Cellular Design for a Liquid Argon Time Projection Chamber

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Abstract

There is a competition between water Cherenkov detectors and liquid argon time projection chambers to be the next generation of neutrino oscillation detector. Liquid argon detectors combine bubble chamber like imaging with total absorption calorimetry, making it a very appealing option; however, many physicists are reluctant to use liquid argon, largely because the is less experience with the liquid argon technology. We attempt here to address concerns relative to the long wires required for a 50-100kton detector, especially with respect to the electronic noise, maximizing fiducial relative to total volume, wire installation, the possibility of wire breakage, and track reconstruction relative to wire configuration. To alleviate these challenges, we propose a Cellular Detector design, which separates the wire planes into 3m wide panels which the wires wrap around, combined with light detecting sheets. Ultimately, we find that the Cellular Detector alleviates four of the challenges and may complicate track reconstruction; fortunately, the addition of light collecting sheets likely rectifies our reconstruction sensitivity.

1 Introduction

One of the major challenges in the construction and operation of massive Liquid Argon Time Projection Chambers (LArTPCs) relates to the readout planes of the TPC. The readout uses three planes of wires: two angled planes and a vertical plane – all read out at the top. There are at least five issues surrounding these long wires:

1. Electronic noise due to the capacitance and resistance of the wires.
2. The incomplete coverage of the entire tank by all three wire planes.
3. The safety, time and logistical issues of installing the wires in the tank at the correct tension.
4. The danger and consequences of wire breakage, particularly on cool-down.

5. Reconstructing events and associating signals in the different planes

This note introduces a possible solution (called a Cellular Design) to some problems caused by the long wires needed for the readout planes of a massive LArTPC. The Cellular Design could, but does not necessarily, address the first issue and may complicate the fifth, but it virtually eliminates the other three.

This note begins by discussing issues 1 through 4, then introduces the Cellular Design, showing how it remedies those issues, and then describes how the Cellular Design can be realized. A brief status is given on our work to understand the effect Cellular Design has on issue 5. We conclude by discussing a possible technique for light collection which extends the capability of the detector for non-beam associated events and may reduce the reconstruction burden.

2 The Problems with Long Wires

Issue 1 is largely a result of the length of the readout wires. Using beryllium copper (BeCu) wires (resistivity of 8.62E-05 Ω-cm) with a diameter of 2.00E-04 m and perpendicular wire spacing of 5 mm, the wires have a capacitance of 12 pF/m and resistance of ∼25 Ω/m, which, over 30+m of wire is ∼400pF and ∼800Ω, adding a significant amount of capacitive and Johnson noise.

Issue 2 (coverage of the entire tank) simply arises from the geometry of putting angled wires which are read out on the top into a tank with a rectangular cross-section. As seen in Figure 1 below, not all angled wires can reach the bottom, leaving typically about 75% tank uncovered by one or the other set of angled wires and only 25% covered by both.

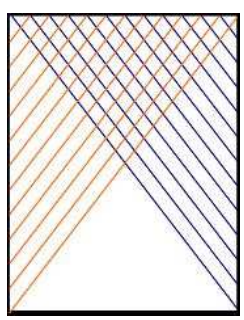

Figure 1: Drawing of wires showing their incomplete coverage of the tank.

Issue 3 is a result of the large size of the tank. Take for example a 50kton detector. The longest wires will span a cross-sectional square of ∼30m by ∼30m. With an angle of ±30 with respect to the vertical for the angled wires, the longest wire will be ∼41m long. With a little common sense, it is easy to see that stringing hundreds of thousands of ∼200μm diameter wires of lengths up to ∼41m long to exact tensions will be time consuming, difficult and dangerous. Additionally, the stress on the wire frame due to the tension of the wires must be carefully managed.

The non-uniform cooling of the tank as filled with liquid argon causes issue 4. As the wires have a very small volume to surface area ratio, they will cool to the temperature of the interior of the tank (be that 273K or 87K) effectively instantaneously. The tank itself will cool much more slowly, and as a result, if the tank is filled with LAr from room temperature, the tank will nominally be at its room-temperature size while the wires have undergone extensive linear contraction, putting extra tension on the wires. Although the tank could be cooled over a long period of time to ensure a small temperature gradient (and hence small increases in tension), this only lessens and does not eliminate the possibility of breakage. Further, the first time that the wires are cold tested is in the detector when it is being filled to take data; they cannot be tested beforehand. If one breaks, there is no way to repair it. An unbound 41m long, light wire could cause numerous problems in the LArTPC, worst case causing tank-wide shorts in the electronics.

