Characterisation of capacitively coupled HV-CMOS devices using the CLICpix ASIC and AIDA telescope

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(on behalf of the CLICdp Collaboration)

Capacitively coupled hybrid pixel detectors

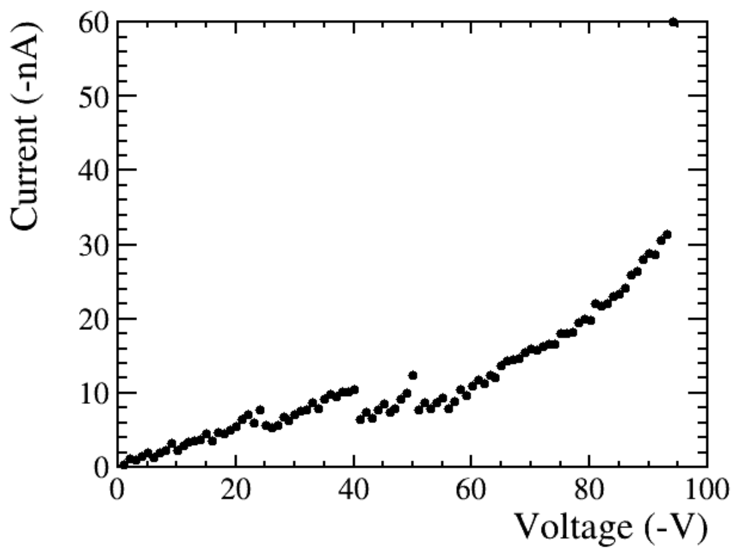
- CLIC vertex detector R&D has to fulfill some quite stringent requirements
  - Low material budget (0.2 % X_0 per layer)
  - Fast signal generation and time-stamping (10 ns resolution)
  - High spatial resolution (single hit precision of 3 μm)

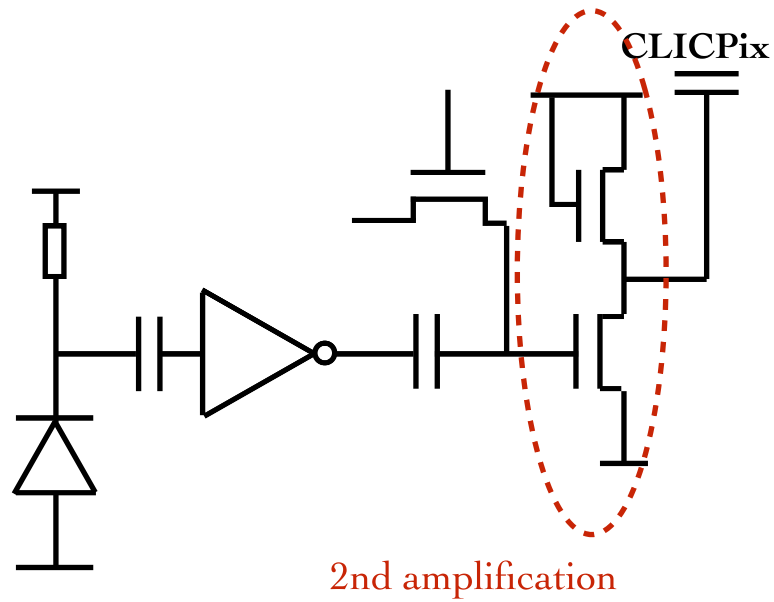
- Previous work involved thin hybrid pixel options
  - Thinned (100 μm) ASICs bump-bonded to thin (100 μm) sensors and operated at high voltage
  - Bonding of such thin (or thinner) samples costly, time-consuming and complex

- Emergence of "active sensors" in the form of HV-CMOS (and related technologies) could allow a more robust, cost-effective and performant route
  - Use industry-standard deep n-well technology in order to create a simple diode with active components
  - Signal amplification allows capacitive coupling between the "sensor" and the readout ASIC - just glue!
  - More complex designs can be implemented to improve performance over standard diodes

HV-CMOS, the CCPDv3 chip

- CCPD (Capacitively Coupled Pixel Detector) version 3 designed by I. Perić
  - 25 µm square pixels, 64 × 64 matrix designed to fit the CLIC prototype readout ASIC
  - 60 columns contain two-stage amplification (negative signal), while 4 columns contain a single amplification stage (positive signal)
  - Relatively simple pixel architecture, limited standalone readout capabilities (analogue output possible from ~few pixels for debugging)
  - Fabrication in 180 nm AMS technology (deep n-well shielding, ~60 V tolerance)

