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Capacitively coupled pixel detectors for the CLIC vertex detector

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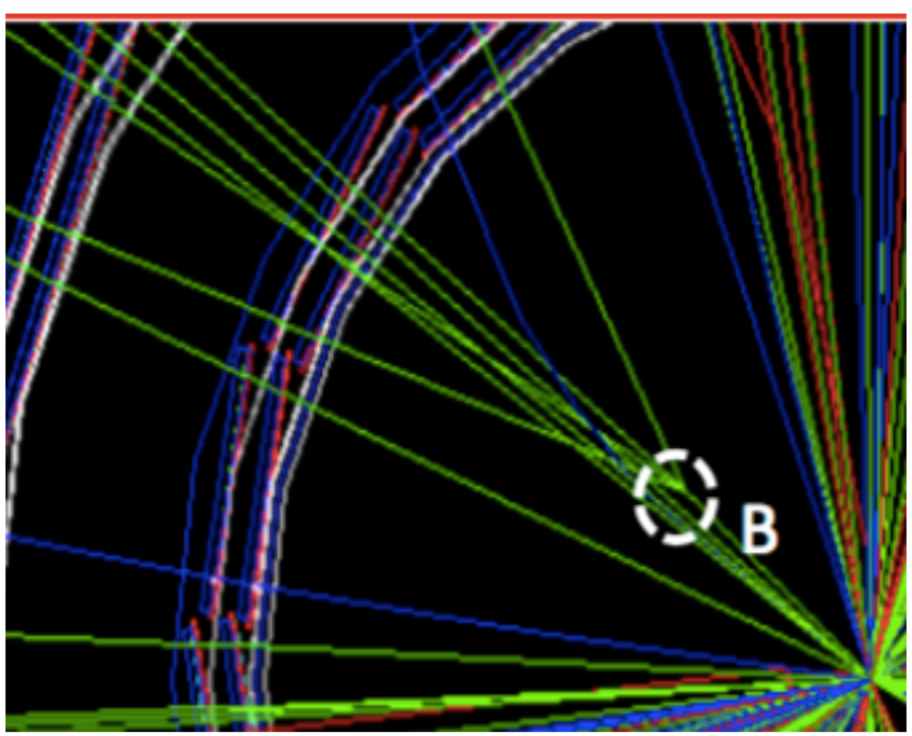
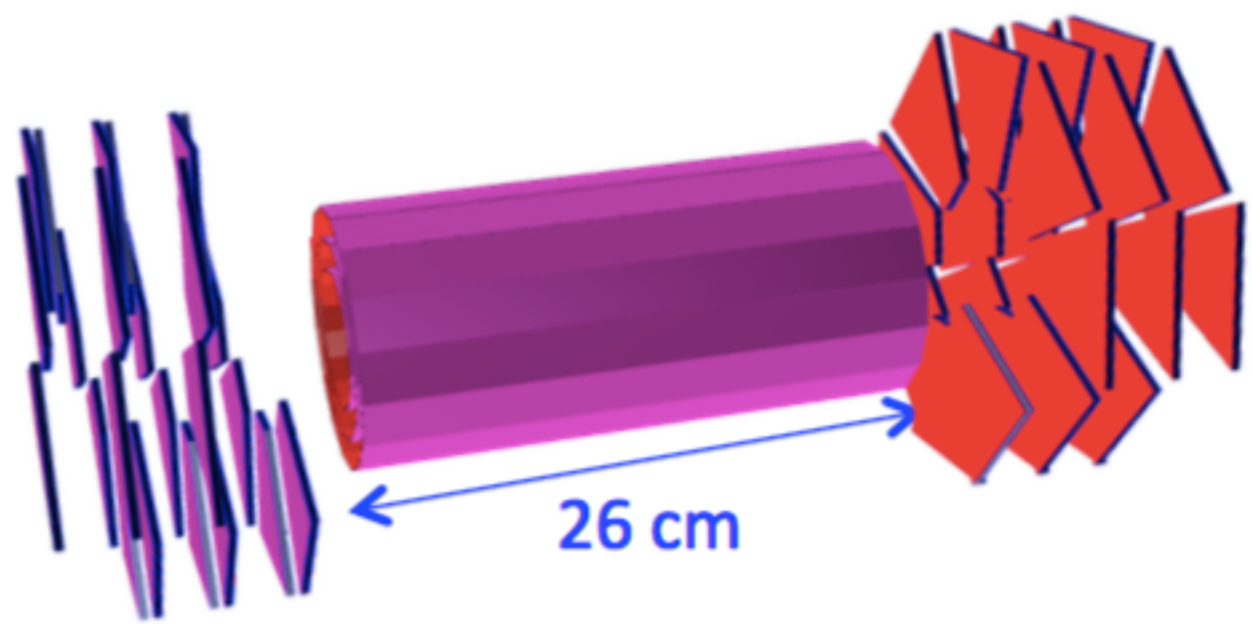
3-11-15

Introduction

- For the CLIC vertex detector we need high spacial resolution (3 μm single point spatial resolution) and low material content (0.2% of a radiation length per layer). Both are important for accurate heavy-flavor tagging through the measurement of displaced vertices.

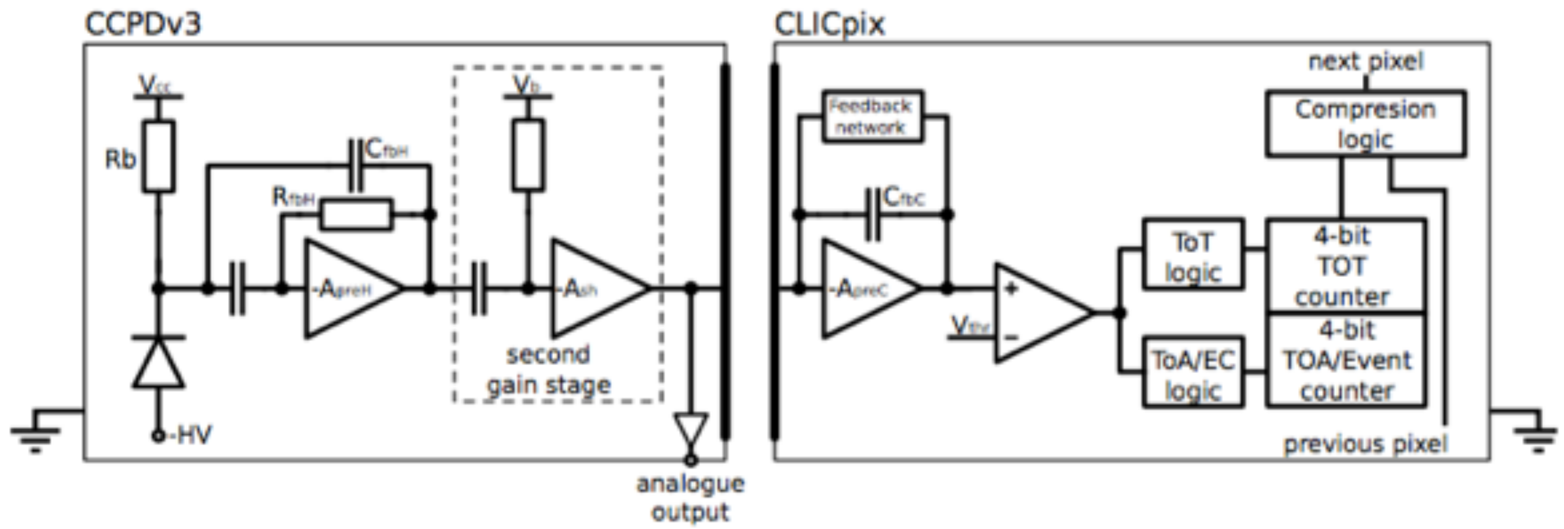
- As the vertex detector is close to the interaction point, the beam-induced background is large. Therefore, timing information, of the order of 10 ns, is needed to veto these hits.



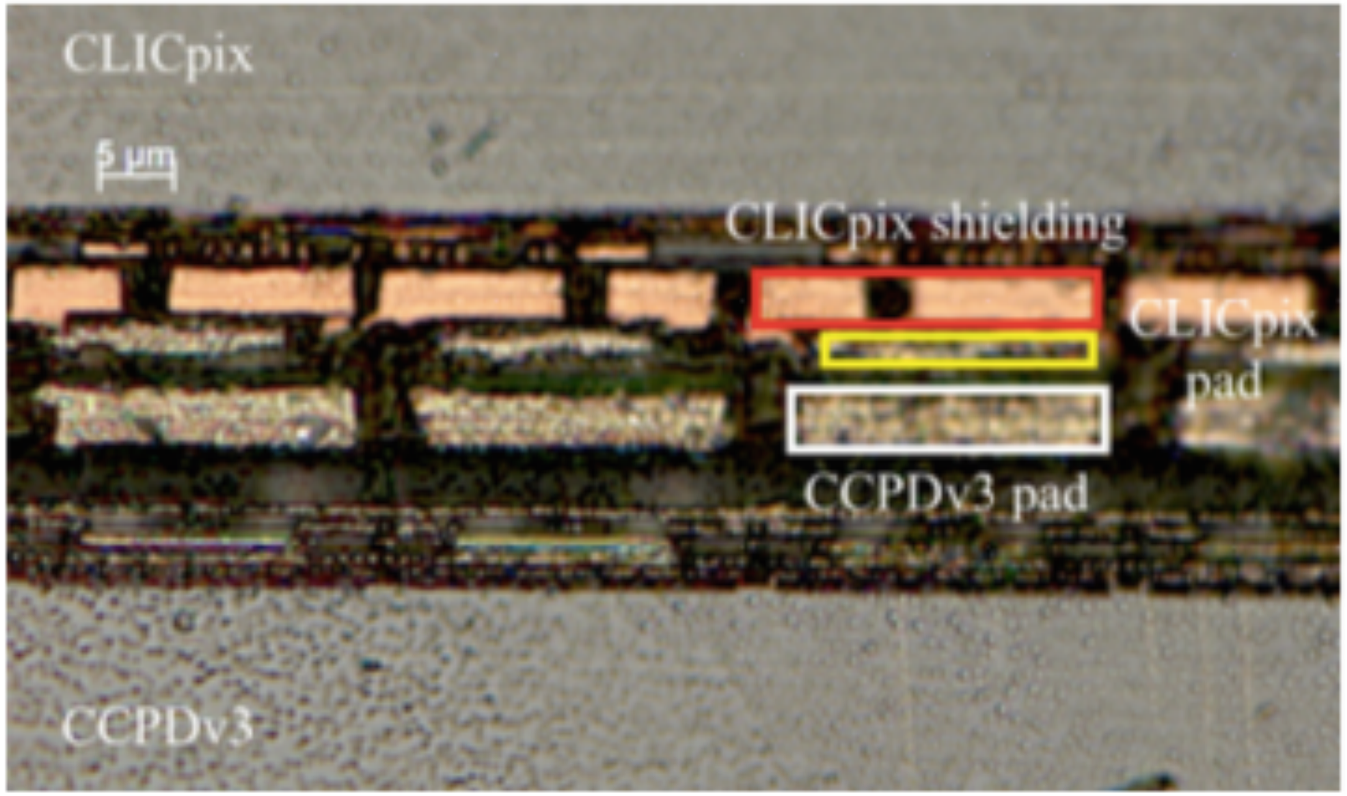


Introduction

- This study looks at the application of a charge coupled pixel device (CCPD), in a high voltage complimentary metal oxide semiconductor (HV-CMOS) process.
- The signal from the HV-CMOS is then capacitively coupled, via a thin gluing layer, to a the readout application specific integrated circuit (ASIC). The ASIC used in this case is the CLICpix sensor.



Schematic diagram of the CCPD and CLICpix sensors

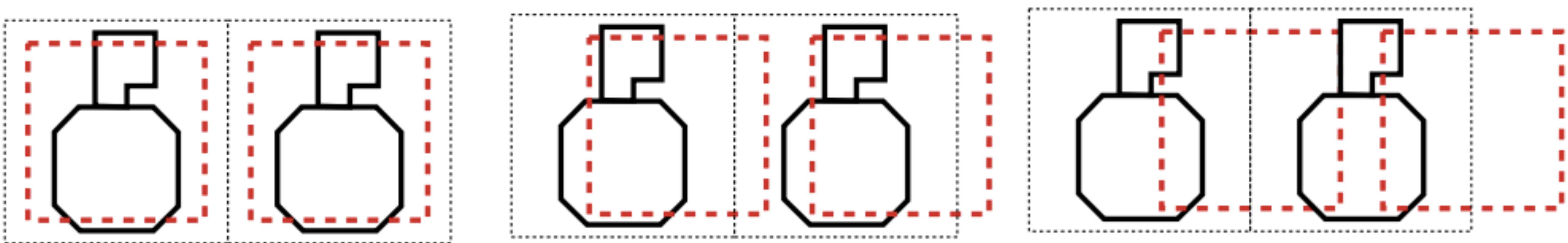


Cross section of the CCPD and CLICpix sensors

Samples

- Here we wish to present two studies examining the response of the sensors when we vary:

1. The alignment of the HV-CMOS and the CLICpix sensors. To that extent several samples have been made, which vary this alignment:



Fully Aligned | Quarter Pixel Misaligned | Half Pixel Misaligned

2. The bonding force applied to samples when being glued. Samples have been made with (i) a nominal bonding force, 5 N, and (ii) a low bonding force, 0.2-0.5 N.

- However, after some destructive testing of samples, it was found that the bonding force did not effect the pad-pad distance. The differences in performance for samples produced with different bonding forces (and same alignment) was negligible.

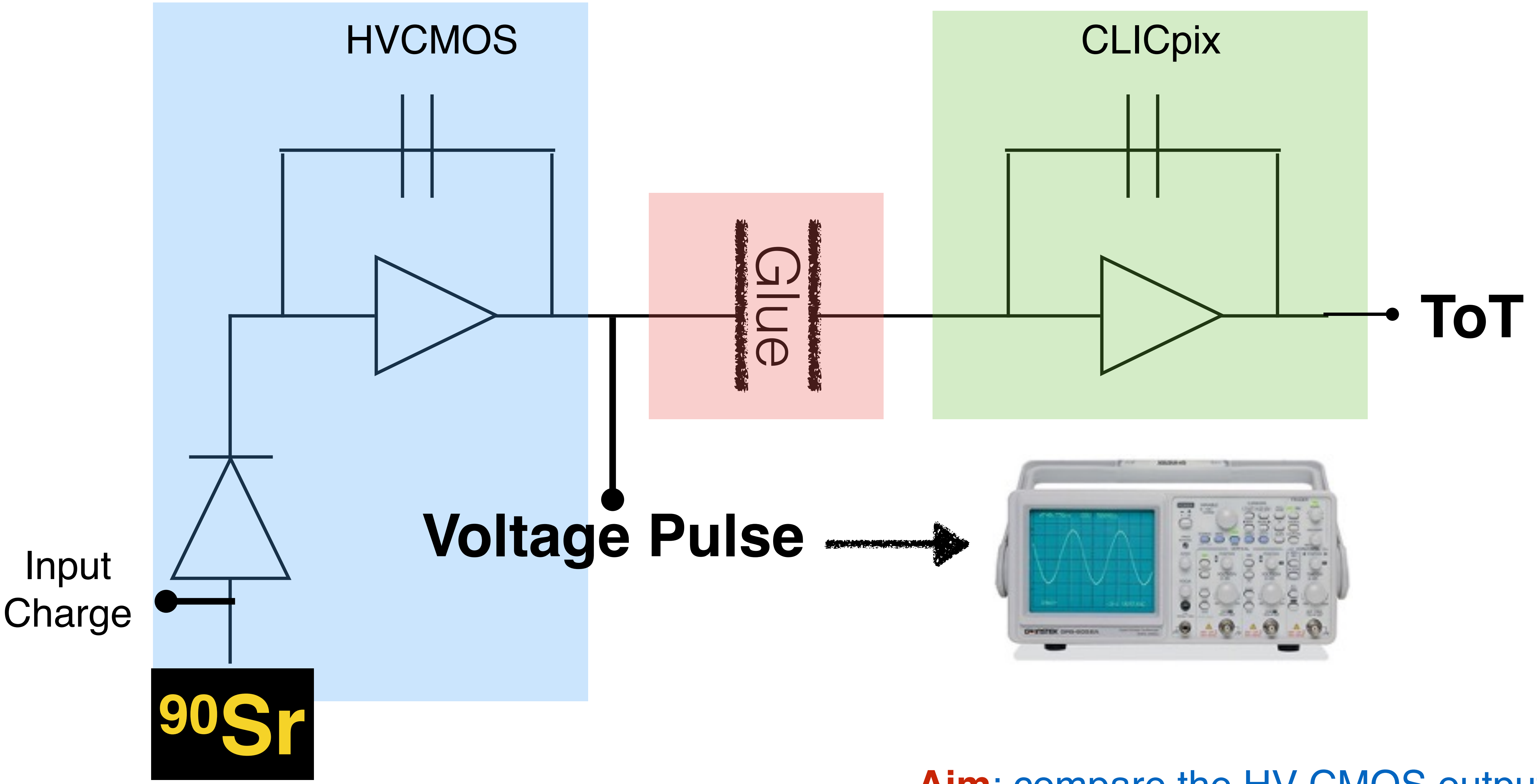
Analysis

* Here we present results from several analyses of these samples including:

1. Radioactive source calibration;
2. Test pulse calibration;
3. Test beam;
4. HV-CMOS TCAD simulations.

Radioactive Source Calibration

Radioactive Source Calibration - Setup



Aim: compare the HV-CMOS output voltage to the ToT recorded on the CLICpix using a radioactive source.

