Warm Electronics Design for the Liquid Argon LBNE Detector

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Introduction

Much of the design effort to date has focused on placing the preamplifiers and perhaps some of the multiplexing circuits in the cryogenic liquid inside the detector. This has the advantage of locating the preamp close to the detector so that the total capacitance of the detector system is minimized. This usually results in the best signal to noise ratio. However, a successful design for the cold electronics has not yet been demonstrated. Therefore it seems prudent to look at designs where all the active electronics are located outside the cryostat. In the following two designs only the blocking capacitors and cables are inside the cryostat.

Since there is no intrinsic amplification of a signal in liquid argon, the input signals are expected to be on the order of a few fC. With such a small signal, it is important to minimize the noise in the front end system. Since noise is proportional to the input capacitance of the detector, the main design effort for warm electronics is in minimizing the added capacitance that is necessary to bring the signals to the outside of the cryostat.

There are also several secondary considerations. For safety and ease of construction, the number of penetrations of the cryostat need to both be minimized and also made fail safe. The signal is strongly attenuated by impurities in the liquid argon so any additional material installed in side the cryostat should be kept as small as possible and also be easily cleaned. Finally, all connections should be robust and allow the detector to have few failures in a life of at least 20 years.

Section 1 describes the main features of the detector that is used for these designs. Section 2 describes a design that has electronics located above and below the detector while section 3 describes a design that has electronics located only at the top of the detector.

I. Detector Overview

The detector is a large (40 by 20 by 14 meter) liquid argon time projection chamber (TPC). Impurities restrict the drift distance to about 2.5 meters and mechanical consideration limit the size of the wire planes. Thus, we choose a drift cell that is 2.5 meters wide by 7 meters tall by 10 meters long. The cell has a high voltage plane on one side and 3 wire readout planes on the other. One wire plane has vertical wires and the other two are at an angle of 45 degrees arranged in a U-V-Y configuration (fig. 1).