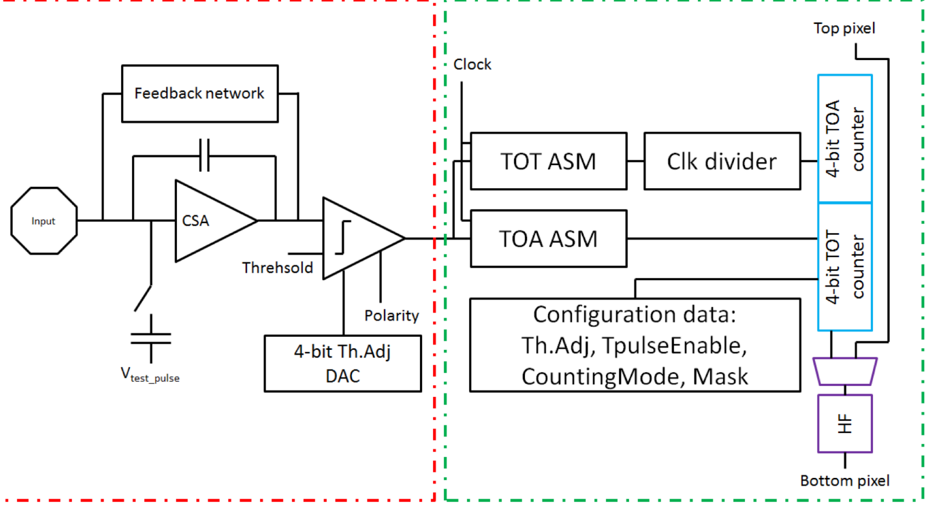




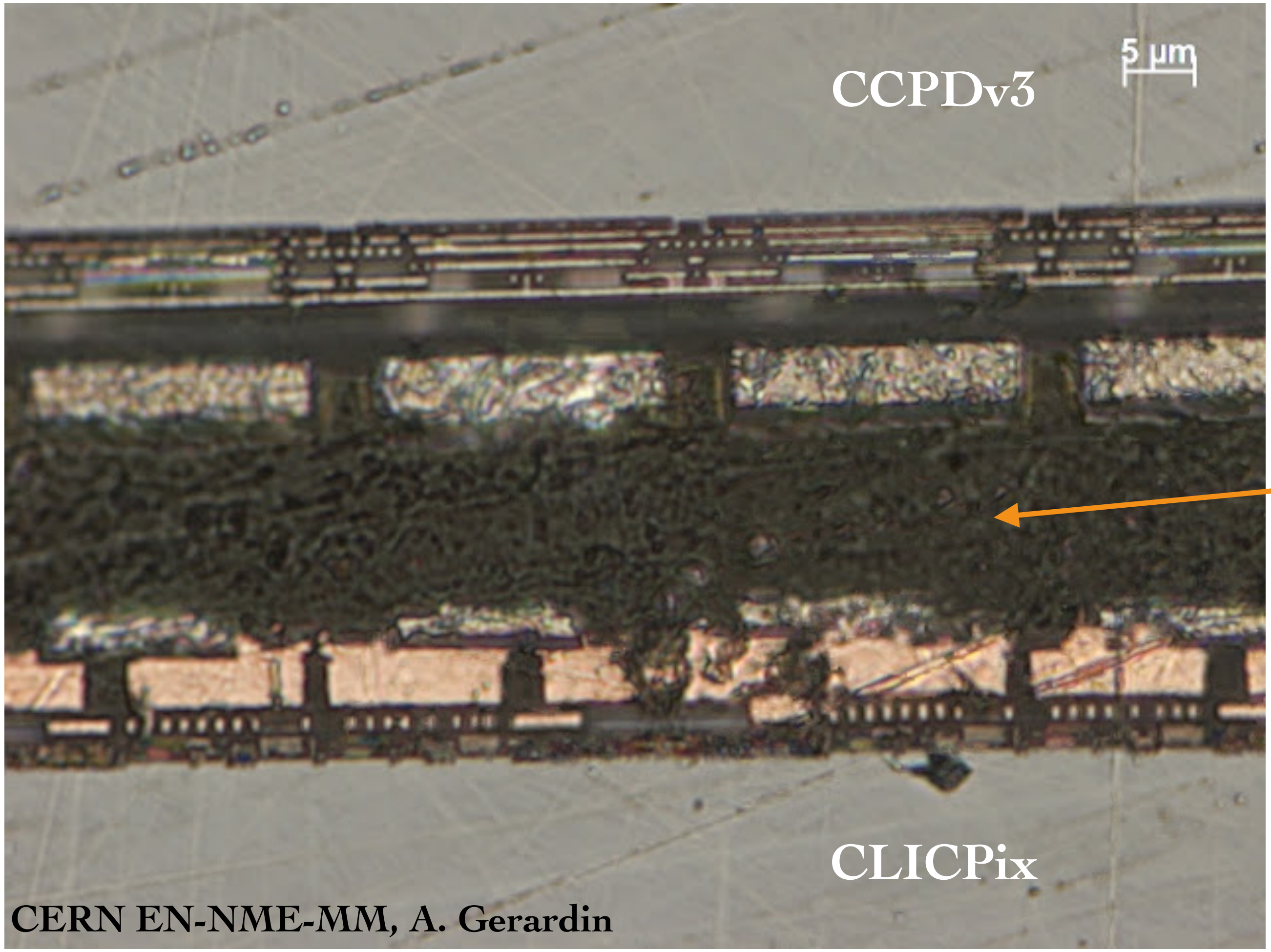
CLICpix

- CLICpix is the prototype readout ASIC designed to fit CLIC vertex detector specifications
  - Manufactured in 65 nm CMOS with small pixel size (25 µm × 25 µm) and containing a matrix of 64 × 64 pixels
  - Two 4-bit counters on each pixel for simultaneous ToT and ToA (or ToT and counting…)
  - Shutter-based data acquisition but with optional on-chip data compression
  - Power pulsing of the front end

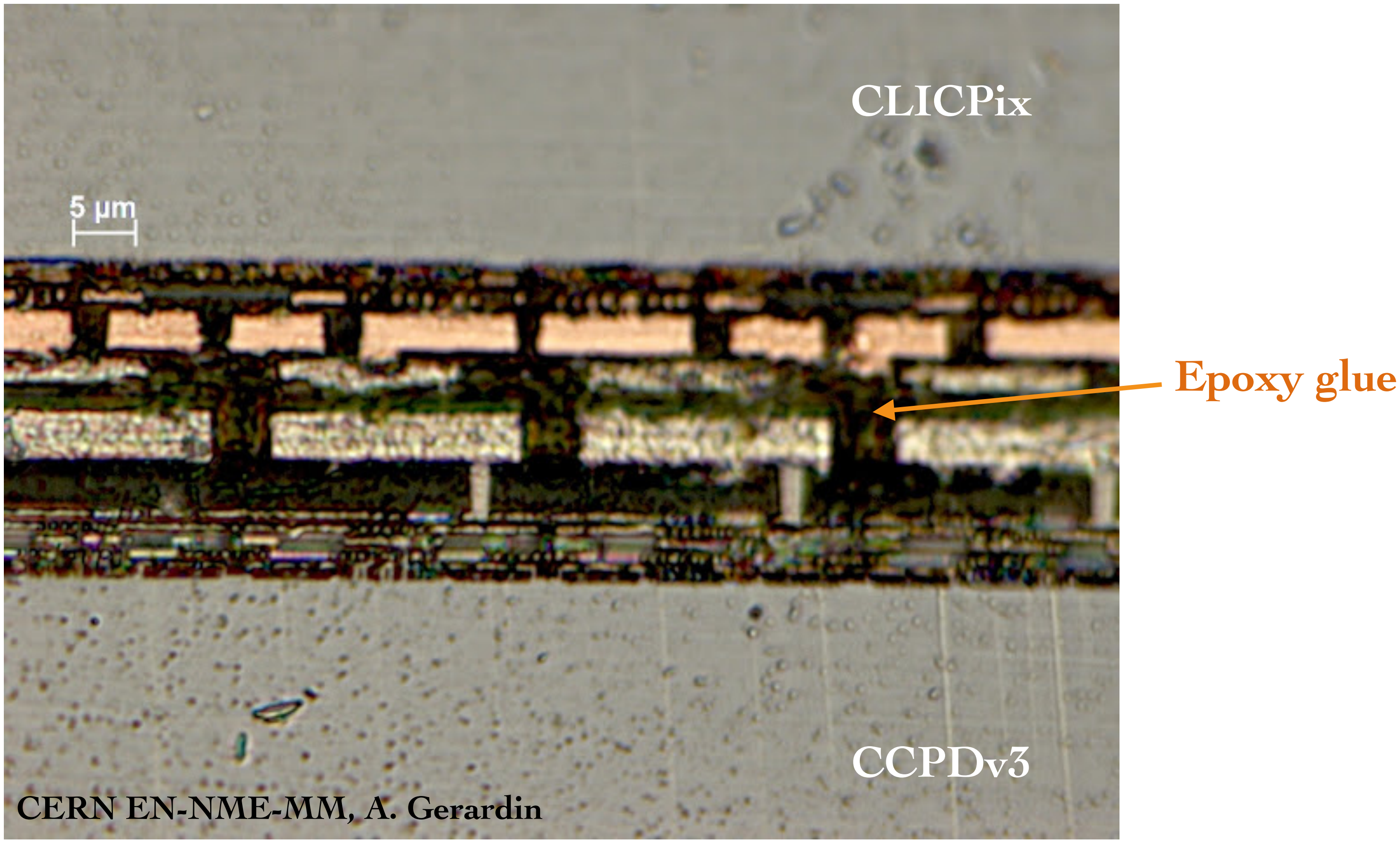
- Known issues:
  - Small overlap of discriminator signal line with CSA input pad => negative pulse injected into the front end when the discriminator starts firing