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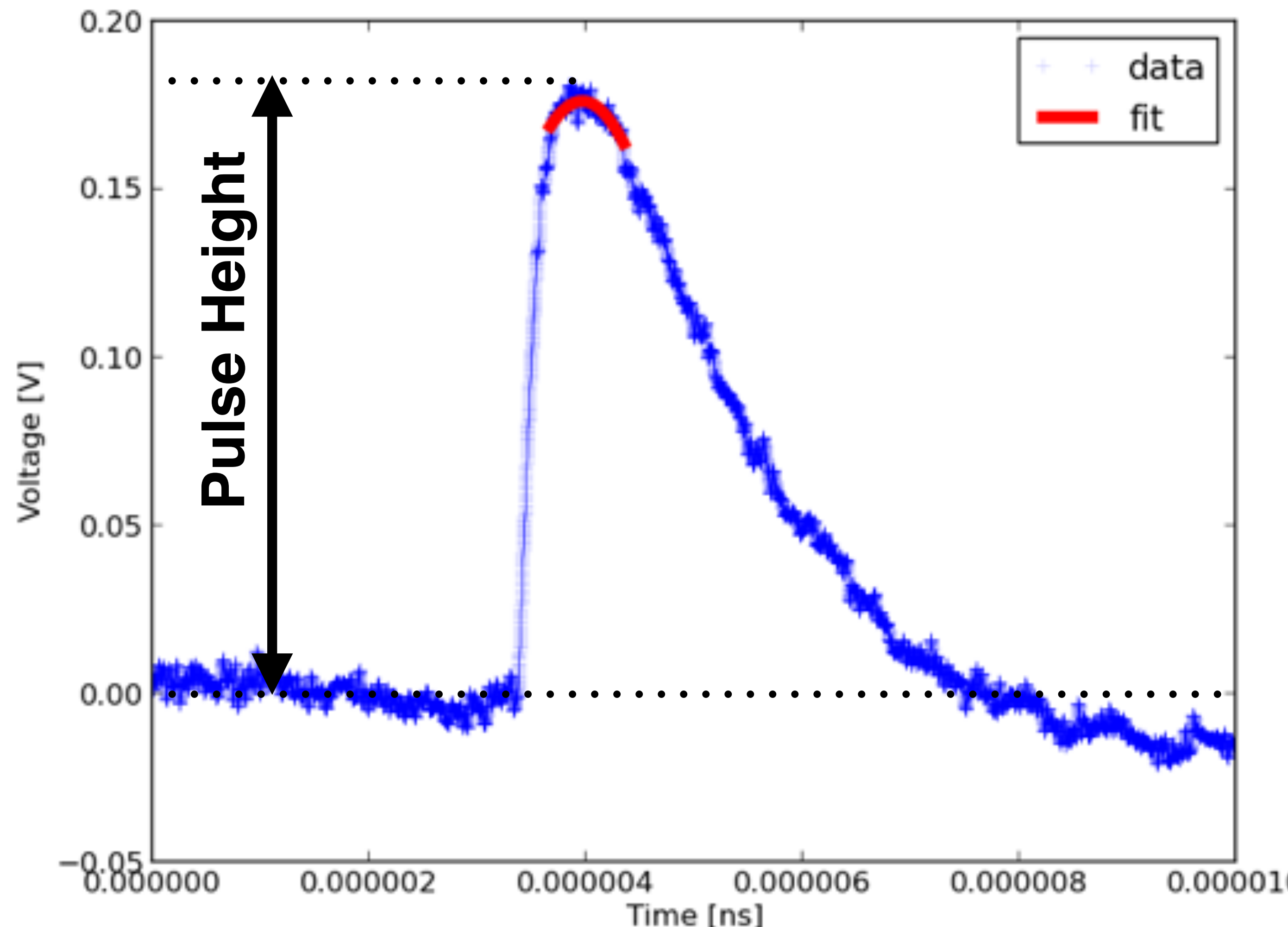
Radioactive Source Calibration - Pulse Shape

HV-CMOS

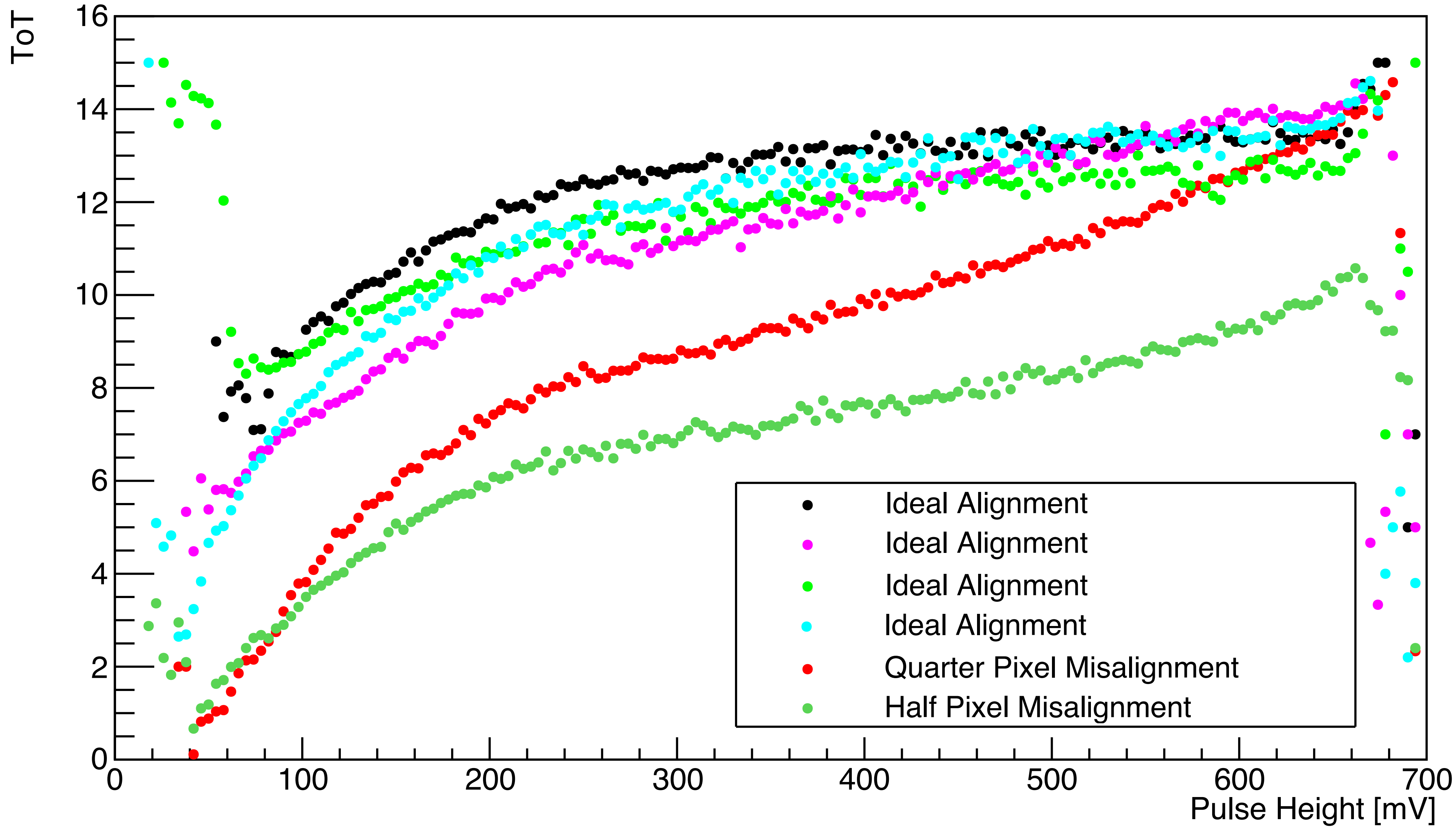
- The analytic form of the HV-CMOS pulse shape is an exponential rise, with saturation, followed by an exponential decay, both with different rise/fall times.
- For simplicity we fitted a Gaussian to the HV-CMOS pulse data to model the peak height of the pulse.
- For each pixel in the matrix we looked at how the ToT varies with the pulse height being injected into it.

Example Pulse from HV-CMOS using Radioactive Source



ToT ← CLICpix | Glue ←

Radioactive Source Calibration - ToT vs Pulse Height

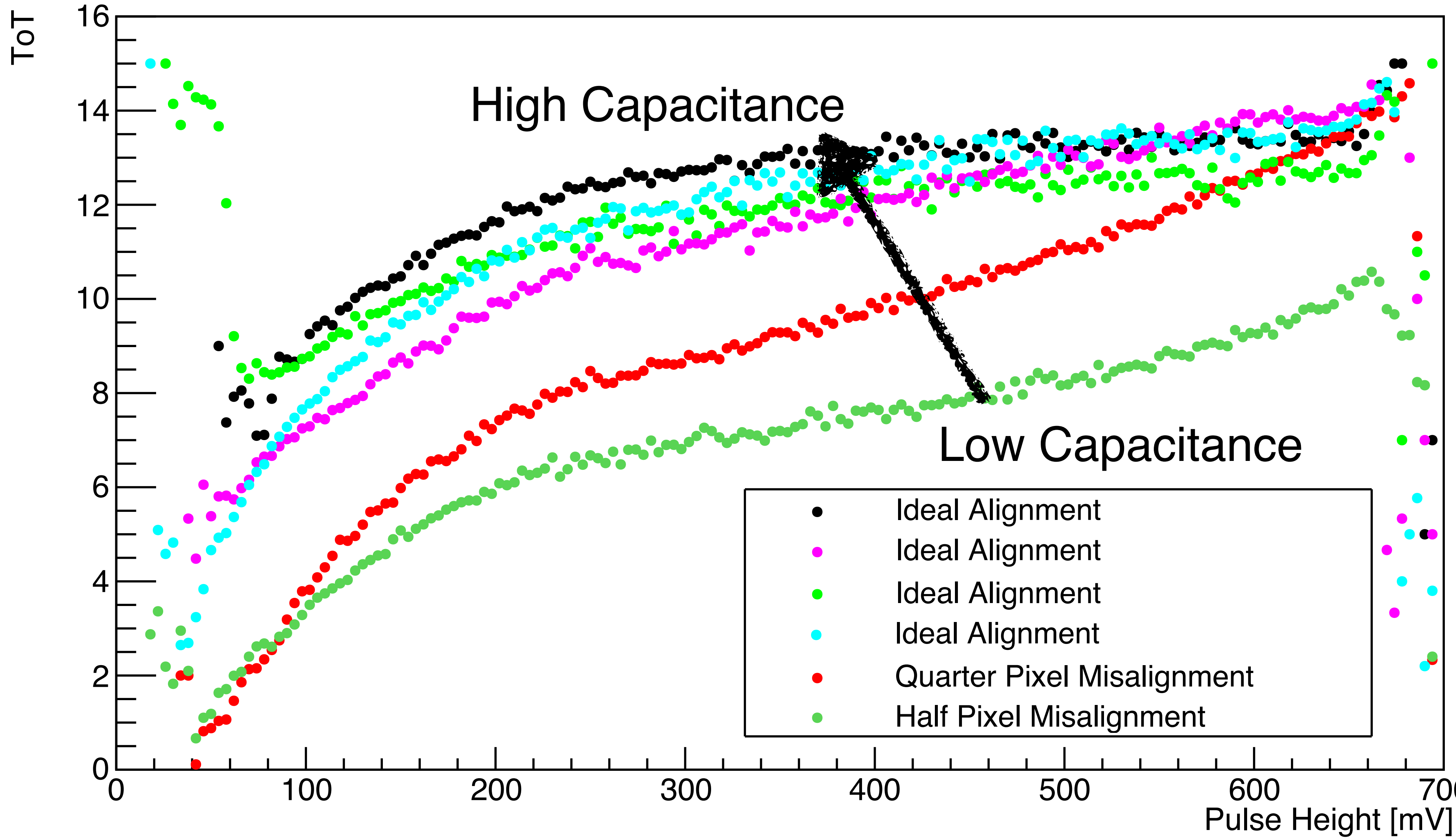


- Similar performance for all the ideally alignment samples, irrespective of gluing thickness.
- The observed charge in the CLICpix is proportional capacitance produced by the gluing layer.

High Capacitance Low Capacitance

Fully Aligned > Quarter Misaligned > Half Misaligned

Radioactive Source Calibration - ToT vs Pulse Height



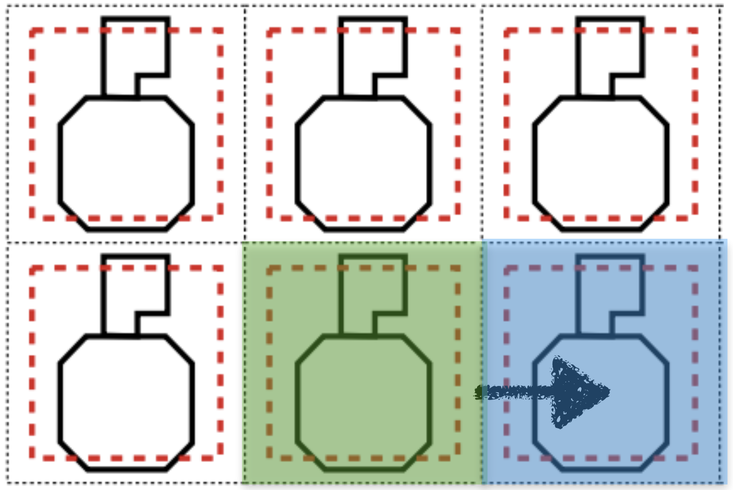
- Similar performance for all the ideally alignment samples, irrespective of gluing thickness.
- The observed charge in the CLICpix is proportional capacitance produced by the gluing layer.

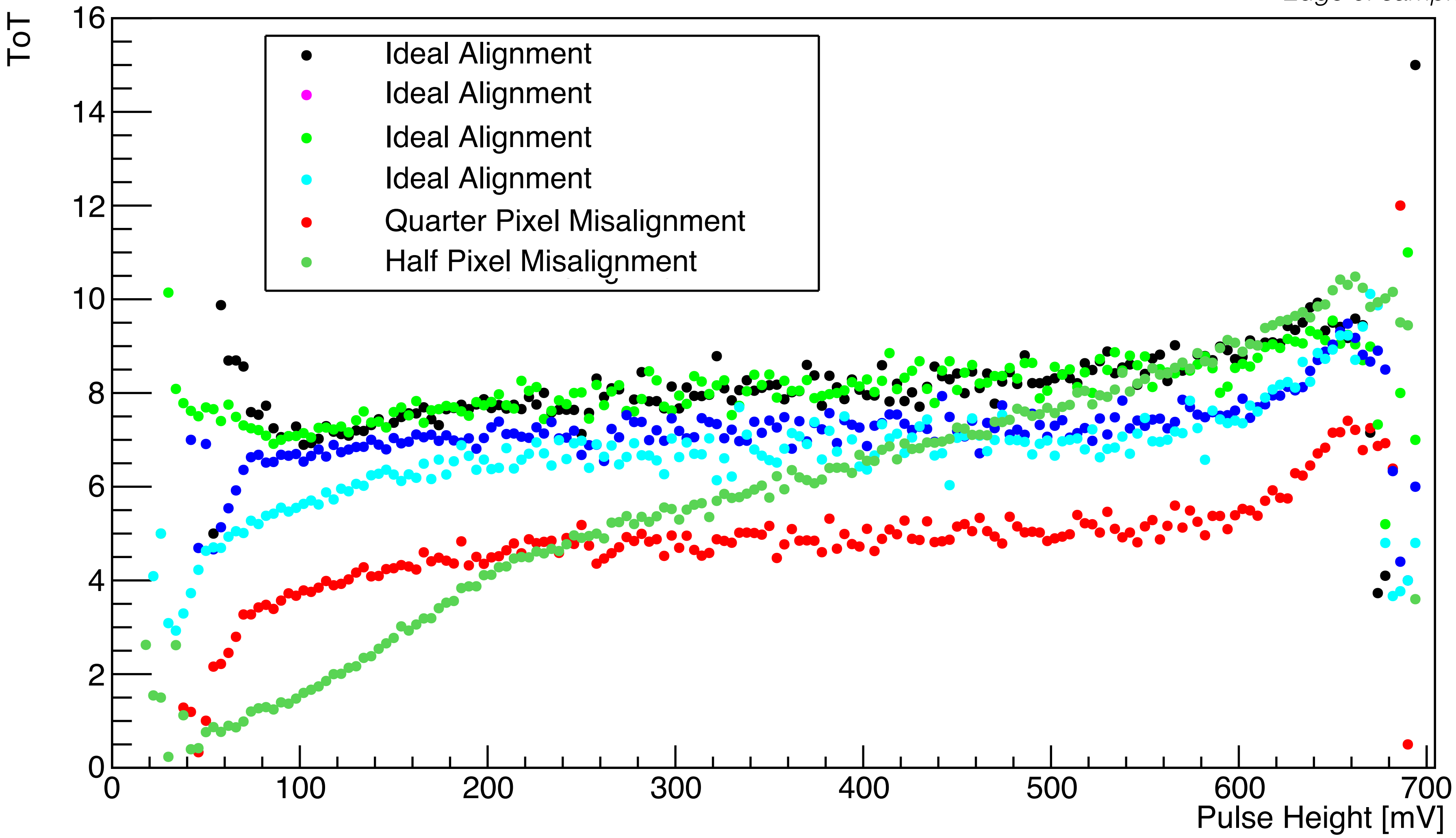
High Capacitance Low Capacitance

Fully Aligned > Quarter Misaligned > Half Misaligned

Radioactive Source Calibration- Adjacent ToT vs Pulse Height

- Now we examine how the ToT on the adjacent neighbouring pixel varies with pulse height injected into the target pixel.
- This should allow us to determine whether we understand the effect of the misalignment on the CLICpix readout.

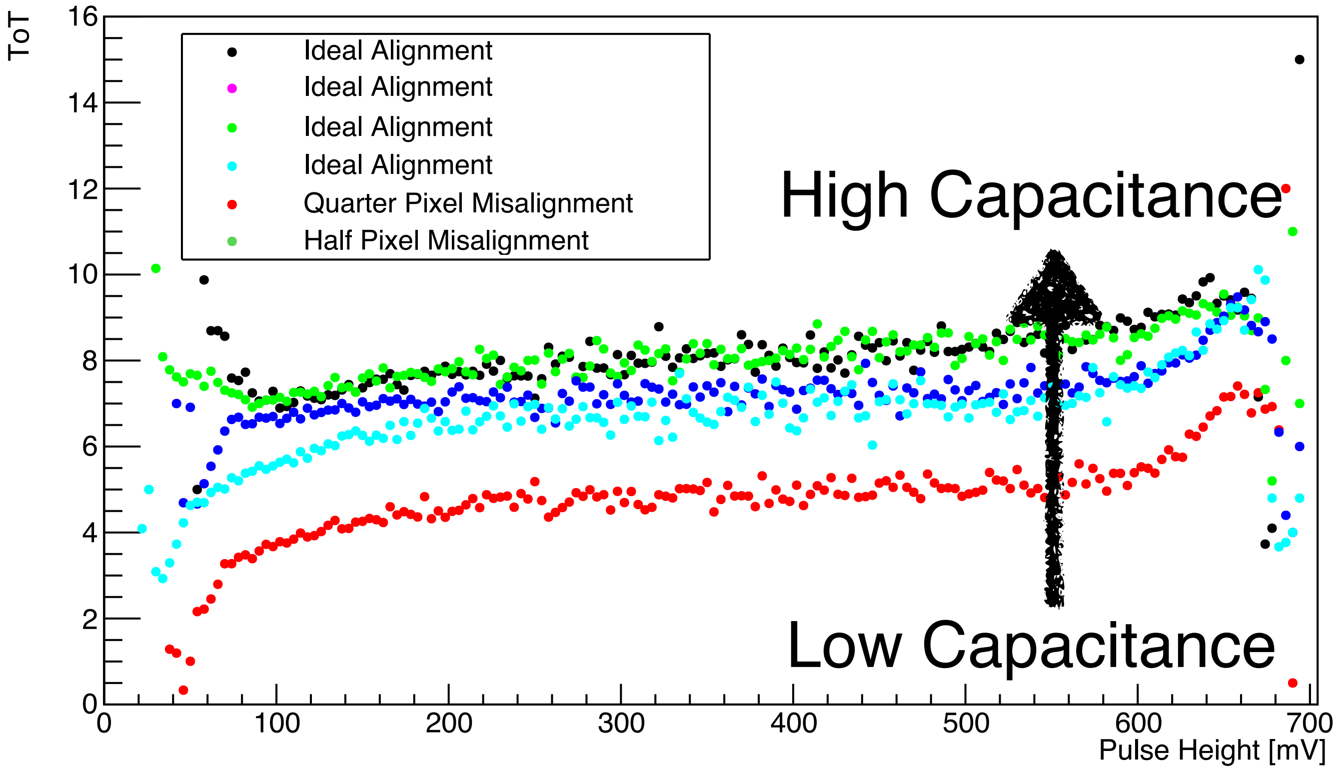


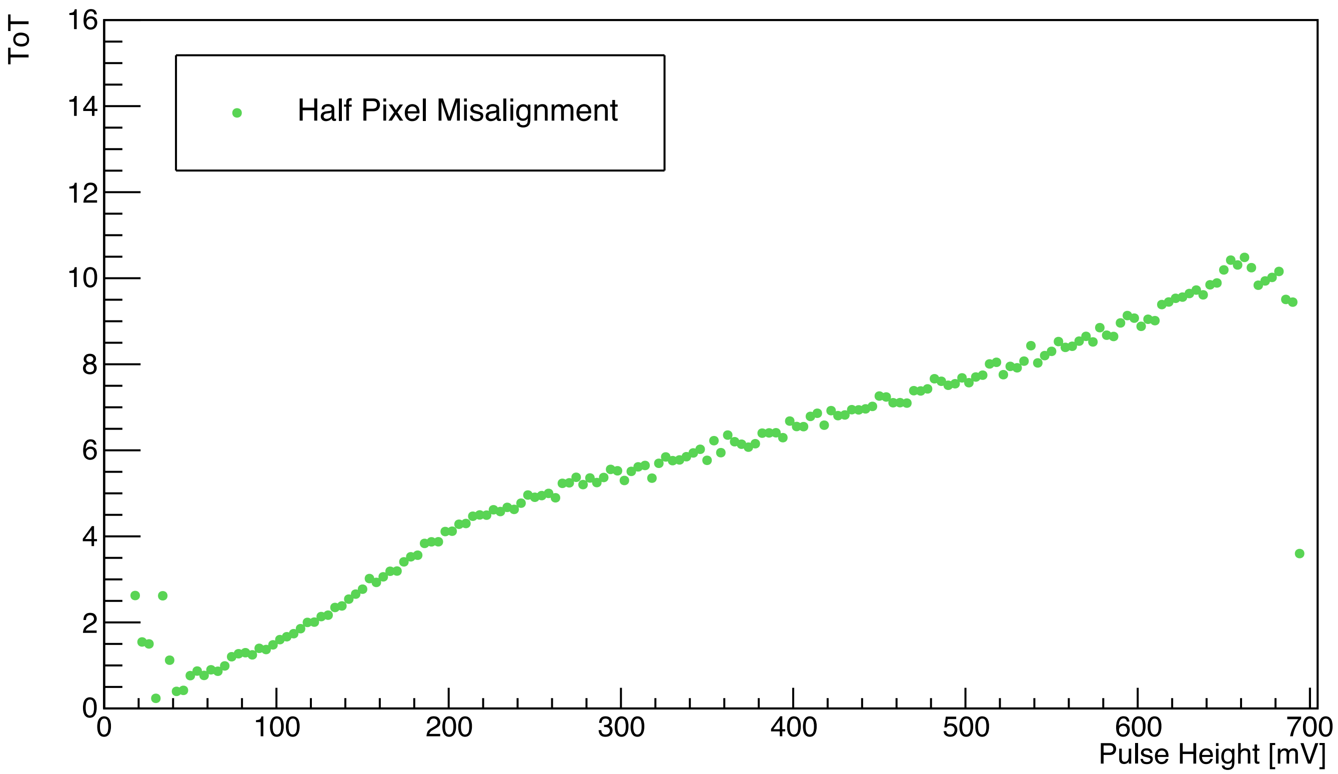


Radioactive Source Calibration- Adjacent ToT vs Pulse Height

- For the fully aligned samples and the quarter misaligned sample, there is weak correlation between adjacent pixel ToT and pulse height entering the target pixel.

