology explores the geometry of the induction gap a new perspective applying a micro-structure to get a homogeneous induced current over the pixelated anode. This invention allows to increase the electrostatic screening efficiency of the "Frisch grid" located on the anode. Moreover, the technique also minimizes the intensity of the indirect influence currents, which are usually present on certain segmented elements of the anode and do not directly collect moving electrons. The low currents induced by the drift of charge carriers under the electric field inside liquid xenon could thus be precisely measured. This provides the possibility to build a segmented ionization chamber incredibly efficient for measuring both energy and position. This invention is particularly strategic for the development of the XEMIS2 LXe Compton camera for medical imaging.

The MIMELI-1 anode is a multilayer ceramic circuit (thick film technology) whose pixels, tracks and pillars are made of copper. A picture of the prototype from which it is possible to observe the presence of the tracks between the pixels as well as the presence of the micro-pillars is presented in Figure 3.1. The golden color of the circuit comes from the passivation Ni-Au layer, which was deposited at the copper surface. The test prototype used in XEMIS1 contains 64 patterns divided into 8 x 8 pixels/micro-pillars. The pattern is defined around a pitch of 3.1 mm, the micro-pillars of 130 μ m high and 130 μ m wide, the tracks connecting the micro-pillars in the x and y directions are 80 μ m wide. The isolation between the pixels and the tracks is 80 μ m.

A grid was then mounted using a frame around the 64 patterns. Several types of grids have been considered whose parameters are summarized in the right table of Figure 3.2. During the assembly, the grid does not touch all the conductive pads, its parallelism being very difficult to guarantee given the surfaces involved. In operation-mode, when the grid is polarized, the electrostatic attraction force exerted between the grids and each pixel compensates for the geometric imperfections so that all the conductive pads of thickness $130 \pm 5 \ \mu m$ come into



Fig. 3.1 Picture of the MIMELI anode prototype: (a) the entire anode, (b) the zoom picture in which the micro-pillars and conductive tracks could be observed, (c) Picture taken using an electron microscope.

		Grid	Tech	Pitch	Thickness	Bar thickness
		500 LPI	MM	50.8 µm	5 µm	12 µm
		200 LPI	MM	127 µm	5 µm	24 µm
Metallic Woven	Micro-mesh	100 LPI	MW	254 µm	50 µm	25 µm
(MW)	(MM)	70 LPI	MM	362 µm	5 µm	18.5 µm

Fig. 3.2 Parameters of different grids.

contact with the micro-grid. With this technology, the applied grids should be elastic and able to be deformed under the action of the electric field in order to compensate for the parallelism defects. The Metallic Woven (MW) grids formed by steel wires are difficult to use due to lack of elasticity. In contrast, the copper micro-meshes (MM) produced by electroplating are good candidates. This type of grid is also used with gas detectors with microstructures of the Micromegas type.

The constitution of MIMELI anode and 500LPI micro-mesh grids with a gap of 125 μ m is chosen to be used as charge collecting electrodes in the XEMIS2 TPC. To properly understand the charge collecting mechanism, a simulation study on the electric field has been done under the new electrode geometry. The simulation results¹ are shown in Figure 3.3. These simulations show that only 1% of the induced charge is generated on the pixels by the electronic cloud before it passes through the grid. The efficiency of the Frisch grid is therefore 99% in the case of MIMELIequipped with a 500 LPI grid. The prototype has also been tested in XEMIS1. The induced current is read out by the ultra-low noise front-end electronics IDeF-X. The experimental result will be discussed at the end of the section.

¹This simulation work was realized by Jean Pierre Cussonneau.



Fig. 3.3 Iso-potential for real electric field (left) and weighted potential (right).

3.1.1.2 Analog front-end electronic: IDeF-X HD-LXe

IDeF-X HD-LXe (Imaging Detector Front-end for X rays High Dynamic for LXe) is a lownoise, low-power front-end ASIC adapted for LXe operation conditions. It is composed of 32 independent analogue electronic channels to read out the induced current generated on the pixels. The analog circuit is inherited from the IDeF-X HD [160]. Each channel includes a charge sensitive preamplifier (CSA), a variable gain stage, a Pole-Zero Cancellation (PZC) stage, and a shaper. The general architecture of one channel is schematized in Figure 3.4.



Fig. 3.4 Schematic of IDeF-X HD-LXe ASIC.

It is designed to be connected to the anode of the detector. Each pixel is directly connected to one readout electronic channel. The CSA integrates the induced current at its input into a voltage step by an integration capacitance C_f . The active reset system with PZC stage is is based on PMOS feedback transistor considering that the anode is polarized at the channel input. The PCZ is equivalent to a several G Ω resistor for baseline restoration that can compensate the pulse long duration undershoots by preventing pile-up and saturation of closely consecutive events [161]. Moreover, the circuit provides a dynamic range of 50–200 mV/fC through a variable gain stage. The signal conditioning circuit is completed by the RC^2 second-order low pass filter. A variable shaping time (0.73-10.73 μ s) is also adjustable to adapt the different induced signals generated on the anode. In addition, there is an injection capacitance of 50 fF, C_{inj} , integrated to each channel for circuit tests and calibrations.

The main characteristics of the IDeF-X HD-LXe are summarized in Table 3.1. To fit XEMIS2 requirements, the chips were configured with a peaking time value of 1.39 μ s and a gain value fixed to 200 mV/fC. The output pulse waveform is shown in Figure 3.5 (right). In addition, to directly read out the induced current generated on the anode, the IDeF-X ASIC is bonded on a printed circuit board (PCB). A standard 32 channels mini edge card connector is employed to couple perpendicularly the IDeF-X card to the anode backplane. The IDeF-X cards are designed to be placed in the inner vessel of XEMIS2, which will be totally immersed in LXe during operation. The various materials composing the PCB circuit are the same as those used for the anode manufacturing to comply with the pressure-temperature requirement. Different versions of PCB cards (Figure 3.5 left) have been developed and tested for improving electric routing and reducing the card size to economize the volume of LXe required.

Parameter	Value
Number of channels	32
Technology	$0.35 \ \mu m CMOS$
Supply voltage	3.3 V
C_{f}	50 fF
Power consumption	27 mV (800 μ W/channels)
Gain	50, 100, 150, 200 mV/fC
Dynamic range	1.3 MeV for LXe at 200 mV/fC
Peak time	0.73 to 10.73 μ s (16 values)
ENC (RMS)	150 e^- (at room temperature) [160]
Leakage current tolerance	up to 4 nA

 Table 3.1 Main properties of the IDeF-X HD-LXe chip.

3.1.1.3 Performance in XEMIS1

The MIMELI prototype and IDeF-X ASIC have been tested in XEMIS1 at the beginning of this thesis work. The XEMIS1 experimental set-up was then updated for the research and development of the new acquisition chain dedicated to XEMIS2. The configuration of the facility is described in Section 3.4.1.1. Here, only a brief overview of the experimental results about charge measurements is presented.

During these tests, the entire MIMELI prototype is immersed in ultra-pure liquid xenon with less than 1 ppb of residual impurities. The drift electric field applied in the TPC was 1 kV/cm. The front-end electronics IDeF-X was operating in the vacuum and its temperature was controlled



Fig. 3.5 Picture of IDeF-X HD-LXe card (left). Output pulse waveform with a peak time of 1.39µs (right).

through a dedicated stainless-steel cooling system. The 64 IDeF-X output analog signals are transmitted from the vacuum vessel into the air via 64 standard wires and sent to the acquisition board where they are digitized at a sampling rate of 12.5 MHz by an external 12-bit FADC. The experimental results² of the pulse shape and the electronic transparency measurements of 511 keV photoelectric events are shown in Figure 3.6. The distortions of the induction signal



Fig. 3.6 Amplitude of the induction signals (left) and electronic transparency (right) measured at the pixel level of the read anode for different Frish grids, and for different induction gap heights. With MIMELI, the induction gap is 130 μ m high.

observed at the level of the pixels are represented in the left of Figure 3.6. An "ideal" signal is also represented which is the expected signal generated by an electronic cloud with a perfect screening of the Frisch grid. The effect of the geometry of MIMELI combined with the 500 LPI grid allows to measure an almost perfect induction signal. Meanwhile, in order to get a 100% electron transparency, a ratio of 15 between the electric field applied in the gap and drift area

²The experimental work was done by Eric Morteau and Lucia Gallego Manzano (during her postdoc at SUBATECH).

needed to be applied. In addition, an electronic noise of the order of 85 ± 5 electrons [159] has been achieved thanks to the dedicated electronic devices, which is well suited to accurately measure small charges.

3.1.2 Requirements for new data acquisition system

Unlike in XEMIS1, the scintillation light will no longer be used to trigger the ionization charges DAQ in XEMIS2. Conventionally, for each event, the whole data acquisition system needs to wait for a detector drift length, to collect all possible ionization signals in the sensitive volume after a scintillation light trigger signal. For example in XEMIS2, under the electric field of 2 kV/cm, the signal takes about 52 μ s to travel a drift distance of 12 cm. Therefore, the non negligible drift time of charge carriers in LXe limits the acquisition rate, and thus the detection efficiency. Despite not being an issue for experiments looking for rare event interactions as for example Dark Matter detection, it might be an issue for nuclear medicine where the radiation activity is several orders of magnitude higher. The first phase of XEMIS2 is conceived to achieve a small animal imaging with a source activity of 20 kBq corresponding to an event every 50 μ s on average; while in a future phase the source will be increased to 200 kBq (5 μ s per event). For this reason, a novel signals acquisition system needs to be developed to prevent the event loss due to the dead time resulting from the electron drift process.

To optimize the event efficiency with a negligible dead time (of order of 52 μ s), we chose a low threshold self-triggered data acquisition mode. Instead of using the scintillation light signal to trigger the ionization signals readout, two synchronized self-trigger readout systems were developed to measure both signals, respectively. The basic concept is schematized in Figure 3.7. The system records independently the currents induced in the anode and the PMTs signals generated by prompt light emission. The self-triggering systems can record signals with almost no dead time, solving the limitation due to the detection of high flux radiations. The drift time of charge carriers is then obtained by matching both signals (scintillation and ionization) offline when analyzing data. In this way, the recorded signals of the two systems could be realigned to find the reference time of each event. Moreover, an accurate synchronization between both DAQ chains is achieved through offline corrections.

Besides, in order to ensure the detector performance several additional requirements should be considered in the charge readout electronics due to the huge number of pixels. The specifically crucial issue for Compton reconstruction is the accurate energy and position measurement of the small signals due to the charge sharing effects. Therefore, ultra-low electronic noise is required in the first place to measure small charges collected by neighboring pixels. Moreover,



Fig. 3.7 Basic concept of the event builder in XEMIS2.

the self-trigger approach needs to use thresholds to enable acting over a certain noise level for pulse discrimination. This leads to considerable degradation of signal detection and an inevitable rise of the threshold level. To reach a sufficient signal over noise ratio, the trigger threshold has to be set to about 3 times the standard deviation of the electronic noise. For small animal imaging of 20 kBq activity, an adverse effect of a low threshold is the rapid increase in the data flow, dominated by the electronic noise. The conventional approach used in XEMIS1 that continuously samples the analog signal is no more adaptable for XEMIS2 due to the massive number of channels used for ionization signal collection. The XEMIS2 DAQ has to deal with a huge data flow due to this low threshold triggering. Based on these reasons, a new ultra-low noise self-trigger electronic circuit named XTRACT (Xenon TPC Readout for extrAction of Charge and Time) has been developed for ionization signal data readout of XEMIS2. In light of the massive number of pixels, the idea of signal information extraction has been brought out to reduce the readout data flow. The system is designed to control the data volume at an accessible level by extracting only the necessary information (amplitude and time) for each signal.

An expected data acquisition strategy is schematized in Figure 3.8. The fast flashing light is first collected by the UV-sensitive PMT and converted into an electronic signal. Then it is shaped and sent to the leading edge discriminator for the self-triggering process. Only the information related to time of the leading edge and TOT (time-over-threshold) time are stored. On the other hand, the ionization charge carriers are read out by MIMELI and IDeF-X, generating an analog-shaped signal. The output analog signal of IDeF-X then passes through a Constant Fraction Discrimination (CFD) module being part of the XTRACT ASIC chip to achieve self-triggering performance. Meanwhile, for each fired pixel, instead of sampling the entire analog signal, only the time, amplitude and channel address information corresponding to the CFD trigger moment are extracted in order to reduce the data flow. For the purpose of managing XTRACT output

data flow, a processing unit (PU) card is also utilized, working at the same time as an Analog-to-Digital Converter (ADC) module. Two sets of data are collected in the acquisition FPGA to realize data storage and preliminary online data processing. The new acquisition chain requires a specific development of the following electronics as XSRETOT (XEMIS Scintillation Readout for Extraction of Time Over Threshold), XTRACT (Xenon TPC Readout for extrAction of Charge and Time), XPU (XEMIS processing unit) and XDC (XEMIS Data concentrator), which will be described in the following chapter.



Fig. 3.8 Schematic of the data acquisition mode applied in XEMIS2.

3.2 Characterization of a new ASIC for signal extraction: XTRACT

As part of the XEMIS2 project, the XTRACT circuit was developed in collaboration between the SUBATECH laboratory and the MICRHAU pole³. In order to reconstruct the position of the interactions in the TPC in three dimensions, it is important to know precisely the deposited energy and the occured time of of the interaction. The role of the XTRACT ASIC is to extract these two pieces of information from the signals coming from the front-end electronics (IDeF-X HD LXe). It thus offers the possibility of considerably reducing the quantity of data leaving the TPC by storing only the essential data. In association with the rest of the acquisition chain, this ASIC could also reduce the number of connections traversing the chamber and limit the dead time linked to the extracted data reading.

³Pôle de MICroelectronique RHone AUvergne

Global architecture The XTRACT is a multi-channel(x32), low-power ASIC with analog and digital common blocks. Each channel includes a Constant Fraction Discrimination (CFD) block which performs the self-triggering function with a limited time walk error and an improved timing resolution [162]. It is designed to operate at a temperature of approximately -80 °C. The global architecture is schematized in Figure 3.9. It consists of several operational blocks: a CFD



Fig. 3.9 Illustration of the XTRACT architecture.

block per channel, a common ramp generator for dating events (time/amplitude conversion), a dual-port analog memory for events analog recording (amplitude and time), a binary-tree asynchronous multiplexer (MUX) for analog signals, a digital control block, and a I2C slave for ASIC configuration.

3.2.1 Principle of signal extraction

One of the main feature of this circuit is to send a trigger signal when the analog input signal exceeds the preset threshold. Aiming towards the optimization of the amplitude and time resolution of the ionization signals, a CFD type of architecture has been adopted to limit the influence of the time walk. Based on the CFD block, when the analog input signal exceeds the programmed threshold, the CFD block is used to send a trigger signal. The architecture of one channel is illustrated in Figure 3.10.

Constant Fraction Discrimination The CFD operation is based on a zero-crossing (ZC) discrimination validated by a threshold (THD) discrimination. The zero-crossing information is obtained by subtracting a fraction of the input signal to its delayed copy. It has been demonstrated that the trigger timing delivered by a CFD is theoretically independent of the amplitude and the rise time of the input signal [163], and that the best timing performance is obtained



Fig. 3.10 Illustration of the architecture of one channel of XTRACT

when the zero-crossing is set on the maximum slope of the input signal [164]. The operation principle of the CFD is illustrated in Figure 3.11.



Fig. 3.11 Illustration of the CFD operation and signal measurement .

The attenuated signal and delayed signal are represented by A(t) and A(t - n) respectively. The bipolar pulse CFD(t) shows the subtraction of those two signals. A zero-crossing comparator performs this subtraction and produces a digital pulse whenever its differential input crosses zero. A trigger pulse will be sent only if zero-crossing point of the CFD signal is within the over-threshold window.

As illustrated in Figure 3.10, an incoming analog pulse is split into four halves. Except for the first one that is sent to the memory block, all others are used for the CFD operation. One of them is sent to a leading edge discrimination (LED) comparator. An over-threshold logical pulse will be sent if the input signal exceeds the threshold level. The other two halves are modified and applied to the zero-crossing discrimination (ZCD) comparator, one of which is attenuated by a fraction of about 70% of its maximum amplitude via a voltage divider and the other delayed with a tunable delay time by a Bessel filter (represented as signals A(t) and A(t - n) respectively in Figure 3.11). The ZCD comparator subtracts those two modified signals and generates a logical pulse whenever the bipolar pulse crosses a reference value. The zero-crossing point of the CFD signal corresponds to the moment that the input signal reaches its maximum value. A trigger pulse for time and amplitude memorization will be sent only if the zero-crossing time is within the over-threshold windows. It should noticed that an external trigger signal "trig in" integrated in the ASIC allows the amplitude and time of a signal to be directly registered independently of the CFD via the veto option.

DAC functionality To optimize the CFD operation of each channel, two 6-bit resolution digitalto-analog converters (DACs) are integrated into each channel. The first is used to adjust the threshold voltage (*TH*), while the second is used to adjust the DC input level of the zero-crossing comparator in order to compensate for the intrinsic offset of the comparator. The values of *ZC* and *TH* can be set independently for every pixel. The adjustment process and experimental results will be presented in the next chapter.

Common ramp generator Once a pulse is detected by the CFD module, a channel flag is set to 1, and a trigger is generated and sent to the PU card (whose architecture and operation principle are explained in the next section) to inform the detection of pulses. At this point, a voltage ramp is started with constant slope by the common ramp generator. It is based on a time-to-amplitude converter (T2AC) in which a capacitor is charged linearly via a constant current circuit until the end. This ramp is used to measure the time between the first pulse and the following events inside the detector. For each detected pulse, the amplitude, the address of the affected channel and the amplitude of the ramp are stored. The timing of the trigger event thus reproduces the arrival time of the first event t_0 . The ramp starts to discharge the moment that all memorized information are read by the PU card. The ramp lasts at least 1 μ s if none of the pulses are detected, and the minimum duration can be regulated through the slow control interface.

Analog memory It is used to store two analog values of IDeF-X HD-LXe output signal, triggered by the CFD operation, namely the signal amplitude at the zero-crossing point and the



Fig. 3.12 Architecture of the analog memory block of XTRACT.

corresponding time delivered by the voltage ramp. The architecture of the analog memory block of XTRACT is illustrated in Figure 3.12. Each XTRACT electronic channel has its own memory block which is made up of two completely identical separate memories (for amplitude and time). Every memory module is made up of two sub-memories that operate in a complementary way. When the *Mem1* sub-memory is in read-mode (rd), the *Mem2* sub-memory goes into write-mode (wr) and vice versa. In version 2 of the circuit, in order to limit reading noise, memory reading has been subdivided into two blocks of 16 channels. All 32 input signals are connected separately to 32 amplitude memory cells, while the 32 of time memory channels are linked by a common time ramp.

Readout process The 32 memory channels of each type (amplitude and time) are read by two double read stages each, i.e. one sense amplifier for 16 amplitude cells and another for 16 time channels. This is possible thanks to a multiplexing system which consists in selecting a single memory channel to be read at a time. Once a pixel is fired, its flag signal will switch to 1 and be recorded through the **derandomizer**. In the case that multiple pixels are fired, this derandomizer module can handle all arrival information, thereby preventing the information loss whether a new flag arrives during the reading process. It also allows addressing information to the **control unit**. This block performs a logical OR engagement between receiving flags and sending a trigger signal to the **PU card**. After the PU card is ready, the chip selection block will send a signal, named chip select (CS), to start the reading process among one of the eight XTRACTS. Then, a read command is sent through the multiplexer to extract the information stored in

the analog memory. When the reading process is completed, the flag of the associated pixel is reset from 1 to 0. A chronogram of signals detection and read-out processes is illustrated in Figure 3.13. A physical event is collected by three different pixels corresponding to the



Fig. 3.13 Example of the detection and read-out process of three different signals.

readout channels 22, 3 and 4. The output signals from IDeF-X HD-LXe are delivered to the XTRACT chip. When the CFD module detects the arrival of the first pulse and sends a trigger pulse, the fired pixel flag (22) turns to *1* and a voltage ramp is started to record the time of possible next events. The trigger signal warns the reading electronics (PU card) that at least one event has been detected. The arrival time of this trigger will be memorized by the PU card and allows resetting in time the arrival of the following pulses.

Meanwhile, the flag signals of the fired pixels are sent to the memory control unit to start the reading process by the PU card. When the PU card, which manages up to 8 XTRACTs, is available, it launches a read procedure by first sending a CS, and then it sends a succession of reading orders to read the memories of the affected channels. A de-randomizer (DRND) is used to select the memory to be read and sends back the information of the amplitude, time and address of the affected channel. If more than one channel is fired during the voltage ramp, the DRND sequentially sends the information through a multiplexer (MUX). The reading sequence generated by the DRND can be different from that of detection. When all the memories are read, the trigger is reseted, and the PU card releases the CS for reading another XTRACT. Once the CS returns to zero, the time ramp is also reseted pending a new event. The reading chronogram is schematized in Figure 3.14.



Fig. 3.14 Schematic diagram of XTRACT reading chronogram.

3.2.2 Simulation studies on double trigger for CFD operations

Before experimental testing of the new XTRACT ASIC, a set of simulation studies have been conducted to evaluate the performance and parameter selection. In this part,we will focus only on double trigger simulation studies.

Phenomenon description When there are double triggers from one pad during the ramp/read time, this phenomenon is referred as to a double trigger. It is a normal phenomenon during data recording in detector DAQ due to the influence of electronic noise. The XTRACT has been designed to record either the last value (default choice) or the first one (option that could be chosen) when a double trigger occurs. It might result in a false charge measurement, especially when a high amplitude noise arrives just before or after the physical signal. Furthermore, it could also result in events loss when the occupancy rate is important. Besides the size and frequency of noise, there is another factor, the signal waveform, which also contributes to this phenomenon. The re-triggering effect is more likely when the signal duration is long.

Method In order to reproduce the detector response, the physical and noise signals used in the simulation are tuned based on data collected using the XEMIS1 experimental facility. Table 3.2 lists the main parameters used in the CFD simulation for signals generation. Noise will affect the signal waveform, especially in the low-energy regime resulting in an important contribution to data analysis. In order to achieve a complete simulation of the detector, a noise signal simulation has been performed. The noise at the output of IDeF-X has a Gaussian amplitude distribution. The Discrete Fourier Transform (DFT) method has been used to convert the signal from the time domain to the frequency domain. The simulation was realized with ROOT where the physical pulses and noise pulses are simulated with a sampling time of 80 ns.

The simplified simulation is done under several approximations:

Digital signal info	CFD1 signals parameters		
Anode	MIMELI	Signal amplified factor	1.5
Grid	Micro-mesh 500 LPI	Signal delay time	$0.72~\mu s$
IDeF-X peak time	1.39 µs	CFD2 signals parameters (XTRACT)
ENC (RMS)	80 electrons	Signal attenuation factor	0.7
Analog-to-digital sample time	80 ns	Signal delay time	$0.72~\mu s$

Table 3.2 Main parameters used in the simulation for signals generation.

- The XTRACT circuit handles continuous analog signals (the output signal of IDeF-X). In the simulation, we use continuous digital signals with the same sampling rate as the data collected by XEMIS1. This approximation is established under the assumption that the sampling rate (80 ns) is less than the time resolution of DAQ electronic components. *However, the digital time delivered by the PU card is 10 ns, which corresponds to its internal clock of 100 MHz. Therefore, the time resolution obtained in the simulation is worse than the actual situation.*
- In order to simplify the simulation related to the CFD processing of XTRACT, the zerocrossing time is obtained by subtracting the original signal from the modified signal (the amplification factor is 1.5, and the delay of 9 duguts i.e. 0.72μ s). In fact, the CFD operation of the circuit compares the delayed signal with the attenuated signal in a zero-crossing comparator. The following simulation results (Figure 3.15) show that the zero-crossing time obtained by these two different CFD simulation methods is the same, so that the simplification is valid.



Fig. 3.15 CFD operation simulation on physical signal (top) without noise (bottom) with noise. The simulated pulses presented in the figures are: S_0 original signal without modification, S_m signal delayed (0.72 μ s) and amplified (1.5), S_{cfd1} subtraction of S_m and S_0 , S_a signal attenuated by a factor of 0.7 (attenuated signal of XTRACT), S_d signal delayed 0.72 μ s (delayed signal of XTRACT), S_{cfd2} subtraction of S_d and S_a (CFD signal of XTRACT).

- DC of the zero-crossing comparator is considered as perfect, i.e., the offset between the DC of two compared signals is zero. Table 3.3 summarizes the CFD configuration considered in this simulation.
- A second threshold, normally at (n 1) times the noise where n is the leading edge discriminator, is considered to avoid a new CFD at the same pixel outside the interval of interest. Therefore, we assumed that the hysteresis that exists in the threshold comparator is about one sigma of noise, i.e., the difference between the high level (used to open the TOT window) with the low level (used to close the TOT window) is about one ENC. The existence of two thresholds is important to guarantee a stable time window to those signals near the threshold. In fact, that value is more important than the considered one sigma of noise according to the experimental results. The hysteresis defect will be discussed in the next chapter.
- The ramp time of XTRACT is set to 1 μ s while the read time is omitted.

-	
XTRACT configuration parameters	Values
Number of channel	1 (not considering the occupation of multi-channel)
Threshold of the leading edge discriminator (TH)	3 SNR
Hysteresis in the threshold discriminator	1 SNR (corresponding to a second threshold of 2 SNR)
DC of zero-crossing discriminator (ZC)	0 (considered as perfect)
Hysteresis in the zero-crossing discriminator	0 (considered as perfect)
Ramp time	1 µs
Reading time	0 (considered as immediate)

Table 3.3 CFD configuration considered in the simulation.

Results and discussions The first step of the simulation study is to ensure the effectiveness of CFD operation. Since the Equivalent Noise Charge (ENC) has not been evaluated during the simulation. The physical and noise signals are normalized and represented with the unit of Signal-Noise-Ratio (SNR) in the following discussion. A total number of 10⁷ physical signals including noise have been generated whose amplitude values follow a uniform distribution in the range of 1-350 SNR. The leading threshold value is set to 3 SNR corresponding to the second threshold of 2 SNR. Figure 3.16 and Figure 3.17 represent the amplitude and time measured by the CFD compared to those of generated peak values as a function of the simulated signal amplitude.

The two distributions corresponding to single-trigger and multi-trigger are shown separately. Based on the results shown in the figure, we could infer that the CFD performs perfectly in the strong amplitude regime. In the small charge area, the noise threshold effect combines with the amplitude and time uncertainty. More details will be given in the next section where a



Fig. 3.16 The difference between the simulated amplitude and measured amplitude as a function of the simulated charge (in SNR units). $Amp_{diff} = Amp_m - Amp_s$



Fig. 3.17 The difference between the simulated peak time and measured CFD time as a function of the simulated charge (in SNR units). $T_{diff} = T_m - T_s$

complete study about time and amplitude measurements will be presented. Concerning the double-trigger, Figure 3.18 (left) shows the distribution of the zero-crossing points in the CFD simulation, that confirms our initial understandings. The leading and trailing parts of the signal increase the noise baseline, making it easier to pass the threshold. The normalized waveform is shown in Figure 3.18 (right), where the possible trigger areas have been circled in different colors. In order to take the electronic components effect into consideration, a more realistic simulation has been done with the LabVIEW software. The simulations results presented in Figure 3.19 and Figure 3.20 show that the memorized signal depends certainly on the common ramp/read time.

Conclusion This section describes a simplified simulation based on ROOT and LabVIEW. The simulation has been carried on to understand the possibility of using two successive triggers during the CFD operation of XTRACT. The simulation results show that this phenomenon does exist in the signal processing of XTRACT. It is the result of the superposition of physical signals



Fig. 3.18 Distribution of the zero-crossing points (left) and the possible trigger areas represented in the normalized waveform (central and left).



Fig. 3.19 XTRACT simulation with LabVIEW: the memorized signal in case of a false trigger arriving before the true one, with a ramp time of 960 ns (left) and 2.4μ s (right).



Fig. 3.20 XTRACT simulation with LabVIEW: the memorized signal in case of a false trigger arriving after the true one, with a ramp time of 960 ns (left) and 2.4μ s (right).

and noise. Besides, the ramp/read time impacts the signal that will be memorized. A short ramp/read time can record more signals (physical and noise), thus preventing event loss. On the other hand, it will also lead to a significant increase of counting rate. Since all 32 channels in XTRACT share a common voltage-to-time ramp, the high count rate will extend the ramp

duration, thus, on the contrary, resulting in a dead time of each channel. A trade-off should be made to improve performances. Research on this issue will continue in follow-up experimental tests. Besides, given that the waveform of IDeF-X is an incompletely symmetrical Gaussian shape, the probability of a second trigger at the tail is higher than the leading part. We have integrated the option that records the first event instead of the last one into XTRACT.

3.2.3 Analog test bench

The test bench for the analog part of the acquisition chain is mounted as shown in Figure 3.21. The left picture shows the test card of the XTRACT_V2 in which the XTRACT ASIC is bonded



Fig. 3.21 Picture of the test bench set-up of the XTRACT_V2 chip.

in the center. The test card is equipped with three connection ports for communication with the IDeF-X, ARDUINO, and PU cards. Besides, a test voltage input end and 5 analog signal output ends. The right picture represents the experimental set-up, that includes a standard IDeF-X HD-LXe card, the test card, and an Arduino card used to configure IDeF-X and XTRACT.

