Fast timing and radiation hard tracking with 3D and 3D trench electrodes silicon sensors

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Future UK Silicon Vertex & Tracker R&D Workshop, Birmingham 7-8 September 2022

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Collaboration with:

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TIPFA, University of Trento, and FBK, Trento Italy

Benedikt Bergman, IEAP Detector Group

Institute of Experimental and Applied Physics, CTU in Prague

Applications and Synergies:

4D Radiation Hard Tracking

→FCC, but also ATLAS Forward Physics (AFP-UK), NA62 Upgrade UK (HIKE) which could be excellent small size demonstrators, LHCb upgrades

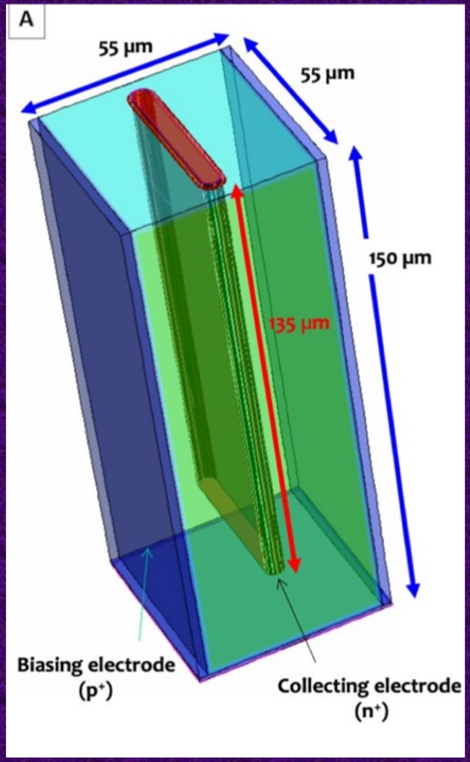
Industrial Contacts:

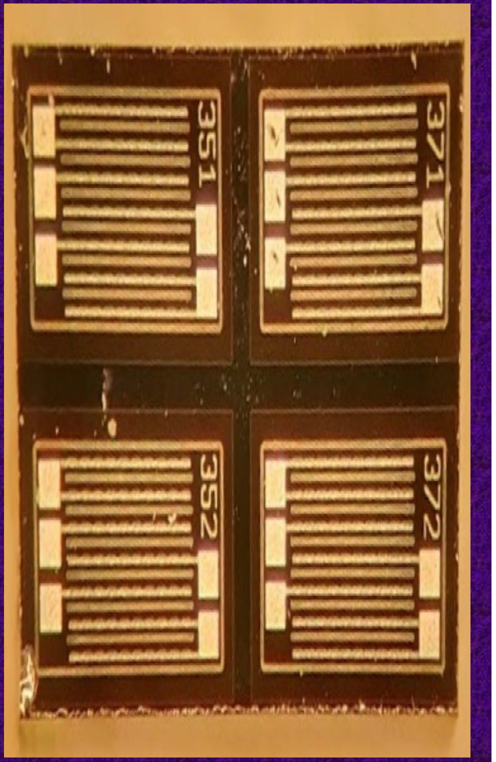
CNM Barcelona, Spain, FBK, Trento, Italy for 3D sensor fabrication

