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Section A

The ICARUS liquid argon TPC: a complete imaging device for particle physics

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1. Introduction

A liquid argon time projection chamber (LAr-TPC) working as an electronic bubblechamber, continuously 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 the following years experiments were undertaken to verify the feasibility of such a detector. It was soon realized that the main technological problems to be solved were:

1) the liquid argon purity that has to be kept at the level of 0.1 ppb of electronegative molecules to allow the ionization electrons for long drift distances;

2) the extreme cleanliness of the material employed in the contruction of the detector and the complete reliability of the feed-throughs between pure argon and outside world to avoid contamination due to degassing or leaks;

3) the realization of wire chambers able to perform a nondestrucitve read-out (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) development of very low noise preamplifiers to get a good signal to noise ratio.

All that was successfully achieved on small scale tests [2,3,4] when in 1989 the ICARUS collaboration presented a proposal [5] for the construction of a large scale prototype. At that time it was clear to us which difficulties we were going to face as well as the way to overcome them, namely to simplify as much as possible the chosen technical solutions.

At present a 3 tons complete detector is working at CERN under stable conditions from several months. This step from small to large volumes has been made possible by:

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

b) the use of a recirculation system that purifies continuously 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 electronegative 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.

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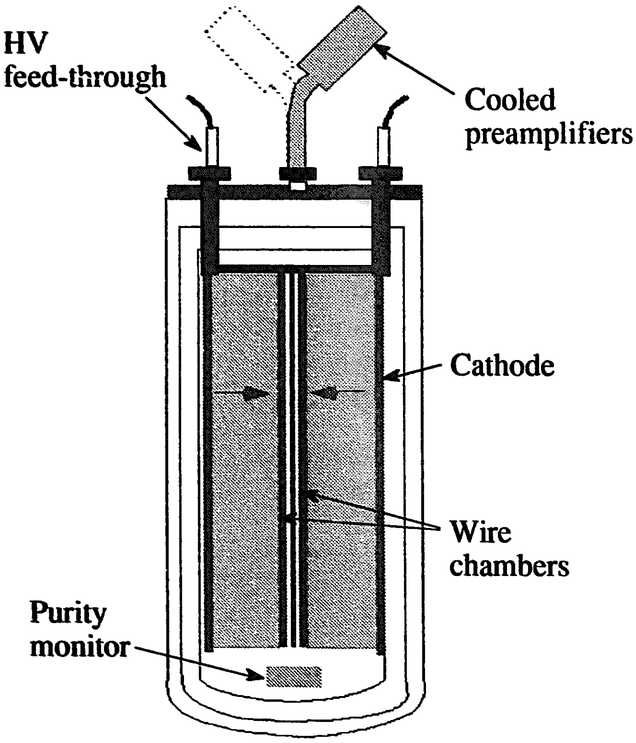

Fig. 1. LAr-TPC body: the active volume is split into two independent semi-cylindrical sections. The drift volume is defined by the cathode at one end, the wire chamber at the other; a series of field shaping rings is used to avoid electric field distortions in the drift region due to the walls of the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

a) The active volume is split into two independent semi-cylindrical sections, each one a mirror image of the other (fig. 1).

b) Each section is faced by a wire chamber that covers a surface of 2.4×0.9 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 if 42 cm. The chambers are constituted of 3600 vertical wires (stainless steel, 100 μs 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 pF/m). The 2100 signal feed-throughs are grouped in 8 flanges located on top of the dewar. Low noise pre-amplifiers are placed inside cooled boxes mounted directly on top of the signal feed-throughs flanges.

c) The electron lifetime in LAr inside the detector is monitored continually by mesauring 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]. Fig. 2 shows that the lifetime steadily increases during filling and reaches a stable value higher than 5 ms (corresponding to an attenuation length of more than 10 m). This result is mainly due to the recirculation system (fig. 3) 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.