This test bench aims to get a preliminary performance evaluation before the integration with the rest of the acquisition chain. In the next chapter a comprehensive evaluation of the entire acquisition chain will be presented, for this reason the analog test bench results will not be described in this section. Only one test example is given here. A schematic diagram of the analog test bench process is illustrated in Figure 3.22. During the test, the SC (slow control) program of the PC end controls four devices through three USB ports: two generators, an Arduino card and an oscilloscope. The Arduino card is powered by a DC source of 5V and connected with the test card for I2C commands transmission and LVDS signal communication. During the test, the PC will first send a set of configuration commands to the Arduino card in order to configure the IDeF-X and XTRACT. Later, via the USB1 represented in the top-right part of the figure, the PC will send a command to control two connected generators. A square


Fig. 3.22 Schematic diagram of the analog test bench process.

signal S_1 from the generator1 passes through the injection port of the test card then is shaped by IDeF-X, delivering an analog signal at the input of XTRACT. S_1 is collected, meanwhile, by the CH1 probe to the oscilloscope and it is used as t_0 . The analog signal of time S_{time} and amplitude S_{amp} are also collected via two probes to CH2 and CH4 of the oscilloscope. The logic signal output of the CFD trigger $S_{trigger}$ transmits through the Arduino card to CH3 of the oscilloscope. Figure 3.23 shows an example. The signals collected by the oscilloscope are treated in the PC end to realize the measurement. The waveform generator G2 is synchronized (or optional delayed) with waveform generator G1 via a TTL signal. A logic signal of 5V is sent to the Arduino card, transmitting a Trig_in to XTRACT. It allows XTRACT to send a trigger signal without CFD discrimination.

This experiment set-up has been used to characterize parameters such as, the zc (offset of zero-crossing discriminator), the amplitude linearity, and the time walk. Figure 3.23 shows an example of time walk measurement where two different test voltages, 20 mV and 300 mV, are sent to the injection capacitance (50 fF) of IDeF-X, corresponding to the yellow signal S_1 . It is also used to indicate the reference time t_0 . The output signal (red) of IDeF-X delivered to the XTRACT passes through the CFD discrimination and generates a trigger signal $S_{trigger}$ (blue). The difference between the leading edge is, therefore, the CFD trigger time. By continuously





Fig. 3.23 Example of time walk measurement.

The analog signal S_1 (yellow) is the test voltage delivered by G1 to the injection port of IDeF-X, which gives us the reference time t_0 . The analog signal S_{amp} (red) is the output signal of IDeF-X corresponding to the injection signal S_1 . The logic signal $S_{trigger}$ (blue) is the CFD trigger relating to the signal S_{amp} .

changing the amplitude of the test impulsion, we can measure the CFD trigger time variation with respect to the signal amplitude, known as the *Time Walk*. A complete Time Walk measurement has been done with the entire acquisition chain, including the digital part, which is described in the next chapter. The main properties of the XTRACT ASIC are listed in Table 3.4.

Technology	AMS $0.35\mu m$ CMOS		
Area	21 mm2		
Supply Voltage	3.3 V		
	Requirements	Measured results	
Non-linearity of amplitude and time measurements	<1%	<1%	
Consumption (32 channels) @ -80°C	50 mW max.	52 mW	
Output noise voltage (rms value) @ -80°C	<1 mV	2.25 mV	
Jitter (rms value) @ 3 σ with IDeF-X	<250 ns	200 ns	
Time walk $(3\sigma \text{ to } 30\sigma)$	<250 ns	<200 ns	

Table 3.4 Main properties of the XTRACT chip.

3.3 Principle of operation of complete acquisition chain

Besides what described in the previous sections, the rest of the acquisition chain includes the fast light measuring electronic named XSRETOT⁴, the XPU card used for XTRACT reading

⁴Ph.D thesis of Yuwei ZHU

and ionization data serializing processes, and the central data collection management (i.e., the XDC card) for managing scintillation and ionization data. The XDC card consists of a Field-Programmable Gate Array (FPGA) component. Its basic function is to control the data flow and synchronize the ionization and scintillation DAQ systems. The first version (NI FlexRIO) was completed and implemented in the XEMIS1 set-up, whose acquisition framework will be described in Section 3.4.2. This section mainly describes the operation principle of the XPU card and XSRETOT circuit.

3.3.1 Digital acquisition hardware of ionization signal: XPU

The XEMIS Processing Unit (XPU) card is a home-made PU card dedicated to managing the output signals of the XTRACT cards. As mentioned in the previous section, the XTRACT reading process, related to the emission pixel information on the address, time and amplitude, requires the assistance of a XPU card. Besides, in each XPU FPGA board , a 100 MHz clock is used for relative dating of TPC data in a time slot.

XPU features As shown in Figure 3.24, a PU card can manage a maximum number of 2 x 8 XTRACTs (i.e. 2 x 256 pixels) independently, then multiplexes the data on the same LVDS serial line. Together with an acquisition FPGA framework, they compose the digital part of the acquisition system. As an inter-stage between XTRACT signal extraction and acquisition FPGA, the principal function of the XPU card is to handle trigger information, manage the XTRACT reading process, realize analog-to-digital signal conversion (ADC) and serialize digital data to the central collection management, i.e., the XDC FPGA.



Fig. 3.24 Schematic diagram of the principal function of a XPU card.

Principle Each XTRACT can send a trigger signal to notify the PU that one or more events have been detected. The general architecture of the PU card is shown in Figure 3.25. The trigger



Fig. 3.25 General architecture of a half-XPU card.

management block resynchronizes the triggers sent by 8 XTRACTs with the internal clock (100 MHz) of the FPGA and time stamping. Triggers are stored in a double-port for preparing the XTRACT read. Once the XPU card is ready, the XTRACT reading block will send a signal (CS), to start the reading process among one of the eight XTRACTs. The analog signals related to the time and amplitude are then digitized by the ADC management block before being stored in the FIFO module. Finally, the data are serialized and sent to the central collection management through a single 200 Mb/s LVDS (Low Voltage Differential Signaling) link. The serializer is shared by the two half-XPU ("smart" multiplexing). The serialization process and XTRACTs reading procedure are working in parallel.

A prototype digital acquisition chain has been built and tested. Figure 3.26 shows the benchmark set-up. The NI FlexRIO realizes the acquisition FPGA framework in the prototype, used to collect all light and charge data. The acquisition procedure used in XEMIS1 is described in Section 3.4.2.

Fig. 3.26 Picture of the test bench set-up of the digital acquisition chain.

3.3.2 Scintillation signal readout: XSRETOT

In XEMIS2, the principal use of the scintillation signal consists in recording the initial interaction time used to calculate the drift distance. This recorded time is used to extract the longitudinal z-position of γ -ray interactions. Furthermore, the scintillation light can also be employed for the

spatial pre-localization of the physical event. The number of UV photons collected by each PMT could serve as a virtual fiducialization of the active volume, in order to reduce the occupancy rate. A low-cost *scintillation signal measurement electronic chain*⁵ was developed to deliver a convenient and efficient data readout and acquisition process (Figure 3.27). The XSRETOT diagram is shown on a gray background in the figure.



Fig. 3.27 General architecture of the scintillation readout chain. The XSRETOT diagram is shown on a gray background in the figure.

The elementary circuit is composed of a pulse-shaping amplifier and a discriminator, operating at room temperature. The PMT output signal is first integrated and shaped by the pulse-shaping amplifier powered by a ± 5 V DC source. The crucial part is composed of a passive *RLC* network. Then the shaped pulse passes to the discriminator on which a constant threshold voltage is applied. A logical output signal is delivered by the XSRETOT that allows to further Time-Over-Threshold (TOT) measurement. The corresponding digital information on the leading edge, trailing edge, and PMT address are finally readout via high-speed LVDS line to XDC for data acquisition. A prototype card (Figure 3.28) consisting of two electronic channels has been developed and tested in XEMIS1.



Fig. 3.28 The XSRETOT prototype card used in the XEMIS1 test.

⁵Here only a brief description is provided. For more details on the development and calibration processes refers to Yuwei ZHU PhD thesis.

3.4 Implementation of acquisition chain in detector

To prepare XEMIS2, an entire prototype of the acquisition chain was developed and integrated into the XEMIS1 detector. A complete performance test has been carried on the system. This section will mainly describe the experimental set-up, including the XEMIS1 facility and the prototype chain implementation. The slow control, data acquisition process as well as the delivered experimental results on the DAQ chain characterization and optimization in XEMIS1 will be detailed in the next chapter. Moreover, the general architecture and electronics assembly strategy of the data acquisition chain of XEMIS2 that is being prepared for installation, will be described in the second part.

3.4.1 Integration of acquisition chain prototype in XEMIS1

The prototype acquisition chain is presented in Figure 3.29. It consists of two IDeF-X cards, two XTRACT cards, an Arduino card, and a prototype PU card connected to the FlexRIO via LVDS cable. Besides, two interface cards are equipped, one of which is used to connect the PU card and the XTRACT card, while the other is the I2C bus transfer interface between Arduino and XTRACT/IDeF-X. The test voltage produced by the LFG (Low Frequency Generator) injects



Fig. 3.29 Picture of the prototype acquisition chain on the workbench.

through the input port of the first interface card. The injection signal is then sent to the test capacitor in the entrance of IDeF-X to simulate the induced current from the detector. The shaped analog signals output from two IDeF-X cards are directly read out by two XTRACT cards connected by a standard connector. The output digital and analog signals of the address, amplitude and associated time of the fired pixels are sent to the PU card via two interface cards. Later, the collected digital data is sent to the FlexRIO via a LVDS cable. Finally, the FlexRIO sent the data to the PC processor for storage. Additionally, an Arduino card, connected on two sides to the PC and the second interface card, is used to configure both XTRACT and IDeF-X.

3.4.1.1 Overview of XEMIS1 facility

The experimental facility of the XEMIS1 prototype is represented in Figure 3.30. It consists of the XEMIS1 TPC, which is encapsulated in an external cryostat, the cryogenic equipment used for xenon liquefaction and purification, the scintillation and ionization data acquisition system, and the rescue tank to recuperate the xenon in in case of emergency.



Fig. 3.30 General view of the XEMIS1 facility.

The experimental set-up is installed in the SUBATECH laboratory including: ① inner vessel holding the XEMIS1 TPC which is cover by MLI to reduce the thermal exchange, ② external cryostat, ③ injection and security panel, ④ cooling tower consisting of a double-tube heat exchanger and a pulse tube refrigerator (PTR), ⑤ rescue tank, ⑥ high voltage supply system and control panel, ⑦ data acquisition and storage PC (also worked as ionization measurement chain calibration workbench), ⑧ scintillation measurement chain calibration workbench.

Cryogenics of liquid xenon During the operation of XEMIS1, the TPC is placed inside the cryostat immersed in LXe, working at a stable temperature of 168 K and a pressure of 1.2 bar. The internal container of the cryostat is designed as a double-walled stainless-steel container, which can hold approximately 36.5 kg of LXe. Like the XEMIS cryostat, it is also placed in a vacuum enclosure for thermal insulation, which is composed of a double-wall stainless-steel container. The schematic diagram of the XEMIS1 LXe cryogenic device is presented in Figure 3.31 (right), it consists of a high pressure bottle used to store the gaseous xenon when the detector is not in operation, a purification system consisting of two rare-gas getters connected in parallel to purify xenon in gas-phase, a cooling tower containing a Pulse Tube Refrigerator (PTR) and a coaxial heat exchanger for xenon liquefaction, a cryostat that host TPC operating in liquid



Fig. 3.31 (left) 3D drawing of the PTR, heat exchanger and the connection with cryostat. (right) Schematic of XEMIS cryogenic system (Figure taken from [165]).

xenon, and a rescue tank of 4 m³connected with the cryostat in order to recuperate xenon in case of emergency. The xenon from the storage bottle is liquefied and filled into the cryostat by the remote PTR after being purified by the getter (rare gas purifier) and passing through outer shell of the heat exchanger.



Fig. 3.32 Pictures of cryogenic devices.

① the water-cooled helium compressor (CryoMini Compressor OW404), ② the pulse tube refrigerator(Iwatani PC150), ③ two SAES PS4-MT3-R/N rare-gas purifier getters connected in parallel, ④ a high-pressure bottle used to store the gaseous xenon and a liquid nitrogen bottle used for xenon recovery.

The cryogenic process of xenon liquefaction in XEMIS1 is similar to that in XEMIS2 (described in the Section 2.3), except the main part of the cooling system which is based on Iwatani PC150 PTR. It is especially developed and optimized to liquefy xenon gas and keep it at a constant LXe low temperature. It works with a water-cooled helium compressor (CryoMini Compressor OW404). The PTR provides stable cooling power up to 200 W at 165 K to liquefy xenon gas and keep it at constant temperature. The built-in heater is integrated between the PTR and the copper cold head to compensate for the additional cooling power of the PTR. Figure 3.31 (right) gives a 3D schema of the connection between the PTR, the coaxial heat exchanger and the inner vessel of cryostat. The PTR is installed on the top of the coaxial heat exchanger, 2 meters away from the thermostat to reduce the electronic noise caused by mechanical vibrations.

3.4.1.2 Configuration of updated TPC

The small-scale XEMIS1 TPC was developed to demonstrate the feasibility of the proposed detector concept. The updated configuration shown in Figure 3.33 conforms better to the XEMIS2 TPC set-up. The charge collecting electrode uses the same MIMELI technique as that in XEMIS2, which is composed of a segmented anode equipped with micro-pillars and a 500LPI micromesh with a gap of 125 μ m above. The active area of the anode is 2.5×2.5 cm² including 64 pixels of 3.1×3.1 mm². Two IDeF-X HD-LXe cards are connected perpendicularly to the anode



Fig. 3.33 Configuration of the XEMIS1 TPC.

① Position of XEMIS1 TPC in the cryostat, ② TPC assembly in clean-room, ③ segmented anode equipped with micro-pillars including of 64 pixels of $3.1 \times 3.1 \text{ mm}^2$, ④ 500LPI micromesh with a gap of 125 μ m, ⑤ IDeF-X HD-LXe cards perpendicularly connected to the anode, ⑥ PMTs support made of Macor ceramic, ⑦ 1" VUV-sensitive Hamamatsu R7600-06 MOD-ASSY PMT, ⑧ installation of PMTs in the support.

in LXe at -104°C, to readout 64 independent analog signals with ultra low electronic noise. For scintillation light detection, two 1" VUV-sensitive Hamamatsu R7600-06 MOD-ASSY PMTs are placed at the TPC periphery side by side through specific support. An active length of 12 cm was chosen in XEMIS2 to ensure a high detection efficiency of 88% in the energy range of the third gamma-ray. However, the source is disposed about 1 cm away from the cathode, which

implies a smaller solid angle covered by the electron collecting surface when the drift length is higher. In XEMIS1, the drift length of the chamber has been reduced to 6 cm by considering the solid-angle acceptance of incident photons in front of the smaller charge collecting surface. Besides, to increase the light collection efficiency, we reduced the number of shaping field rings. A set of 6 copper field rings with a gap of 9 mm between each other is located between the cathode and the anode, aiming to provide a uniform electric field. A simulation study has been done which proves that this modification will not significantly impact the homogeneity of the electric field. The TPC set-up is placed horizontally inside the external cryostat and entirely immersed in about 30 L of LXe during operation phase. Therefore, all components are fixed on a stainless-steel flange and held by four Macor ceramics rods in the peripheral. A group of four stainless-steel springs is used to fix the entire assembly and to counterbalance the change of material sizes due to thermal contraction while cooling of the detector. To avoid device deformation and guarantee high xenon purity, all materials used for the TPC construction have a small thermal expansion coefficient and low outgassing character.

3.4.1.3 Implementation of acquisition chain prototype

Figure 3.34 shows the experimental configuration of the prototype acquisition chain integrated in XEMIS1. To reduce the electronic noise which is dominated by the preamplification of the front-end electronics, two IDeF-X cards are directly connected to the anode and immersed in LXe. Two XTRACT ASIC treat the 64 analog output signals of IDeF-X. A standard connector and the interface card are linked to the two ends of XTRACT cards, intending to link the XTRACT ASIC with IDeF-X and PU card. The entire unit operates in the vacuum enclosure, cooled by the heat conduction from the inner vessel interface. The ionization signal information of the detector is then sent to the external cryostat by 64 wires. The rest of the acquisition chain is placed on the outside of the cryostat working at room temperature. The Arduino card is connected to the PC via a USB port. The power source of IDeF-X and XTRACT is linked to the interface card. Besides, the scintillation chain is also integrated in air working at room temperature.

3.4.2 Architecture and integration of electronics in XEMIS2

As described in the previous chapter, XEMIS2 consists of two identical cylindrical LXeTPCs. The scintillation light and ionization charge are respectively collected by the peripheral 64 PMTs (in the first phase) and by two end-side MIMELI anode each one composed of more than 10,000 pixels of 3.1×3.1 mm². The data acquisition system of one TPC is schematized in Figure 3.35, including signal readout and data acquisition electronics. The information of



Fig. 3.34 Experimental configuration of the prototype acquisition chain integrated in XEMIS1. ① Inner vessel of XEMIS1 cryostat, ② Two XTRACT_V2 cards are connected with two standard connectors, then attached to the slot located in on the stainless-steel flange vacuum/xenon interface, ③ The XTRACT_V2 card and a standard connector, ④ The interface card linked two XTRACT_V2 cards and the rest of the acquisition chain, ⑤ The Arduino card and PU card are installed at the outside the cryostat working at room temperature, ⑥ FlexRIO is also installed outside of the croystat, connected with LVDS cables to collect the digital data of both light and charge signals.

ionization and scintillation are extracted independently through two individual measurement systems, synchronized and processed in the XDC (XEMIS data concentrator) card.



Fig. 3.35 Schematic diagram of the data acquisition system of XEMIS2 (one TPC).

Ionization signals measurement system The Ionization signal provides not only the information on the deposited energy but also the 3D position reconstruction. Optimizing the

energy and position resolutions is fundamentally needed for the Compton scattering sequence reconstruction. Besides, to realize an ultra-low activity imaging of small animals, maximizing the event efficiency in the XEMIS2 ionization signal measurement system is fundamental. Finally, due to the low-threshold self-triggering mode, it is necessary to reduce the output data stream and maintain processability in high-rate signal readout without affecting essential information. In order to perform a continuous readout for 20 minutes with almost negligible dead time, a high performance ionization signal readout and data acquisition (DAQ) chain was developed specifically for XEMIS2. It consists of three basic functional units: IDeF-X HD-LXe (Imaging Detector Front-end for X rays) [166], XTRACT_V2 (Xenon TPC Readout for extrAction of Charge and Time), and XPU (XEMIS processing unit). The picture of each electronic component is shown in Figure 3.36. IDeF-X HD-LXe and XTRACT_V2



Fig. 3.36 Electronic components for ionization signals readout in XEMIS2.

compose the front-end readout electronics unit, and each of them is a multi-channel (32) ASIC (Application-specific integrated circuit) bonded on a PCB. One unit can be connected to 32 channels of the segmented anode, i.e., each pixel is read out by its individual ultra-low noise electronic channel. The induced current generated on a pixel is first integrated by the charge-sensitive preamplifier in IDeF-X, generating an analog signal. The output analog signal of IDeF-X then passes through a Constant Fraction Discrimination (CFD) block inside the XTRACT chip allowing for a self-trigger. In addition, XTRACT includes analog and standard digital blocks to memorize and deliver the fired pixel address, amplitude and CFD time of each over-threshold ionization signal. A XPU card could connect a maximum of 16 XTRACTs devoted to data collection and analog-to-digital conversion. The collected digital data of the XPU card are finally sent to the XDC via a LVDS cable to realize a preliminary online data processing.

To deal with the enormous quantity of ionization signal channels and to facilitate their management , XEMIS2 picks scalable signals readout arrays. The electronics assembly layout of one



half TPC is illustrated in Figure 3.37. For a half-TPC, a total of 5000 pixels are directly readout



- (1) 1×Anode and Frisch Grid
- (2) 162×IDeF-X Front-End Electronic
- (3) 1×Xenon/Vacuum Interface common to IDeF-X/XTRACT modules
- (4) 162×XTRACT Front-End Electronic
- (5) 28×Cluster Card grouping XTRACTs by 4, 5, 7 or 8
- 6 28×Kapton Cable connecting Cluster Card and XPU Card
- (7) 16×XPU Card (each can manage 2 XTRACT Clusters)
- (8) 16×3 Cables (ALIM-PU, SATA-PU, JTAG-PU)
- (9) 1×Dispatch Card comprising 16 XPU Cards
- (10) 1×LVDS Cable and 1×Dispatch Card Power Supply
- (1) 1×Vacuum/Air feedthrough Card

via 162 IDeF-Xs connected to the backside of the anode plane. The output end of IDeF-X is coupled to XTRACT through a standard connector on the Xenon/Vacuum Interface, one-to-one correspondence. The Figure 3.38 (a) presents the photo of the Xenon/Vacuum Interface common to IDeF-X/XTRACT modules. A sum of 162 XTRACTs is regrouped by 28 Cluster Cards, with each associating 4,5,7 or 8 XTRACTs. An example of a XTRACT-Cluster assembly and connection is shown in Figure 3.38. One XPU card can handle two XTRACT-Clusters by Kapton cables. A dispatch card comprising 16 XPU Cards manages all 28 XTRACT-Clusters. The XPU cards operate in the vacuum layer, cooled by a heat exchanger with water circulation. Information of all 5000 ionization signal channels is extracted to the outside of the cryostat via only one high-speed LVDS line, realizing an optimized communication strategy and a minimized power consumption.



Fig. 3.38 Pictures of electronics assembly in XEMIS2. (a) The Xenon/Vacuum Interface common to IDeF-X/XTRACT modules, (b) An example of XTRACTs cluster: seven XTRACT cards are connected by one Cluster card, (c) Installation example in the case of one row of interface panel consisting of eight standard connectors, (d) Connection of three cables with PU card.

Scintillation signals measurement system In XEMIS2, instead of accurate energy measurement, the principal role of the scintillation signal is to record the original interaction time for drift distance calculation. A low-cost scintillation signal measurement system was developed to deliver a convenient and efficient data readout and acquisition process. The scintillation light is collected by the VUV-sensitive PMT then readout through the self-developed XSRETOT card. The latest XSRETOT card (Figure 3.39) consists of 16 identical self-triggering electronic circuits to process 16 PMTs output signals in parallel. Each elementary circuit is composed of a pulse-shaping amplifier and a discriminator, operating at room temperature. The schematic operation diagram is shown in Figure 3.27. The PMT output signal is first integrated and shaped by the pulse-shaping amplifier. Then the shaped pulse passes to the discriminator on which a constant threshold voltage is applied. The data acquisition system will be triggered if the signal amplitude is greater than the applied threshold so that the Time Over Threshold (TOT) signal will be readout. The corresponding digital information on the leading edge, trailing edge, and PMT address are finally readout via high-speed LVDS cable to XDC for data acquisition. Besides, during off-line data processing, the number of photoelectrons collected by the VUV-sensitive PMT can be deduced via a threshold time-out method.





(a) Frontal view (b) Bottom view Fig. 3.39 XEMIS Scintillation Readout for extraction of Time over Threshold (XSRETOT).

XEMIS Data Concentrator (XDC) An updated version of the XDC (Figure 3.40) aiming at a real-time image reconstruction conception is currently under development, with continuous high-frequency DAQ capacity and event builder treatment. One XDC card is envisaged to manage 10,000 ionization channels and 32 PMTs output signals, i.e., all data of a TPC, with a flow up to 8 Gb/s. Given that the expected raw data can reach up to 1 To for a 20-minutes image, a real-time data filter is also proposed to be implemented further. The R&D work is underway at SUBATECH in collaboration with IMT Atlantique Brest Campus. The aspects of hardware acceleration, data reduction, and pretreatment for data acquisition are under study in cooperation with the electronics department. At the same time, the LATIM laboratory participates in the research on the acceleration and optimization of 3-gamma imaging reconstruction with XEMIS2 via artificial intelligence approaches.



Fig. 3.40 Experimental set-up for the test bench of the digital acquisition chain (version 2).

3.5 Conclusions Chapter 3

The primary goal of the first phase of the XEMIS2 Compton camera is to achieve small animal imaging with a source low activity of 20 kBq in 20 minutes of exposure. To continuously readout with negligible dead-time during 20 minutes, a specific high-rate data acquisition system was developed and tested during this thesis work. This chapter consists of three parts that describe the novel acquisition chain of XEMIS2 from the design requirements, operation principle, up to the electronic readout chain implementation.

The first part focuses on the requirements for the new data collection. In order to perform accurate charge measurements, our research team proposed an innovative segmented electrode geometry MIMELI to optimize the induced current generation in LXeTPC. The experimental test in XEMIS1 combined with an ultra-low-noise front-end electronic ASIC called IDeF-X HD-LXe has shown encouraging results. A brief review was done at the beginning of this section. In XEMIS2, in order to obtain the expected image quality with lower activity with respect to other technologies currently in use, we need to extrapolate the same/better performance from 64 pixels to more than 20,000 pixels while achieving higher event efficiency under a manageable data flow/volume. The new signal readout electronics system needs firstly to meet self-triggering, high-rate acquisition, and low electronic noise. Furthermore, a signal information extraction ASIC was developed to reduce the storage data volume. A new data acquisition system was proposed based on the above listed requirements.

In the second section and the third section, the operation principle of the new DAQ is specified. The former describes the core electronic components used in this thesis work, XTRACT, which is also specifically important for the entire ionization signal measurement chain. Instead of sampling all analog output signals of the IDeF-X chip, the role of the XTRACT circuit is to extract and store the valuable information about amplitude, peak time, and fired channel address. Therefore, offering the possibility of considerably reducing the quantity of data by storing only the essential ones. In addition, combined with the PU card used to read and serialize XTRACT data based on internal FIFO and dual-port memory, this circuit can also reduce the number of connections traversing the chamber and limit the dead time of the read link with the extracted data. Finally, the ionization signal data and the light signal data are concentrated in the XDC card, deserialized by its FPGA framework, and then stored on the PC side.

The final part describes the experimental set-up, including the XEMIS1 facility and the implementation of the prototype acquisition chain. Besides, the data acquisition chain of XEMIS2 is also under preparation for installation, its general architecture and electronics

assembly strategy are also described. The next chapter will introduce the calibration process of the new DAQ prototype for optimizing charge measurements.



Optimization of Charge Measurement with New DAQ Prototype

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A new data acquisition system designed for the XEMIS2 has been developed to guarantee A continuous readout with negligible dead-time during 20 minutes. There are two main innovations brought by it. The self-triggering implementation aims to maximize the detection efficiency. Extracting amplitude and time information from analog signal allows reducing the data flux and the storage volume. The architecture and operation principles of the concerned electronic devices are detailed in Chapter 3. To study the operational calibration and performance characteristics, a prototype has been developed and integrated into XEMIS1. The corresponding experimental results will be reported in this chapter. The introduction provides an overview of the entire data acquisition process and presents the critical parameters from basic concepts. In the second part, we focus on the calibration of those adjustable parameters related to the CFD performance and the threshold setting. It constitutes an essential step to operate the core ASIC chip, XTRACT. The measurement optimization dedicated to the concrete observed phenomena such as the threshold effect and fake triggers is discussed in the third section. At the end of the chapter, an overview of the calibration performance will be given, including the charge and time response. Besides, the self-developed slow control system for automatic measurement will also be presented.

4.1 General overview

The operational principle of the overall data acquisition process is schematized through the diagram in Figure 4.1. A summary description of the data acquisition system components provided below.

- **IDeF-X** The ultra-low noise front-end electronic working as shaping-preamplifier, is directly connected to the anode. The optimized operational parameters have been identified, configured with a rise time of 1.39 μ s and a gain of 200 mV/fC. The semi-gaussian waveform of the output signal is illustrated in Figure 4.1. The electronic response has also tested and it shows a perfectly linear behavior. The electron noise (ENC) has been optimized to a value as low as 80 electrons under operational conditions, i.e., connected to the entire detector and working at -80 °C. Based on this experimental result, the targeted ENC of the overall DAQ chain was defined to 100-120 electrons to optimize the energy and position measurements.
- **XTRACT** The core ASIC chip of the new DAQ system is the main electronic device to be characterized and calibrated. The IDeF-X signal is split into four branches at the chip entrance. They are used for self-trigger and the remaining one is continuously tracked by the analog memory to register the amplitude at the trigger timing point. For time recording, in the case of multiple trigger channels, the PU card only directly records the first trigger time, and the other possible times are provided by the voltage ramp common to all 32 channels. The voltage ramp starts from the first trigger process, as the principal



Fig. 4.1 Operational principle of the overall DAQ chain.

chip function, works for physical signals identification and triggers timing flag delivery. It directly impacts the data acquisition quality. Its operational performance is the main focus of this chapter.

- **PU card** It can manage a maximum of 16 XTRACTs in parallel, handling the trigger flags and reading out the amplitude and time data. The internal FPGA is equipped with a 100 MHz clock to record the first trigger time of XTRACT. The readout information about analog amplitude and time is converted into digital data in the ADC module then stored in the FIFO, waiting to transmit to FlexRIO via LVDS. In this calibration experimental set-up, the PU card prototype handle two XTRACTs instead of 16.
- **FlexRIO** It is the headquarters of the data collection process. The calibration and physical data are both segmentally registered per bunch of 80 ms duration. This time segmentation method is chosen to allow a precise synchronization of both light and charge DAQ branches. To this end, FlexRIO records the time of the former, and PU records the latter. The time reset command is sent by the FlexRIO's FPGA to the PU cards. During the data acquisition process, the data is consecutively recorded in the FIFO-A during 800 μ s and then sent to the FIFO-B during 1 μ s. It is important to note that there is no data

loss during the transmission time between two FIFOs, thanks to the FIFO inside the PU card. FiFO-B will then send the data to the processor of the PC for data storage. Two FIFOs are working in parallel in order to provide continuous data recording without dead time. After 100 cycles, i.e., 80 ms, FlexRIO will stop the PU reading and process light data. Unlike the charge data, during 80 ms, the light data is stored in another FIFO of FlexRIO without sending it to the PC. Only after the charge data recording, the light data memorized in FIFO will be sent to the PC and be written following the end of charge data. Until all the light data will be correctly written in binary through the PC processor, the acquisition segment is complete, and a reset flag will be sent to PU to restart. The time difference between two bunches of 80 ms depends, therefore, on the light data volume.

The correct operation of PU and FlexRIO is a prerequisite for DAQ calibration. Many short acquisition runs have been taken to validate their performances. The binary data decoding and debugging, loss data checking, and events order verification are complicated processes that will not be discussed here. The experimental results reported in this chapter, except some of them obtained with oscilloscope, are all based on the analysis of binary data with ROOT.

