3D Detector Response Calculations Using **B**oundary **E**lement **M**ethod

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Outline

Motivation

Procedure

Current Results

Todo

What Determines TPC Detector Response

Two types of fields:

- $\vec{E}_{drift}$ applied electrostatic potential determines electron drift path.
- $\vec{E}_{weight,i}$ Shockley-Ramo potential for a given wire determines the **current response** for a given drift path.

$$\vec{v} = \mu \vec{E}_{drift}$$
$$I_i = q * \vec{v} \cdot \vec{E}_{weight,i}$$

- $\vec{v}$ instantaneous velocity of a charge at a given location.
- μ electron mobility, function of $|\vec{E}_{drift}|$ and temperature.
- I_i current on wire i evaluated over drift path.

Why Calculate Fields

Fields critical for:

- realistic TCP readout simulation (see Xiaoyue's talk).
- extracting an accurate measure of drifting charge topology.

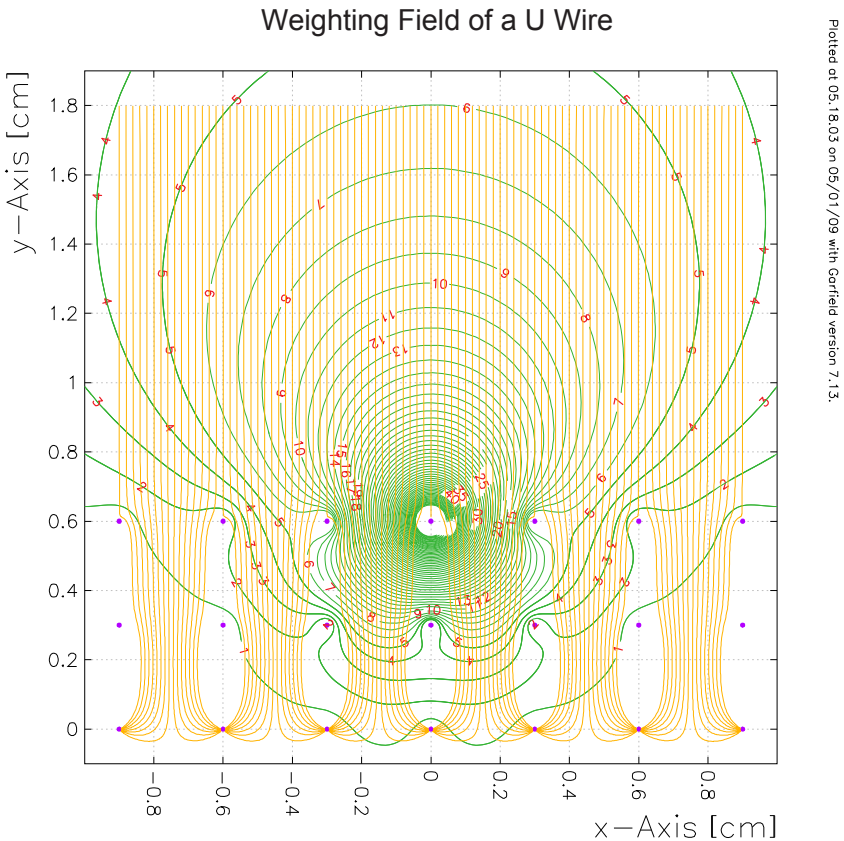
Enables host of reconstruction technologies:

$\rightarrow$ Deep Learning, Wire Cell, Gaussian hit finding, ...

Also critical:

- **validate** response calculations, such as with in-situ measurements and dedicated experiments (eg, LAr Field Response Calibration System).
- understand electronics response and irreducible noise.
- hardware suppression and software removal of excess noise.

2D Field Calculations



Bo Yu using Garfield

- **F**inite **E**lement **M**ethod, high precision over a limited 2D region.
- Reproduces major field features, especially distant from the wire planes.
- Relatively fast calculation, allows exploring (2D) parameter space.

Why 3D?

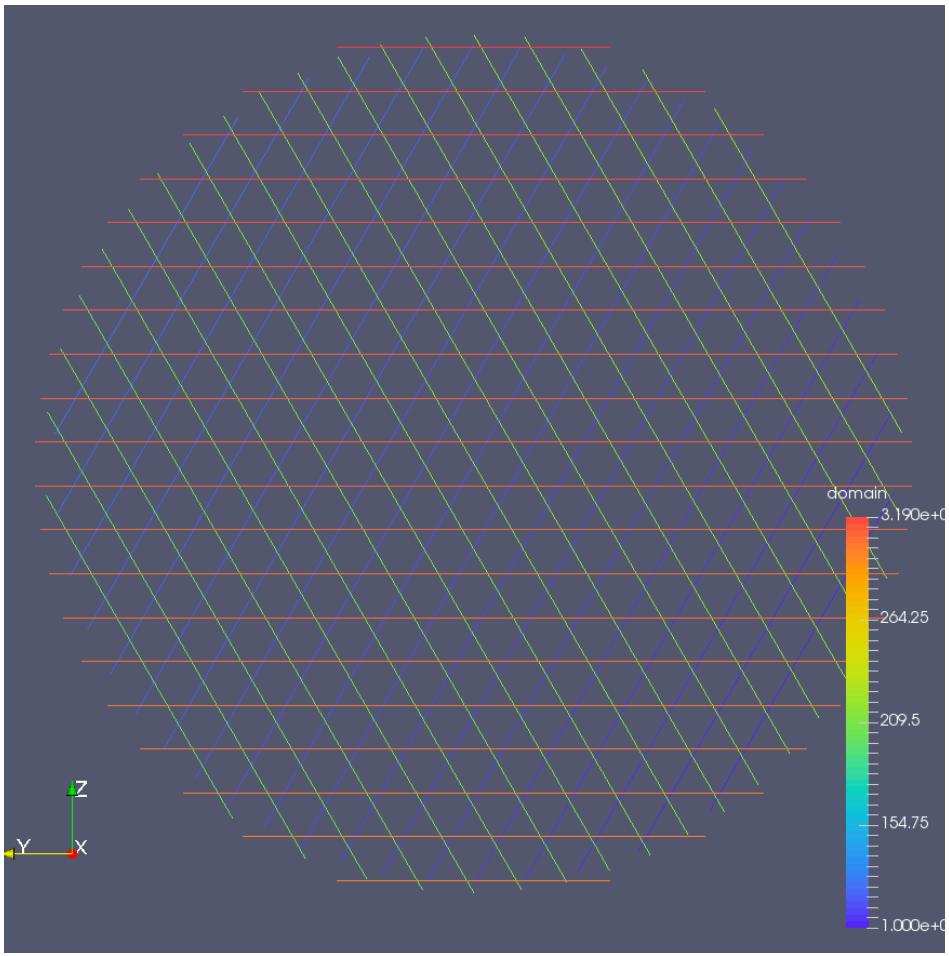
- MicroBooNE sees U-plane signal features explained by **long range inductance** from large signals.
  - $\rightarrow$ turns out that these effects can largely be reproduced using just 2D fields but out to ± 10 wires
- See also some V-plane signal features which are expected to be explained by 3D wire structure.
- DUNE wire crossing pattern relatively irregular, concerned about location-dependent systematics.
- Novel wire readout schemes have been proposed for detector design optimization which are more sensitive to 3D wire crossing patterns.
- Detector edge effects are inherently 3D.

