

Test-beam results of CLICpix2 planar sensor assemblies

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CLIC Detector and Physics Collaboration Meeting

01 / 10 / 2020

Content

Introduction

Laboratory characterisation:

- interconnect quality
- calibration measurements

Test-beam results:

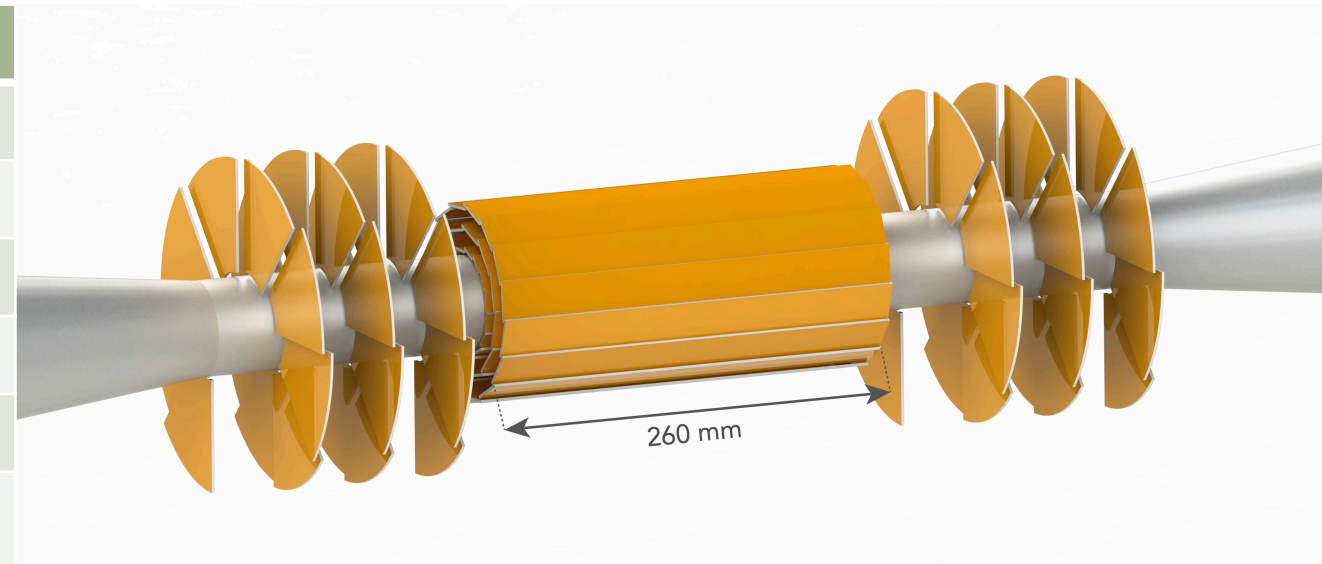
- set-up
- nominal conditions
- threshold scan

Summary

Requirements of the CLIC vertex detector

CLIC physics programme puts strict requirements on the vertex detector of CLICdet.

Parameter	Requirement
Single point resolution	3 μm
Pixel size	$\leq 25 \mu\text{m} \times 25 \mu\text{m}$
Material budget per layer	0.2 % X_0
Timing resolution	5 ns
Hit efficiency	99.7 - 99.9 %
Average power dissipation (using power pulsing)	$< 50 \text{ m W cm}^{-2}$



CLICpix2 hybrid ASIC

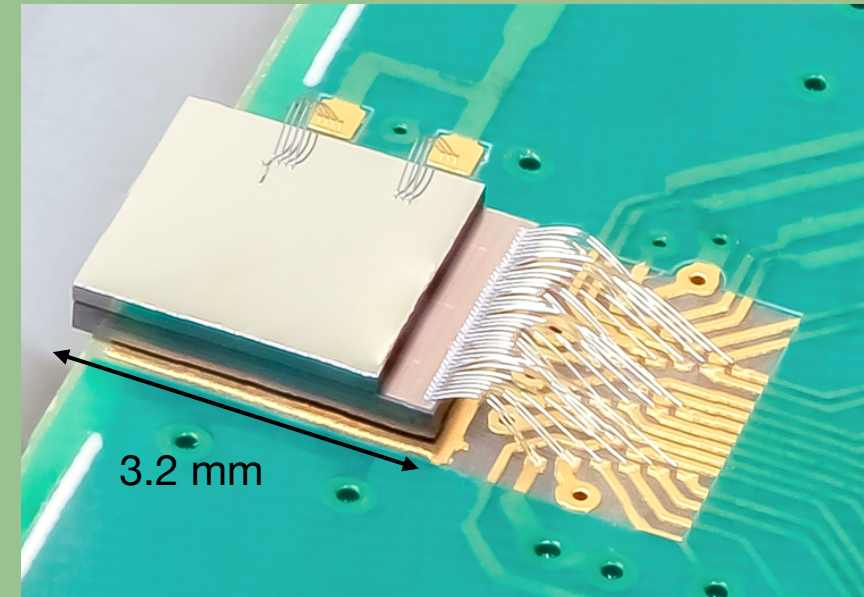
Hybrid technologies currently foreseen for vertex detector.

CLICpix2 readout ASIC:

- 128 x 128 pixels
- Pitch = 25 x 25 μm
- Simultaneous 5bit ToT and 8bit ToA
- Designed in 65nm CMOS process
- Part of Timepix/Medipix family

CLICpix2 ASICs hybridised to active-edge, N-in-P planar silicon sensors

→ bump-bonding challenging for single chips and for small pixel pitch



CLICpix2 readout ASIC bump-bonded to a planar silicon sensor

Laboratory characterisation

Assembly characterisation

Assembly No.	Sensor type	Sensor thickness	Maximum operational bias	Interconnect yield	Conclusion of laboratory testing
9	ADVACAM	100µm	-60V	-	UBM-bump material incompatibility
14	FBK	130µm	-60V	30.8%	68% of pixels unconnected
15	ADVACAM	150µm	-60V	-	UBM-bump material incompatibility
16	FBK	130µm	-60V	99.6%	High interconnect yield
18	ADVACAM	100µm	-	-	Unresponsive due to ASIC damage
19	FBK	130µm	-60V	97.8%	2.2% pixels have significant noise
20	FBK	130µm	-60V	97.6%	High interconnect yield
21	ADVACAM	100µm	-50V	39.2%	UBM-bump material incompatibility
22	ADVACAM	50µm	-0.4V	-	UBM-bump material incompatibility

- All identified interconnect issues communicated to the manufacturer for processes optimisation.
- Clear proof of concept, study limited by number of ASIC and sensors.

Calibration

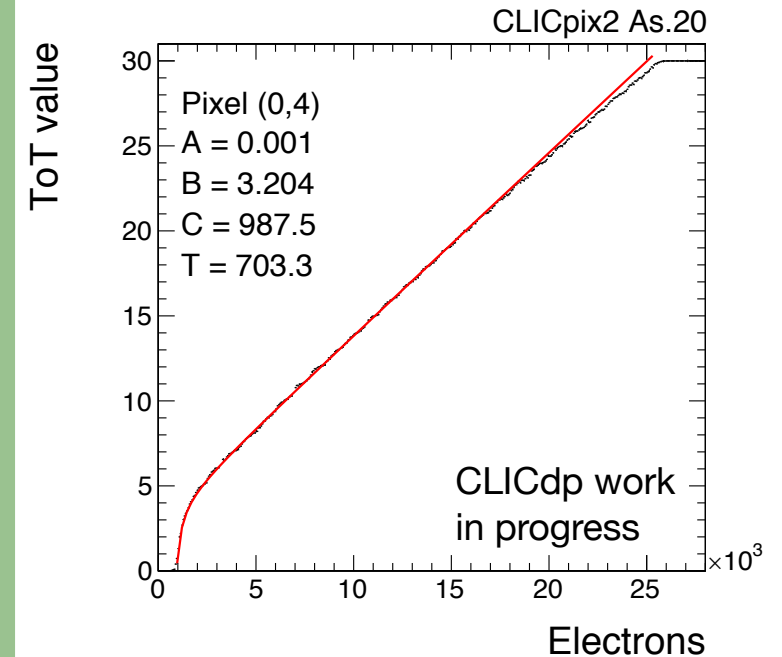
Want to compare amount of energy deposited in the sensor to theoretical expectations, simulations, or other pixel devices

→ requires the units of charge and threshold to be calibrated into physical units.

- Threshold DAC-to-electrons calibration carried out using X-ray fluorescence measurements.
- ASIC's mirrored column design causes differences in parasitic capacitance of odd and even columns, ∴ separate value.

