Tracking charged particles with 10 ps timing precision: 3D-trench silicon pixels

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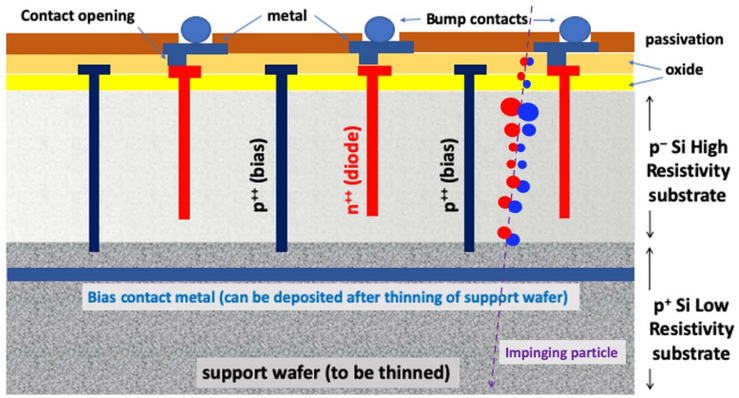
For the TimeSPOT *TIME and SPace real-time Operating Tracker* **team**

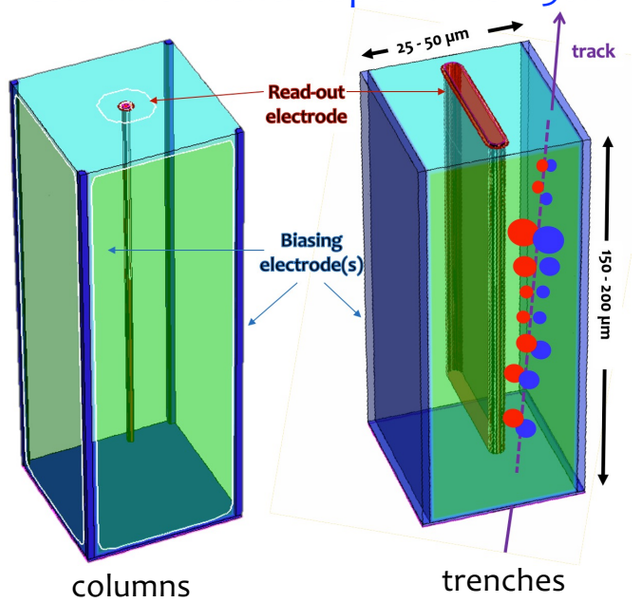
EPS-HEP Conference 2021
Still virtual again ☹

The Geometric approach and MEMS technology



Deep Reactive Ion Etching

Column or trench aspect ratio ≈ 30:1



Concept

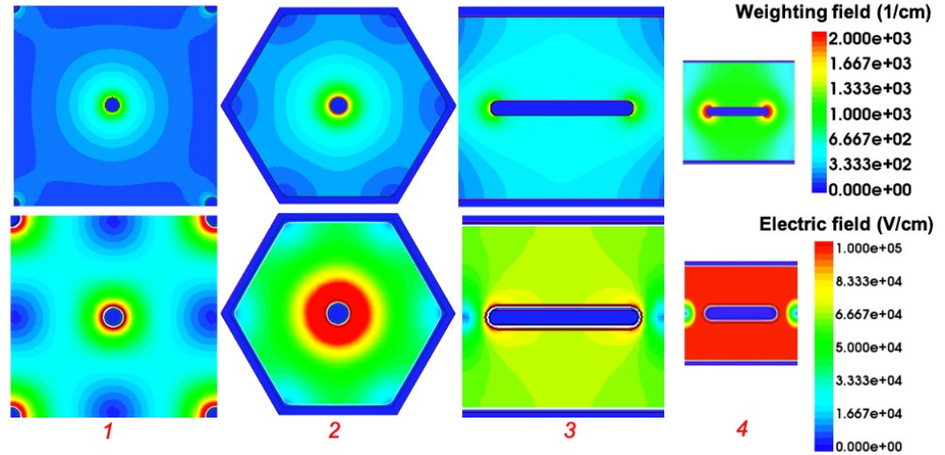
(S. Parker et al., 1997):
Perpendicular electrodes

↓

Inter-electrode distance d independent of sensor thickness z

↓

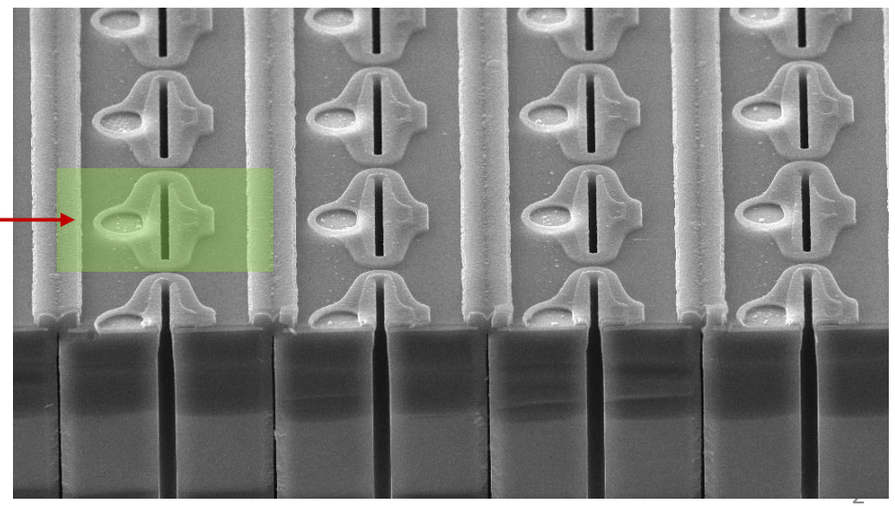
Sensitive volume and electrode shapes can be designed for maximum performance



