PROGRESS TOWARDS SEAMLESS LARGE AREA X-RAY AND GAMMA-RAY DETECTORS

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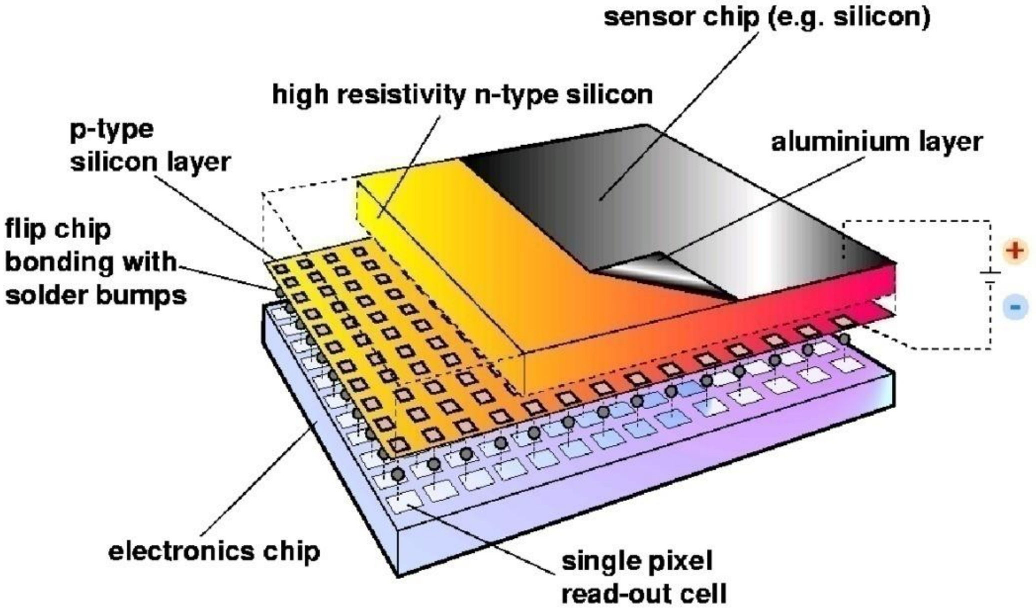
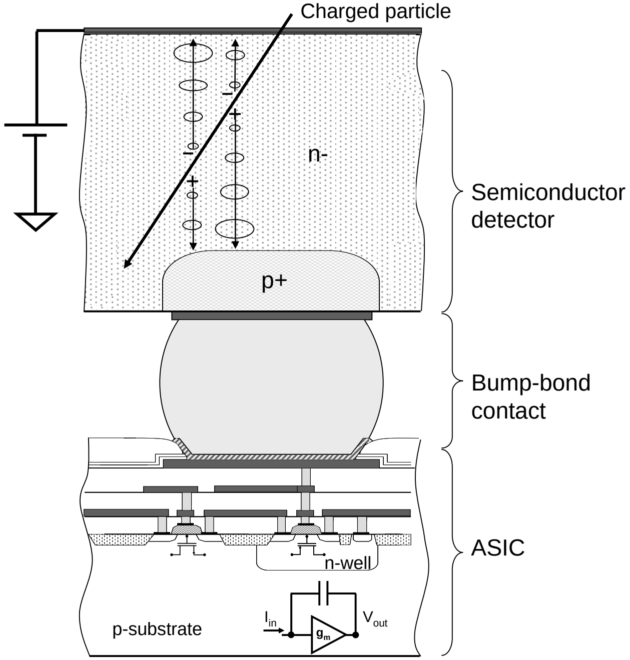
Hybrid Silicon Pixel Detectors

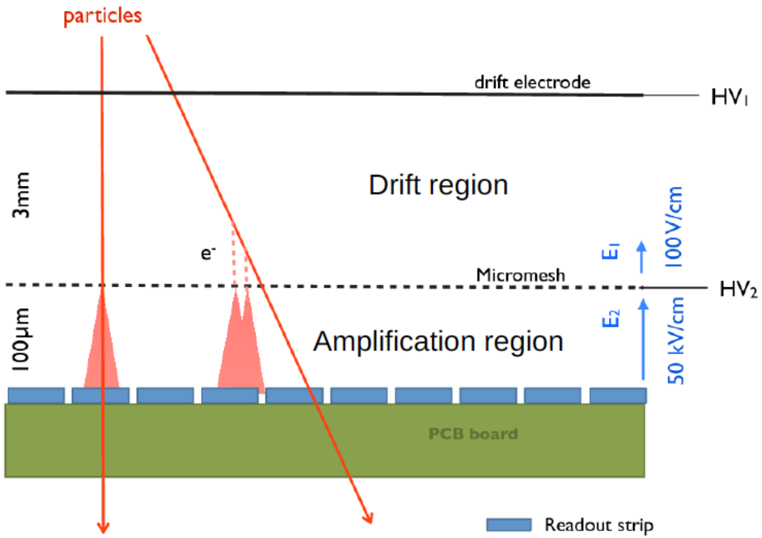


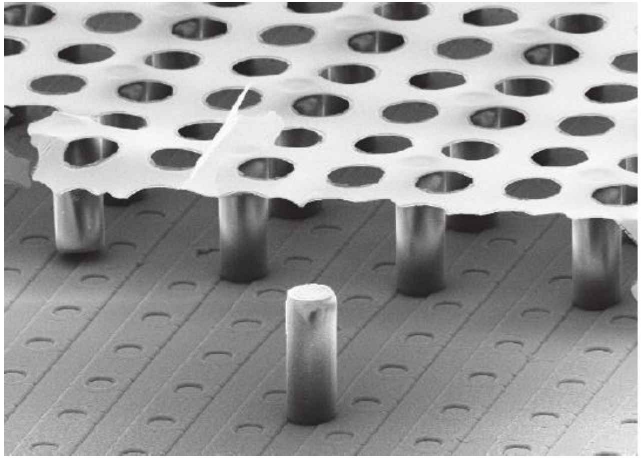


Standard CMOS can be used allowing on-pixel signal processing

Sensor material can be changed (Si, GaAs, CdTe..)

Gas detector readout - InGrid

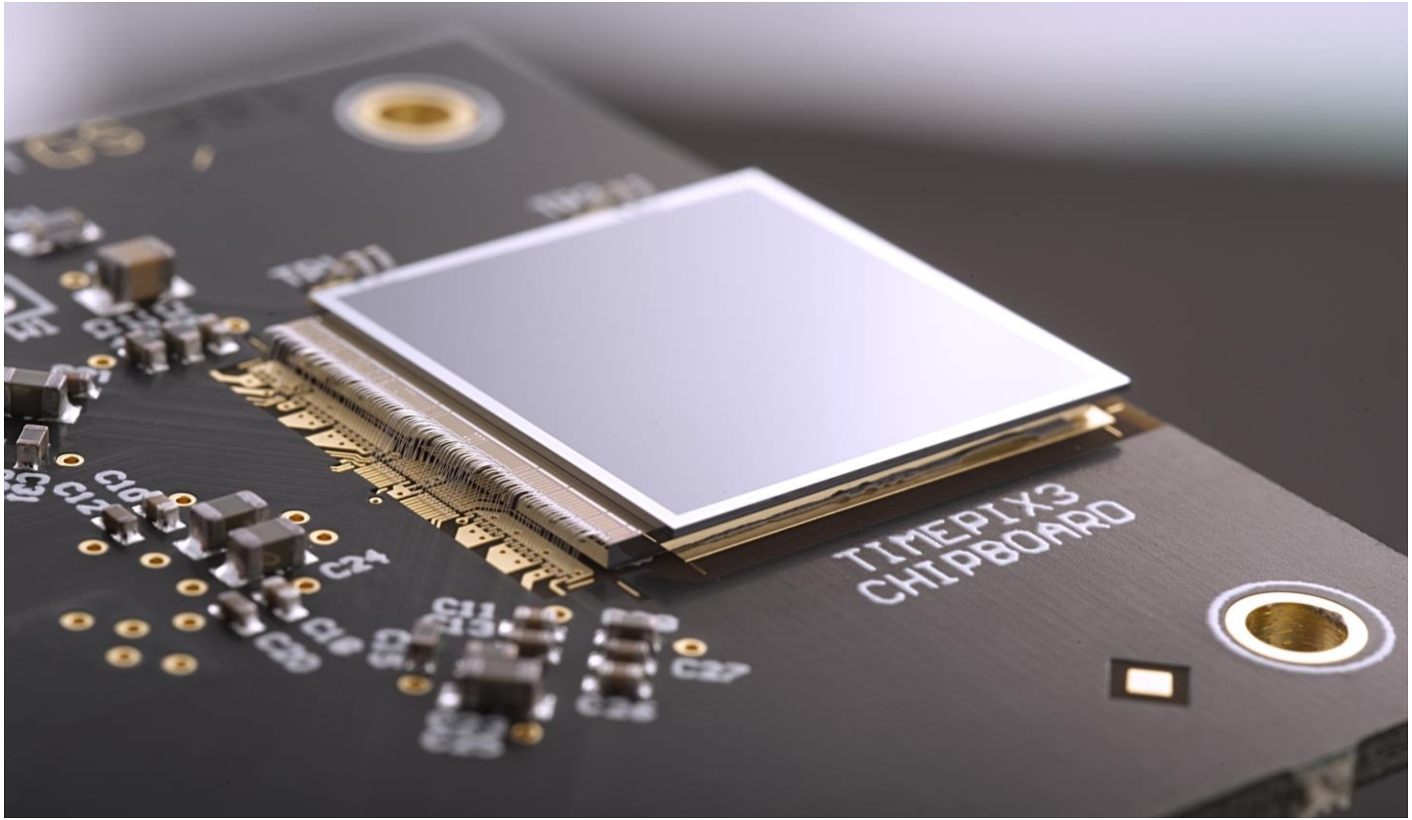




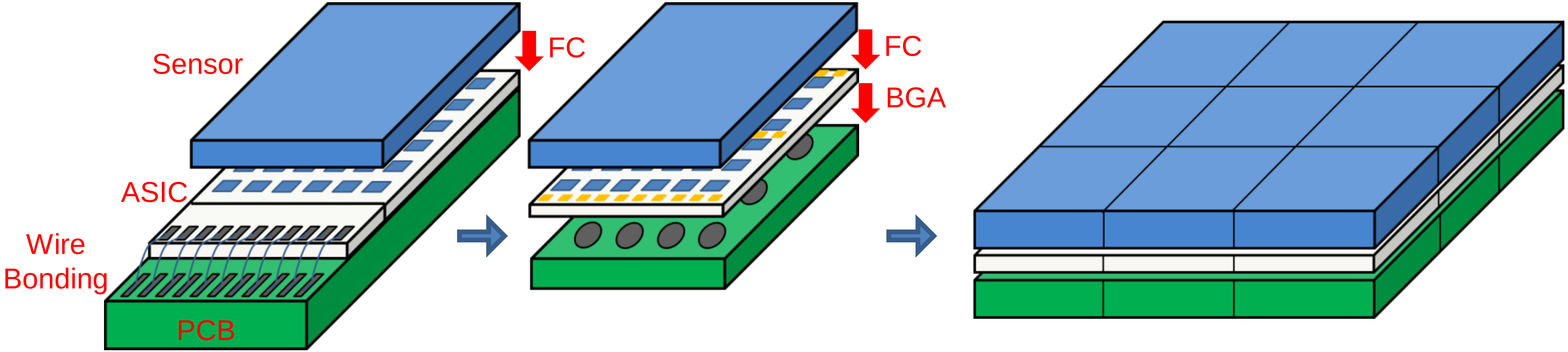
Semiconductor detector is replaced with charge amplification grid
Permits lower energy events to be detected
NB: GEM foils may be used in place of the InGrid foils

If placed in a photo tube together with a MCP visible photons may be detected (see: M. Fiorini et al 2018 J.Instrum 13 C12005)

Timepix3 Photo



Tiling larger areas



- Target to build large area detectors by combining single chip modules.
- Through-silicon vias (TSVs) are the key technology enabler.
- Medipix4 and Timepix4 use on-chip interposer for bump to pixel redistribution layer (RDL).
- The detector is fully sensitive: even above the peripheral circuit and I/O pads.

Medipix2 (1999 ->)

- Albert-Ludwig Universität Freiburg, Germany
- CEA, Paris, France
- CERN, Geneva, Switzerland
- Czech Academy of Sciences, Prague, Czechia
- ESRF, Grenoble, France
- IEAP, Czech Technical University, Prague, Czech Republic
- IFAE, Barcelona, Spain
- Mid Sweden University, Sundsvall, Sweden
- MRC-LMB Cambridge, England, UK
- NIKHEF, Amsterdam, The Netherlands
- University of California, Berkeley, USA
- Universität Erlangen-Nurnberg, Erlangen, German
- University of Glasgow, Scotland, UK
- University of Houston, USA
- University and INFN Section of Cagliari, Italy
- University and INFN Section of Pisa, Italy
- University and INFN Section of Napoli, Italy

Medipix3 (2005 ->)

- Albert-Ludwig Universität Freiburg, Germany
- AMOLF, Amsterdam, The Netherlands
- Brazilian Light Source, Campinas, Brazil
- CEA, Paris, France
- CERN, Geneva, Switzerland
- DESY-Hamburg, Germany
- Diamond Light Source, England, UK
- ESRF, Grenoble, France
- IEAP, Czech Technical University, Prague, Czech Republic
- KIT/ANKA, Forschungszentrum Karlsruhe, Germany
- Mid Sweden University, Sundsvall, Sweden
- NIKHEF, Amsterdam, The Netherlands
- Univesridad de los Andes, Bogota, Columbia
- University of Bonn, Germany
- University of California, Berkeley, USA
- University of Canterbury, Christchurch, New Zealand
- Universität Erlangen-Nurnberg, Erlangen, German
- University of Glasgow, Scotland, UK
- University of Houston, USA
- University of Leiden, The Netherlands
- Technical University of Munich, Germany
- VTT Information Technology, Espoo, Finland

Medipix4 (2016 ->)

- CEA, Paris, France
- CERN, Geneva, Switzerland
- DESY-Hamburg, Germany
- Diamond Light Source, England, UK
- IEAP, Czech Technical University, Prague, Czeciah
- IFAE, Barcelona, Spain
- JINR, Dubna, Russian Federation
- NIKHEF, Amsterdam, The Netherlands
- University of California, Berkeley, USA
- University of Canterbury, Christchurch, New Zealand
- University of Geneva, Switzerland
- University of Glasgow, Scotland, UK
- University of Houston, USA
- University of Maastricht, The Netherlands
- University of Oxford, England, UK
- INFN, Italy
- Chinese Spallation Neutron Source, Dongguan City,China
- Brazilian Light Source, Campinas, Brazil
- Philippine Nuclear Research Institute, Manila, Philippines