3 The Cellular Design

The Cellular Design separates each plane into narrow panels. Thus a 50kton tank is full of 30m long by 3m wide readout panels (they are henceforth referred to as 'panels'). Each of the panels has three layers of wires which wrap around its edges onto both sides (two angled layers and a vertical layer) and two collection layers. See the Fig 2 and 3 below for the configuration of each plane and how they are laid out in the detector.

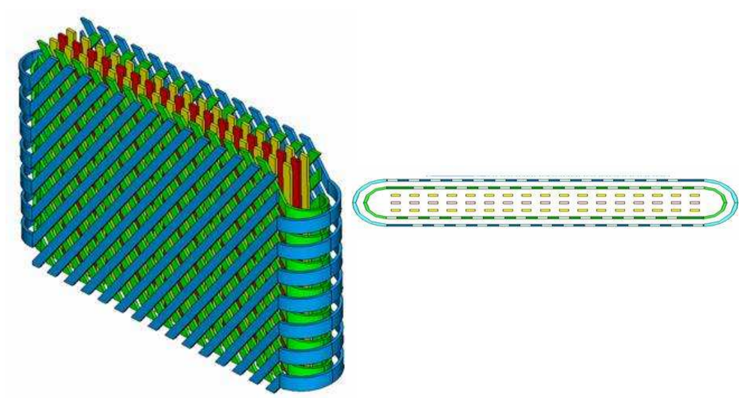

Figure 2: Right: 3-Dimensional view of one panel. Left: Top view of one panel. The pink layer is the ground plane; the yellow layer consists of the vertical wires on each side; both the blue and green planes are angled. This is true of image at left as well.

Issue 1 can be much improved if we use cold electronics. By putting the preamps and/or multiplexers in the LAr, we significantly lessen cable capacitance, increasing signal to noise. Further, the signals would then be low impedance, allowing for simpler feedthrough design.

This design resolves issue 2: the panels effectively span the entire height and breadth of the tank. There will be minimal dead space between adjacent panels and between the last panels in each row and the wall of the tank. Thus we achieve a high fiducial to total volume ratio while still reading all signals out at the top of the tank.

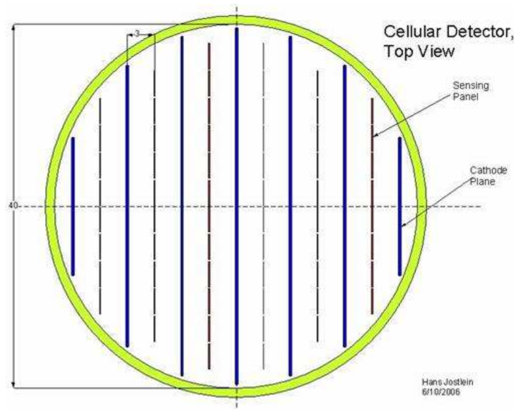

Figure 3: A top view of an entire Cellular Design detector with many panels inside.

Also, the Cellular Design alleviates issue 3. As each panel is an entity independent of the tank, they can be mass produced off-site at the same time as the tank is prepared (not after, as would be without the Cellular Design), saving time and money. The tank and panels will be designed such that once they are both finished, the panels can be lifted and hung into in tracks along the top tank, rolled to their position inside the tank and then secured in place with a bolt (or similar mechanism); a relatively quick and low risk process (from both a human safety and equipment breakage standpoint).

Further, the Cellular Design lessens the impact of Issue 4; as the panels are produced at a factory off-site, they can be cold-shocked and tested at the factory to ensure that there are no wire breakage problems. Further, each of the wires will be mechanically fastened to the panel at periodic intervals, limiting the maximum length of wire which could become unraveled. However, with careful planning it is doubtful that any wires will break at all.

As will be discussed in the following section, the panels will likely be constructed as a stainless steel frame (coefficient of thermal expansion 1.73E-05 K-1) with beryllium copper (BeCu, 1.78E-05 K-1) wires [1]. The wire angles and dimensions of the tank are unrelated to the changes in tension; the change in tension is only a function of the change in temperatures of each material separately. Starting from 293K and cooling the tank 30K at a time down to the temperature of liquid argon (∼87K), the largest tension the wire will be under is ∼15% higher than its original tension, and the largest increase in tension between temperature levels would be a ∼9% increase (from equilibrium at 103K to wires 93K and frame 103K).