$$i = qE_w \cdot v$$

High and uniform E field

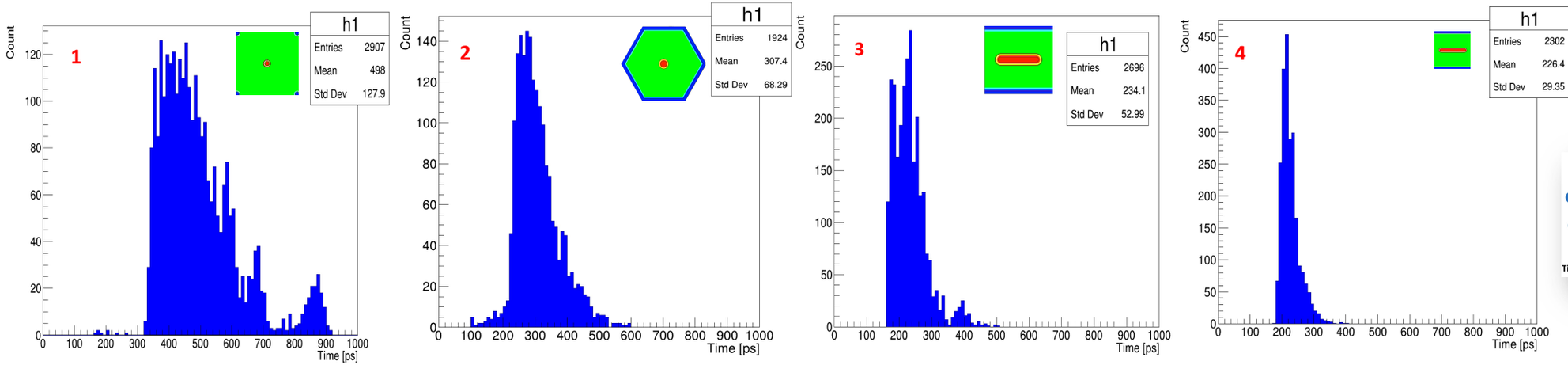
TimeSPOT pixel (size 55x55x150 µm³) 2 fC MPV



trench electrodes:
SEM image from **TimeSPOT** production batch#2 (Dec 2020)

The Geometric approach and sensor speed: CCT

Comparing timing performance of different 3D geometries

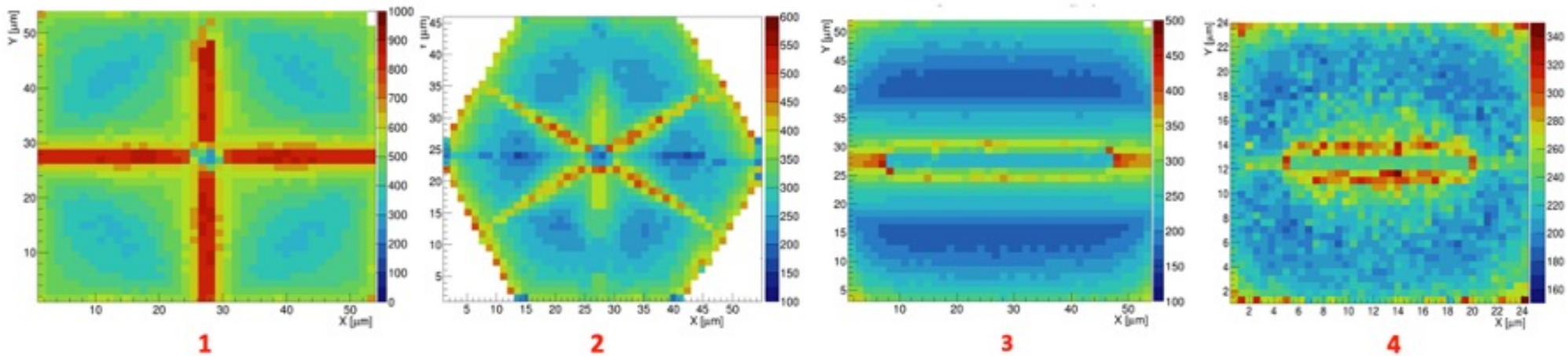


TCoDE
TimeSPOT Code for Detector simulation

Charge **C**ollection **T**ime distributions for different 3D geometries (total drift times of charge carriers)