4.1.1 Self-trigger principle and affected parameters

Figure 4.2 illustrates the self-trigger principle which is based on:

- Leading Edge Discriminator (LED) or voltage over Threshold Discriminator (THD) are utilized to detect the presence of a signal and to prevent CFD from noise trigger. This electronic circuit constantly compares the input signal pulse with an adjustable threshold voltage. If the value of the signal exceeds the reference value, the comparator output level switch to logical state *1*. When the signal is below the threshold, the output returns to logical state *0*. The Time-Over-Threshold (TOT) is thus the positive logic window of the LED.
- The Constant Fraction Discriminator (CFD) is used to provide a *trigger timing flag*¹ according to which the signal amplitude has be recorded. It comprises :
 - a **Bessel-filter** to delay the input signal;
 - an Attenuator to have an attenuated copy of the original IDeF-X signal;
 - a **Comparator** to emulate the subtraction of the two previous (delayed and attenuated) signals. The attenuated signal is compared to the delayed signal. When the two signals are

¹In fact, LED can also be used to determine the time of the present signal whose rise time is always the same regardless of the amplitude change (signal of IDeF-X). However, leading-edge timing is affected by time-walk, i.e., the measured time varies with the amplitude. The use of CFD can theoretically provide a trigger timing position eliminating the dependence of the amplitude variation.

equal, or the delayed signal is greater than the attenuated signal, the comparator output is high. The output of the comparator block then goes high on the rising edge.

• Logical AND is used after the output signals of two discriminators in order to eliminate the noise trigger. A trigger pulse will be sent only if the CFD signal is within the *TOT* window.



Fig. 4.2 Illustration of the self-trigger principle of XTRACT.

Leading edge discriminator (LED)

In XTRACT, we have added a leading-edge discriminator with an adjustable threshold for signal selection. Unlike thresholds that are directly applied to software during data analysis, hardware thresholds can introduce discriminator noise. Besides, the instantaneous signal level is also modulated by noise. Both types of noise will cause the threshold crossing point to fluctuate. The principle is illustrated in Figure 4.3.

Considering the standard deviation of the electronic noise of discriminator is σ_{N_T} and the noise imported by the input signal is σ_{N_S} , the convolution of two types of noise can be expressed as:

$$\sigma_N{}^2 = \sigma_{N_T}{}^2 + \sigma_{N_S}{}^2 \tag{4.1}$$

we can therefore deduce that:

$$\sigma_N = \sqrt{\sigma_{N_T}^2 + \sigma_{N_S}^2} \tag{4.2}$$

Besides, the timing uncertainty at the leading-edge, namely time jitter σ_t , can be written as:

$$\sigma_t = \frac{\sigma_{N_T}}{\left. \frac{dV}{dt} \right|_{V_T}} \tag{4.3}$$



Fig. 4.3 Illustration of the leading-edge discriminator response.

(a)Principle of leading-edge discriminator used in the XTRACT circuit. V_T is the threshold voltage. Due to the hysteresis of the comparator, the reference voltage at the trailing edge is normally smaller than V_T . The differential time between the leading and trailing edge is the time over threshold, namely TOT. Only those trigger times that arrive within TOT could be valid. The TOT could therefore achieve signal selection and eliminate the noise trigger.

(b) Resolutions of time and amplitude at leading-edge threshold due to the noise of input signal blue and that of discriminator red.

Many researches have been conducted in those LED-based timing measurement detectors, including time-walk and time-jitter. The method used for the scintillation light measurement in XEMIS2 has the following characteristics:

- *Leading-edge timing* is affected by time-walk, i.e., signals with the same shape and different amplitude cross the threshold at different times.
- *Time-walk* is a deterministic effect that can be corrected by measuring the curve of delay time as a function of the signal amplitude.
- *Time over Threshold (TOT)* is an efficient way of registering the amplitude, requiring also the calibration of the TOT dependency as a function of the signal amplitude.

In this work, since the timing trigger is provided by CFD instead of LED, those features will not be detailed here.

Constant-Fraction-Discriminator (CFD)

The operation principle of the CFD block is shown in Figure 4.4. The input signal $(S_{in}(t))$ is firstly split into two signals, then it generates a delayed signal $(S_d(t))$, through a delay filter based on a second-order Bessel filter, and an attenuated signal $(S_a(t))$, via a divider bridge attenuator. Later, those two signals pass through an amplitude comparator delivering a trigger timing flag (t_{CFD}) at their cross position. Therefore, the trigger timing point is located on the constant fraction of the input signal, insensitive to the input signal amplitude for a given



Fig. 4.4 CFD principle of the XTRACT chip with the IDeF-X pulse shape produced by the PSpice simulation.

normalized pulse shape (S(t)). The theory of CFD can be demonstrated as follows. The input signal could be expressed as:

$$S_{in}(t) = V_{in}S(t) \tag{4.4}$$

where V_{in} is the maximum of the input signal. Then, the attenuated and delayed signals could be therefore defined as follow:

$$S_a(t) = \alpha V_{in} S(t) \tag{4.5}$$

$$S_d(t) = V_{in}S(t-t_d) \tag{4.6}$$

where α is the attenuation factor related to the attenuated signal and t_d is the delay time corresponding to the delayed signal. Since the CFD time (t_{CFD}) is determined by the intersection of the delayed signal and the attenuated signal, we thus have:

$$S_d(t_{CFD} - td) = S_a(t_{CFD}) \tag{4.7}$$

The amplitude voltage of the input signal V_{in} appears in the two side of Equation 4.7 that can thus be simplified as

$$S(t_{CFD} - td) = \alpha S(t_{CFD}) \tag{4.8}$$

As expected, t_{CFD} is not depending on the signal maximum V_{in} . The trigging ratio r at t_{CFD} is expressed as :

$$r = S(t_{CFD}) = \frac{S(t_{CFD} - td)}{\alpha}$$
(4.9)

The dependence of the trigging ratio r is only on the delay time t_d and the attenuation coefficient α . When α and t_d remain unchanged during the measurement, r becomes constant and independent from the input signal amplitude, allowing to reach an ideal CFD performance.

However, in practice, the zero-crossing comparator might have an offset which introduces a differential voltage² V_{ZC} between the compared attenuated and delayed signals. Equation 4.9 should thus be changed to:

$$r = S(t_{CFD}) = \frac{S(t_{CFD} - td)}{\alpha + \frac{V_{ZC}}{V_{in}}}$$

$$(4.10)$$

In this case, the trigging ratio r is no longer a constant but dependent from the input signal amplitude, i.e., *Time Walk*. To reduce the impact of this phenomenon, a direct-current (DC) bias has been added onto the attenuated signal. This adjustable parameter is named *ZC* correction in this work, and it is meant to compensate the offset V_{ZC} .

Conclusion

This section gives a general overview of the entire DAQ chain and explains the operation principle from a theoretical point of view. In order to optimize the self-triggering operation concerning the time and amplitude acquisition, four critical parameters should be taken into consideration:

- Threshold (TH) and Hysteresis of the LED which defines the signal section range.
- Delay time (t_d) and DC current of zero-crossing comparator (ZC) of the CFD which impacts the trigger timing position.

Other than hysteresis that is an inherent property of comparator, all the rest of parameters are adjustable. Their calibration characteristics will be reported in the next section.

4.2 Calibration characteristics of XTRACT parameters

The goal of the XTRACT chip is to provide an ionization signal self-trigger and to record the corresponding time and pulse voltage value. The basic design and operating principles have been

²Bedsides, a light shift of baseline might also be produced during the signal split, attenuated or delayed processes. Here all the factors are simplified and expressed as V_{ZC} .

described in Section 4.1. In this section, we will mainly discuss the adjustment and calibration process dedicated to performance optimization.

4.2.1 Delay time

The impact of V_{ZC} offset could be ignored when the input signal amplitude V_{in} is big enough, i.e., when V_{ZC} / V_{in} is approaching zero. Under this condition, the CFD operation can be considered perfect. As demonstrated in the previous section, in an ideal CFD, the trigger ratio r depends entirely on the delay time t_d and the attenuation coefficient α . In the XTRACT circuit, α is fixed at 70%, nonadjustable and constant for all 32 electronic channels. The delay time becomes, therefore, the unique adjustable parameter for the time ratio selection. In our case, the ideal trigger ratio is **1** that the amplitude of input signal could be directly obtained. From Equation 4.8, we have:

$$r = S(t_{CFD}) = 1$$

$$t_{CFD} = t_r$$

$$S(t_r - t_d) = \alpha = 0.7$$
(4.11)

Slow Control In order to adapt the different peak times of the input signal, the XTRACT circuit is equipped with a 3 bit DAC (8 different values from 0 to7) that allow for delay time adjustment. t_d is common for all 32 channels of one chip. The control is realized via the register I2C of the Bessel filter to activate the auxiliary capacitors.

Objective This test mainly aims to find such an optimized delay time that the voltage at the CFD trigger timing point could be maximized. The maximization of the trigger ratio can improve the accuracy of the induced current (deposited energy) measurement and optimize the signal-to-noise ratio. Besides, since the adjustable values of delay times are unknown and not ordered, this work can also be used to calibrate and reorder the DAC values in the delay time.

Method Since the time of the signal maximum is hardly affected by other factors, we chose to calibrate it in the first place. The effect of different delay positions was determined by injecting a high amplitude step pulse of 100 mv through the injection capacitor of IDeF-X. The shaping time of the IDeF-X chip was configured at 1.39 μ s, and its gain was set to 200 mV/fC. The threshold value was set to the maximum possible value to eliminate the noise triggers. Only the time and amplitude (ADC digital value) were registered with the novel DAQ chain. By analyzing the measured amplitude and trigger time, we could therefore characterize the performance of each delay time.

Result and discussion

An example of the experimental measurement result of one channel is shown in Figure 4.5. It presents the delay time response of the pixel #0 of XT0. For each delay value, the measured amplitude and time have a Gaussian distribution. The experimental result allows associating and reordering the delay times according to the DAC values, whose main characteristics are summarized in Table 4.1. Four of the delay values make the trigger time point before the peak time ($t_{CFD} < t_r$), and the others define a bigger time ($t_{CFD} > t_r$). Among all the optional delays, **delay1** (DAC value) makes the time point closest to the peak time, maximizing the measured amplitude value.



Fig. 4.5 CFD delay time measurement (one channel): output amplitude with the experimental cross-time of all 8 delay times are superposed. The projection on the x-axis shows the measured time distribution fitted by a Gaussian function.

Table 4.1 Main characteristics of the delay time parameter	Table 1.1 Main characteristics of the delay thic parameter.
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DAC value (LSB)	0	1	2	3	4	5	6	7
Experimental results of pixel #0 of XT0 (injection amplitude of 100 mv)								
Amplitude (ADC channel)	3115	3345	3286	3328	3230	3340	3326	3305
Cross time (ns)	1061.83	1397.56	1227.23	1505.73	1158.62	1459.07	1304.45	1558.92
Time jitter (ns)	7.35	7.40	7.30	7.55	7.30	7.41	7.27	7.49
Associated (Reordered) capacity value and delay time								
Capacity (datasheet) (fF)	700	1500	1050	1850	900	1700	1250	2050
Delay time (simulation) (ns)	295	620	430	780	390	705	520	820



Fig. 4.6 Characteristics of the delay time: (left) delay time simulation and (right) variation of crossing time with delay time.

Since the delay time is in common for all 32 channels of one XTRACT, a follow-up test was established to calibrate the dispersion of their performance. The experimental results are shown in Figure 4.7a and Figure 4.7b, where the variation of the amplitude and time measurements with different delay times of all channels can be seen.



Fig. 4.7 Delay behavior of 64 channels of two extracts for an input voltage of 100 mv

The mean values were obtained by performing a Gaussian fit. We can see that all 32 channels of the two XTRACTs have a quite uniform performance. The maximum amplitude is always achieved with delay time at *delay1*. Besides, the cross-time distributions of two XTRACTs with delay time set at delay1 are shown in Figure 4.8a and Figure 4.8b.



Fig. 4.8 Dispersion of time measurement of XT0 and XT1 with delay time set at delay1: (left) superposition of measured value, (right) distribution of mean value on time measurement.

Conclusion

In this part, an optimal delay time has been found corresponding to the DAC value of delay1. The trigging time, in this condition, is about 1.4 μ s approaching the shaping time of IDeF-X. Therefore, the trigging ratio is almost equal to 1, i.e., XTRACT is well performing and is able to record the maximum value of the IDeF-X signal.

4.2.2 Zero-Crossing (ZC) correction

As mentioned in Equation 4.10, we have:

$$r = S(t_{CFD}) = \frac{S(t_{CFD} - td)}{\alpha + \frac{V_{ZC}}{V_{in}}}$$

where the trigging ratio depends on the input signal amplitude V_{in} of the CFD. The offset V_{ZC} of the Zero-Crossing comparator introduces hence a time walk, breaking the requirement or a perfect CFD. To eliminate its impact on the accuracy of the trigger timing point, a direct-

current (DC) bias V_{DC} should be added to compensate V_{ZC} as much as possible, that is:

$$ZC = ZC0 \quad \Rightarrow \quad V_{DC} = V_{ZC} \quad \Rightarrow \quad r = S(t_{CFD}) = \frac{S(t_{CFD} - td)}{\alpha}$$
(4.12)

where **ZC0** represents the optimum ZC value which allows to eliminate the time walk effect. Several simulations have been done with PSpice, LabVIEW and ROOT to estimate the performance. Since other factors may be involved, such as the baseline shift of the split signals (attenuation or delay or both), simulations cannot accurately reproduce the observed behavior. A set of experimental measurements has been done to investigate its impact and find the optimum ZC value (**ZC0**).

Slow Control The DC input level of the Zero Crossing comparator is adjusted by a 6-bit resolution DAC via the register I2C. The chosen architecture is a classic R-2R ladder type. This functionality allows to compensate for the variations in the DC level introduced by component offsets. Thanks to an adaptation stage, the initial adjustment range of the DAC (\pm 43 mV) has been reduced to \pm 20 mV, corresponding to a LSB (Least Significant Bit) value of 0.625 mV.

Objective This part of the work is mainly divided into two objectives. On the one hand is to measure the time and amplitude for different *ZC* values. On the other hand, it is necessary to find a fast and effective method to determine *ZC0* in order to calibrate more than 20,000 electronic channels in XEMIS2.

Effects on time measurement

A full measurement on each channel has been done to observe the response of time and amplitude measurements to different ZC values. Figure 4.9 provides an example of channel #3 of XT0. We can observe the average time measurement results with all 64 DAC ZC values. In this test, we sent a set of injection pulses of different amplitudes to the injection capacitor (50 fF) at the entrance of IDeF-X, namely 3 mV, 5 mV, 12 mV, 25 mV, 50 mV, and 100 mV. The threshold was set to approximately 3 times the noise level, which corresponds to an input voltage of about 2.5 mV. The shaping time of the IDeF-X chip was configured at 1.39 us, and its gain was set to 200 mV/fC. From the figure, we can clearly observe that the ZC value impacts the time measurement, especially for small-signal near the threshold. Even for bigger signals, it slightly changes the time of the trigger t_{CFD} . To find the optimum ZC value, we exploited the measured time as a function of ZC values, shown in Figure 4.10. From this measurement, we can extract lots of useful information. Firstly, for an input voltage of 100 mV, equivalent to 5 fC (~ 31000 electrons, around the collecting charge of 511 keV deposit energy) after the injection capacitor



Fig. 4.9 Response of time measurement with input amplitude for different ZC. Each point represents the average measured time for a given input voltage and a value of ZC (DAC value [LSB]). All mean values have been obtained by performing a Gaussian fit.



Fig. 4.10 Comparison of the impact of different ZC values on time measurement.

of 50 fF, the variation is slight, less than 50 ns in all ZC dynamic range. This result proves the hypothesis of the previous delay time measurement: the impact of V_{ZC} is negligible for large input amplitude. It also confirms that the baseline deviation value is much smaller than 1 V (the gain of IDeF-X is set to 200 mv/fC). Besides, an inappropriate ZC value could induce more than 700 ns time walk in the range of 3 mV to 100 mV of input voltage, corresponding to the

collecting charge from 30 keV to 511 keV of deposit energy. Finally, the optimum ZC value, i.e., *ZC0*, can be easily found at a DAC value of 18, for which the time walk is perfectly compensated.

ZC0 determination with noise triggers

For each electronic channel, we aim at finding the ZCO by using the same method as presented above. It provides a precise evaluation of all ZC values. The measurement and analysis process is so complicated and time-consuming that it is challenging to implement this kind of procedure for all the 20,000 electronic channels in XEMIS2. For example, the previous measurements on all 32 channels of XT1 need 64×6 injections for each channel. If each injection, configuration and measurement are performed manually, it would not be possible to estimate the required time because each injection needs a change of the parameter value of XTRACT and the generator simultaneously. Based on this, we wrote a self-developed Slow-Control program with LabVIEW to realize automatic measurements, based on I2C Arduino card communication for XTRACT configuration and generator control. Nevertheless, the time required is still unacceptable for large quantities of electronic channel calibration. Considering that the injection frequency is 1 kHz, each measurement takes about five seconds on average since we need enough statistics to have the precise average value to achieve the ZC determination. One channel finally takes about 30 minutes. We spent almost 17 hours calibrating one XTRACT (32 channels). In XEMIS2, there are more than 20,000 electronic channels, that corresponds to more than 600 XTRACT cards. The total required time is therefore about 15 months, more than one year. Of course, we can simplify the test procedure, in order to shorten the acquisition time and reduce the injection measurement points. However, considering the different distribution of ZC in each channel, a non negligible number of measurements are still needed. Given this, a new fast and efficient calibration method needs to be established.

We proved that when the offset is well compensated, the discriminator has the highest counting rate. Therefore, we proposed the idea of obtaining *ZC0* through noise triggering with a threshold under the signal baseline level. Figure 4.11 shows the variation of the noise trigger rate with ZC values, the curve follows a Gaussian distribution. The position of maximum noise trigger counts corresponds to the *ZC0* value. This result is consistent with our assumption and proves the feasibility of this approach. In this measurement, neither a threshold nor an injected pulse signal is required, greatly simplifying the operation processes and the required time.

Calibration results

The ZCO values of two XTRACTs have been determined at room temperature and at operation condition. i.e., -80 °C. The corresponding distributions at room temperature is shown in Figure 4.12 while its dependence on the temperature is presented in Figure 4.13. The possible



Fig. 4.11 The noise trigger rate as a function of the ZC values showing a Gaussian behavior.



Fig. 4.12 ZC0 distribution of the two XTRACTs at room temperature (20 °C).



Fig. 4.13 ZCO values of XTO, at room temperature (20 °C) and at operational condition (-80 °C).

ZC0 values distribute in the whole dynamic range of DAC adjustment, gathering in the central zone. However, there are still two channels whose ZC0 is out of range. Given the importance of this compensation, we decided to expand the adjustment range of the DAC from \pm 20 mV to \pm 43 mV in the next version (XTRAXCT_V3) which will be used in XEMIS2. Besides, we can observe that the effect of temperature is not obvious. In most cases, changes are limited to one or two LSB units.

Conclusion

In this section, we introduced and observed the impact of ZC deviation from a theoretical point of view and we discussed the experimental aspects. According to the experimental results, we proved that the ZC value affects the time measurement, especially for small signals near the threshold. Two methods to determine the optimum ZC are proposed: time walk measurement and noise trigger count rate. Both methods showed satisfactory results, while the latter can greatly simplify the calibration process and reduce the required measurement time. Besides, a slowcontrol program has been developed based on LabVIEW to realize the automatic measurement of each channel that need to be calibrated in XEMIS2. The ZC tuning processes of a XTRACT chip can be accomplished within one second in the 32 multi-channel parallel measurement mode.

4.2.3 Threshold calibration

As described in the first section of this chapter, the amplitude measured at the threshold level is affected by the electronic noise of the input signal and the discriminator. The objective of this part concerns uniquely the calibration of the DAC threshold. The impact on the charge measurement will be detailed in the next section.

Slow Control The voltage of threshold of LED discriminator is adjusted by a 6-bit resolution DAC via the register I2C. The chosen architecture is a classic R/2R type architecture, same as the one used for DC current adjustment. This functionality allows to set the threshold at the desired value in considering different situations (gain, noise). The adjustment range of the DAC is \pm 43 mV corresponding to the LSB value of 1.344 mV.

S-curve fit

To calibrate the threshold DAC, we used the S-curve fit whose principle is shown in Figure 4.14. Considering that the electronic noise follows a Gaussian distribution, the detection efficiency is dependent on the utilized threshold level for a given amplitude signal at the LED input. The relation between the detected event number and the threshold value follows a Gaussian error function. The input signal amplitude and the threshold voltage have the same value when the detection efficiency is 50%.



Fig. 4.14 S-curve principle. Consider an input signal whose amplitude is the center value. The blue curve is the amplitude distribution of the signal under the effect of noise, which follows the Gaussian distribution. For a given number of shots, the detection count will vary with the threshold value, in the form of a Gaussian error function. The input signal amplitude and the threshold value are equivalent when the detection efficiency is 50%.

An example of experimental result is given in Figure 4.15. It represents the threshold DAC calibration of channel #0 of XT0. In this measurement, we sent a set of injection pulses of different amplitudes to the injection capacitor (50 fF) at the entrance of IDeF-X, namely 5 mV, 7 mV, 9 mV, and 11 mV. The number of injected pulses is 96000 for each amplitude. We scan the threshold across its whole DAC dynamic range for each input pulse and record the corresponding detection counts. The shaping time of the IDeF-X chip was configured at 1.39 μ s, and its gain was set to 200 mV/fC. A S-Curve fit was then performed to the histogram of the count number varied with the threshold DAC value. It is named the complementary error function (erfc) with the following expression:

$$f(x) = a \cdot \left(1 - \operatorname{Erf}\left(\frac{x-b}{\sqrt{2} \cdot c}\right)\right) \quad with \quad \operatorname{Erf}(x) = \frac{2}{\sqrt{\pi}} \cdot \int_0^x e^{-t^2} dt \quad (4.13)$$

where the parameters have the following impact:

- **a:** Scales the Erf-function, which is normalized to 1, to the number of triggers. The default value of a is set to 5,000 for 10,000 triggers. (a = p0 in our fit result.)
- **b**: Provides the desired threshold value V_T . It is the value of the x, at which the f(x) function reaches 50% of its maximum. The default value of b is determined dynamically and may be in the whole DAC-range. (b = p1 in our fit result.)



c: It represents the noise uncertainty σ_N , introduced in Equation 4.2, which is the convolution of the signal noise and the electronic noise of discriminator. (c = p2 in our fit result.)

Fig. 4.15 S-curve fit for threshold calibration of a single channel.

According to the S-Curve fit, we could therefore obtain the gain curve of threshold DAC, as shown in Figure 4.16. The data are well described by a first-order polynomial and show excellent linear behavior in the measured range. The DAC offset value corresponds to the fitting parameter p0, namely *TH0*. Its voltage is equal to the input signal baseline, i.e., the input amplitude is zero. The DAC gain can be calculated by 1/p1, representing the voltage value of the input signal corresponding to a LSB unit. It can also be converted to a charge value knowing the value of the injection capacitor.



Fig. 4.16 Threshold calibration results of a single channel.
Calibration results

The threshold calibration result of XT0 is shown in Figure 4.17. The fluctuation of all 32 channels in TH0 and gain is not notable. Non-correlation between two variables could be observed. Besides, the comparisons of the discriminator characteristics of two XTRACTs on TH0 and gain are given in Figure 4.18 and Figure 4.19, respectively.

All those distributions follows a Gaussian distribution showing good uniform performance.



Fig. 4.17 Offset (TH0) and gain values of threshold DAC (XT0).

The average TH0 is about 30 DAC value placed in the center of the dynamic range. The average gain is about 0.52 mV/LSB. Considering that the injection capacitor is 50 fF, we have, therefore, that a LSB corresponds to \sim 26 pC, i.e., \sim 167 electrons. This value will be compared with the noise level of our electronics chain in the following discussion.



Fig. 4.18 Distribution of TH0 DAC value of the two XTRACTs.



Fig. 4.19 Distribution of threshold DAC gain of the two XTRACTs.

Conclusion

In this part, we discussed the threshold DAC calibration of both XTRACTs. A brief theoretical introduction about the leading-edge discriminator has been given at the beginning of the section. The threshold determination is based on the S-curve fit technique. To accomplish the calibration of all 64 channels, 4 x 64 pulse injections are needed, together with 4 x 64 x 64 measurements, 4 x 64 S-curve fits, 64 linear fits. Given the numerous operations, we developed a Slow-Control program, similar to that used in the ZC determination, to realize the automatic measurement. The experimental results show the excellent homogeneous performance of the two XTRACTs whose average TH0 value is 30 with a 4-6 RMS fluctuation over the 64 channels. The DAC gain is about 26 pC/LSB, corresponding to 167 electrons per LSB. The threshold value used in the operating conditions will be discussed in the next section.

Section conclusion

We achieve to find the expected delay time with which the registered amplitude is located on the signal peak position at the CFD trigger timing. The delay time parameter is in common for all 32 electronic channels of a XTRACT chip. The standard deviation of the crossing time is less than 20 ns per XTRACT. Then we introduce the impact of ZC value on the time-walk. ZC0 conduces a quasi-perfect time measurement with a slight time-walk that can be neglected. Meanwhile, it leads to a minimum voltage difference between the delayed signal and attenuated signal at the Zero-Crossing comparator, resulting in a maximum noise trigger count rate which can be used in return to determine the ZC0 DAC value. This determination method significantly reduces

the complicity of the ZC calibration process. At the end of the section, the threshold DAC calibration is presented. It has an excellent linear behavior whose offset and gain are measured. The overall DAC calibration result is promising. In the next section, a further adjustment will be discussed with the aim of optimizing the charge measurement.

4.3 Charge measurement optimization

For Compton sequence identification and reconstruction, the detector requires both good energy and position resolution, obtaining through the charge measurement. Using the segmented anode optimized with the MIMELI technique, we have achieved an exceptional performance of charge extraction from the LXe TPC. Meanwhile, the downstream electronic chain was carefully optimized to measure small charges. This section discusses the DAQ performance at the tiny charge level and the optimization process.

4.3.1 Low noise and threshold requirement

Compared to the whole signal sampling with an external trigger, the self-trigger detection method demands threshold discrimination for signal selection and noise elimination. For the signals whose amplitude is around the threshold level, the detection efficiency and measurement uncertainty are both impacted. A low threshold level is therefore strongly required in our detection set-up.

Nonlinear response: threshold effect

The use of thresholds also produces a non-linear charge response in a small amplitude range. This phenomenon has been studied via simulation. It is interesting to have an experimental measurement to compare the amplitude measured by the "CFD" with and without setting a threshold.

Method The standard operational process of XTRACT directly provide CFD measurements that can be used to study the impact of a threshold. The use of the trig_in mode of XTRACT is intended to operate an ideal CFD measurement. As presented at the beginning of the chapter, the trig_in way provides an external trigger without CFD while the amplitude and time memorizing process are the same. This approach has been chosen by considering that the ideal CFD trigger timing point is constant (at the peak time) with no dependence on the input signal amplitude. To fix the trig_in timing position, the amplitude measurement for different value of trig_in

time has been studied in the first place. The output data reproduce the IDeF-x output signal waveform. We set, therefore, the trig_in time at 1.61 μ s to measure the peak amplitude.



Fig. 4.20 The waveform of the IDeF-X output signal measured by DAQ with trig_in mode.

Result and discussion The experimental results are showed in Figure 4.21. A set of injection charges in the range of [0.05, 5] fC has been realized via two methods. A first-order polynomial is used to fit the measurements (red line) in the chosen range showing a good linear response. However, as mentioned, we can observe a non-linearity with the threshold at small amplitude in the zoomed figure. This phenomenon is the typical effect related to the electronic noise and



Fig. 4.21 Comparison of linear responses between the ideal CFD (trig_in at the peak time) and the XTRACT (CFD + threshold comparator). (right) zoom in the region of interest.

threshold. It can be explained through Figure 4.22. For the same input charge, we superimposed the distributions of measured amplitudes applying or not a threshold. The blue line histogram (H1) correspond to the case where no threshold has been applied: it follows a Gaussian distribution represented by the blue line (function G). The black-filled histogram (H2) is the amplitude measured with a threshold whose distribution is no longer symmetric. Instead of characterized by a product of H1 and Heaviside, H2 is well described by a semi-Gaussian distribution that can be explained as the result of a convolution between the noise introduced from the input signal and the discriminator effect. The threshold effect has been taken in consideration of the discriminator effect. The simulated threshold effect is represented by the function (T) and it is represented by the red line in the figure. The distribution of the measured amplitudes when applying a threshold can be well reproduced by the multiplication of G and T.



Fig. 4.22 Threshold effect simulation. The blue line histogram (H1) corresponds to the amplitude without threshold: it follows a Gaussian distribution represented by the blue line (function G). The black-filled histogram (H2) is the amplitude measured with a threshold whose distribution is no longer symmetric. The red line is the simulated threshold effect (function T) considering the discriminator electronic noise fluctuation. The product of those two functions, G and T, shows a perfect fit on the histogram H2.

Threshold determination

To reduce the impact of the non-linearity on small charge measurement, the direct method is to decrease the threshold as low as possible. However, there is a trade-off between threshold level and noise triggers occupation rate. Figure 4.23 shows the simulation result of the noise count rate over the threshold with and without CFD. Obviously, the noise count rate explodes with the threshold level reduction. The limit acquisition rate per electronic channel is 4000 c/s, corresponding to an extreme threshold about 3 times of SNR. It is thus the desired threshold, namely THC, during the operation. The THC could be calculated through the threshold DAC



Fig. 4.23 Simulation result of noise count rate over threshold with and without CFD in logarithmic scale.

calibration presented in the previous section. However, such a complicated experimental process is not adapted for XEMIS2 with more than 20,000 electronic channels. Another method has been adopted and the corresponding results are shown in Figure 4.24. It consists in using only one S-curve for the injection signal of six noise sigmas per channel instead of completing the whole calibration process. The reason not to choose a standard three noise sigmas is to avoid noise triggers on the measurement efficiency. Since the threshold value is related to the noise level, an iterative approach will be needed to find the new threshold. Even with 32 channels, the S-curve is too complicated, let alone the 20,000 channels of XEMIS2. Finally, an empiric



(b) 32 channels of XT0

(a) Channel #7 of XT0 Fig. 4.24 S-curve of an injection signal of 6 noise sigmas.

method is adopted to determine the THC level with the noise trigger rate without injection. So, a rapid daily repetition is acceptable, providing an adjustment before each physical running.