- The half misaligned sample shows correlation of adjacent pixel ToT with pulse height on target pixel. This is what we would expect and is encouraging for our understanding of the behaviour of misaligned samples.

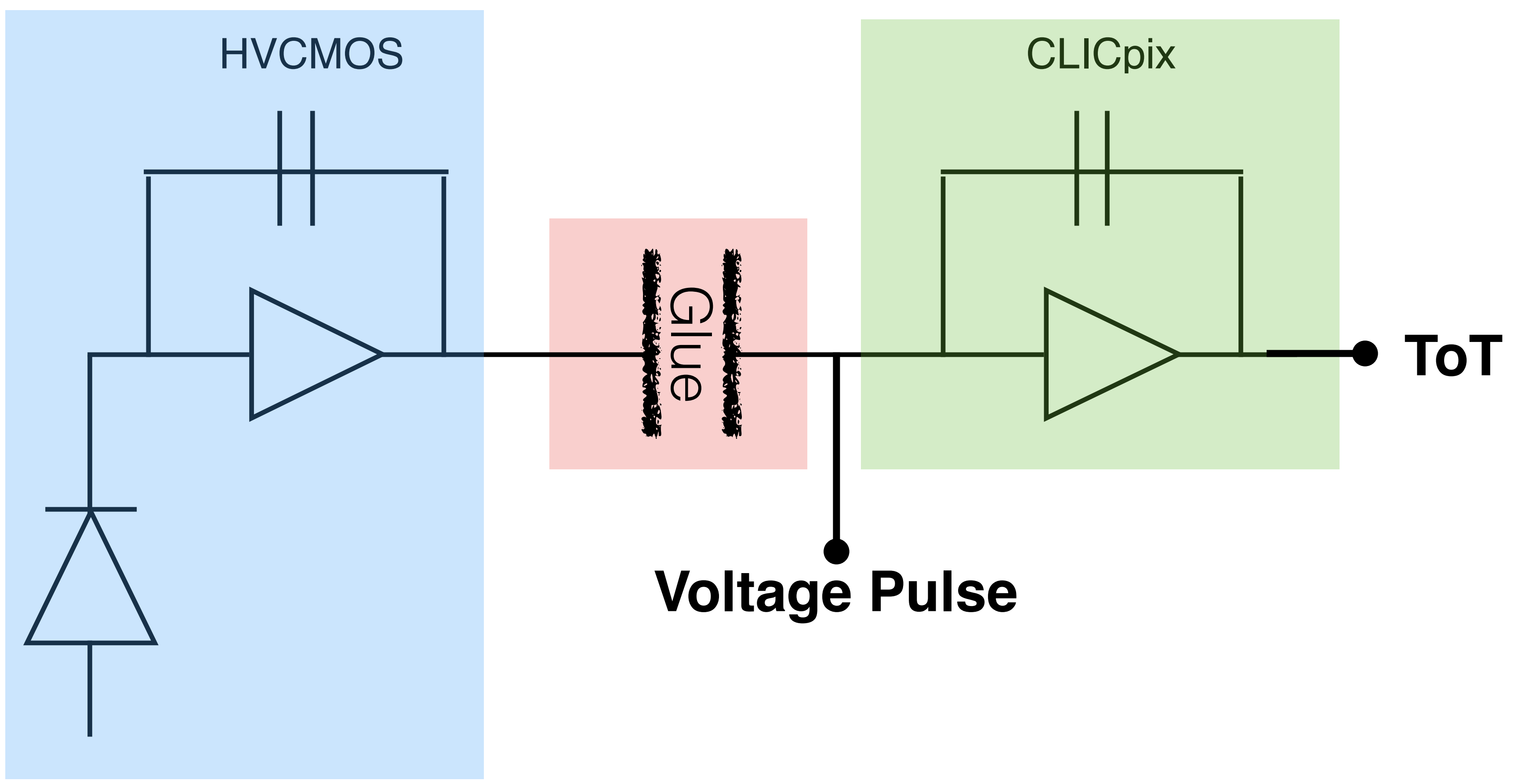




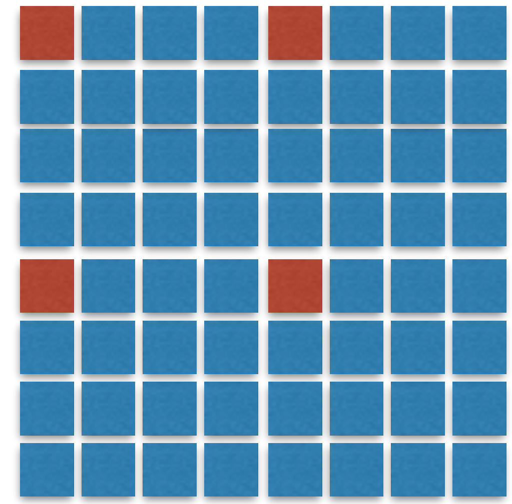
Test Pulse Calibration

Test Pulse Calibration

- Here we inject a voltage pulse directly into the CLICpix sample and record the ToT output.
- This is designed to record the response of the CLICpix in the samples and not the HVCMOS or the gluing layer.



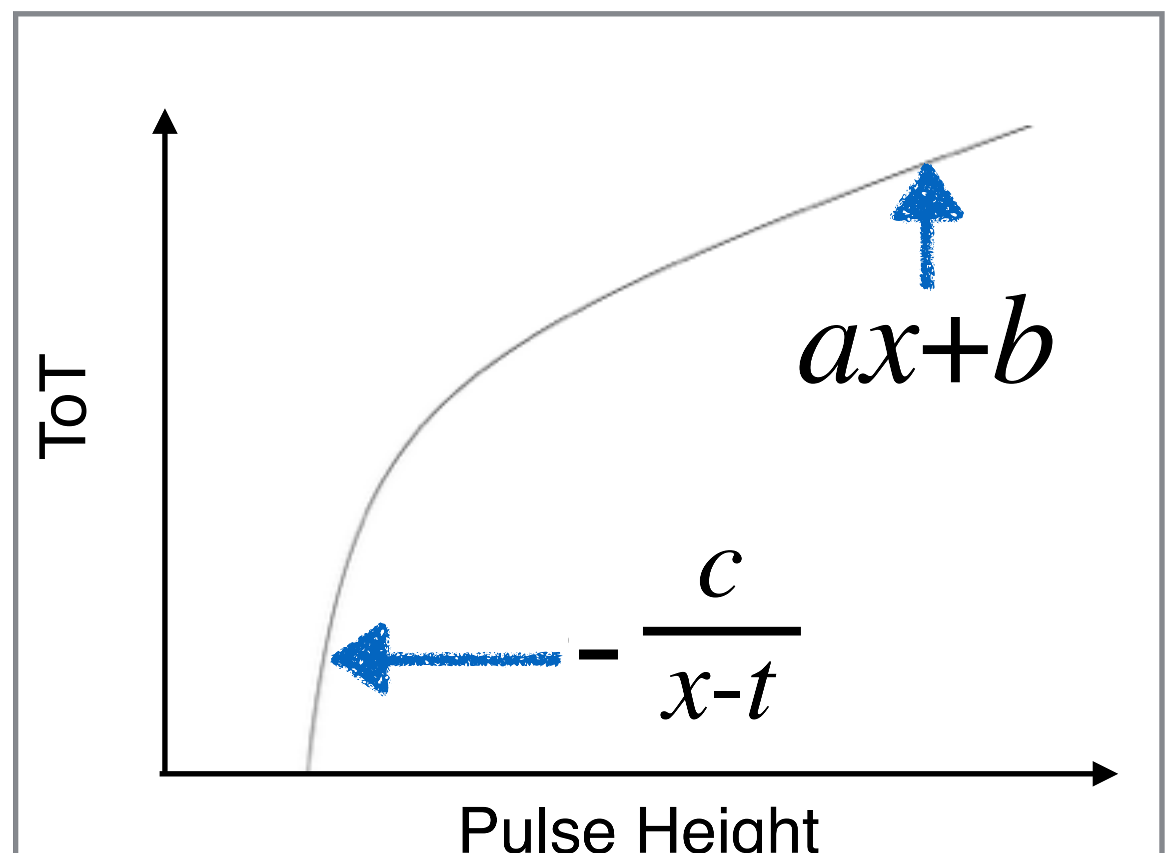
Test Pulse Calibration



- We inject the test pulse to 1 in every 16 pixels, masking the others, and record the ToT for that pixel. Then we scan across all 16 configurations to cover the entire matrix.
- The analysis involves making plots of the average ToT vs pulse height and then performing fits to those plots, on a pixel by pixel basis, using the surrogate function:

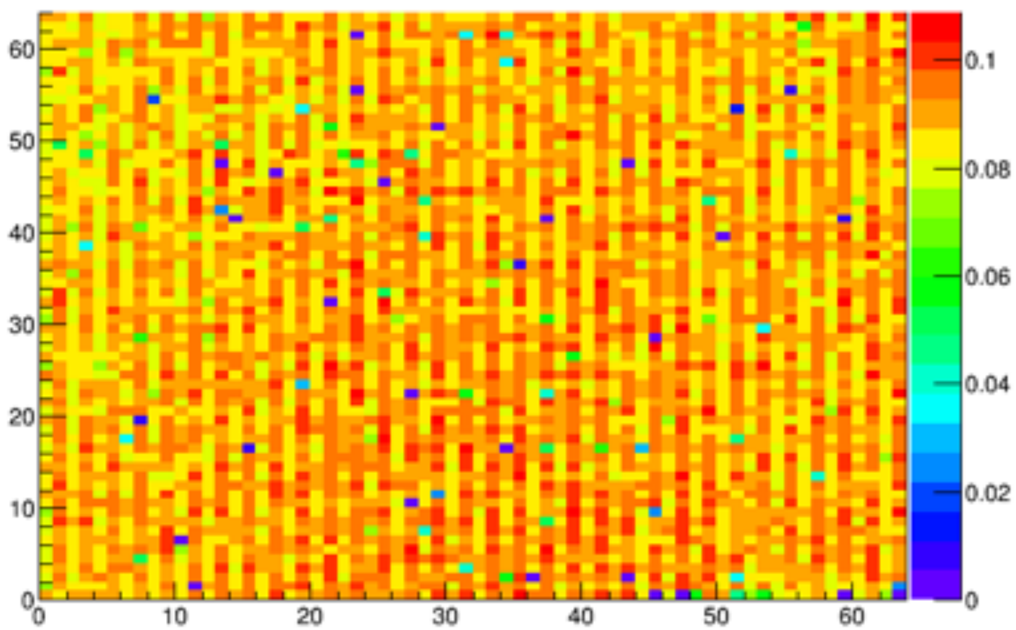
$$y = ax + b - \frac{c}{x - t}$$

- The fit is limited to a range of 1.0 < ToT < 14.5 to not fit to saturated ToT points (saturates at a ToT of 15) and unresponsive pulse heights.

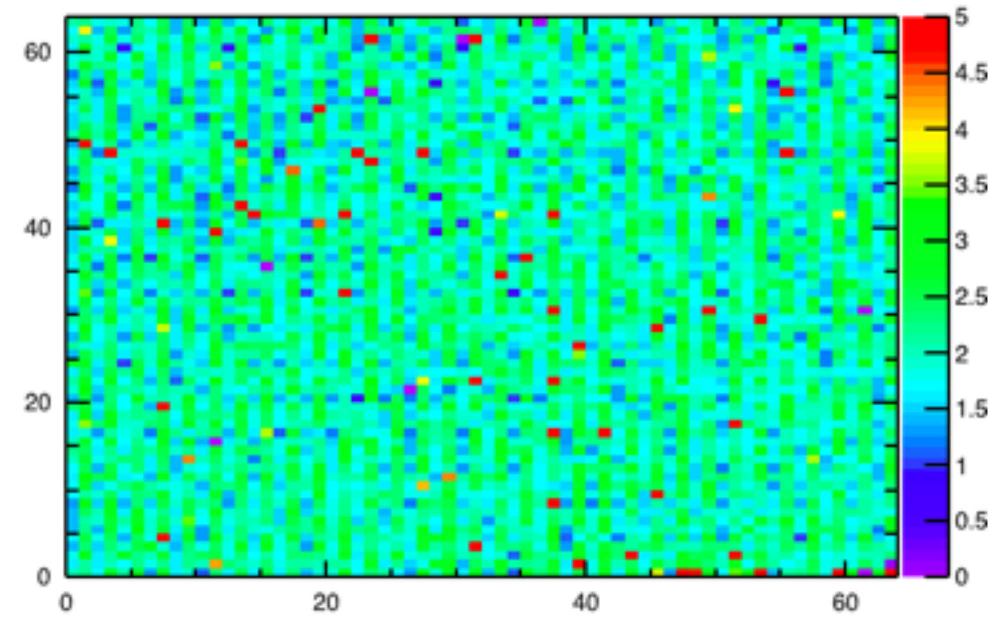


Test Pulse Calibration of CLICpix - Results Ideal Alignment

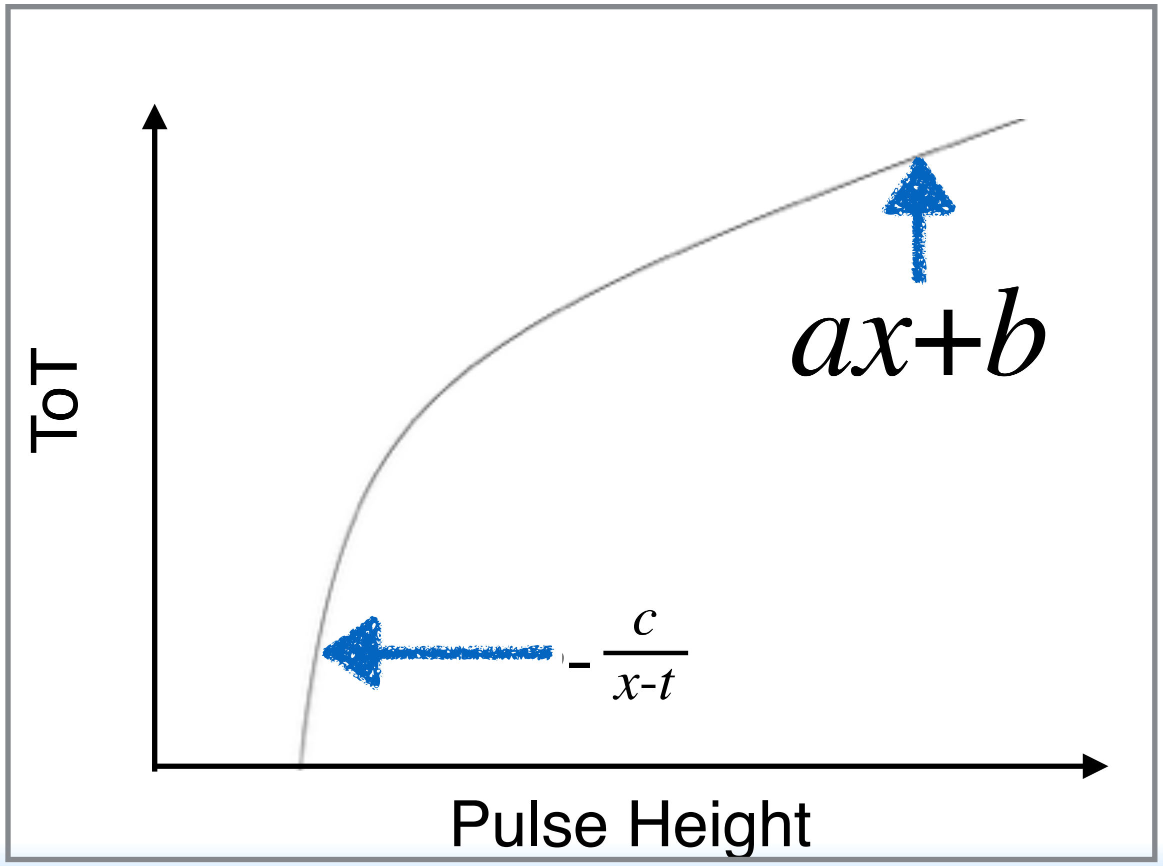
A



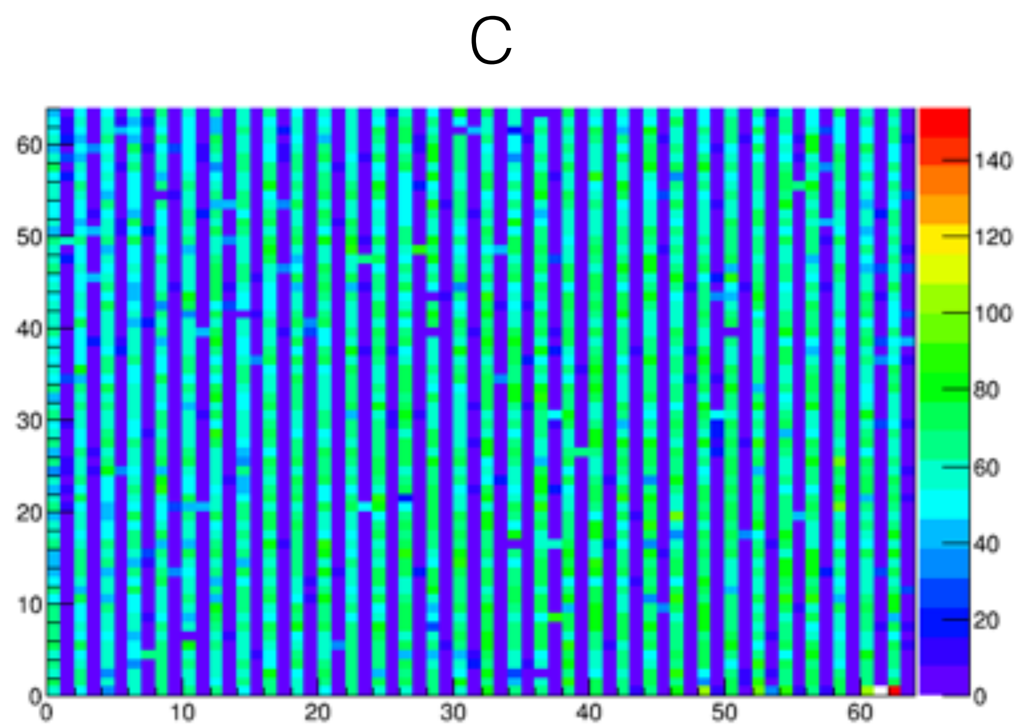
B

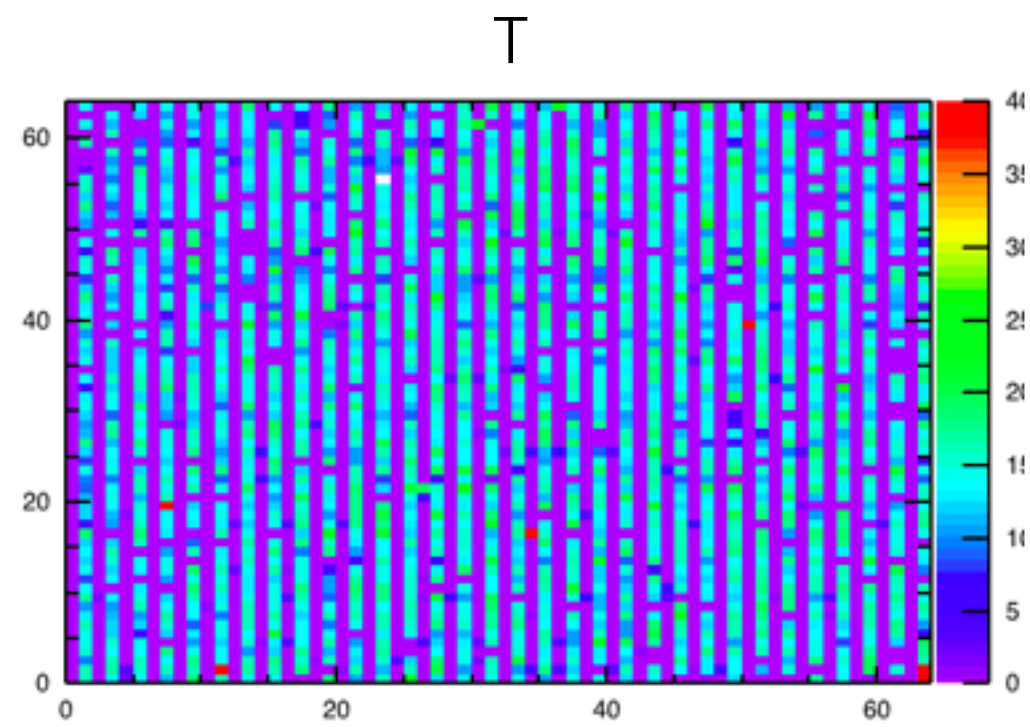


* A and B parameters largely uniform.
* Same linear part of expression of surrogate function across the matrix.

