Wire-Cell TPC Sim and Implications for Vertical Drift

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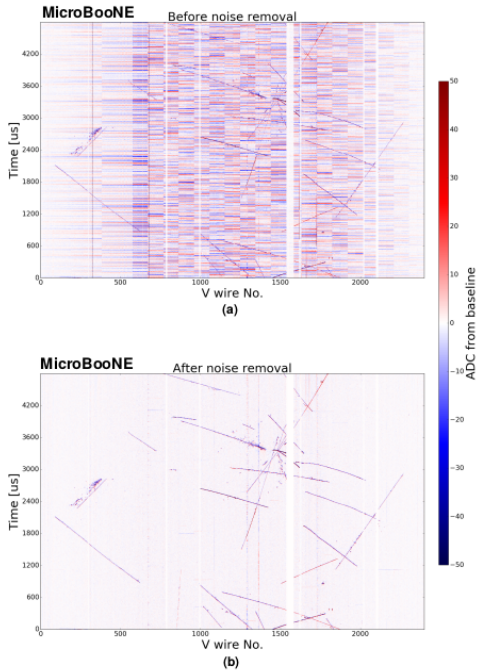
Wire-Cell Toolkit (WCT) Overview

- C++ shared libraries, portable build system, well documented.
- Follows multi-level toolkit paradigm up to a main `wire-cell` or integration into the *art* framework.
- Provides plugin, component and configuration management, single and multi-threaded data-flow processing graphs.
- **LArTPC batteries included**: field and electronics response functions, signal and noise simulation, noise filtering, signal processing, the titular 3D "wire cell" ionization reconstruction algorithm and 3D clustering, various IO formats.
- Experimental: multi-host file and GPU services, Kokkos parallelization.

`https://wirecell.bnl.gov/`
`https://github.com/wirecell/`

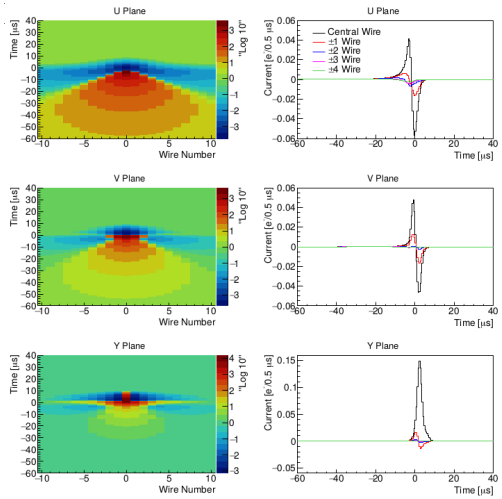
Wire-Cell performance on MicroBooNE

Wire-Cell software **noise filter** applied to MicroBooNE data event.

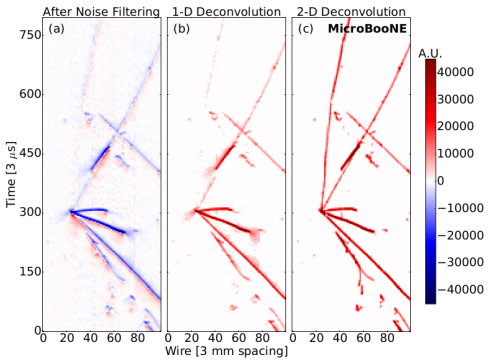


Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC MicroBooNE Collaboration arXiv:1705.07341, JINST 12 P08003 (2017).

Wire-Cell **field response** (averaged over each wire region).

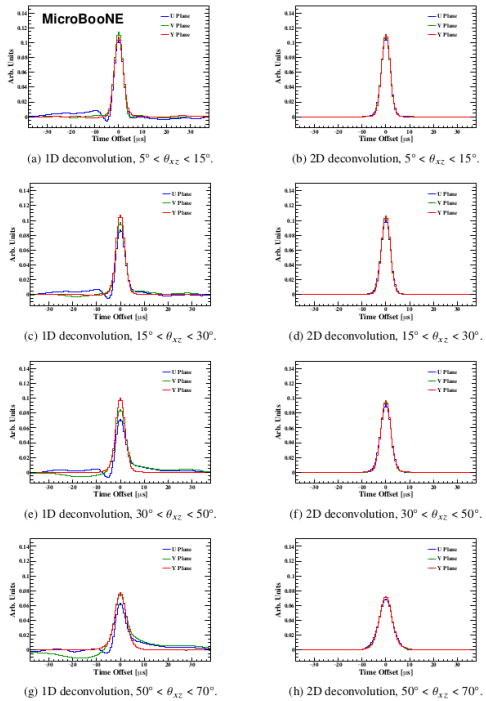


Wire-Cell **signal processing**.



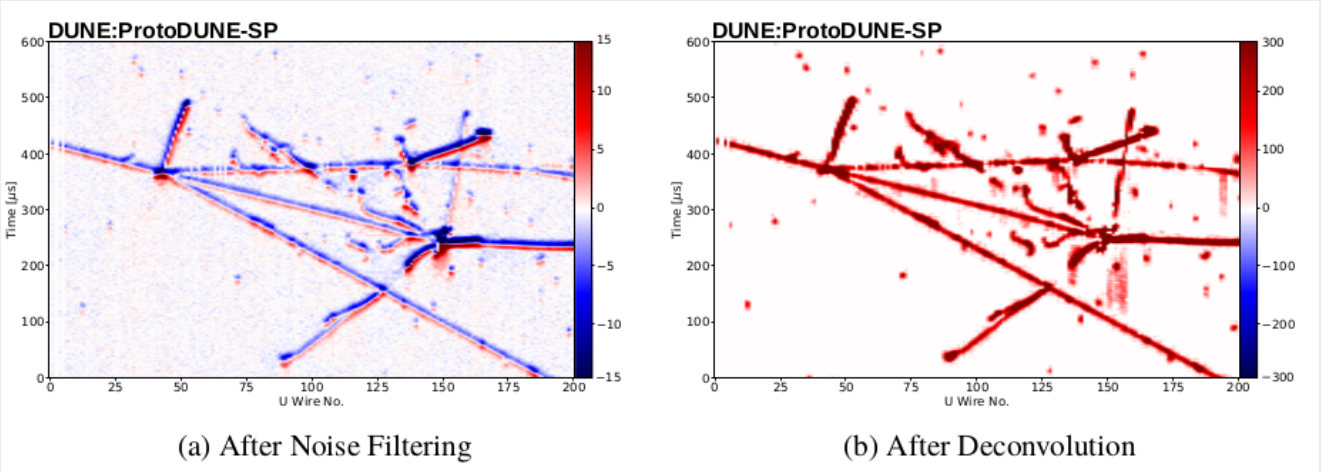
Ionization Electron Signal Processing in Single Phase LArTPCs I. Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation MicroBooNE Collaboration arXiv:1802.08709, JINST 13, P07006 (2018).

Simulation and signal processing compared to data. 1D model and **Wire-Cell's 2D model**.