4 Panel Construction

Building such panels is physically feasible if they are structurally built as ladders (see Fig. 4 below). There are four main engineering issues which must be addressed in their construction:

A. Eliminating strain on the panels and tank arising from the stress of the wire tension (both bending and buckling strains) and mass of the panels

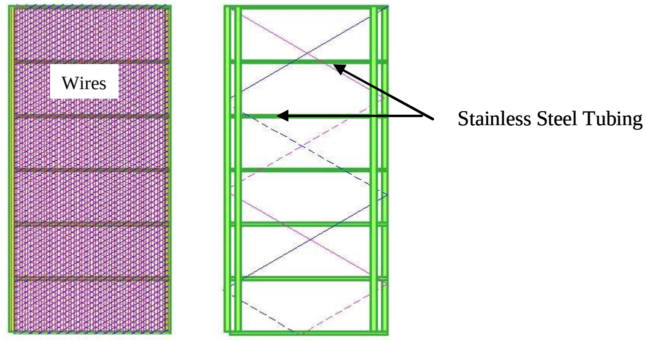

Figure 4: A panel with and without wires, showing the stainless steel structural tubing with two stiles on each side.

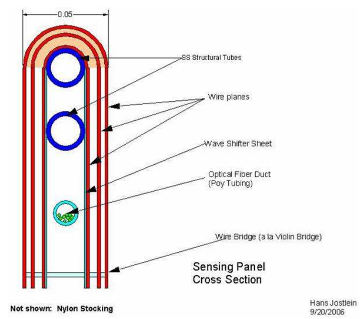

Figure 5: A cross-sectional view of the sensing panel, highlighting the dual-stile design to minimize deflection due to wire tension.

B. Maintaining exact wire alignment

C. Ensuring that the panels are correctly placed and immobile when in the tank

Issue A addresses the possibility of bending of the stiles, buckling of the rungs and the stress on the tank from the weight of the panels. All stress and strain calculations are done as per Roark [7]. As the bending strain is inversely proportional to the moment, we propose that two stiles are used, each a stainless steel tube (see Fig. 5 below). This calculation assumes that the two structural tubes have been connected such that they act physically as one member. The rungs act as columns under a compressive stress, and, because of their large length to radius ratio, they are more susceptible to buckling instability. These effects, along with the weight of the panels, are summarized in the following table.

Stainless Steel Properties		
	Modulus of Elasticity	2.76E+07 lb/in^2
	Modulus of Elasticity	1.90E+11 Pa
	Yield Strength	2.00E+08 Pa
	Density	7.80E+03 kg/m^3
Ladder Properties		
	Length	30 m
	Width	3 m
	Drift length	3 m
	# of Complete Wraps	5 wraps
BeCu Wire Properties		
	Tension	2.5 N
	Perpendicular Wire Spacing	5.00E-03 m
	Wire angle to Vertical	45 degrees
	Wire Spacing on vertical parts of frame	7.07E-03 m
	Wire Spacing on horizontal parts of frame	7.07E-03 m
	Diameter	2.00E-04 m
	Density	8778.56 kg/m^3
	Total Wire Mass	6.32 kg
Ladder Stiles Properties		
	Outer Radius	0.0127 m
	Inner Radius	0.0117 m
	Wall thickness	0.001 m
	Separation of Tube Centers	0.06 m
	Thickness of strips connecting Tubes	0.001 m
	Maximum Deflection	8.74E-04 m
	Mass of Stiles	85.79 kg
Ladder Rung Properties		
	Rung Spacing	1 m
	Outer Radius	0.0127 m
	Inner Radius	0.0107 m
	Wall thickness	0.002 m
	Length of Rung	2.8292 m
	Number of Rungs	32
	Maximum Load	3028.03 N
	Load per rung of the wires	1325.83 N
	Factor of Safety against Buckling	2.28
	Mass of Rungs	103.83 kg
Mass Totals		
	Total mass of Ladder and Wires	195.93 kg
	# of panels (for length $\times$ length fiducial)	39
	Total mass of all Panels	7641.464802 kg

In the table, the inner and outer radii are those of the stainless steel tube used for that component. '# of Complete Wraps' is explained in the 'Reconstruction Burden' section of this note. Physical properties of stainless steel and BeCu were found in reference [1]. We see that the stiles will deflect ∼1mm, that the rungs are supporting less than half what will theoretically result in elastic instability, and that each of the ladders will have a mass of ∼200kg and altogether they will mass ∼7700kg.

It is important but not critical that Issue B is resolved and the wires are all perfectly parallel and evenly spaced. The vertical wires will be controlled as by if a violin bridge. Intermittent notched G-10 strips will run parallel to the rungs of the structural ladder, with each of the wires lying in a notch. The wires can then be held in place there by a drop of epoxy. Not only will this help to keep the wire in place, but, also, if there is any breakage, it minimizes the length of wire (which will likely have a sharp edge) floating about the detector, creating a risk of discharge currents. The angled wires are to be separated from the stiles by insulating (ie G-10) half-tubes (see Fig. 5 above) which can be similarly notched and held in place by epoxy.