Procedure Overview

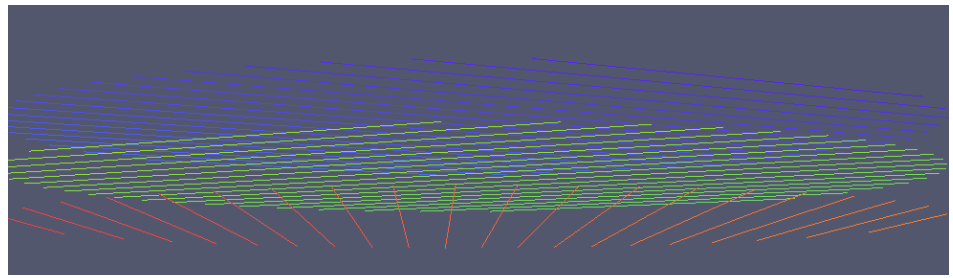
1. Define the **wire geometry**.
2. Generate a **surface mesh** on wires and artificial electrodes needed to set up drift field.
3. Solve **surface boundary conditions** for each field type
   → fields: a common **drift** and one **weighting**/wire
4. Define electron drift path **starting points**
5. Step through **drift field** to produce **drift paths**.
6. Sample a **weighting field** along a path to produce corresponding **current waveform**.
7. Define an average over paths to produce a **response function** for a given wire as a function of wire pitch number.

Also: sample full-volume raster of field for debugging.

Wire Geometry

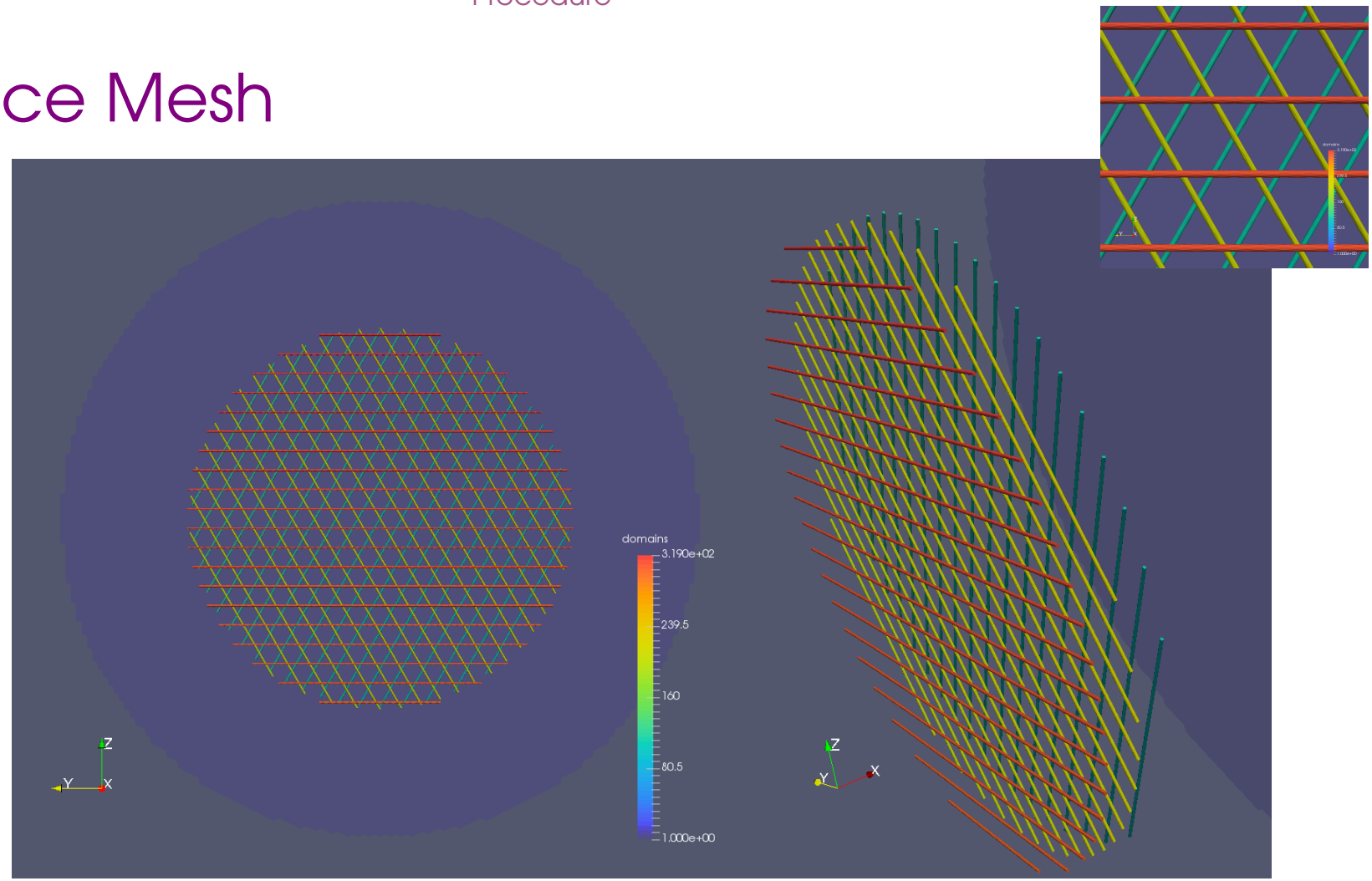


μBoone-like, color is wire index



- Wires specified by their endpoints and a radius, different wire envelopes possible.
- A parameterized wire generator is included, covers DUNE, μBoone and others.
- Wire geometry used to seed a surface mesh and to detect electron/wire "hits" to stop path stepping.
- The extent/number of wires drives CPU/RAM needed for calculation.