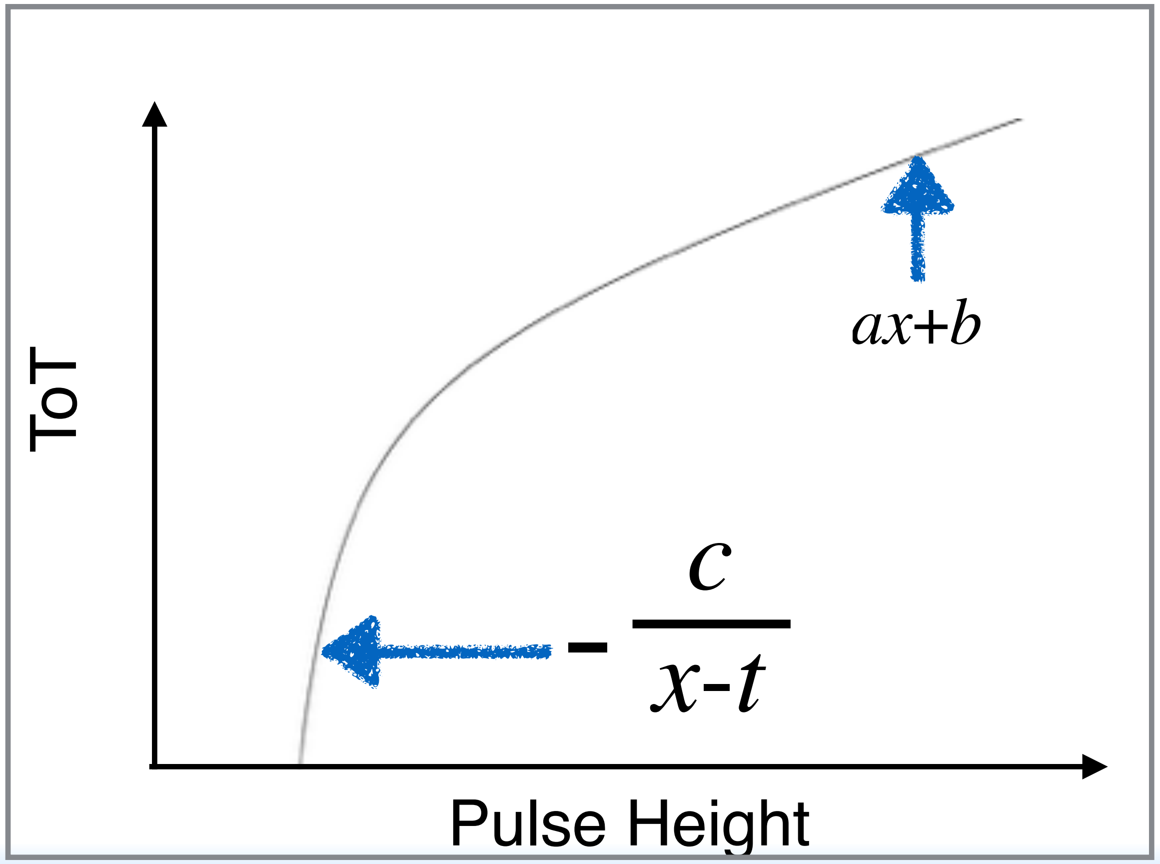


Test Pulse Calibration of CLICpix - Results Ideal Alignment

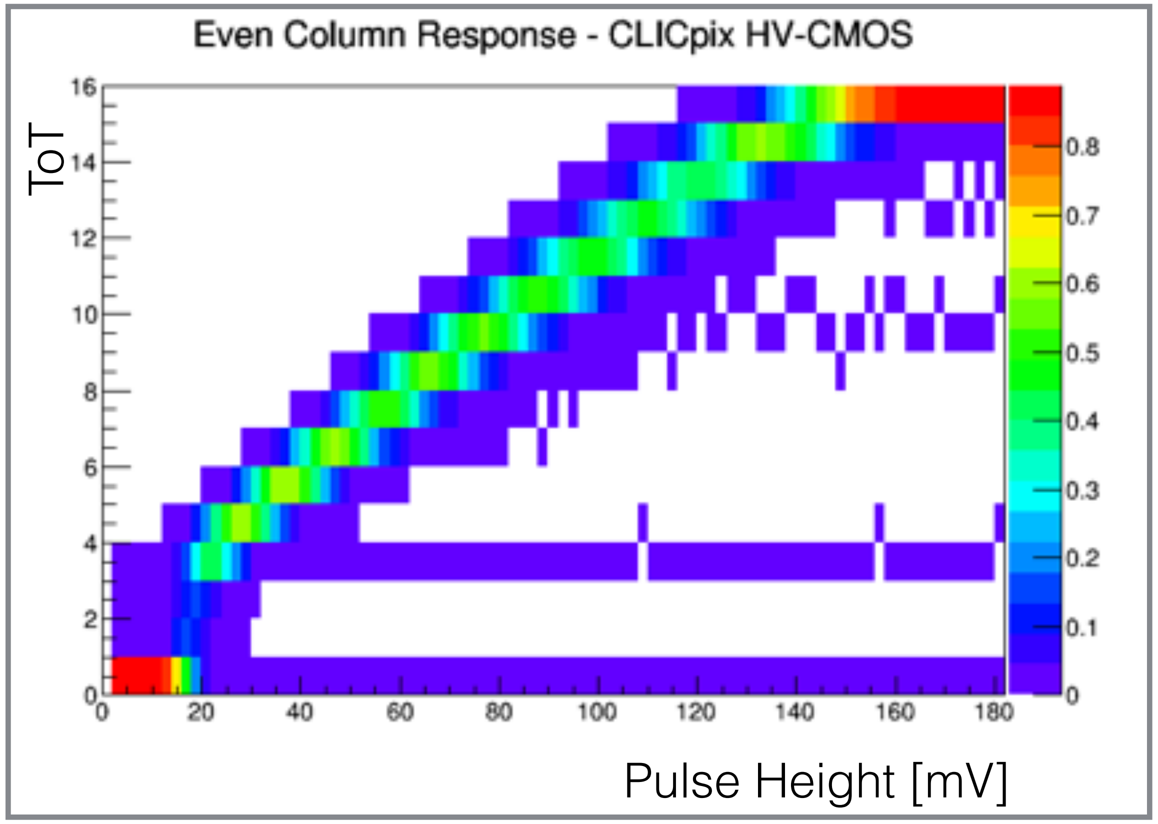


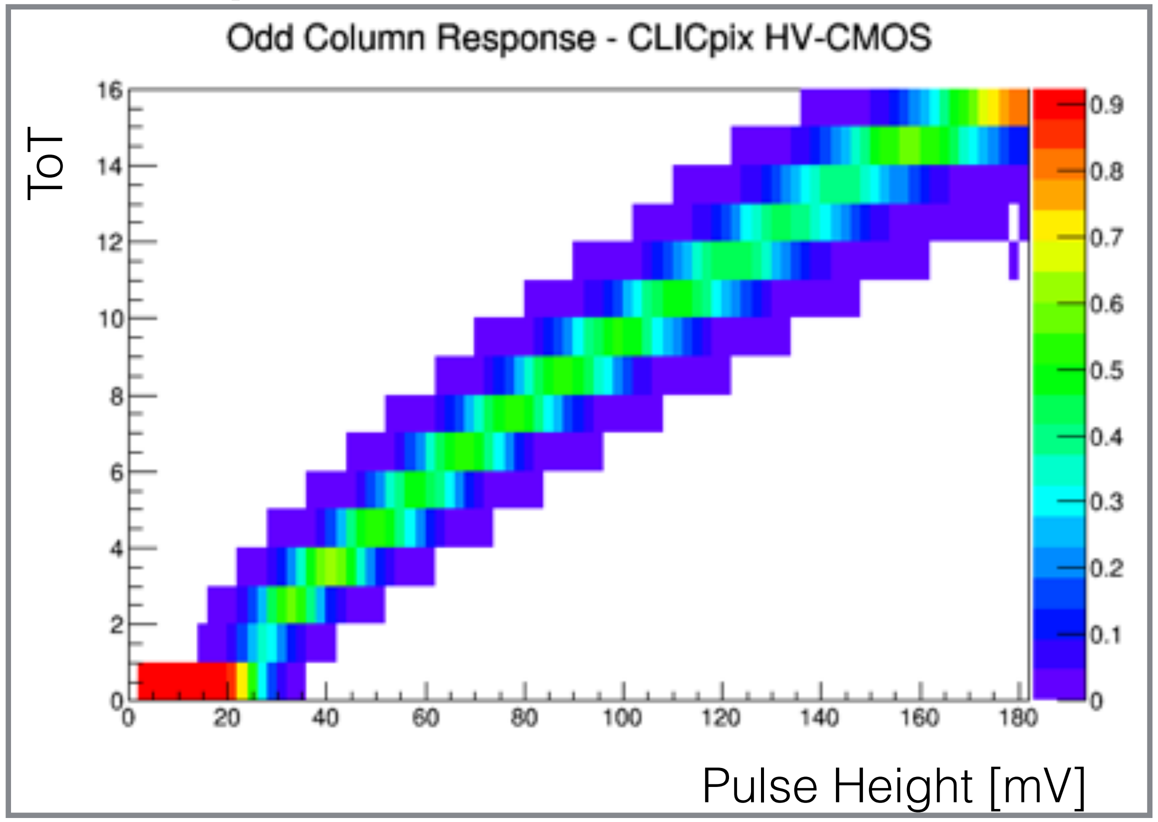


- C and T have definite column structure.
- This is expected due to different effective thresholds between alternate columns, which is a known feature of the CLICpix chip.

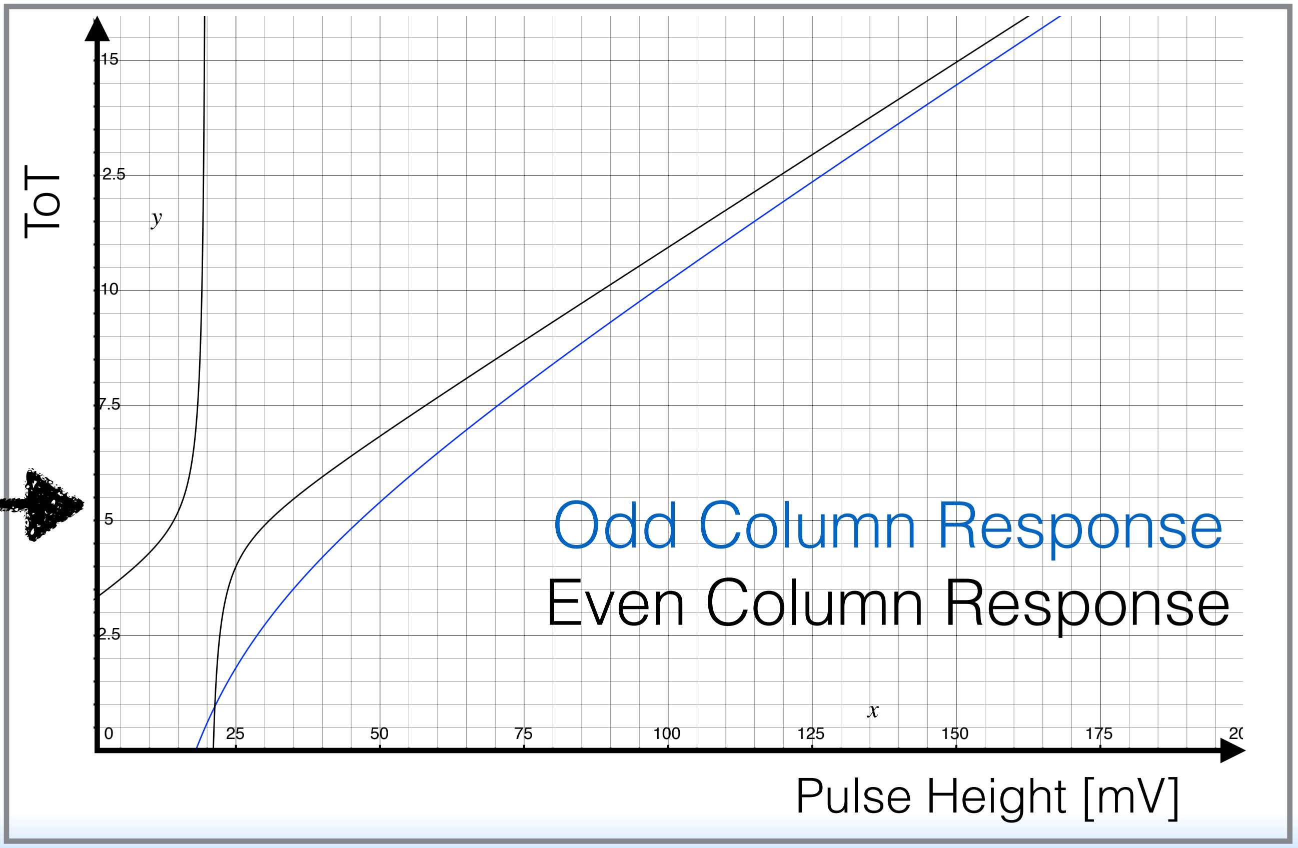


Test Pulse Calibration of CLICpix - Column Response





- Here we compare the raw data and the fit to that data for the even and odd columns across the full matrix.
- The fit appears a good model of the data indicating we can apply it to the test beam data (on a per pixel basis).



Test Beam Analysis

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Test Beam

- The HV-CMOS CLICpix samples were tested at the CERN test beam site in May 2015 and August 2015.

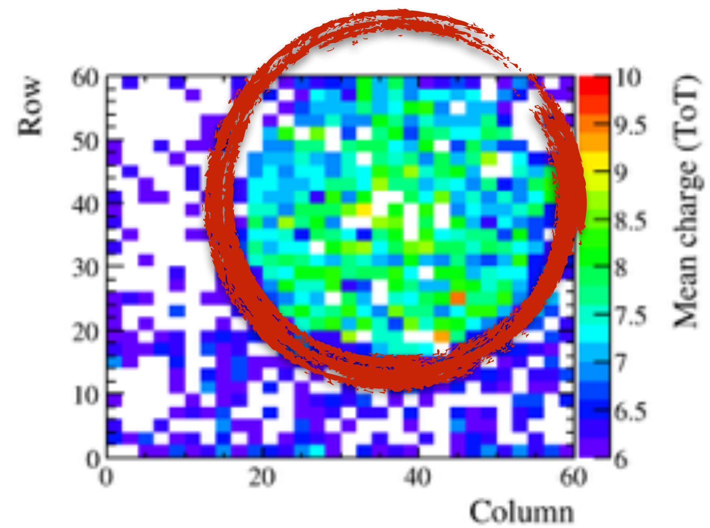
- The measurements were performed in the SPS H6 beamline inside the EUDET telescope and with a pion beam of 120 GeV momentum.

- The threshold, number of electrons needed to be collected by the CLICpix to produce a signal, was varied and the efficiency of each sample recorded.

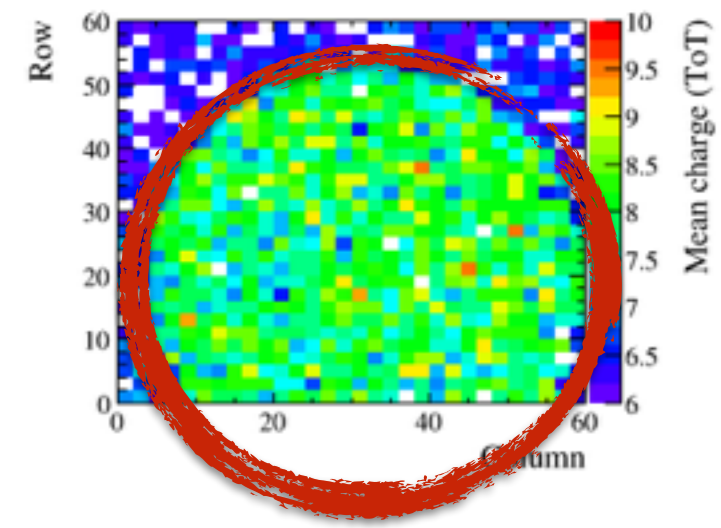
- Efficiency is defined as the number of clusters on the CLICpix associated to tracks divided by the number of tracks passing through the CLICpix. The distance cut for associating tracks and clusters used was 50 μm.

Test Beam - Charge Distribution

Quarter Pixel Misalignment

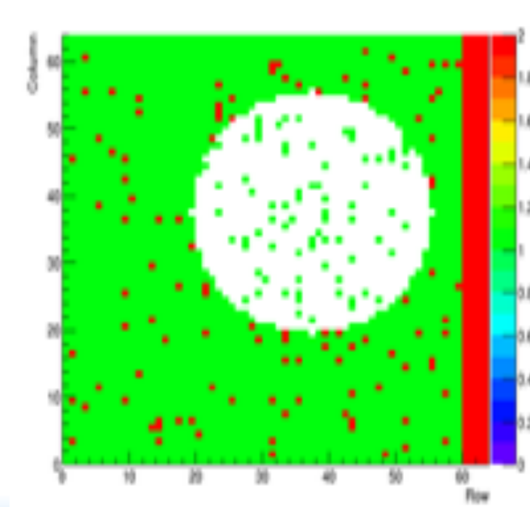


Ideal Alignment

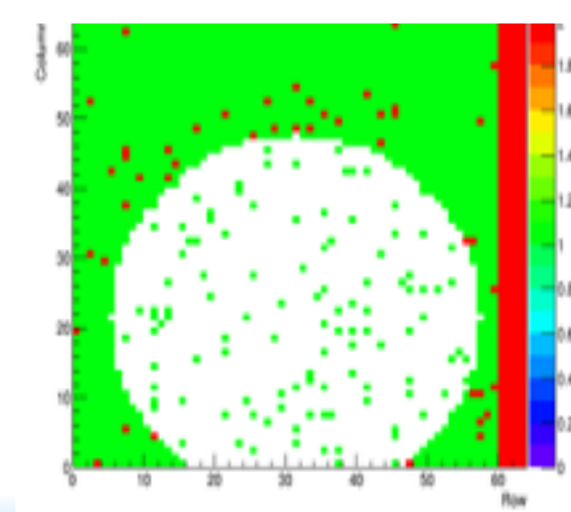


- It was found that there were some interesting features in the ToT map across the matrix for two of the samples.
- It is believed that this is due to the manufacturing process:
  - Glue was applied manually to the samples by placing one droplet close to the centre of one of the chips before pressing them together.
  - If insufficient glue is applied (to reduce the total glue thickness) there can be regions not covered by the glue layer - showing lower capacitance between the chips.

Quarter Pixel Misalignment Mask



Ideal Alignment Mask



- For this test beam analysis the regions of low capacitance (outside the circles) was excluded by applying a mask.

