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First operation of a liquid-argon TPC embedded in a magnetic field

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Abstract. We have operated for the first time a liquid-argon TPC immersed in a magnetic field up to 0.55 tesla. We show that the imaging properties of the detector are not affected by the presence of the magnetic field. The magnetic bending of the ionizing particle allows one to discriminate their charge and estimate their momentum. These figures have up to now not been accessible in the non-magnetized liquid-argon TPC.

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1. Introduction

Among the many ideas developed around the use of liquid noble gases, the liquid argon time projection chamber [1, 2] certainly represented one of the most challenging and appealing designs. The technology was proposed as a tool for uniform and high accuracy imaging of massive detector volumes, ideally suited e.g. as a neutrino observatory and/or as a detector for...
a sensitive search for nucleon decays [3]. The operating principle of the liquid argon (LAr) TPC was based on the fact that in highly purified LAr ionization tracks could indeed be transported undistorted by a uniform electric field over distances of the order of metres. Imaging is provided by wire planes placed at the end of the drift path, continuously sensing and recording the signals induced by the drifting electrons. LAr is an ideal medium since it provides high density, excellent properties (ionization, scintillation yields) and is intrinsically safe and cheap, and readily available anywhere as a standard by-product of the liquefaction of air. Non-destructive readout of ionization electrons by charge induction allows one to detect the signal of electrons crossing subsequent planes with different wire orientation. The first wire planes are biased with potentials, so that they are transparent for the drifting electrons and only pick up the induced signal from the electron cloud passing the plane. On the last plane, the drift electrons are collected, and the measured charge can be used to determine the specific energy loss $dE/dx$. However, there is no charge amplification possible in LAr, so that a very low noise preamplifier is needed for the measurement of the charge collected (or induced) on a wire from a minimum ionizing particle, which is typically about 15 000 electrons for a wire pitch of 3 mm. Each wire plane provides a two-dimensional projection (wire number versus drift time) of the same event. Combining two (or more) planes allows the three-dimensional reconstruction of tracks, and hence, a precise calorimetric measurement.

The feasibility of this technology has been demonstrated by the extensive ICARUS R&D program, which included studies on small LAr volumes about proof of principle, LAr purification methods, readout schemes and electronics, as well as studies with several prototypes of increasing mass on purification technology, collection of physics events, pattern recognition, long duration tests and readout. The largest of these prototypes had a mass of 3 tons of LAr [4, 5] and has been continuously operated for more than four years, collecting a large sample of cosmic-ray and gamma-source events. Furthermore, a smaller device with 50 litres of LAr [6] was exposed to the CERN neutrino beam, demonstrating the high recognition capability of the technique for neutrino interaction events. The realization of the 600 ton ICARUS detector culminated with its full test carried out at surface during the summer 2001 [7]. This test demonstrated that the LAr TPC technique can be operated at the kton scale with a drift length of 1.5 m.

2. LAr TPC in a magnetic field

The bubble-chamber-like reconstruction capability of the LAr TPC provides simultaneously (1) a tracking device with unbiased imaging and reconstruction, and (2) full sampling calorimetry. The detector is fully active, homogeneous and isotropic. The resolution is very good, both for energy (calorimetry) and for angular reconstruction (tracking). The possibility to complement the features with those provided by a magnetic field has been considered and would open new possibilities [8]–[10]: (a) charge discrimination, (b) momentum measurement of particles escaping the detector (e.g. high energy muons), (c) very precise kinematics, since the measurements are limited by multiple scattering (e.g. $\Delta p/p \simeq 4\%$ for a track length of $L = 12\, \text{m}$ and a field of $B = 1\, \text{tesla}$). The challenging possibility to magnetize a very large, multikton, volume of argon has been addressed in [11].

The orientation of the magnetic field can be chosen such that the bending direction is in the direction of the drift where the best spatial resolution is achieved. The magnetic field is hence perpendicular to the electric drift field. The Lorentz angle is expected to be very small in the
liquid (e.g. \( \approx 30 \) mrad at \( E = 500 \) V cm\(^{-1} \) and \( B = 0.5 \) tesla). Embedding the volume of argon into a magnetic field should therefore not alter the imaging properties of the detector and the measurement of the bending of charged hadrons or penetrating muons would allow a precise determination of the momentum and a determination of their charge.

