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A global R&D program on liquid Ar Time Projection Chambers under execution at the University of Bern

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Abstract

A comprehensive R&D program on LAr Time Projection Chambers (LAr TPC) is presently being carried out at the University of Bern. Many aspects of this technology are under investigation: HV, purity, calibration, readout, etc. Furthermore, multi-photon interaction of UV-laser beams with LAr has successfully been measured. Possible applications of the LAr TPC technology in the field of homeland security are also being studied. In this paper, the main aspects of the program will be reviewed and the achievements underlined. Emphasis will be given to the largest device in Bern, i.e. the 5 m long ARGONTUBE TPC, meant to prove the feasibility of very long drifts in view of future large scale applications of the technique.

Keywords: Time Projection Chamber (TPC), Liquid Argon, Large mass detectors, Neutrinos

1. Introduction

In the last decades the neutrino oscillation phenomenon has been established in many sectors such as in the field of solar [1], atmospheric [2], and reactor neutrinos [3]. Almost all parameters of the mixing matrix of the flavor and mass eigenstates have been determined apart from θ_{13}. Only recently the T2K experiment [4] has shown an indication of a non-vanishing value of θ_{13} with a statistical significance of 2.5 sigma. Future measurements envisaged in the field of neutrino oscillations must provide a precise determination of θ_{13} investigating possible CP violating effect in the lepton sector. Furthermore, the problem of the hierarchy of the ν mass eigenvalues will be the next open issue.

All the measurements mentioned so far are expected to show only tiny effects and for this reason large sample of events are needed in order to reveal them. Such large samples can only be obtained with a synergic use of high flux neutrino beams and large mass detectors. Our research program is focused on the development of detector technology that allows to conceive detectors of very large masses with the use of Liquid Argon Time Projection Chambers (LArTPC).

One possibility to build a large-mass LArTPC has been discussed in [6] where the conceptual idea of the GLACIER detector is presented. In particular, the GLACIER concept is based on a single cylindrical volume of 70 m diameter

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and 20 m in hight. In this volume a LArTPC would be installed, with the drift coordinate parallel to the height of the cylinder. GLACIER foresees a read out system able to work in the gas phase on top of the liquid where the electron yield can be amplified.

The main issue of such a detector is the very long drift distance, whose feasibility was never shown before. In fact, so far the longest drift path has been shown by the ICARUS collaboration with 1.5 m length.

Such very long drift distances require high purity of LAr (impurity of 0.1 part per billion, ppb, of Ar) to prevent large electron yield depletion because of attachment of electrons with electro-negative impurities (i.e. O^2, H^2O). Furthermore, a very high voltage is needed to make a sizable drift field over such a distance, i.e. 0.5 – 1 MV. Our Research and Development (*R&D*) program on the LArTPC is mainly devoted to prove the capability of drifting electrons over at best 5 m drift distance.

So far three LArTPCs with increasing drift distance, 1 cm, 57 cm and 500 cm have been conceived at the LHEP, where the first two have been built and run. The three detectors are named micro-ARGONTUBE, medium-ARGONTUBE and ARGONTUBE to recall the increasing drift distance. During the development of the program not only the issues related to the 5 m drift capability have been studied, but also other aspects have been investigated such as the multi-photon ionization of the LAr with a UV laser beam, and also possible applications of the LArTPC in the field of the homeland security.

The paper is structured through three sections where firstly the ARGONTUBE detector is described in details and the status of the construction is presented. In the following two sections the medium-ARGONTUBE and micro-ARGONTUBE are described and the developments done in view of the construction of the ARGONTUBE are shown.