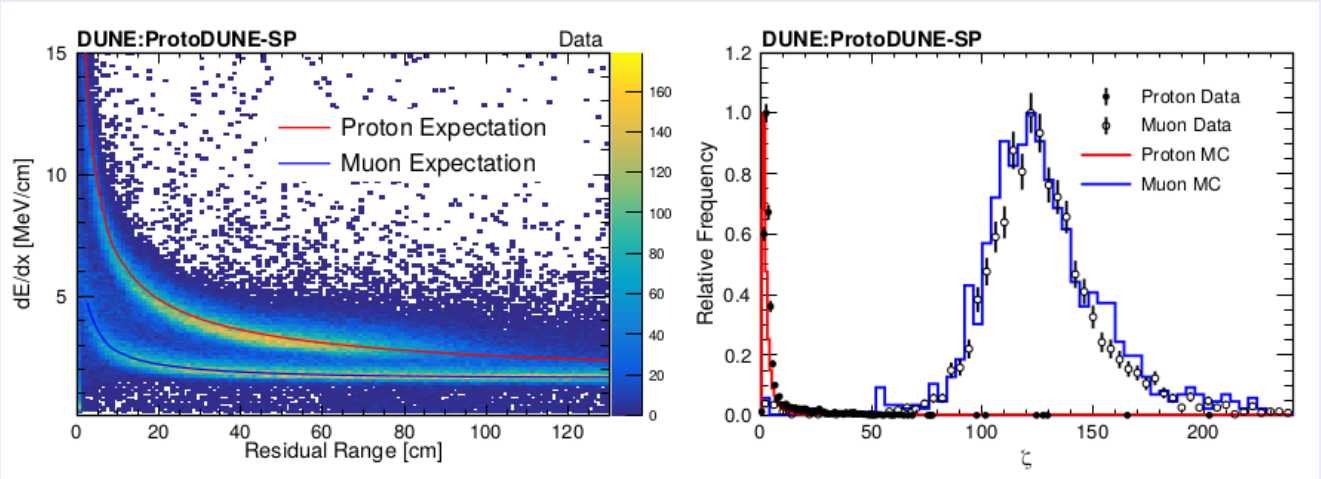
Ionization Electron Signal Processing in Single Phsae LArTPCs II. Data/ Simulation Comparison and Performance in MicroBooNE MicroBooNE Collaboration arXiv:1804.02583, JINST 13, P07007 (2018).

Wire-Cell signal processing on ProtoDUNE-SP data



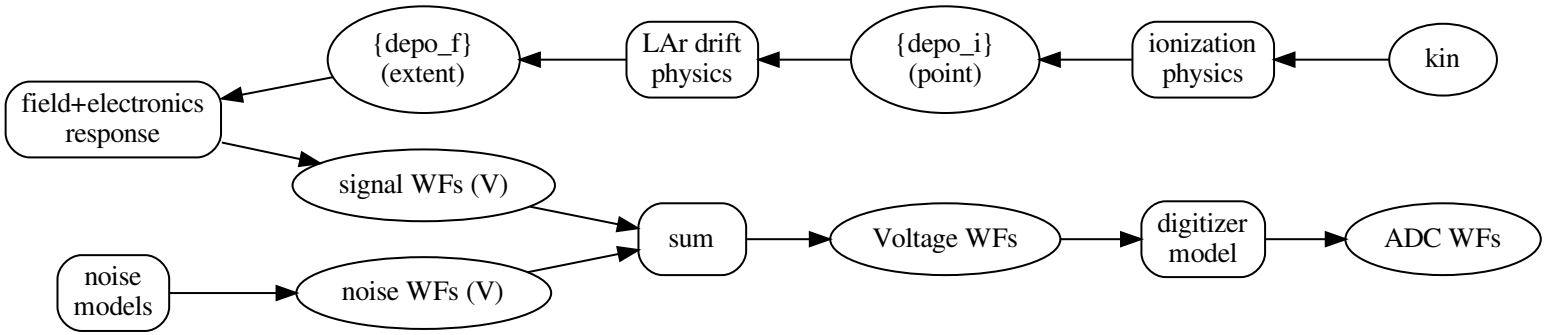
(a) After Noise Filtering (b) After Deconvolution

Wire-Cell simulation/data comparison dE/dX for μ and P on PDSP



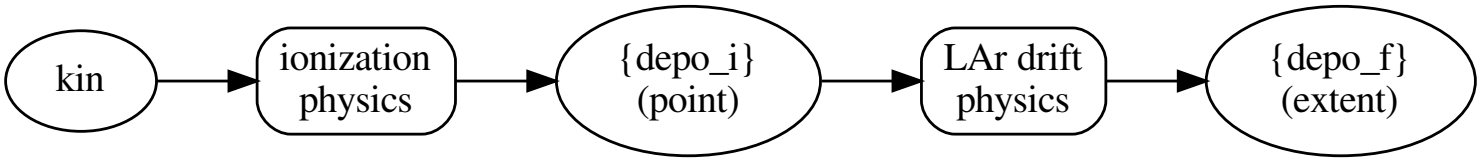
First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform. arXiv:2007.06722, JINST 15 (2020) P12004.

Conceptual WCT Signal Simulation Graph



- Major processing features (boxes) and data product types (ellipses).
- Actual data-flow graph nodes are implemented at a per-anode or a per-plane level.
  - Fine-grain processing: reap multi-threading benefits, efficiently handle large detectors and varieties between detectors.

WCT Signal Simulation - *depos*: input and drift



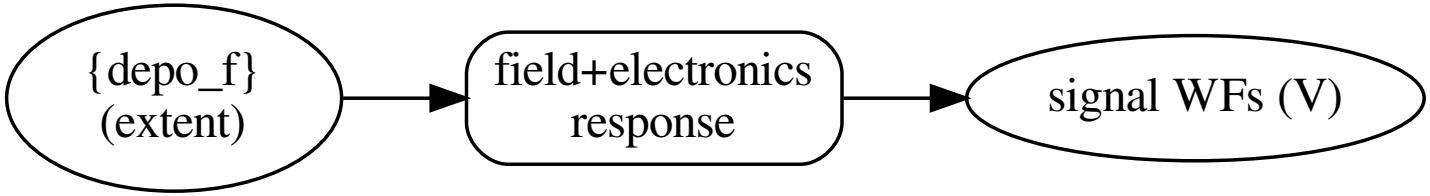
$$gen(kin) \rightarrow \{depo_i\}; depo_i = (\vec{r}, t, N_{ele})_i$$

- Input is a set of point-ionization depositions ("depos"), eg one per particle "step".
- $gen()$ = Geant4, file input or WCT-provided ideal tracks or ^{39}Ar decays.

$$drift(\{depo_i\}) \rightarrow \{depo_f\}; depo_f = (\vec{r}, t, N_{ele}, \sigma_\perp, \sigma_\parallel)_f$$

- Absorption, transverse/longitudinal diffusion, stochastic variation.
- Drifted depo is $\mathcal{N}\sigma$-truncated 2D Gaussian distribution at *response plane:*
  - $\vec{r}_f = (x_f, y_i, z_i)$; $x_f \approx$ 10 cm from anode and coincident with start of field response functions.

WCT Signal Simulation - field and electronics response



$$V = depos \circledast FR \circledast ER$$

- Per anode plane convolution of drifted ionization distribution, *field response* (FR) and electronics response (ER).
- Result in voltage waveforms on a set of *sensing conductors*
  - ie, the anode "wires" or "strips" near to drifted charge
  - apply channel map to sum up to per-channel waveforms to handle wrapped or jumpered conductors.

Field response

$$I(t_i) = q\vec{W}(\vec{r}_i) \cdot \vec{v}(\vec{r}_i); \vec{r}_i = \vec{r}(t_i); t_i = t_0 + i\Delta t$$

Calculate the induced current I at time t_i from a drifting charge at $\vec{r}(t_i)$ with Schokley-Ramo formula applied to the volume between the *response plane* to somewhat behind the anode (wire/strip) planes.

- $\vec{W}$: *weighting field* is $\vec{E}$-field with conductor-of-interest at 1V, all else at 0V
- $\vec{v}$: drift velocity along path $\vec{r}$ calculated from LAr physics and solving $\vec{E}$-field
- q: "small" element of distribution of drifted ionization electrons.