The required magnetic field for charge discrimination for a path \( x \) in LAr [9] is given by the bending \( b \) (\( b \equiv 4 \) times the sagitta):

\[
b \approx \frac{x^2}{2R} = \frac{0.3B(\text{tesla})(x(\text{m}))}{2p(\text{GeV})} ,
\]

where \( R \) is the radius of curvature of the charged track due to the effect of the magnetic field, \( p \) is the momentum of the track and \( B \) the magnetic field strength. The multiple scattering contribution is

\[
MS \approx \frac{0.02(x(\text{m}))^{3/2}}{p(\text{GeV})}.
\]

At low momenta, we can safely neglect the contribution from the position measurement error given the readout pitch and drift time resolution. The momentum determination resolution is then given by

\[
\frac{\Delta p}{p} \approx \frac{0.13}{B(\text{tesla})(x(\text{m}))^{1/2}}
\]

and the statistical significance for charge separation can be written as (\( b^{\pm} \) are the bending for positive and negative charges):

\[
\sigma \approx \frac{b^{+} - b^{-}}{MS} \approx \frac{2b}{MS} \approx 15B(\text{tesla})(x(\text{m}))^{1/2}.
\]

For example, with a field of 0.55 tesla, the charge of tracks of 10 cm can be separated at 2.6\( \sigma \). The requirement for a 3\( \sigma \) charge discrimination can be written as: \( b^{+} - b^{-} = 2b > 3MS \), which implies a field strength

\[
B \geq \frac{0.2(\text{tesla})}{\sqrt{x(\text{m})}}.
\]

For long penetrating tracks like muons, a field of 0.1 tesla allows us to discriminate the charge for tracks longer than 4 m. This corresponds for example to a muon momentum threshold of 800 MeV \( c^{-1} \). Hence, performances are very good, even at very low momenta. Unlike muons or hadrons, the early showering of electrons makes their charge identification difficult. The track-length usable for charge discrimination is limited to a few radiation lengths after which the showers make the recognition of the parent electron more difficult. In practice, charge discrimination is possible for high fields \( x = 1X_0 \rightarrow B > 0.5 \) tesla, \( x = 2X_0 \rightarrow B > 0.4 \) tesla, \( x = 3X_0 \rightarrow B > 0.3 \) tesla. From simulations, we found that the determination of the charge of electrons of energy in the range between 1 and 5 GeV is feasible with good purity, provided the field has a strength in the range of 1 tesla. Preliminary estimates show that these electrons exhibit an average curvature sufficient to have electron charge discrimination with an efficiency of 20% for a contamination with the wrong charge of less than 1% [10]. Further studies are on-going.
An R&D programme to investigate an LAr TPC in a magnetic field was initiated. The goal was to study the drift properties of free electrons in LAr in the presence of a magnetic field and to prove that the imaging capabilities are not affected. The test programme included (1) checking the basic imaging in the $B$-field, (2) measuring traversing and stopping muons, (3) test charge discrimination, and (4) check Lorentz angle. We report here on preliminary results obtained. A complete report is in preparation [12].

3. Experimental setup

The experimental setup (see figure 1) was custom built for this test.

We first designed and assembled a LAr TPC with a width of 300 mm, a height of 150 mm and a maximal drift length of 150 mm (see figure 2). Its dimensions were chosen to fit in the recycled SINDRUM I magnet, which allows us to test the chamber in a maximal field of 0.55 tesla. At the maximal field, the dc current is 850 A corresponding to a power consumption of 220 kW. The electrical power and the water cooling circuit necessary to operate the magnet in the laboratory had to be specially installed by ETH.

The cryostat is made of three concentrical cylinders: the innermost with a diameter of 250 mm contains the purified LAr with the drift chamber; the second cylinder is a LN$_2$ bath kept under an absolute pressure of 2.7 bar in order not to freeze out the LAr at about 1 bar, it is wrapped with 25 layers of superinsulation; the outermost cylinder is for the insulation vacuum.