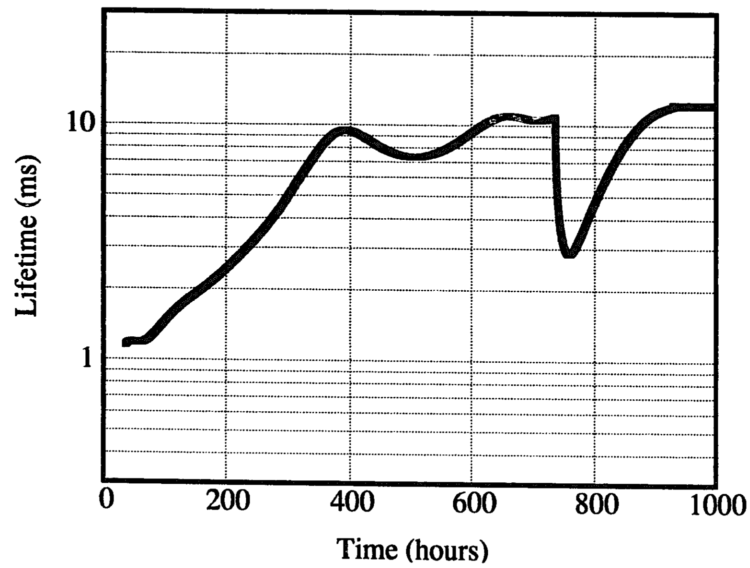

Fig. 2. Electron lifetime in LAr inside the 3 ton prototype as a function of the time. Liquefaction of ultrapure LAr into the dewar starts at $t = 0$ and lasts for 380 h; during that time interval lifetime keeps increasing and stabilizes at the end of liquefaction (5 ms). At $t = 730$ h the recirculation has been stopped during 10 h; the sudden decrease of the lifetime and the successive restoring to a very high value demonstrate the necessity of a continous purification.

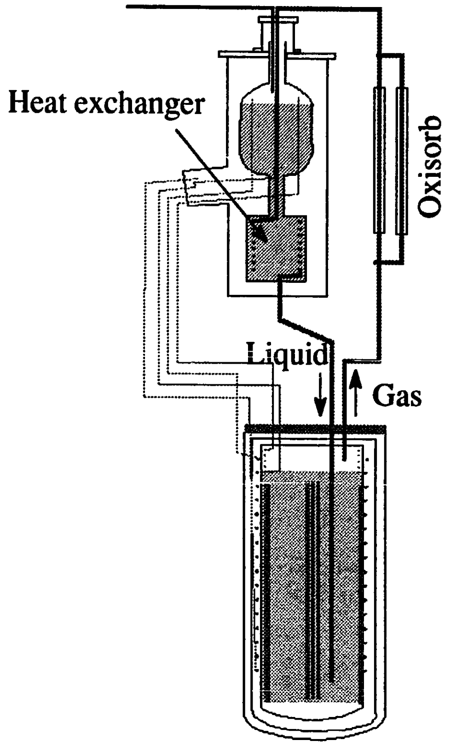

Fig. 3. Recirculation system (not in scale with respect to the dewar) including purifier units.

An event that illustrates very well the peculiar characteristics of the detector is shown in fig. 4: a 210 MeV cosmic muon stopping with electron decay. It proves, with the many others we are collecting, that the LAr-TPC works as an electromagnetic calorimeter with high granularity (222 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.

3. Detector response

A large amount of data have been collected both with a small LAr-TPC (8 l, 24 cm drift) in a beam and 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. As an example in fig. 5 we show a muon crossing the drift volume and producing a delta ray of 3 MeV. The event is seen in two orthogonal views: the induction plane (non-destructive read-out) and the collection plane (destructive read-out) with the sense wire direction at 90 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 6 for the induction wires and 10 for the collection ones. The electric field in the drift volume is 330 V/cm corresponding to an electron drift velocity of 1.25 mm/μs. The sampling time is 200 ns. In fig. 6 we present a two dimensional view of a cosmic ray shower in a window of 4040 cm^2.

From the analysis of 5 GeV pions and muons crossing the 24 cm TPC [3] it has been possible to extract a high energy Landau distribution (fig. 7). From the residual to a linear fit for the coordinate along the drift direction an rms spatial resolution of 58 μm has been found for $S/N = 10$ (fig. 8) [6]. By isolating from high energy tracks the delta rays it has been possible to extract informations such as dE/dx, recombination, diffusion, etc. for low energy electrons. This informa-