SINTEF Norway for active edges

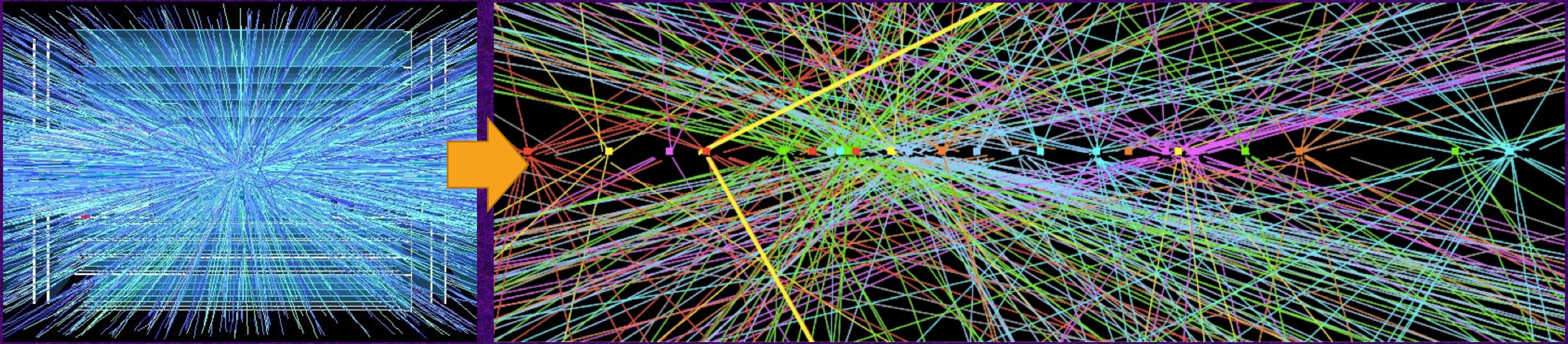
IZM Berlin, Ge, ADVACAM Helsinki Fi, for interconnection

Pictures from A. Lampis, IWORID 22





Why Fast Timing and Radiation Hard Tracking for LHC++ and FCC



When 4D tracking (fine-pitch pixels with timing) is concerned, we should NEVER NEGLECT the following mandatory additional requirements (wise quote from A. Lai, IWORID 2022):

1. High luminosity implies high intensities of interactions and therefore high fluences (for sensors) and high doses (for electronics).
In the inner regions of the apparatus, numbers are close to fluences $\Phi > 10^{17}$ 1 MeV n_{eq}/cm^2 and > 2 GRad
2. A detection efficiency of $\varepsilon > 99\%$ per layer is typically required (high fill factor)
3. Material budget must be kept below 1 and 0.5 % radiation length per layer
*4. Very challenging **front-end electronics** must be developed. Today a complete solution for that is FAR rom being available.*

… and what is more important: All the above requirements must be met at the same time, along with high time resolution !!!

Why 3D sensors are a viable solution for timing

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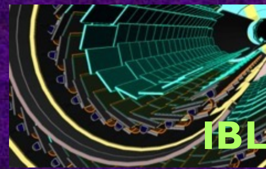
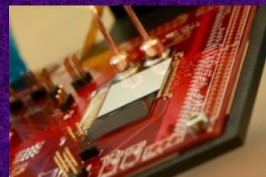
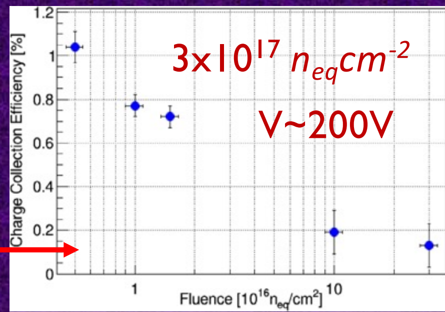
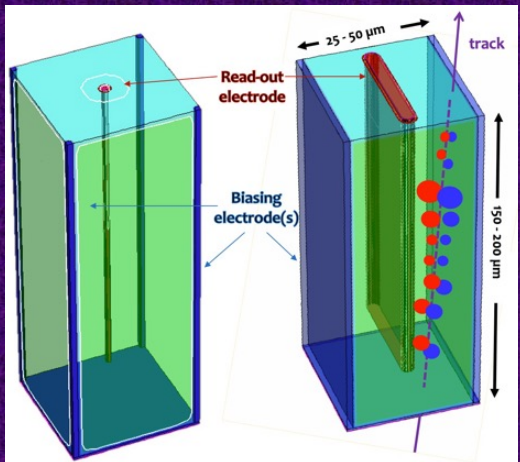




