Recent Results from Liquid Argon R&D at KEK

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Abstract. A Giant Liquid Argon TPC detector is considered as next generation neutrino and nucleon decay detector. In this article we report about recent liquid argon R&D activities at KEK. Starting in Summer 2008 we have built and successfully operated two different detectors: a 10L size double phase argon TPC and a 250L size single-phase TPC. So far we established liquid argon purities of (1) ∼ 10 ppb in the 10L detector and (2) ∼ 1 ppb in the 250L detector.

1. Overview of KEK Liquid Argon Test Stand

The Liquid Argon Time Projection Chamber (LAr TPC) is considered to be one of the most powerful charged particle imaging detectors. It’s possible to cover a large volume (\(\mathcal{O}(100)\) kt) with excellent position and energy resolution and real time readout. We are interested in applying this technique for the next generation neutrino and nucleon decay detector and have started R&D efforts at KEK in summer 2008. In January 2010 we have proposed a program to the J-PARC PAC: “Towards a Long Baseline Neutrino and Nucleon Decay Experiment with a next-generation 100 kton LAr TPC detector at Okinoshima and an intensity upgraded J-PARC Neutrino beam” (P32).

Although LAr is an excellent material for detecting charged particles it is known that the lifetime of drift electron strongly depends on the purity of the LAr (electronegative impurities such as oxygen capture drift electrons) and the attenuation length (\(\lambda\)) of the drift electrons is effectively parameterized in terms of the impurity concentration (\(\sigma\))

\[
\lambda(m) = 0.5/\sigma(ppb).
\]

This means that even small detectors with a maximum drift length of 5 cm require a LAr purity of ∼ 10 ppb in order to observe the ionization electron signal. For 5 m drift length we need to achieve ultra pure LAr with \(\mathcal{O}(10)\) parts-per-trillion (ppt) of impurities. The technique to obtain ultra high purity LAr has been pioneered by ICARUS, a ∼ 1 kt LAr-TPC with a drift distance of ∼ 1.5 m[1]. Based on this achievement our goal is to study the possibility of a 100 kT scale detector with a \(\mathcal{O}(10)\) m drift distance. Currently we are concentrating the effort to:

- establish basic techniques of LAr TPCs at KEK (cryogenic vessel, LAr purification, ionization charge and scintillation light readout, electronics, etc.) so that we can catch up with the current forefront.
- study the realization of large (∼ 100kt) LAr TPC detectors (establish long drift, high voltage, etc.)
understand the physics performance of LAr TPC detectors using charged particle and neutrino beams.

We have built two test setups with different sizes: the so called "10L setup" and the "250L setup". The 10L setup consists of a small 20cmφ×25cmL vacuum chamber and its goal is (1) to establish 5 cm drift of ionization electrons which corresponds to 10 ppb of impurities in the liquid argon and (2) to establish the double phase argon TPC detector. The 250L setup consists of a 70cmφ×100cmL cryogenic vessel and its goal is (1) to establish the technique to build a double phase LAr-TPC with 150 kg active medium and 40 cm drift length, (2) to test the detector performance under a charged particle beam (e,mu,pi,K) of 100-1000 MeV/c and (3) finally to expose it to a neutrino beam.

In this article we report on the current status of the 10L and the 250L setup.

2. Results from the 10L Test Stand
2.1. 10L Test Chamber
We have designed and built the 10L setup based on previous studies done by other groups [2, 3]. Figure 1 shows schematics of the 10L setup. We have built two vessels with the sizes of 20 cmφ×25 cm and 30 cmφ×45 cm, respectively. The larger vessel is a dewar, used as LAr bath to refrigerate the smaller vessel which is our test chamber.

![Figure 1](image_url)

The argon gas we used for the test was "G3" grade which ensures the contamination of oxygen to be less than 0.2 ppm. Then argon gas is purified by using small cartridges of Hydrosorb® and Oxysorb® by Messer. These filters are specified to achieve better than 5 (20) ppb of oxygen (moisture) contamination if the initial contamination is less than 10 ppm. Since the test chamber is cooled by liquid argon boiling at atmospheric pressure, by applying certain overpressure (+0.5 bar typically) inside the chamber, the argon gas gets liquefied. Using this setup, we have achieved to liquefy 3 L/hour of high purity LAr inside the chamber.

Although the argon gas right after the output of the filter is pure, it can degrade because of several reasons. The following is a list of such sources and actions we took to solve the problems.

- Out-gassing of the material inside the chamber. We have baked-out the test chamber at 100 °C while we were evacuating the chamber with a molecular turbo pump (80 L/sec capacity) directly mounted on the top flange for few days. Figure 2 shows a profile of the baking process. The test chamber was kept at high temperature for 80 hours, then it cooled down...
to room temperature. The achieved vacuum level is $\sim 1 \times 10^{-4}$ Pa at room temperature and the out-gassing rate is measured to be 0.01 Pa/hour which is improved by a factor of 100 compared to before the baking.

