HYBRID PIXEL DETECTORS – THE TIMEPIX ASIC FAMILY

M. Campbell[1], J. Alozy, R. Ballabriga, P. Christodoulou[2], E.H.M. Heijne[2], T. Hofmann, X. Llopart, and L. Tlustos[2]

CERN, PH Department

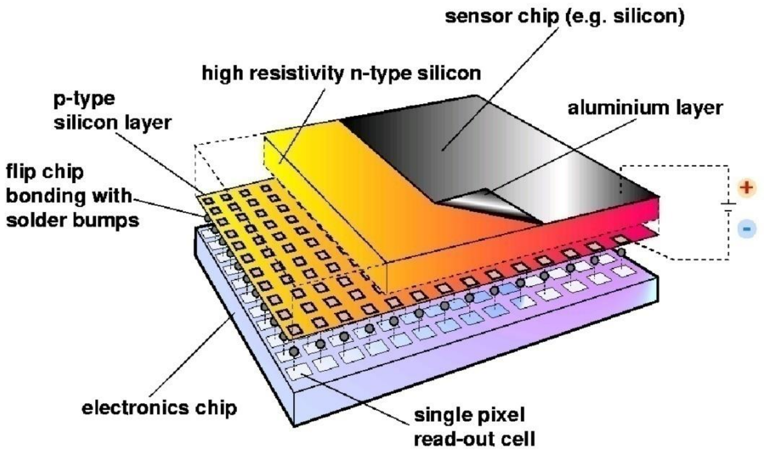
1211 Geneva 23

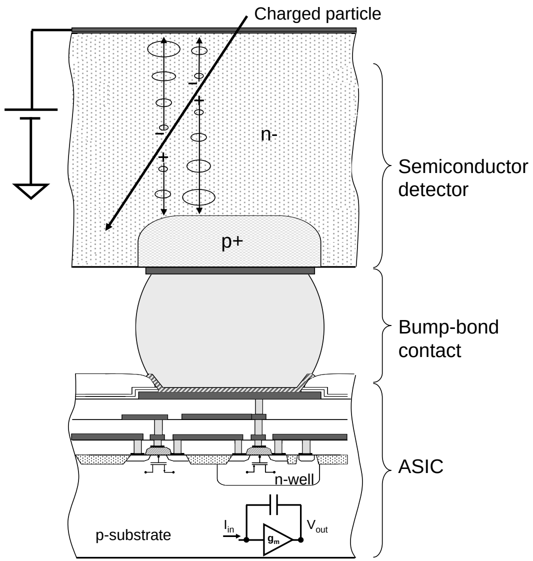
Switzerland

[1] Honorary Professor at Glasgow University

[2] also with IEAP, Prague

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

Outline

- The Medipix and Timepix family timeline
- Timepix
  - Schools
  - Dosimetry for manned space flight
- Timepix2
- Timepix3
  - Single layer particle tracking
  - Velocity map imaging
  - Visible photon imaging and quantum applications
- Timepix4
  - 4DPhoton
- LA-Picopix
- Summary and Conclusion

Medipix2 (1999 ->)	Medipix3 (2005 ->)	Medipix4 (2016 ->)
Albert-Ludwig Universität Freiburg, Germany	Albert-Ludwig Universität Freiburg, Germany	CEA, Paris, France
CEA, Paris, France	AMOLF, Amsterdam, The Netherlands	CERN, Geneva, Switzerland
CERN, Geneva, Switzerland	Brazilian Light Source, Campinas, Brazil	DESY-Hamburg, Germany
Czech Academy of Sciences, Prague, Czechia	CEA, Paris, France	Diamond Light Source, England, UK
ESRF, Grenoble, France	CERN, Geneva, Switzerland	IEAP, Czech Technical University, Prague, Czeciah
IEAP, Czech Technical University, Prague, Czech Republic	DESY-Hamburg, Germany	IFAE, Barcelona, Spain
IFAE, Barcelona, Spain	Diamond Light Source, England, UK	JINR, Dubna, Russian Federation
Mid Sweden University, Sundsvall, Sweden	ESRF, Grenoble, France	NIKHEF, Amsterdam, The Netherlands
MRC-LMB Cambridge, England, UK	IEAP, Czech Technical University, Prague, Czech Republic	University of California, Berkeley, USA
NIKHEF, Amsterdam, The Netherlands	KIT/ANKA, Forschungszentrum Karlsruhe, Germany	University of Canterbury, Christchurch, New Zealand
University of California, Berkeley, USA	Mid Sweden University, Sundsvall, Sweden	University of Geneva, Switzerland
Universität Erlangen-Nurnberg, Erlangen, German	NIKHEF, Amsterdam, The Netherlands	University of Glasgow, Scotland, UK
University of Glasgow, Scotland, UK	Univesridad de los Andes, Bogota, Columbia	University of Houston, USA
University of Houston, USA	University of Bonn, Germany	University of Maastricht, The Netherlands
University and INFN Section of Cagliari, Italy	University of California, Berkeley, USA	University of Oxford, England, UK
University and INFN Section of Pisa, Italy	University of Canterbury, Christchurch, New Zealand	INFN, Italy
University and INFN Section of Napoli, Italy	Universität Erlangen-Nurnberg, Erlangen, German	Chinese Spallation Neutron Source, Dongguan City,China
	University of Glasgow, Scotland, UK	Brazilian Light Source, Campinas, Brazil
	University of Houston, USA	Philippines Nuclear Research Institute, Manila, Philippines
	University of Leiden, The Netherlands	Czech Academy of Sciences, Prague, Czech Republic
	Technical University of Munich, Germany	Univeristy of Tennessee, Knoxville, USA
	VTT Information Technology, Espoo, Finland	

Commercial Partners

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

X = commercial licensee X = R and D licensee

Motivation for Medipix/Timepix Developments

- Hybrid pixel detectors for the LHC are designed to do one thing extremely well
  - Tag each traversing particle to one bunch crossing (25ns)
  - On-chip (or on-pixel) hit buffering and selection (only triggered events are read out)
  - Tolerate extreme radiation environment
- The Medipix/Timepix chips were intended to use the same technology for other applications
  - Not so Application Specific Integrated Circuit
- The Medipix family aims primarily at spectroscopic X-ray imaging in medicine
- The Timepix family is better suited to detecting single particles
- The experience gathered has led to innovative solutions for the LHC machine and experiments (e.g. VELOpix development)

The Medipix and Timepix ASICs - Timeline

Collaboration	2003	2006	2013	2014	2017	2018	2020	2021	2025?
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

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Medipix2	Medipix2	Timepix				Timepix2			
Medipix3			Medipix3	Timepix3				Medipix4	
Medipix4							Timepix4		
LHCb					VELOpix				LA-Picopix

- 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

Timepix miniaturised readout

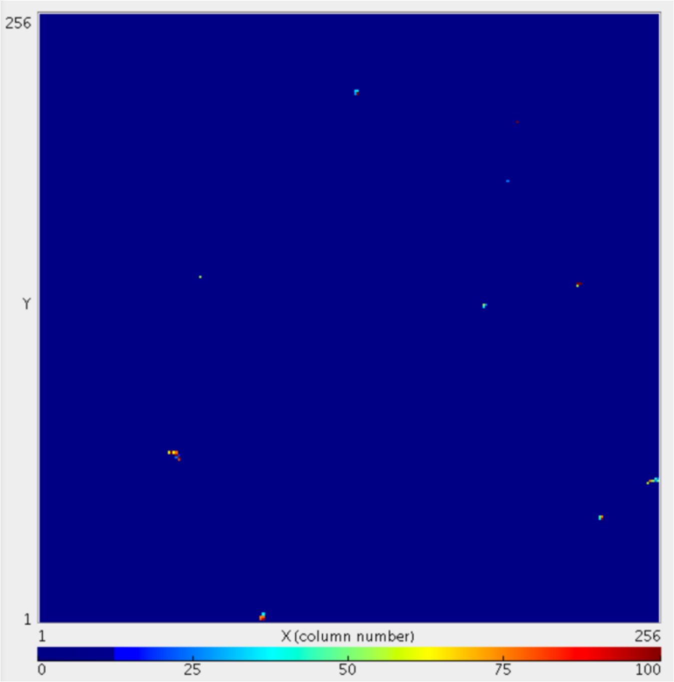
IEAP/CTU, Prague

Timepix for schools

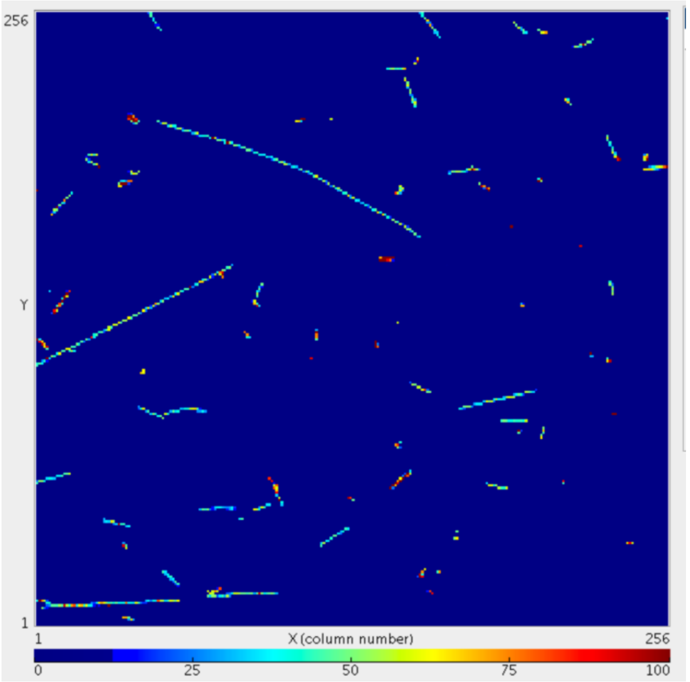
Advacam s.r.o., Prague

Timepix Demo

Timepix chip – 60s exposures



Near sea level



34 000 feet

TIMEPIX@school project

https://cernandsocietyfoundation.cern/projects/timepix

- Several successful pilot projects in the UK, Spain and other countries, have demonstrated that TIMEPIX stimulates and enhances the interest of high school students (especially girls) in STEM subjects
- It also improves the motivation of science teachers.
- Capturing the interest of high school students in STEM is vital for future recruitment for the microelectronics industry
- The CERN & Society Foundation is raising funds to make the technology more widely available in schools

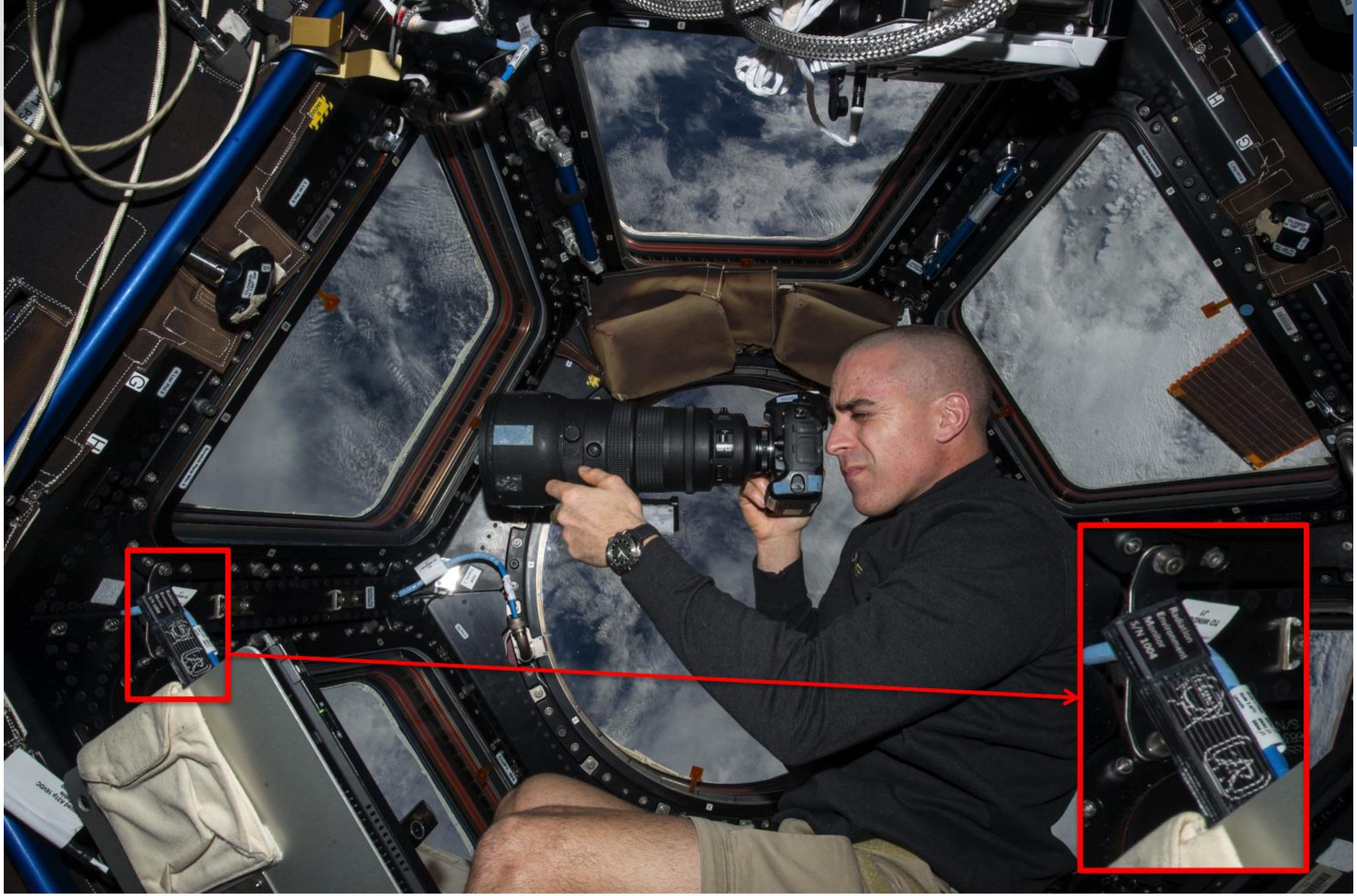
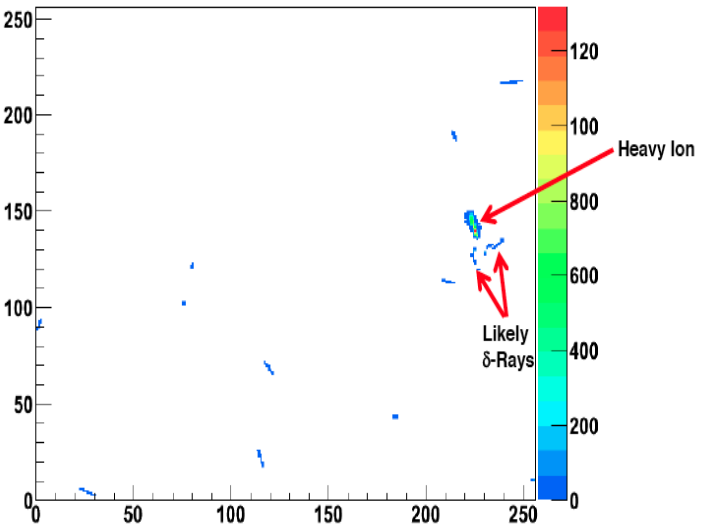
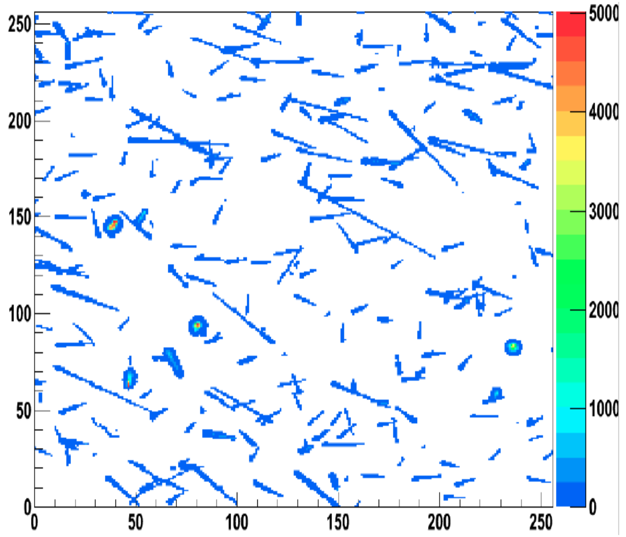


Image of the astronaut Chris Cassidy working near the Timepix USB on the International Space Station (Courtesy of NASA, photo ref. no. iss036e006175)