For full correctness

- Must solve Laplace eqn for $\vec{E}$-field with entire, as-built detector as boundary conditions.
  - Even with BEM this is effectively computationally impossible.
- Solve Laplace eqn for $\vec{W}$-field, once for every of $\mathcal{N}$ sense wires/strips.
  - $\mathcal{N}\times$ impossible!
- Calculate all possible drift paths - Runge-Kutta stepping - at suitable density $\approx$ 1/10 wire/strip pitch (forget it!)

Need approximations! $\rightarrow$ exploit symmetries

1D Model

Assume:

- A drifting electron only induces on single nearest wire on each plane
- Response independent from location within one pitch

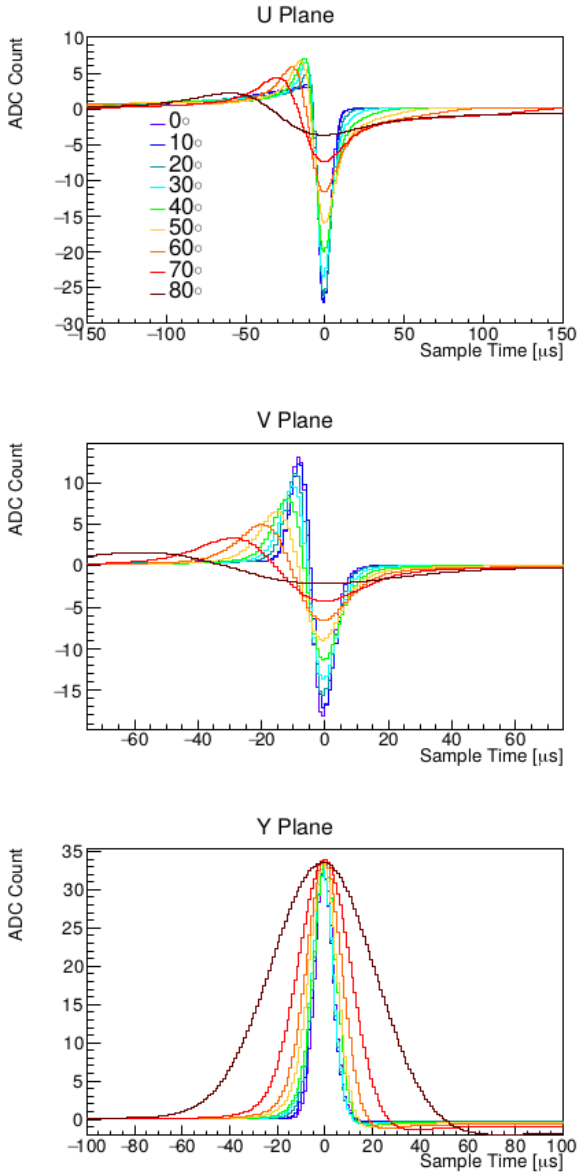
Computationally easy:

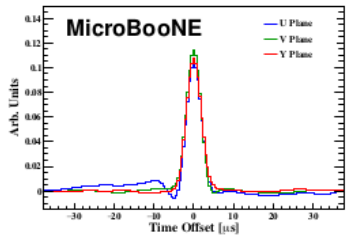
- Response requires a single, 1D convolution per wire.
- The original, and sometimes still used LArTPC simulation in LArSoft.

Reality:

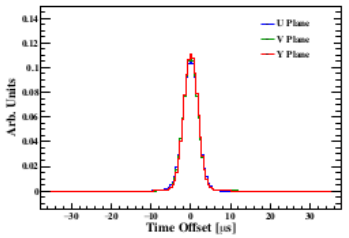
- MicroBooNE and ProtoDUNE-SP data demonstrated this model is too simplistic.
- Even with DUNE'style "grid plane" we must include "long range induction" effects.
- In any case, need to include fine-scale (sub pitch) field variations.

Long-range induction effects in MicroBooNE

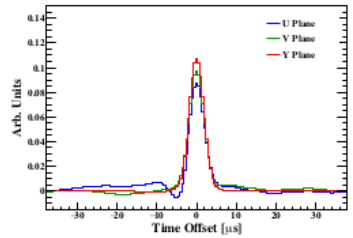




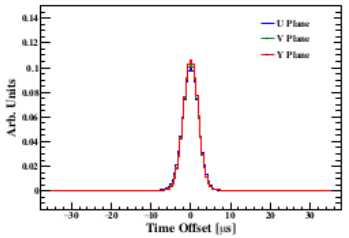
(a) 1D deconvolution, $5° < \theta_{xz} < 15°$.



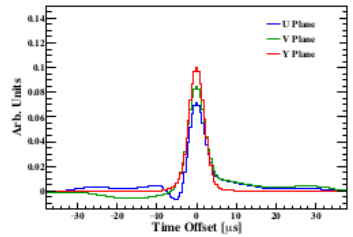
(b) 2D deconvolution, $5° < \theta_{xz} < 15°$.



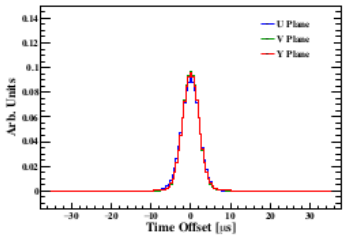
(c) 1D deconvolution, $15° < \theta_{xz} < 30°$.



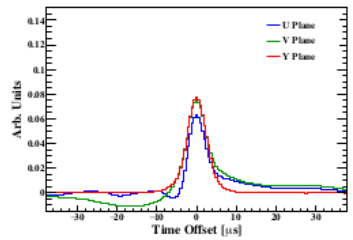
(d) 2D deconvolution, $15° < \theta_{xz} < 30°$.



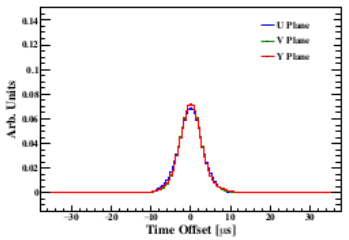
(e) 1D deconvolution, $30° < \theta_{xz} < 50°$.



(f) 2D deconvolution, $30° < \theta_{xz} < 50°$.



(g) 1D deconvolution, $50° < \theta_{xz} < 70°$.

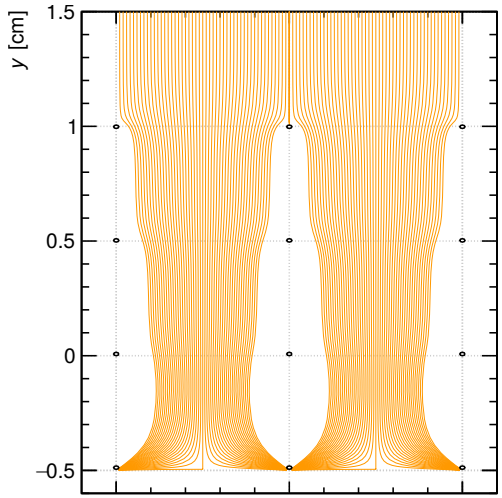


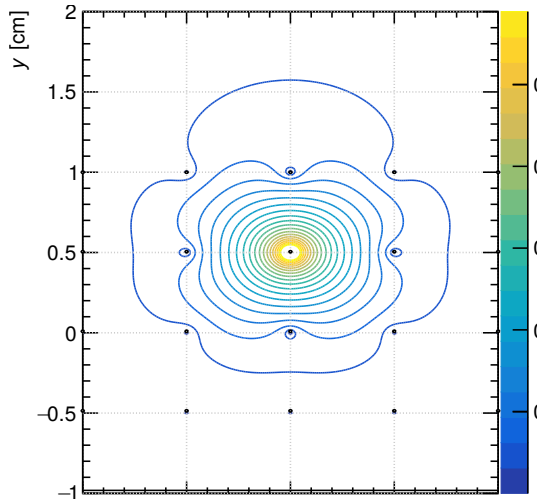
(h) 2D deconvolution, $50° < \theta_{xz} < 70°$.

