Signal Processing in the ProtoDUNE-SP LArTPC

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University of CINCINNATI

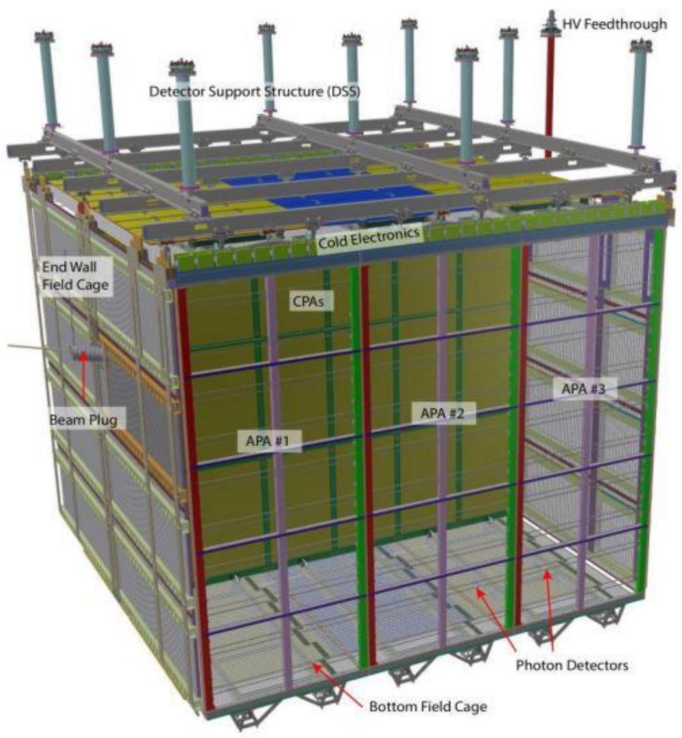
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Outline

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

The ProtoDUNE-SP Detector

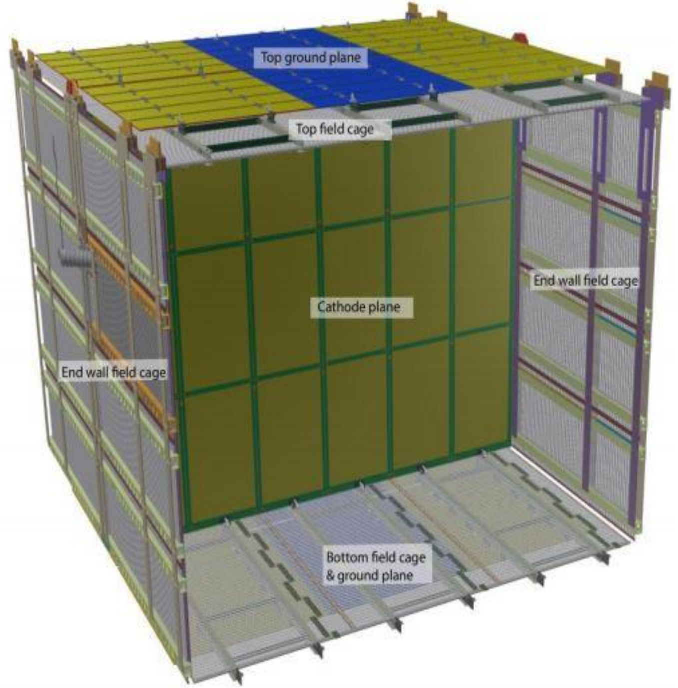
- The prototype of the DUNE single phase (SP) far detector technology
  - Full scale components
- 0.77 kt liquid argon (LAr) mass
  - World largest LArTPC build to date using SP technology
- Exposed to a dedicated charge particle beam (0.3 -7 GeV/c)
  - Similar momenta to those of particles produced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



