Test-beam performance evaluation of CLICpix2 fine-pitch hybrid silicon pixel detector prototypes

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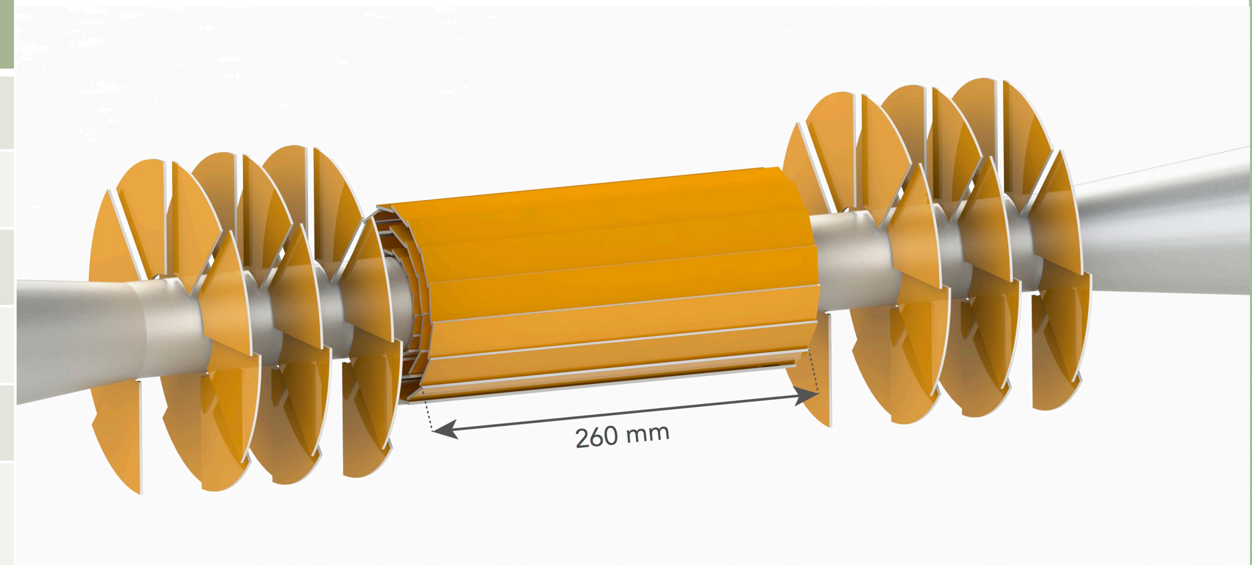
Requirements for future colliders

Experimental conditions at future colliders pose new challenges for silicon pixel technologies.

For example, vertex detector of Compact Linear Collider (CLIC):

Parameter	Requirement
Single point resolution	3 μm
Pixel size	≤ 25 μm x 25 μm
Material budget per layer	0.2 % X_0
Timing resolution	5 ns
Hit detection efficiency	99.7 - 99.9 %
Average power dissipation (using power pulsing)	< 50 $mWcm^{-2}$

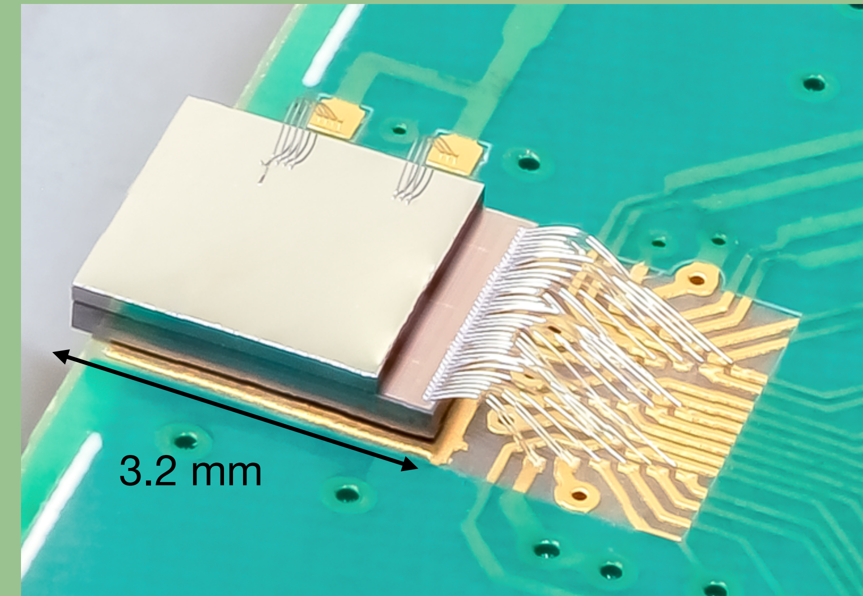


CLICpix2 hybrid ASIC

Aims to fulfil challenging requirements of the vertex detector of CLIC.