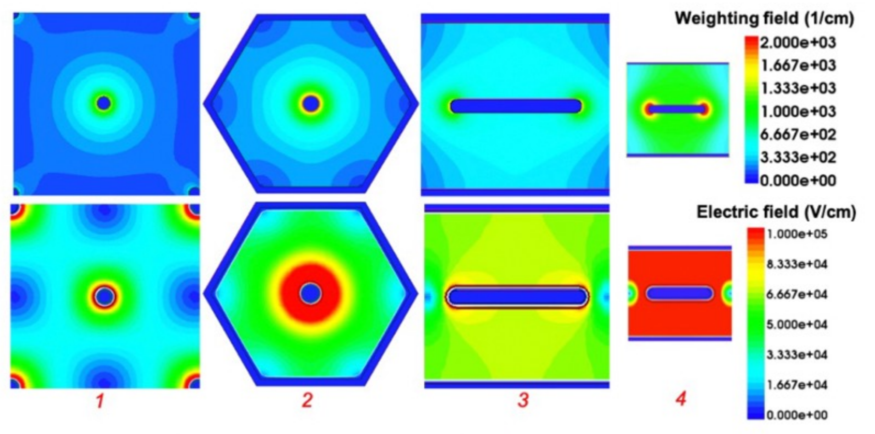
- *Proposed by Sherwood Parker (1997)*
- *Industrialized by the 3D ATLAS R&D Collaboration (2007)*
- *Installed in the ATLAS IBL (2011* NIMA 694 (2012) 321–330 2012 JINST 7 P11010.*)*
- *Work on 3D+Timepix3 and vertically integrated cooling (doi :10.3389/fphy.2021.633970)*
- *ATLAS ITK inner layer (*Front. Phys., 21 April 2021 | https://doi.org/10.3389/fphy.2021.624668
- ***Demonstrated radiation hardness >10^{17} $n_{eq}cm^{-2}$ (NIMA, 979 (2020) 164458)***
- *Current **Timing layouts** optimization (*IEEE Trans. Nucl. Sci., **58** (2011) 404, *2018 J. Phys.: Conf. Ser.* ***956*** *)*012012





