

Liquid Xenon Detectors for Medical Imaging

Vitaly Chepel

Physics Dep., University of Coimbra, Portugal

Resumo - O presente artigo apresenta uma breve revisão do desenvolvimento dos detectores de raios gama com xénon líquido como meio detector para a imagiologia médica, nomeadamente para a imagiologia com fotões únicas e com emissão de positrões.

Abstract - The paper presents an overview of developments of liquid xenon gamma-ray detectors for medical imaging including Single Photon Imaging technique as well as Positron Emission Tomography.

I. INTRODUCTION

The possibility of application of liquid xenon detectors to medical imaging started to be considered in early 1970s, not long after the “discovery” of liquefied noble gases for detection of ionising radiation. Significant advancements have been made since that time, both concerning the technology and the understanding of underlying physical processes, that lead to construction of a number of large detectors mostly for particle physics, but also for astrophysics and nuclear physics. Many of them exploit a unique combination of the properties of liquid noble gases, which are, on the one hand, very good scintillators and, on the other, perfect dielectrics, in which electrons, once in the conduction band, can move freely thus allowing the ionisation signal due to a particle to be detected.

We shall briefly discuss what makes liquid xenon so attractive for detection of gamma-rays and for medical imaging, in particular, and review some of the recent advancements in this field.

II. LIQUID XENON AS DETECTION MEDIUM FOR GAMMA-RAYS

Atomic number of xenon is $Z = 54$ and the liquid density at triple point is about 3 g/cm^3 , being both numbers close to those for NaI(Tl) – the best known scintillator ($Z = 53$ and $\rho = 3.7 \text{ g/cm}^3$). The attenuation length for 511 keV gamma-rays in liquid xenon is about 3.7 cm; for 140 keV it is about 0.4 cm, similarly to NaI(Tl).

In what the scintillation properties are concerned, liquid xenon is as efficient as NaI(Tl) – it emits about 40 000 photons per MeV, but much faster. It has three scintillation components, 3 ns, 27 ns and 45 ns, with practically the same wavelength. In the case of gamma-rays, the first component gives small contribution, but even so the scintillation decay time of liquid xenon is in

the range of that of the fastest known scintillator crystals. If electric field is applied, the recombination component (45 ns) is suppressed, resulting in the reduction of the total scintillation light yield by a factor up to 3.

A 511 keV gamma-ray produces in liquid xenon $\approx 30\,000$ electrons due to ionisation of the liquid, from which $\geq 90\%$ escape recombination in a field of $\geq 2 \text{ kV/cm}$. Taking into account that preamplifiers with the input noise of a few hundreds of electrons are readily available nowadays, becomes clear that a good signal-to-noise ratio can be obtained. The electron drift velocity at these fields is $2.3 \text{ mm/\mu s}$. The distance, an electron can travel in the liquid before being captured to form a slow negative ion, depends on concentration of electronegative impurities. Nowadays, quite simple and commercially available purifiers can provide the level of impurities in xenon as low as $\sim 10^{-10}$ thus allowing the electrons to travel up to tens of cm.

III. SINGLE PHOTON IMAGING

The first attempt to use liquid xenon as detection medium for gamma camera – a device for imaging with single gamma-photons – has been undertaken by the group of Lawrence Berkeley Laboratory in early 1970s [1]. A small liquid xenon multiwire chamber was developed with the wires of only few micrometers diameter, around which a strong electric field of $\sim 10^6 \text{ V/cm}$ was generated. The electrons, produced by a gamma-ray in the liquid, drifted to the wires where they were accelerated by the field to the sufficiently high energies to ionise the liquid thus giving rise to electron avalanche, similarly to what happens in a traditional gaseous proportional counter. However, in contrast with gas, where multiplication gains of 10^4 to 10^6 are easily obtained, it was not possible to achieve gains

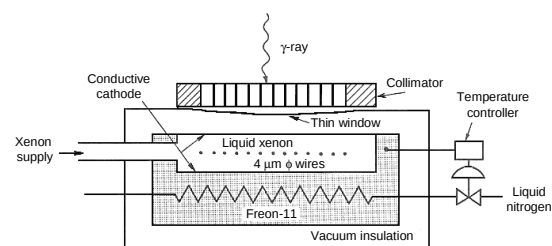


Fig.1 Liquid xenon multiwire proportional chamber for single photon imaging (after [1]).