2. The ARGONTUBE project

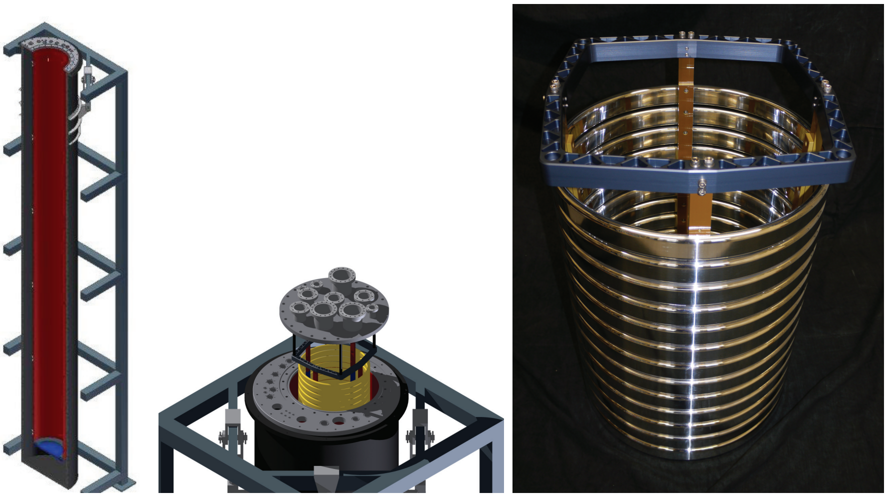
Before proceeding to describe the ARGONTUBE project we will introduce the LArTPC detector concept and shortly summarize its features and peculiarities. A LArTPC consists of a LAr volume, where the Argon acts simultaneously as target and active medium, well suited for neutrino physics given its high density (1.4 g/cm^3). In the instrumented volume an electric field is applied to prevent the electron-ion pairs from recombination and to drift the electrons towards the read out planes. The latter consist of two wire planes, in most of the cases, or even more, like in the ICARUS detector [5]. A uniform field is obtained thanks to a cathode and field shaper electrodes installed at fixed pitch and biased at a given ΔV. The wire planes function as anode. The ΔV is provided by a voltage divider that can be realized with several technique and later we will show one possible implementation.

In Fig. 1, (a) and (b), the drawings of the ARGONTUBE detector are shown and in Fig. 1 (c) one can also see a picture of a part of the field cage of the ARGONTUBE already assembled. In particular, in Fig.1 (a) the dewar, where the LAr will be boiling off at ambient pressure, is visible together with the inner tube where the TPC will be hosted. In Fig. 1 (b) a part of the field cage (a few rings out of 125 in total) are visible with some details of the system to attach the detector to the top flange. The optimal size, the shape and the cross section of the field shapers have been studied by means of numerical calculations of the electric field in the inner volume, paying attention to avoid any point where the field would have exceeded the limit of 1 MV/cm. The latter is the maximum voltage the LAr can withstand before self ionization is taking place.

The dewar and the inner tube are in thermal contact, while the liquids are separated to avoid to pollute the LAr in the instrumented volume, which is one of the most critical aspects of a LArTPC. To reduce as much as possible the sources of pollution, the internal surface of the inner tube has been electro-polished removing 100 μm of material, which traps molecules that could be later released into the LAr.

The geometrical reconstruction of particle tracks is realized by recording the electric signal generated by ionization electrons on the wires, whose position correspond with to the transverse coordinates, and the third coordinate is given by means of the measurement of the drift time (reference time t_0 minus arrival time to the wires t) and assuming as known the drift velocity at a given electric field. A photomultiplier is used to provide the t_0 and the trigger signal for the DAQ. A TPC offers the possibility to have a homogenous sensitive volume, with a three dimensional reconstruction capability and a charge read out that allows to measure the energy released by particles.

The full *R&D* program under development at the LHEP, University of Bern, is devoted to show the feasibility of the LArTPC depicted so far. In particular, to accomplish the ARGONTUBE project, which aims at proving the capability of drifting ionization electrons over long distance, as required in a very large mass detector [6].



(a) (b) (c)

Figure 1: (a) Drawing of the dewar where the inner tube of the ARGONTUBE detector is immersed. (b) Drawing of the top flange with all the feed throughs, a part of the field field cage and some details of the fastening system to the top flange. (c) Picture of the first modules of the ARGONTUBE field-cage assembled. It is visible also the support structure that will fasten the detector to the flange.

