ND LAr TPC Calibration System

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Motivation

- ND measurements of the neutrino flux and extrapolation of measurements to FD must have systematic error subdominant to FD systematic error.

- The calibration program should:
  - Deliver calibration correction function – corrects estimated ionization deposition of charge at a position → to obtain true value of ionization deposition of charge at a true position
  - Verify detector performance at a few percent or better level
  - Achieve sufficient spatial granularity in the detector volume
  - Calibrate detector movements
  - Track detector changes over its lifetime.

- Dedicated calibration system combined with abundant rock is planned to fulfil this task.

Calibration System Overview

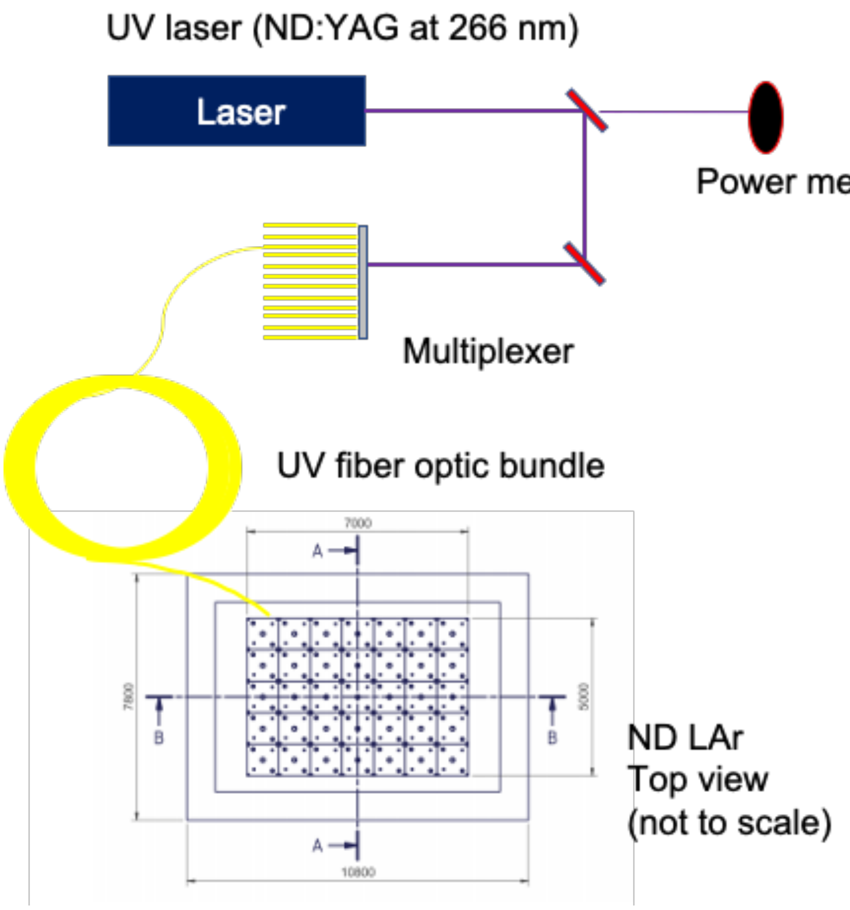
- Tracks of rock muons crossing from cathode to anode are well constrained by their entry point on cathode and exit point on anode.

- Hit pixel signal pinpoints the position of the rock muon exit point, while the calibration system on the cathode provides calibration of the position on the cathode.

- Localized electron clouds generated in predetermined locations on the cathode, provide an effective way of calibrating position and ionization charge deposition at cathode.