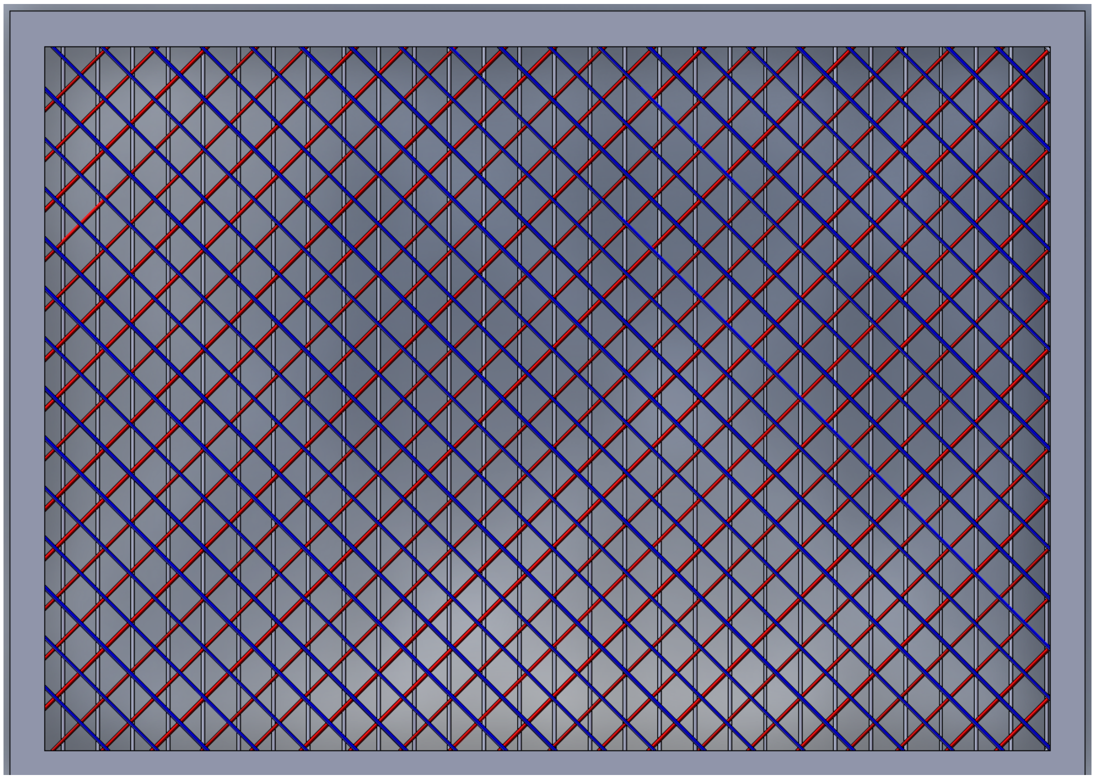


Fig. 1. Sketch of a TPC wire plane showing the Y (gray), U (red) and V (blue) planes. The frame size is 7 by 10 meters but the wire spacing and wire size have been scaled so that they are easily visible in the drawing.

The wire spacing and wire plane separation are both 5 mm and the wire diameter is 150 μm. The 5 mm spacing both lowers the capacitance and increase the amount of charge collected thereby increasing the signal to noise. Two of these cells are place back to back to form a detector module. Thirty two of these modules form the detector.

The wire arrangement shown in fig. 1 requires part of the readout of the U and V planes to be on the side edges of a module. Locating the readout on the sides increases the dead space between modules and also the length of cable needed to get outside the cryostat. A better design would have readout only along the bottom or top edge.

A design that accomplishes this is shown in fig. 2. For clarity only the U plane wires of the front half of a module and the V plane wires of the back half are shown. The U wires at the right edge are wrapped around and connected to the V wires in the back cell. The same wrapping is done at the left edge. The wrapped channels then form a “v” with one leg of the “v” reading out one TPC cell and the other leg reading out the other TPC cell.

Since this design mixes readout from two TPC cells, it has the potential to create readout ambiguities. This is not the case for 2 reasons. First and most important is that the arrival time for all 3 coordinates will differ by the drift time across the 5 mm plane separations. This is not foolproof since a track could point directly at the plane so that charge would be collected at one point for a significant fraction of the drift time.

Second, the wrapped V wires cross different U wires so a common point on one side does not reconstruct to a common point on the opposite side.   This is also true for 2 hits on either side. For cases with more than 2 hits on a side, one probably needs a monte carlo simulation to fully understand the possible ambiguities.