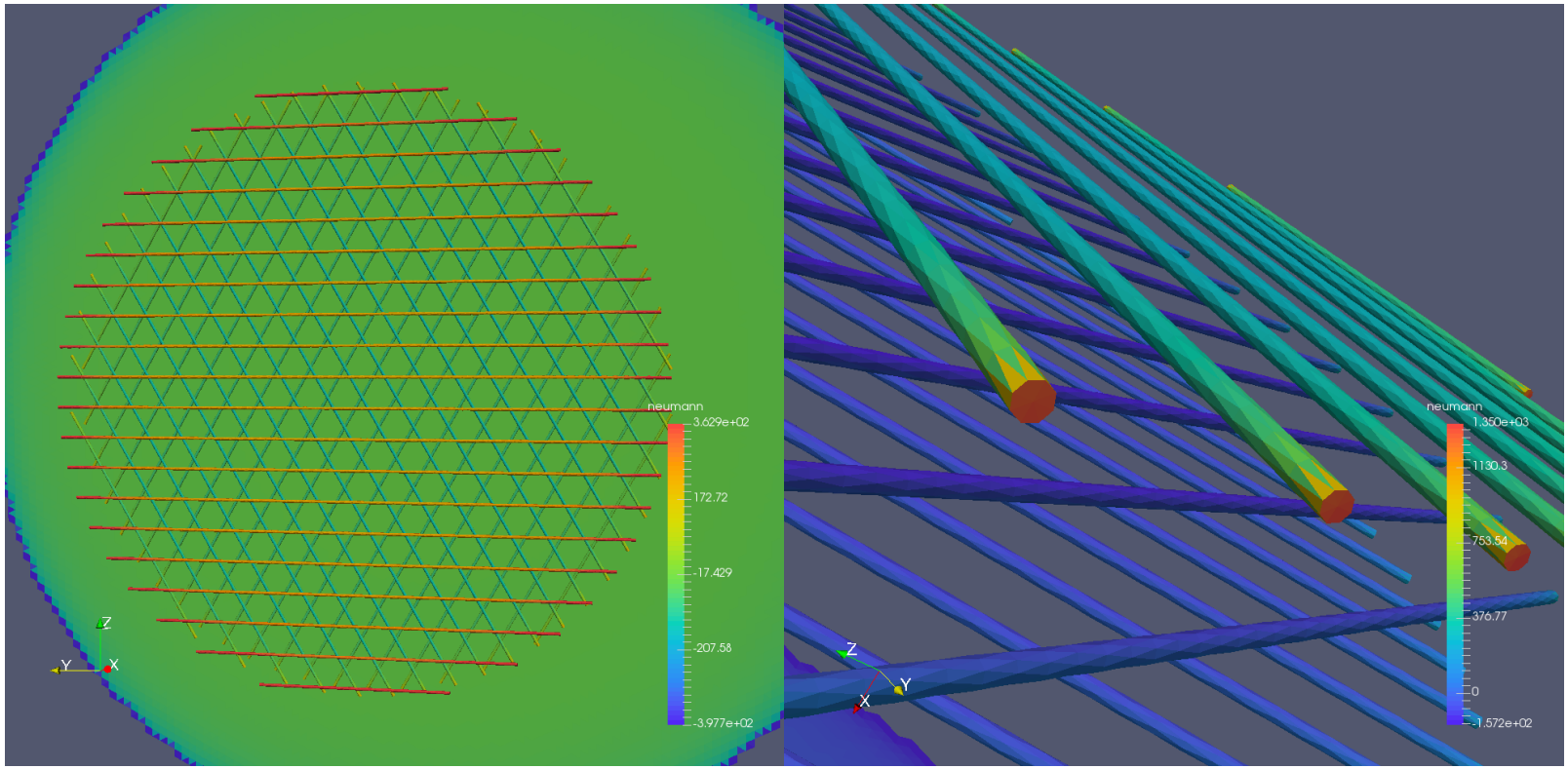
Surface Mesh



Cylindrical envelope of wire planes and a flat disk "cathode".

- These are "hand made" meshes, can also use GMSH, or make your own.
- Mesh size drives accuracy and precision (and CPU time).

