Space Charge Effect at protoDUNE: Laserless Calibration Strategy

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We have heard recently that it is very likely that there will be no UV laser system at protoDUNE with which to calibrate out space charge effects (SCE), among other things.

This will impact our calibration strategy significantly!

Talks at protoDUNE Science Workshop highlight this:

- [https://indico.fnal.gov/getFile.py/access?contribId=10&sessionId=8&resId=0&materialId=slides&confId=12042](https://indico.fnal.gov/getFile.py/access?contribId=10&sessionId=8&resId=0&materialId=slides&confId=12042)
- [https://indico.fnal.gov/getFile.py/access?contribId=42&sessionId=8&resId=0&materialId=slides&confId=12042](https://indico.fnal.gov/getFile.py/access?contribId=42&sessionId=8&resId=0&materialId=slides&confId=12042)

As mentioned at this workshop, must have a sample of muon tracks with known $t_0$ in order to know track location in drift direction

- It has not been shown yet at MicroBooNE that we can obtain a clean sample of $t_0$-tagged tracks with the light-collection system, without significant efficiency hit (looking for low-track events with minimal cosmics activity)
- At protoDUNE, expect significantly more tracks per readout window...

Highlight considerations for cosmic ray tagger (CRT) in this talk, including placement and how to do calibration.
Quick Look at SCE Impact

$E_{\text{nominal}} = 500 \text{ V/cm}$

Nominal SP Geometry

Actual $\Delta E_x/E_{\text{nominal}}$ [%]: $Z = 3.60 \text{ m}$

Actual $\Delta E_y/E_{\text{nominal}}$ [%]: $Z = 3.60 \text{ m}$

$E_X$

$E_Y$

cathode

$\Delta X$

$\Delta Y$
Quick Look at SCE Impact

**Nominal SP Geometry**

At 500 V/cm, for protoDUNE-SP:

- Impact on recombination: $\sim 10\%$
- Impact on spatial distortions (drift): $\sim 5$ cm
- Impact on spatial distortions (transverse): $\sim 20$ cm

Much worse for protoDUNE-DP
Much worse for lower drift field
Two samples of $t_\circ$-tagged tracks can provide SCE corrections:

- **Single tracks** – enable corrections at TPC faces by utilizing endpoints of tracks (correction vector approximately orthonormal to TPC face)
- **Pairs of tracks** – enables corrections in TPC bulk by utilizing unambiguous point-to-point correction looking at track crossing points

- Require high-momentum tracks (plenty from cosmics, beam halo)
♦ Claim on previous slide is that the correction at TPC faces using single tracks is the correction vector obtained by projecting the track end point onto the closest TPC face.

♦ True at most boundaries as only one SCE component is large.

♦ TPC edges (boundaries in $Y$ and $Z$) will still need pairs of tracks.
Why Crossing Points?

- As Igor pointed out at protoDUNE Science Workshop, a single laser track is not enough to obtain the SCE correction vector.
- Principle applies to calibration with muon tracks as well!
Recently discussed with Flavio possible arrangement of CRT panels on front and back of detector

- 8+8 panels on front, 8+8 panels on back

- Would be useful to tag $t_0$ for both muon halo tracks and cosmic muon tracks

- 32 panels in total, but possibly more to use elsewhere?
With anode planes and front/back CRT panels, you get three samples of $t_o$-tagged tracks:

- Cosmics crossing both anode planes (left)
- Cosmics crossing a CRT panel (middle)
- Muon halo tracks crossing a CRT panel (right)
Combining these $t_0$-tagged track samples, we get complete coverage for single tracks!

However, if you want to calibrate in the bulk, you need track pairs, and they should be at relatively large angle w.r.t. each other.

Near top of TPCs would have much lower statistics – CRT coverage on top helps (muon halo, tag from top CRT)

• Front/back CRT cosmics will help fill in these areas as well (not shown)
Combining these $t_0$-tagged track samples, we get complete coverage for single tracks!

However, if you want to calibrate in the bulk, you need track pairs, and they should be at relatively large angle w.r.t. each other.

