

## The ICARUS R & D program and results

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The 3 ton liquid-argon time-projection chamber for the ICARUS project has been in operation since May 1991 collecting events from cosmic rays and monocromatic gamma ray source. Recent results are reported as well as an overview of the possible physics applications of this promising technique.

### 1. Introduction

A liquid-argon time-projection chamber (LAR-TPC) working as an electronic bubble chamber, continually sensitive, self-triggering, able to provide 3-D imaging of any ionizing event together with a good calorimetric response was first proposed by Rubbia in 1977 [1]. In order to verify the feasibility of such a detector, the ICARUS collaboration started in 1985 an intensive R&D program aiming to solve the main technological problems:

- 1) the liquid-argon purity that has to be kept at the level of 0.1 ppb of electro-negative molecules to allow the ionization electrons for long drift distances;
- 2) the extreme cleanliness of the material employed in the construction of the detector and the complete

reliability of the feed-throughs between pure argon and out-side world to avoid contamination due to degassing or leaks;

- 3) the realization of wire chambers able to perform a nondestructive readout (in order to get a 3-D image of the event) made of several wire planes with few mm pitch; this requires high precision, very reliable mechanics and very good knowledge of the electric field in the detector;

- 4) the development of very low noise preamplifiers to get a good signal to noise ratio.

The very satisfactory results obtained on small scale tests [2–4] allowed us to start in 1989 the construction of a 3 ton prototype [5] which is presently working at CERN under stable conditions without interruptions since May 1991.

The step from small to large volumes has been made possible by:

a) the argon purification performed in gas phase with industrial methods with special care for the cleaning of the materials that come in contact with the purified argon [4];

b) the use of a recirculation system that purifies continually the gas due to the heat leakage of the dewar and liquefies it back into the detector. This inhibits the diffusion inside the liquid of electro-negative impurities produced by degassing of materials in the high temperature region of the detector;

c) the use of signal feed-throughs made on vetronite support with the technique of the printed circuit board and welding each pin on it.

## 2. General features

The 3 ton detector configuration is well described in our proposal [5]. Here we want to remind the following aspects.

a) The LAr is contained in a stainless steel cryogenic vessel. The detector set is suspended from the top flange together with all the service elements (heat exchanger, purity monitor, level and pressure indicators). The active volume, defined by the wire chamber and the field shaping electrodes, is split into two independent semi-cylindrical sections (fig. 1).

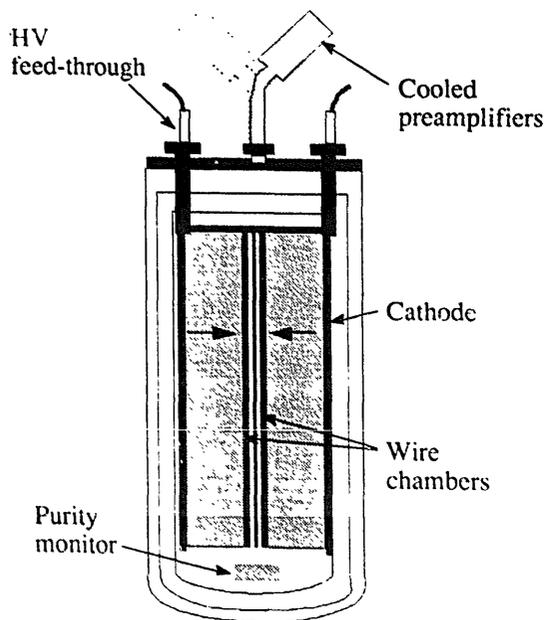


Fig. 1. LAr-TPC body: the active volume is split into two independent semi-cylindrical sections. The drift volume is defined by the cathode at one end, the wire chamber at the other; field shaping rings are used to avoid electric field distortions in the drift region due to the walls of the dewar.

b) Each section is faced by a wire chamber that covers a surface of  $2.4 \times 0.9 \text{ m}^2$  and consists of three parallel grids. Drifting electrons go successively through the following wire planes:

- 1) a plane with the function of screen transparent to the electrons;
- 2) a sense wire plane where the electrons give an induction signal (again completely transparent);
- 3) a plane with the wires perpendicular to the previous ones where the charge is collected.