Boundary Conditions

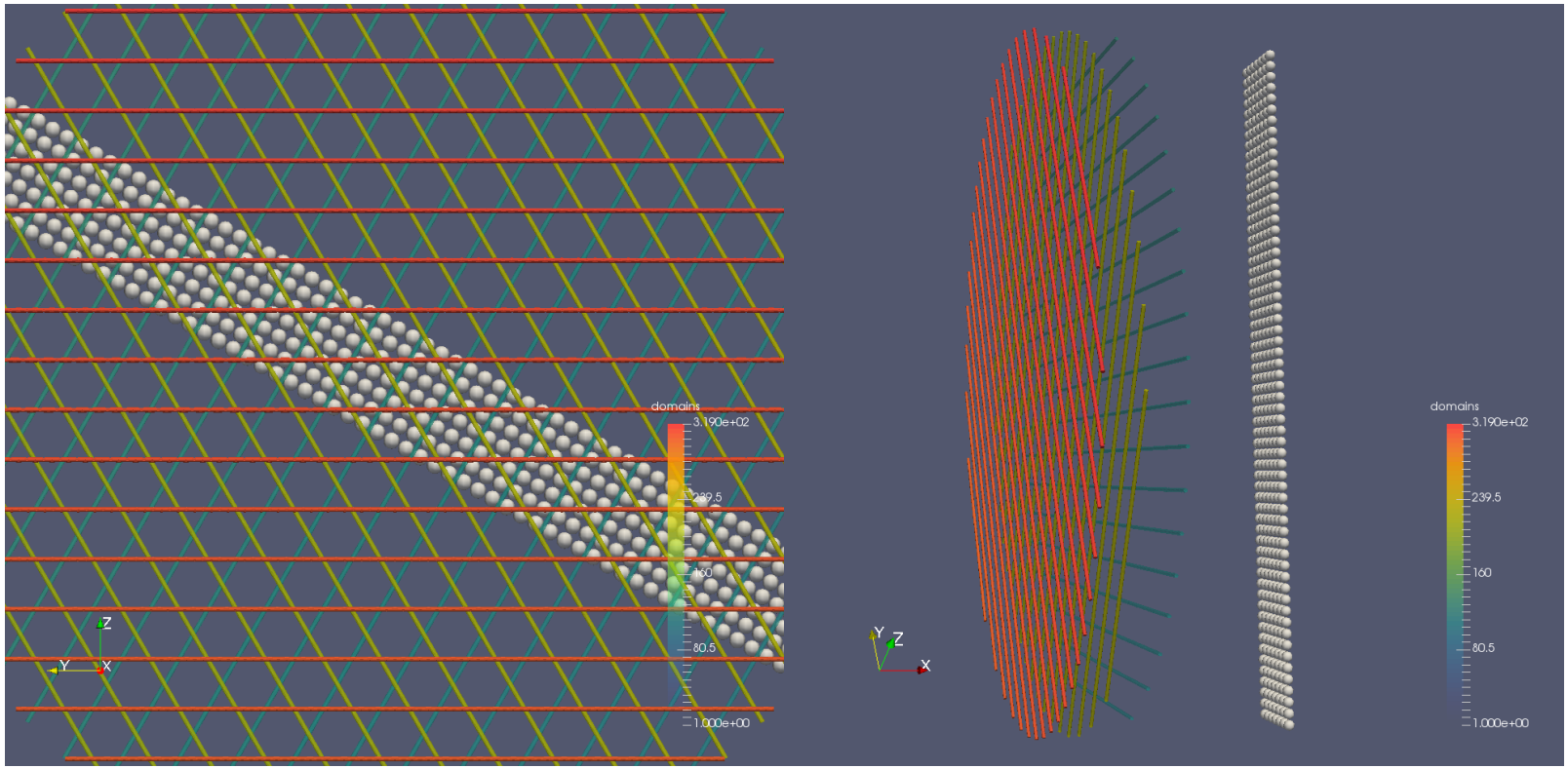


Color is Neumann b.c. Note, color scaled to show edge effects.

- Apply scalar potential (Dirichlet) boundary conditions.
- BEM solves for $|\hat{n} \cdot \vec{E}_{drift}|$ (Neumann) boundary conditions.
  - $\rightarrow$ once solved, can evaluate potential anywhere in space.

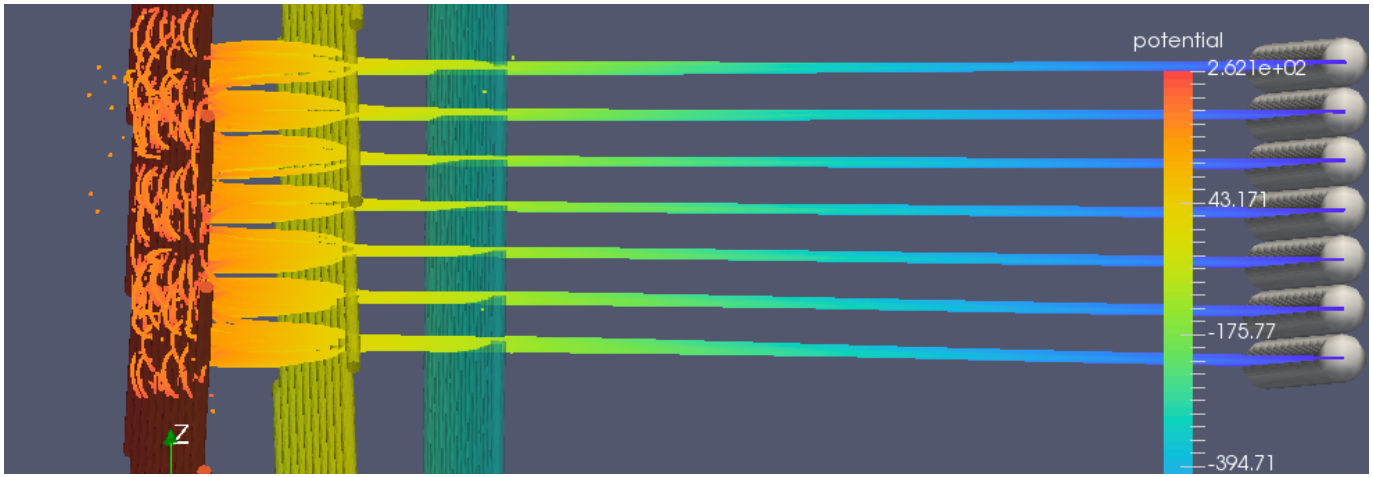
$\Rightarrow$ Finite sized geometry leads to **unwanted edge effects**. More on this later.