Near top of TPCs would have much lower statistics – CRT coverage on top helps (muon halo, tag from top CRT)

- Front/back CRT cosmics will help fill in these areas as well (not shown)
We can perform a calibration of space charge effects without a laser system using cosmic tracks and muon halo tracks IF we can tag $t_0$ with high reliability

- Use both single tracks and track pairs for calibration of TPC faces and TPC bulk, respectively

Best way to do this is extensive CRT system

Light-collection system likely not able to reliably (high degree of certainty as required in calibration) tag $t_0$

- At least this has not been shown yet in an existing LArTPC experiment with a light-collection system – and track environment at protoDUNE busier

Installing CRT panels on front/back of detector in discussion

Might consider adding additional CRT panels on top for additional coverage in an important part of detector (has large distortions)

- May not be necessary if enough cosmics from CRT front/back panels
Space Charge Effect

- **Space charge**: excess electric charge (slow-moving ions) distributed over region of space due to cosmic muons passing through the liquid argon
  - Modifies E field in TPC, thus track/shower reconstruction
  - Effect scales with $L^3$, $E^{-1.7}$

Ion Charge Density

\[
\alpha = \frac{D}{E_0} \sqrt{\frac{K}{\epsilon \mu}}
\]

\[
v = \mu E
\]

Approximation!

B. Yu

K. McDonald

No Drift!
SpaCE: Overview

♦ Code written in C++ with ROOT libraries
♦ Also makes use of external libraries (ALGLIB)
♦ Primary features:
  • Obtain E fields analytically (on 3D grid) via Fourier series
  • Use interpolation scheme (RBF – radial basis functions) to obtain E fields in between solution points on grid
  • Generate tracks in volume – line of uniformly-spaced points
  • Employ ray-tracing to “read out” reconstructed \{x,y,z\} point for each track point – RKF45 method
♦ First implemented effects of uniform space charge deposition without liquid argon flow (only linear space charge density)
  • Also can use arbitrary space charge configuration
    – Can model effects of liquid argon flow (however, interpretation is difficult)
Two separate effects on reconstructed tracks:

- Reconstructed track shortens laterally (looks rotated)
- Reconstructed track bows toward cathode (greater effect near center of detector)

Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven calibration.
♦ Looking at central z slice (z = 5 m) in x-y plane (MicroBooNE)
♦ Very good shape agreement compared to Bo Yu's 2D FE (Finite Element) studies
♦ Normalization differences understood (using different rate)
♦ Looking at central z slice (z = 5 m) in x-y plane (MicroBooNE)
♦ Very good shape agreement here as well
  • Parity flip due to difference in definition of coordinate system
Compare 30 x 30 x 120 field calculation (left) to 15 x 15 x 60 field calculation with interpolation (right) – for MicroBooNE

Include analytical continuation of solution points beyond boundaries in model – improves performance near edges

Actual $\Delta E_x/E_{\text{nominal}}$ [%]: $Z = 5.00$ m

Interpolated $\Delta E_x/E_{\text{nominal}}$ [%]: $Z = 5.00$ m
Example: track placed at $x = 1 \text{ m}$ (anode at $x = 2.5 \text{ m}$)

- $z = 5 \text{ m}, y = [0, 2.5] \text{ m}$

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**MicroBooNE**
Sample “Cosmic Event”

Nominal Drift Field
500 V/cm

Half Drift Field
250 V/cm

MicroBooNE
♦ Not accounting for non-uniform charge deposition rate in detector → significant modification?

♦ Flow of liquid argon → likely significant effect!
  • Previous flow studies in 2D... differences in 3D?
  • Time dependencies?

No Flow  Flow w/o Turbulence  Flow w/ Turbulence
Liquid Argon Flow
Smoking-gun Test for SCE

- Can use cosmic muon tracks for calibration
  - Possibly sample smaller time scales more relevant for a particular neutrino-crossing time slice
  - Minimally: data-driven cross-check against laser system calibration

- **Smoking-gun test:** see lateral charge displacement at track ends of non-contained cosmic muons → space charge effect!
  - No timing offset at transverse detector faces (no $E_x$ distortions)
  - Most obvious feature of space charge effect
35-ton with LAr Flow

