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The Yale liquid argon time projection chamber

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Abstract. In this paper we give a thorough description of a liquid argon time projection chamber designed, built and operated at Yale. We present results from a calibration run where cosmic rays have been observed in the detector, a first in the US.

1. Introduction

Liquid argon time projection chambers (LAr TPC) are nearly optimal detectors for neutrino experiments looking for ν_e appearance in a ν_μ beam in the energy range 0.5 – 5 GeV. The LAr TPC technology has been proposed for the measurement of θ_{13} , CP violation in the neutrino sector and determination of the mass hierarchy (e.g. [1, 2, 3]), and to study the MiniBooNE low energy anomaly [4, 5]. The technique is equally promising for proton decay searches and astrophysical applications [6]. A LAr TPC for neutrino physics was first proposed in 1977 by Carlo Rubbia [7]. The ICARUS collaboration established a vigorous R&D program, which produced decisive steps in defining the technology and its applicability to particle physics (e.g. [8, 9, 10]).

Images taken in a LAr TPC are comparable in quality with pictures from bubble chambers. As it is the case in bubble chambers, events can be analyzed by reconstructing 3-momentum and particle type for each track in the event image, with a lower energy threshold of few MeV for electrons and few tens of MeV for protons. The particle type can be determined from measuring the energy loss along the track (dE/dx) or from topology (i.e. observing the decay products). The calorimetric performance of a LAr TPC ranges from good to excellent, depending on event energy and topology; for details, see the very descriptive experimental paper [10], and references therein.

Liquid argon has a density of 1.4 g/cm³, is fairly inexpensive (~ 1 USD/liter) and readily available in large amounts. This makes LAr an attractive option as active medium for very massive detectors (several tens of ktons), as required by most applications in contemporary neutrino physics. The TPC technology offers a practical way to image volumes as large as several thousands of cubic meters.

A staged program toward a very massive (50-100 kton) LAr TPC for neutrino physics is ongoing in the United States, following the recommendations of the Neutrino Scientific Assessment Group (NuSAG) in 2007 [11]. As part of this larger, comprehensive US effort, a LAr TPC has been developed at Yale starting in 2005. The detector was commissioned in early 2007, and cosmic ray tracks were imaged. This is the first LAr TPC prototype developed in the US to image tracks.

In this paper we give a detailed description of the experimental apparatus (Sec. 2), present results from the calibration runs (Sec. 3), and comment on foreseen developments (Sec. 4).

2. Description of the detector

A LAr TPC is a position sensitive liquid ionization chamber. When the LAr in the active volume is ionized by a charged particle, a number of free electrons, equal (on average) to the energy lost by the particle divided by the W-value, is produced in LAr. The W-value in LAr is 23.6 eV [12]. The ionization electrons drift under the action of a uniform electric field over the distance between the interaction point and the readout electrodes. In this TPC the maximum distance is 16 cm; over this distance, in a dense

medium as LAr, the lateral spread of the drifting charge due to diffusion is negligible. The drifting charge induces a signal on the readout electrodes, two parallel planes of wires in our case. Free electrons can attach to electronegative impurities and be lost in the drift region, drastically reducing the size of the induced signal. For this reason the concentration of electronegative impurities in the drift region has to be less than one part per billion. A first signal is induced on the wires immediately facing the drift region (*induction plane*). In this detector this wire plane also acts as a Frisch grid for the second plane (*collection plane*). The electric field between the two wire planes is at least twice the one in the drift region in order to have good transparency through the induction plane for the drifting charge. Only when the drifting electrons are past the induction plane is a signal induced on the collection plane. The field lines terminate on the collection wires, where the charge is collected. The wire number defines one spatial coordinate, therefore two wire planes provide two spatial coordinates, and the third spatial coordinate is measured by the drift time. The energy deposition is measured from the amplitude of the induced signal.

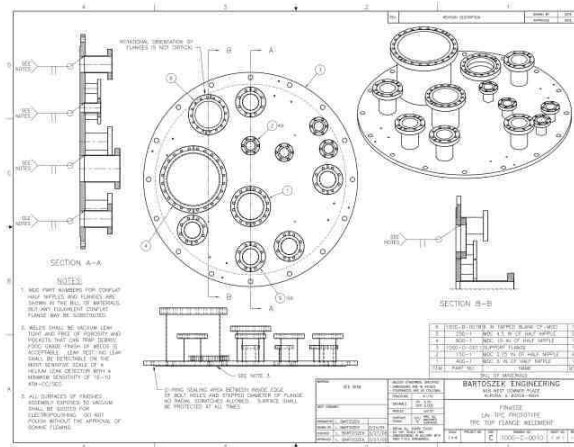


Figure 1. *Left:* Picture of the top flange, described in the text. *Right:* Top flange, technical drawing.