The desired purity of the LAr is reached by making a vacuum at the level of 10^{-6} mbar in the inner tube before the LAr filling. The latter takes place through a cryogenic filter [7], which prevents the impurities to reach the inner tube. To further increase the LAr purity and to fight against possible out-gassing of detector components in the warm phase, the inner volume is equipped with two cryogenic pumps capable of recirculating the LAr through a filter analogous to the one mentioned above. The two pumps can work either in parallel, doubling the LAr recirculation rate, or in series, keeping one of them as a backup in case of failure of the other pump.

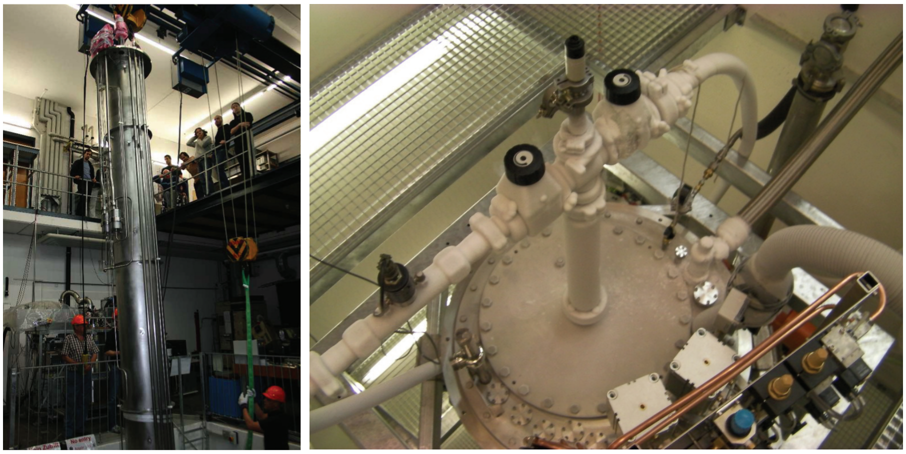
The conceptual design of these bellow pumps is based on a piston driven, by pressurized gas Nitrogen, that pushes a bellow which forces the recirculation of the liquid. The pumps, together with the pressure-meters, the level-meters and the flux-meters, are controlled by a Programmable Processing Unit (PLU) that can also be read out via ethernet. The optimal working parameters of the pumps give a cycle period of 3 s with a recirculation rate of almost 100 l/h.

The bellow pumps require no lubricant that would pollute the LAr nor brush contacts, thus reducing the possibility of mechanical failures. In this case the only weak points are the bellows withstanding a finite number of cycles. This number was measured to be around severals 10^6.

All the cryogenic components of the ARGONTUBE detector have been installed in the pit of the LHEP laboratory as shown in Fig. 2 (a) and the vacuum tightness was tested to 7×10^{-5} mbar after 12 h running of vacuum pumps to evacuate the inner tube volume of 1.1 m^3. The ARGONTUBE was also tested in cold, as seen in Fig. 2 (b). The vacuum insulation of the dewar and the recirculation capability of the two bellow pumps were found to be in agreement with the specifications of the design.

As already mentioned, in such a long drift TPC a critical point is the high voltage needed to generate the drift field. Given the difficulty to feed the required voltage ($\sim$ 500 kV) from outside through the gas phase of the Ar without provoking discharges, we have chosen to install in the LAr a Greinacher/Cockroft-Walton (*GCW*) circuit consisting of a chain of rectifying cells. This exploits the very good insulation properties of the LAr,[8, 9]. The conceptual schema of a *GCW* is shown in the Fig. 3, where it is visible that an *AC* input voltage is required ($2V_0$ peak-to-peak voltage) and each cell of the circuit will rectify the *AC* signal providing an overall voltage of $n \times 2V_0$, where n is the number of cells. In Fig. 3 (c) we report on the results of measurements done with a *GCW* prototype circuit with which a voltage of 110 kV has been reached. Above 110 kV some sparks started, due to the limitations of the setup where the test was executed. Indeed, it was not very clean and many bubbles where presents, both causing discharges. With the ARGONTUBE we do not expect such problems.