$\Delta x$

**Without LAr Flow**

$X_{\text{reco}} - X_{\text{true}}$ [cm]: $Z = 0.80$ m

**With LAr Flow**

$X_{\text{reco}} - X_{\text{true}}$ [cm]: $Z = 0.80$ m

central z slice

Q map from E. Voirin
35-ton with LAr Flow (cont.)

\[ \Delta y \]
Without LAr Flow

\[ \Delta z \]
Without LAr Flow

\[ \sim 0 \]

\[ \Delta y \]
With LAr Flow

\[ \Delta z \]
With LAr Flow

Q map from E. Voirin

central z slice
Can use SpaCE to produce displacement maps

- **Forward transportation**: \( \{x, y, z\}_{\text{true}} \rightarrow \{x, y, z\}_{\text{sim}} \)
  - Use to simulate effect in MC
  - Uncertainties describe accuracy of simulation

- **Backward transportation**: \( \{x, y, z\}_{\text{reco}} \rightarrow \{x, y, z\}_{\text{true}} \)
  - Derive from calibration and use in data or MC to correct reconstruction bias
  - Uncertainties describe remainder systematic after bias-correction

Two principal methods to encode displacement maps:

- **Matrix representation** – more generic/flexible
- **Parametric** representation (for now, 5\(^{th}\)/7\(^{th}\) order polynomials) – fewer parameters
  - Uses matrix representation as input → **use for LArSoft implementation**
Nominal SP protoDUNE geometry:
• Drift (X): 3.6 m
• Height (Y): 5.9 m
• Length (Z): 7.0 m

Dimensions used for simulations slightly different (to simplify calculations):
• Drift (X): 3.6 m
• Height (Y): 6.0 m
• Length (Z): 7.2 m
Nominal SP protoDUNE geometry:
- Drift (X): 3.6 m
- Height (Y): 5.9 m
- Length (Z): 7.0 m

Dimensions used for simulations slightly different (to simplify calculations):
- Drift (X): 3.6 m
- Height (Y): 6.0 m
- Length (Z): 7.2 m

Results here shown only for nominal geometry – for modified geometry with reduced maximal drift length, see backup slides.
Modified E Field (Central Z)

Nominal Geometry

\[ E_{\text{nominal}} = 500 \text{ V/cm} \]

Actual \( \Delta E_x / E_{\text{nominal}} \) [%]: \( Z = 3.60 \text{ m} \)

\[ E_{\text{nominal}} = 250 \text{ V/cm} \]

Actual \( \Delta E_x / E_{\text{nominal}} \) [%]: \( Z = 3.60 \text{ m} \)

Ex cathode

Ey anode

\( E_x \)

\( E_y \)
Modified E Field (TPC End)

Nominal Geometry

\[ E_{\text{nominal}} = 500 \text{ V/cm} \]

\[ E_{\text{nominal}} = 250 \text{ V/cm} \]

Actual \( \Delta E_z/E_{\text{nominal}} \) [%]: \( Z = 0.20 \text{ m} \)

cathode

anode
Spatial Distortions (Central Z)

\[ E_{\text{nominal}} = 500 \, \text{V/cm} \]

\[ E_{\text{nominal}} = 250 \, \text{V/cm} \]

\[ \Delta X \]

\[ \Delta Y \]

Nominal Geometry

\[ X_{\text{reco}} - X_{\text{true}} [\text{cm}]: Z = 3.60 \, \text{m} \]

\[ Y_{\text{reco}} - Y_{\text{true}} [\text{cm}]: Z = 3.60 \, \text{m} \]
**Spatial Distortions (TPC End)**

Nominal Geometry

\[ E_{\text{nominal}} = 500 \text{ V/cm} \]

\[ E_{\text{nominal}} = 250 \text{ V/cm} \]

\[ \Delta Z \]

**cathode**

**anode**

Z_{\text{reco}} - Z_{\text{true}} [cm]: Z = 0.20 m
SP/DP Comp. – E Field Dist.

**SP** (500 V/cm)  **DP**

Actual $\Delta E_x/E_{\text{nominal}}$ [%]: $Z = 3.60$ m

Actual $\Delta E_y/E_{\text{nominal}}$ [%]: $Z = 3.00$ m

Nominal Geometry

$E_x$  $6$ m $\times$ $6$ m  $6$ m $\times$ $6$ m

$cathode$  $anode$

$E_y$
SP/DP Comp. – E Field Dist.