2D Field Response Calculations

Assumptions and features of 2D

- A drifting electron induces on nearest and $\pm\mathcal{N}$ conductors, typical:
  - $\mathcal{N}_{wires} = \pm 10, \mathcal{N}_{strips} = \pm 5$
- Response varies within each pitch
  - sample $\frac{1}{10}^{th}$ pitch "impact position" bins
- Wires are effectively infinitely long
  - and no features along "into the page"
- No transverse boundary effects
- Artificial wire "crossing" pattern





Drift paths and U-wire weighting field for ProtoDUNE-SP calculated by drifires/Garfield++.

- 121 FR waveforms per plane at 10 MHz sampling with O(1k) samples
  - 1D "pre" convolve with ER to get down to 2 MHz sampling
- Exploit assumptions → computational simplifications:
  - No 3^{rd} dim. Do not care where along the wires a depo lands.
  - No edge effects: 2D convolution → 10 "interlaced" 2D FFTs (one per impact position).

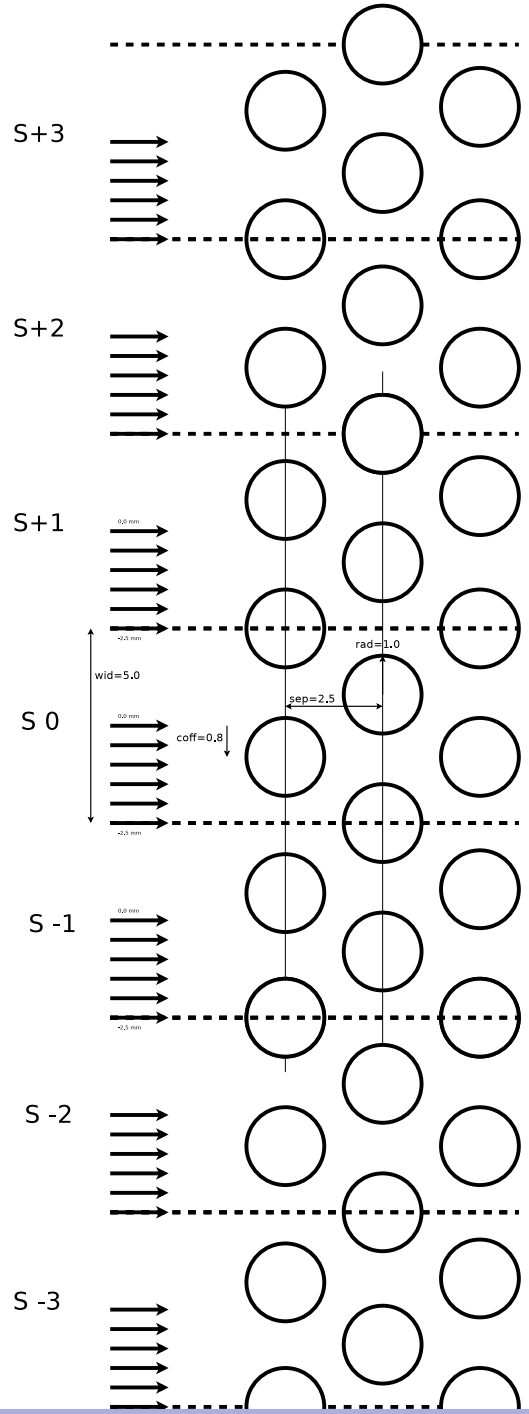
2.5D model for holey strips

The hole pattern makes strips nonuniform along their length.

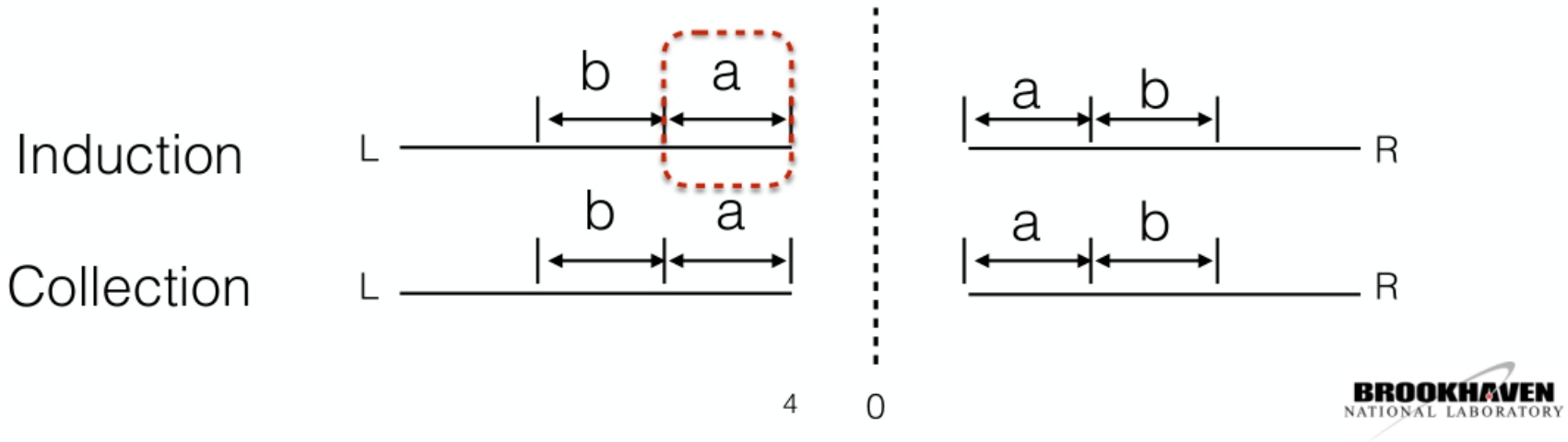
- At a fixed pitch position, the drift paths and weighting fields vary as one runs along a strip direction.
  - Adding drift/time, it's really a 3D geometry.
- Extra challenge: 50-L ind/col strips have differing hole patterns.
  - But at least the pattern repeats every-other hole. As the pattern repetition distance grows, so does the size of the FR calculation.

"2.5D" trick: coerce 3D $\rightarrow$ 2D by averaging the 2D FRs calculated at a given impact position on **multiple 2D slices** across a strip.

- "multiple" is 2 for 50-L, based on number of holes until repeat starts.
- It's still "wrong" but less wrong than ignoring holes.
- Easier than full 3D but rather more challenging to calculate than with wires.
  - Requires laborious human work as well as more CPU.



