Abstract—Large Liquid Argon (LAr) Time Projection Chambers (TPCs) are becoming very attractive for long baseline neutrino and proton decay experiments because of their imaging capabilities and their excellent energy resolution.

In the design of large LTPCs, with wire lengths of several meters (~5m, and up to 10-20m for proposed multi-kiloton detectors), the noise generated by the resistance of the wire needs to be taken into account. The wire cannot be modeled simply as a capacitance connected to the preamplifier: its resistance, coupled capacitively to adjacent wires constitutes a distributed RC diffusive line, which injects a noise current into the preamplifier. It will be shown that for most practical cases the noise source can be modeled as an equivalent noise generator corresponding to a resistance of $R_{\text{wire}}/3$, in series to an impedance equal to the wire capacitance.

This simple models allows the use the familiar formulas for the noise analysis of capacitive sources. The wire resistance noise for a typical 5m long, 150μm stainless steel wire (3mm wire spacing, and 3mm wire planes separation) increases the total noise by about 20% at 1μs shaping time, and becomes dominant for wire lengths >10m. It can be reduced by plating the stainless steel wire with high electrical conductivity metals.

I. INTRODUCTION

LAr TPCs were first proposed [1] in the late’70s as massive detectors with high resolution imaging capabilities for neutrino experiments. For very large volumes, such as a multi-kiloton detector for a Long Baseline Neutrino Experiment (LBNE) at the proposed Deep Underground Science and Engineering Laboratory (DUSEL) [2], the key issue is feasibility of scaling in size before reaching the fundamental limits in terms of the signal-to-noise, and technological limits in terms of the readout complexity and cost.

Traditionally, LAr TPCs have been read out by external, room temperature preamplifiers. This approach adds the capacitance of the readout cable (2-3m in small TPCs and up to 20m in multi-kiloton detectors) parallel to the wire capacitance, increasing total readout noise. It also requires a large numbers of signal feedthroughs, which quickly becomes a limiting factor in the design of large detectors.

The use of low-noise electronics operated in liquid argon allows a high degree of multiplexing, thus reducing the number of signal feedthroughs. This will allow greater freedom in the detector segmentation, and in the choice of the drift distance. The cryogenic electronics at the electrodes will also reduce the overall input capacitance, leading to a superior signal to noise (S/N) performance and detection sensitivity.

As a first step the proposed MicroBooNE experiment [3] has developed a cryogenic JFET preamplifier, operating at $T=120$K in the gas volume inside the MicroBooNE cryostat, greatly reducing the preamplifier readout noise. A multiplexed readout in CMOS technology is also under development.

This approach led also to study an additional noise source: the noise generated by the resistance of the wire itself. Wires used in a TPC need to withstand the tensioning force, and are traditionally made of stainless steel, which has a resistivity of 72μΩ·cm at 300K, which is reduced by about 10% (64.6μΩ·cm) at 90K. For a typical wire of 150μm diameter, the wire resistance is about 36Ω/m at liquid argon temperature (90K), or about 200Ω for a typical length of 5m.

The distributed wire resistance, coupled to adjacent wires (about 20pF/m for the central plane, with 3mm wire spacing and 3mm wire plane separation) constitutes a diffusive line, which injects an additional noise current into the low noise preamplifier.

II. DISTRIBUTED RC DIFFUSIVE LINE NOISE

The wire noise contribution can be calculated by means of Nyquist theorem, which states that the noise power spectrum of any electrical network is related to the terminal impedance by the relation [4]:

$$\epsilon_n^2 = 4 \cdot k_B \cdot T \cdot Re[Z] \quad (1)$$

where $k_B=1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$ is the Boltzman constant and $Re[Z]$ the real part of the network impedance (the impedance of an open ended diffusive line in this case).