Assembly	THL calibration even	THL calibration odd
16	18.1 ± 0.2	18.5 ± 0.2
20	18.7 ± 0.2	19.3 ± 0.2

- Per-pixel Time-over-Threshold units calibration into electrons using test-pulse injection measurements.
- Each ToT calibration curve parameterised with surrogate function fit.

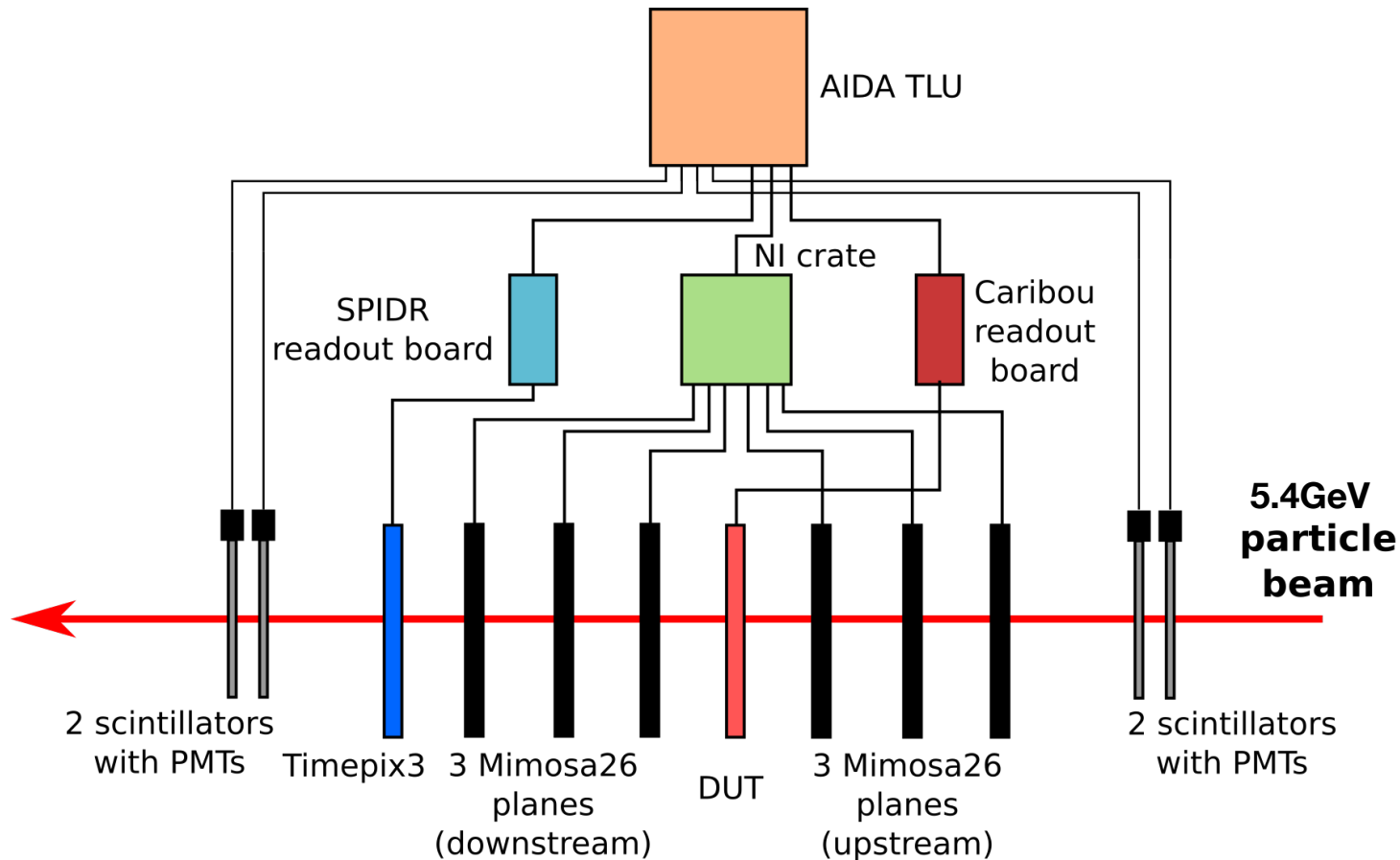


$$\text{surrogate function} \\ = Ax + B - \frac{C}{x - T}$$

*ToT calibration curve of pixel 0,4
of CLICpix2 planar assembly 20.*

Test-beam results

DESY test-beam set-up



Schematic of the EUDET test-beam telescope used at DESY.

Telescope:

- 6 Mimosa26 planes
- up to 4 coincident scintillators for trigger signals via a TLU
- Additional Timepix3 for track timing reference

DAQ using EUDAQ2 framework

CLICpix2 DUT operated in free running mode with fixed shutter length

Test-beam data analysis used Corryvreckan reconstruction software

Thank you to the DESY test-beam maintainers for their help during test-beam measurements.

Results at nominal conditions

Assembly:

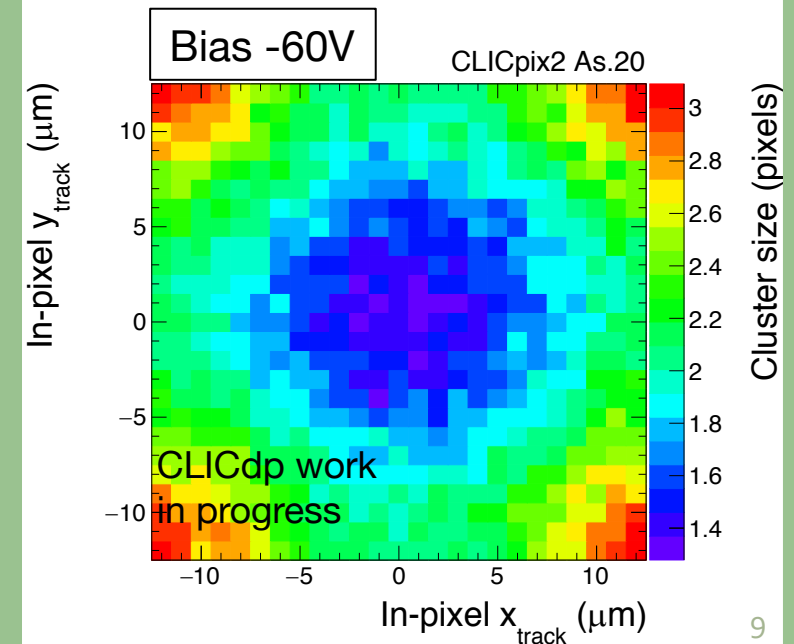
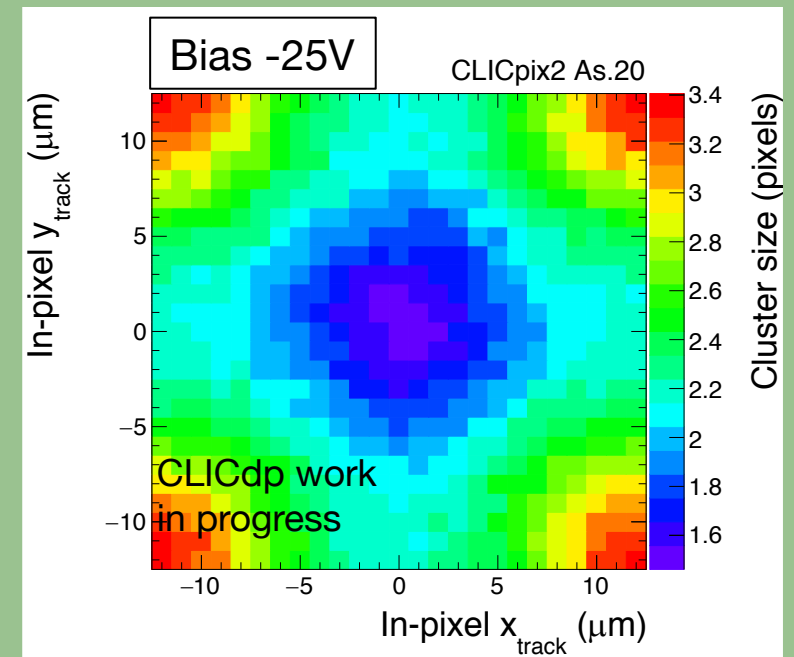
- Sensor 130 μm thickness
- Pixel pitch 25 x 25 μm

Nominal:

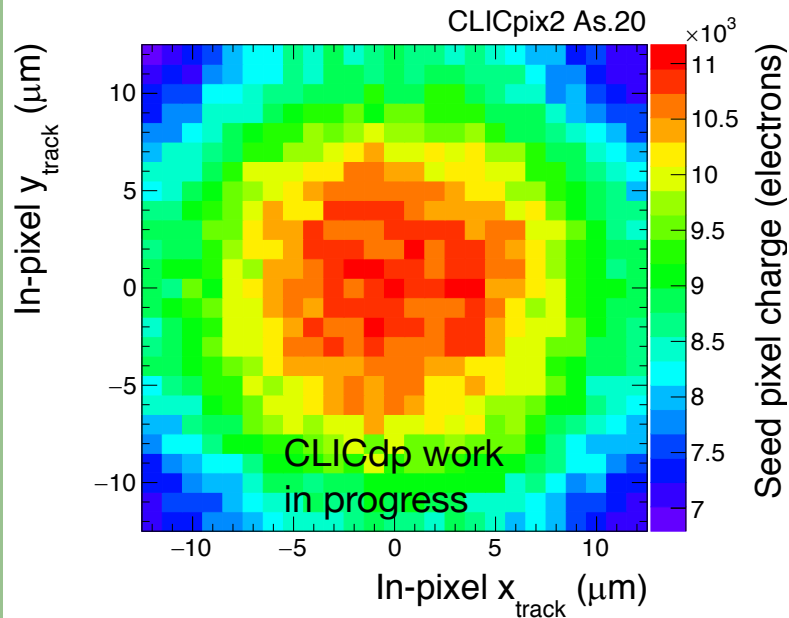
- Threshold (893 +/- 9) electrons
 - lowest noise-less operating threshold
- Applied bias voltage of -25V
 - found to be the optimal bias voltage for charge sharing

Top: In-pixel associated cluster charge, applied bias voltage of -25V.

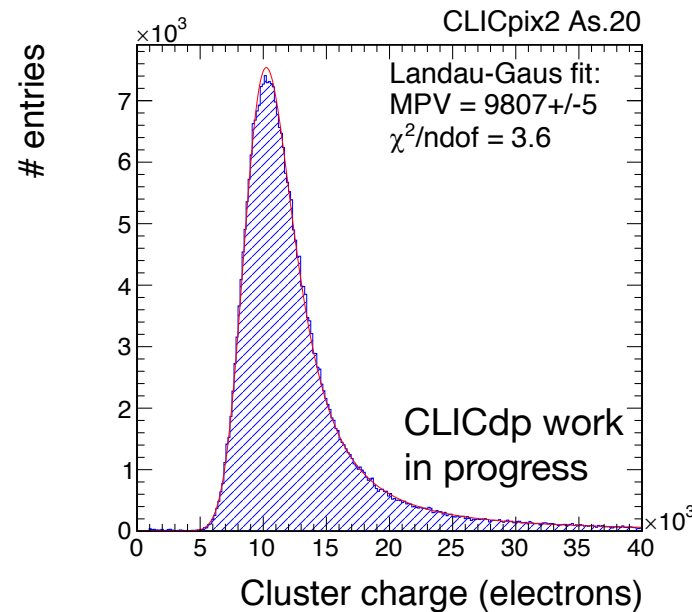
Bottom: In-pixel associated cluster charge, applied bias voltage of -60V.



Results at nominal conditions



In-pixel charge of associated cluster seed pixel.



Associated cluster charge, with a Landau-Gaus fit function.

Cluster charge MPV occurs at 9807 electrons.

What do we theoretically expect?

Assume 73.7 electrons created per μm of silicon

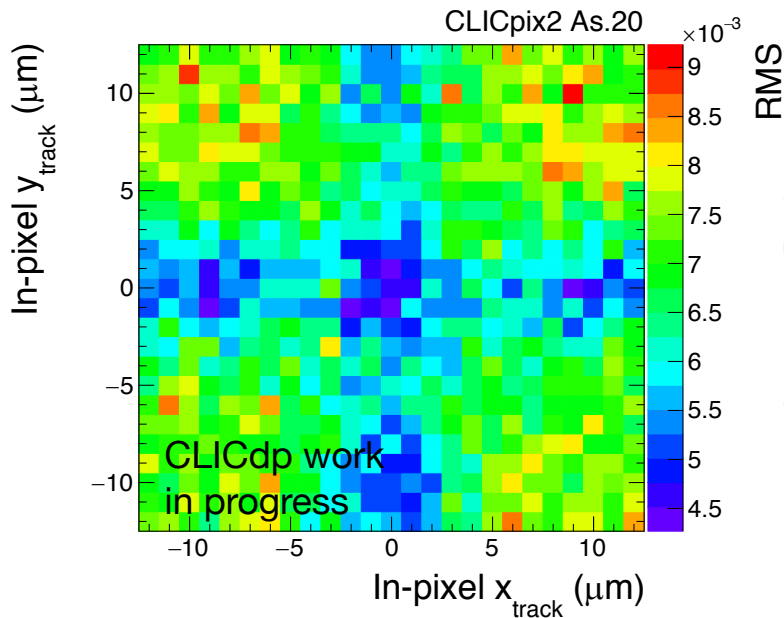
using equation from doi:10.1103/RevModPhys.60.663

Sensor thickness is 130 μm

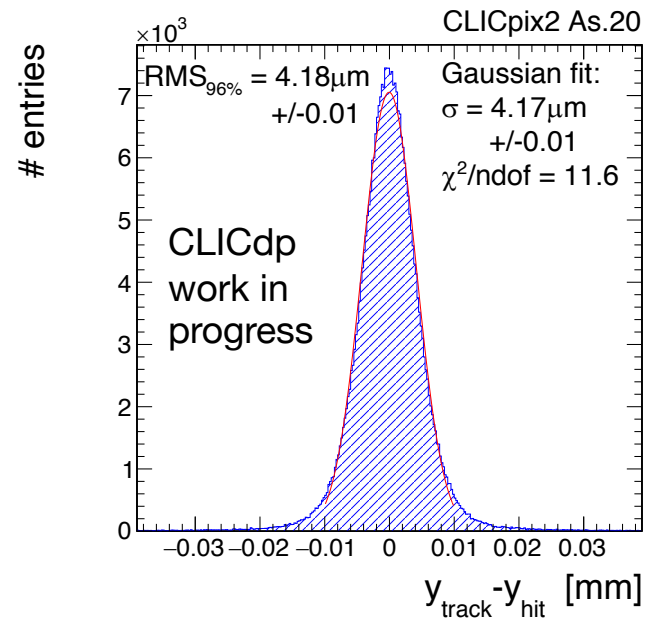
Deposited charge = 130 * 73.7
= 9593 electrons

→ Measured value is within 2% of theoretical value.

Results at nominal conditions



In-pixel combined resolution.



Spatial residual along the Y axis, with a Gaussian fit function.

Note: high χ^2 due to non-Gaussian tails from δ -electrons

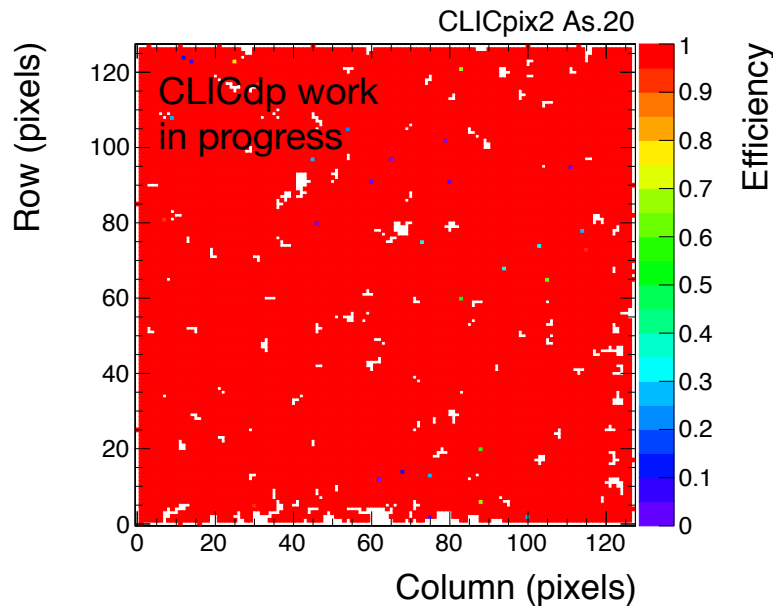
Spatial residual width is $4.17\mu\text{m}$

$$\sigma_{\text{residual}} = \sqrt{\sigma_{\text{telescope}}^2 + \sigma_{\text{intrinsic}}^2}$$