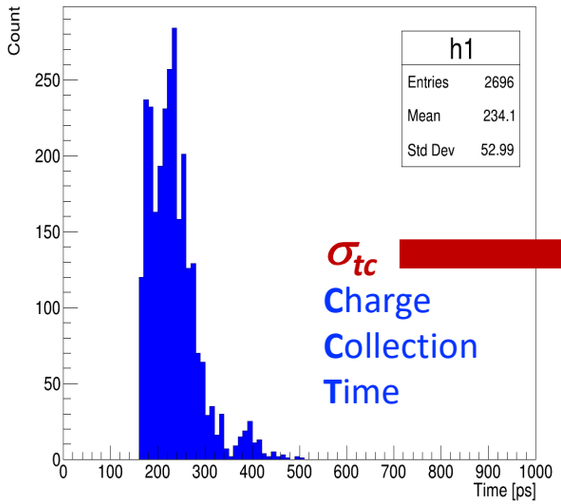
CCT distributions is strictly related to the corresponding ToA distributions and time resolution σ_t (according to the specific F/E stage)

Small CCT gives also better radiation resistance

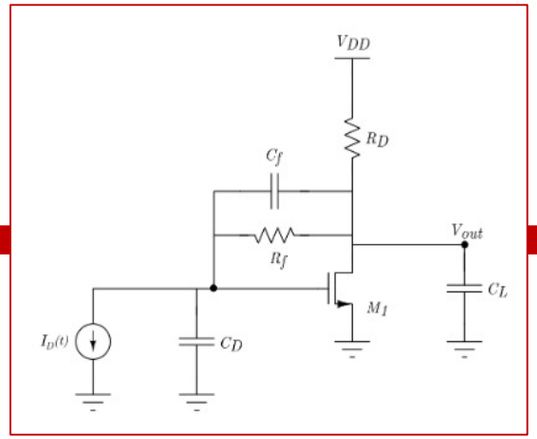


CCT vs ToA distributions

And the real limit to system performance

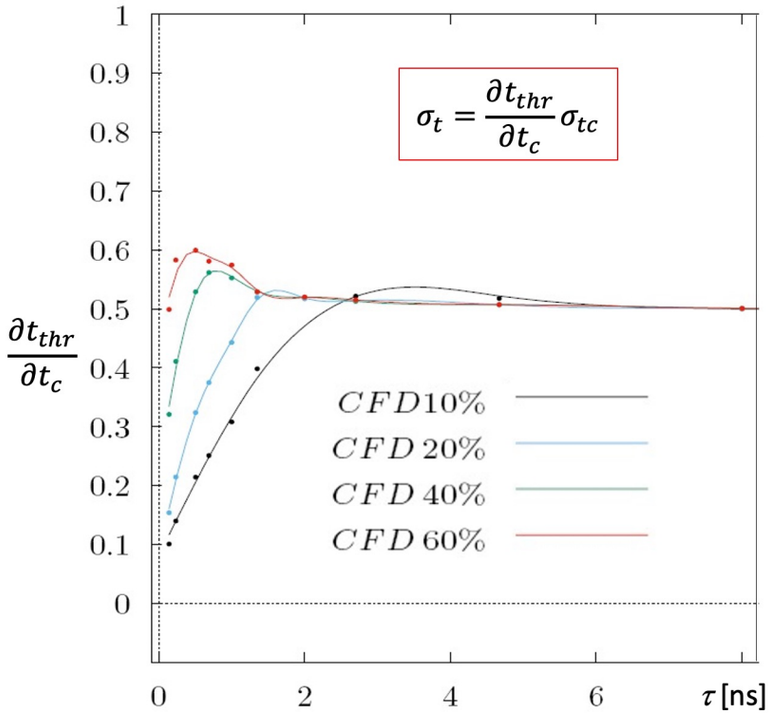


σ_{tc}
Charge
Collection
Time

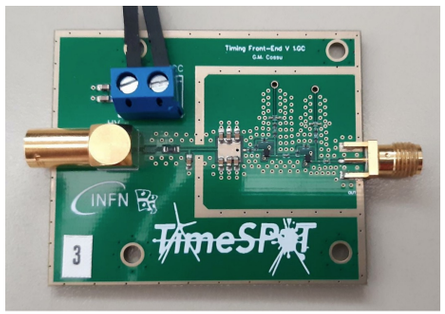


Trans-Impedance-Amplifier with shunt-shunt feedback (FB–TIA).

σ_t
Time
of
Arrival



Si-Ge input stages $t_r \approx 100$ ps



G.M. Cossu – INFN Cagliari

According to the FB parameters used, this scheme can range from an integrator (Charge Sensitive Amplifier) to a fast Current-Sensitive front-end. The role of the specific transistor technology (BW) used is decisive, especially when very high speed is pursued (Si-Ge vs CMOS).

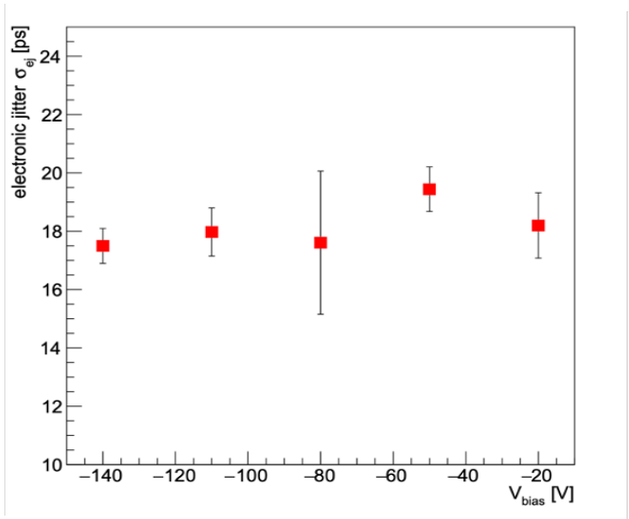
Derivative of time at threshold t_{thr} with respect to average CCT t_c (or time centroid) as a function of the amplifier peaking time τ, at t_c = 250 ps for various CFD fractions.