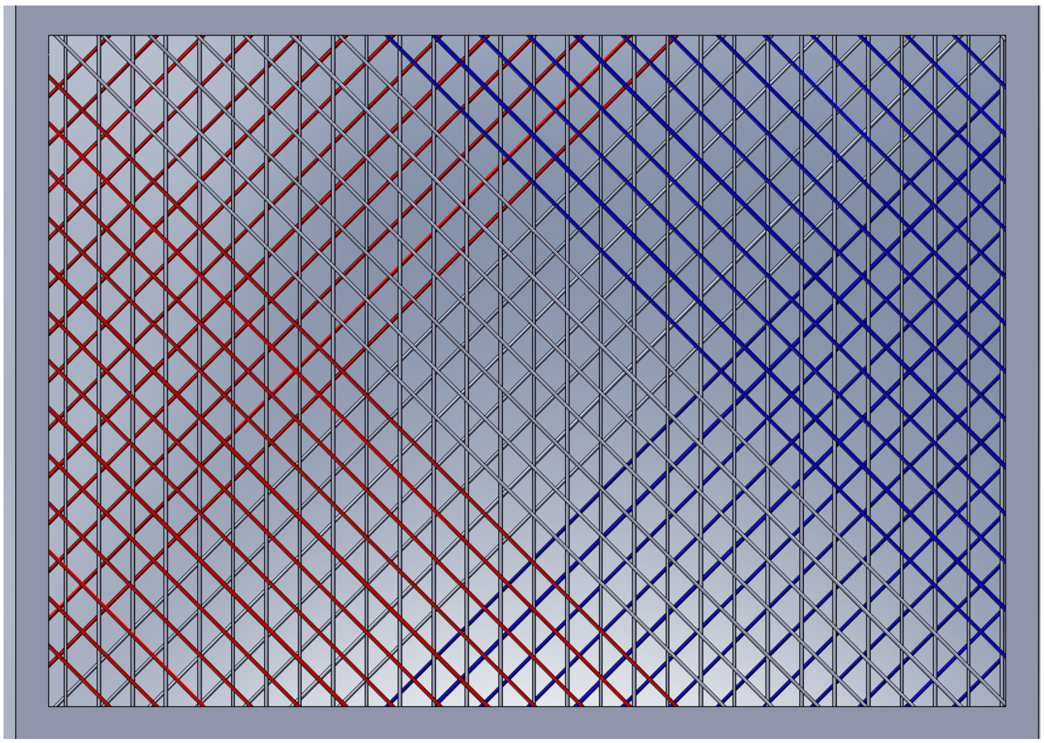


Fig. 2. This shows U layer for both the front and V layer for the back section of a TPC module. For clarity the V layer is not shown. The red wires from the rear cell wrap around the frame so that they are read out from the bottom of the front cell. The blue wires on the front cell wrap around the frame and are read out on the bottom of the rear cell.

Sixteen of these modules are assembled into one layer of the detector. The complete detector has 2 of these layers. This is shown schematically in fig. 3.

Fig. 3. Simplified plan view of a liquid argon TPC. A module consists of 2 TPC grid assemblies mounted back to back with the associated high voltage planes. Each module is 10 m long by 7 meters high. There are 4 modules longitudinally and 4 horizontally for a total of 16 on one layer. There are two vertical layers for a total of 32 modules for the complete detector.

Since noise is proportional to the total detector capacitance, the goal of this design is to transport these signals to the outside of the cryostat with as little additional capacitance as possible. There are at least 2 ways to do this. The method with the least added capacitance brings the signals directly through the top and bottom plates of the detector cryostat. Signals are brought to the top edge of the top layer of TPC modules and the bottom edge of the bottom TPC modules and then brought directly out of the cryostat through the top or bottom plates on short (3 meter) cables.

A second method brings all the signals through the top of the detector by running cables an additional 7 meters from the lower layer of TPC modules to the top of the upper layer of modules and then another 3 meters through the top of the cryostat. These two designs are described in more detail in the next two sections.

Signal to Noise

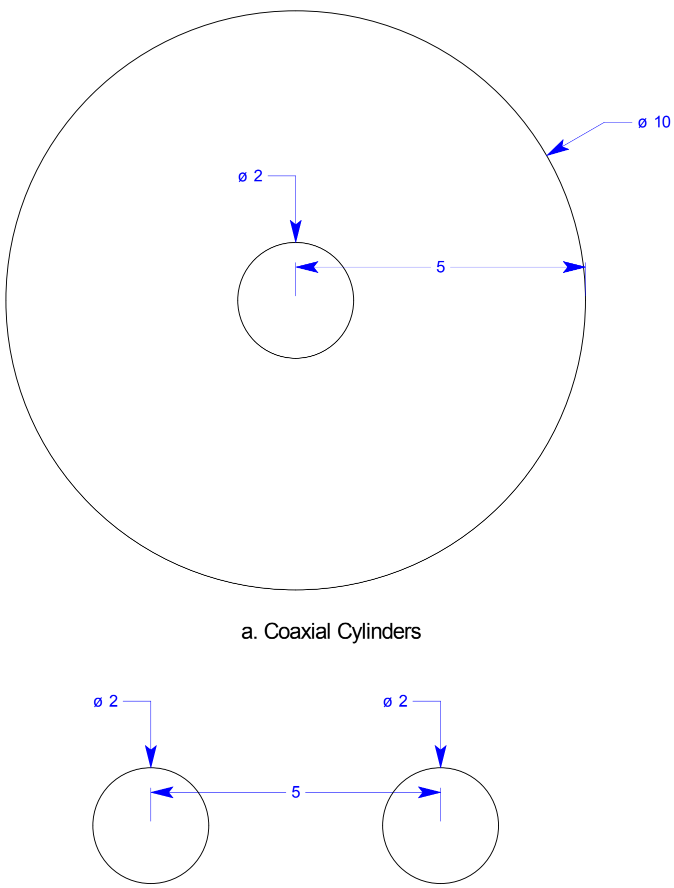
Noise is directly proportional to the input capacitance so low capacitance is always desirable. However, a signal to noise ratio above 10 is likely to be adequate. Increasing this to 15 to 1 gives a safety margin for common mode noise.