Timepix - 4s exposures



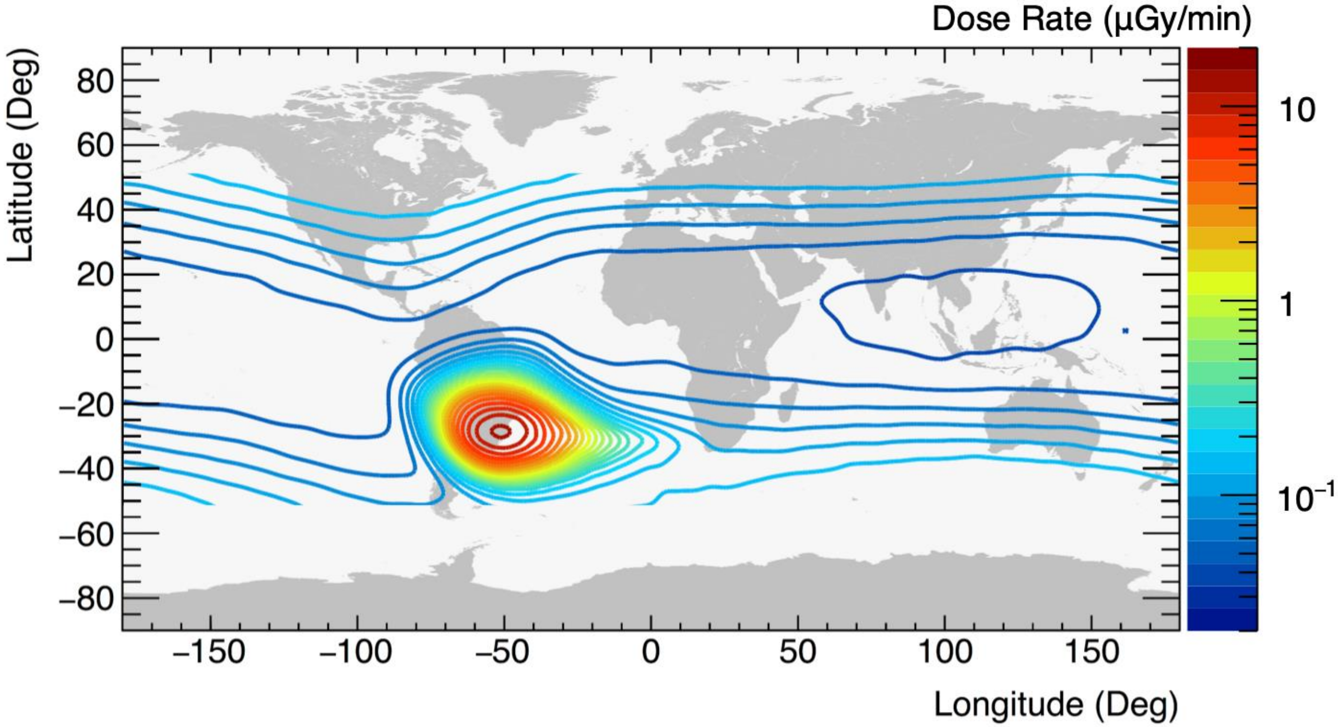
South China Sea



South Atlantic Anomaly

University of Houston, IEAP Prague, NASA

REM Dose Rate Data (μG/min)



Timepix dose rates measured in 2014 on ISS

University of Houston, IEAP Prague, NASA

Timepix on Artemis 1

- Artemis 1 launch Wednesday Nov 16 2022
- Carrying 4 Timepix detectors from the Medipix2 collaboration at CERN on board to measure radiation
- Part of a larger program at NASA using Timepix based instruments for radiation measurement
- 3 devices part of HERA radiation dose monitoring hardware. Successful operation from just after launch to just before splashdown
- 4th device no board Biosentinel cubesat (now at > 50Mkm from earth

Timepix-based flight hardware

Name	Date Flown	Mission	Location	Objective	Vehicle	Number TPX
REM	2012	ISS	LEO	Demo	ISS	5
BIRD	2014	Orion EFT-1	LEO/MEO	Demo/Science	Orion	2
REM2	2018	ISS	LEO	Ops	ISS	7
MPT	2017	ISS	LEO	Science	ISS	2
Biosentinel	2020	ISS	LEO	Science	ISS	1
ISS-HERA	2018	ISS	LEO	Demo	ISS	3
AHOSS	2020	ISS	LEO	Demo/Ops	ISS	3
LETS(1)	2023	Astrobotic 1	Lunar Surface	Science	Peregrine	1
LETS(2)	2024/5	Berensheet 2*	Lunar Surface	Science	Berensheet 2	1
HERA	2022	Artemis 1	Lunar Orbit	Ops	Orion	3
Biosentinel	2022	Artemis 1	Solar Orbit	Science	Cubesat	1
HERA	2023	Polaris Dawn	MEO	Science	Crew Dragon	1
HERA	2024	Artemis 2	Lunar Orbit	Ops	Orion	6
HERA	2025	Artemis 3	Lunar Orbit	Ops	Orion	6
ARES	2025	Artemis 3	Lunar Surface	Ops	Starship	>=1
LEIA	~~2024	CLPS Lander	Lunar Surface	Science	TBS Lander	1
ARES	2026	Artemis	Lunar Orbit	Ops	Lunar Gateway	2

***Evaluating mission possibility**

7 missions flown, 4 missions next six months, 6 missions manifested, > 23 Timepix in Space to date

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

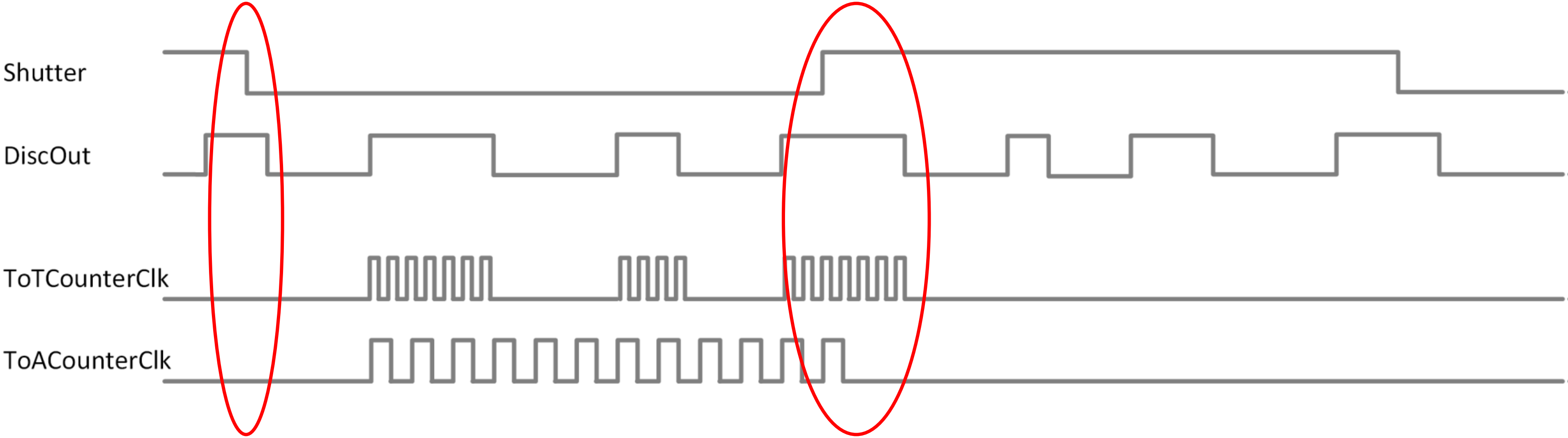
Timepix2 modes of operation

Main features and modes:

- Frame based readout only (256x256 pixels, 55 um pitch).
- 4 multipurpose counters per pixel: 2x 10 bits + 2x 4 bits
- Three modalities: Event counting, Energy (ToT) or Time of Arrival (ToA).
- Continuous measurement modes with zero dead time: One counter is used for measurement while the other is being readout then their roles swap

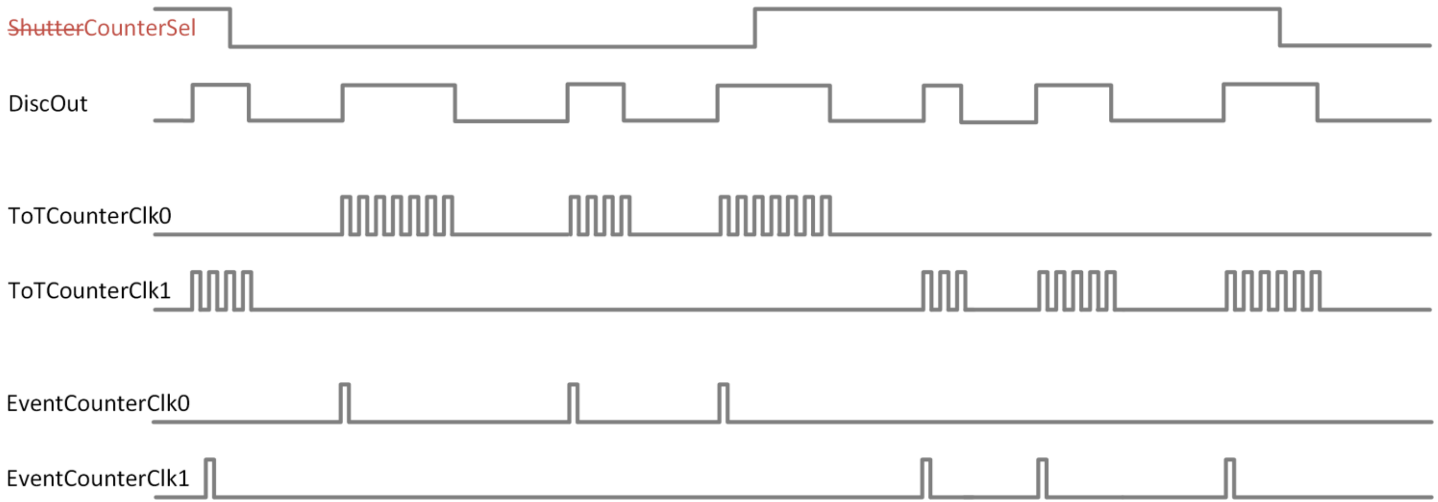
Mode Name	Description	1st Counter	2nd Counter
ToT10/ToA18	Simultaneous ToT and 1st hit ToA (with sequential read/write) Mode options (programmable): 1) 1st hit or integral ToT 2) Overflow (wraparound) of ToA counter	10-bit ToT {CounterA}	18-bit ToA {CounterD, CounterC, CounterB}
ToT14/ToA14		14-bit ToT {CounterD, CounterA}	14-bit ToA {CounterC, CounterB}
ContToT10/ Event4	Continuous read/write ToT Mode options: 1) 1st hit or integral ToT (programmable) 2) Supplementary 4-bit eventing counting (readout optional)	10-bit ToT {CounterA} 4-bit #Events {CounterD}	10-bit ToT {CounterB} 4-bit #Events {CounterC}
ContToT14	Continuous read/write ToT Mode option: 1st hit or integral ToT (programmable)	14-bit ToT {CounterD, CounterA}	14-bit ToT {CounterC, CounterB}
ContToA10	Continuous read/write 1st hit ToA	10-bit ToA {CounterA}	10-bit ToA {CounterB}
ContToA14		14-bit ToA {CounterD, CounterA}	14-bit ToA {CounterC, CounterB}
ContEvent10	Continuous read/write event counting	10-bit #Events {CounterA}	10-bit #Events {CounterB}
ContEvent14		14-bit #Events {CounterD, CounterA}	14-bit #Events {CounterC, CounterB}

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

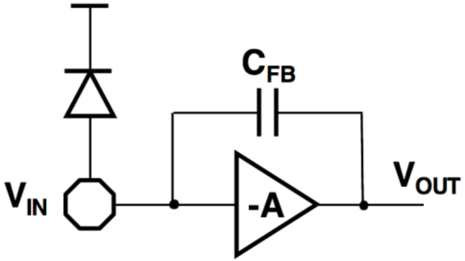
Continuous R/W – ToT and event counting



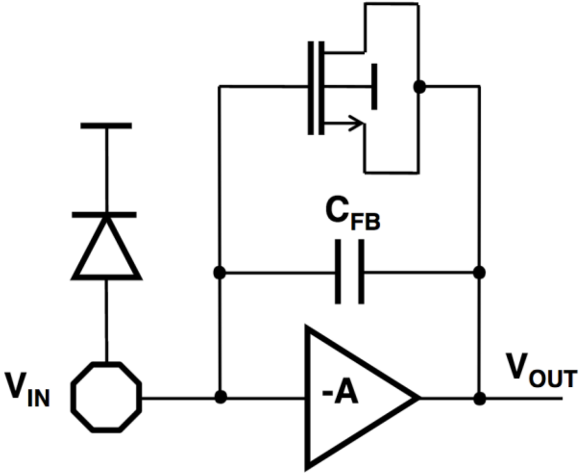
<u>Other modes in Continuous R/W</u>

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

Pixel Frontend



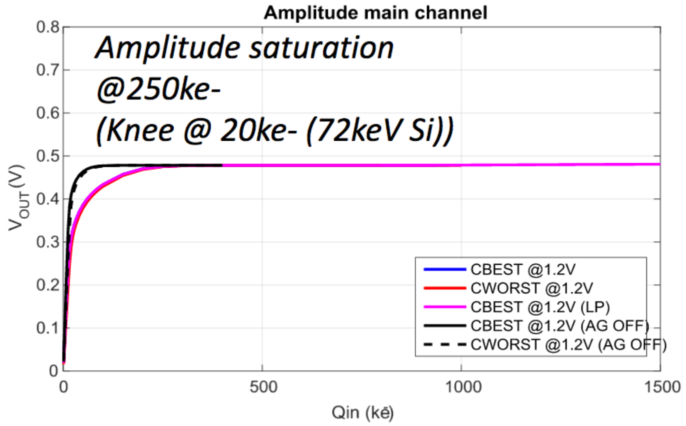
$$\frac{\Delta V_{OUT}}{\Delta Q_{IN}} = \frac{1}{C_{FB}}$$

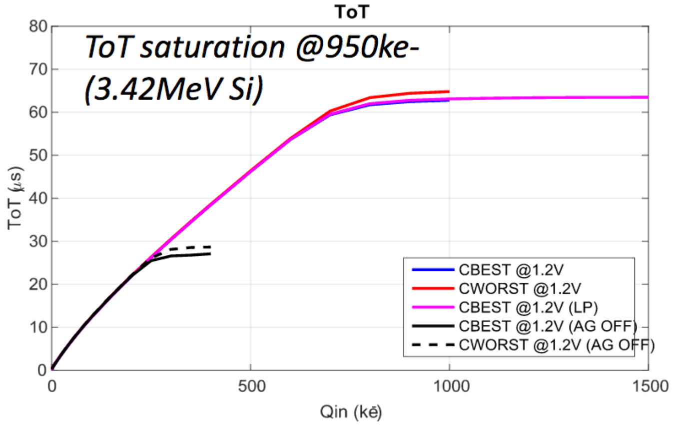


When the transistor is active, the feedback capacitance is ~125fF (Dimensions transistor 1/10)

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

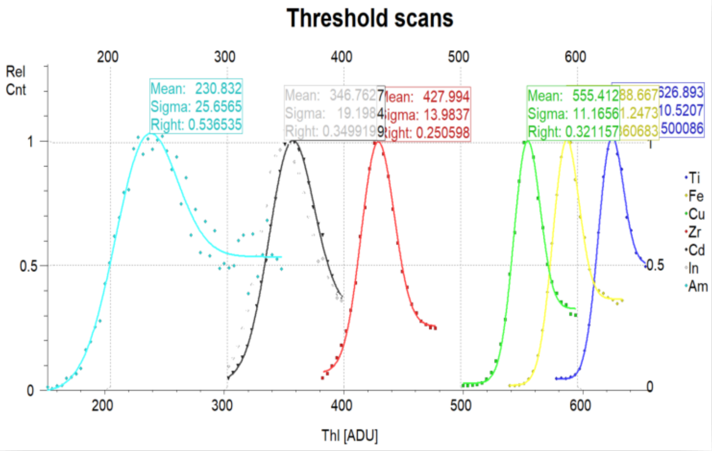
Pixel Frontend



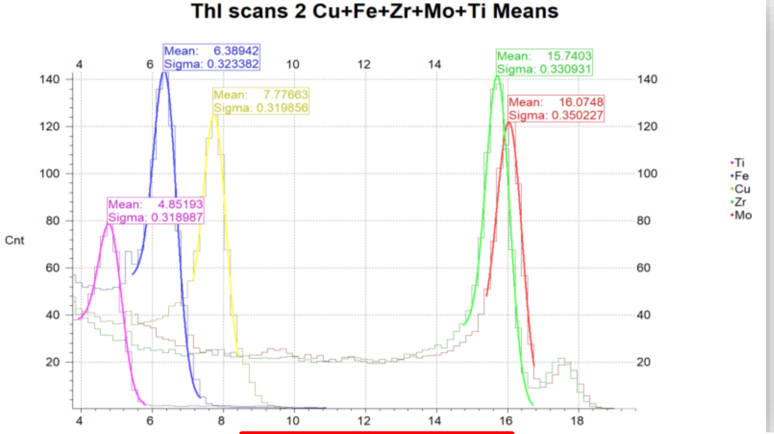


Timepix2 500 µm Si sensor – improved equalisation

Before (standard equalization)