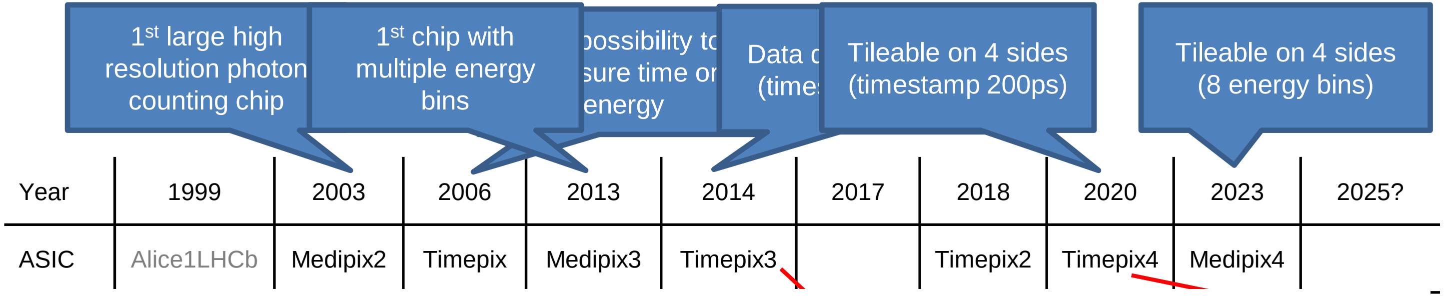
Acknowledgements – Commercial Partners

COLLABORATION NAME	Medipix2			Medipix3		Medipix4	
ASICS	Medipix2	Timepix	Timepix2	Medipix3	Timepix3	Medipix4	Timepix4
ADVACAM s.r.o., Czech Republic	X	X	X	X	X		X
Amsterdam Scientific Instruments, The Netherlands	X	X	X	X	X		X
Kromek, UK	X	X	X		X		
Malvern-Panalytical, The Netherlands	X	X	X	X			
MARS Bio Imaging, New Zealand				X			
PITEC, Brazil				X			X
Quantum Detectors, UK				X	X		X
Sydor Technologies, USA							X
X-ray Imaging Europe, Germany	X	X	X				
X-spectrum, Germany				X			X

X = commercial licensee

X = R and D licensee

The Medipix and Timepix ASICs - Timeline



1st large high resolution photon counting chip

1st chip with multiple energy bins

ossibility to
sure time or
energy

Data d
(times

Tileable on 4 sides
(timestamp 200ps)

Tileable on 4 sides
(8 energy bins)

Year	1999	2003	2006	2013	2014	2017	2018	2020	2023	2025?
ASIC	Alice1LHCb	Medipix2	Timepix	Medipix3	Timepix3		Timepix2	Timepix4	Medipix4	

- Medipix chips aim at energy sensitive photon counting and typically use frame-based readout
- Timepix chips are more oriented towards single particle detection
- This talk will focus on Timepix4 and our efforts towards large area tiling

Timepix3 Specs

CMOS node	130nm
Pixel Array	256 x 256
Pixel pitch	55μm
Charge collection	e$^-$, h$^+$
Pixel functionality	TOT (Energy) and TOA (Arrival time)
Preamp Gain	~47mV/ke$^-$
ENC	~60e$^-$
FE Linearity	Up to 12ke$^-$
TOT linearity (resolution)	Up to 200ke$^-$ (<5%)
TOA resolution*	Up to 1.6ns
Time-walk	<20ns
Minimum detectable charge	~500e$^-$ → 2 KeV (Si Sensor)
Max Analog power (1.5V)	500 mA/chip
Digital Power (1.5V)	~400mA data driven
Maximum hit rate	80Mhits/sec (in data driven)
Readout	Data driven (44-bits/hit @ 5Gbps)

* Thanks to V. Gromov, et al. Nikhef, C. Brezina et al., Bonn

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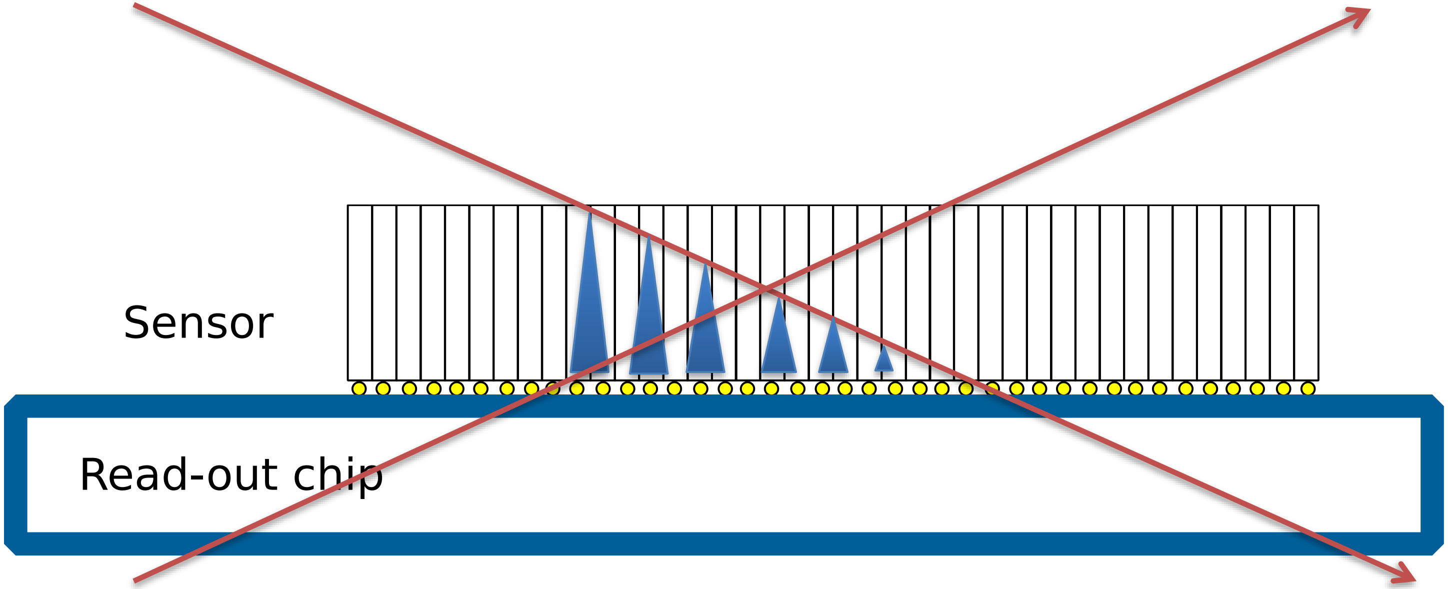
Timepix3 miniaturised readout

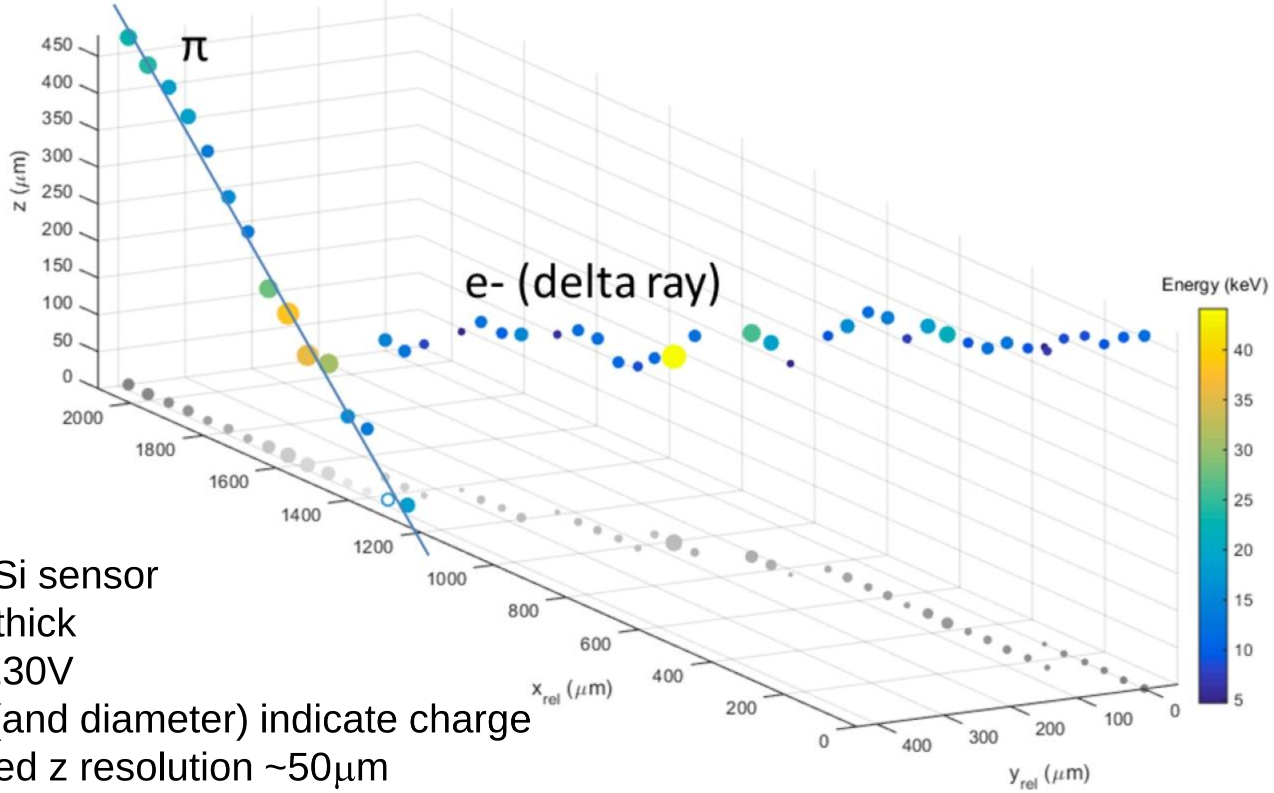
Advacam s.r.o., Prague

Timepix3 Demo

Tracking in a single Si layer



Test with 120GeV/c Pion Track



60 deg
p+ in n Si sensor
500µm thick
V_{bias} = 130V
Colour (and diameter) indicate charge
Measured z resolution ~50µm

Slide courtesy of B. Bergmann, S. Pospisil, IEAP, CTU, Prague

Single Layer Compton Camera with MiniPIX TPX3

Compton camera principle

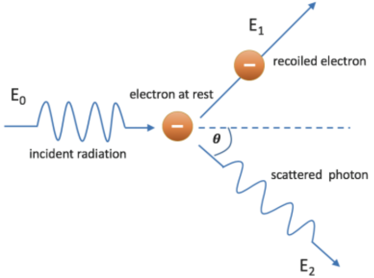
- Typical two detectors
- primary gamma is scattered in first detector (position and energy recorded), scattered gamma continues to second detector (absorbed, position and energy recorded)
- from energies - > scattering angle calculated
- from position and energies -> possible position of the source on the surface of a cone
- Multiple cones intersection - > source position

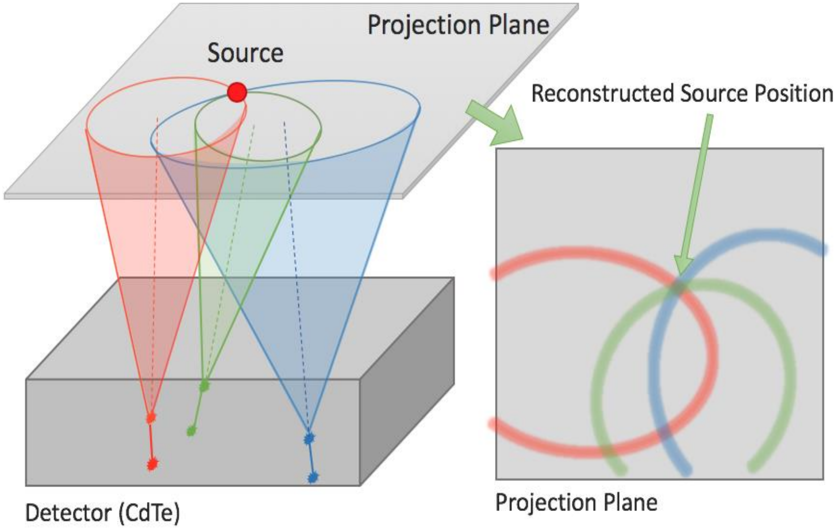
- Single Timepix3 layer camera
  - Instead of 2 detectors, only single TPX3
  - Using time of charge collection to determine relative depth

Courtesy of D. Turecek, Advacam s.r.o

$$\cos\theta = 1 - m_e c^2 \frac{E_1}{E_0(E_0 - E_1)}$$

$$E_0 = E_1 + E_2$$

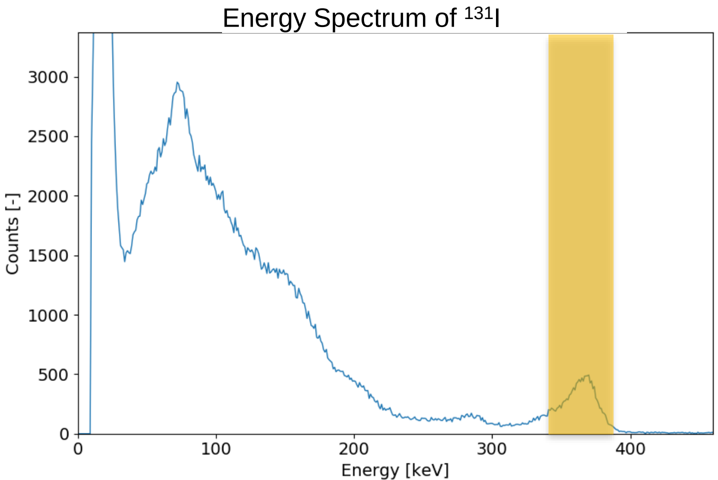




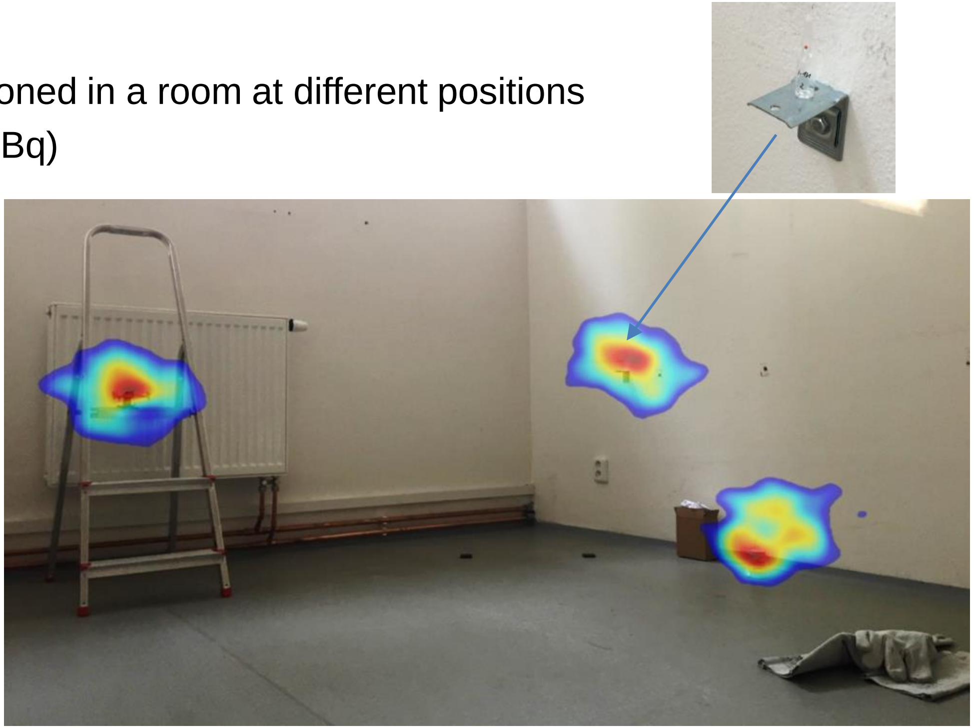
Single Layer Compton Camera with MiniPIX TPX3

