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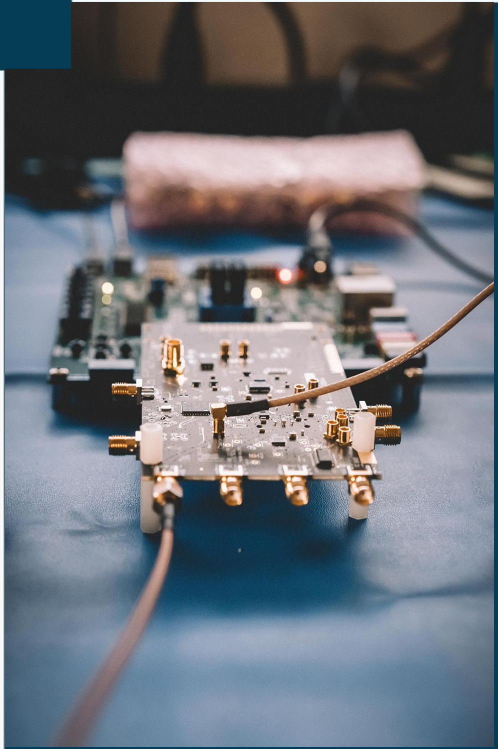

LAPPD Readout Plane - Modelling and Optimization

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High Fluence Project

1. Phase I SBIR funded by DoE - **DE-SC0021437**
2. **Target of evaluating and optimizing the performance of separately engineered “Readout-plane” boards for LAPPDs using capacitive coupling**
3. Main components (of Nalu involvement):
   a. **Electrical modeling** of induction/signal propagation/crosstalk (Nalu, Luca Macchiarulo)
   b. **Design and fabrication of custom board with different array geometries** (Nalu, Ryan Pang)
   c. **Testing of boards with and without LAPPD** (Incom, Mark Popecki)
   d. **Data analysis and modeling validation** (Incom, Mark Popecki, Nalu, Kevin Flood and Luca Macchiarulo) - some conclusions consistent with independent work of Alexander Kiselev’s

PRESENTATION SUMMARY

TOPICS COVERED:

Modeling:

- Model properties
- Induced charge integration
- Readout plane board coupling
- Readout coupling

Validation boards:

- Design and geometry choices
- Measurements and Data Analysis

Comparisons with models:

- Qualitative consistence
- Modeling successes and failures

Conclusions

Model Properties

The **electrical behavior of an LAPPD** is the result of the interaction of several physical phenomena that include both weak as well as more strongly correlated phenomena:

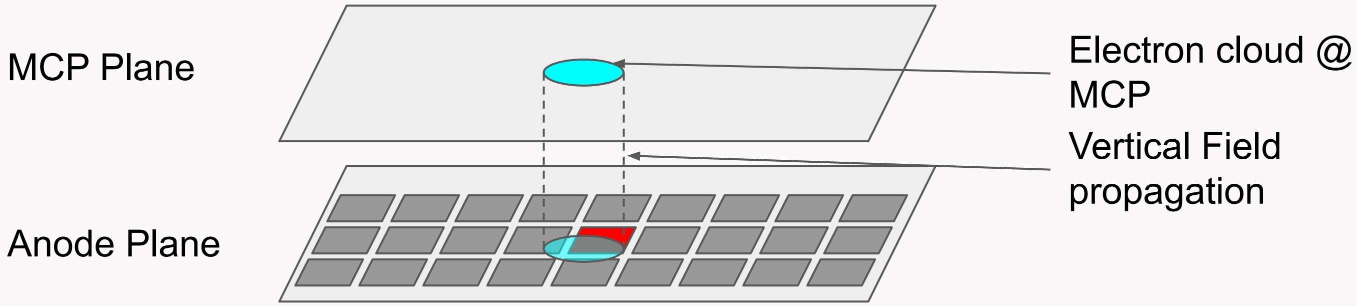
- **Generation of the electron cloud** from the MCP structure and its propagation toward the anode;
- **Induction of charge** from the electron cloud to strips (for strip-based readout), to pixel pads (for direct readout) or to an internal resistive ground (for capacitively coupled readout);
- **Crosstalk** between strips, sensor pixels or readout pixels and the resistive ground;
- **Signal distribution in the readout board** from anodes to connectors or reading pads;
- **Crosstalk within the multilayer PCB** distribution board;
- The **advantage of capacitive coupling is that the readout pattern may be easily and arbitrarily changed** without affecting the construction of the LAPPD itself. However, such a readout scheme introduces additional considerations in modeling:
  - **Propagation of the induced charge** through the distributed RC network of the internal ground;
  - **Frequency-dependent electromagnetic coupling** with readout pixels.

Modelling ideas

1. Assume electron **cloud distribution** appearing right **below last MCP** and propagating based on known E field
   a. Backreaction of charges or from induced charge effect not modelled (requires full EM simulation, possibly multiphysics package)
2. Use **Shockley-Ramo theorem** to estimate current induced on each anode per single electron propagating - integrate effect of all electrons
3. **Model multi-anode** structure (including capacitively-coupled) **as a network of R and C** - possibly L if necessary
4. **Feed currents** generated in 2. and perform simulation to obtain:
   a. Voltage profiles at probing nodes
   b. RMS of values (MonteCarlo) for noise
   c. Dependency on geometric parameters