The bottom plot of Fig. 3 (c) shows the discharge of the GCW as function of time once the input AC was turned



(a) (b)

Figure 2: Pictures of the ARGONTUBE detector. In (a) the inner tube is visible during the installation phase in the dewar where the LAr will boil off at ambient pressure. In (b) one can see details of the bellow pumps and of the cryogenic recirculation circuit.

off. It is visible that after 20 min only 4% of the voltage(charge) was lost. The very low discharge rate is an important feature in case the *AC* induces noise on the read/out channel. In this case we can turn off the *AC* in coincidence with a trigger and record the data without any noise and without suffering of significant voltage drop. The voltage was monitored with a ”field mill” device [10], built in house and capable to work in cold.

We have chosen a configuration in which each stage of the *GCW* will bias one field shaper (rings in Fig. 1). With a distance between each rings of 4 cm and an input voltage of 2 kV (4 kV peak-to-peak) we obtain the required field of 1 kV/cm (500 kV DC total).

The most challenging aspect of the implementation of the *GCW* is to find the electric components (diodes and capacitors) capable to work at the LAr temperature. In our case we have chosen diodes (M160UMG, 16 kV reverse bias) from VMI [12], and ceramic capacitors (maximum *DC* voltage 4 kV) from NOVACAP [11]. All the components have been tested in cold before being implemented in the *GCW*.

The field cage, the read-out wire planes, the recirculation circuit and all the cryogenic parts of the ARGONTUBE have been produced and tested and a first ARGONTUBE test run is in preparation.

3. medium-ARGONTUBE

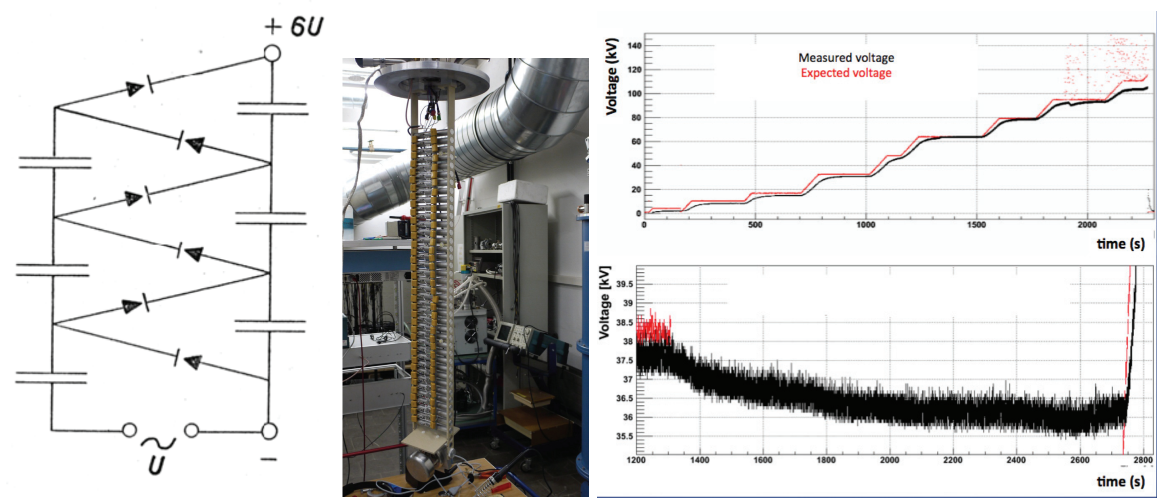
The medium ARGONTUBE is a LArTPC where the instrumented volume is a cylinder of 40 cm in diameter and a height (drift length) of 60 cm. As visible form Fig. 4, the medium-ARGONTUBE has the same structure of ARGONTUBE, i.e. cylindrical field cage with a cathode and field shapers to obtain a uniform field. The thermal equilibrium of the LAr is kept thanks to a LAr bath boiling off at ambient pressure.