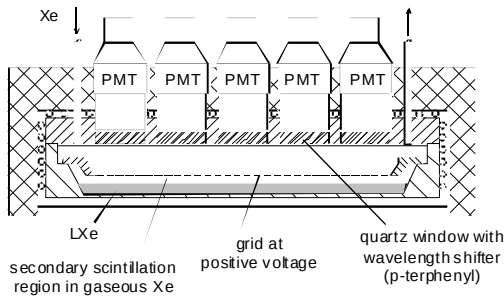


Fig.2 Electroluminescence two-phase gamma-camera (after [3]).

higher than a few tens. The signals at the wires were read with 24 low-noise charge sensitive preamplifiers (very expensive at that time), one per wire. The difficulty to obtain sufficient amplification in the liquid lead the group to experiment with a dual phase – liquid/gas – system, in which the gamma-ray absorption takes places in the liquid phase, the ionisation electrons drift from the liquid to gas (possible with the electric field of ~ 4 kV/cm) and are multiplied around the wires in gas. Higher gains ($\sim 10^2$) can be achieved in this system but not high enough to allow using cheaper preamplifiers [2]. The gain limitation is mostly because of a large amount of ultraviolet photons emitted by xenon gas in the course of avalanche development (xenon is a good scintillator), which leads to emission of secondary electrons from the surfaces and, thus, to an uncontrollable discharge.

Take profit of this light was a natural solution, put into practice in [3]. In this design, which had already clinically relevant dimensions (25 cm diameter of active area), the secondary scintillation was produced in the gas phase in a uniform electric field and detected with an array of 19 photomultiplier tubes. The coordinates of the scintillation region were determined by weighting the photomultiplier amplitudes, in the way identical to that used in a conventional gamma-camera with scintillation crystal. The advantage of using liquid xenon instead of a crystal was better energy and position resolution (2.5 mm and 15% for 122 keV, respectively) thanks to higher light yield of secondary scintillation. The drawback is the presence of the liquid surface, which sets some constraints from the practical point of view (it makes impossible to use the detector in a non-horizontal position, for example).

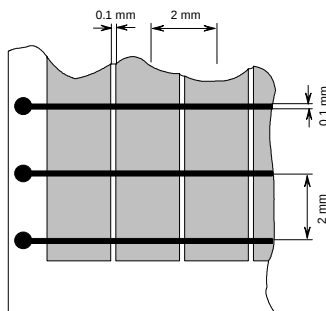


Fig.3 Mini-strip plate for 2D readout in the liquid xenon ionisation gamma-camera (after [4]).

Significant advancements in the low-noise multichannel electronics allowed the single-phase approach to be re-considered. A design with thousands of readout channels and the noise of a few hundred electrons per channel is quite thinkable nowadays. This was the approach followed at LIP-Coimbra [4,5]: a single phase liquid xenon gamma-camera with purely ionisation readout (i.e. without charge multiplication in the detector). A special arrangement of collecting and induction electrodes in the form of strips, each being connected to an input of a multichannel integrated amplification and shaping circuit, was used to measure position of the interaction point. The resolution of 2 mm was obtained with 122 keV gamma-rays.

IV. POSITRON EMISSION TOMOGRAPHY

In what PET imaging is concerned, the advantage of liquid xenon is twofold, as it was pointed out already in 1976 [6]: fast scintillation of the liquid can provide a very good coincidence time resolution thus reducing the probability of detection of uncorrelated photon pairs, while detection of the ionisation signal allows a variety of precise localisation methods to be used. Moreover, good time resolution makes possible to use information on the difference between the arrival times of the two annihilation photons for rough estimate of the event position (TOF-PET – time-of-flight PET; for example, time resolution of 1 ns translates to position sensitivity of 15 cm, which is incomparably poorer than that typically achievable with traditional back projection method, but even so can provide valuable information on source localisation and significantly reduce noise in the reconstructed images).

The above ideas were further developed in [7] and put into practice at LIP-Coimbra by construction of a test multiwire chamber with the readout of both scintillation and ionisation signals [8,9]. In this design, scintillation is

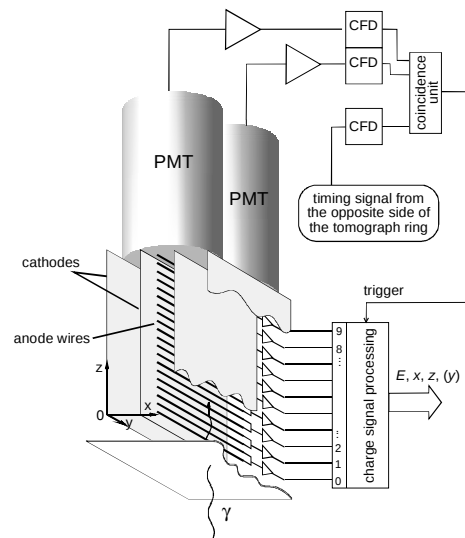


Fig.4 Liquid xenon module for PET with detection of both scintillation and ionisation (after [8]).