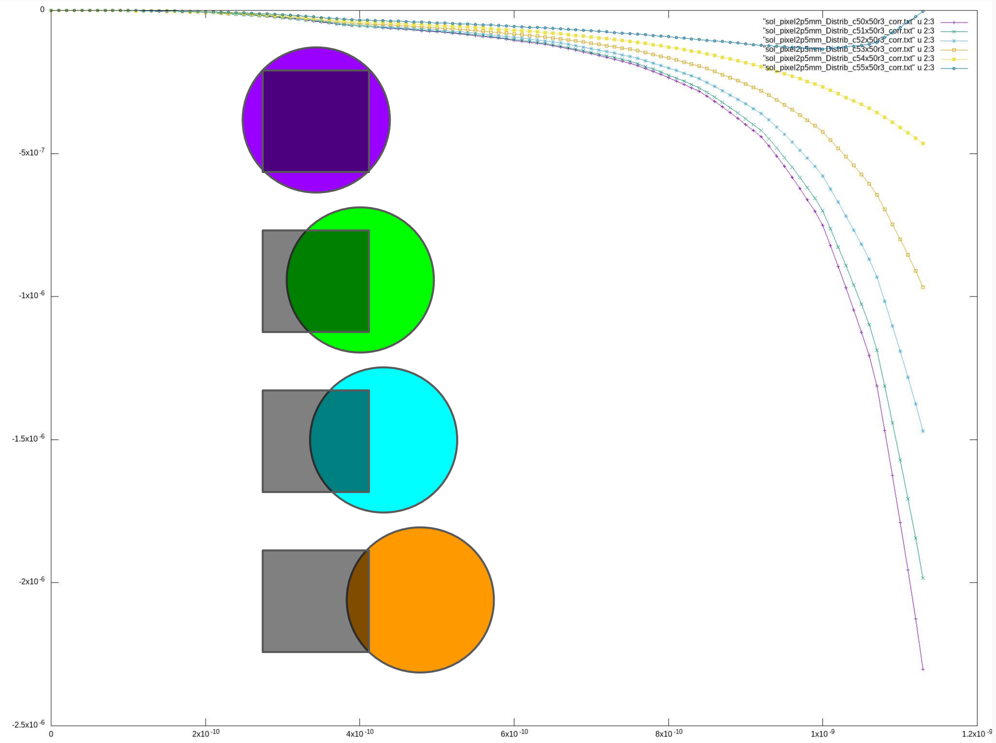
Induction model

1. “Flat” distribution of charge:
   a. All charge appearing at the same instant below MCP at time 0+
   b. Square or spherical distribution
   c. Uniform (non realistic)
2. Show effect of charge position w.r.t. Anode (effective velocity used)
3. Overall shape as a function of distribution center



Current vs time for different position of center

- Using a spot size of 3 mm (~diagonal length of anode)
- Similarly shaped currents
- Approximately proportional to “shadow” on anode
    - Intuitive
    - Due to very well defined shape of probing field next to anode



Capacitance and resistance extraction

1. **Capacitances**: A simple Laplace solver
   a. From V to q
   b. Inclusion of different dielectric interfaces
   c. Validated with simple geometries
   d. A note on extraction:
      i. FastCap (free academic tool) difficult to use for proper extraction of thin structures (traces, ground planes)
      ii. Most results using home-grown Laplace solver for planar geometries
2. **Resistances**:
   a. Simple model - use of sheet resistance (Ohm/square)
   b. Might require refinement for current paths/frequency dependence?

Modeling

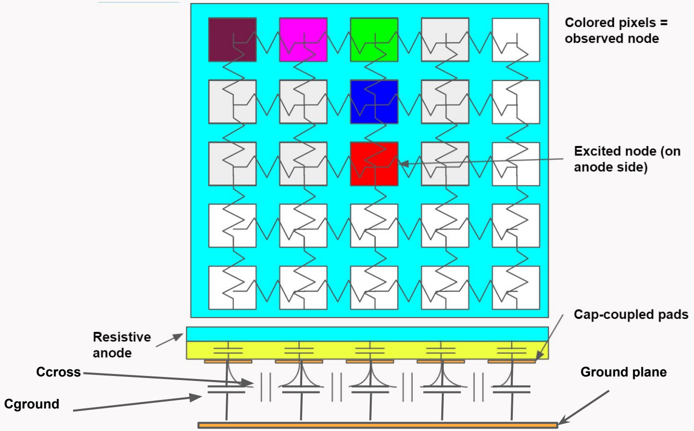


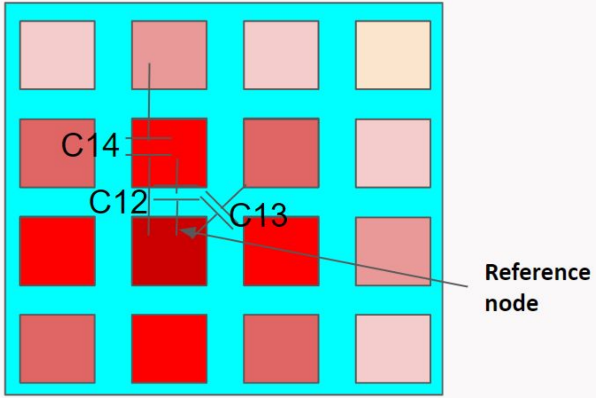
Diagram of the readout geometry showing the effective resistive coupling between anodes (the light blue plane with colored pixels) as well as the capacitively coupled readout pads shown as a cross-section at the bottom of the figure

C_{ground} decreasing w/increasing thickness

- signal amplitude improves

C_{cross} increasing

- Crosstalk increasing



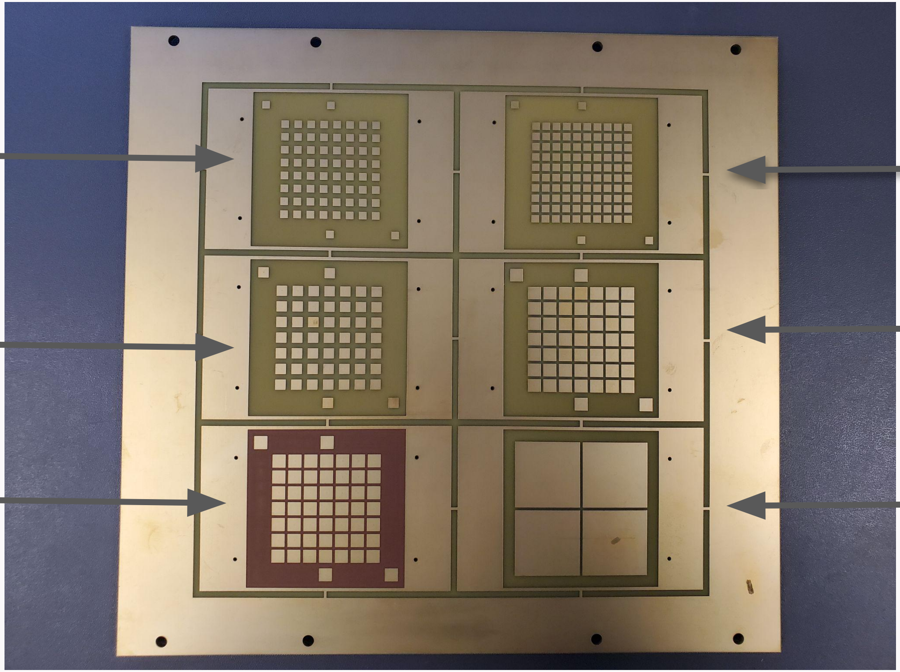
Modeling of capacitive couplings at the anode plane.