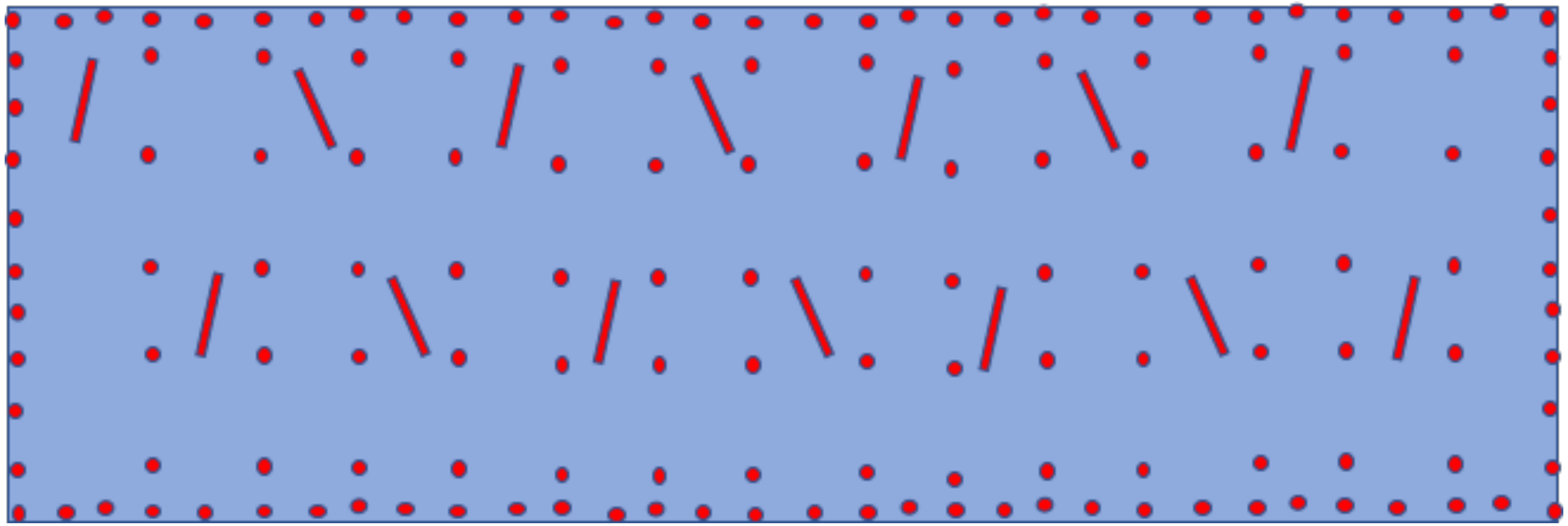
- Localized electron clouds can be generated via dedicated Photoelectron (PE) laser system shining on photoelectric targets on the cathode (first choice) or via localized radioactive sources placed on the cathode (second choice).

Photoelectron Calibration System



- NdYAG laser beam is injected in optical fibers
- Optical fibers deliver 266 nm photons to individual TPC modules
- Optical diffusers inside modules diffuse light in TPC and llumnate cathode
- 266 nm light hits metal targets on the cathode
- Localized clouds of electrons are released from the targets via photoelectric effect
- Targets made of aluminum or silver have work function lower than energy of 266 nm photons

Metal targets on Cathode



- Preliminary plan is to place targets every 10 cm along the edge and every 20 cm inside, to account for anticipated higher field distortions along the edge
- Targets placed on both sides of the cathode
- Two target sizes under consideration: 2.5 mm and 5 mm.
- Metal strips 0.5 cm x 20 cm provide measure of transverse diffusion in the TPC
- Total of 300 disc targets and 28 strip targets per module
- Due to cathode height, 3 fibers per volume foreseen, and 6 per TPC module

Calibration goals

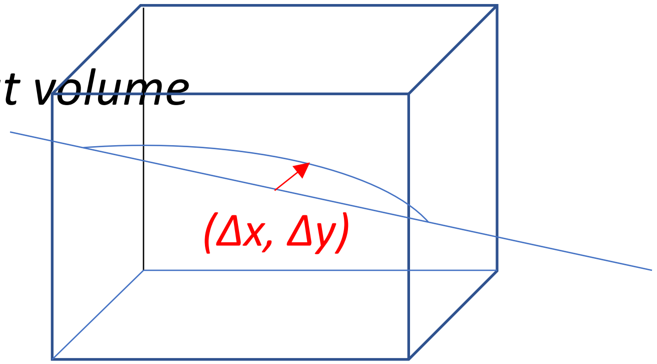
- Address effects that contribute to the deviation of the true and uncalibrated signal positions:
  - Incorrect assumption of 3D shape of the TPC modules (e.g. manufacturing tolerances)
  - Change of module 3D shape/position following cryogenic cooldown or following PRISM movement
  - Incorrect assumption of mean electric field strength, and thereby electron drift velocity
  - Nonuniformity of electric field (e.g. anode-cathode co-planarity, field cage imperfections, material charge-up, space charge effects)
- Address effects that contribute to the deviation of the true and uncalibrated signal charge:
  - Inaccurate corrections for electron drift losses due to liquid argon impurities
  - Inaccurate corrections for electron recombination due to deviations in local electric field strength
  - Inaccurate model of the pixel response to drifting charge
  - Inaccurate model of the front-end electronics channel gain and/or linearity