Estimates of the signal size arriving at a wire after the maximum drift distance (2.5 meters) range from 11,000 to 22,000 electrons. In a presentation to the 2004 FLARE workshop at Fermilab, Paul Rubinof has estimated that a good low noise amplifier with 1 μs shaping will have an intrinsic noise given by

$$\sigma_N = 125e + 2.6\frac{e}{pf}$$

where e is the electron charge. If we assume a signal to noise ratio of 14 to 1 and use the above signal range, we get values for total capacitance between 254 pF and 556 pF.

There are analytic formulas[1] for the capacitance between two parallel cylinders for the cases when one is coaxial with the other and when they are outside each other (fig. 4). If one evaluates the capacitance for the two cases, one finds that the ratio approaches 2 for large separations and small wire diameters. Even for the case in fig. 4 where the separation is only 5 times the radius, the ratio deviates from 2 by only 2%.



b. Parallel Cylinders

Fig. 4. Example of 2 parallel cylinders with a radius of 1 mm separated by 5 mm and a coaxial pair with inner radius of 1 mm and outer radius of 5 mm. Assuming a relative dielectric constant of 1.6 for liquid argon, the coaxial case has a capacitance of 55 pF and the parallel case has a capacitance of 28 pF.   As the wire radii decrease, the capacitance ratio approaches 2.

A wire in the two out side wire planes in the TPC have wires on 3 sides. A wire in the center plane has wires on all 4 sides. The capacitance for these cases can be calculated by solving Poisson’s equation with a finite element model (fig. 5). The calculations show that the 4 wire case has about 90% of the capacitance of coaxial case and the 3 sided case is about 87% of the coaxial case. These calculations are for parallel wires whereas two of the planes are at a 45 degree angle. However, the results are so close to the coaxial case that it is very likely that the real case will also be close to the coaxial case. Thus, we take 20 pF/meter as the capacitance for all the wire planes.

A Y wire has a length of 7 meters so it has a capacitance of 140 pF. A U or V wire at 45 degrees has a length of 9.9 meters so its capacitance is about 200 pF. The worst case signal to noise would allow only an additional 54 pF for cabling while the best case would allow 356 pF. It is obvious that the design depends critically on the signal size.