Array Layout

3mm x 3mm
2mm gap

4mm x 4mm
2mm gap

5mm x 5mm
1mm gap - far
ground plane



3mm x 3mm
1mm gap

5mm x 5mm
1mm gap

25mm x 25mm
1mm gap

Board design - connectorized High Density Interconnect

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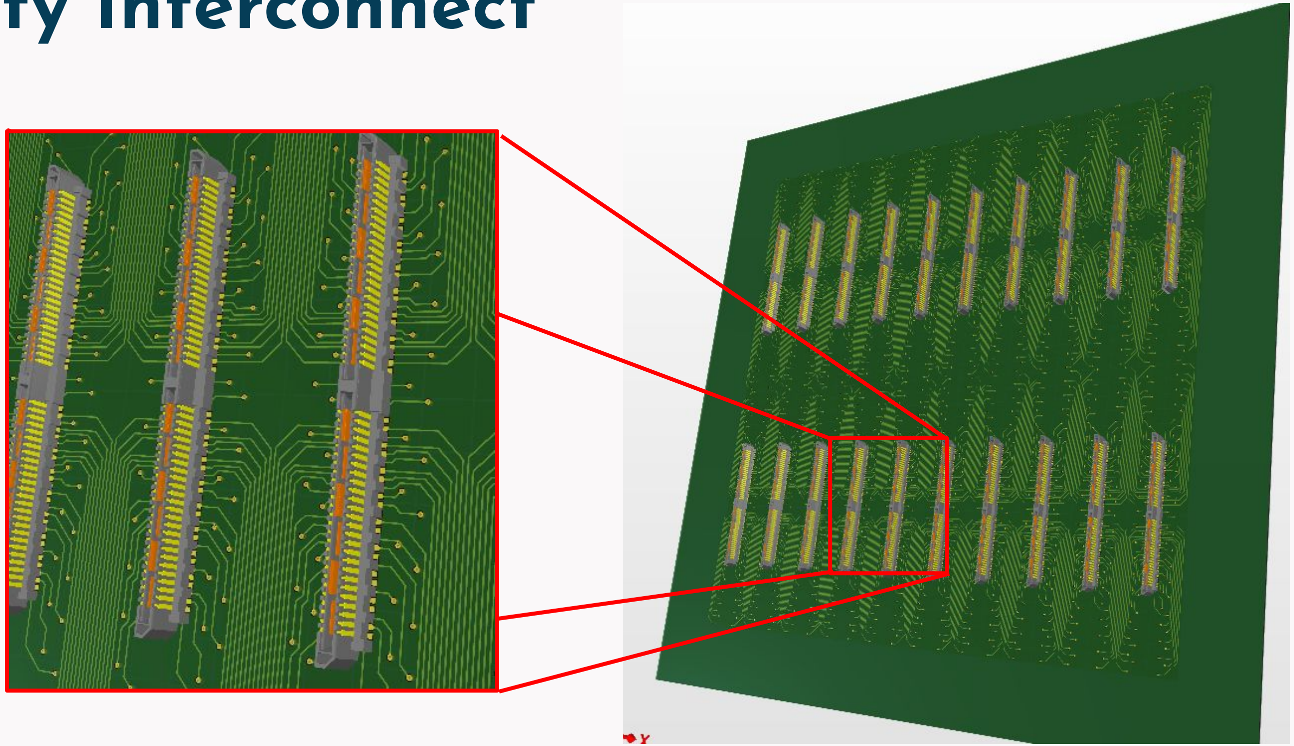
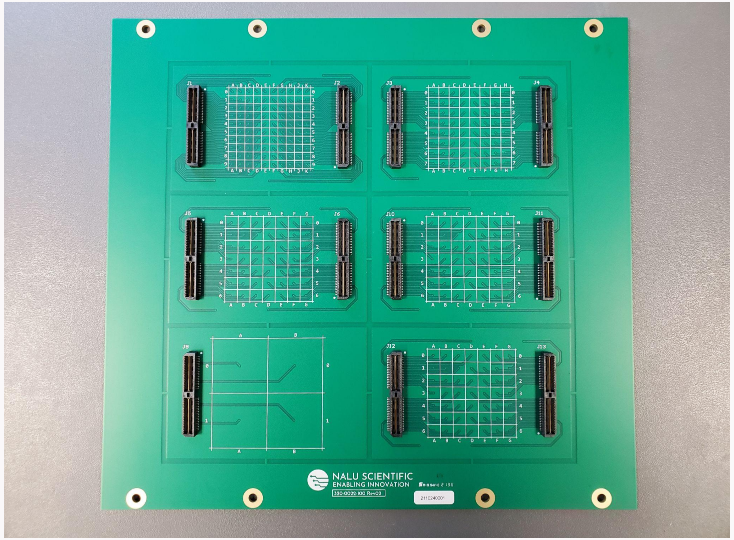