Assembly

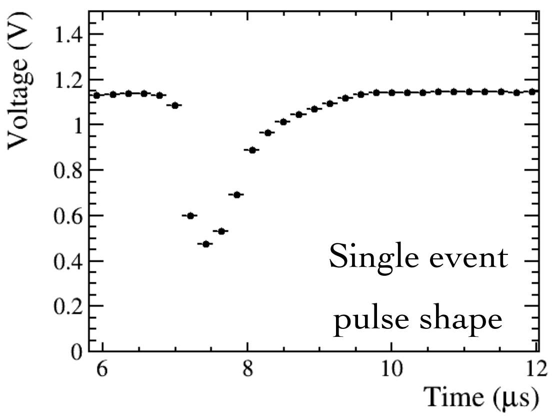


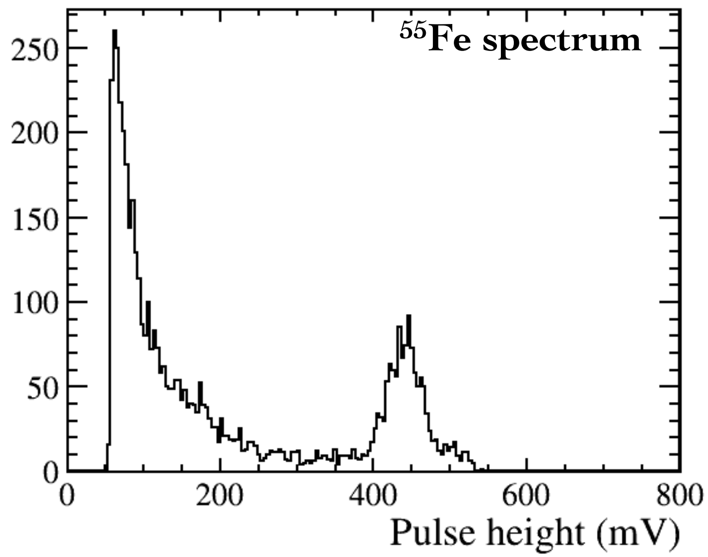
Assembly

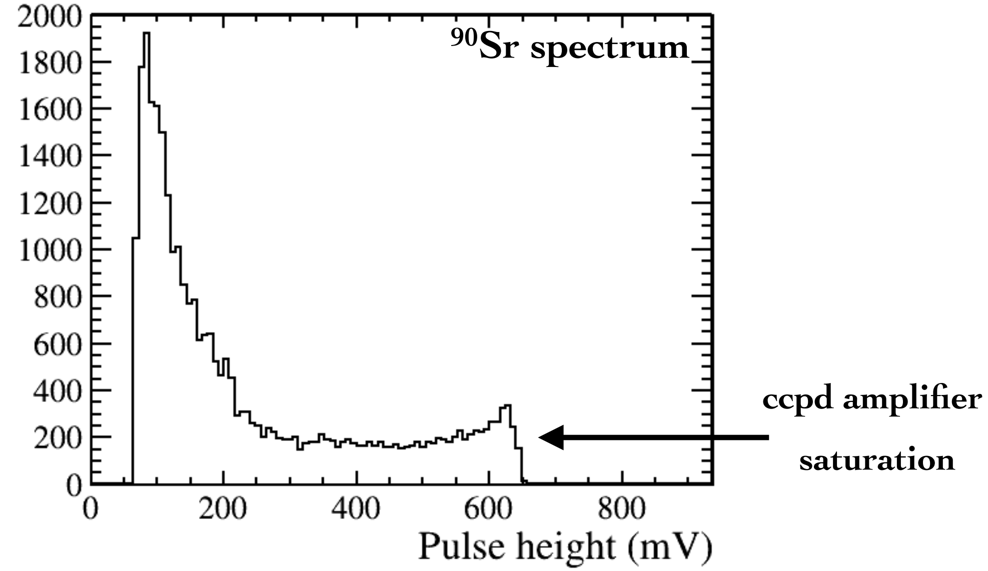


Charge spectra with HV-CMOS

- Lab tests performed on the CCPDv3 using single pixel analogue output to investigate signal shape and charge spectra with sources
  - Preamplifier run at full strength
  - Front-impinging ^{55}Fe on bare CCPDv3 assembly (~6 keV)
  - Back-impinging ^{90}Sr on full CCPDv3 + CLICpix assembly



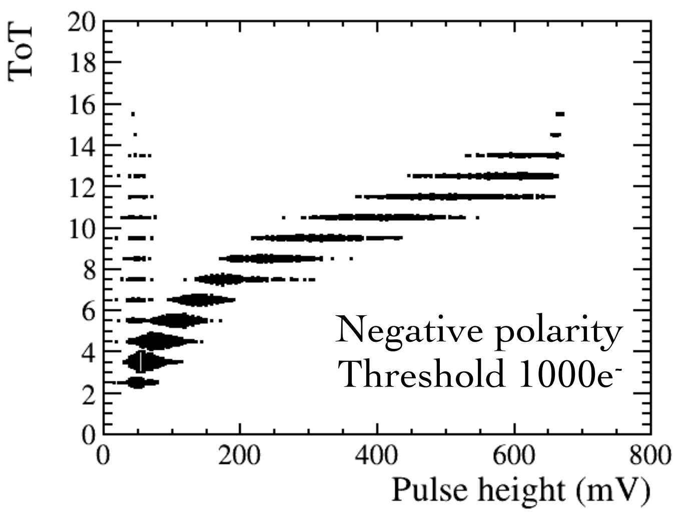


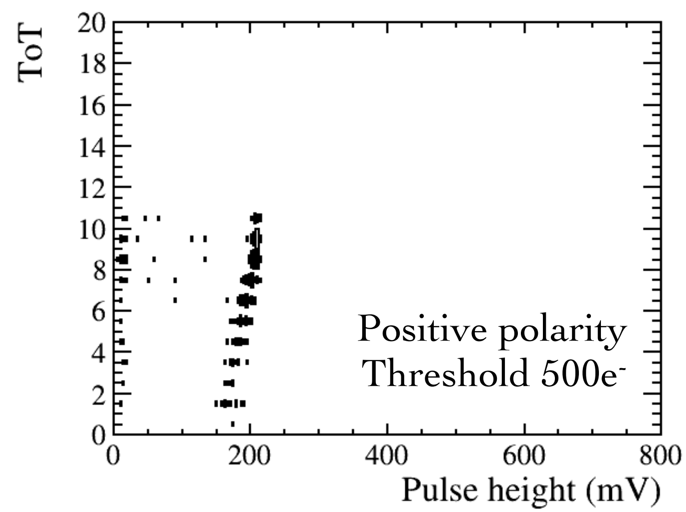


Induced signal in CLICPix

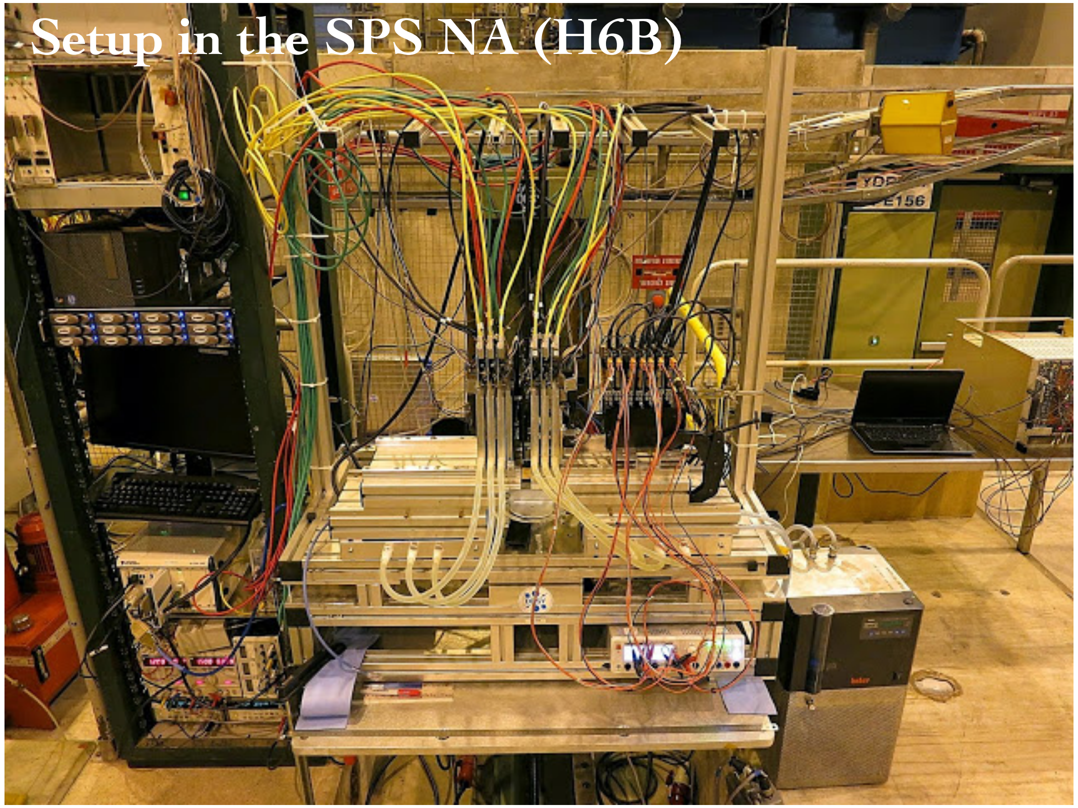
- Analogue output from several pixels on the CCPDv3 can be monitored individually
  - Can take data in parallel with the CLICpix, correlate the pulse shape with the ToT
  - Open shutter, wait for signal on scope, close shutter and read out before subsequent hits
  - Use the 2nd on-pixel counter to veto events with more than 1 hit

