Occupancy of a Large Liquid Argon TPC due to Cosmic Rays

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Introduction

A large ($\approx$ 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

$dN / d\Omega = N_0 \cos^2 \theta$ /cm²/sr/s, where θ is the polar angle with respect to a vertical axis. The total rate

impinging on a **horizontal** detector is $N_H = 2\pi \int_0^1 d \cos\theta \ dN / d\Omega = 2\pi N_0 / 3 \approx 0.017$ /cm²/s.

Thus, $N_0 = 3 N_H / 2\pi \approx 0.008$. In a large LArTPC, the relevant readout cell lies in a **vertical** plane.

For such a cell with area A_V, muons arriving at angle (θ, φ) cross a horizontal area

$A_H = \tan\theta \cos\varphi A_V$ in line with the top of area A_V. The total rate N_V of muons impinging on a vertical

strip from both sides(!) is twice that obtained on integrating over θ from $-\pi / 2$ to $\pi / 2$, and over the

azimuthal angle ϕ only from 0 to π, which leads to

$N_V = 2 \int_0^1 d \cos\theta \int_{-\pi/2}^{\pi/2} d\phi \ \tan\theta \cos\phi \ dN / d\Omega = 2 N_H / \pi \approx 0.01$. Thus, the total rate of muons

impinging on (both sides of) a vertical detector is about 2/3 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 $0.06 / 8000 = 7.5$ x 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.[4]

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".

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[4] This turns out NOT to be a good strategy. A much better approach is discussed on p. 5 (added June 10, 2006).

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.

Reduction of Occupancy due to Ranging Out of the Cosmic Rays (added June 11, 2006)

The above estimate assumes that all cosmic rays penetrate the entire detector. However, many low-energy cosmic rays come to rest inside the detector, so the readout-cell occupancy is smaller than $p = 0.012$.

For a revised estimate we follow a suggestion by Stephen Pordes. We now consider the rate of cosmic rays entering the surface of a large LArTPC in the form of a right circular cylinder of diameter = height = d. Then, we estimate the number of readout-cell time slices occupied by these cosmic rays, based on their path length projected onto a (horizontal) axis perpendicular to the (vertical) readout planes.

For this estimate, we specify the arrangement of readout wires more completely. With diameter d = 40 m, and a drift length of 5 m, there are 8 drift modules in the detector. The readout planes are located at $z' = \pm 5, \pm 15$ m, where z' is the horizontal axis of the coordinate system described in footnote 2. The widths of the readout wire planes along the $x' = x$ coordinate are 39.7 and 22.4 m. With a wire spacing of 5 mm there are 200 wires per meter, so the total number of (vertical) wires in the detector is $200 \times 4 \times (39.7 + 22.4) \approx 50,000$. Each of these wires is read out in ≈ 4000 time slices during the 3-msec drift time over 5 m, so the total number of readout-cell time slices for vertical (x) wires is $T_x = 2 \times 10^8$. There are roughly the same total numbers T_u and T_v of readout-cell time slices for the tilted wire planes.

Following the argument in footnote 2, the rate R_{top} of cosmic-ray muons entering the (horizontal) top of the detector, whose area is $\pi d^2 / 4$, is $R_{top} = N\pi d^2 / 4$. The rate R_{side} of muons entering the (vertical) sides of the detector, whose area is $2\pi d^2$, is $R_{side} = (N/4)2\pi d^2$, where we use $N/4$, rather than $N/2$ as in footnote 2, since now we count only those muons entering the detector from the outside. The total rate R of cosmic-ray muons entering the detector is therefore $R = 3N\pi d^2 / 4$.

With $N = 0.02$ /cm^2/s, and $d = 40$ m, we have $R \approx 750,000$ /s. During the 3-msec live time of the readout, $M \approx 2250$ cosmic-ray muons enter the detector.

The average energy of these muons is 4 GeV, so the average path length P of the cosmic rays in liquid argon, for which $dE/dx \approx 200$ MeV/gm/cm^2, is $P = 20$ m. The angular

distribution of the cosmic rays is $dN'/d\Omega' = (3/\pi)\sin^2\theta'\sin^2\phi'$, where now I normalize this distribution to unity over one hemisphere in the (x', y', z') coordinate system. The average path length as projected onto the (horizontal) z' axis is

$$P' = \int_0^1 d\cos\theta' \, P\cos\theta' \int_0^\pi d\phi'(3/\pi)\sin^2\theta'\sin^2\phi' = \pi P/12 = 5.2 \text{ m.}$$

Thus, the average number of time slices occupied by a cosmic ray is $5.2 / 0.00125 \approx 4160$.[5]

The total number of occupied readout-cell time slices (in one readout coordinate) is approximately $4160 \, M \approx 9 \times 10^6$. The revised estimate of the probability p that a readout-cell time slice is occupied by a cosmic ray muon is therefore, $p \approx 9 \times 10^6 / 2 \times 10^8 = 0.045$.

This is a factor of 3 lower than our first estimate, but it still is a large occupancy.

Better "Ghost" Rejection due to Finding Tracks in Projection before 3-d

The ranging out of low-energy cosmic rays yields an additional improvement in the task of reconstructing 3-d space points from the hits in the readout-cell time slices.

Namely, the average projected path length P' is only 1/8 of the diameter of the detector, so the typical cosmic ray track has a well-defined end point in the detector. So, the pattern recognition could proceed by first reconstructing track projections in each of the x, u and v coordinates separately, using the time-slice data corresponding to each coordinate. That is, the timing information gives the z' coordinate of a hit, so we can reconstruct track projections in the x-z', u-z' and v-z' planes.[6]

Suppose the beginning and end points of these track projections can be determined to an accuracy of $z' = 1$ cm. Then, when forming 3-d tracks, we need only consider triplets of track projections whose beginning and end points agree to within 1 cm. For a detector diameter of $d = 40$ m, the probability that two different cosmic rays out of the total of $M = 2250$ have the same end point in z' to within 1 cm out of the total range $d = 4$ m is roughly $q = M / 4000 = 0.56$, assuming the distribution of end points is uniform in z'.

In a detector that is a right circular cylinder, the distribution of beginning points of cosmic ray tracks along coordinate z' has the form $\sin\theta' + 2/\sin\theta'$, which is not uniform – but it is not a δ-function either. Hence, the number of candidate matches of track projections can be further reduced by a requirement that their beginning points, as well as their end points, match in z'.

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[5] For cosmic rays with $\theta' \approx \pi/2$ more than one adjacent wire will be "hit" during each time slice. We ignore this small effect for now.

[6] The relatively high occupancy of 0.045 per readout-cell time slice means that the reconstruction of track projections will not always be free from ambiguities. Because the cosmic rays have a broad angular distribution, I am cautiously optimistic that the quality of reconstruction of track projections will be high enough that the following argument is roughly correct.

However, the result that the probability q of two muons having the same end point is only 0.56 implies that 3-d track reconstruction is simple and reliable. The number of track projections in, say, the u and v coordinates that might match a projection in x is seldom more that one, so the use of 3 coordinates to eliminate "ghost" tracks will be highly successful.

The above considerations of pattern recognition beginning with formation of track projections in the x-z', u-z' and v-z' planes before reconstruction of 3-d tracks have largely restored my confidence that a large LArTPC can be used successfully for long-baseline neutrino physics on the Earth's surface.