A fraction of σ_{tc} is "transported" onto σ_t, depending on the amplifier and discriminator performances and typology

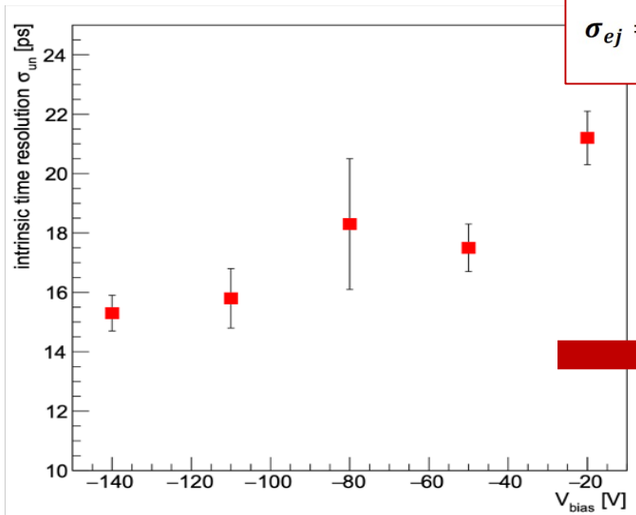
Demonstrations and details on:
A. Lai and G.M. Cossu, *High-resolution timing electronics for fast pixel sensors*, arXiv:2008.09867

Intrinsic resolution of a 3D-trench sensor

Separation of the electronics contribution and first estimate of the "intrinsic" resolution of the sensor

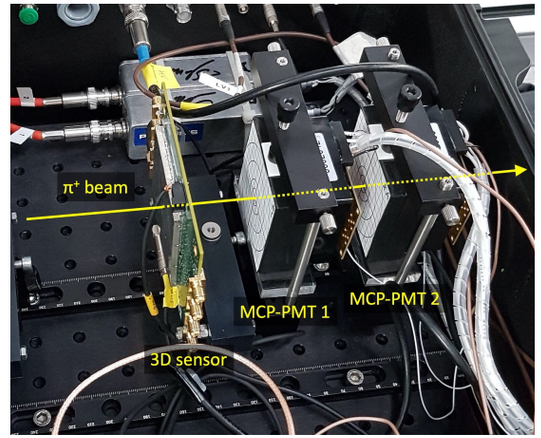


Jitter (electronics only, estimate [1])



Intrinsic (sensor only, estimate [1])

$$\sigma_{ej} = \sigma_n \left[\frac{dV}{dt}\right]^{-1}_{Thr} \approx t_r \left(\frac{S}{N}\right)^{-1}$$



σ_t is obtainable as the quadrature sum of the two contributions.

σ_t is dominated by the contribution of the front-end electronics

This estimate is pessimistic especially for the intrinsic resolution as includes inextricable systematic effects (correlations, extrinsic noise)

Simulation [2]			Measurement [2]	
V_{bias} [V]	$\sigma_{intrinsic}$ [ps]	σ_t [ps]	V_{bias} [V]	σ_t [ps]
−50	9.6 ± 0.1	18.9 ± 0.2	−50	20.7 ± 0.3
−100	8.0 ± 0.1	16.7 ± 0.2	−110	19.8 ± 0.2
−150	7.0 ± 0.1	16.3 ± 0.2	−140	19.0 ± 0.2

Impinging particles: π^+ @ 270 MeV/c

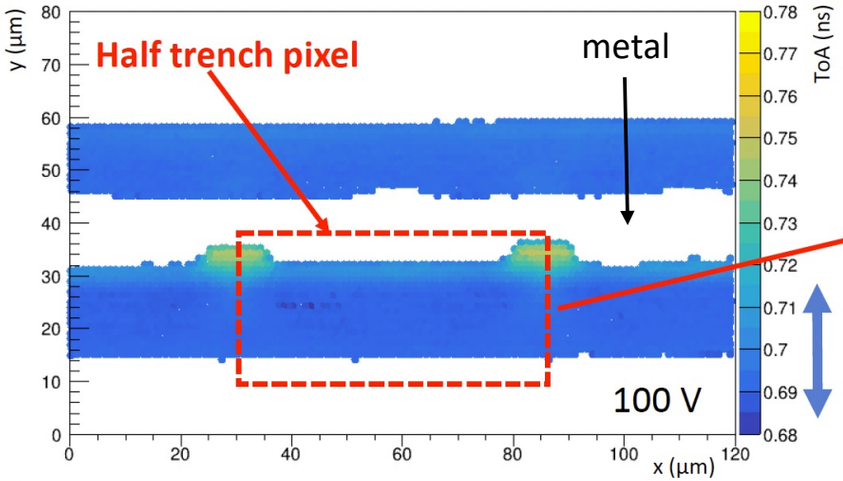
For further details:

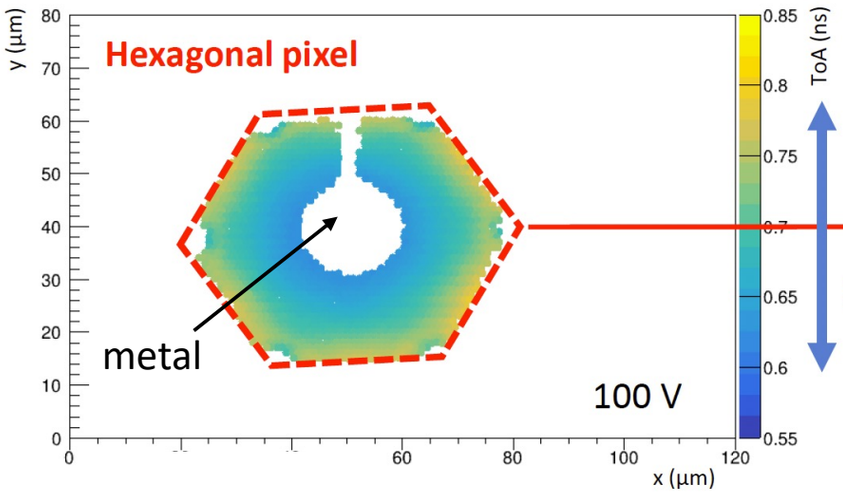
[1] L. Anderlini et al., Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection. *Journal of Instrumentation, 15, P09029*, 2020.

[2] D. Brundu et al., Accurate modelling of 3D-trench silicon sensor with enhanced timing performance and comparison with test beam measurements. arXiv:2106.08191v1 [physics.ins-det], in press on JINST (2021).

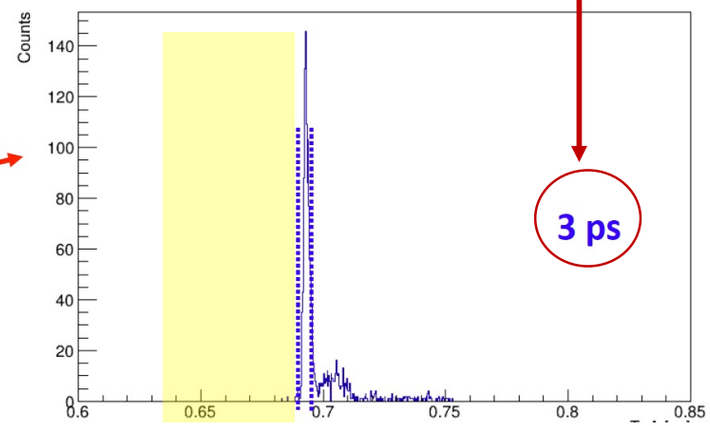
Speed and uniformity: 3D-trench vs 3D-hexagonal
BEWARE the tails !!!