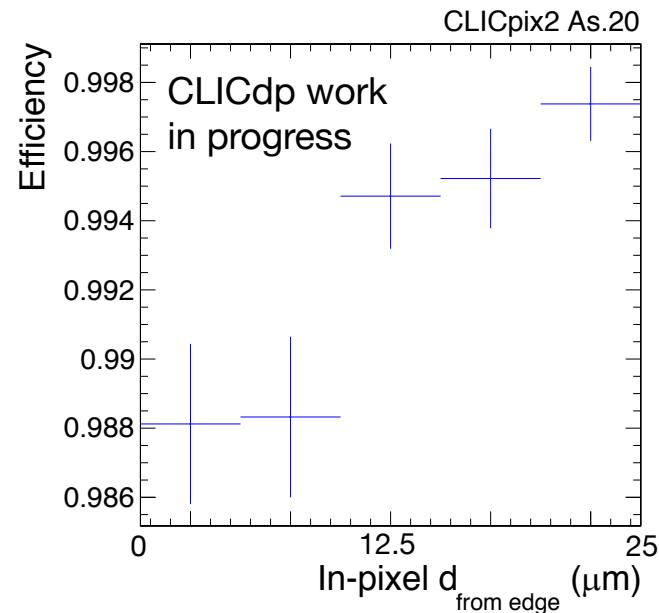
Telescope resolution $2.64\mu\text{m}$ for this dataset from Monte-Carlo simulation \therefore :

$$\sigma_{\text{intrinsic}} = 3.2\mu\text{m}$$

Results at nominal conditions



2D efficiency map



Efficiency as a function of distance from the edge

Total efficiency at nominal conditions of $(99.96 \pm 0.01 - 0.00)\%$

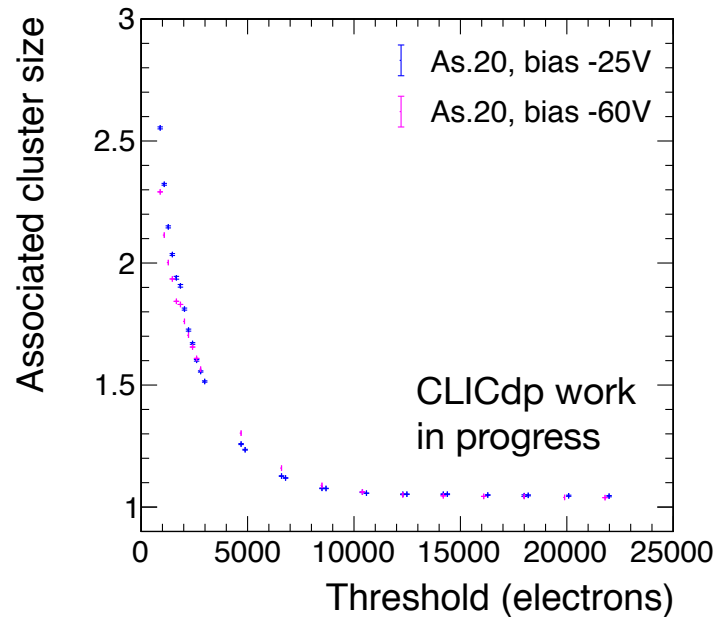
Note: efficiency value does not take masked or unresponsive pixels into account, which show as white areas on the pixel matrix

See efficiency across the matrix is even with random outliers

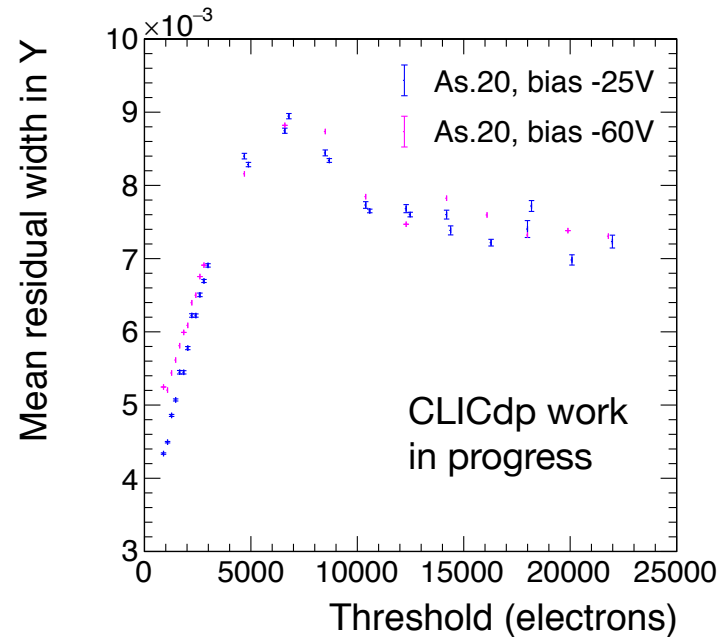
Right: histogram of efficiency as a function of distance from the matrix edge, spanning one pixel pitch.

Can see slight decrease in efficiency towards the matrix edge, but still at a high overall value.

Results of threshold scan



Associated cluster size as a function of threshold



Mean residual width in Y as a function of threshold

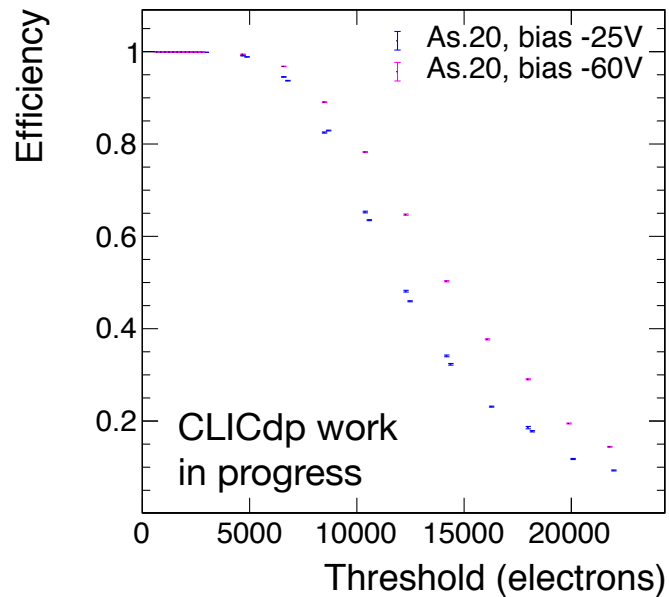
Analysed test-beam data of a threshold scan for two bias voltages

Cluster size greatly reduces with threshold: approximately only have single pixel clusters after ~8.5ke

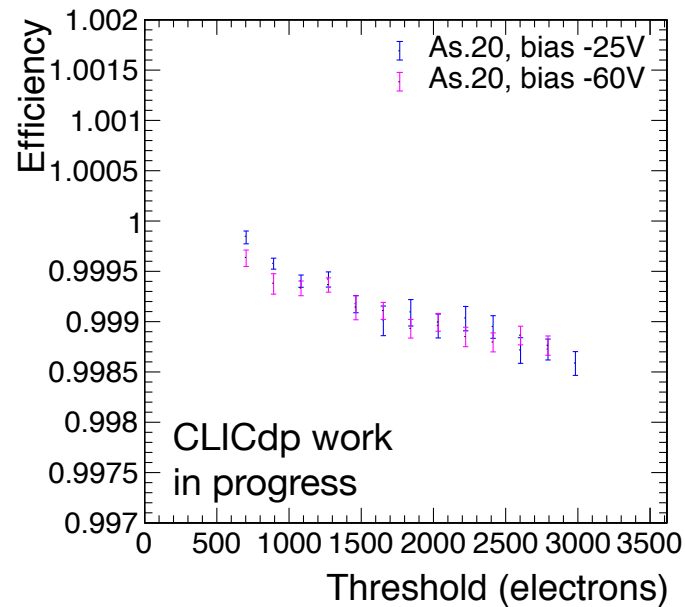
Can see the effect in residual width. For threshold $< \sim 7\text{ke}$: increase in residual width as charge sharing reduces

For threshold $> \sim 7\text{ke}$: decrease in hit detection efficiency at pixel borders causes reduction in width.

Results of threshold scan



Efficiency as a function of threshold



Efficiency as a function of threshold, zoomed into the low threshold region

Efficiency decreases faster for a bias voltage of -25V as there is more charge sharing at this bias.

High-efficiency plateau (>99.7%) at thresholds up to ~5ke.