CLICpix2 readout ASIC:

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



CLICpix2 readout ASIC bump-bonded to a planar silicon sensor

CLICpix2 planar sensor assemblies

CLICpix2 ASICs hybridised by IZM to active-edge, N-in-P planar silicon sensors from FBK and from Advacam

Bump-bonding challenging for single chips and 25μm pitch

→ Achieved interconnect yields of up to 99.6% using the bonding process

→ Proof of concept: next phase of interconnect studies are ongoing, aiming for a good yield of thinner sensors

The two assemblies with highest interconnect qualities had their test-beam performance evaluated

	As. 16	As. 20
Sensor thickness	130μm	130μm
Well-interconnected pixels	99.6%	97.9%
Nominal threshold	0.6 ke	0.7 ke
THL dispersion	0.04ke	0.04 ke

Laboratory testing results of the two best performing CLICpix2 planar sensor assemblies

Test-beam data taking

Test-beam data taking

- CLICpix2 has fine pitch and precise timing

  → requires telescope set-ups with high-resolution tracking in space and time

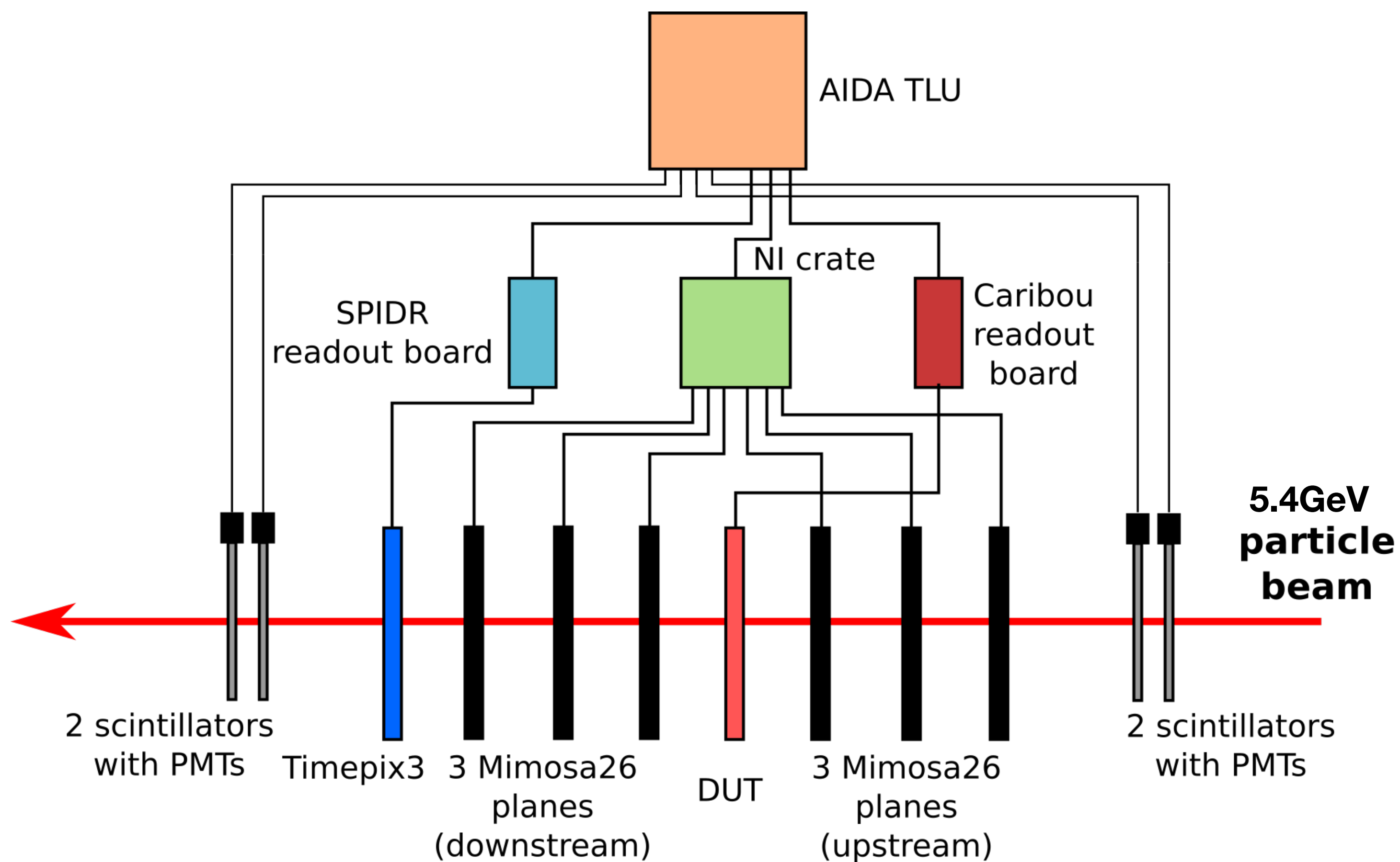
- Different test-beam telescopes used for each assembly:

  As20: EUDET DATURA telescope @ DESY

  As16: CLICdp Timepix3 telescope @ CERN SPS

  → requires precise data reconstruction

Test-beam set-up: DESY



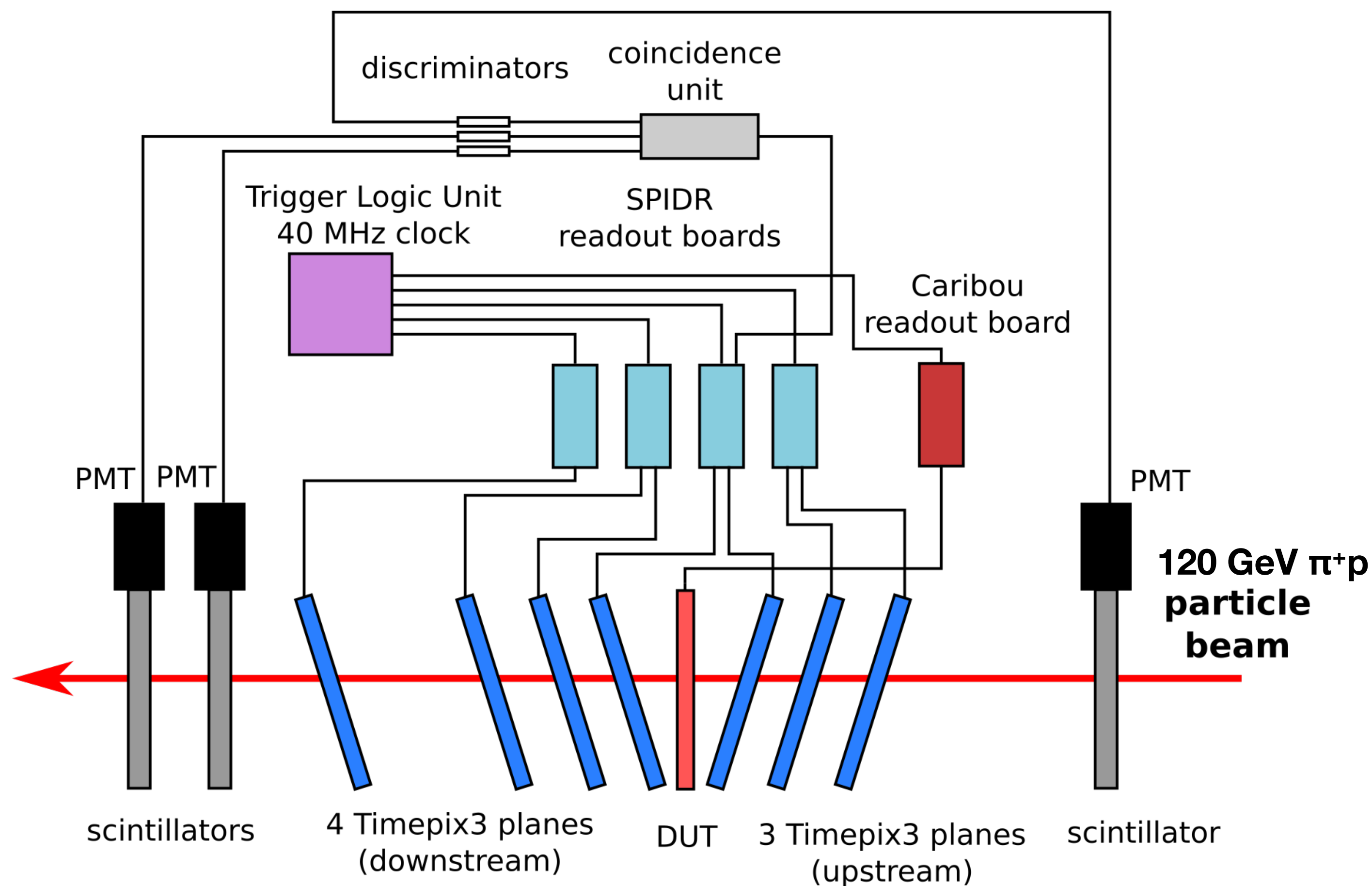
Schematic of the EUDET test-beam telescope used at DESY.

