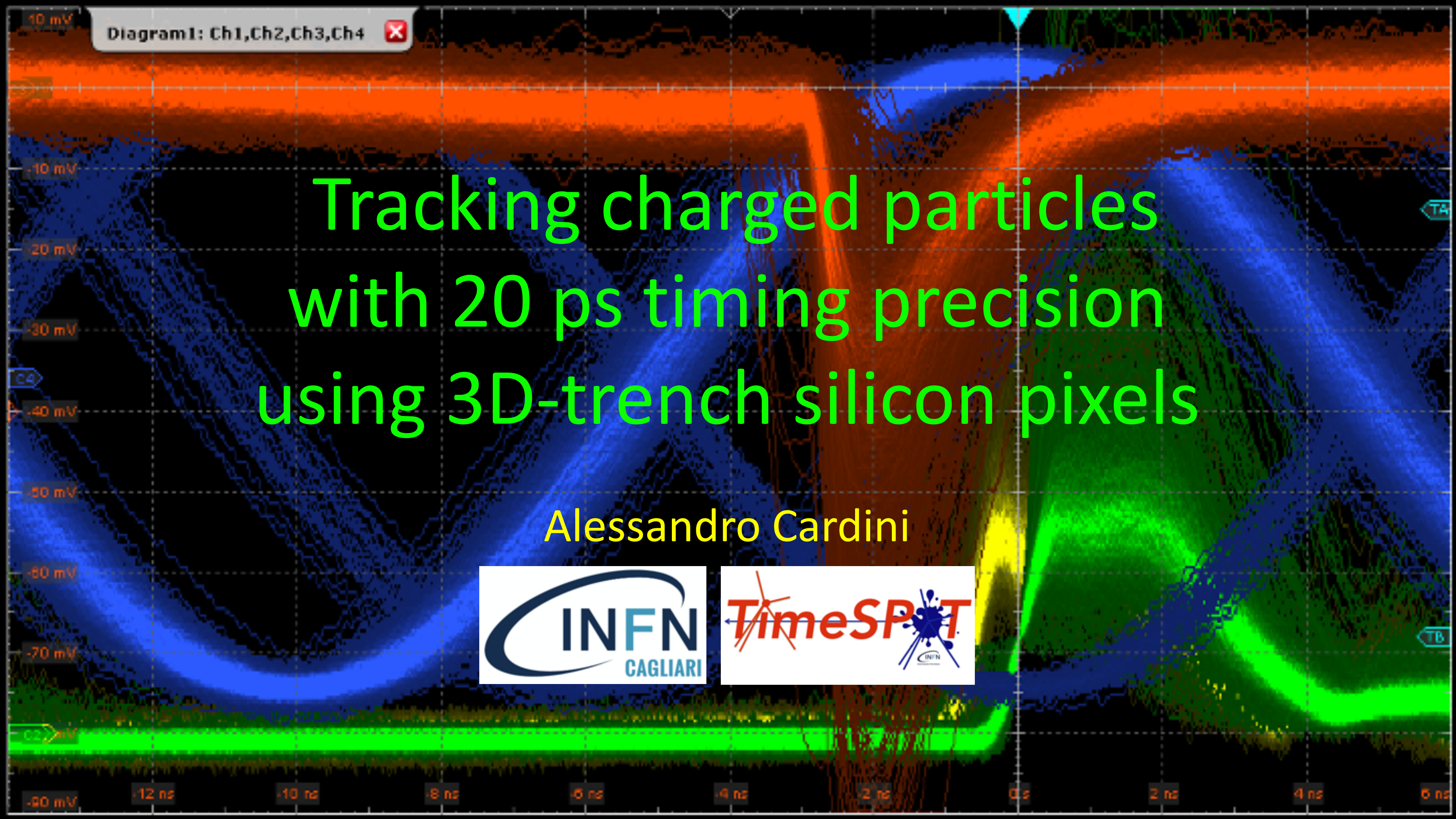


Tracking charged particles with 20 ps timing precision using 3D-trench silicon pixels

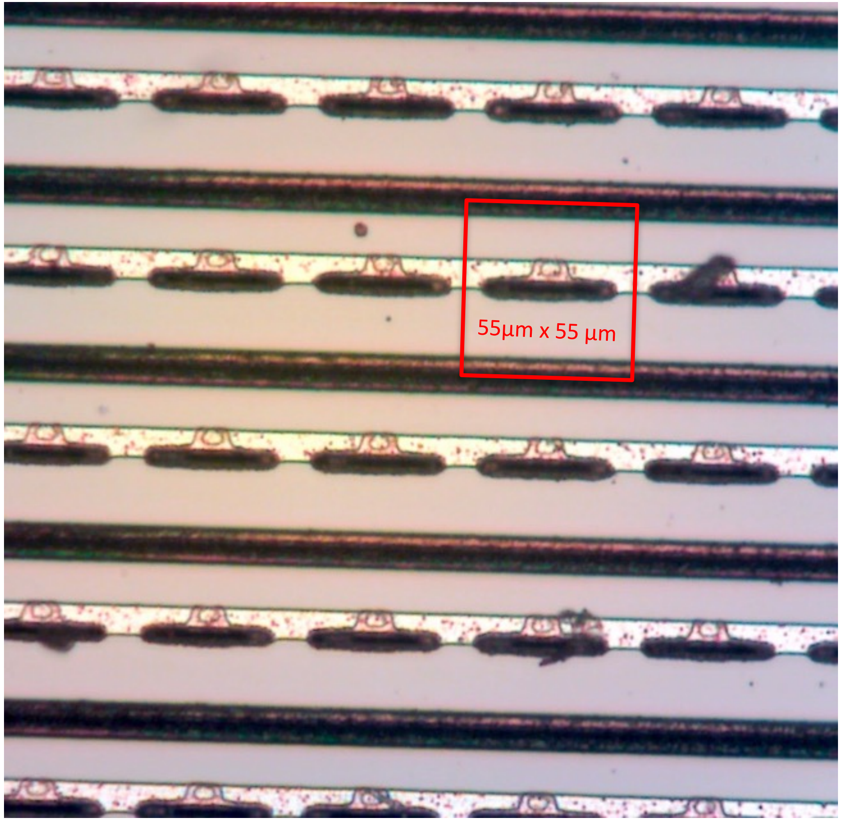
Alessandro Cardini

INFN CAGLIARI

TimeSPOT

Outline

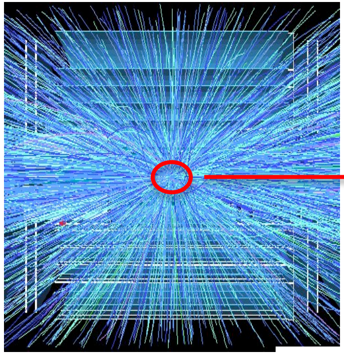
- Needs of future HEP tracking systems for high luminosity operations
- The TimeSPOT 3D-trench pixel design
- The 2019 PSI beam test
- Laboratory testing of 3D-trench pixels
- Conclusions and outlook



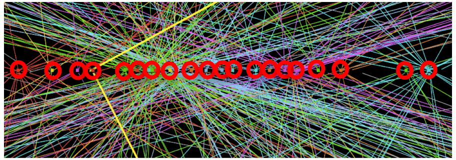
TimeSPOT 3D-trench pixels in a strip-like configuration

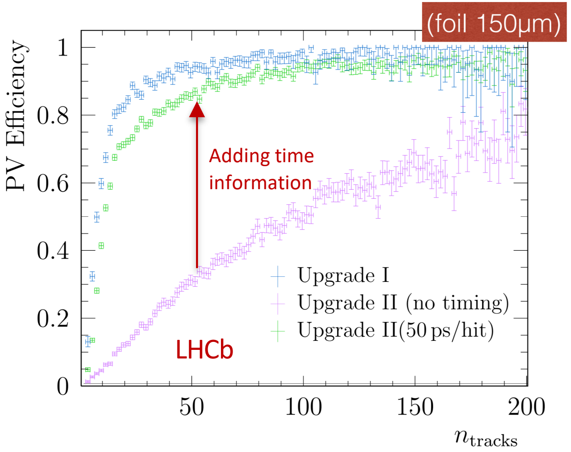
Present and future challenges in tracking