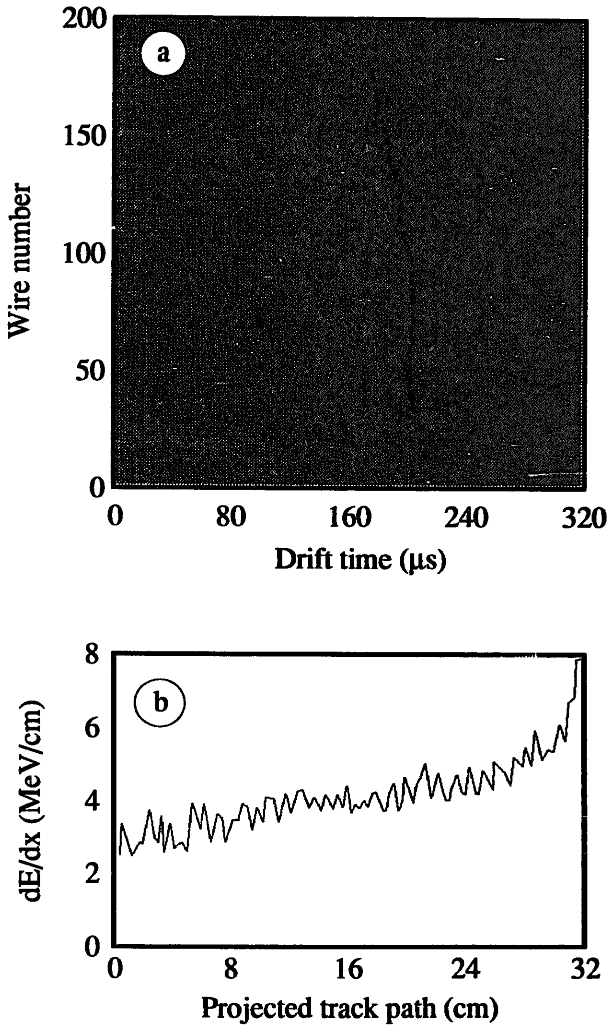

Fig. 4. (a) Muon stopping and successive electron decay as seen by the collection plane in a window of 4040 cm^2 (the maximum allowed by the number of read-out channels available at present). Increasing grey intensity is proportional to the energy deposited on each wire. The total energy deposited along the muon track is 210 MeV and (b) it is shown as dE/dx vs track path; the electron energy is 21 MeV.

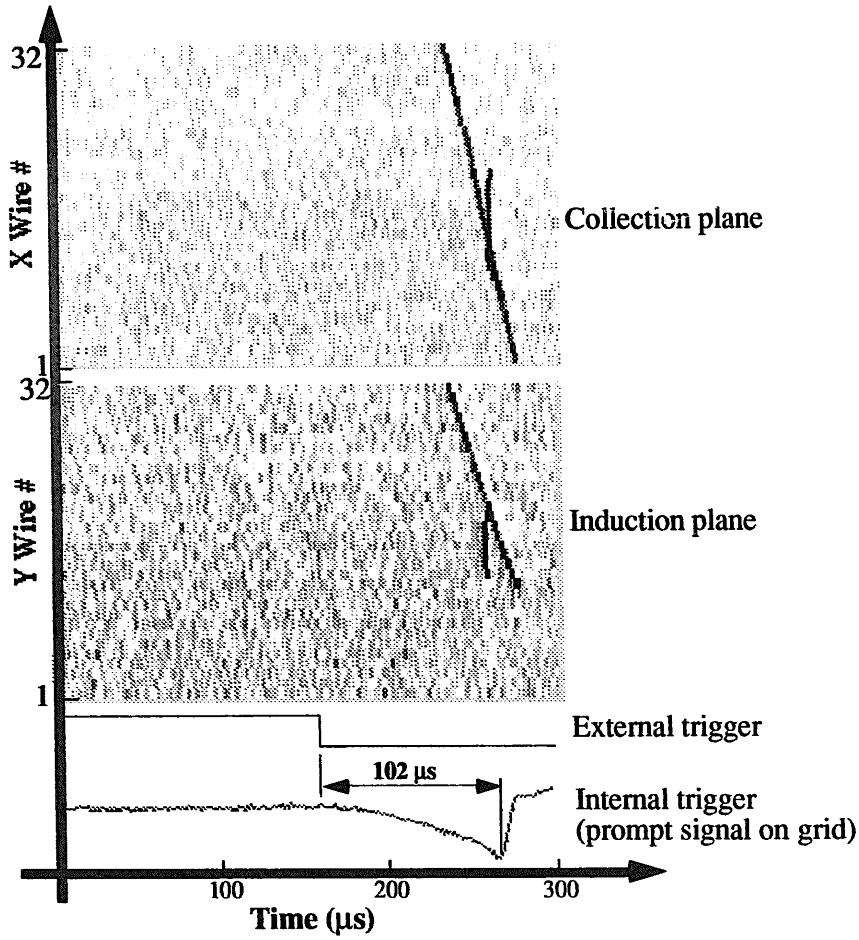

Fig. 5. Two orthogonal views of a cosmic muon crossing the drift volume and producing a delta ray of 3 MeV.