- Data taken for As. 20 at DESY using EUDET Datura telescope with additional Timepix3 for track timing reference:
  resolution ~2.6µm

→ *For full telescope description, see talk previous talk at this workshop from Jens Kroeger*

- DAQ using EUDAQ2 framework and Caribou system
- CLICpix2 DUT operated in free running mode with fixed shutter length

Test-beam set-up: CERN



Schematic of the CLICdp Timepix3 test-beam telescope used at SPS.

- Data taken for As. 16 at CERN SPS using CLICdp Timepix3 telescope:
  - 7 angled Timepix3 planes
  - Resolution ~1ns and <2μm
- DAQ using SPIDR and Caribou system
- CLICpix2 DUT operated in free running mode with fixed shutter length

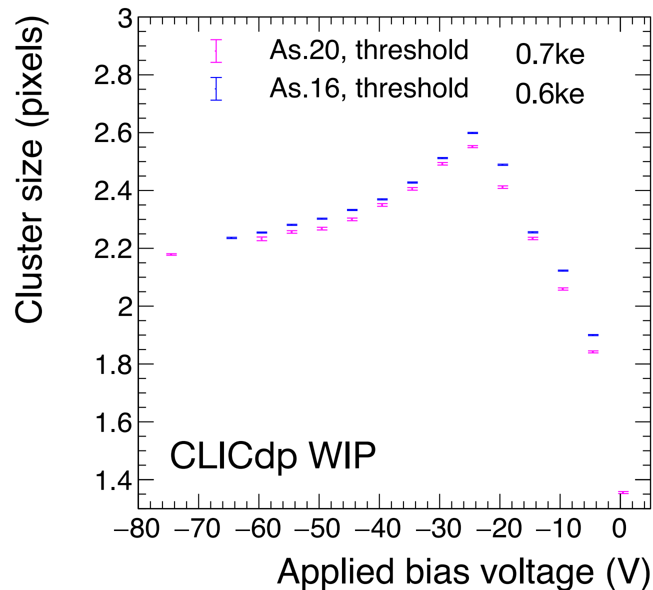
For each DUT, used different telescope systems with different conditions, resolutions, and event building schemes in Corryvreckan