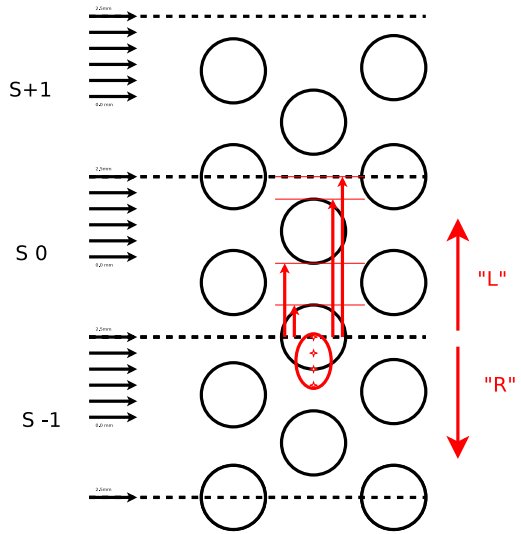
Details of the 2.5D trick



GARFIELD setup for 2D single-hole (Yichen Li)

Clever work-around to limitations of 2D and GARFIELD:

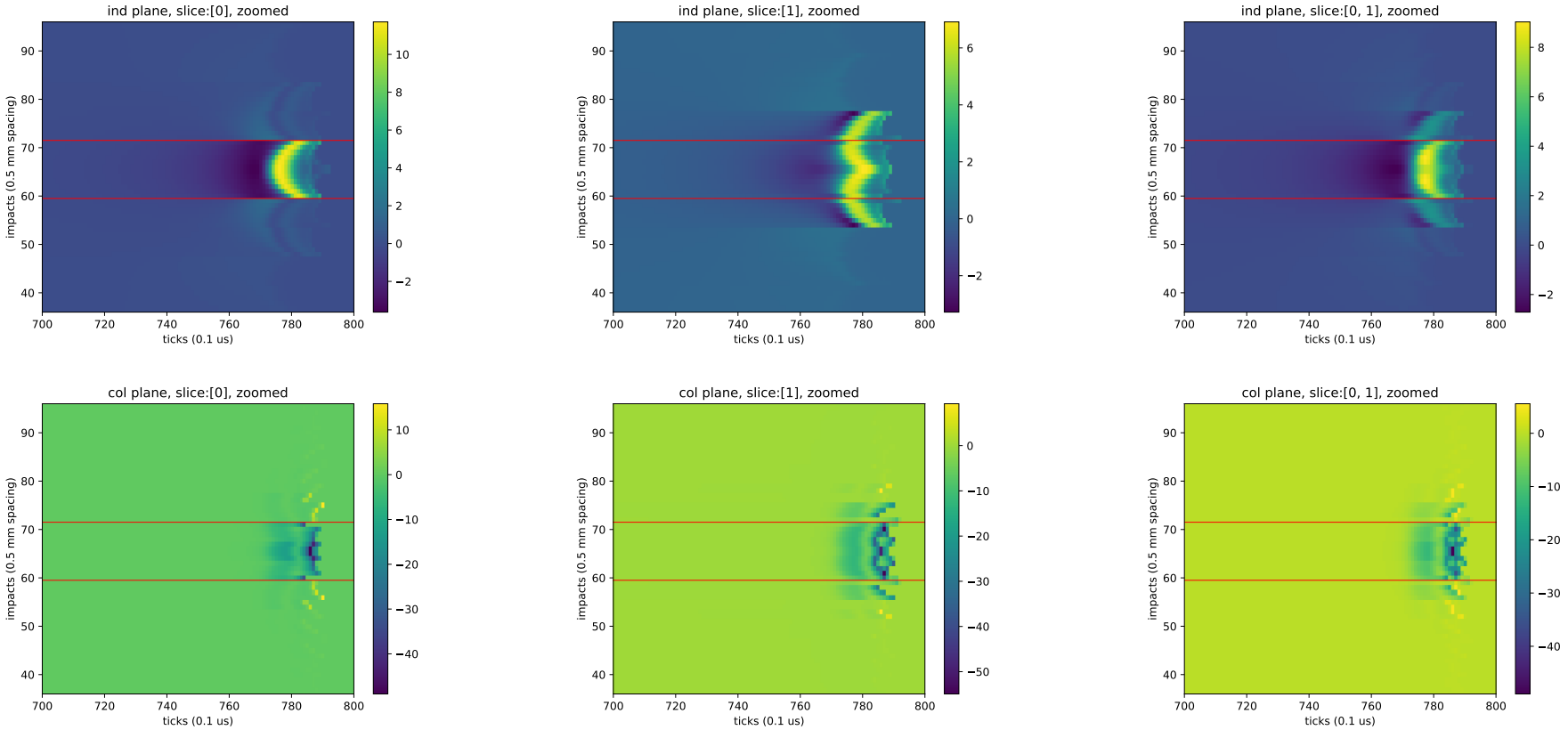
- Single hole, 2D geometry with strips constructed as array of hundreds of “micro wire” sensing conductors
- Left/Right and A/B blocks due GARFIELD limits.
- Drift paths defined depending on pattern and averaging scheme.
- Post-process sampling of “micro wire” responses and form average over some number (eg 2) of “slices” at points along the strips.



“2.5D” responses for 50-L

After laborious manual cataloging, the PCBro (PCB anode readout) package can processes and averages the GARFIELD responses at 2 “slices” across strip for the 50-L geometry.

(induction plane and collection plane)



Slice 1. Slice 2. Slices 1 + 2.