Fig. 1 shows a lumped-element representation of a section dx of sense wire modeled as a distributed RC diffusive line. By writing the incremental current $i(x+dx,t)$ and the incremental voltage $v(x+dx,t)$ across a section dx of the line, one can write the differential equation of the diffusive line, a particular case of the more general telegrapher’s equation. The solution...
of the telegrapher’s equation is carried out in [5]. By imposing the boundary conditions, an expression which relates the impedance seen into an open ended transmission line can be written as [5]:

\[ Z_{in} = \frac{Z_\infty}{\cosh(\gamma l)} \]  

(2)

where \( \gamma = \sqrt{Z_\infty} = \sqrt{\frac{r}{j\omega c}} \) is the propagation constant and \( Z_C = \sqrt{Z_\infty} = \sqrt{\frac{r}{j\omega c}} \) is the characteristic impedance, \( r, c \) are the wire resistance and capacitance per unit length and \( l \) is the wire length.

The sense wire as seen from the preamplifier side constitutes an open-ended distributed RC diffusive line. By substituting \( \gamma \) and \( Z_C \) into Eq. (2), we can compute the diffusive line equivalent noise resistance \( R_{eq} \):

\[ R_{eq} = \frac{r \cdot 1 \cdot (\sin(A) - \sinh(A))}{\omega \cdot (\cos(A) - \cosh(A))} \]  

(3)

where \( A = \sqrt{\frac{2}{3}} \cdot 1 \cdot \sqrt{\frac{2}{3} \cdot \frac{1}{\omega c r}} \).

Fig. 2 shows that the wire impedance is capacitive with very good approximation in the frequency range of interest. Only at much higher frequencies the resistance in series with the wire increases the impedance.

Up to a frequency corresponding to the noise corner time constant \( \tau_c = 2/9 R_w C_w \), the noise is white, and equal to the noise of a resistor of value \( R_{eq}/3 \). The case plotted in the figure corresponds to a 5m, 150μm diameter stainless steel wire (\( r = 362 \Omega/m \) at 90K). \( R_w \) and \( C_w \) are the total resistance and capacitance of the sense wire.

The equivalent noise resistance is plotted in Fig. 2. The low frequency limit is a pure resistance of value \( R_{wire}/3 \). It decreases asymptotically as \( f^{-1/2} \). It shows a noise corner time constant \( \tau_c = 2/9 R_w C_w \) where \( R_w \) and \( C_w \) are the total resistance and capacitance of the sense wire. For shaping times longer than \( R_w C_w \) (several times longer than \( \tau_c \)), the RC diffusive line noise generator is approximately white.

To compute the noise Thevenin equivalent circuit, the magnitude of the wire impedance is calculated from Eq. (2):

\[ |Z_{in}| = \frac{r}{\omega c} \left( 1 + \frac{2\cos(A)}{\cosh(A) - \cos(A)} \right) \]  

(4)

where \( A = \sqrt{\frac{2}{3}} \cdot 1 \cdot \sqrt{\frac{2}{3} \cdot \frac{1}{\omega c r}} \) as in Eq. (2).

Fig. 3 shows that the wire impedance is capacitive with well within the frequency range of interest, the impedance is capacitive and equal to \( C_W \).

Fig. 4 shows the equivalent circuit for noise analysis, including the sense wire noise. The sense wire noise \( \left( \epsilon_{n,w} = 4kT(R_w/3) \right) \) and the preamplifier noise (series noise \( \epsilon_{n,p}^2 \) and parallel noise \( \epsilon_{n,par}^2 \)) are independent sources and their respective contributions are summed in quadrature. \( C_{IN} \) includes all capacitances at the input of the preamplifier, except the sense wire capacitance. Typically \( C_{IN} = C_{PA} + C_F + C_{RO} + C_S \), where \( C_{PA} \) is the preamplifier input transistor capacitance, \( C_F \) is the feedback, \( C_R \) is the stray and \( C_{RO} \) is the read-out cable capacitance, which is zero in the case of cryogenic readout.