arXiv:1706.07081

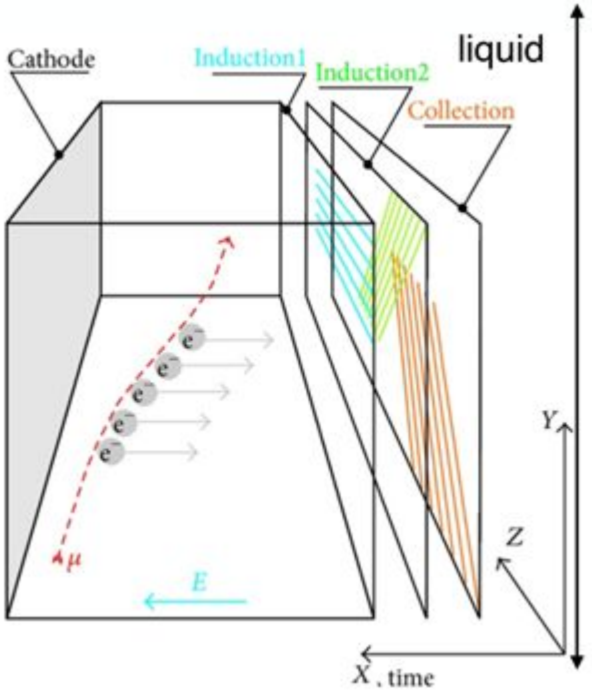
The ProtoDUNE-SP Detector

- 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



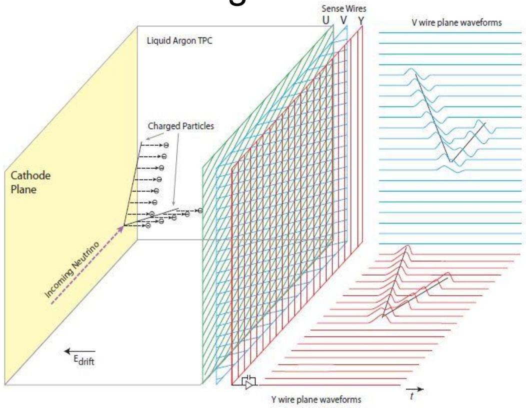
Principle of Operation

- 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

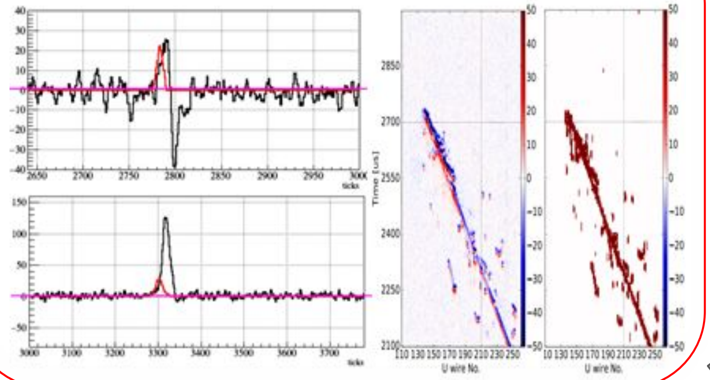


Overview of LArTPC Reconstruction

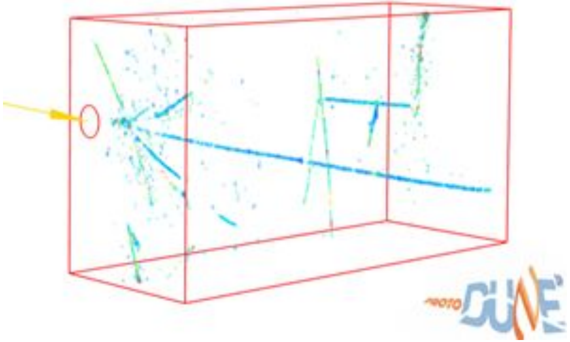
Signal Formation



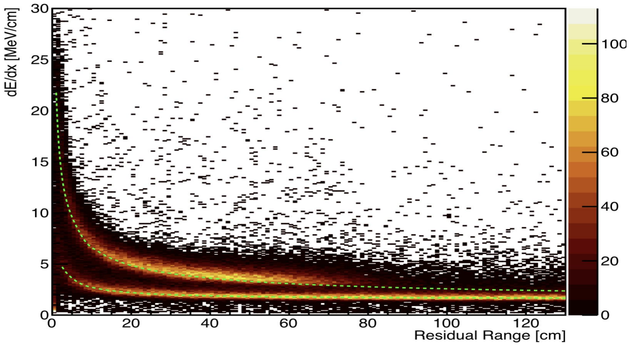
Noise Filtering & Signal Processing



3D Reconstruction



Kinematic Reconstruction

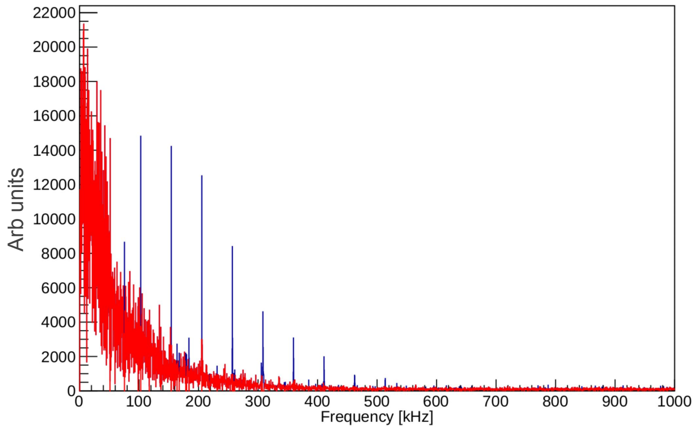


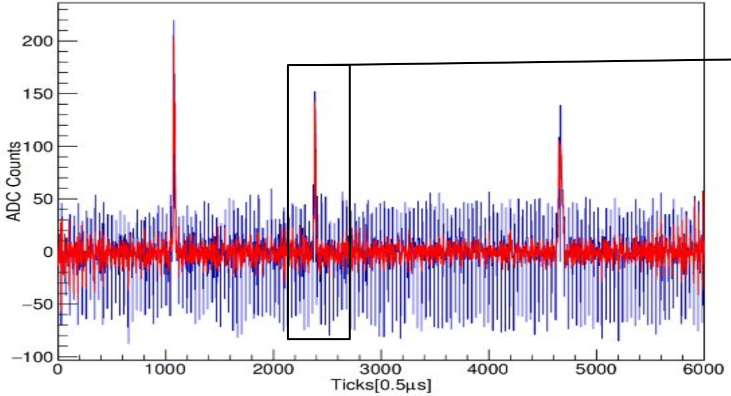
Noise Filtering

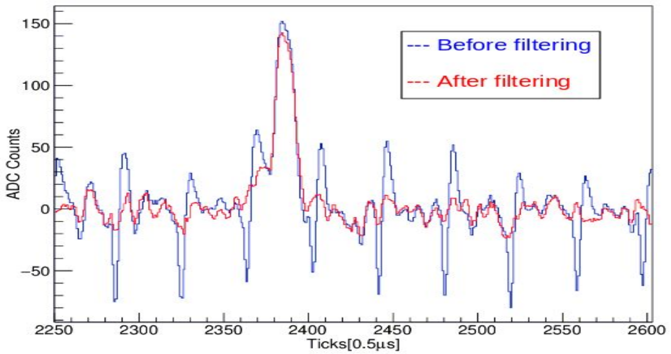
- Noise filtering is a key step towards a high-quality signal processing
- low-noise operation of the readout electronics is critical to properly extract the distribution of ionization electrons
- Different types of noise were found in protoDUNE
  - Coherent noise, sticky code, slower sampling rate in 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