Issue C must be resolved in order to ensure a uniform electric field and proper reconstruction of events. This issue can be easily solved by creating tracks (see Fig. 6 below) along which the panels can roll along the top of the tank and clamps across the bottom of the tank.

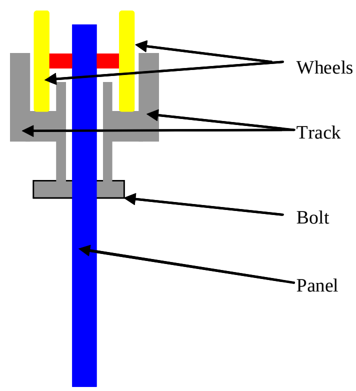

Figure 6: Sketch of tracks on which the panels could be moved when they are put into place.

5 Reconstruction Burden

Understandably, having the wires wrap onto both sides seems to complicate the reconstruction process because we have no simple way of discerning which side of the readout plane the track came from or whether the track occurs at the top or bottom of the detector. In the least, the proposition requires thought.

For example, there is a point at which the wire configuration repeats itself. This becomes readily apparent if we construct a two dimensional view of the arbitrary 'front' side of a panel as in Fig. 7 below.

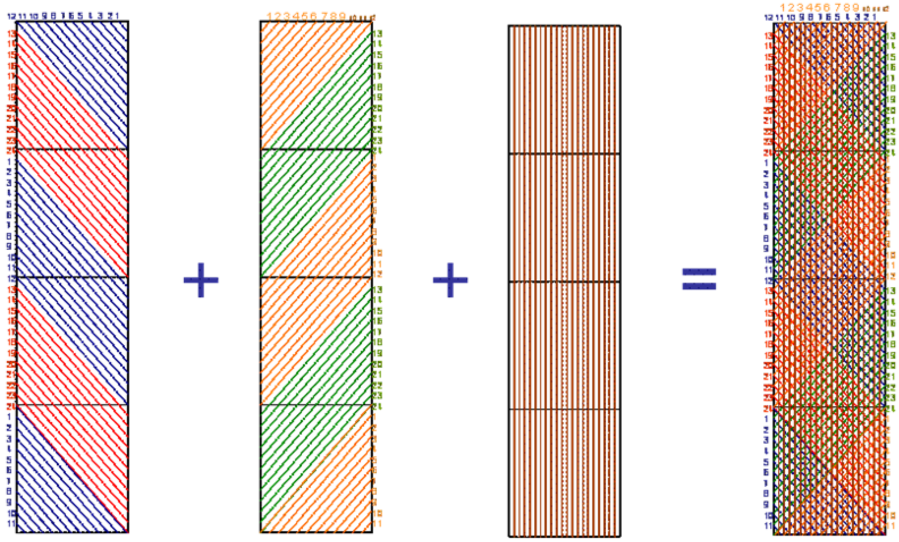

Figure 7: Graphically constructing one 'front' side of a panel

In this figure, each successive piece represents a layer of wires. Hence, we could think of the blue and red wires as the outer layer, the orange and green wires as the middle layer and the brown wires as the inside vertical layer of one half of a panel. The reason for distinction in each layer between colors is on which side ('front' or 'back') of the panel the wires reach the top and are thus read out on. As we have labeled this side as the 'front' side, the blue and orange angled wires and brown vertical wires are read out on the 'front' side, and the red and green angled wires are read out on the 'back' side. The numbering system is arbitrary.

We can see that at the first and third lines down from the top in Fig. 7, wires are configured just as they are at the top of the 'back' side, and at the middle line the wires are the same as they are at the top of the 'front' side. Thus the orange wires will be oriented as they are at the top of the plane for four sections of the panel; twice on the 'front' side and twice on the 'back' side, meaning that the readout for the orange wires is like having four pictures put on top of one another. This effect makes the numbering system-although arbitrary-very important to keep track of where something is coming from.

We have chosen to force each of the wires to fully wrap around the panel an integer number of times, as they do in Fig. 7 because we believe it will simplify the reconstruction process, but it is not obvious whether or not it does. More investigation is needed. To ensure that this happens, the wire angle cannot be decided. Rather, the trigonometric relations between height of the panel, width of the panel, and number of wraps determine the angle. If, as in Table 1, the panel is 20m tall, 3m wide and there are 5 full wraps (there are two in Fig. 7), then the angles are ±55 degrees to the vertical.