Array connections and readout boards

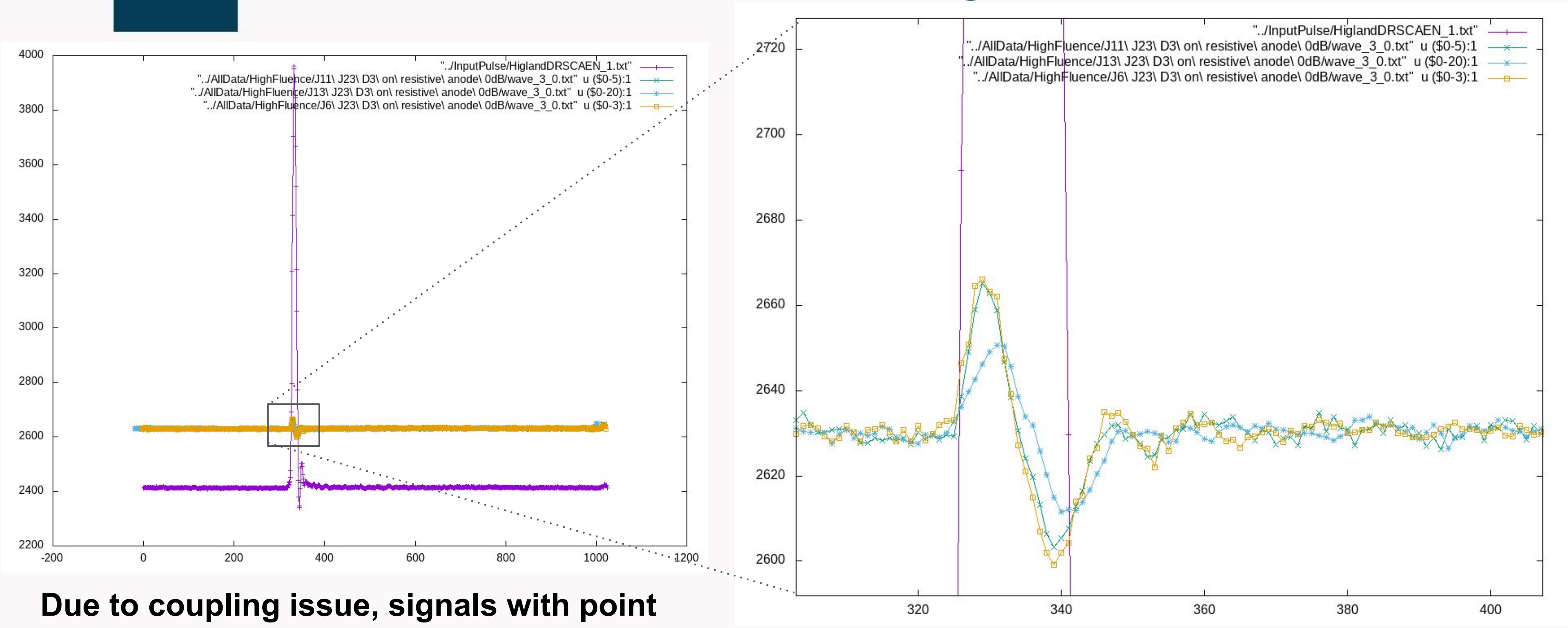


Datasets

For each of the six array layouts, the experimental setup and data collection was done by Mark Popecki, Incom

- **“Direct coupling”** datasets provided estimate of readout board-generated crosstalk
  - Most signals showed very small crosstalk (<5%)
- **“Resistive anode coupling”** with three variations
  - Point source
  - 7mm “disk” source
  - 3mm “disk” source
- **Board + LAPPD** was tested using fine-stepped laser scans across one array element on

Point source data signal shapes

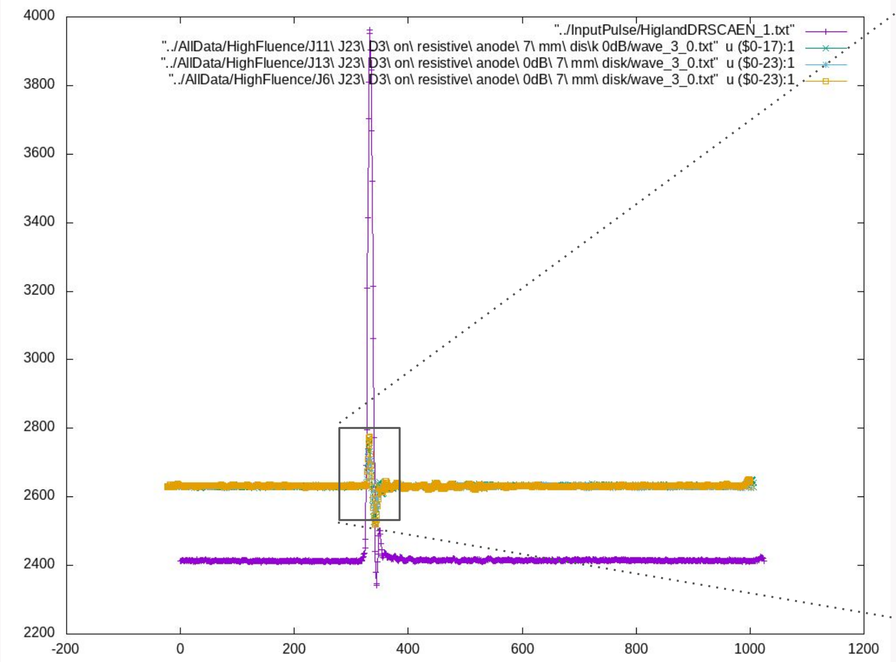


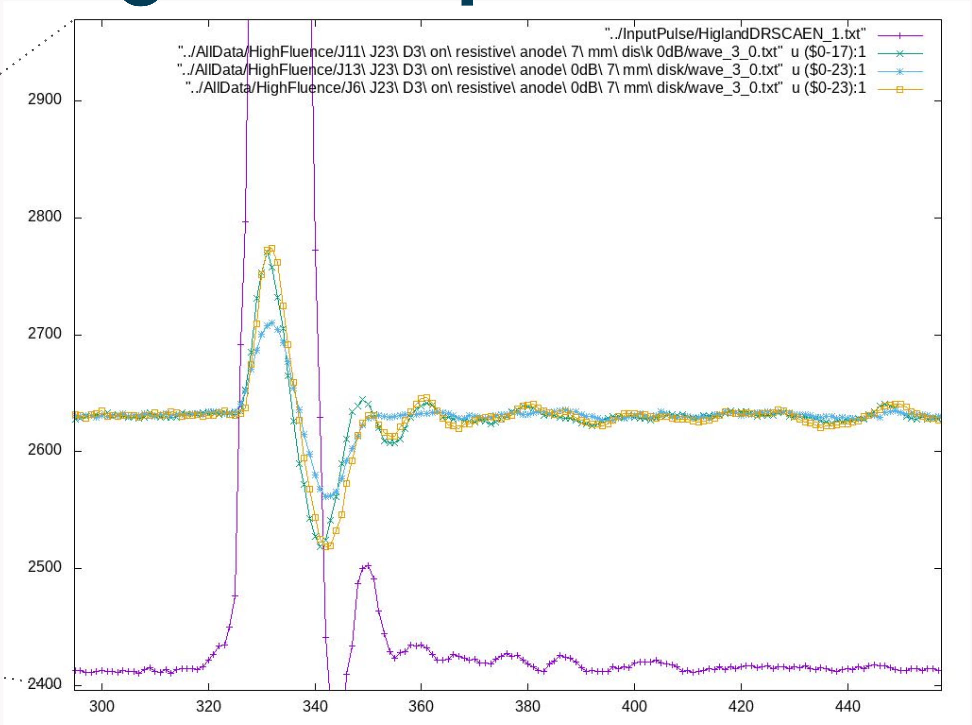
Due to coupling issue, signals with point source are very small

Point Source: Resistive anode-top signal amplitudes

- **Input signal: 390 mV**
- 4mm x 4mm, 2mm gap: 8.1mV measured
- 5mm x 5mm, 1mm gap
    - Close ground: 5.1mV measured
    - Far ground: 9.4mV measured
    - Factor of 2 difference between close and far grounds
        - Consistent with simulations
- Signal absolute values much smaller than expected likely due to large mismatch at feed-in pad
- Measurements have relatively large errors (~10-20%)
    - SNR 10-20 for 390mV input signal
    - SNR 5-10 for first neighbors