Conclusion

This part gave a brief description and demonstration of the non-linear charge measuring response just above threshold as expected. It is a reasonable phenomenon due to the signal selection method. Still, it will significantly impact small charge measurement since no pulse waveform would be registered in our DAQ. The energy reconstruction is directly based on the measured amplitude, which is biased by this non-linearity response. To reduce the impact, we need to use as small as possible the hardware threshold. Nevertheless, this threshold should not be much smaller than three times the sigma noise level in order to reduce the trigger noise. Thus, that dependence conduces a lower possible ENC (equivalent noise charge) level presented in the detector and the whole DAQ electronics.

4.3.2 Studies of fake triggers

After the XTRACT DAC parameters calibration process, we started the first physical run with the XEMIS1 detector under operating conditions. As mentioned above, we set the DC correction current to ZC0 and set the threshold to 3 times to the noise level, $TH_{3\sigma}$. In the first test run, two hours of physical operation data have been acquired and analyzed. For several pixels, the noise occupancy rate is so important that there is not enough useful physical data. This section will focus on this phenomenon and carry out the investigation.

Phenomenon description

In this paragraph we will discuss an example of the most affected electronic channel to describe this phenomenon more clearly. However, it is worth noting that not all tested channels have such severe defects. Figure 4.25 shows the raw data of amplitude measured near the threshold of channel #31 of XT1 (corresponding to the pixel #63). The distribution is displayed in logarithmic scales on the y-axis. In addition to the expected signals exceeding the threshold (corresponding to the peak above threshold), there is an apparent second peak in the colored part below the threshold (i.e., 1025 ADC), corresponding to a huge number of events. Besides, we can even observe a part of events under the baseline (i.e., 976 ADC). Such important fake triggers cause a high DAQ occupancy rate, increasing the acquisition dead time. This phenomenon dramatically affects the detector performance, so the following tests have been conducted to identify the issue.



Fig. 4.25 The amplitude distribution measured near the baseline. The blue part indicates the amplitude lower than the set threshold.

In the first step, using the same settings as for the physic run, an injection test was performed on the observed channel (pixel #63) to reproduce the phenomenon. The measurement result of an input voltage of 80 mv is shown in Figure 4.26. The measured amplitude is shown as a function of the measured time, where the injection time is set to zero on the x-axis. The injection pulse signals are well measured. The zoomed image is displayed in the inset black frame. Nevertheless, after 5 μ s of the pulse signals, a spot of noise signals was recorded. It shows the same amplitude distribution with the noise peak present in the physic data. Other noise signals are discretely distributed over the entire time range except for the zoomed area. This result indicates that those abnormal registered noise signals mainly appear following the physic signals. Given that their amplitude is under threshold. The problem may come from the threshold comparator.

When needed, each XTRACT is equipped with an electronic channel for chip debugging, that can output a single analog signal among the attenuated, delayed, CFD, or threshold. Figure 4.27 shows the observation of false triggers observed with the oscilloscope. There are three trigger signals (red) in the TOT window (green). However, by observing the output attenuated analog signal (blue), only the first trigger corresponds to an over-threshold signal while two others are generated by electronic noise. As mentioned in the previous chapter, the presence of double trigger at the leading or trailing pulse is expected as it is due to the noise impact. However, we observed a 16 μ s TOT window which was unexpected. This phenomenon can only be explained by the fact that the hysteresis of the comparator is bigger than expected, leading to a trailing



Fig. 4.26 Measured amplitude as a function of the time difference between the injection pulse and the measured time. Zoom in the regions of interest.

threshold (the difference between the set threshold of hysteresis) lower than the baseline. The following part will describe the hysteresis measurement and a new ZC value adapted to reduce the noise trigger and optimize the charge measurement linearity.



Fig. 4.27 Observation of fake triggers with the oscilloscope (channel #31 of X1 - pixel #63). Signals presented in the screen are: (blue) attenuated injection signal, (green) over threshold time window, (red) trigger signals. Two false triggers are following the true pulse signal.

Hysteresis measurement

We have tried to qualitatively estimate the hysteresis value from the physic data, as shown in Figure 4.25. There is no suitable method to evaluate the hysteresis with registered data from XTRACT. Given that the test channel of XTRACT could deliver the attenuated and delayed analog signals, the hysteresis was measured with an oscilloscope. The amplitude difference between the leading edge and trailing edge give the hysteresis with an attenuation factor. It required firstly to determine the attenuation factor before calculating the hysteresis value.

Attenuation factor The maximum amplitudes of the attenuated (subscript denoted as a) and delayed (subscript denoted as d) signals, averaged on 1000 samples are:

$$\overline{Amp}_{a} = 10.010 \ mV$$
 and $\overline{Amp}_{d} = 13.240 \ mV$

assuming the delayed signal is also slightly attenuated by a factor of 5 %, we have therefore:



$$\alpha = \frac{Amp_a}{\frac{\overline{Amp_d}}{95\%}} = 0.718$$

Fig. 4.28 Measurement of the attenuation factor of channel #31 of the XT1.

The attenuation factor of the test channel #31 of XT0 is 0.721 following the same measurement. The experimental result is in agreement with the design specification value, which is 0.7 within a deviation of 5%.

Hysteresis For channel #31 of XT1, on the attenuated signal, we measured with a probe $\times 10$ during 1000 samples:

- 1. The amplitude of the leading trigger position: $\overline{Amp}_l = 56.480 \text{ mv}, \sigma_{Amp_l} = 0.067 \text{ mv}$
- 2. The averaged and standard deviation of the amplitude at the trailing trigger position: $\overline{Amp}_t = 55.374 \text{ mv}, \sigma_{Amp_t} = 0.069 \text{ mV}$



Fig. 4.29 Hysteresis measurement on the attenuated signal on channel #31 of XT1.

The hysteresis is thus:

$$hys = \frac{(\overline{Amp}_l - \overline{Amp}_t)}{\alpha} \times 10 = 15.404 \ mV \tag{4.14}$$

The hysteresis of the test channel #31 of XT0 was 15.589 mV, it has been obtained using the same procedure previously described for the test channel #31 of XT1. The experimental result shows a hysteresis of about 15.5 mV for the two channels #31 of the two XTRACTs. Considering the gain of 200 mV/fC, the hysteresis is therefore 484 electrons, equivalent to 6 times the ideal noise (80 electrons) or 3.2 times the current noise (150 electrons).

Please note that, it could not be considered as a defect since, as mentioned in many articles, the hysteresis of comparator used in the ASIC is generally about dozen millivolts. The design specification on current consumption mainly limits it. Besides, those two test channels present a more important hysteresis than others (observed with physic data) meaning that the average hysteresis is lower than 15 mv. We observed the phenomenon, namely hysteresis "defect", which results from the low threshold used in our set-up. The following part will describe a new ZC tuning adapted to reduce the trigger rate and optimize the charge measurement linearity.

4.3.3 ZC tuning for charge measurement

In the previous section, we find a ZCO allowing XTRACT to perform a perfect CFD operation. i.e., no time-walk. It also corresponds to the setting for which the trigger rate was maximum without any threshold. This feature enables us to determine ZCO by the noise trigger rate. In addition to minimizing the time step, the DC bias added to the CFD discriminator in the actual operation conditions is also intended to reduce noise triggering by producing a smaller offset. In our case, the primary purpose is to optimize the amplitude measurement to ensure the reconstruction of the deposited energy. A new ZC setting value is required to reduce noise triggers and optimize the amplitude measurement based on this goal.

Effect on charge measurement

Figure 4.30 shows a study of the non linearity on the amplitude measurement induced by ZC settings. The test procedure is the same as that of the charge linearity measurement, described in Section 4.4.2. For each input charge, the mean value (\overline{Amp}_m) of the ADC amplitude of detected



Fig. 4.30 Nonlinearity of amplitude measurement with the ZC setting.

events is provided by a Gaussian fit. The behavior of ZC in the large charge range is pretty uniform, as discussed in Section 4.2.2. A first-order linear fit function describes the charge measurement performance, which is also discussed in this section.The differential non-linearity (DNL) is calculated as:

$$DNL = \frac{\overline{Amp}_m - Amp_{fit}}{Amp_{fit}} \times 100\%$$
(4.15)

where Amp_{fit} is the value calculated with the linear fit function. Since the same analysis is performed for all ZC values, the standard binning error is not considered. Different ZC responses are not homogeneous in the small charge range under the same measurement condition. We compared the time and amplitude measurement response between two ZCs: ZC0 (DAC = 18), showing the best CFD timing performance, and the ZC (DAC =29) with which the DAQ presents the most desirable charge linearity. Figure 4.31 shows the experimental result. The corresponding trigger rate rates are given in Figure 4.32. The noise trigger rate of 20 kHz was then chosen as the desired setting for ZCC determination. A slow-control program has been developed to auto-set the parameters, and is presented in the next chapter, where the uniform response of ZCC is also discussed.



Fig. 4.31 Comparison of the time and amplitude measurement response between two ZCs: ZC0 (DAC = 18), showing the best CFD timing performance, and the ZCC (ZC for charge measurement) (DAC =29) with which the DAQ shows the most desirable charge measuring linearity.

Section conclusion

This section discussed the choice of parameters used in operational conditions for charge measurement optimization. A non-linearity amplitude measurement due to the use of threshold has been discussed in the first place. The low electronic noise and hardware threshold are therefore required to have an excellent small charge measurement. Meanwhile, the LED comparator hysteresis might cause an overmuch noise trigger rate with the ZCO setting. After the experimental



Fig. 4.32 The noise count rate corresponding to the ZC0 (red dashed line) and ZCC (black dashed line).

investigation, the phenomenon results from the ultra-low threshold has been employed in our detection set-up. We discussed how increasing the electronic gain or reducing the fake triggers are two possible solutions to this problem. Given that the gain of IDeF-X is already set to its maximum value (200 mV/fC), a favorite ZC setting shift is proposed to reduce the false triggers and optimize charge measurement linearity. The ZC bias is a pretty typical method for reducing the noise trigger from the CFD discriminator, working as a threshold [167]. After studying the relation between the ZC and charge measurement response, we choose ZCC, whose noise count rate is about 20 kHz, as the desired setting parameter. The following section will give the self-developed slow control program of parameters self-finding and the corresponding calibration results.

4.4 Overall performance calibration

This section will show the calibration results of the novel DAQ chain prototype in the operation condition. They are essential for the following physical data analysis, which will be discussed in the next section. The performances on both charge and time measurements are presented, including the linear response of electronics, the nonlinearity of the employed threshold, and the corresponding time walk and time jitter of amplitude variation.

4.4.1 Calibration procedure

Since, about 20000 electronic channels need to be individually calibrated in XEMIS2, we develop a method to obtain all parameters with only one data taking. The method is illustrated in Figure 4.33. The data taking was realized with the help of the scintillation DAQ chain to provide the reference time (see Figure 4.33). Firstly, we need to launch the noise triggers rate



Fig. 4.33 Diagram schematic of the experimental calibration set-up.

measurement, which is discussed above. This step has been optimized and automatized to generate the configuration file containing the *ZCC* and *THC* value of all 64 channels. After the configuration of two IDeF-X and XTRACT units, the slow control program (presented in the next section) will send the command to the pulse generator to produce 30 signals with amplitudes in the range of 1 mV to 200 mV. The variable amplitude signal was sent to the input capacitor of IDeF-X for DAQ calibration. Its synchronized logic signal (\pm 5 V) first passed through two attenuators of 14 dB to reduce the amplitude, then it is sent to the XSRETOT as a time trigger. The recorded data of two synchronized systems need matching during the offline analysis to provide the time-related information.

Slow control development for automatic measurement

During the whole DAQ testing procedure, lots of short slow control programs have been developed to reduce the experimental operation time. This part will briefly introduce three self-developed slow control programs dedicated to optimizing and automatizing the calibration process, including ZC, threshold, and overall calibration. Those prototype programs were specially developed for XEMIS1. However, the methodology will be implemented in the future PU card for the XEMIS2 electronics calibration.

ZC settings For XEMIS2 calibration process, select the noise trigger count rate as the measurement method to determine the ZCO and ZCC corresponding to peak value and 20 kHz

count rate. To realize the daily calibration of the detector data acquisition system, we developed a Slow-Control program with LabVIEW to realize automatic measurement. The user interface (UI) is shown in Figure 4.34. The UI is intended for daily use by non-expert people. The default values of IDeF-X and XTRACT configuration parameters are programmed internally such that no additional setting is demanded. To start the measurement, we need only to choose the corresponding address of XTRACT and click the start button. Then the program will scan all ZC values and record the noise counts channel by channel. The results, i.e., the values of ZC0 (and ZCC) of all 32 channels in hexadecimal, are registered in a text file at the local disk.



Fig. 4.34 Slow control interface dedicated to automatic ZCC determination.

The program was not originally designed for multi-channel parallel operation to avoid overloading the acquisition system due to high occupancy. However, the current test results proved that 32 channels could be operated at the same time. The comparison is shown in Figure 4.35. Compared with single-channel measurement, the maximum count rate is slightly degraded. This phenomenon is explicable by considering that multi-channel triggers could result in the time ramp extension, leading to the dead time increase. Nevertheless, the peak position is always located at the ZC0 value and the counts at 20 kHz is not degraded. In other words, the result will not be changed, and the calibration duration could be further reduce by a factor 32.



Fig. 4.35 Comparison of ZC searching results in different measurement modes: the red curve is measured in the one channel mode and the white curve corresponds to the 32-channel mode.

TH settings The interface of the same type of slow control program for TH setting is shown in Figure 4.36. Since it is also based on the noise trigger rate, we need to choose the desired ZC file

before launching the program. A considerable deviation exists around the desired 1500 counts per second. The step of a threshold ADC is more than 150 electrons (sigma noise presented in this calibration work while the actual noise level has been reduced to less than 120 electrons). The searching process is optimized with the Bisection method to find the desired TH. When the count rate arrives at the demand window and close to 1.5 kHz, the TH DAC value will be written in the text file. Like the ZC program, the THC program was not designed for multi-channel



Fig. 4.36 Slow control interface dedicated to automatic THC determination.

parallel operation to avoid overloading the acquisition system due to high occupancy. Figure 4.37 shows the comparison of the 32 multi-channel (white points) with single-channel (red points) modes. No significant difference can be observed: this allows determining all THC at once.



Fig. 4.37 Comparison of TH searching results in different measurement modes: the red curve is measured in one-channel mode and the white curve is the result obtained in 32-channel mode.

Calibration program Once loading the correct ZCC and THC configuration files, the slow control program sends the command to the pulse generator to produce 30 pulse signals with predefined injection amplitudes in the injection text file. Its synchronized logic signal (\pm 5 V)

first passed through two attenuators of 14 dB to reduce the amplitude then sent to the XSRETOT as a time trigger.

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	4 5 6 7 8	9 10 11	12 13	14 15	16 17 18 1	9 20 21 22	23 24 25	26 27 28 29	30 31

Fig. 4.38 Slow control interface dedicated to automatic calibration process.

Data acquisition and processing

For each input voltage with the generator frequency of 1 kHz, a packet of 20 x 80 ms data is registered per channel, corresponding to 1,600 events. Since the threshold is so low (noise count rate about 1.5 kHz) a comparable quantities of pulse and noise signals are recorded. To avoid the noise bias to the calibration, the first step of the calibration data process is the signal matching. A time window of 2 μ s after the "PM" leading edge time is opened for "charge" data matching. This process allows removing most of the noise signals. We then use a Gaussian fitting to estimate the mean value and the standard deviation of the distributions, since Gaussian parameters are less affected by the remaining noise signals within the matching window. A measurement example after matching procedure is shown in Figure 4.39. We can clearly observe the variation of the output time and amplitude with the different input voltages.



Fig. 4.39 Results of time and amplitude measurement with different input voltages.

4.4.2 Electronic response to charge measurement

4.4.2.1 Charge linearity

Figure 4.40 shows the measured amplitude, the mean value of the Gaussian fit over the 1600 events, as a function of the injected charge of all 64 electronic channels of XEMIS1 at the detector operation conditions. The red lines are the first-order polynomial fit functions. The following



Fig. 4.40 The linear response of all 64 electronic channels in XEMIS1.

results could be concluded from this data analysis:

A. Linear Response Figure 4.41 (a) shows the central value of the Gaussian fit of measured amplitude over the 1600 events, as a function of the injected charge. A first-order polynomial excellently describe the linear behavior in the dynamic amplitude range. The IDeF-X ASIC starts to saturate at an input voltage of 220 mV for a gain of 200 mV/fC. For an injection capacitor of 50 fF, the saturation charge is about 12.5 fC (\sim 7.8×10⁴ electrons). This roughly corresponds to the charge generated by a photoelectric effect of 1.4 MeV under an electric field of 2 kV/cm (calculated with NEST). The dynamic range effectively satisfies the required energy interval, i.e., maximum 1.274 MeV, for the detector calibration. However, a slight non-linear response could still be observed in the domain of small charge (see Figure 4.41 (b)) just above threshold. The percentage of non-linearity will be given later.



Fig. 4.41 Measured amplitude as a function of the injected charge for pixel #1 of the anode. The first-order polynomial fit shows the perfect linear response of the electronic device in all dynamic ranges except a slight non-linear response in the small charge region due to the threshold.

B. Signal conversion from ADC to electrons From the fit function, the conversion between input charge (Q_{in}) and measured amplitude in ADC counts (Q_{ADC}) is given by the following formula:

$$N_{ADC} = p1 \times Q_{in} + p0 \tag{4.16}$$

where p0 and p1 are the parameters of the linear fit. We can therefore calculate Q_{in} from the recorded amplitude in ADC counts (Q_{ADC}) through:

$$Q_{in} = \mathcal{K} (N_{ADC} - \mathcal{B}) \quad with \quad \begin{cases} \mathcal{B} = p0\\ \mathcal{K} = \frac{1}{p1} \end{cases}$$
(4.17)

where \mathcal{B} is the baseline offset in ADC counts (pedestal) and \mathcal{K} is the conversion coefficient, i.e., the input charge that is equivalent to an ADC unit. Both ADC-amplitude parameters are required for each electronic channel during the data conversion. Figure 4.40 presents all the linear fits of 64 electronic channels of XEMIS1 at operation condition. The distribution of the offset or baseline \mathcal{B} and the conversion coefficient \mathcal{K} could be found in Figure 4.42 and Figure 4.43. The data shows that the baseline \mathcal{B} t is significantly related to the memorization of the signal by XTRACT, which manages 16 electronic channels in common. This translates into the fact that the baseline voltage of each memory module is different. On the contrary, the



Fig. 4.42 Offset distribution of the amplitude-ADC (64 electronic channels). The data displays that the ADC channel number is related to the amplitude memory of XTRACT, which manages 16 electronic channels in common.

ADC-amplitude gain \mathcal{K} distribution shows a perfectly homogeneous response whose averaged value is about 31.5 e⁻/ADC with a Gaussian-fit RMS of less than 0.2 e⁻/ADC.



Fig. 4.43 Amplitude ADC gain of all 64 electronic channels. A Gaussian fit characterizes each set of 32 channels belonging to one XTRACT.

C. Electronic gain According to the experimental results, Figure 4.44 shows the electronic gain \mathcal{G} of the overall electronic chain, calculated as:

$$\mathcal{G} = \frac{\mathcal{U}_{ADC}}{\mathcal{K}} \tag{4.18}$$

where \mathcal{U}_{ADC} is the voltage step corresponding to a single ADC channel. As the signal amplitude is encoded by a 12-bit resolution ADC in the PU card with a dynamic range of \pm 2 V, then the \mathcal{U}_{ADC} is equal to 0.977 mV. From the distribution, we observe:

- 1. The output electronic gain \mathcal{G} is globally lower than the IDeF-X gain (i.e., 200 mV/fC) of less than 4%. The relative gain difference is within a 5% tolerance range of the IDeF-X fabrication specification. Additionally, it might also be affected by the CFD settings and amplitude memory block gain dispersion.
- The 32 channels output from the same IDeF-X and XTRACT ASIC have minimal gain deviation of about 5‰. This result proves the excellent consistency of the electronic modules.



Fig. 4.44 Electronic gain at the output of the whole DAQ chain.

Conclusion The study of electronic linear response has shown satisfactory results. Despite a slight non-linear response near the threshold, it shows an excellent linearity performance within the dynamic range. Using a first-order polynomial to fit the data, the offset and gain of the amplitude ADC can be obtained, that is essential for physical data analysis. Also, we estimated the amplitude gain of the entire signal acquisition chain. The deviation from IDeF-X gain is less than 5‰, and the homogeneity response observed over 32 electronic channels in a unit module is within 1%.

4.4.2.2 Equivalent noise charge

The equivalent noise charge of the entire DAQ chain is extracted by the parameter sigma of the Gaussian fit of the input signal amplitude. The experimental result for all 64 channels is presented in Figure 4.45. The electronic noise of a DAQ unit (32 channels) is pretty homogeneous with a sigma of less than 5 electrons respecting the Gaussian fit. The average ENC of two units is around 141 ± 5 electrons.



Fig. 4.45 Equivalent noise charge of 64 electronic channels. The distribution per ASIC is well described by a Gaussian function.



Fig. 4.46 Observation of noise source of 15 kHz: distribution of the time difference between two successive triggers measured under condition of charge injection.

As discussed in the previous section, an ultra-low noise level is required in our experiment. Compared to the desired ENC of 100 electrons, noise minimization work is still undergoing. Recently, we have identified a noise source of 15 kHz by measuring the time intervals between two successive triggers, see Figure 4.46. This is caused by the device components of the detector that are powered by different power supplies in the experiment. Using a single power source for all devices, the noise level at room temperature is reduced to about 120 electrons. Further testing is in progress.

4.4.2.3 Quasi-linear response near threshold level

Figure 4.47 shows the relative non-linearity of the amplitude response, calculated from Equation 4.15. All 64 electronic channels show a high level of uniformity under the experimental



Fig. 4.47 Relative non-linearity on amplitude measurement.

settings. The maximum non-linearity, 30-50%, appears for an input charge of around 300 electrons. The non-linearity is largely related to the threshold value as discussed previously. Since the threshold is set according to a predifined count rate of around 1.5 kHz (Figure 4.48 (a)), its equivalent charge is not known in advance. Figure 4.48 (b) shows the threshold estimation through the S-curve fit of the detection efficiency as a function of the input charge. The fit is not precise enough, limited to the minimum increment of the input voltage. A more tiny injection increment should be implemented during the future calibration process. The estimated equivalent threshold charge of each electronic channel is presented in Figure 4.49. The missing channels are those that could not be well fitted. For those channels presented in the figure, their equivalent threshold charge looks relatively homogeneous, with an average value of around 350 electrons and a standard deviation of 40 electrons. This result translates into an observed



Fig. 4.48 The threshold value estimated by the detection efficiency as a function of the input voltage.

non-linearity of 30-50% for an input charge of about 300 electrons. It corresponds to about 150 electrons. i.e., one sigma of noise level, of charge measurement error.



Fig. 4.49 The distribution of estimated equivalent threshold charge.

Conclusion

This part presented the calibration result related to the charge measurement. A satisfactory linear response has been observed. The slight non-linearity near the threshold is about one sigma of noise level, not more significant than the contribution of the noise itself to the amplitude measurement. The overall DAQ performance for the charge measurement is promising.

4.4.3 Time measurement discussion

Since the overall setting of DAQ prioritizes charge measurement as a result a non-negligible time walk is introduced, which needs to be corrected during the physical data analysis process. This section will present the calibration results of time walk and time jitter.

4.4.3.1 Time walk

Time-walk is the deviation of the trigger timing point with the input signal amplitude, especially for small amplitude. As mentioned above, in the high input voltage range, the measured time is very stable and hardly affected by other factors, that is, the constant \mathcal{T} . Since we have matched the "charge" data with the "PM" data, the measured time is the delay time relative to the leading edge trigger time of the synchronous "PM" signals. Figure 4.50 displays the distribution of trigger time \mathcal{T} of all 64 channels. \mathcal{T} is obtained by the average value in the measurement input



Fig. 4.50 Average delay time relative to the synchronized PM signal (injected).

range of 100-200 mV. The result of the gaussian fit indicates an excellent uniformity of all tested electronics channels. The average CFD triggering time of all 64 channels is about 1750 ns with a standard deviation lower than 15 ns. This time is slightly different from the previous test because we changed the experimental settings between them.

The time-walk of 64 electronic channels has been measured and displayed in Figure 4.51. Except for the two channels whose ZCC is out of the dynamic range of the DAC, the remaining 30 channels all show an homogeneous response. The time-walk effect increases with the decrease in the signal amplitude. In this test, a shifted time difference of \mathcal{T} could rise at 600 ns at the



threshold level. This deviation is not negligible, it should be corrected during the physic data analysis. The time-walk correction result will be presented in the next chapter.

Fig. 4.51 Time walk measurement results as a function of the input charge for the 64 channels.



Fig. 4.52 Time jitter measurement results as a function of the input charge for the 64 channels.

4.4.3.2 Time Jitter

For a given input pulse, time jitter is the fluctuation of the trigger timing position, which is affected by the electronic noise from the input signal and the discriminator. Its value can be extracted by the sigma of the Gaussian fit on the measured time distribution. The measurement

result is displayed in Figure 4.52. Like for the time walk performance, the time jitter of all electronics channels presents a homogeneous response in the small and large charge measurement intervals. Low-amplitude measurements near the threshold are highly impacted by a large noise fluctuation effect, resulting in a time jitter of about 500 ns r.m.s.

On the contrary, in the large amplitude region, the influence of electronic noise is negligible. The ADC clock inside the DAQ limits the time measurement accuracy, 100 MHz in our case. The resolution of the clock $(10/\sqrt{2} ns)$ is in good agreement with the measured jitter of about 7 ns. A comparison (Figure 4.53) has been made with the previous work consisting in a simulation study (with ROOT and Geant4) of the recoil electron trajectory in LXe³. Considering the drift velocity of about 2.3 mm/ μ s under an electronic field of 2 kV/cm, the time jitter effect dominates the Z position resolution of the detector in the charge range under 12,000 electrons, i.e., about 220 keV. Above 12000 electrons, the Z position resolution is dominated by the uncertainty of the position of the electronic cloud. The best z-position resolution is achieved at about 200 keV. An excellent z-position resolution of 100 μ m could be obtained within a range of around 5000-22000 electrons, i.e., 100-400 keV.



Fig. 4.53 Contributions detector and liquid xenon on Z position resolution.

Section conclusion

This section gives a general description of the calibration procedure to be used to XEMIS2 in the future. The experimental results showed in this section have been obtained in XEMIS1 under the same operating conditions that will be applied to XEMIS2. The response of the entire system to

³The subject of my Master's thesis.

the charge measurement is satisfactory: a good linearity and a negligible non-linearity near the threshold (of less than one sigma of noise) have been obtained. The time-walk induced by the measurement settings can be corrected using the calibration results, which will be discussed in the next section. In the small charge range, time jitter is the dominant factor to the z-position resolution.

4.5 Conclusion Chapter 4

This chapter reports the experimental calibration and optimization of the novel DAQ prototype electronic chain in XEMIS1 under the operational condition of XEMIS2. It consists of one theoretical introduction section and three experimental sections.

The first part summarizes the overall DAQ electronics operation principle and data acquisition process, where the self-triggering operation concerning the time and amplitude acquisition is detailed. Furthermore, we present and discussed the impact of the four critical parameters: the threshold (TH) and hysteresis of the Leading Edge Discriminator (LED) (that defines the signal section range), the delay time and DC of the zero-crossing comparator (ZC) (that impacts the trigger timing position). Except the hysteresis which is a comparator technical property, all others parameters are adjustable.

The second part of the chapter is dedicated to the DAC parameters calibration. The optimized delay time allows registering amplitude on the signal peak position at the CDF trigger timing. The delay time parameter is in common for all 32 electronic channels of a XTRACT chip. The standard deviation of the crossing time is less than 20 ns per XTRACT which is satisfactory for the spatial resolution. Considering the impact of the ZC value on the time-walk, we found a ZC0 value for which the DAQ has a quasi-perfect time response with negligible slight time-walk. The threshold DAC calibration is presented at the end of the section. It has an excellent linear behavior whose offset and gain are measured.

The third part discusses the choice of parameters uses in the operational condition for charge measurement optimization. A precise small charge measurement is critically required due to the charge sharing effect at the anode level. The utilization of a threshold conduces a non-linearity response at the tiny charge range. Thus, an as low as possible electronic noise and threshold level is required. The threshold during the operation condition is determined at the noise trigger of about 1.5 kHz, corresponding to three times the noise level. However, given that the comparator hysteresis is much higher than one sigma of noise, such a low threshold might result in the inefficiency of the trailing edge threshold. This phenomenon conduces a series of failure triggers in certain electronic channels. The ZC bias is a typical method for reducing the noise trigger in the CFD discriminator, working as a threshold, which could compensate for the hysteresis

effect. After studying the dependence of the ZC value with the linear charge response, another ZC value, namely ZCC, is chosen to be used during the experiment.

A non-linearity amplitude measurement due to the use of threshold has been discussed. A low electronic noise and hardware threshold are therefore required to guarantee an excellent small charge measurement. Moreover, the LED comparator hysteresis might cause an exposed noise trigger rate in the ZCO setting. After the experimental examination, the phenomenon results from the ultra-low threshold employed in our detection set-up. Increasing the electronic gain or reducing the noise triggers are two possible solutions. Given that the gain of IDeF is already set at 200 mV/fC (maximum), a favorite ZC setting shift is proposed to reduce the false triggers and optimize charge measurement linearity. The ZC bias is a pretty typical method for reducing the noise trigger in the CFD discriminator, working as a threshold. After studying the ZC and charge measurement response relation, we choose ZCC, whose noise count rate without threshold is about 20 kHz, as the desired setting parameter. This choice enables reducing failure triggers and optimizing the linear response on charge measurement.