→ large operational margin with high efficiency

Summary

- CLICpix2 ASICs bump-bonded to planar active-edge sensors
- Laboratory testing:
 - interconnect quality up to 99.6%
 - threshold and ToT calibration performed
- Test-beam analysis of assembly with 130 μ m sensor:
 - intrinsic spatial resolution of 3.2 μ m at nominal conditions
 - efficiency of 99.96% at nominal conditions
 - high edge efficiency
 - threshold scan shows large operational margin with high efficiency



Part of the measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654168



Back-up slides

References

- CLICpix2 lab and testbeam studies:

Morag Williams, IPRD conference 2019: *R&D for the CLIC Vertex and Tracking detectors* (2020), DOI: [10.1088/1748-0221/15/03/C03045](https://doi.org/10.1088/1748-0221/15/03/C03045).

CLIC and CLICdp collaboration, *Detector Technologies for CLIC* (2019), DOI: [10.23731/CYRM-2019-001](https://doi.org/10.23731/CYRM-2019-001).

Single chip bump-bonding performed by IZM

1. Deposition of a thick photoresist onto the matrix.
2. Lithography to create a mask layer of the required pattern, such that the solder bumps are the correct size for the pixel pitch and separated by $25\text{ }\mu\text{m}$.
3. Galvanic deposition of the SnAg solder.
4. Removal of the photoresist and etching of any UBM outside bumps.
5. Reflow of solder bumps into a sphere-like shape at high temperature.
6. Removal of ASICs from carrier wafer.

Summary of CLICpix2 planar sensor assemblies produced

Assembly number	Serial number	Sensor producer	Active edge	Guard ring (GR)	Sensor thickness	UBM
9	ADV100-S4	Advacam	Continuous	Grounded GR	100 μm	NiAu
14	FBK-398-01	FBK-CMM	Staggered	No	130 μm	TiWCu
15	ADV150-S9	Advacam	Continuous	Grounded GR	150 μm	NiAu
16	FBK-398-02	FBK-CMM	Staggered	No	130 μm	TiWCu
18	ADV100-S5	Advacam	Continuous	No	100 μm	NiAu
19	FBK-398-03	FBK-CMM	Staggered	No	130 μm	TiWCu
20	FBK-398-04	FBK-CMM	Staggered	No	130 μm	TiWCu
21	ADV100-S3	Advacam	Continuous	Floating GR	100 μm	NiAu
22	ADV050-S2	Advacam	Continuous	Floating GR	50 μm	Pt

Summary of equalisation and noise measurements of CLICpix2 planar sensor assemblies

Assembly number	Sensor type	Sensor thickness (μm)	Maximum operational bias voltage (V)	Baseline (DAC)	Operational threshold (DAC)	Threshold dispersion (DAC)	Average noise (DAC)	Number of masked pixels
9	Advacam	100	-60	1187	1295	4.5	16.0	1
14	FBK-CMM	130	-60	1200	1250	2.4	5.4	50
15	Advacam	150	-60	1166	1235	3.6	8.0	71
16	FBK-CMM	130	-60	1148	1190	2.9	7.6	19
19	FBK-CMM	130	-60	1113	1190	3.1	7.8	270
20	FBK-CMM	130	-60	1244	1290	3.0	7.8	32
21	Advacam	100	-50	1184	1285	3.6	12.6	23
22	Advacam	50	-0.4	1183	1335	3.7	16.9	135

Definition of categories used to assess interconnect yield

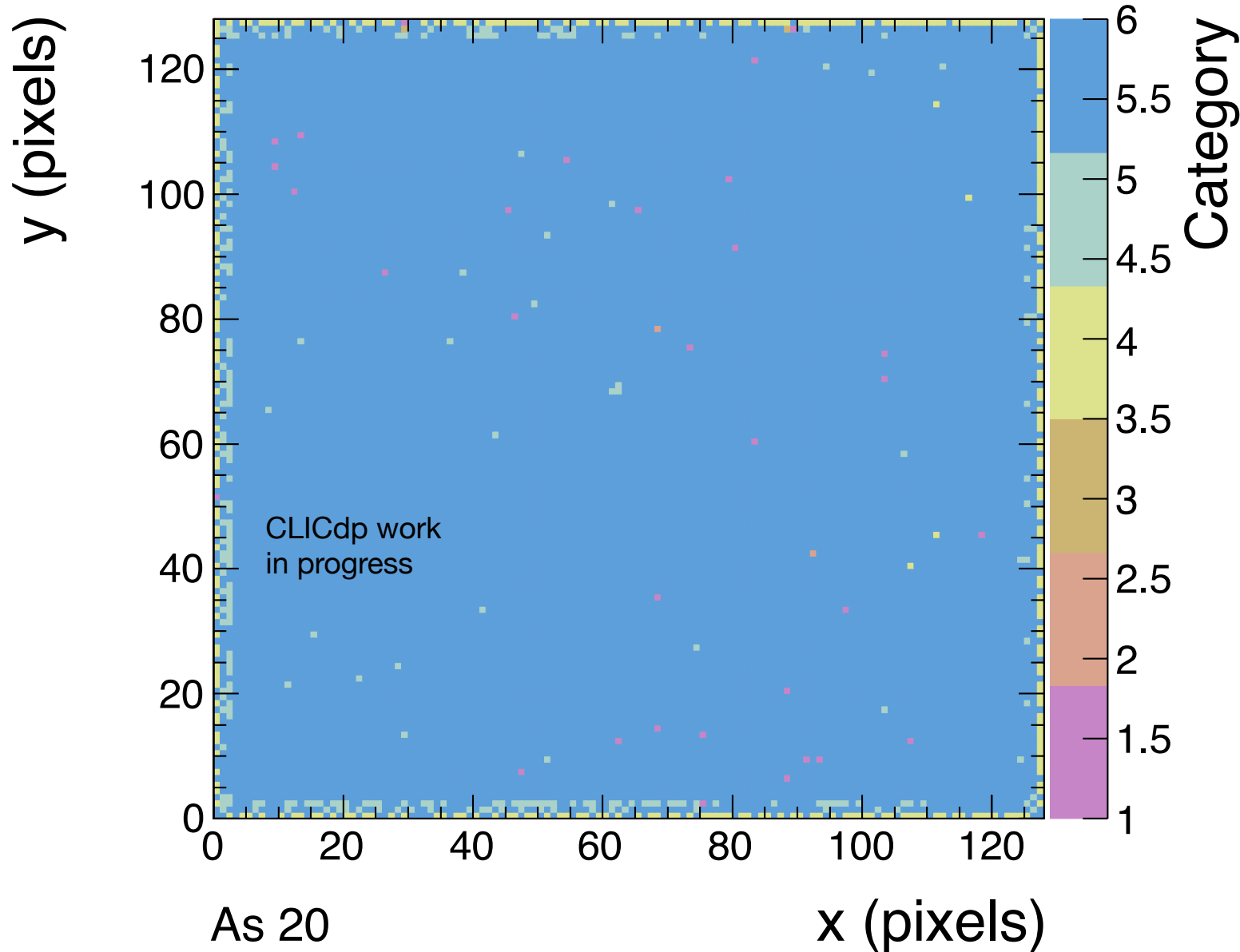
1. Masked: Pixels of this category have been masked by the user due to observed large noise or during threshold equalisation as discussed in Subsection 4.2.3. No information is gathered from these pixels, therefore their response cannot be characterised further.
2. Unresponsive: Pixels in this category responded less than 10% of the time to direct charge injection.
3. Shorted: These pixels record unexpected hits when one or more neighbouring pixels are pulsed $\geq 90\%$ of the time, indicating an electrical connection between pixels caused by an interconnect issue.
4. Bonding or sensor issues: Pixels in this category were found to be low rate during source exposure but have the expected test pulse performance. These are said to have bonding or sensor issues, as these two causes could not be decoupled with the available information.
5. High rate: This set of pixels were found to have a high rate during a source measurement. This could be due to noise, electrical shorts, or a non-linear charge sharing region.
6. Expected response: The expected responses are seen in all tests for this pixel: normal test pulse response, normal rate from source measurement, no other issues identified.