7mm disk data signal shapes





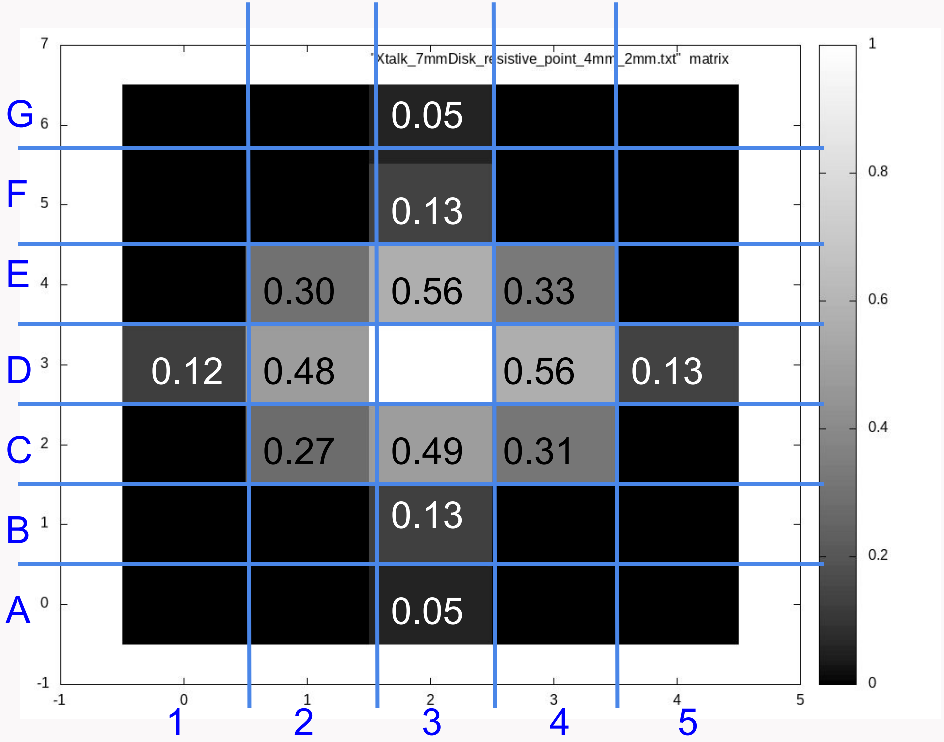
Disk feed guarantees better coupling/signal levels

<u>7 mm disk</u>: Resistive anode-top signal amplitudes

- Input signal: 390 mV
- 4mm x 4mm, 2mm gap: 34mV measured
- 5mm x 5mm, 1mm gap
  - Close ground: 20mV measured
  - Far ground: 38mV measured
  - Same behavior expected from model - Uncovered dependence on rise time of signal in simulation (effect more nuanced than in “delta function” sims).
- Absolute value more reasonable (if signal at “0dB”):
  - Mismatch at pad reduces
  - Now SNR is 40-80 - expected accuracy < 2.5%
  - Note that for 7mm coverage there is no “good crosstalk effect” (only one pixel with applied charge) - this is probably the best data to use.

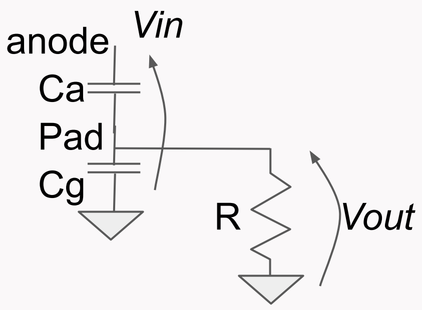
7mm disk: Crosstalk

- Example plot (right) shows 4mm x 4mm, 2mm gap; input at center (D3)
  - 4mm x 4mm, 2mm gap crosstalk <u>greater</u> than 5mm x 5mm, 1mm gap
    - contrary to expectations but very small difference
  - Further ground crosstalk generally <u>greater</u> than closer ground
    - As predicted by model



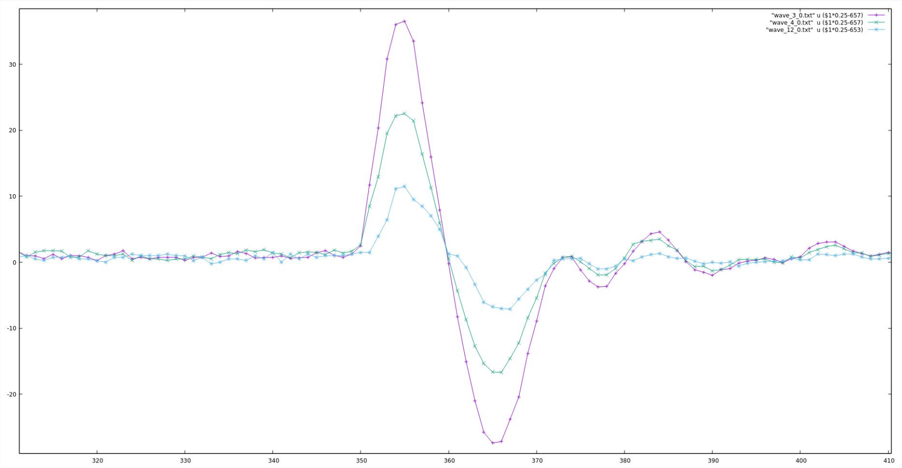
Peak signal on target pixel

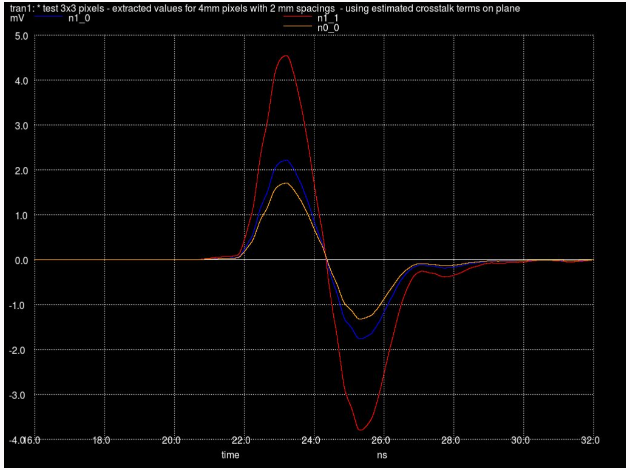
- Variation captured by the model:
    - Effectively a very simple RC network with performance depending primarily on:
        - Coupling capacitance: +
        - Ground capacitance: -
        - <u>Termination resistance: shunts the ground capacitance : +</u>
        - Input signal slope - distinguishes between Cg dominated and R dominated
    - Vout/Vin=sCaR/(1+s(Cg+Ca)R)
        - If s->∞ (high speed signal): Ca/(Cg+Ca)
        - If s->0 (slow signal): sCaR
        - "Slow" vs "fast": t><((Cg+Ca)R) ~ 30-50 ps -> most signals are "slow" <u>IF R=50 ohm</u>
            - But effect measurable (factor of ~1.7 for larger pixel geometries)