The pitch of each sense wire is 2 mm. The separation between planes is also 2 mm. The maximum drift path is 42 cm. The chambers are constituted of 3600 vertical wires (stainless steel,  $100 \mu\text{s}$  diameter) 2.4 m long and 4800 horizontal wires 0.9 m long. The signal cables are Kapton flat cables 3.5 m long inside the detector with low capacitance ( $40 \text{ pF/m}$ ). The 2100 signal feed-through are grouped in eight flanges located on top of the dewar. Low noise pre-amplifiers are placed inside cooled boxes mounted directly on top of the signal feed-through flanges.

c) The electron lifetime in LAr inside the detector is monitored continually by measuring the attenuation of an electron cloud photo-produced by a laser UV pulse impinging on a metallic cathode and moving in a small drift gap [4]. A lifetime well above 2.5 ms (corresponding to an attenuation length of more than 5 m) has been measured for several months. This stability is mainly due to the recirculation system mentioned above.

d) The detector also exhibits the important feature of being self-triggering. This has been obtained exploiting the prompt current signal, proportional to the total charge of the track moving in the drift space, induced on the electrodes facing the drift volume.

## 3. Detector response

A large amount of data have been collected with the 3 ton prototype using cosmic rays and 6 MeV monochromatic gamma rays to study the response of the detector in a wide range of energy from few MeV to several GeV. An event that illustrates very well the peculiar characteristics of the detector is shown in fig. 2: a 210 MeV cosmic muon stopping with electron decay. The event is seen in two orthogonal views: the induction plane (nondestructive readout) and the collection plane (destructive readout) with the sense wire direction at  $90^\circ$  in one plane with respect to the other and with the drift time (third orthogonal coordinate) in common to both of them; the last feature together with the charge deposited along the tracks allows a 3-D reconstruction. The signal to noise ratio is  $\approx 6$  for the induction wires and  $\approx 10$  for the collection ones. The electric field in the drift volume is  $355 \text{ V/cm}$  corre-

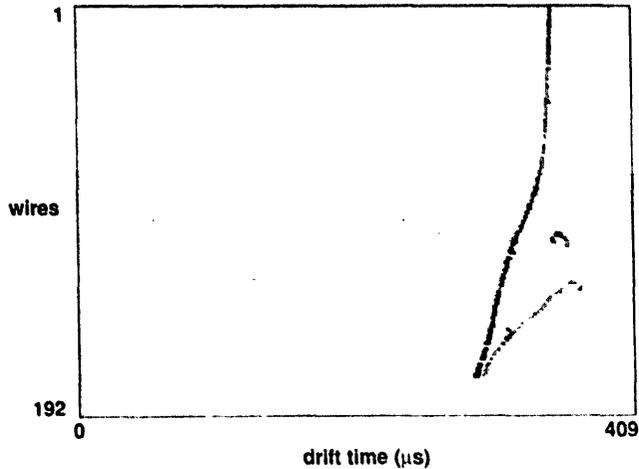


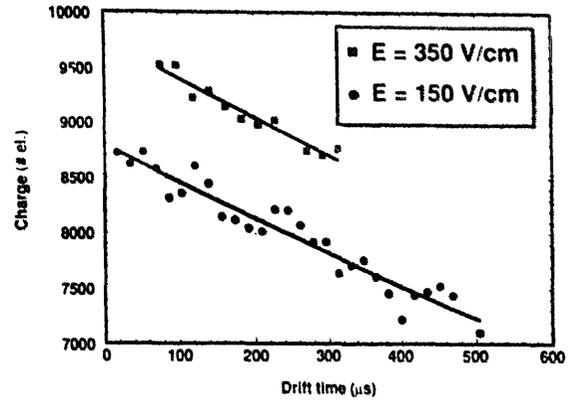
Fig. 2. Plane view (collection wires) of a track produced by a stopping muon and the successive electron decay seen in a window of  $40 \times 40 \text{ cm}^2$ . Increasing grey intensity is proportional to the energy deposited on each wire. The gap between the muon end point and the electron is due to the muon lifetime.

sponding to an electron drift velocity of  $1.38 \text{ mm}/\mu\text{s}$ . The sampling time is 200 ns. It proves, with the many others we are collecting, that the LAr-TPC works as an electromagnetic calorimeter with high granularity ( $2 \times 2 \times 2 \text{ mm}^3$  cell) and low electronic noise (equivalent to 25 keV); in fact this detector allows to measure the  $dE/dx$  along the track with the increase of ionization near the decay, the exact point of the decay and the track of the electron whose total energy is about 21 MeV.