2.1. Cryogenics

The LAr TPC is housed in a cylindrical stainless steel vessel, 111 cm long with a diameter of 72.4 cm, for a total volume of about 460 l. The inner surface of the vessel has been

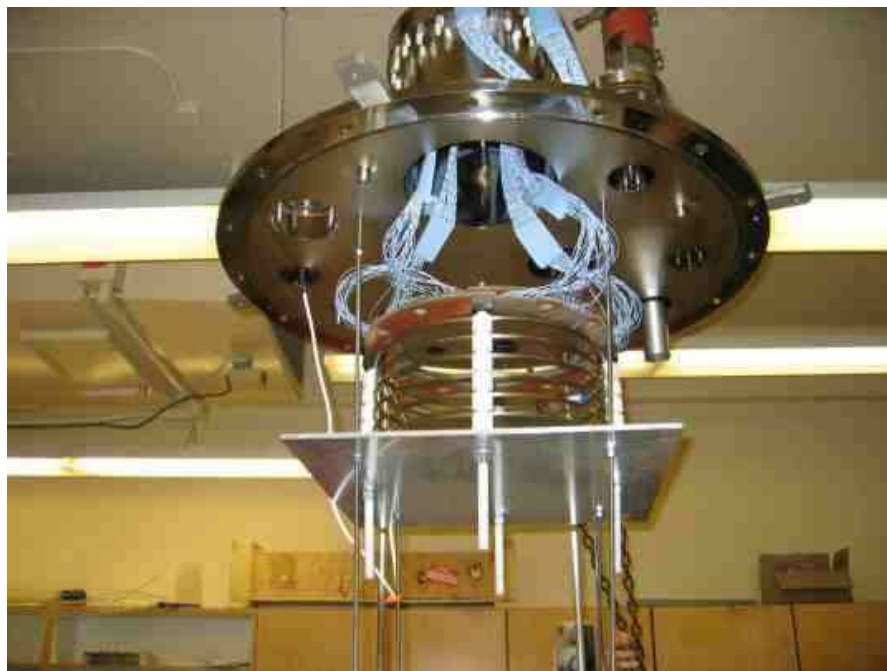


Figure 2. The TPC, fully cabled, hanging from the top flange.

electropolished. Prior to filling with ultra pure LAr, the vessel is evacuated to few 10^{-6} mbar at LAr temperature (87 K). The vessel is cooled to LAr temperature by an open bath filled with commercial, non-purified LAr. It takes about five hours to cool down the system and fill the inner vessel up to the level where the TPC structure is fully covered by LAr, equivalent to ~ 250 l of ultra-pure LAr. The total LAr consumption is $\sim 1,000$ l for a 24 hr long experiment, about half of it going directly to the open bath, and half through the purification system to the inner vessel.

The top flange of the TPC vessel (Fig. 1) houses several ports: feedthroughs for the TPC high-voltage, signal cables, test pulse and capacitive level meter, high voltage feedthrough and optical feedthrough for a purity monitor mounted inside the vessel, pumping line, filling line, relief valve, pressure gauges, and a window. All the seals on the top flange are either CF or VCR. The top flange itself is sealed using a Viton O-ring, therefore the system is not designed to be vacuum-tight at LAr temperature in steady state. The adopted filling procedure is to break the vacuum using ultra-pure cold Ar gas when the outer LAr open bath is about half full. Once in steady state the system runs at an overpressure of 0.3 atm ‡.

2.2. TPC and Electronics

The instrumented volume of the LAr TPC (Fig. 2) is a cylinder of 33 cm diameter and 16 cm tall. A schematic of the TPC is shown in Fig. 3. The field cage is made of 6 hollow stainless steel rings (6 mm diameter), separated by Teflon spacers, and

‡ The relief valve has been provided by H. Jostlein of FNAL.