The bias voltage to the cathode and to the field shaper rings is provided by means of a conventional power supply and distributed thanks to a feed-through, with a maximum withstandable voltage of up to 30 kV [13]. We feed the voltage from outside of the inner tube to the cathode through the gas phase of the Argon. A resistive voltage divider has been used to distribute the voltage to the rings.

The trigger signal is given by a photomultiplier installed in the gas phase, which is able to detect the scintillation light of the Ar, allowing to provide also the t_0 for the offline reconstruction. The photomultiplier has been coated with a layer of ThetraPhenilButadiene (TPB) to match the scintillation light spectrum and the quantum efficiency curve of the photocathode.

The medium-ARGONTUBE is a test-bench for the ARGONTUBE, in particular for the following items:

- A laser based device to monitor the purity and the energy calibration of the LArTPC



(a) (b) (c)

Figure 3: (a) schema of the *GCW* circuit. (b) picture of a GCW prototype with 37 stages. (c) result of the measurement done the the GRW prototype. In the top and bottom plots the rump up and the discharge of the circuit are shown, respectively.

- A purification system with bellow pump
- The DAQ and the front-end preamplifiers.

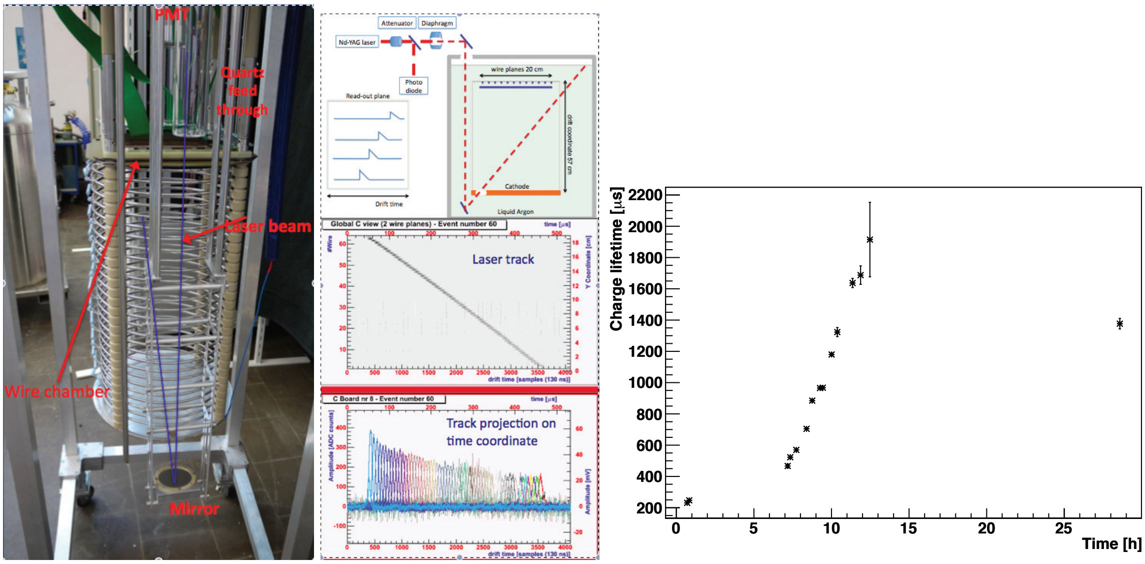
We studied the use of a laser as a device to monitor the purity of the LAr. We measured in detail its energy calibration and the multi-photon cross section of the LAr. Three photons ($\lambda = 256$ nm) can ionize an Ar atom making an electron-ion pair, similarly to what happens when charged particles pass through the LAr. The use of the laser as a purity monitor relies on the knowledge of the multi-photon ionization cross section of Ar to estimate the ionization electron yield. By comparing the latter with the measured one, the attenuation of the electron yield due to the electronegative impurities (equivalently the purity of the LAr) can be measured. Once this effect is taken in to account, the prediction of the ionization yield allows also to define the energy scale of the LArTPC with high precision, i.e. the relation between the energy released and the number of electrons that can be measured by the preamplifiers. The studies just mentioned are summarized in [14, 15] where it is shown that three photons are involved in the process and the cross section is measured.

