THE TIMEPIX FAMILY OF PIXEL DETECTOR READOUT CHIPS

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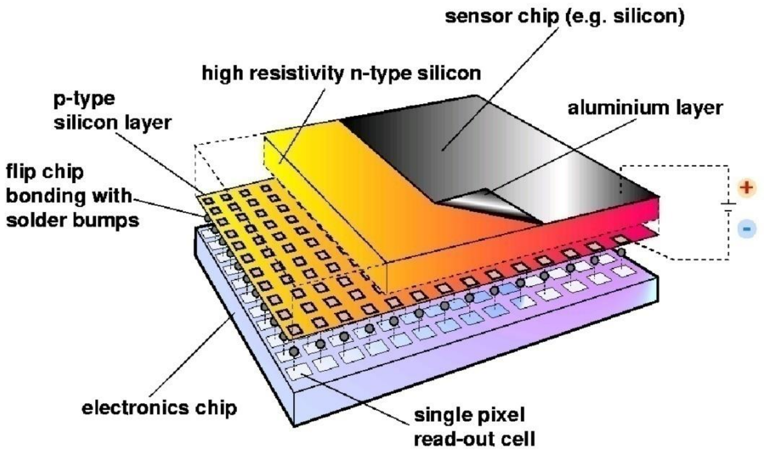
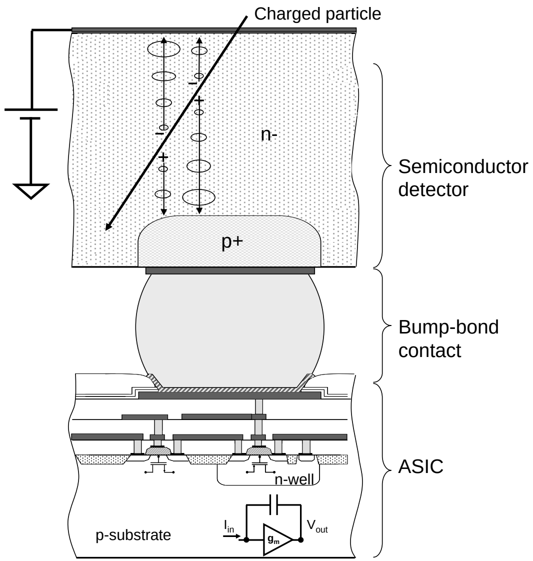
Hybrid Silicon Pixel Detectors





- Noise-hit free images possible (high ratio of threshold/noise)
- Standard CMOS can be used (follow industry)
- Sensor material can be changed (Si, GaAs, CdTe..)
- Semiconductor sensor can be replaced by a gas gain grid or MCP

Acknowledgements – Collaboration Members

COLLABORATION NAME	Medipix2	Medipix3	Medipix4
ASICS	**Medipix2 Timepix Timepix2**	**Medipix3 Timepix3**	**Medipix4 Timepix4**
Albert-Ludwig Universität Freiburg, Germany	X	X	X
AMOLF, Amsterdam, The Netherlands		X	
Brazilian Light Source, Campinas, Brazil		X	
CEA, Paris, France	X	X	X
CERN, Geneva, Switzerland	X	X	X
Czech Academy of Sciences, Prague, Czech Republic	X		
DESY-Hamburg, Germany		X	X
Diamond Light Source, England, UK		X	X
ESRF, Grenoble, France	X	X	
IEAP, Czech Technical University, Prague, Czech Republic	X	X	X

Acknowledgements – Collaboration Members

COLLABORATION NAME	Medipix2	Medipix3	Medipix4
ASICS	**Medipix2 Timepix Timepix2**	**Medipix3 Timepix3**	**Medipix4 Timepix4**
IFAE, Barcelona, Spain	X		X
KIT/ANKA, Forschungszentrum Karlsruhe, Germany		X	
Mid Sweden University, Sundsvall, Sweden	X	X	
JINR, Dubna, Russian Federation			X
MRC-LMB Cambridge, England, UK	X		
NIKHEF, Amsterdam, The Netherlands	X	X	X
Univesridad de los Andes, Bogota, Columbia		X	
University of Bonn, Germany		X	
University of California, Berkeley, USA	X	X	X
University of Canterbury, Christchurch, New Zealand		X	X
Universität Erlangen-Nurnberg, Erlangen, German		X	

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COLLABORATION NAME	Medipix2	Medipix3	Medipix4
ASICS	**Medipix2 Timepix Timepix2**	**Medipix3 Timepix3**	**Medipix4 Timepix4**
University of Geneva, Switzerland			X
University of Glasgow, Scotland, UK	X	X	X
University of Houston, USA	X	X	X
University of Leiden, The Netherlands		X	
University of Maastricht, The Netherlands		X	X
University of Oxford, England, UK			X
University and INFN Section of Cagliari, Italy	X		
University and INFN Section of Pisa, Italy	X		
University and INFN Section of Napoli, Italy	X		
Technical University of Munich, Germany		X	
VTT Information Technology, Espoo, Finland		X	

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		
Amsterdam Scientific Instruments, The Netherlands	X	X	X	X	X		
Kromek, UK	X	X	X				
Malvern-Panalytical, The Netherlands	X	X	X	X			
MARS Bio Imaging, New Zealand				X			
PITEC, Brazil				X			
Quantum Detectors, UK				X	X		
Technologies de France, France					X		
X-ray Imaging Europe, Germany	X	X	X				
X-spectrum, Germany				X			

Outline

- The Medipix and Timepix family timeline
- Timepix2
- Timepix3
- Timepix4
- Applications
- Summary and Conclusion

The Medipix and Timepix ASICs - Timeline

Collaboration	2003	2006	2013	2014	2017	2018	2020	2021	2023?
Medipix2	Medipix2	Timepix				Timepix2			
Medipix3			Medipix3	Timepix3				Medipix4	
Medipix4							Timepix4		

- Medipix chips aim at energy sensitive photon counting and typically use frame-based readout
- Timepix chips are more oriented towards single particle detection

The Medipix and Timepix ASICs - Timeline

Collaboration	2003	2006	2013	2014	2017	2018	2020	2021	2023?
Medipix2	Medipix2	Timepix				Timepix2			
Medipix3			Medipix3	Timepix3				Medipix4	
Medipix4							Timepix4		
LHCb					VELOpix				VELOpix2

- 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 the recent Timepix chips

Timepix readout chips - single particle detection

	Timepix	Timepix2	Timepix3	Timepix4
Tech. node (nm)	250	130	130	65
Year	2005	2018	2014	2019
Pixel size (mm)	55	55	55	55
# pixels (x x y)	256 x 256	256 x 256	256 x 256	448 x 512
Time bin (resolution)	10ns	10ns	1.5ns	200ps
Readout architecture	Frame based (sequential R/W)	Frame based (sequential or continuous R/W)	Data driven or Frame based (sequential R/W)	Data driven or Frame-base (sequential or continuous R/W)
Number of sides for tiling	3	3	3	4

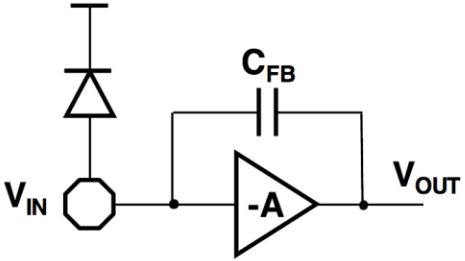
Timepix2 Specs

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 (linear/adaptive)	~25mV/ke$^-$ (19mv/ke$^-$)
ENC	~60e$^-$
FE Linearity (linear/adaptive)	Up to 20ke$^-$ (Up to 250ke$^-$)
TOT linearity (linear/adaptive)	Up to 300ke$^-$ (Up to 950ke$^-$)
TOA bin size	10ns
Minimum detectable charge	~750e$^-$ → 2.7 KeV (Si Sensor)
Power consumption	450mW/cm^2 (nominal 100MHz clocks)
Readout	Frame-based (serial or parallel) @100MHz

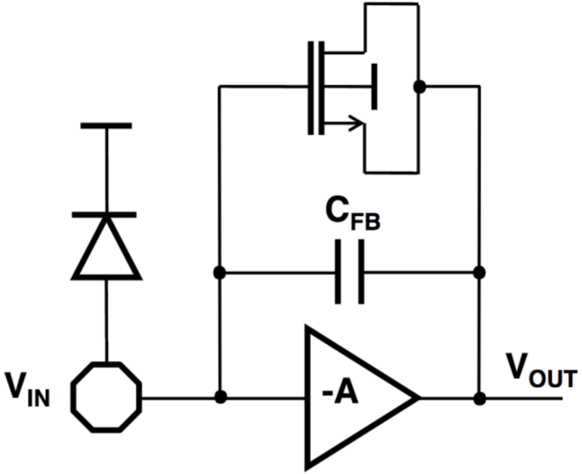
Other new features (compared with Timepix):

- Improved shutter functionality
- ROI readout
- Possibility to power off unused pixels
- etc

Pixel Frontend



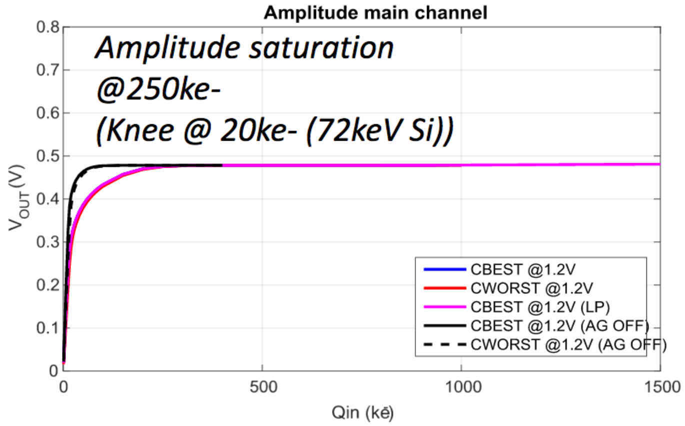
$$\frac{\Delta V_{OUT}}{\Delta Q_{IN}} = \frac{1}{C_{FB}}$$

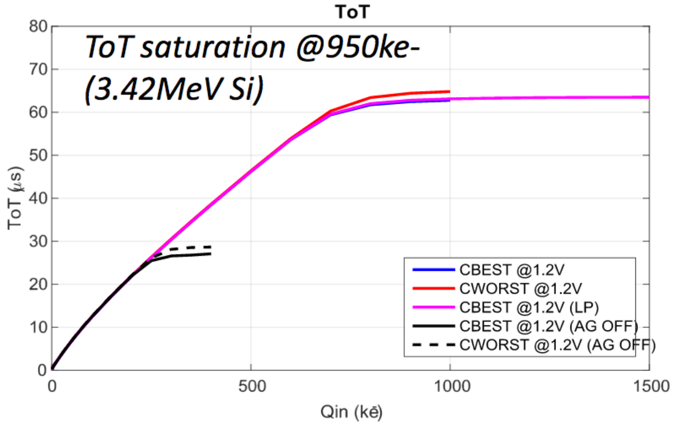


When the transistor is active, the feedback capacitance is ~125fF (Dimensions transistor 1/10)