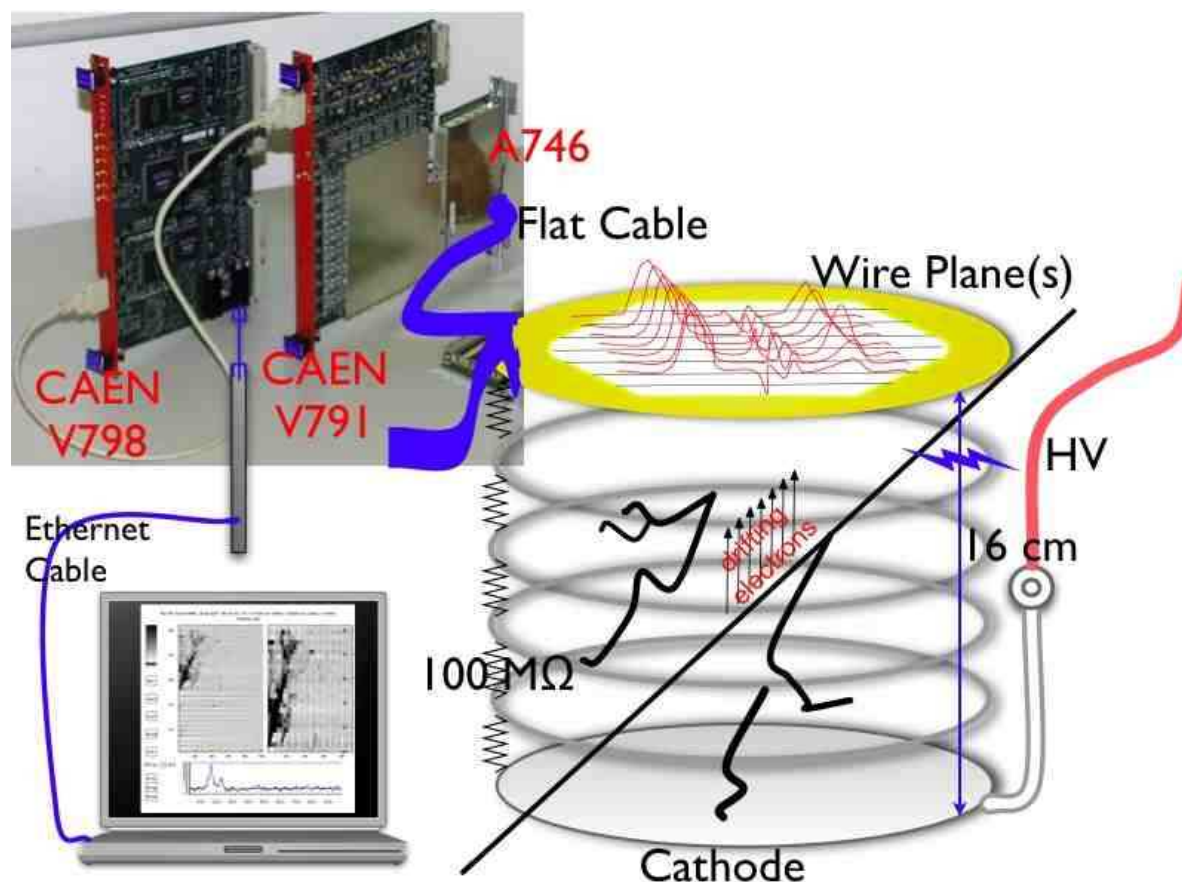


Figure 3. Schematic of the TPC readout and electronic chain, not-to-scale. (See text.)

electrically connected through a chain of $100\text{ M}\Omega$ resistors. There are two parallel readout wire planes of hexagonal shape with smooth edges. Each plane has 50 wires with a wire pitch of 5 mm. The longest wire is 26 cm long, the shortest 13 cm. The wires are soldered on a G-10 frame, 6 mm thick with a layer of etched copper on one side. The first wire plane, directly facing the drift region, acts as an induction plane, with the collection plane 6 mm behind it. The collection wires run at a 60 degree angle with respect to the induction wires. The induction plane was intended as a Frisch grid for the collection plane, and little care has been taken in decoupling it from the high-voltage chain. Nonetheless, it was connected to the readout chain. Flat cables are soldered to the wire planes and reach the readout electronics through a signal feedthrough §, which holds 512 channels. The readout electronics and data acquisition (DAQ) have been provided by the INFN-Padova / ICARUS group. A detailed description of these can be found in [10]. To summarize, the front-end electronics consists of three main modules:

- (i) a decoupling board (A746) mounted on the back side of a VME-like crate, which receives 32 analog signals and passes them to the analog board;

§ From INFN-Padova / ICARUS.

- (ii) an analog board (CAEN V791), housed in the VME-like crate, with 32 amplifiers, which also performs multiplexing and the analog-to-digital conversion (10 bits, 40 MHz). The front-end preamplifiers have a short time constant (1.6 μ s) and behaves as an approximate differentiator;
- (iii) a digital board (CAEN V798), in a separate VME crate. Each pair of analog/digital boards is connected through a serial link, and the data are then transferred through the VME bus.

Each board has 32 channels; in order to match the configuration of our TPC, where the wires are grouped in bunches of 25, 2 bunches per plane, we send the signal from 25 wires to each board, leaving the remaining 7 channels floating.