Preliminary investigations of a GEANT3 Monte Carlo cosmic muon simulation [2] of a Cellular Detector have shown that it is fairly easy to hand scan simulated wire readouts. This MC simulates 1000 cosmic muons incident on a 1kton rectangular parallelepiped of liquid argon (see Fig. 8). We then separated this 1kton parallelepiped into 12 drift regions (6 panels) as shown in Fig. 9.

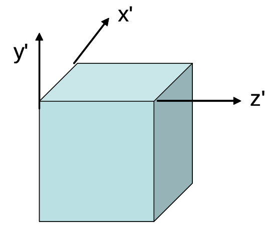

Figure 8: The parallelepiped that the cosmic muons are incident upon.

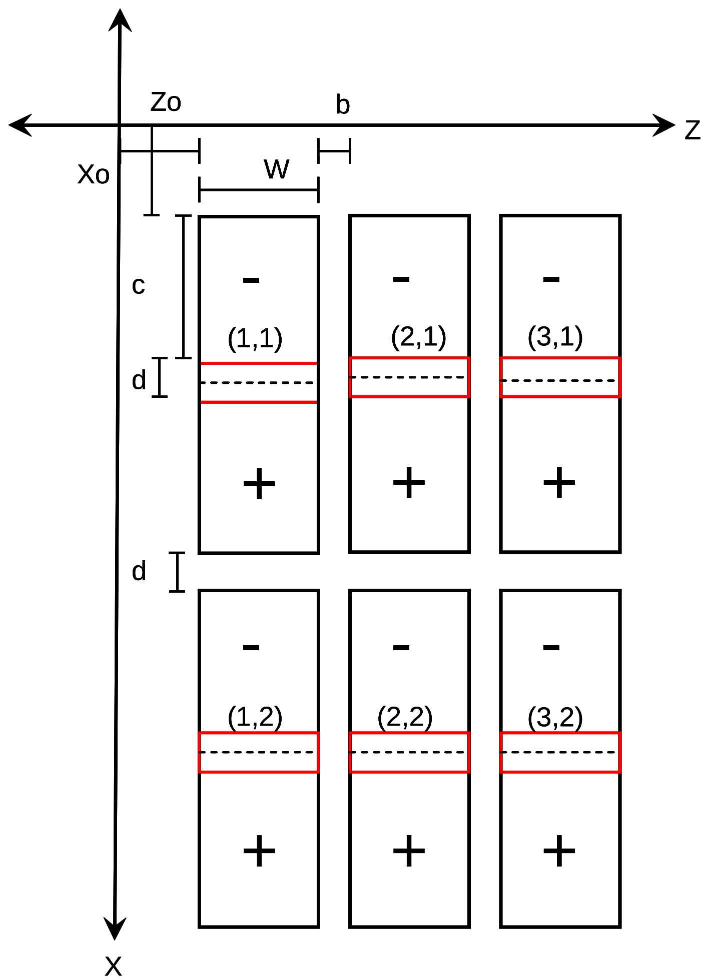

Figure 9: The way that the cells were constructed inside for the 1kton parallelepiped of liquid argon. The numbers are coordinates of the cells

The electronics readout of the cosmic ray tracks in a detector segmented thus was then simulated in PAW [6]. Part of the output of the simulation is shown below in Fig. 10 and 11, where 15 cosmic muons are incident on the detector.

As shown above, we can discern which track is which in images which are clear, greatly simplifying vertex identification. However, we must be sure to remember that these are images of the top and bottom of the panel's readouts put on top of each other. Further, the vertical planes enable us

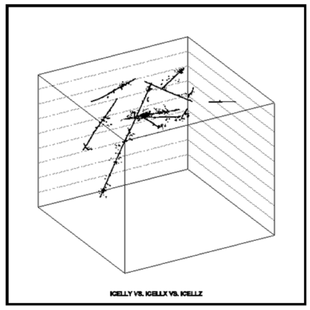

Figure 10: The 15 cosmic muons are shown as they occur in the parallelepiped of liquid argon.