After (equalization using targets)



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

Parameters:

- Ikrum=2, Preamp=255
- Bias = 400 V
- **Equalized for Cu XRF**

J. Jakubek, Advacam

XRF	Sigma [keV]	FWHM [keV]	Energy [keV]	Resolution [%]
Ti	0.319	0.751	4.501	16.7%
Fe	0.323	0.762	6.398	11.9%
Cu	0.320	0.753	8.04	9.4%
Zr	0.331	0.779	15.744	5.0%
Mo	0.350	0.825	17.441	4.7%

Status of Timepix2

- Timepix2 is available for use
- It is well adapted to applications which use frame-based readout
- It is being incorporated in a number of space applications
- It can be bought commercially from Advacam Sro
- It will gradually replace Timepix in educational kits

Timepix readout chips - single particle detection

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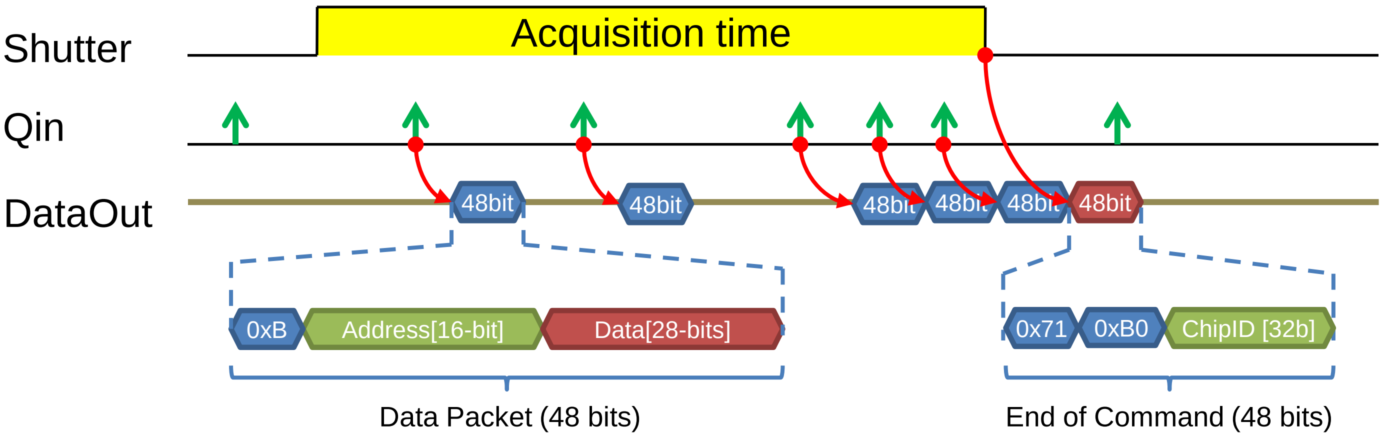
Tech. node (nm)	250	130	130	65
Year	2005	2018	2014	2019
Pixel size (mm)	55	55	55	55
# pixels (x x y)	256 x 256	256 x 256	256 x 256	448 x 512
Time bin (resolution)	10ns	10ns	1.5ns	200ps
Readout architecture	Frame based (sequential R/W)	Frame based (sequential or continuous R/W)	Data driven or Frame based (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)

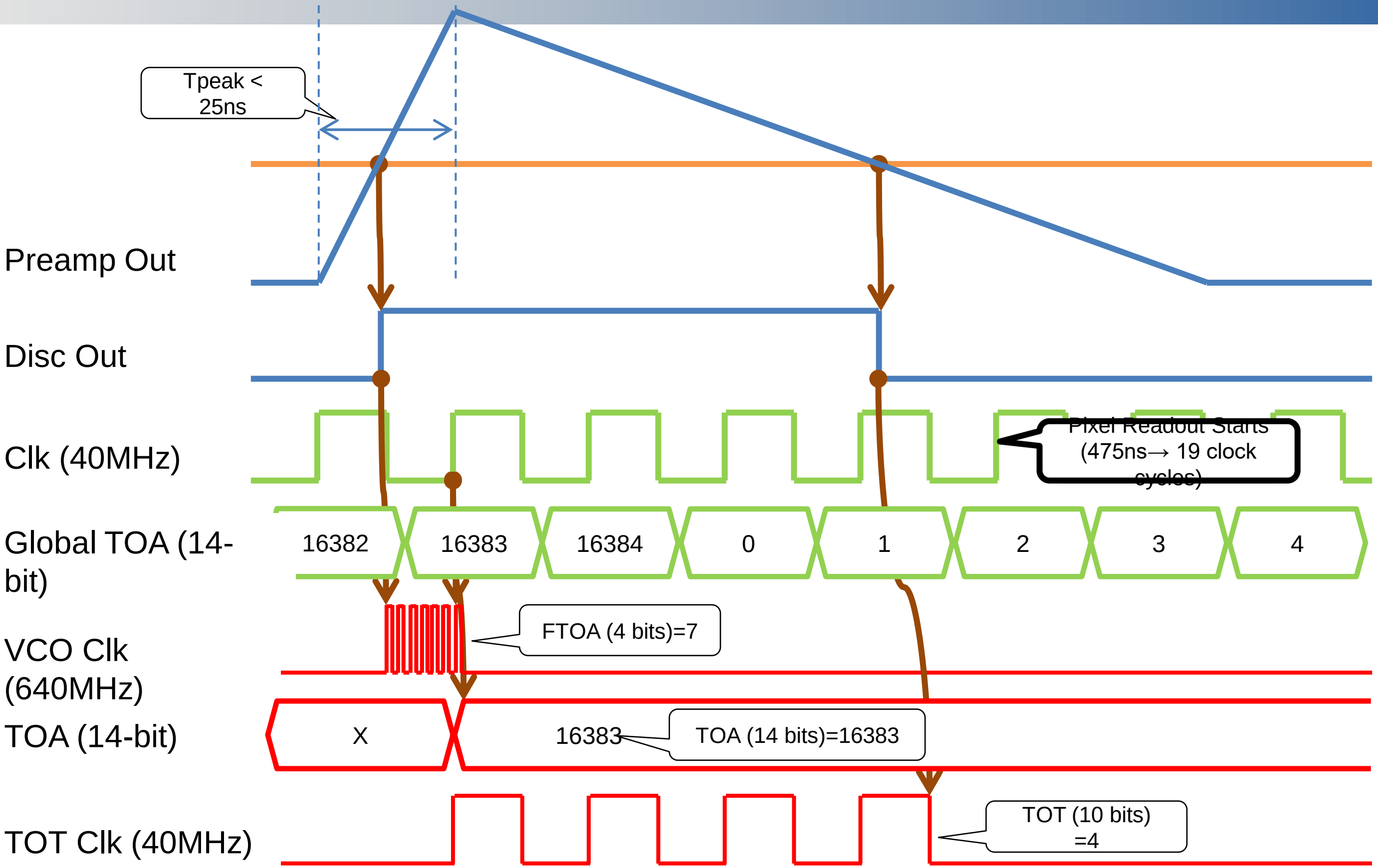
* Thanks to V. Gromov, et al. Nikhef, C. Brezina et al., Bonn

Timepix3 readout - Trigger-less and event driven



- Achievable count rate:
  - uniformly distributed events → ~43 Mhits/s/cm^2 @5.12Gbps
- Full matrix readout: ~800 µs @5.12Gbps

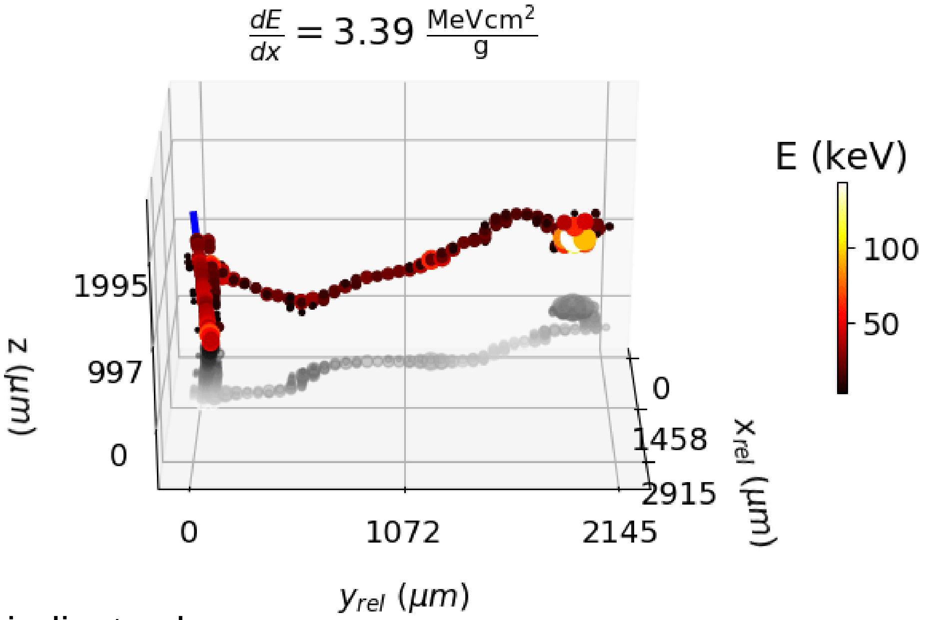
Pixel Operation in TOA & TOT



Timepix3 miniaturised readout

Advacam s.r.o., Prague

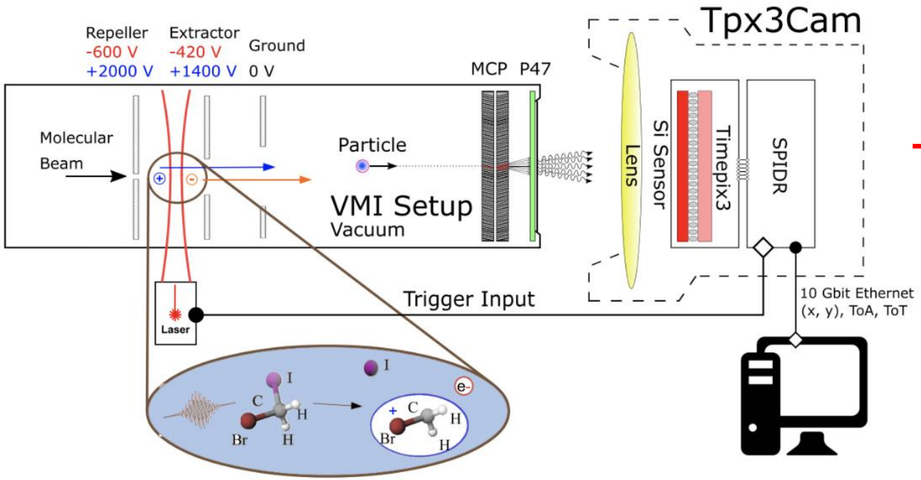
3D rendering of traversing particle with delta electron



45 deg
CdTe sensor
2mm thick
V_{bias} = 130V
Colour (and diameter) indicate charge

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

Velocity Map Imaging - Timepix3CAM



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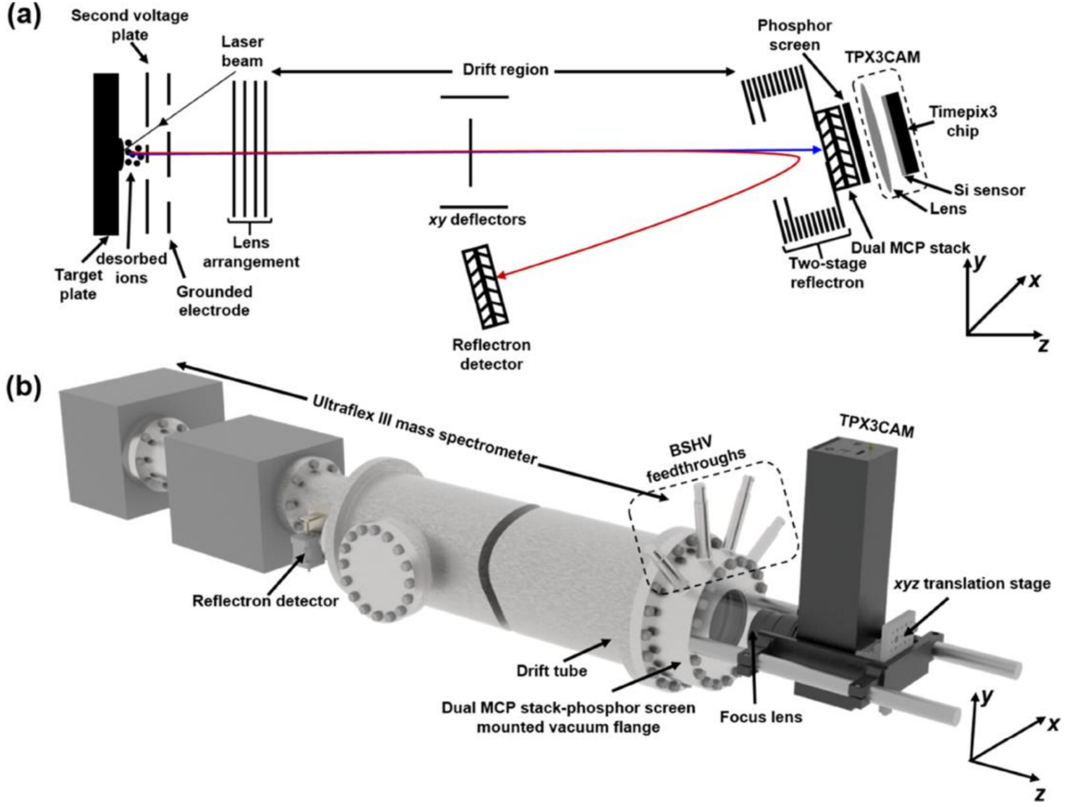
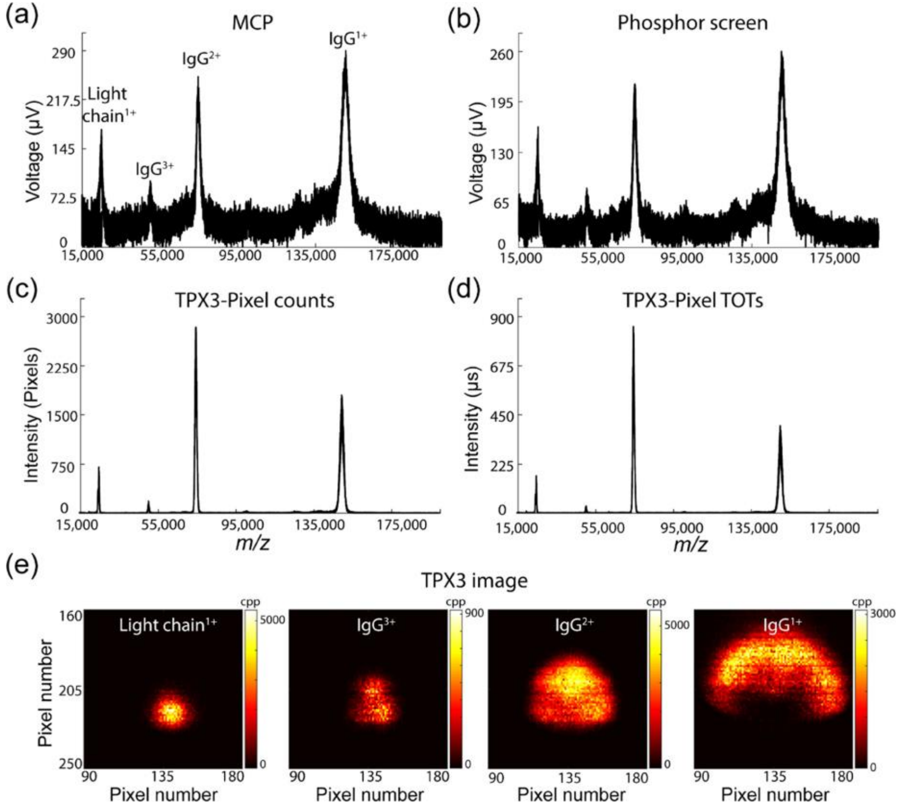
Imaging Time of Flight Mass Spectrometry - setup