From the analysis of passing-through cosmic muons it has been possible to extract several parameters characterizing the detector: electron lifetime, free electron yield, electron diffusion, energy resolution, space resolutions.

The electron lifetime value given by the purity monitor has been checked by means of cosmic ray muons crossing vertically the drift volume: the distribution of the charge deposited along the tracks is measured for each drift time slice with a beginning of  $17 \mu\text{s}$ , the most probable value is extracted and plotted as a function of the drift time (fig. 3); an exponential fit to this plot gives directly the free electron yield and the electron lifetime. This measure has been repeatedly performed giving a stable value of lifetime of about 2.5 ms, in agreement with the data from the purity monitor.

Varying the electric field applied in the drift region from 150 to 350 V/cm we measured a free electron yield of 0.49 and 0.55 respectively. These data are slightly different from other experimental results, especially for 150 V/cm where we have a free electron yield  $\approx 20\%$  higher than that found in ref. [6]. This is probably because we use minimum ionizing particles



E.F. (V/cm)	Lifetime ( $\mu\text{s}$ )	Free charge (# el.)
350	2584	9775
150	2540	8800

Fig. 3. Released charge vs the drift time  $T$  measured from high energy crossing muons at 350 and 150 V/cm. The exponential fit gives directly the lifetime. The extrapolation at  $T = 0$  gives the free electron yield.

(crossing muons) instead of low energy electrons ( $\leq 1 \text{ MeV}$ ) where the end point recombination acts largely to reduce the overall electron yield. A more extensive scan as a function of the electric field is under way for a careful measure of the electron-ion recombination at low fields.

The energy resolution for minimum ionizing particles can be extracted from the width of the charge distribution over one wire which is due both to the intrinsic fluctuations and to the electronic noise (fig.4):

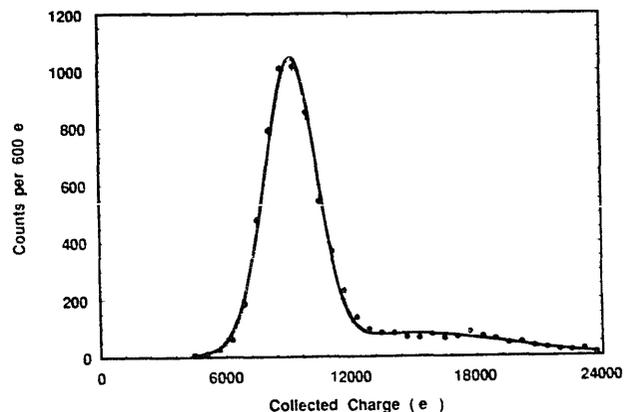


Fig. 4. Distribution of the collected charge. The width of the distribution is dominated by the electronic noise (900 electrons). The second peak is produced by low energy delta rays superimposed to the main track.

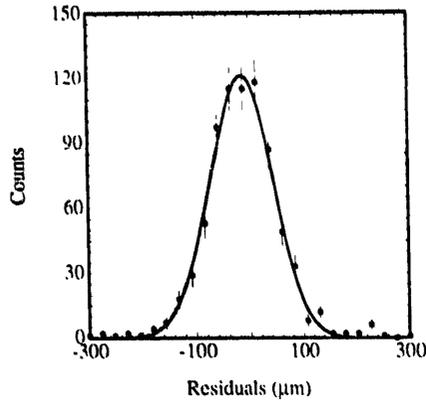


Fig. 5. Distribution of the residual to a linear fit of the measured coordinates along the drift direction (r.m.s. =  $58 \mu\text{m}$ ).

the measured value of  $\approx 900$  electrons states the electronic noise dominates, limiting the energy resolution to  $\approx 10\%$  for  $380 \text{ keV}$  of deposited energy.