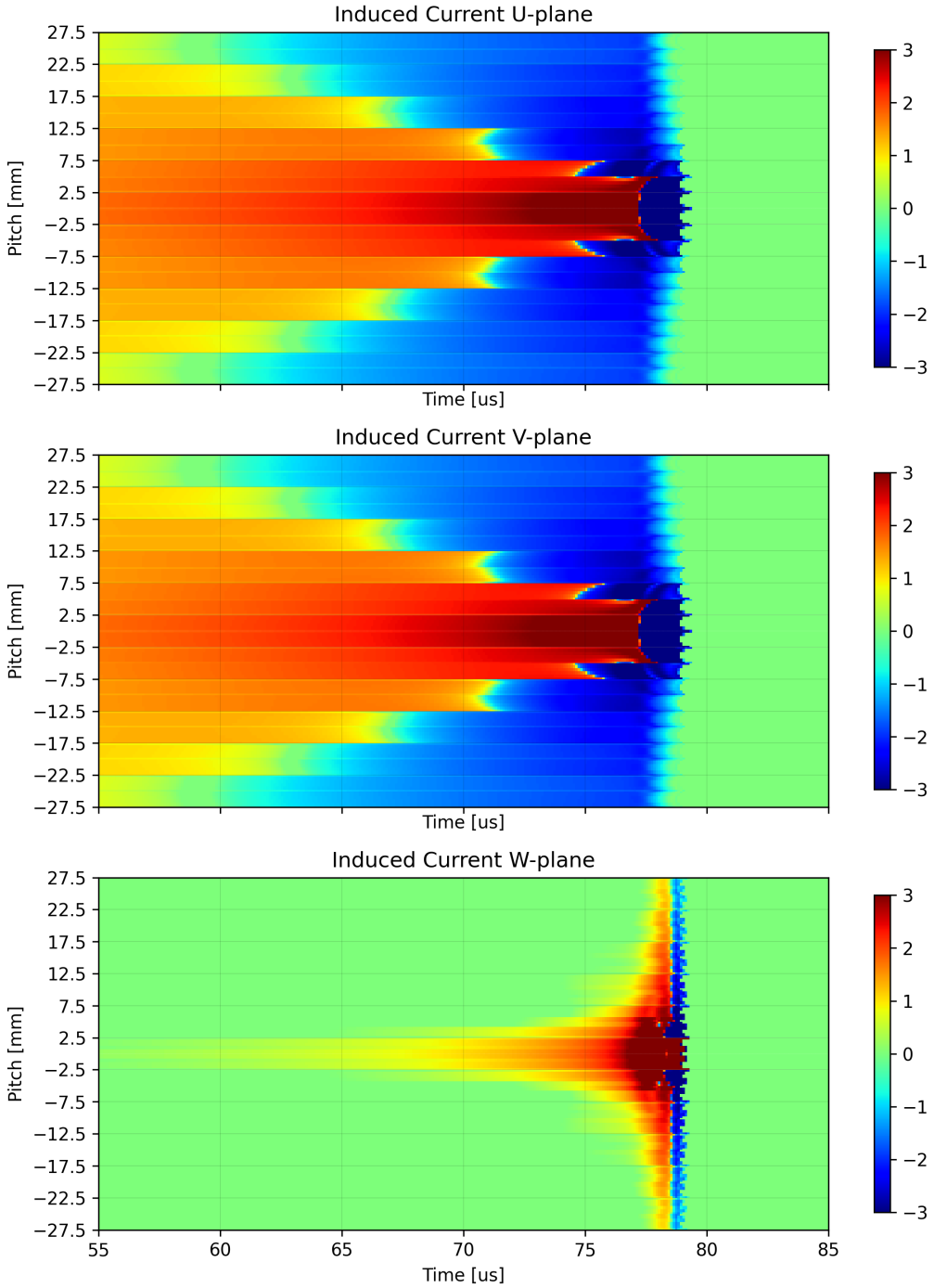
50-L response functions - next 3 slides

What follows are the responses in “log 10” scaling to better show tails.

Each slide shows an slice-average or a specific slice:

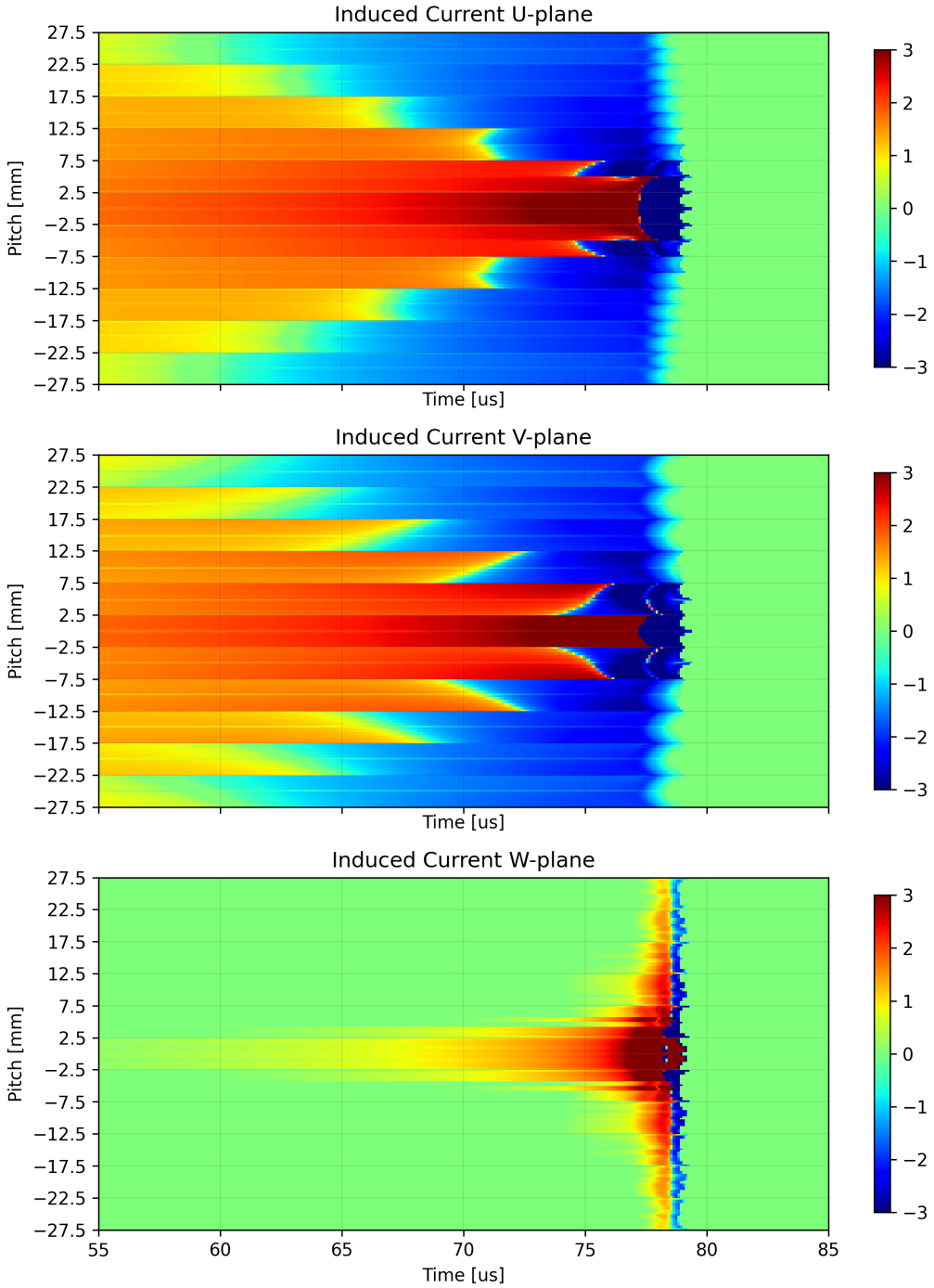
- average over both slices
- highlight slice 0
- highlight slice 1

The “U” and “V” labels indicate different forms for the induction plane.
The “W” is the collection plane.