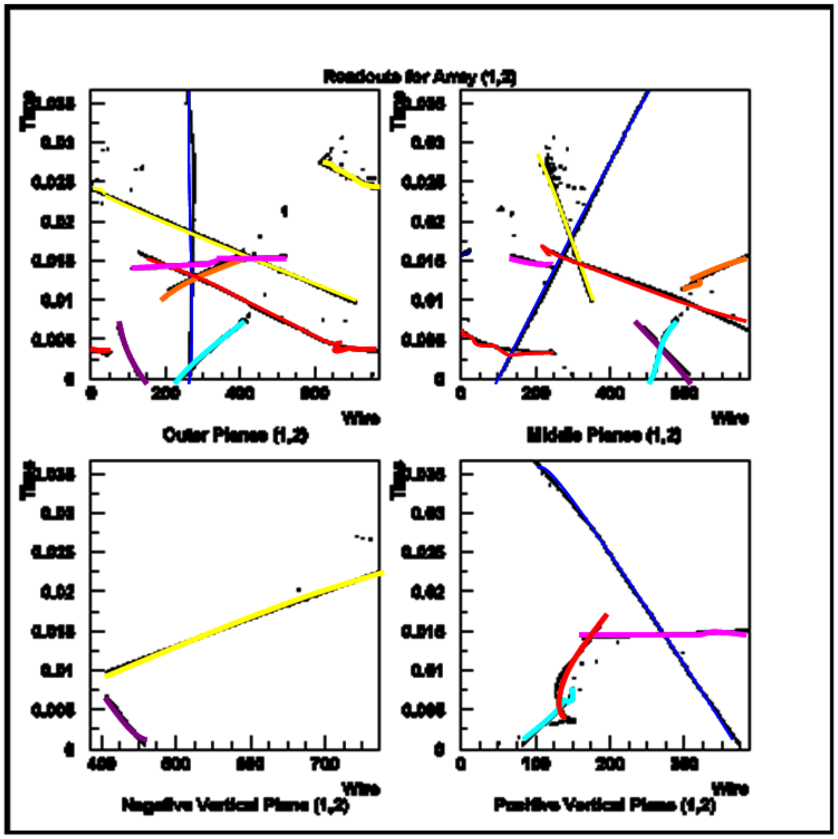

Figure 11: The simulated electronics readout for array (1,2), as noted in Fig. 9. Each plot is plotted with time on the vertical axis and wire number on the horizontal axis. the title of each plot is below it. The 'Outer' and 'Middle' planes are angled planes, with opposite angles of each other. Tracks have been hand-scanned and color coded (as best as possible). The simulation only gives a black and white readout.

to discern from which side the track came from. However, as alluded to above, there is still the ambiguity as to whether the tracks occur in the top or bottom half of the detector (as there are only two wraps).

In a 50kton detector , the panel length dictates more complete wraps of the wires around the panel, possibly complicating reconstruction. Such a panel would be ∼30m long and ∼3m wide; for an angle of 45 to vertical, 5 wraps are needed. Let us consider a single ionization electron left by a muon passing through the detector with wires that wrap around the panels five times. Assuming that the panel it will be drifted to is 100% effective, it creates three data points (one for each wire it passes), each with three coordinates (wire number, time and magnitude). With a 10ms drift-time and 1MHz data collection, one would think that the position of the electron on the panel can be narrowed down to 5 different 2.5E-5 m parallelepiped blocks of liquid argon by reconstruction, each separated vertically by ∼8.5m, the distance between 'repeats' of the wire configuration. However, due to what we will call the conveyor belt problem, the time of arrival of the electron does not tell us everything that we think it does and the electron could have originated in any of the cross section any given triplet of wires is incident to because separate events do not happen at the same time. The volumes in which it could have originated are still separated vertically by ∼8.5m.

The electric field causes all negatively charged particles to drift towards the wires as if they were on a conveyor belt. The particles which pass through the argon make marks on the conveyor belt and the wires record where the marks were made. Fortunately, the particles have a high enough velocity that the mark they make on the conveyor belt is within ≪1% of being their actual path. (Imagine slowly dragging a pen across a conveyor belt perpendicular to its motion; the mark on it will not be perpendicular to its motion. If the pen is moved much quicker than the speed of the conveyor belt, it will be perpendicular.) However, not all the marks will happen at the same time. For example, the belt could be marked at some point 2m away from where it is read and then marked again at the same point when it is 1m away. There is then no way of separating these two marks and determining which happened when and where, undermining our ability to fully reconstruct everything that happens in the tank.

Each event as itself should be unaffected however. Although we cannot determine the absolute position of the event in the detector, the relative positions and angles between different tracks of the same event/interaction will be maintained. Further, the entirety of the event happens effectively instantaneously. Thus, the intrinsic properties of each event should be independent of the conveyor belt problem, but their chrono-spatial relation to other events is impossible to determine.

Additionally, there is no way to discern in which of the five blocks the electron actually originated. As discussed above, each of them have the exact same configuration. Further, if another electron hits the same triplet of wires at the same time in a different part of the detector, there is no way of separating the two hits. This can be particularly troublesome with electron showers.