2.3. Liquid Ar purification

The necessity to drift free electrons in LAr over distances ranging from tens of centimeters to several meters sets very stringent requirements on the purity of LAr. For an applied electric field of 100V/cm the drift velocity of electrons in LAr is 0.5 mm/ μ s, therefore an electron lifetime of several hundreds μ s is required for a drift region with a depth of 10 cm. This corresponds to a contamination of O₂-equivalent impurities at the level of few tens of parts per trillion (cf. few parts per million in commercially available ultra-pure LAr). The ICARUS collaboration has demonstrated that Ar can be purified to this level in liquid phase, with high throughput [13]. The technology for the filters used to purify LAr for the Yale LAr TPC has been developed at FNAL [14]. A detailed paper is in preparation. The filter is made of a copper alumina catalyst ||, packaged in a CF nipple with sinterized steel caps; the filter used at Yale measures 55 cm long, with a diameter of 7 cm. Once exhausted, the filters can be regenerated in house, heating them to 250° C while flushing with a mixture of Ar gas and hydrogen (with a ratio of Ar:H of 95:5). The filter used at Yale has been provided by the FNAL group, and is routinely regenerated at Yale. Before introducing purified LAr the filling lines are kept under vacuum, and the first ten liters of LAr passed through the filter are dumped in a separate vessel, to reduce the risk of contamination. Commercial grade LAr, with an O₂ contamination of few ppm, is purified with a single pass through the filter, at a rate of \sim 60 l/hr. A purity monitor ¶ was mounted underneath the TPC. This has allowed quick and reliable measurements of the electron lifetime independently of the TPC operation. A loss of drifting charge due to attachment to impurities of less than 40% over a drift time of 0.5 ms (equivalent to an electron lifetime better than 1 ms) has been repeatedly measured in the TPC vessel, stable over a period of 24 hours without recirculation. Using the same filter in two back-to-back experiments, without regeneration, we have noticed a drastic deterioration in the purity during the second experiment. This may be an indication that the filter itself is exhausted after purifying 500 to 700 l of commercial Ar. The issue is currently being addressed in a more systematic way.

|| Engelhard Copper Alumina catalyst CU-0226S

¶ Built according to the ICARUS design [10] and provided by the FNAL group

3. Results

The LAr TPC has been tested on readily available cosmic rays. During data taking the electric field in the drift region was 100 V/cm, and 300 V/cm between the induction and the collection planes. The data acquisition was triggered on the sum coincidence of hits on one board (25 channels) of the collection plane. The drift velocity in LAr at 100 V/cm is ~ 0.5 mm/ μ s, with a maximum drift time of approximately 320 μ s.

Some events recorded during a cosmic ray run are shown in Fig. 4, 5, 6, 7 and 8.

- (i) *Fig. 4:* Display of an electromagnetic shower (collection view). In this and in all the figures shown here, the 2D view displays wire number *vs.* drift time (in units of 0.4 μ s). The gray-scale is linear with the amplitude of the signal on each wire. On the left is the full 2D image of the fiducial volume. On the right is the zoomed view, with contrast increased by a factor of two. At the bottom is a digitized wire waveform for one of the wires in the above plots. Two peaks (tracks) are clearly identified. The display show the raw data, i.e. no filter has been applied offline.
- (ii) *Fig. 5:* Image of a muon crossing the TPC (collection view).
- (iii) *Fig. 6:* A low multiplicity hadronic interaction (display as in Fig. 4).
- (iv) *Fig. 7:* Hadronic interaction with a high density of ionization (collection view); individual tracks are not resolved.
- (v) *Fig. 8:* An electromagnetic shower that extends over the entire fiducial volume; the core of the shower saturates the dynamic range of the electronics (collection view and single wire waveform with several tracks identified).

The average noise is ~ 2.5 ADC counts (RMS), giving a signal-to-noise ratio of ~ 4 for a minimum ionizing particle (mip)⁺. Given the wire pitch of 5 mm and an energy loss of 2 MeV per cm for a mip in LAr, the noise is roughly equivalent to 250 keV of energy lost through ionization by a relativistic particle (Fig. 9 and 10). Given a W-value of 23.6 eV in LAr, this corresponds to $\sim 10,000$ electrons produced in LAr by ionizing radiation.

The signals from 50% of the induction wires were noisy due to capacitive coupling with the high voltage in the drift region, therefore the induction plane has not been used systematically to provide full 2D images. Examples of partial 2D images and signal waveforms are shown in Fig. 11. For the “quiet” wires, the noise was comparable with the noise from the collection plane, as shown in Fig. 10.