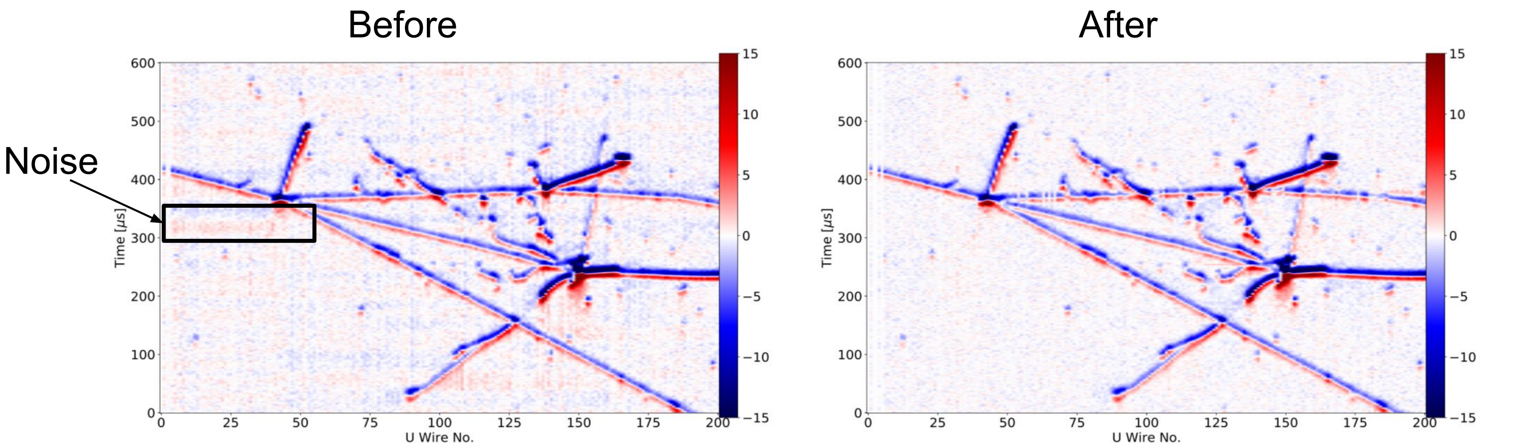






Coherent Noise

- 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

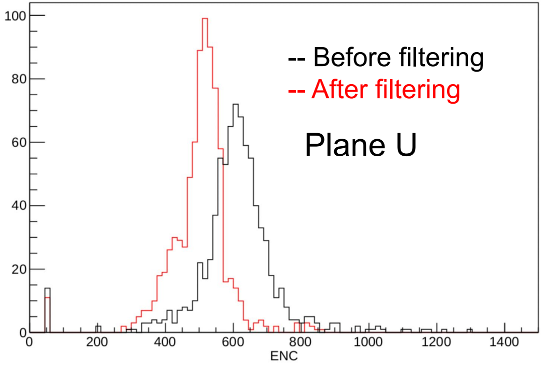


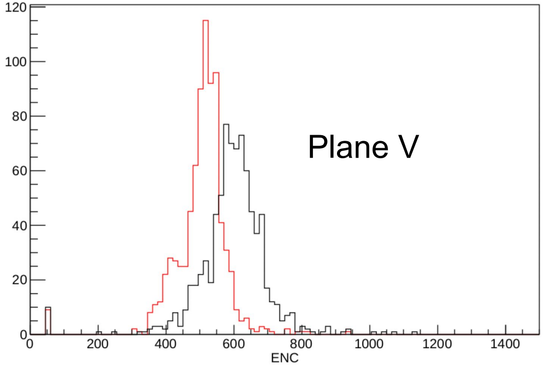
Interaction vertex from the 7GeV beam data (run 5152, event 89) measured on the U plane

