Timing characterization of 3D-trench silicon sensors

Adriano Lai*
for the TIMESPOT team
*INFN – Sezione di Cagliari – Italy

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TimeSPOT – TIME and SPace real-time Operating Tracker

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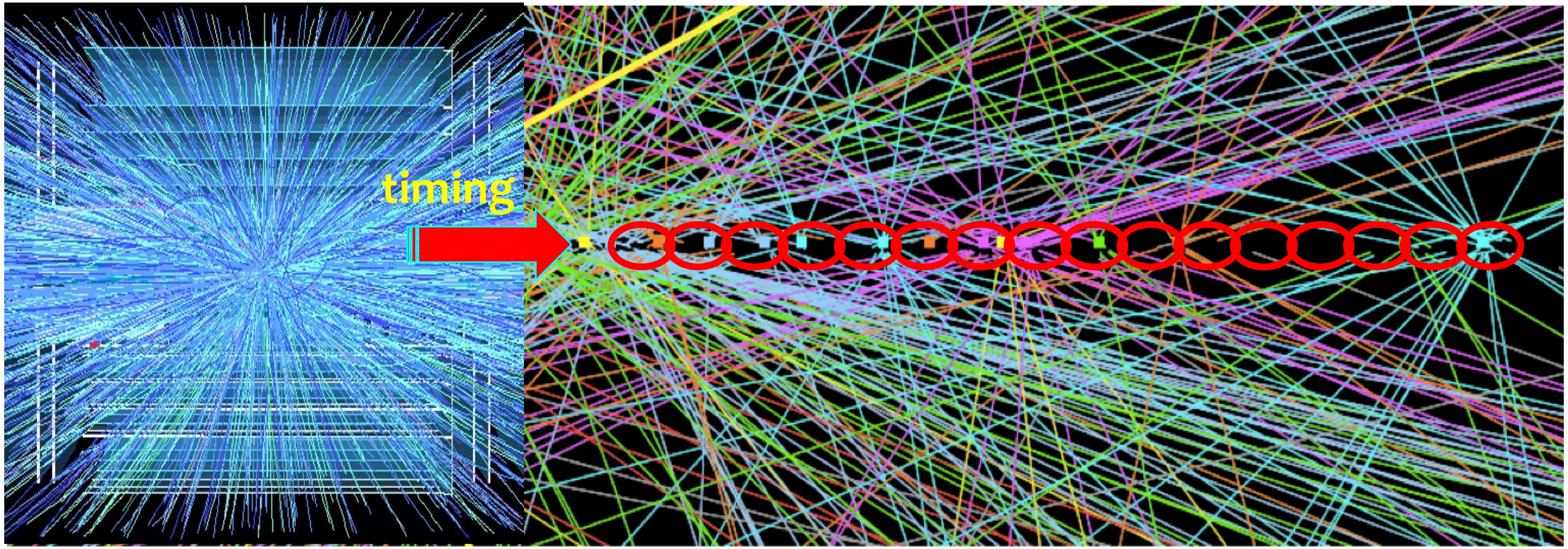
Scope of TIMESPOT R&D

TIME and SPace real time Operating Tracker

TimeSPOT
TIME and SPace real-time Operating Tracker

Scope:

Trend for future tracking at future colliders: Timing at the pixel level. Highly demanding characteristics



Crucial importance and strong interest in:

- ATLAS phase2 & CMS phase2 (Timing layers – LGAD based detectors)
- LHCb Upgrade 2 (Vertex detector: no technical solution yet, Ecal with timing)
- NA62 GTK upgrade
- FCC-hh, -ee …

Structure, organization and objectives of TimeSPOT

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Project "specifications"

- Space resolution: O (10 μm)
- Radiation hardness: > 10^{16} 1 MeV n_{eq}/ cm^2 (sensors) and > 1 Grad (electronics)
- Time resolution: ≤ 50 ps per pixel
- Limited power per F/E channel (10's of μW)
- Real time track reconstruction algorithms and fast read-out (data throughput > 1 TB/s)

4 years work program (3+1) 2018-2021

Activities are organized in 6 work packages:

1. 3D silicon sensors: development and characterization
2. 3D diamond sensors: development and characterization
3. Design and test of pixel front-end
4. Design and implementation of real-time tracking algorithms
5. Design and implementation of high-speed readout boards
6. System integration and tests

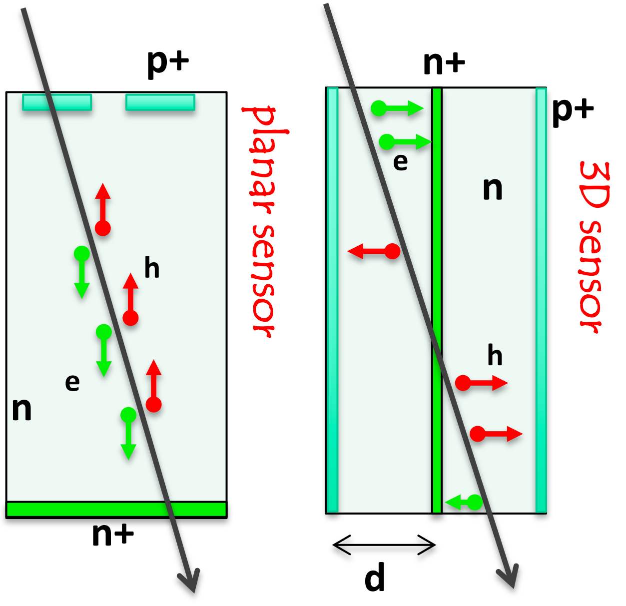
Final Target:
Develop and realize a demonstrator consisting of a complete yet simplified tracking system, integrating O(1000) read-out pixels

10 Italian Institutes: Bologna, Cagliari, Genova, Ferrara, Firenze, Milano, Padova, Perugia, Torino, TIFPA. ≈ 60 heads, ~ 25 FTE. LHCb, ATLAS, CMS + others

3D silicon sensors: key performance points

Established (well known) properties

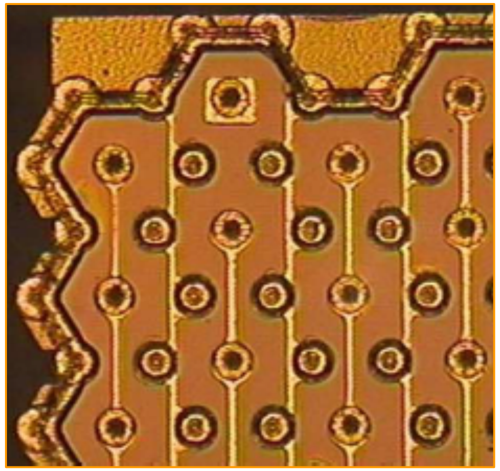
- Short inter-electrode drift distance (tens of μm): extremely fast signals
- Strong mitigation of Landau fluctuation by geometry
- Un-matched radiation hardness ($> 10^{16}$ 1 MeV n_{eq}/cm^2)
- 3D column geometry is a production ready technology (ATLAS IBL, ATLAS-ph2)

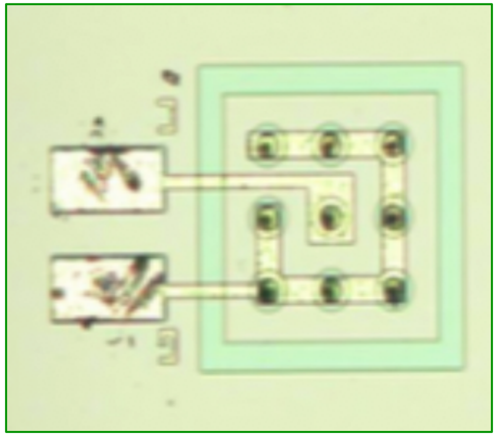


3D and timing (some history)

S. Parker et al. IEEE TNS 58(2) (2011) 404

Column hexagonal geometry *l*=50 μm. 20 V bias
Tested under ^{90}Sr β source. Room temperature
σ_t ranges from 177 to 31 ps (according to signal amplitude)
Limited by RO electronics noise



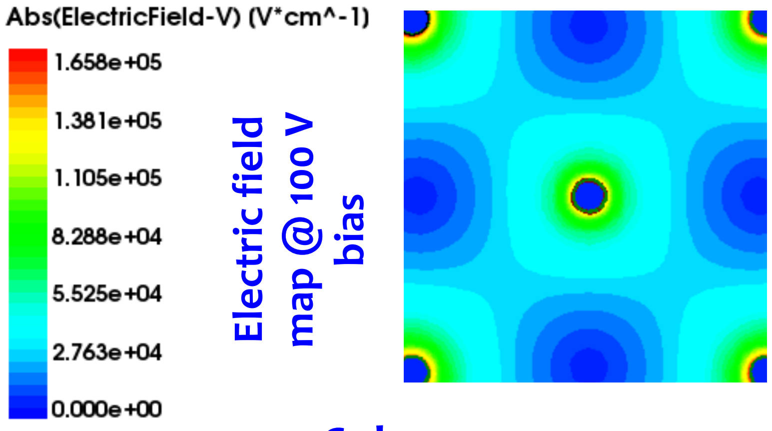


G. Kramberger et al., NIMA 934 (2019) 26-32

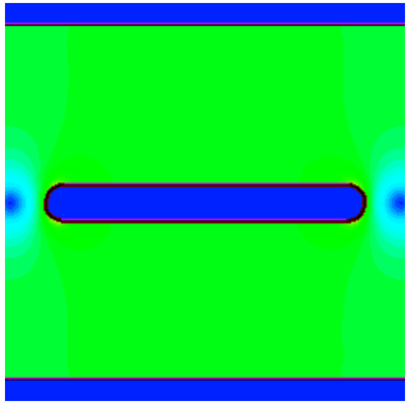
Square geometry *l*=50 μm. Depth = 300 μm. 50 V bias
Tested under ^{90}Sr β source. Room temperature.
σ_t = 75 ps. Dominated by hit position inside cell (time walk)

Preliminary tests (TREDI 2020 Workshop) with ^{106}Ru source give resolutions $\sigma_t \approx 40$ ps (to be better verified)

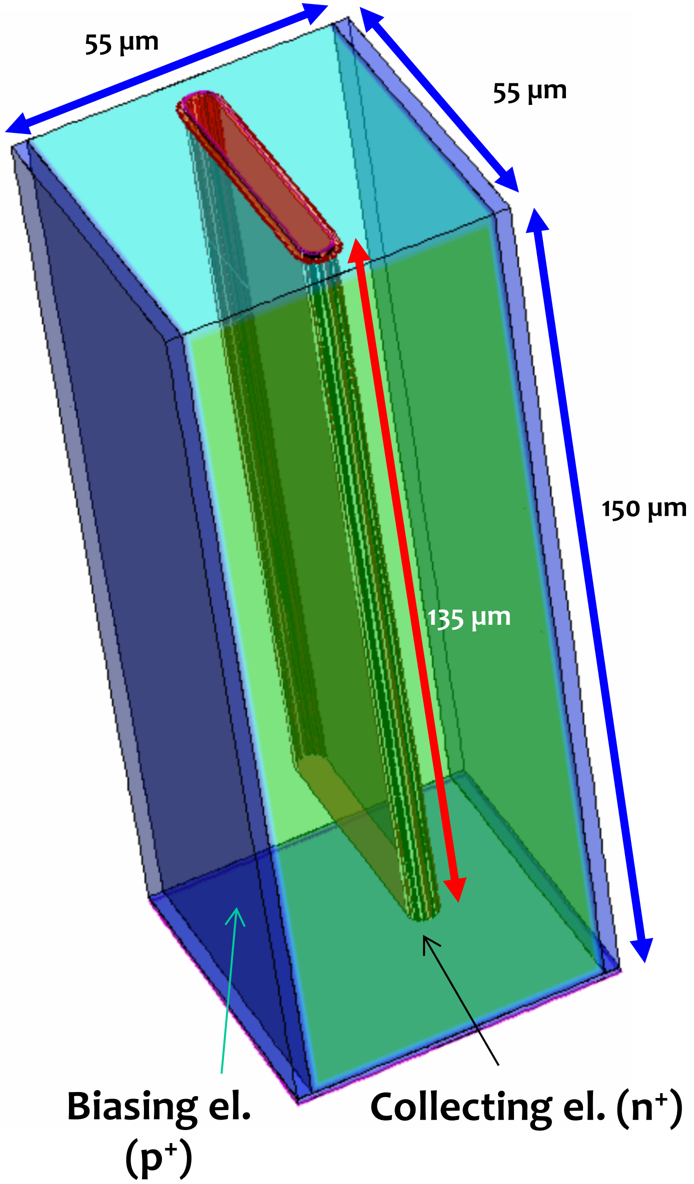
3D-trench geometry and characteristics



Column square geometry (e.g. ATLAS ITk phase2)