→ important to consider when comparing analysed test-beam data

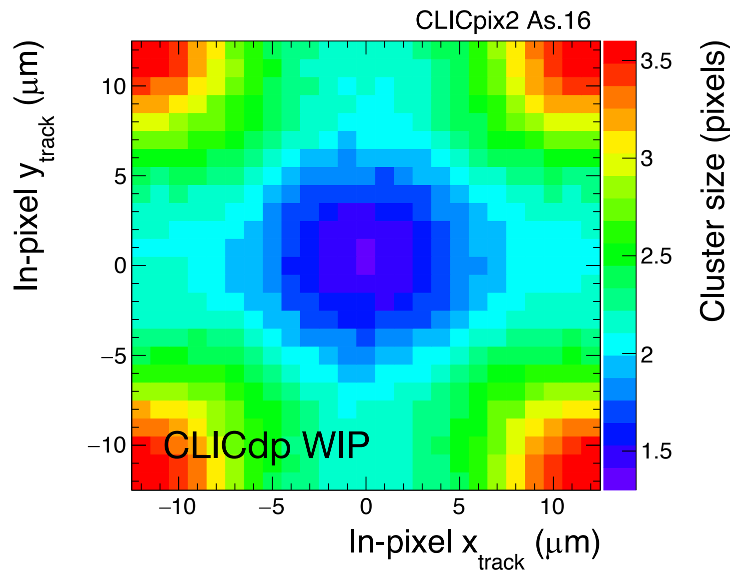
Performance evaluation

clusters, spatial resolution, efficiency, timing resolution

Cluster size



Mean associated cluster size vs. applied bias voltage



In-pixel associated cluster size distribution of assembly 16

Aim of fine-pitch design to increase charge sharing

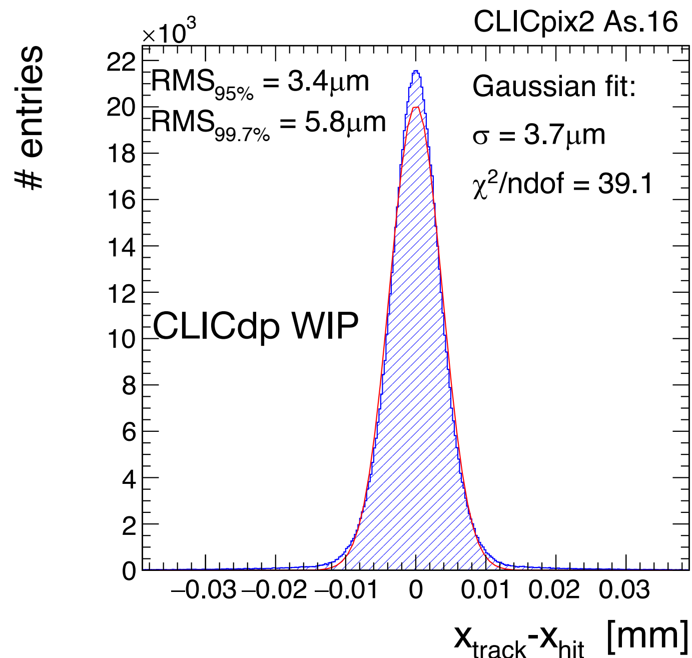
→ What level of charge sharing do we achieve?

- Optimal bias voltage for charge sharing is -25V for both assemblies

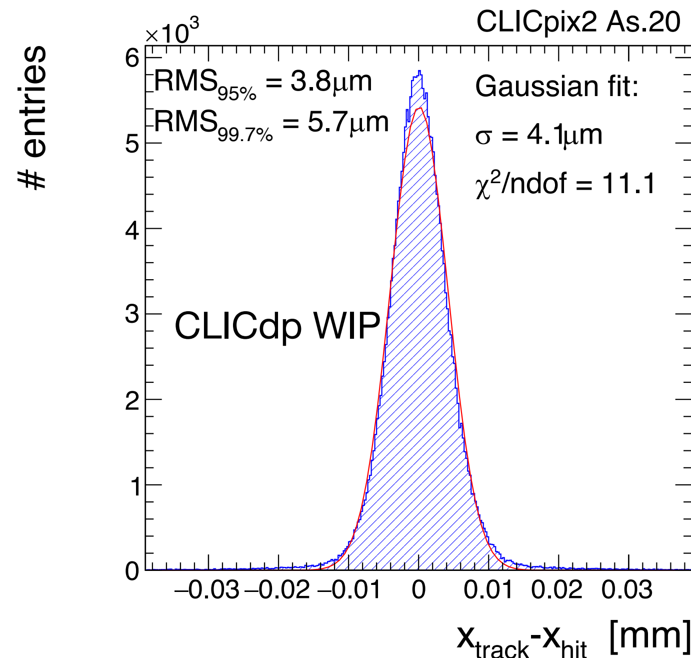
  → Mean cluster size larger for As. 16, in accordance with the lower threshold

- Large amount of charge sharing means one-pixel sized clusters confined to small central in-pixel area

Spatial resolution



Spatial residual distribution in X of As. 16 at -25V (130µm sensor, 25µm pitch)



Spatial residual distribution in X of As. 20 at -25V (130µm sensor, 25µm pitch)

What do we gain from increased charge sharing?

