Occupancy of a Large Liquid Argon TPC due to Cosmic Rays

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Introduction

A large (≈ 100 kton) liquid argon TPC is likely to be affordable only if it can be constructed using existing techniques of the cryogenic liquid industry. That is, an affordable, large LArTPC must be built on the surface, meaning that the top of the cryogenic tank is not below grade.

Such a surface tank is exposed to a flux of cosmic rays[1] (mostly muons) of about 0.01 per cm^2 per sec.[2] The mean energy of these muons is about 4 GeV, so to cut this rate in half requires at a shield of about 10 m of dirt.

Options to deal with the cosmic-ray problem include:

1. Solve the problem via software. *This note sketches some details of the software challenge.*
2. Build lots of small LArTPC modules, rather than one, or a few, big module(s). *Expensive.*
3. Reduce the drift length. *Increases the cost of readout electronics.*
4. Use a pad readout scheme (as in the original TPC of Nygren) instead of wires. *Requires a large number of channels, and considerable R&D.*[3]
5. Build a roof over the detector and cover it with dirt. *Cost study should be made.*
6. Bury the detector deep underground. *Very expensive.*

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[1] http://pdg.lbl.gov/2005/reviews/cosmicrayrpp.pdf

[2] The angular distribution of the muons impinging on a horizontal surface is roughly $dN/d\Omega = A\cos^2\theta$ /cm^2/sr/s, where θ is the polar angle with respect to a vertical axis. The total rate impinging on a **horizontal** detector is $N = 2\pi\int_0^1 d\cos\theta\,\cos\theta\; dN/d\Omega = \pi A/2 = 0.02$ /cm^2/s, since muons at angle θ have relative probability $\cos\theta$ of crossing a horizontal detector. Thus, $A = 2N/\pi$. In a large LArTPC, the relevant readout cell lies in a **vertical** plane. For such a cell, solid angle should be measured in a coordinate system (x', y', z') with its polar axis horizontal. Compared to the original coordinate system (x, y, z) in which the z-axis is vertical, we can take $x' = x$, $y' = z$ and $z' = -y$. Then, $\cos\theta = \sin\theta'\sin\phi'$, and $dN'/d\Omega' = A\sin^2\theta'\sin^2\phi'$. The total rate N' of muons impinging on a vertical strip from both sides(!) is twice that obtained on integrating over θ' from 0 to $\pi/2$, and over the azimuthal angle ϕ' only from 0 to π, which leads to $N' = 2(2N/\pi)\int_0^1 d\cos\theta'\,\cos\theta'\int_0^\pi d\phi'\,\sin^2\theta'\sin^2\phi' = N/2 = 0.01$, *i.e.*, the total rate of muons impinging on a vertical detector is the half that impinging on a horizontal detector.

[3] See pp. 23-24 of http://www.hep.princeton.edu/~mcdonald/nufact/neutrinotrans19.pdf

Cosmic-Ray Rates in a Large LArTPC

We consider a large LArTPC with wire length L = 40 m as an example. We suppose the wire spacing is 5 mm, and each time step in the detector readout to correspond to 1.25 mm (*i.e.*, 4098 time steps for a 5-m drift distance). The effective area of a readout cell is therefore about 40 m x 5 mm = 2000 cm^2. The rate of cosmic rays crossing such a cell at the Earth's surface is about 2000 x 0.01 = 20/sec. If the drift length in the LArTPC is 5 m, then the drift time is about 3 msec, which is the sensitive time of a cell to cosmic rays. Hence, the probability that a readout cell contains a cosmic ray is p = 20 x 0.003 = 0.06.

This is a high occupancy! (And it implies that the readout event size will be quite large.)

However, if the analysis software can successfully convert signals in readout cells into signals in pixels, the pixel occupancy is actually quite low.

The pixel size is 5 mm x 5 mm, so a 40-m long readout cell is to be subdivided in software into 8000 pixels. The occupancy of pixels due to cosmic rays is therefore only 0.06 / 8000 = 7.5×10^{-6}.

Can the Software Successfully Reconstruct Pixels Given the High Rate of Cosmic Rays?

This key question is insufficiently well answered at present.

If the cosmic rays deposited energy in readout cells completely at random, the task of pixel reconstruction would be very difficult. However, cosmic rays leave long tracks in the detector, so we may be able to devise an algorithm that correlates the hit patterns in different readout time slices to reconstruct pixels with improved reliability.

Here, I only comment on the difficulty of reconstructing pixels in a single time slice.

A single time slice corresponds to a volume of about 40 m x 40 m x 1.25 mm, and contains hit data from 3 wire planes of $n \approx$ 8000 wires each, which measure x, u, and v coordinates. The number of hits due to cosmic rays in each wire plane is np. Hence, the hits in two of these three planes form $(np)^2$ candidate signal pixels, of which all but np of these are "ghosts".

The "ghosts" can be eliminated if their positions as projected onto the third wire plane do not match hits in that plane. The number of "ghosts" per wire in the third readout plane is $(np)^2/n = np^2$. If this number is larger than 1, the analysis cannot eliminate the "ghosts". Hence, the wire occupancy p must be less than $1/\sqrt{n}$ for the 3-coordinate readout to successfully eliminate the "ghosts".

In a detector with n = 8000 wires per readout coordinate, the cosmic-ray occupancy p should be less than $1/\sqrt{8000} = 0.011$ for successful pixel reconstruction in an individual time slice.

Given our estimate of p = 0.06 for the cosmic-ray occupancy, the success of the software reconstruction is not guaranteed.

This tends to reinforce my prejudice that it would be better to go from a wire-based readout to a pad-based readout in large LArTPC's.