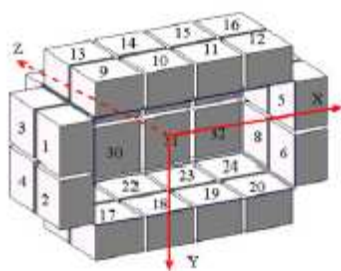


Fig.5 Homogeneous scintillation detector for PET (after [10]).

detected with fast photomultiplier tubes with quartz window immersed into the liquid in order to improve the light collection efficiency. Coincidence time resolution of 1.5 ns was obtained for a pair of 511 keV gamma-rays (in coincidence with a BaF₂ crystal). It was also shown, partly with the multiwire readout and partly with the mini-strip plate instead of the wires, that the system provides position resolution of 0.8 mm (fwhm) in two dimensions, as well as localisation precision of 5 mm or better (down to 2 mm, in the present design) in the interaction depth thus making the detector free of the parallax error (in fact, 5 mm resolution in the depth of interaction is sufficient for correction of the parallax). The energy resolution of 17% (fwhm) for 511 keV photons was obtained, which can be improved to 15% at some loss of efficiency.

In attempt of obtaining a faster detector response, a purely scintillation readout was also considered recently [10,11]. The Japanese group [10] has proposed a homogeneous liquid xenon scintillation detector, in which the sensitive volume of the liquid in the shape of parallelepiped is surrounded by photomultiplier tubes from 5 sides, thus increasing the light collection efficiency and leaving the sixth plane oriented in the direction to the positron source. Specially developed photomultiplier tubes with the enhanced quantum efficiency in the VUV region and extremely fast response, are used to detect the liquid xenon scintillation. The time resolution as good as 0.3 ns was measured with this detector. Such resolution allows the positron source to be localised with a precision of about 5 cm along the trajectory of the two annihilation photons.

Another approach, also using scintillation only, is adopted in [11]. The liquid xenon scintillator is highly segmented with thin separators, with enhanced reflectivity in the VUV wavelength region, to form a large number of

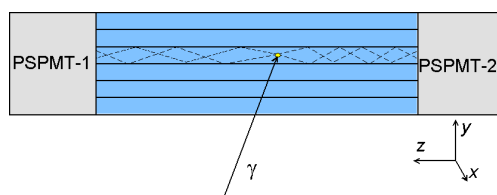
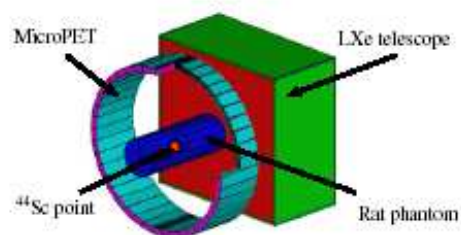


Fig.6 Liquid xenon scintillation module for PET with high granularity (after [11]).

parallel cells of $2 \times 2 \times 50 \text{ mm}^3$, read with a pair of position sensitive (in 2D) photomultiplier tubes, one at each end. The hit cell is thus identified with the photomultipliers, providing position precision of 2 mm in two dimensions, while the third coordinate is measured by comparison of the amount of light reaching each end of the cell. The resolution varying between 2 mm and 12 mm along the cell has been reported, being the poor reflectivity of the separators largely responsible for the resolution degradation.

An interesting suggestion to use liquid xenon detector for the additional gamma-ray, which in some isotopes follows the β -decay, is recently made in [12]. In this case, apart from the pair of back-to-back annihilation photons, a third gamma-ray is emitted from the same source. If it interacts with the detector through one or more Compton scatterings, one can use the cinematic equations to define a conical surface, to which the incoming photon trajectory belongs. The intersection of this surface with the line of response to the pair of 511 keV gamma-rays identifies the region of their origin. Therefore, it is proposed to complement the traditional PET system with a liquid xenon Compton telescope, triggered by the scintillation of the liquid and with localisation of the interaction sequences through measurement of the ionisation signals.

Fig.7 Liquid xenon Compton telescope for 3γ imaging in PET (after [12]).

V. LIQUID XENON TECHNOLOGY AND INDUSTRY

The growing interest in the liquefied noble gas detectors, mostly from particle and astroparticle physics, created a growing demand for industrial solutions for some specific issues related to this technology. A number of companies have found this demand strong enough to respond to it. Thus, the Hamamatsu Co, for example, has developed new photomultiplier tubes optimised for using in liquid xenon detectors, i.e. with the enhanced quantum efficiency in the vacuum ultraviolet region, improved timing characteristics and capable to operate at low temperature. Various modifications of silicon avalanche photodiodes have also been developed by different companies keeping in mind detection of liquid xenon scintillation (although not only for that). The traditional cryogenics using liquid nitrogen stepped back to give place to refrigerating machines tuned specifically for liquid xenon temperature (i.e., -100°C) and with significantly reduced mechanical vibrations.

These examples represent significant changes in the relationship between the developers of the liquefied gas detectors and industry. If some 20 years ago the physicists were obliged to design and produce ourselves almost every piece of the detector, gas system and electronics, it is no longer necessary. The industry offers nowadays a variety of highly reliable and efficient solutions.

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