tion has been integrated into a MC program, based on GEANT, used to generate single electrons and photons; from these data the energy resolution for electrons and photons in the few MeV energy range has been estimated to be in the range of 3%. Identification of charged particles stopping inside the detector is obtained comparing the range with the dE/dx along

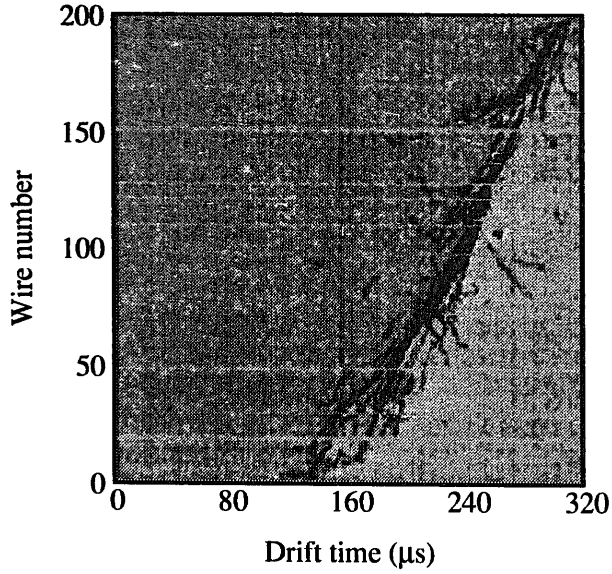

Fig. 6. Cosmic ray shower. The detector configuration is as in fig. 4.

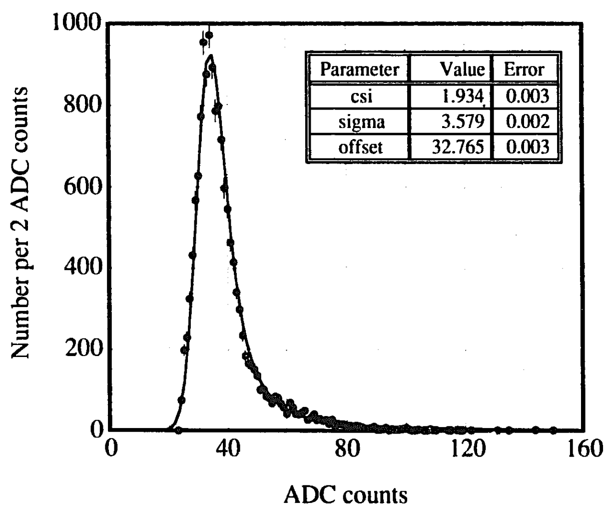

Fig. 7. Landau distribution obtained with a 5 GeV pion beam crossing the 24 cm TPC.

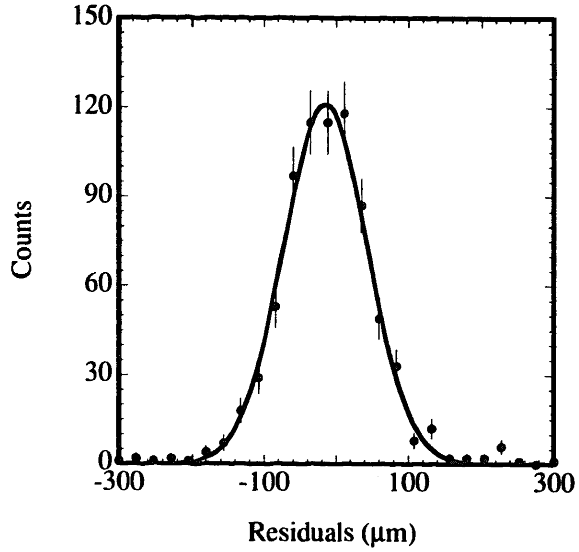

Fig. 8. Distribution of the residual to a linear fit of the measured coordinates along beam tracks in the 24 cm TPC.