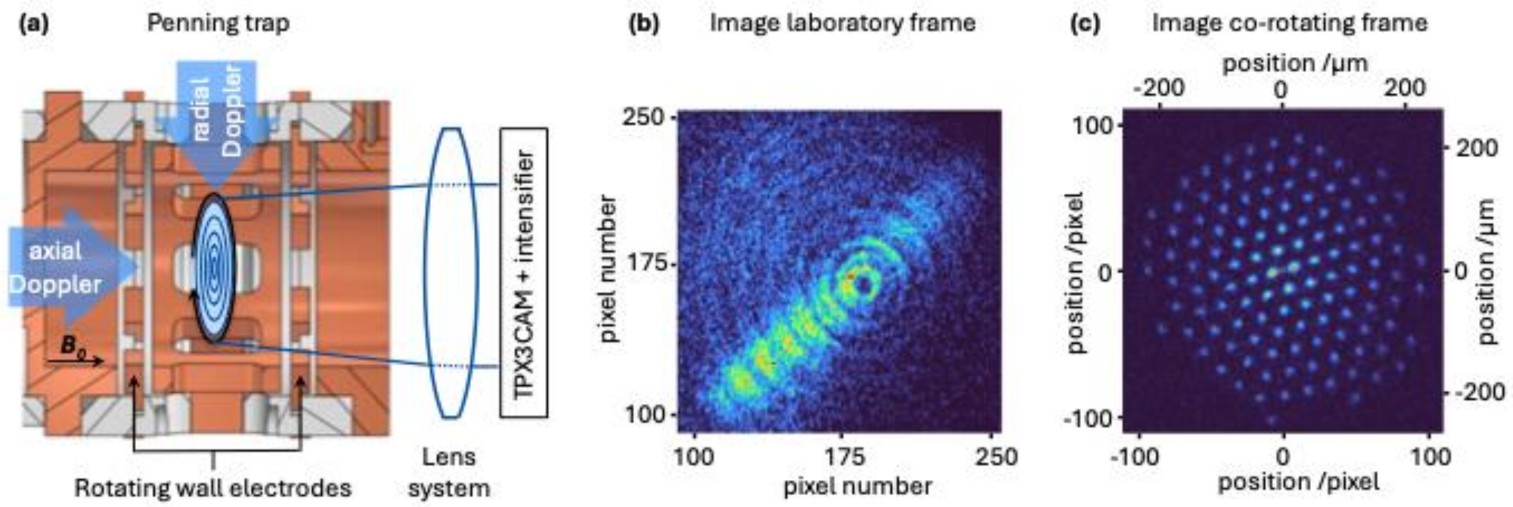
DOI: (10.1021/acs.analchem.2c04480)

Imaging Time of Flight Mass Spectrometry - results



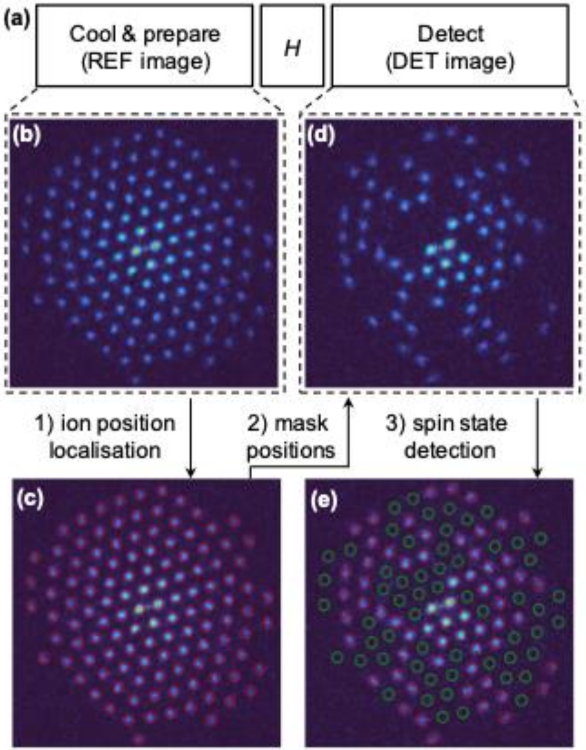
DOI: (10.1021/acs.analchem.2c04480)

One example of quantum application of TPIX3CAM



Robert N Wolf et al., “Efficient site-resolved imaging and spin-state detection in dynamic two-dimensional ion crystals”, arXiv:2303.10801v4 [quant-ph] 16 Sep 2024

One example of quantum application of TPIX3CAM



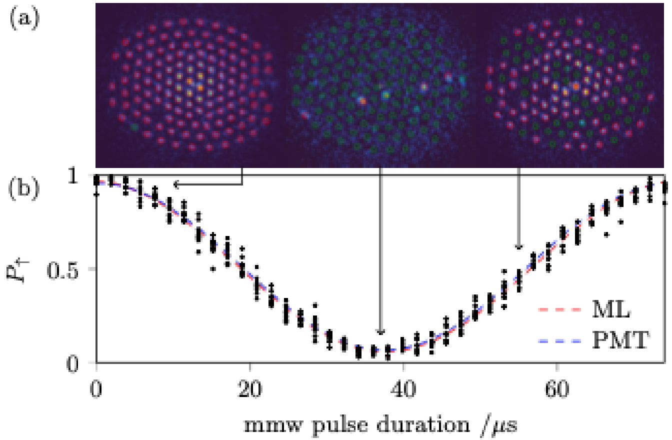


Figure 5. Individual spin-state detection after global spin-flip excitations. (a) A crystal of about 120 ions is shown at different millimeter wave (mmw) pulse durations of $t = 0$, $t \approx 39\,\mu$s and $t \approx 57\,\mu$s, as indicated by the arrows. (b) Bright-state fraction, $P_\uparrow = N_B/N$, determined from individual images (dots) by counting the total number of ions, N, via the neural network, and the number of bright ions, N_B, via the time-binned maximum likelihood (ML) method. The red dashed line is a sinusoidal fit to the data. The blue dashed line is a fit to the photon counts (not shown) obtained simultaneously with a photomultiplier tube (PMT). The crystal's

Robert N Wolf et al., “Efficient site-resolved imaging and spin-state detection in dynamic two-dimensional ion crystals”, arXiv:2303.10801v4 [quant-ph] 16 Sep 2024

Publications in quantum applications of TPIX3CAM

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Category	Publication	Author	Link
Quantum Science	Fast quantum ghost imaging with a single-photon-sensitive time-stamping camera	Alex Mavian, Yang Xu, Cheng Li, Robert Boyd, Optica Publishing (2025)	
Quantum Science	Biphoton state reconstruction via phase retrieval methods	N.Dehghan et al. Optica Publishing (2024)	
Quantum Science	Engineering quantum states from a spatially structured quantum eraser.	Carlo Schiano et al. Sci. Adv (2024)	
Quantum Science	Background resilient quantitative phase microscopy using entangled photons	Yingwen Zhang et al. arXiv (2024)	
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Quantum Science	Intensified Tpx3Cam, a fast data-driven optical camera with nanosecond timing resolution for single photon detection in quantum applications	A. Nomerotski et al. IOP Science (2023)	
Quantum Science	Characterisation of a single photon event camera for quantum imaging	V. Vidyapin et al. Nature (2023)	
Quantum Science	Snapshot hyperspectral imaging with quantum correlated photons	Y.Zhang et al. Optica (2023)	
Quantum Science	Study of afterpulsing in optical image intensifiers	R Mahon et al. arXiv (2023)	
Quantum Science	Spectral characterization of a SPDC source with a fast broadband spectrometer	B Farella et al. arXiv (2023)	
Quantum Science	Experimental Work Towards an Individually-Addressed-Ion Penning Trap Quantum Simulator	B McMahon et al. Bulletin of the American Physical Society (2023)	
Quantum Science	Full spatial characterization of entangled structured photons	X Gao et al. arXiv (2023)	
Quantum Science	Full spatial characterization of entangled structured photons	X Gao et al. arXiv (2023)	

https://amscins.com/resources/publications/?category=quantum-science

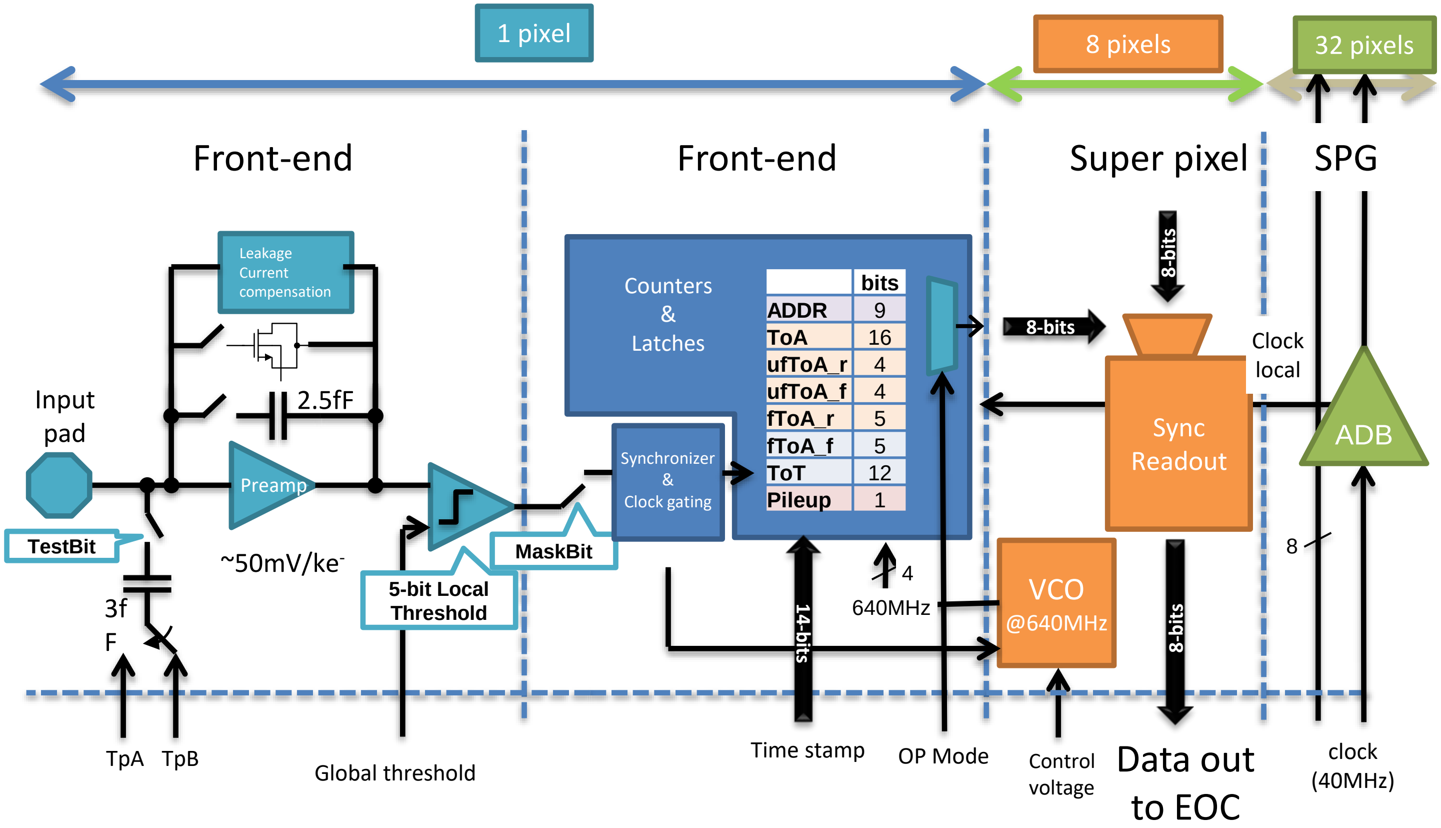
Timepix readout chips - single particle detection

	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 → Timepix4

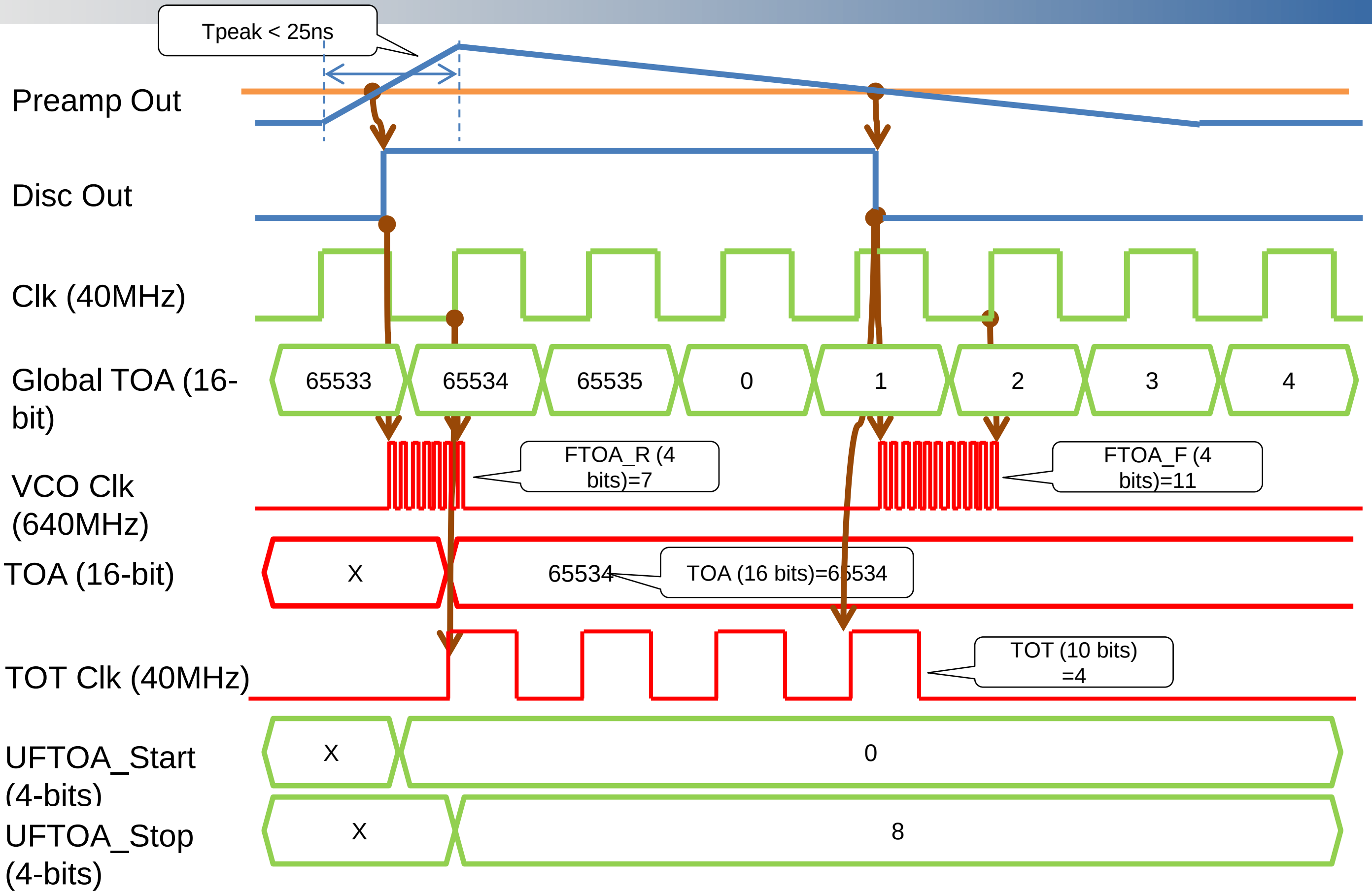
			Timepix3 (2013)	Timepix4 (2018/19)
Technology			130nm – 8 metal	65nm – 10 metal
Pixel Size			55 x 55 µm	55 x 55 µm
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448
Sensitive area			1.98 cm^2	6.94 cm^2
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	
		Event Packet	48-bit	64-bit
		Max rate	<0.43 $Mhits/mm^2/s$	<3.58 $Mhits/mm^2/s$
		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