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

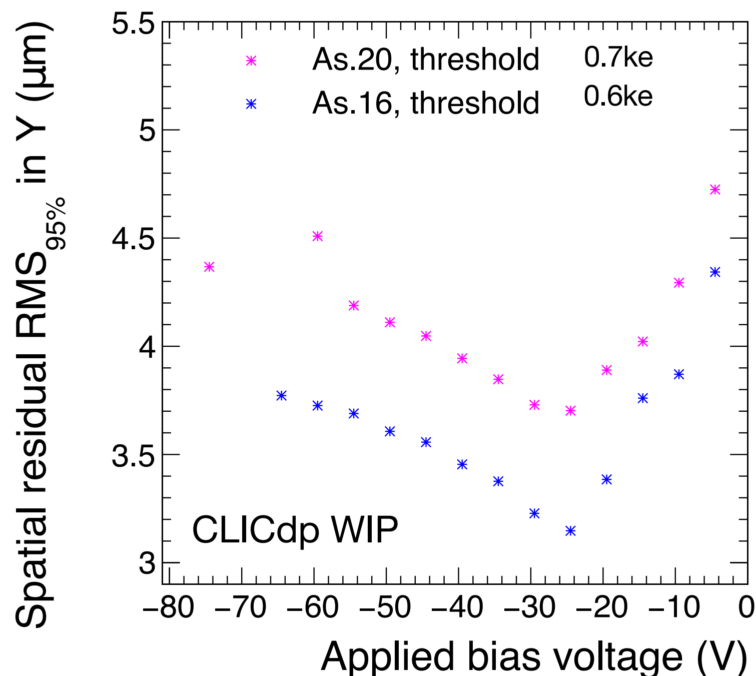
	As 16.	As. 20
X $\sigma_{intrinsic}$	2.9 µm	2.7 µm
Y $\sigma_{intrinsic}$	2.5 µm	2.6 µm

→spatial resolution below 3µm required for CLIC vertex detector

- ~4 µm for CLICpix hybrid assemblies with 200 µm thick active-edge planar silicon sensor

→ CLICpix2 improves on this value with a 70 µm thinner sensor through lower threshold and fixed noise-injection issue

Spatial resolution



Spatial residual width in Y vs. applied bias voltage

Smallest residual width for both assemblies at -25V, where the charge sharing is highest

What do we gain from increased charge sharing?

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

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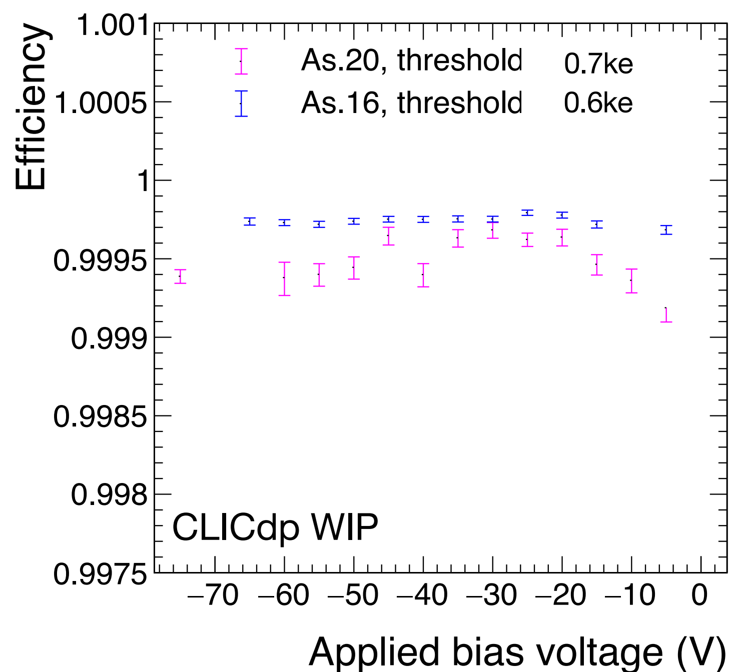
Total hit detection efficiency