“Best fit”

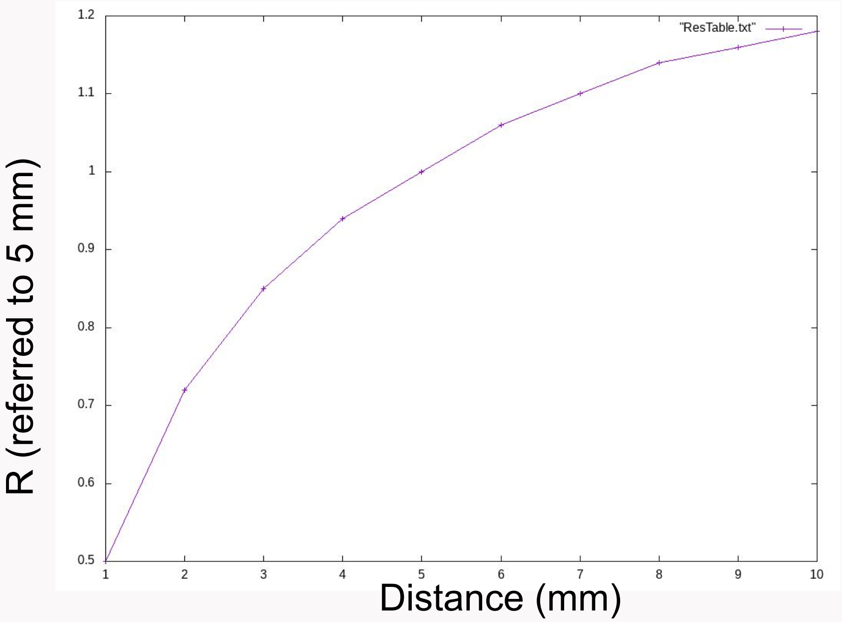
- Simulations repeated (<u>with real input signal shape</u>) to reproduce shape of signals:
  - Resistance has big impact - need to confirm values - might be too high for observed waveforms (impact on delay between far nodes)
  - Much greater cross-coupled capacitance would explain most crosstalk
  - Pad coupling relatively minor effect (which explains why no big differences between geometries.





Resistance vs. distance on anode

- Model uses a mesh of R and C (and L - see below)
    - Elementary R used in model needs to be connected to the measured resistance
    - Simulation of pure R network used to correlate Rmeasured to Rmodel
    - For neighboring pixels, a good approximation is: Rmodel=2*Rmeasured
    - Using the same model, possible to estimate resistance as a function of distance between points



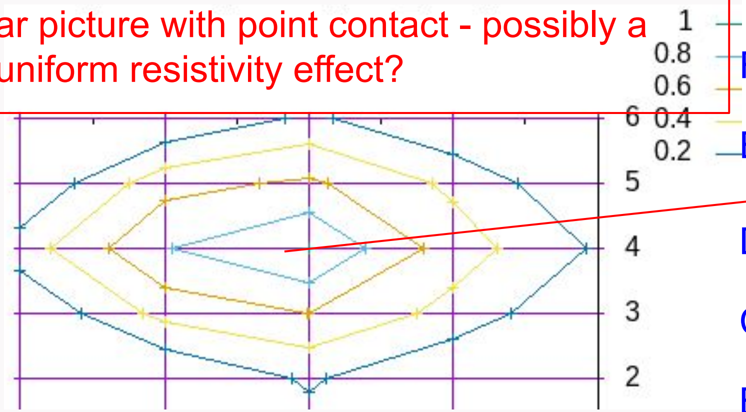
Measured resistance

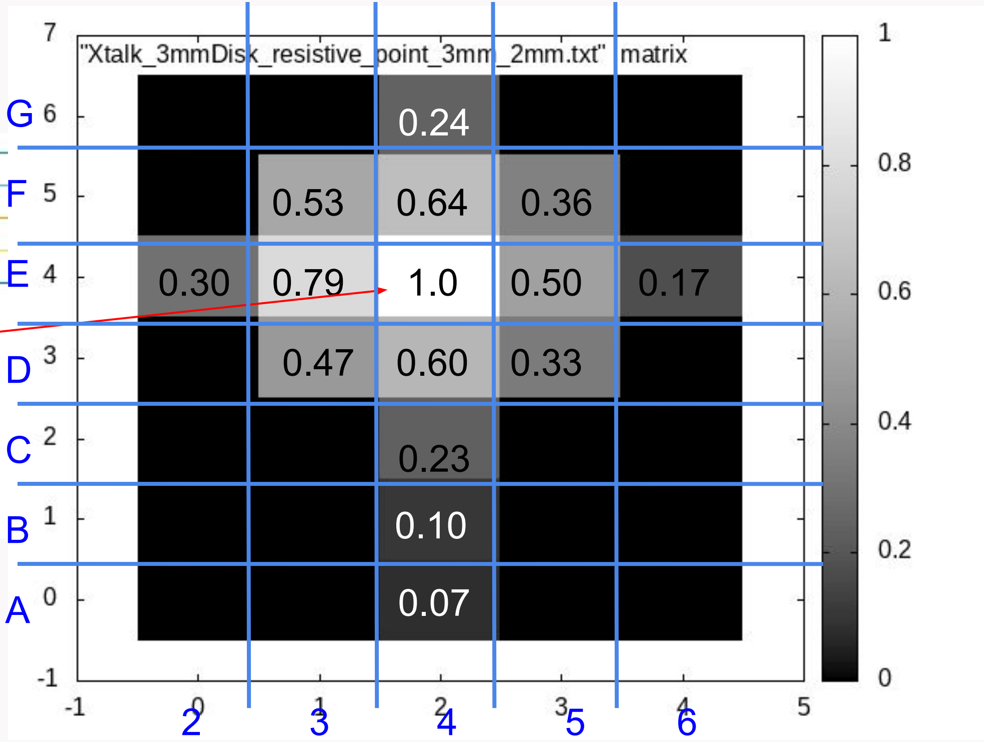
- Mark's measurements
  - **<u>R quite variable as a function of position in plane</u>** (even taking into account measurement error)
    - Neighbor pixel R for cases with 6 mm pitch varied from 97kOhm to 161kOhm
    - R value important effect on crosstalk
    - Model assumed uniform distributed R