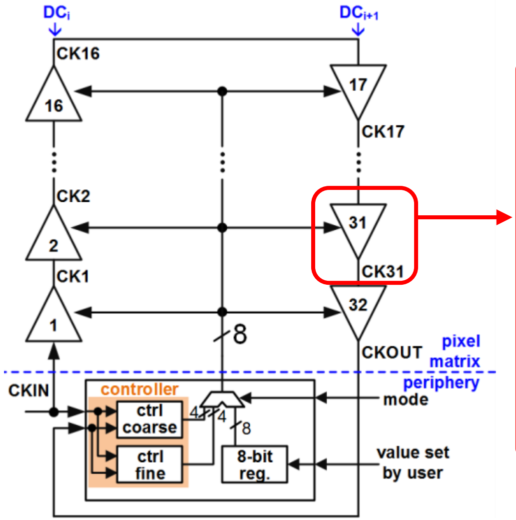
Pixel Operation in TOA & TOT [DD]

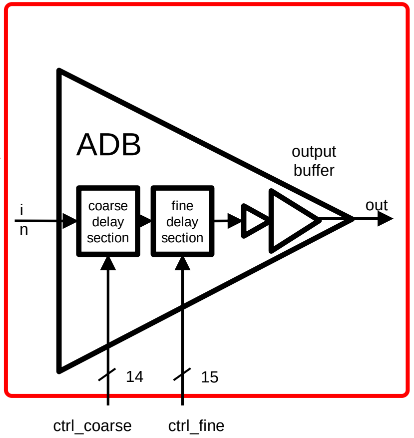


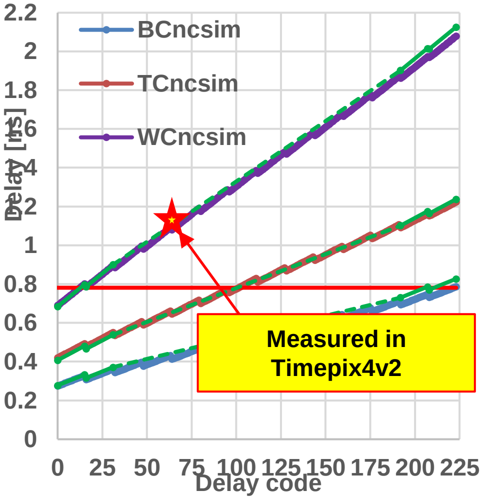
Full digital double column DLL

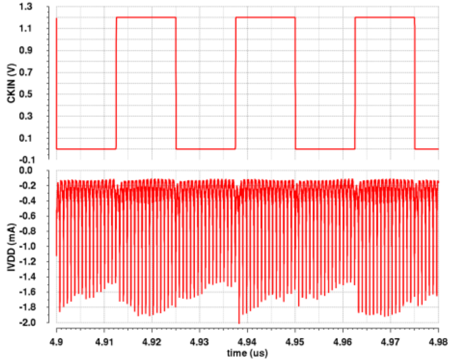
[448 dDLL: 224 Top Matrix and 224 Bottom Matrix]

iWoRID 2018
X. Llopart et al 2019 JINST 14 C01024





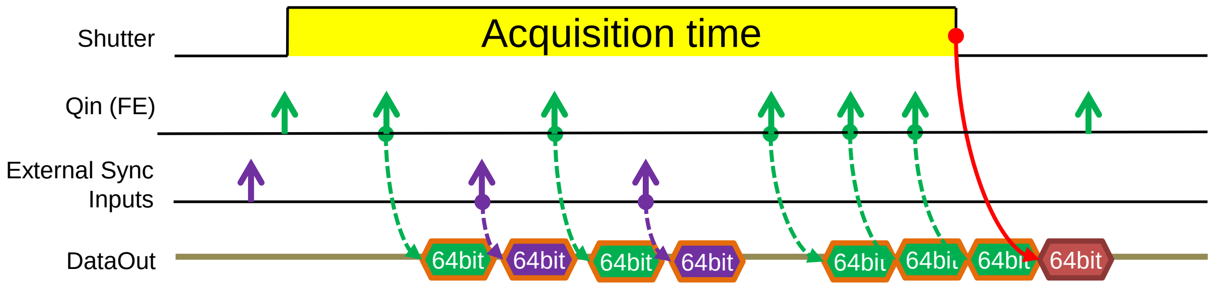




- Timepix4 ~23 mW/cm^2 @40MHz clock with a 100 ps$_{rms}$
- Timepix3 ~100mW/cm^2 @40MHz clock with ~1.2ns skew
- Dynamic digital power consumption is distributed across the clock period

Timepix4 Readout Modes : Data-Driven

- Zero-suppressed continuous data-driven
  - Output bandwidth from 40 Mbps (2.6 Hz/pixel) to 160 Gbps (10.8 KHz/pixel)
  - Uses Aurora 64b/66b standard encoding communication protocol
- 4 External Sync Inputs to synchronize/align external signals with data



SPEC: Packet specifications ToA/ToT				
Name	**Width**	**MSB**	**LSB**	**Bits**
Top	1	63	63	[63:63]
EoC	8	62	55	[62:55]
SP	6	54	49	[54:49]
Pixel	3	48	46	[48:46]
ToA	16	45	30	[45:30]
ufToA_start	4	29	26	[29:26]
ufToA_stop	4	25	22	[25:22]
fToA_rise	5	21	17	[21:17]
fToA_fall	5	16	12	[16:12]
ToT	11	11	1	[11:1]
Pileup	1	0	0	[0:0]

Address: 18 bits

Time: 29 bits

Energy: 21 bits

Timepix4 Readout Modes : Frame-based

- Full frame non-zero suppressed readout with continuous read-write (CRW):
  - 8-bits or 16-bit counter depth
  - Frame rate limited by bandwidth (and probably power):
    - Required Readout bandwidth before counter overflow:
      - 8-bit @ 1Gc/mm^2/s >20.48 Gbps
      - 16-bit @ 8Gc/mm^2/s >1.28 Gbps
    - Minimum → Maximum Frame Rates:
      - 8-bit 338 fps @40Mbps → 86.5 Kfps @160 Gbps
      - 16-bit 169 fps @40Mbps → 43.2 Kfps @160 Gbps

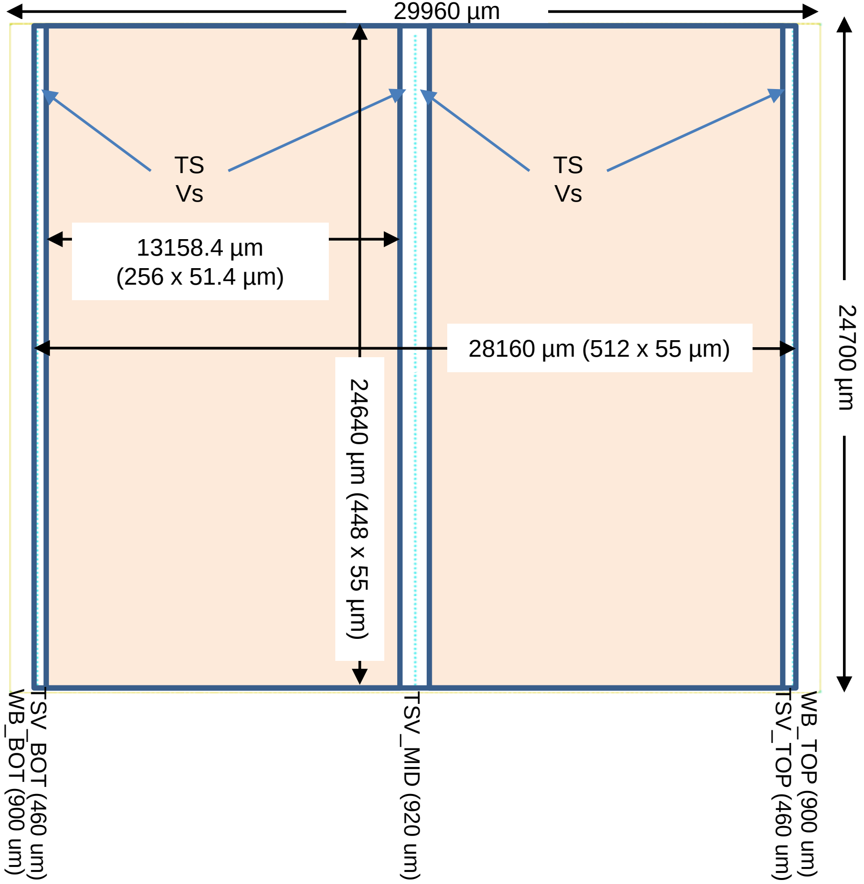
16-bit frame

Name	Width	MSB	LSB	Bits
Pixel 3/7	16	63	48	[63:48]
Pixel 2/6	16	47	32	[47:32]
Pixel 1/5	16	31	16	[31:16]
Pixel 0/4	16	15	0	[15:0]

8-bit frame

Name	Width	MSB	LSB	Bits
Pixel 7	8	63	56	[63:56]
Pixel 6	8	55	48	[55:48]
Pixel 5	8	47	40	[47:40]
Pixel 4	8	39	32	[39:32]
Pixel 3	8	31	24	[31:24]
Pixel 2	8	23	16	[23:16]
Pixel 1	8	15	8	[15:8]
Pixel 0	8	7	0	[7:0]

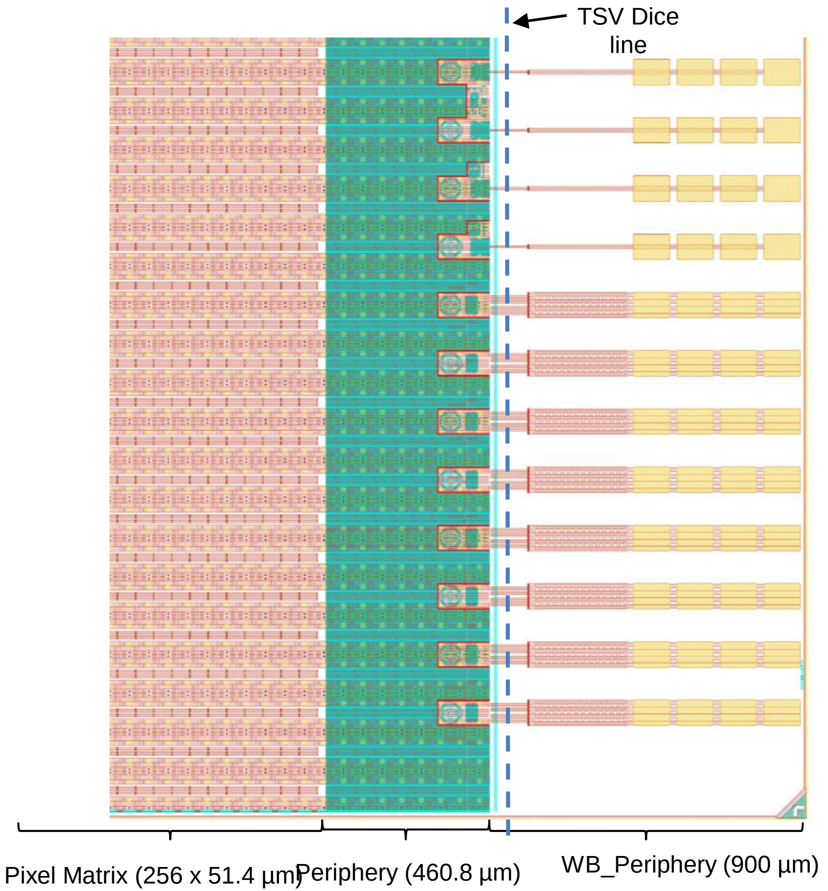
Timepix4 Floorplan



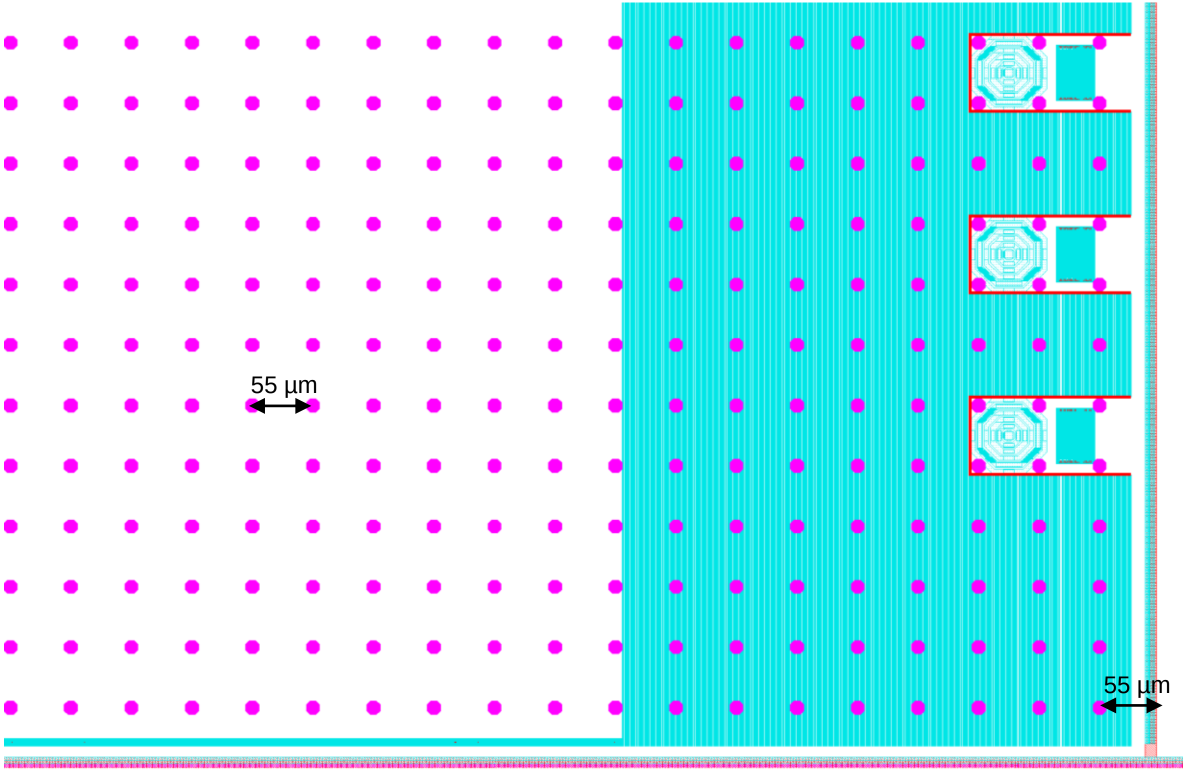
Edge periphery floorplan

- 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)