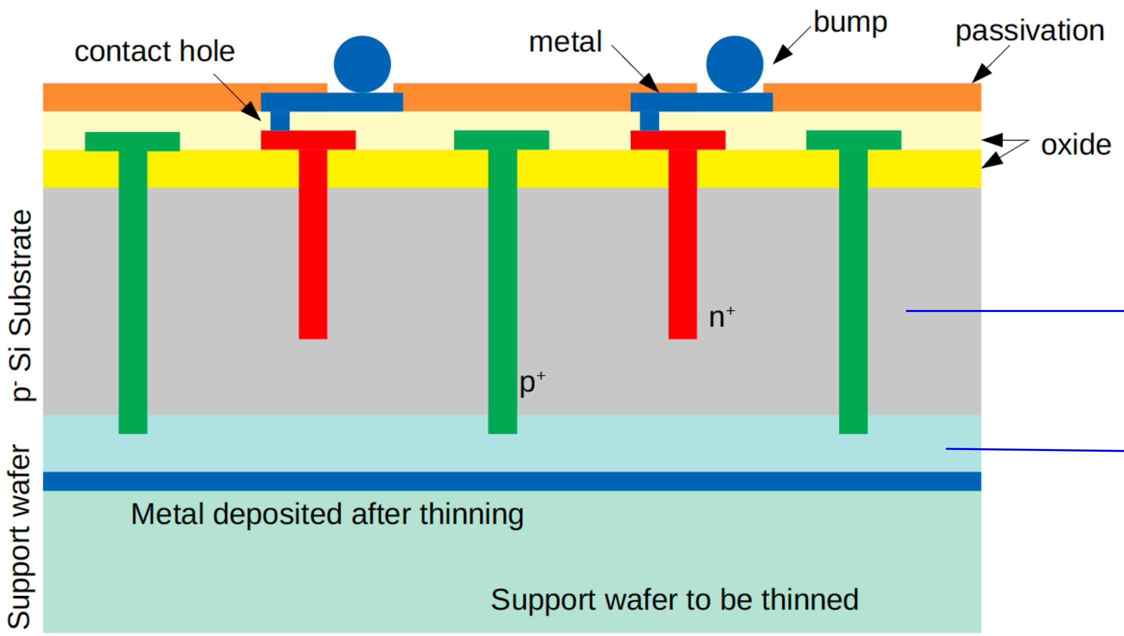
Trench geometry (TIMESPOT)



$$\sigma_t^2 = \sigma_{disunif}^2 + \sigma_{TW}^2 + \sigma_{elJ}^2 + \sigma_{TDC}^2$$

- σ_{TDC}^2: TDC resolution
- σ_{elJ}^2: Electronics (noise and rise time)
- σ_{TW}^2: Amplitude variations (physics)
- $\sigma_{disunif}^2$: Field and velocity maps (geometry of the electrodes)

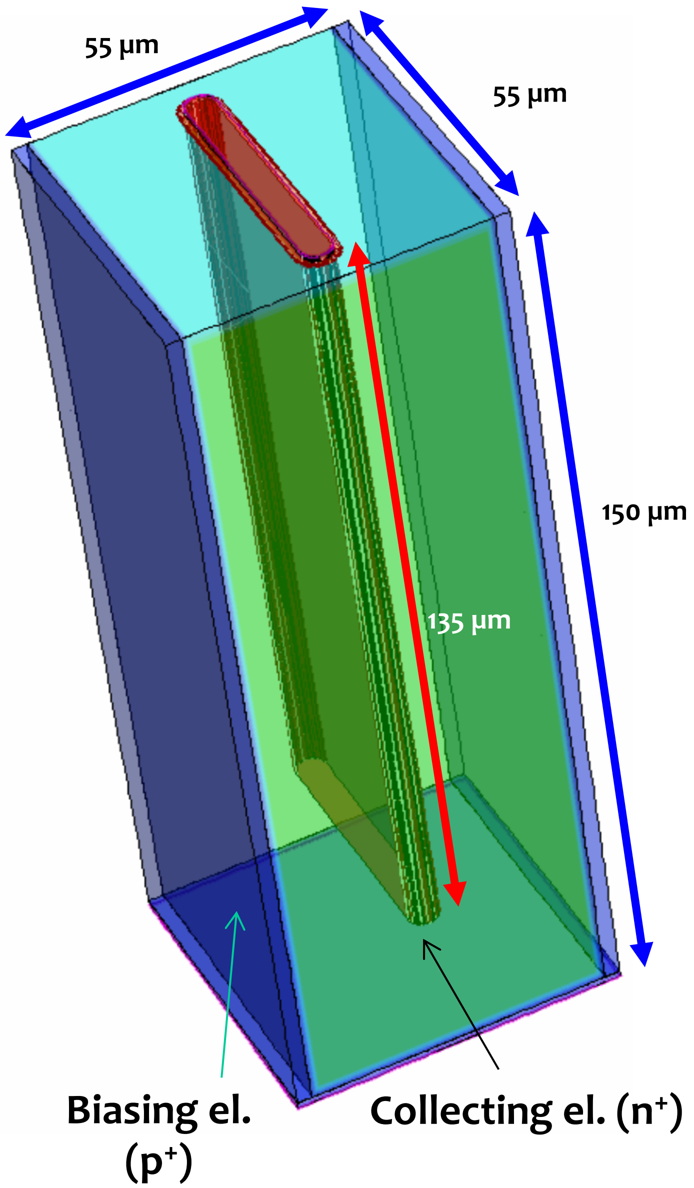
3D-trench geometry and characteristics (2)



HR Si (~ 5kΩ cm)
(sensitive volume)

LR Si (<Ω cm)

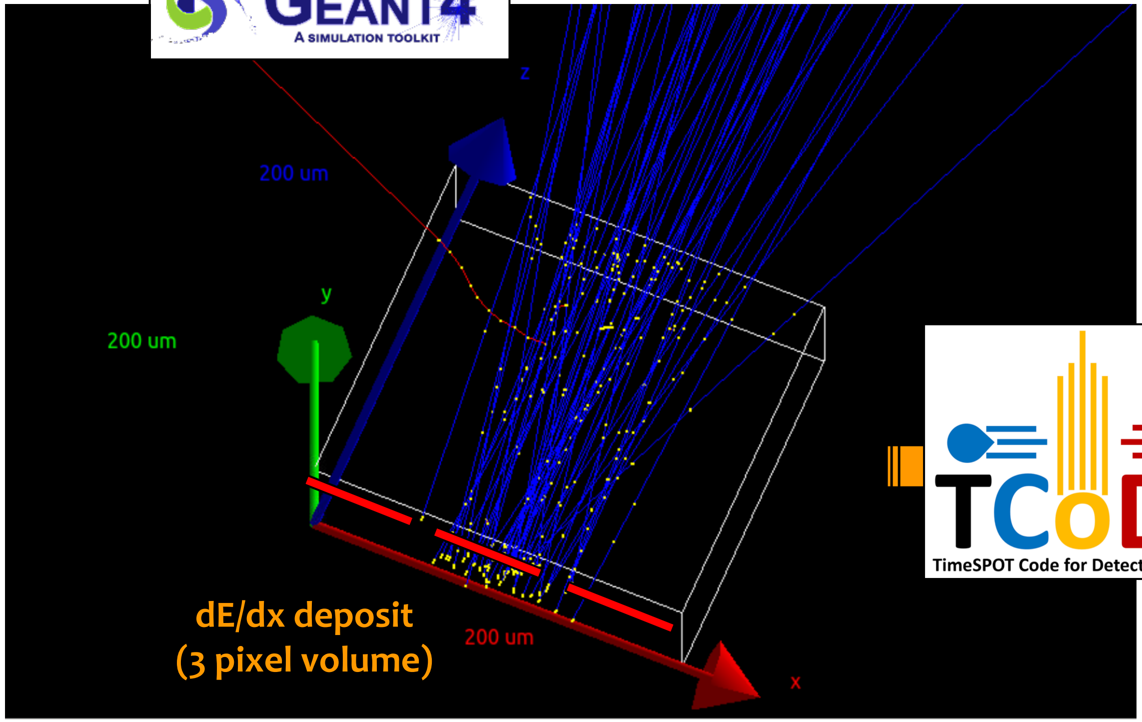
Single-Side
production method



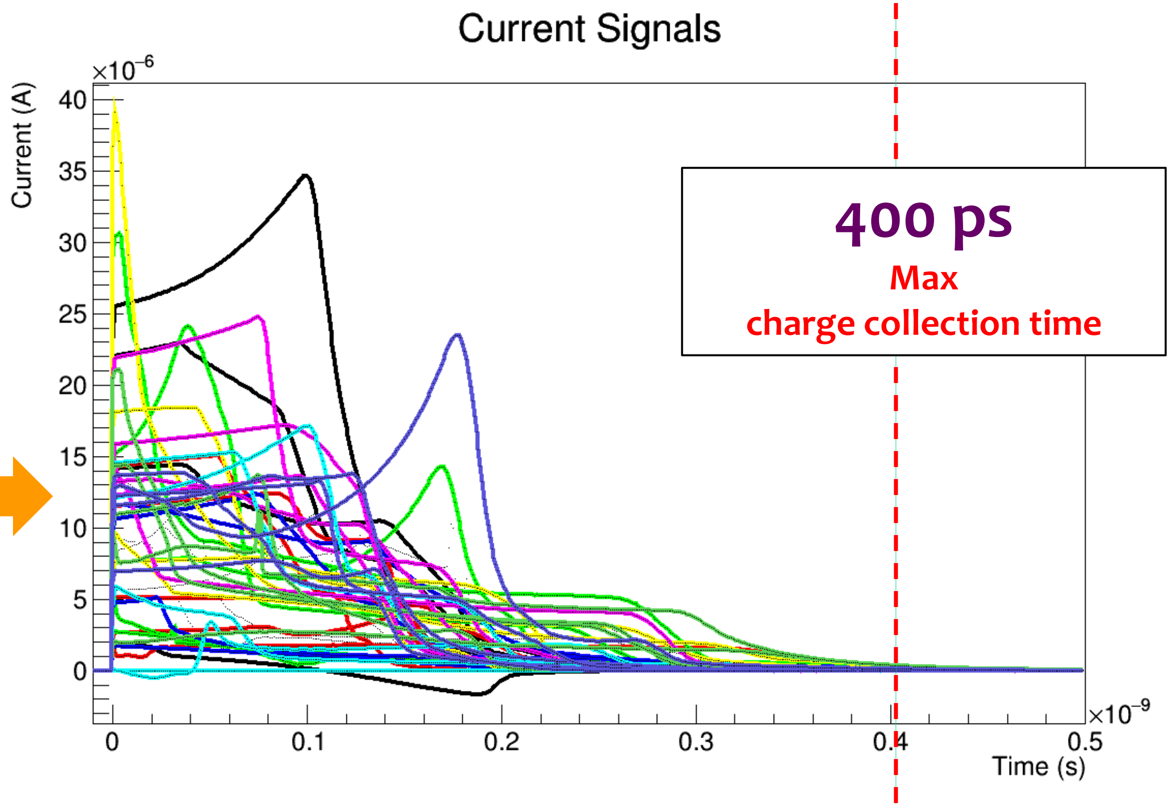
- Total charge deposit for MIP ≈ 2 fC
- Full depletion @ few Volts, Velocity saturation @ > 30 V
- Pixel capacitance (from simulation) ~110 fF
- 55x55 μm^2: TIMEPIX family-compatible pitch

Signals: full-3D model. “Statistics”

https://github.com/MultithreadCorner/Tcode



TCoDE
TimeSPOT Code for Detector simulation



Geant4 generated dE/dx deposit
Electric, Weighting and Velocity fields map from TCAD Sentaurus
Carrier dynamics from TCODE custom multithread code