^{131}Iodine gamma source

- 3 different Iodine solution in small bottles positioned in a room at different positions
- Distance from detector 3.5 m (activity 10's of MBq)
- Mapped on photograph of the room
- Sources located correctly within minutes
- Image took hours to collect



Courtesy of D. Turecek, Advacam s.r.o

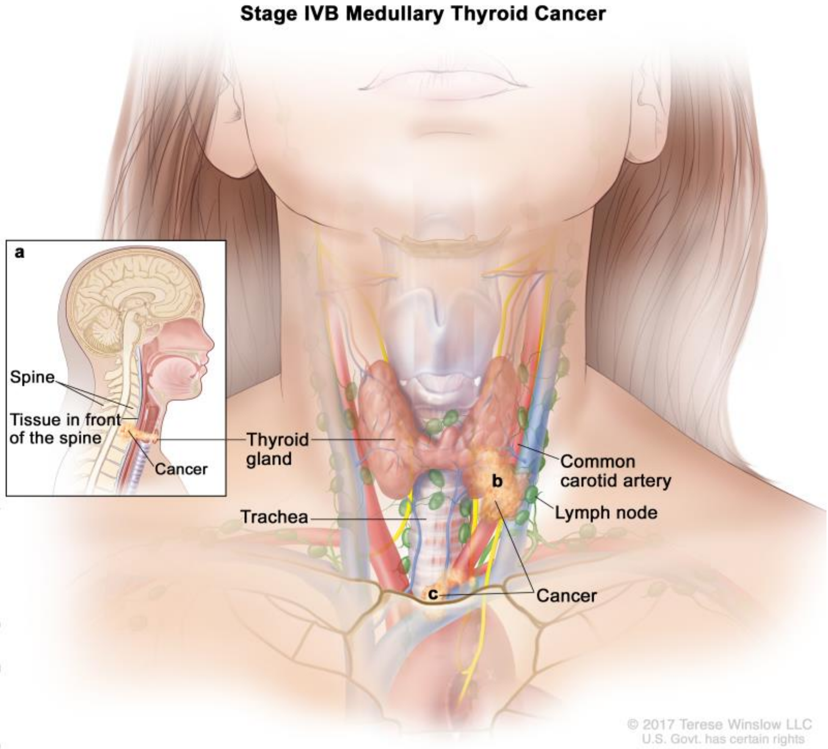


Reconstruction of position of three ^{131}I gamma sources (364 keV)

Gamma camera application: Thyroid diagnostics

Thyroid cancer diagnostics and treatment monitoring:

- The second most frequent cancer for women (after breast cancer)
- Current imaging methods offer resolution of about 12 mm in 2D
- Our technology allows
  - 5 times better resolution and 3D (2.5 mm)
  - 4 times lower dose

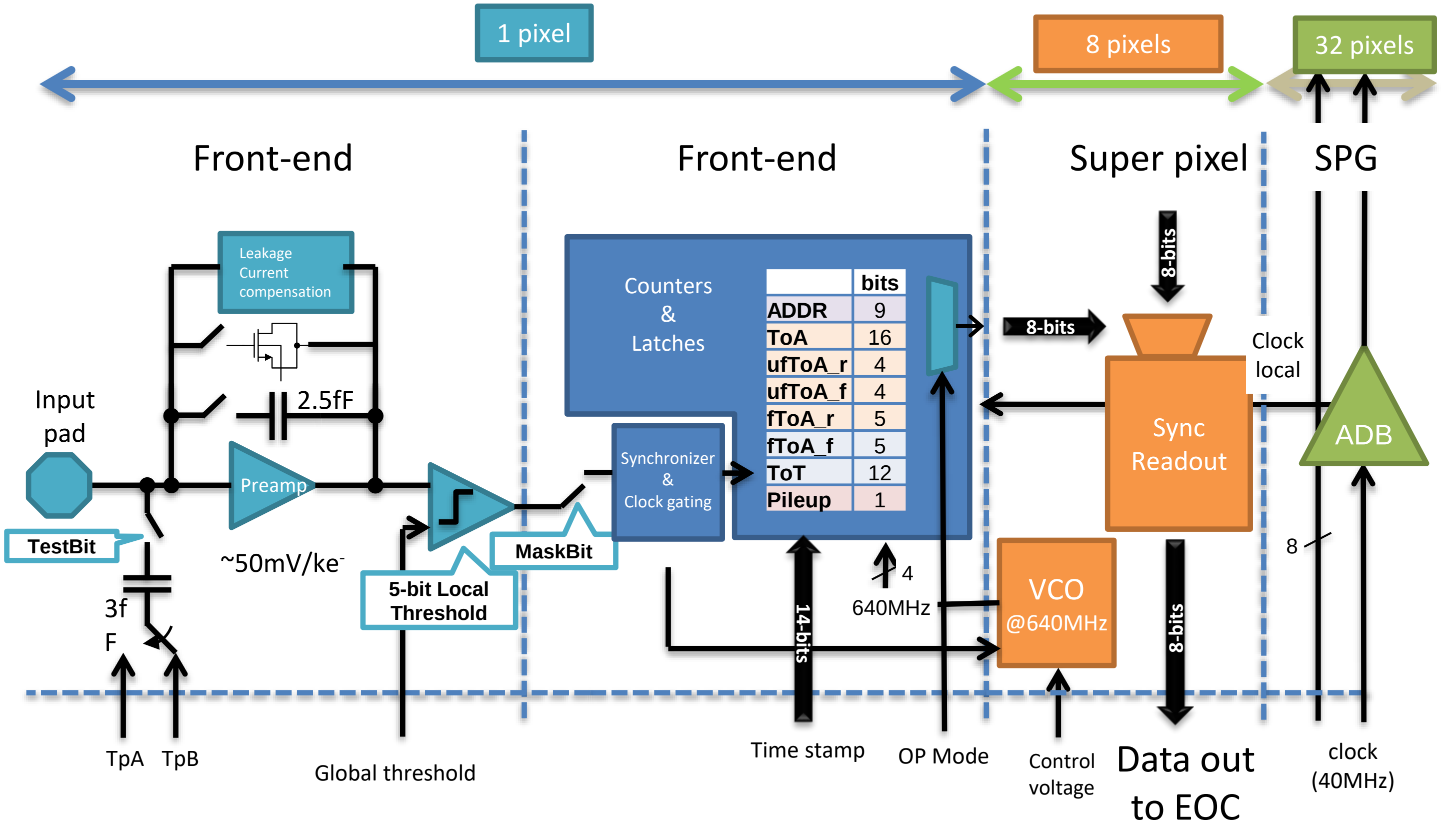


Courtesy of D. Turecek, Advacam s.r.o

Timepix3 → Timepix4

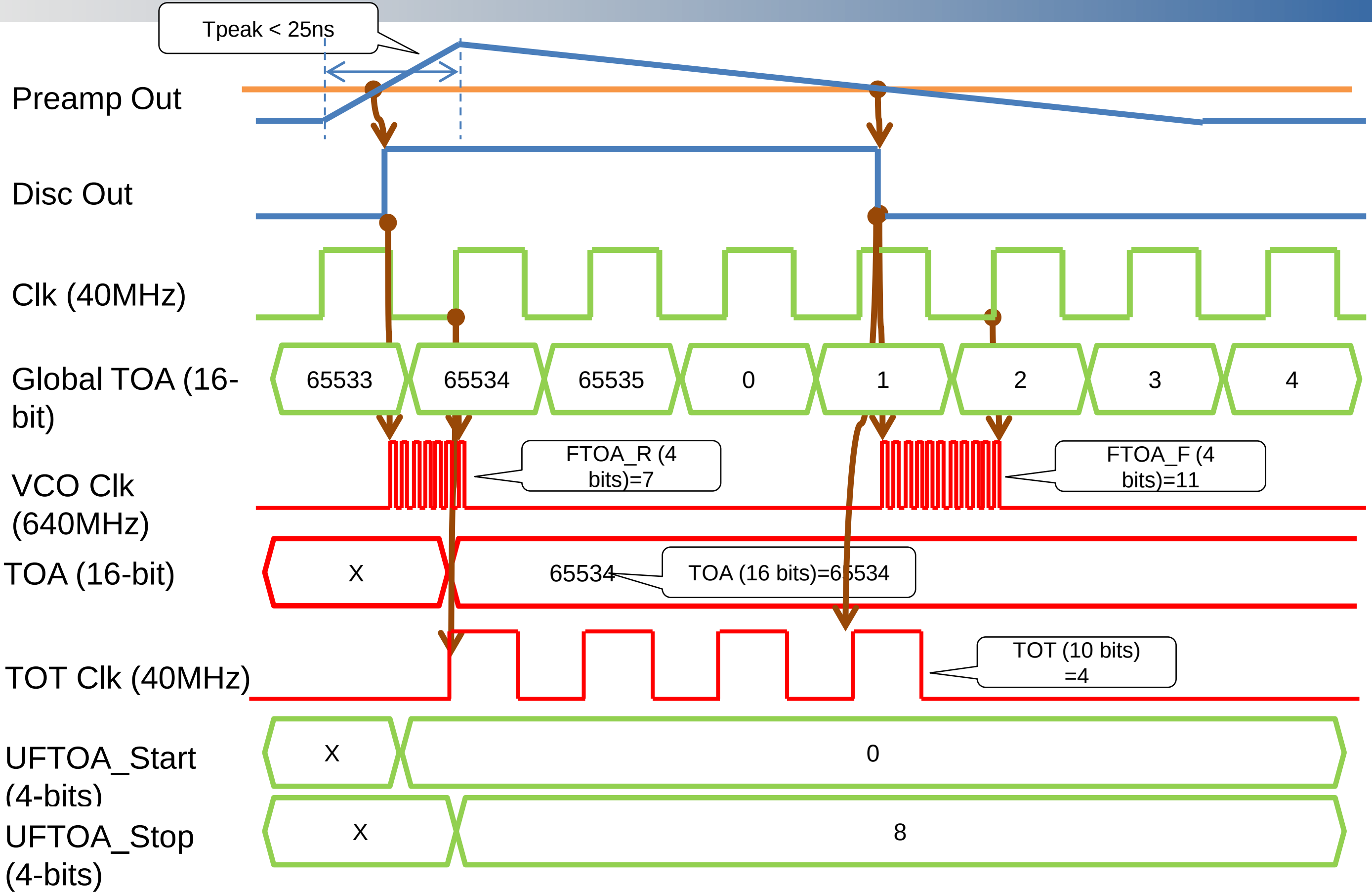
			Timepix3 (2013)	Timepix4 (2018/19)
Technology			130nm – 8 metal	65nm – 10 metal
Pixel Size			55 x 55 µm	55 x 55 µm
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448
Sensitive area			1.98 cm^2	6.94 cm^2
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	
		Event Packet	48-bit	64-bit
		Max rate	<80 Mhits/s	<365 $MHz/cm^2/s$
		Max pix rate	1.3kHz/pixel	10.6kHz/pixel
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr) CRW (8-bit / 16-bit) Up to 44 KHz frame @8b
		Max count rate	82 $Ghits/cm^2/s$	~800 $Ghits/cm^2/s$
TOT energy resolution			< 2KeV	< 1Kev
Time resolution (bin size)			1.56ns	~200ps
Readout bandwidth			≤5.12Gb (8 x SLVS@640 Mbps)	≤163 Gbps (16 x 10.24 Gbps)
Target global minimum threshold			<500 e^-	<500 e^-

Timepix4 Pixel Schematic



	bits
ADDR	9
ToA	16
ufToA_r	4
ufToA_f	4
fToA_r	5
fToA_f	5
ToT	12
Pileup	1

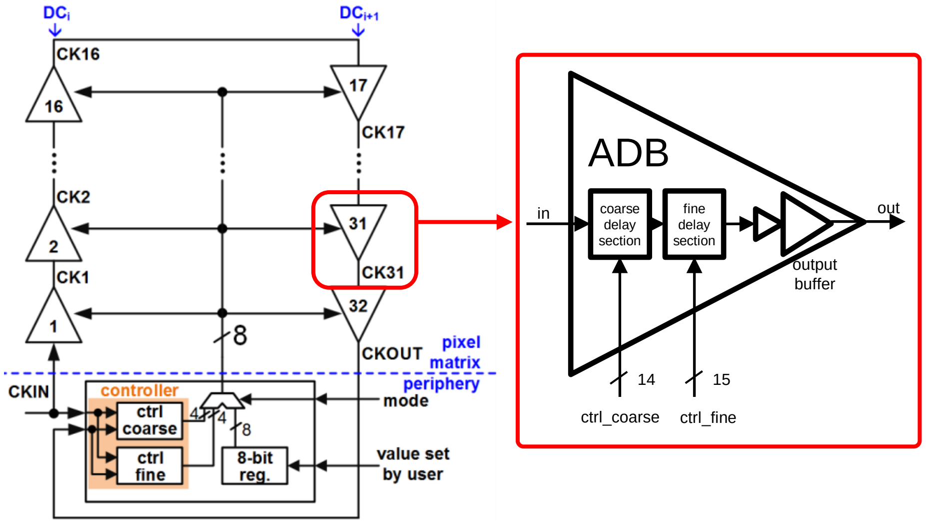
Pixel Operation in TOA & TOT [DD]