- The contamination from the transfer line between the output of the filter and the test chamber. We shortened the transfer line as much as possible by directly mounting the filter cartridge to the test chamber.
- Leaks from flanges, feed-throughs and valves of the test chamber. The leak-rate at room temperature was checked by using a He leak detector which is able to detect leaks down to the level of $10^9$ Pa $m^3 s^{-1}$. We have also observed that the CF flange leaks at liquid argon temperature because of the different thermal expansion coefficients of flange (SUS) and gasket (Cu). Thus we keep the LAr level of the bath inside the dewar lower than the flange of the test chamber.

Using the above procedure we have successfully filled the test chamber with less than $\sim 5$ ppb of impurities in the liquid argon.

![Figure 2. Vacuum level while baking process of the 10L system.](image)

2.2. 10L Detector

Inside the test chamber we put a double-phase TPC detector with an active volume of $9\text{cm} \times 9\text{cm} \times 5\text{cm}$ (Figure 3). The detector consists of a cathode plate, field shaping electrodes, 2 extraction grids, a THGEM (thick Gas Electron Multiplier) and a readout anode.

The cathode plate is a $9 \times 9 \times 1\text{mm}$ copper plate and the field shaping electrodes are $10 \times 10 \times 0.8\text{mm}$ stainless steel plates with a $9 \times 9 \text{cm}$ hole inside. The distance between each electrode is 1 cm. As extraction grids we soldered $100 \mu m$ stainless steel wires with a pitch of 5 mm on such a field shaping ring. The surface of the liquid argon is adjusted to be in the center of the two extraction grids within 1 mm accuracy. By applying an electric field of $\geq 3kV/cm$, the drift electron is extracted from liquid to gas phase. The used THGEM was produced by REPIC (Fig. 3). Its base is made of glass epoxy (G10) with gold plated copper electrodes. The geometry is:

- thickness 400 $\mu m$
- hole diameter 300 $\mu m$
- hole distance 700 $\mu m$
The 9cm×9cm anode is segmented into 4 pads with a size of 9 cm×2.2 cm. The electric signal is extracted from the test chamber through a vacuum tight BNC connector (Kyocera). Finally a charge sensitive preamplifier (Amptek A250, 1 V/pC) and a post shaper amplifier (Hosin N012, shaping time 1 µs) were used to amplify and shape the signals. A typical voltage setting for operating the detector is listed below:

- $E_{\text{drift}}$: Cathode-Bottom extraction grid (≡Drift field) : 300 V/cm
- $E_{\text{ext}}$: Between extraction grids (≡Extraction field) : 5 kV/cm
- $E_{\text{ind1}}$: Top Extraction grid - THGEM : (≡Induction field 1): 700 kV/cm
- $V_{\text{THGEM}}$: Between THGEM electrodes: 400~1750 V
- $E_{\text{ind2}}$: THGEM - Anode (≡Induction field 2): 1 kV/cm

Figure 4 shows a typical signal of cosmic muon track. To ensure to trigger on the cosmic muons passing through the TPC detector we have arranged two scintillation trigger counters with the TPC detector in between. The top plot shows the signal waveform for 4 TPC channels. Black, red, green, and blue lines correspond to channel 1,2,3, and 4, respectively. Figure 5-Left shows the gain of the THGEM as a function of the voltage between THGEM electrodes. The triangle (circle) points are with an induction 2 field equal to 1.0 kV/cm (3.5 kV/cm). Up to now the maximum achieved gain with this configuration is $\sim 2.5$.

Figure 3. Pictures of 9x9x5cm$^3$ double phase TPC detector (left) and the THGEM (right).

2.3. THGEM Performance at Cryogenic Temperature

The mean free path of drifting electrons inside argon gas depends on the molecular density of the argon gas and is proportional to pressure (atm)/temperature (K). An electron needs to be accelerated to at least $\sim 25$ eV within the mean free path in order to produce secondary electrons and initiate gas multiplication. This means that the breakdown voltage increases with increasing molecular density. At LAr temperature (90K) the molecular density is $\sim \times 3$ larger compared to room temperature. For this reason it is rather difficult to achieve high gas gains at low temperature.

Figure 5-right shows the measured gain of the THGEM as a function of P/T. These measurements were taken by varying the gas pressure between 1-2 atm at room temperature (300 K) with a constant THGEM voltage of 800 V. The data points show good agreement with an function $e^{\alpha T}$. The plot also shows the gain with liquid argon temperature equivalent density (P/T = 1/100 = 0.01), is about 50 lower than the gain at room temperature (P/T = 1/300 = 0.003), keeping the voltage constant.
Most of the gas multiplication devices developed so far are designed to operate at room temperature and standard pressure. So there is still room for improvement to achieve high gain at cryogenic temperatures. Recently it has been successfully achieved a gain >10 using Large Electron Multipliers (or thick GEM/THGEM) produced at CERN, which is already sufficient for neutrino physics application [4].