Summary of pixel categorisation of CLICpix2 planar sensor assemblies

CLICpix2 assembly:	Assembly 14	Assembly 16	Assembly 19	Assembly 20	Assembly 21
Sensor type and thickness:	FBK-CMM, 130 µm	FBK-CMM, 130 µm	FBK-CMM, 130 µm	FBK-CMM, 130 µm	Advacam, 100 µm
Category 1: Masked	50 (0.31%)	19 (0.12%)	270 (1.65%)	32 (0.20%)	23 (0.14%)
Category 2: Unresponsive	12 (0.07%)	157 (0.96%)	10 (0.06%)	2 (0.01%)	0 (0.00%)
Category 3: Shorted	23 (0.14%)	4 (0.02%)	359 (2.19%)	2 (0.01%)	8646 (52.77%)
Category 4: Bonding or sensor issues	11265 (68.76%)	57 (0.35%)	3 (0.02%)	344 (2.10%)	1306 (7.97%)
Category 5: High rate	200 (1.22%)	1212 (7.40%)	59 (0.36%)	247 (1.51%)	59 (0.36%)
Category 6: Expected response	4834 (29.50%)	14935 (91.16%)	15683 (95.72%)	15757 (96.17%)	6350 (38.76%)

Interconnect yield:

$$Interconnect\ yield(\%) = \frac{N_6 + N_5}{128 \times 128 - N_1 - N_2}$$



Pixel categorisation map
for assembly 20
(130um sensor, same as on slide 4)

1. Pixels masked due to noise
2. Unresponsive to test pulsing
3. Shorted pixels
4. Bonding/sensor issue
5. High rate pixels
6. Expected response

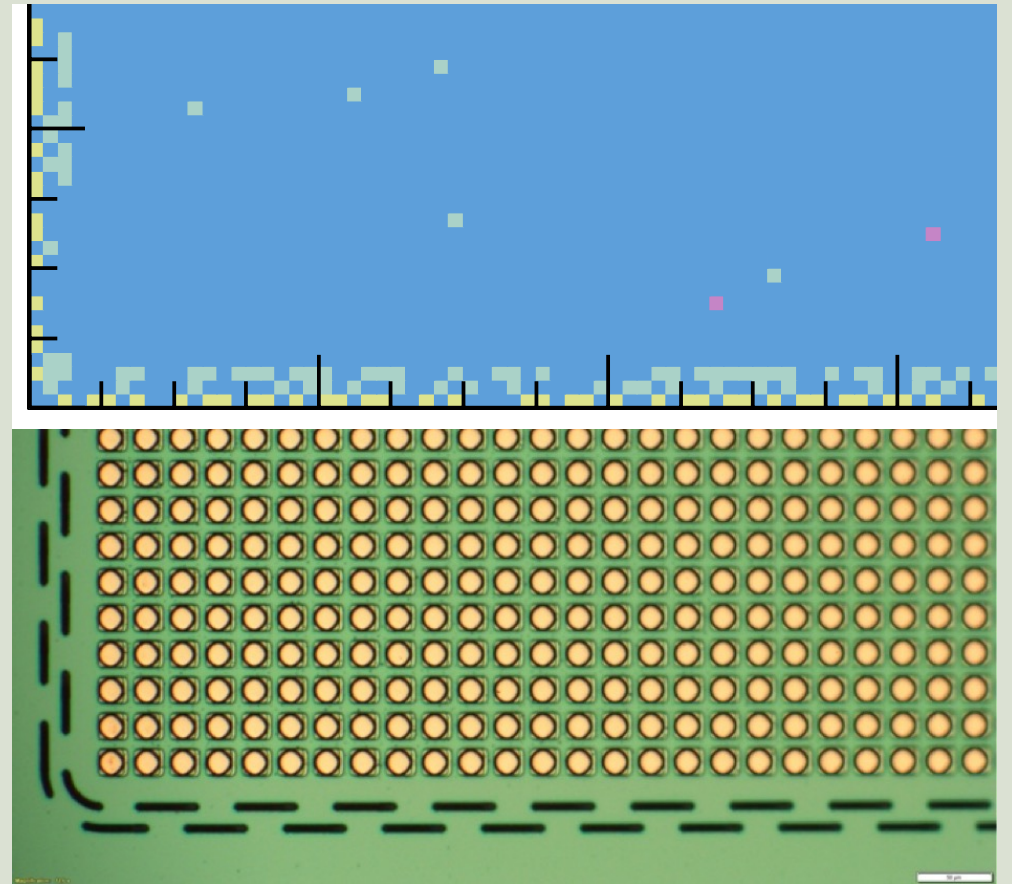
Pixel categorisation

Results:

- Up to 99.6 % interconnect yield achieved
- FBK active-edge sensors found to be of high quality
- Effect on edge pixels of staggered active-edge sensor design discovered
- Also able to identify smaller process issues, such as Z-misalignment of a sensor.
- 2/9 assemblies of very high quality

All identified issues communicated to IZM for processes optimisation.

Clear proof of concept, study limited by number of ASICs and sensors.

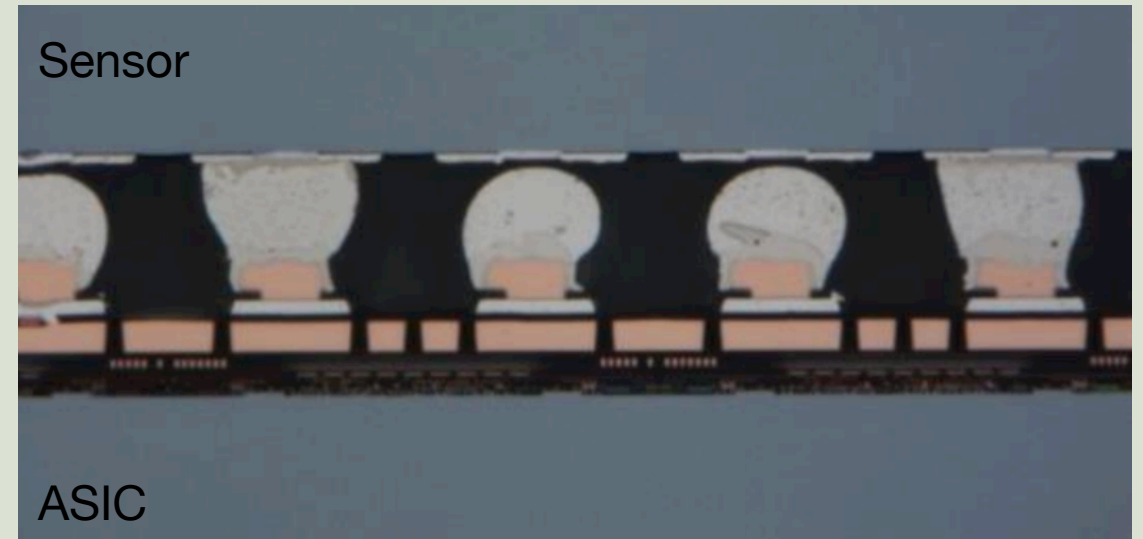
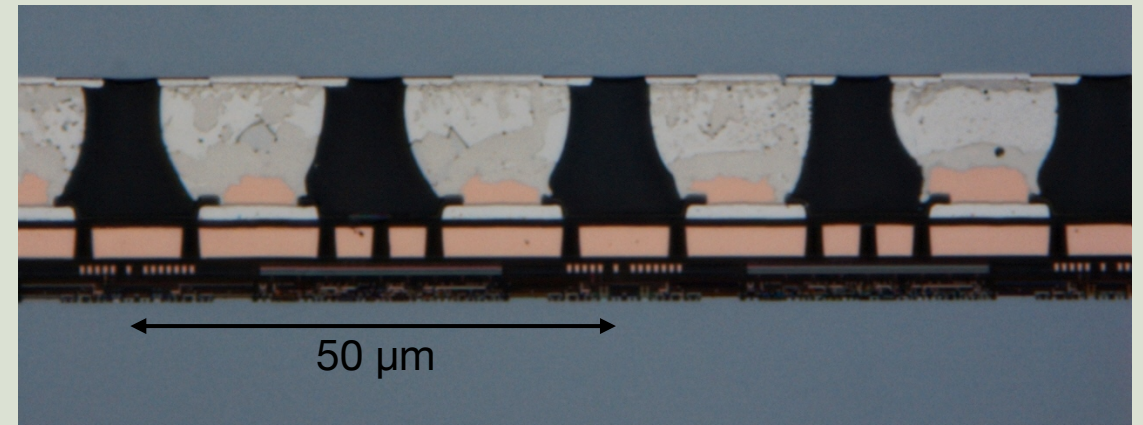


Top: Pixel categorisation results of CLICpix2 assembly 20, zoomed.

Bottom: Cropped image of staggered active-edge design of sensors from FBK.