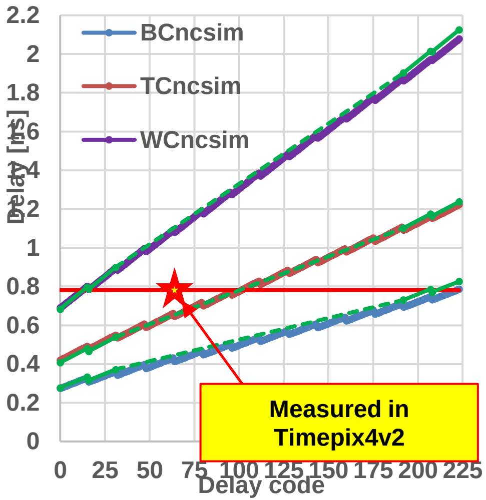


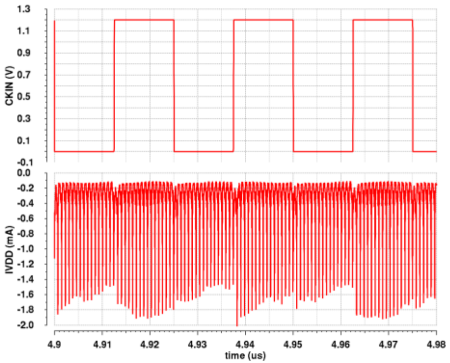
Full digital double column DLL

[448 dDLL: 224 Top Matrix and 224 Bottom Matrix]

iWoRID 2018
X. Llopart et al 2019 JINST 14 C01024



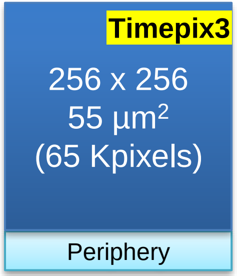


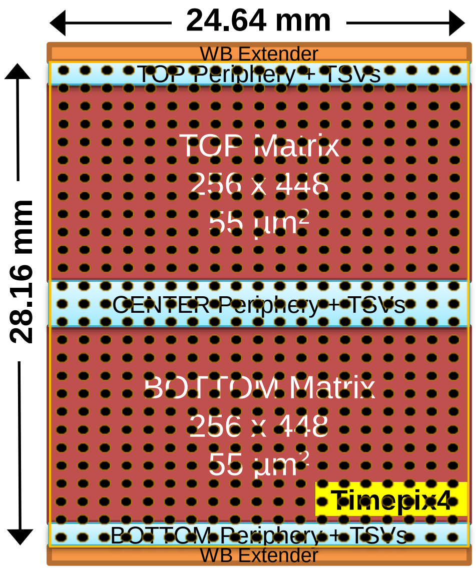


- Timepix4 ~23 mW/cm^2 @40MHz clock with a 100 ps$_{rms}$
- Timepix3 ~100mW/cm^2 @40MHz clock with ~1.2ns skew
- Dynamic digital power consumption is distributed across the clock period

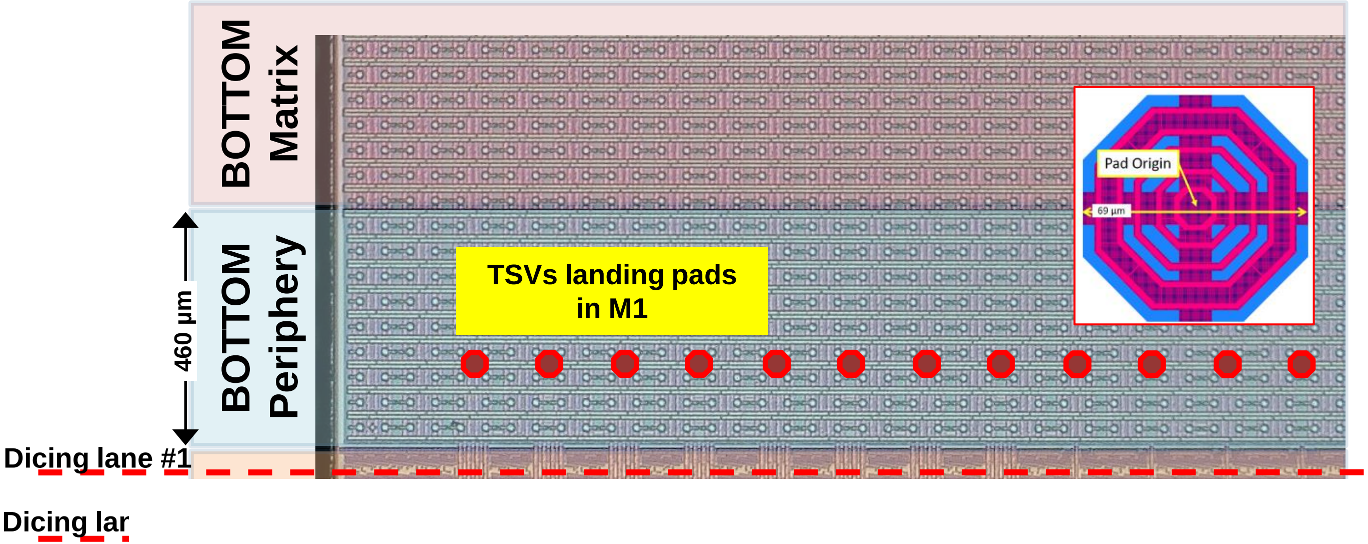
Timepix4 floorplan

- 512 x 448 of 55 x 55 µm pixels
  - 2 Matrices (TOP and BOTTOM)
- 3 ‘peripheries’ with TSV (Through-Silicon-Vias):
  - TOP, BOTTOM (TSV, WB): Data Readout (16x 10.24 Gbps Serializers)
  - CENTER (TSV): Analog Blocks (DACs, ADC, Band-Gap…)
- On-chip bump to pixel redistribution layer (RDL):
  - Pixel matrix pixels are shorter (51.4 µm) than sensor pixels (55 µm)
  - Equalized Cin for all pixels → ~46 fF increase for a 460 µm periphery
- Edge peripheries include 1mm Wire Bond Extender
- Dicing options:
  - With WB (Wire-Bonds Extenders): 29.96 mm x 24.7 mm
    - >93.7% active area (28.16mm x 24.64mm)
  - Without WB (TSV Only) : 28.22 mm x 24.7 mm
    - >99.5% active area (28.16mm x 24.64mm)
    - Through Silicon Vias (TSV) requires post processing at wafer level to create TSV and on the ASIC back sides RDL + BGA pads





Timepix4 Bottom left detail



BOTTOM Matrix

BOTTOM Periphery

460 µm

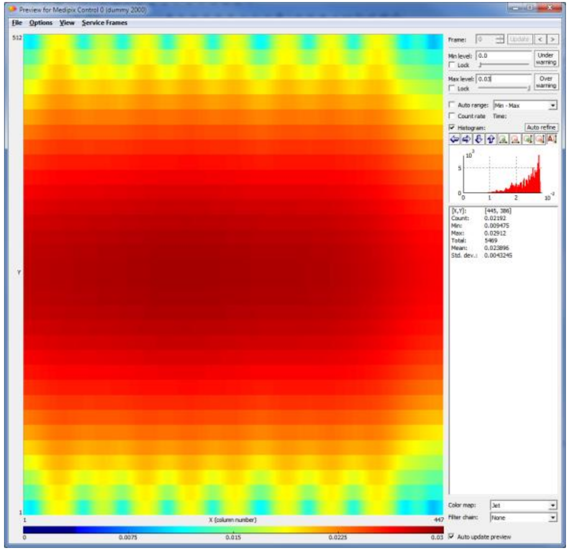
TSVs landing pads in M1

Dicing lane #1

Dicing lar

Analog (static) power supply distribution

	Total I (chip)		2 WB	3 TSV
Nominal Analog Power **[10 µA/pixel]**	**~2300 mA**	V_{drop} [VDDA-GNDA]	**19.6 mV**	**6.9 mV**
		Imax pad	**60 mA**	**57 mA**
Low Analog Power **[1 µA/pixel]**	**~230 mA**	V_{drop} [VDDA-GNDA]	**1.96mV**	**0.69mV**
		Imax pad	**6 mA**	**5.7 mA**



Frame: 0

Min level: 0.0 ☐ Lock

Max level: 0.03 ☐ Lock

☐ Auto range: Min - Max

☐ Count rate Time:

☑ Histogram:

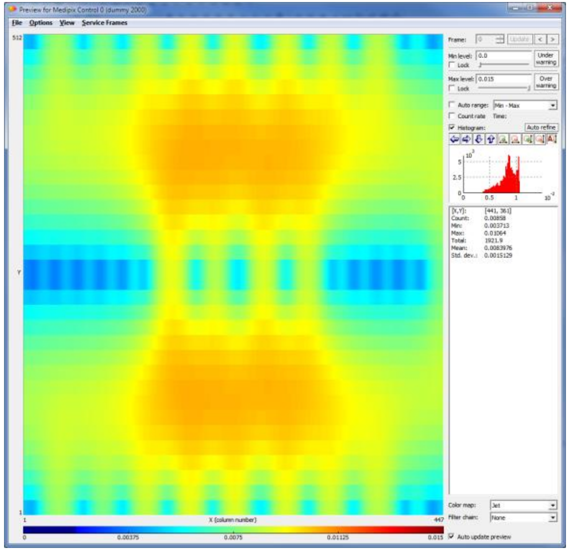
[X,Y]: [445, 386]
Count: 0.02192
Min: 0.009475
Max: 0.02912
Total: 5469
Mean: 0.023896
Std. dev.: 0.0043245

Color map: Jet

Filter chain: None

☑ Auto update preview

2 wire bonds



Frame: 0

Min level: 0.0 ☐ Lock

Max level: 0.015 ☐ Lock

☐ Auto range: Min - Max

☐ Count rate Time:

☑ Histogram:

[X,Y]: [441, 361]
Count: 0.00858
Min: 0.003713
Max: 0.01064
Total: 1921.9
Mean: 0.0083976
Std. dev.: 0.0015129

Color map: Jet

Filter chain: None

☑ Auto update preview

3 TSV

Timepix4 submissions

Q4 2019

Timepix4v0

Full mask engineering run

6 wafers received

Chip is operational

1) Excess noise coupling from peripheries to FE
2) 640 MHz clock in edge peripheries
3) VCO not oscillating at nominal frequency

Q3 2020

Timepix4v1

4 BEOL masks changed

Small test VCO chip

6 wafers received

1) Improved RDL shielding in peripheries
2) 640MHz in peripheries recovered

1) VCO not oscillating at nominal frequency

Q2 2021

Timepix4v2

4 FEOL + 4 BEOL masks changed

19 wafers received

1) TDC and High speed links working as expected
2) Further improvement in RDL shielding in peripheries

Chip at its final version

Q3 2022

Timepix4v3

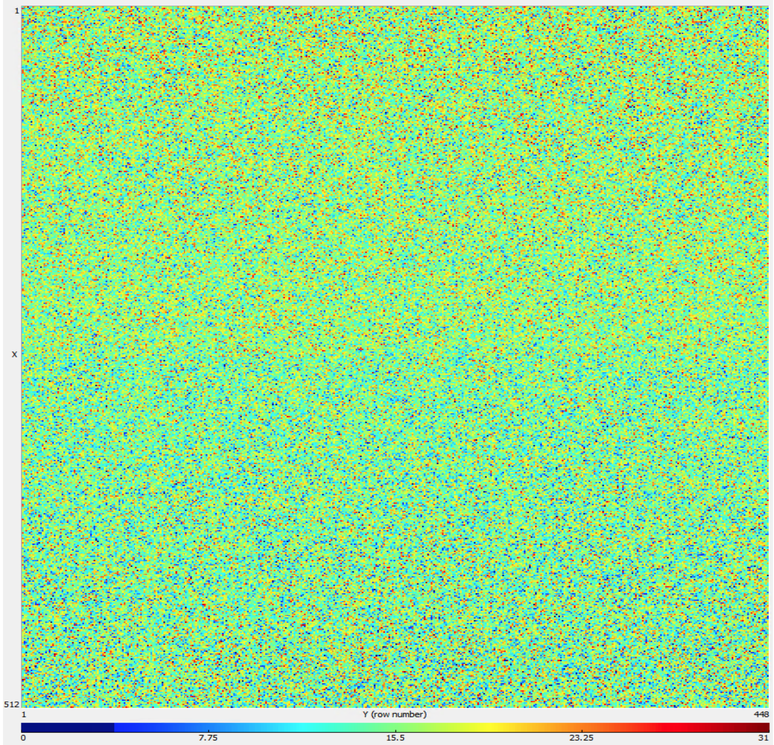
2 BEOL masks changed

25 wafers received

1) Larger IO Pads

Chip at its final version

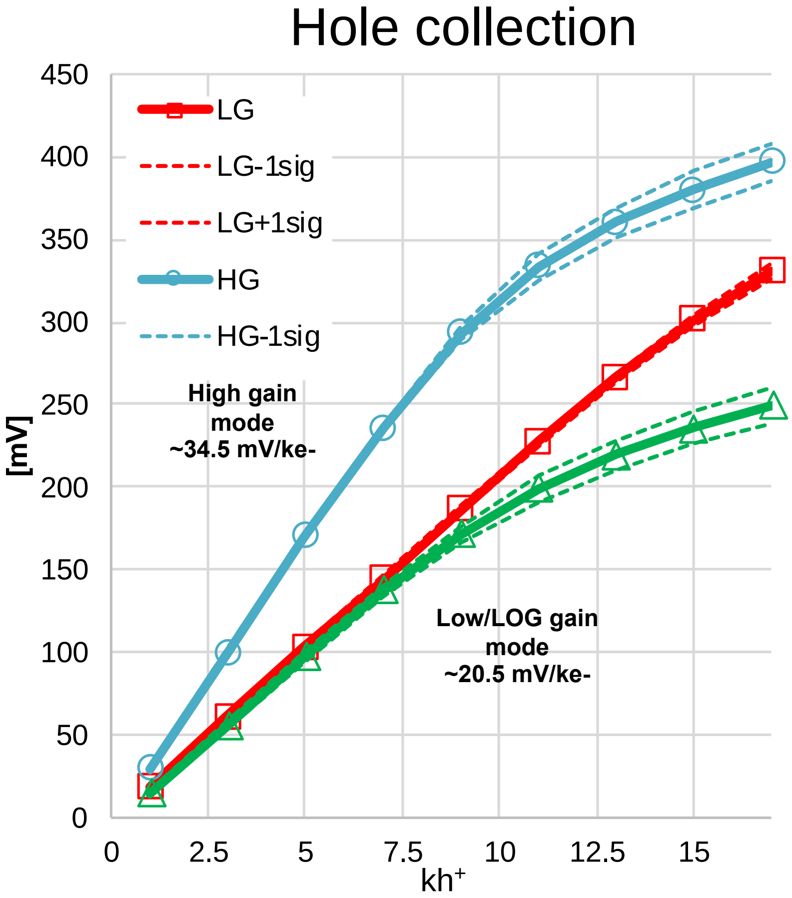
Uniformity of response Timepix4 (all versions)