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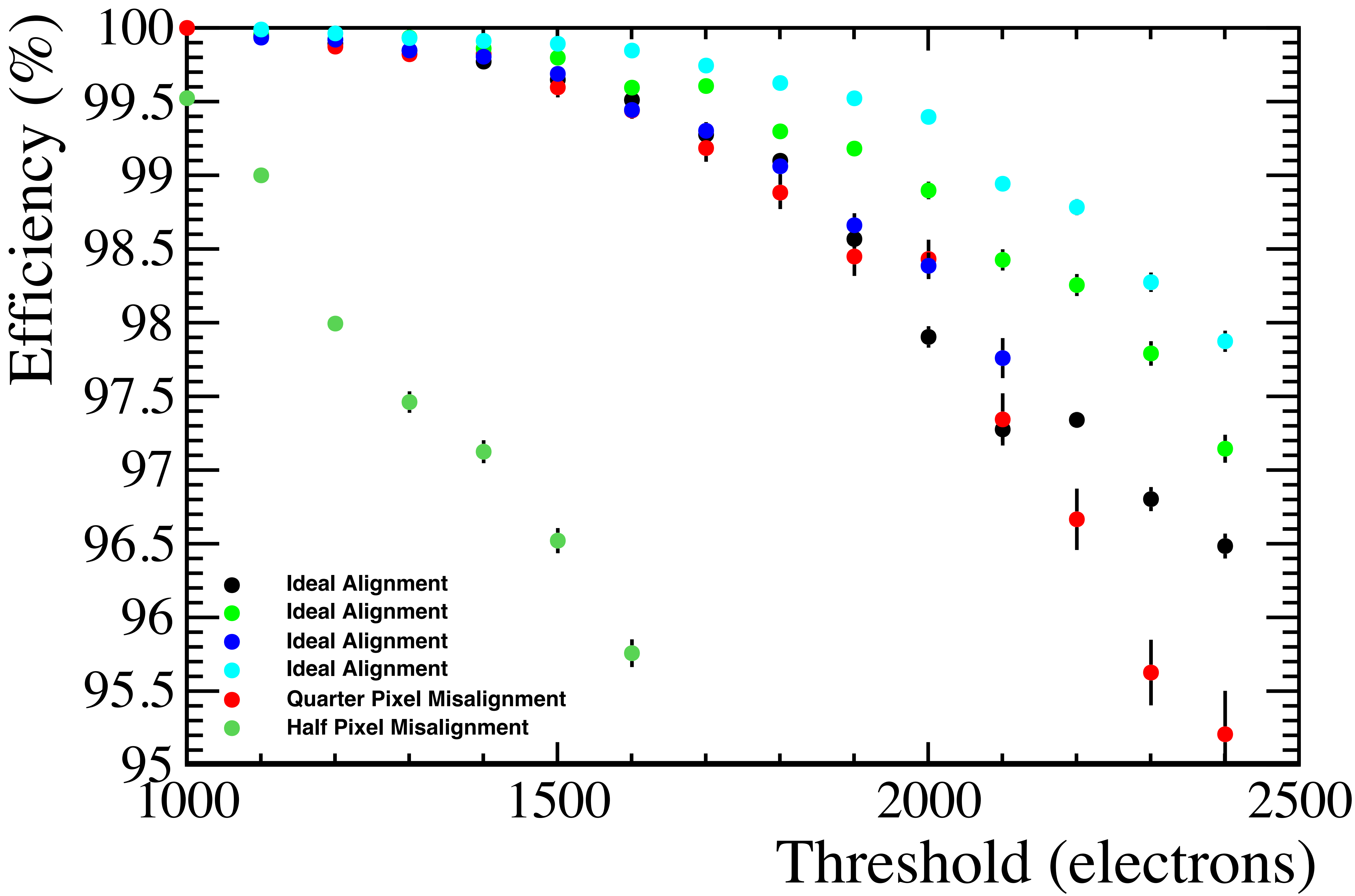
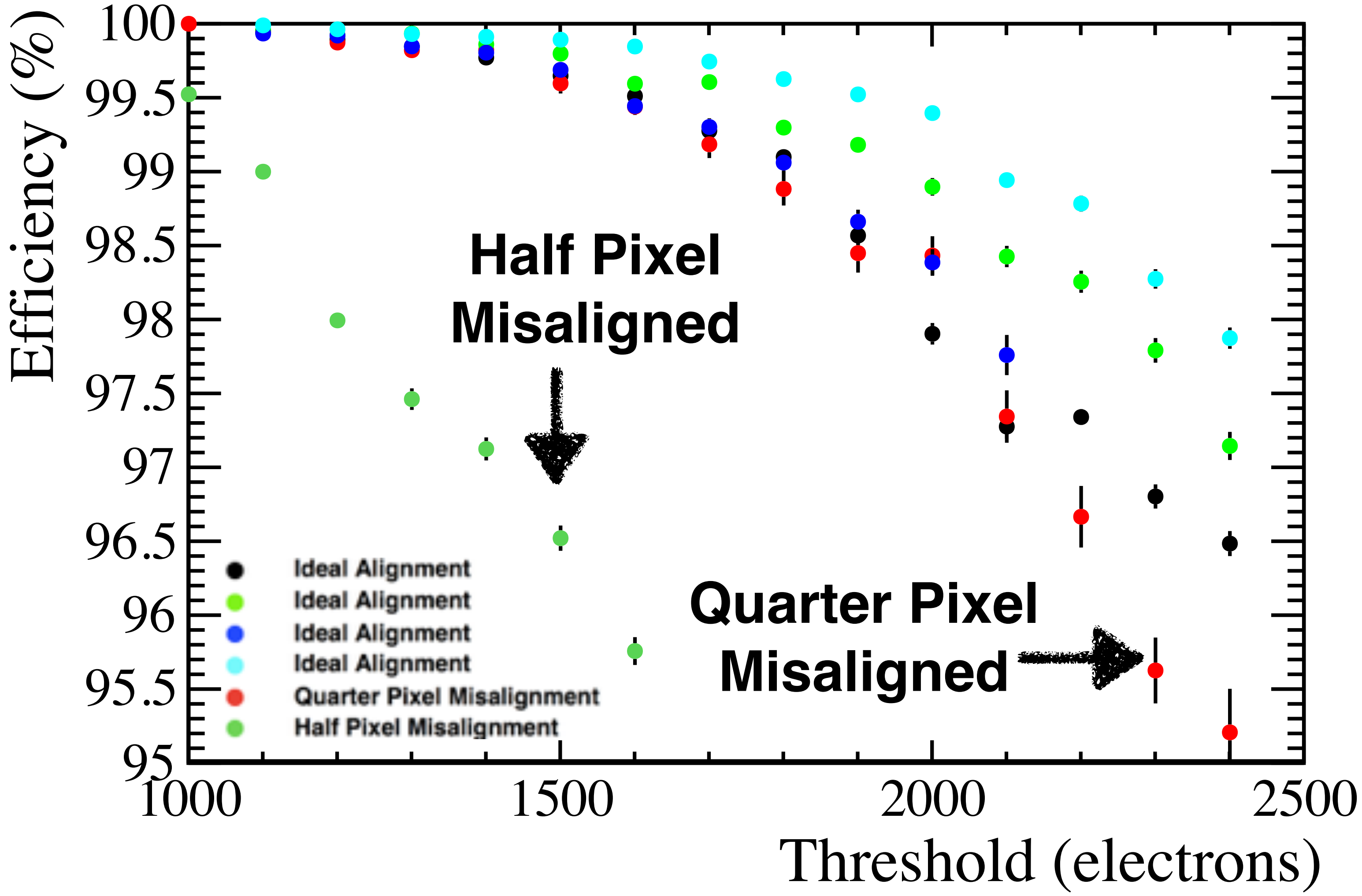
Test Beam - Efficiency Plot



Test Beam - Efficiency Conclusions



- As expected for all samples the efficiency falls as the threshold rises.
- For the ideally aligned samples we find similar behaviour for both glue thicknesses considered.

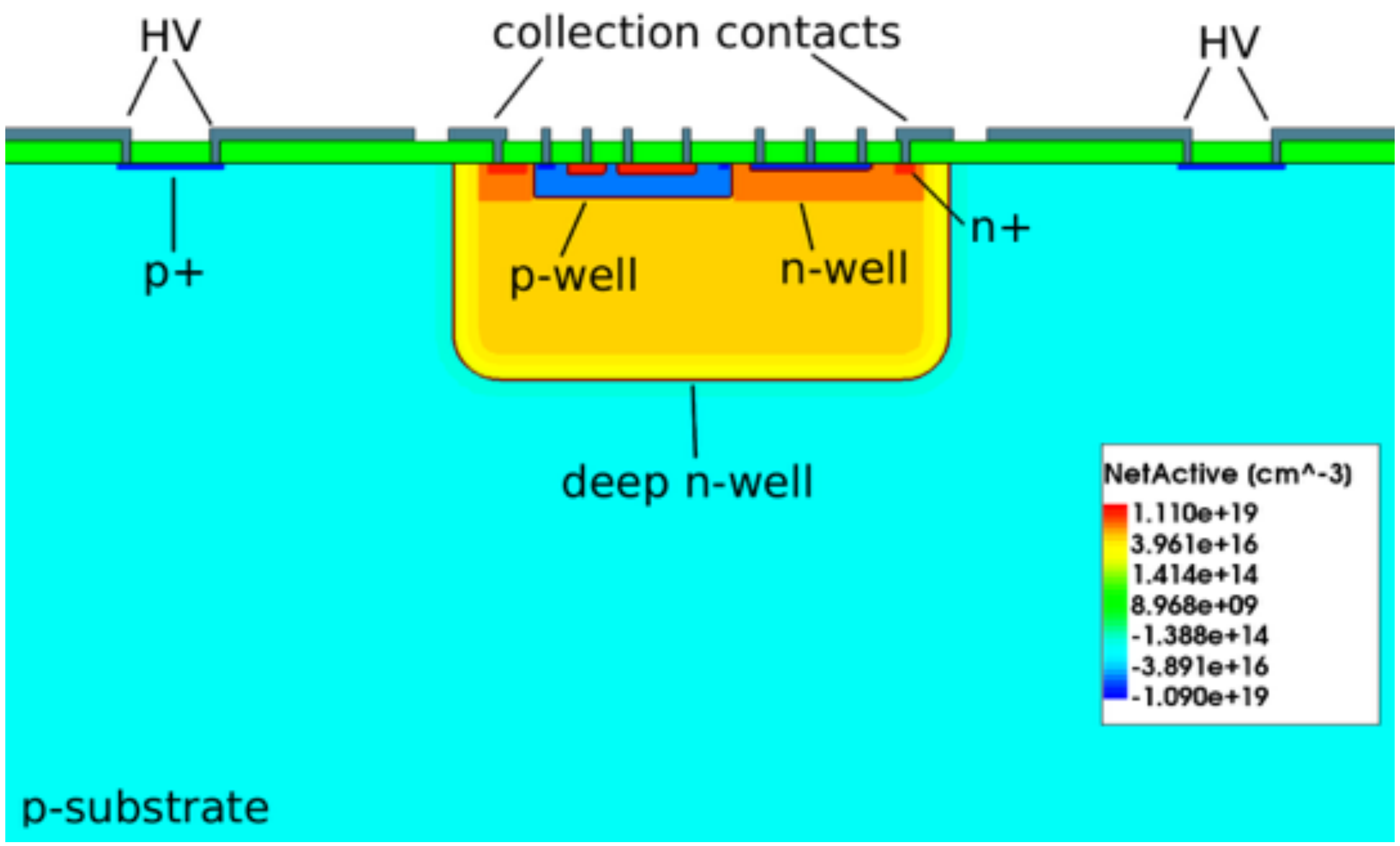
- The quarter pixel misaligned sample shows some degradation in comparison to the ideally aligned samples, but the half pixel misalignment shows significant degradation in performance.

HV-CMOS TCAD

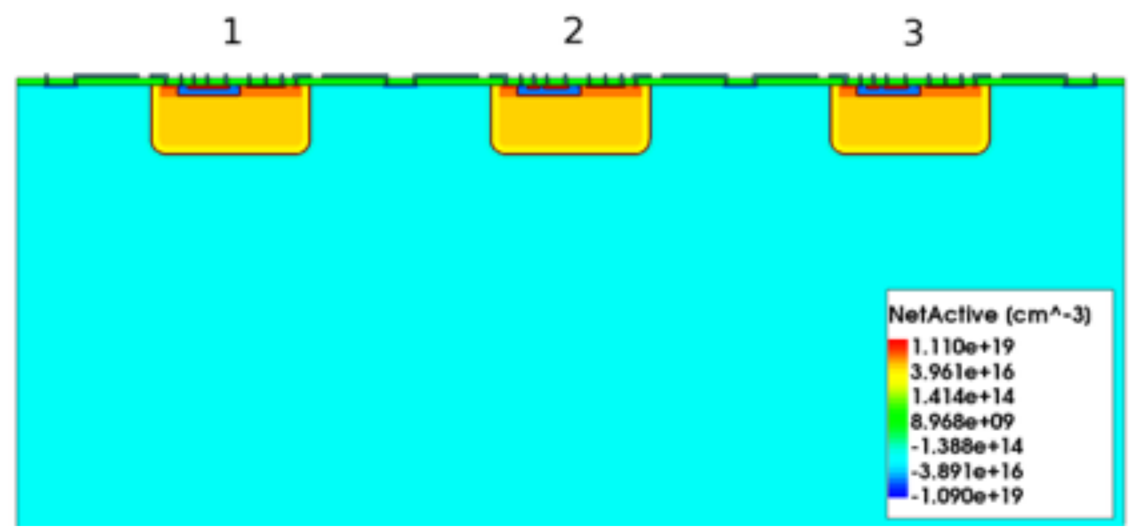
Thanks to M. Buckland.

HV-CMOS TCAD - Principle

* A series of simulations have been performed modelling the HV-CMOS sensor.
* TCAD enables modelling of the electric fields present in the sensor as well as making measurements of the deposited charge when a particle passes through such a sensor.
* In these simulations three adjacent HV-CMOS pixels have been simulated so that the effect of charge loss to neighbours can be determined.



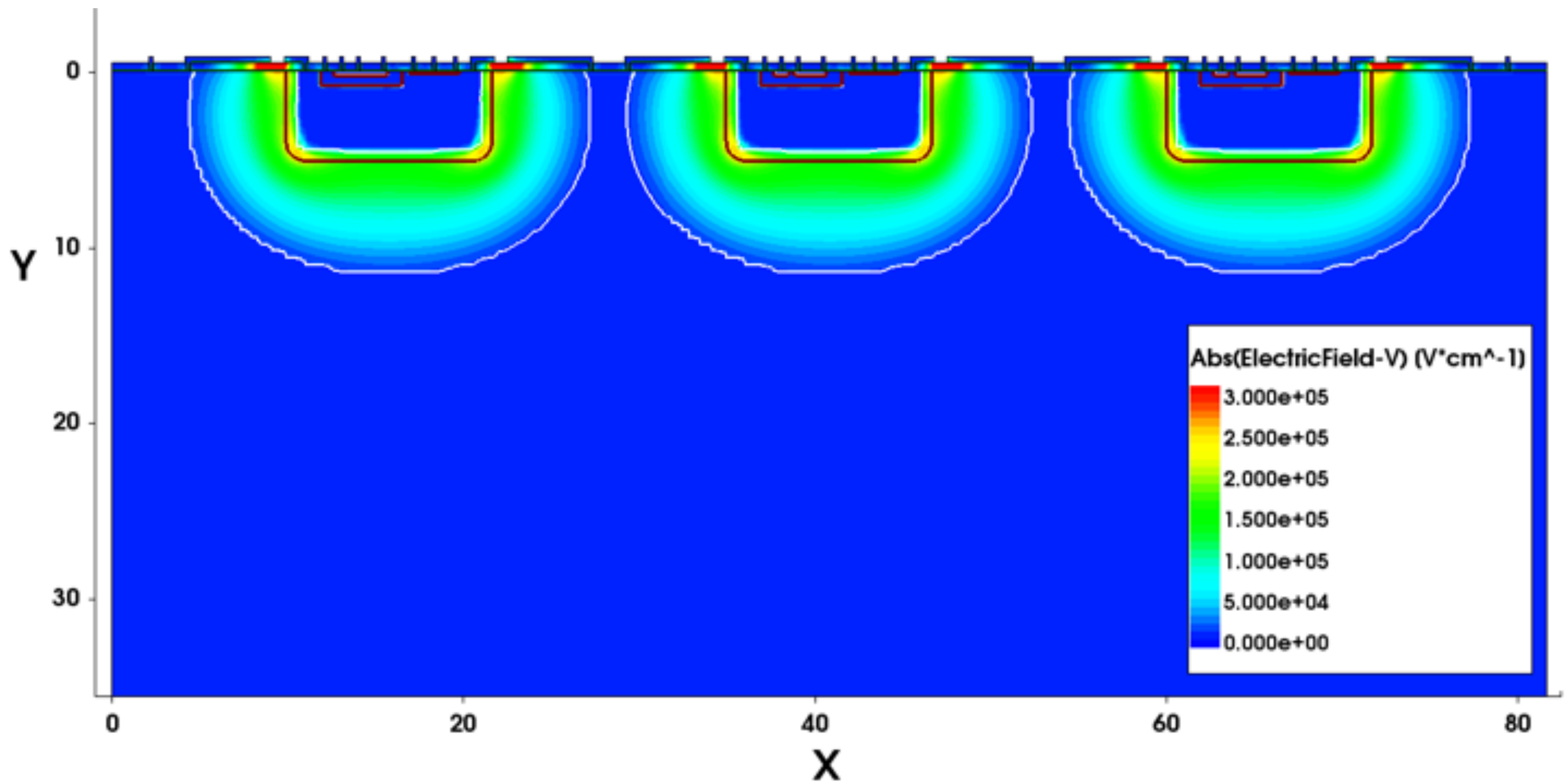
Schematic Diagram of the HV-CMOS Sensor



Configuration being simulated

HV-CMOS TCAD - E Field

- For the three pixel simulation the electric field map is as follows when using HV-CMOS sensors with a substrate resistivity of 10 Ω cm:



This is what the electric field looks like for the current HV-CMOS CLICpix sensors looks like.

- Here the bias voltage for the HV-CMOS pixels is set to -60 V. This is the nominal operating voltage for these sensors.

HV-CMOS TCAD - Simulation

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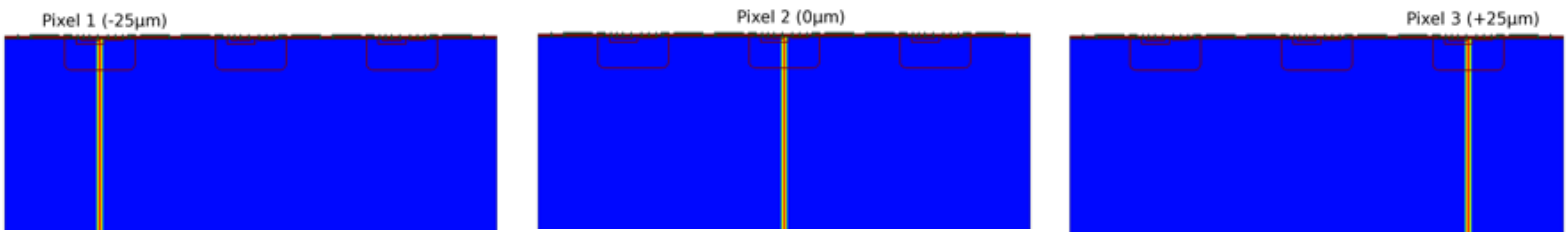
* A series of normal incident MIPs were simulated as passing though the three pixel setup at various different positions across the row and the sensor performance analysed.