MIP-equivalent laser scans

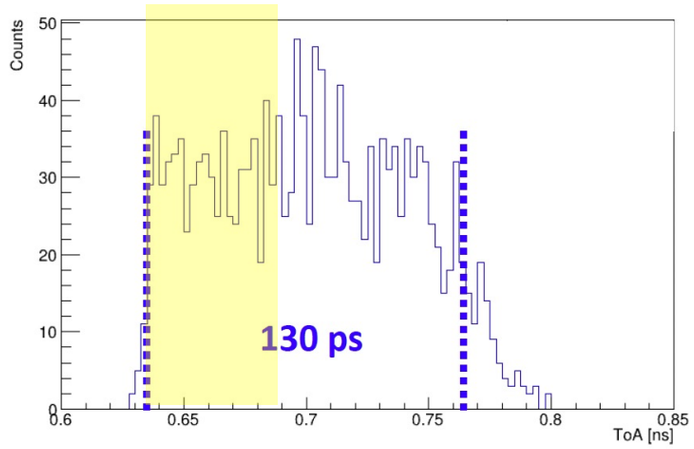




An experimental look at $\sigma_{intrinsic}$



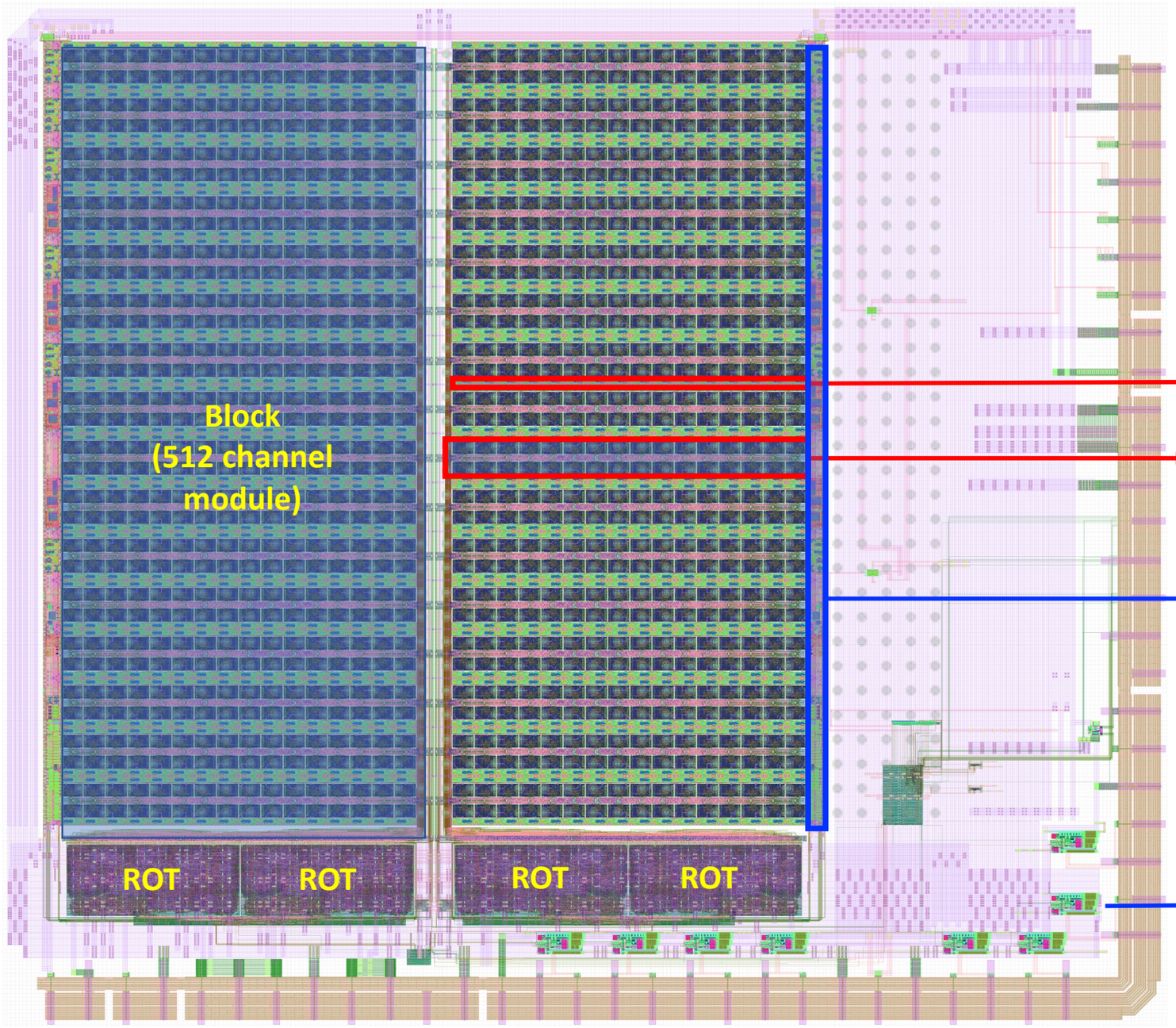
Signals arrive later but all almost synchronously
→ much higher time resolution



Timespot1 ASIC 28-nm CMOS

Presently under test

INFN Cagliari, Milano, Torino
(Bergamo: LVDS drivers)



Analog row (16x2 AFE)

Digital row: 16x2 TDC + Controls, Conf. registers, I²C I/F)

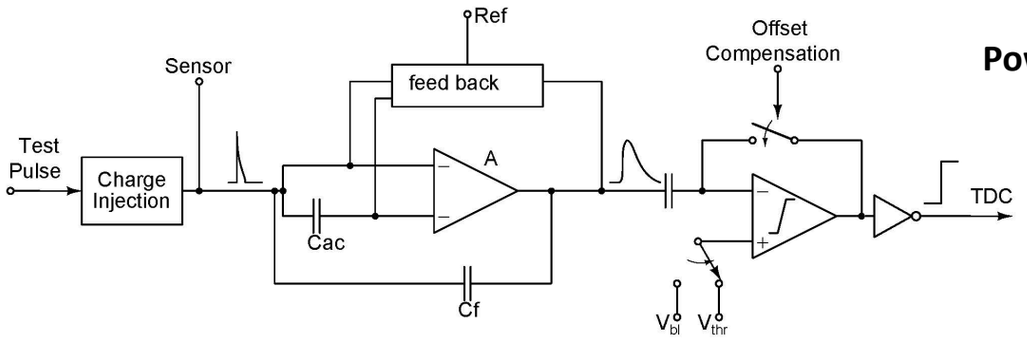
Analog (service) column:

- 1 BandGap
- 5 DAC sigma-delta (producing analog levels used by pixels)
- Programmable bias cell (for power consumption)
- bias replicas with source followers.