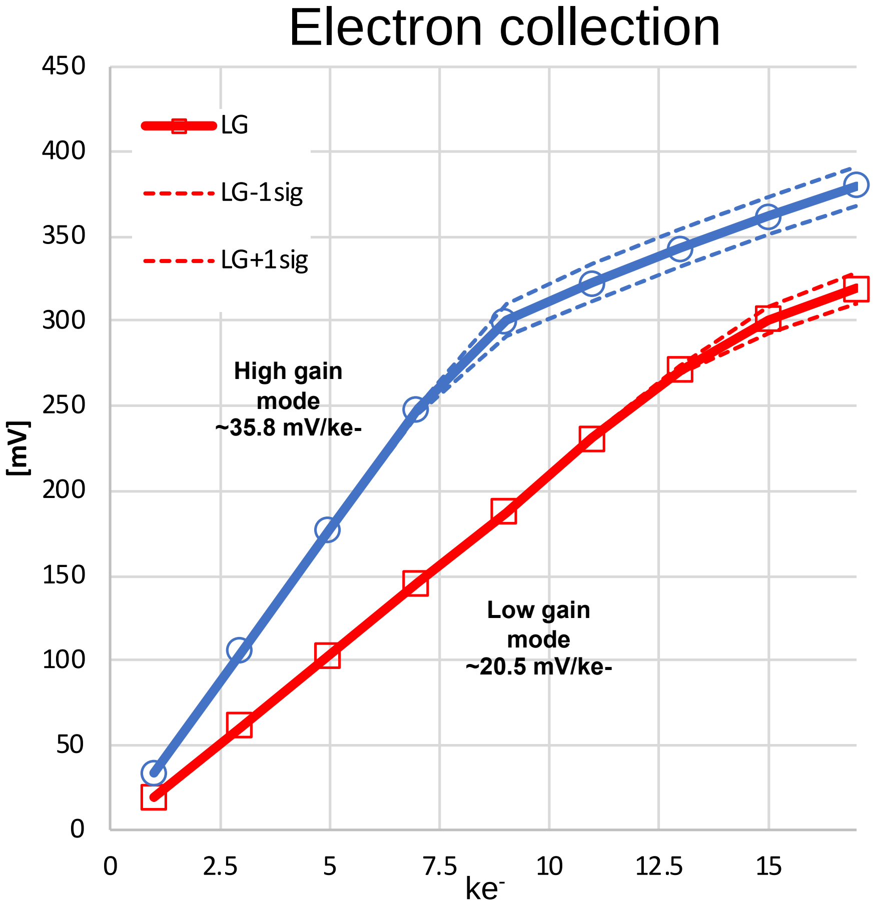


Threshold adjustment bits

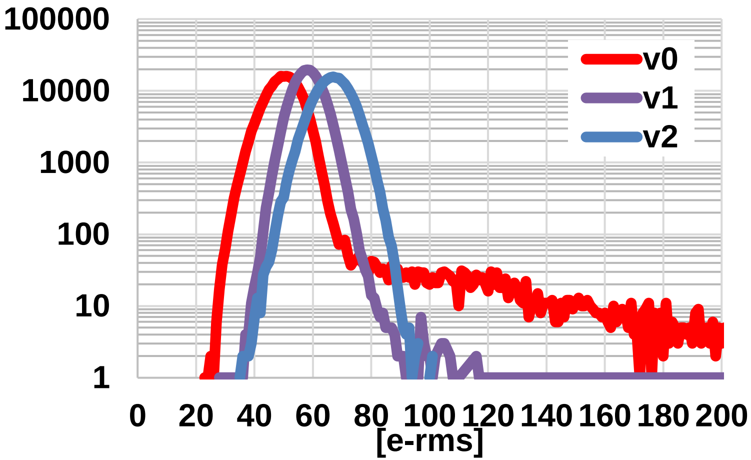
Gain slopes for different FE Gain

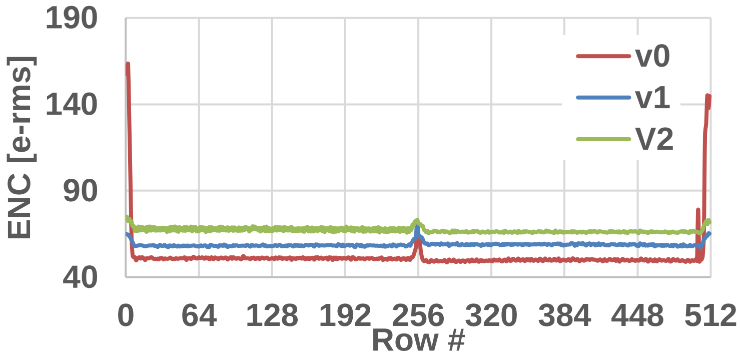
[TOA-TOT, few pixels]

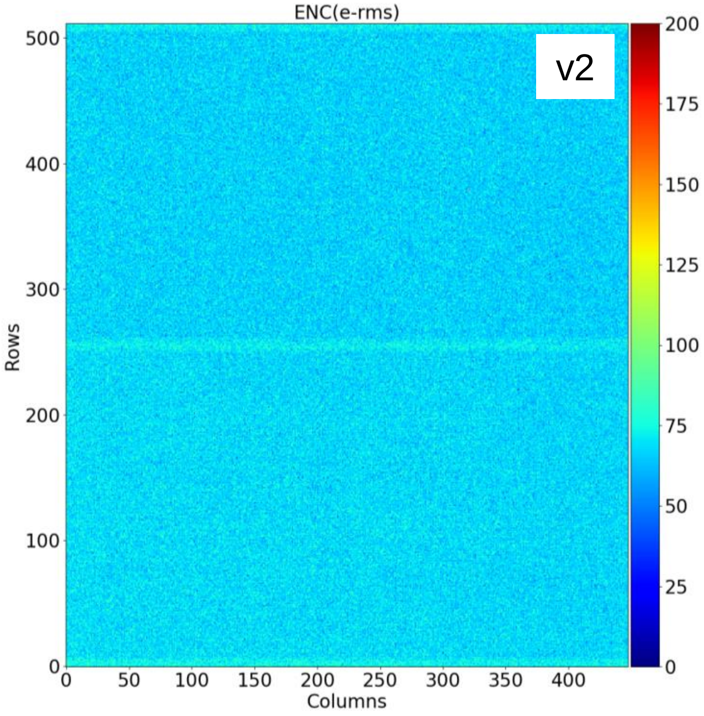




Noise uniformity - Timepix4v0, v1 and v2



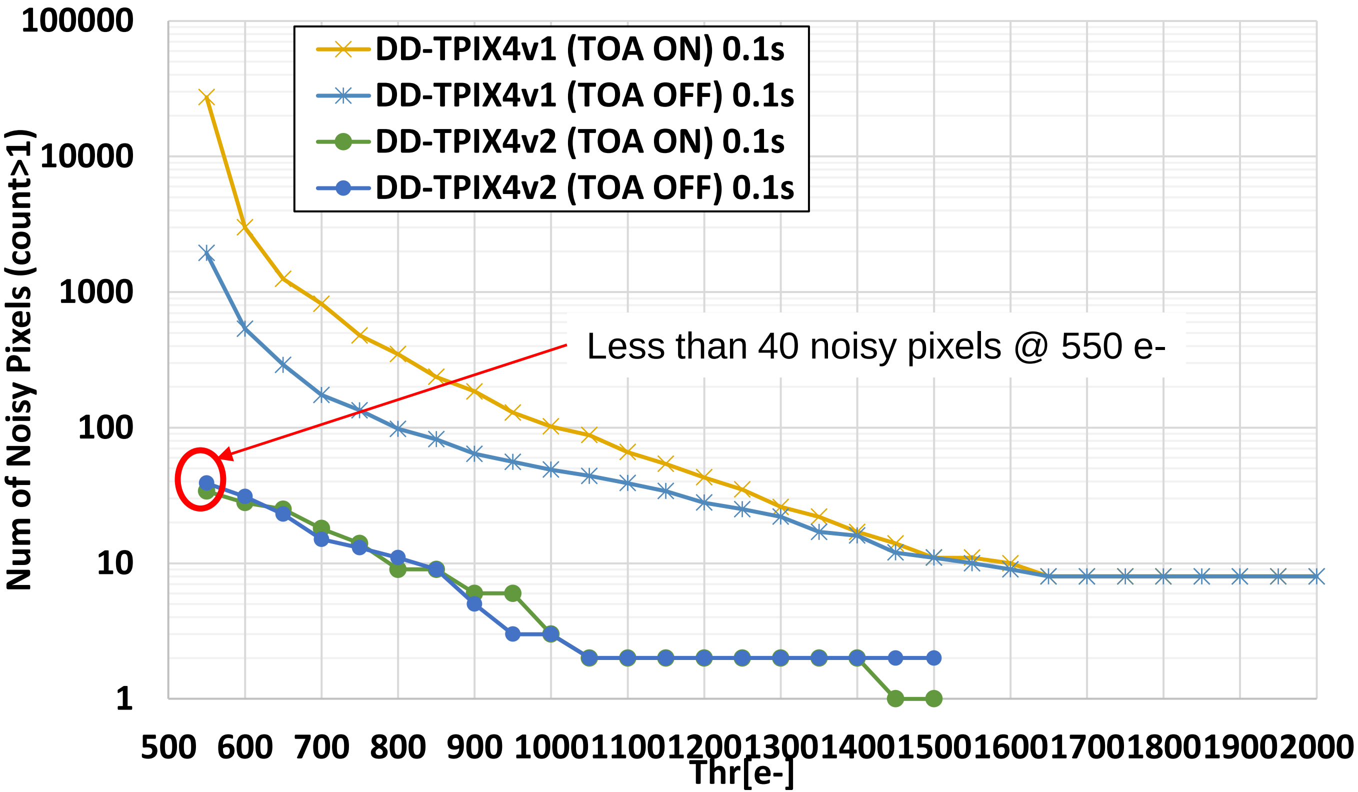




When a Si sensor is attached the noise slightly increase ~3e$^-$ / pixel

Timepix4v1 and v2: Number of Noisy pixels (>1 count)

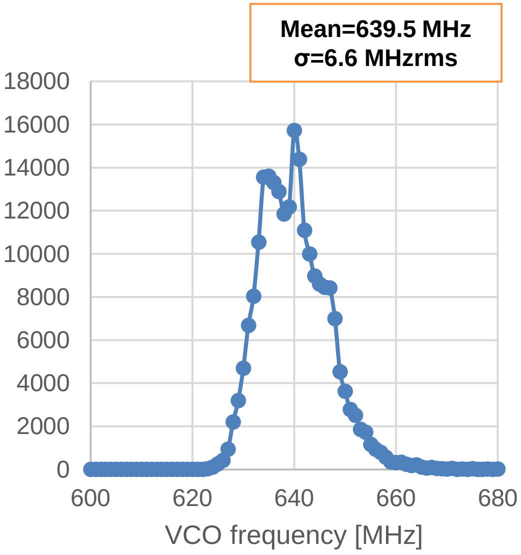
Data-Driven mode [DD]



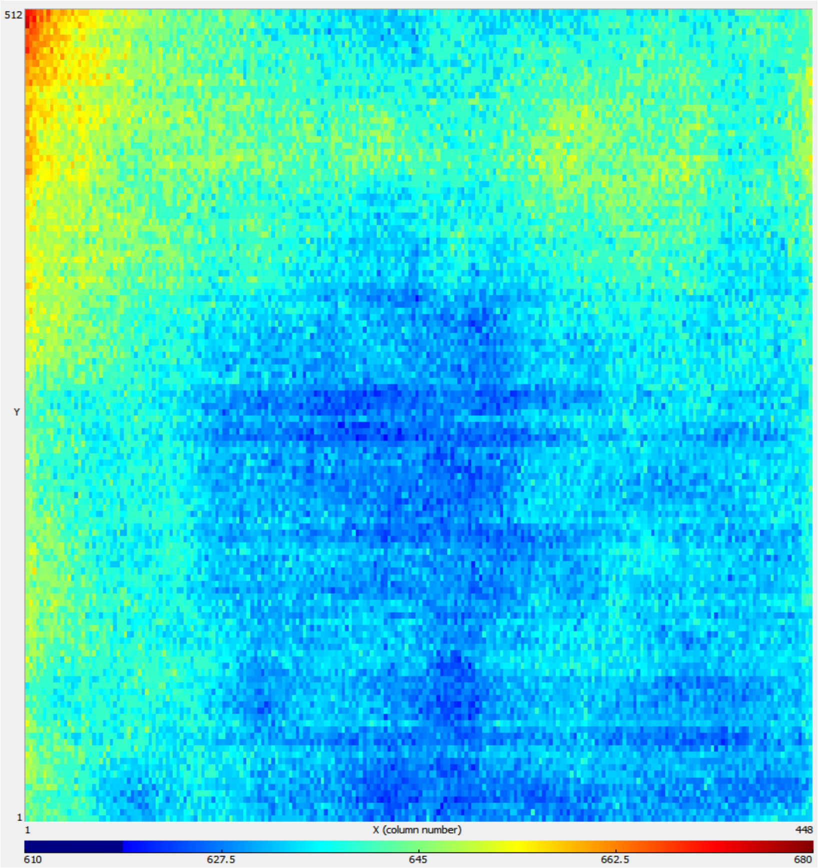
Less than 40 noisy pixels @ 550 e-

Timepix4v2 2D VCO frequency distribution

- Measured VCO oscillation frequency in Timepix4
- Calibration is required in order to get to the designed time resolution (~60psrms)
- How could this be improved/simplified?