When considering the sense wire noise contribution, the capacitance \( C_{IN} \) is shorted by the virtual ground at the input of the charge sensitive preamplifier (represented by the short in the preamplifier block). The noise current injected into the preamplifier is \( i_{n,par}^2 = \epsilon_{n,par}^2/(\omega^2 C_w^2) \) and \( i_{n,w}^2 = \epsilon_{n,w}/(\omega^2 C_w^2) \). When considering the preamplifier series noise contribution, the capacitances \( C_W \) and \( C_{IN} \) are in parallel, and the noise current injected into the preamplifier is \( i_{n}^2 = \epsilon_{n,w}^2/(\omega^2 C_w^2) \). This total capacitance limits the signal-to-noise ratio and is the dominant factor on which the feasibility and scalability of a LAr TPC design critically depends.
The equivalent noise charge can be calculated by means of the well established methods for noise analysis of capacitive sources [6].

Fig. 5 shows the total equivalent noise charge (ENC) for a 150μm diameter stainless steel wire assuming (blue line) a readout with a remote preamplifier (outside the cryogenic volume) connected to the sense wire with a 3m readout cable with a total capacitance of 300pF and a cryogenic preamplifier case (green line) which achieves a noise reduction by eliminating the connection capacitance. The same equivalent series noise is assumed for both cases. The dashed lines plot the case in which the sense wire resistance noise is disregarded.

Fig. 5 shows that in the case of a low noise readout employing a cryogenic preamplifier, the wire noise starts to become an important contribution already for sense wire lengths of 4-5m, and becomes the dominant contribution for wires of 10m or longer.

A copper plated (Cu thickness: 2μm) stainless steel wire, with a gold flash metallization to prevent oxidation, has a resistance of only 3Ω/m has been developed by the MicroBooNE collaboration [3] to reduce the wire noise. The use of a plated stainless steel wire is preferable for LAr TPC applications due to its higher strength (break tension ~4kg at cryogenic temperature), compared with low resistivity metals like beryllium-copper. The flash gold metallization prevents copper oxidation and insures a low resistance contact of the connection to the preamplifier.

Fig. 6 plots the calculated noise with the Cu/Au plated wire. The sense wire noise contribution is less than 1% of the preamplifier noise for lengths up to 5m, and it will start to give an appreciable contribution for a sense wire more than 10m long.

III. EXPERIMENTAL VERIFICATION

Short “wire mockups” were built by winding 5m of wire on a teflon threaded rod, inserted into a copper tube with I.D.=8.8mm. The dimensions were chosen so that the capacitance of the wire mockups is ~20pF/cm.

The wire mockup and the preamplifier were cooled in a liquid Argon dewar for ENC noise measurement.

Two wires, both L=5m and 150μm diameter, were tested:

- 304 stainless steel (CSS=105pF, RSS=236Ω at LAr, r~47.2Ω/m)
- 2μm Copper plated 304 SS wire with flash gold metallization to prevent oxidation (CCuAu=107pF, RCuAu=15.8Ω, r~3.2Ω/m)
- A reference mica capacitor Cd=107pF

As plotted in fig. 7, the high resistance stainless steel wire (RSS=236Ω at LAr, r~47.2Ω/m) shows an increase in noise of about 17% with respect of the low resistance copper/gold plated wire (RCuAu=15.8Ω, r~3.2Ω/m). The noise of the copper/gold plated wire is almost identical to the case of a pure capacitance. At longer shaping times, the additional series noise contribution of the wire resistance plays a lesser role.
since the parallel noise (independent of capacitance) is increasing.

IV. CONCLUSION

It has been shown that low noise readout of large liquid argon time projection chambers needs to take into account the contribution of the sense wire resistance. For a wide range of applications, the wire noise can be modeled as a white noise source equal to a resistance of 1/3 of the total sense wire resistance, in series with the capacitance of the wire itself. Such a model allows the treatment of this noise contribution as an additional term added in quadrature to the preamplifier noise, and calculated using the same equations. For a preamplifier noise of ~500 electrons rms, the noise of a 150μm diameter stainless steel wire gives a 20% contribution for lengths of ~5m. Plating the stainless steel wire with 2μm copper (and a gold flash metallization to avoid oxidation) reduces the sense wire resistance to 3Ω/m, and its noise contribution becomes negligible. To achieve a signal to noise ratio of ~10, a low noise cryogenic preamplifier and a sense wires no longer than 5-10m must be used.

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VI. REFERENCES