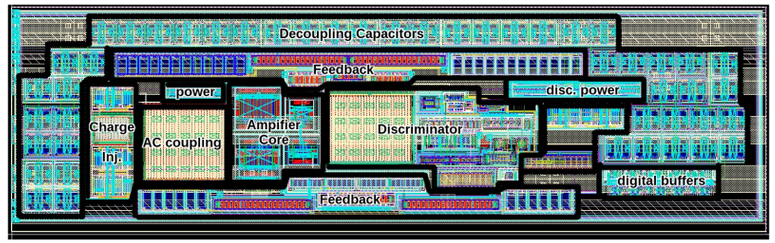
LVDS driver

Timespot1: Analog Front End and TDC

Inverter core amplifier with double Krummenacher FB



Power ≈ 15-30 µW (regulable)



50x15 µm²

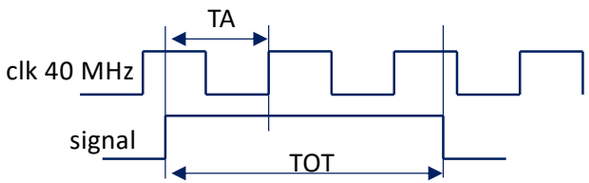
L. Piccolo – INFN Torino

High resolution – "low" consumption TDC based on DCO and a Vernier architecture

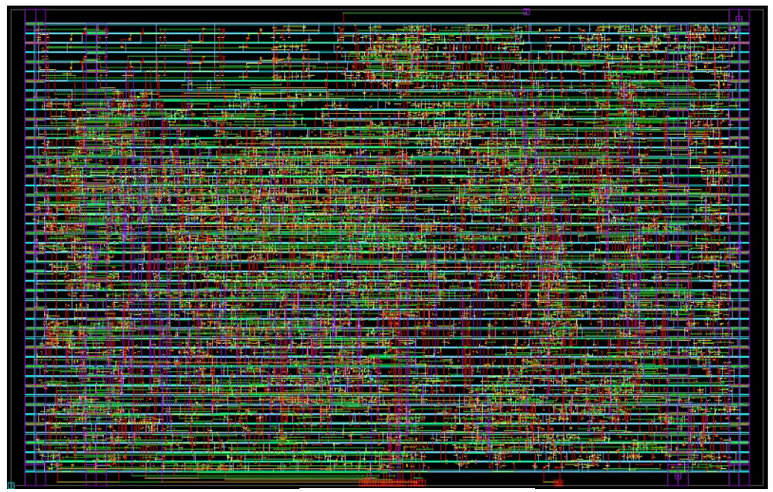
To maximize sustainable rate, **1 TDC per pixel channel** has been integrated

Maximum input signal TDC rate = 3 MHz
24 bits output word (ToA + ToT) serial @160 MHz

Power depends on input rate ≈ 20 µW (stby) – 175 µW (3 MHz)



The TDC gives the phase of the signal wrt the master 40MHz clock
The TDC and the counter use the same DCO-generated Clk (~1 GHz)