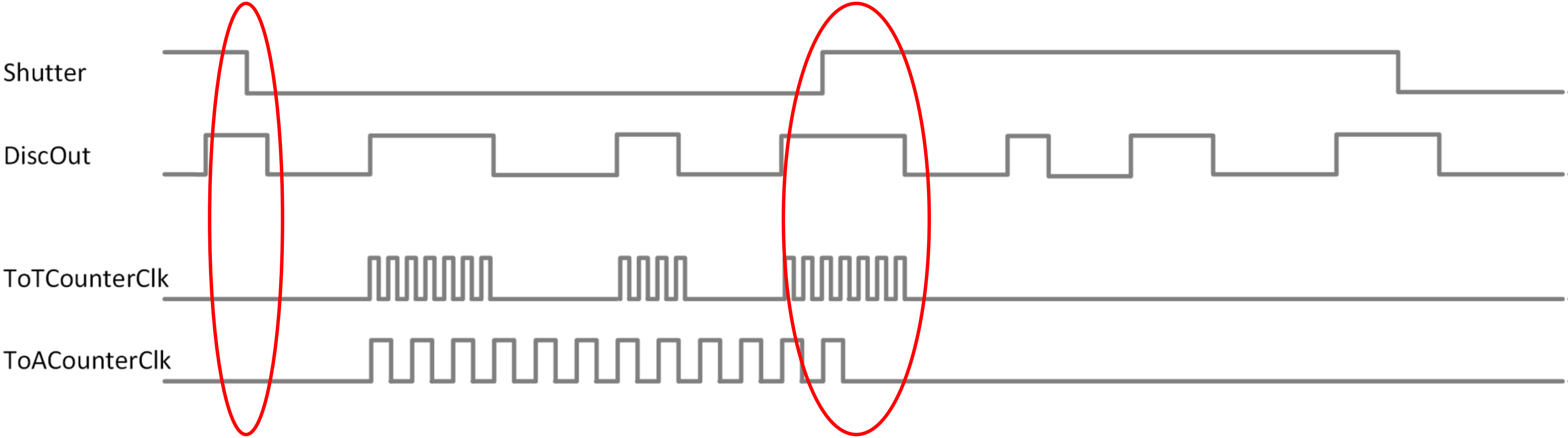
M.Manghisoni et al., “Dynamic Compression of the Signal in a Charge Sensitive Amplifier: From Concept to Design”, IEEE TNS, vol. 62, pp. 2318-2326, Oct. 2015

Pixel Frontend



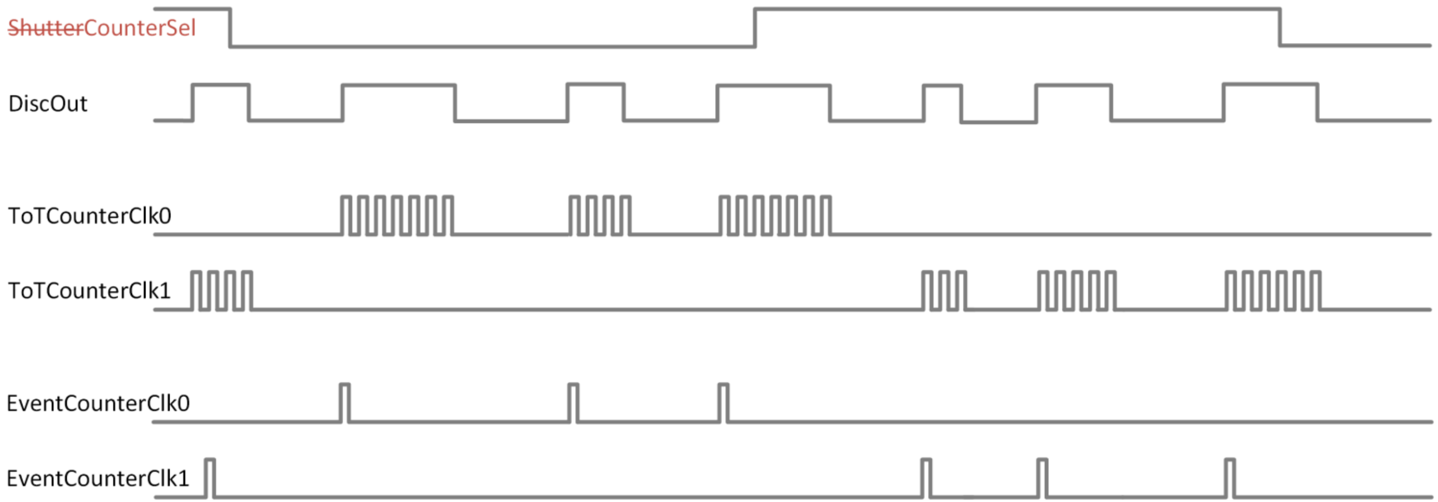


Sequential R/W - ToT (first hit or total) and ToA (first hit)



ToT (first hit)
ToT (total)
Note shutter does not truncate last hit
It also ignores hits which are active at start

Continuous R/W – ToT and event counting



Other modes in Continuous R/W

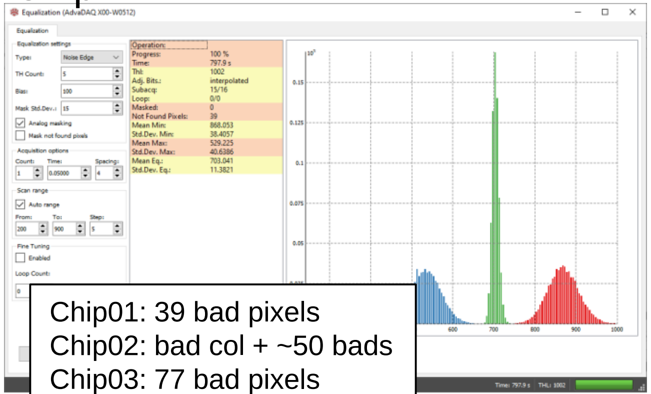
- First hit ToT or total ToT
- Also can ToT ONLY or event counting ONLY

Equalization and threshold calibration

All devices were successfully equalized and threshold calibrated with sources.

Very similar behavior for all chips !!!

Chip1:

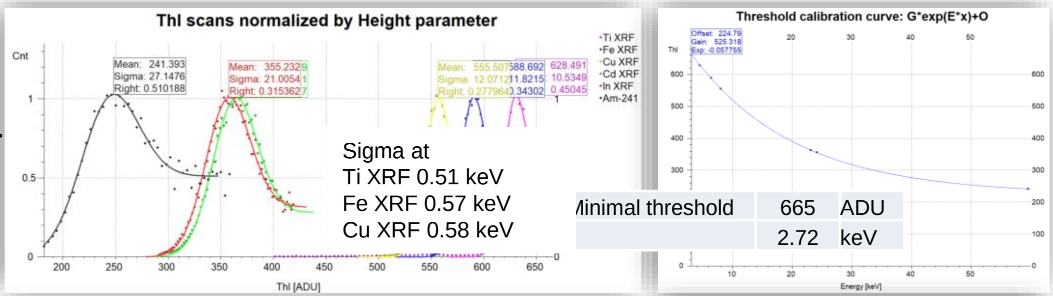


Chip01: 39 bad pixels
Chip02: bad col + ~50 bads
Chip03: 77 bad pixels

Ikrum	5
ThlCoarse	6
FBK	165
THS	60
PreampOn	110
Polarity	Positive

J. Jakubek, Advacam

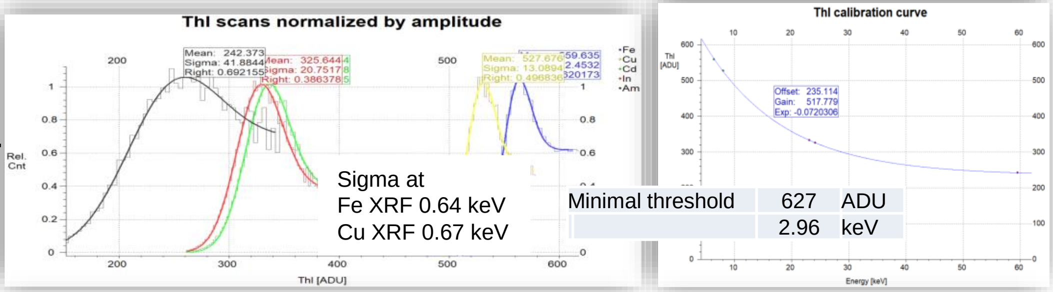
Chip1



Sigma at
Ti XRF 0.51 keV
Fe XRF 0.57 keV
Cu XRF 0.58 keV

Minimal threshold	665	ADU
	2.72	keV

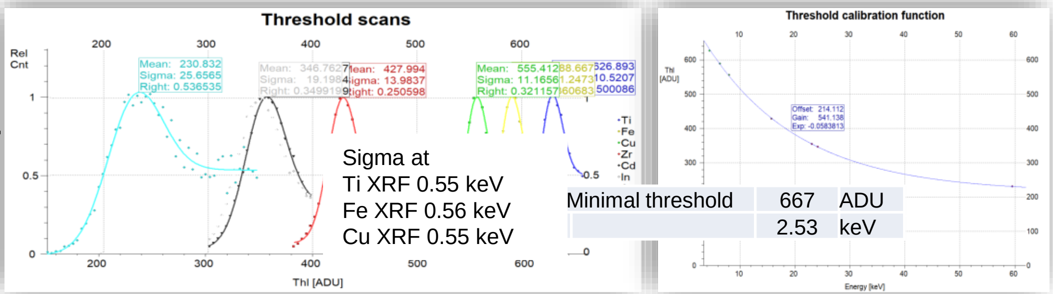
Chip2



Sigma at
Fe XRF 0.64 keV
Cu XRF 0.67 keV

Minimal threshold	627	ADU
	2.96	keV

Chip3

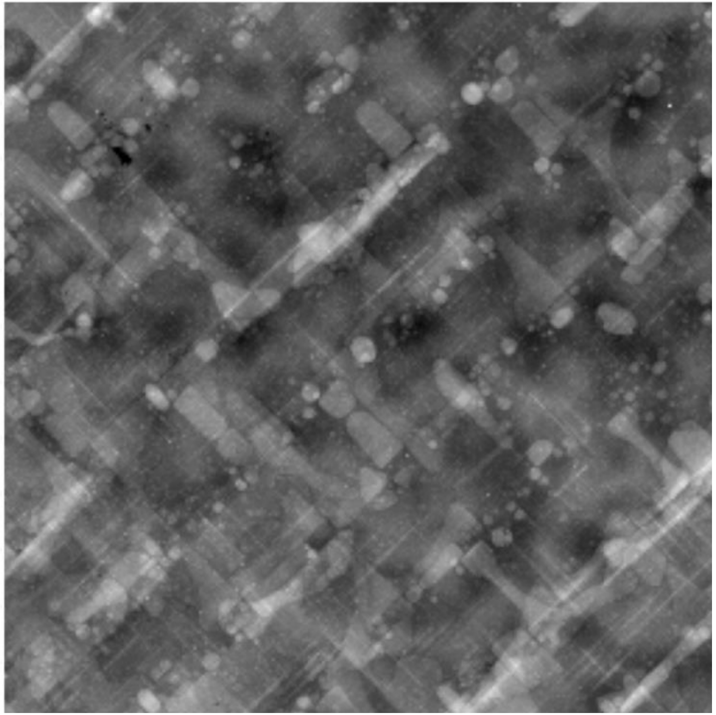


Sigma at
Ti XRF 0.55 keV
Fe XRF 0.56 keV
Cu XRF 0.55 keV

Minimal threshold	667	ADU
	2.53	keV

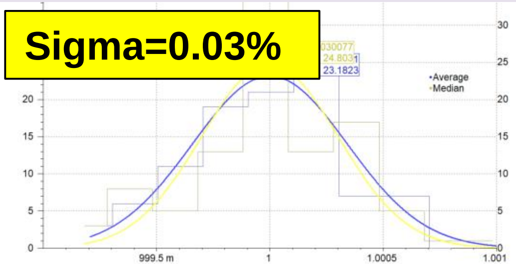
Assembly 03: X-ray imaging performance

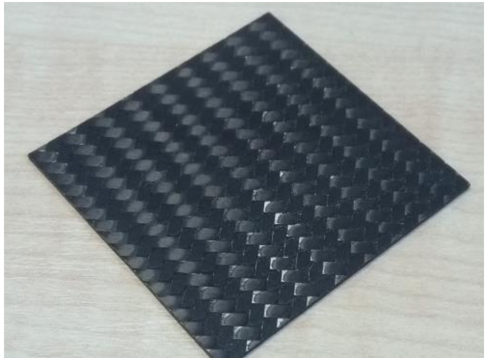
Detector: Thl=4.65 keV, Bias=200 V, 22°C
Tube: HV=50 kVp, Current=100 uA



Excellent global stability over 50 s:

Sigma=0.03%

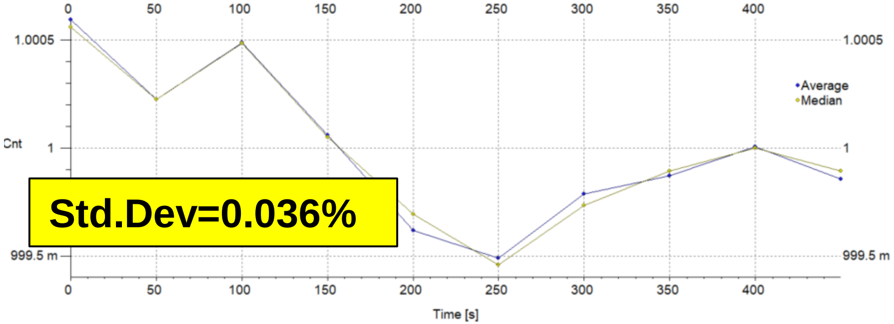




Sample: CFRP, about 0.5 mm

Excellent global stability over 10 minutes:

Std.Dev=0.036%



J. Jakubek, Advacam

Status of Timepix2

Feature	Solution/Workaround
Pixel masking rather late in digital chain	Threshold tuning algorithm developed to avoid noise injection
Random telegraphic noise near to threshold	Does not impact real life applications – do not fix
Bandgap more sensitive to threshold than foreseen	Re-programme of bandgap code

Minor resubmit underway to fix bandgap
Wafer probing started (yield ~50% Class A, but may improve)

Timepix readout chips - single particle detection

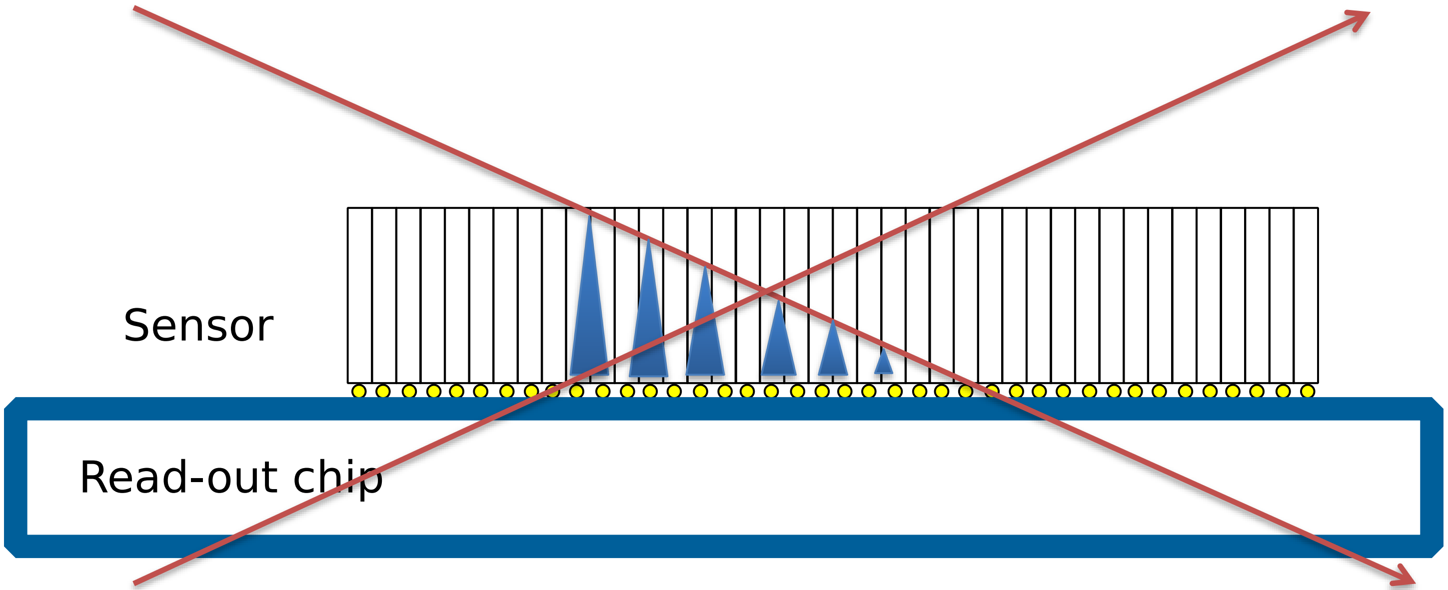
	Timepix	Timepix2	Timepix3	Timepix4
Tech. node (nm)	250	130	130	65
Year	2005	2018	2014	2019
Pixel size (mm)	55	55	55	55
# pixels (x x y)	256 x 256	256 x 256	256 x 256	448 x 512
Time bin (resolution)	10ns	10ns	1.5ns	200ps
Readout architecture	Frame based (sequential R/W)	Frame based (sequential or continuous R/W)	Data driven or Frame based (sequential R/W)	Data driven or Frame-base (sequential or continuous R/W)
Number of sides for tiling	3	3	3	4

Timepix3 Specs

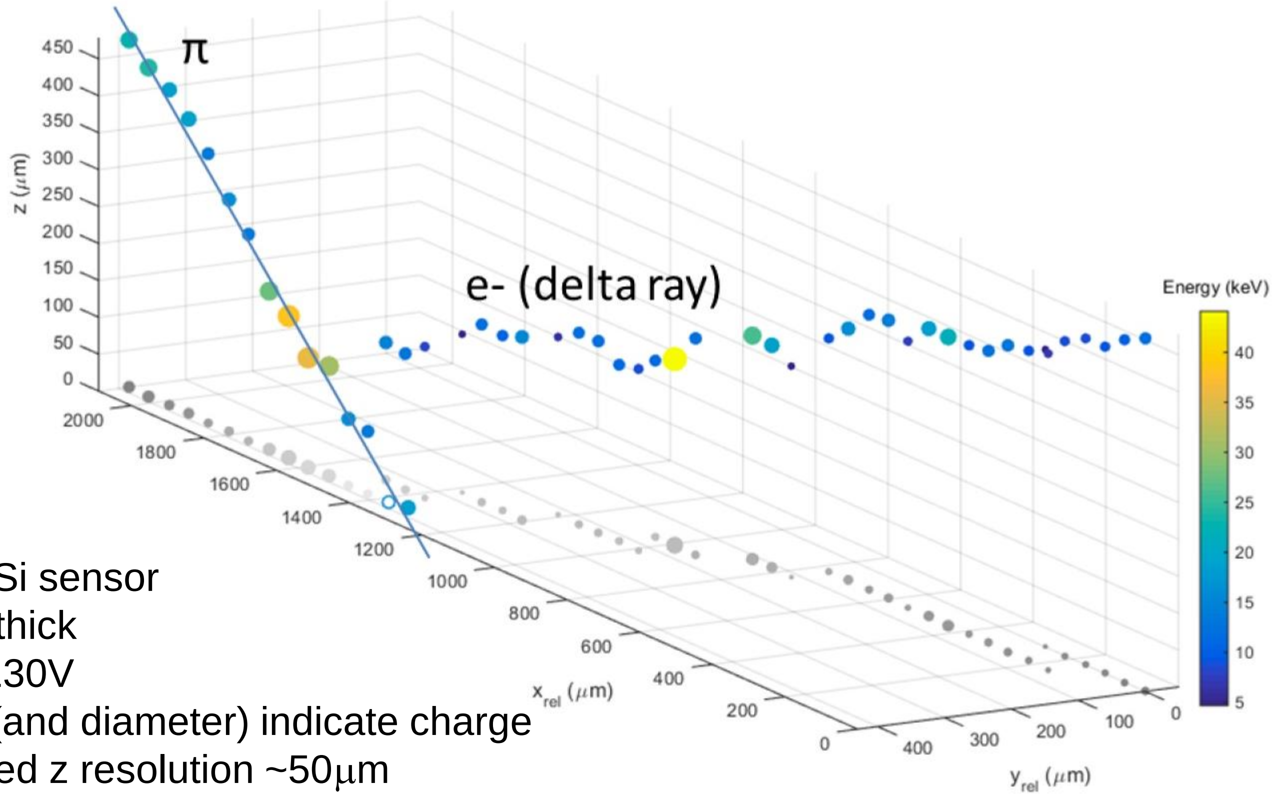
CMOS node	130nm
Pixel Array	256 x 256
Pixel pitch	55μm
Charge collection	e^-, h^+
Pixel functionality	TOT (Energy) and TOA (Arrival time)
Preamp Gain	~47mV/ke$^-$
ENC	~60e$^-$
FE Linearity	Up to 12ke$^-$
TOT linearity (resolution)	Up to 200ke$^-$ (<5%)
TOA resolution*	Up to 1.6ns
Time-walk	<20ns
Minimum detectable charge	~500e$^-$ → 2 KeV (Si Sensor)
Power power (1.5V)	700 mW/cm^2
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