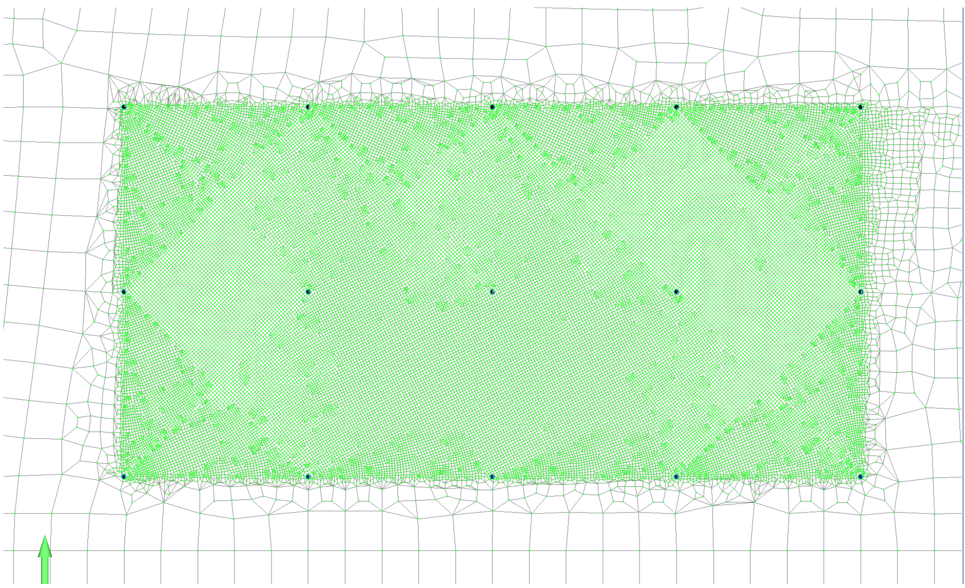


Fig. 5. Section of a 2 D finite element model used to calculate the capacitance of wires in a grid. Since this is only a 2D model, all wires are assumed to be parallel. The 15 dots arranged in 3 rows of 5 are 150 μm wires spaced 5 mm apart. Each wire has 6 nodes on its circumference and the mesh between the wires is very dense so the model is likely to be quite accurate. The capacitance of the wire in the center with all other wires grounded is 19.2pF/meter. The capacitance of the top center wire with all the other wires grounded is 18.4 pF/meter. The capacitance between 2 isolated parallel wires is 10.6 pF/meter and the capacitance of a coaxial system with a 150 μm inner diameter and 10 mm outer diameter is 21.2 pF/meter. Thus, the case with the centered wire is 90% of the coaxial case and the wire surrounded by 3 wires is 87% of the coaxial case.

II. Electronics Above and Below the Detector

In this design the TPC signals are all brought to the top or the bottom of the modules as shown in fig. 2. Cables from the TPC are brought directly to the cryostat wall and then through a feedthrough to the warm electronics. Given that there may be nearly 1 meter of insulation, it is likely that 3 meters of cables will be needed to make the penetration. The difference between a warm and a cold design is then the 3 meters of cables and the cryostat feedthroughs. Note that the DC blocking capacitors are still located at the ends of the wires.

Cables

The shaping time for the TPC signals is likely to be around 1 μs so the cables do not need to be high speed. Since we are interested in low capacitance, we use cables with no ground wires. We also need to minimize the dielectric constant. The dielectric of liquid argon is 1.6 so the best choice would be bare wire surrounded by liquid argon, i.e., identical to the signal wires. We can approach this by using a woven cable that uses magnet wire. Magnet wire is copper wire coated with a thin (few micron) coating on the wire. The wire is made into a ribbon cable by weaving it into cloth ribbon (figs. 6 and 7). The weaving process allows one to space the wires to keep the capacitance low and also to minimize the amount of material next to the wire (a lose weave). By using wire diameters in the range of 75 to 200 micron one can realistically achieve cable capacitances of 33 pF/meter. The coaxial solution for a 200 μm diameter wire spaced 4 mm apart in liquid argon gives 24 pF/meter. The weaving material and the ends of the cable will increase this but if the weave is loose, it should be less than 50%. These cables can be made up to 125 mm wide and any length. Special weaving can be done at the ends for easy connector attachment.