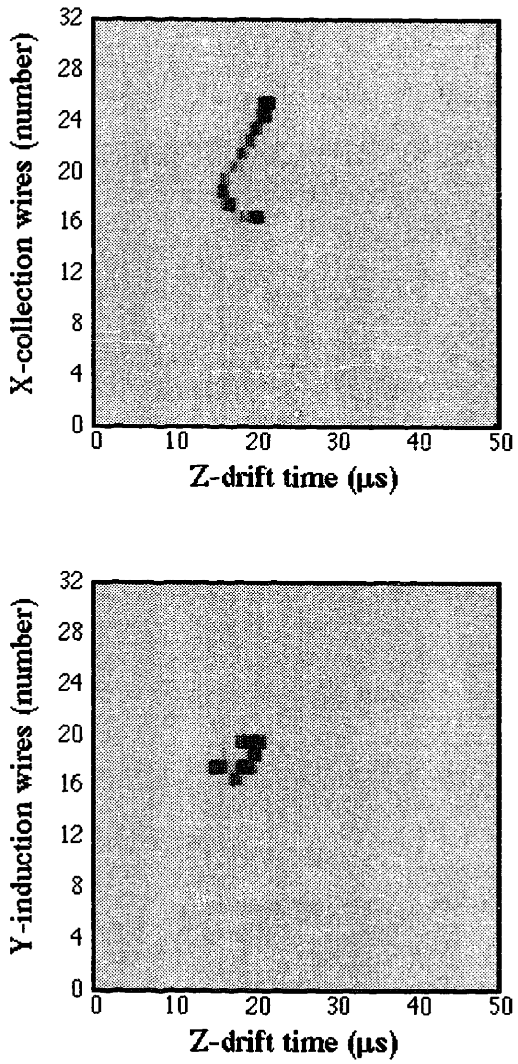

Fig. 9. Two orthogonal views of an isolated pair produced inside the detector by a 6 MeV gamma.

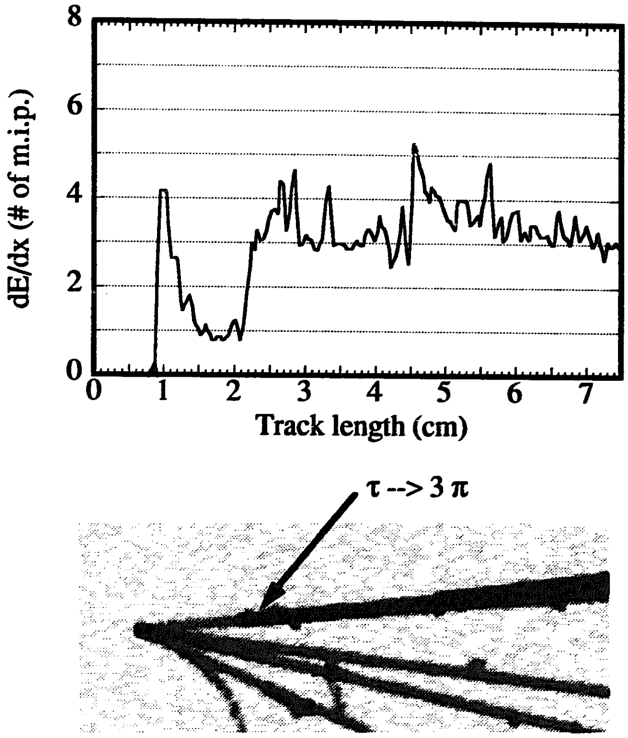

Fig. 10. (top) Simulation of a ν_τ CC interaction followed by τ decaying in 3π. Detection technique consists in identifying the secondary vertex by the sudden increase in the dE/dx ($+2$ minimum ionizion particles) exiting the main vertex (bottom). The charmed particle background could be suppressed by requiring no single muon/electron from the main vertex. The background due to pair production along the track can be reduced exploiting the different hadron/electron energy loss development in the first 15 cm of the event (before shower take place).

the track; the expected π/μ separation for kinetic energies around 100 MeV is 1%.

All the data taken with the 3 ton prototype exploit the self-triggering capability of the detector. In fig. 5 the signal induced on the screening grid is visible: the fast component is used to trigger the data acquisition, the slow one gives indication on the absolute position inside the detector where the ionizing event has occurred. At present we are able to trigger on isolated events with energy down to 1 MeV; in fig. 9 we show, as an example, an isolated pair produced inside the detector by a 6 MeV gamma. In a large volume detector 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.

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.

The experience with the 3 ton prototype, equipped with complex mechanical and electrical apparata immersed in the liquid and with hundreds of feedthroughs, has shown that the ultrapure liquid argon technique is fully reliable since, after several months of continous operation, no degradation of the very high electron lifetime has been observed.

This detector provides electronic bubble-chamber quality images with millimeter size bubbles. It is continously sensitive, it can be built with high sensitive mass and it is self-triggering. Spatial resolution is in the range of 100 μm. Energy resolution of 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 homogenous detector for contained events and for vertex identification. Infact 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:

Solar neutrinos @ GRAN SASSO
Proton decay
CP violating interference @ DAΦNE
Direct ν_t detection at LHC (fig. 10)
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