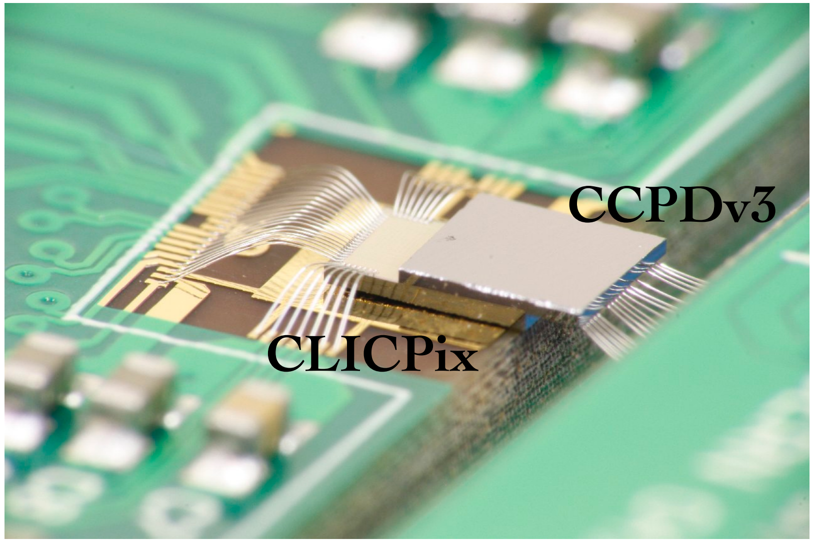
- Clear difference in behaviour!
  - Using the expected value of 1 THL DAC (~10 e^-) can estimate the injected charge ~625 e^-
  - Should see a clear difference in performance…



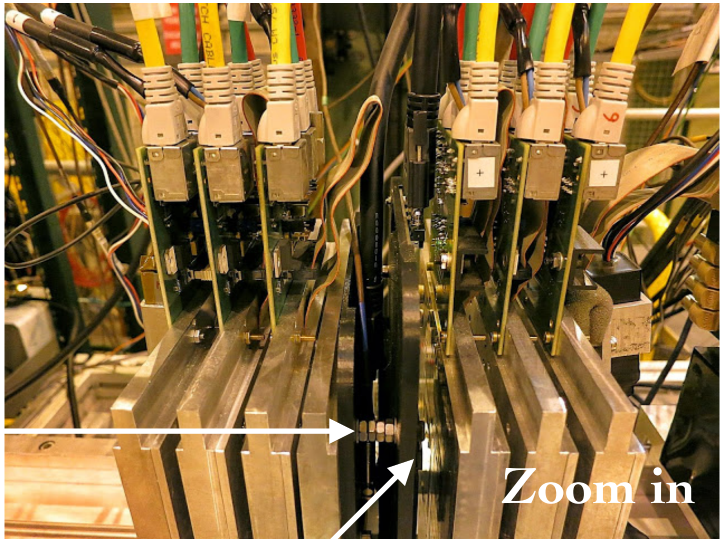


Setup





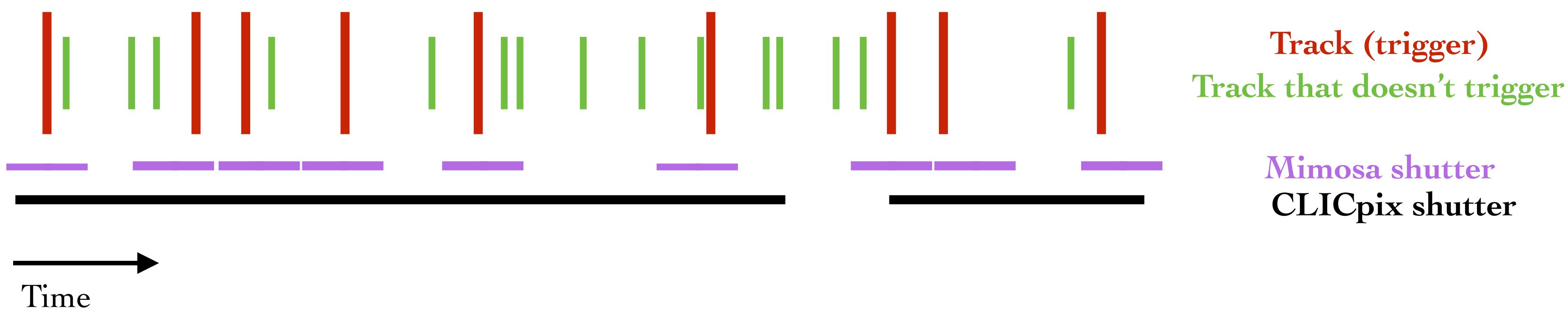
Timepix3



CLICPix

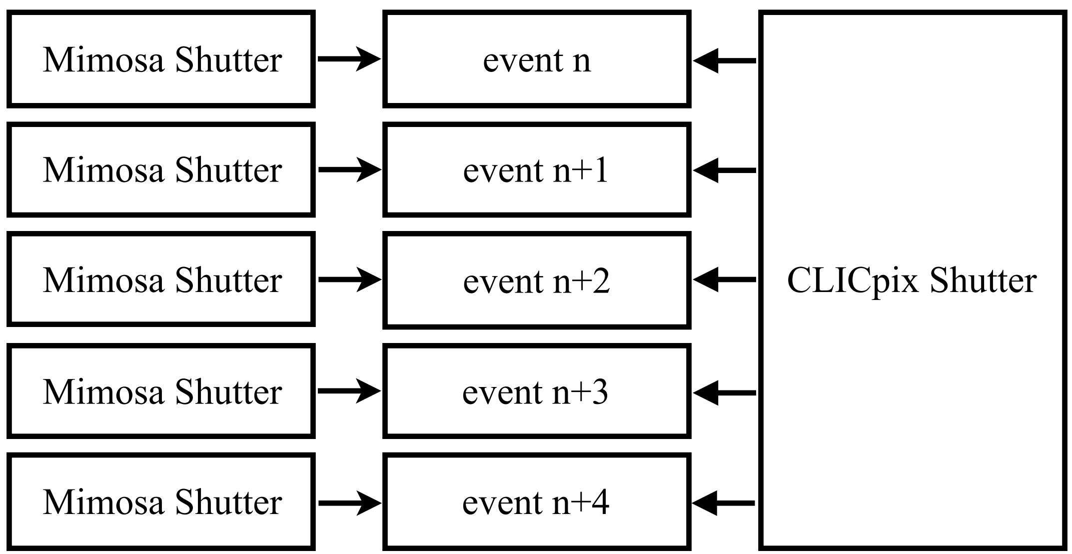
Data taking scheme

- Useful to highlight how data is taken with the telescope
  - Mimosa chips work on their continually rolling shutter
  - Three scintillators are used in conjunction with the FE-I4 region of interest trigger, to trigger Mimosa readout when tracks pass through the telescope + CLICpix assembly (1.6×1.6 mm^2)
  - Several additional tracks may pass through the CLICpix during the Mimosa rolling shutter
  - Due to long readout time of CLICpix (~20 ms) and low occupancy, shutter is held open for several (typically 20-40) Mimosa rolling shutters, until significant number of hits are recorded by CLICpix device



