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Demonstration of electron drift over 1 m with a dual-phase Xe TPC for the XENON Dark Matter search program

Elena Aprile, Ranny Budnik, Hugo Contreras, Luke Goetzke, Antonio J. Melgarejo Fernandez, Marcello Messina[*†], **Guillaume Plante, Alfio Rizzo,**
Physics Department, Columbia University, New York, NY 10027, USA
Columbia University, Physics Department, 530 West 120th Street New York, NY 10027

Junji Naganoma, Peter Shagin
Department of Physics and Astronomy, Rice University, Houston, TX 77005 - 1892, USA

The next generation dual-phase (liquid/gas) xenon Time Projection Chamber (TPC) Dark Matter detectors will require a total mass of LXe on the multi-tonne scale to reach the desired sensitivity to WIMP-nucleon interactions. One natural and effective way to increase the target mass is to build a TPC with larger cross-sectional area and longer drift distance. Construction and operation of such a detector leads to many new issues and technological challenges which need to be addressed. One example is that the cooling system has to to be efficient and reliable to handle the large volume of Xe gas which has to be continuously purified to reduce signal loss over time. Another major challenge for a tonne-scale detector is the requirement of very high voltage (50 – 100 kV across 1 m) to generate a suitable drift field inside the TPC. A prototype facility, the XENON1T Demonstrator, has been built at Columbia University to study these and other challenges related to the construction and operation of a multi-tonne scale detector. The facility was built to enable TPCs of varying drift length to be tested, each optimized to study a different problem to demonstrate a different technological solution.

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[*]Speaker.
[†]E-mail: mmessina@astro.columbia.edu

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1. Introduction

The XENON dark matter program is devoted to the search for Weakly Interacting Massive Particles (WIMPs) by detecting particles created by the scattering of a WIMP off a xenon nucleus [1]. For many years, the Columbia XENON group has been committed to the search for WIMP-like Dark Matter (DM) using a dual-phase (gas-liquid) xenon TPC, as can be seen from [2] and references therein. The XENON project is entering its third phase, a multi-ton detector designed to reach a sensitivity to WIMP-nucleon interaction cross sections as low as $2 \cdot 10^{-47}\,\text{cm}^2$. Such an ambitious goal requires the demonstration of all novel features of the detector, the realization of which has led to the development of a dedicated research facility. In this paper we will report on the achievements of the XENON1T Demonstrator (XE1TD) facility. XE1TD has been built and operated at Columbia University's Nevis Laboratories. The group led by professor Elena Aprile has been involved in the development of the dual-phase Time Projection Chamber (TPC) technology since the beginning of the XENON project. Dual-phase TPCs are detectors where liquid Xe (LXe) is used as both target and detection media for particle interactions. Both prompt scintillation photons (178 nm wavelength) and ionization electrons are generated at the interactions site. The photons are measured by arrays of photomultiplier tubes (PMTs) installed at the top and the bottom of the field cage of the TPC. The signal generated by the prompt photons is typically referred to as the $S1$ signal. The ionization electrons are extracted into the gas phase by applying an electric field (E_{gap}). These electrons are then accelerated in the gas phase generating a second signal (referred to as the $S2$ signal), proportional in size to the number of electrons extracted from the liquid phase. This $S2$ signal is detected by the same PMTs used to detect the prompt photon signal. The time difference between the $S1$ and $S2$ signals allows events to be localized in z, exploiting the known electron speed at a given drift field. The transverse coordinates (x, y) of the interaction vertex are measured by the position of the reconstructed $S2$ signal in the top PMT array. Combining this with the drift time measurement of the z coordinate allows for a full, 3D reconstruction of the interaction vertex.

The construction of a large size TPC impose sever requirements of two main topics, such as feeding a very high voltage in to a cryogenic liquid to generate a suitable drift field (up to 1 kV/cm), and a implementing a purification system able to reduce the electronegative impurities at the ppb level. Both these technological aspect will be discussed in detail in the following.

2. The Demonstrator facility

The cryogenic system of the XE1TD consists of a Pulse Tube Refrigerator (PTR) with maximum cooling power of 200 W. The cooling power is transmitted through a dedicated copper cold-finger that connects the PTR to the vacuum vessel in which the LXe and the TPC are located. A full description of the cryogenic features of the XE1TD facility was presented in [4].