Laboratory testing

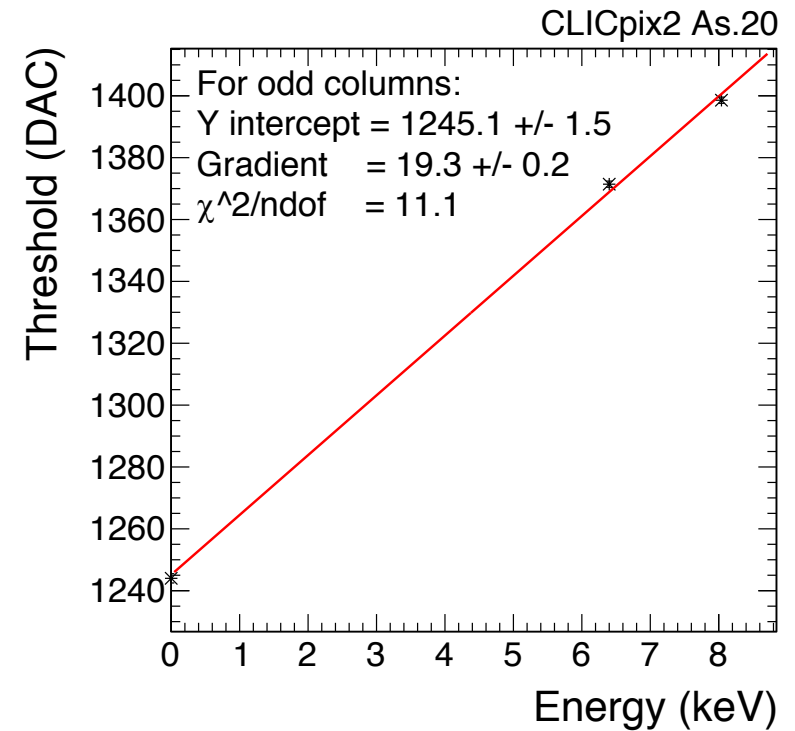
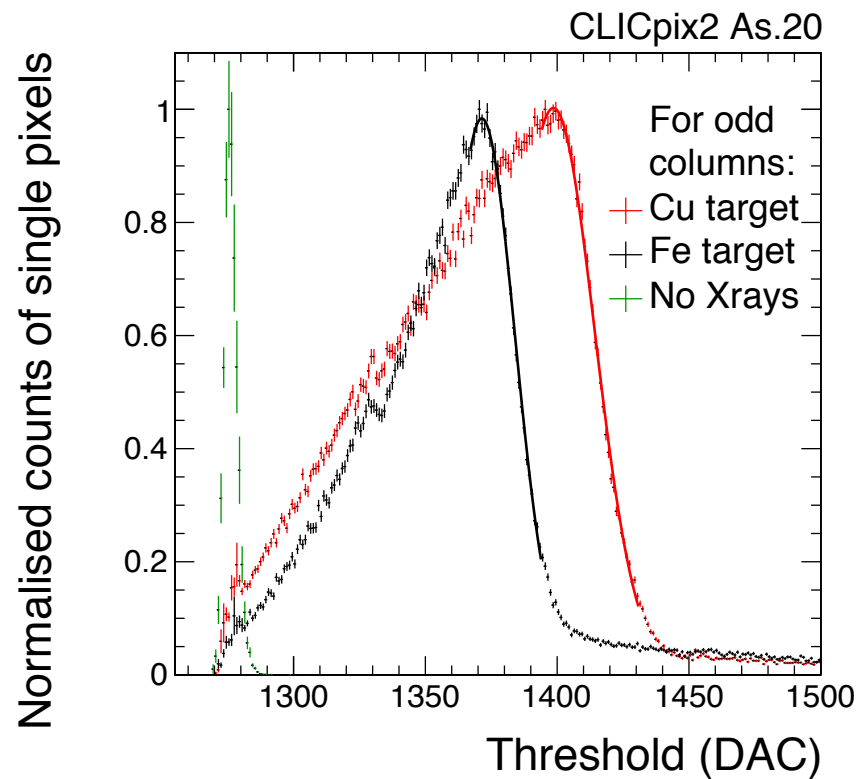
Discovered incompatibility between the thin-film Ni/Au UBM of the ADVACAM sensors and the IZM bump-bonding process.



Cross-section of bump bonds by IZM of CLICpix2 assembly 9

*Top: well connected region with pillar-like bumps
Bottom: poorly connected region with spherical bumps*

Threshold calibration



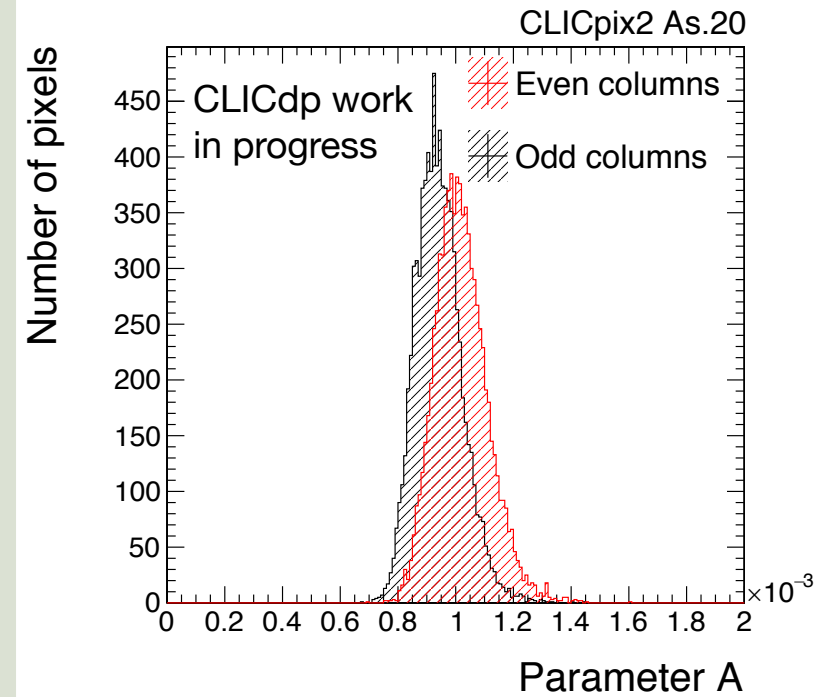
ToT calibration

Per-pixel Time-over-Threshold units calibration into electrons using test-pulse injection measurements.

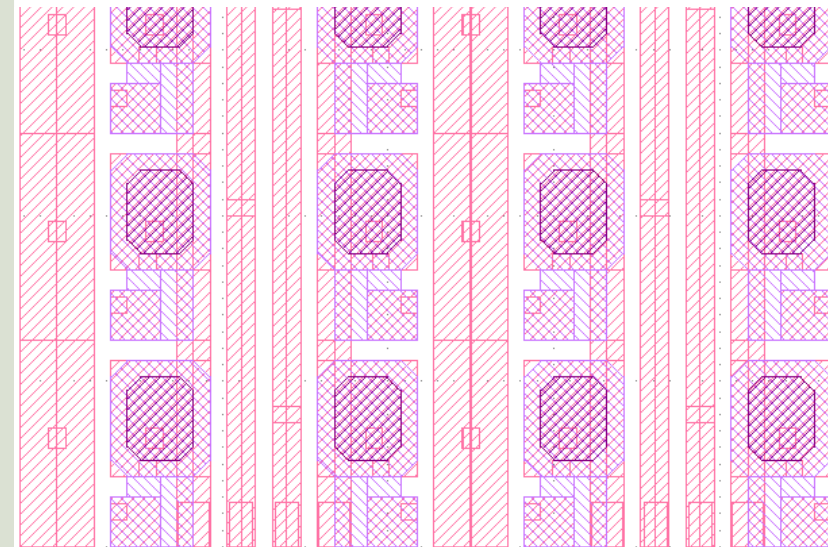
Each ToT calibration curve parameterised with a surrogate function fit.

$$\text{surrogate function} = Ax + B - \frac{C}{x - T}$$

Discovered a small difference in gain between odd and even columns due to mirrored column design of the CLICpix2 ASIC.