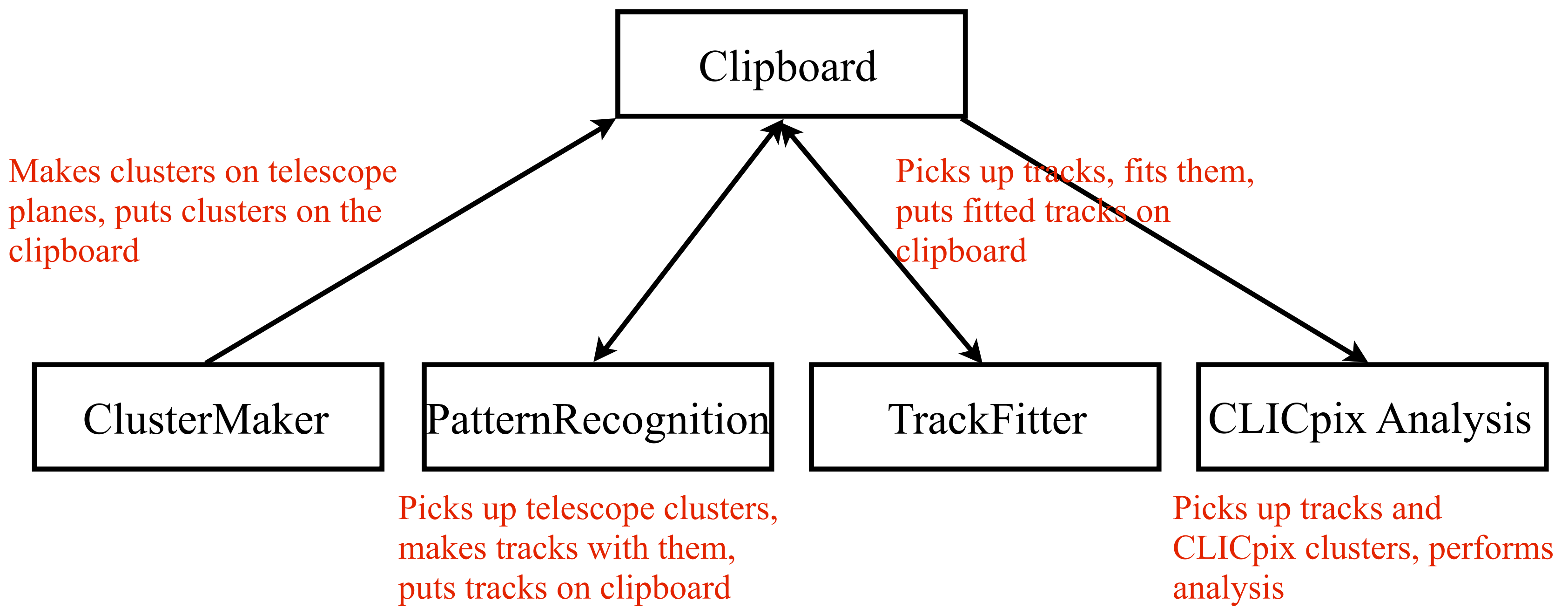
Data taking scheme

- CLICpix producer takes the CLICpix frame (covering many triggers/Mimosa readouts) and copies the data into each event built
  - Each data event is therefore a Mimosa rolling shutter, but contains extra hits from the CLICpix assembly which were acquired over proceeding/succeeding events
  - Track reconstruction environment is reasonably clean - occupancy a factor 20-40 lower than CLICpix
  - Issue with FE-I4 inclusion in the data stream so no time-stamping available offline



Software

- Software used for analysis was the previous LHCb Timepix Telescope analysis code (Due to my arrival in CLIC on testbeam day 1!)
  - Relatively little overhead, lightweight framework
  - Modular code written c++, dependency on ROOT (libraries) and BOOST (headers)
  - Sequential algorithms, with some classes to deal with testbeam objects and a way to pass information between algorithms
  - List of algorithms run event by event