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

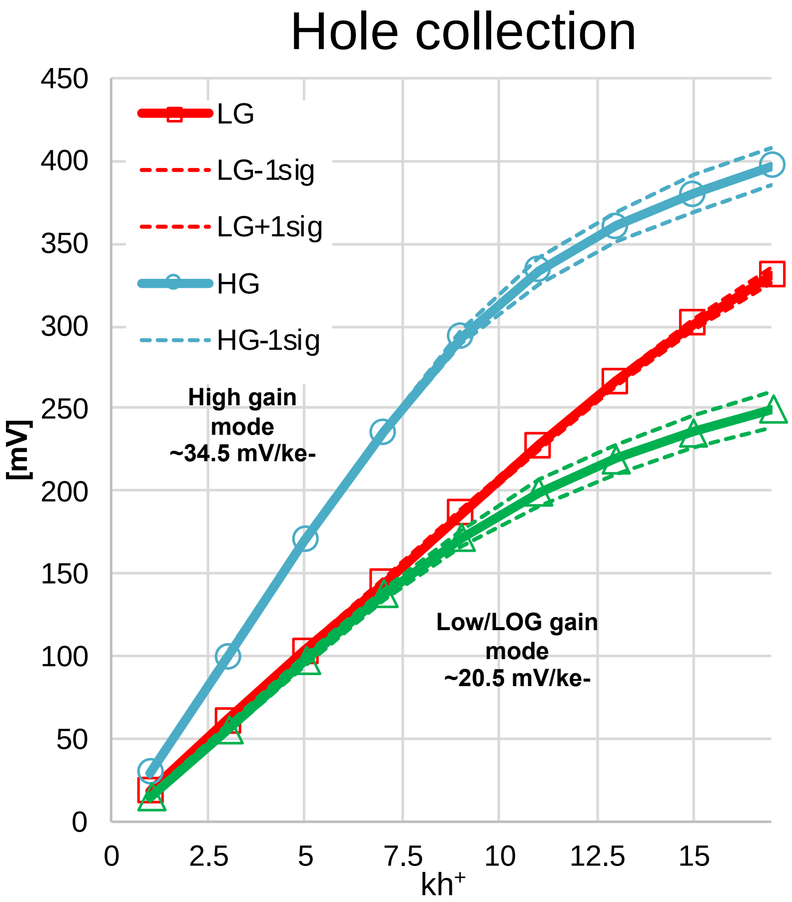
19 wafers received

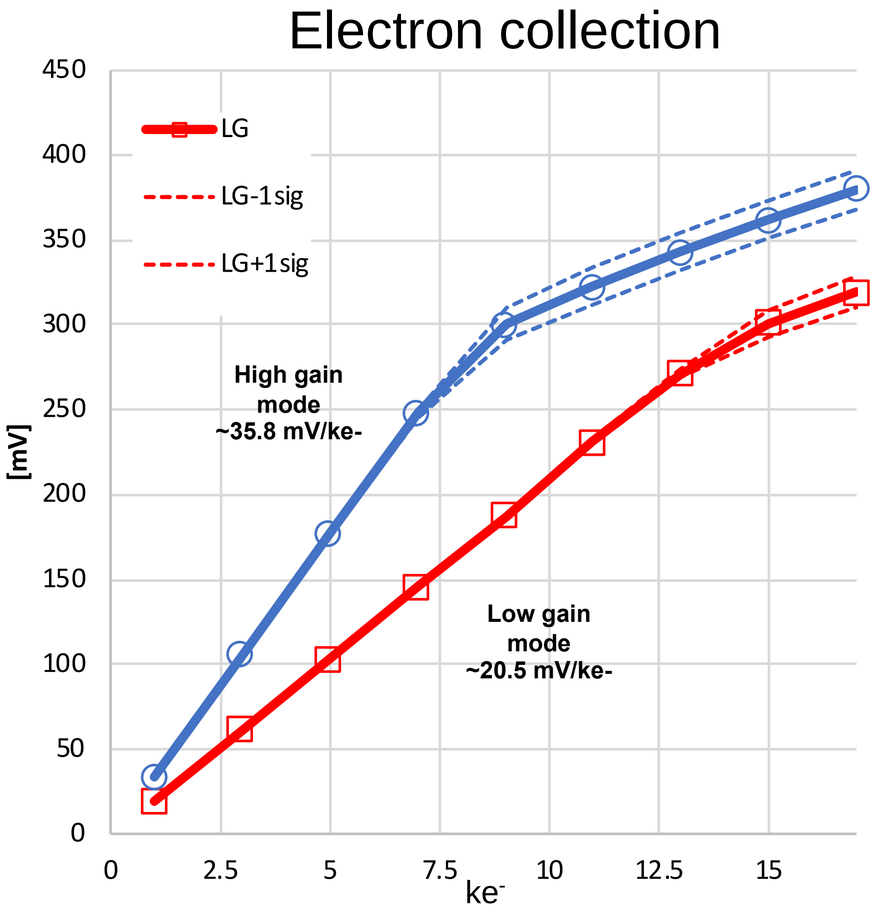
1) TDC and High speed links working as expected
2) Further improvement in RDL shielding in peripheries

Chip at its final version

Gain slopes for different FE Gain

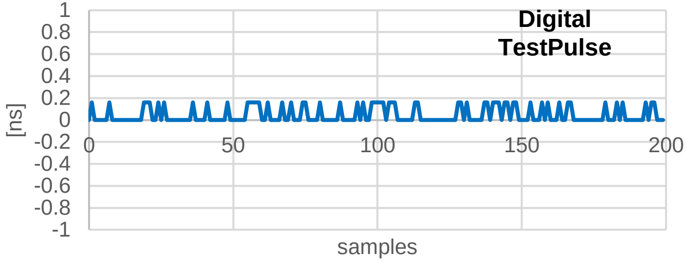
[TOA-TOT, few pixels]

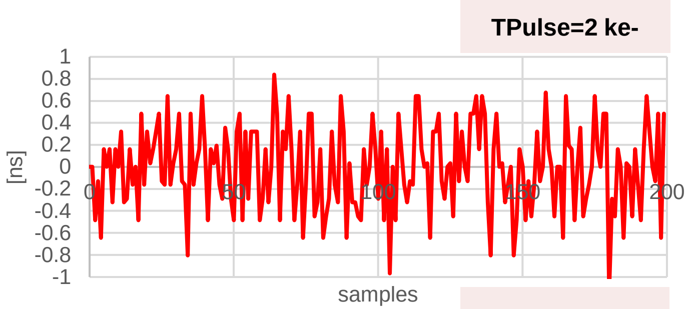


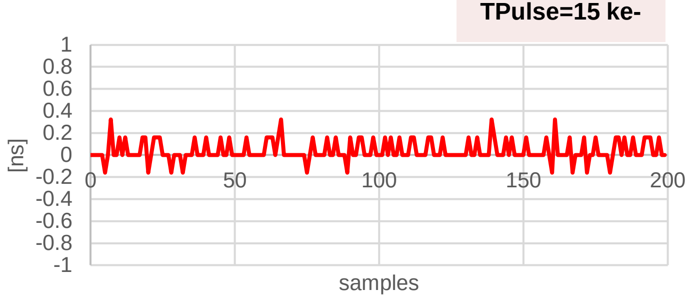


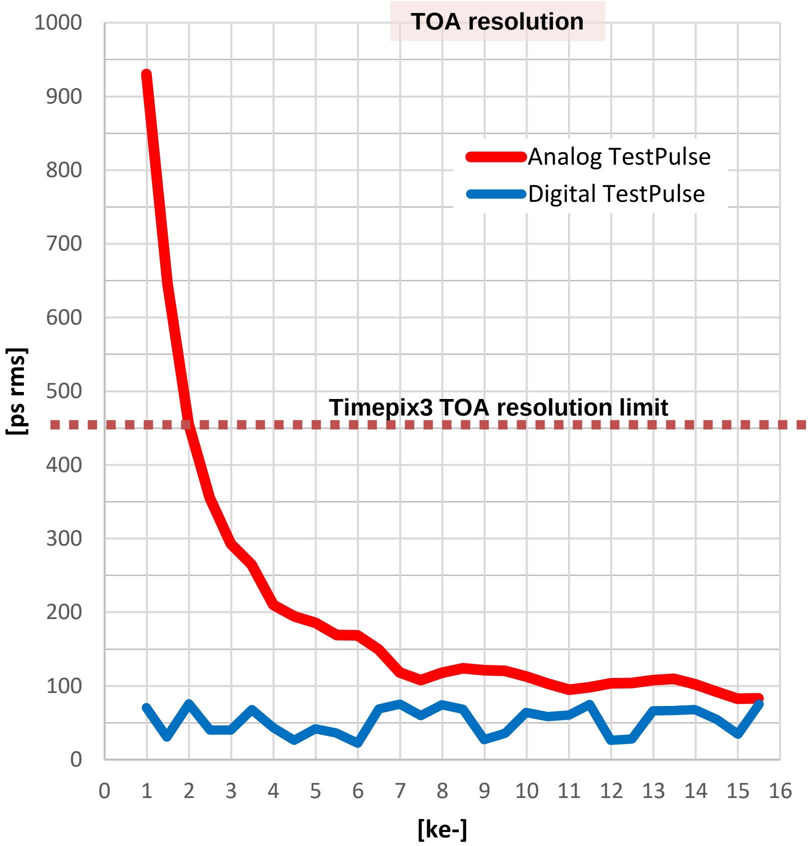
TOA Resolution

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









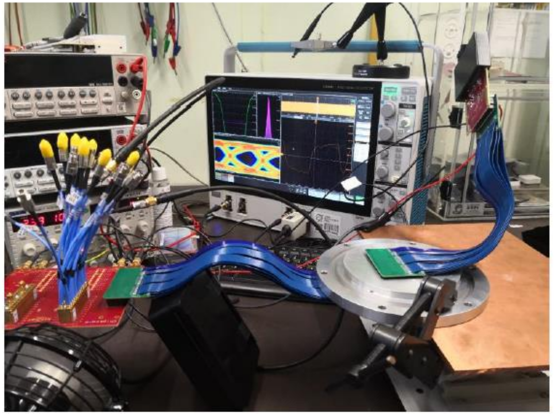
Analog pixel summary measureament

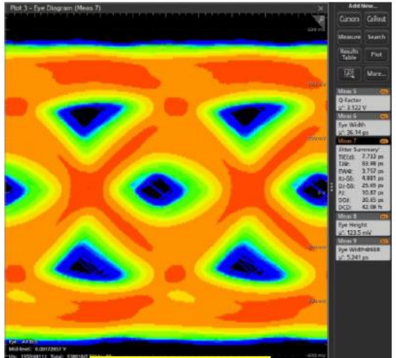
- Preliminary results
- FE settings in nominal power mode
- Pixels on top of peripheries not described here
- Ctest=3.2 fF assumed

	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

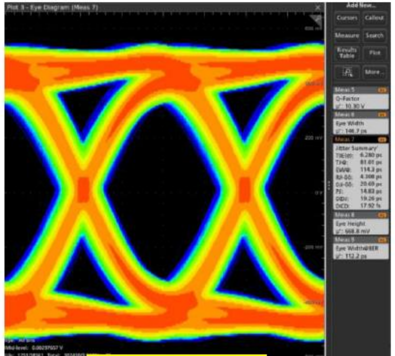
High speed links

- Timepix4 uses a novel low power serializer developed at Nikhef (GWT):
  - 16 links: 8 in each side
  - Configurable bandwidth from 40Mbps to 10.24Gbps
- Using Tektronix scope with 6GHz Bandwidth
- All links enabled
- PRBS-31 pattern
- Pixels above serializers works as others

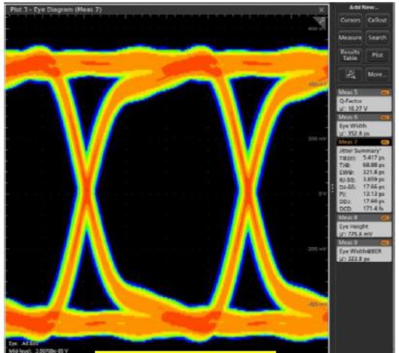




10.24 Gbps



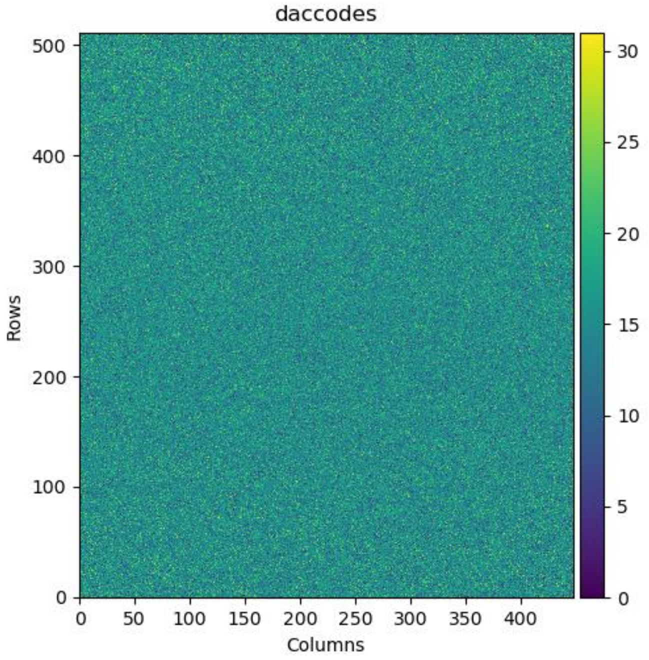
5.12 Gbps

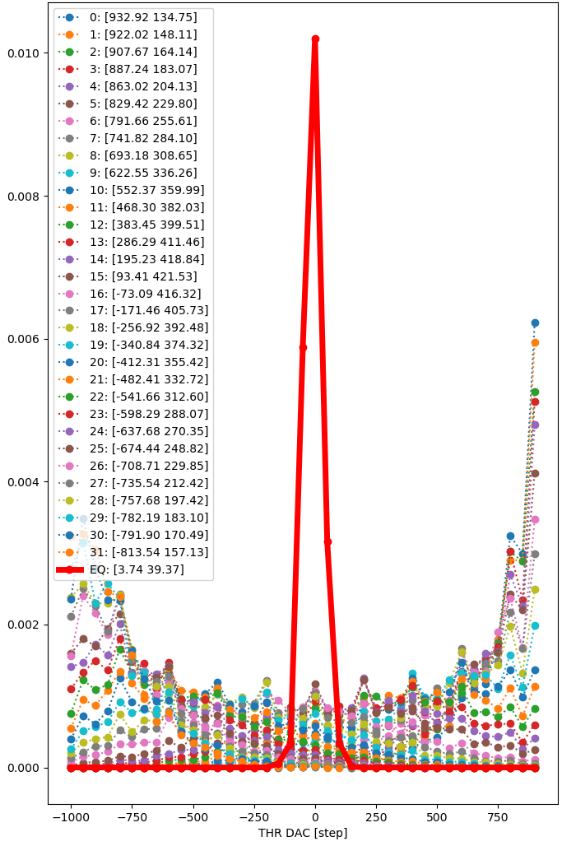


2.56 Gbps

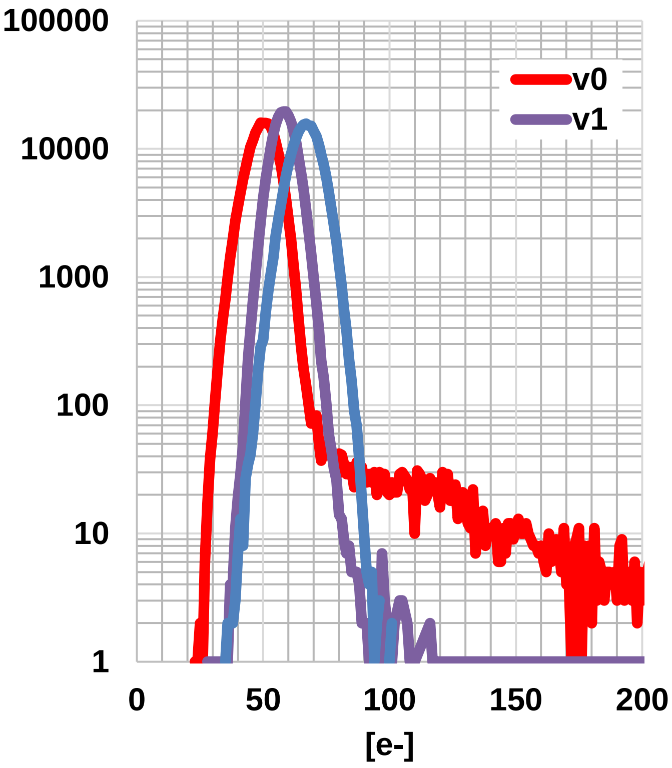
Equalization at nominal settings

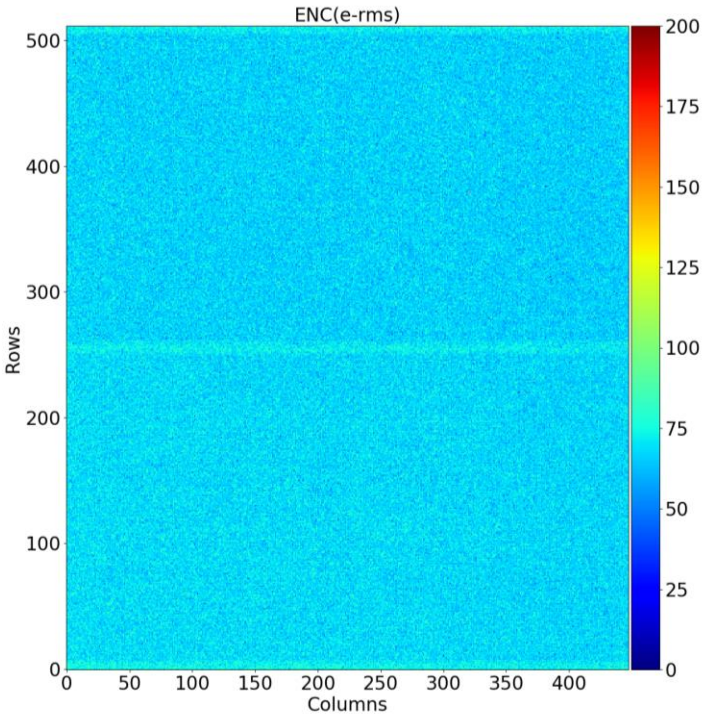
2 masked pixels !!!