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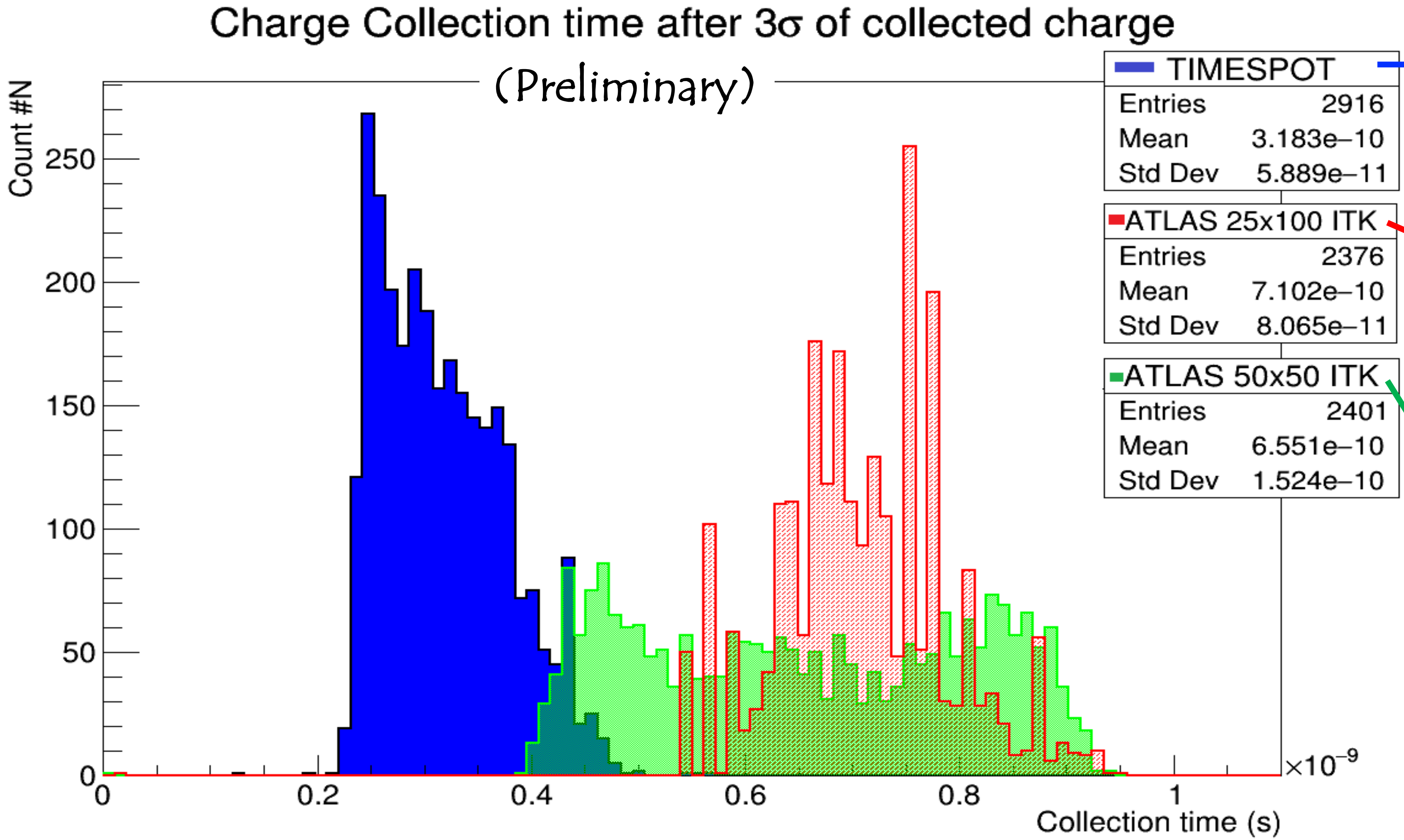
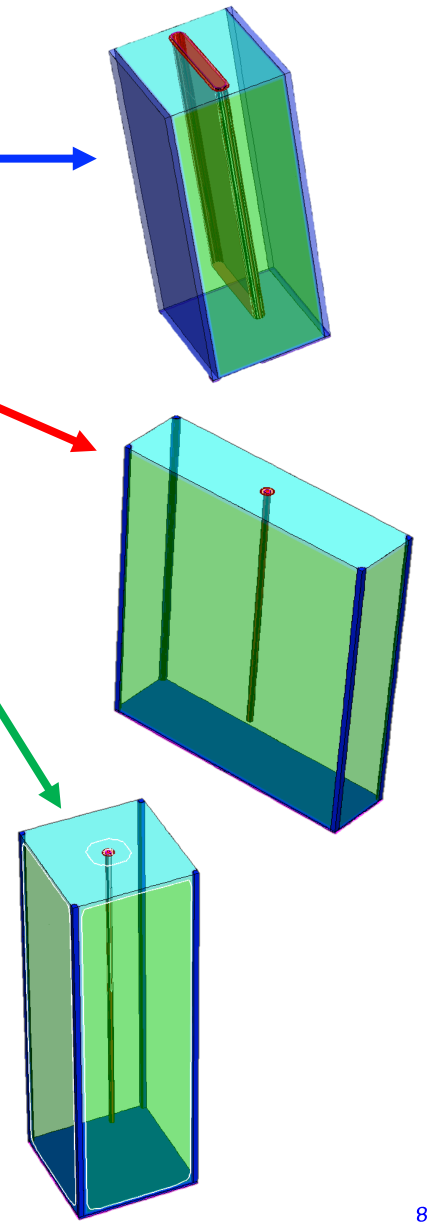
Signals: full-3D model. 3D geometry comparison





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1st 3D-trench batch: delivered June 2019

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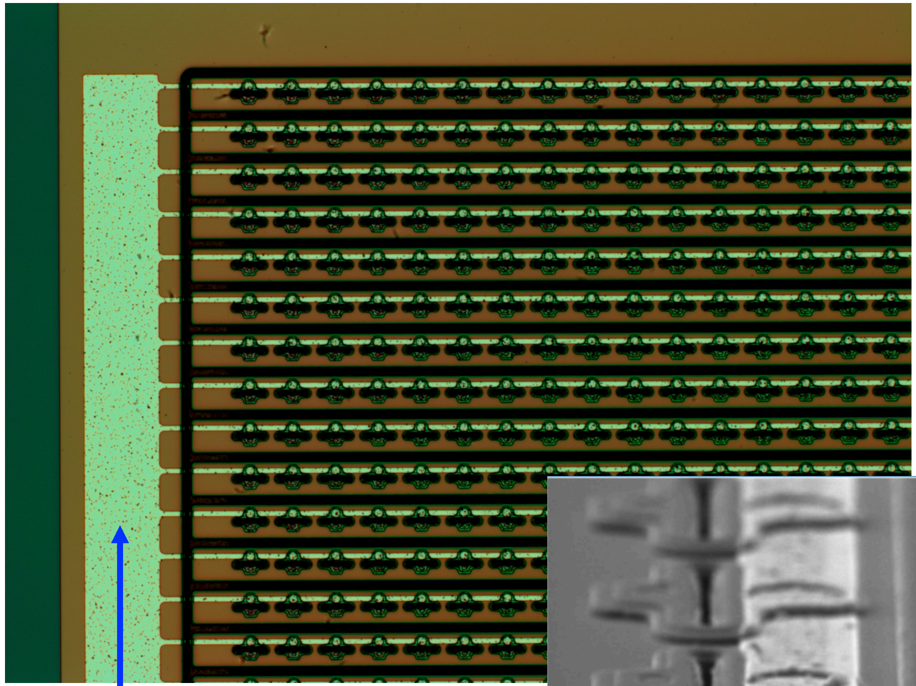
Photolithography with stepper machine. Characteristics:

- Minimum feature size 350 nm
- Alignment accuracy 80 nm
- Max exposure area ~2x2 cm^2
- Full size reticle for two blocks:

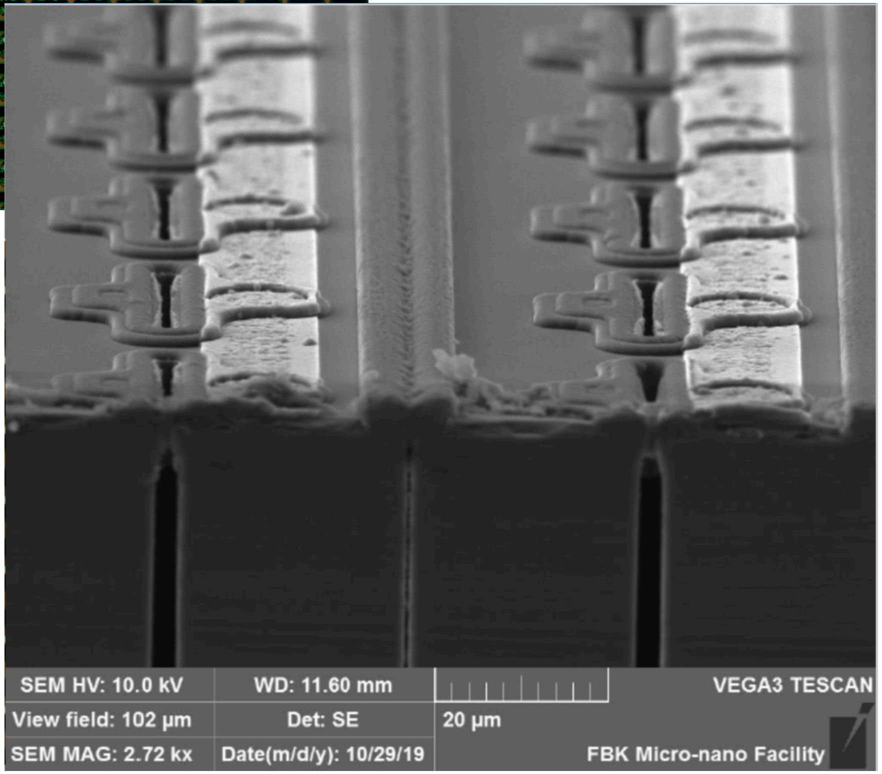
  Timepix sensor and test structures

FONDAZIONE BRUNO KESSLER

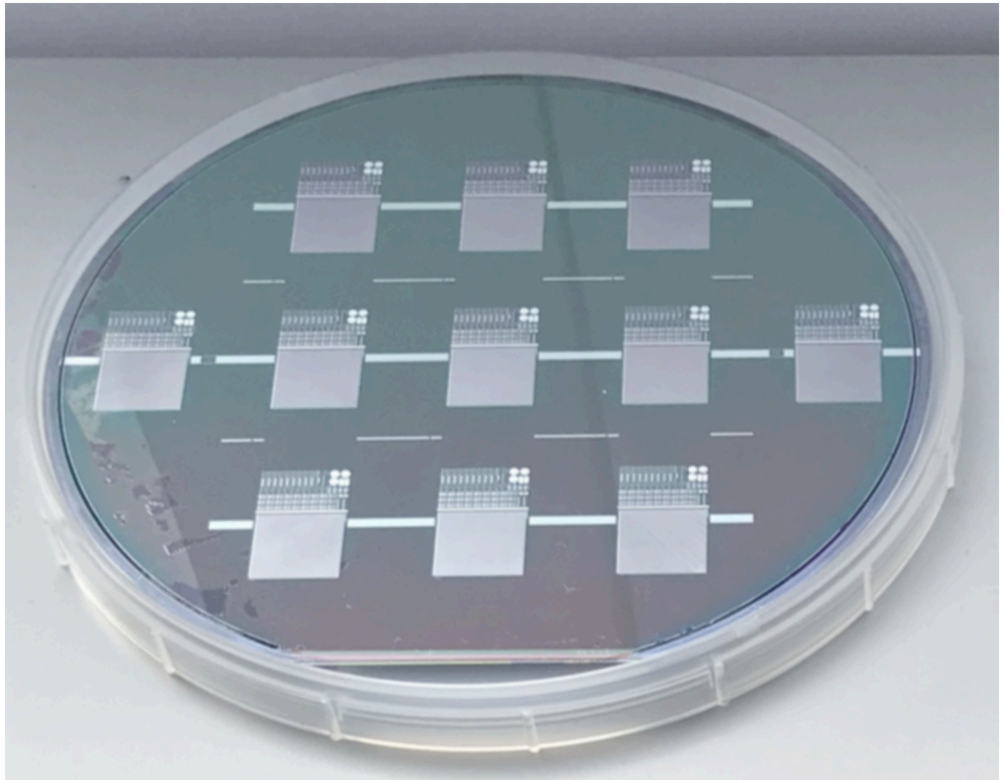


Temporary metal (removed after static electric measurements)

Portion of a 256x256 pixel matrix



10x 6 inches wafer



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1st 3D-trench batch: Electrical («static») characterization