- Future and today's upgraded colliders will operate at extremely high instantaneous luminosities
  - Very important radiation damage to tracking detectors
  - Extremely difficult event reconstruction due to large pile-up: ➔ adding the time information (at the track or hit level) will help recovering tracking and vertexing capabilities
- ATLAS & CMS Phase-II upgrades (2026): mostly "traditional" tracker + single timing layer
  - $\sigma_t \approx 30$ ps, $\sigma_s \approx 100\text{-}300$ µm
  - F ≈ 10^{15} 1 MeV n_{eq}/cm^2
  - Approaching production phase
- LHCb Upgrade-2 (2030s): time information on each pixel
  - $\sigma_t = 30\text{-}50$ ps per hit (pixel) → 10-20 ps per track
  - $\sigma_s \approx 10$ µm (pixel pitch 40-50 µm)
  - F = 10^{16} 1 MeV n_{eq}/cm^2 to 10^{17} 1 MeV n_{eq}/cm^2
- FCC-hh (2040s ?): further improve the radiation hardness
  - (Numbers still under discussion)
  - $\sigma_t = 10\text{-}20$ ps per hit (pixel) → 5-10 ps per track
  - $\sigma_s \approx 10$ µm (pixel pitch 40-50 µm)
  - F = 10^{17} 1 MeV n_{eq}/cm^2 to 10^{18} 1 MeV n_{eq}/cm^2



Adding the track time information





LHCb upgrade-2 Workshop, March 2020

Spatial resolution, time precision and radiation hardness are required at the same time!

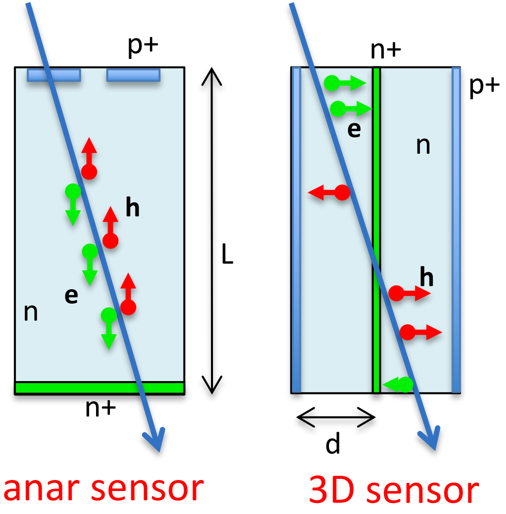
What’s on the market today?

Technology	Space [μm]	Time [ps]	Radiation hardness [1 MeV n_{eq}/cm^2]
LGAD	**≈ 100-300 (traditional)** (1) **10-100 (LGAD^{++})** (4–7)	50-20 (2,3)	5x10^{15} (2,3)
MAPS **(Si-Ge BiCMOS)**	**100** (8)	**50** (6)	**Untested: expected ~10^{15} in CMOS MAPS**
3D	**~15** (9)	**20** (9)	**> 10^{17} (10)** Very promising!

References

1) N. Cartiglia et al., Design optimization of ultra-fast silicon detectors, Nuclear Instruments and Methods A796(2015) 141
2) Y. Zhao et al., Comparison of 35 and 50 μm thin HPK UFSD after neutron irradiation up 6 × $10^{15} n_{eq}/cm^2$, NIM A924(2019) 387 , 11th International Hiroshima Symposium on Development and Application of Semiconductor Tracking Detectors
3) H. F.-W. Sadrozinski et al., Ultra-fast silicon detectors (UFSD), NIM A: 831(2016) 18, Proceedings of the 10th International “Hiroshima” Symposium on the Development and Application of Semiconductor Tracking Detectors
4) M. Ferrero et al., Evolution of the design of Ultra-Fast Silicon Detector to cope with high irradiation fluences and fine segmentation, JINST 15(2020) C04027
5) S. Hidalgo et al., New iLGAD detector development at CNM, 26th RD50 Workshop, Santander, 23th June 2015
6) M. Mandurrino et al., Analysis and numerical design of resistive AC-coupled silicon detectors (RSD) for 4D particle tracking, NIM A: 959(2020)
7) N. Cartiglia and M. Mandurrino, Innovative silicon sensors for future trackers, CERN Detector Seminar, June 5th 2020, https://indico.cern.ch/event/915984/
8) G. Iacobucci et al., A 50 ps resolution monolithic active pixel sensor without internal gain in SiGe BiCMOS technology, 2019 JINST 14 P11008
9) L. Anderlini et al., Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection, JINST 082 P0420 (2020), arXiv:2004.10881
10) M. Manna et al., First characterization of 3D pixel detectors irradiated at extreme fluences, NIMA, 979 (2020) 164458, https://doi.org/10.1016/j.nima.2020.164458

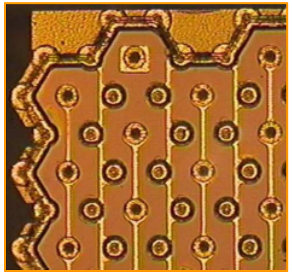
Why 3D sensors?

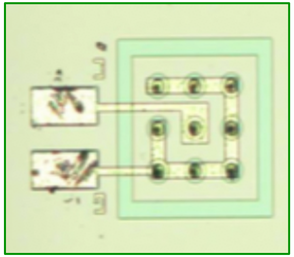


- Original idea: S. Parker, 1997

- Key points
  - Short inter-electrode drift distance (tens of µm): extremely fast signals (d<<L)
  - Active volume and electrode shape can be designed for maximum performance
  - Unmatched radiation hardness (> 10^{17} 1MeV n_{eq}/cm^2), NIMA, 979 (2020) 164458
  - Largely immune to Landau fluctuation by geometry
  - 3D columnar geometry is today a production-ready technology (ATLAS IBL, ATLAS-P2)

- Timing performances
  - S. Parker et al., IEEE TNS 58(2) (2011), 404
    - Column hexagonal geometry, 50µm pitch, 20V bias
    - Tested under ^{90}Sr beta source @ room temperature
    - Time resolution: 31-177ps (depending on signal amplitude)
    - Limited by front-end electronics noise
  - G. Kramberger et al., NIMA 934 (2019), 26
    - Square geometry, side = 50 µm , 300 µm thick, 50 V bias
    - Tested under ^{90}Sr beta source @ room temperature
    - Time resolution of ~75ps, dominated by hit position inside cell
    - New tests (TREDI 2020 Workshop) with ^{106}Ru source indicate an improved timing resolution of about 40 ps





TimeSPOT in a glance

TIME and SPace real-time Operating Tracker

- 4 years INFN R&D program (2018-21)

- Develop innovative 3D pixel sensors + readout system
  - Space resolution: O(10µm)
  - Radiation hardness: $>10^{16}$ 1 MeV n_{eq}/ cm^2 (sensors) and >1Grad (electronics)
  - Time resolution: ≤ 50ps per pixel
  - Limited power per FE channel, O(10µW)
  - Real time track reconstruction algorithms and fast read-out (data throughput > 1 TB/s)

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

- Activities are organized in 6 work packages – PI: Adriano Lai / INFN Cagliari:
  - 3D silicon sensors: development and characterization (resp. G-F Dalla Betta, Trento)
  - 3D diamond sensors: development and characterization (resp. S. Sciortino, Firenze)
  - Design and test of pixel front-end (resp. V. Liberali, Milano)
  - Design and implementation of real-time tracking algorithms (resp. N. Neri, Milano)
  - Design and implementation of high-speed readout boards (resp. A. Gabrielli, Bologna)
  - System integration and tests (resp. A. Cardini, Cagliari)

- 10 Italian Institutes: Bologna, Cagliari, Genova, Ferrara, Firenze, Milano, Padova, Perugia, Torino, TIFPA, approximately 60 persons and 25 FTE from LHCb, ATLAS, CMS + other activities

In synergy with:

ATTRACT
INSTANT

ATTRACT program Phase-1
Cagliari, Manchester,
Milano, Trento, FBK

The time resolution

- At a first order *simplified analysis* the following terms contribute to the time resolution σ_t of a silicon detector (with no internal gain but with its front-end) when measuring the time of arrival of a high-energy charged particle:

$$\sigma_t = \sqrt{\sigma_{tw}^2 + \sigma_{dr}^2 + \sigma_{un}^2 + \sigma_{ej}^2 + \sigma_{TDC}^2}$$

physics

  - σ_{tw} = jitter due (average) event-by-event fluctuations of the signal amplitude, the so-called time walk
  - σ_{dr} = jitter due to delta rays, which do not only give an event-by-event charge fluctuation but, since they could be created at different depths, this could also result in signal shape variations

detector

  - σ_{un} = jitter due to the non-uniformities in the weighting field and carrier velocities inside the detector sensitive unit, which modifies the signal shape on an event-by-event basis

electronics

  - σ_{ej} = jitter due to the analog noise of the preamplifier used to readout the sensor
  - σ_{TDC} = jitter due to the digital resolution of the electronics used to measure the signal

Limits to the time resolution of a 3D sensor

$$\sigma_t = \sqrt{\sigma_{tw}^2 + \sigma_{dr}^2 + \sigma_{un}^2 + \sigma_{ej}^2 + \sigma_{TDC}^2}$$

- $\cancel{\sigma_{tw}}$: the time-walk effect can be eliminated by triggering at a constant fraction of the signal amplitude
- $\cancel{\sigma_{dr}}$: negligible in a 3D sensor since all the charge deposits created at various depths contribute in the same way at the total signal because the charge collection occurs in a direction which is perpendicular to the charged particle path (and in general to the delta-rays produced)
- σ_{un} : non-uniformities in the weighting field and charge carrier velocities inside the detector sensitive unit give the ultimate limit on the time resolution that can be achieved with a 3D sensor (if the information on the point of impact on the detector sensitive unit is not know or no correction is applied)
- σ_{ej} : the analog noise of the preamplifier limits the sensor's time resolution, scales as $\sim \frac{\sigma_{noise}}{Amplitude}$
- $\cancel{\sigma_{TDC}}$: an adequate TDC will make this term negligible

$$\boxed{\sigma_t \cong \sqrt{\sigma_{un}^2 + \sigma_{ej}^2}}$$

Toward an optimized 3D sensor design

- σ_{un}

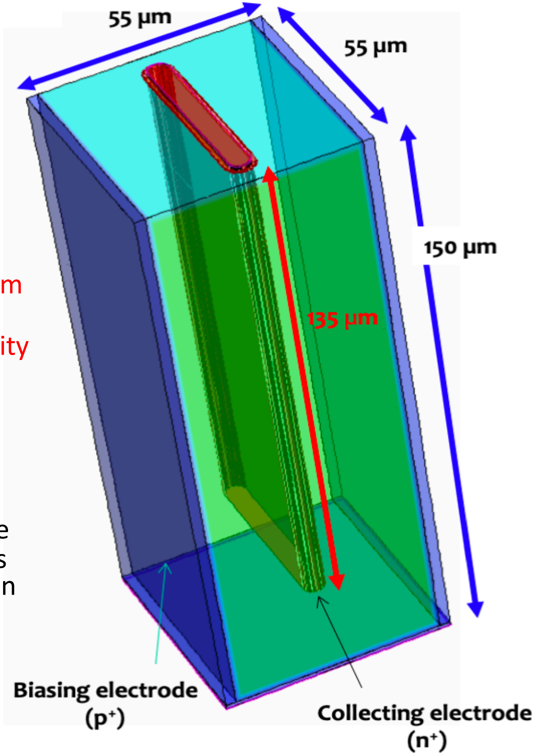
  Ramo: the detector signal is produced by the drift of the charge carriers created along the path of the (charged) particle across the pixel volume, which creates an instantaneous current i defined as

  $$i = q\,\vec{E}_w \cdot \vec{v}_d$$

  where $\vec{E}_w$ is the weighting field and $\vec{v}_d$ is the carrier's drift velocity. A detector where $\vec{E}_w \cdot \vec{v}_d$ is as uniform as possible inside the charge drift volume will create signals that do not depend on where the charged particle has crossed the detector. So one needs to (1) make $\vec{E}_w$ uniform by design and (2) work in a velocity saturation regime

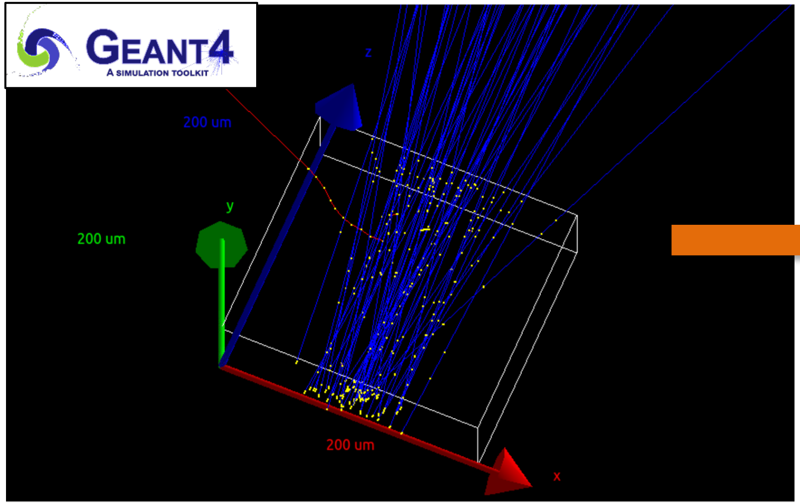
- σ_{ej}

  To fully exploit the sensor's capabilities one needs to reduce the front-end amplifier noise (e.g. reduce the pixel capacitance – we assume here that we cannot increase the signal: increasing the sensor's thickness is not an option because of multiple scattering, radiation length consideration, and there is no internal gain in our pixels)

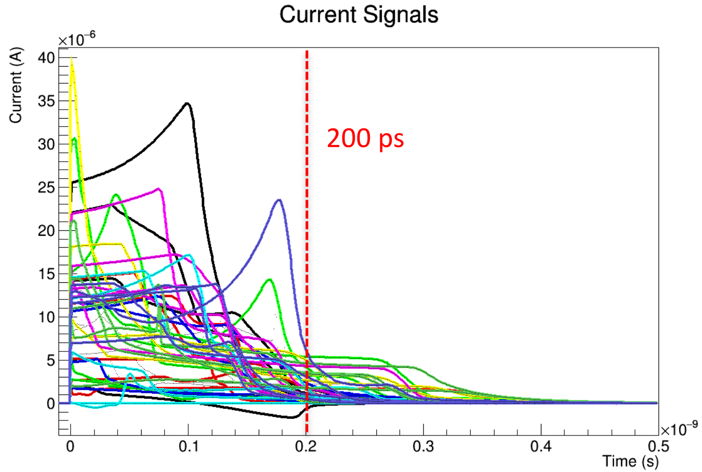


➔ TimeSPOT 3D trench-type silicon pixel detectors

Simulation-aided sensor design



TCoDE
TimeSPOT Code for Detector simulation

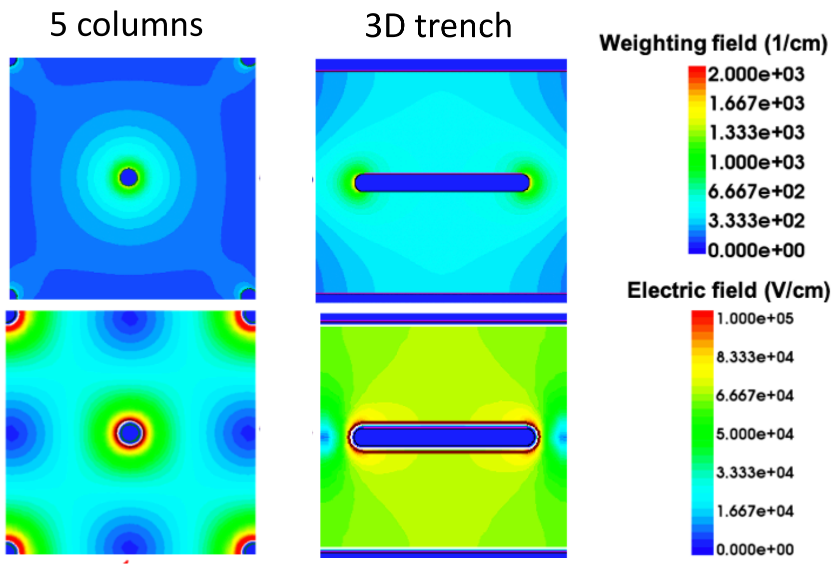


An essential tool for sensor design and optimization

- GEANT4 generated dE/dx deposits in silicon
- Electric, Weighting and Velocity pixel field maps from TCAD Sentaurus
- Carrier dynamics from TCODE custom multithread code (https://github.com/MultithreadCorner/Tcode)