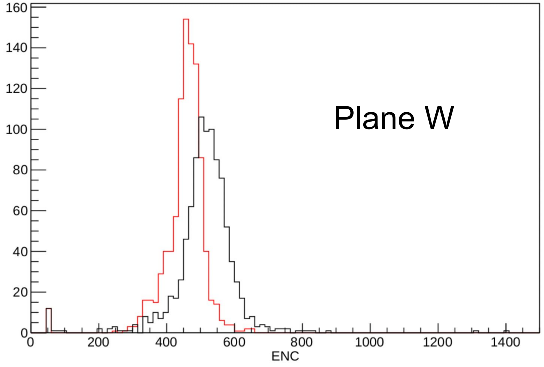
Noise Performance

99.96% of the channels are working with excellent noise performance

	ENC Before NF	ENC After NF
U Plane	606	499
V Plane	595	503
W Plane	511	453







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

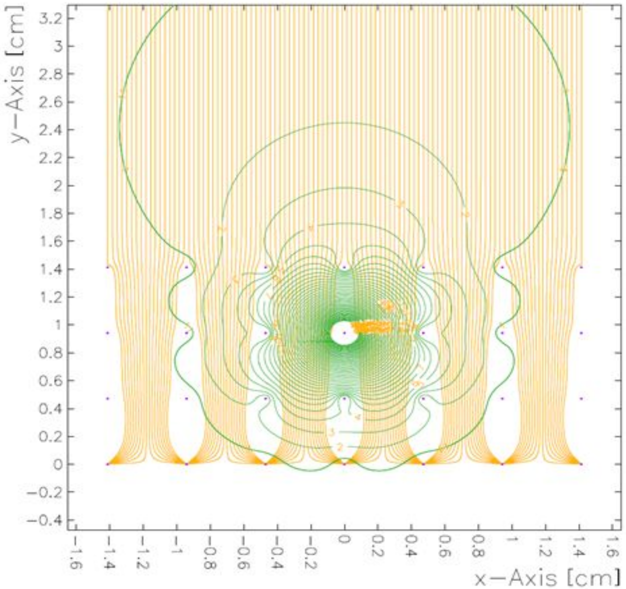
- The principle of current induction is described by Ramo's theorem

Ramo's theorem

$$i = -e\vec{v} \cdot \vec{E}_v = -e\vec{v} \cdot (-\nabla\phi)$$

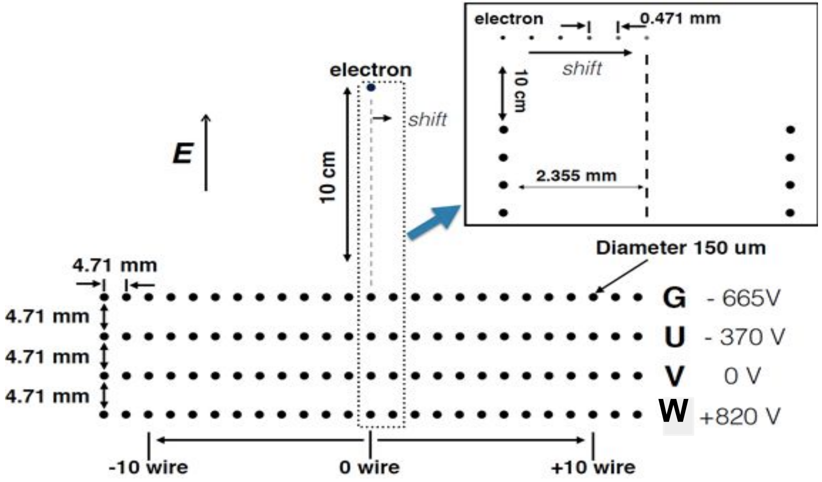
Weighting potential ϕ

- 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)

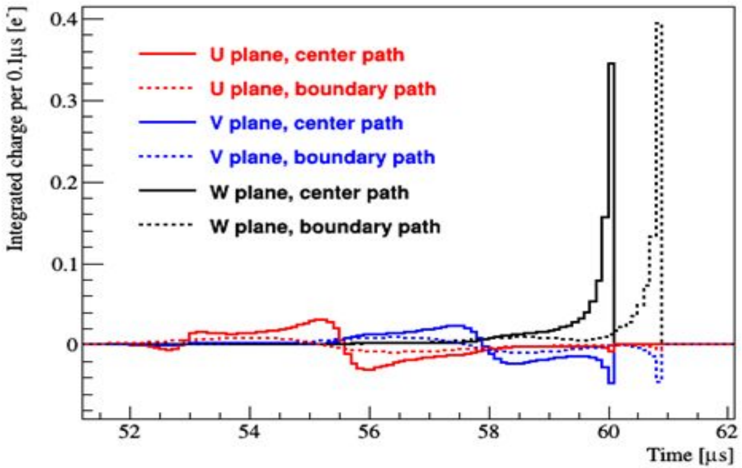


Garfield, a drift-chamber simulation program User's Guide, Veenhof, R. (1993)

Field Response Function

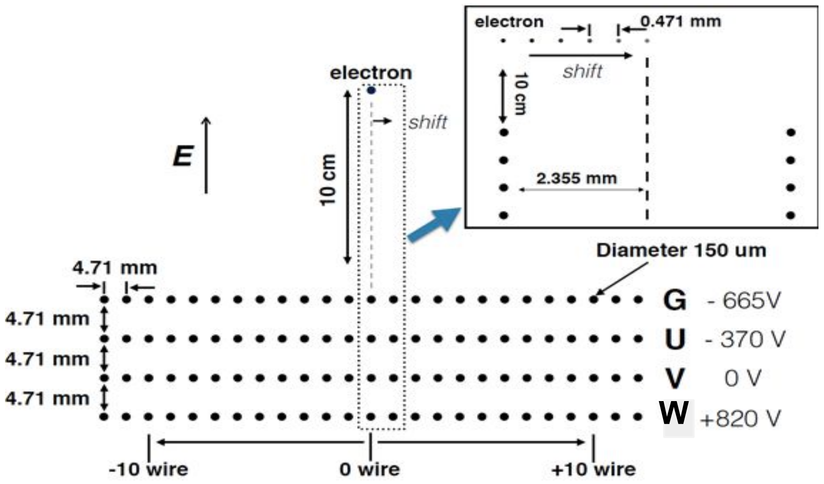


- 2D scheme for the Garfield simulation
  - The field response for the central wire and +-10 wires on both sides are calculated