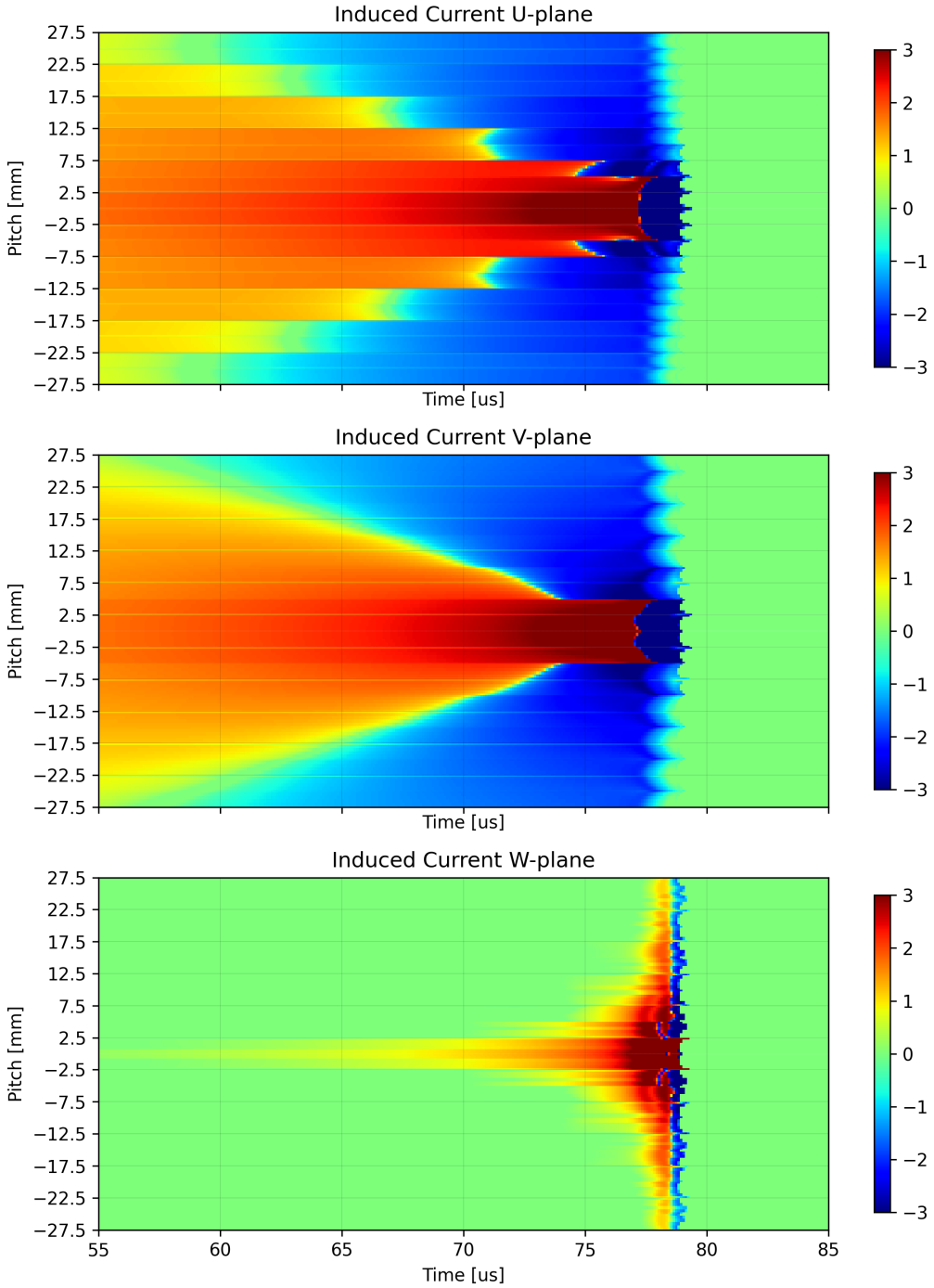
50-L field response functions

1. U is average over the two induction slices.
2. V is average over the two induction slices.
   - (the two are identical)
3. W is average over the two collection slices.



50-L field response functions

1. U is average over both induction slices
2. V is induction slice 0
3. W is collection slice 0



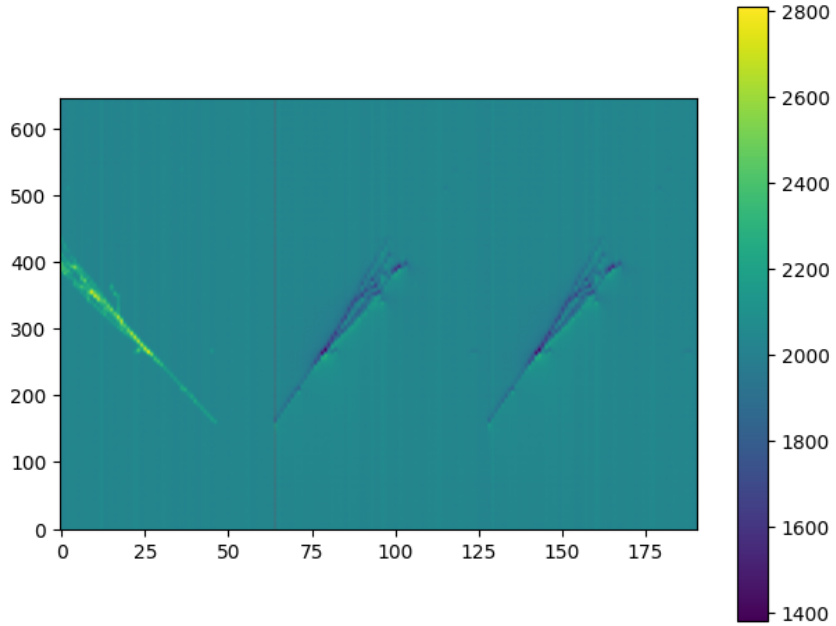
50-L field response functions

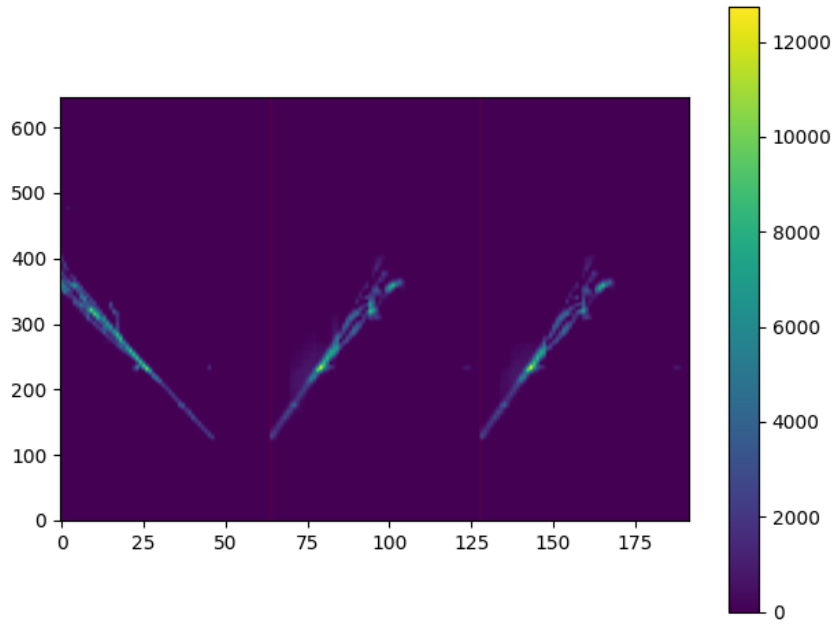
1. U is average over both induction slices
2. V is induction slice 1
3. W is collection slice 1

50-L raw data and WCT sigproc

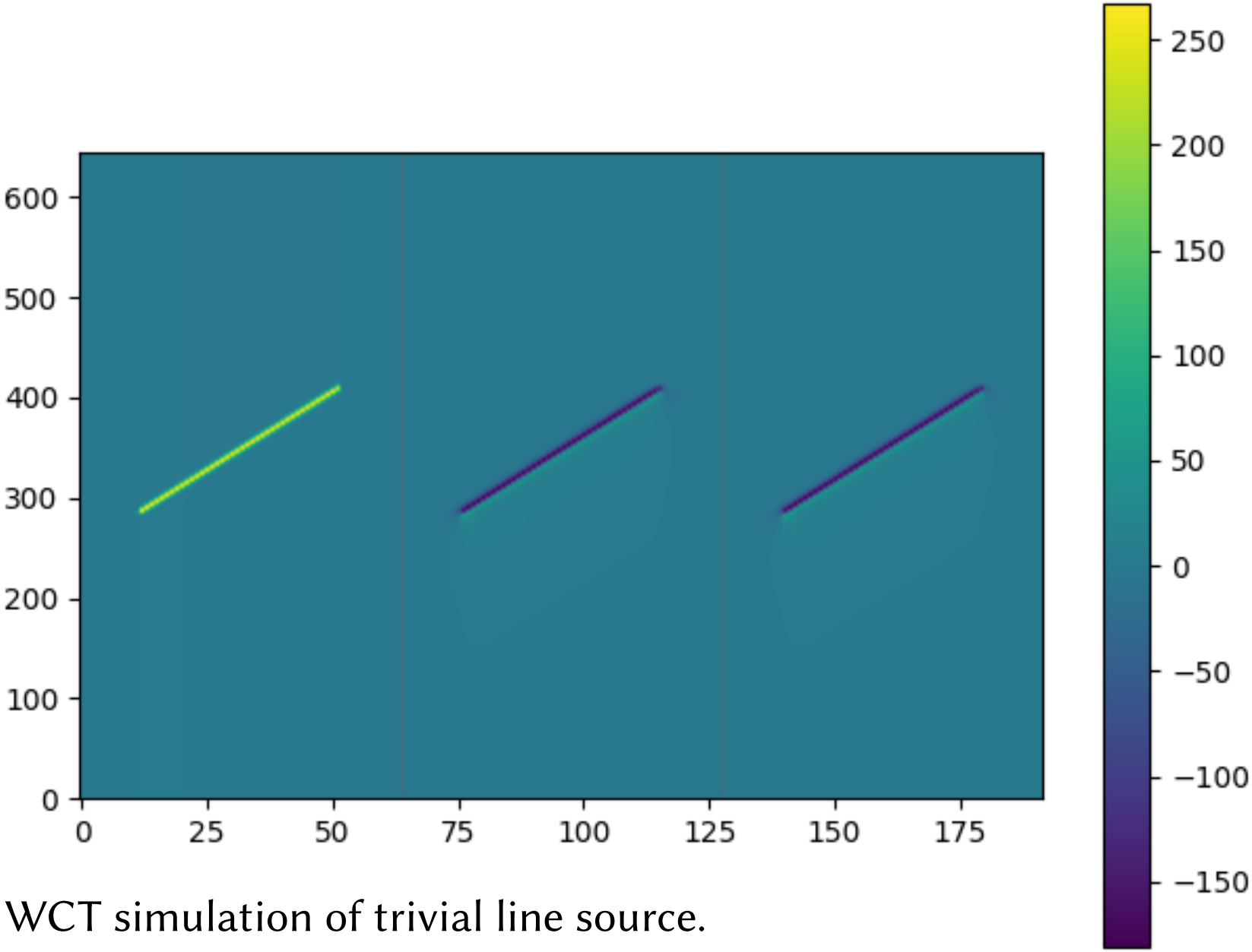
The PCBro package also provides a 50-L raw data decoder and hooks to run Wire-Cell Toolkit for simulation and signal processing of 50-L data.