From the residuals to a linear fit for the coordinate along the drift direction an r.m.s. spatial resolution of  $300 \mu\text{m}$  has been found roughly independent from the electric field. In a dedicated test on a small scale with the preamplifiers immersed in LAr and a low input capacitance we got a signal-to-noise ratio of  $S/N \approx 20$  and a spatial resolution of  $58 \mu\text{m}$  [7] (fig. 5).

The analysis of the signal risetime allows the determination of the longitudinal diffusion as a function of the drift time. The risetime (RT) is proportional to the spread ( $\sigma$ ) of the signal due to diffusion and  $\sigma^2 = 2Dt$  (where  $D$  is the longitudinal diffusion coefficient and  $t$  is the drift time), hence a linear fit of  $RT^2$  versus drift time gives directly  $D$ . The data taken at  $250$  and  $350 \text{ V/cm}$ , shown in fig. 6, give a value of  $D = 6.0 \pm 0.2 \text{ cm}^2/\text{s}$  in agreement with the calculated value if one takes into account the Coulomb repulsion of the electrons along the track [8]. At lower fields the measure

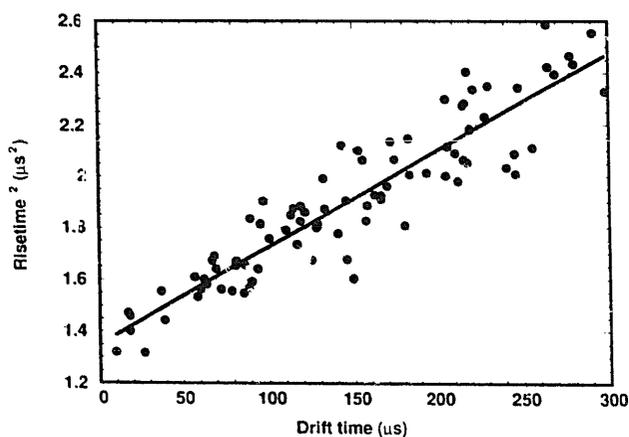


Fig. 6. Squared rise time vs the drift time at  $350 \text{ V/cm}$ . The fit of the data gives a diffusion coefficient  $D = 6.0 \pm 0.2$ .

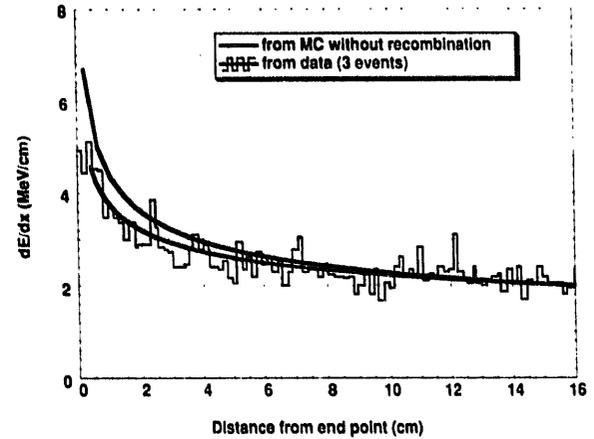


Fig. 7. Collected charge vs the distance to the decay point for an atmospheric stopping muon.

becomes more difficult because the finite lifetime and the higher recombination dramatically reduce the  $S/N$  ratio.

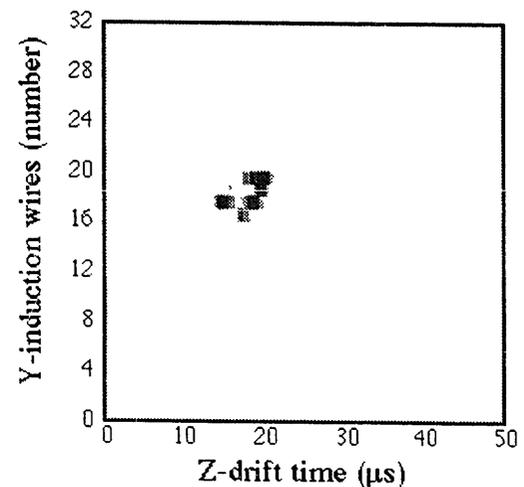
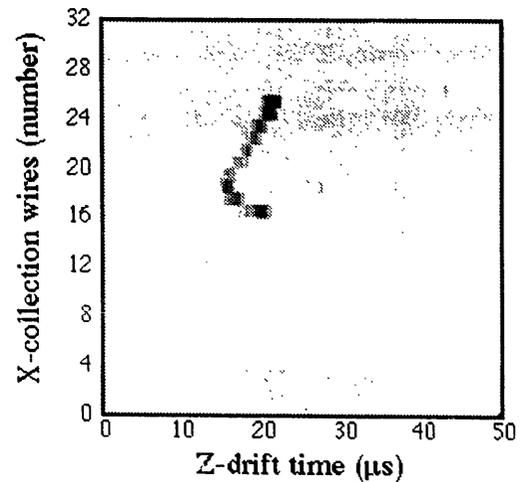