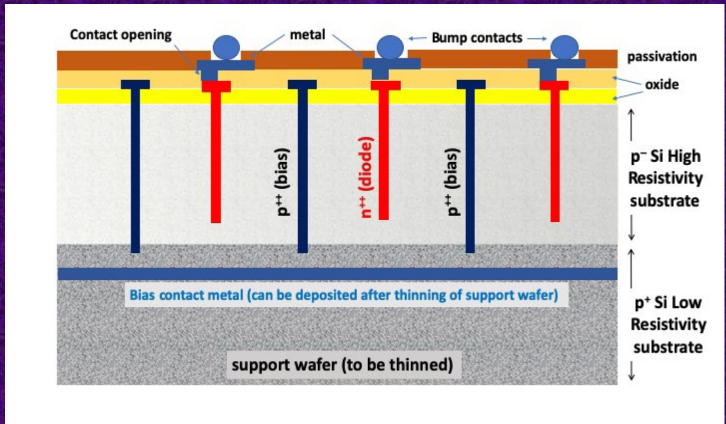
TimeSPOT

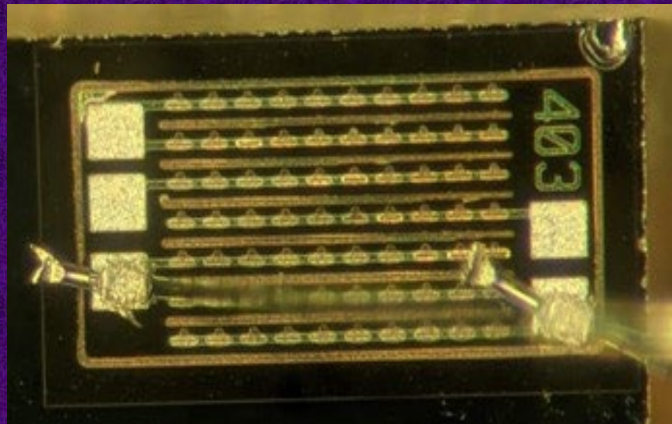
$$i = qE_w \cdot v$$

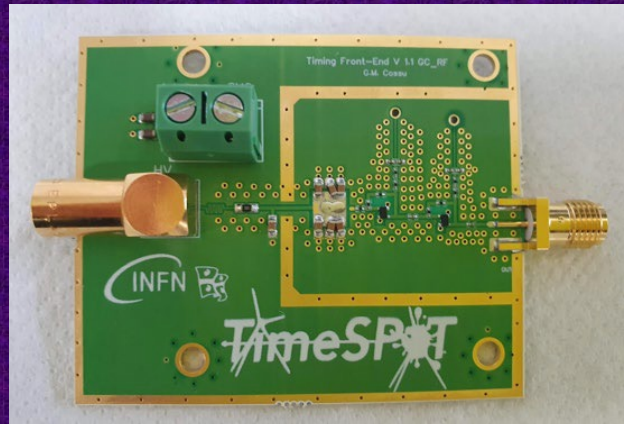


– Future UK Silicon Vertex & Tracker R&D Workshop Birmingham – 7th September 2022 -

3D and 3D Trench devices for timing are currently fabricated at FBK Trento with different geometries

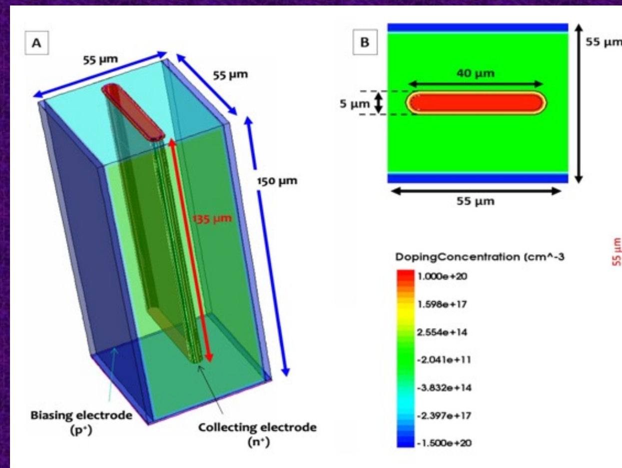






3D trench parameters:

- **55µm x 55µm pixels** (to be compatible with existing FEE, for example the Timepix family)
- In each pixel **a 40µm long n++ trench** is placed between continuous p++ trenches used for the bias → **excellent electric field homogeneity!**
- **150µm-thick active thickness**, on a **350µm-thick support wafer**
- The collection electrode is 135µm deep



Started a measurement campaign in Cagliari, Italy in the TimeSPOT Collaboration Lab

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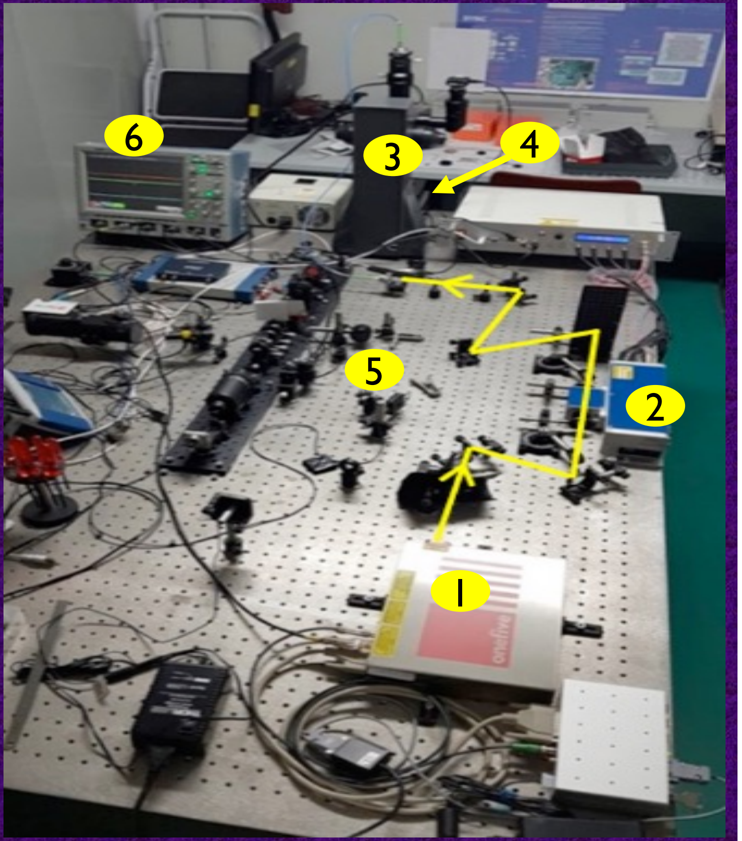
Measurement procedure:

- Pixel being tested (and attached PCB board was connected to set-up).
- Laser was focused onto pixel surface, followed by an extra quarter turn on the focusing screw.
- Using LabView, motorized stage was moved to find min and max *x* and *y* values to obtain full scan of pixel.
- 2D scan was performed in 1 µm increments in both *x* and *y*.
- For each position, 1000 waveforms of both the reference and test signal were recorded.

Measurement Setup:

- . Laser – Infra-red (1030 nm), ultra-short ~200 fs pulse, 40 MHz. Laser energy is adjusted using neutral filters close to the laser output port.
- 2. Pulse-picker – selects pulses from the 40 MHz pulse train
- 3. Microscope, single mode optic fiber and spatial filter – allows emulation of 1 MIP of energy deposition where a collimated laser spot is incident on the surface of the sensor
- 4. Translation mount – *x-y* translation amount allows the point of energy deposition on the sensor surface to be changed
- 5. Optical time reference – 3D sensor that intercepts unfocused laser reflection, where energy deposited is equal to roughly 10 MIPS and has a timing accuracy of ~ 900 fs.
- 6. Data acquisition system, 20 GSa/s 8 GHz Rhode & Schwarz Oscilloscope RTP084 – digitizes signals from both the sensor and time reference.



Mauro Aresti et. al, A Sub-Picosecond Precision Laser-Based Test Station for The Measurement of Silicon Detector Timing Performances, 2020 IEEE Nuclear Science Symposium and Medical Imaging Conference.

Tests performed in Cagliari in April 2022

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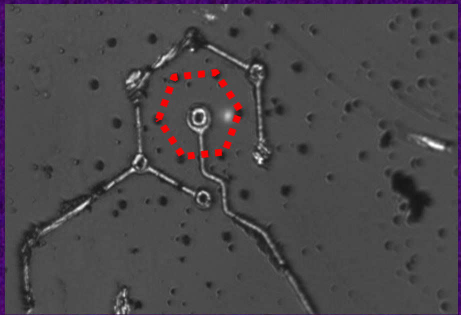
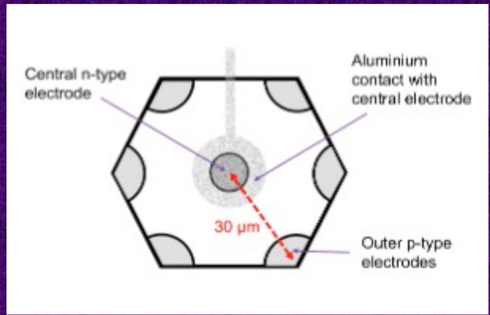
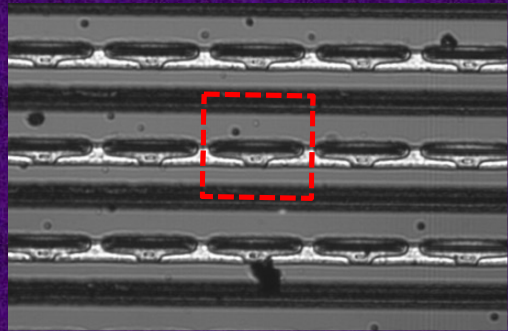
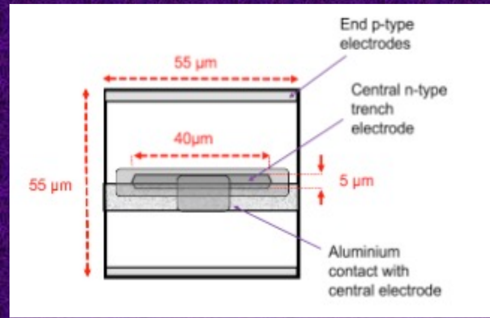
3D Hexagonal