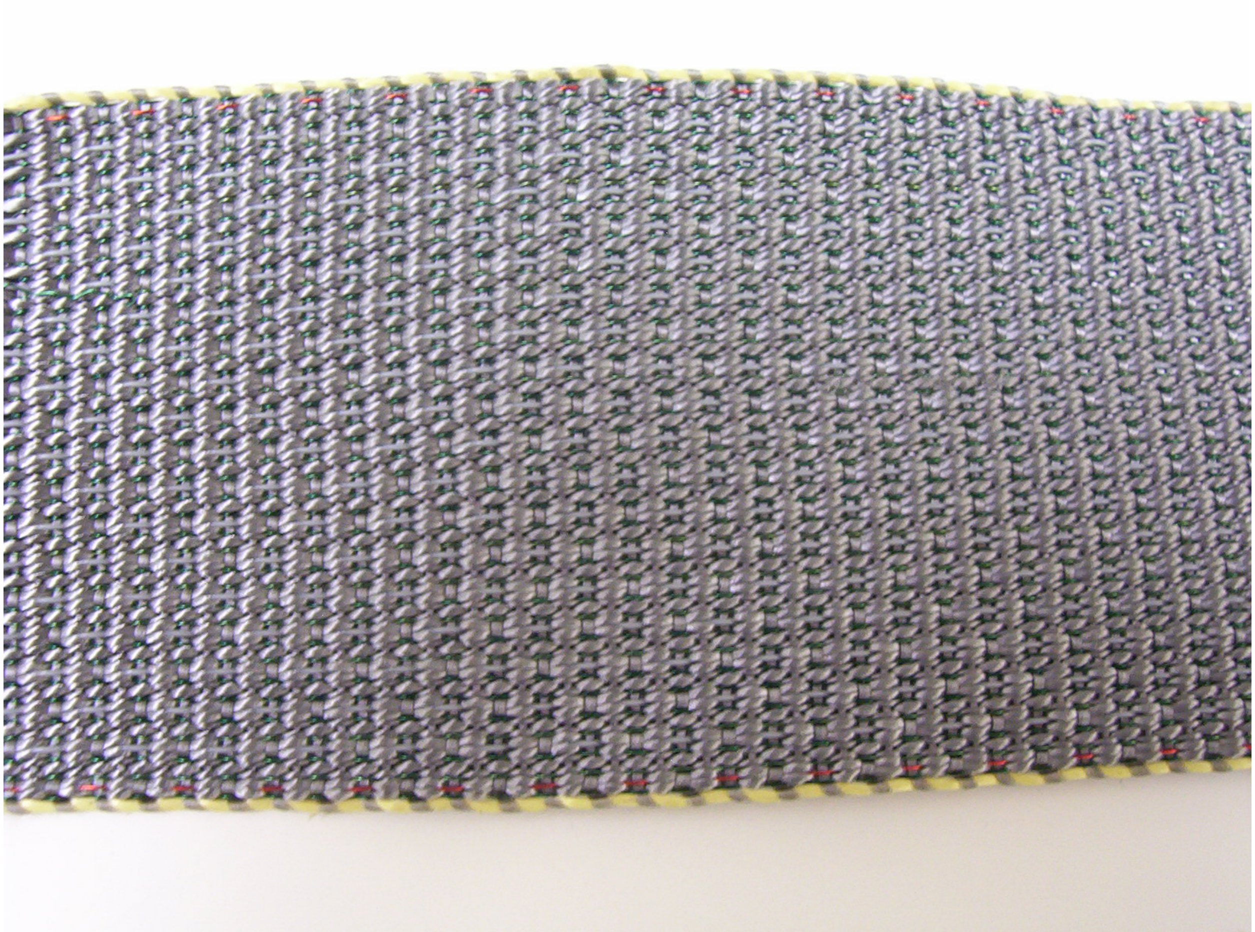


Fig. 6. Example of a woven cable.