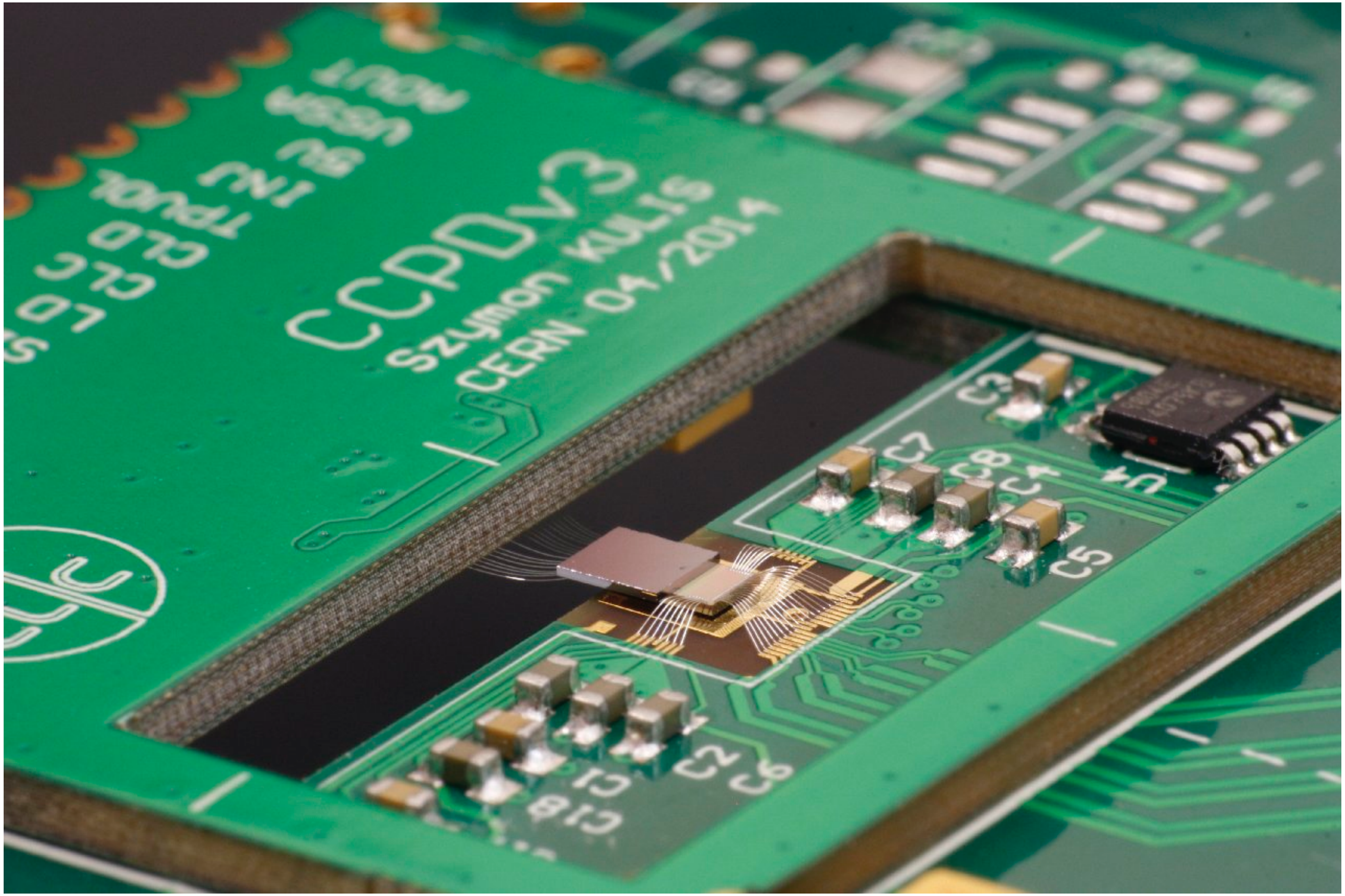


Software

- Data conversion from lcio is not "optimal" - done quickly during beam time
  - Online monitor used to access raw data
  - Raw data converted to Timepix data format
  - Data read in as Timepix data to produce structured event ntuple for running analysis on

- Minimal code changes required to deal with Mimosa and CLICpix
  - Pixel pitch and number of pixels in each direction configurable for each device
  - Tracking method identical to previous Timepix strategy - spatial tracking starting with a seed on the first (upstream) plane
  - Linear track fit sufficient for SPS data taking (unedited)
  - Restricted reconstruction window added - only reconstruct tracks likely to go through the DUT (spatial cut on global XY of seeding clusters)
  - Fast reconstruction - used extensively during beam time to give fast efficiency measurements a few minutes after data taking started

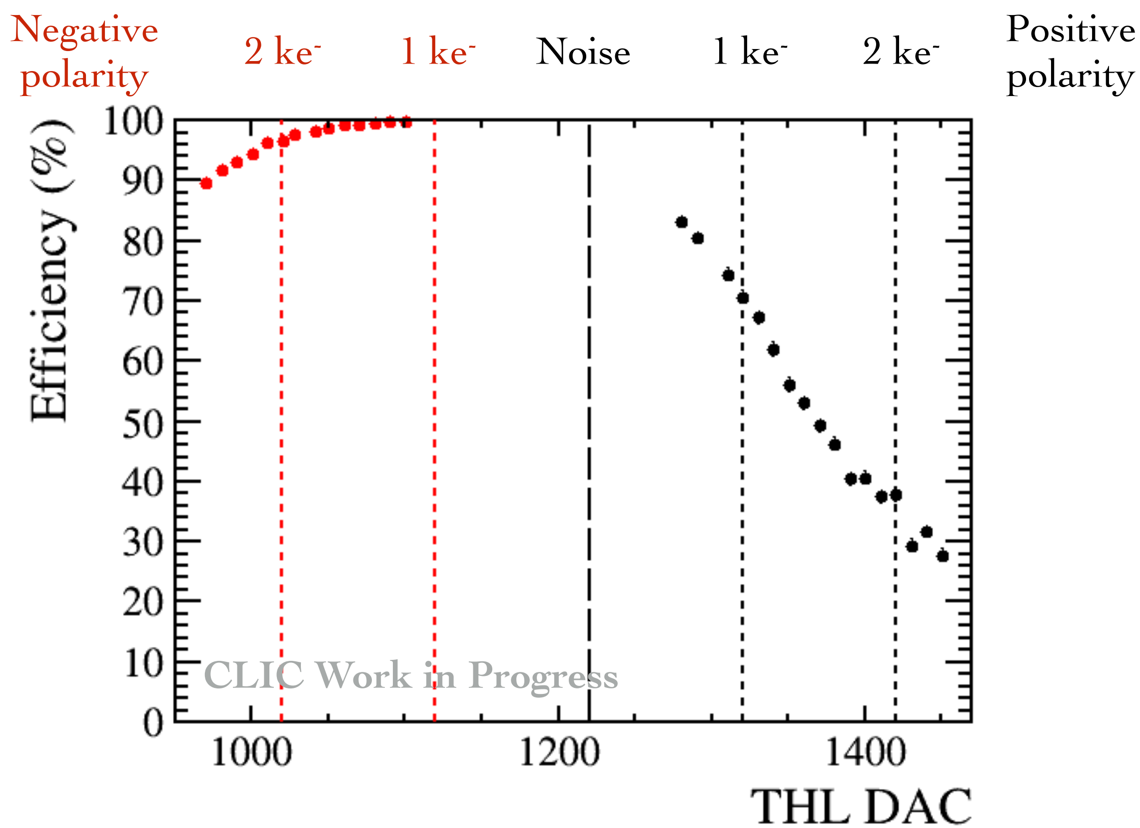
Some results



Threshold scan

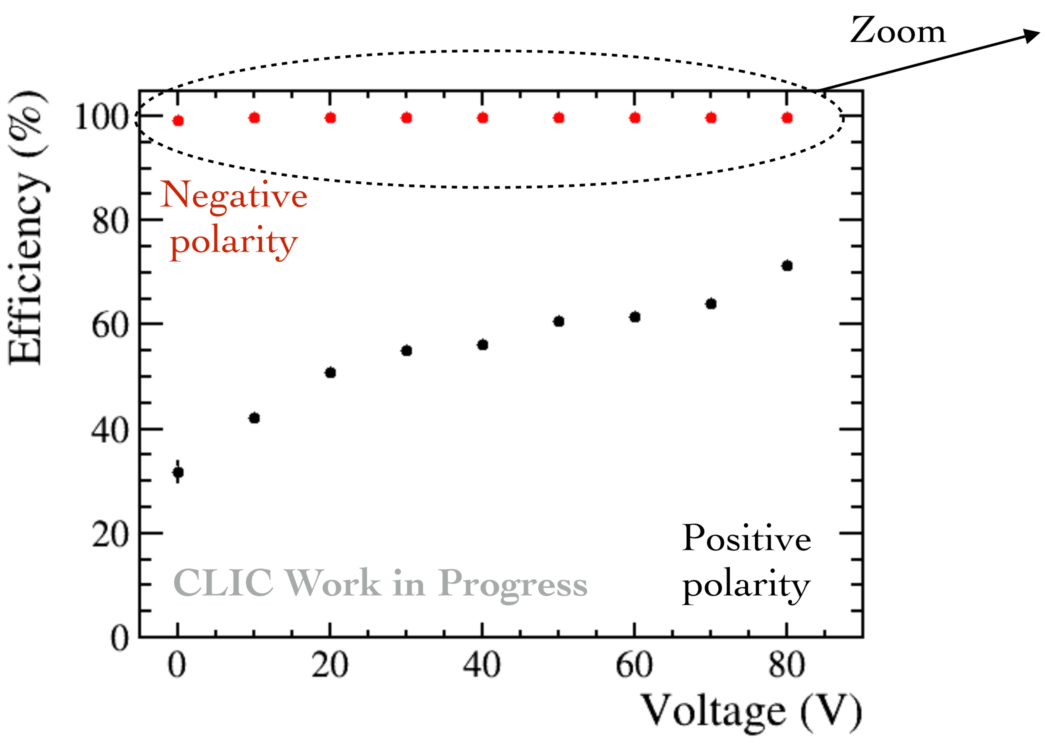
- Efficiency versus threshold for both polarities measured (60 V)
  - Pointing resolution from the telescope estimated < 2 µm