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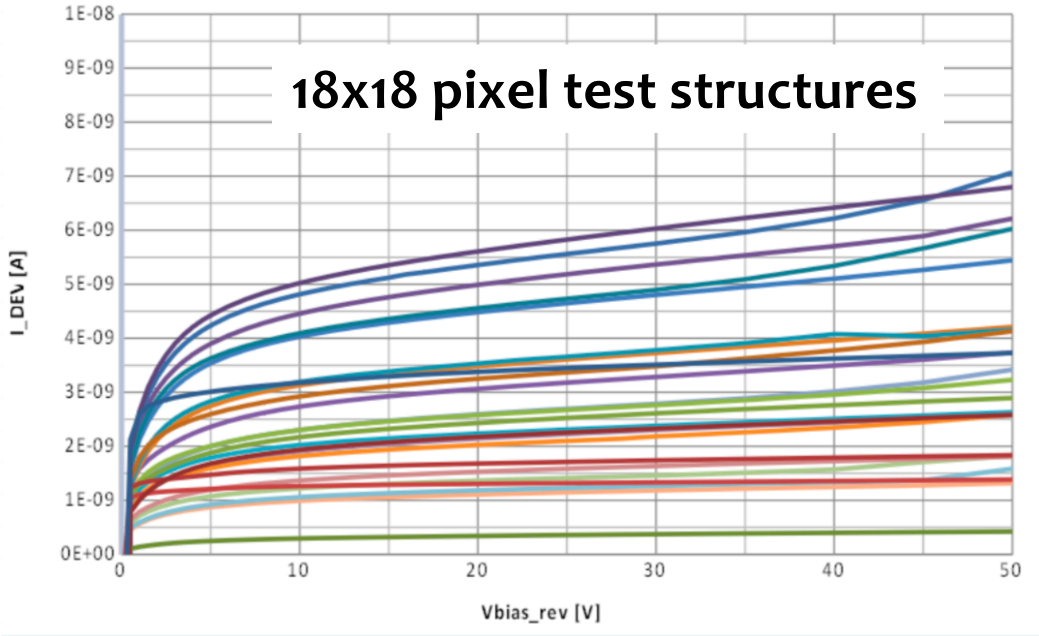
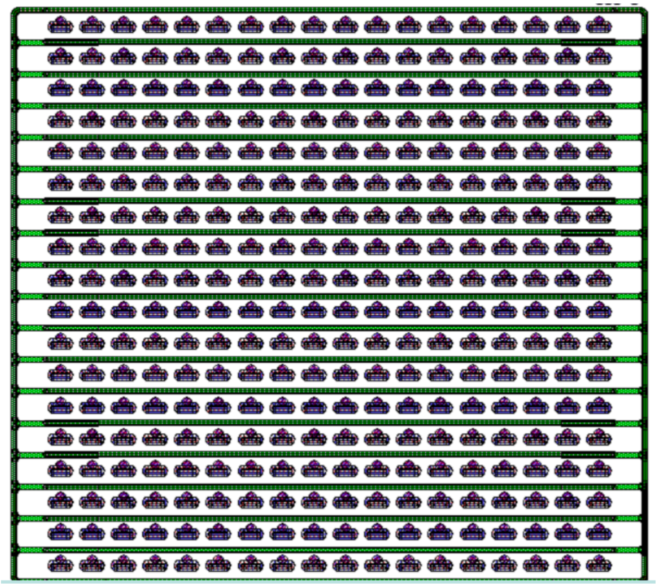
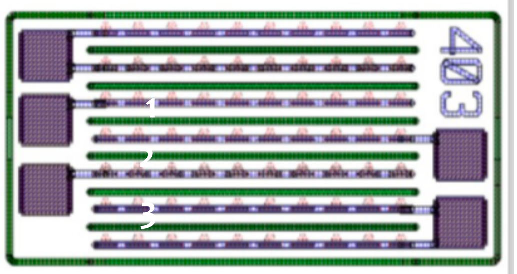


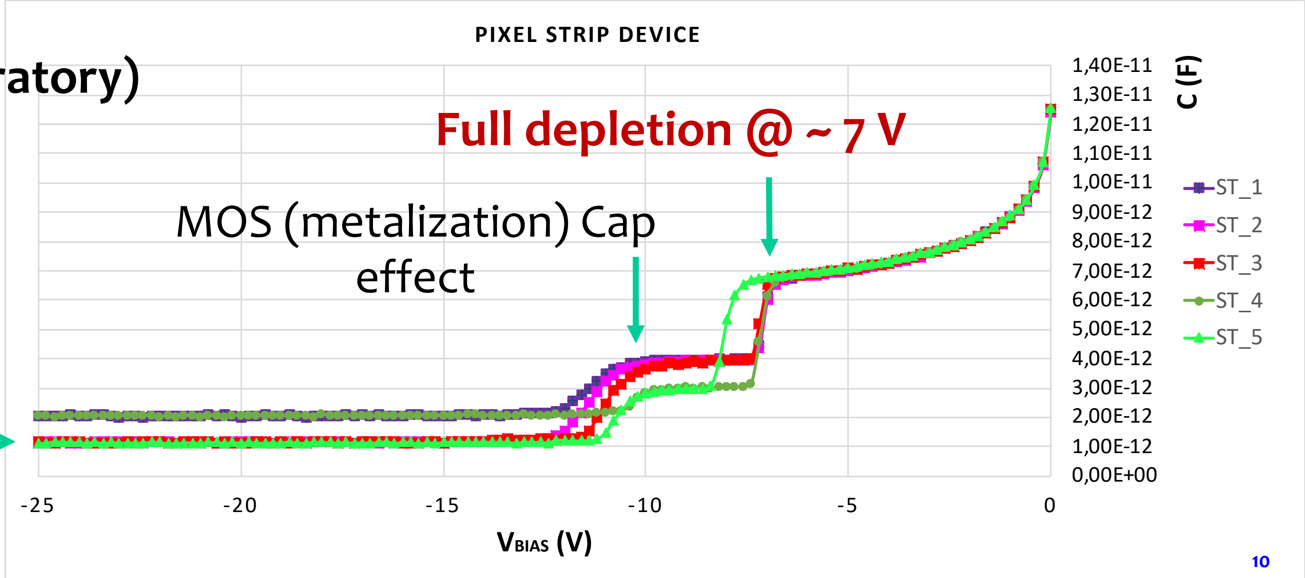


Measurements on wafer (FBK)

~10 pA/pixel on good devices

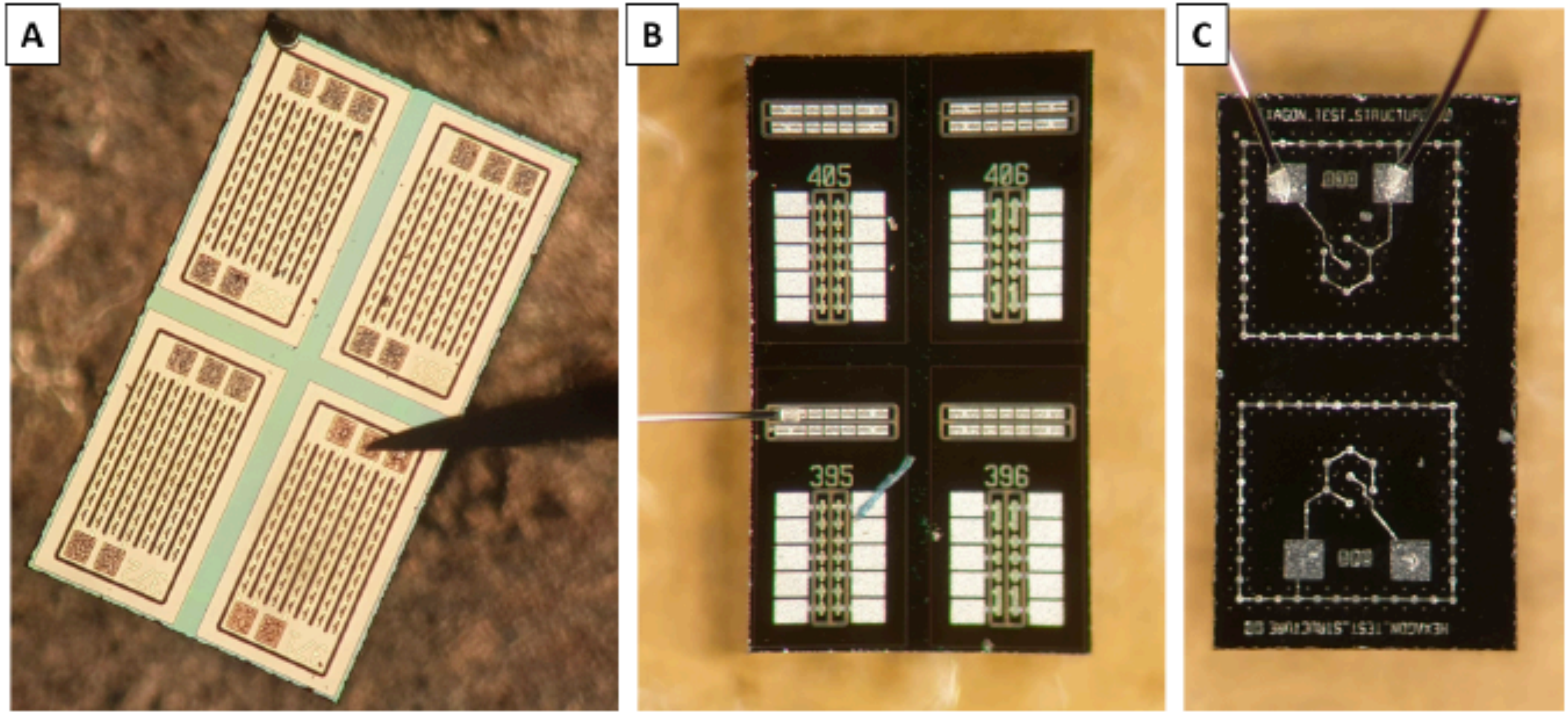
Measurements after dicing (Torino and Trento laboratory)





Measured capacitance ~100 fF/pixel (in agreement with simulation)

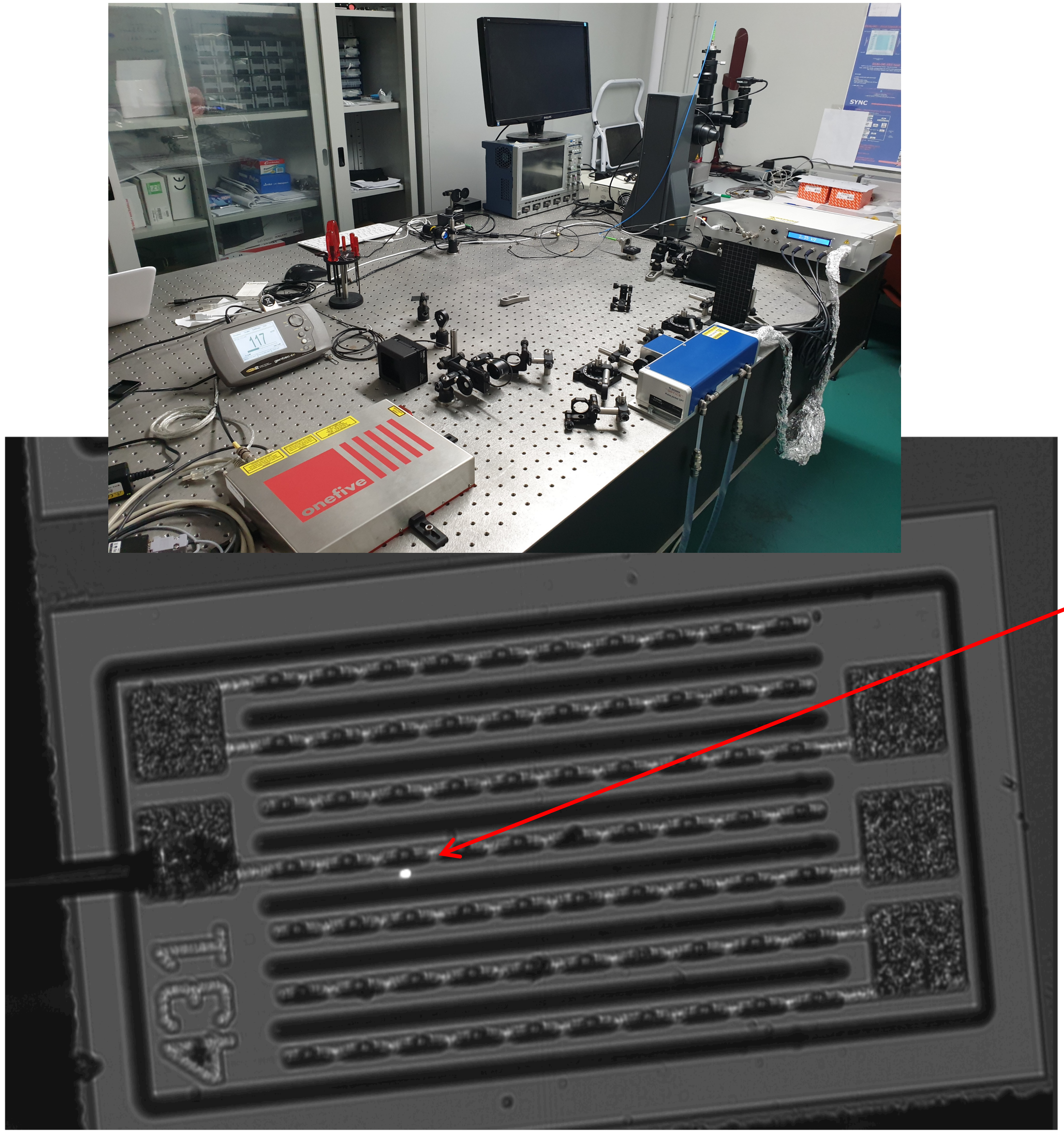
3D structures under «dynamic» tests
In lab & under-beam measurements