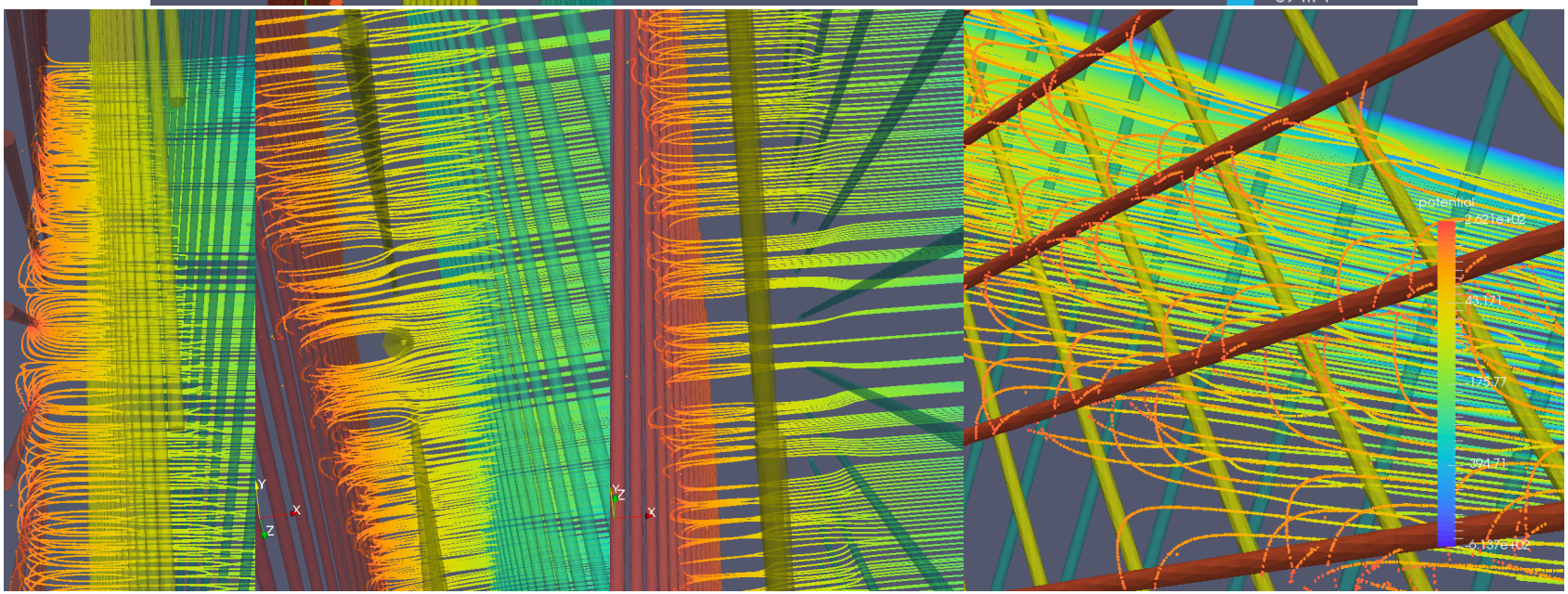
Path Starting Points



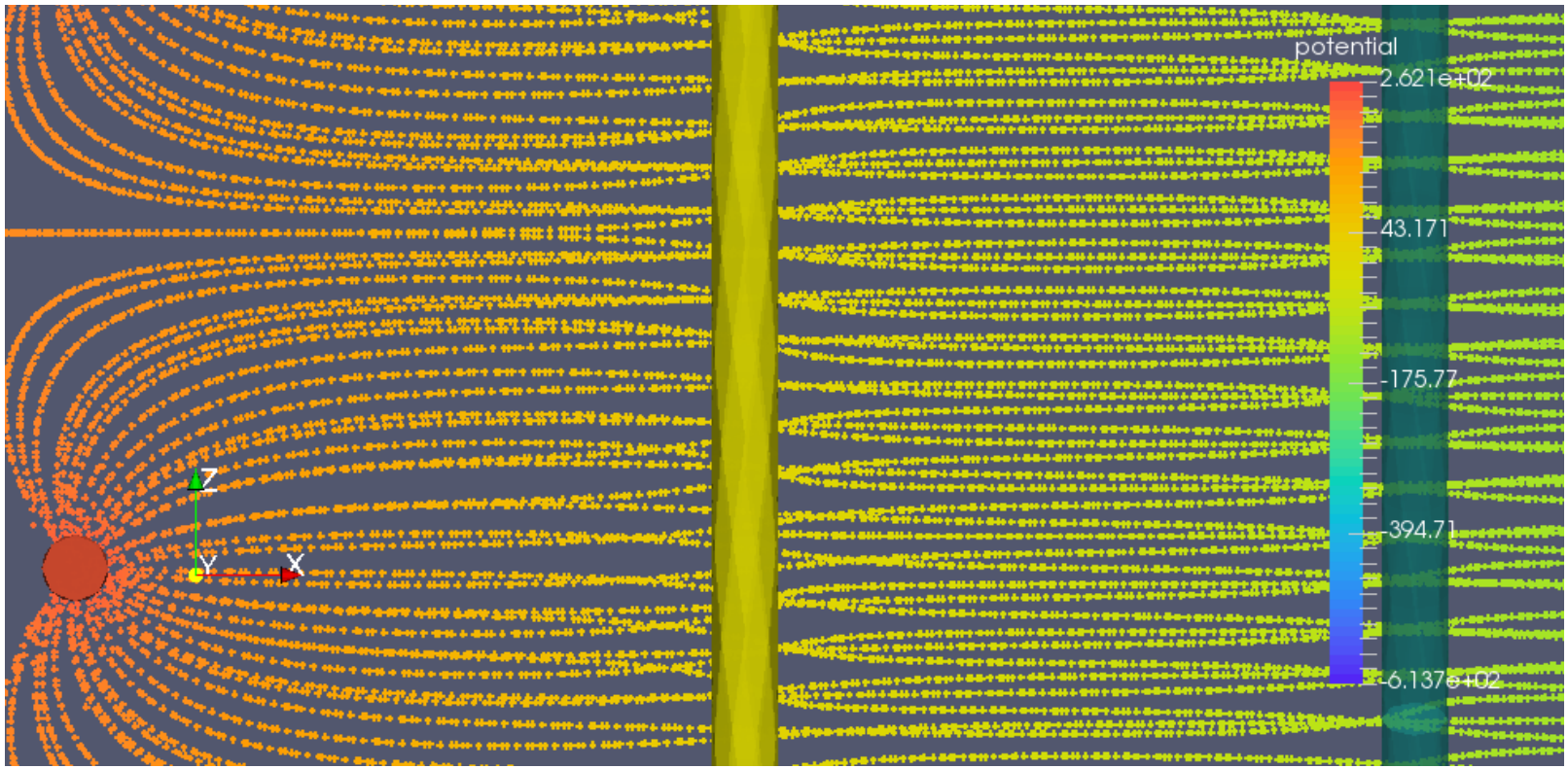
- Generate starting points for drift paths.
- Various possible schemes, this one aligns with central U-wire.
  - → spans ∼2 periods of crossing pattern in longitudinal direction.
  - → spans ±9 transverse wire regions in addition to central region.
    - Turns out, this is relatively coarse. More on this later.