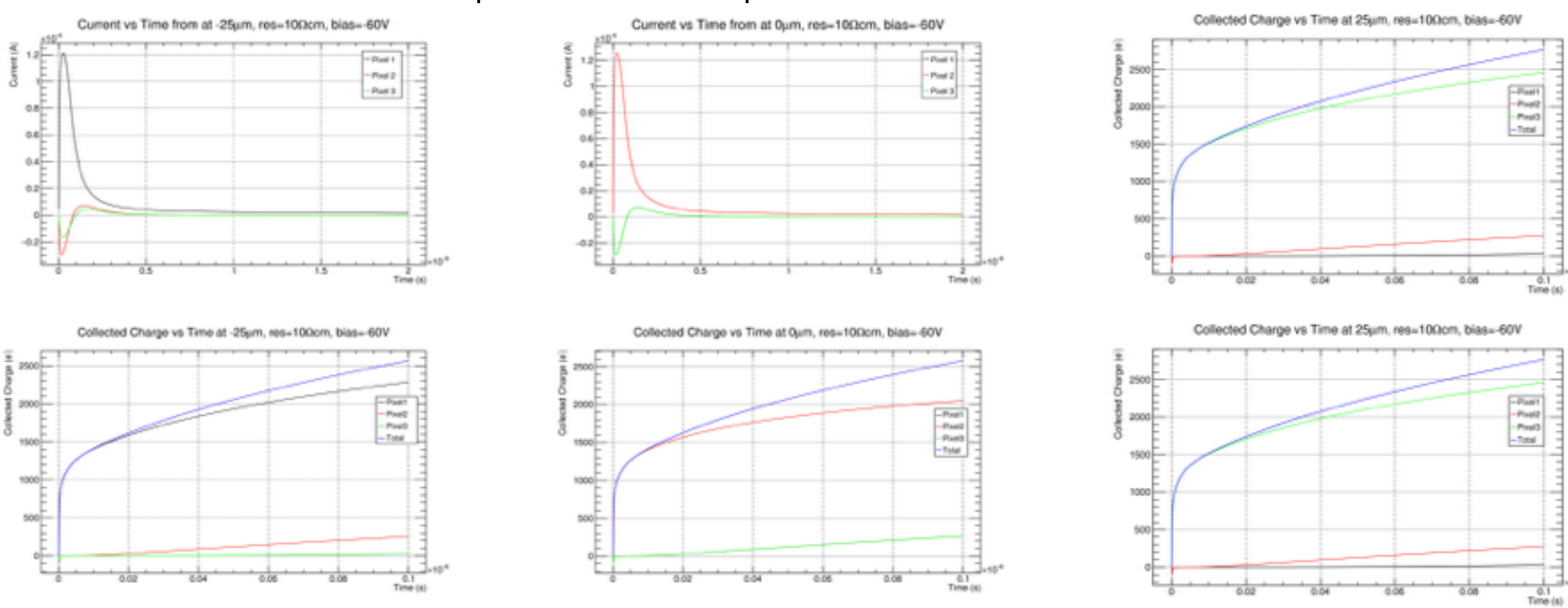
Simulation



MIP position at various positions across the simulation

Current

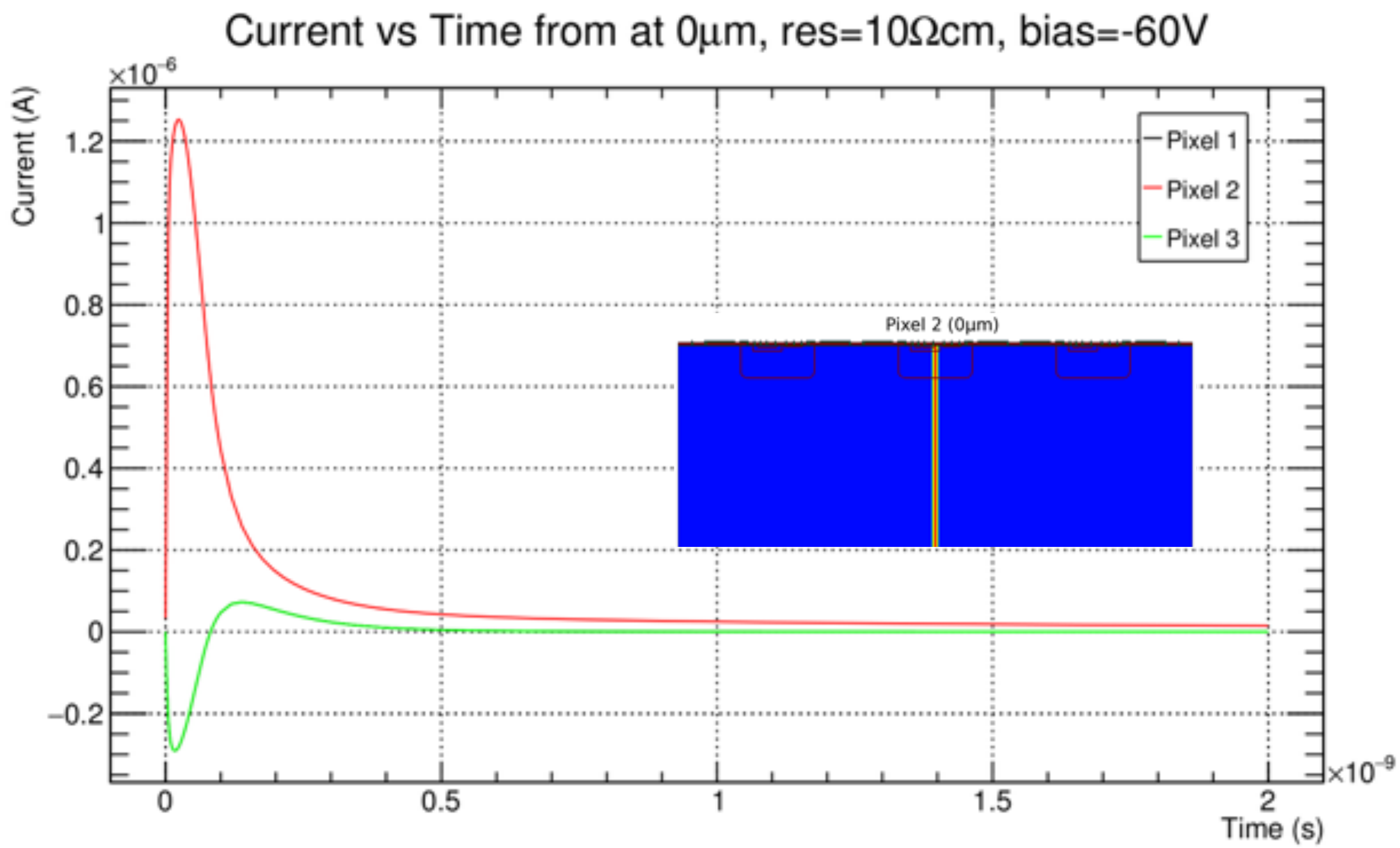
Collected Charge

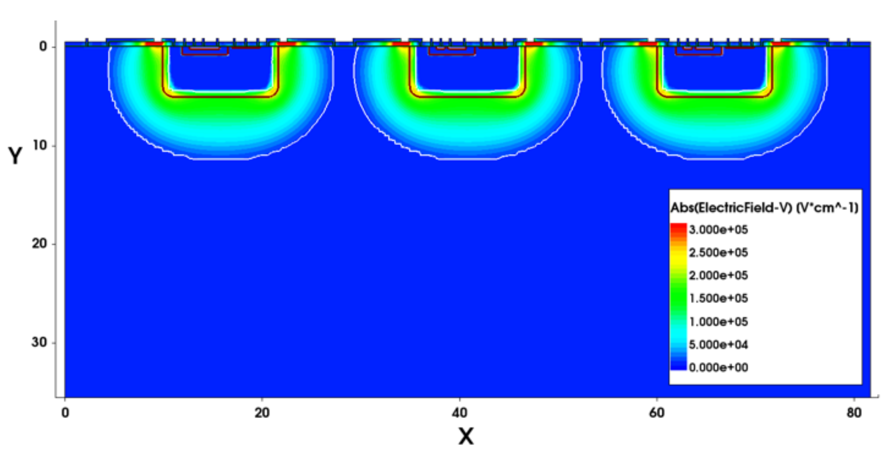


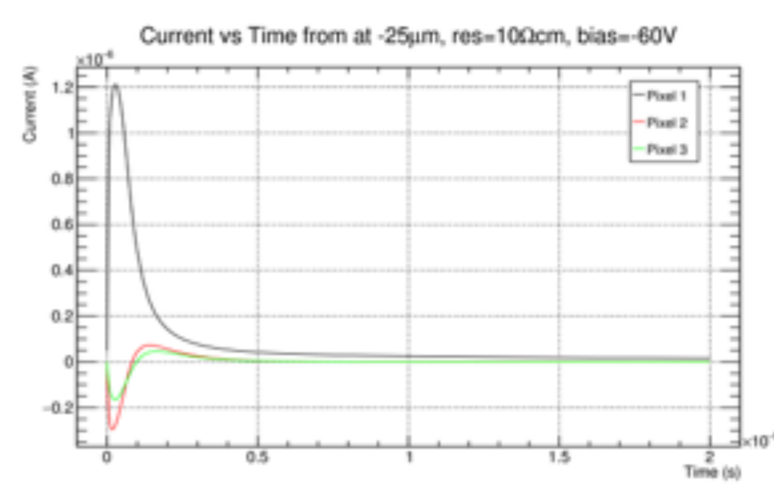
HV-CMOS TCAD - MIP Response Over Time

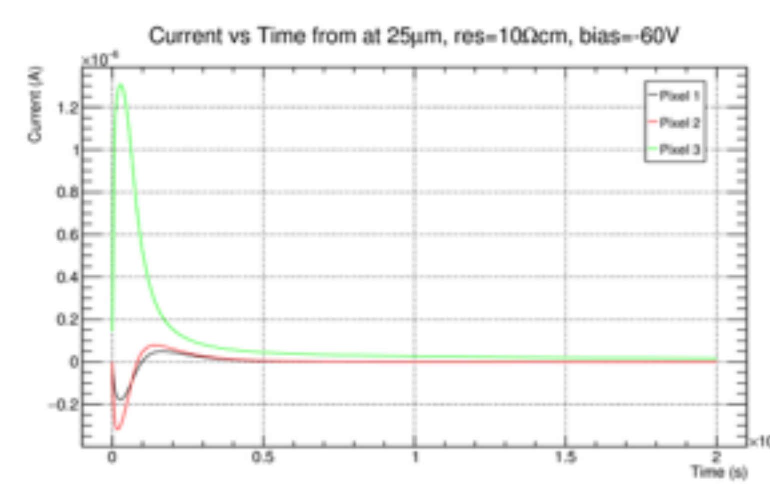
* For all pixels there is a fast component of the total charge collected, followed by a much slower contribution.

* The slow contribution will be caused by diffusion from charge deposited in regions without an electric field.





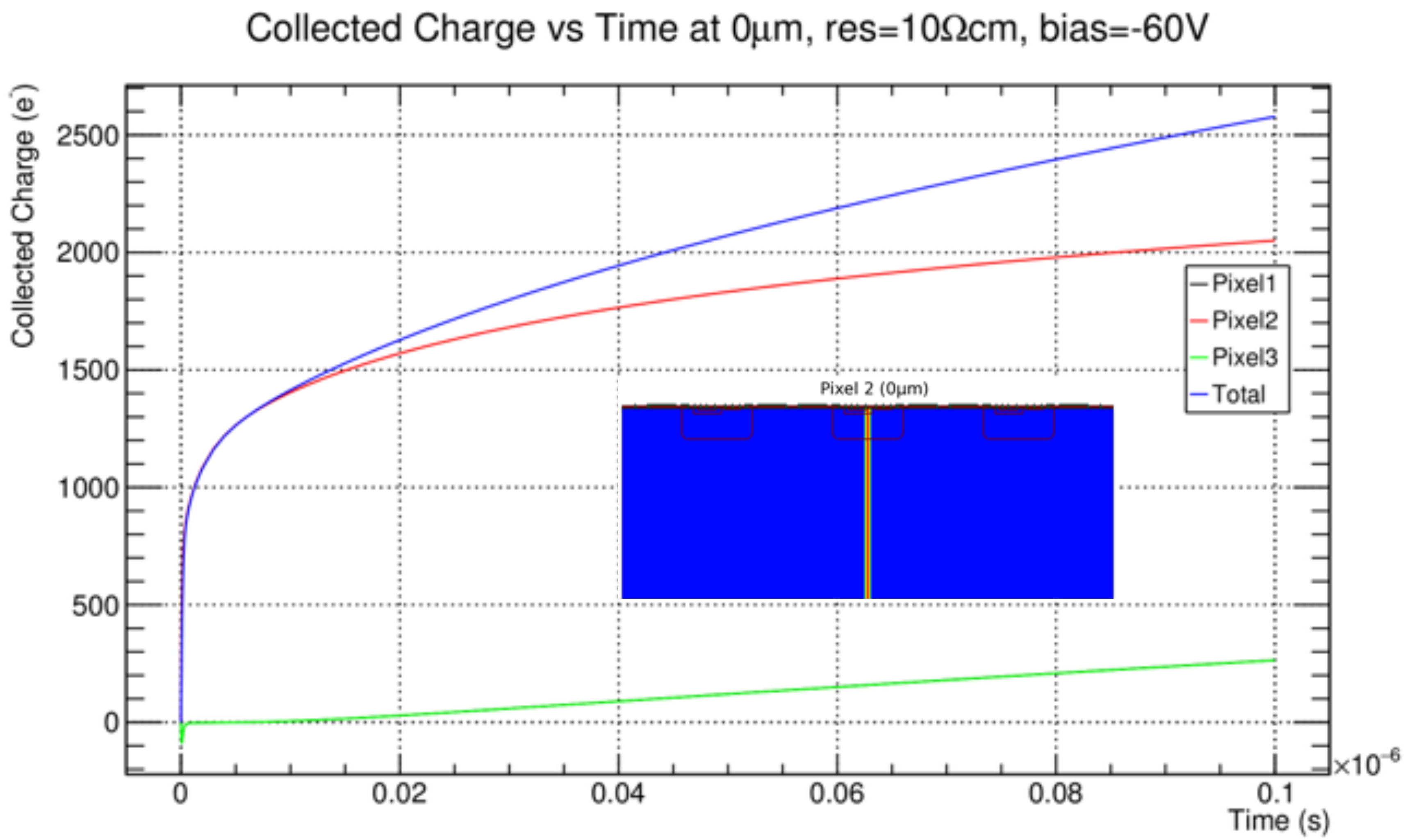


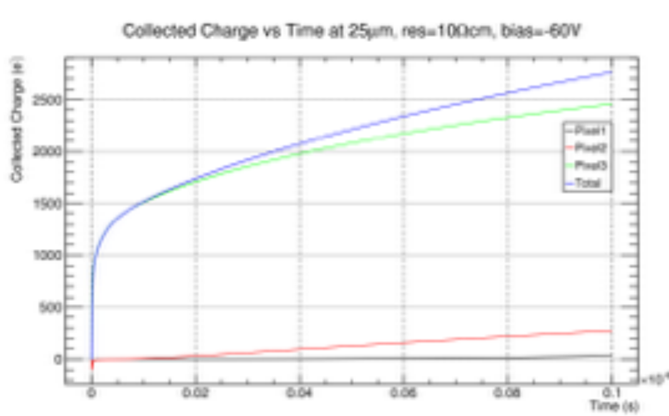


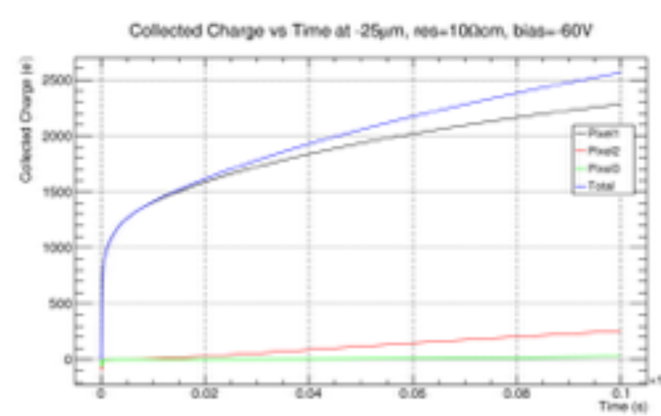
HV-CMOS TCAD - MIP Response Over Time

- This interpretation is backed up by the charge collection profiles as a function of time for MIP positions of -25 *μ*m, 0 *μ*m and 25 *μ*m from the central pixel.

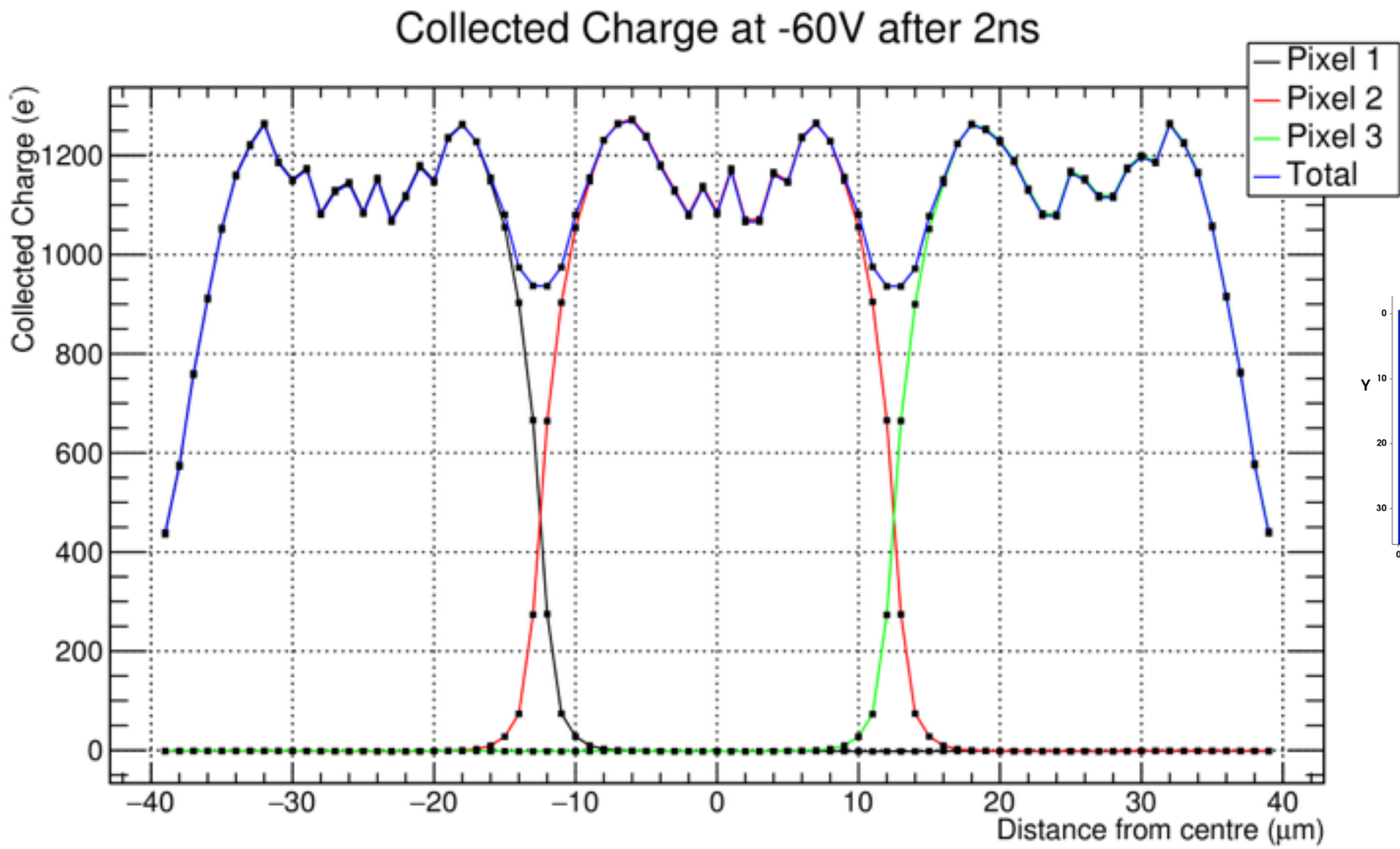
- These plots also show the fast collected charge contribution followed by a slower contribution.