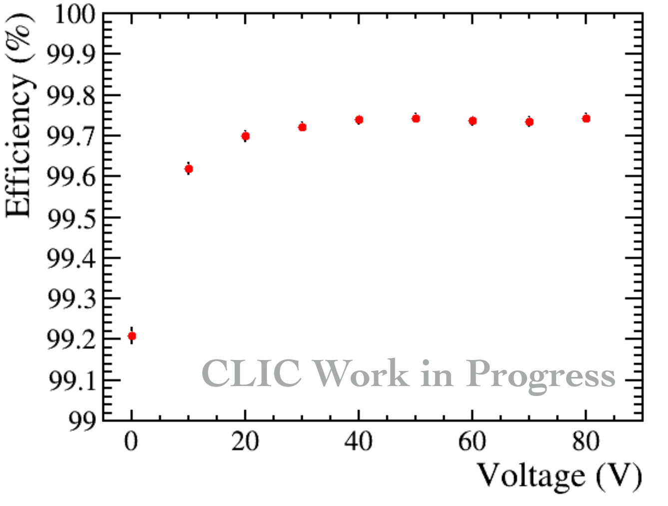
- Clear difference in performance
  - Able to reach high efficiency in negative polarity mode (2-stage amplification) with nomial threshold ~ 1100 e⁻ (roughly 625 e⁻ injected charge)
  - Single amplification pixels suffer from lower signal **and** subtraction of charge, but given fall off in 2-stage pixels it seems likely that with a new chip 500 e⁻ threshold will require 2nd stage



Bias scan

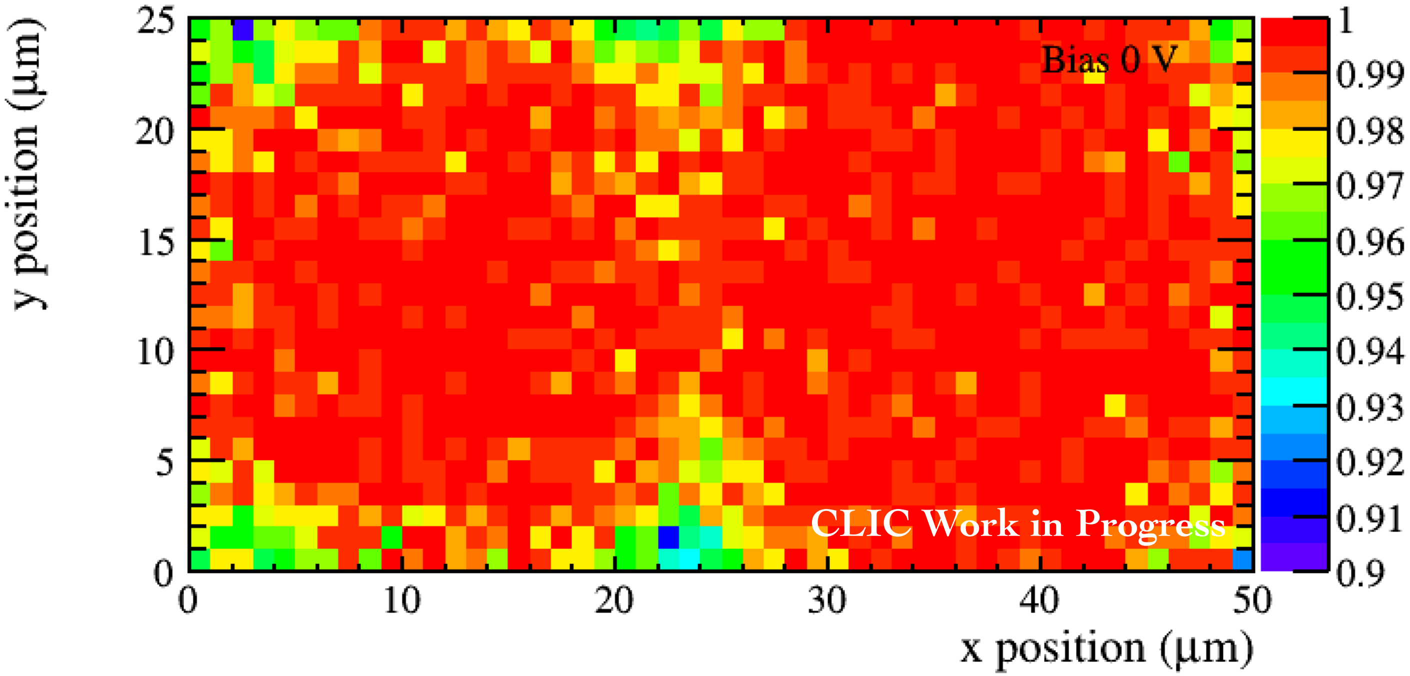
- High efficiency observed in negative polarity mode without bias on the HV-CMOS
  - Large component of collected charge from diffusion? Or large built-in depletion layer?