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

Timepix readout chips - single particle detection

	Timepix	Timepix2	Timepix3	Timepix4
Tech. node (nm)	250	130	130	65
Year	2005	2018	2014	2019
Pixel size (mm)	55	55	55	55
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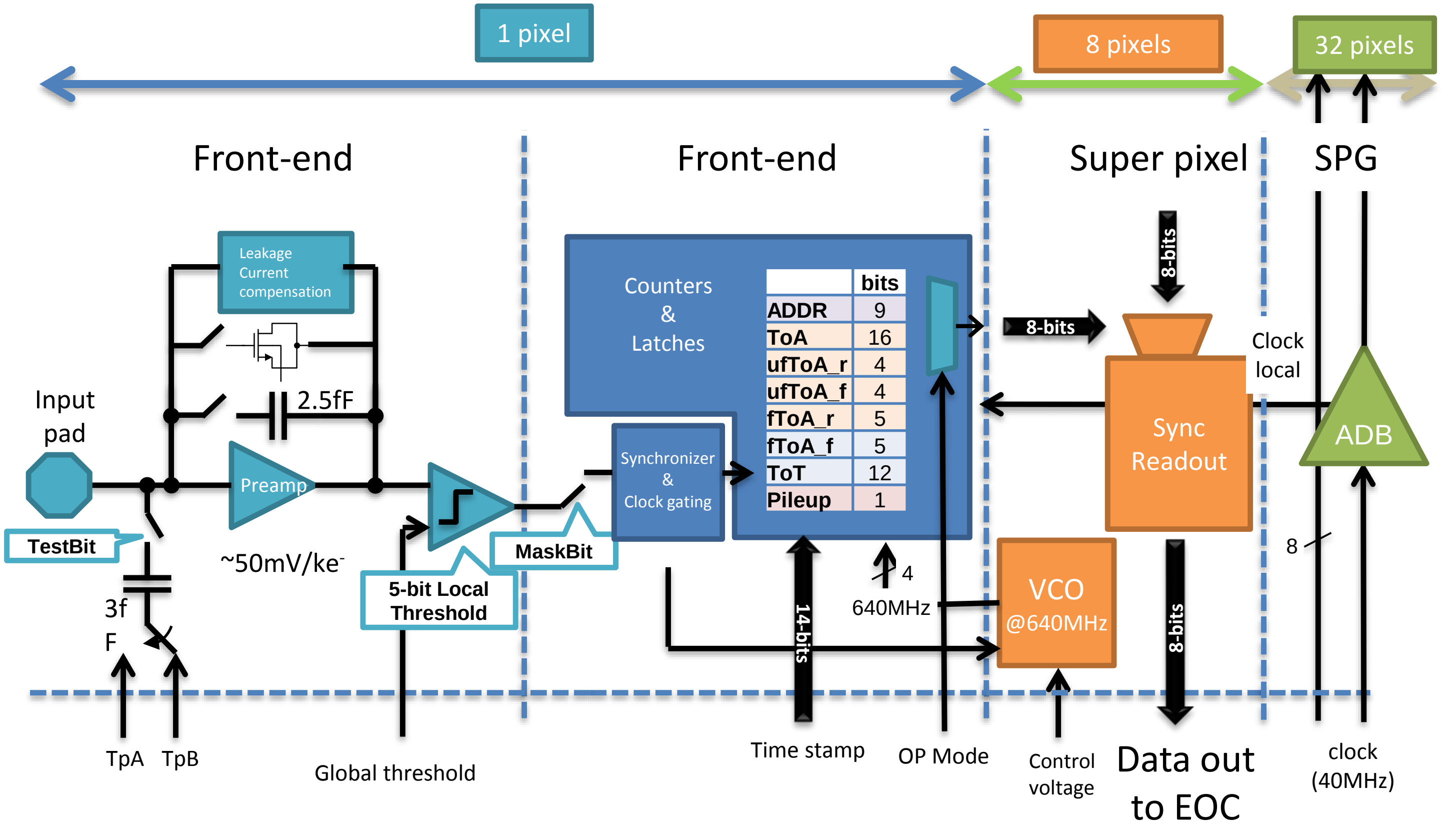
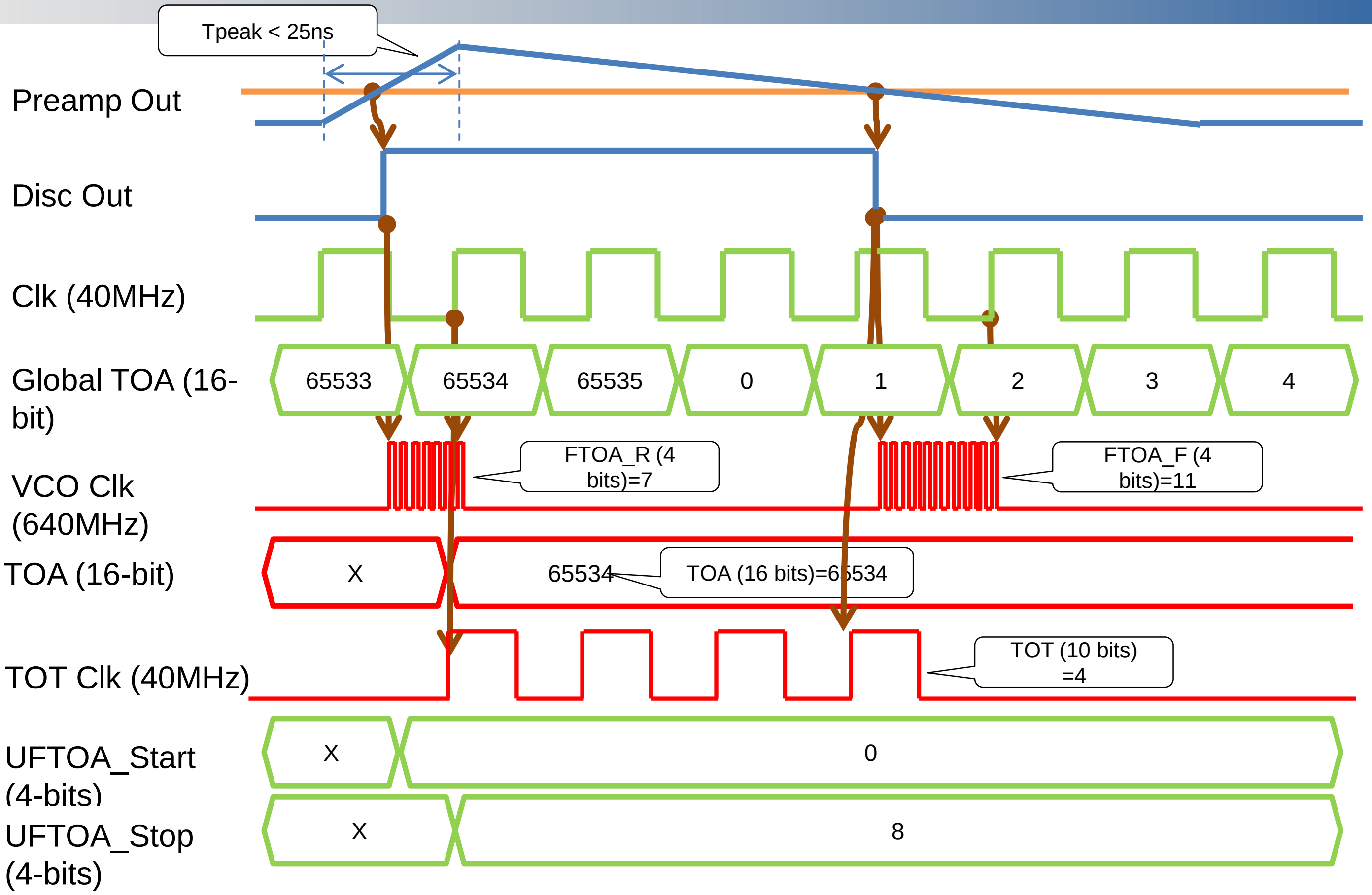
Timepix3 → Timepix4

			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	<715 $MHz/cm^2/s$
		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^-

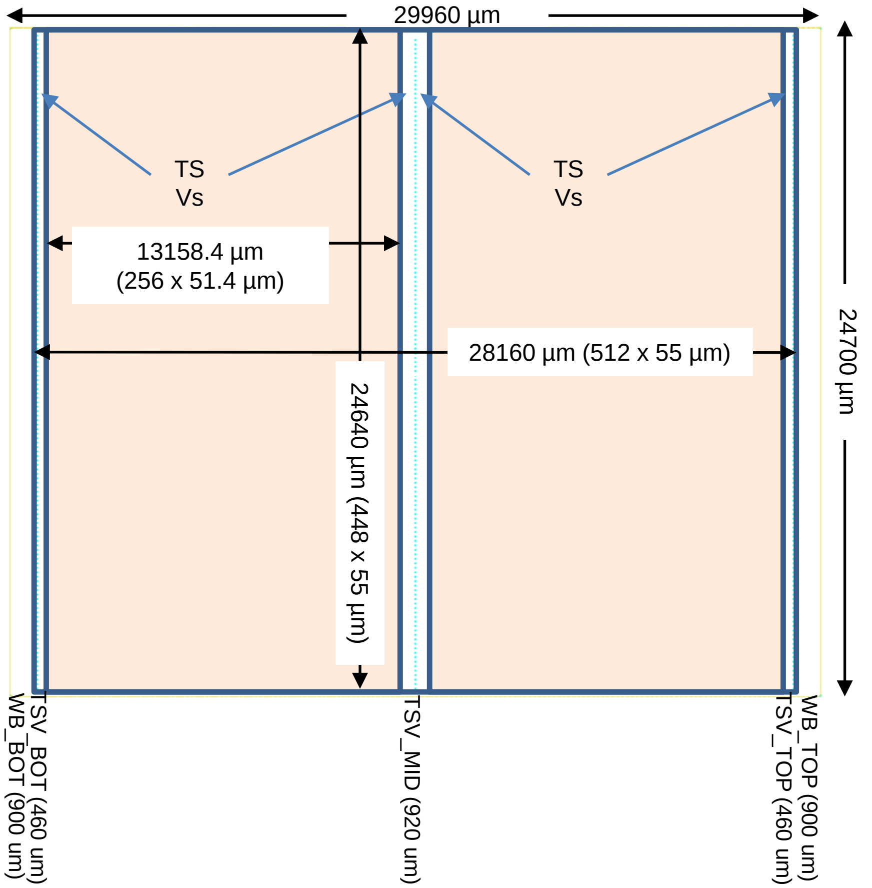
Timepix4 Pixel Schematic



Pixel Operation in TOA & TOT [DD]