The drift chamber consists of a rectangular cathode, 27 field shaping electrodes spaced 5 mm and the three detector planes. The first two detector planes are wire chambers with the wires oriented at ±60° to the vertical; the stainless steel wires have a diameter of 100 µm and a pitch of 2 mm. The wire chambers are operated at potentials such that they are transparent to the drifting electrons and only pick up an induced signal from the electron cloud passing the planes. The third plane is a printed circuit board with horizontal strips with a width of 1 mm and a pitch of 2 mm on which the drift electrons are collected. The wires and the strips are connected by 3 m long twisted pair cables to the feedthroughs on a flange, from the feedthroughs the signals are connected through 20 cm cables to the analogue boards (CAEN-V791) of the ICARUS readout electronics; the VME-like analogue board contains the low-noise preamplifiers for 32 channels and four multiplexed 10 bit FADC running at 20 MHz; the digitized data of two channels (21 bits including a control bit) are sent to a serial link at a rate of 40 MHz; each wire (strip) is sampled with 2.5 MHz. The readout electronics works as a continuous wave form digitizer: the digitized data are stored in a buffer, large enough to contain the data of a time interval of about 1 ms for each channel; the maximal drift time during this run was about 150 µs. When a trigger occurs, the filling of the buffer is stopped and the data are transferred to a PCI card in a PC, the PCI card is read out with a LabView program. A high voltage up to a maximal value of 22.5 kV is applied to the cathode and is connected through a resistor chain to the field shaping electrodes in order to produce a homogeneous electric drift field (horizontal and perpendicular to the solenoid axis).

There were two different triggers used: to trigger on cosmic ray muons passing through the magnet, plastic scintillators mounted on top and at the bottom of the magnet were used (see figure 1). The trigger counters also define the time $t_0$ of the event, needed to determine the drift

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Figure 1. Cut through the magnet with the LAr cryostat containing the drift chamber. The cryostat consists of three cylinders: the purified LAr container (red), the LN$_2$ bath (blue) and the vacuum insulation (green).

Figure 2. Left: cut through the drift chamber; and right, view into the assembled drift chamber with the cathode plate removed.

time from the chamber signals. The sum-output from the chamber signals allows us to trigger on low-energy events, as e.g. muons stopping in the chamber. In this case, the scintillators on the top of the chamber are used to define the $t_0$.

4. Results

In November 2004 the setup was ready for a first test. Before filling with LAr, the cylinder containing the drift chamber was pumped for four weeks; the final vacuum was better than
$5 \times 10^{-6}$ mbar. After cooling down for a few days with LN$_2$, the cylinder was filled through a purification cartridge with LAr; the same LAr filling was used for all the three weeks of data taking, without recirculating it through the purification cartridge. By starting the tests without magnetic field and triggering with the scintillator counters, clean cosmic ray tracks were immediately observed at a drift field of 500 V cm$^{-1}$. About 100 passing-through muons per hour were stored. From the observation of a decreasing collected drift charge with increasing drift time, the mean lifetime of the free electrons in LAr was estimated to be about 100 $\mu$s; it did not decrease significantly during the whole period of the run.

After a few days of commissioning, the magnetic field was turned on to the maximal value of 0.55 tesla. The signal-to-noise ratio of the chamber signals did not change significantly with the magnet on. Figure 3 shows the raw data (from the collection plane) of events with the magnetic

**Figure 3.** Eight examples of real events collected with the LAr TPC prototype immersed in a magnetic field of 0.55 tesla. The horizontal axes correspond to the time coordinate and the vertical axes are the wire coordinate; the full scale of both corresponds to 150 mm.
field turned on and with a drift field of 300 V cm\(^{-1}\); the intensity of the black colour is a measure of the collected charge. The horizontal axis corresponds to the drift time and the vertical axis to the wire number. The figures show the two-dimensional projection of tracks in the plane perpendicular to the magnetic field. Combining clusters with equal drift time from two (or three) planes allows the three-dimensional reconstruction of the track \cite{12}. These events are interpreted as cosmic muons either crossing or stopping and then decaying in the detector. Delta-rays or converted e\(^+\)e\(^-\)-pairs are also easily identifiable.

5. Conclusions

We have built a small LAr test TPC and operated it for the first time in a magnetic field (0.55 tesla) perpendicular to the electric drift field. The quality of cosmic ray tracks is not significantly decreased with the \(B\)-field turned on. The setup will be used to study the drift properties of electrons in LAr in a magnetic field and a measurement of the Lorentz angle is foreseen. A complete description of this work is in preparation \cite{12}. Combining the excellent imaging and calorimetric properties of a LAr TPC with a magnetic field opens new experimental possibilities. The magnetic bending of charged particles allows the momentum determination also for particles leaving the sensitive volume and the determination of the sign of the electric charge. The latter feature is a must in future neutrino experiments searching for CP-violating effects in the lepton sector.

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