- ***Simulation models demonstrate effects of sheet resistance on neighboring pixels' signal amplitude -> R variability has an impact on effective cross-signal effects***

3mm feed (3/2mm) -crosstalk

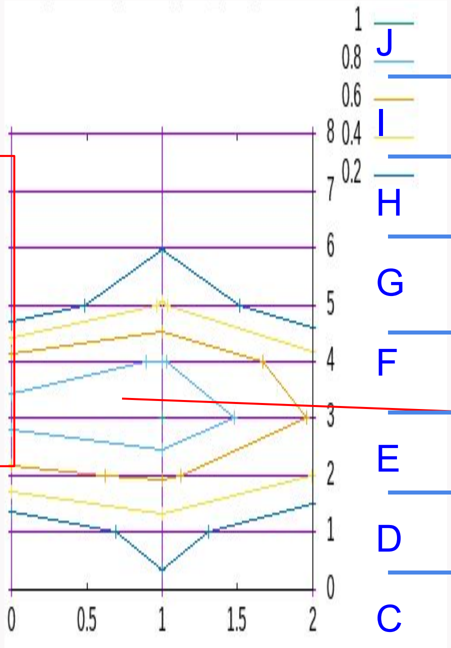
There seems to be a skew toward the left - similar picture with point contact - possibly a non-uniform resistivity effect?

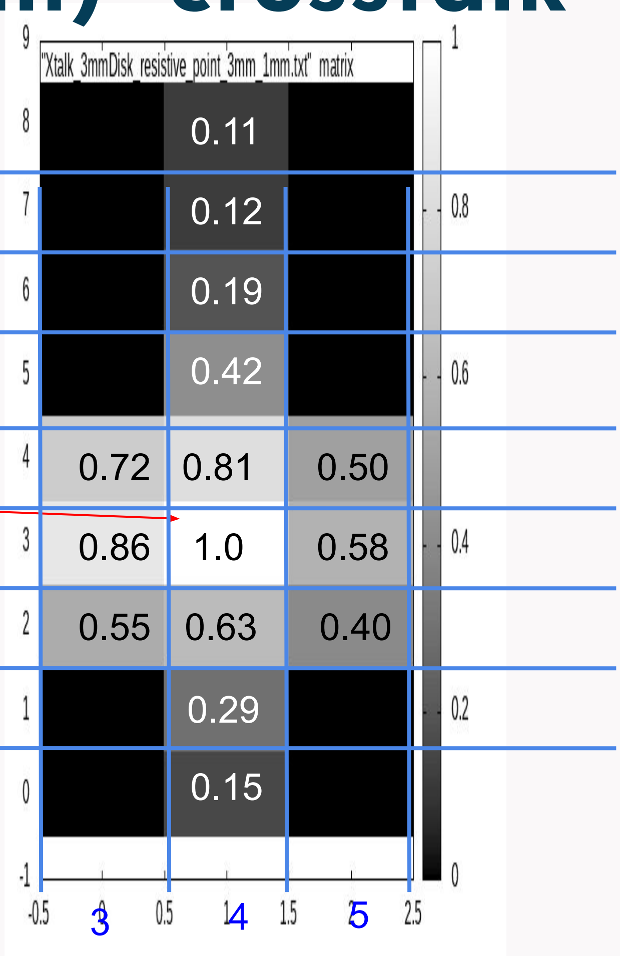




3mm feed (3/1mm) -crosstalk

There seems to be a skew toward the left - similar picture with point contact - possibly a non-uniform resistivity effect?





Comparison with Model - Xtalk Results

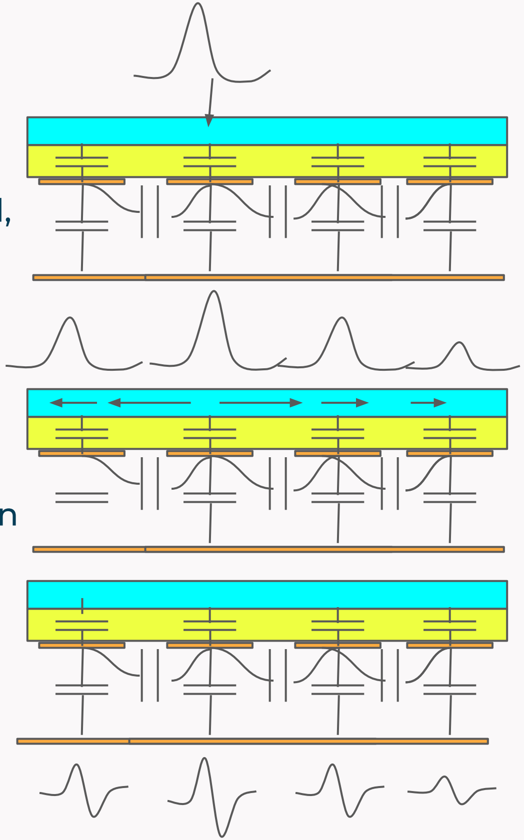
- Model:
  - 3mm/1mm (signal: 43 mV)
    - First neighbor: 21mV (~50%)
    - Diagonal neighbor: 14,5mV (~30%)
  - 3mm/2mm (signal: 49 mV)
    - First neighbor: 18mV (~36%)
    - Diagonal neighbor: 10mV (~20%)
  - 4mm/2mm (signal: 42 mV)
    - First neighbor: 13mV (~30%)
    - Diagonal neighbor: 6.3mV (~15%)
- Note:
  - only ratios relevant

- Measurements:
  - 3mm/1mm (averages)
    - First neighbor: (~72%)
    - Diagonal neighbor: 14,5mV (~54%)
  - 3mm/2mm (averages)
    - First neighbor: (~63%)
    - Diagonal neighbor: ??mV (~42%)
  - 4mm/2mm (signal: 36 mV)
    - First neighbor: 15mV (~52%)
    - Diagonal neighbor: 9mV (~30%)

Consistently higher (up to 2x more)
- >50% difficult to fully justify with any model (see next slides)

A discussion on crosstalk mechanisms

1. Signal couples to spot on resistive anode:
   a. With electrical experiments (spring-loaded, 7mm, 3mm for 3/1 and 3/2) only region below pad affected
2. Signal propagates on anode toward ground returns:
   a. Simpler understanding: CR network (diffusion-like propagation)
   b. More complex model: RLC network - analogous to high attenuation transmission line, but in 2D
3. Each pad-to-anode capacitance couples the anode signal to collection board:
   a. AC-coupling - derivative - proportional to risetime and capacitance
   b. Reduced by capacitance to ground and low load resistance