Drift Path Visualizations



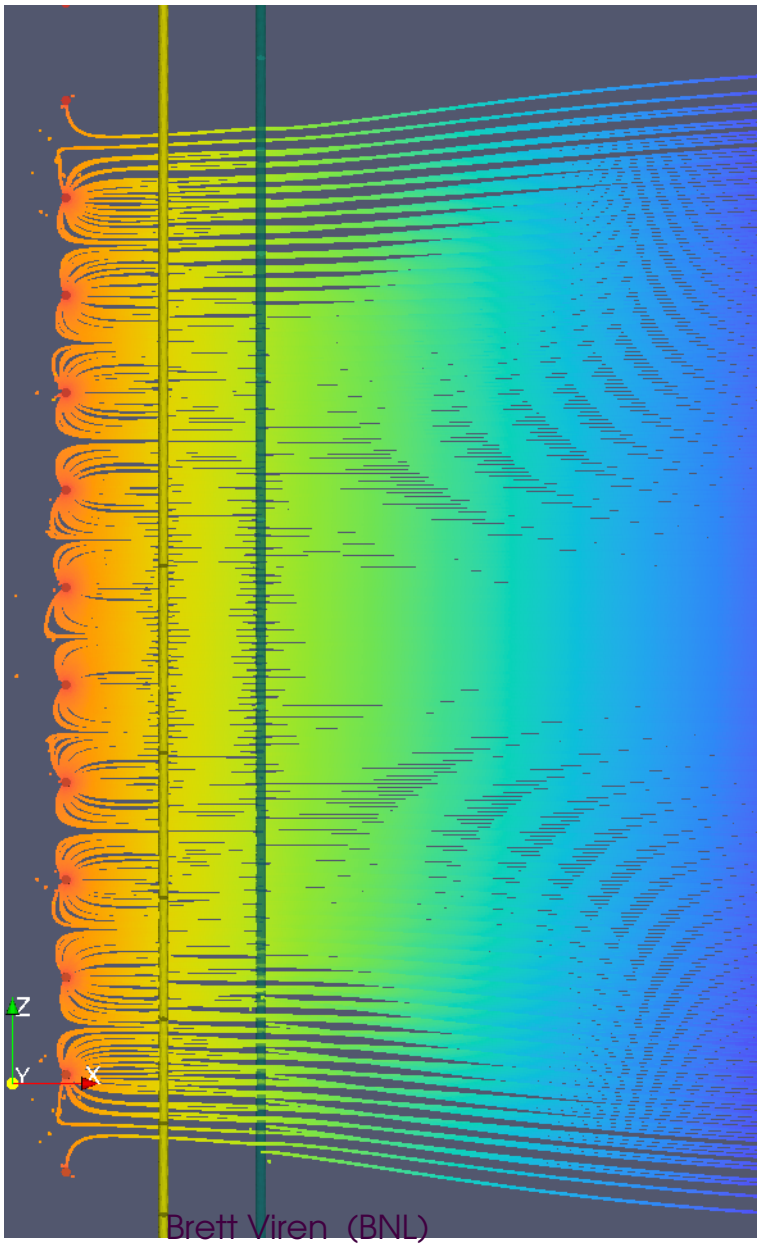


Stepping to Produce Paths



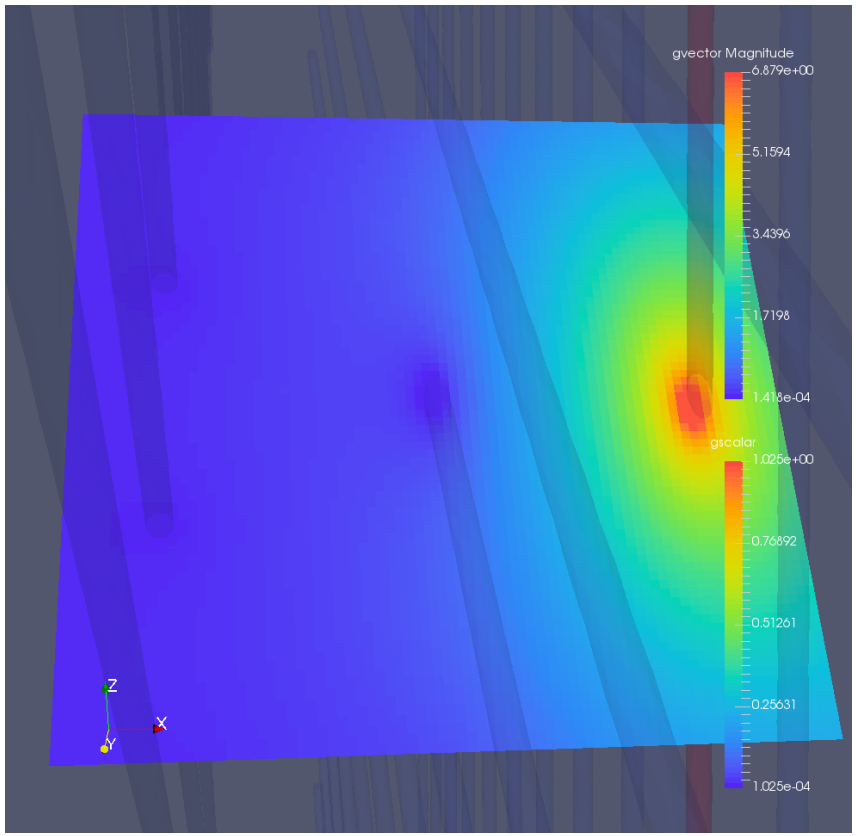
- Steps use 5th order Runge-Kutta with fixed step size (0.1μs).
- Each sub-step evaluates potential on 7 points to form gradient.
- Steps terminate when they pass inside a wire's radius.

Edge Effects due to Finite Geometry

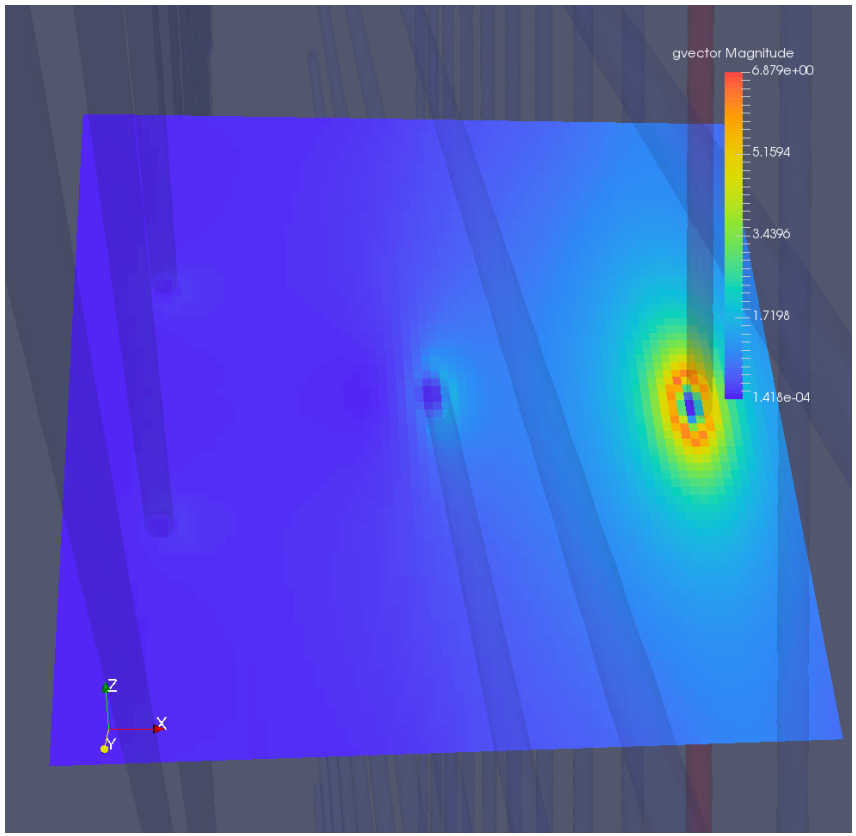


- Finite size "cathode" and wire planes lead to non-uniform fields near edge.
  - Drift fields "pinch in" toward W-wires.
- Need to explore ways to shape field. Some possibilities:
  - Smaller "cathode" disk?
  - Larger "cathode" disk with a grounded annulus disk at X=0?
  - Coaxial rings (ersatz field cage) along X-axis with stepped voltage?
- For now, live with small error.
  - Charge drifting near edge contributes $< 1\%$ to wire-of-interest.

Weighting Field for U-wire



Weighting **potential**.