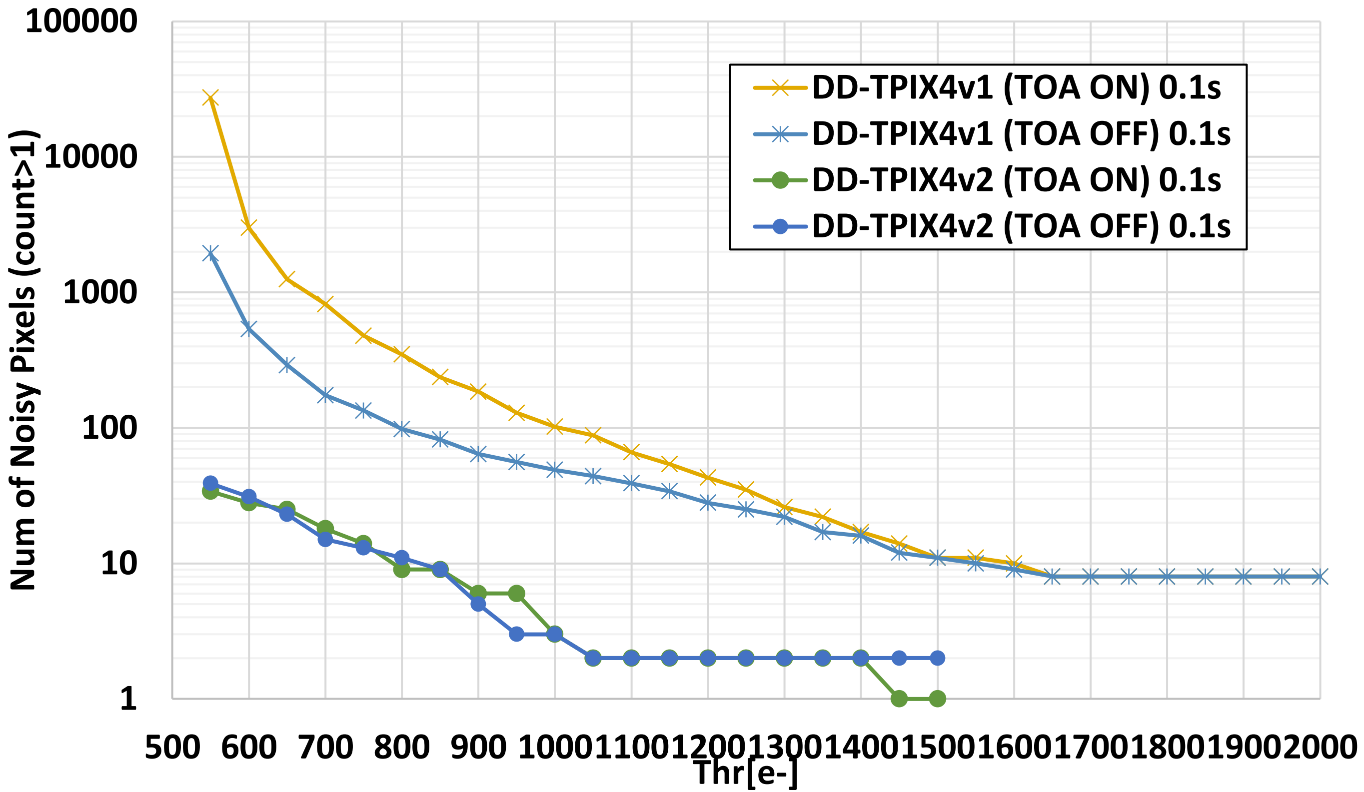


Timepix4v2 ENC



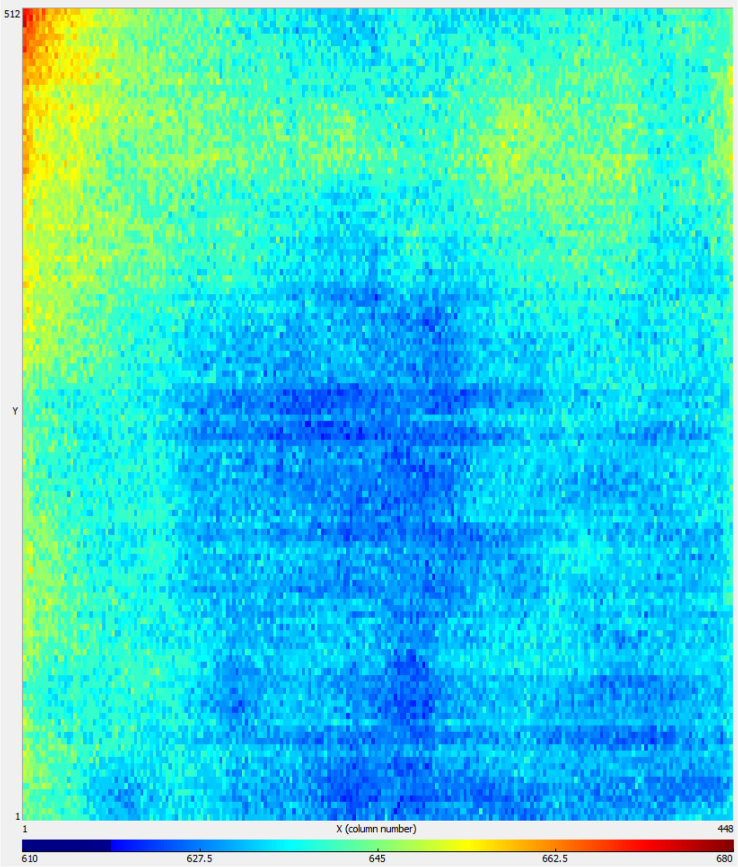


Timepix4v1/2: Number of Noisy pixels (>1 count) in DD

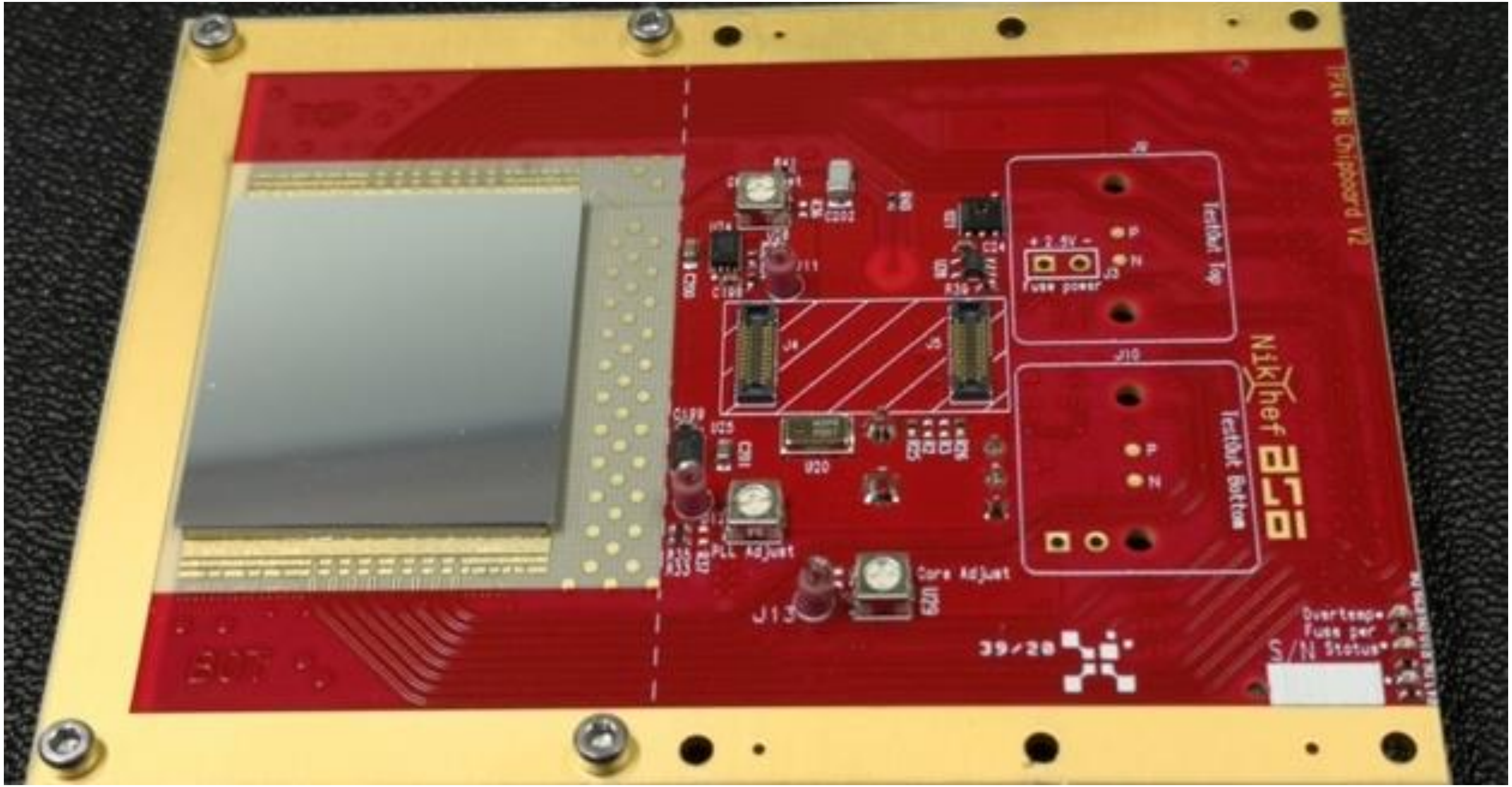


Timepix4 2D VCO distribution

- Map done pulsing 224 pixels simultaneously (max expected 150)
- Main systematics due to digital power supply:
  - At the PCB?
- This should largely improve with TSVs (extra center power supply row)
- Through TDC measurement we have a nice way to measure power supply distribution in 2D

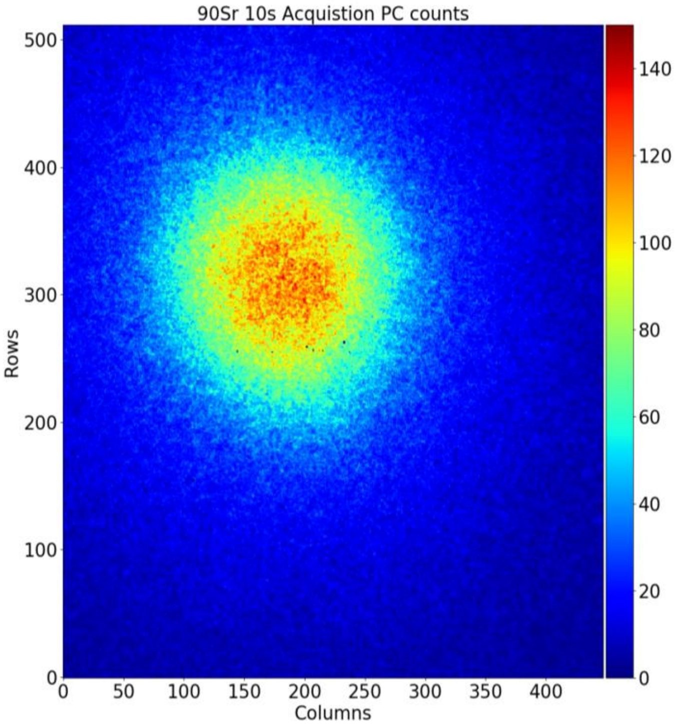


Timepix4 assembly (300μm Si sensor)

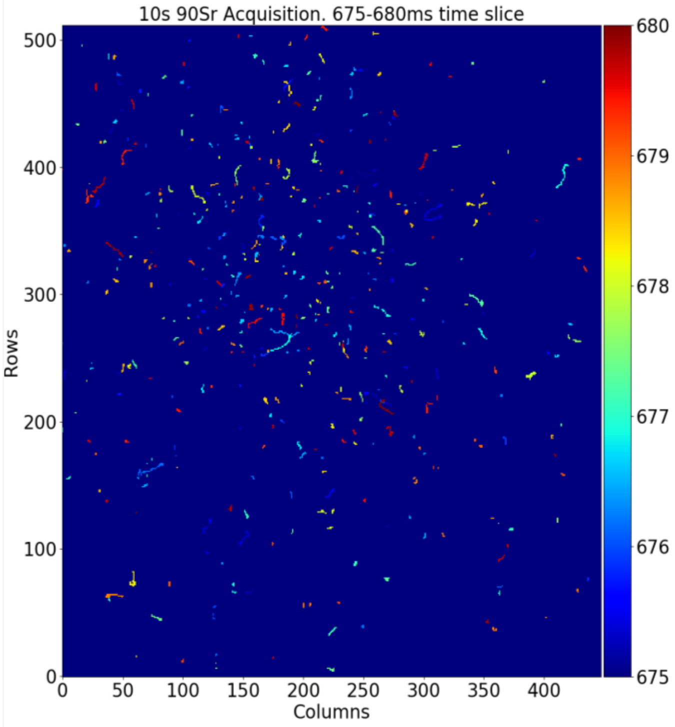


Timepix4 – works! ☺

10 s exp. ^{90}Sr



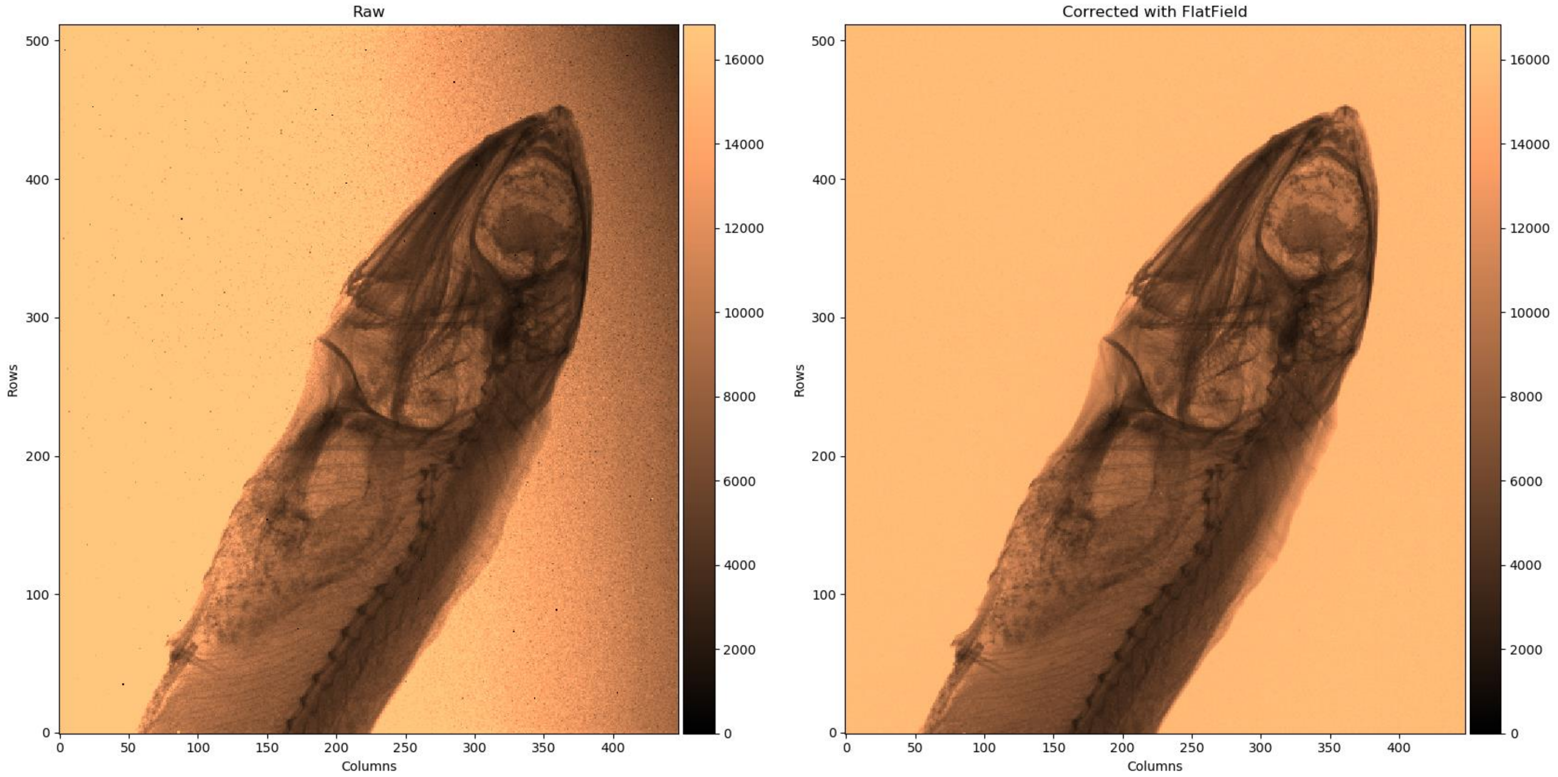
5 ms timeslice



Threshold ~ 800e$^-$

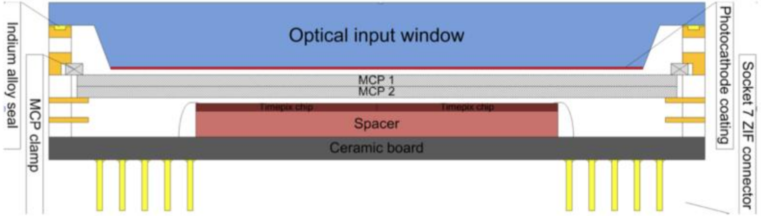
6.1 M packets @ 5 Gbps

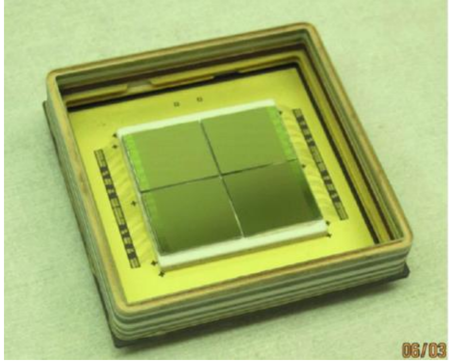
Photon counting image Timepix4



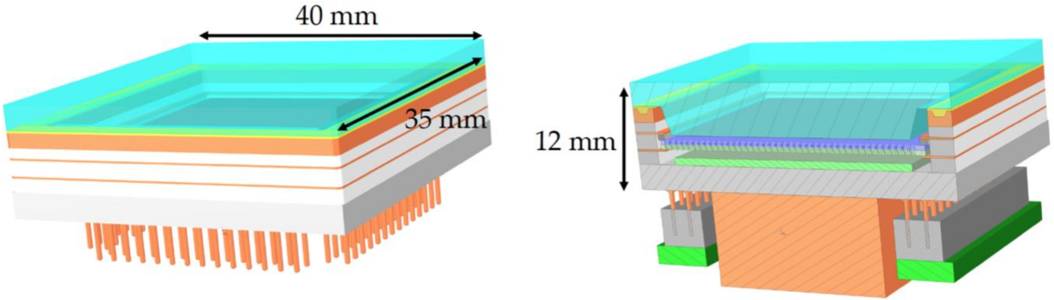
Timepix4 paper:
X. Llopart *et al* 2022 *JINST* **17** C01044