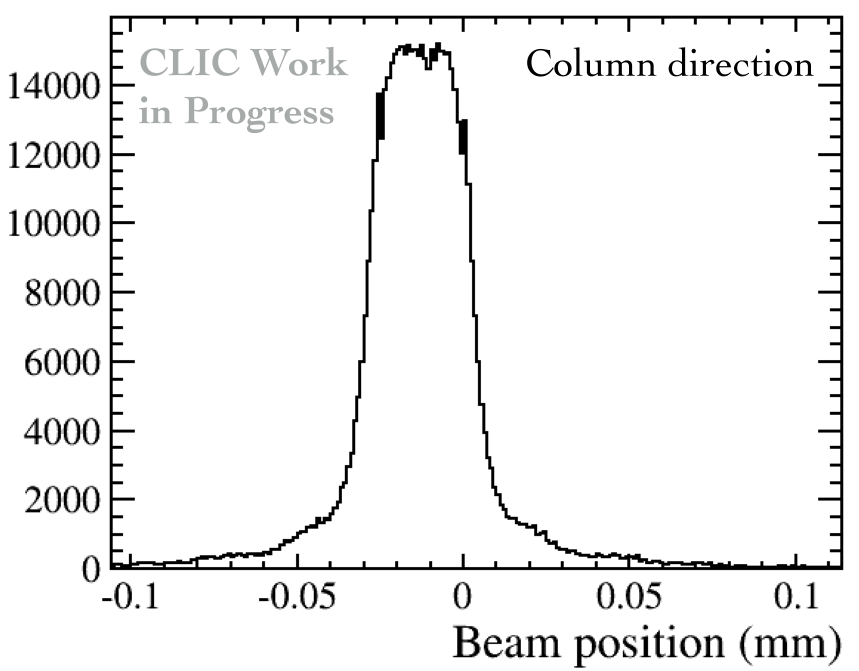
Bias scan

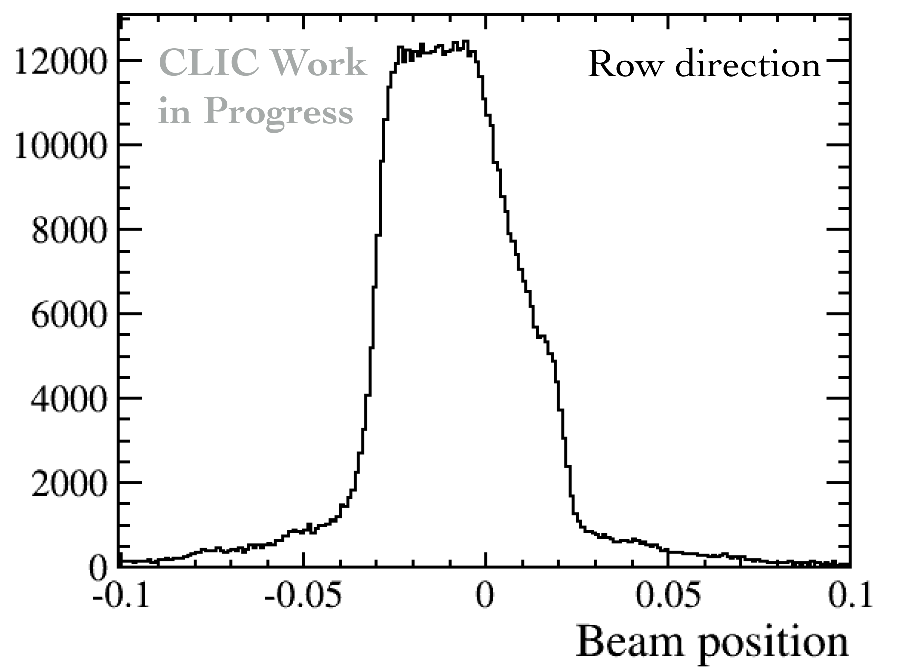
- Can map the variation in efficiency across the 2-pixel unit (to account for differences between odd and even columns - different levels of injected charge)
  - Efficiency loss in the pixel corners for no applied bias
  - Clear difference between odd and even columns



Pixel cross-coupling

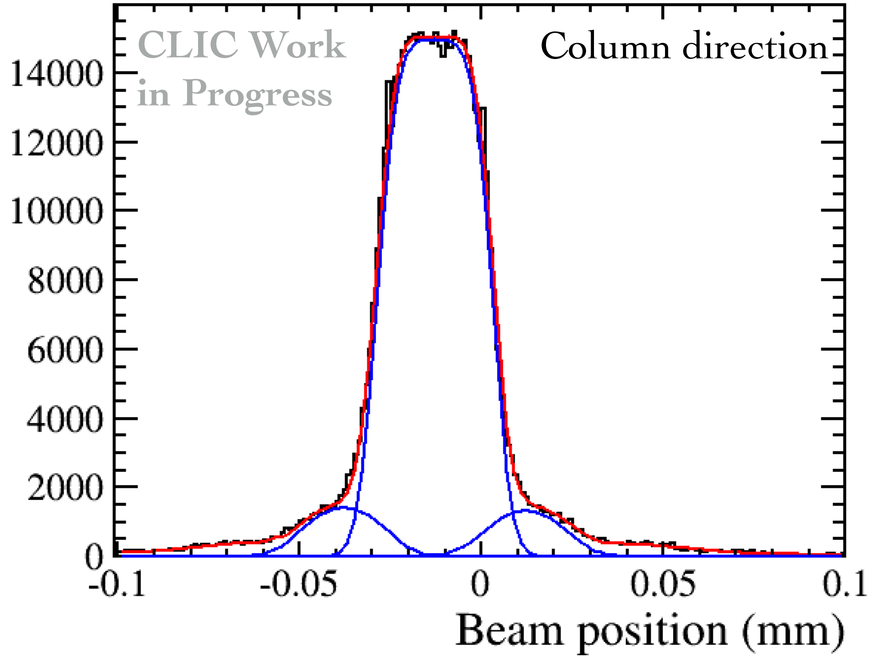
- Now scan the beam across the matrix and observe the behaviour of all pixels
  - Look at when pixel starts seeing charge, and when it stops
  - Ideal function (no charge sharing) should be top hat function with width described by the lateral charge diffusion

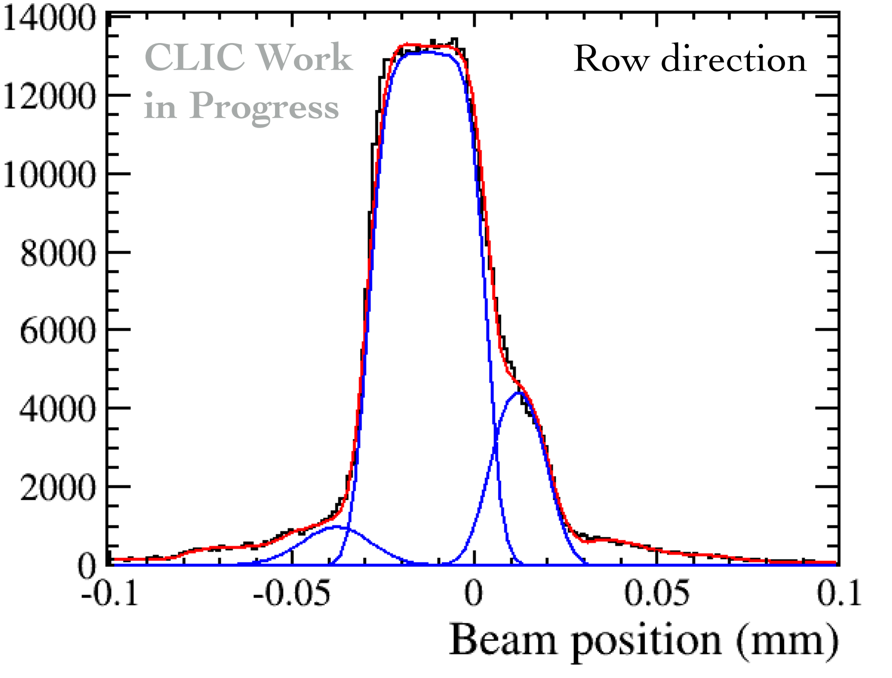




Pixel cross-coupling

- These side contributions appear to come from coupling to the neighbouring CCPDv3 pixels
  - Can fit for the contribution from each
  - In the row direction there is a large contribution from the pixel immediately to the right/left
  - Strongly suggests misalignment in the row direction





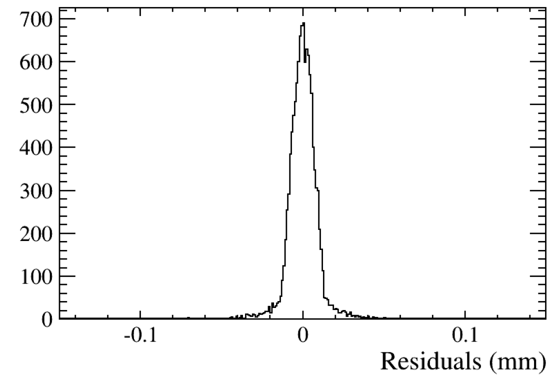
Summary and plans

- Promising early results from capacitively coupled assemblies
  - Simple pixel layout with 2-stage analogue amplification shows high efficiency
  - High efficiency (>99%) without applied bias voltage, 30 - 40 V required to reduce inefficiencies between pixels
- Fabrication steps
  - Larger (and injection-free) version of CLICpix under development
  - New HV-CMOS devices planned on higher resistivity substrate - possible digital version(s) in addition to straightforward 2-stage amplifier
- Studies
  - Measurements of coupling capacitance (and cross-capacitance) due to gluing
  - Beam measurements to evaluate power-pulsing of the front end and timewalk of the assembly
  - Active depth measurements to measure depleted depth and active depth

BACKUP

Beam data - overview

- Full matrix appears responsive
  - Small number of hits observed on positive polarity pixels, due to undershoot of the signal pulse
  - Reconstruction performed and residuals good
  - Slight variation in hits with column?



- Main studies on efficiency, versus bias voltage and threshold