(A) Pixel-strip (10 pixels connected on the same read-out pad); (B) Single and double pixel; (C) Hexagonal (column) pixel device, based on FBK 3D Double Side Technology (not from TIMESPOT batch).
Devices are connected to electronics by wire bonding (Al, 25 μm diameter, ~ 5 mm length)

Laser on test structures

Measurements on 1st batch in Cagliari lab



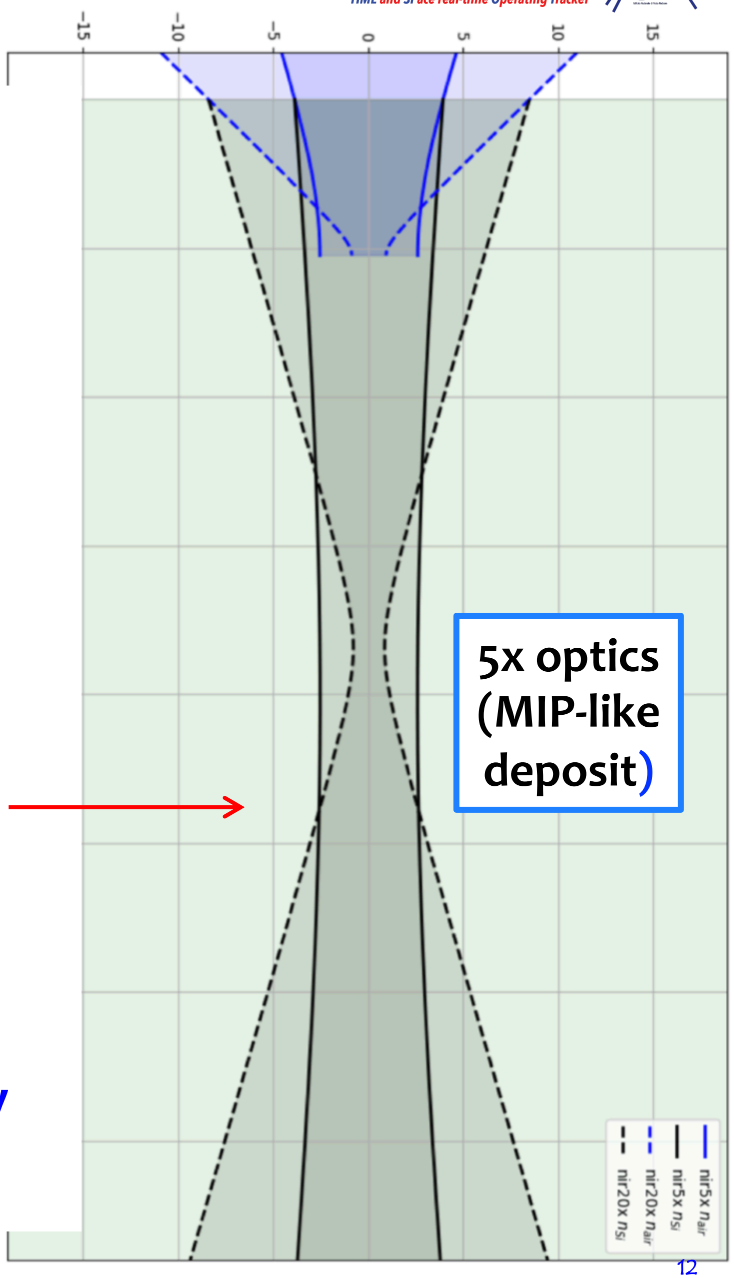
Pixel strip device: 10 pixels read-out together

Test setup:

1030 nm pulsed LASER
200 fs native jitter
1 ps on scope ("setup" jitter)
Repetition rate from single pulse to 40 MHz

Cylindrical spot 5 μm diameter
MIP-like deposit shape

MIP (~2 fC) deposit amount estimated by means of Charge amplifier, adjustable by optical filtering



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Time response vs Charge

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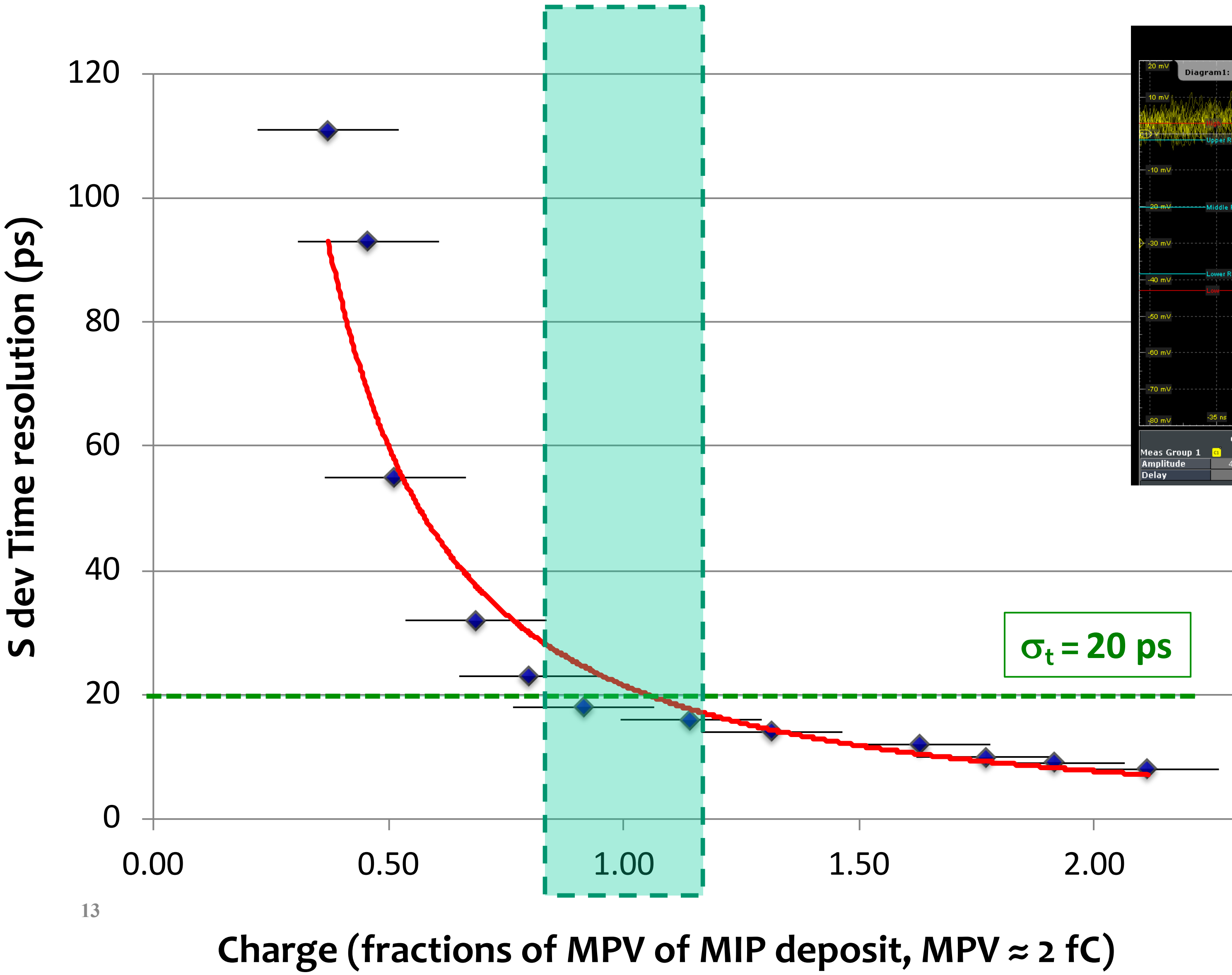

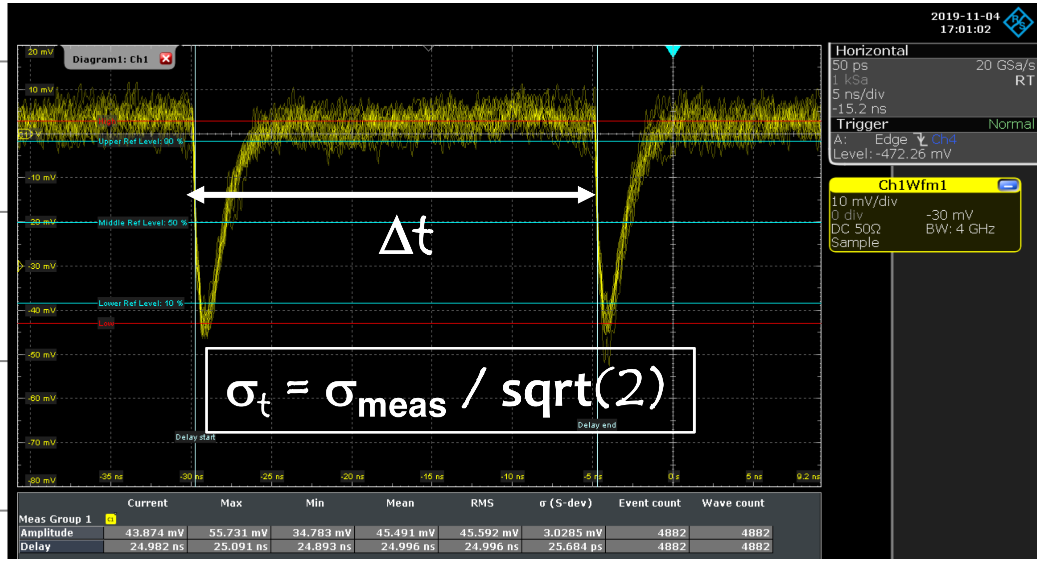

- **Pixel Strip @ V_{bias} = – 60 V @ room temperature**
- **Descrete component Front-end from Kansas University design (not optimized)**
- **Numerical CFD (on scope)**
- **10 pixel strip + wire bond connection ($C_{tot} \approx$ 1.5 pF)**
- **Charge deposit estimate by separate calibrated CSA readout**

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Tests beam @ PSI accelerator (πM1)