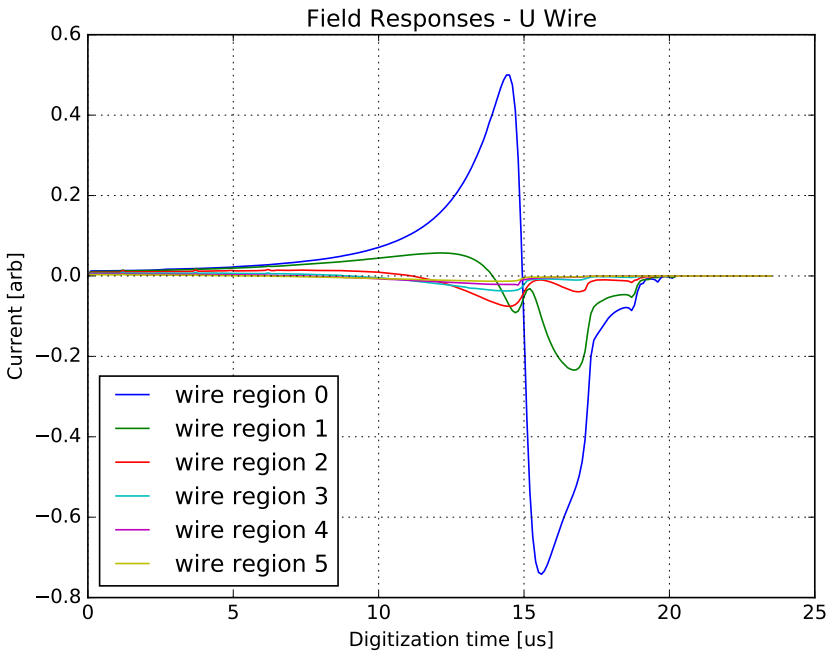


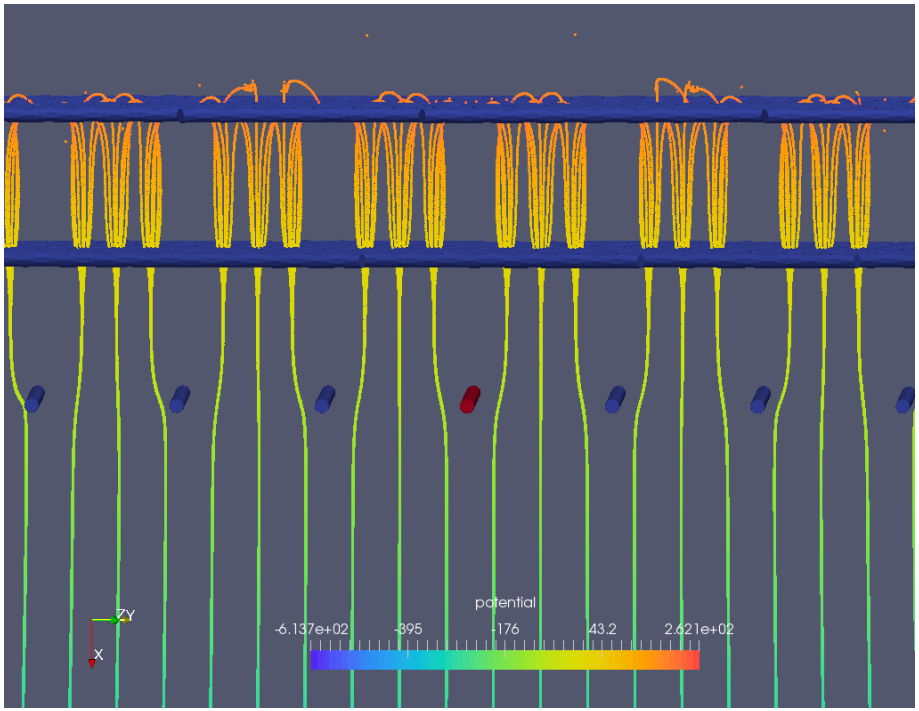
Weighting **field magnitude** ($|\vec{E}_{weight}|$).

- View is zoomed in to the inter-plane region, wires partially transparent.
- Reminder: this field is next sampled along drift paths to finally get current.

$$I_i = q * \vec{v} \cdot \vec{E}_{weight,i}$$

Response Functions - U-Wire

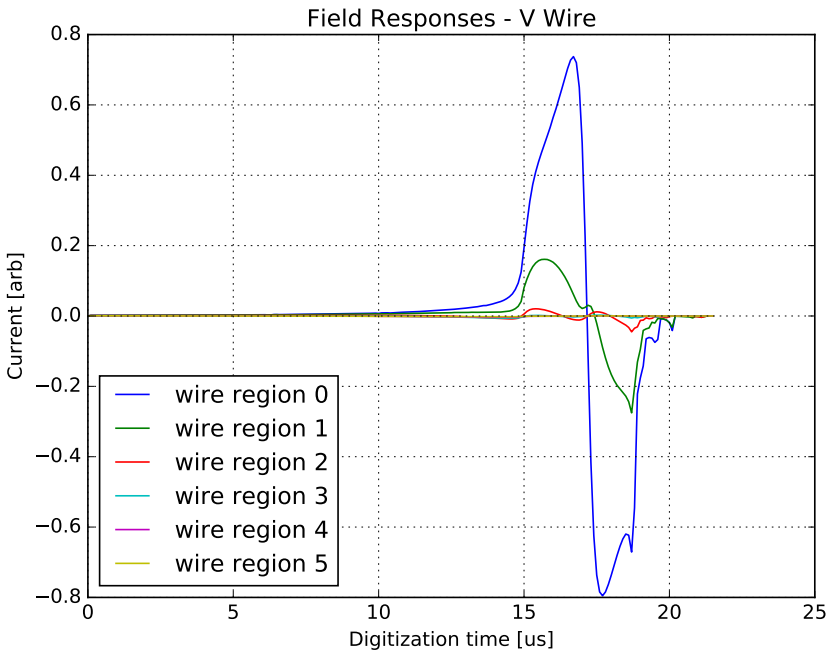


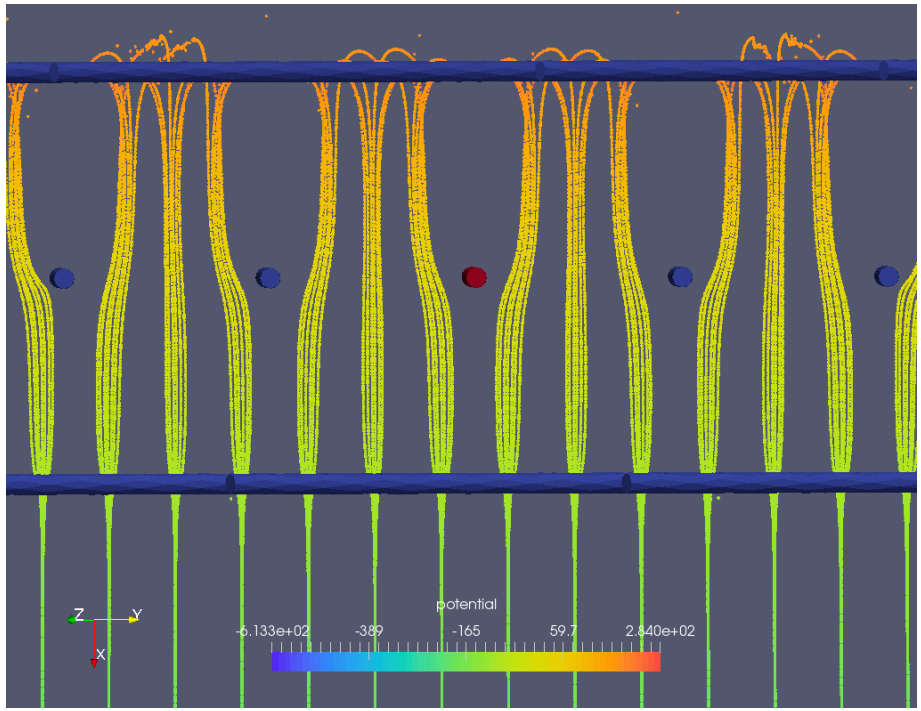


Average over 3mm in longitudinal direction and paths w/in $\pm$1.5mm of wire.