Comparison between 3D geometries

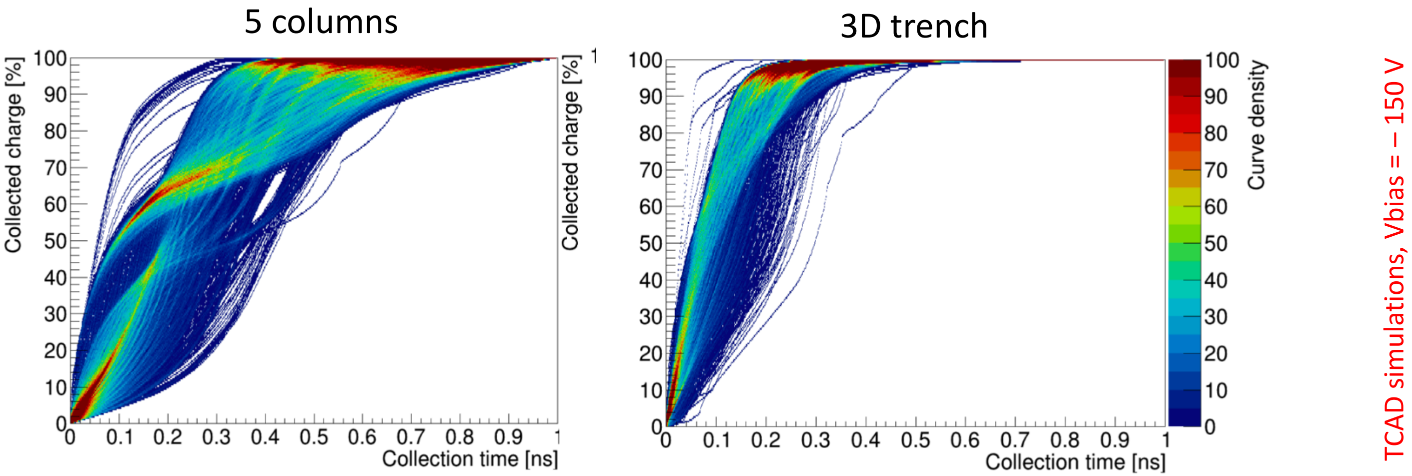
$$i = q\,\vec{E}_w \cdot \vec{v}_d$$



TCAD simulations, Vbias = – 150 V

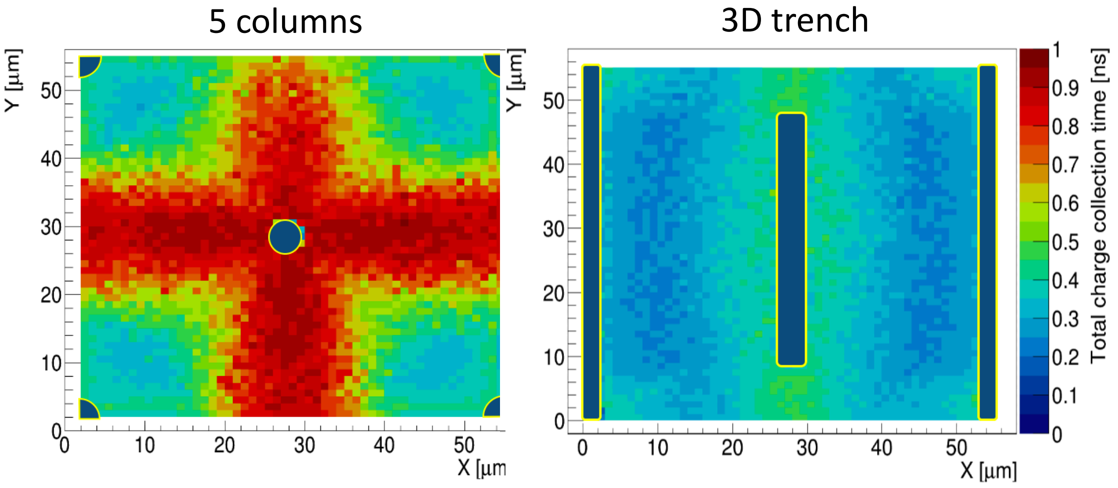
- Simulated weighting field and velocity maps are much more uniform in the trench geometry - both in magnitude and direction - thanks to the vertical “planar” design
- This is essential to guarantee, via Ramo theorem, <u>signals which are largely independent on where the charged particles crossed the detector</u>

Comparison between 3D geometries



- Simulated charge collection curves for 3000 minimum ionizing particles uniformly crossing a pixel over its active area, in two different 3D pixel geometries, obtained with our simulation
- Shorter and much more uniform charge collection time for the 3D trench geometry

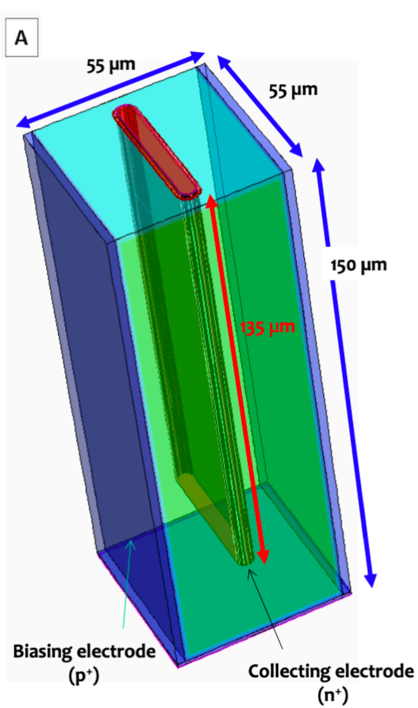
Comparison between 3D geometries

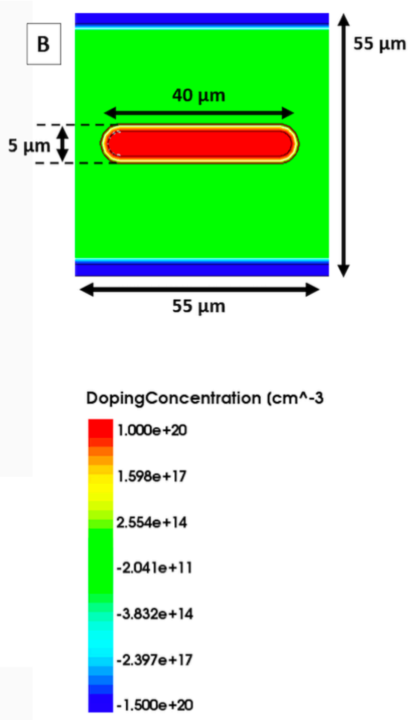


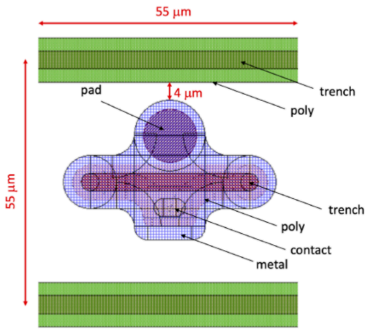
TCAD simulations, Vbias = – 150 V

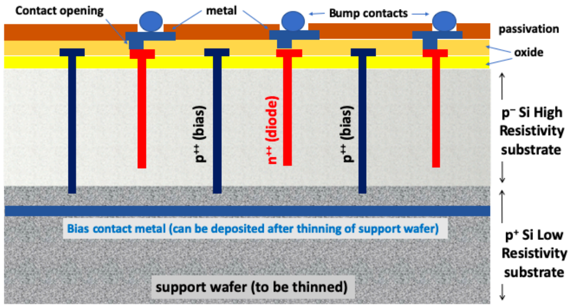
- The time for total charge collection varies strongly as a function of the particle impact point on the pixel in the 5 columns geometry
- <u>This dispersion will strongly affect the overall pixel time resolution</u>
- The ”planar” trench design provides a very fast and uniform charge collection time