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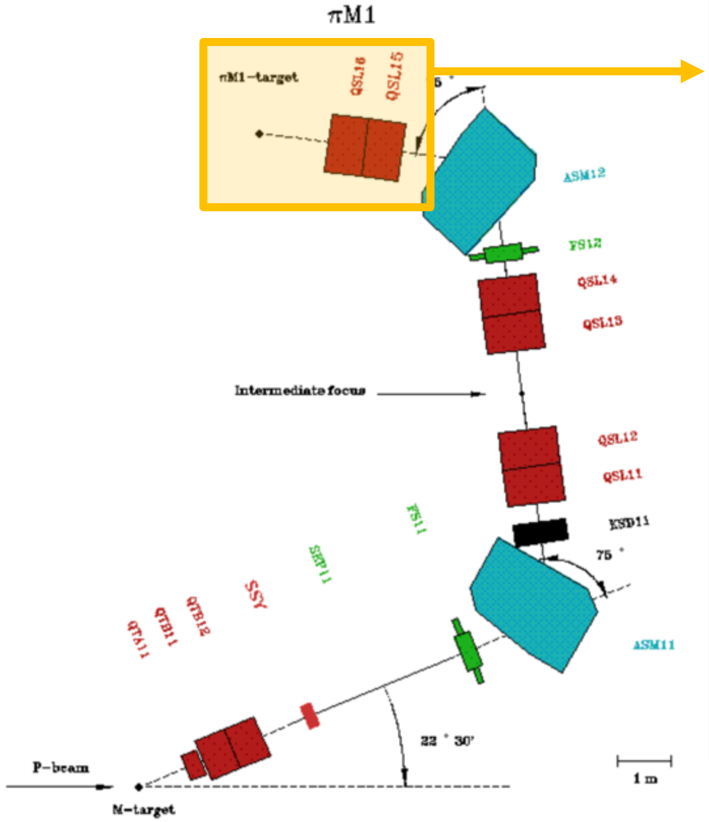
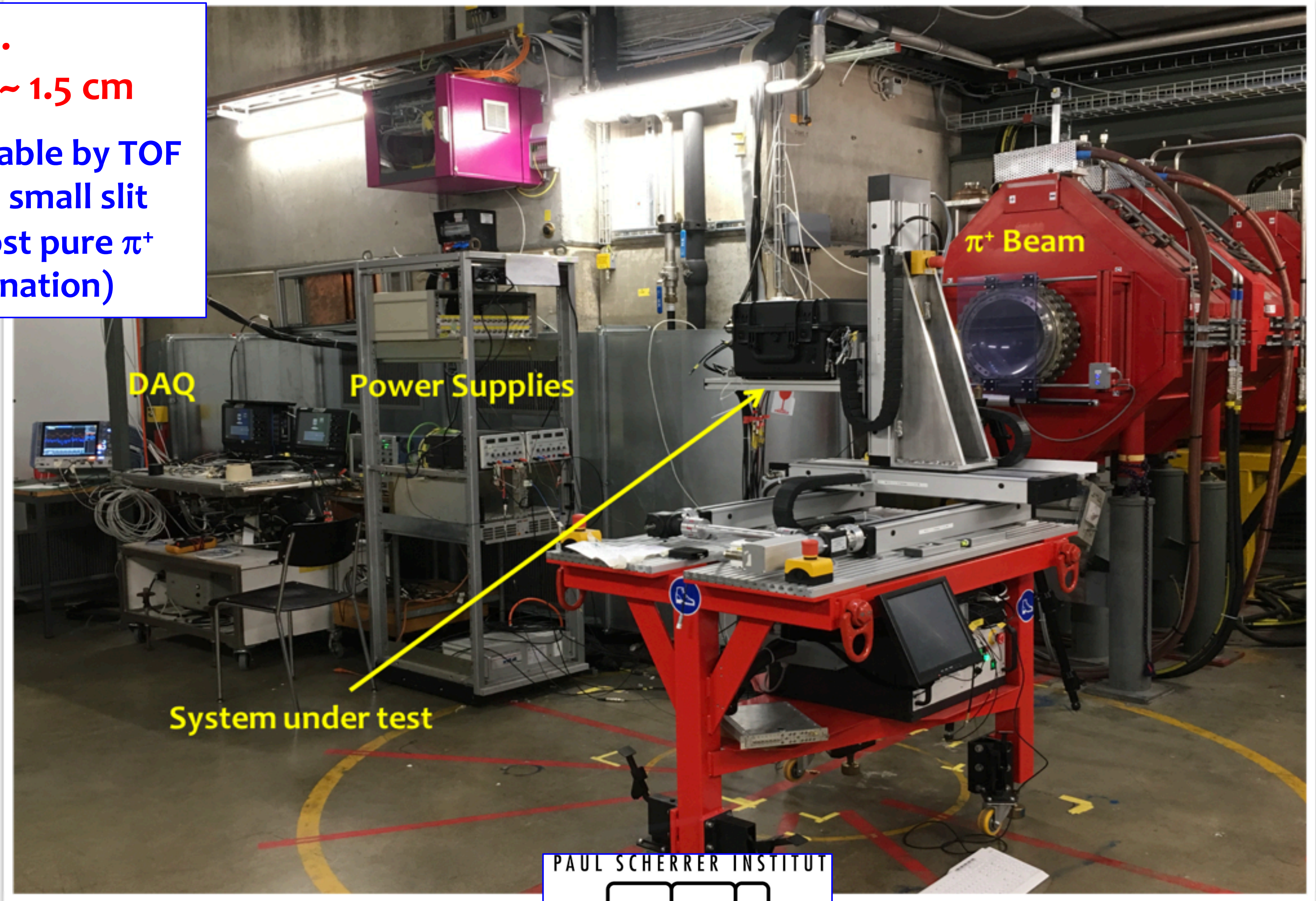
Beam E = 270 MeV/c.
Beam radius on the spot $\sigma \sim 1.5$ cm

Original beam: p, e^+, μ^+, π^+ Selectable by TOF
Using a plexiglas degrader and small slit apertures we obtained an almost pure π^+ beam (negligible e+ contamination)





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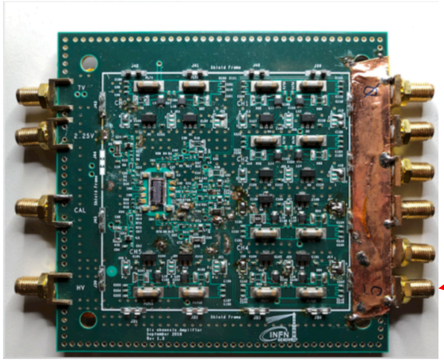
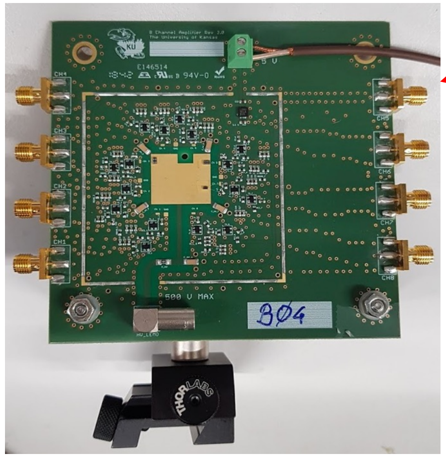
Tests beam @ PSI πM1
System inside the black box

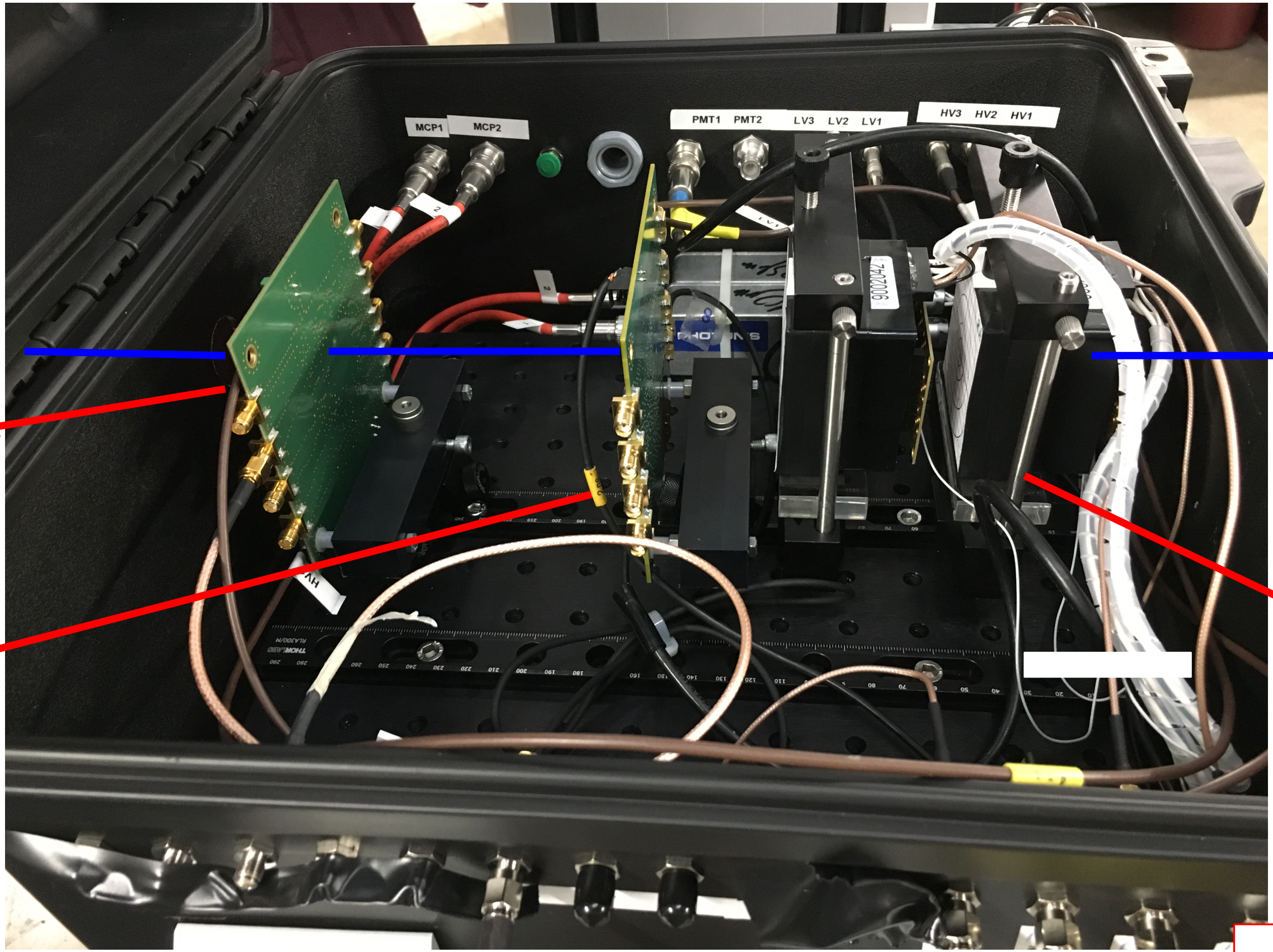
DUT front end:
broadband amplifier board with discrete components

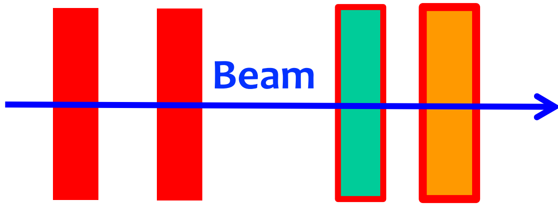


INFN-Ge Front End



KU Front End





π^+ Beam

Time Taggers:
Quarz Cherenkov radiator + MCP

$\sigma_t \approx 15$ ps (each tagger)

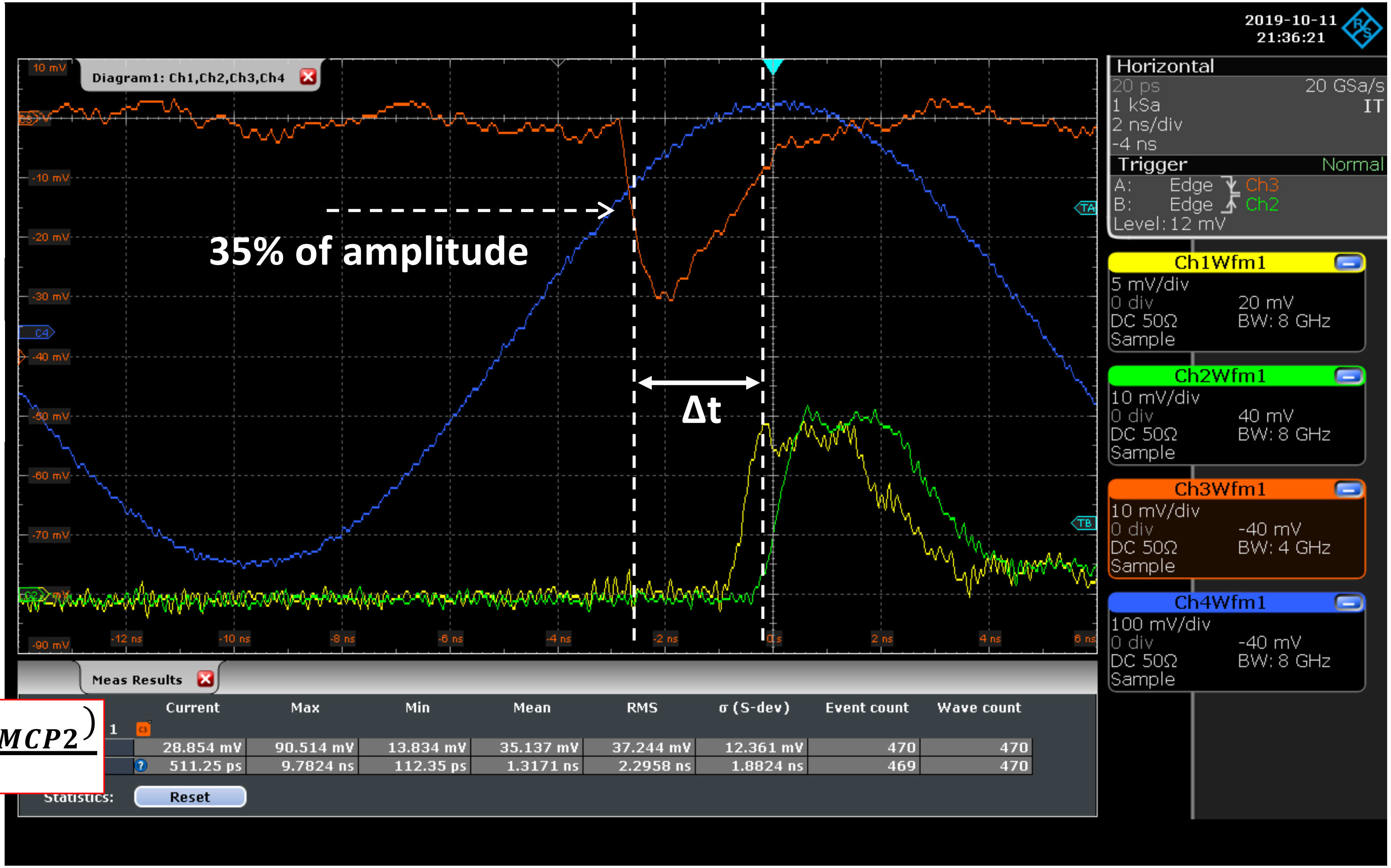
Tests beam @ PSI πM1

Waveforms acquired

DUT signal (trigger)
Exposed Area of DUTs
<< 1 mm²
Each DUT has a different DAQ chain (8 GHz BW scope)

