Signal Processing in the ProtoDUNE-SP LArTPC

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Outline

- The ProtoDUNE-SP Detector
- Noise Filtering
- Signal Processing
- Summary
The ProtoDUNE-SP Detector

- The prototype of the DUNE single phase (SP) far detector technology
  - Full scale components
- 0.77 kt liquid argon (LAr) mass
  - World largest LArTPC build to date using SP technology
- Exposed to a dedicated charge particle beam (0.3 - 7 GeV/c)
  - Similar momenta to those of particles produced in neutrino interactions at DUNE
- Currently exposed to cosmic rays

[arXiv:1706.07081]
The ProtoDUNE-SP Detector

- **Cathode Plane Assemblies (CPA)**
  - Held at 180 kV providing an E field of 500 V/cm
  - 2 drift regions of 3.6m

- **6 Anode Plane Assemblies (APAs)**
  - 6m long x 2.3m wide
  - 3 planes of sense wires /APA
  - 15360 sense wires (99.74% active channels)

- **60 Photon Detectors**
  - Light collecting bars read out by SiPMS installed in the APA frame (10 detectors/APA)
  - 3 different versions installed
Principle of Operation

- Ionization electrons drift towards the APAs
  - Induce current in planes U, V
  - Collected in plane W
- Scintillation light is collected by the photon detection system
- Signal is read out by low noise electronics
Overview of LArTPC Reconstruction

Signal Formation

Noise Filtering & Signal Processing

Kinematic Reconstruction

3D Reconstruction
Noise Filtering

- Noise filtering is a key step towards a high-quality signal processing
- Low-noise operation of the readout electronics is critical to properly extract the distribution of ionization electrons
- Different types of noise were found in protoDUNE
  - Coherent noise, sticky code, slower sampling rate in 1 FEMB, ledge effect, “50 kHz” harmonic noise, etc
- Various strategies have been developed to minimize the sources of noise
“50 kHz” Harmonic Noise

- Distortion in the waveform
- Characterized by large spikes in the frequency domain
- Observed in collection wires only
- The source was found to be the HV power supply
  - This noise was significantly suppressed after the replacement of the HV power supply in 12/2018
- Can be mitigated by removing the large spikes in the frequency domain iteratively
Coherent Noise

- Found to be correlated across groups of channels in the same FEMB
- Prominent at ~45 kHz
- Can be mitigated by constructing a correction waveform across sets of 40(48) channels of plane U and V (W) and subtracting it channel by channel

Interaction vertex from the 7GeV beam data (run 5152, event 89) measured on the U plane
Noise Performance

99.96% of the channels are working with excellent noise performance

<table>
<thead>
<tr>
<th>Plane</th>
<th>ENC Before NF</th>
<th>ENC After NF</th>
</tr>
</thead>
<tbody>
<tr>
<td>U Plane</td>
<td>606</td>
<td>499</td>
</tr>
<tr>
<td>V Plane</td>
<td>595</td>
<td>503</td>
</tr>
<tr>
<td>W Plane</td>
<td>511</td>
<td>453</td>
</tr>
</tbody>
</table>
Signal Processing

- Raw digitized TPC signal is a convolution of:
  - Arriving electron distribution
  - The field response function
  - Electronics response (preamp, shaping, etc)

- The goal of signal processing is to convert the recorded waveform into ionization electron distribution:
  - Appropriate signal processing techniques
  - Accurate calculation of the field response
Field Response Function

- The principle of current induction is described by Ramo’s theorem
  
  \[ i = -e \dot{v} \cdot \vec{E}_v = -e \dot{v} \cdot (-\nabla \phi) \]

- Garfield program is used to calculate the field response functions
  - Two stages to calculate the field response functions
    - Electron drift paths
    - Weighting potential

- Current is also induced on nearby wires (long-range induction)

Field Response Function

- 2D scheme for the Garfield simulation
  - The field response for the central wire and +-10 wires on both sides are calculated