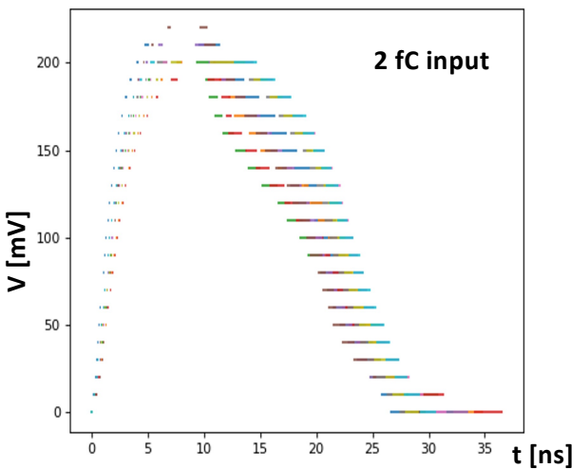
50x31.5 µm²

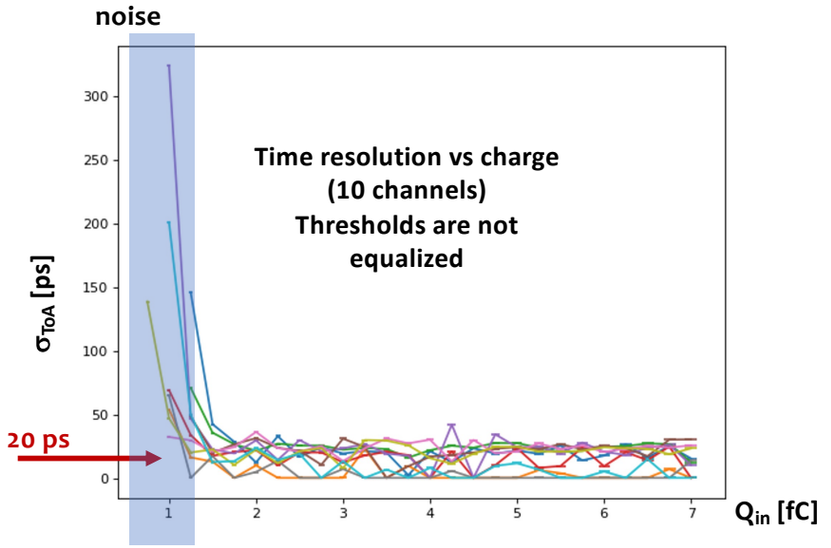
S. Cadeddu – INFN Cagliari

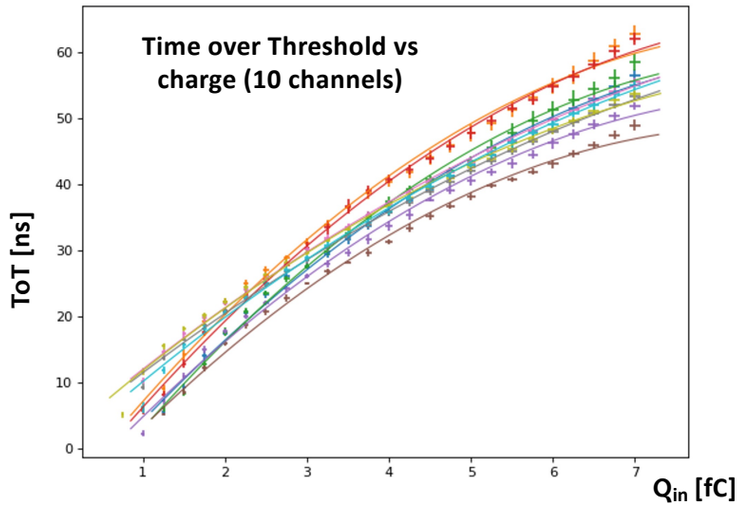
Timespot1 ASIC operation

Still very preliminary results, to be taken as an indication of correct circuit operation.
Circuit performance still to be analyzed and understood in detail

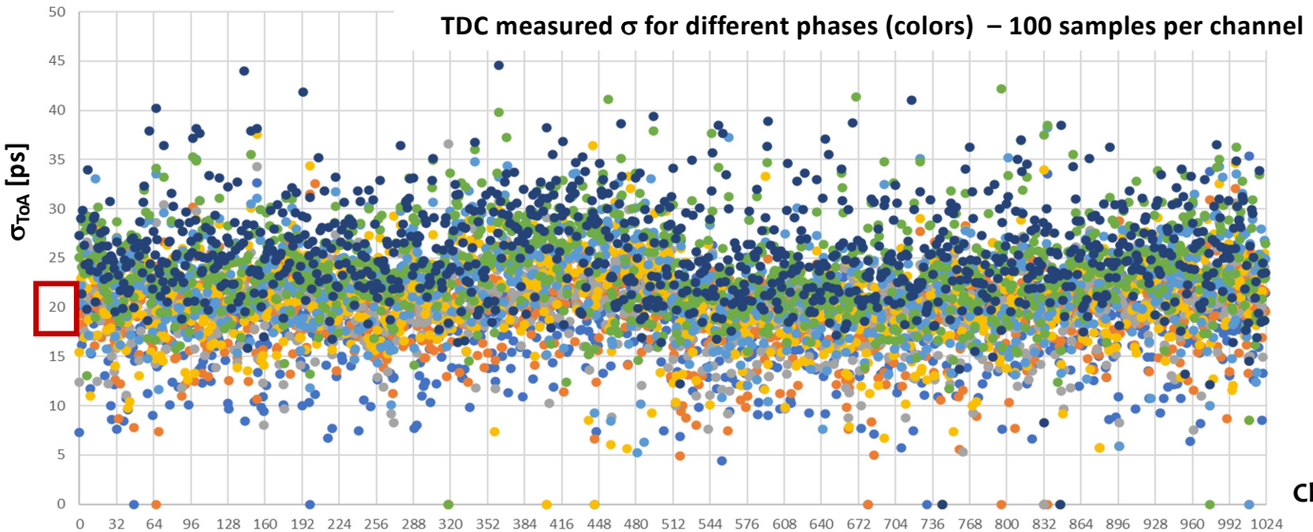
Signal reconstruction by thr scan (10 channels)

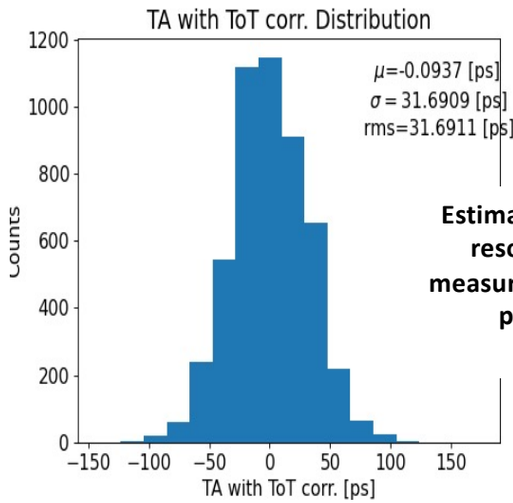






TDC measured σ for different phases (colors) – 100 samples per channel





Estimate of full chain resolution using measurement-extacted parameters ≈ 30 ps

Conclusions and perspectives

- 3D-trench silicon sensors reach intrinsic time resolutions of ≤ 10 ps
- They keep to the minimum the impact of slower spots which can cause tails in the ToA distributions
- This is not the case for different, though fast, 3D geometries

- The bottleneck in time resolution is by far due to the electronic stage
- Discrete–component Si-Ge front-ends can reach $\sigma_{ej} \leq 15$ ps with MIPs (TimeSPOT result)
- In CMOS technology limitations are even higher, especially in large matrix readout (power constraints, uniformity among channels)
- The CMOS 28nm Timespot1 ASIC shows that ≤30 ps on the full chain can be obtained at a reasonably low power consumption. Is this sufficient? How to exploit the higher sensor potential in time resolution?
- The really great challenges on pixel with timing for the inner trackers of the future are
  1) integrated electronics,
  2) integrated electronics,
  3) integrated electronics …
- More studies and R&D are imperative in this respect.

Thank you all