The trench-type TimeSPOT 3D pixels





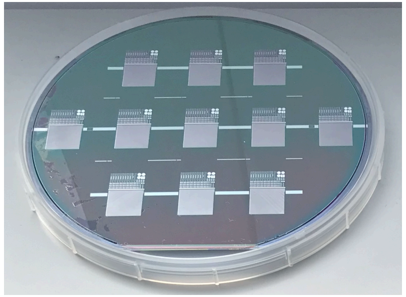


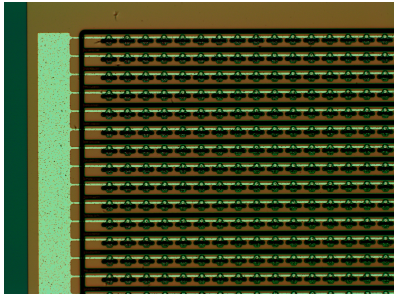


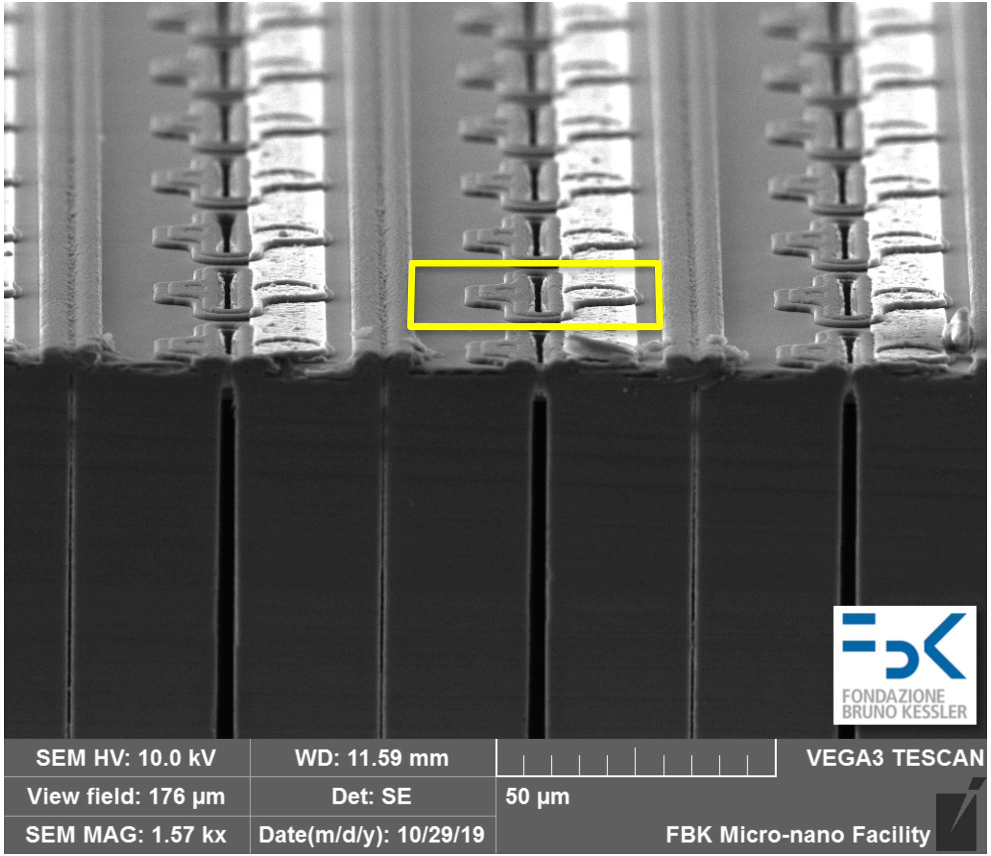
- 55µm x 55µm pixels (to be compatible with existing FEE, for example the Timepix family)
- In each pixel a 40µm long n++ trench is placed between continuous p++ trenches used for the bias
- 150µm-thick active thickness, on a 350µm-thick support wafer
- The collection electrode is 135µm deep

The TimeSPOT 3D sensors fabrication

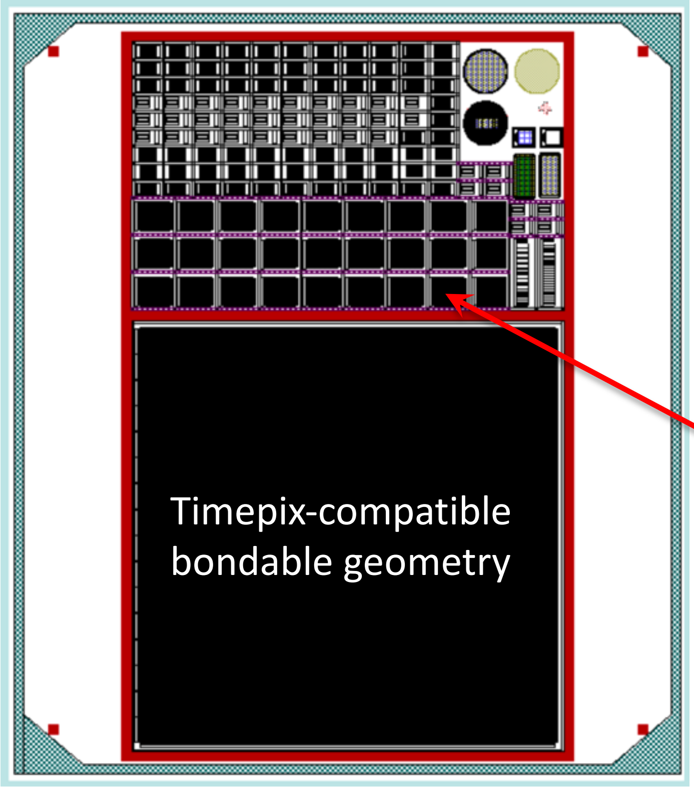
- Single sided (Si-Si) process with a support wafer
- First batch produced in 2019 at Fondazione Bruno Kessler (FBK, Trento, Italy) using the Deep Reactive Ion Etching Technique (DRIE) Bosch process, 10 x 6” wafers
- High aspect ratios (30:1) and good dimensional uniformity
- Photolithography performed with a stepper machine:
  - Minimum feature size 350nm
  - Alignment accuracy 80nm
  - Maximum exposure area 2x2cm^2
- Many devices were designed and fabricated (single, double pixels, 10 pixel-strips, 18x18 and 256x256 pixel matrices, …)