50-L raw data event and after WCT sigproc.





The "double induction" plane is merely duplicate to fit Wire-Cell Toolkit assumptions of 3 planes. The PCBro package uses this "extra" in some places to test different field response "slices".



50-L WCT simulation of trivial line source.

Just an existence proof.

Need some Geant4 depos to compare to data.

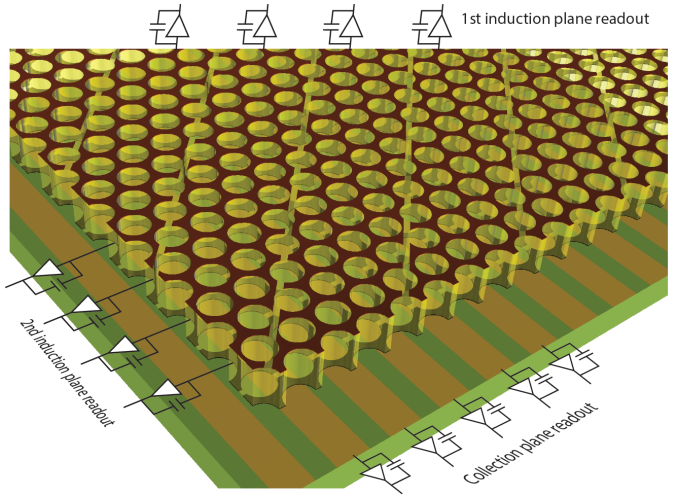
50-L data / WCT sim comparison

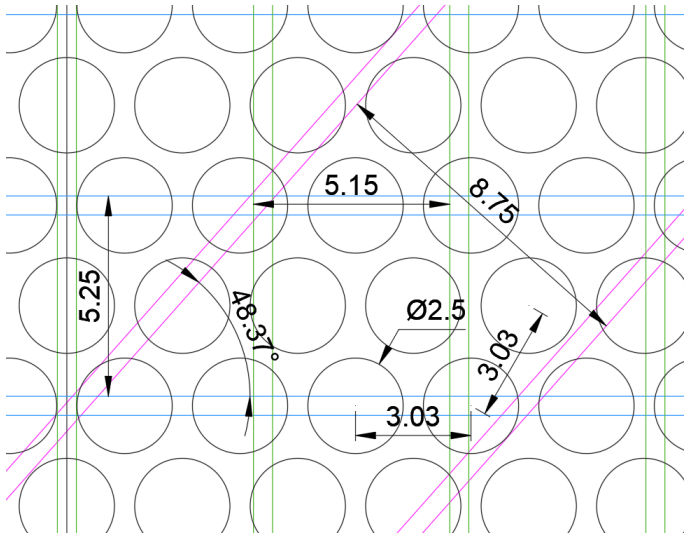
t.b.d.

- 39Ar blips
- single, similar data/mc track
- in different track direction bins

2.2D, 2.5D, 2.7D?

- Initial "eyeballing" checks of simulation and signal processing show no clear problems with the "2.5D" trick with 50-L.
- Detailed mc/data tests are needed to determine.
  - Such tests showed that 2D was "good enough" for wires, and we dropped 3D FRs.
- The 2-slice "2.5D" average requires about 100× more human effort to post-process GARFIELD than does simple 2D.
  - Effort probably grows linear with an N-slices.
  - We should likely avoid strips with a variety of cross-sectional hole patterns. Ie, more like 50-L, less like "**skewed pattern**" ⟶
  - Strip angle can make it so **no slice** goes only through hole diameters.
    - ★ Want rectangular 2-plane or isosceles 3-plane!
  - Even if we go to full 3D FRs, such regularity will be welcome to reduce problem size, hopefully exploit more transnational symmetry.





From Bo's presentation at the recent DUNE collab call

So, why not 3D FRs?

Some work on 3D FRs exist.

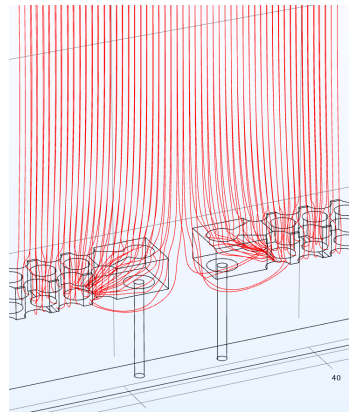
- Mostly for "near by" fields or "far fields" but for **wires**.
- Far field 2D calculation takes minutes-hours, 3D calculations take hours-days (using BEM, effectively impossible with FEM).
- 3D BEM with strips+holes will take longer than with wires
- More non-repetitive variety along a strip, more FRs calculation.

Once given 3D FRs, sim must contend with an explosion of data.

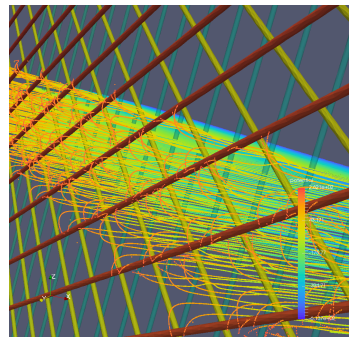
- Field response functions per plane (some estimate/guesses)
  - 2D wires: 126,
  - 2.5D strips: O(100) for 50L, O(1,000) for skewed hole pattern, but results in usual 2D simulation
  - 3D: **O(50,000)**, old simulation must be thrown out.

3D simulation

- Same concepts as 2D sim, but need all new algorithms/code.
- 2D exploits 10-way interlacing across common impact position in order to use 2D FFT + 10-way sum for fast convolution.
  - How to even apply this trick in 3D? More variety along the strip direction will increase interlacing $\longrightarrow$ harder/slower.



From Bo's talk again



LARF