Crosstalk mechanisms

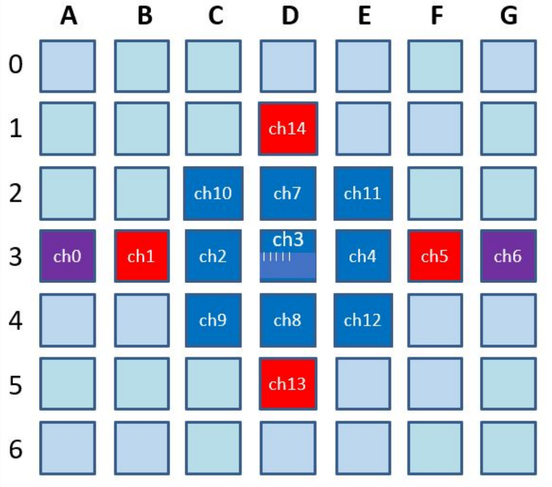
1. **Critical step** for crosstalk is 2. -> **propagation on resistive anode**:
   a. Coupling is proportional to signal slope, in turn proportional to peak amplitude
2. Other cross capacitance contributing a minor effect (proven in simulations)
3. **RC-only** propagation:
   a. Neglecting L component in most modelling for simplicity
   b. Various attempts have been made to generate high crosstalk by adjusting parameters based on empirical evidence: Hard to obtain more than 50% crosstalk
      i. Effectively maximum crosstalk is purely resistive - assuming fairly uniform resistivity value fixed by ratio of input versus “terminating” resistance at anode edge
4. Attempts to justify by using full **RLC model**:
   a. Also in this case no large crosstalk unless lower resistance between nodes.

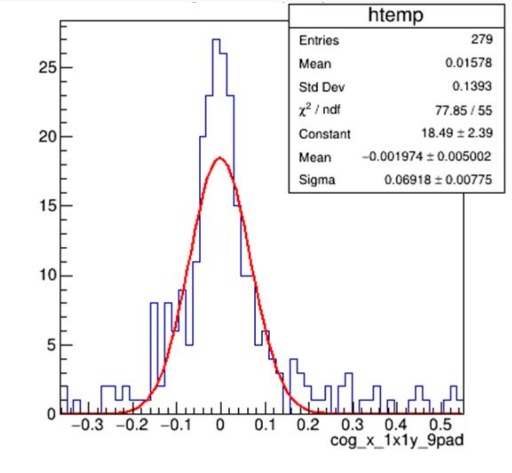
Laser Data

- Laser data collected at the end of the project
- Analysis confirms the features of crosstalk seen with electrical stimulation of resistive anode
    - Data matches the overall trend of model in terms of charge developing at anode node.

Laser Data Analysis (fine scan)

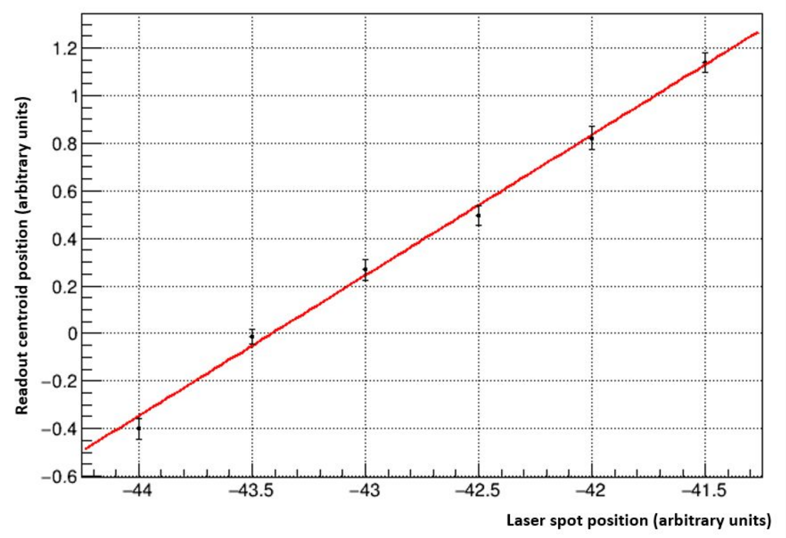
- 7x7 array 5mm x 5mm, 1mm gap
- D3 (ch3): laser spot scanned in 0.5 mm steps, ~250 waveforms/step
- The dark blue pixels used to calculate the laser position by centroiding.
- Far right plot shows distribution of calculated centroid positions in the horizontal direction for the laser pulse at center of D3 (i.e. at x=0.0)
- Gaussian sigma ~7%.





Laser Data - accuracy of positioning

- Mean centroid position on the vertical axis (arbitrary scaled units based on the 7x7 pixel geometry) vs actual laser position (in the readout test board coordinate frame).
- Gaussian sigma error bar on each point
    - < ~10% uncertainty
- Linear response across the entirety of the anode pad from edge (top right plot point) to one step beyond the center of the pad (bottom left plot point). No data was taken across the remainder of the pad.



Conclusions (I)

- **Modeling**
  - Important trends confirmed
    - Effect of readout impedance
    - Dependence on ground plane thickness
    - Overall crosstalk dependency
  - Quantitative mismatch: Larger crosstalk than R(L)C models
    - Lumped modelling inaccurate
    - L modelling difficult (frequency dependency)
    - Resistive anode variability likely important for neighboring pixels
  - Accurate modelling likely requires distributed EM sim
  - Semi-empirical modeling possible using attenuation coefficient and geometric factors.

Conclusions (II)

- **Position Discrimination**
  - Position discrimination at <u>subpixel level</u> was demonstrated
  - Analysis of laser scan data for 7x7 array 5x5mm^2, 1mm gap showed ~500um position resolution with good linearity (<u>note</u>: results quite consistent with Alexander Kiselev's measurements - see previous presentation in workshop)
  - Characterization at Incom showed that with proper charge sharing between 4mm sized pixels, 600um spatial resolution can be achieved
- **Design considerations**
  - Engineering and good control of board parameters (spacing, ground plane, termination R) will allow signal optimization and crosstalk control
  - Current sim tools are robust enough to provide ~optimized designs
  - Process control of resistivity for predictable crosstalk effects, particularly when sub-pixel precision is desired
  - Detector performance can be customized to meet the particular needs of various end users, for example,
    - Applications requiring signals confined to a single anode, with little to no signal in adjacent regions, or
    - Applications requiring enhanced sensitivity at the sub-pixel level to the initial position of an impulsive signal, calculated using a centroiding center-of-gravity technique.

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