Calibration Procedure to Address Calibration Goals

- **Part I - Position calibration**
  Step 1 - creation of the integral 2D spatial correction map using the photoelectric targets on the cathode
    - *With PE laser generate electron clouds at targets on cathode, that will drift toward anode*
    - *Compare reconstructed positions of the targets on cathode, based on hit pixel reconstruction, with surveyed target positions at the time of installation → [Δx, Δy] correction map at each target x and y*
- *Step 2 - Deviation in the anode-cathode coplanarity correction - 3D corrected photoelectric target spatial map*
    - *Compare drift times for electron clouds from different targets, calculate drift velocity and its variation to detect deviation from anode-cathode coplanarity*
    - *Based on the drift times, correct z coordinate of targets on cathode with Δz at each target*
    - *Generate integral 3D spatial correction map [Δx, Δy, [Δz] for the reconstructed position at each target*

Calibration Procedure to Address Calibration Goals

- **Part I - Position calibration**
  Step 3 - 3D spatial correction map for intermediate volume using crossing rock muons tracks due to non-zero transverse electric field
    - *Determine rock muon entry point on the cathode by interpolating 3D correction map obtained in Step 2*
    - *Determine rock muon exit point based on the coordinates of hit pixel*
    - *Divide intermediate volume into xy planes and for each voxel identify crossing rock muons passing through that voxel*
    - *Calculate average deviation in xy plane between straight true track and reconstructed curved track*
    - *Construct (Δx, Δy) for each z drift direction coordinate throughout volume*



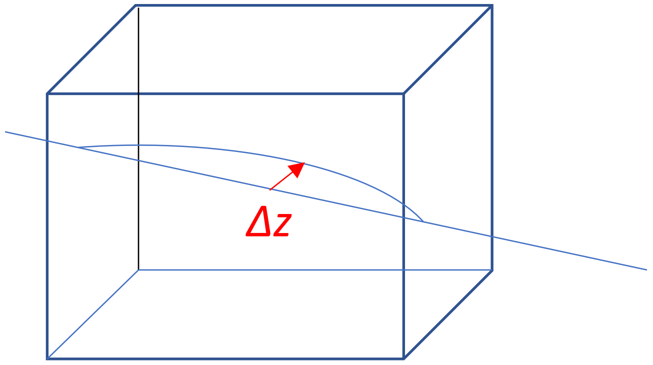
Calibration Procedure to Address Calibration Goals

Part I - Position calibration

Step 4 - 3D spatial correction map for intermediate volume using crossing rock muons tracks due to changes in the electric field magnitude in the drift direction

- *Using the same set of crossing rock muons from Step 3, determine deviation in z between straight and reconstructed track*
- *Calculate average deviation in Δz for given xyz plane between straight true track and reconstructed curved track*
- *Construct (Δx, Δy, Δz) for each (x, y, z) voxel in intermediate volume*

Step 5 - Time variation of the 3D spatial correction map for intermediate TPC volume



Calibration Procedure to Address Calibration Goals

Part II – Ionization charge calibration
Typical minimum ionizing muon has energy 4-6 GeV and deposits about 1.7 MeV/cm of track. Based on MicroBooNE and ProtoDUNE charge calibration method

