Status and perspectives of the PETALO project

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\textbf{Abstract:} PETALO (Positron Emission Tof Apparatus with Liquid xenOn) is a novel concept for positron emission tomography scanners, which uses liquid xenon as a scintillation medium and silicon photomultipliers as a readout. The large scintillation yield and the fast scintillation time of liquid xenon, as well as its scalability, makes it an excellent candidate for PET scanners with Time-of-Flight measurements, especially for total-body machines. A first prototype of PETALO, devoted to demonstrate the potential of the concept, measuring the energy and time resolution and to test technical solutions for a complete ring is fully operational. The prototype consists of an aluminum box filled with liquid xenon, with two arrays of SiPMs on opposite sides facing the xenon. A $\beta^+$ emitter source generating 511-keV pairs of gammas is placed in a central port and the SiPMs record the scintillation light produced by the gamma interactions, allowing for the reconstruction of the position, the energy and the time of the interactions.

\textbf{Keywords:} Noble liquid detectors, PET
Introduction

Positron Emission Tomography (PET) is an imaging technique which scans the metabolic activity of the body and is widely used to monitor tumours, neurodegenerative disease like Alzheimer’s, epilepsy or cardiovascular diseases. Glucose molecules, modified with a $\beta^+$ emitting atom like $^{18}$F, are injected into the body of the patient as they tend to concentrate in regions of higher metabolic activity. The positron emitted in the decay annihilates with one of the electrons of the surrounding atoms, creating two high energy photons of 511 keV emitted at, or close to, 180° to each other. These photons can be detected in time coincidence in a ring of scintillators placed around the patient. Each coincidence forms a line and the intersection of several of these lines can be used to reconstruct the image of the region where the radioisotope concentrates. If, in addition to position reconstruction, one is able to measure the interaction times of the photons with high precision (a Time-Of-Flight measurement), a segment on the line can be identified as having higher probability of containing the origin of the gammas. This capability results in an improvement in the quality of the image proportional to the time resolution achieved in the scanner [1]. As a consequence, smaller lesions can be imaged for the same amount of received dose of radioisotope or, conversely, an image of the same quality can be obtained in a shorter time, thus reducing the dose received by the patient.

A liquid xenon PET scanner

Xenon is a noble gas, which produces approximately 60 scintillation photons per keV of deposited energy when ionizing radiation interacts with its atoms [2]. When a 511 keV gamma interacts in liquid xenon (LXe) (through photoelectric interaction or Compton scatter) it produces secondary electrons which in turn propagate for a short distance in the liquid, ionizing and exciting the medium. The scintillation signal is primarily produced by the de-excitation of the xenon atoms to dimers which in turn decay producing ultraviolet (VUV) radiation peaked at 178 nm with characteristic decay constants of 2.2 ns (singlet mode) and 27 ns (triplet mode) [3]. There is also a slower contribution (tens of nanoseconds) from the electron-ion recombination. In its liquid phase xenon has a reasonably high density (2.98 g/cm$^3$) [5] and as a result an attenuation length of 3.7 cm for
511-keV gammas [6] and a long Rayleigh scattering length compared to typical size of a scanner (36.4 cm) [7], which makes it suitable for PET applications.

The PETAŁO concept [8, 9] proposes a PET scanner based on the use of liquid xenon, with silicon photomultipliers (SiPMs) to read out the xenon scintillation light only. Such a scanner can provide excellent performance in terms of energy, spatial and time resolution. SiPMs are widely used to read scintillation light produced in PET scanners due to their fast response, high granularity, large gain and compatibility with magnetic fields (allowing for combined PET-NMR scanners). In the case of liquid xenon, a further advantage is that they have an extremely low dark count rate at cryogenic temperatures. Moreover, since xenon is a continuous medium, the scanner could be made of a single, continuous volume, instead of thousands of small crystals. This simplifies the construction and lowers costs, especially for total-body PET scanners which have axial lengths of up to 2 m. The reconstruction of the interaction points would also benefit from reduced border effects and the purity of the liquid can be kept to the desired level through purification in gas phase, therefore ensuring the highest possible scintillation yield.

Recent Monte-Carlo studies suggest that a total-body PET based on liquid xenon can reach an energy resolution of 15-17% FWHM for 511-keV gammas which is of the same order as that of current scanners based on crystals. This can be achieved in conjunction with a spatial resolution for the interaction point of the gammas in the LXe of the order of 1 mm and a time resolution of a few hundred ps FWHM [10].

3 First prototype

A first prototype of PETAŁO has been built and is currently operating at Instituto de Física Corpuscular, in Valencia (Spain). It consists of an aluminum cube of 10 cm side, filled with liquid xenon, kept in a vacuum vessel for thermal insulation. The xenon is continuously recirculated in gas phase by a double diaphragm compressor and is purified by passing through a hot getter to remove impurities such as nitrogen, water and oxygen, which can quench xenon scintillation light [4]. The cube is cooled directly by a CH-110 cold head from Sumitomo via a set of custom-made copper thermal links. The cold head can reach a temperature of -240 degrees Celsius using a HC-4E helium compressor. The gas enters and exits the cube through a heat exchanger, where the cold gas on the way out contributes to the initial cooling of the warm gas on the way in, maximising cooling efficiency. In the event of overpressure in the cube, the gas is evacuated to a recovery tank, which can stand up to 3 bar of pressure, through a release valve. In normal operation, recovery of the xenon is achieved via the gas system lines to a cryogenic bottle. Figure 1 shows the LXe container, together with the cold head and the thermal links and the fully assembled system.

The prototype is instrumented with two planes of VUV-sensitive SiPMs, mounted on opposite sides of the cube. The SiPMs have an active area of $6 \times 6$ mm$^2$ and are arranged in arrays of $8 \times 8$ sensors in each plane, facing the LXe (see figure 2). A $^{22}$Na calibration source is inserted through a port in the middle of the xenon volume. When the 511-keV gammas emitted by the positron annihilation interact with LXe, the emitted scintillation light is detected by the two arrays of SiPMs. The detected light is used to determine the energy, the position of interaction and the arrival time of the gammas. Read-out takes place via two TOFPET2 ASICs [11, 12], which integrate the charge and provide a fast timestamp. The acquisition system has been custom designed with the aim of being
scalable to larger prototypes and, finally, to a real PET scanner. It makes use of a novel, modular scheme with synchronization over data links, which can be expanded to any number of channels with low hardware cost and no extra channels or signals. Moreover, a compression system that cuts down the amount of data sent to the servers and inline preprocessing of the information allows for the reduction of the speed required in the data links, thus decreasing complexity. The DAQ is made of two boards: on the one hand, a front-end adapter reads the signal from the ASICs and sends it to the processor. It is also in charge of the control of the temperature sensors, the SiPMs read-out, and the clock distribution among ASICs. On the other hand, a data processor distributes configuration and data between the computer and the ASICs as well as manages clock synchronization. The
Figure 2. Array of 64 Hamamatsu S15779 SiPMs, sensitive to the VUV light with a photodetection efficiency of around 30%.

signals of the sensors are extracted through a set of custom-made feedthroughs, which also support the SiPM boards, reducing the space needed; they are filled with high performance cryogenic epoxy, which is stable down to -200 degrees.

4 Conclusions

The first prototype of the PETALO concept has been built and is fully operational at the Instituto de Física Corpuscular, in Valencia (Spain). The commissioning phase has shown system stability, with more than two months of continuous operation without loss of xenon or any major issues. Recently, data have started being taken with a $^{22}$Na calibration source. Measurements of the energy and time resolution of the system are underway and results will be published soon.

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