Fig. 4 (a) shows a picture of the medium-ARGONTUBE and in Fig. 4 (b) the steps required to make the purity measurement with laser are depicted. From top to bottom in Fig. 4 (b) one can see the laser track with the inclined path crossing the instrumented volume, the display of a real laser track and the projection of the hits generated by the track on each wire projected on the time-coordinate axis, respectively. In the bottom plot of Fig. 4 (b) the exponential decay of the pulse heights as function of the time-coordinate is visible, and the decay time $\left(\tau = \frac{300(\mu s)}{purity(ppb)}\right)$ of the exponential corresponds to the electron life time or equivalently to the electronegative impurity present in the LAr volume.

In Fig. 4 (c) the measured τ is plotted as function of time and the effect of the purification circuit, when the pump is turned on at $t = 7$ h, is visible. After 5 hours of running, the pump was stopped and the purity measurement was done again after almost 12 hours at $t = 23$ h. The deterioration of the purity is explained by the outgassing of the components of the TPC immersed in the warm phase of the Ar.

The largest purity that has been reached was around 2000 μs corresponding to impurity of better than 0.15 ppb. This value is not limited by the performance of the purification device but by the measurement of the purity given the limited drift distance (57 cm). Indeed, the purity measurement has a good sensitivity only up to a τ value five times longer then the drift time ($\sim 400\ \mu$s), then the exponential fitting procedure fails.

Given the successful operation and the good performance of the purification system, a similar one will be used for the ARGONTUBE where the only upgrade is a recirculation rate increased by a factor five.



(a) (b) (c)

Figure 4: In (a) one can see a picture of the medium-ARGONTUBE detector with a superimposed sketch of the laser path. In (b) we show the logical steps needed to make the purity measurements. For more details see the text. The plot in (c) shows the purity measured as function of time. One can see the increase of the purity when the system is running (time interval 7 h÷ 12 h) and also the decrease of the purity (t = 28 h) due to the outgassing of the detector components in the warm phase.

VME crate	1
ADC board (V1724 CAEN)	16
Channel per board	8
Memory per board	8 Mb
VMR controller (V2718 CAEN)	1
Data flow (optical link)	70 Mb/s
Sampling time	10-200 ns
Event size for different sampling time	67 -4 Mb/event

Table 1: Main components and features of the DAQ of the middle-ARGONTUBE ready to be employed also for the ARGONTUBE.

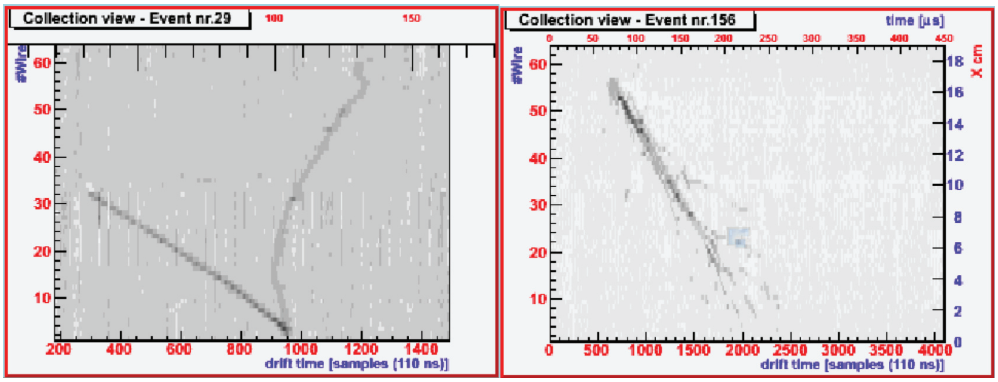
With medium-ARGONTUBE we also designed and developed the DAQ, with which the laser track in the Fig. 4 (b) was recorded. It is based on commercial VME technology and in Tab. 1 the main components and features of the DAQ system are summarized.