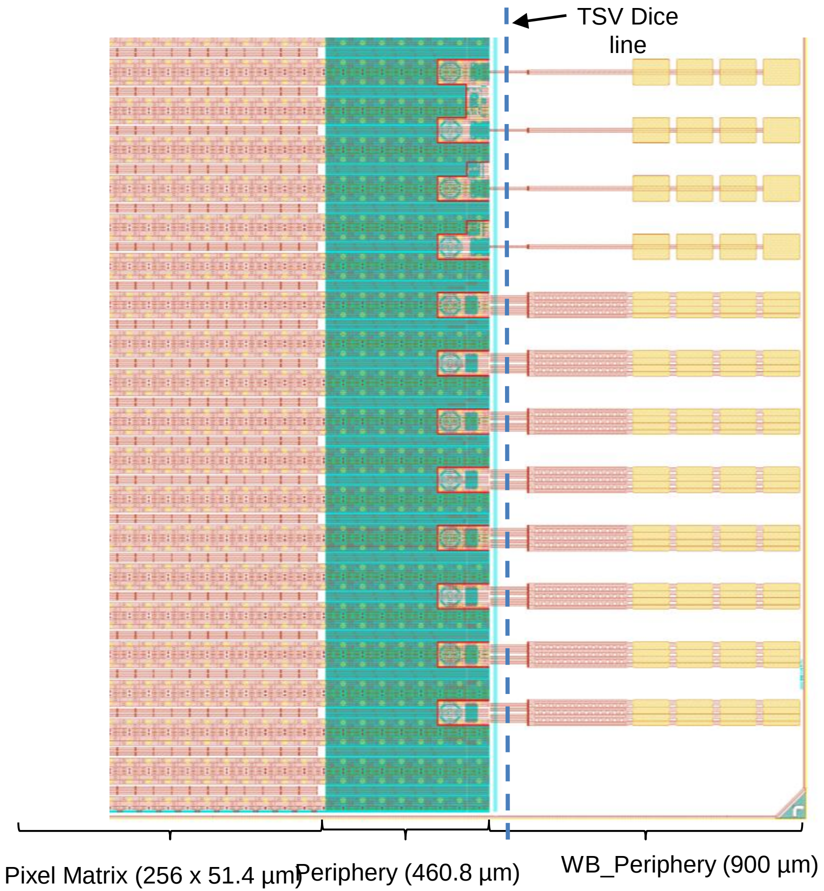
Timepix4 Floorplan



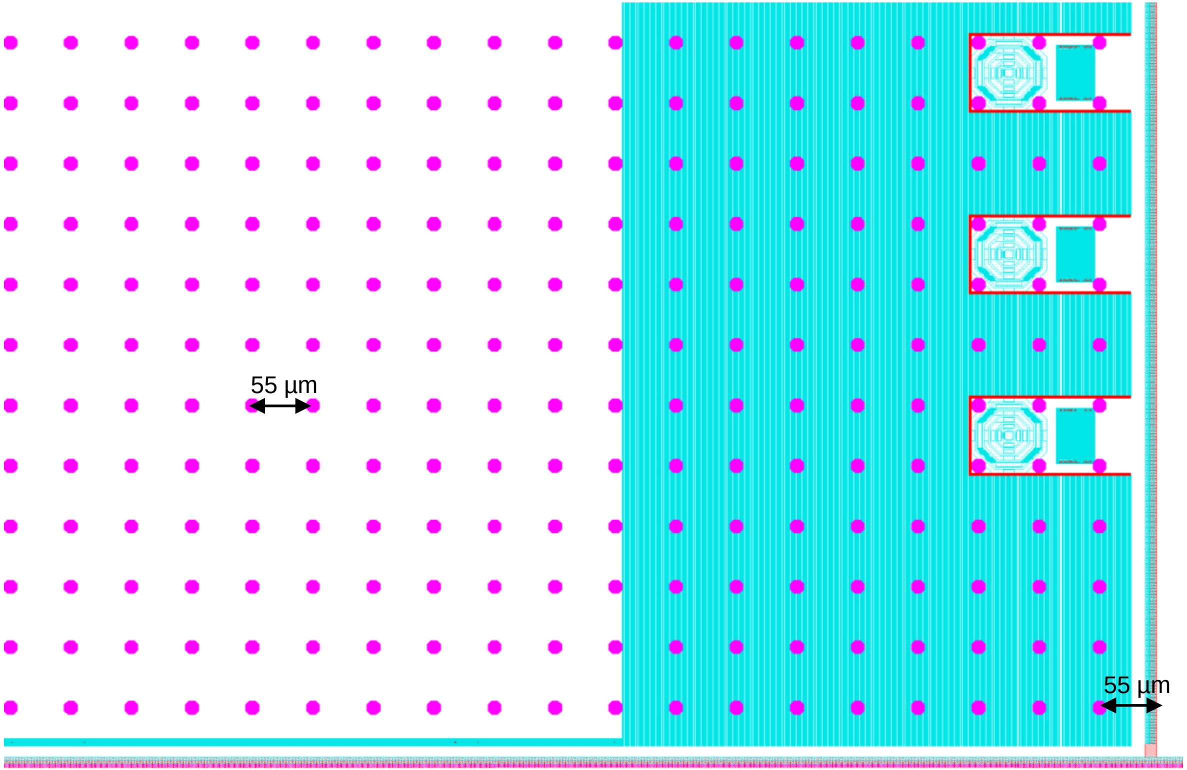
Edge periphery floorplan

- Digital on top design:
  - Default periphery size is 460.8 µm
  - Scripted to allow different periphery sizes
- WB openings 4x 100x70 µm
  - Multiple probing pads
- TSV M1 octagons of 69 µm

- First version of edge routing
  - 13158.4 x 5.4 µm
  - Buffer routing between peripheries

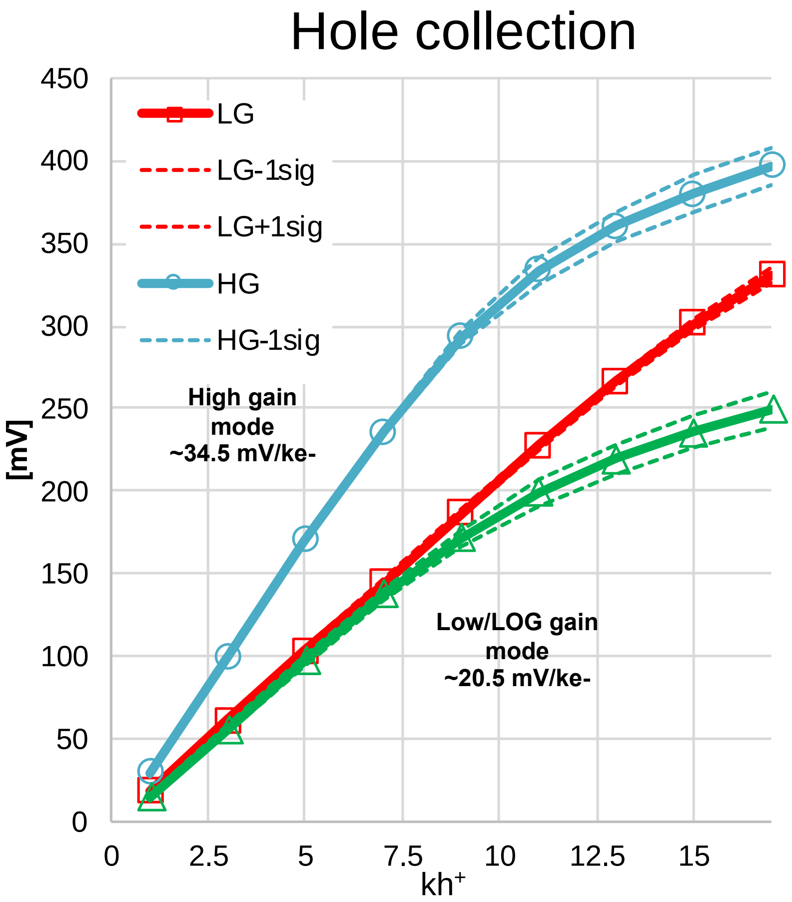


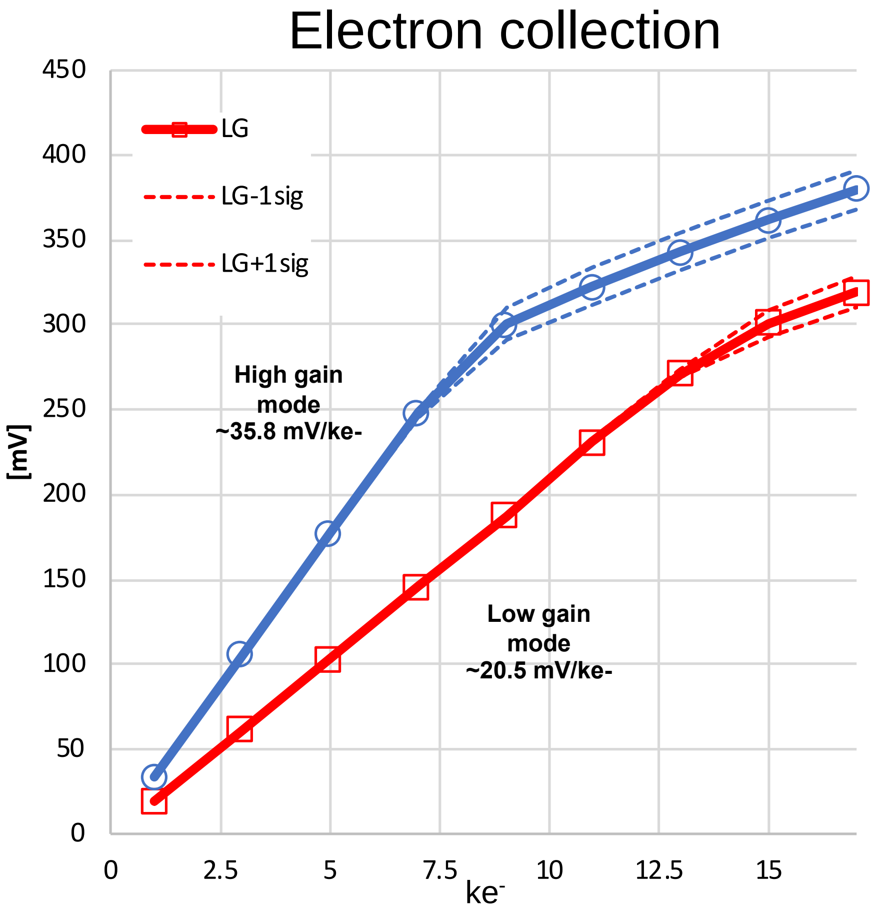
TSV (on M1) and BUMPs (on M10)



