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Technical Notes

Gravity assisted recovery of liquid xenon at large mass flow rates

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ABSTRACT

We report on a liquid xenon gravity assisted recovery method for nuclear medical imaging applications. The experimental setup consists of an elevated detector enclosed in a cryostat connected to a storage tank called ReStoX. Both elements are part of XEMIS2 (XEnon Medical Imaging System): an innovative medical imaging facility for pre-clinical research that uses pure liquid xenon as detection medium. Tests based on liquid xenon transfer from the detector to ReStoX have been successfully performed showing that an unprecedented mass flow rate close to 1 ton per hour can be reached. This promising achievement as well as future areas of improvement will be discussed in this paper.

1. Introduction

Over the past decades, researchers have employed pure liquid xenon in many different fields including astrophysics, particle physics and medical imaging techniques because of its intrinsic radiation detection properties. In particular, Liquid Xenon Time Projection Chambers (LXeTPC) represents an ideal option for γ-ray detectors in a wide energy range from several tens of keV to tens of MeV [1].

LXeTPC detectors require a sophisticated and reliable cryogenic infrastructure [1]. The cooling system, located remotely from the detector (enclosed in a cryostat), includes a pulse tube refrigerator coupled to a copper cold finger [2] or a specific exchanger supplied by liquid nitrogen [3]. Moreover, as discussed in [4,5], the required level of xenon impurity (O_2 equivalent) must be kept on the order of ppb or even lower. In particular, commercial getters working at "high" temperature (>300 K), plumbing, counter-current coaxial exchanger and double-diaphragm pump are suitable for this purpose [6].

Most Liquid Xenon (LXe) facilities include a storage equipment, that may also work during a detector extended shutdown, to keep the xenon safe. The need of a safe and efficient cryogenic procedure to recover the liquid xenon toward the storage tank strongly impacts the facility design. For small or medium detectors such as XAMS [7] or XEMIS1 [8], a cryopumping operation in bottles is enough for the xenon recovery. However, bigger facilities with hundreds kilograms of liquid xenon such as XENON1T [9], MEG [10], XMASS [11], LUX [6] or XEMIS2 (Section 2.2) require another approach. One solution consists in the development of a "liquid xenon storage system employing the zero boil-off condition" [12]: the liquid xenon vaporization rate (boil-off), generated by all the heat losses, is balanced by the condensation rate of xenon vapors by means of the cooling system. Furthermore, a cryogenic centrifugal pump may also be used for liquid xenon recovery [13].

We have carried out the commissioning of the XEMIS2 facility: it includes the implementation of the liquid xenon recovery process. XEMIS2 is an innovative system designed for 3γ pre-clinical imaging of small animals in hospital centers [8]. It uses nearly 200 kg of pure

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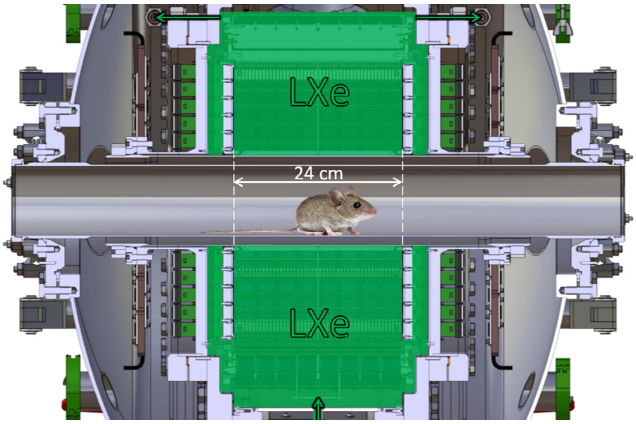

Fig. 2.1. Cut view of the detector: the LXe volume is visible.

liquid xenon. Due to specific design choices, the liquid xenon recovery is gravity assisted. This method safely enables unprecedented transfer rates.

This paper focuses on the liquid xenon transfer from the cryostat to the storage vessel (ReStoX) with special emphasis on the experimental conditions and transfer rate. It is organized as follows: Section 2 presents the XEMIS2 facility, its condenser and the heat losses of ReStoX; Section 3 describes the liquid xenon transfer method using a theoretical approach, experimental results and discussions; finally the conclusion and prospectives are given in Section 4.