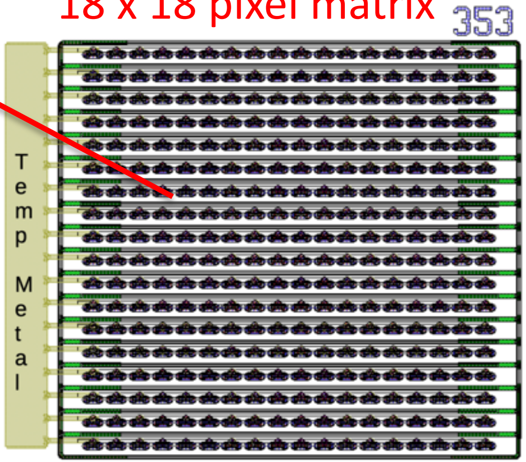


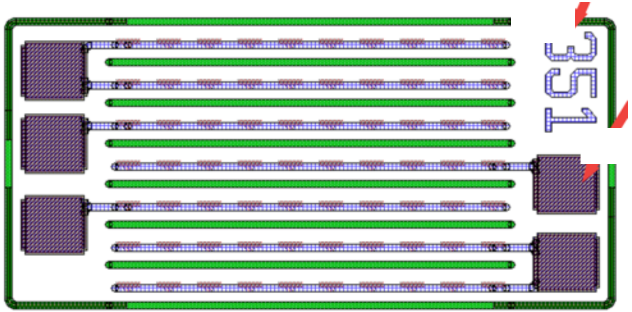


TimeSPOT 2019 3D pixel production

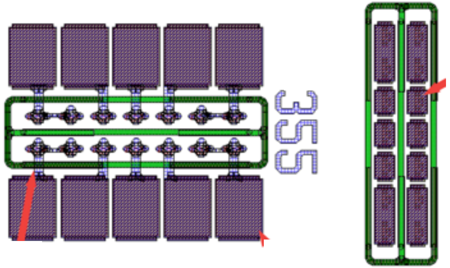


18 x 18 pixel matrix



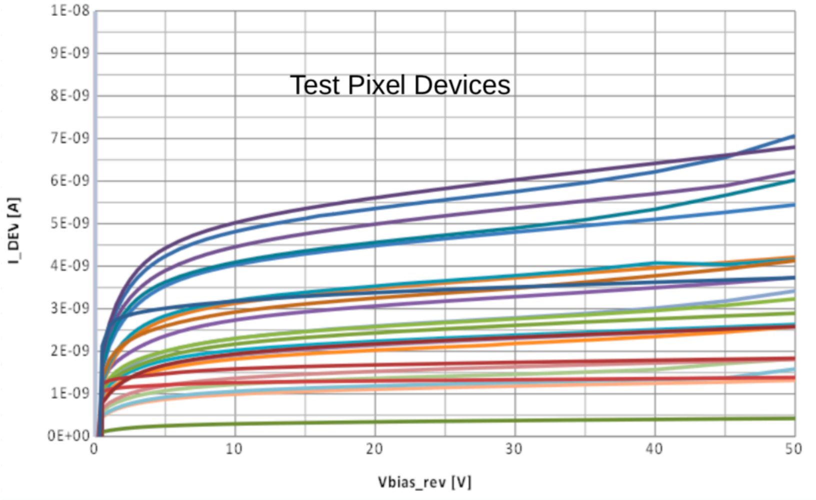


Pixel-strips

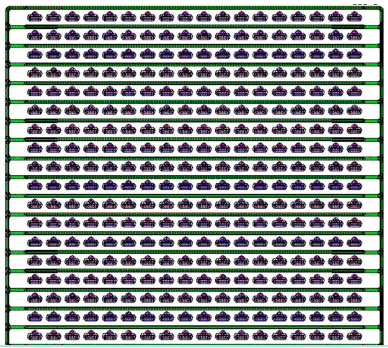


Single- and double-pixels

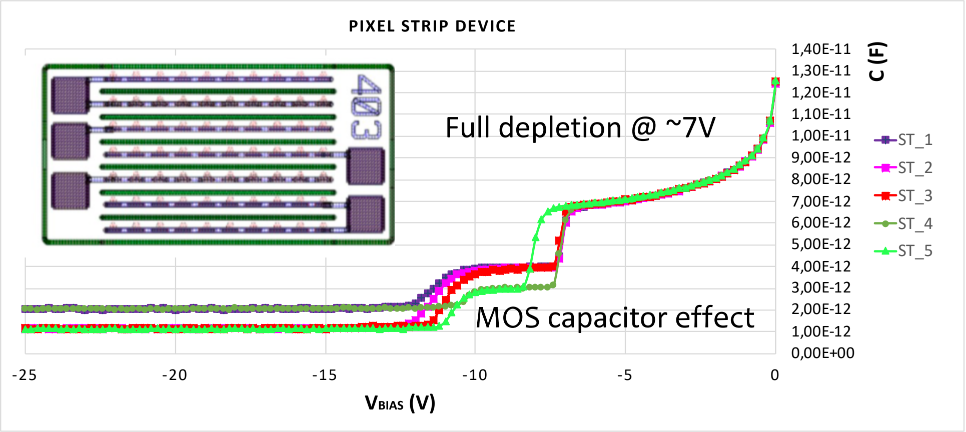
First batch DC electrical characterization



<u>IV-curves</u> on 18x18 pixel matrices (pixels connected with temporary metal): ~10 pA/pixel – good!



Measured <u>capacitance</u> ~100 fF/pixel, in agreement with simulation

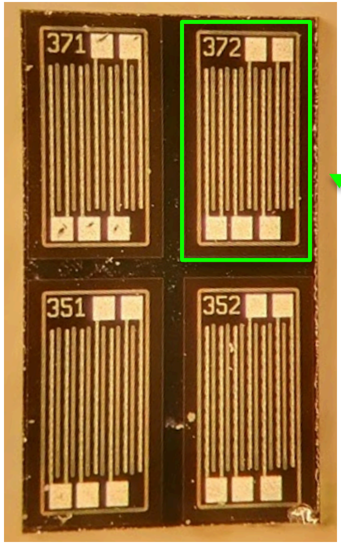


Full depletion @ ~7V

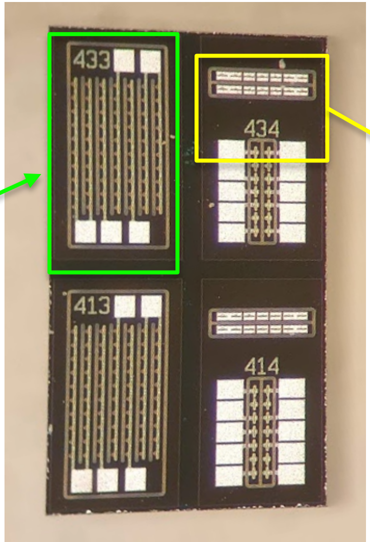
MOS capacitor effect

3D structures “dynamically” tested in 2019

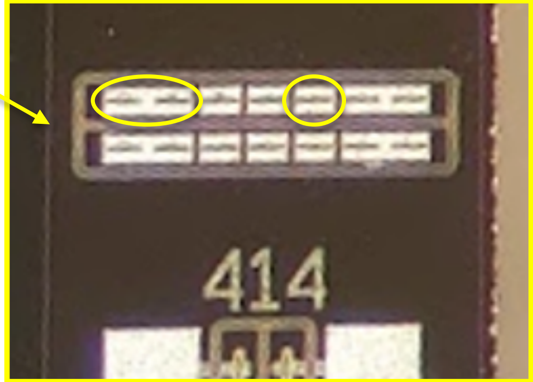
We characterize single- and double-pixels, and pixel-strip (10 pixels) test structures, connected to custom-made front-end electronics, both with beam and under a pulsed IR laser



Pixel-strips (10 or 20 pixels shorted together)