4. Conclusions and outlook

A prototype LAr TPC has been designed, built and tested at Yale over a period of two years. It has been developed as a handy R&D tool, with the possibility of repeated runs

⁺ This is more than a factor of two worse than the signal-to-noise reported in [10] or in [9] (with different front-end electronics); a large fraction of the noise in the present setup is microphonic, due to difficulties in shielding the signal cables between the signal feedthrough and the front-end electronics.

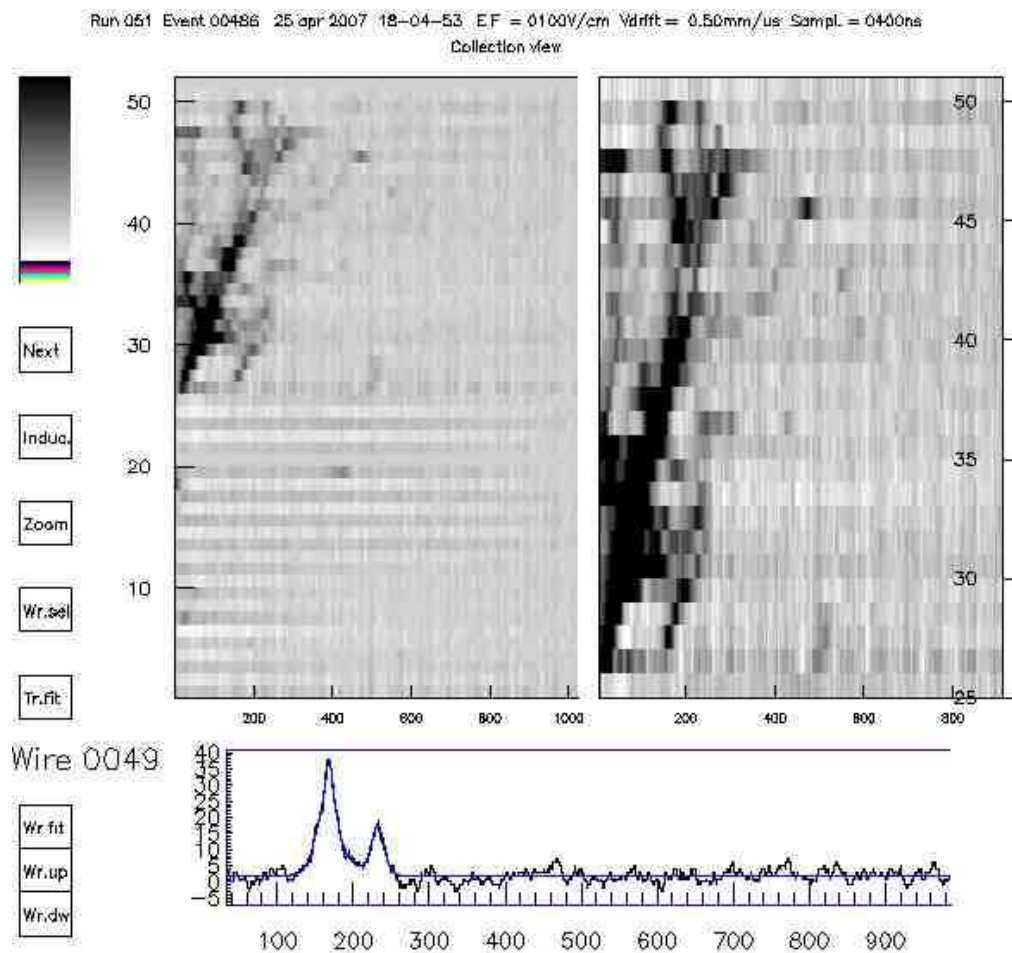


Figure 4. Display of an electromagnetic shower, collection view. *Left:* full 2D image of the fiducial volume, shown as wire number *vs.* drift time (in units of $0.4 \mu\text{s}$). The gray-scale is linear with the amplitude of the signal on each wire. *Right:* zoomed view, with contrast increased by a factor of two. *Bottom:* a digitized wire waveform, showing amplitude (in ADC counts.) *vs.* drift time, with two peaks (tracks) clearly identified.

over a short period of time. The LAr purification is a recent development, applied for the first time to a working imaging instrument, while the readout electronics has been provided by the ICARUS collaboration. The success in imaging cosmic rays marks an important milestone in terms of technology transfer for the US LAr TPC effort.