During many campaigns of measurements the DAQ system has shown to be very stable both from the side of the hardware and of the software. Thus, the same DAQ as for the middle-ARGONTUBE will be used for ARGONTUBE detector having the same number of channels. In Fig. 5 two events are shown, one with a muon decay topology and one with an electromagnetic shower topology.

The front-end electronics is custom made in collaboration with IN2P3 Lyon and ETH Zurich. To read out the wires of both planes we use the same amplifiers, where only the shaping time is optimized to make the amplifier response sensitive to the current or to the collected charge.

4. micro ARGONTUBE

The micro-ARGONTUBE detector is shown in Fig. 6 (a). It is a short-drift TPC with 1 cm drift distance and a cross section orthogonal to the drift coordinate of 10×10 mm^2. There is one read out plane with 20 wires. Eight

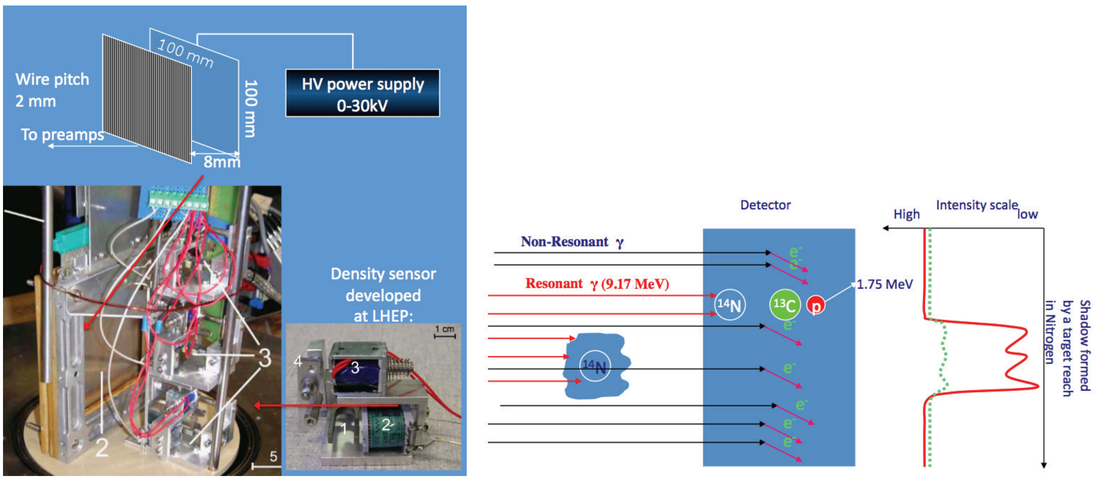


(a) (b)

Figure 5: Collection view of a muon decay (image (a)) event and an electromagnetic shower (image (b)) events. The transverse coordinates (wire positions) and the drift coordinates (drift time) are reported on the vertical and horizontal coordinates, respectively.

middle wires are instrumented with charge pre-amplifiers and the lateral wires are used as field shapers to make drift field uniform. The drift distance is short to study the electron drift properties in presence of a sizable amount of electronegative contaminants in the LAr.

The eight instrumented wires are read-out by the same pre-amplifier already mentioned in the previous section. In particular, the shaping of the signal was studied in view of using them for drift distance from 60 cm to 500 cm. After the characterization of the preamplifiers, the micro-ARGONTUBE was devoted to the study of a possible application of the LAr TPC technology in the field of the homeland security.