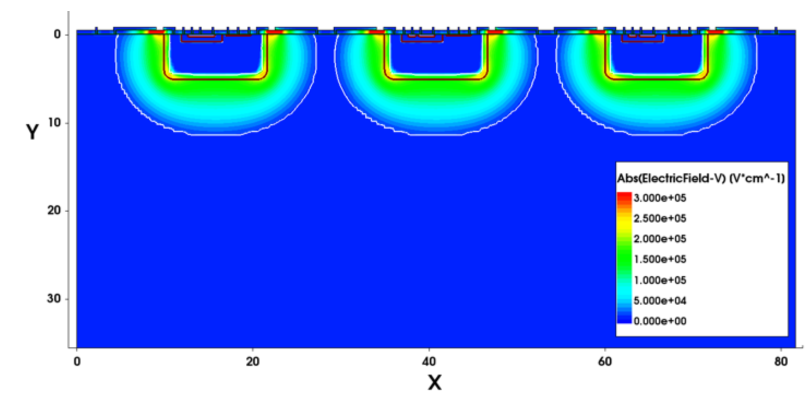






HV-CMOS TCAD - MIP Response





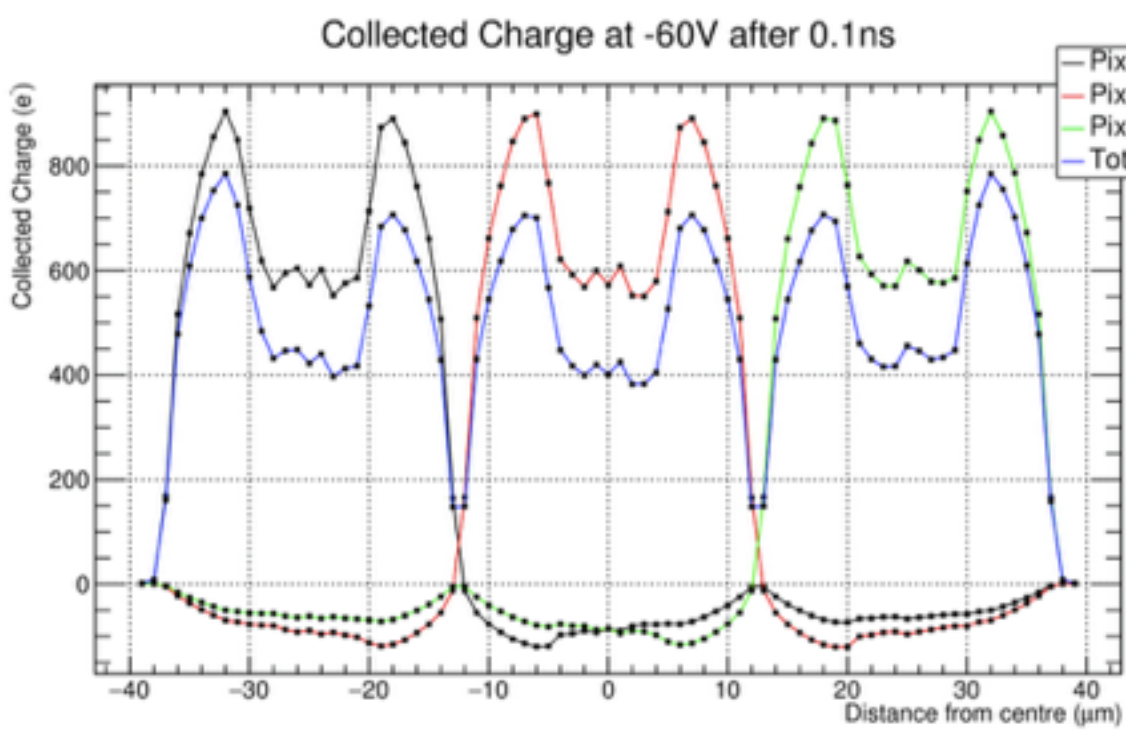
- The sum of the deposited charge for each of the 3 pixels after 2 ns contains primarily the fast, i.e. not charge from diffusion, component of the deposited charge contribution.

- The non uniformity of the total response mimics the non uniformity of the E-field in the pixels.

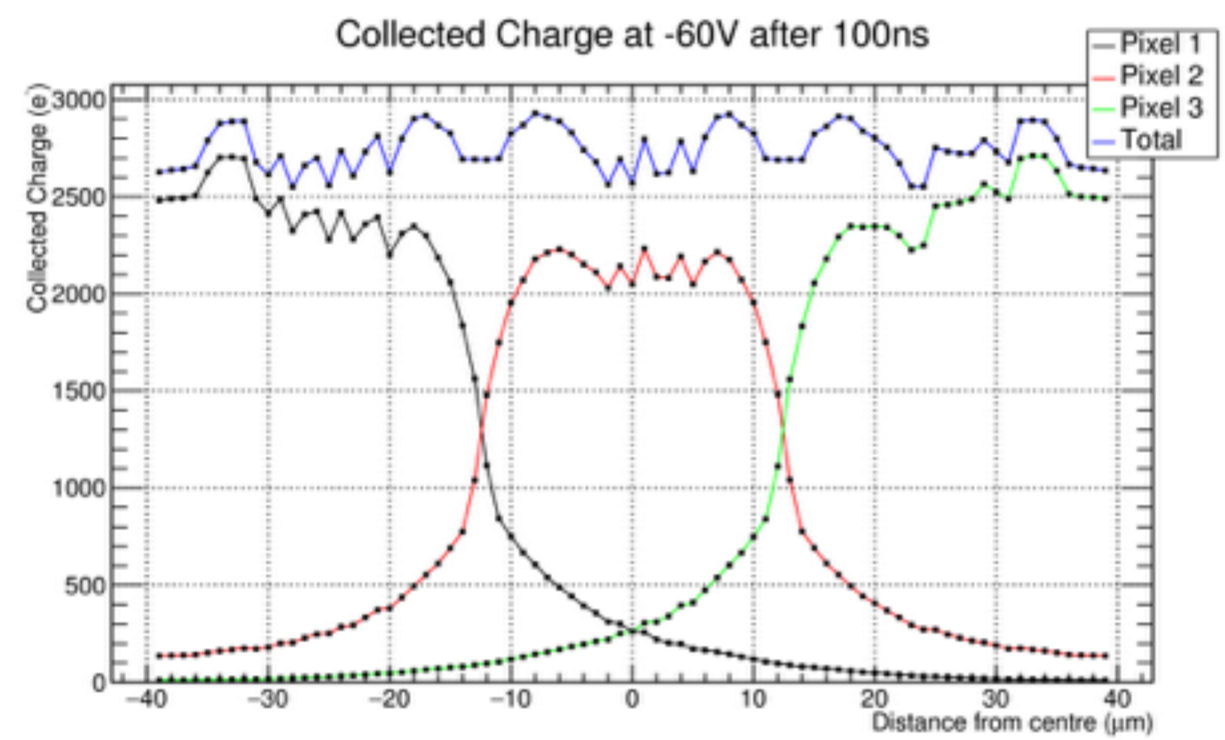
HV-CMOS TCAD - MIP Response Over Time

- Over time any slow collected charge contribution, from diffusion, is collected by the HV-CMOS.

- The charge collection profile becomes more uniform over time once the remaining charge is collected, although the general shape of the profile is formed in the first 0.1 ns, if not before.



Fast Contribution



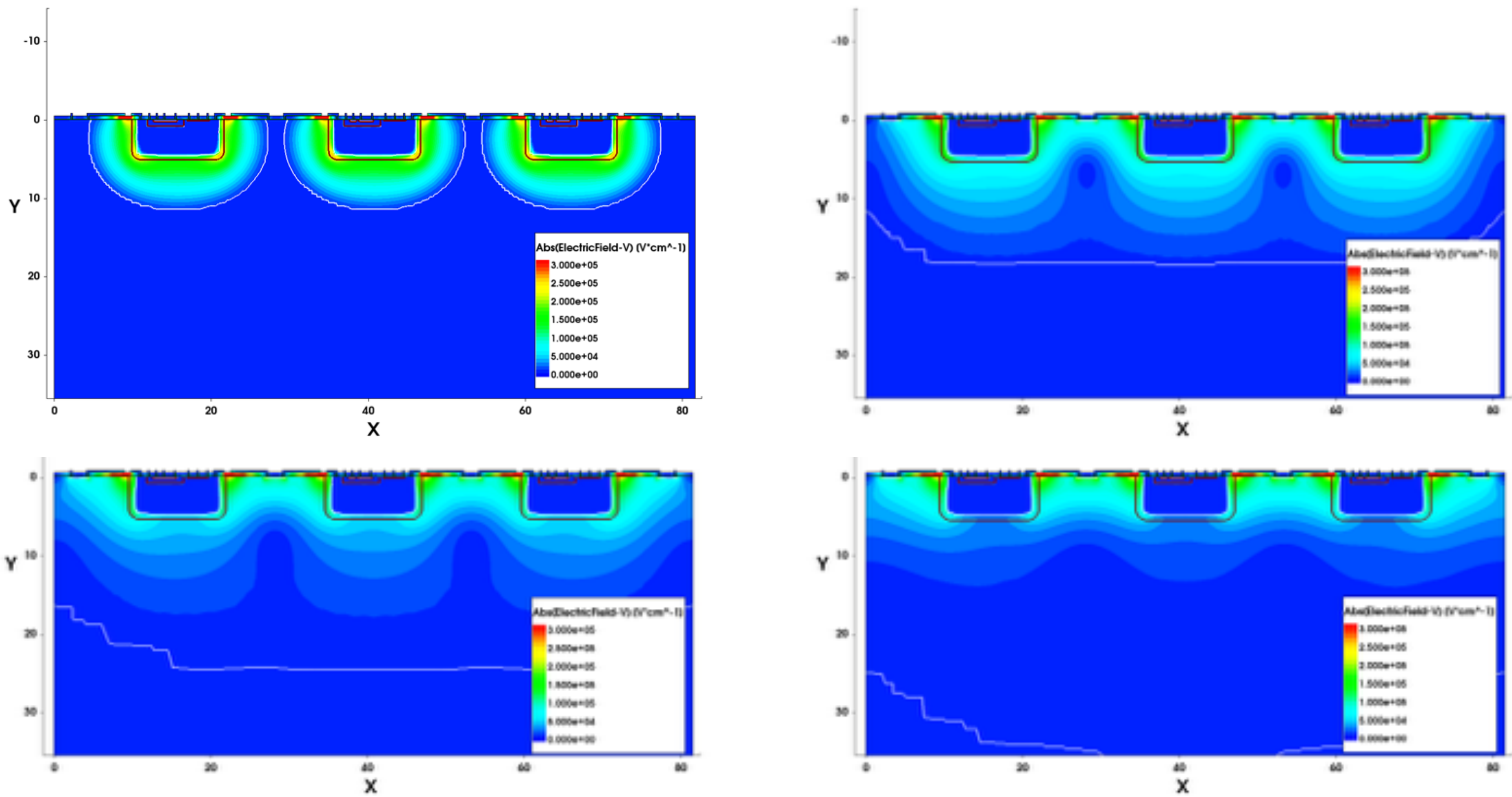
Fast and Slow Contribution

HV-CMOS TCAD - Controlling E Field

- By varying the resistivity of the HV-CMOS substrate, it is possible to manipulate the electric field map in the sensor.
- This is beneficial because a higher resistivity produces a better response, more uniform, and has a larger depletion region.
- This is one of the design goals for the next generation HV-CMOS sensors for CLICpix.

10Ωm

80Ωm



200Ωm

1000Ωm

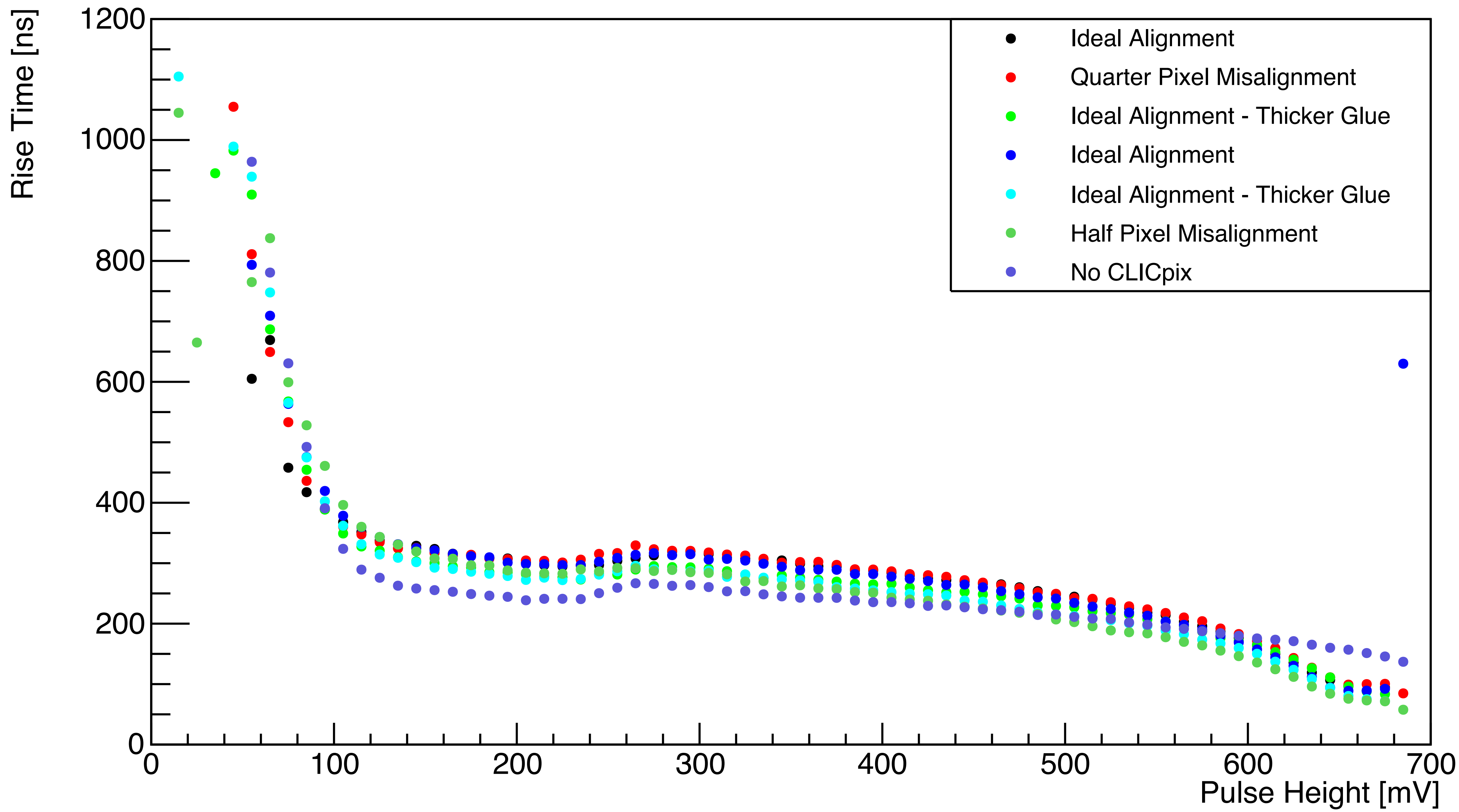
Conclusions

- Extensive testing of the capacitively couples HV-CMOS CLICpix sensors has been performed on a series of samples with different manufacturing methods.
- The manufacturing process has a clear impact on the performance of the sensors and the conclusions indicate that the alignment of the HV-CMOS to the CLICpix is very important in the final performance of the sensor.
- We have shown that the manufacturing tolerances on the samples we have examined here have been reached and the samples behave as expected.
- It was found that the bonding force used in the gluing process did not affect the performance of the sensors for the range of bonding forces considered here.
- A series of TCAD simulations of the HV-CMOS sensor have been performed and the results are consistent with expectations. These simulations will greatly aid the design of future HV-CMOS sensors.

Thank You For Your Attention!

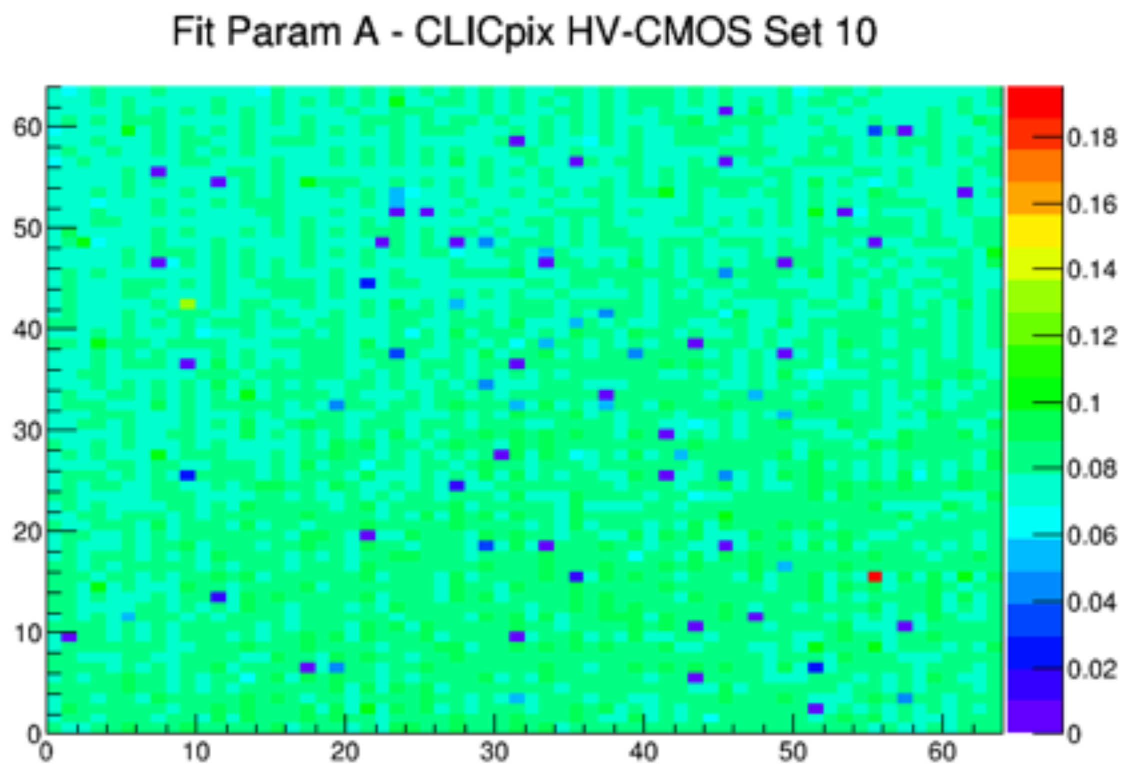
Back Up

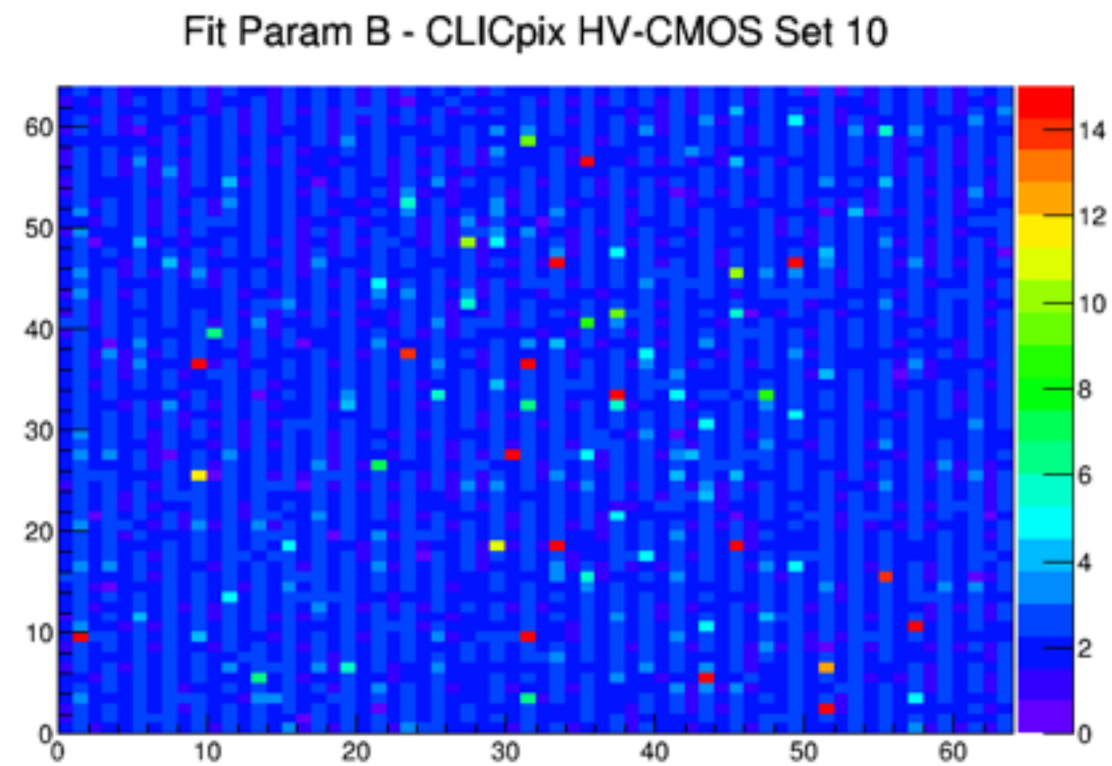
Radioactive Source Calibration- Rise Time vs Pulse Height