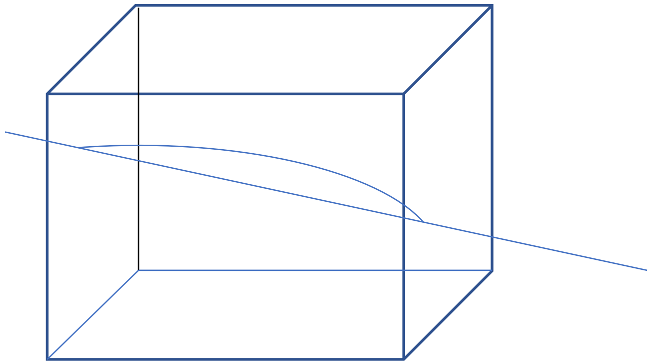
Step 1 - Transverse charge calibration in the XY plane

- *Generate global dQ/dx map for each xy plane and matrix of dQ/dx offsets at each voxel*

Step 2 - Drift direction charge calibration

- Generate global dQ/dx along z direction and for each (x, y, z) voxel generate matrix of dQ/dx offsets in drift direction

Step 3 - Time dependent calibration of the detector



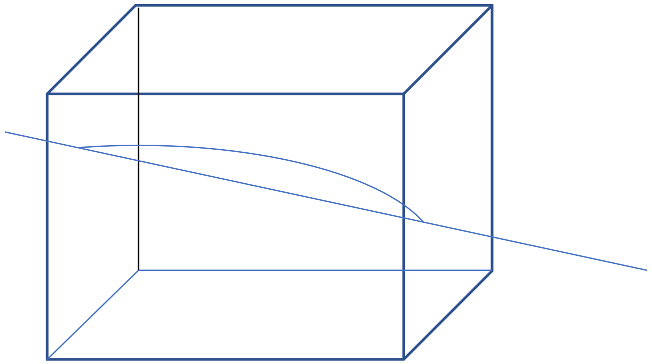
Calibration Procedure to Address Calibration Goals

- **Part III – Cross-calibration among individual LAr TPC modules**

Select minimum ionizing muons crossing multiple detector modules

Compare charge and position calibration for different modules with the same muon track

Repeat after every PRISM movement



Calibration Procedure to Address Calibration Goals

- **Part IV - Absolute calibration of the TPC modules with respect to the Near Detector Experimental Hall**
- Add external muon detection system to track same muons on the outside and inside cryostat
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Calibration Procedure to Address Calibration Goals

- **Part V - Addressing the effects contributing to deviation of the true and uncalibrated signal positions**
  - Incorrect assumption of 3D shape of the TPC modules will be detected and corrected for by measuring the time of drift for electron clouds originating from photoelectric targets with very small uncertainty.
  - Applying photoelectron calibration procedure on a daily basis between beam spills will enable the photoelectric laser system to detect changes in the shape and position over time and due to PRISM movements.
  - Besides measuring relative differences in the time of drift between targets, the drift time itself will be measured very accurately. Based on the average time of drift and average drift distance z, electron drift velocity will be calculated and compared with nominal value of mean electric field strength.
  - The nonuniformity of the electric field in the intermediate volume is observable in the position and charge correction matrices outlined in previous steps.
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Calibration Procedure to Address Calibration Goals

- **Part VI - Addressing the effects contributing to deviation of the true and uncalibrated signal ionization charge**
  - Based on the charge correction map we can create a map of the overall correction due to electron drift caused by liquid argon impurities and electron recombination that affects field strength locally.
  - With accurate knowledge of the photoelectron yield emission from the phototarget, and charge collection correction map, accuracy of modeling the pixel response to drifting charge will be verified.
  - Varying light illumination will lead to production of photoelectron clouds of different densities and overall charge. By correlating the changes in the cloud electron density, i.e. net charge, with the pixel readout, inaccuracies in the model of the front-end electronics channel gain and/or linearity will be corrected for.

Summary of the ND LAr TPC Calibration System

- Combination of engineered PE laser calibration system and crossing rock muons as a natural source can deliver calibration correction function to determine true position and deposited ionization charge throughout detector volume
- Requires high rock muon statistical sample in combination with PE laser calibration for full volume calibration
- Tracks detector response changes over time via daily monitoring
- PE laser calibration system is preferred over radioactive sources
    - Can be turned off – use between beam spills
    - Precise timing – 5 ns pulse duration
    - Electron cloud charge density variability for the pixel response linearity studies