2. The XEMIS2 cryogenic facility

2.1. The XEMIS2 detector and infrastructure

Following the success of XEMIS1: a small LXeTPC that showed the potential of the 3γ imaging technique [14], a larger monolithic pure liquid xenon (at 1.2 bar abs and 168 K) cylindrical camera, XEMIS2, for pre-clinical applications is under construction. With a long 24 cm axial field of view, the XEMIS2 detector entirely surrounds the small animal (Fig. 2.1). The detector active volume is covered by $1''$ Hamamatsu PMTs to detect the VUV scintillation photons generated from γ-ray interactions within the xenon. Moreover, the ionization electrons are detected by two circular segmented anodes located at the edges of the detector. The compact XEMIS2 camera also includes a fast DAQ, a traditional purification system and a storage tank called ReStoX assuring the "zero boil-off condition".

The cryogenic infrastructure consists of an elevated low pressure cryostat (< 2 bar abs) surrounding the camera, a high pressure resistant (71 bar abs) storage tank (ReStoX) and a purification loop (Fig. 2.2).

Since XEMIS2 is intended to be employed in a hospital center, compactness, convenience of use and safety criteria must be respected. A particular attention is devoted to the vulnerability of the cryostat to pressure rise. To overcome any possible damage to the detector induced by an unexpected pressure increase, we consider a gravity assisted recovery. The liquid xenon transfer toward ReStoX is a simple and reliable operation explained in Section 3.2.

2.2. The XEMIS2 tank storage ReStoX

ReStoX is a cryogenic tank. It controls the overall system pressure. The metallic structure of ReStoX is easily cooled by a massive aluminum condenser located on the top of ReStoX. This exchanger includes two liquid nitrogen coils in which nitrogen film boiling occurs. It offers a temperature adaptation between the nitrogen and the xenon boiling points. The available cooling power is proportional to the nitrogen mass flow rate for a nominal temperature of 170 K. The condenser features a wide cooling power range: from a few W up to 11 kW limited by the exchange surface. Due to their high heat capacity and mass, the condenser (260 kg) and ReStoX structure (440 kg) have an important thermal inertia. Consequently, thermal transient heat loss of ReStoX will not significantly affect the pressure of the facility.

ReStoX pressure is governed by the heat losses and the applied cooling power. Consequently, its pressure can be increased or decreased by adjusting the heat losses balance. A preliminary warm-up test during its storage phase provides an estimation of the heat losses in the condenser, the metallic shell and the xenon. The three later warm-up were slow enough to consider a constant thermal equilibrium over their entire surface. This is justified by the small temperature gradient close to 1 K measured between the top and bottom of ReStoX.

The temperature rise curve was analyzed using the National Institute of Standards and Technology data [15] for the aluminum block, stainless steel vessel and xenon properties. The enthalpy/energy differences are directly calculated from temperatures variations for several time periods of 6 h (Fig. 2.3).

We notice a global heat flux of 17.3 W. Specifically, we estimate a net flux of 7.5 W, 6.8 W and 3.0 W for the aluminum block, stainless steel structure and xenon respectively. As expected, the latter is low: less than 20% of the total: it represents a tiny xenon boil-off rate of $0.03\ \mathrm{g \cdot s^{-1}}$. Finally, by adding the heat losses of the cryostat (84 W) and the purification circuit (15 W) we determine a net flux, or an equivalent cold power, close to 116 W dispensed by the condenser in normal regime.

3. Liquid xenon transfer: filling & draining of the cryostat

3.1. Cryostat filling procedure

Before filling the detector, we cool it down by introducing the liquid xenon inside (Fig. 3.1). This stage may happen after an extended

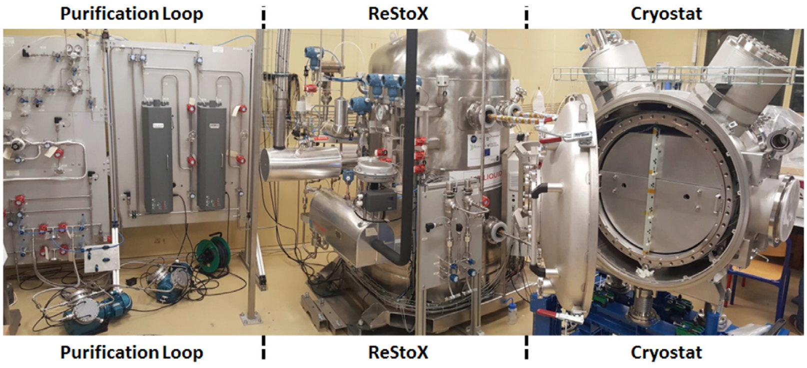

Fig. 2.2. Picture of the XEMIS2 facility with its three subsystems.