Beam RF signal
(50 MHz)

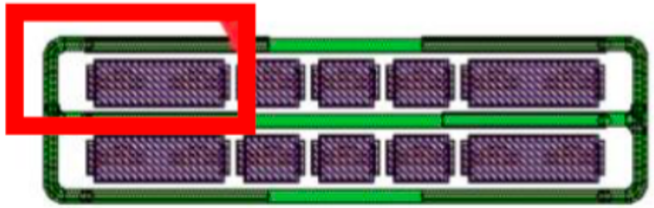
2 MCP signals
(time references)
Exposed area ≈ 5x5 cm²



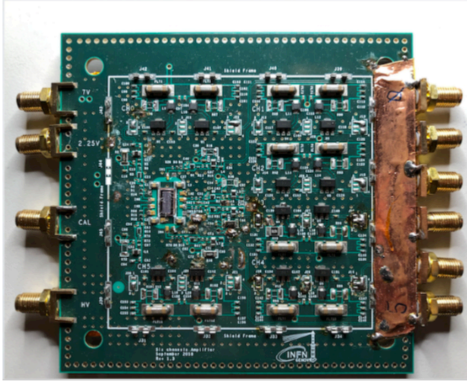
$$\Delta t = t_{h_{sgn}} - \frac{(t_{th_{MCP1}} + t_{th_{MCP2}})}{2}$$

Test beam results

Measurements depends strongly on the specific F/E electronics used.
In the following, results obtained with DUT2 (INFN-GE F/E are illustrated)



DUT: Double pixel



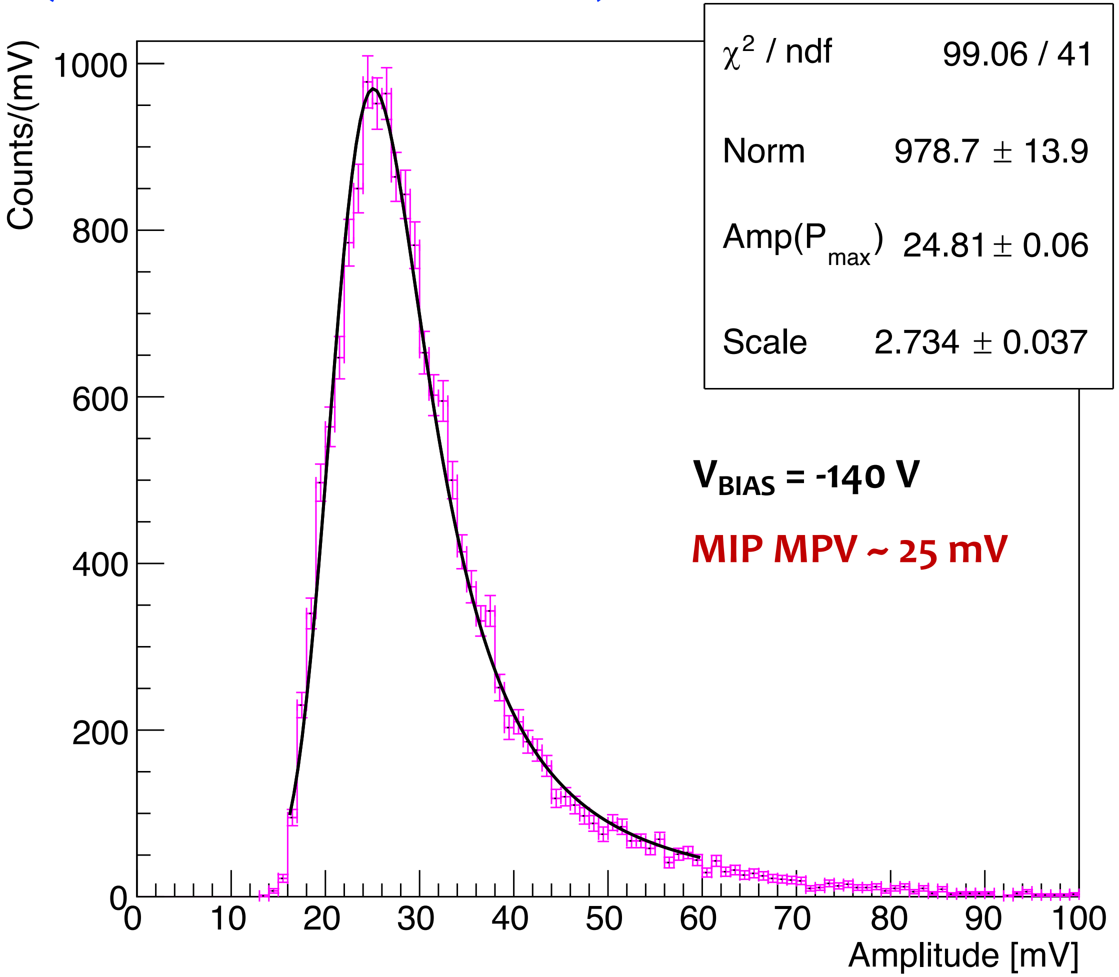
INFN-Ge Front End Board

(1 amplification stage, G~30
2 GHz bandwidth)

+ **external broadband amplifiier**
(G=10, 2 GHz bandwidth)

V_{BIAS} (V)	N of events
-20	20k
-50	20k
-80	3k
-110	20k
-140	20k

Measurements perfomed at different V_{BIAS}



V_{BIAS} = -140 V

MIP MPV ~ 25 mV

FIT: Gaussian (noise) + Landau (signal) + error step function (trigger)

The Max/FWHM ratio is compatible with a Landau distribution of a 150 µm thick silicon

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Test beam results: Time resolution

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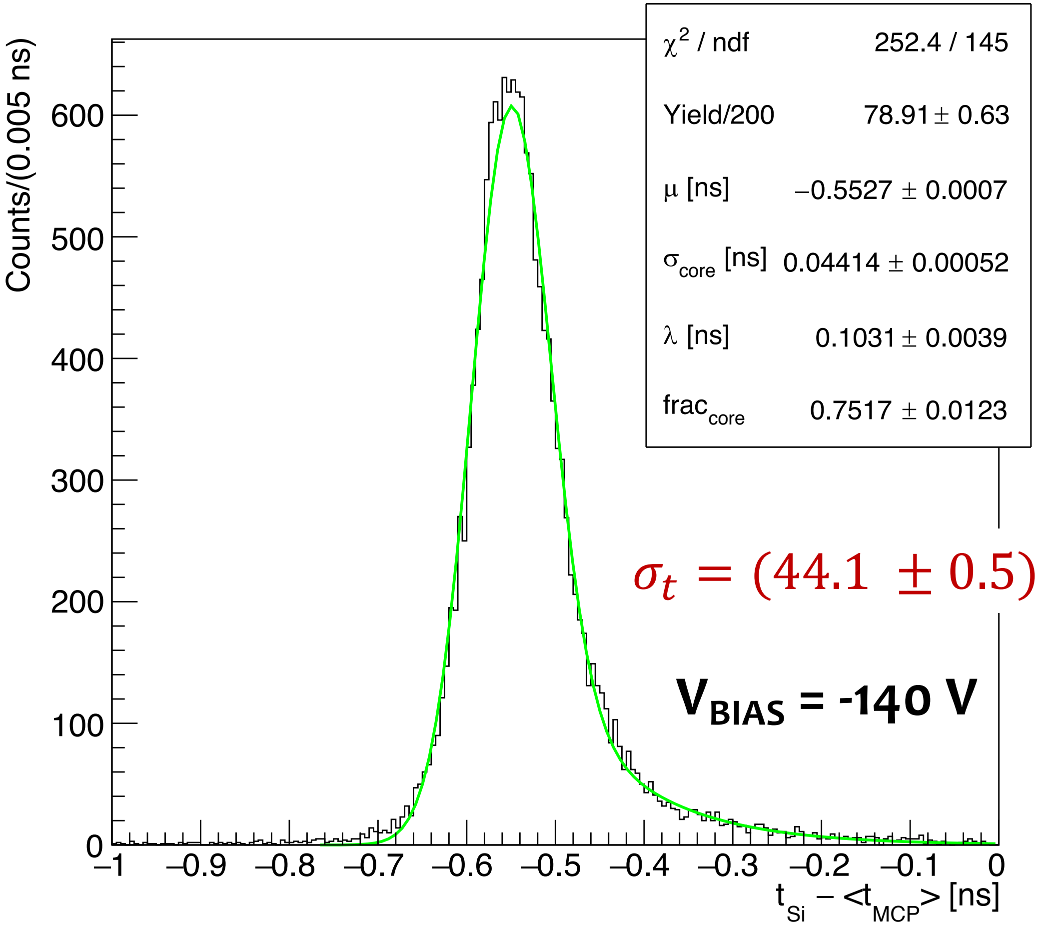
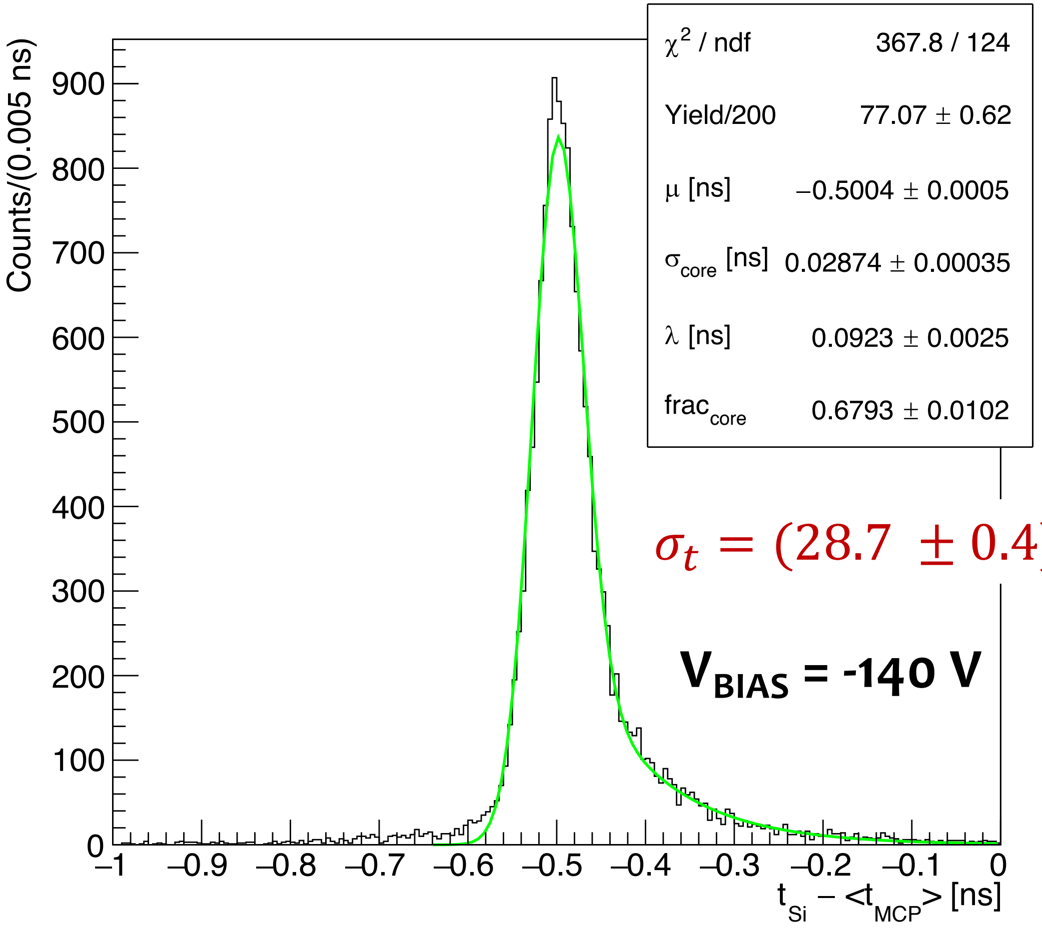
- ☞ ToA: numerical **leading edge** discriminator with a fixed threshold Th=5mV (**no TOT correction**)