3. LAr Purification for the 250L Test Stand
For a first test campaign in October 2010, of a 250L TPC in the K1.1BR beamline of the J-PARC slow extraction facility (see [5] for a detailed description of the setup), we built a prototype detector with coarse readout sampling, operated in liquid argon phase. The setup is housed in a cryostat originally built as a prototype liquid Xenon calorimeter for the MEG ($\mu \rightarrow e\gamma$) experiment [6]. The cryostat consists of two transverse cylindrical vessels (inner vessel and outer vessel). The inner vessel is filled with liquid argon and has ~70 cm diameter and ~100 cm length, thus the volume of the cryostat is about 400L. The maximum size of cuboid which fits inside the inner vessel is ~50×50×100 cm$^3$ (250L). The volume between inner and outer vessels is for vacuum insulation and super insulator (20 layers of aluminum mylar films) is inserted to reduce thermal radiation. The total heat input of the cryostat is ~30W at LAr temperature (90K).
The TPC detector has an active volume of $40 \times 40 \times 76 \text{ cm}^3$. For this test, instead of a double-phase TPC, we use a single-phase grid chamber with the anode segmented into 76 strips ($40 \text{ cm} \times 1 \text{ cm}$ strip).

In the 250L setup the maximum drift distance is 40 cm, thus we need to achieve at least 1 ppb of LAr purity so that the attenuation of the signal does not cause significant charge attenuation. Figure 6 shows a schematic drawing of the cryogenic and purification system for the 250L test. The procedure to fill the chamber and to achieve and maintain high purity liquid argon in the vessel is as follows:

- Evacuate the inner vessel with a molecular turbo pump (Edwards, 300L/s capacity) and a getter pump (SAES, 40 L/s capacity) directly mounted on the top flange for $\sim 1$ week. The achieved vacuum level is $1 \times 10^{-4} \text{ Pa}$ and the out-gas/leak rate is $\sim 1 \text{ Pa/hour}$. Since the 250L cryostat is a thermal insulated vessel, it is difficult to heat the material inside the inner vessel while evacuation. Thus we separately bake-out some of the detector components in another vacuum chamber to reduce the out-gassing of the material efficiently.
- Fill the inner vessel with argon gas from LAr tank through the purification cartridge up to 80–100 kPa(Gauge). We have developed the purification cartridge based on Fermilab’s study [7]. Figure 6 shows the purification cartridge which consists of activated copper (Angelhard Cu-0226, black granules) and molecular sieves (Union Showa type 4A, while granules).
- Start cooling down the vessel using a Gifford-McMahon (GM) cryocooler made by Sumitomo Heavy Industries and a LN2 heat exchange coil. The cooling power of the GM cryocooler is 160 W at LAr temperature (90K) and the LN2 heat exchange coils provide up to 600 W.
- The gas recirculation is turned on at the same time with a typical gas flow of 70L/min. For the gas purification, we use a commercial filter (SAES microtor).
- As temperature and pressure inside the vessel go down, we add argon gas and keep the pressure at 80 kPa (Gauge).
After ∼5 hours, the vessel is cooled down and LAr begins to be accumulated at the bottom of the vessel. At this stage, argon gas is still liquefied by cryocooler and LN2 coil. The typical liquefaction speed which is limited by the cooling power is 10 L/hour.

- At this point, we start filling the vessel with LAr from LAr tank. It takes another ∼3 hours until the purification cartridge is completely cooled down and we are directly filling the vessel with LAr. After that the filling speed is ∼ 50 L/hour which is limited by the impedance of the purification cartridge.
- We stop filling once the detector inside is completely immersed.
- Further purification to improve and/or keep the initial purity by recalculating the argon gas. Evaporate liquid argon inside the cryostat using cryogenic heater and purify the argon gas, then liquefy using the GM cryocooler and the LN2 coil. The system is designed to recirculate one full volume of the LAr inside the vessel in few days.

By using the procedure explained above we have successfully filled the 250L vessel at J-PARC K1.1Br beamline on October 2010, and exposed it to a charged particle (K, π, p, e) beam (see [5] for a detailed report). Figure 7 shows an event display of a cosmic muon track. The horizontal axis shows the TPC channel, the vertical axis shows drift time in µs and the color of the plot corresponds to the signal pulse height in ADC counts after pedestal subtraction. By an analysis of the released ionization (dE/dx) versus drift distance, for cosmic muon tracks, we measured an electron lifetime in LAr better than 300 µs, corresponding to an upper limit of <1 ppb of electronegative impurities.

![Figure 7. Typical cosmic track event recorded with the 250L detector](image)

### 4. Summary

We started a LAr R&D program at KEK mainly concentrating on LAr purification techniques. We also tested a double-phase LAr TPC detector, where ionization electrons extracted from the liquid are amplified in the gas phase by means of Gas Electron Multipliers. We have built two different test stands for LAr TPC R&D, namely “10L setup” and “250L setup”. In 10L setup, we have established better than 10 ppb LAr purity and 4 ch readout double phase readout TPC. In the 250L setup, we have achieved better than 1 ppb LAr purity and observed cosmic muon tracks as well as charged particles from an accelerator beam with a 76 channel readout single phase TPC.
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