Field response function in the central wire and two different drift paths
Field Response Function

- 2D scheme for the Garfield simulation
  - The field response for the central wire and +10 wires on both sides are calculated

Overall response function: Field response function $\otimes$ Electronics response (Log10 scale)
2D Deconvolution

- Deconvolution is a technique to extract charge information from the digitized waveform
- Involve time and wire dimension
  - Include naturally long-range induction
- Accurate recovery of the ionization electron distribution

\[ M_i(t_0) = \int_{t} (R_0(t_0 - t) \cdot S_i(t) + R_1(t_0 - t) \cdot S_{i+1}(t) + \ldots) \cdot dt \]

- \( M_i \) represents the measured signal from wire \( i \)
- \( S_i \) and \( S_{i+1} \) are the real signal in the wire of interest and adjacent wires respectively
- \( R_0 \) and \( R_1 \) are the average response functions within the wire pitch
2D Deconvolution

- Bipolar signal deconvolved into an unipolar charge distribution
- Cancellation of successive bipolar signals are recovered via the 2D deconvolution
Summary

- Noise levels has been reduced significantly by using different filtering techniques
- Signal processing is a key step for 3D event reconstruction
- Field response function has been calculated using the Garfield program
- 2D deconvolution technique yields to accurate recovery of ionization electron distribution
THANKS
Backup slides
## Detector Components

<table>
<thead>
<tr>
<th>Detection Element</th>
<th>Approx Dimensions</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA</td>
<td>6 m H by 2.4 m W</td>
<td>3 per anode plane, 6 total</td>
</tr>
<tr>
<td>CPA module</td>
<td>2 m H by 1.2 m W</td>
<td>3 per CPA column, 18 total in cathode plane</td>
</tr>
<tr>
<td>Top FC module</td>
<td>2.4 m W by 3.6 m along drift</td>
<td>3 per top FC assembly, 6 total</td>
</tr>
<tr>
<td>Bottom FC module</td>
<td>2.4 m W by 3.6 m along drift</td>
<td>3 per bottom FC assembly, 6 total</td>
</tr>
<tr>
<td>End-wall FC module</td>
<td>1.5 m H by 3.6 m along drift</td>
<td>4 per end-wall assembly (vertical drift volume edge), 16 total</td>
</tr>
<tr>
<td>PD module</td>
<td>2.2 m × 86 mm × 6 mm</td>
<td>10 per APA, 60 total</td>
</tr>
</tbody>
</table>
Anode Plane Assemblies

- Each Anode Plane consist of
  - 3 Anode Plane Assemblies (APAs) that are 6m high by 2.3m wide
  - Each APA holds three parallel planes of sense and shielding wires at varying angles with respect to each other (±35.7° w.r.t. vertical)
  - 2560 wires per APA (15360 sense wires total)
  - 99.74% active channels
Coherent Noise

Before NF

After NF
Clock Issue in one FEMB

FEMB 302 was found to be running at a slower sampling rate
Clock Issue in one FEMB

This issue can be corrected by resampling the waveform through FFT.
Noise Filtering

50 kHz Noise

Ledge Effect

Deconvolved charge

Evidence in < 1% of total channels
Ledge Effect

- Occurs sometimes after a long period of charge deposition
- Due to saturation of the preamplifier
- Causes loss of information
- This type of noise cannot be mitigated, but can be identified → This region of the waveform is not included in further steps of signal processing
Sticky Bits

- Performance instability of the ADC
  - Fails to keep the codes in the 6 LSB and changes them to 000000, 111111
- Can be mitigated by linear interpolation
  - If the sticky bit is in the signal region, an interpolation via FFT is applied (see backup slides)

Evidence in 3% of total channels
Basics of (1D) Signal Processing

- Principal method to extract wire charge $S(t)$ is deconvolution.
- By given a response function $R(t)$, signal $S(t)$ can be easily derived via Fourier transform.
- A filter function $F(\omega)$ introduced to suppress the big fluctuation after deconvolution.