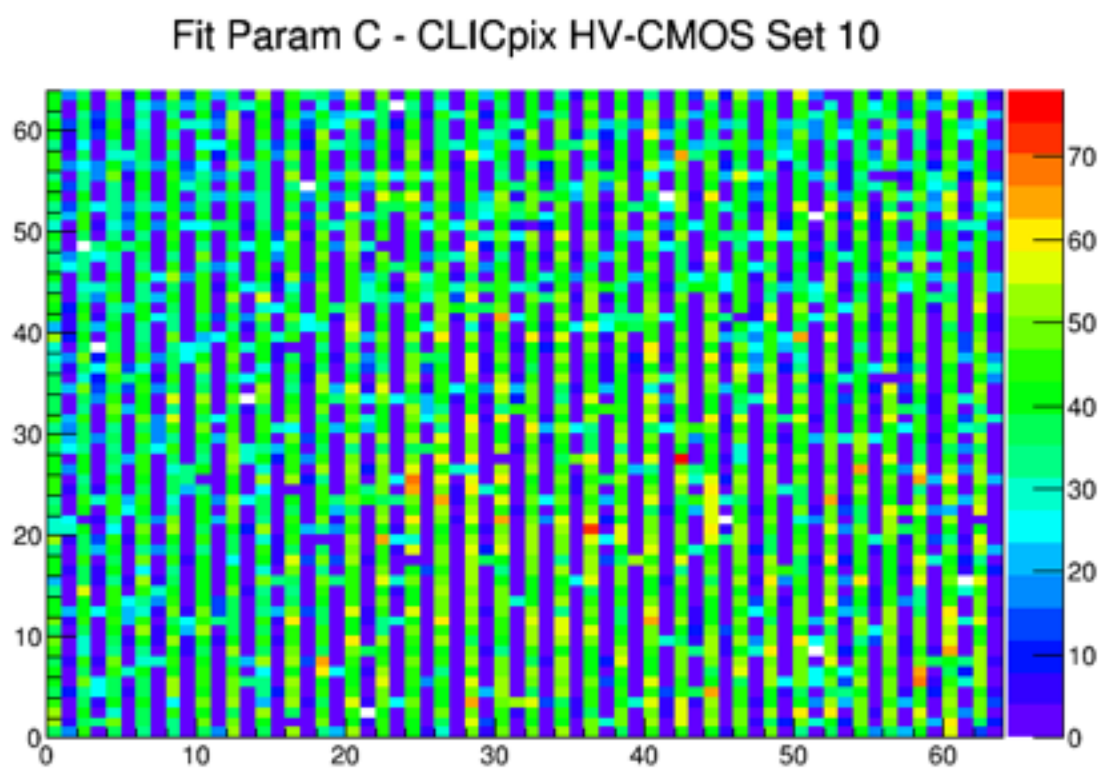


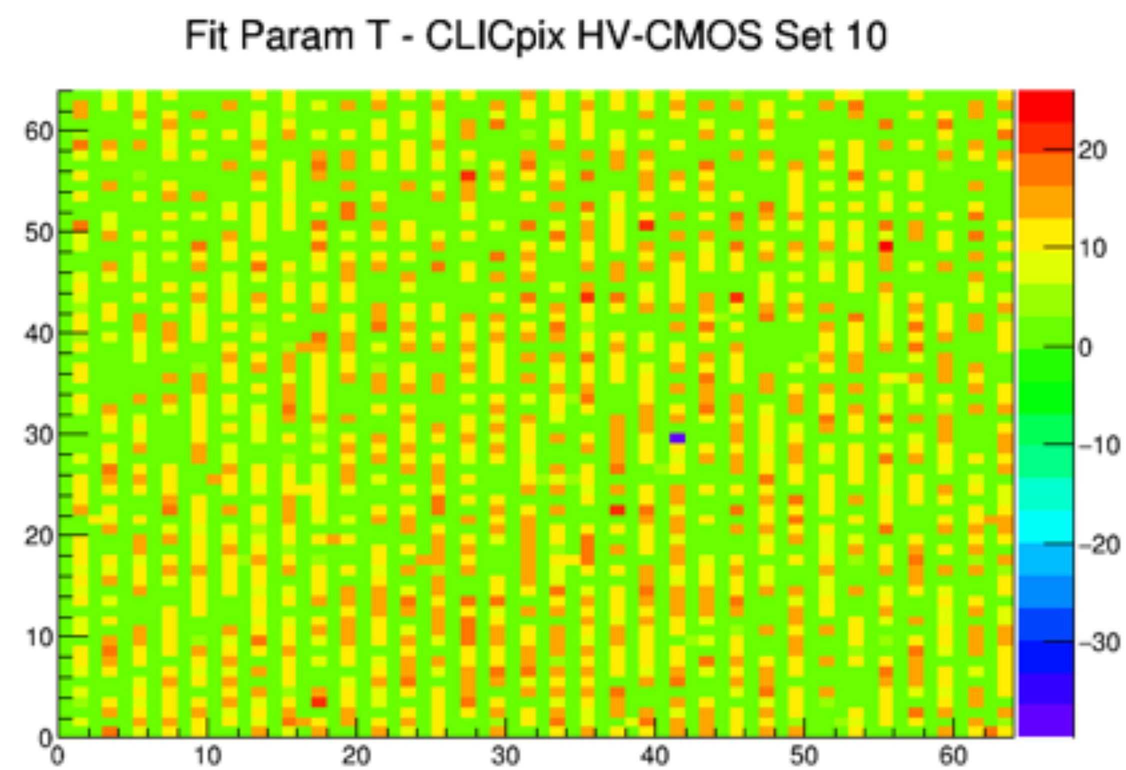
* The mean rise time for the HVCMOS samples in the study is roughly 300ns and is unaffected by the presence of the CLICpix.

Test Pulse Calibration of CLICpix - Quarter Pixel Misaligned

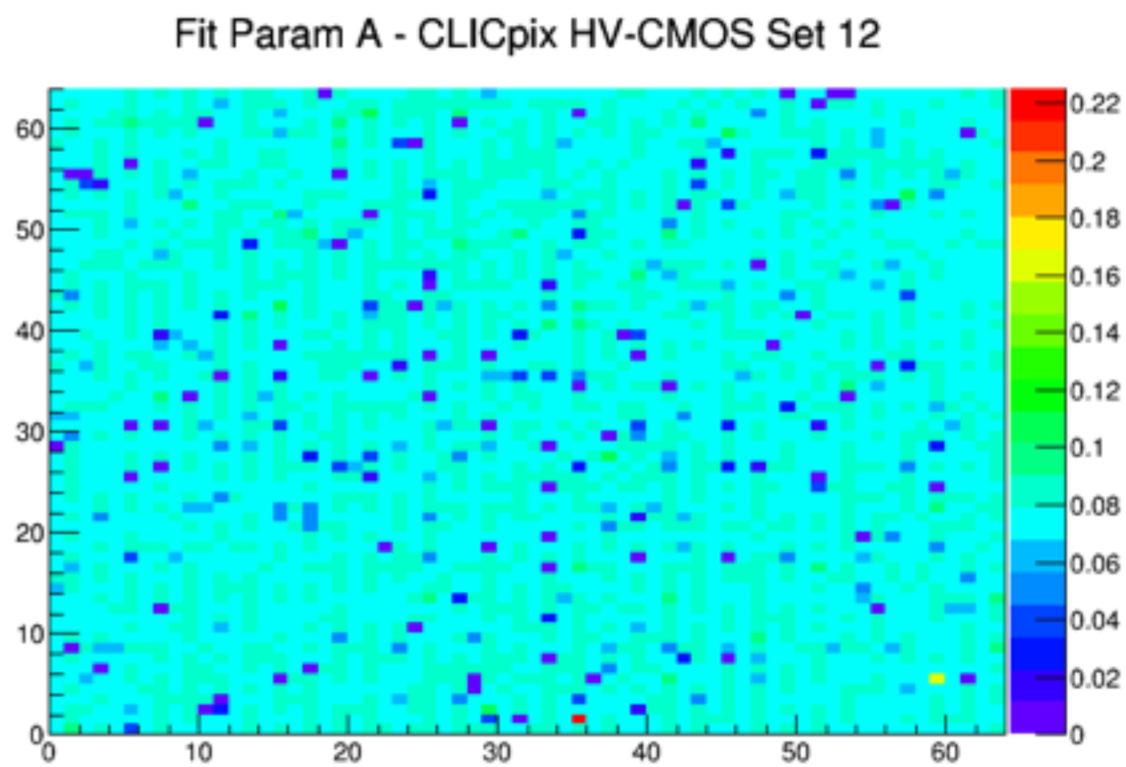


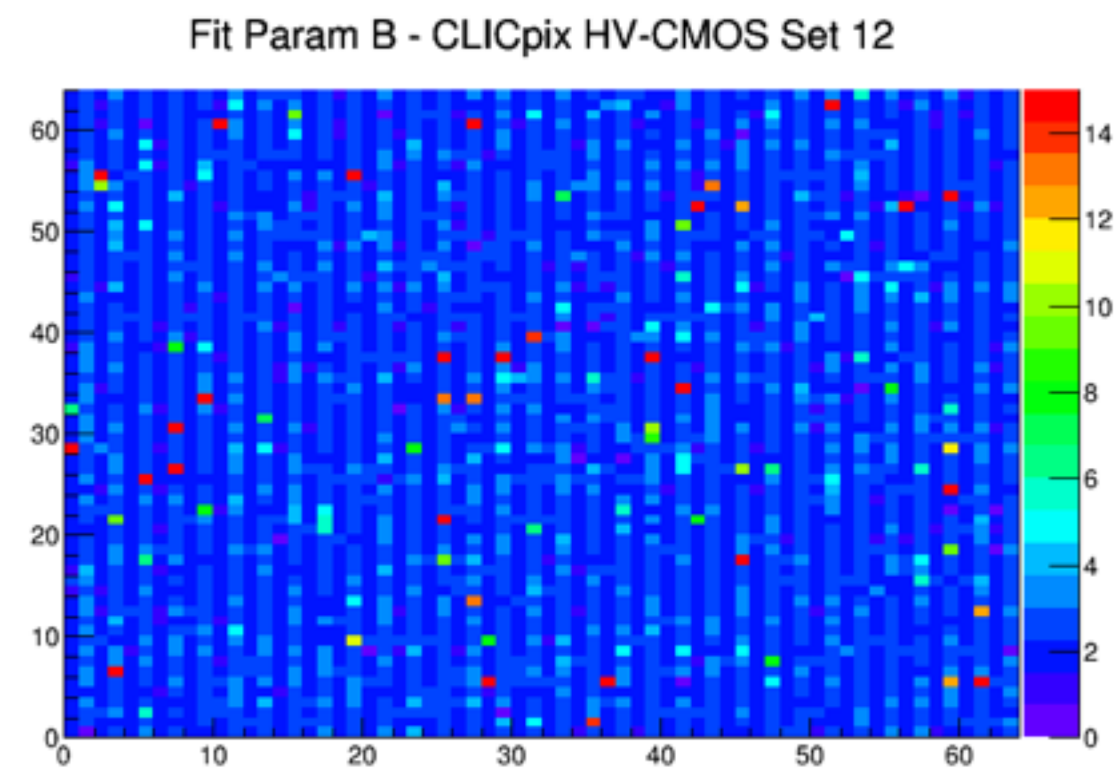


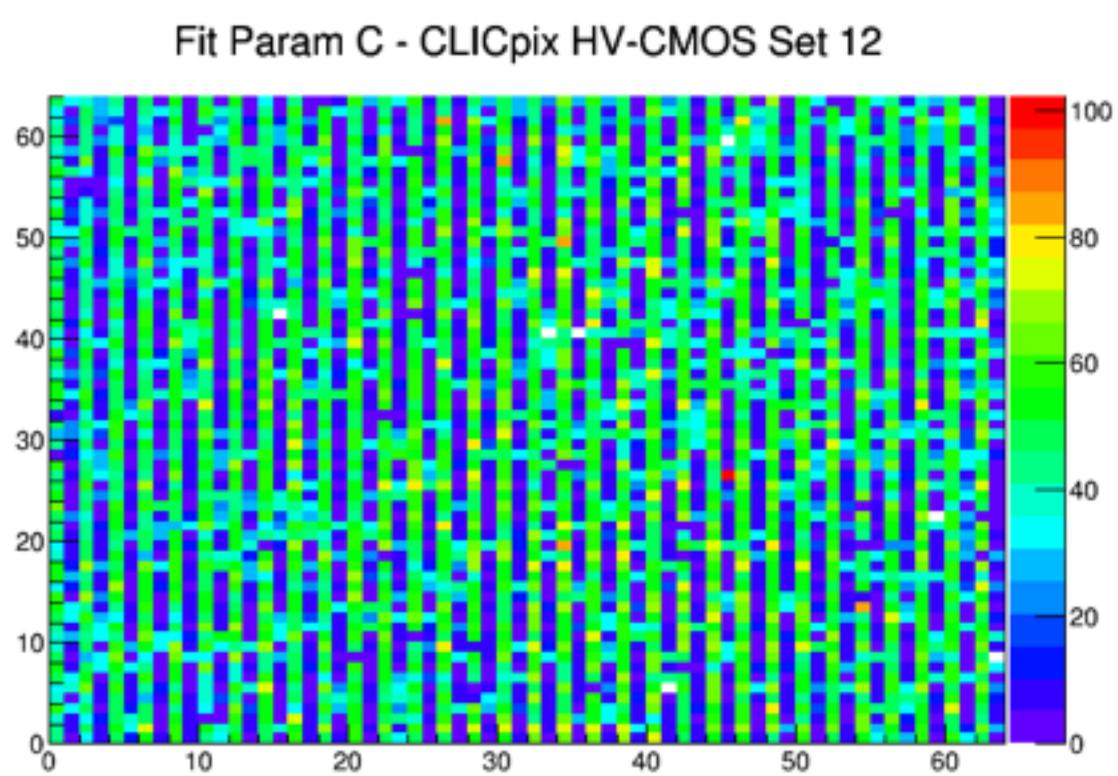


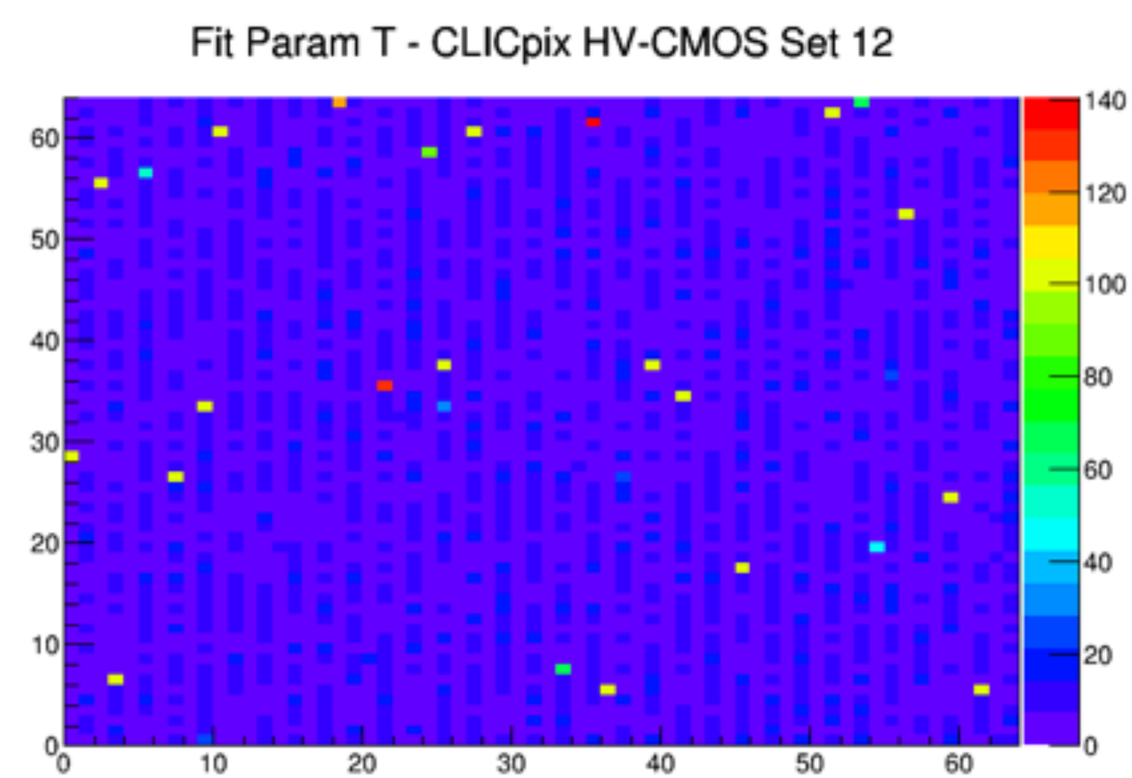


Test Pulse Calibration of CLICpix - Ideal Alignment - Thicker Glue

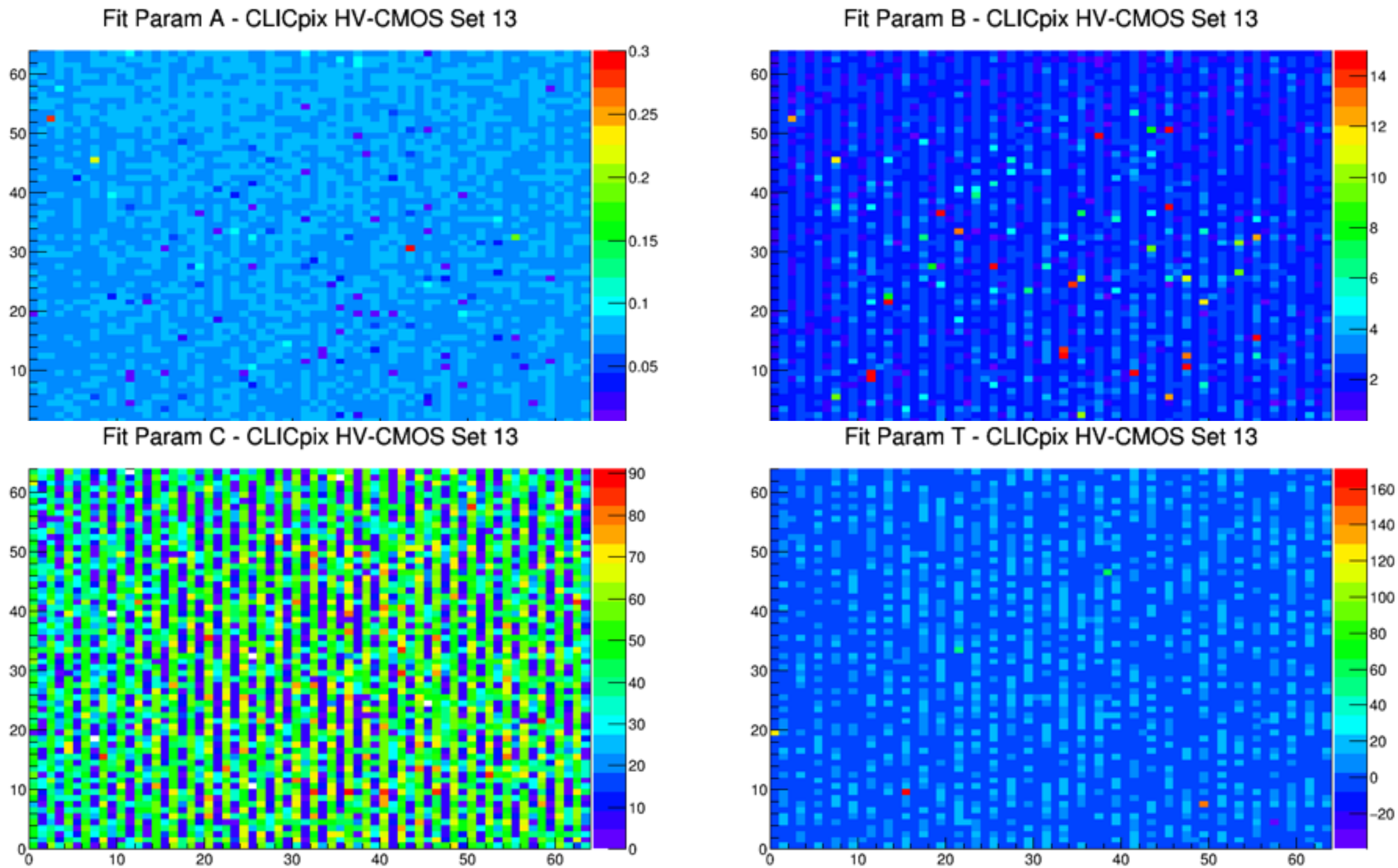








Test Pulse Calibration of CLICpix - Ideal Alignment



Test Pulse Calibration of CLICpix - Ideal Alignment - Thicker Glue