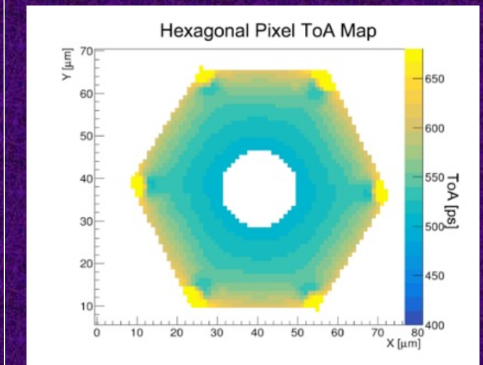


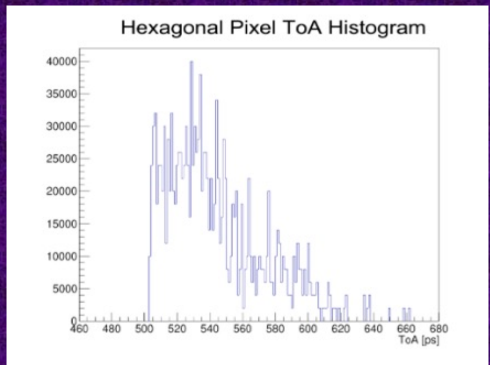


3D Trench

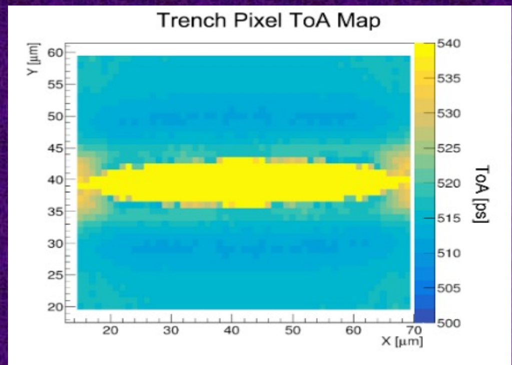


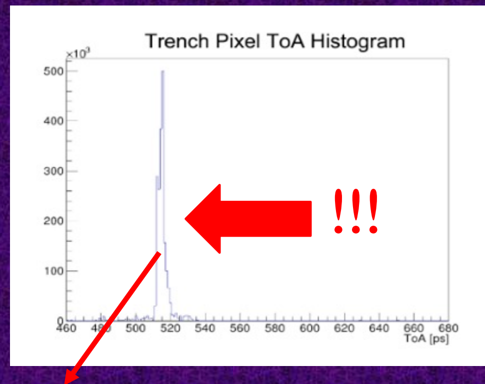






ToA = (544 ± 29.8) ps





ToA = (515 ± 8.2) ps

High and low field regions present – ToA changes significantly over sensitive volume as a result.
Histogram has pronounced tail due to slow periphery of pixel – suggests potential presence of inefficiencies of charge collection when collected using fast electronics.
Lowest field regions are between adjacent electrodes of the same doping type.
Highest field region at the centre of the pixel is covered by the aluminum contact – does not contribute to the results.

Electric field over sensitive region is mostly uniform – mean ToA changes minimally over the area of the pixel and timing resolution is small.

Lowest field regions are between adjacent trenches – covered by the aluminum contacts and hence do not contribute to the results shown.