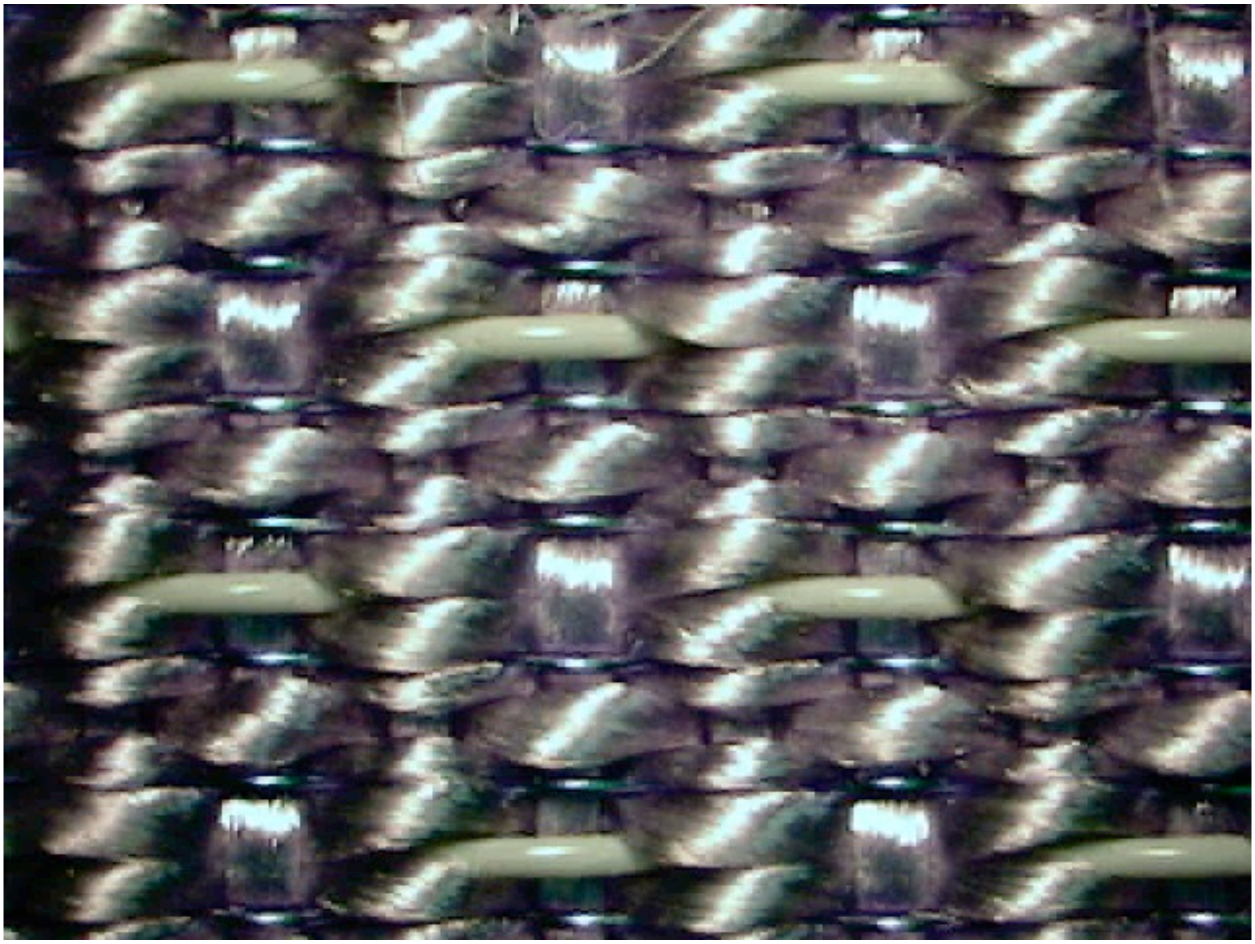


Fig. 7. Close up view of the cable shown in fig. 5.

Three meters of 33 pF/m cable adds 100 pF to the wire capacitance. For the worst case this reduces the signal to noise ratio to 12 but this is still probably acceptable

Another possibility is to use polyimide cables such as those used in the D0 layer 0 silicon detector. These cables can be made on 50 μm substrate so the substrate has little impact on the capacitance. Cables without a ground plane were used in the D0 layer 0 silicon detector. This type of cable is usually constrained to lengths of a meter or so. They ave the advantage that they are easier to clean than a woven cable. If the length is not a constraint, this would be the best cable to use.

Getting a cable that has both low capacitance and low contamination risk will require development effort. Many of the performance features depend on the details of cable construction so cable properties can only be determined by testing samples.

Cryostat Feedthroughs

The ATLAS experiment at CERN has approximately 219,000 feedthroughs into the liquid argon calorimeter[2]. The liquid side of these feedthroughs sees pressures that range from full vacuum to a maximum of 4.5 meters of liquid Argon plus some overpressure. The LBNE detector has 14 meters of argon plus around 3 psi overpressure so the ATLAS feedthroughs have around 30% less design pressure. It is very likely that the connectors will withstand the added pressure so only the metal support needs to be modified. If there is a problem with the connectors holding off the added pressure, there are companies like SEA CON that make connectors for submarines that can easily handle the higher pressure.

The bottom layer of the LBNE detector with 5 mm wire spacing has about 154,000 signals. This is 70% of the existing ATLAS system. Each ATLAS feed through is 300 mm in diameter and caries 1920 lines so 80 feedthroughs would be required. There are 4 rows of TPC modules in this LBNE design so each row would have 20 feedthroughs or one every 2 meters. Fig. 7 shows a possible conceptual design. Details of mounting the feedthroughs are beyond the scope of this analysis.