Steps are now being taken to expand upon this result. In addition to reducing the electronic noise in the system, the existing Yale TPC will be augmented with a PMT to study the detection of scintillation light in a LAr TPC. Other studies involving thick gaseous electron multipliers (THGEM) [15] coupled with a LAr TPC are also being undertaken at Yale. The ArgoNeuT (Argon Neutrino Test) experiment [16] has been designed and is currently being built, with the goal to begin running in 2008 and to amass a large sample of neutrino interactions, about 200 per day, in the Fermilab Low Energy (LE) NUMI beamline. This test beam experiment, using front-end and DAQ electronics designed and built by US institutions, will provide valuable experience in

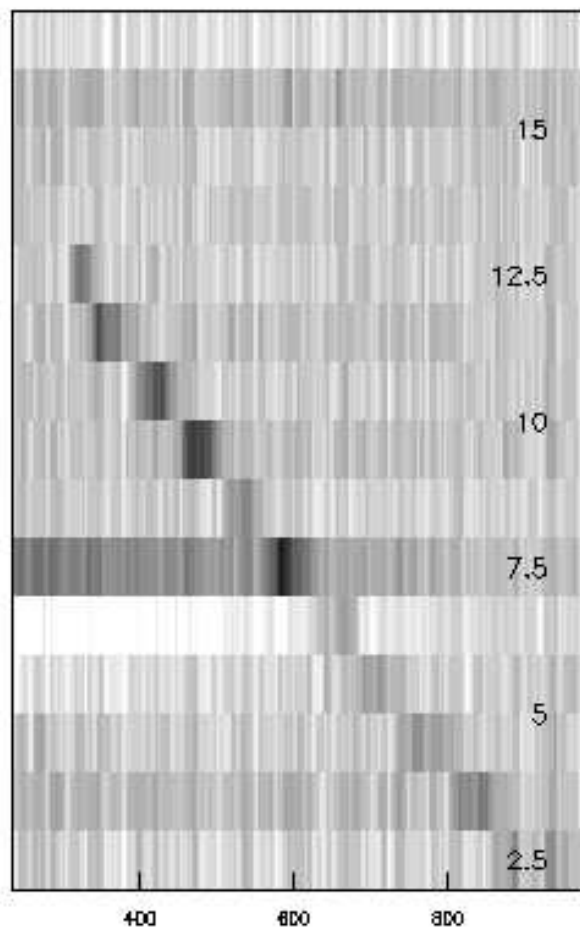


Figure 5. Muon crossing the TPC (collection view).

operating a LAr TPC in a real beam environment, and a large sample of low energy neutrino interactions.

Acknowledgments

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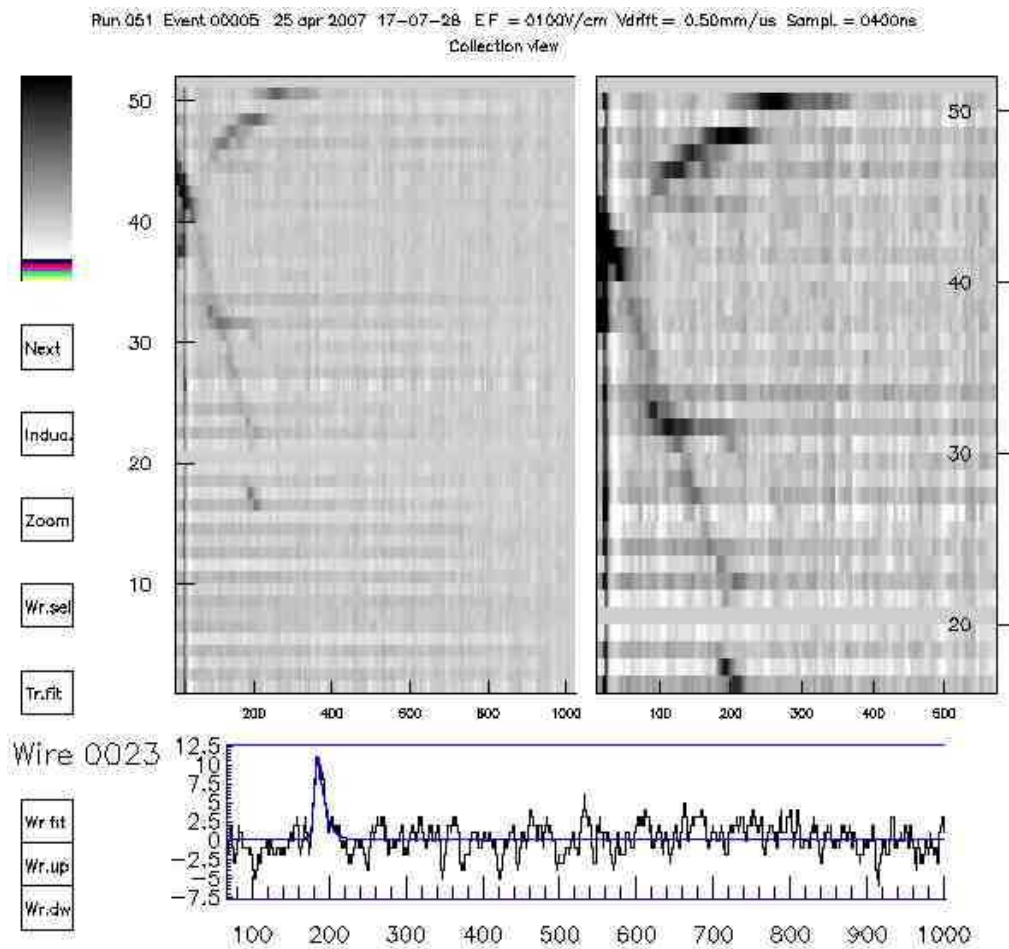


