Technical Proposal: Calibration for the DUNE Far Detector

DUNE collaboration

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Contents

1 Introduction to Calibration - 2 pages

How physics proceeds in a LAr TPC; TPC response model overview. Why calibration is needed. How the sections are organized. Motivate need for redundancy, model parameter determination and also test limits of the model. Enormous correlation between parameters may make it hard to isolate effects.

2 Physics Requirements for Calibration Systems - 3 pages

DUNE has a broad physics program with needs served by calibration. Section 2.1 describes the impact of calibration-driven physics on the long baseline program, Section 2.2 describes the supernova physics program which relies on low energy interactions, and Section 2.3 describes exotic physics model searches, including nucleon decay.

Most of the studies done so far are generic, that is they demonstrate the impact of categories of effects. For example, the impact of energy bias is discussed for the long baseline analysis, and such bias can stem from: the neutrino interaction model, insufficient calibration, or reconstruction pathologies. For this note, we take as a target that calibration, by itself, needs to be sufficient for DUNE's program; other issues which limit the physics program are out of scope and errors always add in quadrature.

2.1 Long baseline physics

DUNE's long baseline program (LBL) uses measurements of ν_e, $\overline{\nu}_e$ appearance and ν_μ disappearance, to probe for new physics with neutrinos, including a search for CP violation, and the mass hierarchy. Additional far detector physics includes measurements with atmospheric neutrinos, ν_τ appearance, and non-standard matter interactions or other effects. These programs all rely on neutrinos of energies 0.2-10 GeV.

In the DUNE Physics CDR [1], Figure 3.23 shows that increasing the uncertainties on the ν_e event rate from 2% overall[1] to 3% results in a 50% longer run period, The CDR also assumes that the fiducial volume is understood at the 1% level. Thus, calibration information needs to provide approximately 1-2% understanding of normalization, energy and position resolution within the detector. Studies by E. Worcester in March 2016 [2] expanded the simple treatment of energy presented above. In particular, 1% bias on the lepton energy has a significant impact on the sensitivity to CP violation, and 3% bias in the hadronic state (excluding neutrons), is important as well.

Due to the enormous size of the DUNE FD, relative differences throughout the volume will need to be monitored and corrected; this is also true for changes which occur in time requiring detection and correction. *Size of relative E scale effects studied in LBL so far?*

The estimate of the calibrated signal received at the anode (dQ/dx) depends on*Reference!*:

[1] This uncertainty is an uncorrelated normalization uncertainty on the far detector ν_e rate, after the near detector information is included.

$$dQ/dx = dE/dx \times \frac{1}{W} \times R \times L \times D \times C \tag{1}$$

where dE/dx is the energy lost by the initial particle through ionization through a distance dx, W is the energy needed to free an electron, R is the recombination of electrons to Ar^- atoms, L is the lifetime of electrons, D is diffusion, and C is the calibration of electronics response. For a particle not traveling parallel to the wire, $dx = |dy + dz + v_d t|$, where dy and dz are the distances in the y and z direction, and the x (drift) direction position depends on the drift velocity (v_d).

The electric (E) field has a critical role in the DUNE as the E field impacts drift velocity, recombination, and therefore the energy estimate (dQ/dx). Approximately, a 1% distortion to the E field will correspond to a 0.25% distortion to dQ/dx. Distortions of the E field can occur locally or globally, and are due to a variety of effects. For example, CPA misalignment, CPA structural deformations, and APA/CPA offsets may create E field distortions localized in space. Non-uniform resistivity in the voltage dividers which create the E field may create a net E field distortion localized in space, and a failure of a resistor will create a sudden change in time. Penetrations to the field cage will also create distortions to the E field. Finally, accumulation of slow moving positive ions, created from cosmic rays or from Ar39 localized in space ("space charge") will distort the E field. Each individual E field distortion sources may add in quadrature with other effects, and can exceed 1-4% overall E field distortion. We note that if DUNE does not run at nominal E field, then recombination is higher, and the drift time is longer. Both of these effects make make the understanding of E field in-situ even more important.

Distortions to the electric field also create spatial deformations which propagate to dQ/dx. Examples of this include space charge, and misalignments. These distortions occur in three dimensions, but the dominant effect is in the drift direction (the direction of the nominal E field, x), so for this document, we estimate the scale of these effects only in x.

Spatial deformations within the detector can also impact the energy estimator. Particles in the detector will repeatedly (elastic) Coulomb scatter with the liquid resulting in small, randomized deviations to their path. Multiple Coulomb Scattering (MCS) is used estimate the particles initial energy, but relies on a known distance the particles traveled. If the distance is different than expectation due to misalignments or E field spatial deformations, then this may bias the estimator.

Particle ID: How well does the calorimetry identify particles?

The fiducial volume (and position resolution) is impacted by our understanding of the distances within the detector, drift velocity and electric field. Like the energy scale case, fiducial volume is affected by relative distortions across the detector either from spatial or temporal causes.

The stringent physics requirements on energy scale and fiducial volume therefore put similarly stringent requirements onto E field, spatial deformations (alignment), drift velocity, electron lifetime, and the time dependences of these quantities.