- Wire region 0 is $\pm$1.5mm around central U-wire.
- Wire regions 1-5 progressively further in transverse direction.
- Wire regions 6-9 not shown here.

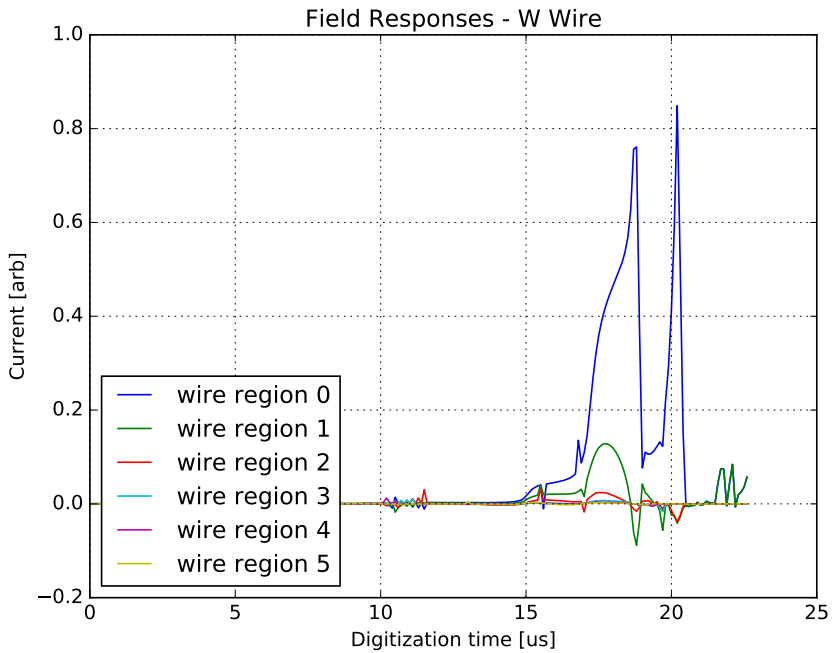
Response Functions - V-Wire

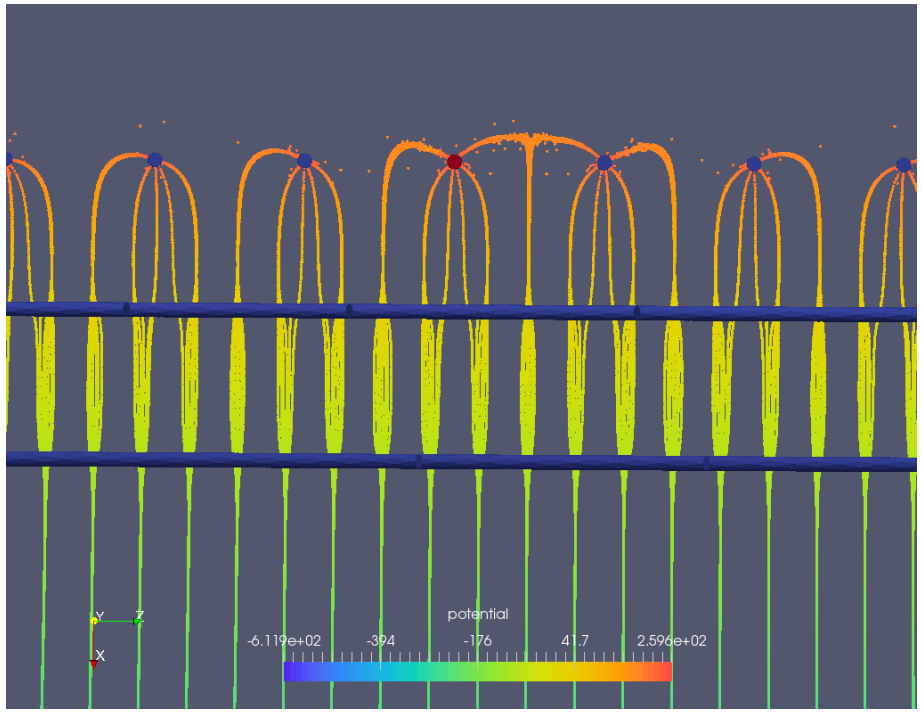




- Some end-of-track jaggies need checking,
  - maybe be due to paths on a "lucky" line of symmetry.
  - more severe example in W-wire.

Response Functions - W-Wire





- One set of paths precisely on line of symmetry take an extra-long time.
  - $\Rightarrow$ Need to fill in phase space with more intermediate paths.
- Non-unipolar signals from charge in wire region ≥ 1

Work Still To Do

- Finish with the μBoone-like wires crossing pattern.
  - Fill in with more paths, especially in wire regions 0, 1, 2.
- Start on DUNE-like wire pattern.
  - $\sim$30 unique weighting fields needed compared to μB's 3!
- Investigate edge effects
  - near field cage
  - inside/between APAs
- Wire plane configurations from proposed LArTPC design optimizations.

I welcome others to get involved in this work.

Software

- BEM++ for the heavy lifting:
  http://www.bempp.org/
- ParaView for visualization:
  http://www.paraview.org/
- LARF to glue it all together:
  https://github.com/brettviren/larf

extras

Why BEM? (Why Not FEM?[1])

Boundary **E**lement **M**ethod

- Handles 3D geometry (also 2D)
- Scales as the surface (FEM scales as the volume)
  - $\rightarrow$ 3D BEM requires less CPU than 3D FEM (hours vs days).
- Solution and evaluation are decoupled. (FEM uses single volume mesh for both).
  - $\rightarrow$ can evaluate potentials at arbitrary points in space.
- BEM has fewer available high-level tools (compared to FEM)
  - $\rightarrow$ development against s/w libraries required, expertise and effort needed to validate and tune.

[1] Leon Rochester @ SLAC pushing state-of-the-art in 3D FEM for LArTPC.