The final section gives a general description of the calibration procedure to be used for XEMIS2 in the future. Furthermore, the current experimental results have been obtained in XEMIS 1 under the same operating conditions that will be used for XEMIS2. The response of the entire system to the charge measurement is satisfactory: a good linearity and a negligible non-linearity near the threshold of less than one sigma of noise) have been obtained. The time-walk imported through the measurement settings can be corrected using the calibration results, which will be discussed in the next section. In the small charge range, time jitter is the dominant factor to the z-position resolution. An excellent z-position resolution of 100 μ m could be achieved within a range of around 5000-22000 electrons, i.e., 100-400 keV.

XEMIS2 Performance Estimation using ^{22}Na source in XEMIS1

Data Processing and Event Builder

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 $S_{\rm signals}$ but also noise events are continuously recorded. An offline code has been developed

to reconstruct the physics interaction vertices starting from those raw data. In this experiment, XEMIS1 was operated in the conditions foreseen for XEMIS2. A low-activity ^{22}Na source with similar characteristics to those of ^{44}Sc is employed. This chapter reports the work devoted to the data processing development in view of the application to XEMIS2.

5.1 Experiments with ${}^{22}Na$ in XEMIS1

In order to prepare the XEMIS2 operation and to evaluate the Compton cone reconstruction performances, an experiment using the source of ^{22}Na has been carried on in the XEMIS1 prototype. In order to fit the future operating conditions to the best of our knowledge, the detector components are arranged similar to the XEMIS2 geometry. The experimental setup is identical to that used during DAQ calibration, whose characteristics have been described in Chapter 3.

A full Monte Carlo simulation of particle interaction with matter and detector response was carried out using Geant4 and ROOT. Comparison with experimental measurement results will be discussed in Chapter 6. The TPC geometry construction is shown in Figure 5.1. The active length of the detector is 65.1 mm with an anode of 64 pixels of 3.1×3.1 mm² (red square area). Two IDeF-x cards (green plates) are directly connected to the anode and immersed in LXe. A set of 6 copper field shaping rings (yellow rings) with a gap of 9 mm between each is located between the cathode and the anode aiming to provide a uniform electric field. Two PMTs (blue blocks) are placed at the TPC periphery side by side for scintillation light detection. The source holder (dark red cylinder), supported by the Aluminum cathode of 1.5 cm (silver cylinder), is located of about 1 cm far from the edge of the detector active zone.

5.1.1 Source description

The characterization of the detector is performed by means of a low activity ${}^{22}Na$ source of about 3.3 kBq. Similar to the candidate source ${}^{44}Sc$ used for 3-gamma imaging, the ${}^{22}Na$ is also emitting a positron and a γ -ray of 1.274 MeV in quasi-coincidence. The radioactive source is encapsulated in a plastic casing of 9 mm thick (H) with a radius (R) of 15.75 mm. The geometry of the source ${}^{22}Na$ is represented as a point-like cylinder with a height (h) of 3 mm and a radius (r) of 1.5 mm. The configuration of the source is illustrated in Figure 5.2.

In parallel to the experiment, a Monte Carlo simulation using Geant4 is carried out to study the event topology inside the active volume of TPC. The simulation results of the total deposited energy in the TPC per event is shown in Figure 5.3. Without considering the scattering multiplicity, three general contributions of events could be identified:



Fig. 5.1 Wire frame representation of the XEMIS1 TPC constructed with Geant4. The origin is located in the center of the anode. During the experiment, the TPC is entirely immersed in about 30 L of liquid xenon holding by the cryostat.



Fig. 5.2 Schematic diagram of the ^{22}Na source configuration.

- γ -ray of 511 keV The red curve represents the case where all deposited energy in TPC comes from single or double γ -ray of 511 keV. Normally, only one of two γ -rays of 511 keV could interact inside the TPC since they are emitted in opposite direction from the position of the positron annihilation. However, the part of distribution above the energy of 511 keV well indicates the presence of the second annihilation gamma ray. This additional energy is likely to come from the interactions of the correlated gamma ray. It first occurs in Compton backscatter outside the TPC, and then the remaining energy is lost in the TPC. To reduce this miss-matching in Compton reconstruction, a fiducial volume is employed during event selection.
- γ -ray of 1.274 MeV The presence of the γ -ray of 1.274 MeV should be considered as the reference Photo peak absorption for energy calibration source. However, a saturation of the IDeF-x below the energy of 1.274 MeV is observed during the experiment. A significant degradation of the efficiency results in a reduction of the resolution which leads to a more complicated data analysis.

Mixture of γ -rays of 1.274 MeV and 511 keV Since there is no ambiguity on the third peak with an energy of 1.785 MeV, it could be thus used as to perform an energy calibration. However, the energy range of interest to study Compton scatters is well below this energy. The gain of the whole DAQ has been optimized to accurately measure small charges. This high energy peak will result in a DAQ saturation during the experiment. For this reason, this type of event can be considered as a background that will reduce the efficiency of the PE peak and the Compton sequence reconstruction.



Fig. 5.3 Spectrum of deposited energy per event in the active zone.

An event selection is proposed in this chapter. A list of cuts have been selected to eliminate the bias described above. Besides, more detail about the data analysis and experimental results are given in Chapter 6.

5.1.2 Overview of data processing

The precise measurement of small ionization signals is the critical point for the Compton telescope performance. As discussed in Section 3.1.2, a low threshold self-trigger DAQ system has been designed to maximize the detector performance for small charge measurement. The entire newly developed DAQ system was described in Chapter 3, and its calibration performance is detailed in Chapter 4. In the case of 64 electronic channels used in XEMIS1, the new DAQ is programmed to read out data at a trigger rate of about 1.5 kHz per pixel with negligible dead time. A two-hour run produces 6.5 GB of data with around 3.4x10⁶ raw events. The significant number of electronic channels in XEMIS2 should produce a considerable data volume of 350 GB during an imaging exam of 20 minutes. Online data processing is being considered in XEMIS2

to reduce the DAQ data flow. An offline study of the needed data treatement is presented in this section. The objective is to correct the raw signals by making use of the DAQ calibration parameters and trying to reduce the data flow while keeping the valuable information for image reconstruction. This part describes a preparation study that is realized via an offline data treatment. The diagram of the main data treatment steps is given in Figure 5.4.



Fig. 5.4 Diagram of the principal data treatment steps.

The first step consists in decoding and converting the binary pixel raw data files into ROOT [168] format files. The relevant decoding process is crucial to verify that the DAQ acquisition is working correctly and to ensure that the data are not corrupted. The ionization signal information about pixels is stored in a ROOT tree as *Digit* objects, while the scintillation signal is stored in another tree named *Lisig* objects. Each *Digit_i* can be noted as $D_i(x_i, y_i, t_i, Amp_i)$: it contains the information about the affected pixel:

- the coordinates of the correponding pixel (x_i, y_i) ;
- the time measured through CFD, t_i ;
- the measured signal amplitude, Amp_i .

Once all information have been correctly converted and registered in the ROOT files, several data processing steps are required for the ultimate objective of the TPC event reconstruction. The DAQ calibration results will be applied in the first place for signal amplitude-to-charge conversion and time correction. Then the next step is data filtering aiming to eliminate noise and reduce the data volume. Later a clustering algorithm will aggregate those *Digits* neighbor in time and space to the same *Cluster*. The TPC event could be finally reconstructed after matching the *pixel Cluster* with the *PMT Cluster*. The number of *pixel Clusters* per event indicates the nature of the interaction inside the TPC as belonging either to single-scatter or to a multiple-scatter.
5.2 Optimization of time measurement

The results of the DAQ calibration are employed to correct the measured amplitude and time for every Digit.

Amplitude gain application Since the amplitude measurement has been optimized during the calibration process by appropriate settings of electronic parameters, no other corrections are needed in this step apart from the gain application. The Amp_i which belongs to $Digit_i$ will be converted to q_i using electronic calibrated gain. The information of a $Digit_i$ becomes thus D_i (x_i, y_i, t_i, q_i) for the further data processing. Besides, a slight charge loss caused by DAQ saturation has been corrected in the range of charge from 5.5x10⁴ to 6.5x10⁴ electrons.

5.2.1 Signals synchronization

As presented in Section 4.1, the scintillation light and ionization charge signals are self-triggered through two independent DAQ systems and centralized in the FlexRIO board before being sent to the PC processor. The former *Lisig* data is tune stamped by the 100 MHz counter in the FPGA of the FlexRIO card, while the latter *Digit* data is tune stamped through the 100 MHz internal clock of the PU board. Considering the precision and the stability of these oscillators (a few ppm), the relative error between the different clocks can exceed 100 ns over a time slice of 100 ms. For the DAQ synchronization, a reset signal generated by the FlexRIO forces all the acquisition counters that rely on independent clocks to be reset to 0 each 80 ms.

Meanwhile, an experimental calibration has been done in order to evaluate the frequency slip between the clocks of FPGA and PU during 80 ms. The test used the same experimental method as the time walk measurement presented in Section 4.4.3.1. Thanks to the external synchronized signal delivered by the pulse generator, the relative time between the two DAQ systems could be obtained. An example of measurement result is given in Figure 5.5. A significant relative time shift can be observed and needs to be corrected for a precise time measurement. A PU time shift of about 200 ns was measured with respect of the FlexRIO time during 80 ms (see Figure 5.6a). A synchronization correction is applied to all Digits and the result is shown in Figure 5.6b.

The absolute PU time (t_{PU_f}) corresponding to the end of each acquisition period of 80 ms (absolute time given by FlexRIO) is now recorded in the raw data file used for signal synchronization. Therefore, the first trigger time (t_0) is given by:

$$t_0 = t_{PU} \times \frac{t_{PU_f}}{80 \ ms} \tag{5.1}$$



Fig. 5.5 The measured calibration signal of same channel (a) before and (b) after the clock synchronization of data processing. The abscissa is the time difference between scintillation and ionization DAQ chain for the measurement of two synchronized signals, and the ordinate is the measured amplitude.



Fig. 5.6 Clock slip measurement and correction results. (a) The measured PU time as a function of the FlexRIO time during a slice of 80 ms (black line) before and (red line) after time correction. (b) The calibration results of a series of injected pulses with variable amplitudes (left) before and (right) after the time correction (same measurement as Figure 5.5).

5.2.2 Ramp time measurement

As detailed in Chapter 4, when multiple pixels are fired within a short time, only t_0 , the time of the first affected channel ($Digit_0$), is directly recorded by the PU card (t_{PU}). A common

voltage ramp inside of each XTRACT is used to measure the time between the first pulse and the following signals. This time difference is named t_{XT} to distinguish from first trigger time t_{PU} . Therefore, the new DAQ system could provide the time (t_i) of each signal $(Digit_i)$ measured in a XTRACT:

$$\forall i > 0, t_i = t_0 + t_{XT}$$
 (5.2)

Results obtained by DAQ calibration In this part, we report the time dependence of the voltage ramp that has been measured during the DAQ calibration process. To measure the dependence of ramp voltage with the time difference of two signals, it must affect two channels in a time interval successively since one channel could not be retriggered before the ramp stop (CS returns to zero). More details about the DAQ design could be found in Chapter 4. During the test, a high injected voltage of 100 mV has been used to avoid the impact of time walk on the time ramp calibration. The experimental measurement is, therefore, more tricky than other tests in which only the PU time is employed. The measurement process is not detailed here. Figure 5.7a shows the measurement result of 32 channels of XT0 at detector operating conditions. Two groups of 16 experimental data (colorful line) are displayed. Each ramp time data is characterized by a first-order polynomial (red line), presenting an excellent linear behavior in the measured range. The maximum ramp duration is about 1 μ s in the condition that only one signal is delivered after the first trigger during the ramp generation time. The experimental result is coherent with the DAQ timing schematized in Figure 5.8. Besides, as shown in Figure 5.7b, the key information for t_{XT} calculation can be obtained by the slope (α) and the baseline (V_0) resulting from the linear fit on the experimental data. In addition, a small voltage gap (ΔV) at





(b) Channel #0 of XT0

Fig. 5.7 Dependence of ramp voltage with the trigger time interval of (a) 32 channels and (b) channel #0 of the XTRACT XT0. The experimental data are represented as colorful markers, while the red lines are the linear fits of ramp and baseline curves.

the beginning of the curve can be identified as the difference between the intercepts of the two fitting functions. Therefore, the time of a $Digit_i$ is calculated from Equation 5.3 :

$$\forall i > 0, \ t_i = t_0 + \alpha_i \times (V_{r_i} - V_{0_i} - \Delta V_i) \tag{5.3}$$

where V_{r_i} is the measured ramp voltage value of $Digit_i$.



Fig. 5.8 Schematic of DAQ read out in the case of only one channel is affected.

All 64 channels have been calibrated. With the same data treatment described above and whose method has been applied in Figure 5.7b, the slope, baseline and gap of 32 channels of the XTRACT XTO have been obtained. Their values are summarized in Figure 5.9 and Figure 5.10 at the detector operating condition. The slope is pretty uniform for all 32 channels: their mean value is about 3.5 ± 0.3 ns/ADC. Similarly, 3.7 ± 0.4 ns/ADC was obtained for the other chip, XT1. Besides, the baseline values are grouped in two blocks of 16 channels, similarly to



Fig. 5.9 Time ramp slope values of 32 channels of XT0 measured at the detector operating condition.

what presented in Figure 5.7a. The voltage gap is limited in the range of 4-8 ADC channels, corresponding a time difference of less than 30 ns.



Fig. 5.10 The distribution of the voltage gap at the beginning of time ramp of 32 channels of XTO at detector operating condition. The black marker is the measured baseline (same value at the beginning and after complete falling down of the ramp). The red marker is the intercept of ramp linear fit. Their distributions are quite uniform for each group of 16 channels. The difference represents the voltage gap (blue marker) of each channel. The blue band is the 95% confidence interval of the constant fit.

An identical experimental measurement has also been done at room temperature, whose experimental results will not be detailed here. The remark which is worth to emphasized is that the slope value depends on the operating temperature of the XTRACT chip. The voltage of the time ramp generator increases more slowly at room temperature, whose behavior is closer to the datasheet.



Fig. 5.11 Time ramp slope values of 64 channels of two XTRACTs measured at room temperature.

Validation of DAQ readout of multi-pixel fired events with physics data Multi-pixel fired events commonly occur in our detector due to the electron cloud diffusion. The DAQ readout validation is essential to make sure that the timing of each Digit is correct. This work was realized through the analysis of physics raw data. The relationship between the chip readout time (quasi-equivalent to the ramp duration in normal condition) and the time gap between two successive trigger flags (begins of ramp) of the same chip (XT0) is plotted in Figure 5.12a. The ramp duration shows a discrete behavior and almost independent on the time gap between two ramps, except when the new trigger flag (f_t) arrives just at the end of the former ramp. An example is shown in Figure 5.12b. If f_t arrives in 300 ns behind the end of the chip readout, a delay time is added to wait to complete the precedent chip readout. In fact, the read out of the



Fig. 5.12 (a) Dependence of time ramp duration with the time gap between two successive ramps in the same chip (XT0). (b) Zoom picture of the case in which only one trigger is detected in the ramp.

first signal $Digit_0$ takes a time of T_0 longer than the following $Digit_i$ since PU and common unit needs to prepare the lecture in ~ 720 ± 10 ns. The remaining Digits are readout with the identical Δt . The time of readout (or ramp duration) T_i can then be expressed as:

$$\forall i \ge 0, \ T_i = T_0 + \Delta t \tag{5.4}$$

 T_i can be obtained from Figure 5.12a with the ramp time projection. The projecting plot is given in Figure 5.13a. The Δt is calculated by the time difference between two successive T_i s whose distribution is shown in Figure 5.13b. The mean time required to read out a new *Digit* is about 370 ns with a deviation of less than 3 ns.



Fig. 5.13 Characteristics of DAQ readout time (quasi-equivalent to the ramp duration in normal condition). (a) Distribution of the discrete ramp duration. (b) Calculated Δt for reading out one supplementary *Digit*.

 t_{XT} correction under special circumstances As mentioned above, the $Digit_0$ sends the trigger flag to PU and means the start of a new time ramp with voltage of V_{r_0} . The time of the following $Digit_i$ is thus calculated based on the relative voltage to V_{r_0} . The new ramp is normally considered to start from "0", after the former ramp complete falling down. However, as discussed in Figure 5.12b, there are some situations where the time gap between two successive ramps $(t_{PU_i+1} - t_{PU_i})$ is too short and, as a result, the new ramp starts from the tail of the former. This phenomenon is observed in Figure 5.14a. Besides, the distribution of the V_{r_0} after subtraction of the baseline voltage is displayed in Figure 5.14b. The dominating high peak verifies the ramp start typically from baseline in most cases. The other peaks represent the voltage at the end of the previous ramp. In this case, the Equation 5.3 should be modified as:

$$\forall i > 0, \ t_i = t_0 + \alpha_i \times (V_{r_i} - V_{0_i} - \Delta V_i) - \alpha_0 \times (V_{r_0} - V_{0_0})$$
(5.5)

where α_0 and V_{0_0} present respectively the ramp slope value and baseline voltage of the $Digit_0$ fired channel.

Time ramp characterized with physics data From Figure 5.13a and Figure 5.14b, we can calibrate the dependence of the ramp time with the ramp voltage (see Figure 5.15). The linear behavior induces a ramp slope of \sim 3.5 ns/ADC, in agreement with the previous calibration result (Figure 5.9). This finding can simplify the calibration process. We can calibrate the time



Fig. 5.14 The ramp voltage V_{r_0} of the first trigger $Digit_0$ (a) as a function of the time difference between the starts of two successive ramps and (b) its distribution. The red line in (a) is the fit curve of Figure 5.15 discussed later. The peaks in (b) are fitted by Gaussian functions whose mean values are reported in the figure.

ramp with only 30 minutes of raw physics data, instead of applying the complex measurement with two injection pulses during the DAQ calibration.



Fig. 5.15 Dependence of the ramp time with the ramp voltage obtained by physics data analysis.

5.2.3 Time walk correction

The final step for timing improvement consists in correcting the time measurement dependence on the signal amplitude (Time walk). This correction is based on the calibration result presented



Fig. 5.16 Illustration of time measurement sequence and the contribution of time error.

in Section 4.4.3.1. For each $Digit_i$, the time walk on the CFD measurement (t_{CFD_i}) can be obtained through Figure 4.51 according to its measured amplitude. The time t_i of $Digit_i$ could be finally written as:

$$\forall i > 0, \ t_i = t_{PU} + \alpha_i \times (V_{r_i} - V_{0_i} - \Delta V_i) - \alpha_0 \times (V_{r_0} - V_{0_0}) - t_{CFD_i} (Q_i^m)$$
(5.6)

while the time t_0 of $Digit_0$ can be written as:

$$t_0 = t_{PU} - t_{CFD_0} \left(Q_0^m \right) \tag{5.7}$$

5.2.4 Time measurement error and experimental result

The time measurement sequence and the contribution of time error are illustrated in Figure 5.16. From Equation 5.6 and Equation 5.7, the time error σ_{t_i} of $Digit_i$ can be expressed as:

$$\sigma_{t_i} = \begin{cases} \sqrt{\sigma_{PU}^2 + \sigma_{CFD_i}^2} & \text{if } i = 0\\ \sqrt{\sigma_{PU}^2 + \sigma_{CFD_i}^2 + \sigma_r^2} & \text{otherwise} \end{cases}$$
(5.8)

where

• σ_{PU} is the time error on the trigger flag of the PU board:

$$\sigma_{PU} = \frac{Clock_{PU}}{\sqrt{12}} = 2.8ns \quad with \quad Clock_{PU} = 10ns \tag{5.9}$$

- σ_{CFD_i} is the CFD time jitter calibrated in Section 4.4.3.1. The resolution depends on the amplitude of signal;
- σ_r is the noise of the voltage ramp (equivalent to 5 ns).

Since the CFD time walk is negligible for large-signal measurements, we analyzed the time deviation Δt of the small charge measured by adjacent pixels relative to the time of the central pixel. The experimental result of time correction is shown in Figure 5.17. A significant Δt can be observed in Figure 5.17a, presenting the same tendency as seen from the time walk calibration curves in Figure 4.51. The time measurement resolution is estimated in Figure 5.18. The curve is fitted by a sum of three Gaussian functions and a constant. The contributions to time resolution are respectively of ~50 ns, ~140 ns and ~350 ns.



Fig. 5.17 Time deviation of the adjacent pixel relative to the central pixel as a function of the charge of the adjacent pixel (a) before and (b) after the time correction.



Fig. 5.18 Relative time measurement resolution of adjacent pixel regarding the central pixel after time correction.

5.3 Data filtering

Data filtering aims to eliminate noise data without degrading information about physical events as much as possible. In this step, two kinds of noise will be recognized and treated.

5.3.1 Rejection of fake double-trigger

The phenomenon of double-trigger is the detection of one or more fake triggers following a true physic signal. This behavior is due to the contribution of electronic noise and hysteresis effect which have been studied and discussed in Chapter 3 and Chapter 4. To identify the representation of double-trigger in physics data, we plot the relationship between the time difference and amplitude ratio of two consecutive *Digits* when the latter amplitude is smaller than the previous one. An example of experimental data results of pixel #9 is given in Figure 5.19. The noise/small signals is distributed quasi-uniformly during all analysis time window shown in Figure 5.19b. By contrast, in the time region immediately following the large signal, we observe densely distributed fake signals due to double-trigger (see Figure 5.19b). The distribution of the signal amplitude ratio with respect to the time difference follows the shape of the pulse tail. This observation proved that double triggers occurred in the physics data due to the CFD measurement method. Besides, in the same area, lots of signals whose amplitude ratio is close to 0 (might be even below 0) are caused by the hysteresis. Data in this time window are therefore eliminated by applying the same analysis method used for the observation of this phenomenon.



Fig. 5.19 Relationship between the time difference and amplitude ratio of two consecutive *Digits* when the second amplitude is smaller than the first one (pixel #9) in (a) the entire analysis time window and (b) the region of interest.

In addition, another noteworthy phenomenon is that because we use the noise rate method to determine the hardware threshold, a significant double trigger events (i.e., a relatively important hysteresis) will increase the signal measurement threshold. This phenomenon has also been observed and confirmed in this physics data analysis. As shown in Figure 5.20, a more important re-triggering effect is observed on pixel #62 compared to pixel #9. Due to the obvious hysteresis effect, the over-threshold time window cannot be closed immediately after the true signal, a delay of up to 40 μ s can be observed (see Figure 5.20b). In this case, we can see that less noise is detected out of this time window due to the higher threshold setting of this channel to keep a constant trigger rate.



Fig. 5.20 Same plots as in Figure 5.19 for pixel #62.

An overview of all 64 channels is plotted in Figure 5.21. Thanks to the setting of ZC introduced in Chapter 4, most channels present a normal double-trigger time interval distribution resulting from the CFD measurement. Nevertheless, about a quarter of the channels still exhibit more pronounced hysteresis. These pixels are concentrated in the positive X half-axis area of the anode (i.e., XT1), which will cause the measurement result on this site to be smaller due to the threshold effect. This DAQ behavior causes slight deviations of the measurement along X-axis. This phenomenon has been observed in the physics data analysis and will be presented in Chapter 6.

5.3.2 Rejection of noise events isolated in time

Other than the above fake triggers caused by double-trigger, the other type of noise recognized and excluded in the next step is the small-amplitude signal isolated in time. An interaction vertex is reconstructed from a group of *Digits* (named *Cluster*), which are close in time and



Fig. 5.21 Relationship between the time difference and amplitude ratio of two consecutive *Digits* when the second amplitude is smaller than the first one (all 64 pixels corresponding to the real position on anode).

position. The *Cluster* is supposed to be generated by a unique electronic recoil. The method to reconstruct Cluster is called Clustering that will be detailed later. Based on the nature of Cluster, a Cluster containing only one pixel or Digit isolated in time with a small charge is likely to be considered as a noise event. The method adopted to eliminate this part of the noise is based on two offline thresholds $(th_{high} \text{ and } th_{low})$ and an isolated time window $(\Delta T_{isolated})$. The value of th_{high} is set to the minimum amount of charge required to identify a *Cluster*. Once a signal exceeds this threshold th_{high} , all Digits close in time are potential candidates for Cluster construction. Therefore, we open a time window $\Delta T_{isolated}$ centered on this signal to collect all compatible signals. If another signal with an amplitude bigger than th_{high} occurs within this time interval, a new time window centered on this new signal will be created to extend the current one. In this way, depending on the signal distribution, a variable Digits selection time intervals can be generated. Digits that are isolated from other signals will not be collected and thus eliminated. Meanwhile, a th_{low} lower than the hardware threshold will be imposed on all collected signals gathered in time, to avoid the bias caused by hysteresis effects. The data rejection factor is defined as the ratio of the number of Digits in the raw data to the number of Digit after filtering. It can be presented as a function of each parameter separately whose

relationship is presented in Figure 5.22. The rejection factor significantly increases with higher thresholds while it decreases with the extend of the time window.



Fig. 5.22 Dependence of filter ratio with (a) applied high threshold th_{high} (with $th_{low} = 2\sigma_{noise}$ and $\Delta T_{isolated} = 2 \ \mu$ s), (b) applied low threshold th_{low} (with $th_{high} = 4\sigma_{noise}$ and $\Delta T_{isolated} = 2 \ \mu$ s) and (c) isolated time window $\Delta T_{isolated}$ (with $th_{high} = 4\sigma_{noise}$ and $th_{low} = 2\sigma_{noise}$). The first point in (b) represents the filter ratio using only double-trigger removing without applying a low threshold.

In XEMIS2, this step will be integrated into the FPGA of the XCD card to realize online data processing. Differently from offline data treatment the data removed during acquisition cannot be recovered for further analysis. Therefore, we need to choose relatively conservative selections in order to reduce the amount of data without degrading physics information. Figure 5.23 shows the experimental results on the *Digit* rate per pixel before and after data filtering. The count rate could reach up to 2000 c.p.s (count per second) for some pixels while less than 1 kHz for others. The dispersion comes from the difference of hysteresis in the comparator of each pixel and the precision of threshold settings. More details have been discussed in Chapter 4. In Figure 5.23b, the number of residual Digits per pixel has been reduced to less than 100 c.p.s for a threshold th_{high} 4 times larger than the equivalent noise charge (ENC or σ_{noise}). The value decreases to less than 30 c.p.s when the th_{high} is equal to $5\sigma_{noise}$. In Figure 5.23c, the distribution tends to be more uniform and concentrated in the center, characterizing the distribution of physics signals, which coincides with the position of the point-like source. Therefore, a threshold of $5\sigma_{noise}$ is considered as the minimum charge collecting needed to measure low energy electronic recoils. Based on the reasons previously discussed, th_{high} is set at $4\sigma_{noise}$ instead of $5\sigma_{noise}$ to prevent situations that require minimal signal analyzing. Similarly, the th_{low} is programmed at $2\sigma_{noise}$ or even without th_{low} application, depending on the physics events to be analyzed. Besides, a precise time window study has been done to estimate the suitable isolated time interval presented in Figure 5.24 by processing the experimental physics data. Two situations have been synthesized: the red curve shows the raw data rejection rate resulting from an application of isolated time



Fig. 5.23 *Digit* rate per pixel (a) before and (b)&(c) after data filtering. High thresholds of (b) $4\sigma_{noise}$ and (c) $5\sigma_{noise}$ are applied respectively with a time window of 2 μ s.

window, while the blue one includes also the spatial position of each *Digit*, it thus corresponds to a case of real *Clustering*. Both results are obtained with a th_{high} of $5\sigma_{noise}$ and a th_{low} of $3\sigma_{noise}$. The filter ratio in both cases decreases with longer time window $\Delta T_{isolated}$ and presents a turning point at about of 1 μ s. When $\Delta T_{isolated}$ is smaller than 1 μ s, a substantial fall could be remarked. This region indicates therefore a loss of physics events. Moreover, considering that the CFD time jitter measured for tiny signals is about 500 ns, a time window of at least three times the DAQ time measurement resolution is required. Combining the above reasons, a conservative value of the time window of 3 μ s has been chosen for data filtering, which is large enough to ensure no physics signal rejection.



Fig. 5.24 Dependence of raw data rejection on the clustering time window when applying a high threshold of $5\sigma_{noise}$. The trendlines of experimental results are represented by red and blue dot lines. The vertical solid lines indicate the location of change of global trends.

5.4 Event reconstruction

The next phase in the data analysis following the data filter is the TPC event reconstruction. During this step, neighbor *Digits* will be first aggregated into the same *pixel Cluster* and then matched with the scintillation *Lisig Cluster* to build the TPC events. A mis-association of either information will result in reduced energy and spatial resolution of detector. Given the diversity and complexity of event topologies, the clustering and matching are one of the most challenging parts of data analysis.

5.4.1 Clustering

The *Clustering* method is used to reconstruct the interaction sites of gamma-rays, regardless of the physics process involved, i.e. Compton scatter or photoelectric effect. The most considerable difficulty related to clustering is to identify the measured charges (*Digits*) really contributing to the same interaction. This could happen in the case of Compton backscattering where the distance of two interactions is small comparing the pixel size. To prevent the constructed *Cluster* from containing a part of the charge belonging to another interaction, i.e., charge carriers from two interactions reach the same pixel, we choose a clustering algorithm to first create a large cluster containing all potential candidate *Digits* and then apply selection criteria on this cluster as the time correlation between *Digits* and the *Cluster* size. Our clustering algorithm is composed of a pre-clustering in time and a clustering in space.

5.4.1.1 Pre-clustering in time

The pre-clustering algorithm is the same as that used for eliminating noise isolated in time, except that a more tiny time window is utilized. As previously discussed, a Δt of 1.5 μ s is necessary considering the CFD time resolution for small signals of about 500 ns. All *Digits* in filtered data are aggregated firstly in a set of *pre-Clusters*. Similar to that mentioned in Section 5.3.2, a variable time interval might be built depending on the event topology. The experimental results show that a deviation time between the adjacent *Digits* to the reference one, could reach more than 3 μ s.