$\sigma_t = (44.1 \pm 0.5)\ ps$

V_{BIAS} = -140 V

- ☞ Numerical filters to reduce high frequency noise applied
- ☞ ToA: Numerical **CFD** with a 35% threshold



$\sigma_t = (28.7 \pm 0.4)\ ps$

V_{BIAS} = -140 V

FIT: $f \cdot Gaus(\mu,\sigma) + (1-f)\exp(\lambda) \otimes Gaus(\mu,\sigma)$

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Test beam results: Time resolution (2)

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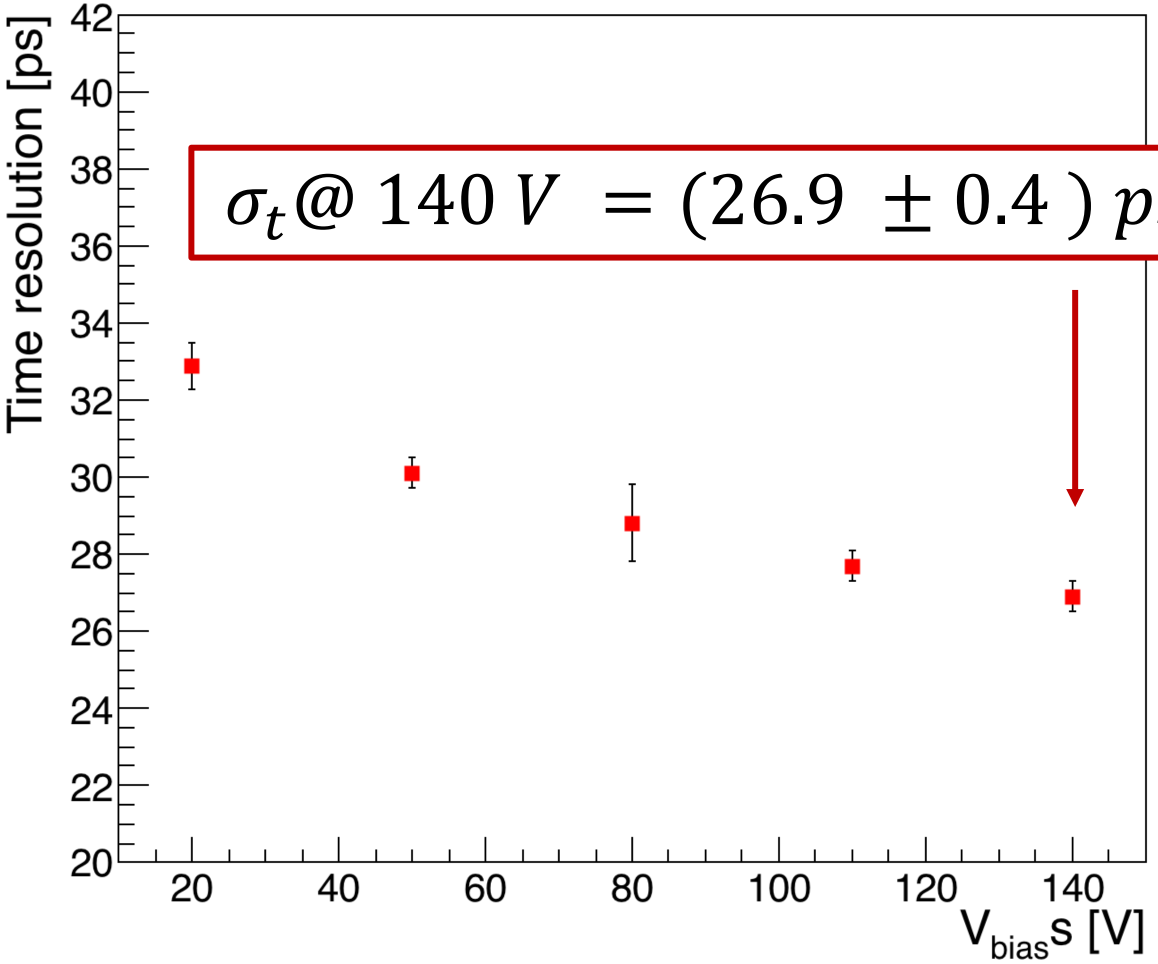
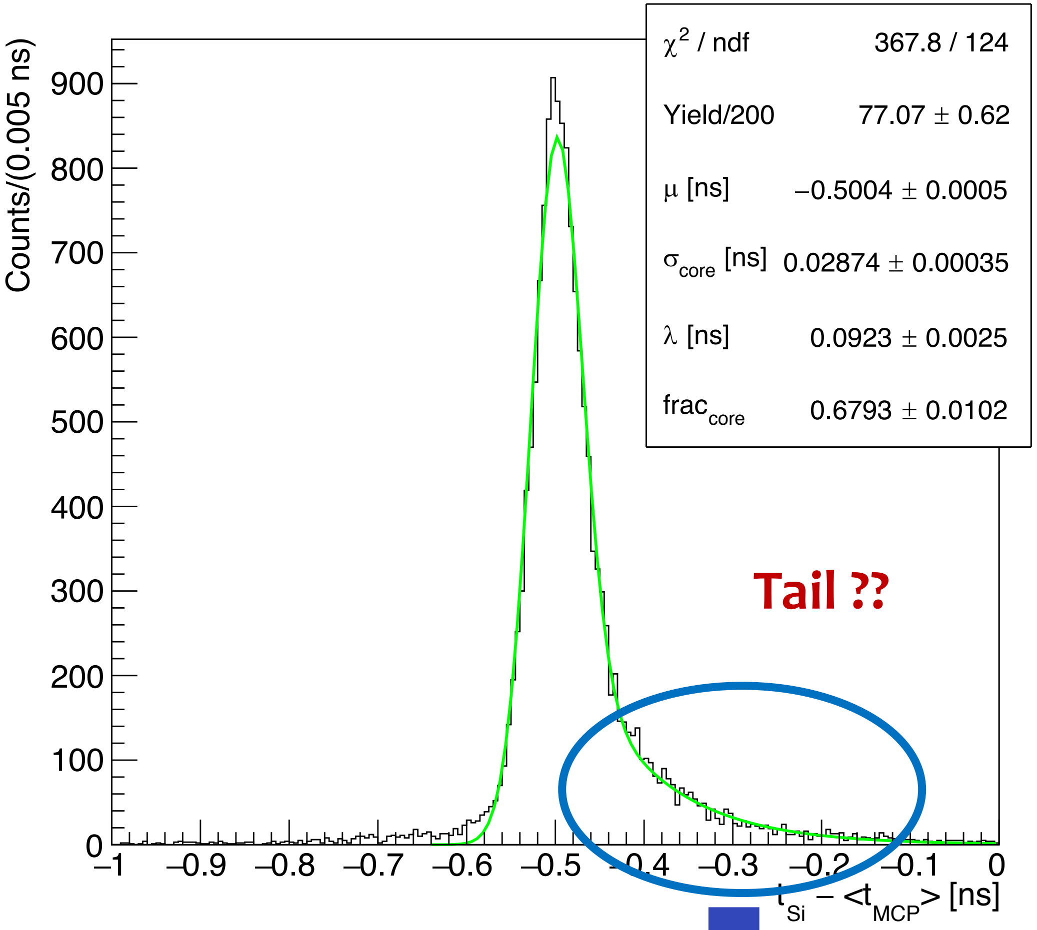


$$\sigma_t @ 140\,V = (26.9 \pm 0.4)\,ps$$

Si-sensor time resolution after MCP time resolution subtraction for different Vbias



Combination of 3 main effects:

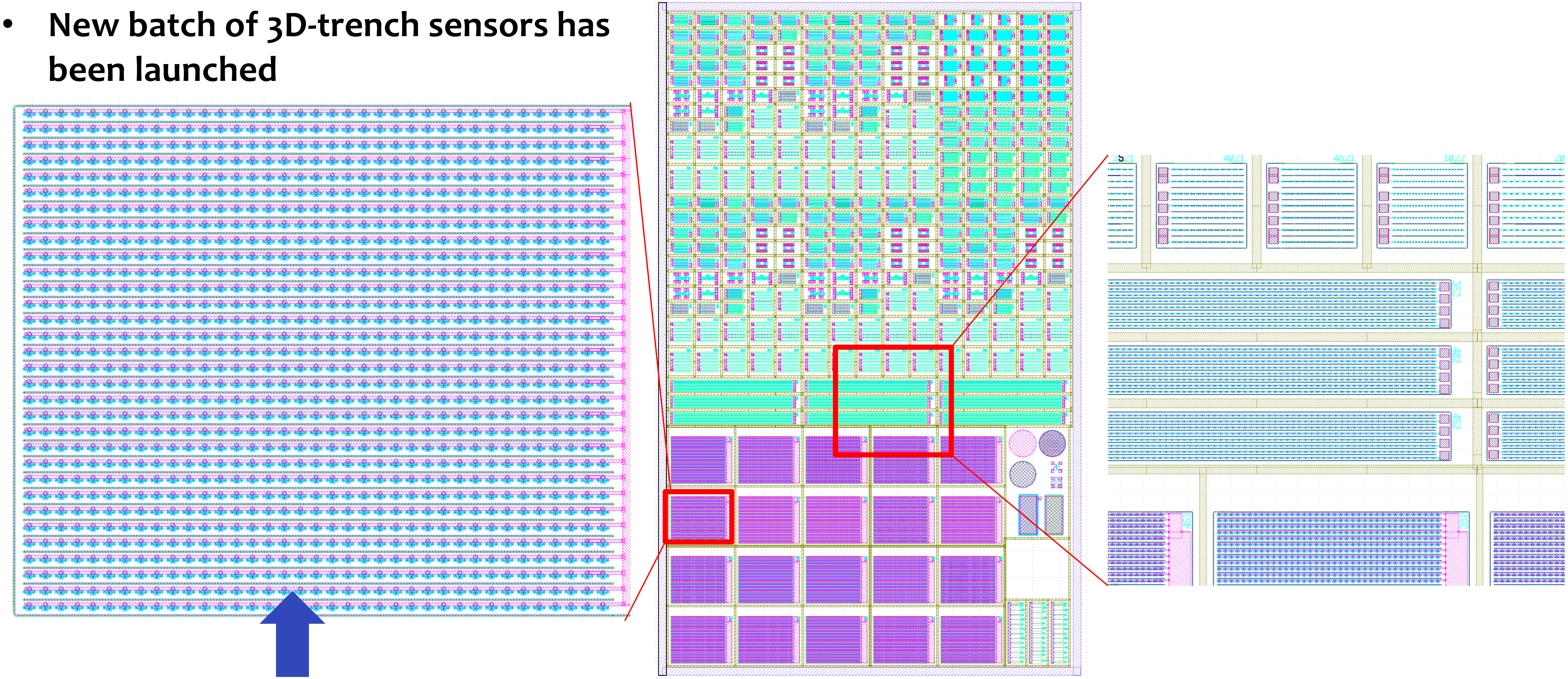
- Spurious signals (algorithm and in-time EMI noise)
- Boundary effects (neighbour un-read pixels)
- Weak field spots

Conclusions …

- Unprecedented results on trench 3D Si pixels timing performance have been presented
- Results were obtained on wire-bonded sensors (x10 of nominal pixel capacitance)
- The time resolution of trench 3D sensor, 55x55x150 μm^3 , under laser beam has been measured being around 20 ps under 1-MIP-estimated deposit charge.
- The time resolution of the same sensor measured under a 270 MeV/c π^+ beam has been measured ≈ 27 ps @ Vbias = – 140 V
- O(6%) Tails require further studies. However they are naturally suppressed in a (multi-point) tracking system.
- 3D devices confirm their theoretical excellent performance in timing. Trench geometry shows up being the right direction to go
- Up to now, electronics is the limiting factor to sensor and system performance
- TIMESPOT is developing optimized electronics necessary to possibly increase the obtainable target performance

… and very next Perspectives

- New batch of 3D-trench sensors has been launched



- Electronics: design of a 28-nm CMOS ASIC is at an advanced stage. A 32x32 pixels readout circuit will be submitted for production next summer.