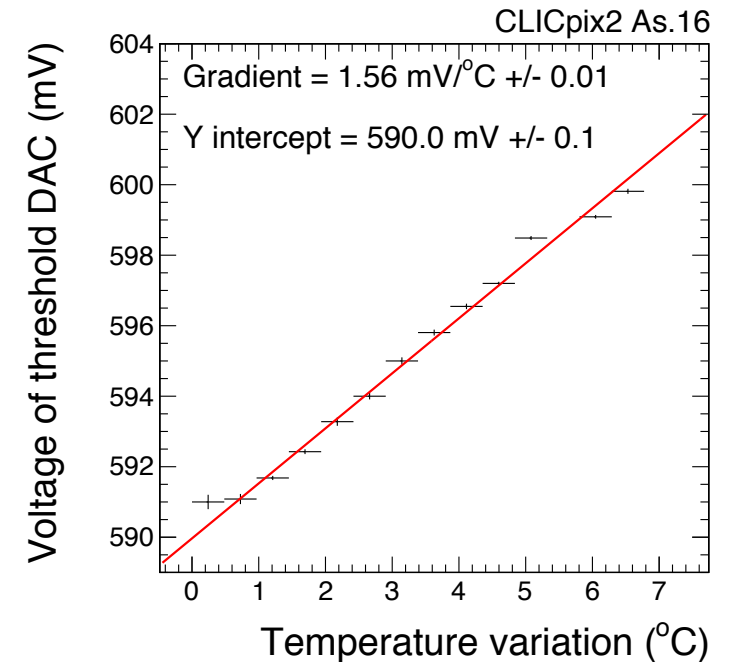
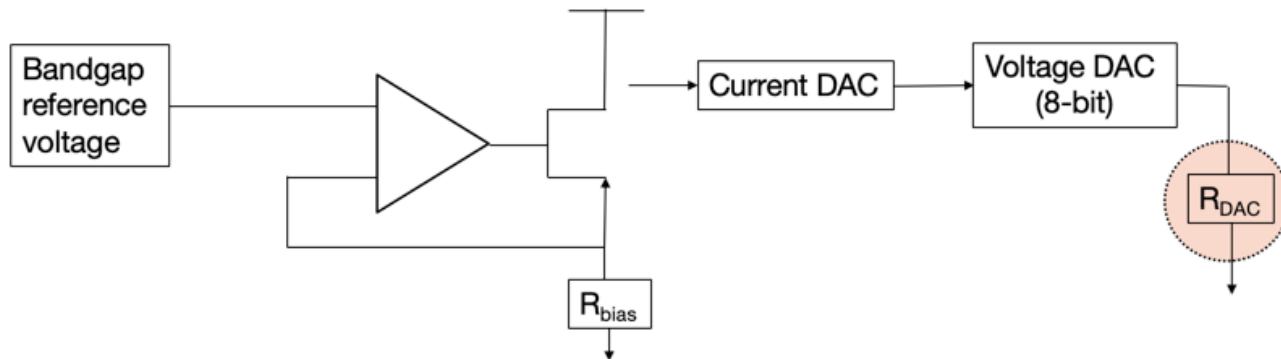
Top: Difference in A parameter of surrogate function fit for odd and even columns.



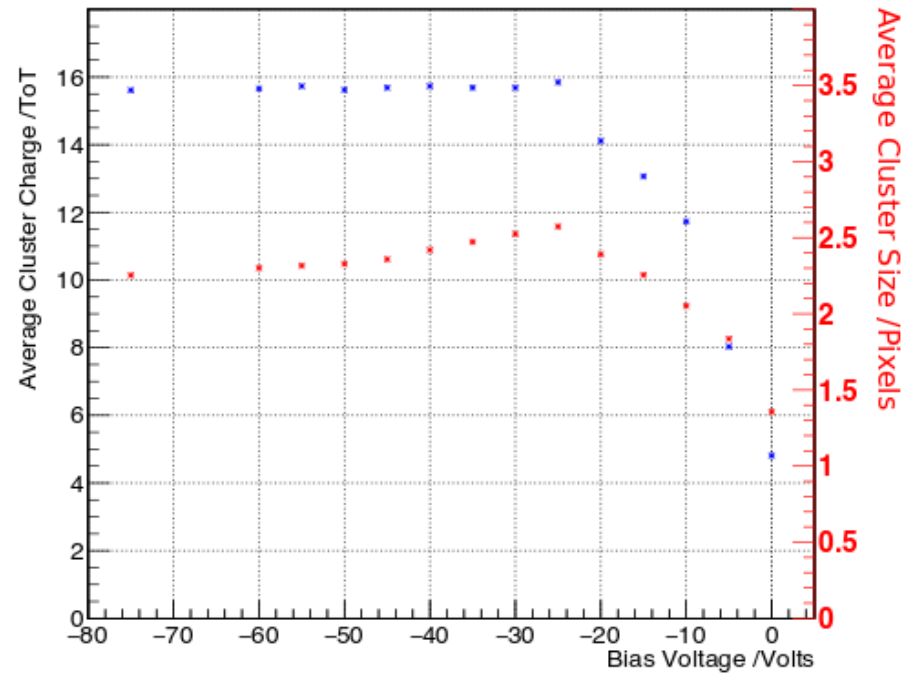
Bottom: top-metal layer design showing mirrored column design.

CLICpix2 temperature dependence

- Discovered that a resistor within the voltage DACs of the CLICpix2 ASIC had a low temperature coefficient that did not match those of the other resistors in the circuit.
- This causes the output of all voltage DACs to fluctuate with temperature.



Optimal bias for charge sharing

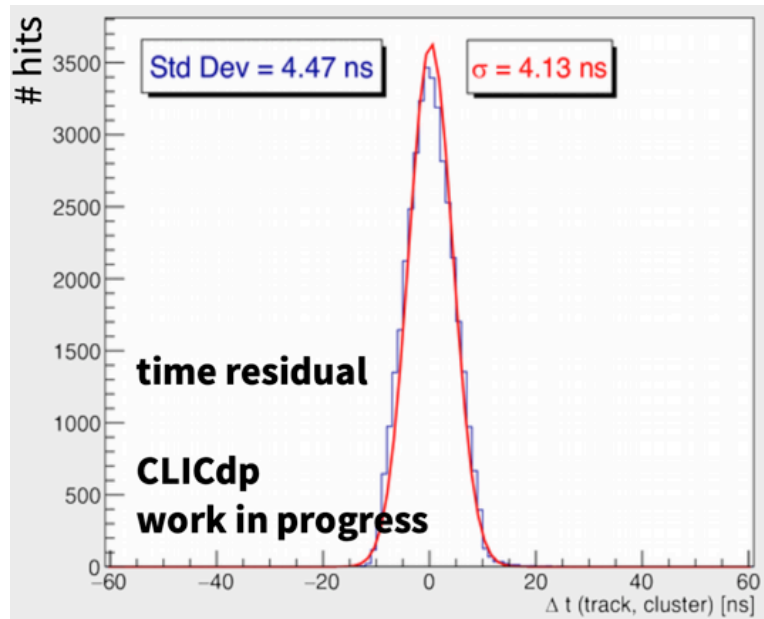


Graph of average cluster size and average cluster charge as a function of applied bias voltage

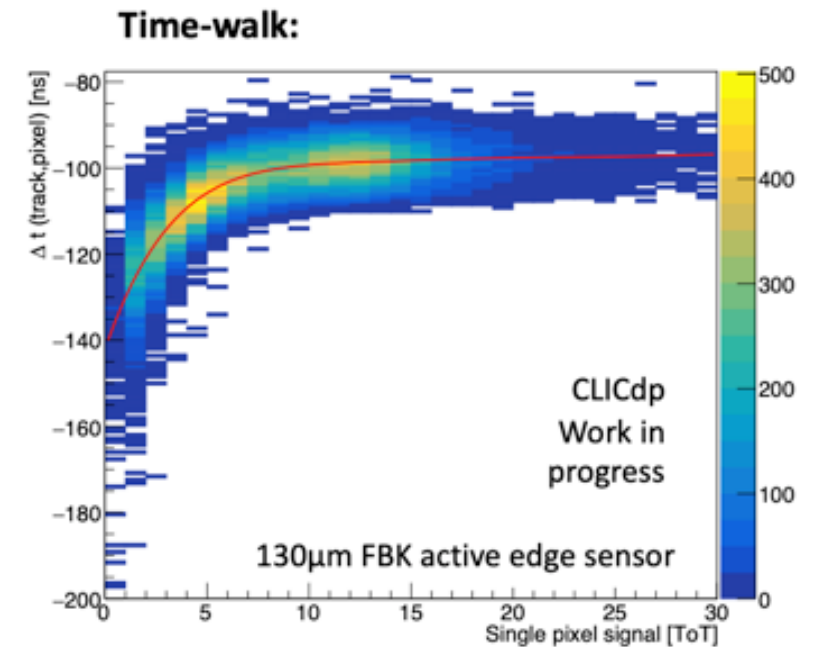
- Calculated depletion voltage = -24V

Test beam analysis: Timing analysis

After time-walk correction, timing resolution around 4ns. Further studies envisaged to look at the effect of bias voltage and threshold on the timing residuals obtained.



Timing residual of CLICpix2 planar assembly 16 (Magdalena Munker).



Time-walk correction applied to CLICpix2 planar assembly 16 (Magdalena Munker). 30