5.4.1.2 Clustering in space

After pre-clustering of *Digits* in time, the next step is aggregating the spatial adjacent *Digits* into a *Cluster* corresponding to the same interaction vertex. The list of *Digits* is firstly sorted in descending order of amplitude. Considering that the charge carriers undergo Gaussian diffusion in liquid xenon, the clustering starts from the *Digit* with the largest amplitude (D_0) as the central

point of the new *Cluster*. The clustering algorithm is schematized in Figure 5.25. A parameter R is used for *Digit* selection based on the distance between $D_i(x_i, y_i, t_i)$ and $D_0(x_0, y_0, t_0)$ following the expression:

$$r = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (t_i - t_0) \times v_{drift}^2}$$
(5.10)

where v_{drift} is the electron drift velocity. If r < R, D_i is inside the same *Cluster* of D_0 (case 1 shown in Figure 5.25a). Any *Digit* with an over-threshold amplitude in the current *Cluster* could become the new center point of the *Cluster* expending. This might result in a *Digit* belonging to the list of *pre-Cluster* being added to the current *Cluster* even though it is not close to D_0 (case 2 shown in Figure 5.25b). For constructing a *Cluster*, the clustering algorithm needs to loop over all *Digits* in the list of the same *pre-Cluster* to search the candidates that meet the above conditions. Once a *Cluster* is formed, all associated *Digits* will be removed from the *pre-Cluster* to search for a new *Cluster*. The next maximum *Digit* in the list becomes the new D_0 of a new *Cluster*. The procedure stops when all *Digits* have been clustered, or no more over-threshold *Digit* is left.



Fig. 5.25 Schematic representation of the clustering algorithm. (a) All D_i inside the sphere of D_0 belong to the same *Cluster*. (b) D_5 is also belonging to the *Cluster* created from D_0 since its position is inside the sphere of D_4 . Both (a) and (b) represent a single cluster under our clustering algorithm.

Based on this method, certain huge *Clusters* might be created. For example, a *Cluster* might contain more than twenty *Digits* in the case of cosmic rays traversing the detector. An event selection is crucial to reconstruct good interaction vertices which will be presented in the next section.

5.4.1.3 Characterization of Cluster

A reconstructed $Cluster_j$ can be noted as C_j (X_j, Y_j, T_j, Q_j) , depending on the information constructed of the N parent $Digit_i$ $(D_i (x_i, y_i, t_i, q_i))$ inside of $Cluster_j$:

- N the multiplicity of $Cluster_j$ indicate the number of *Digits* inside this $Cluster_j$;
- Q_j the total charge of $Cluster_j$ as the sum of the individual charges of $Digit_i, q_i$:

$$Q_j = \sum_{i=0}^{i < N} q_i$$
 (5.11)

• (X_j, Y_j) — the XY position is estimated through the center of gravity method, as first approximation, expressed by the following formulae:

$$X_{j} = \frac{\sum_{i=0}^{i < N} q_{i} \cdot x_{i}}{\sum_{i=0}^{i < N} q_{i}} \quad and \quad Y_{j} = \frac{\sum_{i=0}^{i < N} q_{i} \cdot y_{i}}{\sum_{i=0}^{i < N} q_{i}}$$
(5.12)

• T_j — well approximated by the time of the *Digit* with the maximum charge in the case of a *Cluster* corresponding to a single interaction. However, the clustering algorithm applied in our data analysis might build some super *Cluster*. A time fit method is proposed to estimate the true time of the interaction vertex and give an indicator for *Cluster* events selection.

5.4.1.4 Time fit method for events selection

The method of finding the accurate time of the interaction vertex (t_v) of the *Cluster* is based on the time measured on each pixel (t_i) and a χ^2 minimization, which is expressed as follows:

$$\chi^{2} = \frac{1}{n-1} \sum_{i=1}^{n} \left(\frac{t_{i}-t}{\sigma_{i}} \right)^{2}$$
(5.13)

where *n* is the number of pixels in the *Cluster* and σ_i represents the time resolution that is composed of two contributions of the DAQ time resolution σ_{mi} of $Digit_i$ and the electron range fluctuation σ_R . The σ_i of $Digit_i$ can therefore be written as:

$$\sigma_i^2 = \sigma_{mi}^2 + \sigma_R^2 \tag{5.14}$$

The σ_{mi} could be obtained through the calibration curve (Figure 4.52) which is a function of the measured charge of $Digit_i$. Besides, the diffusion in liquid xenon of ionized electron cloud

generated along the recoil electron track would also impact the time measurement. This effect is estimated by the Monte Carlo simulation and presented in Figure 4.53. The range resolution σ_R thus could be identified through the deposited energy, i.e., the total charge measured in the *Cluster*.

This method is equivalent to a fit with only one parameter t. The minimum variance of the χ^2 is obtained at:

$$\frac{\partial \chi^2}{\partial t} = 0 \tag{5.15}$$

From Equation 5.13, χ^2 expressed as a linear combination of t_i , the interaction time t_v could thus be estimated as:

$$t_{v}\Big|_{\frac{\partial \chi^{2}}{\partial t}=0} = \frac{\sum_{i=1}^{n} \frac{t_{i}}{\sigma_{i}^{2}}}{\sum_{i=1}^{n} \frac{1}{\sigma_{i}^{2}}}$$
(5.16)

The χ^2 value calculated for the fitted interaction time t_v is a statistical indicator of the quality of the reconstructed cluster. It can contribute, therefore, to the event selection for separating those clusters associated to overlapping physics interactions. However, the time correlation between pixels are not considered in Equation 5.13 due to the complexity of the electron track topology. A further simulation study should be performed to improve the accuracy.

5.4.2 Matching

During the previous steps of data processing, the PMT raw data (Lisig) and the pixel raw data (Digit) have been corrected, filtered, and aggregated in clusters. This step aims to match the two types of Clusters, scintillation and ionization, for the TPC event construction. For a physics event occurring in the TPC, the scintillation signal gives the reference time to calculate the drift time of ionization charge carriers. This principle is used in the Event Builder for signal matching. Considering the time of a Lisig Cluster as t_0 , within a time window equal to the maximum possible drift time of charge carriers inside the TPC of about 28.1 μ s, all compatible *Digit Clusters* are associated to the *Lisig Cluster* to form a TPC event (Figure 5.26). One or several *Digit Clusters* could be attached to the same *Lisig Cluster* depending on the true event topology, single or multiple interaction of gamma-rays. Conversely, if one Cluster is grouped with more than one *Lisig Cluster*, this event is considered as a pile-up event. The time window could not be precisely defined at the very beginning of the experiment since the drift velocity has not been precisely measured. A default time interval of 30 μ s is set to ensure that all *Clusters* inside the same event would not be eliminated.



Fig. 5.26 Illustration of the matching mechanism (left) and visualization of the reconstructed event (right) with the position of *Lisigs* (green points) and *Digit Clusters* (blue and purple points).

5.4.3 Event selection

Pile-up and DAQ Saturation Events Suppression As discussed in Section 5.1.1, the DAQ has been optimized for small charge measurement. The deposited energy in the range of Photoelectric peak from the γ -ray of 1274 keV saturates the IDeF-x in case of only one fired pixel (observed in Figure 5.27a). Besides, the mismatching of scintillation light with ionization signal might generate pile-up events defined in Section 5.4.2. This part of the events accounts for 15% of the total number of reconstructed events (see Table 5.1). This number is probably overestimated because two events are rejected each time a cluster is identified as a pile-up, while in reality only 1 event is lost. The cut efficiency could be slightly improved by applying an appropriate time window of 28.1 μ s during the matching procedure instead of using the default value of 30 μ s.



Fig. 5.27 Multiplicity of Cluster as a function of the charge of Cluster (a) before and (b) after the event selection.

- **Fiducial Volume Application** The fiducial volume consists in removing of 3.1 mm (size of a pixel) from the boundary of the active area on each axis to eliminate the bias of partial charge collection. All clusters whose center of gravity is located on the anode boundary (pixels at the first and last rows and columns) should be removed from the data analysis list. This selection is motivated by the uncertainty on the charge collection efficiency. In addition, as discussed at the beginning of this chapter, the deposited energy in the TPC boundary may be caused by the backscattering of gamma rays injected outside the TPC. The application of fiducial volume benefits from the self-shielding ability of liquid xenon. As summarized in Table 5.1, the reduction of the reference volume leads to a significant reduction in the efficiency of event reconstruction. This phenomenon is mainly limited by the geometry of XEMIS1. In XEMIS2, the impact will not be so significant.
- Time Fit Cut Some multi-scattering events inside the TPC could not be effectively separated due to the short distance between them not resolvable by the size of pixels. As presented in Section 5.4.1, the choice of clustering algorithm in our data analysis is in favor of potentially large clusters to aggregate all the relevant information from neighboring Digits. The time dispersion inside a Cluster can be enormous due to the mix of noise and overlapping interactions (see Figure 5.28a). A cut of $\chi^2 \leq 5$ has been used to eliminate those biases (see Figure 5.28b). A more strict cut could be employed to improve the detector resolution. However, the event measurement efficiency is identically important for a low-activity imaging camera.



Fig. 5.28 Time difference between adjacent pixel and the central pixel as a function of the charge of the adjacent pixel (a) before and (b) after the event selection.

Table 5.1 List of cuts used for event selection. The residual event number and cluster number after each cut are given. Efficiency is defined as the number of events after the cut divided by the number of events before the cut. The cuts are applied one after the other.

Event Selection (36 h Data Acquisition))							
Operation	Nevent	Ncluster	Ncluster/Nevent	Cumulative efficiency			
Raw Data	$6.08\ 10^7$	8.04 107	1.32	100%			
Pile-up & DAQ Saturation Cut	$5.18 \ 10^7$	$6.73 \ 10^7$	1.298	85%			
Fiducial Volume (X,Y∈[-9.3, 9.3], Z∈[1, 64] mm)	$2.15 \ 10^7$	$2.54 \ 10^7$	1.182	42%			
Fiducial Volume (X,Y∈[-9.3, 9.3], Z∈[3, 62] mm)	$1.76 \ 10^7$	$2.11\ 10^7$	1.201	29%			
Time Fit ($\chi^2 \leqslant 5$)	$1.43\ 10^7$	$1.68\ 10^7$	1.178	24%			
Cluster Size (L ≤15 mm)	$1.40 \ 10^7$	$1.62 \ 10^7$	1.166	23%			

Cluster Size Cut The Cluster size is calculated as $L = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$, where Δx , Δy and Δz are respectively the maximum distance between the Digits inside of a Cluster on axis X, Y, and Z. L depends on the size of the electrons cloud, i.e., the deposited energy and drift length. A part of small charge Cluster possess a huge *Cluster* size and *Digits* multiplicity. A contribution of cosmic rays or noise events might be identified. During the event selection, a last operational step is to put those Clusters aside to eliminate the possible bias.

5.5 Conclusion Chapter 5

In this chapter, we presented the development of data processing devoted to XEMIS2. The physics data are taken from the XEMIS1 prototype using a ^{22}Na source operating under the same conditions foreseen of XEMIS2. The event topology displayed in the TPC has been first discussed. Neither using a collimator nor applying an external coincident trigger, deposited energy in the TPC may come from the gamma-ray of 511 keV or 1.274 MeV or both. The background coming from other gamma-ray will impact the calibration done using with a single energy peak source. The effect of the above mentioned background will equally affect the Compton sequence reconstruction, inducing a considerable data analysis challenge, especially limited by the small-scale TPC geometry of XEMIS1.

The first step of data treatment using the DAQ calibration consists in extracting signal corrections. The time measurement of the pixel signal depends on the clock stamping time of PU, the common voltage ramp and time memory block of XTRACT, and the CFD time walk and jitter. A set of corrections to optimize the time measurement has been detailed in the second section of this chapter.

The third part presented the data filtering dedicated to lower the noise present in the raw data to further reduce the storage volume. Two sub-steps have been investigated to remove the

impact of fake double-triggering resulting from the electronic noise and hysteresis effect as well as additional isolated background noise from the clustering time window. A raw data rejection ratio could vary from 20 to 50 depending on the applied amplitude threshold and isolated time window. The data filtering process will be integrated into the XCD for online data processing.

The last section of this chapter reported the algorithm of the event reconstruction and selection. We presented the pixel signal clustering method and the signals matching approach. To eliminate the bias due to the overlapping interaction vertices, the clustering algorithm is optimized to increase the cluster size to include all relevant information. A dedicated selection is then necessary to eliminate the bias events. A time fit method was proposed for event selection by estimating the time measurement variance inside a cluster. It accounts for the contributions of the DAQ measurement and electrons range of all Digits in the Cluster. Other cuts were also employed and listed in the last part of this chapter. The cumulative cut efficiency is 23%. The fiducial volume cut is the main responsible for the loss of efficiency: this can be explained as due to by the small-scale geometry of XEMIS1. This impact will not be so significant in XEMIS2 thanks to the larger detector size.

The next chapter will be dedicated to the physics analysis results on signal scattering events based on the data treatment presented in this chapter.



High-Energy Calibration with Photoelectric Peak of 511 keV and 1.274 MeV γ -rays

Data Analysis and Experimental Results

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The precise energy measurement in a single-phase liquid xenon detector depends on many parameters. Various factors could impact the charge measurement from the aspect of the detector construction to the data acquisition process. Under the operating condition of XEMIS2, the XEMIS1 detector performance is firstly estimated with the calibration of the photoelectric (PE) peak of 511 keV and 1.274 MeV gamma-ray. The associated data analysis

and experimental results are reported in this chapter. In the first part, the study is oriented toward the correction of charge measurement distortion, thus improving detector energy and spatial resolution. Then, the second part presents the position reconstruction results based on the data after charge loss correction. In the last part, we talk about the energy reconstruction. The collected charge degradation regarding the pixel multiplicity is observed during the analysis process, whose calibration result is also introduced.

6.1 Charge loss correction

The processes that impact the charge measurement has been discussed from the ionization signal production up to the DAQ system in Chapter 2 and Chapter 3. Three contributions to the charge measurement distortion are discussed in this part, including

- Cluster charge loss effect caused by threshold and electron diffusion;
- Ballistic deficit effect regarding the non-negligible high-energy electronic recoils range;
- Electrons attenuation related to liquid xenon purity.

All experimental results are based on the single-cluster events after the data treatment presented in Chapter 5, whose events topology is shown in Figure 6.1. The dependence of the collected charge on the z position indicated in Figure 6.1a will be corrected during the data analysis. Besides, the number of events reduces significantly near the anode due to the decrease of solid angle and absorption of gamma in the LXe (mean free path). A reduction factor of more than ten can be observed in the middle of TPC compared to events rate at the cathode level (Figure 6.1b).



Fig. 6.1 Events topology of single-cluster events. (a) Scatter plot of the reconstructed cluster charge as a function of the electron drift time after events selection. (b) Drift time distribution for different multiplicities of clusters. The Frisch grid is located at z = 0 (anode end) while another extreme is close to the source (cathode end).

6.1.1 Charge sharing effect

Phenomenon description The transverse size of the electron cloud produced by the ionization of a recoiling electron depends mainly on the drift distance to the anode through the diffusion of charge carriers in liquid xenon. Therefore, the ionization charge can be shared by several pixels. The mechanism of electrons diffusion and collection in liquid xenon TPC has been described in (see Section 2.2.2). The current will not be induced on the segmented anode until the charge carriers generated by the interaction reaching the Frisch grid. The size of the electron cloud generated far from the anode side might be large enough to become comparable to the pixel size and inducing signals on multiple adjacent pixels.

Impact on detector efficiency Charge sharing could result in the degradation of detector energy resolution due to the applied threshold on each pixel [169]. In the setup of XEMIS2 (same situation as this experiment), the source (small animal) is located in the center hollow tube (see Chapter 2), where the majority of interactions will occur at the cathode side. Most ionization electrons will be collected after a long drifting distance. The charge sharing is unavoidable for



Fig. 6.2 Fraction of single-pixel event and all types of multi-pixel events across the whole detector with different energy cut.

those signals with high deposited energy near the source. The fraction of events for different cluster multiplicity and different energy cuts measured in this experiment is shown in Figure 6.2. The fraction of single-pixel events is dominant in the short TPC of 6 cm regardless of the energy cut. Due to the IDeF-X saturation, all single-pixel events are removed in the energy window arround 1.274 MeV. Figure 6.3 displays the average multiplicity of different energy window events as a function of the drift length. Considering the electron diffusion along the transverse direction, it is expected to observe the pixel multiplicity increase with the drift distance. Besides, the range of recoil electrons increases the size of the electron cloud leading to a slight multiplicity rise regarding the deposited energy. Here, the energy window of 1.274 MeV is not considered since its multiplicity is probably not good because of the saturation problem.



Fig. 6.3 Average multiplicity of different energy cut events as a function of the drift length.

Simulation studies A low threshold of about 3 σ_{noise} has been employed to minimize the charge loss from the sharing effect. However, whether the impact could be negligible or, inversely, should be corrected has not been discussed. A simplified MC simulation is realized with ROOT framework under the following context:

- The experimental event topology is not considered in this simulation. Events are generated uniformly in the charge window ($N_{e-} \in [500, 85000]$) and in space (whole detector length in the surface of one pixel) to observe the general effect.
- The charge distribution in (x, y) plane of the anode is following a Gaussian law where the sigma is increasing with z as $\sigma_{TD}[mm] = 0.230\sqrt{z} \ [cm]$ to simulate transverse diffusion in liquid xenon.

- The longitudinal diffusion and electron attenuation are not taken into account.
- The charge per pixel is calculated as the integral of the Gaussian law over the surface of each pixel. Only the 8 pixels surrounding the central pixel are considered.
- A random Gaussian noise per pixel is added to the calculated charge;
- The noise values σ_{noise} and hardware threshold effect th_{hard} are fed with the calibration results;
- The cluster charge correction ΔQ is the mean value of the difference between the cluster charge and the generated charge.

Figure 6.4 shows the simulation results of ΔQ as a function of the *z* position and cluster multiplicity, respectively. For the entire simulated charge range, the average cluster charge decreases with the drift distance (Figure 6.4a), indicating that the cluster loss below threshold increases for bigger electron clouds. Besides, the measured charge could be overestimated near the anode due to the contribution of over-threshold noise. However, the corresponding average charge distortion is limited below the ENC level (~140 e-) and can be considered as negligible. The similar case can be also found in Figure 6.4b. The distortion is not significant apart from the high-multiplicity clusters with small charges where the noise pixels are dominant.



Fig. 6.4 Simulation results of cluster charge loss with respect of (a) drift length (all multiplicities) and (b) multiplicity (whole drift length).

However, the impact becomes more visible when we separate the average result of Figure 6.4a to different multiplicity events (Figure 6.5). A maximum of over 1000 e- is reached due to the loss of under-threshold fired pixel. Under these circumstances, a cluster charge correction might be useful to improve the detector energy resolution. The correction application result will be discussed in Section 6.1.4.



Fig. 6.5 Dependence of cluster charge loss on the drift length with (a) single-pixel, (b)double-pixel and (c) triple-pixel events.

6.1.2 Ballistic deficit effect

Phenomenon description The amplitude of the analog signal delivered by the front end electronic should be ideally proportional to the charge produced in the TPC. It requires the independence between the rise time of output signal of shaper on the charge collection time. However, only a very long integration time could accomplish this requirement that is not the case of IDeF-X, whose rise time is about 1.4 μ s (see Figure 6.6). The large electron cloud generated by high-energy recoil electrons could increase the electron collection time on the pixel resulting in the defect of amplitude measurement, this effect is known as ballistic deficit.



Fig. 6.6 Experimental result of the amplitude defect with respect to the induced current duration. The gap means the distance between the Frisch grid and anode.

Impact estimation We measure the amplitude of the signal output of the IDeF-X through various pulse injections to estimate its ballistic deficit effect. The experimental results is shown in Figure 6.6. Then we could estimate the influence of electron range for these test results. The estimation result is show in Figure 6.7. Figure 6.7a is the simulation result of electron range with respect to the electron energy from Geant4 simulation. Figure 6.7b shows the evolution of ballistic deficit with respect to the electron energy after applying the electronics response of Figure 6.6. A degradation of amplitude could reach to more than 2% considering the recoil electron is emitted along the drift direction and only one pixel is fired. Besides, the same



Fig. 6.7 Evolution of (a) Electron range and (b) ballistic deficit with the energy of recoil electron (considering the recoil electron is emitted along the drift direction and only one pixel is fired).

evolution with respect to the collected charge could be obtained by applying the ionization charge yield (Figure 6.8). It could contribute to correct the ballistic deficit effect during the data analysis process. However, the impact is multi-parameter-dependent. We should consider the momentum of recoil electron, the topology of fired pixels and z position, etc. The correction should be improved with more in-depth studies.

6.1.3 Electrons attenuation correction

A vital charge loss source is the attachment of electrons due to electronegative impurities present in liquid xenon, e.g., O_2 or H_2O . The released electrons during an interaction are captured as they drift towards the anode, resulting in an exponential attenuation of the measured charge carriers. The drift-length-dependent charge loss leads to a non-negligible worsening of detector energy resolution that should be corrected. The evolution of the charge (Q) as a function of the electron drift time (t_{drift}) from the interaction vertex to the Frisch grid level is written as:

$$Q(t) = Q_0 e^{\frac{-t_{drift}}{\tau}}$$
(6.1)



Fig. 6.8 (a) Ionization charge yield as a function of the energy of recoil electron (NEST data). (b) Evolution of ballistic deficit with the collected charge.

 Q_0 is the actual deposited charge at the point of interaction t_0 and τ represents the electron lifetime which has been discussed in Section 2.2.2.

The electron lifetime τ can be deduced by monitoring the dependence of measured amplitude on the drift time. In our experiment, we measured the evolution of the photoelectric peaks of 511 keV and 1274 keV γ -rays with respect to t_{drift} . Here, the electrons drift time t_{drift} is equal to the difference time Δt between the matched ionization and scintillation cluster time.

6.1.4 Experimental results

Here, the experimental results before and after the charge and attenuation correction are introduced and discussed.

Analysis method The evaluations of cluster charge on the drift time with different event multiplicities have been treated for those events located in the 511 keV and 1274 keV photoelectric peak, respectively. The employed analysis method finds the collected charge of interest peak range through Gaussian fit per drift time slice to obtain the evolution plot. The delicate points concerning the fit process mainly result from the background events in the photoelectric peak energy band and the intense decreasing of events distribution anti-dependent on the drift length. The former leads to important fit uncertainty depending on the fit interval, while the latter could introduce a statistic bias concerning the fit result. It is almost impossible to avoid the two effects completely, but we have tried to reduce their influence.

1. The histogram with variable bin width is generated to ensure that the integrated number of events per bin is constant.

2. A specific fit method is applied to eliminate the impact of background events on the collected charge estimation. A fit example is given in Figure 6.9. The event distribution (*h*) is not symmetric due to multi-factors, such as the diffusion before interaction in the TPC, the electron cloud fusion of two adjacent interactions of backscattering, and the Compton plateau of 1274 keV (for 511 keV). We firstly release the constraints on peak and background auto-finding to extract the good events (h_{phy}). Then a Gaussian fit is applied to the entire interval to characterize h_{phy} . In order to optimize the fit uncertainty, a second Gaussian fit is used in total event distribution *h* in a variable interval. For 511 keV events, the asymmetry phenomenon is normally more important compared to that of 1274 keV. A shorter interval is therefore used. For both two cases, in each slice, we search an optimized fit with minimum χ^2 where the mean and sigma are recorded as collected charge and sigma of charge measurement corresponding to the photoelectric peak energy.



Fig. 6.9 An example of peak fit for events energies of (a) 511 keV and (b) 1274 keV. The blue markers with error bar (*h*) represent the charge distribution of all physics events. The blue line (h_{bg}) is the self-find background distribution. The red markers with error bar (h_{phy}) are the substraction of the two above distributions representing the good events. The red line is the Gaussian fit of h_{phy} in whole interval. The black line is the Gaussian fit of h in a variable interval to minimize the χ^2 . Only the fitting results of the black line are used, and the other fittings belong to the peak finding method.

Photoelectric peak of 511 keV

No correction application The analysis results on the no corrected data are show in Figure 6.10. To reveal the impact of cluster multiplicity on the charge measurement, the analysis process is applied firstly on events integrated with all multiplicities (Figure 6.10a), then particularly to single-pixel (Figure 6.10b), double-pixel (Figure 6.10c), triple-pixel (Figure 6.10d) and high multiplicity (Figure 6.10e) events. A comparison of the evaluation of all the above cases has been summarized and plotted in Figure 6.10f. Based on the those results, we find that:

- A difference in collected charge between the different multiplicities is similar to the one studied at the beginning of the section.
- The exponential fit of each curve is not consistent (parallel), indicating that the dependence of collected charge on z position of different multiplicity events is not the same. That means there exist other contribution apart from the attenuation.

Cluster charge loss due to pixel threshold might be a good candidate to explain those phenomena. The cluster charge correction is thus applied in the next step.



Fig. 6.10 Scatter plot of the measured cluster charge (**without any correction**) as a function of the electron drift time for 511 keV events with (a-e) different multiplicities. The red points represent the collected charge obtained by Gaussian fit per slice in the interval of interest, and the solid red line represents the exponential fit of the collected charge. The comparison of all fit results is presented in the figure (f).

Application of cluster charge correction In this step, we use the simulation results to correct the measured charge of clusters. A charge correction is applied for each measured cluster charge according to the z position and the pixel multiplicity. Then a similar data treatment has been done. The synthesized result is shown in Figure 6.11b. To compare with that without correction,

we re-build Figure 6.10f and put it with the corrected result side by side (Figure 6.11). We find that:

- A more consistent behavior between the events of different multiplicities concerning the drift time dependency can be observed after the charge correction, indicating that the charge loss of those events far from the anode has been effectively corrected.
- Two groups of exponential slope between multiplicity 1&2~(gr1) events and that of 3&4~(gr2) are observed. The different behavior could result from several factors.

- As presented in the first part, the average multiplicity of collected charge of 511 keV should not be higher than 2.5 even located at the cathode side. Those clusters of high multiplicity (gr2), potentially contains the over-threshold noise pixel, showing a different performing with respect to the z position, compared with the proper events gr1.

- Apart from the noise pixels presented inside gr2, another possibility is that two neighbor interactions, e.g., the backscattering events, are miss-associated into the same cluster driving the different collected charge.

- The response of the readout electronics could also play a role in this observation. More details will be discussed in the part of event energy reconstruction.

• The electron lifetime is then taken from the exponential fit result of gr1 of about 221.533 \pm 0.094 μ s, corresponding to an attenuation length of 510.633 \pm 0.216 mm calculated with a drift velocity of 2.305 mm/ μ s. This distance is about 8 times the full TPC drift length which implies a charge loss of about 10%.



Fig. 6.11 Comparison of the measured cluster charge as a function of the electron drift time for 511 keV events (a) before and (b) after the cluster charge correction.

Application of attenuation correction We integrate the attenuation coefficient into the data analysis and the same study as before could be observed in Figure 6.12.

- A perfect correction is obtained for those events of multiplicity 1&2 (Figure 6.12b and Figure 6.12c).
- The dependence of collected charge against the z position is still existing for those events with high multiplicities implying a reduction of energy resolution (Figure 6.12d and Figure 6.12e). Other mechanism as discussed previously could contribute to this behavior.
- A charge loss for large multiplicities defecting charge measurement will be discussed in the following section (Figure 6.12f).
- The dependence shown in Figure 6.12a for total events regardless of multiplicity. The evaluation of the multiplicity fraction on the z position is presented at the beginning of the chapter. The strong variation of multiplicities proportion and their different behaviors degrade the energy resolution.



Fig. 6.12 Scatter plot of the measured cluster charge (after cluster charge and attenuation corrections) as a function of the electron drift time for 511 keV events with different multiplicities (Same interpretation as Figure 6.10).

Photoelectric peak of 1274 keV

The same data analysis is also performed to the events located at 1274 keV events. The overall result is shown in Figure 6.13. The attenuation correction used the electron lifetime obtained with 511 keV photoelectric peak. A very similar conclusion can be drawn as for the analysis at 511 keV and will not be repeated here. However, for this high-energy, there are less backscattered events since the diffusion gamma has more energy and interacts farther. The collected charge degradation and energy resolution with multiplicity will be detailed later.



Fig. 6.13 Dependence on the measured cluster charge on the electron drift time for 1274 keV events with different multiplicities (a) without any correction (b) after cluster charge correction and (c) after attenuation correction.

6.2 Space point reconstruction

The event 3D position reconstruction is an essential step for imaging cameras. The importance of precise space point localization has been reported in Chapter 2. This section will present the 3D position reconstruction and the time resolution observed on high-energy events.

6.2.1 XY position reconstruction

Impact factors A distortion of XY position is possible due to the non-homogeneous electric field resulting from the imperfections in the field shaping rings. Drifting electrons are deflected from ideal drift, contributing to a non-uniform response in the XY plane. This is why a XY position calibration is necessary for the large dimension TPC detector, where the deviation of the electron along drifting axis might be significant. Besides, the induced current generated in the adjacent pixel could also affect the electron collection, thus degrade the position resolution. To eliminate those potential influences, the high-quality shaping rings and innovative MIMELI
anode has been implemented in both XEMIS1 and XEMIS2, detailed in Chapter 2 and Chapiter 3. The distortion is considered negligible in XEMIS1 since the active area of the anode is much smaller than the inner radius of the shaping field. A perfect electric field can be considered.

Experimental result Two XY position reconstruction method has been used in our Event Builder. The first one is to determine the center of gravity (detailed in Chapter 5) of charges collected by pixels inside clusters. Figure 6.14a shows the distribution of XY position reconstructed by determining the center of gravity. Events with the center of gravity at the boundary pixels are rejected during the data analysis process. The high event density presents at the intersection of high intensity lines is the center of the pixel. The deducing of events density presents on the top sous from the cycle is caused by the pixel # 27 (red box), whose ZC is over range resulting in a high threshold compared to other pixels.



Fig. 6.14 XY position reconstructed by determine the center of gravity. (a) Distribution of cluster in XY plane (b) projection along the x-axis. The point of intersection is at the center of the pixel.