6 Light Detection

There may be a way to simplify the reconstruction effort by using light detection to determine in which vertical section of the panel the hit occurs. Particles in liquid argon produce a substantial amount of far-ultraviolet (∼128nm) scintillation light. With a combination of waveshifting sheets, scintillator, green and then clear fiber optic cables and photodiodes (Fig. 12 below), we can determine in solve many reconstruction issues.

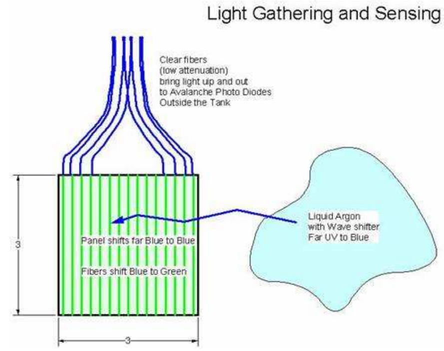

Figure 12: 3m × 3m scintillator panels bring light up and out of the tank.

There are five points surrounding the light detection issue which need to be discussed:

I. The feasibility of the plan

II. How it reduces the computing burden

III. How it aids in discerning vertical event position

IV. How it aids in discerning event time and thus its position in the drift direction

V. How it could be a quick scan for electron showers

Discussing point (I.), the largest impediment to the effective operation of the light detection sheets (they shall henceforth be referred to as 'sheets' to avoid confusion with the entire 'panels' of wires) is the purity of the argon (i.e. the scintillation light must be transmitted at a high rate over 3m). Azmoun, et al. [4] extensively studied the transmittance of VUV range light through gaseous argon with O2 and H2O impurities. They found the transmittance percentage to be heavily dependent on the wavelength of light. At 128nm, the wavelength at which argon emits scintillation light, the cross-section of H2O (∼5.67 Mbarn) is ∼3.7 times greater than the O2 cross-section (∼1.54 Mbarn) [3]. Azmoun, et al. note that the nitrogen cross-section is negligible and treat the argon cross section as negligible, although their data fit such an assumption. Assuming exponential attenuation in liquid argon at 87K and 1atm, the intensity of the light can be expressed in equation 1.

$$I(\rho_{H2O}, \rho_{O2}, \ell) = I_0 e^{-(11.907\rho_{H2O} + 3.234\rho_{O2})\ell} \tag{1}$$

where ρ_{H2O} is the water impurity (ppm), ρ_{O2} is the oxygen impurity (ppm), and ℓ is the distance the light travels (m). If purity levels are as proposed in [5] at ∼10 ppt (1E-11) for all contaminants, then transmittance should be ∼99.96% from 3m away, which should be better than acceptable. Thus, using the panels is feasible.

The panels can be used to reduce the computing burden, point (II.). Using panels, the entire volume of the tank can be segmented into 3m × 3m × 3m cubes. It may seem that the panels would only divide the tank into 3m × 3m × 6m parallelepipeds, but as each scintillator sheet need be no more than 2mm thick and because each sheet is effectively opaque to the 128nm scintillation light of LAr, we can easily put two sheets in each panel and feed all the optic fibers up through some sort of duct, as depicted in Fig. 13 below.

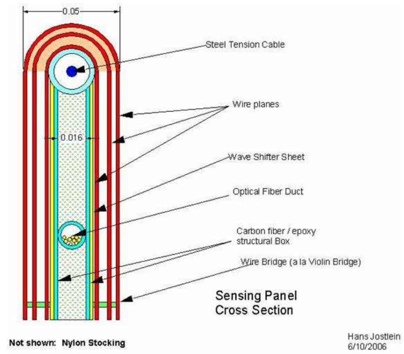

Figure 13: Cross-section of an array with two scintillator sheets and an optical fiber duct for light collection.

As such, light detection can then be used to greatly lessen the computing burden as a trigger, because only those cubes which record a hit in light detection need to have its panel read out. Consider for example, a single highly energetic cosmic muon which travels completely through the detector. This will appear as depicted below in Fig. 14:

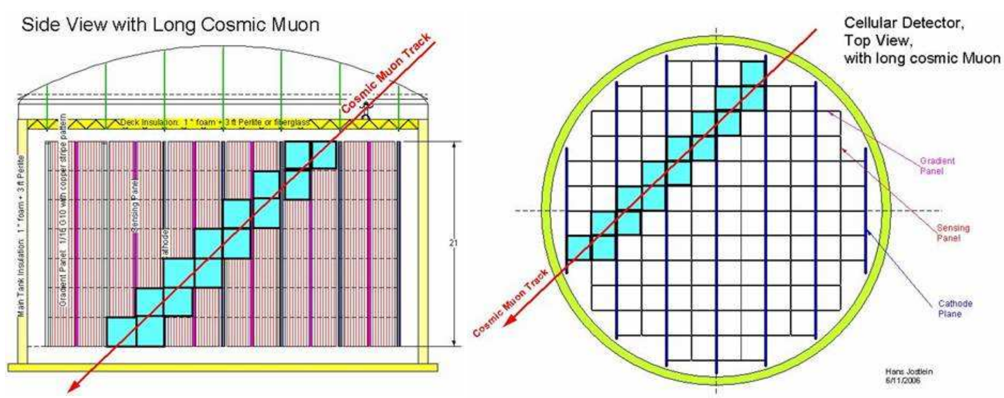

Figure 14: Left: Side view of the detector with a long cosmic muon. The detector has been segmented into 3m × 3m × 3m cubes by the light detection panels. Those cubes in teal are those which will register a hit from the cosmic muon. Right: Top view of the detector with the same long cosmic muon. Again, the detector is segmented, and only those cubes which are teal have a hit from the muon.

The most startling effect the light collection has on the reconstruction burden is as a trigger. Only panels which have teal cubes need be read out. In this example, only about 20% of the panels would have to have their data processed and recorded.

In cases where there is more than one track, light detection can help to determine (III.) the vertical position of a track. In this case, oftentimes the sheets will only be able to indicate where an even did not occur. Let us return to our example of examining a single ionization electron in a 50kton tank as discussed in the final paragraph of the 'Reconstruction Burden' section. There will be 20 sheets in this panel; ten on each side and two in each repetition of the wires. Each panel then is sensitive to a 3m $\times$ 3m $\times$ 3m cube as discussed above, and we know from the data collected by the panel that the electron could have originated from 5 of the 20 cubes of argon and would thus be detected by one of those five sheets. If the muon track that left the electron is the only track incident on those five sheets, then it can be easily discerned in which cube of argon it originated and thus which parallelepiped it originated (although the conveyor belt problem is still not resolved). However, if there is a track passing through part of either of the other five cubes effectively at the same time (within error of the data acquisition of the panels and the sheets), then it could have been in any of those cubes as well. As such, the sheets can only distinguish where the ionization electron did not originate from, namely those cubes which did not excite their sheet.

Nevertheless, the fact that the ionization electrons are a part of a track may enable us to unravel from which cube the electron came from. As discussed above, the combined efforts of the panel and sheets confine the electron to up to 5 different parallelepipeds of argon. For simplicity's sake, suppose that there are only five electrons from the track of this muon in the same cube (of the 20 that the panel is sensitive to) of argon and are suitably 5 signals from this track, and that the electrons each have a uniform probability of being in cubes {2,4,6,8}, {2,6,8}, {2,6,10}, {2,4,6,10} and {4,6,10}. Clearly, the track occurred in cube 6 because that is union of the sets. If a set of points (of which the set of possible cubes for of each point is a subset) can be identified as a single track, the computer can discern which cube is common to all of them. As such, reconstruction must be executed cube by cube (and evaluating the boundary conditions between cubes) and then assembled into an image of the entire detector. However, there will be instances when the union of sets of possible cubes will have more than one element, so the location of the event will not be able to be identified. Further, this method requires a high ability to identify a set of points as belonging to a track.

It may also be possible that light detection can (IV.) solve the conveyor belt problem. As light is 5-6 orders of magnitude faster than the drift velocity, it will not be detectably susceptible to the conveyor belt problem. As such, light detection can be used to more accurately timestamp a track. If panel and sheet track signals can be coordinated such that a set in each can be identified as describing the same event, a comparison of the panel timestamp and sheet timestamp can determine the position of the track in the drift direction. To do this, we need to simply find the difference between the timestamps (the drift time) and multiply it by the drift velocity, resulting in the distance away from the panel that the track was created.

Finally, (V.) the sheets can be used as a quick scan for electron showers. An electron shower will produce a very large amount of light, and thus we can quickly identify that region as having an electron shower.

7 Conclusion

Thus we see that implementing a Cellular Design for a LArTPC remedies four of the problems associated with long wires, makes it possible to use cold electronics to deal with electronic noise problems and likely complicates the problem of reconstruction. We are exploring the possibility of putting light sensing panels inside Cellular Design panels to alleviate the reconstruction burden. We will begin reconstruction efforts soon.

References

[1] All physical properties of materials were found at http://www.matweb.com.

[2] Alessandro Curioni (Yale University) wrote the cosmic muon GEANT3 MC ntuple used.

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