Figure 6. Low multiplicity hadronic interaction (collection view).

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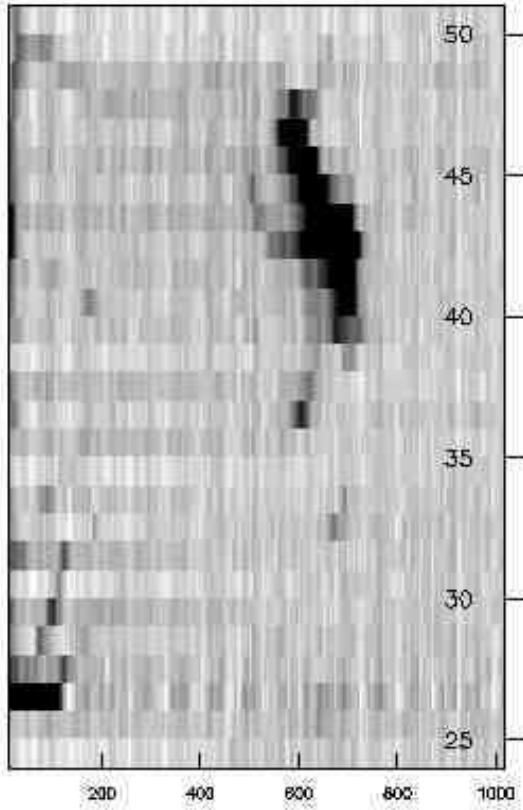


Figure 7. Hadronic interaction with a blob of high density of deposited charge (collection view).

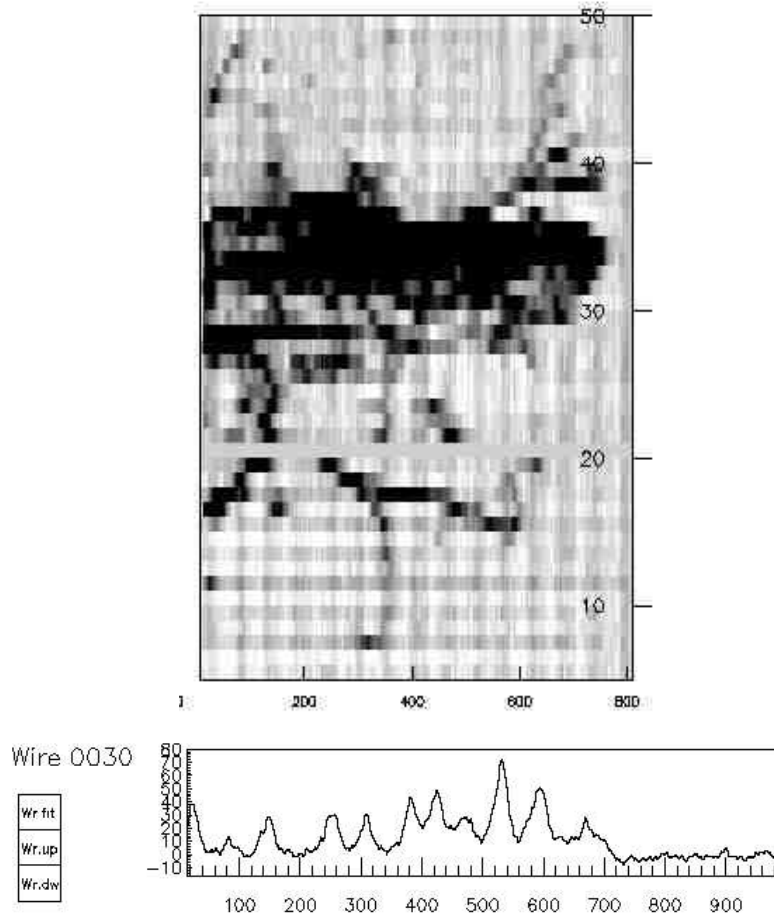


Figure 8. An electromagnetic shower, which fills up the entire fiducial volume. Several individual tracks are visible in the wire waveform shown in the bottom window.