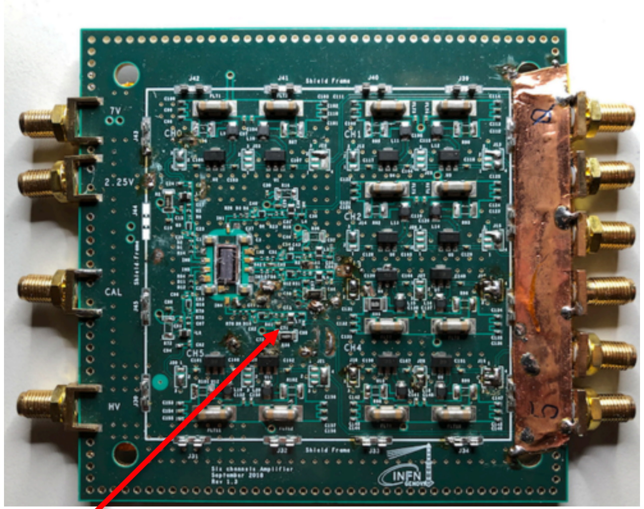


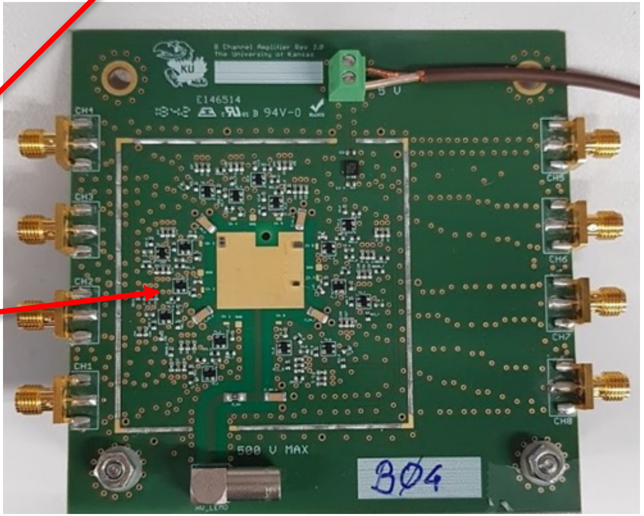
Double and single pixel



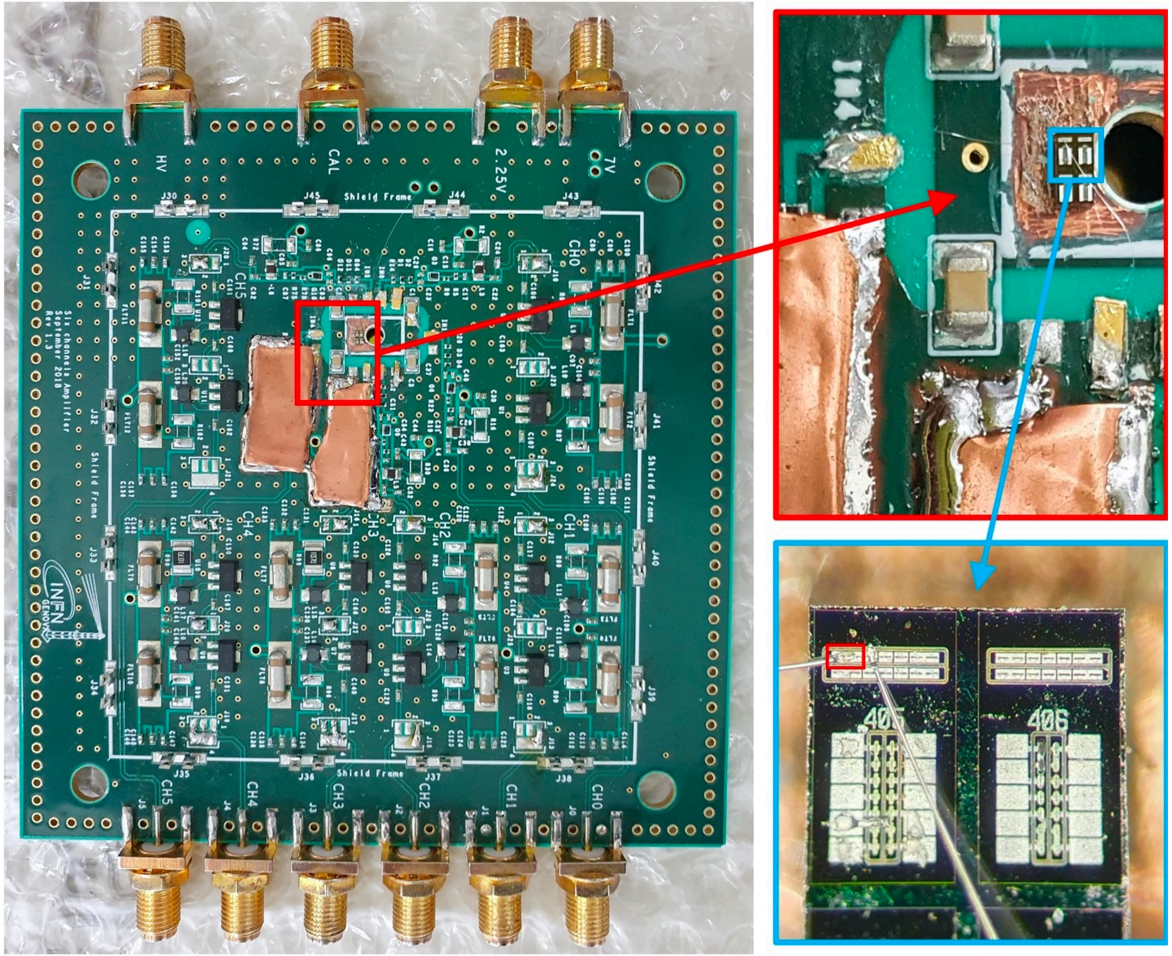
The FEE used for 2019 tests

- We used high-performance FEE boards for the preliminary assessment of the 3D sensors
- Discrete component FEE with a few analog channels, borrowed from various ongoing activities
- Both are transimpedence designs with fast SiGe BJTs: to fully exploit the sensor speed one needs to readout the sensor's current
- Type 1: single stage SiGe BJT + external 4 GHz broad-band amplifier
- Type 2: two stages SiGe BJT