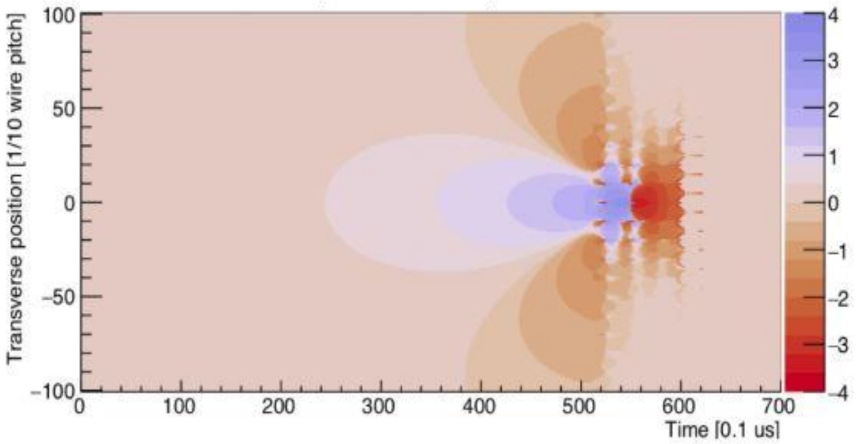
Field response function in the central wire and two different drift paths

Field Response Function



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

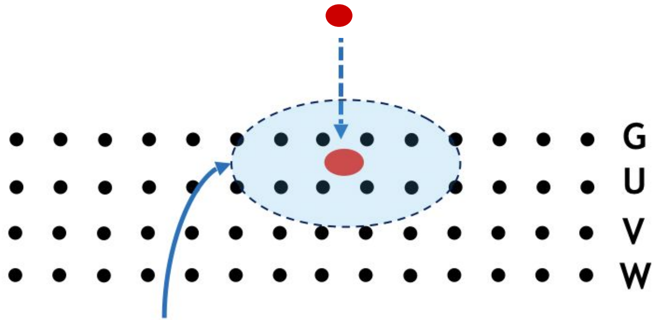
Response Function (U Plane)



Overall response function: Field response function ⊗ Electronics response (Log10 scale)

2D Deconvolution

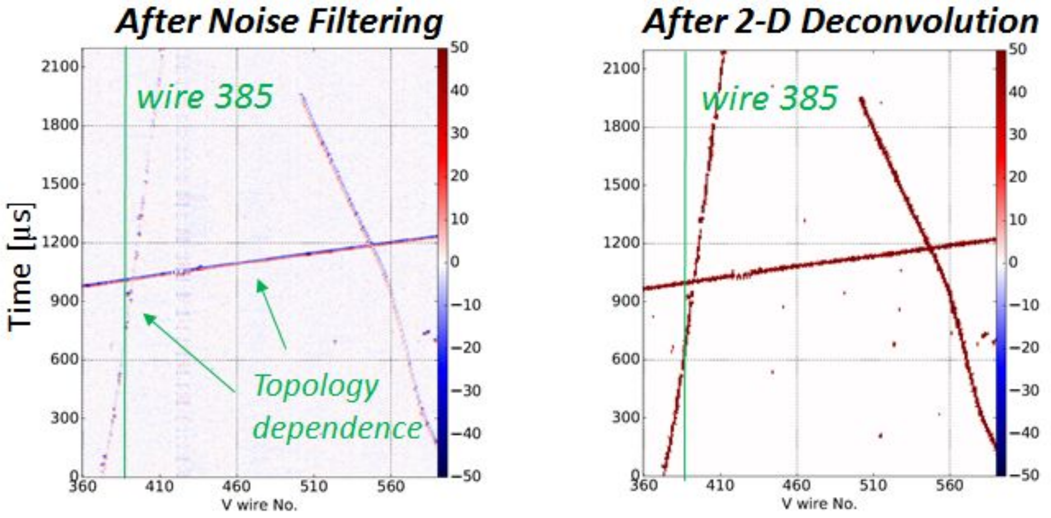
- Deconvolution is a technique to extract charge information from the digitized waveform
- Involve time and wire dimension
  - Include naturally long-range induction
- Accurate recovery of the ionization electron distribution

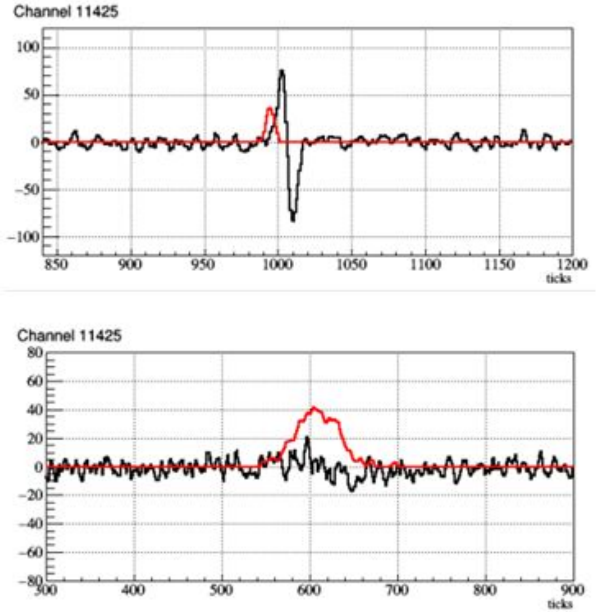


$$M_i(t_0) = \int_t (R_0(t_0 - t) \cdot S_i(t) + R_1(t_0 - t) \cdot S_{i+1}(t) + \ldots) \cdot dt$$