Gain slopes for different FE Gain

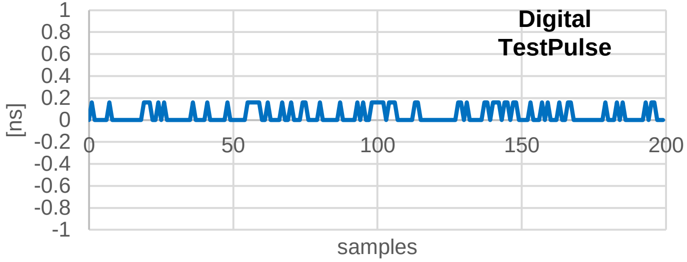
[TOA-TOT, few pixels]

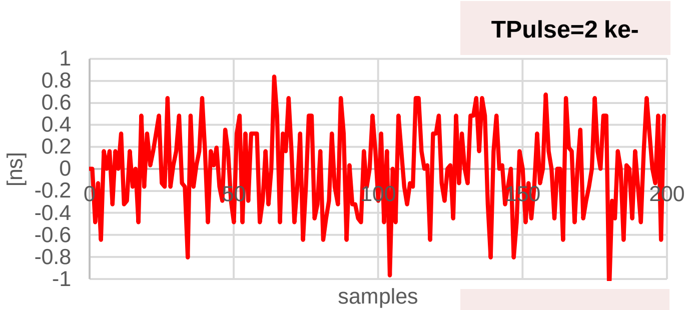


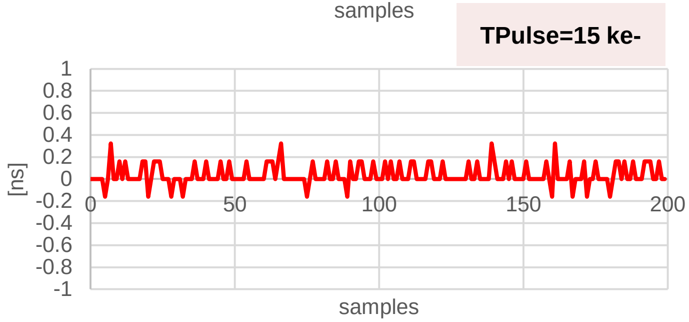


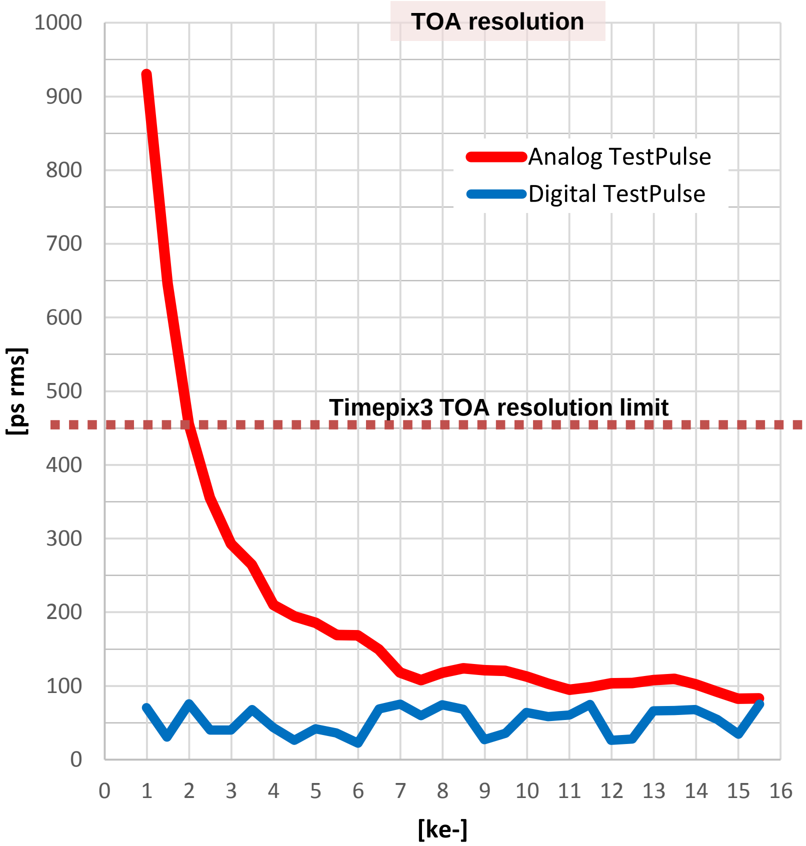
TOA Resolution

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









Analog pixel summary measureament

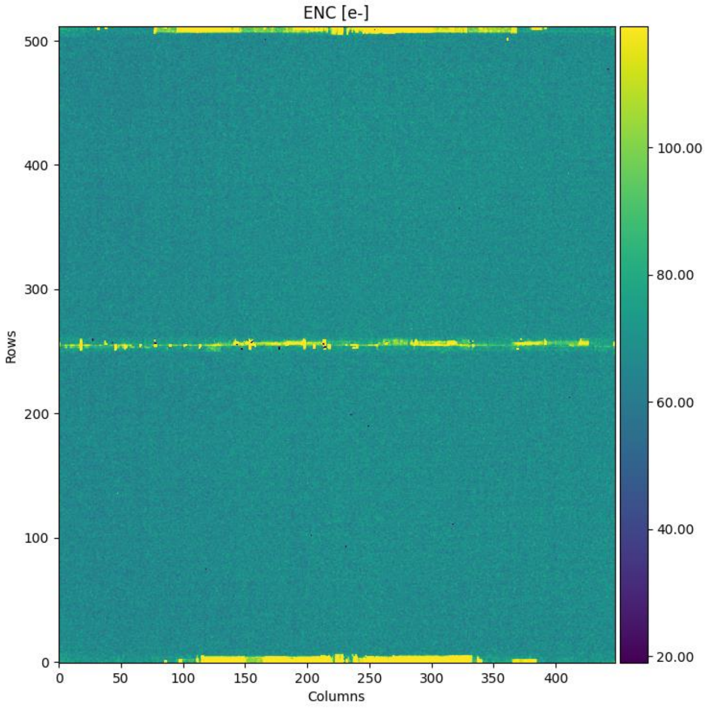
- Preliminary results
- FE settings in nominal power mode
- Pixels on top of peripheries not described here
- Ctest=3.2 fF assumed

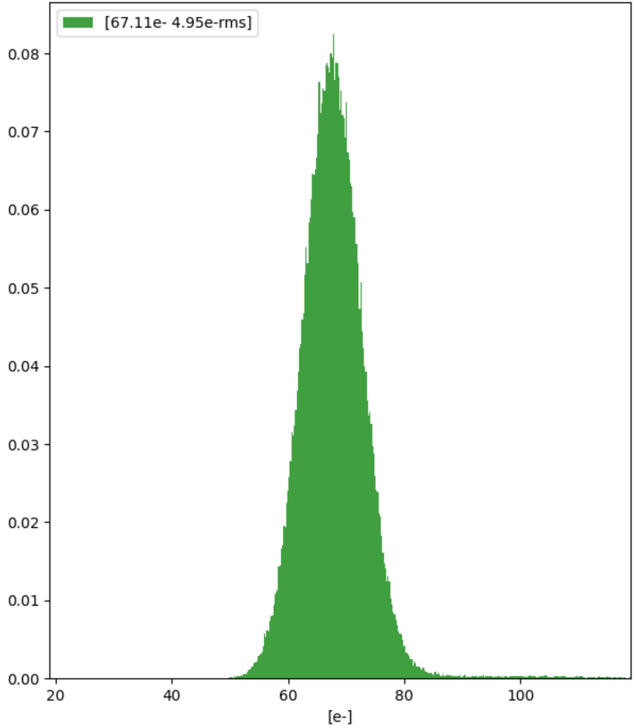
	Electron collection		Holes collection		
	High Gain	Low Gain	High Gain	Low Gain	Log Gain
Pixel gain	~35.8mV/ke-	~20.5mV/ke-	~34.5mV/ke-	~20.5mV/ke-	~20.5mV/ke-
Gain variation	<2%	<2%	<2%	<2%	<2%
ENC	~65 e^-_{rms}	~80 e^-_{rms}	~65 e^-_{rms}	~80 e^-_{rms}	~80 e^-_{rms}
Amplitude Linearity	< 7 ke-	< 12 ke-	< 7ke-	< 13 ke-	< 7ke-
Threshold Eq	< 35 e^-_{rms}	< 60 e^-_{rms}	< 35 e^-_{rms}	< 60 e^-_{rms}	tbd
Min Threshold	< 450 e^-	< 650 e^-	< 450 e^-	< 650 e^-	tbd
TOT Energy resolution (Si) **(@ Qin < ~2ke-)**	<1.5 keV_{FWHM}	tbd	<1.5 keV_{FWHM}	tbd	tbd
TOA bin size	~160 ps (instead of 195 ps)				
TOA resolution **(@Qin>~7ke-)**	<100 ps_{rms}	tbd	<100 ps_{rms}	tbd	tbd

ENC full matrix

[PC8bit, full matrix, e- collection high gain]

- Excess ENC noise on top of peripheries (x2-4):
  - ~26 rows: [0:7] [250:260] [504:511] → poor