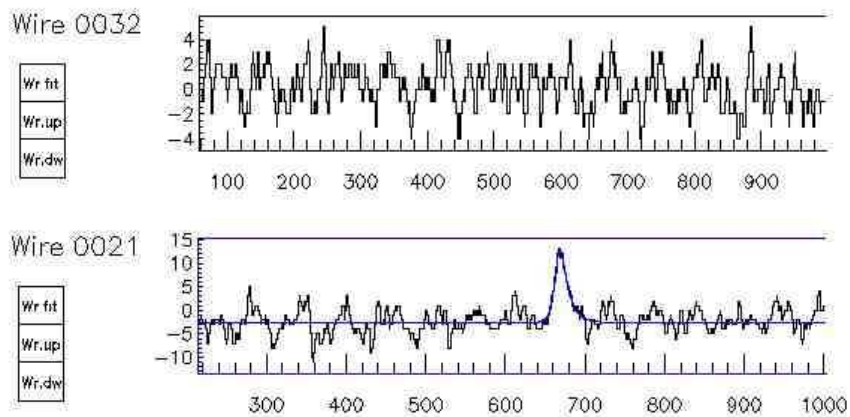


Figure 9. *Top:* Waveform for an empty wire, in ADC counts *vs.* time [0.4 μ s]. *Bottom:* signal induced by a minimum ionizing particle.

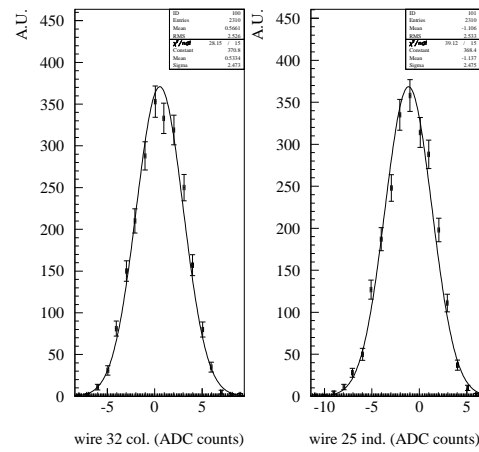


Figure 10. *Left:* distribution of the amplitude in ADC counts for an empty collection wire, i.e. the electronic noise. *Right:* the same for an induction wire.

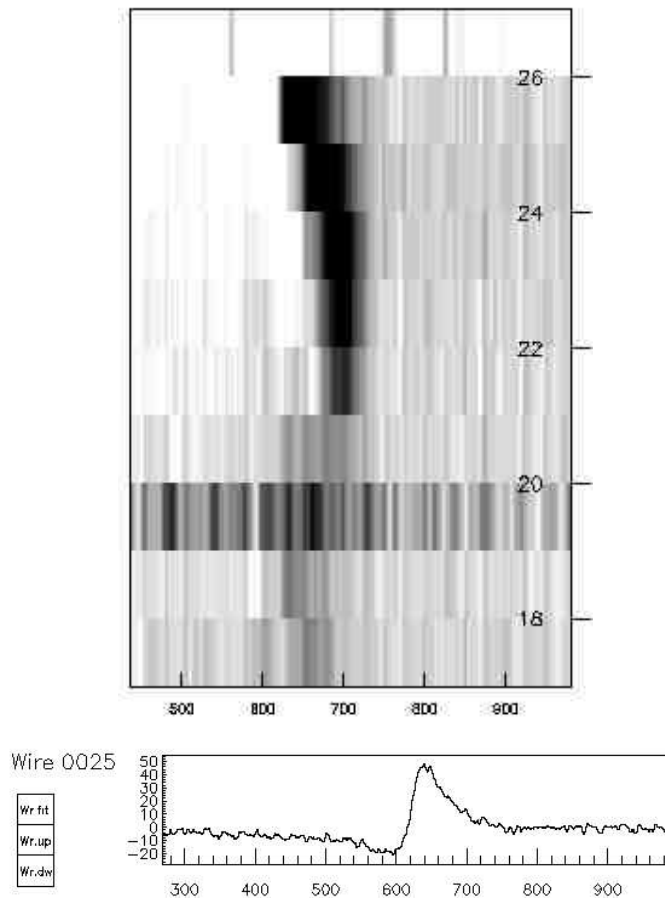


Figure 11. *Top:* Induction view of the events shown in Fig. 7, corresponding to the high density “blob”. *Bottom:* waveform of an induction wire from the same event.