- 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

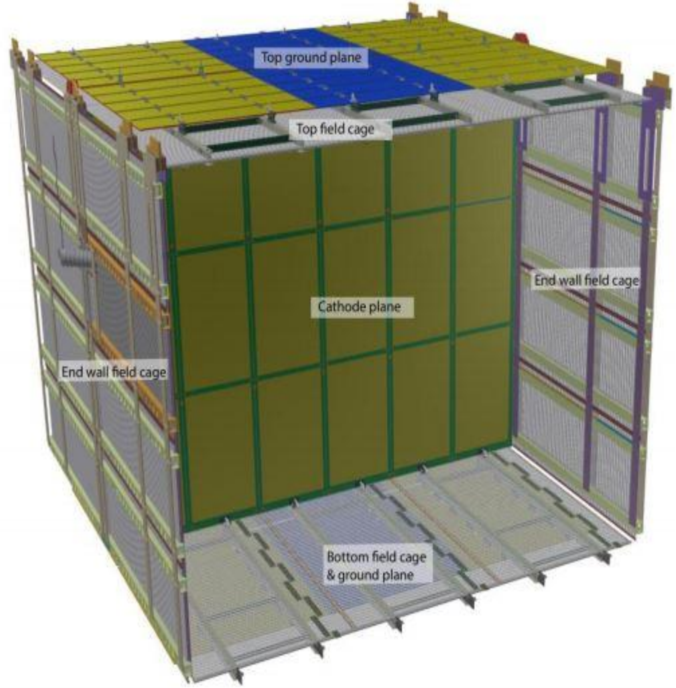
- Noise levels has been reduced significantly by using different filtering techniques
- Signal processing is a key step for 3D event reconstruction
- Field response function has been calculated using the Garfield program
- 2D deconvolution technique yields to accurate recovery of ionization electron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