M. Addison et al., Presented at the Pisa Meeting, La Biodola, May 2022

The BIG challenge is the frontend chip→

TimeSPOT 1

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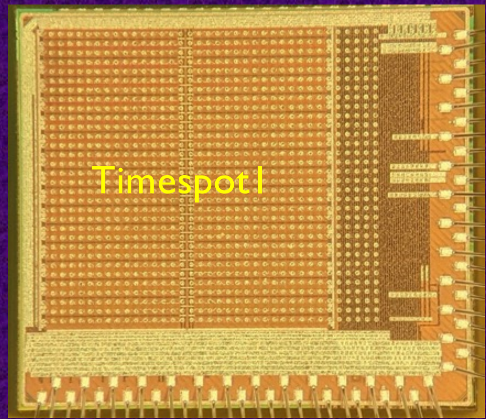
Timespot1 ASIC

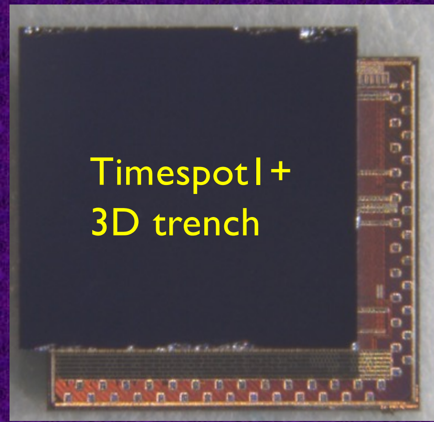
28-nm CMOS

Si-Ge input stages tr ≈ 100 ps

- *Size (1024 pixels, 6 mm^2)*
- *Pitch 55 microns, 32 x 32 matrix*
- *640 MHz master clock*
- *Complete set of functionalities for pixel readout*
- *Slow read-out (demo-test purpose)*
- 1 TDC per pixel to maximise sustainable rate

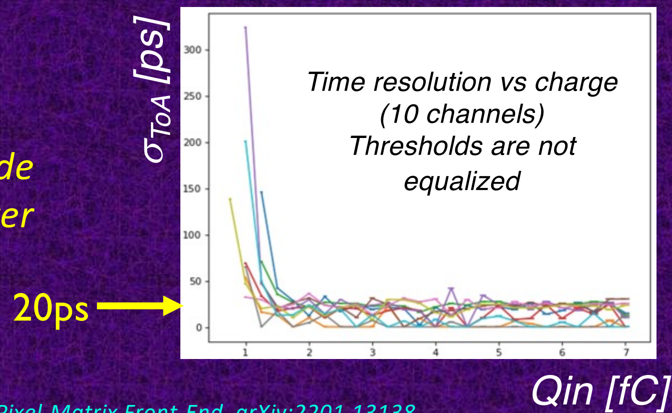
Will be tested at CERN in October 2022

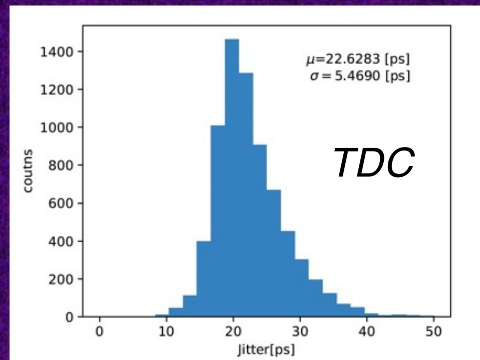




Preliminary tests:

- *The TDC has a typical $\sigma_t \approx 20$ ps, with relatively wide dispersion (5 ps) and is limited by the system clock jitter*
- *In general, global (digital) clock distribution issues Limit the very good resolution at the pixel level.*





Distribution of the TA standard deviation across 1024 channels and 7 phases. Each point is computed from 100 repeated measurements.