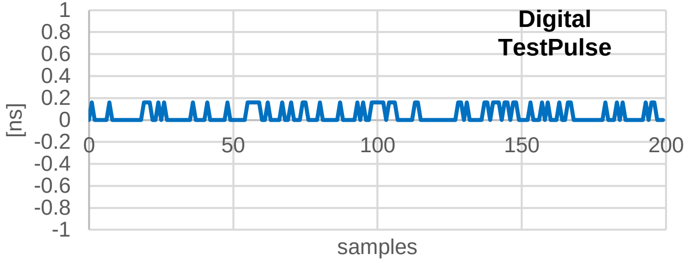


Mean=639.5 MHz
σ=6.6 MHzrms

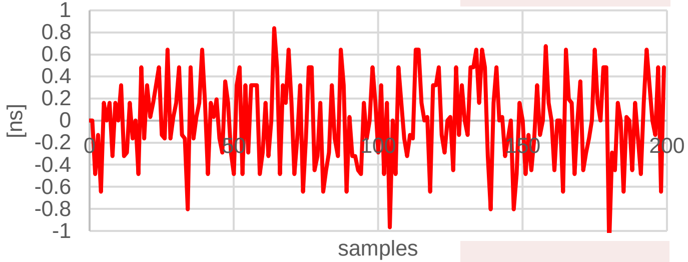


TOA Resolution

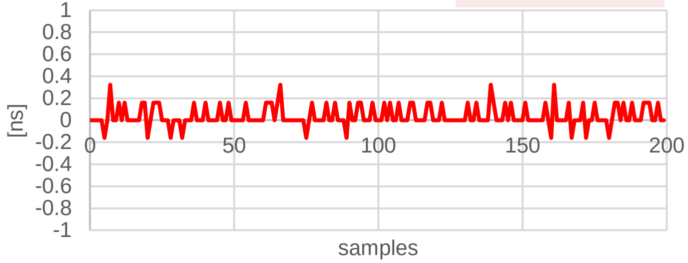
[TOA-TOT, 1 pixel, 10000 samples, HG e-]

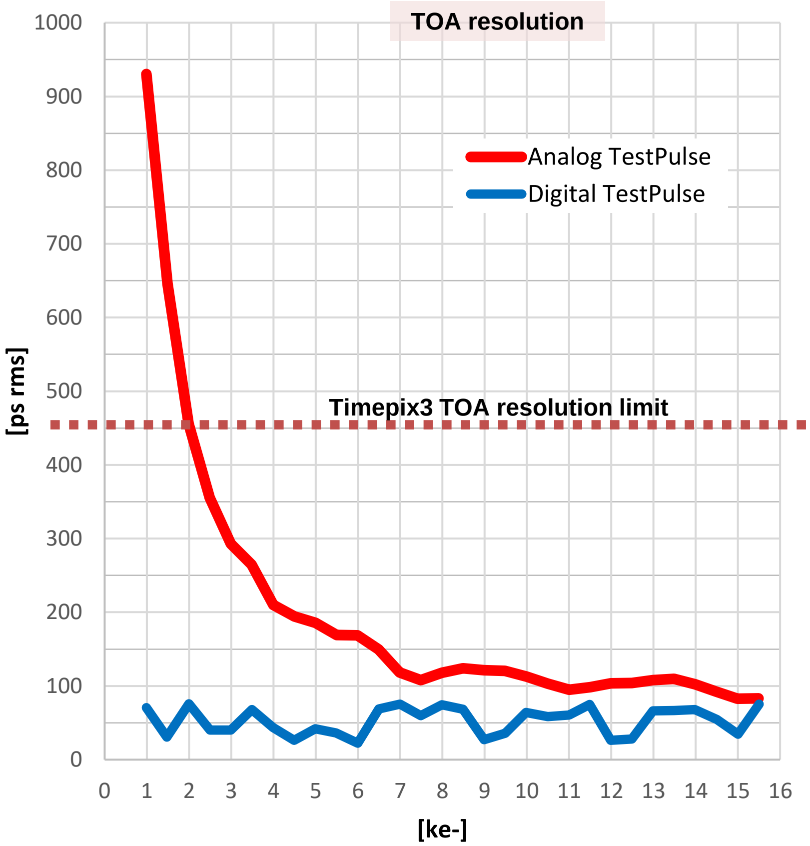


TPulse=2 ke-

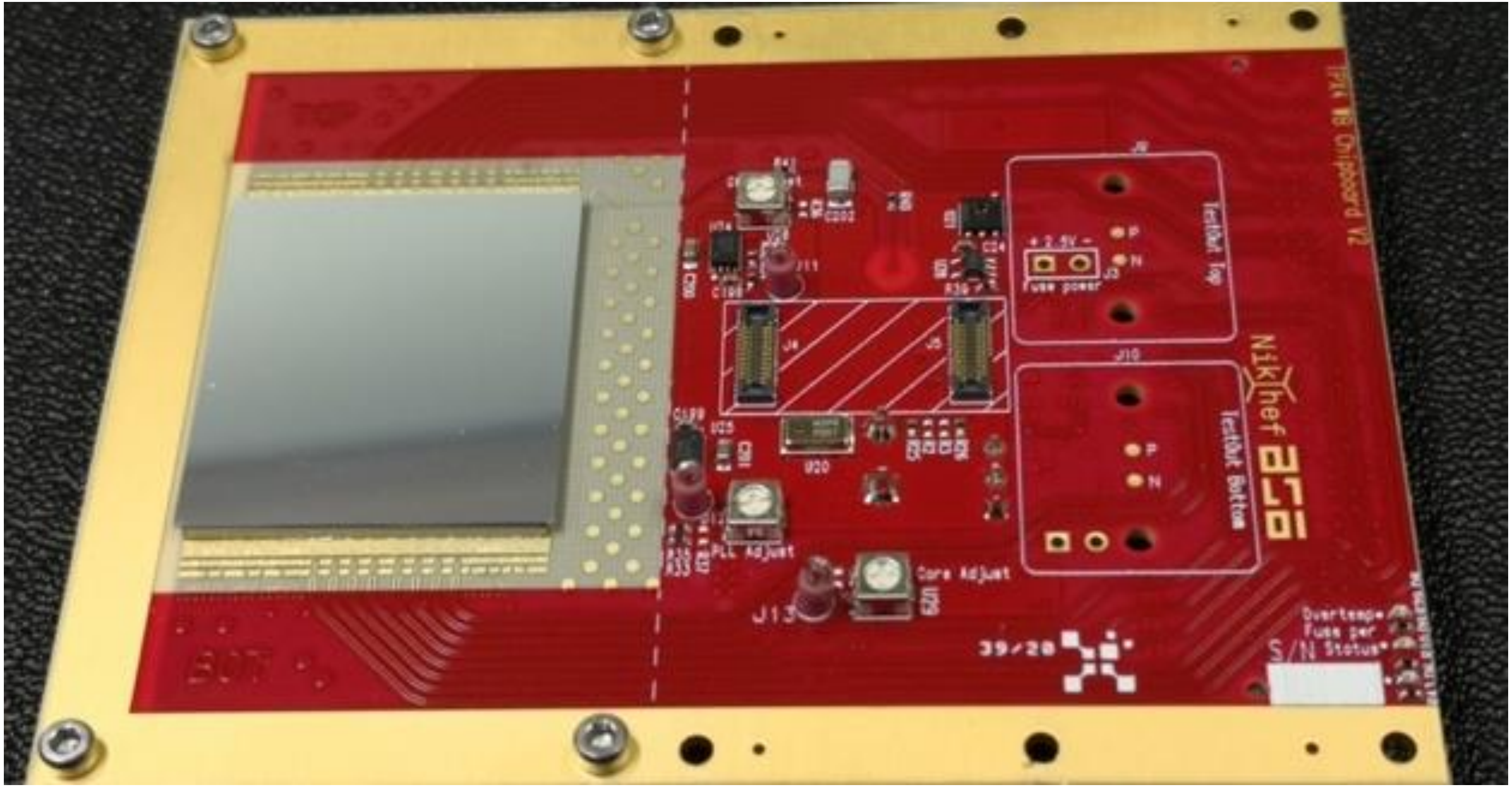


TPulse=15 ke-

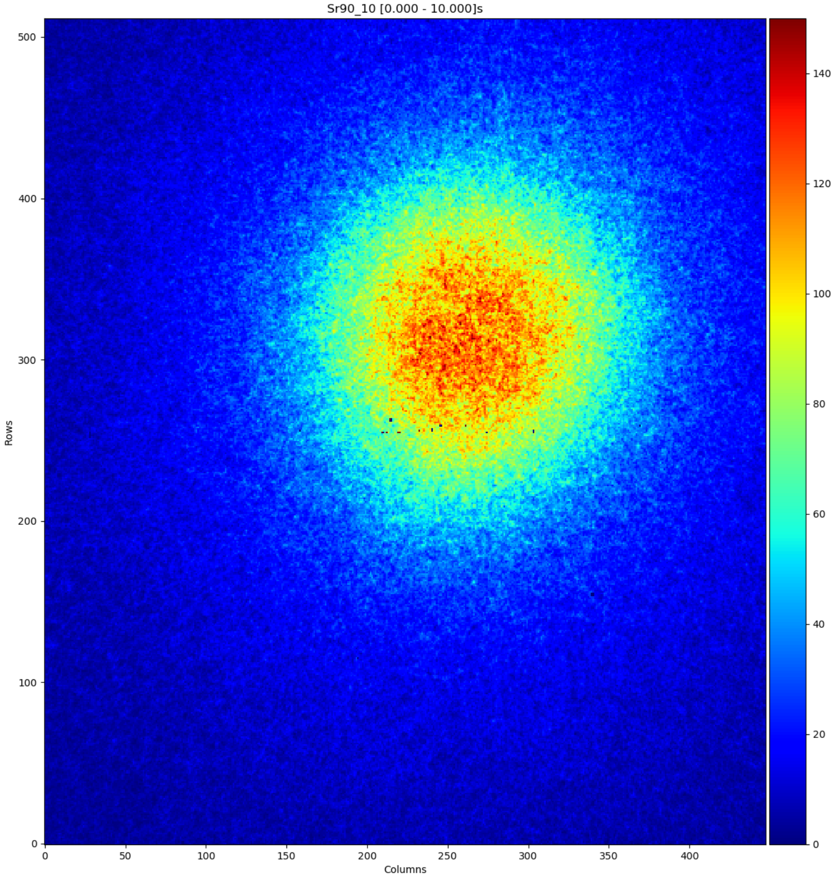




Timepix4 assembly (300μm Si sensor)