In reality, the electron cloud spreads as Gaussian-like distribution due to the transverse diffusion effect. A Gaussian correction is therefore applied to multi-pixel events for spatial resolution improvement [152]. Figure 6.15a shows the distribution of XY position reconstructed with Gaussian correction. As expected, the peak (middle of the pixel) is isolated, because it corresponds to single pixel clusters when the real interaction takes place near the center of the pixel. It is estimated that the resolution of a multi-pixel event is about 150 μ m (average value, different multiplicity has not been analyzed separately). Besides, The events are evenly distributed on the tracks and pillars, indicating that MIMELI and Frisch grid work perfectly.



Fig. 6.15 XY position reconstructed after the Gaussian correction. (a) Distribution of cluster in XY plane (b) projection along the x-axis.

6.2.2 Electron drift velocity and time resolution

The electron drift speed is determined by dividing the TPC length by the maximum drift time. Using the error function Erf (i.e., the S curve with all detailed parameters that has been introduced in Equation 4.13) to fit the distribution of events related to the drift time at the beginning and end of the TPC, we can obtain the total drift time over the entire drift length. Figure 6.16 and Figure 6.17 show the analysis results concerning the events of 511 keV and 1274 keV. A total drift time of about $28.2 \pm 0.1 \,\mu$ s is calculated with the events of 511 keV and $28.0 \pm 0.2 \,\mu$ s using the results of 1274 keV. Considering the total length from cathode to the Fricsh grid is $65.1 \pm 0.5 \,\text{mm}$, a drift velocity could be estimated at $2.309 \pm 0.008 \,\text{mm}/\mu$ s and at $2.325 \pm 0.010 \,\text{mm}/\mu$ s, respectively.

The range of the electron could explain the dependence of measured total drift time on the energy. For example, for a photoelectric effect at 1274 keV, if the recoil electron trajectory is backward, the end of its track may hit the cathode before drifting toward the anode. In this case, the electron cloud will lose part of its charge. The charge defect is related to the distance between the interaction and the electrode. In the case of very close distances to the cathode, a large amount of charge loss appears, which will cause the reconstructed energy to be outside the peak range and not be considered. Therefore, the measured time at the side of two electrodes exists a distance gap in the order of electron range. This impact of electrons track takes place in all energy range while less important at lower energy.



Fig. 6.16 Beginning and end of the TPC for single-cluster 511 keV events. The solid red lines are the Error function fit to the drift time distribution at both edges of the chamber.



(a) Begin of the TPC (anode side) (b) End of the TPC (cathode side) 17 Beginning and end of the TPC for single cluster 1274 keV events The solid red line

Fig. 6.17 Beginning and end of the TPC for single-cluster 1274 keV events. The solid red lines are the Error function fit to the drift time distribution at both edges of the chamber.

Moreover, the width (sigma) of both Erf fits also gives an estimated value of the timing resolution for 511 keV signals of around 88.1 \pm 7.6 ns and for 1274 keV signals of around 133.9 \pm 23.0 ns regarding the average result of both TPC side. Considering the drift velocity is 2.3 mm/ μ s, we could calculate a z-resolution for 511 keV of around 200 μ m and 300 μ m for 1274 keV signal.

6.3 Event energy reconstruction

The collected charge spectrum of all single cluster events after the charge loss correction is presented in Figure 6.18. Due to gamma-ray scattering and overlapping physical interactions, the PE peak shows an asymmetric event distribution. The energy resolution of the all-energy photoelectric peak is about 4.5-5% and 3-3.5% corresponding to the gamma-ray energy of 511 keV and 1274 keV, respectively, slight varying with different fitting intervals.



Fig. 6.18 Collected charge spectrum of single cluster events.

6.3.1 Gain correction

The electronic gain of each pixel could be corrected with the physics peak calibration. The collected charge map on the XY plane is presented in Figure 6.19. A different gain value between pixels at positive and negative x-axis can be observed, corresponding to two XTRACT chips, XT0 and XT1. A variance of more than 1000 electrons is observed. This gain correction is



Fig. 6.19 Charge collection map on the XY plane using the events of (left) 511 keV and (right) 1274 keV.

necessary to improve the energy and position resolution. Considering the various integration capacity inside the IDeF-X chip, all pixel gain is re-adjusted with NEST, i.e., 26467 electrons for photoelectric peak of 511 keV γ -rays.

6.3.2 Charge degradation of multi-pixel events

The collected charge degradation between events of different multiplicity is characterized in this part. The collected charge at the calibration peak of each type of multiplicity is obtained from the mean value of Gaussian fit. To prevent the bias generated by the event statistic, the fit is applied in the same fraction of amplitude interval. The analysis results of 511 keV and 1274 keV are shown in Figure 6.20 and Figure 6.21. In both cases, the collected charge decreases with the increase of event multiplicity. However, the distribution is quite similar between those events own different multiplicities. Only a small shift could be observed directly.



Fig. 6.20 Peak of 511 keV measured with events of different multiplicities.



Fig. 6.21 Peak of 1274 keV measured with events of different multiplicities.

Admitting that those events hold the largest amplitude (i.e., the minimization of multiplicity) has no defects, other event types relative degradation can be calculated. Figure 6.22 shows the reduction of the collected charge relative to the multiplicity for events of 511 keV and 1274 keV. Except for the case of a single-pixel event to a two-pixel event, the reduction in amplitude varies almost linearly with the increase in multiplicity. This behavior is more likely to be caused by DAQ or electronic systems than physical phenomena in TPC.

Actually, a characterized behavior of IDeF-X could be used to explain this observation. A parasitic signal appears in all the pixels of the same chip when the readout chip is fired by a relatively high charge. The negative pole of this bipolar parasitic signal can cause a fall of the baseline of the order of 0.7% of the total collected charge in this chip. However, the degradation per pixel observed in this work is in the range of 1.2-1.7%. However, this phenomenon is still strongly related to this electronic effect.



Fig. 6.22 Energy degradation as a function of the multiplicity for events of (a) 511 keV and (b) 1274 keV.

Other factors contributing to this charge loss should be identified to find a correction method since the impact is important. In addition, it is critical to determine whether smaller deposited energy exhibits the same degree of amplitude reduction because the energy accuracy has a greater impact on Compton reconstruction than the photoelectric peak used for LOR reconstruction.

6.3.3 Energy resolution

The energy resolution (σ/E) is the ratio between the sigma σ and the mean value E of the Gaussian distribution of the measured charges. Considering the charge yield is constant in the high energy range that the energy resolution could be direction calculated with the collected charge. Figure 6.23 gives the energy resolution for events with different multiplicities.



Fig. 6.23 Energy resolution as a function of the multiplicity for events of (a) 511 keV and (b) 1274 keV.

Energy deposited in one or two pixels (4.5% for 511 keV) presents better resolution compared with those high-multiplicity events (4.7% for 511 keV). It mainly caused by the contamination of double interactions and the contribution of over-threshold noise pixel. Besides, the amplitude shift between events of different multiplicities leads to a worse resolution of the integrated spectrum (more than 4.9% for 511 keV). Considering that the amplitude degradation is caused by electronic performance with a constant affecting fraction, a corresponding correction has been applied to compensate this effect. An improved energy resolution of 4.5% can be observed in Figure 6.24 after the correction.



Fig. 6.24 Energy resolution as a function of the multiplicity for events of (a) 511 keV and (b) 1274 keV after the multiplicity-dependent-amplitude correction.

The results of Figure 6.12f and Figure 6.13c have shown the impact of pixel-multiplicitydependent charge measurement results in the gain deviated along drift-axis. In this case, due to the electronics saturation, the single-multiplicity event cut in the case of 1274 keV can reduce the dispersion of event population, leading thus to a more uniform performance along z-axis. Here, the charge yield and resolution along the drift direction after the multiplicity-dependentamplitude correction is also investigated shown in Figure 6.25 and Figure 6.26 for events of 511 keV and 1274 keV. A uniform charge measurement is reconstructed showing a better energy and position resolution.



Fig. 6.25 Evolution of (top) Ionization yield and (bottom) energy resolution of 511 keV as a function of the drift length. The red solid line represents the value obtained from the whole events integrated over all z-values, and the red band is the 0.95 confience zone (after the multiplicity-dependent-amplitude correction).



Fig. 6.26 Evolution of (top) Ionization yield and (bottom) energy resolution of 1274 keV as a function of the drift length. The red solid line represents the value obtained from the entire events integrated overall z-values, and the red band is the 0.95 confidence zone (after the multiplicity-dependent-amplitude correction).

6.3.4 Charge yield

Finally, Figure 6.27 shows the charge yield that is calculated with the entire events integrated from all multiplicity and z slice. The gain of charge measurement is calibrated with the yield of 511 keV given by NEST. However, the yield deviation of 1274 keV of about $1 e^{-}/keV$ can not be compensated. It could be mainly caused by the ballistic deficit effect, related to the electron range, and by the inseparable fusion of adjacent backscattering interactions, increasing the difficulty of the precise high-energy calibration. The Compton geometric calibration method specially used for small signal measurement can avoid these effects, and it is currently being studied to apply it to XEMIS2.



Fig. 6.27 Charge yield measured with this work comparing with NEST. The curves show the results after calibrated with the yield of 511 keV γ -ray given by NEST

6.4 Conclusions Chapter 6

This chapter introduces the data analysis and experimental results related to the calibration of the detector in the high-energy range using the photoelectric peaks of 511 keV and 1274 keV.

The first section investigated three effects that may affect charge measurement. A simulation study was conducted to estimate the charge loss related to the drift length and the multiplicity of the charge clusters. The simulation result was integrated into the data analysis, partially correcting the z-dependence on the collected charge. Then, if the electron is emitted along the drift direction and all charges are collected by a single pixel, an amplitude defect concerning the recoil electron energy is deduced by combining the electron range and the ballistic deficit of

electronics. Then the attenuation correction was applied to eliminate the z-axis dependence. An amplitude degradation with the number of fired pixels was observed during the data analysis processes.

The second part discusses the event position reconstruction. Based on the corrected cluster charges, Gaussian fitting correction was applied that could improve the interactive position in the XY plane. In addition, the drift velocity and spatial resolution on the z-axis are also estimated.

The last part reported the energy measurement results. A charge collection map of all 64 channels was constructed for pixel gain correction, which could improve energy resolution. Then, we calibrated the charge distortion caused by the cluster multiplicity found in the first part. This distortion resulted in a new z-axis dependence of collected charge. The charge yield and resolution were discussed at the end of the section.



Compton Geometric Angular Calibration

Preliminary Experimental Study Results

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Good Compton scattering angular resolution over the low-energy range expected for the 3-gamma imaging is required to make the XEMIS2 camera a success. We propose an innovative Compton Geometric Angular Calibration (CGAC) method specifically for XEMIS2 self-calibration in response to this demand. This new method benefits from a high spatial resolution of our LXeTPC and requires the Compton scattering sequence reconstruction. In this chapter, we present the current status of our work within the context of the XEMIS1 prototype. Its basic concept and algorithm will be first given. Then, the preliminary experimental measurement results are also reported.

7.1 Basic concept

CGAC aims to establish a direct relationship between the number of electrons measured in the first hit (Compton scattering vertex), Q_1^m , and the corresponding theoretical geometric Compton angle, θ^G , using the Compton kinematics equations and the NEST model. In this section, we specify the main motivations, basic principles and potential restrictions concerning the CGAC experiment.

7.1.1 Motivation

The fundamental principle and technical requirements of Compton imaging have been discussed in Section 1.3. For each radiation interaction, both a high-resolution position reconstruction and a precise energy measurement are critically needed to determine the direction of the incident γ -ray based on the Compton scattering kinematics. For scattering angles between 10° and 60°, good angular resolution is expected, which means that the deposited energy of the first scattering hit is between 40 keV and 600 keV. However, the detector performance on the low-energy measurement and the Compton scattering sequence reconstruction in LXeTPC could not be brought out with the previous experiments such as photoelectric peak calibration. This CGAC work aims at providing the first attempt on this topic.

No-linear ER charge yield in LXe The charge yield is not constant due to the recombination process in LXe, especially in the low-energy region (see Chapter 2, Section 2.2.2). The intrinsic uncertainties on the number of released electrons limits the ionization-based energy resolution. Compared with high-energy calibration, this significant non-linearity response of LXe requires consecutive measurements using sources of different energies to establish a proper charge yield curve in this region.

Compton Coincidence Measurements A charge yield measurement method of low-energy ERs in LXe has been proposed in Ref. [170]. The Compton coincidence technique (CCT) used in the neriX detector is based on the combination of Compton kinematics and an external High Purity Germanium (HPGe) detector. The experimental setup is schematized in Figure 7.1. In this experiment, high-energy mono-energetic γ -rays (661.7 keV) with a known direction irradiate in the primary small-scale LXe detector. The second detector is arranged to detect the Compton scattered γ -rays in time coincidence for tagging valid events. The arrangement of detectors and γ -rays source is designed to impose an identified scattering angle θ in the LXe target media.

The energy deposited in LXe $(E_e^{m_1})$ can be directly inferred from the difference between the known initial energy (E_{γ}) and the final energy $(E_{\gamma'}^{m_2})$ measured in the second detector:

$$E_e^{m_1} = E_\gamma - E_{\gamma'}^{m_2} \tag{7.1}$$

According to the Compton kinematic formula Equation 1.5 (see Chapter 1), different ranges of electronic recoil energy can be detected in the primary detector by placing the second detector at a different angle θ to the incident gamma rays. In this experiment, $E_{\gamma'}^{m_2}$ is provided by HPGe detector, whose energy resolution is very good of 1.3 keV (FWHM) at 552 keV [170], accurately measuring scattered gamma-ray energy. The significant distance (17.6 cm between source and neriX detector and 14.6 cm between neriX and HPGe) is arranged to obtain an excellent geometric angle resolution for precise scattered γ -ray energy measurement.



Fig. 7.1 Schematic of the experimental setup used in neriX experiment for Compton Coincidence measurements. Figure taken from [170].

7.1.2 Compton Geometric Angular Calibration

Principle description The basic experimental principle of CGAC technique is similar to CCT: using monochromatic γ -rays to calibrate Compton scattering events. Since LXeTPC itself is an excellent Compton telescope, the calibration process can be carried out in-situ of XEMIS1/XEMIS2 without an external detector. Figure 7.2 schematizes an example of Compton scattering event detection in the experimental setup of XEMIS1. The position of the source (red box) S is known with the mechanic measurement, its spatial barycenter coordinates noted as $S(x_0, y_0, z_0)$. M_i (black star) is the interaction vertex in LXe, whose reconstructed coordinates and measured cluster charge are denoted as $M_i(x_i, y_i, z_i, Q_i^m)$. Considering M1 the Compton scattering vertex, a geometric angle (θ^G) related to the incident gamma rays can be deduced as:

$$\theta^G = \arccos\left(\vec{u}.\vec{v}\right) \tag{7.2}$$



Fig. 7.2 Schematic of the experimental setup used in XEMIS1 detector for Compton Geometric Angular Calibration.

where \vec{u} and \vec{v} are the normalized vectors of $\overrightarrow{SM_1}$ and $\overrightarrow{M_1M_2}$ expressed as:

$$\vec{u} = \frac{\overrightarrow{SM_1}}{\|\overrightarrow{SM_1}\|} \quad and \quad \vec{v} = \frac{\overrightarrow{M_1M_2}}{\|\overrightarrow{M_1M_2}\|}$$
(7.3)

The ER energy E_e^G is calculated from geometric Compton angle θ^G without considering the Doppler effect by:

$$E_e^G = \frac{E_\gamma^2 \left(1 - \cos\theta^G\right)}{mc^2 + E_\gamma \left(1 - \cos\theta^G\right)}$$
(7.4)

Thanks to the NEST model, the theoretical number of released electrons Q_e^G can be estimated from the calculated E_e^G . Then, we apply the Compton sequence reconstruction algorithm to identify the number of electrons measured in the first hit Q_1^m , which corresponds to the Compton scattering vertex under the correct scattering sequence. Finally, Q_1^m can be associated with the geometric Compton angle θ^G to achieve the purpose of CGAC.

Specifications The CGAC method can be established under the following assumptions:

- The source should be point-like or placed far from the detector in order to be considered as a point.
- The source position needs to be well known through mechanics measurement or other calibration methods.
- The spatial and energy resolution of Compton telescope should be good enough to reconstruct the Compton scattering events.
- The adapted algorithm for Compton scattering sequence selection and reconstruction needs to be developed.

7.2 Method

7.2.1 Overall algorithm

The overall algorithm diagram is presented in Figure 7.3a, consisting of five main steps.



Fig. 7.3 Algorithm of Compton Geometric Angular Calibration in XEMIS1. (a) Diagram of the principal data treatment steps for Compton cone reconstruction. (b)A schematic example of event selection and cone reconstruction.

- A. Events selection is an event cut-based analysis that aims at rejecting the potential TPC events containing the mismatching clusters. We use the same analysis processes as those described in Chapiter 5. The fiducial volume cut is used as self-shielding. It can eliminate the radiation interaction from other γ -rays to prevent a miss-matching of Compton scatters. A schematic example is shown in Figure 7.3b. All reconstructed Cluster outside fiducial volume (red dot line) are not taken into account.
- **B. Hit reconstruction** is the next data processing step after the event selection, aiming to reconstruct the physics interactions produced in the TPC. In a TPC event object, each Digit Cluster is affiliated with a Hit object with its associated energy and position. Thus, each Hit represents a physics interaction. In this step, only the TPC events containing two Hits are conserved for selecting multi-hit events. For a calorimeter event, the two Hits correspond respectively to Compton scatter and photoelectric absorption.
- **C. Group reconstruction** algorithm allows building Groups of Hits coming from the same photons (see Figure 7.3b). In the case of CGAC in XEMIS1, rejecting all multi-Group events to maximize the possibility that two Hits in a TPC event are caused by consecutive collisions of the same gamma rays. In addition, an energy cut is used to select those

TPC events with full energy deposition of 511 keV or 1.274 MeV corresponding to the monochromatic γ -ray selection. To identify events from 1.274 MeV γ -rays, an event selection with a total deposited energy of more than 600 keV can also be used to separate events of interest from those of 511 keV γ -rays.

- **D.** Cone builder reconstructs Compton Cones from a pair of Hits, included in a Group, that determines their axis Δ and apex θ . Their aperture is determined using Compton kinetics (Equation 1.5, Chapter 1). A collection of Cones is set by reconstructing cones from all possible order of two hits in the Group. In the case of CGAC, each group contains two HIts, corresponding to a reconstruction of two possible cones.
- **E.** Cone selection is also named Compton scattering sequence reconstruction. The objective is to select the most probable Hits sequence, thus obtain the right Compton angle.

7.2.2 Compton scattering sequence reconstruction

Uncertainty on the Compton geometric angle σ_{θ^G} The Compton geometric angle θ^G is determined through the space position of the source and reconstructed interaction vertex, whose expression is given in Equation 7.2.

$$\cos\theta^G = \vec{u}.\vec{v} \tag{7.5}$$

where the $\sigma_{\cos\theta^G}$ is the uncertainty of $\cos\theta^G$. It can be obtained though the uncertainty propagation formula and written as:.

$$\sigma_{\cos\theta^G}^2 = \sum_{i=0}^2 \left(\frac{\partial\cos\theta^G}{\partial x_i}\right)^2 \sigma_{x_i}^2 + \sum_{i=0}^2 \left(\frac{\partial\cos\theta^G}{\partial y_i}\right)^2 \sigma_{y_i}^2 + \sum_{i=0}^2 \left(\frac{\partial\cos\theta^G}{\partial z_i}\right)^2 \sigma_{z_i}^2$$
(7.6)

where $\sigma_{x_i}, \sigma_{y_i}$ and σ_{z_i} are measurement error of source position and the spatial resolution of detector. In our case, we consider an isotropic spatial resolution of vertex measurement $\sigma_{x_{1,2}} = \sigma_{y_{1,2}} = \sigma_{z_{1,2}} = 0.3$ mm (estimated through the single-cluster analysis results) and the $\sigma_{x_0} = \sigma_{y_0} = \sigma_{z_0} = 0.5$ mm are estimated.

The uncertainty of θ^G can be thus calculated from Equation 7.7 :

$$\sigma_{\theta^{G}} = \left| \frac{d\theta^{G}}{d\cos\theta^{G}} \right| \sigma_{\cos\theta^{G}}$$

$$= \frac{\sigma_{\cos\theta^{G}}}{\sqrt{1 - \cos^{2}\theta^{G}}}$$
(7.7)

Uncertainty of energy geometric angle $\sigma_{E_e^G}$ From Equation 7.2, the uncertainty on the energy geometric angle $\sigma_{E_e^G}$ is deduced as:

$$\sigma_{E_e^G} = \left| \frac{dE_e^G}{d\cos\theta^G} \right| \sigma_{\cos\theta^G}$$

$$= \frac{E_{\gamma}^2 \cdot mc^2}{\left(mc^2 + E_{\gamma}(1 - \cos\theta^G)\right)^2} \cdot \sigma_{\cos\theta^G}$$
(7.8)

Covariance on the measured charge Q_i^m with the geometric reconstructed charge Q_i^G We use a covariance-based uncertainty analysis for the Compton scattering sequence reconstruction. The variance between the measured charge Q_i^m with the Compton geometric angle deduced charge Q_i^G can be expressed as the product of matrices:

$$\chi^2 = Q^T V^{-1} Q \tag{7.9}$$

where

$$Q = \begin{bmatrix} Q_1^m - Q_1^G \\ Q_2^m - Q_2^G \end{bmatrix} = \begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} \quad with \quad \begin{cases} Q_1^G &= f(E_e^G) \\ Q_2^G &= f(E_\gamma - E_e^G) \end{cases}$$
(7.10)

and

$$V = \begin{bmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{bmatrix} \quad with \quad \begin{cases} V_{ii} = \sigma_{Q_i}^2 = \sigma_{Q_i^m}^2 + \sigma_{Q_i^G}^2 \\ V_{12} = V_{21} = cov \left(Q_i, Q_j\right) = -f'(E_1^G)f'(E_2^G)\sigma_{E_1^G}^2 \end{cases}$$
(7.11)

In this formula,

- f is the energy-to-charge conversion function adapted from the NEST database [171].
- σ_{Q^m} is the charge measurement resolution estimated by

$$\sigma_{Q^m}^2 = \sigma_{Q_{noise}}^2 + \sigma_{Q_{NEST}}^2 \tag{7.12}$$

where $\sigma_{Q_{noise}}$ represents the noise contribution to the Cluster charge measurement. $\sigma_{Q_{noise}}$ is estimated as $\sqrt{2}\sigma_{noise}$ of about 220 electrons, with the pixel noise σ_{noise} of about 150 electrons. And $\sigma_{Q_{NEST}}$ is the dispersion of charge measurement caused by the recombination processes. The value is estimated through the Geant4 simulation by adapting the NEST model [171].

• σ_{Q^G} is the charge resolution deduced from Compton geometric angle, computed as

$$\sigma_{Q^G} = |f'(E^G)|\sigma_{E^G} \tag{7.13}$$

• V_{12} is not zero since Q_1^G and Q_2^G are correlated and dependent from Equation 7.14 :

$$E_1^G = E_e^G \quad and \quad E_2^G = E_{\gamma}^G - E_1^G$$
(7.14)

During the data analysis, the sequence of two Hits with the minimum value of χ^2 is considered as the more likely true Compton sequence. The experimental results of this Compton event selection are discussed in the next section.

7.3 Experimental results and discussions

In this section, the preliminary experimental results obtained in the context of this experiment in XEMIS1 are reported. The physics data are the same of those analyzed in the previous chapter for photoelectric peak calibration.

7.3.1 Events topology and detector acceptance

The spatial distribution of all Hits after Group reconstruction is given in Figure 7.4. Each Group consists of two non-ordered Hits with a total energy of more than 600 keV for selecting interactions of the third γ -ray ($E_{\gamma} =$ 1.274 MeV for source ²²Na). The event frequency of



Fig. 7.4 Distributions of (a) Hits on z-axis (The Frisch grid is located at z = 0 (anode end) while another extreme is close to the source (cathode end)) and (b) the distance ΔD between two Hits of same group.

Hits decreases with the distance from the radioactive source and the penetration depth of the liquid xenon, resulting from the decrease in detectable solid angle acceptance and photon attenuation (see Figure 7.4a). At the same time, a second peak at a distance of about 6 mm from the maximum of distribution (source side) can be observed. Combined with Figure 7.4b, the distance between two Hits of the same Group, a critical distance of Hits

separation is about 6 mm. Besides, two straight peaks located at around 3 mm in Figure 7.4b expose the fact that numerous events possess a small distance ΔD between two Hits. The phenomenon is due to the size of the pixels (3.1 mm) and Clustering method. The two Clusters in these events might be piled up or come from the same physical hit. In order to effectively distinguish the true multi-Hits events, an event cut of $\Delta D > 6 mm$ is used in the subsequent analysis. Apart from the Hits separation limit associated with the detector, the global distribution relates to the average free path of scattered γ -rays depending on its energy.

The detector acceptance of XEMIS1 is shown in Figure 7.5. All 180° Compton angle reconstructions is achievable. To investigate the events nature, we use Compton kinetic formula and the NEST model to estimate the deposited charge of Compton scattering as a function of Compton angle, shown as a red curve. The false sequence is reported as the yellow line, where the deposited charge of scattered gamma-ray is mistakenly considered as a scattering hit. Both behaviors are recognized in the experimental data analysis results. In addition, the total energy deposition of 511 keV (black line) and 1.274 Mev (withe line) is also significant in Figure 7.5b, which means that two gamma rays detected in the active area. Hits of the same group are thus non-sequence interactions of the different gamma-ray, registered as random events.



Fig. 7.5 Presentation of deposited charge of the first Hit as a function of the Compton geometric angle θ^G in the case of (a) third γ -ray selection and (b) third γ -ray calorimeter. Two possible sequences have been considered in this direct Compton geometric angle reconstruction. The red curve in each figure represents the theoretic correspondence in the case of the correct sequence, while the yellow curve describes the false sequence. The black line is the event mixed of the γ -ray of 511 keV.

Limited by the small detector size, XEMIS1 is not suitable as a third gamma-ray calorimeter. There are less than one-third of calorimeter events (Figure 7.5a) compared to the total selected (Figure 7.5b). However, since only two first-sequence hits of the third gamma ray are required to achieve Compton cone reconstruction, full energy deposition is not required to achieve determine the incident direction. In the subsequent analysis, we use an energy cut-off of more than 600 keV instead of an energy calorimeter to select the third γ -ray for the CGAC.

7.3.2 Compton scattering sequence selection

Figure 7.6 shows the CGAC results of 1.274 MeV γ -rays reconstructed with two different Compton scattering sequence selection methods.



Fig. 7.6 Reconstructed deposited charge of first Hit Q_1^m as a function of the Compton geometric angle θ^G for events of 1.274 MeV after Compton scattering sequence selection with (a) charge correlation analysis (b) χ^2 covariance uncertainty analysis.

- M1 charge correlation analysis: The first method compares the angle resolution $\sigma_{\theta G}$ and the charge measurement difference ΔQ resulting from the two different Hit-sequences of same Group. The results shown in Figure 7.6a are computed by selecting the right Hit-sequence with $\Delta Q = |Q^m - Q^G| < 3 \sigma_Q (\sigma_Q \text{ has been introduced in Equation 7.11}).$ If both of the two Hits (or neither of them) satisfy the critical condition, the event is rejected.
- M2 χ^2 covariance uncertainty analysis: Figure 7.6b shows the results obtained through the χ^2 covariance uncertainty analysis. The χ^2 of plotted events is less than 20 showing

also a quite proper event selection results. However, only calorimeter events are considered in this selection method, which favors the reconstruction of backscattering events. This aspect will be discussed later, which is impacted by the volume acceptance of the detector. In addition, there exists difficulty to select the true sequence in the area (around 10 degrees) where both orders are possible.

The final CGAC experimental result treated with M1 analysis is given in Figure 7.7. Each measured charge of first HIt (Q_1^m) can find a mean value of geometric Compton cone (θ^G) via Figure 7.7a. The calibration curve can be directly reused for Compton angle reconstruction to recognize the incident direction of the 1.274 MeV gamma-ray. As we can see, a direct reconstruction is available in the angle range of 10°-60° with RMS less than 4.5° (see Figure 7.7b), while the uncertainty in large-angle area (grey area) increases sharply. This result corresponds to the reconstruction range of Q_1^m from a few hundred electrons to 40,000 electrons.



Fig. 7.7 CGAC experimental results with different spatial distance cutoff for events of 1.274 MeV.

The above research is carried out under different spatial distance cutoffs on ΔD in the analysis process. The influence on the average curve is not apparent in the interest area. In contrast, a larger ΔD presents a better angular resolution. The result is evident as discussed in Compton Coincidence Measurements: a considerable distance between two Hits can improve geometric angular resolution. In addition, the size of the source and the distance from the detector are also crucial factors affecting the geometric angular resolution. The yellow area in the figure represents the influence of the radioactive source, showing a significant resolution limit about 2°, which will be discussed in the next section.

Finally, the charge yield of Compton electron recoil can be assessed by converting the Compton angle to the relevant energy. The experimental results compared with the NEST model are shown in Figure 7.8. A slight deviation in the small energy zone (marked with red dotted circle) can be observed. This observation also confirms the necessity of CGAC. In theory, the relationship between the deposited charge of the first Hit Q_1 and the Compton angle θ can be directly established through the Compton kinetic and the NEST model. However, CGAC experiment results have also taken the influence of the detector into consideration, which could improve the accuracy of Compton angle reconstruction.



Fig. 7.8 Charge yield of Compton electronic recoil for events of 1.274 MeV.