Timepix4 with 4x Timepix3 sensors + NIKHEF Board

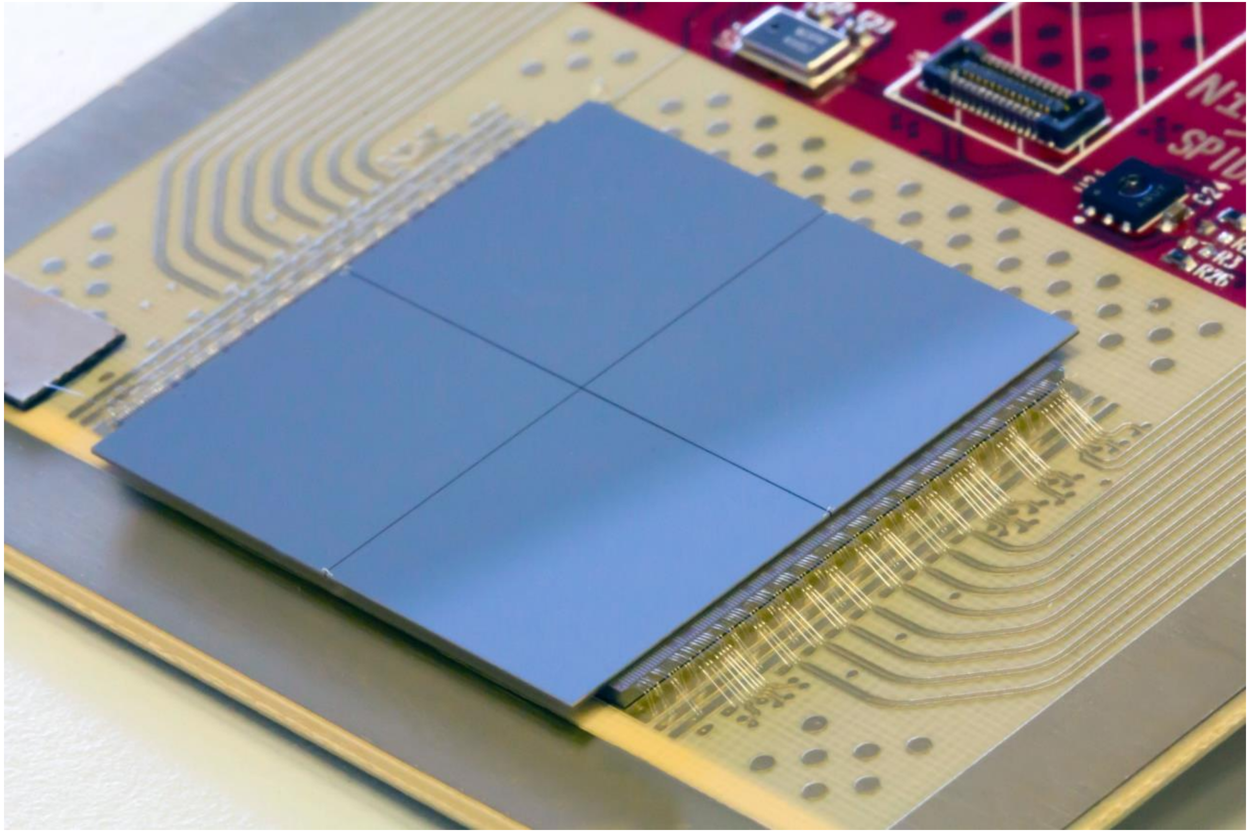
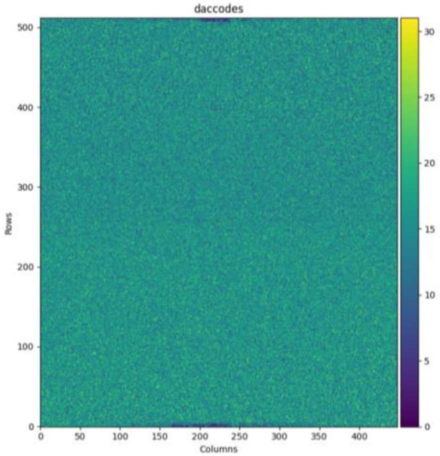
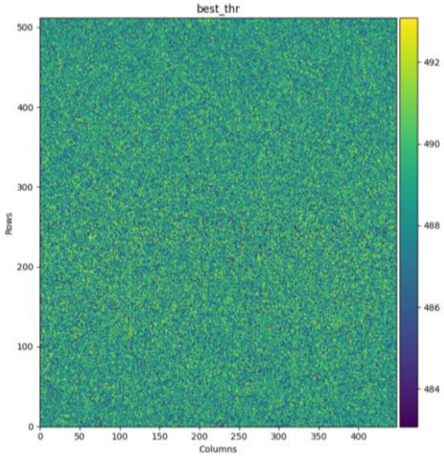


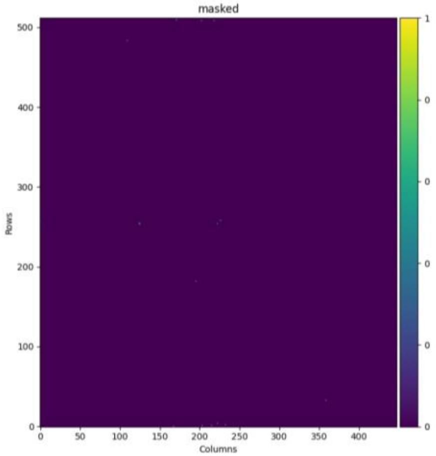
Photo courtesy of M. Fransen, Nikhef

F4_W1 Equalization

- Threshold equalization using PC24bit readout mode through Slow Control → ~ 40 min to do all scans
- Scan 5bit (32) on-pixel threshold DAC and search for ideal value
- No optimization and/or fine tunning
- 11 pixels masked



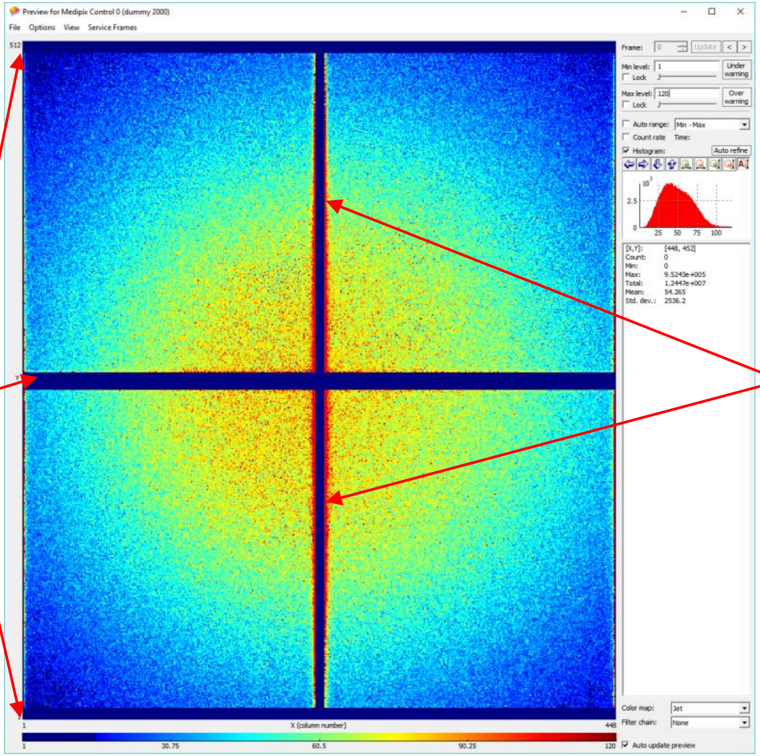




Fe55 1h FB mode Thr=500e-

- PC 8-bit frame based, 3600s acquisition time in CRW but through Slow Control
  - ~1.2 full frame/s → ~3800 individual frames → No visual effect

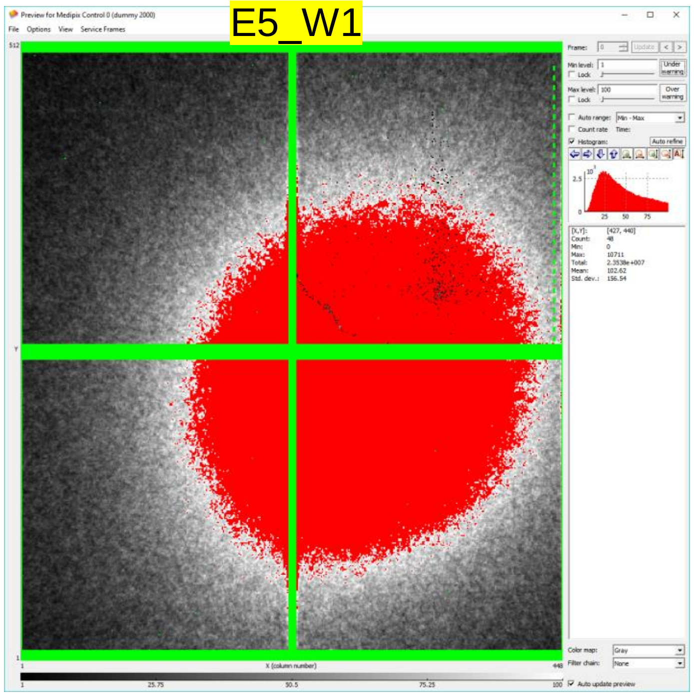
Masked pixels on perpheries:
Top/Bot=8 rows
Center=12 rows