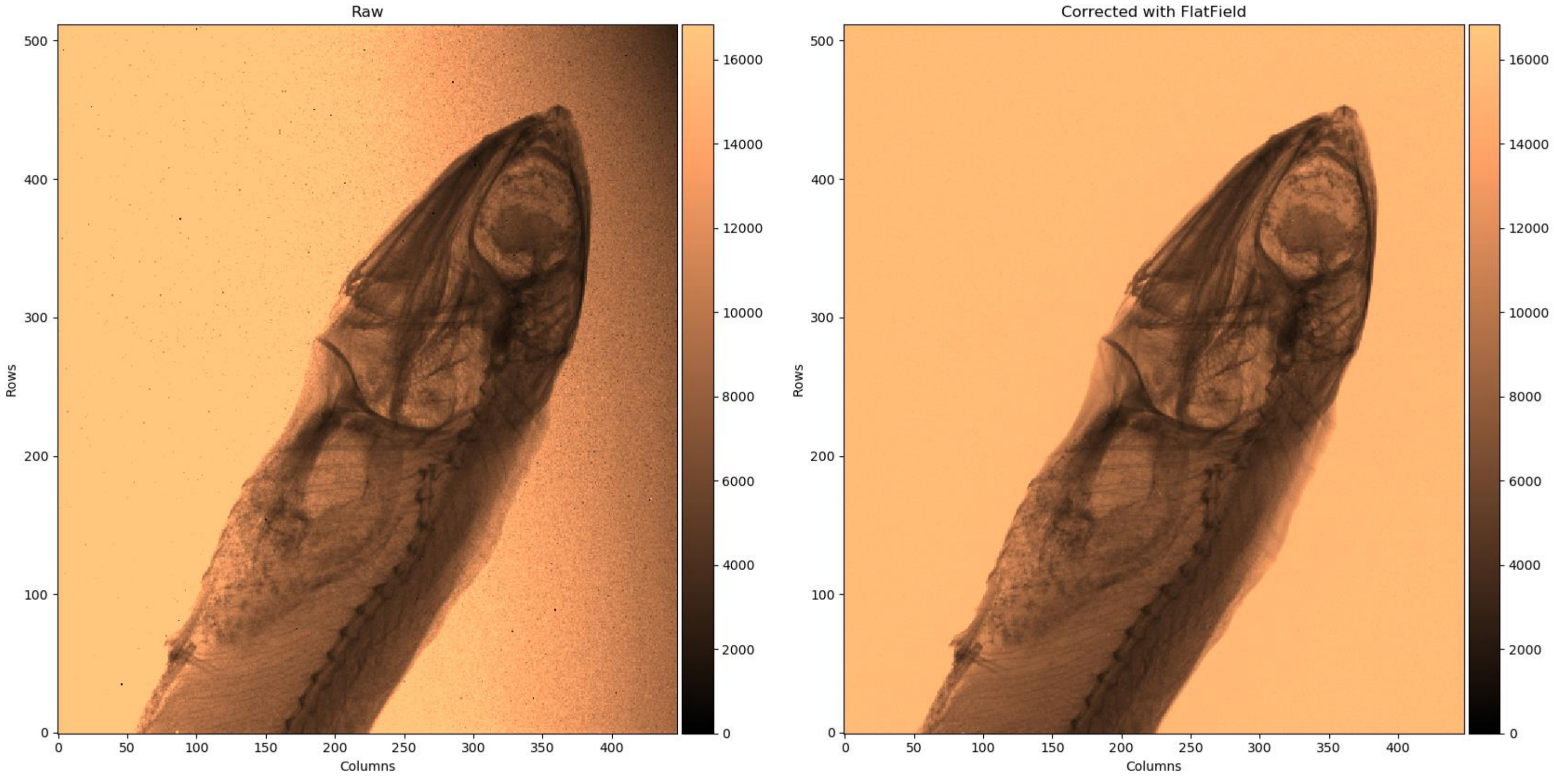
Data driven mode



10s exp. ^{90}Sr

Threshold ~ 800e^{-}
6.1 M packets @ 5 Gbps

Photon counting image Timepix4

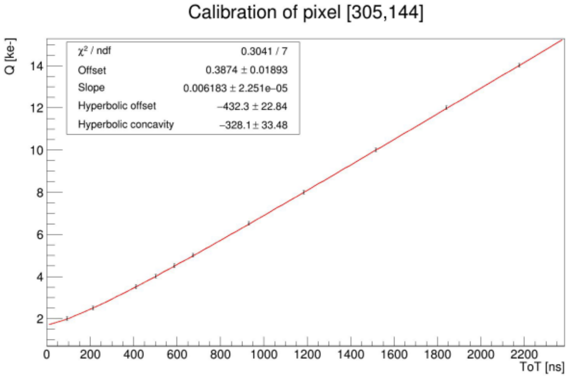


Raw

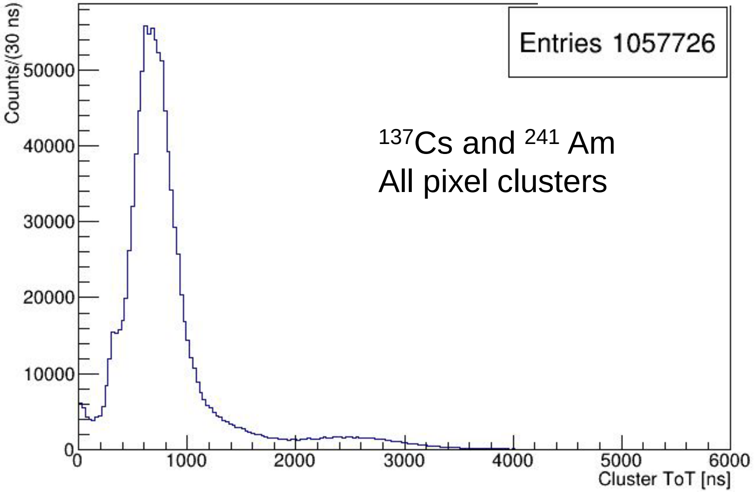
Corrected with FlatField

Energy calibration using test pulses

R. Bolzonella et al., TIPP Cape Town, 4-8 Sept
Under submission to JINST

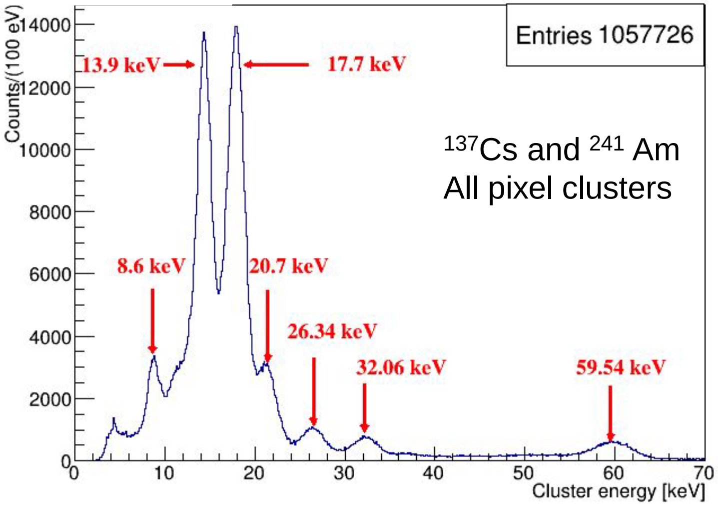


Per-pixel energy vs ToT calibration using test pulses



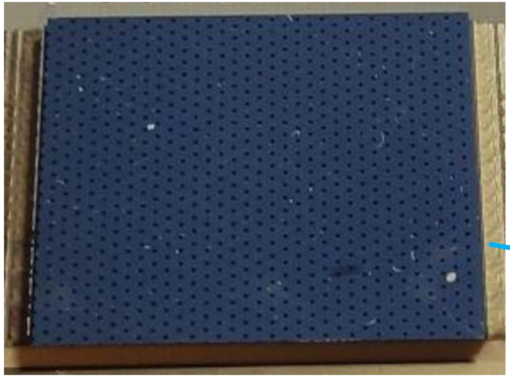
^{137}Cs and ^{241} Am
All pixel clusters

After test pulse calibration

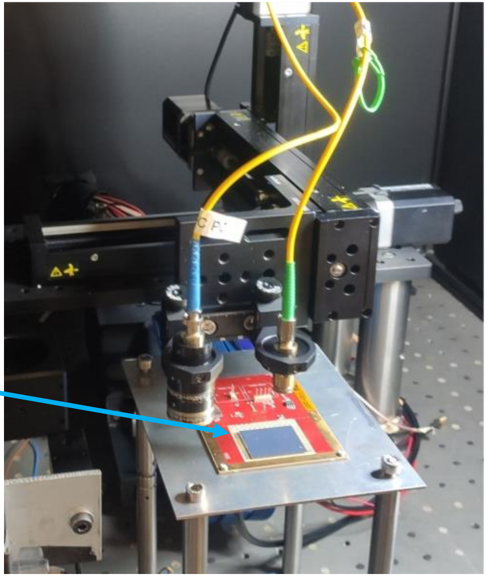


^{137}Cs and ^{241} Am
All pixel clusters

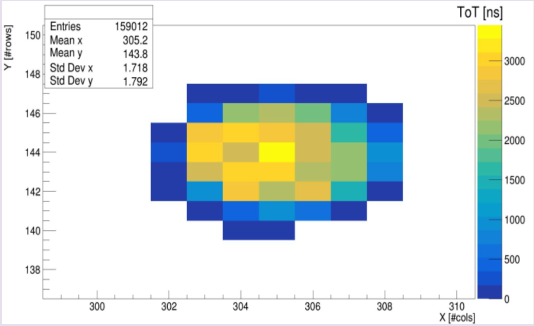
Timing test setup with laser



- Rear side metallization with holes
- Timepix4V2 bonded to a 100µm thick n-on-p Si detector:
- Biased at -150 V



- 1020nm laser pulsed with 6ps jitter generator
- Generator connected to electrical test pixels



- σ = 1.4 pixel = 77 µm
- most of the charge is released in 4-5 pixels
- Wide range of released charge covered

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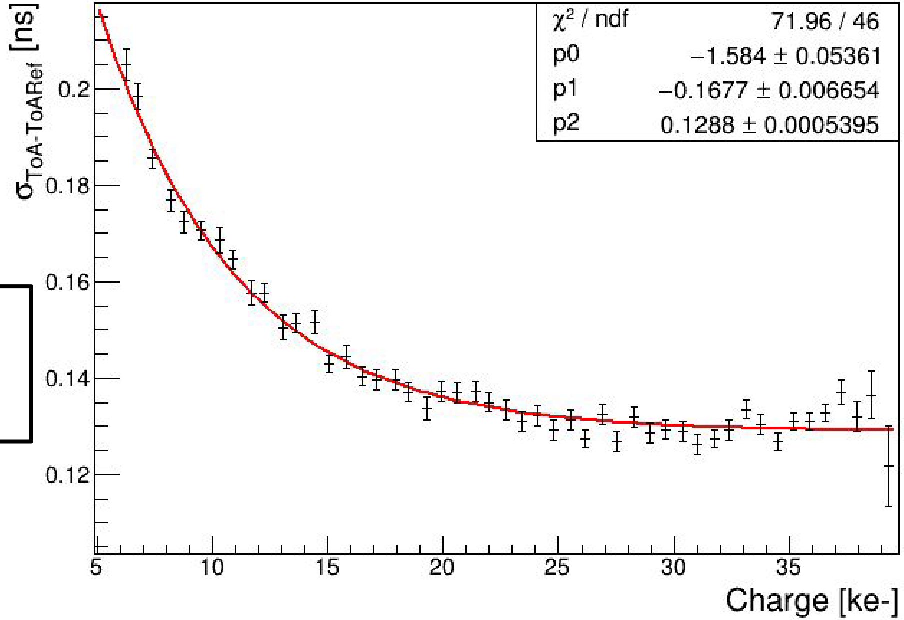
Under submission to JINST

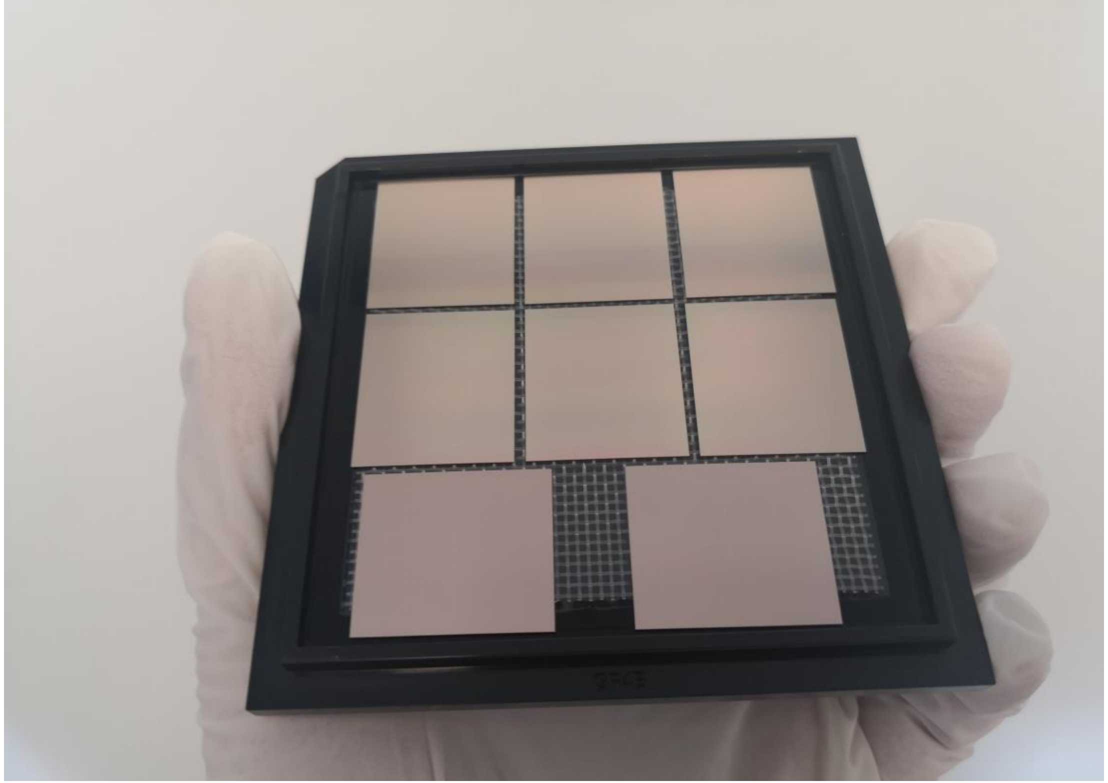
Single pixel pulse resolution



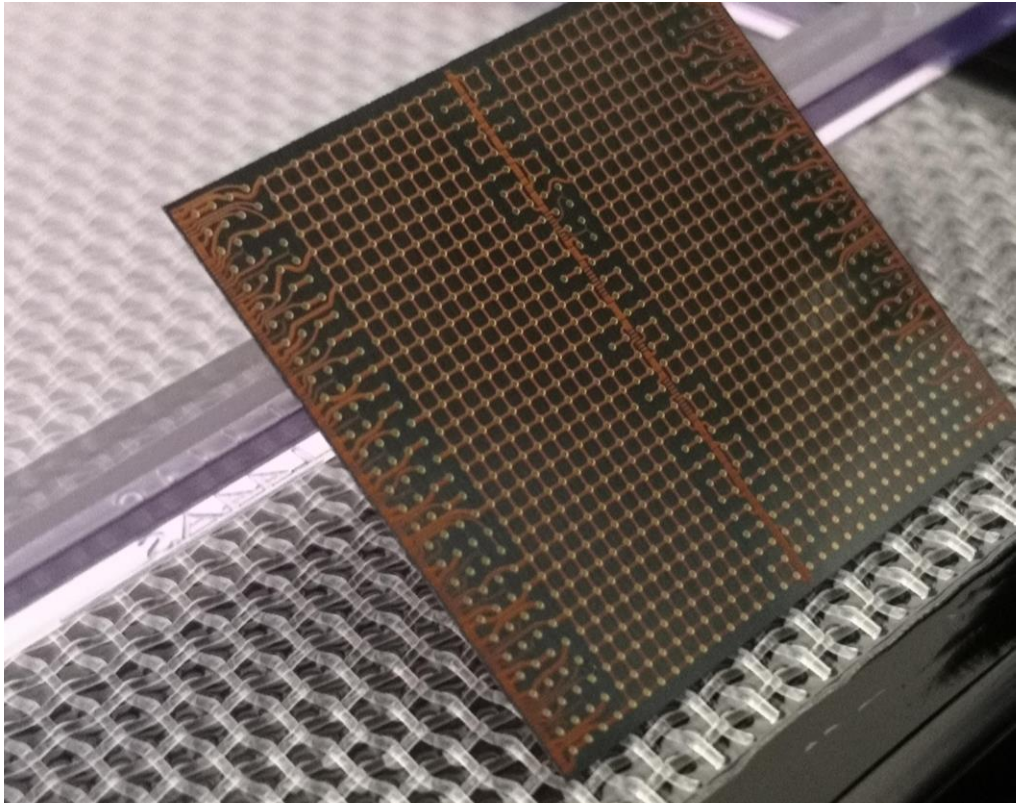
R. Bolzonella et al., TIPP Cape Town, 4-8 Sept
Under submission to JINST

- For the pixel [305,144], where the laser is focused, the standard deviation saturates at 129±1 ps rms
- Subtracting the contribution of the reference TDC (60 ps), a resolution of 111±1 ps rms is obtained
- Timing resolution dependency on cluster charge best result: $\sigma_{ToADiffAvg}$=79 ± 1 ps rms
- Timing resolution subtracting reference TDC contribution: σ_{ToAAvg}=49 ± 1 ps rms

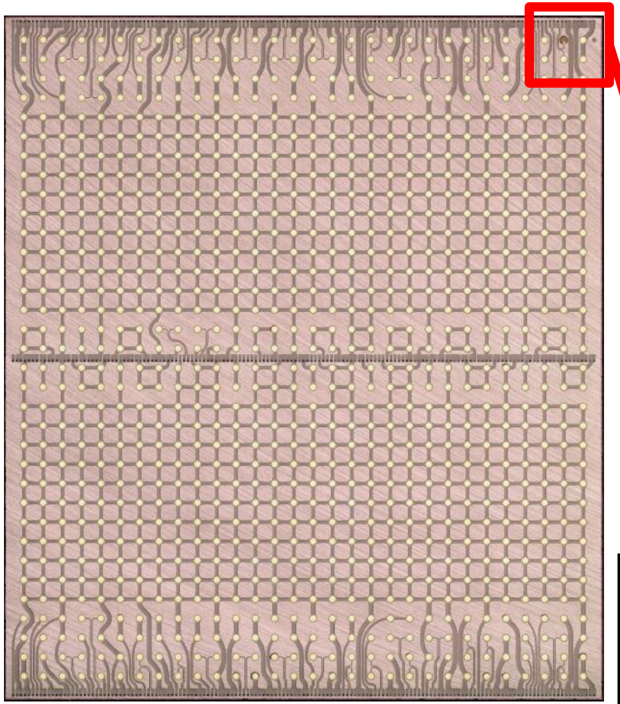
June 2023 – TSV processes TPIX4v0 delivered



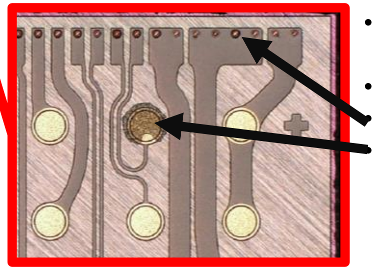
Rear side Re-Distribution Layer (RDL)