7.3.3 Discussions about others contributions

Detector geometry limitation The detector geometry affect significantly the Cone reconstruction due to the volume acceptance. In XEMIS1 setup, the long cylindrical geometry favors the back-scattering events. The energy of the scattered γ -ray is low enough that it is likely to lose all the energy with a small distance. By contrast, a high-energy scattered γ -ray can easily escape the detection volume even with a small diffusion angle. This phenomenon is demonstrated through the experimental results shown in Figure 7.9. For both 511 keV and 1.274 MeV γ -rays, among the correctly reconstructed Cone objects in the XEMIS1 setup, the second hit owns almost always a smaller energy than the first hit. Besides, large numbers of first hits is located in the Compton edge contributing to the backscattering events. As discussed previously, the small distance between two Hits worsens the angle resolution, reducing the image quality during the Compton imaging. This phenomenon explains why the angular resolution measured by this



Fig. 7.9 Measured charge distribution of reconstructed two Hits for events of 1.274 MeV.

method CGAC is not so good in XEMIS1. Unlike the XEMIS1 setup, the XEMIS2 camera is designed to have an acceptance volume of about 70% (detailed in Chapter 2). A much better angle resolution could be expected.

Impact of the source size Apart from the impact of the small-scale active volume, in this experiment, another important factor is source size, whose parameters are detailed in Chapter 5. The uncertainty caused by the non-point-like source size is important. For the Compton geometric calibration, this impact should be reduced by placing the source far from the detector. A new experimental setup with an external movable source support will be installed in XEMIS1 for further studies.

7.4 Conclusions Chapter 7

In this chapter, we proposed the Compton Geometric Calibration (CGAC) method dedicated to the XEMIS2 self-calibration in the low-energy range. The experiment was taken placed in the XEMIS1 prototype for preliminary study. The basic principle was described in the first place. This method benefits the advantage of LXeTPC as an excellent Compton telescope to accomplish the in-situ calibration of Compton scattering events.

The Compton sequence reconstruction algorithm was presented in the second section. We discussed the related variables and uncertainty computing method. A covariance-based uncertainty analysis for the Compton scattering sequence reconstruction was also reported.

In the last part, we reported experimental and analysis results. The event topology was first discussed. Then the data analysis studies and results of the CGAC are presented. The charge yield related to electronic recoils and scattered γ -rays were also investigated in this section.

All results reported in this chapter are still in preliminary study. It gave a first demonstration on the feasibility of the Compton Geometric Calibration in XEMIS LXeTPC. However, the current setup could not provide the optimized results due to the geometry limit of XEMIS1 and the size of employed source. An updated experimental setup and more detail analysis are underway for further researches.

Conclusions and Perspectives

A S the heart of healthcare priorities of the 21st century, personalized medicine requires Anuclear medical imaging having better sensitivity and resolution to reduce the administered dose and shorten the exam time.

Nowadays, PET imaging provides the best reachable sensitivity and quantitative accuracy. For what concerns personalized medicine, advances in PET imaging cameras can be divided into three categories, as presented in **Chapter 1**: the total-body PET (TB-PET), the time-of-flight PET (TOF-PET) and the depth-of-interaction PET (DOI-PET). The TB-PET imaging dramatically reduces the exam time with the same dose as the other two modalities by increasing the field of view. The TOF-PET aims at reducing the length of LOR with the best Coincidence Resolving Time (CTR) resolution targeted at 10 ps. The DOI-PET tries to solve the trade-off between the detectors' sensitivity and spatial resolution caused by the parallax effect that existed in the conventional PET systems. All three approaches proved the capacity to significantly improve the camera sensitivity in terms of higher image quality and faster exam.

The rising development of the Compton camera, in recent decades, showed a promising capacity of γ -ray imaging in a wide energy band and without any need for collimators. The Compton telescope in nuclear medicine brought novel modalities on multi-tracer imaging, range verification in hadrontherapy, and 3-gamma imaging. Multi-tracer imaging provides the opportunity to observe dual or multiple complex molecular and metabolic phenotypes simultaneously. Real-time range verification allows exploiting the hadrontherapy treatment fully. Besides, based on the combination of Compton telescope and special (β +, γ) coincidence emitted isotopes, a novel 3-gamma imaging modality has attracted lots of attention as it constitutes a substantial advancement in the field, as presented in **Chapter 1**.

The work in this thesis basically focuses on the ionization signal measurement in the LXeTPC of the XEMIS system (XEMIS1 and XEMIS2). The XEMIS project is directed to personalized medicine, based on an innovative liquid xenon Compton camera to realize low activity medical

imaging. The LXeTPC is a suitable candidate to build a Compton telescope for nuclear medical imaging applications. It operates primarily with ionization signals combined with the scintillation light information, allowing for 3D position reconstruction, energy measurement, and multi-hit sequence identification. Meanwhile, a pseudo-PET performance could be achieved by applying the innovative 3-gamma imaging modality, measuring the intersection of LOR and Compton cone with good precision to obtain a direct 3D location of the radiotracer. A detailed description of the XEMIS2 system, an innovative Compton camera for small animal imaging based on the LXeTPC technique, was given in **Chapter 2**.

XEMIS2 is developed in the SUBATECH laboratory to demonstrate the advantage of LXe as a detection medium for 3-gamma imaging. It is a monolithic single-phase detector with a large axial field of view, holding up to nearly 200 kg of ultra-high-purity liquid xenon. In XEMIS2, an ultra-high purity level is expected to be achieved through the new purification-cryogenic subsystem ReStoX equipped with a gaseous purification system, realizing a re-circulation closed-loop, as reported.

The first stage of XEMIS2 aims to obtain a small animal image with an ultra-low activity of 20 kBq in 20 minutes while preserving the image quality in oncology diagnosis. To continuously readout with negligible dead-time during 20 minutes, a specific high-rate data acquisition system was developed and tested during this thesis work. The novel acquisition chain of XEMIS2 from the design requirements, operation principle, and electronic readout chain implementation was discussed in **Chapter 3**.

In order to perform accurate charge measurements, our research team proposed an innovative segmented electrode geometry MIMELI to optimize the induced current generation in LXeTPC. The experimental test in XEMIS1 combined with an ultra-low-noise front-end electronic ASIC called IDeF-X HD-LXe has shown encouraging results. In XEMIS2, to obtain the expected image quality with lower activity with respect to other technologies currently in use, we need to extrapolate the same/better performance from 64 pixels to more than 20,000 pixels while achieving higher event efficiency with a manageable data flow/volume. The new signal readout electronics system needs to meet self-triggering, high-rate acquisition, and low electronic noise. A signal information extraction ASIC was developed to reduce the storage data volume. A new data acquisition system was proposed based on the above-listed requirements. The operation principle of the new DAQ was also specified.

As the key electronic component studied in this thesis work, XTRACT is specifically crucial for the entire ionization signal measurement chain. Instead of sampling all analog output signals of the IDeF-X chip, the role of the XTRACT circuit is to extract and store valuable information about amplitude, peak time, and fired channel address. Therefore, offering the possibility of considerably reducing the quantity of data by storing only the essential ones. In addition, combined with the PU board used to read and serialize XTRACT data based on internal FIFO and dual-port memory, this circuit can also reduce the number of connections traversing the chamber and limit the dead time of the read link with the extracted data. Finally, the ionization signal and the light signal data are concentrated in the XDC board, digitized by its FPGA, and then stored on the PC side. The XEMIS1 facility and the implementation of the prototype acquisition chain were also described. Furthermore, the data acquisition chain of XEMIS2 is under preparation for installation, whose general architecture and electronics assembly strategy were also described.

The work of **Chapter 4** was focused on the experimental calibration and optimization of the novel DAQ prototype electronic chain in XEMIS1 under the operational condition of XEMIS2. The overall DAQ electronics operation principle and data acquisition process were summarized in the first part, where the self-triggering operation concerning the time and amplitude acquisition was detailed. The critical parameters concerning the DAQ adjustment were listed and discussed, including the threshold (TH) and hysteresis of the Leading Edge Discriminator (LED) (that defines the signal section range), the delay time and DC of the zerocrossing comparator (ZC) (that impacts the trigger timing position). Except for the hysteresis, which is inherent to the technology of comparators, all others parameters are adjustable.

The calibration processes concerning the above parameters were then described. The optimized delay time allows registering voltage on the signal peak position at the CDF trigger timing. The delay time parameter is common to all 32 electronic channels of a XTRACT chip. The standard deviation of the crossing time is less than 20 ns per XTRACT. Considering the impact of the ZC value on the time-walk, we found a ZC0 value for which the DAQ has a quasi-perfect time response with negligible time-walk. The threshold DAC calibration was presented at the end of the section. The excellent linear behaviors of offset and gain were measured.

The parameters used in the operational condition were optimized for charge measurement. A precise small charge measurement is critically required due to the charge sharing effect on readout pixels. The threshold under operating conditions is adjusted to a trigger rate of approximately 1.5 kHz, corresponding to three times the noise level. However, the comparator hysteresis conduces to a series of fake triggers for some electronic channels caused by the applied low threshold. The characterization of this phenomenon was described. The ZC bias is a typical method for reducing the noise trigger in the CFD discriminator. After studying the dependence of the ZC value with the linear charge response, another ZC value, namely ZCC, was chosen to be used during the experiment.

In **Chapter 5**, we presented the development of data processing devoted to XEMIS2. The physics data were taken from the XEMIS1 prototype using a ^{22}Na source under the operating condition of XEMIS2. The event topology in TPC under experimental setup was first discussed. Then, we presented the data treatment which contains three steps. The DAQ calibration results were applied to the raw data for signal correction at the first approximation during the first phase. Then, for time precision improvement, the measured signal time was corrected according to the clock stamping time of PU, the common voltage ramp and time memory block of XTRACT, and the CFD time walk and jitter.

The second step was the data filtering aiming at eliminating the noise present in the raw data and then reducing the storage volume for the following data analysis. Two sub-steps were investigated to remove the impact of fake double-trigger resulting from the electronic noise and hysteresis effect, and the isolated pixels with noise. Depending on the applied amplitude threshold and isolated time window, a raw data rejection factor could vary from 20 to 50. The data filtering process will be integrated into the XDC of XEMIS2 for online data processing.

The last part of this chapter reported the algorithm of the event reconstruction and selection. We presented the pixel signal clustering method and the signals matching approach. To eliminate the bias of overlapping interaction vertices, the clustering algorithm used in data analysis is oriented to expand the cluster size to aggregate all uncertainties. A time fit method was proposed for event selection by estimating the time measurement variance inside a cluster. It considered the contributions of DAQ measurement and electrons range of all Digits in the Cluster. Other cuts were also employed and listed in this document.

The data analysis and experimental results related to the calibration of the detector in the high-energy range using the photoelectric peaks of 511 keV and 1274 keV were given in **Chapter 6**. The potential sources causing the charge measurement distortion were investigated in the first part, including the charge sharing, ballistic deficit and electron attachment effects. A simulation study was conducted to estimate the charge loss related to the drift length and the multiplicity of the charge clusters. The simulation result was implemented into the data analysis, which partially corrected the z-dependence on the collected charge. Then, if the electron is emitted along the drift direction and all charges are collected by a single pixel, an amplitude defect concerning the recoil electron energy is deduced by combining the electron range and the ballistic deficit of electronics. Then the attenuation correction was applied to eliminate the z-axis dependence. An amplitude degradation with the number of fired pixels was observed during the data analysis processes.

Furthermore, a charge collection map of all 64 channels was constructed for gain correction. An amplitude degradation of more than 1% per the increase of pixel multiplicity was measured. The decrease of charge measurement might be caused by the parasitic signal appearing in all the pixels of the same IDeF-x when a relatively high charge fires the readout chip. The charge yield and resolution were discussed at the end of chapter.

In the last chapter (Chapter 7), a Compton geometric calibration was proposed as a novel modality for detector self-energy calibration. Thanks to a known source position, a geometric angle and a Compton kinetic angle were constructed at the same time according to the interaction vertex and deposited energy. The low energy range calibration was constructed by Combining those two pieces of information. The simulation study and preliminary experimental results were reported in this part. The results determined the feasibility of this new calibration method in liquid xenon TPC. However, the obtained results were significantly limited by the small-scale detector geometry of XEMIS1 and the non-negligible source size. A future study with a variable source position is programmed.

The preparation study work for the XEMIS2 operation has been almost accomplished in the XEMIS1 prototype. Currently, the XEMIS2 camera is being built at Nantes University Hospital, and the first operation commissioning is scheduled to be performed in March 2022. All preparation work can finally be applied in XEMIS2 to evaluate the actual performance. In addition, the Compton geometric calibration, which is primarily limited by the detector geometry of XEMIS1, can also be carried out in XEMIS2.

Résumé de la Thèse en Français

A u des dernières décennies, l'imagerie nucléaire a apporté des améliorations significatives Sur le diagnostic en oncologie. D'autre part, le défi de la médecine personnalisée visant à fournir aux patients des traitements plus ciblés et plus efficaces a également conduit à des avancées dans la technologie des détecteurs de médecine nucléaire, permettant de réduire les doses, d'accélérer les examens et d'augmenter la sensibilité. Sur cette base, une réduction significative de la posologie pour les patients vulnérables (par exemple, les enfants et les femmes enceintes) est également devenue une priorité dans ce domaine.

Comme décrit au **Chapitre 1**, de nos jours, la tomographie par émission de positrons (TEP) offre la meilleure sensibilité et précision quantitative possible. Plusieurs conceptions de scanner TEP avancées ont grandement évolué afin de répondre aux exigences de la médecine personnalisée. L'imagerie TEP corps entier réduit considérablement la durée de l'examen tout en conservant la même dose que les deux autres modalités en augmentant le champ de vu. La TEP temps de vol vise à réduire la longueur de la ligne de réponse avec une très bonne résolution de temps en coïncidence ciblée à 10 ps. La TEP mesurant la profondeur d'interaction des gamma essaie de résoudre le compromis entre la sensibilité et la résolution spatiale des détecteurs causé par l'effet de parallaxe qui existait dans les systèmes TEP conventionnels. Ces approches ont prouvé leur capacité à améliorer considérablement les performances de la caméra en termes de qualité d'image supérieure et d'examen plus rapide. Les techniques de détection sont presque toutes basées sur des scintillateurs solides.

Le groupe Xenon au Laboratoire SUBATECH a mis au point une alternative à la technologie standard, capable de combiner tous ses avantages avec des inconvénients acceptables à un prix raisonnable. Elle est basée sur la combinaison d'une caméra Compton au xénon liquide et d'une technologie innovante d'imagerie 3-gamma. Le but est d'obtenir des images de haute qualité avec une réduction considérable de l'activité administrée au patient par rapport aux examens d'imagerie fonctionnelle classiques.

La technologie de détecteur de type chambre à projection temporelle au xénon liquide (LXeTPC) est une candidate appropriée pour la construction de télescopes Compton. Ses caractéristiques, décrites au **Chapitre 2**, rendent la détection plus efficace et aucun effet de parallaxe. En outre, l'application de la modalité innovante d'imagerie 3-gamma, expliqué au **Chapitre 1**, capable d'avoir une localisation tridimensionnelle directe des porteurs radioactifs en mesurant l'intersection de la ligne de réponse (LOR) et du cône de Compton avec une grande précision, ce qui permet de réaliser une "TEP pseudo temps de vol".

Pour tirer parti de cette nouvelle méthode, un projet XEXIS en trois étapes a été mise en route. Le premier prototype XEMIS1 est une LXeTPC de petite dimension destinée à la démonstration de faisabilité technique. Le système XEMIS2 de taille plus grande est conçu pour l'imagerie des petits animaux. L'objectif à long terme est une caméra à grand champ de vu pour les applications d'imagerie du corps entier ou de contrôle en ligne en hadronthérapie. Les travaux de cette thèse portent essentiellement sur la mesure du signal d'ionisation dans la LXeTPC du système XEMIS (XEMIS1 et XEMIS2).

XEMIS2 est développé au laboratoire SUBATECH pour démontrer l'avantage du LXe comme millieu de détection pour l'imagerie 3-gamma. Il s'agit d'un détecteur simple phase monolithique à large champ de vu axial capable de contenir jusqu'à près de 200 kg de xénon liquide. Dans XEMIS2, un niveau de pureté ultra-élevé devrait être atteint grâce au nouveau sous-système de purification cryogénique ReStoX, qui est équipé d'un système de purification de gaz, réalisant une recirculation en boucle fermée, comme indiqué au **Chapitre 2**.

La première étape de XEMIS2 vise à obtenir une image du petit animal avec une activité ultrafaible de 20 kBq en 20 minutes tout en préservant la qualité de l'image en diagnostic oncologique. Afin de lire en continu, sans temps mort, les données de XEMIS pendant 20 minutes, un système spécifique d'acquisition de données à haut débit a été développé et testé au cours de ce travail de thèse. La nouvelle chaîne d'acquisition de XEMIS2, du principe de fonctionnement et la mise en œuvre de la chaîne de lecture électronique a été discutée au **Chapitre 3**.

Afin d'effectuer des mesures de charge précises, notre équipe de recherche a proposé une géométrie d'électrode segmentée innovante MIMELI pour optimiser la génération de courants induits dans la LXeTPC. Le test expérimental effectué avec XEMIS1 équipé d'un ASIC électronique frontal ultra-faible bruit appelé IDeF-X HD-LXe a montré des résultats encourageants. Dans XEMIS2, pour obtenir la qualité d'image attendue avec une activité moindre par rapport aux autres technologies actuellement utilisées, nous devons conserver, voire améliorer les performances obtenues dans XEMIS1 en passant de 64 à 20000 pixels tout en obtenant une efficacité d'événement plus élevée avec un flux/volume de données gérable. Le nouveau système électronique de lecture du signal doit répondre aux critères de l'auto-déclenchement, à l'acquisition à haut débit et à un faible bruit électronique. Un ASIC d'extraction d'informations de signal a été développé pour réduire le volume de données stockées. Un nouveau système d'acquisition de données a été proposé sur la base des exigences énumérées ci-dessus. Le principe de fonctionnement du nouveau DAQ a également été précisé au **Chapitre 3**.

Les travaux du **Chapitre 4** se sont concentrés sur l'étalonnage expérimental et l'optimisation de la nouvelle chaîne électronique prototype DAQ dans XEMIS1 dans les conditions opérationnelles de XEMIS2. Le principe de fonctionnement global de l'électronique DAQ et le processus d'acquisition de données ont été résumés dans la première partie, où le système d'autodéclenchement concernant l'acquisition du temps et de l'amplitude a été détaillée. Les paramètres critiques concernant les réglages DAQ ont été répertoriés et discutés, y compris le seuil (TH) et l'hystérésis du discriminateur de à front montant (LED) (qui définit la plage de la section du signal), le temps de retard et le courant continu du comparateur de passage par zéro (ZC) (qui a un impact sur la position de synchronisation de déclenchement). A l'exception de l'hystérésis inhérente à la technologie des comparateurs, tous les autres paramètres sont réglables.

Les processus d'étalonnage concernant les paramètres ci-dessus ont ensuite été décrits. L'optimisation du temps de retard permet d'enregistrer le maximum du signal correspondant au temps de déclenchement du CFD. Le paramètre de temps de retard est commun aux 32 canaux électroniques d'une puce XTRACT. Compte tenu de l'impact de la valeur ZC sur le "time walk", nous avons trouvé une valeur ZC0 pour laquelle le DAQ a une réponse temporelle quasi parfaite avec un "time walk" négligeable. L'étalonnage seuil du DAC a été présenté à la fin de la section. Les excellents comportements linéaires d'offset et de gain ont été mesurés.

Les paramètres utilisés en condition opérationnelle ont été optimisés pour la mesure de charge. La mesure précise des petites charges est indispensable en raison de l'effet de partage de charge sur les pixels de lecture. Le seuil dans les conditions de fonctionnement est ajusté à un taux de déclenchement d'environ 1,5 kHz, correspondant à trois fois le niveau de bruit. Cependant, l'hystérésis du comparateur conduit à une série de faux déclenchements pour certains canaux électroniques provoqués par le seuil bas appliqué. La caractérisation de ce phénomène a été décrite. Le réglage du biais du ZC est une méthode typique pour réduire le taux de déclenchement du bruit du au discriminateur CFD. Après avoir étudié la dépendance de la linéarité de la réponse en charge en fonction de la valeur de ZC, une autre, une autre valeur ZC, à savoir ZCC, a finalement été choisie pour être utilisée pendant l'expérience.

Dans le **Chapitre 5**, nous avons présenté le développement des traitements de données consacrés à XEMIS2. Les données de physique ont été extraites du prototype XEMIS1 en

utilisant une source ${}^{22}Na$ dans les conditions de fonctionnement de XEMIS2. La topologie des événements de la TPC dans les conditions expérimentales a d'abord été discutée. Ensuite, nous avons présenté le traitement des données qui comporte trois étapes. Les résultats de l'étalonnage DAQ ont été appliqués aux données brutes pour la correction du signal en première approximation au cours de la première phase. Ensuite, pour améliorer la précision de mesure du temps, le temps du signal mesuré a été corrigé en fonction du temps d'horodatage de PU, de la rampe de tension commune et du bloc de mémoire de temps de XTRACT, et de la marche temporelle et du "jitter" CFD.

La deuxième étape était le filtrage des données visant à éliminer le bruit présent dans les données brutes puis à réduire le volume de stockage pour l'analyse des données suivantes. Deux sous-étapes ont été étudiées pour éliminer l'impact d'une part des faux doubles déclenchements résultant du bruit électronique et de l'effet d'hystérésis, et d'autre part des pixels isolés avec du bruit. En fonction du seuil en amplitude appliqué et de la fenêtre temporelle d'isolation, un facteur de rejet des données brutes pourrait varier de 20 à 50. Le processus de filtrage des données sera intégré au XDC de XEMIS2 pour le traitement des données en ligne.

La dernière partie de ce chapitre a rapporté l'algorithme de reconstruction et de sélection d'événements. Nous avons présenté la méthode de clustering de signaux de pixels et l'approche d'appariement de signaux. Pour éliminer le biais des lieux d'interaction qui se chevauchent, l'algorithme de clustering utilisé dans l'analyse des données est conçu pour étendre la taille du cluster afin d'agréger tous les pixels pouvant s'influencer mutuellement. Une méthode d'ajustement du temps a été proposée pour la sélection d'événements en estimant la variance de la mesure des temps des pixels à l'intérieur d'un cluster. Elle prend en compte les contributions de la mesure DAQ et de la plage d'électrons de tous les chiffres du cluster. En outre, d'autres coupures d'événements ont également été employées et énumérées dans ce document.

L'analyse des données et les résultats expérimentaux liés à l'étalonnage du détecteur dans le domaine des hautes énergies en utilisant les pics photoélectriques de 511 keV et 1274 keV ont été donnés au **Chapitre 6**. Les sources potentielles provoquant la distorsion de mesure de charge ont été étudiées dans la première partie, y compris le partage de charge, le déficit balistique et les effets d'attachement des électrons. Une étude par simulation a été menée pour estimer la perte de charge liée à la longueur de dérive et à la multiplicité des clusters de charges. Le résultat de la simulation a été mis en œuvre dans l'analyse des données, qui a partiellement corrigé la dépendance en z de la charge collectée. Par ailleurs, si l'électron est émis selon la direction de dérive et que toutes les charges sont collectées par un seul pixel, un défaut d'amplitude concernant l'énergie de l'électron de recul est déduit en combinant la portée des électrons et le déficit balistique de l'électronique. Ensuite, la correction d'atténuation a été appliquée pour éliminer la dépendance en z. Une dégradation de la mesure de la charge avec le nombre de pixels touchés a été observée au cours des processus d'analyse des données.

En outre, une carte de collecte de charges de tous les 64 canaux a été construite pour la correction de gain. Une dégradation d'amplitude de plus de 1% par augmentation de la multiplicité des pixels a été mesurée. La diminution de la mesure de charge peut être causée par le signal parasite apparaissant dans tous les pixels du même IDeF-x lorsqu'une charge relativement élevée déclenche la puce de lecture. Le rendement de charge et la résolution ont été discutés à la fin du chapitre 6.

Dans le dernier chapitre (**Chapitre 7**), un étalonnage géométrique Compton a été proposé comme nouvelle modalité pour pour l'auto-étalonnage de la mesure d'énergie du détecteur. Grâce à une position de source connue, un angle géométrique et un angle cinématique de la diffusion Compton ont été construits en même temps en fonction du sommet d'interaction et de l'énergie déposée. L'étalonnage à basse énergie a été construit en combinant ces deux informations. L'étude de simulation et les résultats expérimentaux préliminaires ont été rapportés dans cette partie. Les résultats ont déterminé la faisabilité de cette nouvelle méthode d'étalonnage dans la TPC au xénon liquide. Cependant, les résultats obtenus étaient significativement limités par la géométrie du détecteur de petite dimension XEMIS1 et la taille de la source non négligeable. Une étude future de cette méthode d'étalonnage avec une position source variable est programmée.

Le travail préparatoire à la mise en service de XEMIS2 est quasiment achevé grâce au prototype XEMIS1. Actuellement, la caméra XEMIS2 est en cours de construction au CHU de Nantes, et la première mise en service opérationnelle est prévue en mars 2022. Tous les travaux de préparation pourront enfin être appliqués dans XEMIS2 pour évaluer les performances réelles. De plus, l'étalonnage géométrique Compton, qui est principalement limité par la géométrie du détecteur de XEMIS1, pourront également être effectué dans XEMIS2.
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List of Abbreviations

Roman Symbols

3D	Three-Dimensional
ADC	Analog-to-Digital Converter
APD	Avalanche Photodiode
ASIC	Application-Specific Integrated Circui
CCT	Compton coincidence technique
CFD	Constant Fraction Discriminator
CS	Chip Select
CSA	Charge Sensitive preAmplifier
CT	Computed Tomography
CTR	Coincidence Time Resolution
DAC	Digital-to-Analog Converters
DAQ	Data Acquisition System
DC	Direct Current
DFT	Discrete Fourier Transform
DOI	Depth-Of-Interaction
ENC	Equivalent Noise Charge
FOV	Field Of View

FWHM	Full Width at Half Maximum
I2C	Inter-Integrated Circuit
IDeF - X	Imaging Detector Front-end for X rays
LED	Leading Edge Discrimination
LET	Linear Energy Transfer
LOR	Line Of Response
LSB	Least Significant Bit
LVDS	Low Voltage Differential Signaling
LXe	Liquid Xenon
LXeTPC	Liquid Xenon Time Projection Chamber
MCP	Micro-Channel-Plate
MIMELI	MIcro-MEsh for dense Liquid Ionization chamber
MLEM	Maximum-Likelihood Expectation-Maximization
MM	Micro-Meshe
MPPC	Multi-Pixel Photon Counter
MRI	Magnetic Resonance Imaging
MUX	Multiplexer
MW	Metallic Woven
PET	Positron Emission Tomography
PMOS	P-channel Metal–Oxide–Semiconductor
PMT	Photomultiplier Tube
PTR	Pulse Tube Refrigerator
PZC	Pole-Zero Cancellation
QE	Quantum Efficiency

ReStoX	Recovery and Storage of Xenon
SiPM	Silicon Photomultiplier
SNR	Signal Over Noise Ratio
SPECT	Single Photon Emission Computed Tomography
T2AC	Time-To-Amplitude Converter
TB	Total-Body
THD	Threshold Discriminator
TOF	Time-Of-Flight
ТОТ	Time-Over-Threshold
TPC	Time Projection Chamber
UHV	Ultra High Vacuum
UI	User Interface
XDC	XEMIS Data Concentrator
XPU	XEMIS Processing Unit
XSRETOT	XEMIS Scintillation Readout for Extraction of Time Over Threshold
XTRACT	Xenon TPC Readout for extrAction of Charge and Time
ZC	Zero-Crossing
ZCD	Zero-Crossing Discrimination

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Titre : Études et optimisation de la mesure du signal d'ionisation dans la caméra Compton au xénon liquide XEMIS2 pour imagerie 3-gamma

Mots clés : imagerie 3-gamma, télescope Compton, recul électronique, mesure d'ionisation, xénon liquide

Résumé : Un projet innovant d'imagerie médicale au xénon, appelé XEMIS2, tente pour la première fois de réaliser l'imagerie 3-gamma sur des petits animaux avec une très faible activité injectée. Le principe de cette nouvelle modalité est de détecter simultanément trois gammas en s'appuyant sur un télescope Compton au xénon liquide simple phase et un émetteur spécifique (β +, γ), le scandium-44. Des simulations Monte Carlo ont démontré le potentiel de cette nouvelle imagerie pour réduire l'activité des radiopharmaceutiques administrée tout en conservant la qualité de l'image produite. La précision des mesures de position et d'énergie des reculs électroniques dans le xénon liquide joue un rôle

crucial dans l'identification des séquences Compton et la reconstruction des cônes. Ce travail de thèse est axé sur les performances de XEMIS2 dans le domaine d'énergie de diffusion de Compton. Dans un souci de lecture continue du signal d'ionisation avec un niveau de bruit très faible et un temps mort négligeable, un nouveau système de mesure à déclenchement automatique a été développé. Le prototype d'acquisition de données a été installé et qualifié dans la caméra de petite dimension XEMIS1. En outre, une étude préliminaire d'une nouvelle approche de l'étalonnage angulaire grâce à la diffusion Compton dans XEMIS2 est proposée.

Title: Studies and Optimization of Ionization Signal Measurement for the 3-gamma Imaging XEMIS2 Liquid Xenon Compton Camera

Keywords: 3-gamma imaging, Compton telescope, electronic recoil, ionization measurement, liquid xenon

Abstract: An innovative xenon medical imaging project called XEMIS2 attempts for the first time to realize low radio-activity small animal 3-gamma imaging. The principle of this novel modality is to detect simultaneously three gammas relying on a single-phase liquid xenon Compton telescope and a specific (β +, γ) emitter scandium-44. Predicted by a full Monte Carlo simulation, it has shown a potential alternative to reduce the administered radio–pharmaceutical activities while maintaining image qualities. The accurate position and energy measurements of electronic recoils in liquid xenon

crucial role in Compton play а sequence identification and cone reconstruction. This thesis work is focused on the capability of XEMIS2 in the Compton scattering energy domain. For the sake of continuous read-out with ultra-low noise and negligible dead-time, a novel developed self-trigger ionization measurement system has been accomplished. The data acquisition prototype has been implemented and qualified in the XEMIS1 experimental facilities. Besides, a preliminary study of a new approach to Compton scattering angular calibration in XEMIS2 is proposed.