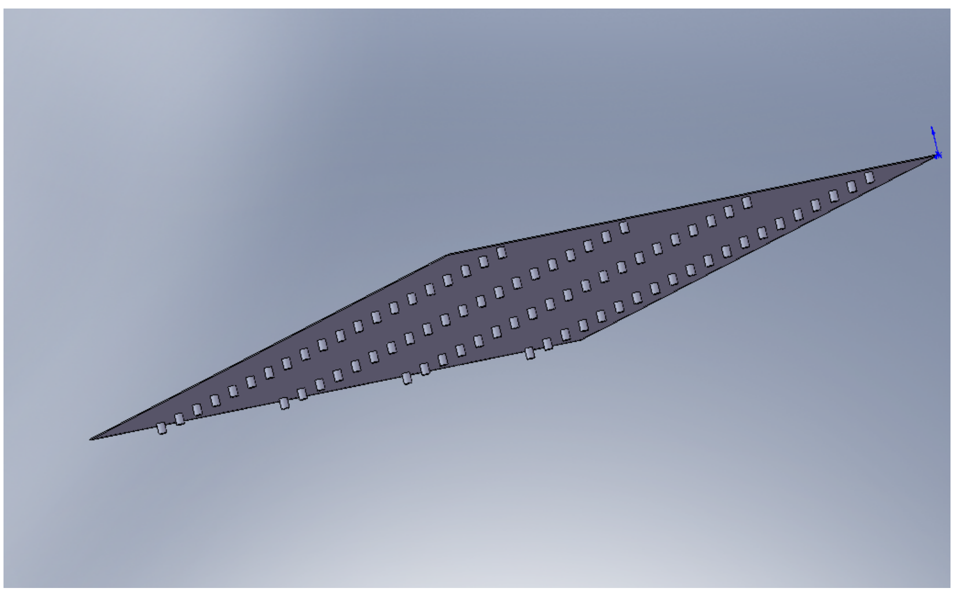


Fig. 7. Conceptual design for the bottom of the cryostat using eighty ATLAS style feedthroughs. Each feedthrough is 300 mm in diameter and 400 mm high.

The feed throughs for cables coming through the top of the cryostat do not need to be as elaborate as those required for immersion in liquid argon. Since the overpressure is small (3 PSI) one could either use PC boards as in the D0 calorimeter (55,000 channels) or polyimide cables as in the D0 VLPC system (102,000 channels). The VLPC system design seems a better choice if long enough cables can be made. It requires no intermediate connectors, is very compact and it operates between 6 degrees kelvin an room temperature in less than 1 meter of cable. Some fraction of the cable would be in gaseous argon or air so the capacitance for these sections would be lower by a factor of 1.6 (dielectric constant of liquid argon).

Each VLPC feedthrough handles 1000 signals and is connected to 2 circuit boards. This could easily be reduced to one board for the LBNE detector. It would also be easy to combine 2 feedthroughs into one unit so that we would have 2000 connections per feedthrough connected to two 9U by 400 mm circuit boards. Thus, the layout would be similar to the bottom one but the feedthroughs would be quite different.

III. All Electronics at the Top

The cables from the top row of TPC modules would be the same as in the previous design. The signals from the bottom layer of TPC modules would be brought to the top by increasing the length of the jumper cable by 7 meters to a total length of 10 meters. The longer cables would most likely need to be woven cable with 33 pF/meter capacitance (231 pF additional capacitance). This will bring the total capacitance of the 10 meter wires from the bottom layer to about 530 pF - an increase by a factor of 2.6 over the bare wire. The large signal still gives a 14 to 1 signal to noise ratio but the smaller one has dropped to 7.3 which is most likely not acceptable.

The feedthroughs at the top would need to be doubled to 4 boards but this still does not look to be a serious problem based on the VLPC design.

IV. Summary

By adopting the ATLAS calorimeter feedthroughs it is possible to use warm electronics and still achieve a good signal to noise ratio. This will require sections of the membrane cryostat to be reinforced so that the feed throughs can be adequately mounted. These feed throughs have nearly the same pressure as the ones used by ATLAS and the ATLAS ones have passed a series of rigid safety testing for use in an underground area. Thus, it is very likely that these could satisfy the safety requirements.

Passing all the cables through the top of the cryostat should not cause many design changes from the current design. However, for the smallest signal estimate, the signal to noise will be around 7 to 1 which is marginal.

References

1. Smythe, *Static and Dynamic Electricity,*Hemisphere Publishing Co., New York, NY, (1989) pp 76-78
2. D. Axen et.al., *Signal feedthroughs for the ATLAS barrel and endcap calorimeters* Rev. Sci. Instrum. 76, 063306 (2005)