Fig. 8. Two orthogonal view of an isolated pair produced inside the detector by a  $6 \text{ MeV}$  gamma.

From the results presented above turns out that a certain amount of technical work has to be done in order to improve the S/N ratio. This can be accomplished by connecting the preamplifiers directly to the wires inside the LAr thus reducing the input capacitance due to the cables and the intrinsic thermal noise.

At present we are working on the analysis on stopping muons to extract informations on the detector capability of separate particles by  $dE/dx$  vs range and on the recombination dependence on the  $dE/dx$ . A preliminary result is shown in fig. 7.

The next step will be implementation of a monochromatic gamma source in order to study the detector response to low energy electron tracks also in relation to the possibility to use this kind of detector for the study of the solar neutrino problem. In this context it is crucial to exploit the self triggering capabilities of our device. Recent test demonstrated that we can trigger on isolated events with energy down to  $\approx 1$  MeV just using the integrated signal coming from the collection wires; in fig. 8 we show, as an example, an isolated pair produced inside the detector by a 6 MeV gamma.

In larger volume detectors both hardware and software improvements must be applied to achieve data reduction (up to now the entire volume has been recorded, for a total of nearly 600 kbytes per event). The self-triggering capability together with a segmentation of the electrodes provides a useful way to data reduction because it selects a window both in time and in space where to look for an event above a given threshold. Optimized algorithms that perform baseline normalization and peak detection can be embedded on the read-out software in order to get on-line determination of the "region of interest" to be stored for the off-line analysis.

#### 4. Conclusions

We believe that a novel detector is now available for physics both in underground laboratories and at accelerator/colliders: the liquid-argon image chamber.

This detector provides electronic bubble-chamber quality images with millimeter size "bubbles". It is continually sensitive, it can be built with high sensitivity mass and it is self-triggering. Spatial resolution is in the range of 300  $\mu\text{m}$ . Energy resolution of  $\approx 3\%$  at few

MeV has been indirectly estimated. Ionization and range measurements provide particle identification. The high granularity enables measurement of particle direction. All these properties make the LAr-TPC a superb homogeneous detector for contained events and for vertex identification. In fact the detector is essentially bias free and it can detect a very broad class of events. We give here briefly a number of possible application keeping in mind that, like in a bubble-chamber, all kind of unexpected phenomena could be observable as well:

- 1) solar neutrinos at Gran Sasso,
- 2) proton decay at Gran Sasso,
- 3)  $\nu_\mu - \nu_e$  and  $\nu_\mu - \nu_\tau$  oscillation using CERN  $\nu$  beam,
- 4) atmospheric neutrinos,
- 5) neutrino burst from supernova collapses,
- 6) relic supernova neutrinos,
- 7) direct  $\nu_\tau$  detection at LHC.

The experience with the 3 ton prototype, equipped with complex mechanical and electrical apparatus immersed in the liquid and with hundreds of feed-throughs, has shown that the ultrapure liquid-argon technique is reliable even if some technical improvements are necessary:

- a) Liquid phase purification to speed up the filling of very large volumes.
- b) Development of low noise low temperature preamplifiers to increase the signal to noise ratio.
- c) Design of very large wire chambers mechanically reliable during the cooling to LAr temperature.
- d) Study of the best  $T=0$  system, especially optimized for solar neutrino search. The next R&D program will be mainly based on the above items.

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