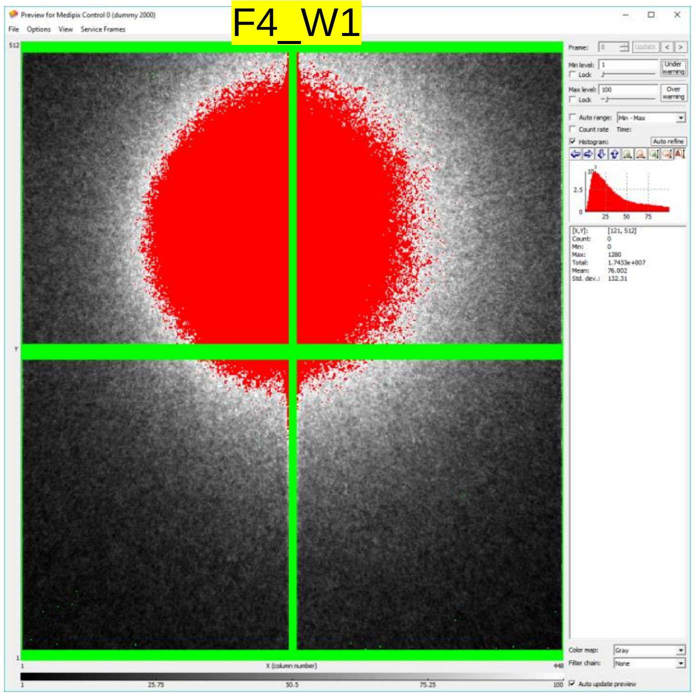


Masked pixels due to sensor edges
7 columns

Sr90 in Frame-base readout PC-8bit

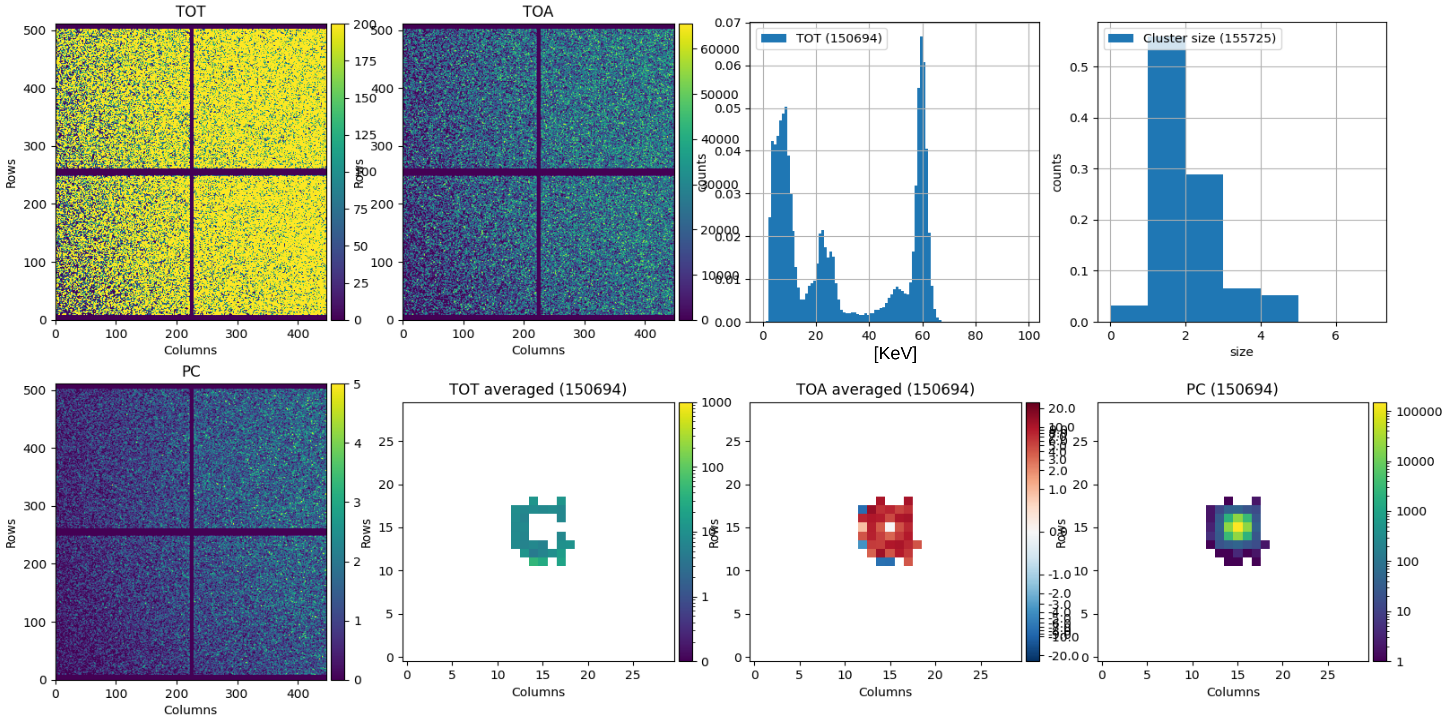
- PC 8-bit frame based, 30s acquisition time in CRW but through Slow Control
  - ~1.2 full frame/s



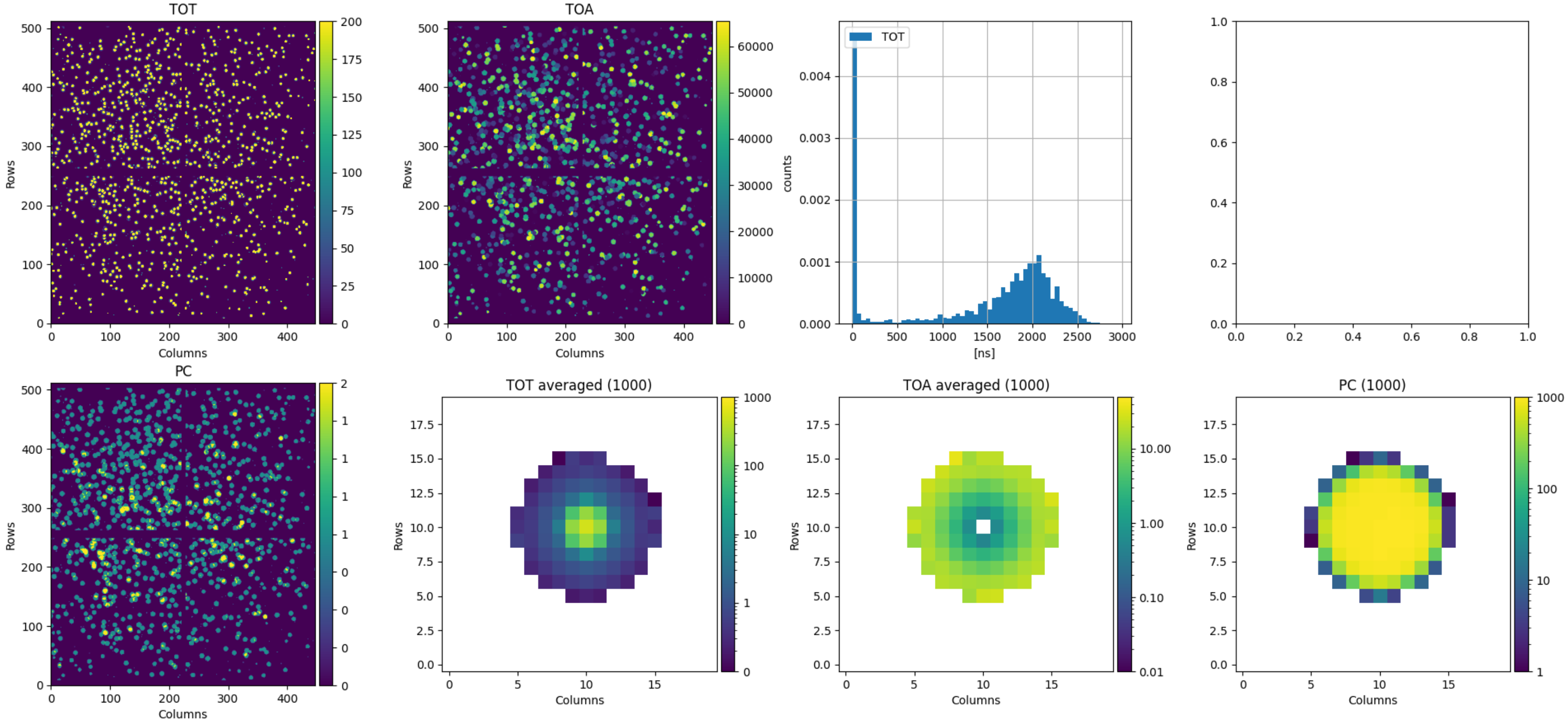


Am241 100s Thr=700e- with TOT calibration [E5_W1]

- First results indicate very good performance of the chip and confirm expected FE gain and noise
- Confirms that RDL strucutre has minimal effect in the charge detection an propagation
- Confirms the unexpected coupling on top of the digital peripheries as already reported



Am241 200ms Thr 50mV (~1450e) HG [E5_W1]



Timepix4 status

Feature	Solution/Workaround
Crosstalk from peripheral logic to pixel front-end	Improved shielding of pixel side RDL
VCO oscillating too fast	Test chip submitted
Fast readout not fully functional	Problem identified and fixed with metal changes

- Metal mask re-spin – wafers in dicing
- VCO test chip to be received November
- Final submission Q1 2021

Examples of other applications

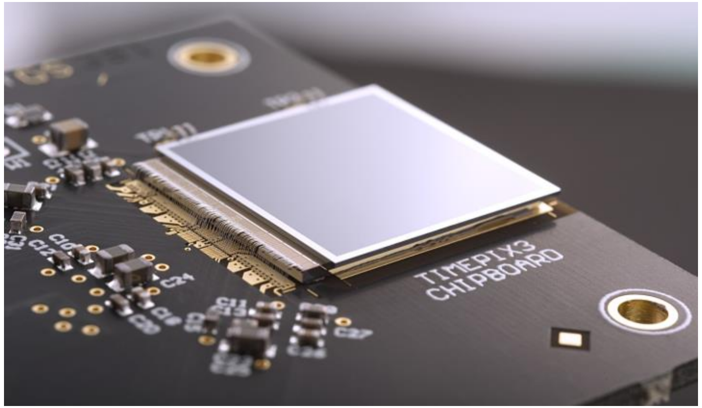
- Spectroscopic X-ray imaging in medical diagnostics
- CERN@school - Timepix use in the classroom
- X-ray materials analysis with diffraction
- X-ray non-destructive testing
- X-ray dosimetry - dosepix chip development
- High resolution imaging of historical artefacts
- Neutron detection and imaging
- Low Energy Electron Microscopy
- Transmission electron microscopy
- Time-of-Flight mass spectrometry
- Dose deposition tracking in hadron therapy
- Numerous satellite systems dedicated to space weather observation

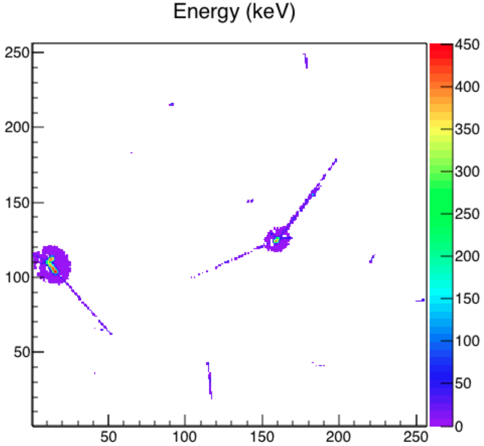
Applications for CERN/Physics

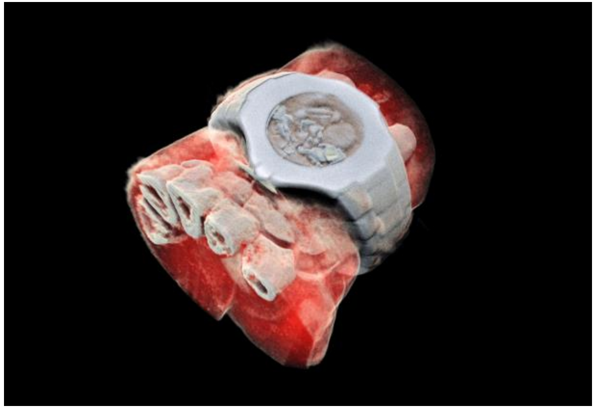
- LHCb VELOpix chip is directly derived from Timepix3
- LHCb Timepix3 telescope – 80 Mhits/cm^2/sec
- Sensor studies for CLIC/LHCb
- Background radiation monitoring at ATLAS and CMS
- Beam Gas Interaction monitor CERN PS
- Beam monitoring in UA9
- Positron annihilation in Aegis
- ASACUSA experiment
- Breit-Wheeler experiment at RAL
- Beta particle channeling in ISOLDE
- Forward physics using Timepix3?
- Axion search at CAST (with InGrid)
- Large area TPC (with InGrid)
- Transition radiation measurements for ATLAS
- GEMPIX development for radiation therapy beam monitoring
- GEMPIX for ^{55}Fe waste management
- Developments for CLIC: CLICpix, CLICpix2, C3PD

Special Symposium @ CERN to mark 20 years of the Medipix2 Collaboration - 18 September 2019

Slides available at https://indico.cern.ch/event/782801/







Summary and Conclusions

- Hybrid pixel detectors were developed as tracking detectors of LHC
- For now hybrid pixels remain the only solution in very high rate environments
- The Timepix family of chips spans 20 years. Each generation provides improved time stamping
- Timepix3 and Timepix4 when combined with a Si sensor provide noise-hit-free bubble-chamber-like imaging with always-on triggerless readout. We believe the potential of this approach is currently underestimated
- Timepix4 (time stamp within 200ps bin) is almost ready for production and can be tiled on 4 sides using TSVs
- Generic developments such as Timepix provide great scientific (and commercial) opportunities but also feed back into High Energy Physics

Thank you for your attention!

Medipix3RX images: S. Procz et al.