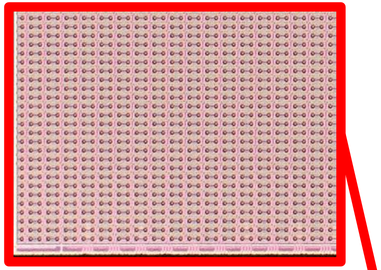
Visual Inspection – front and rear side



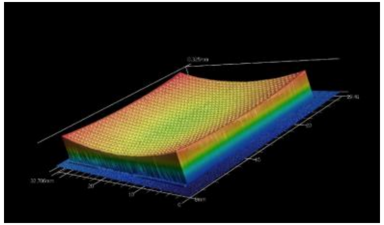
Back Side

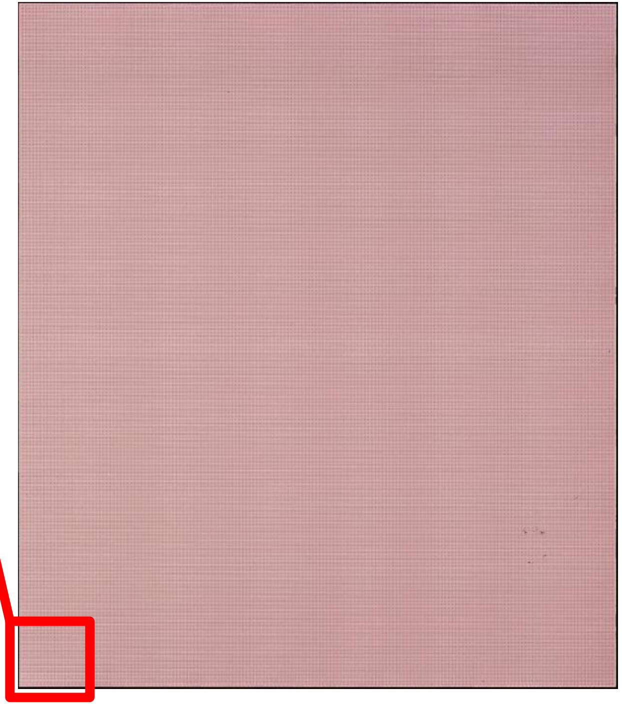


- Redistribution Layer
- 1020 BGA pads
- TSV
- Residues of dicing tape



Pixel side

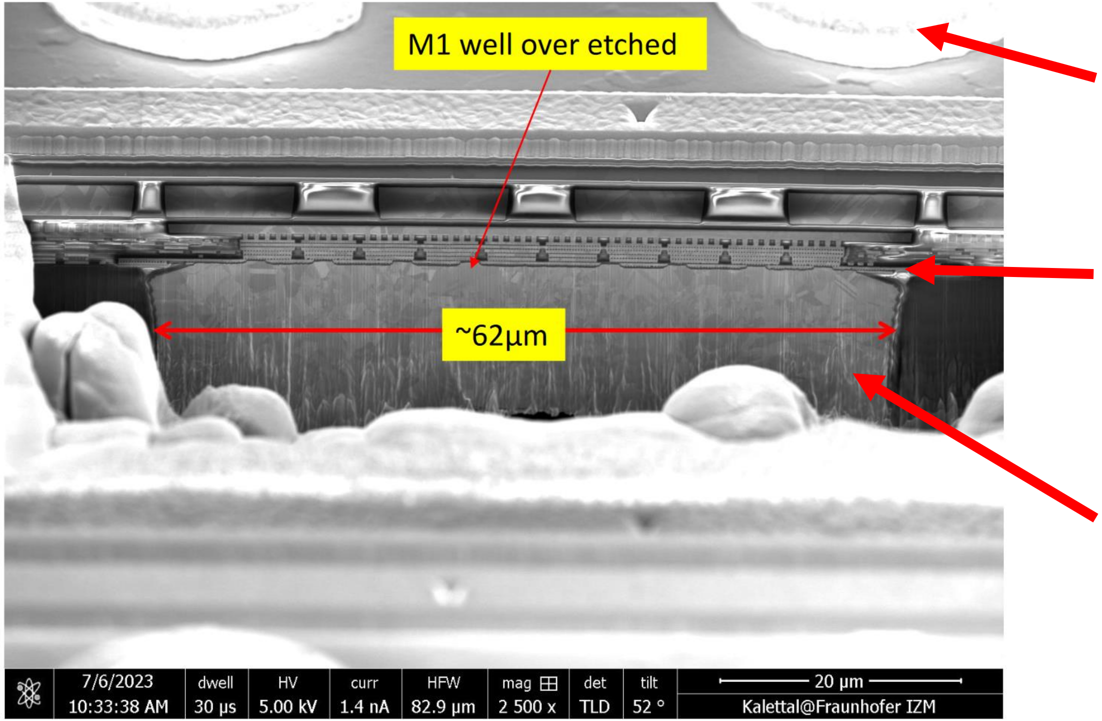




Front Side

Chip bow ~ 100μm (over 3cm)
Magnified bowing (the chip is thin: ~120μm)

Inspection with Electron Microscope of one TSV



Pixel pads

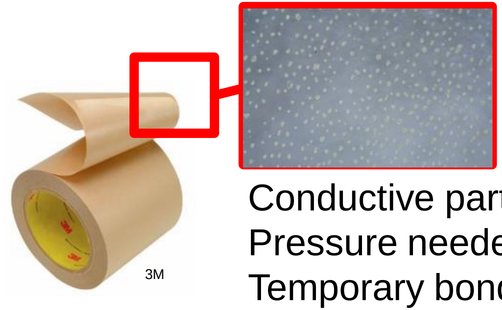
Landing pad of the TSV

Bottom of the TSV

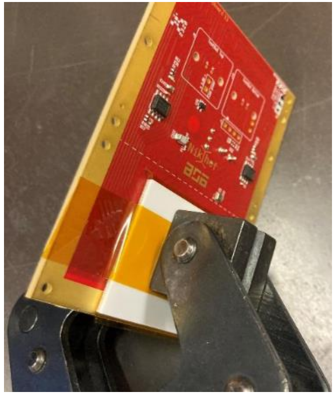
Courtesy of IZM

Mounting of TSV processed chips on Nikhef carrier board

ACF: Anisotropic Conducting Film

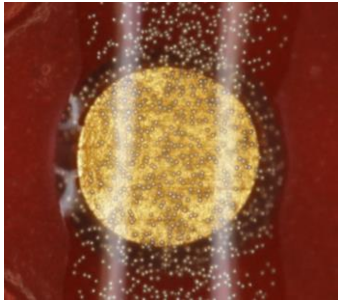


Conductive particles
Pressure needed
Temporary bonding

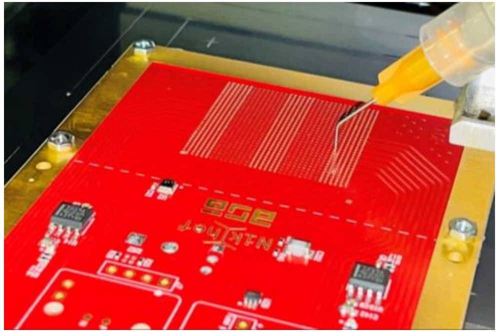


- We could communicate with the chip, test the DAC…
- After releasing the clamp and putting it again, chip not responding, maybe due to reusing the tape.
- Work in progress

ACP: Anisotropic Conducting Paste

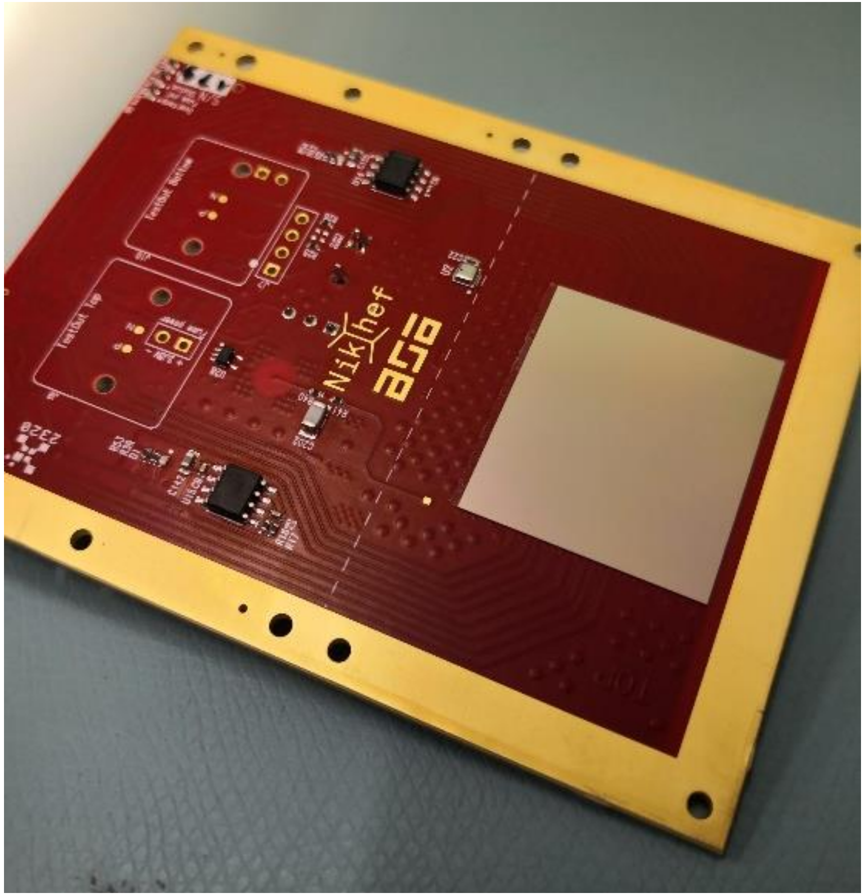


- Araldite with conducting particles
- Done at UniGe (Mateus Vicente Barreto Pinto m.vicente@cern.ch)
- Flip chip bond machine



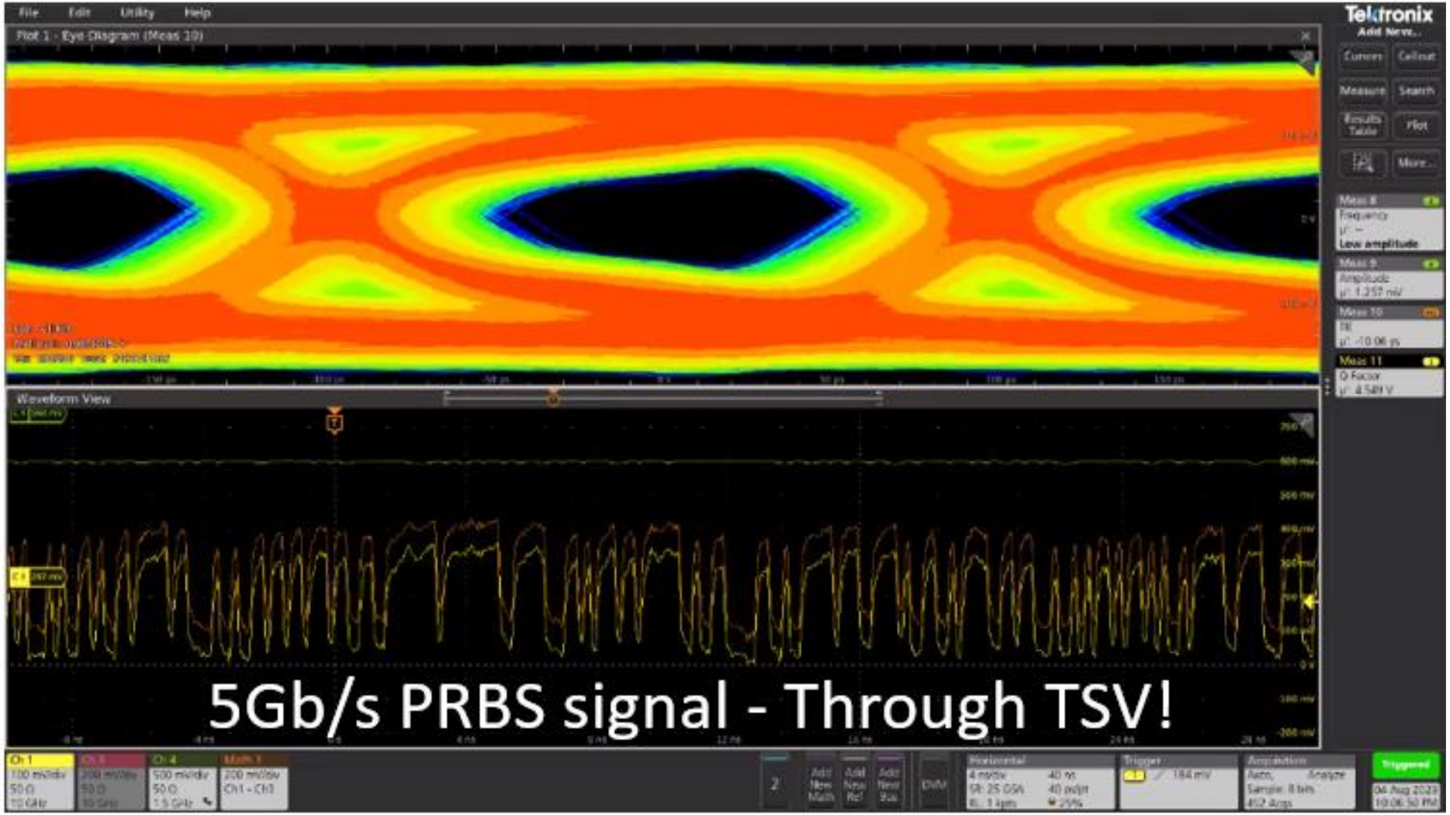
- Results Timepix4V0:
- Good communication with the chip
- Promising low cost approach

TSV-processed successfully mounted



Chip behaves identically to a wire bonded version

Output from TSV processed Timepix4v0



5Gb/s PRBS signal - Through TSV!

Medipix3 → Medipix4

	Medipix3RX (2013)	Medipix4 (2022)
Technology	CMOS 130nm	CMOS 130nm
Pixel Size	55/110 µm	75/150 µm
Matrix Size	256 x 256 / 128 x 128	320 x 320 / 160 x 160
Tile-ability	3-side	4-side buttable
Thresholds	1/4 Continuous RW	2/8 Continuous RW
Readout scheme	Sequential RW & Continuous RW	
Count Rate (10% deadtime loss)	4.3 x 10^6 ph/mm^2/s (CSM 110)	19 x 10^6 ph/mm^2/s (CSM 140)
Dynamic Range	25 Ke-	32 Ke-
CSM energy resolution (FWHM)	~ 4.4 KeV (CSM 110)	~ 2.5KeV (CSM 150)
Readout bandwidth	<1.6 Gbps (8x LVDS)	1,2 Serializers @5.12 or 2.56 Gbps
Power	<1W @1.5V	<1W/cm^2 @1.2V

Status: Medipix4 chip first version under test – bugs being addressed

Conclusions

- Hybrid pixel detectors offer unique solutions for X-ray and gamma-ray imaging and have found widespread applications
- The Timepix4 (and Medipix4) chips are designed explicitly for tiling in 2 dimensions using Through Silicon Vias for IO
- Measurements with Timepix4 in data driven mode are consistent with the design values
- Single pixel time resolution is ~111ps rms
- TSVs have been successfully implemented on Timepix4v0 and the chip behaves as normal
- Future work includes demonstrating a large area implementation with minimal dead area

Thank you for your attention!

Medipix3RX images: S. Procz et al.