THANKS

Backup slides

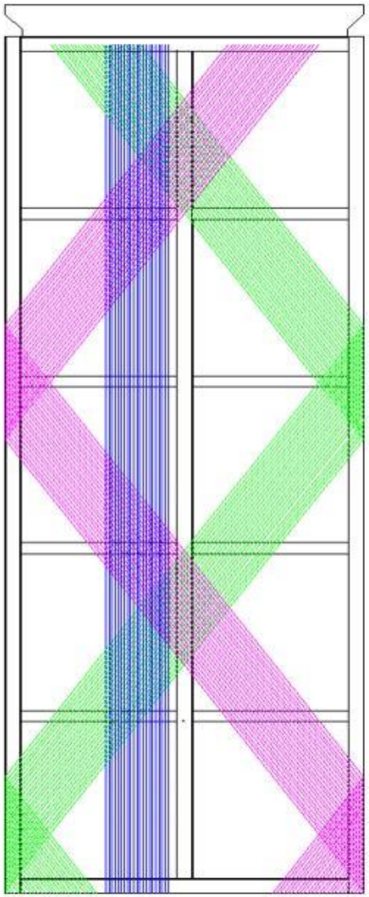
Detector Components

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



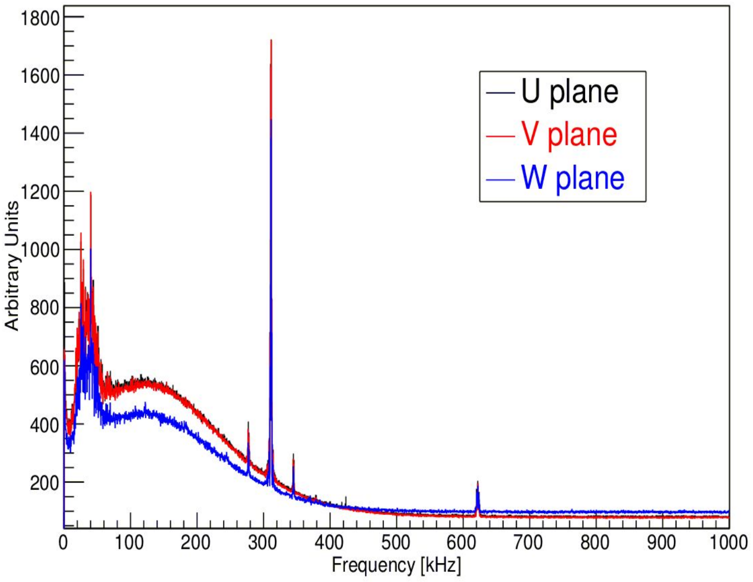
Anode Plane Assemblies

- 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

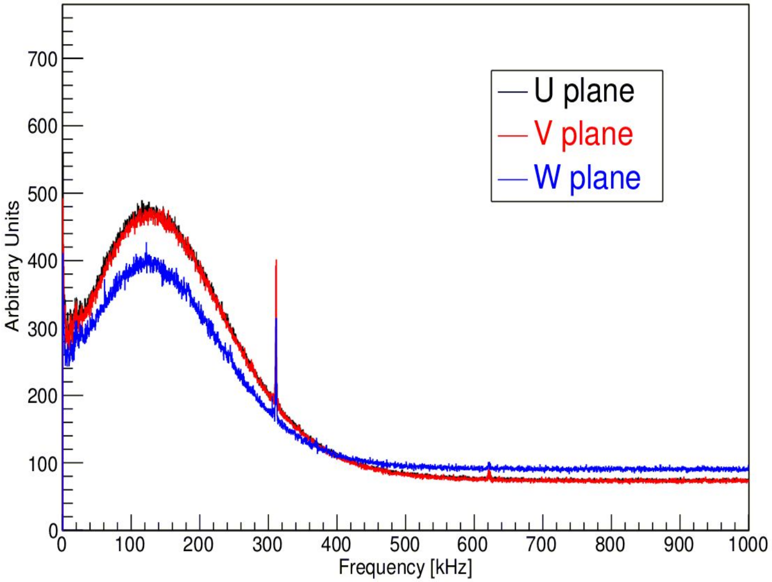


Coherent Noise

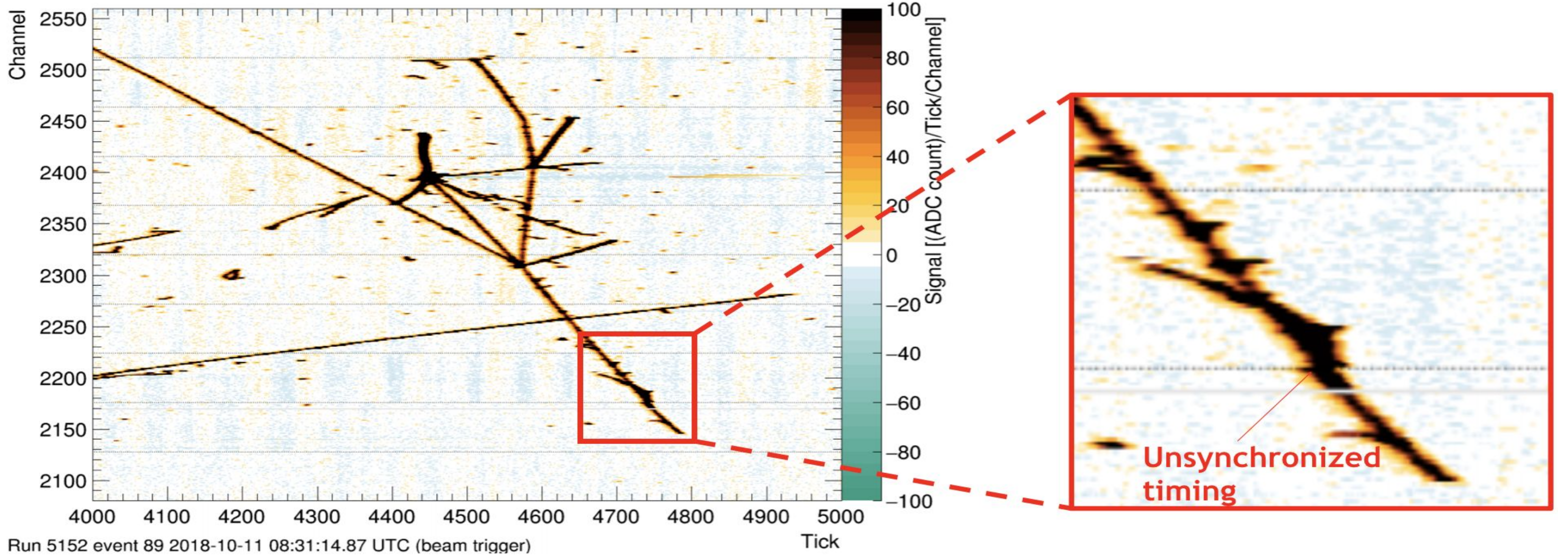
Before NF



After NF

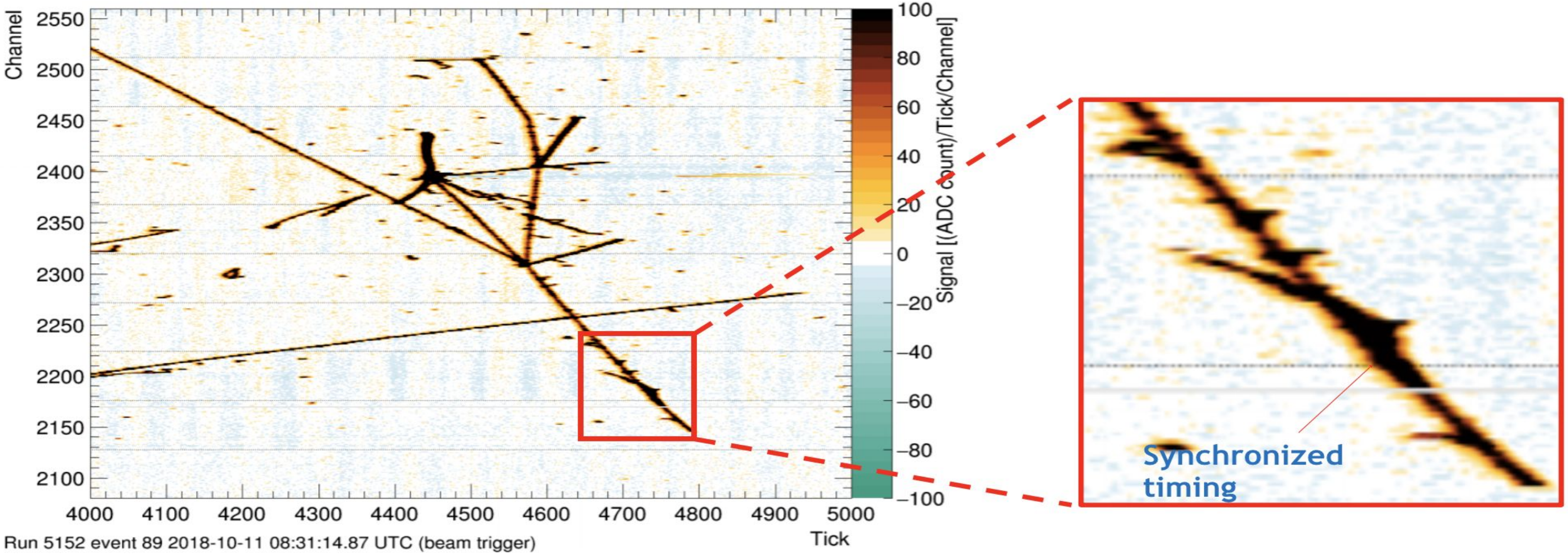


Clock Issue in one FEMB



FEMB 302 was found to be running at a slower sampling rate

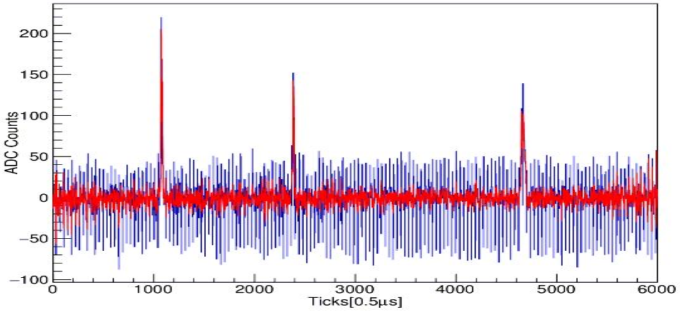
Clock Issue in one FEMB



This issue can be corrected by resampling the waveform through FFT

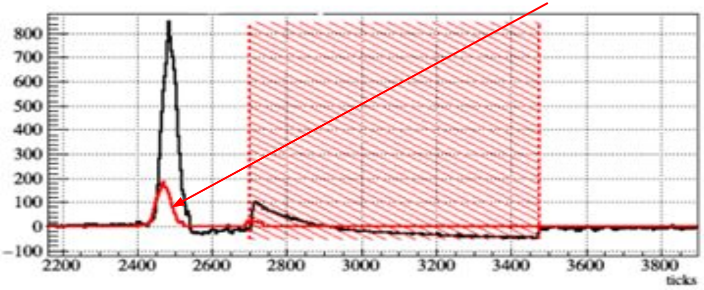