A purification system is in place using a hot metal getter (SAES Monotorr model PS4MT50R1), capable to handle high flows of noble gases. "Dirty" liquid xenon from the active volume is evaporated in a series of two heat exchangers. Two recirculation pumps, connected in parallel, force xenon gas through the getter to achieve the desired purification.The system is designed such that xenon can flow through either recirculation circuit without opening the detector, allowing for greater flexibility. The clean xenon is then re-condensed in the same heat exchanger series and returned to the active volume. The high temperature ($\sim 400\,^{o}$C) of the getter core makes the purification process highly efficient, and the heat transfer through the heat exchanger leaves only a small amount of parasitic heat input to be compensated by the PTR.

A picture of the XE1TD is shown in Figure 1. The tower hosting the heat exchanger and the PTR are visible. The cylindrical vessel, where the TPC is installed, is insulated by a vacuum buffer and a super insulation blanket. The outside of the insulation vessel is also visible in Figure 1.

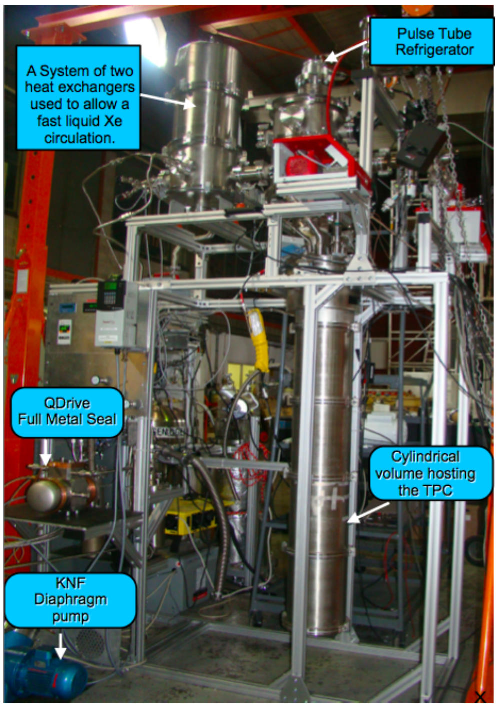

Figure 1: Image of the XENON1T Demonstrator. The left tower houses the heat-exchanger and the right one the PTR. The vacuum vessel housing the TPC is also seen.

Two pumps based on different technologies have been tested to determine which best meets the requirements of XENON1T in terms of flow reliability and minimal emanation of Radon: (i) a KNF diaphragm pump (KNF Inc., KNF 1400 Series No 143), similar to the one in use in the XENON100 experiment [3], and (ii) a full metal body pump (custom made from QDrive Inc., QDriveTM 2S132C ? X) completely sealed to prevent any possible leak. This pump is based on a magnetic circuit pushing back and forth magnetized pistons suspended in the magnetic field of the circuit. Thus, no bearings, piston rods, or lubricant are present. Of the two, the KNF diaphragm pump, modified to have only one diaphragm per piston (instead of two) achieved the highest flow rate with a maximum of 80 standard liters per minute (SLPM). The QDrive has several advantages with respect to the KNF pump: durability, lower Rn emanation, and lower mechanical noise relative to the KNF. The draw back of the present QDrive pump design is that the resonant frequency is too high with respect to the capability of the one-way valves to follow the gas flow. This requires that the pump is operated away from its resonant frequency, resulting in a reduced performance, with a maximum flow of 45 SLPM. However given the advantages, the QDrive was ultimately chosen for use in XENON1T.

The XE1TD facility can also provide high voltage (HV), up to 100 kV by means of a Heinzinger power supply (PNC-series). The HV limit is determined by the total drift length and the required drift field for the particular TPC. This HV system is necessary to generate a drift field of sufficient strength ($0.5-1\,\mathrm{kV/cm}$) across the maximum drift length of about 1 meter. To implement a drift field of this magnitude, the HV must be delivered into the vacuum insulated instrumented volume by means of a feed through (FT). While FTs capable of handling this high voltage are commercially available, they are typically bulky and built with materials not compatible with the low background requirements of a dark matter experiment. In particular, commercial HV FTs rely on large mass ceramic insulators which contains a significant amount of radioactive ^{40}K.