Hit detection efficiency vs applied bias voltage

- Both assemblies achieve efficiency above 99.95% for all bias voltage values

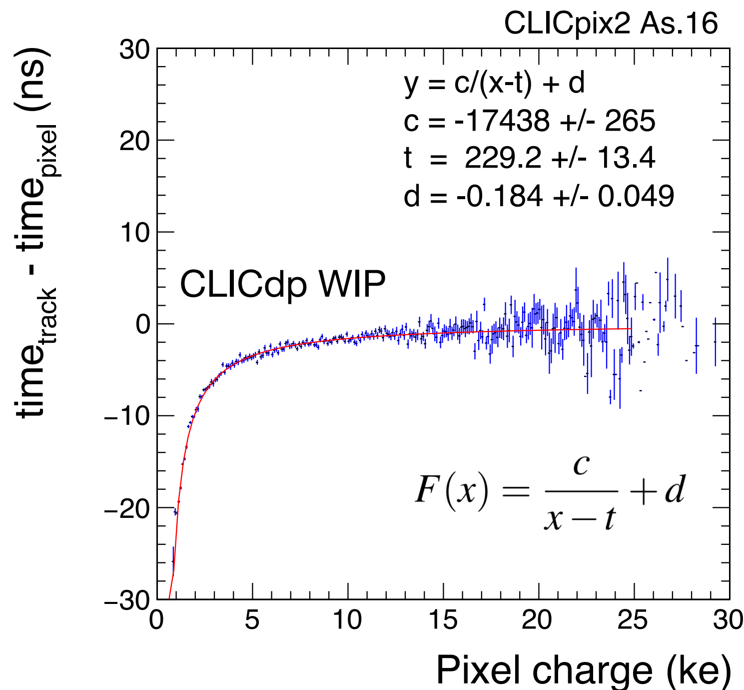
  → note: efficiency value discarded of all pixels with known interconnect issues

- Efficiencies remain above 99.90% for thresholds up to ~1.5ke

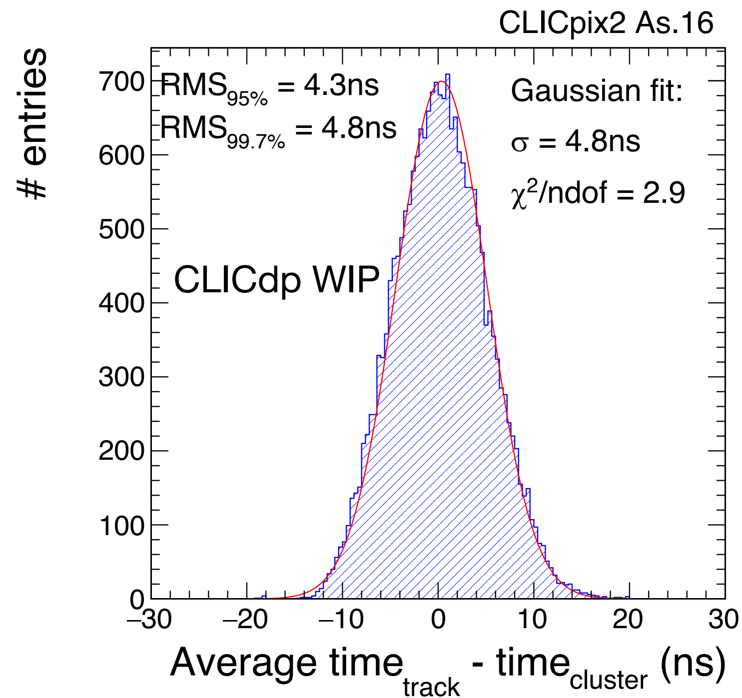
  → large operational margin with high efficiency

- Meets the >99.7% efficiency required for the CLIC vertex detector

Timing resolution



Time-walk correction function for As. 16



Timing residual distribution of As. 16 at -60V

- Time-walk function calculated to correct for non-linear dependence of arrival time on input signal
- After correction, timing resolution is (4.2+0.3-0.4)ns

  → less than the 5ns CLIC requirement

Summary

- Fine-pitch CLICpix2 ASIC designed to meet the challenging requirements of future collider experiments, such as CLIC
- ASICs hybridised by IZM to active-edge, N-in-P planar silicon sensors, achieving interconnect qualities up to 99.6%
- Despite the significant differences in the telescope set-up and reconstruction process used on each of the test-beam data sets, the DUT performance of the assemblies is similar
- Assemblies with 130um sensors meet the hit detection efficiency, spatial resolution, and timing resolution requirements of the CLIC vertex detector, and improve on CLICpix assemblies tested previously
- Challenge: achieving positional resolution with 0.2% per layer material budget limit → topic of ongoing studies

Part of the measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg and the CERN SPS North Area test-beam facility

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

Thank you for your attention

Back-up slides

References

- Morag Williams, PhD thesis: “Evaluation of Fine-Pitch Hybrid Silicon Pixel Detector Prototypes for the CLIC Vertex Detector in Laboratory and Test-Beam Measurements” (2020, pending)