Noise Filtering

50 kHz Noise



Ledge Efect

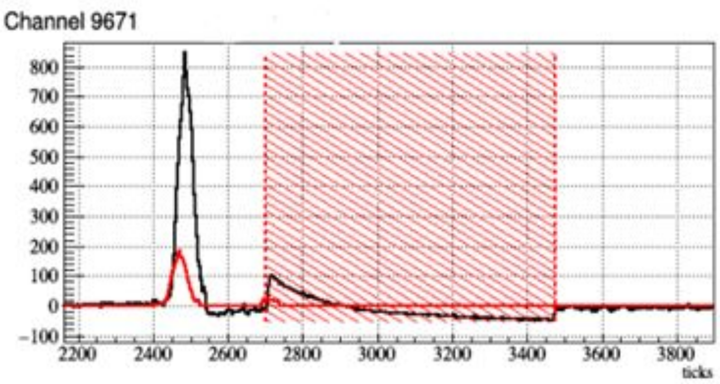
Deconvolved charge



Evidence in < 1% of total channels

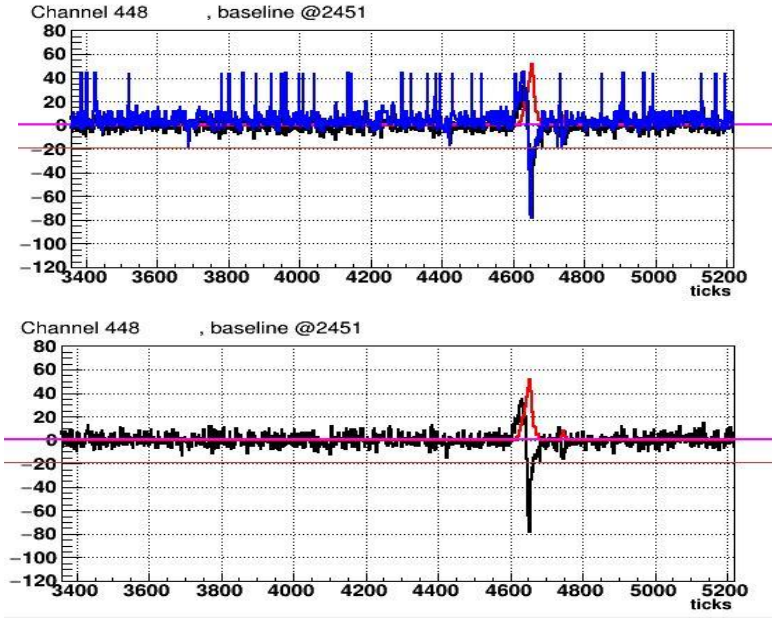
Ledge Effect

- 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

$$\mathrm{M}(t_0) = \int_t R(t - t_0) \cdot S(t) \cdot dt$$

↓ *Fourier transform*

$$M(\omega) = \mathrm{R}(\omega) \cdot \mathrm{S}(\omega)$$

↓ *Deconvolution + Filter*

$$\mathrm{S}(\omega) = \frac{\mathrm{M}(\omega)}{\mathrm{R}(\omega)} \cdot F(\omega)$$

↓ *Inverse Fourier transform*

$$\mathrm{S(t)}$$

- 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(ω) introduced to suppress the big fluctuation after deconvolution