Thus for the XENON1T project it has been necessary to design a custom made FT, evolving from those built and implemented for the XENON10 [2] and XENON100 [3] experiments. The design is based on a cylindrical capacitor with a grounded outer shell. This enables the FT to cross the gas-liquid interface, while the central electrode is biased at the desired voltage. A plastic dielectric capable of withstanding cryogenic temperatures ($\sim 98\,\mathrm{K}$) is placed between the electrodes. Polytetrafluoroethylene (PTFE) was selected for this purpose as it is the cleanest commercially available dielectric. The fact that the dielectric constants of LXe and PTFE are so close helps prevent surface polarization and subsequent discharges under the strong electric field near the FT. A foil of PTFE, 1.5 mm tick, was placed between the FT and the vessel wall (at ground) to compensate for the very short distance (7 mm) between the high voltage electrode and the grounded wall. The FT was designed to accommodate a maximum voltage of 100 kV. This goal was effectively met in the XE1TD where the FT, tested at this stage without any detector, was stably biased at 97 kV while immersed in LXe. The distance between the FT and the ground for XENON1T is, by design, 5 cm, much larger than that used in the tests with the XE1TD.

Given the very high voltage requirements of a meter-length TPC, it is necessary that other components of the TPC, beyond the FT, should be constructed with special attention to prevent sparking under the applied electric fields envisioned for the detector.

3. TPCs tested on the Demonstrator facility

The vacuum vessel at the XE1TD facility was designed to accommodate TPCs of varying length, from about 30 cm to roughly 1 m length with an inner diameter of 15 cm. These dimensions were chosen because the primary aim of the XE1TD program was to demonstrate electron drift while using limited amounts of LXe. The largest amount of LXe needed for the XE1TD was 54 kg, one third of the amount used in the XENON100 experiment.

Two TPCs were tested in the XE1TD. Figure 2 left shows the first 30 cm long TPC. The field shaping rings (FS) and the the 12 cm-diameter PTFE cylinder used as scintillation light reflector and as support of the FS are visible, too. The FS, shown in detail in Figure 2 right, are formed from copper rods, 3 mm with circular cross-section, bent and soldered to form a ring of 12 cm diameter. The distance between two adjacent FS (center to center) is 13 mm. The cathode at the bottom of the field cage and a grounded gate grid installed near the liquid-gas interface closes the active volume. Along with the FS these are designed to make the drift field as uniform as possible. Above the gate grid is the anode, biased at a positive voltage of (4 kV). This anode voltage generates a sufficiently large electric field to extract the electrons from the liquid phase and generate the proportional scintillation signal in gas. The resistors of the voltage divider, meant to fix the voltage drop per stage of the field cage, soldered between each FS, are visible in Figure 2 right. The resistors are installed inside the FS so they are not exposed to the high electric field between these and the cryostat wall, effectively preventing discharges due to imperfections in electric component or poor solder points.

The liquid-gas interface was set by means of an overflow system which allowed the liquid level to be fixed between of the gate grid and the anode. The gap between the gate grid and the anode was 0.5 cm.