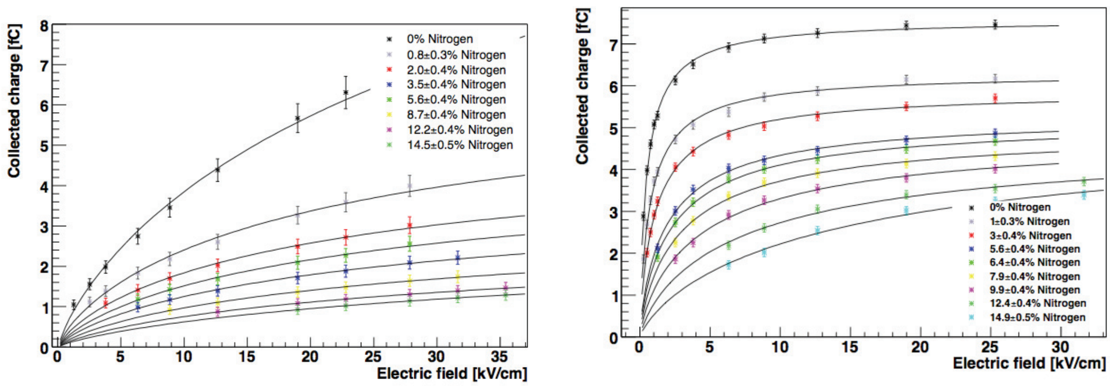
(a) (b)

Figure 6: A picture of the micro-ARGONTUBE TPC where some details are visible. On the left picture one can see the density-meter developed and built at the LHEP with which the mixture of LAr and LN is measured.

The idea is to prove the feasibility of drifting electrons in a mixture of LAr and LN such that the Gamma Resonant Nuclear Absorption (GRNA) [16] could be exploited. Nitrogen nuclei have a high cross section for absorbing gamma rays of 9.18 MeV because of the resonant reaction $\gamma + N \rightarrow^{13} C + p$, where the out-coming proton will have an energy of approximately 1.7 MeV.

As schematized in Fig. 6 (b) any target rich in Nitrogen, as could be chemical explosives, will project a shadow onto a detector when it is illuminated by a gamma source of proper energy. In this case also the detector must be rich in Nitrogen, to be able to enhance the shadow of the body under investigation with respect to the rest of the image. This method is the same as the one used in X-ray radiography, but realized by means of gammas. This could open the way to the radiography of non-biological systems such as a cargo containers to reveal the presence of chemical explosive without the need to open the cargo.

The feasibility of the method described above depends on the capability to distinguish between electrons from the Compton scattering process that will occur copiously with 9.17 MeV gammas, and the protons from the GRNA on Nitrogen. Furthermore, an environment rich with Nitrogen is expected to trap the ionization electrons in conflict with the request of a very pure LAr needed to drift electrons over long distances. For this reason we used a very short drift distance to prove the conceptual idea mentioned above. Also in a real size device, capable of exploiting the GRNA to reveal the presence of explosive, a large drift distance is not required.



(a) (b)

Figure 7: In image (a) the electron yield as function of the drift field is shown for different concentration of the LN in the mixture of $LAr - LN$ and for $alpha$ events. In image (b) the same is shown for $beta$ events

To test the capability to distinguish between protons from GRNA and electrons from Compton scattering we measure the ionization from a beta source and from an alpha source installed in the micro-ARGONTUBE. In this case the alpha source provides highly ionizing particles simulating the protons. In Fig. 7 the pulse heights recorded with different LN concentration in the LAr (from 0 to 20%) as function of the drifting field are shown. One can see that at a sufficiently high field (> 10 kV/cm) the alpha and beta signals are well distinguishable even with LN concentration of the order of 10%. Details about the measurements and the experimental setups can be found in [17, 18]. The preliminary results shown in Fig. 7 show the feasibility of an efficient distinction between electrons and proton, mandatory to be able to realize a GRNA radiography. The latter would be a major breakthrough in the field of homeland security.

Conclusions

In this paper we described the $R\&D$ program under development at LHEP, University of Bern, where the main goal is to establish a LArTPC with the longest drift distance aver built. During the development of the program, three LArTPCs (micro-ARGONTUE, medium-ARGONTUBE and ARGONTUBE) have been conceived and the two with shorter drift distance have been built and successfully run. The results from the operation of the micro-ARGONTUBE and middle-ARGONTUBE have been of fundamental importance to properly design the ARGONTUBE. All technological issues for building a LArTPC with 5 m drift length have been discussed and a solution for all of them has been found. We expect results from ARGONTUBE soon.

Aknoledgment

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