L. Piccolo et al., First Measurements on the Timespot1 ASIC: a Fast-Timing, High-Rate Pixel-Matrix Front-End, arXiv:2201.13138
A. Lai , presentation at the IWORID 2022 Conference, Riva del Garda, June 2022

Comparison of Currently Available FEC with timing

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A. Lai, 4D-pixels – 23rd iWoRiD – Riva del Garda (TN) – June 29th 2022

State of the art

Incomplete list of ASICs for timing pixels (handle with care!)

Adapted from: S. Cadeddu et al., ***Timespot1: A 28 nm CMOS Pixel Read-Out ASIC for 4D Tracking at High Rates***, to be published on IEEE TNS

Name)	Year	CMOS node [nm]	σ_t [ps] on 1 MIP	Pitch [µm]	# pixels	C_{in} [fF]	Power per pixel [µW]	Average power [W/cm²]	MPV per MIP [fC]	Max hit rate [GHz/cm²]	TW correct. type	Sensor tested
Timespot1	2021	28	< 40 (AFE) 20 (TDC)	55	1024	35	20 (AFE) 38 (TDC)*	1.8 (pixel)	2.0	100 (pixel)	ToT	Not yet (3D)
Timepix4	2020	65	70 (AFE) 60 (TDC)	55	229 10³	65	15 (AFE)	0.5 (AFE)	1.6	150 (pixel) 0.36 (R/O)	ToT	planar
TDCpix (NA62)	2014	130	75 (circuit) < 200 (sens)	300	1800	250	300 (FE+disc)	3.3 (pixel)	0.5-10 (range)	0.8	ToT	planar
Fastpix	2021	180	≈ 150	10–20	68	< 1	no TDC	N	N	N	Only analog	MAPS
Fast2	2020	110	15	500	32	3.4 10³	3 10³	1.2	16	120	Only analog	LGAD
Monolith	2021	130 Si-Ge	36 (AFE)	100	144	80	150 (AFE)	1.8 (pixel)	N	N	Ampl. PeriphTDC	MAPS
TOPHIR2X	2021	130	55	3000	32	N	12.4 10³	0.1	N	2.8 10⁻²	ToT	SiPM
ETROC1	2020	65	35	1300	16	3.5 10³	2.4 10³	0.2	6	2.3	ToT	LGAD
ALTIROC1	2020	130	50	1300	25	5 10³	4.4 10³	0.3	4	N	ToT	LGAD

N = not applicable or not known

*at 350 kHz per pixel

Summary of Activities, Funding and Strategies

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- Working in collaboration with TIMESPOT since 2018, with Prague Detector Group since 2012

→ (EU-ATTRACT INSTANT), 3D+Timepix3 (*Tianqi Gao PhD thesis on the timing properties of 3D+Timepix3*)

- In April 2022 started a measurement campaign in Italy (TIMESPOT Lab) and CERN (October), PSI for test beam

→ STFC PhD Studentship, LTA
→ TURING Fellowship

- 3D and 3D Trench devices currently fabricated at FBK Trento (TIMESPOT Collaboration)

Also, historical contacts with SINTEF (technology was transferred there to fabricate active edges in 2007) and CNM

→ There are no industries with MEMS + Detector Technology in the UK !!
→ For the moment we plan to continue our long-lasting collaboration with EU industries to maintain our know-how.

- In Manchester we are setting up a 2-photon system for semiconductors' characterization

→ Plan to bring 3D and 3D trench electrodes + fast readout for tests in Spring 2023
→ 3D silicon will be interconnected with Timepix4 as soon as possible

The key for fast (~10ps) tracking is the development of 28nm (rad hard) frontend electronics!!

- TIMESPOT is in an advanced stage of FEC 28nm design with existing chips and bump-bonded modules and is currently scaling up the chip dimensions to experiment-ready size.

→ We plan to support their development, contribute to the characterization of devices and setup a measurement station in Manchester as soon as 28nm electronics will be available → will need funds!
→ Hope to contribute to UK electronics developments as soon as available
→ NA62 (HIKE) and AFP would benefit from 3D-Trench and TIMESPOT1 developments. They could be ideal test benches before FCC!!!!!