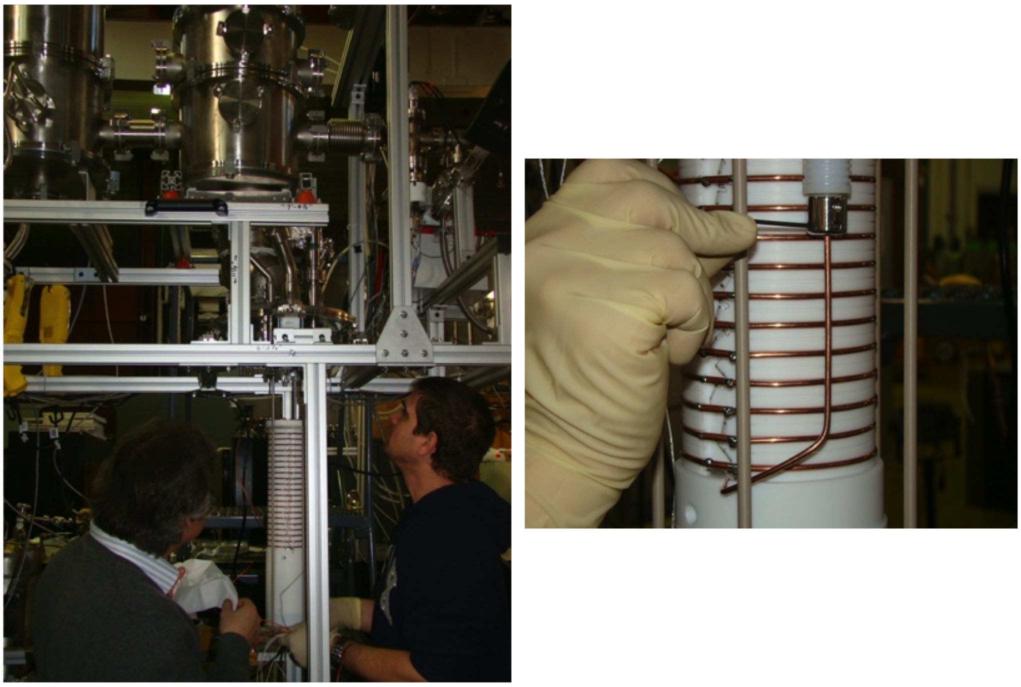

Figure 2: Images of the 30 cm XE1TD TPC. Both pictures show the TPC during the installation phase of the XE1TD.

A Hamamatsu R11410-MOD PMT was installed inside the PTFE cylinder, as shown in Figure 2 (left), and was operated at a bias voltage of 1500 V to detect light from interactions in the LXe. The PMT was protected from the cathode HV by a grid biased at the same voltage as the PMTs photocathode and installed near the PMT window. With a voltage of 15 kV on the cathode, a mean drift field of 0.5 kV/cm was generated.

The second TPC built and operated on the XE1TD facility has the same conceptual design of the one described above, though it is designed to demonstrate the feasibility of a 1 m drift length. Generating the suitable electric field across 1 m distance requires a cathode voltage in the range $50-100$ kV. This requirement imposes severe constraints on the FT, HV system, FS rings, cathode design, and various other electrical components, as well as the machined surface quality of other components of the detector.

Figure 3 shows several details of the design of this TPC. The drawing of the cathode and a picture of the real prototype are shown together with a zoom of the drawing of the inner-bottom side of the 1 m TPC. Finally, a picture of the full TPC installed in the XE1TD facility is also visible in Figure 3. The PMT used in this TPC is a Hamamatsu R11410-20 (photocathode biased at 1700 V),a prototype of the same type as will be used in XENON1T. This TPC also features an array of seven Hamamatsu R8520 PMTs (the same type as are used in XENON100) on top of the field cage, mainly to detect the delayed light. The flattened shape of the rings, shown in Figure 3, prevents points where the field can become too high ($>$ 100 kV/cm). The transverse cross section of the FS rings and cathode prototype are the same as will be used in XENON1T. The diameter of the FS and of the cathode will be much larger in the XENON1T detector (100 cm). The close distance between the rings (0.5 cm) and the FS rings prevents the field lines from escaping outside of the field cage, preserving the mean value of the drift electric field. Furthermore, the large radius of curvature (1 cm) of the bottom part of the cathode support ring, shown in Figure 3 center, is designed to prevent a large field on its surface. For the cathode, this problem is particularly important since it is the last electrode and is exposed to the ground, which drastically increases the probability of a spark starting on its surface.

Figure 3: (Left) A drawing and a picture of the cathode for the long drift TPC . The 200 μm thick wires are also visible on the cathode frame. (Middle) A zoom of the inside of the TPC showing the shaping rings, the cathode with its connection to the FT, the mesh protecting the bottom PMT and the PMT positioning itself. (Right) A picture of the fully assembled TPC on the XE1TD facility.