Nominal Geometry

SP  (500 V/cm)  DP

Actual $\Delta E_x/E_{nominal}$ [%]: $Z = 3.60 \text{ m}$

Actual $\Delta E_x/E_{nominal}$ [%]: $Z = 3.00 \text{ m}$

E field distortions roughly 2× larger at DP compared to SP
SP/DP Comp. – Spatial Dist.

Nominal Geometry

SP  (500 V/cm)  DP

$X_{\text{reco}} - X_{\text{true}} \text{ [cm]: } Z = 3.60 \text{ m}$

$Y_{\text{reco}} - Y_{\text{true}} \text{ [cm]: } Z = 3.60 \text{ m}$

$cathode$  $\Delta X$

$6 \text{ m} \times 6 \text{ m}$  $\times 6 \text{ m}$

$anode$  $\Delta Y$

$X_{\text{reco}} - X_{\text{true}} \text{ [cm]: } Z = 3.00 \text{ m}$

$Y_{\text{reco}} - Y_{\text{true}} \text{ [cm]: } Z = 3.00 \text{ m}$
SP/DP Comp. – Spatial Dist.

Nominal Geometry

**SP** (500 V/cm) **DP**

$X_{\text{reco}} - X_{\text{true}} \ [\text{cm}]: Z = 3.60 \text{ m}$

$X_{\text{reco}} - X_{\text{true}} \ [\text{cm}]: Z = 3.00 \text{ m}$

Spatial distortions roughly $3 \times$ larger at DP compared to SP

$\Delta X$

$cathode$

$\Delta Y$

$anode$

$6 \text{ m} \times 6 \text{ m} \times 6 \text{ m}$
Modified ProtoDUNE geometry:

- **Drift (X):** 2.2 m
- **Height (Y):** 5.9 m
- **Length (Z):** 7.0 m

Dimensions used for simulations slightly different (to simplify calculations):

- **Drift (X):** 2.4 m
- **Height (Y):** 6.0 m
- **Length (Z):** 7.2 m


**Modified Geometry**

- **E**\textsubscript{nominal} = 500 V/cm
- **E**\textsubscript{nominal} = 250 V/cm

Actual $\Delta E_x/E_{\text{nominal}}$ [%]: Z = 3.60 m

Actual $\Delta E_y/E_{\text{nominal}}$ [%]: Z = 3.60 m

- **E**\textsubscript{X} \text{ cathode}
- **E**\textsubscript{Y} \text{ anode}
Modified Geometry

\( E_{\text{nominal}} = 500 \text{ V/cm} \)

\( E_{\text{nominal}} = 250 \text{ V/cm} \)

Actual \( \Delta E / E_{\text{nominal}} \) [%]: \( Z = 0.15 \text{ m} \)
Distortions (Central Z)

\[ \mathbf{E}_{\text{nominal}} = 500 \text{ V/cm} \]

\[ \mathbf{E}_{\text{nominal}} = 250 \text{ V/cm} \]

\( X_{\text{reco}} - X_{\text{true}} \text{ [cm]: } Z = 3.60 \text{ m} \)

\( Y_{\text{reco}} - Y_{\text{true}} \text{ [cm]: } Z = 3.60 \text{ m} \)

\( \Delta X \)

\( \Delta Y \)

Cathode

Anode

Modified Geometry
Distortions (TPC End)

Modified Geometry

\[ E_{\text{nominal}} = 500 \text{ V/cm} \]

\[ E_{\text{nominal}} = 250 \text{ V/cm} \]
♦ Fill in displacement correction map gaps using cosmic muons

♦ One idea: correction from center of line connecting points of closest approach (separation $d$) between two tracks (before and after SCE)
  • Get “true” muon track from PCA fit to already-calibrated points
  • Weight each contribution by $e^{-d/D}$ (where $D$ is tunable parameter)
  • Use only high-momentum cosmics to minimize MCS effects

♦ Relies on first correcting points at boundaries, high stats to average out MCS, and knowing track $t_0$