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

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

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

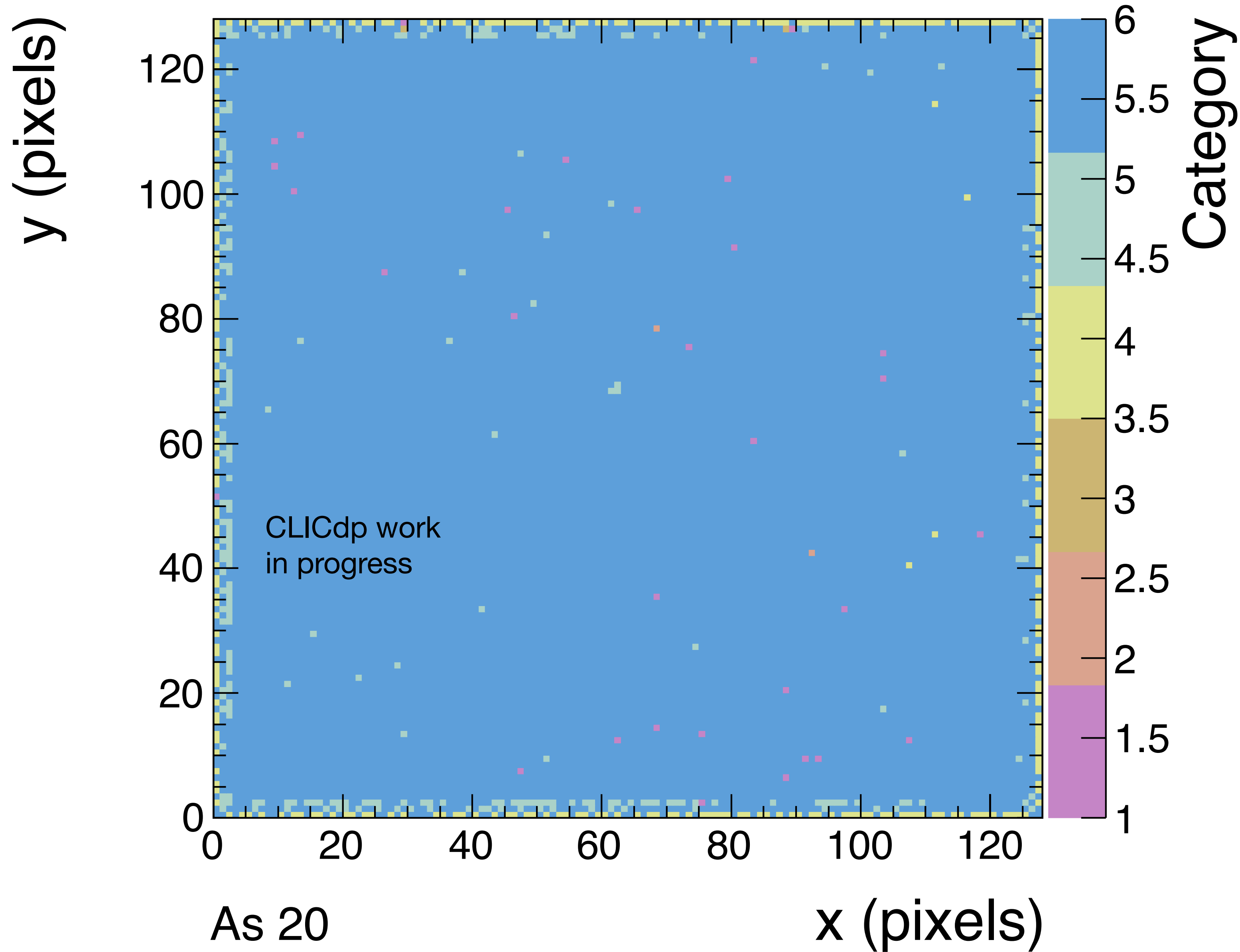
Assembly number	Sensor type	Sensor thickness (µm)	Maximum operational bias voltage (V)	Baseline (DAC)	Operational threshold (DAC)	Threshold dispersion (DAC)	Average noise (DAC)	Number of masked pixels
9	Advacam	100	-60	1187	1295	4.5	16.0	1
14	FBK-CMM	130	-60	1200	1250	2.4	5.4	50
15	Advacam	150	-60	1166	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

Summary of pixel categorisation of CLICpix2 planar sensor assemblies

CLICpix2 assembly: Sensor type and thickness:	**Assembly 14** FBK-CMM, 130 μm	**Assembly 16** FBK-CMM, 130 μm	**Assembly 19** FBK-CMM, 130 μm	**Assembly 20** FBK-CMM, 130 μm	**Assembly 21** 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)

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