In Figure 3 (middle), the region between the cathode and the photocathode surface of the bottom PMTs is visible. The latter is protected by a screening mesh kept at the same potential as the PMT's photocathode to prevent the accumulation of ions on the surface of the PMT's window. This is also a region of high electric field, with a sizable distance between the cathode and the PMT ($\sim$ 5 cm), obtained using a specially designed PTFE spacer. The surface of the spacer is corrugated such that the mobility of the ionization electrons across the field lines is greatly reduced.This is necessary to prevent the production of scintillation light by means of surface conduction between the cathode and screening mesh. Another potential cause of sparking inside the detector is the formation of bubbles, caused by local phase transitions (nucleation). In this case, the gas in the bubble will experience a breakdown at lower field than in the liquid. High temperatures in the bubble produce even more gas, often leading to a chain reaction and eventually a discharge. The removal of impurities from the liquid helps in this respect, since the nucleation takes place around those atoms and molecules liquefying at lower temperature than the liquid.

After taking all of the above into consideration, the 97 cm drift TPC developed as part of the XE1TD project, was operated with very high voltage, up to 75 kV on its cathode in stable condition. In Figure 4, the drift time distributions generated by two collimated gamma sources (^{137}Cs), positioned at the very bottom of the drift volume, 7.5 cm apart, are shown. Drift time distributions for two drift fields, 0.62 kV/cm and 0.77 kV/cm, which correspond to cathode voltages of 60 kV and 75 kV, respectively, are shown. The two peaks in each distribution move towards lower drift time in agreement with the expected behavior as the field increases. The unfavorable aspect ratio of this TPC results in a strong dependence of the light collection efficiency on the drift coordinate. As a result, the measurement of the LXe purity (often indicated as electron life time) is much more complicated than in the smaller TPC. However, the fact that the peak amplitudes in Figure 4 are roughly the same size, for a given field strength, implies that the level of impurities present in the LXe is not sufficient to greatly degrade the charge response.

Details of the TPC design, specifically related to the high voltage and purification systems, used in XE1TD have been included in the design of XENON1T.

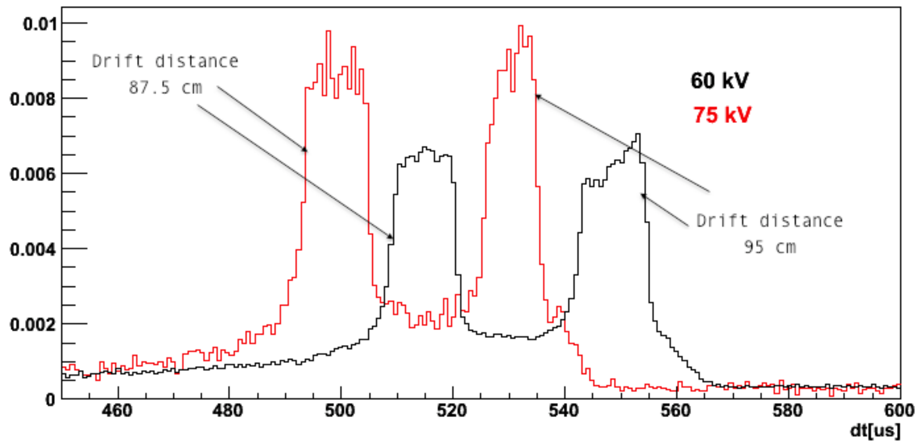

Figure 4: Two distributions of gamma events, at different drift fields, obtained with collimated ^{137}Cs sources installed at the bottom of the drift volume, 7.5 cm apart. are shown. As the drift field increases, one expects the electron drift velocity to increase as well. The effect of this can clearly be seen by comparing the position of each peak for the two different field configurations.

4. Conclusion

Some of the measurements carried out within the R&D program enabled by he XENON1T

Demonstrator Facility developed at Columbia University have been described. In particular we presented the design of two TPCs which have been operated to test long electron drift in LXe, the first of which had 30 cm drift length.

A second TPC with 97 cm drift length was designed, built and operated to demonstrate the generation of a sizable drift field ($0.6-0.7\,\mathrm{kV/cm}$) drifting electrons across the full 97 cm drift length. This is the first time that a two-phase XeTPC has been successfully operated with such a drift distance. Data showing the drift on long distance at two different fields have been presented.

5. Acknowledgment

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