4Dphoton: Integrate Timepix4 in a photo tube





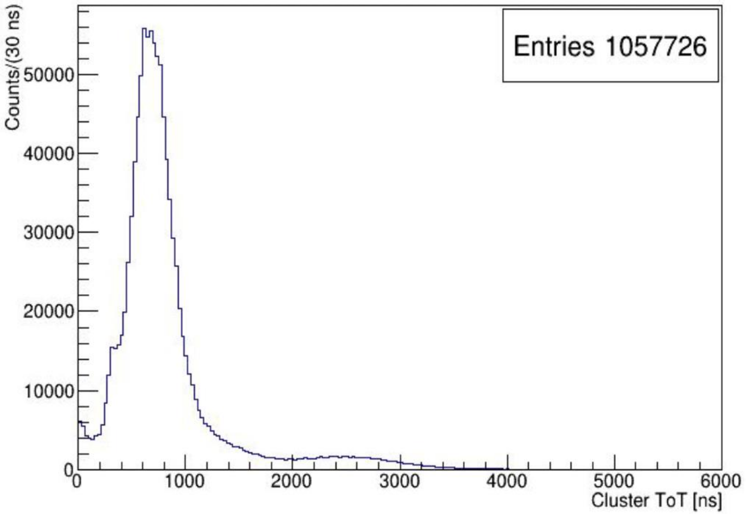
Concept already proven with 4 Timepix chips
See: J Vallerga et al. https://iopscience.iop.org/article/10.1088/1748-0221/9/05/C05055

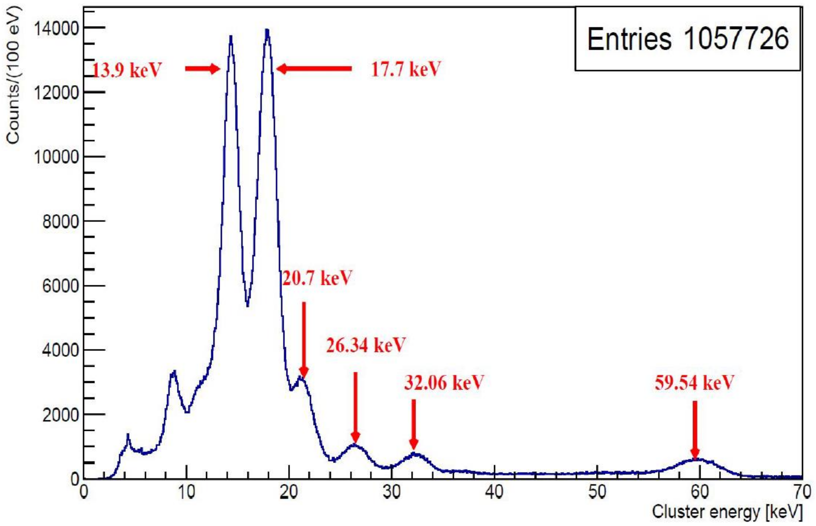


Ongoing effort with Timepix4 started
See: M. Fiorini et al. https://iopscience.iop.org/article/10.1088/1748-0221/13/12/C12005/pdf

Energy calibration with sources

- Validation with radioactive sources(^{137}Cs and ^{241}Am superimposed spectra)





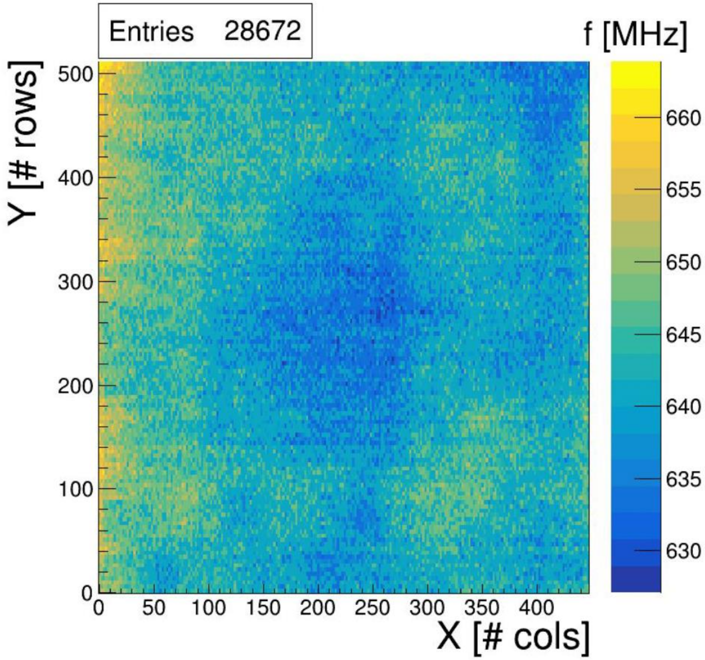
- Up to 1.3 keV FHWM (@ 8 keV)
- Resolution up to 8% (@60 keV)
- ASIC bonded to 100 μm n-on-p Si detector

arXiv:2404.15499

https://indico.global/event/8935/contributions/85485/attachments/39904/74219/iWoRiD_2024_Bolzonella.pdf

Calibration of on pixel VCOs

- On pixel VCO oscillation frequency controlled by a PLL at the center of the chip (@ 640 MHz nominal)
- It has been measured that on pixel VCO oscillate around 640 MHz with a spread of around 40 MHz
- Spread caused by power supply dispersion due to large size and wire bonds: large improvements expected with TSV
- Finer ToA bins generated with different width
- Timing performances heavily affected by this effect
- Internal test pulse tool exploited to **calibrate VCO frequencies for the whole matrix (28672 VCO)**

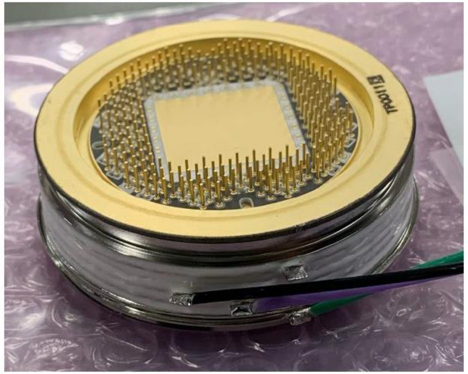


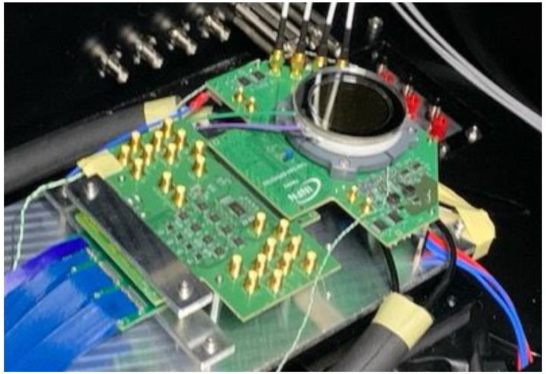
arXiv:2404.15499

https://indico.global/event/8935/contributions/85485/attachments/39904/74219/iWoRiD_2024_Bolzonella.pdf

Integration into photo-sensitive tube

- Prototype vacuum tube produced by Hamamatsu HPK
  - first prototypes received one month ago
- Main characteristics:
  - Multi-alkali S20 photocathode
    - peak QE > 30% at 380 nm
  - 6 µm MCP channel diameter (7.5 µm pitch)
- Several variants for complete characterization
  - 2-MCP stack and 3-MCP stack
  - 1d - 2d - 3d end-spoiling

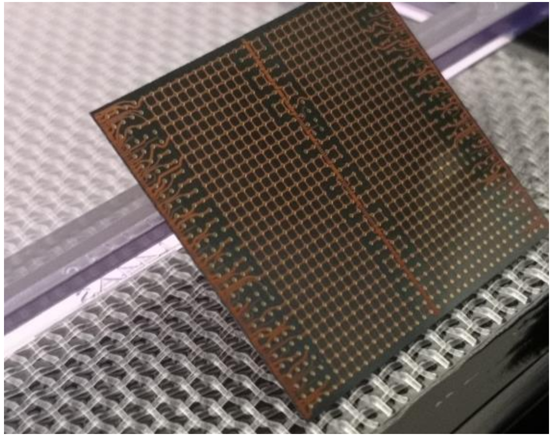




https://indico.global/event/8935/contributions/85485/attachments/39904/74219/iWoRiD_2024_Bolzonella.pdf

TSV processing of Timepix4 - 3 on-going activities

Supplier	IZM (D)	LETI (F)	PTI (TW)
Wafer size (mm)	200	200	300
Front side UBM	Yes	No	Yes
Front side bumps	No	No	Yes
TSV diameter/ thickness (um)	60/120	60/120	38/180
Rear side RDL	Yes	Yes	Yes
Status	Second batch of wafers just completed	First batch of wafers just completed	Starting work



The LA-Picopix project

LA-PicoPix is a large scale hybrid pixel detector with the aim of fulfilling all known requirements for the LHCb VELO upgrade:

- **Large area** → 256x256 pixel array
- **Timing** → <50 ps_{rms} per Hybrid (ASIC + Sensor)
- **Rate** → Worst ASIC in Scenario A ~75 events/BxiD ($3 \cdot 10^9$ clusters $\cdot s^{-1}$)
- **Radiation hardness** → <500 Mrad with full TMR logic design
- **Spatial resolution** → pixel size <55 μm

Design Approach:

- Built from gained experienced from previous hybrid pixel detectors tracking detectors:
  - Timepix (2007) → Timepix3 (2013) → Velopix1 (2016) → Timepix4 (2020)
  - CERN and Nikhef design team
- Directly profiting from EP-RD program:
  - WP5.3: Intelligence on detector, WP5.2: IP blocks, 3EP5.5: 3D interconnects
  - WP6: High Speed links

The Picopix design → LA-Picopix

Why Large Area?

- Precise timing (<50ps) in a large array introduces several additional challenges that need to be faced at the early stage → needs silicon prove on a full-size chip
  - Clock jitter ◆ power distribution ◆ IR-drop induced jitter ◆ Data readout ◆ Time corrections ◆ etc.…
- Wafers available → simplifies bumping and sensor development

A large-area prototype submission requires an engineering run >1.2 M$ but:

- An approach similar to the Medipix and RD53 Collaborations → An ASIC for multiple users
- 3 main potential users:
  - VELO LHCb
  - SY-BI Beam instrumentation
  - Medipix collaboration

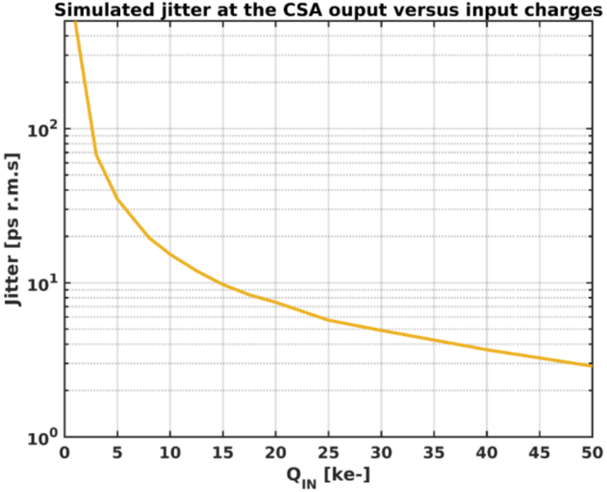
Timing

- **Target resolution of <20ps$_{rms}$** track time is required to distinguish PV
- Single plane resolution of <50ps$_{rms}$ → σ^2_{sensor} (40ps$_{rms}$) + σ^2_{ASIC}
- σ^2_{ASIC} (30ps$_{rms}$)→ $\sigma^2_{analogFE}$ + $\sigma^2_{conversion}$ + σ^2_{clock}
  - $\sigma^2_{conversion}$ → $\frac{TDC_{bin}}{\sqrt{12}}$ → TDC_{bin} = 40ps → 11.5 ps$_{rms}$
  - σ^2_{clock} → Reference clock at pixel level < 10 ps$_{rms}$
  - $\sigma^2_{analogFE}$ → < 25 ps$_{rms}$

Fundamental limits to time resolution in analog front-end

$$Jitter_{FE} \propto \frac{C_{DET}^{3/2}\sqrt{C_{OUT}}}{g_m\sqrt{C_{FB}}} * \frac{\frac{Q_{IN}}{C_{FB}}}{\frac{Q_{IN}}{C_{FB}} - V_{THR}}$$

- C_{DET}, C_{FB}, and C_{OUT} are the front-end input, feedback, and output capacitances, respectively.
- g_m is the input transconductance
- V_{THR} is the threshold of the comparator



→ Minimize the front-end output capacitance.

→ Maximize the input charge and decrease the threshold.

→ Increase the analog pixel power consumption, but a large power drop over the ASIC worsens the timing performances!

→ The front-end input capacitance must be minimized, which depends on the choice of the sensor, pixel pitch…

R.Ballabriga, The Timepix4 analog front-end design: Lessons learnt on fundamental limits to noise and time resolution in highly segmented hybrid pixel detectors https://doi.org/10.1016/j.nima.2022.167489

LA-Picopix: Summary and status

- **LA-Picopix** is a large-area Particle Tracking detector ASIC with < 30 ps_{RMS} timing resolution, on-chip clustering support, data-driven readout up to $3.9 \cdot 10^{9}$ cluster · s^{-1}:
  - Targets all <u>*known*</u> LHCb VELO upgrade requirements
  - Other partners (Medipix and CERN-SY) to contribute on the financing of the engineering submission.
  - Potential applications:
    - ▪ LHCb velo (main specifications) ▪ beam gas monitoring ▪ radiation monitoring ▪ X-Ray imaging ▪ 4D STEM ▪ X-ray photon correlation spectroscopy ▪ Mass spectrometry ▪ Medical applications (SPECT/PET) ▪ etc..
- LA-Picopix builds up from the experience of the design team in previous large area tracking hybrid pixel detectors and CERN EP-RD programs
- Target submission by end of 2025

Examples of other applications

- X-ray materials analysis with diffraction
- Photon counting cameras at synchrotrons
- Time resolved cameras at synchrotrons
- X-ray non-destructive testing
- X-ray dosimetry - dosepix chip development
- Waste sorting using X-rays
- Low Energy Electron Microscopy
- Transmission electron microscopy
- 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

Summary and Conclusions

- Hybrid pixel detectors were developed as tracking detectors of LHC
- 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.
- When combined with an appropriate convertor material, single visible photon hits can be streamed out – extremely useful in quantum sensing applications
- Timepix4 (time stamp within 200ps bin) is in production and can be tiled on 4 sides using TSVs
- LA-Picopix will provide on-pixel timestamping within a bin of 40ps

Thank you for your attention!

Timepix4 paper:
X. Llopart *et al* 2022 *JINST* **17** C01044

Medipix3RX images: S. Procz et al.