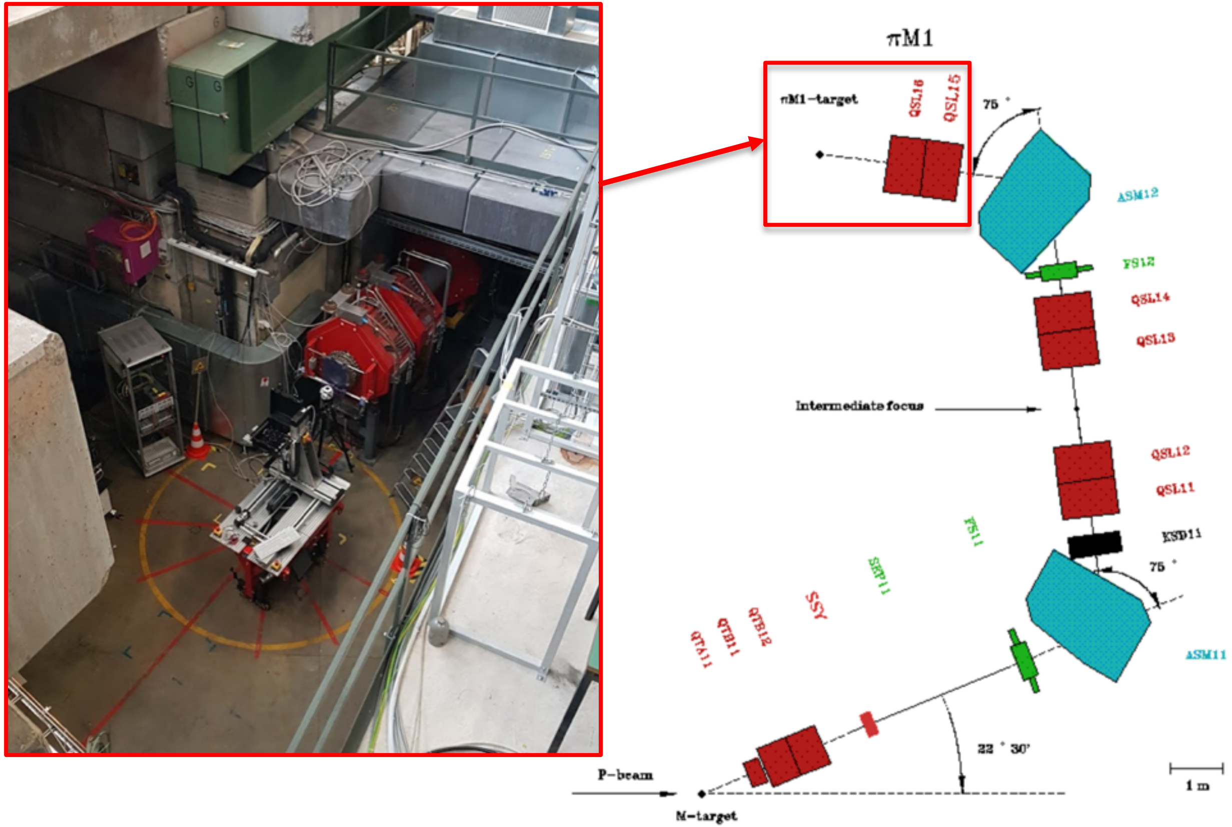


Type 1 board, featuring a double-pixel, prepared for the 2019 beam test

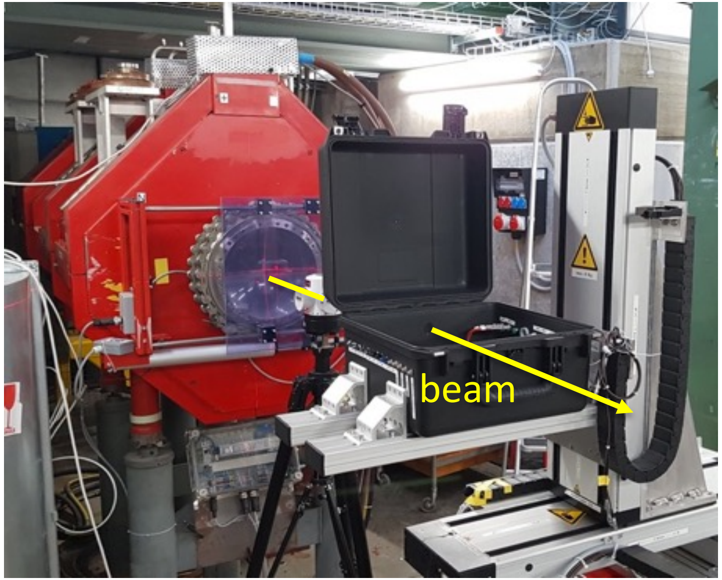


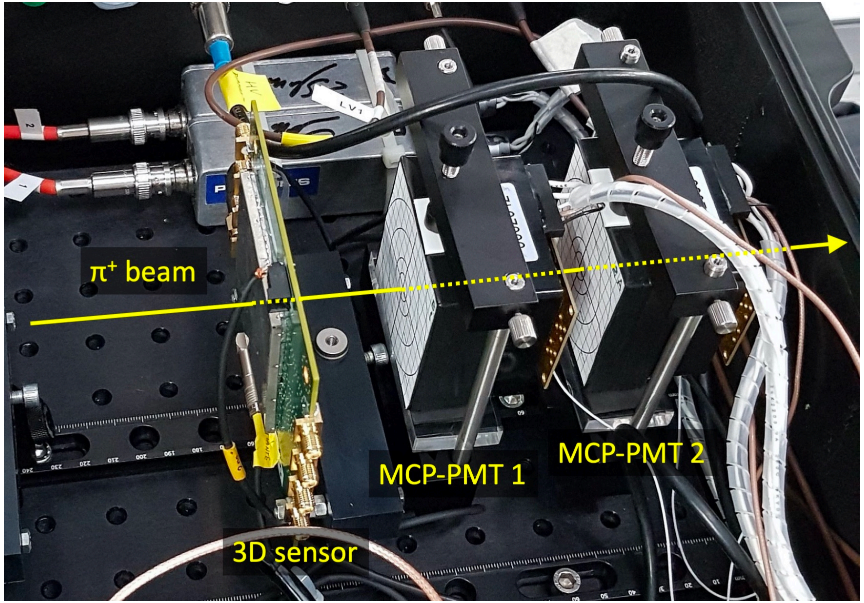
2019 PSI πM1 beam test

- Secondary pion beam: π^+ beam, small contamination from p, e^+, μ^+
- High-resolution beamline, $\Delta p/p \sim 0.1\%$
- Momentum: 100-500 MeV/c
- Nominal spot size: 10mm (15mm) vertical (horizontal)
- We used 270 MeV/c π^+, which are only 6% more ionizing than MIPs

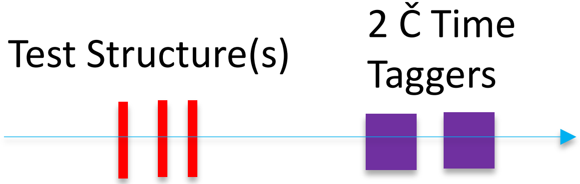


The PSI Setup

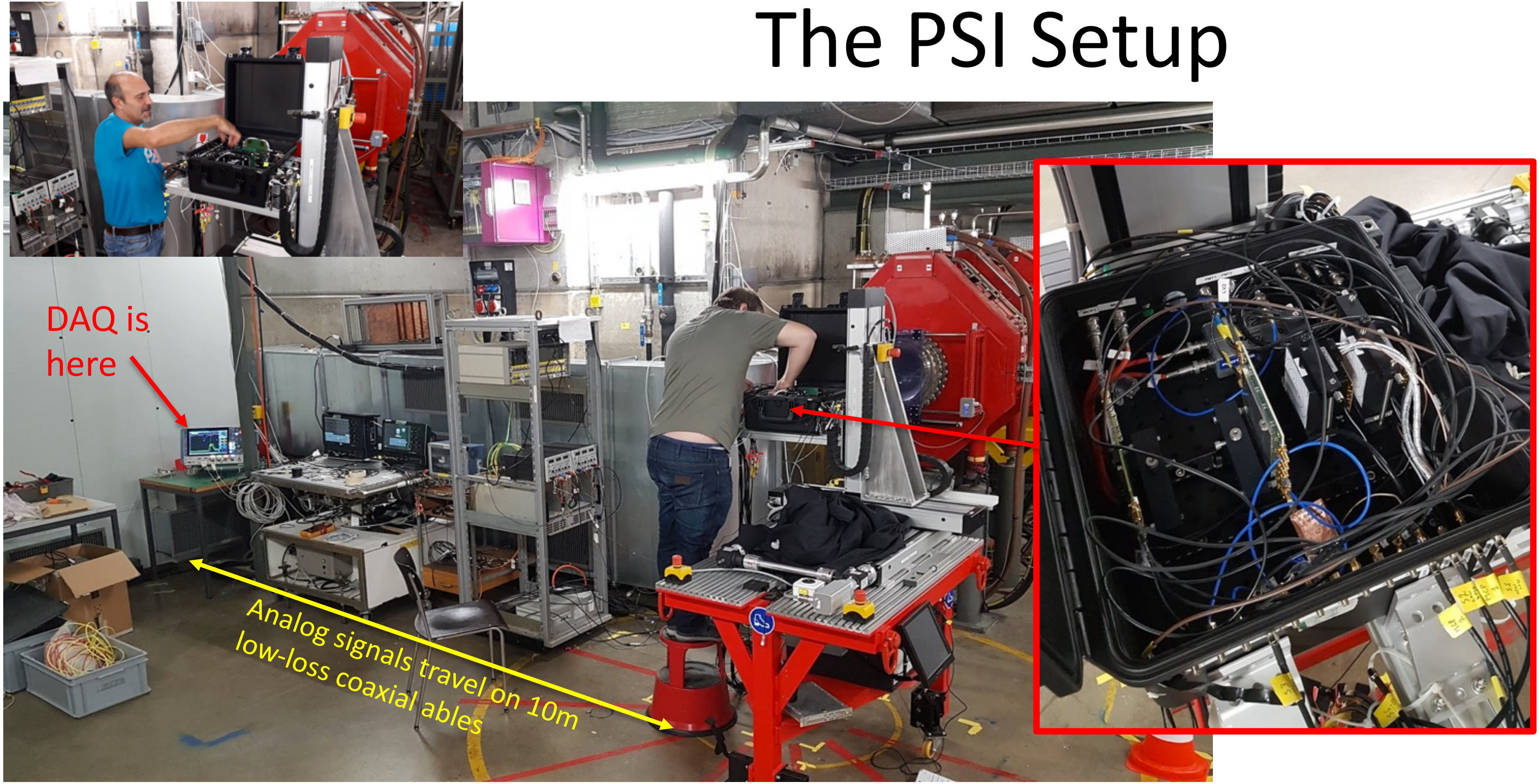




- All installed in light-tight black plastic box
- Box mounted on the XYZ moving system



The PSI Setup

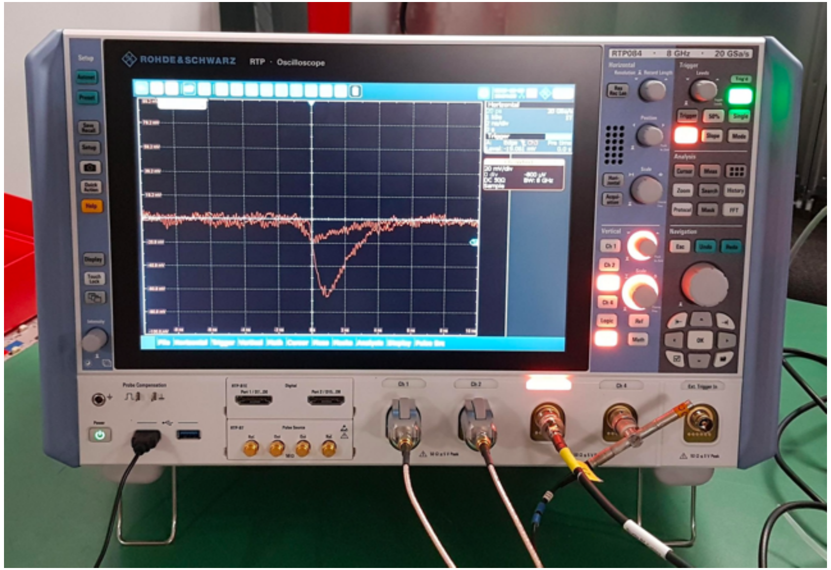


DAQ is here

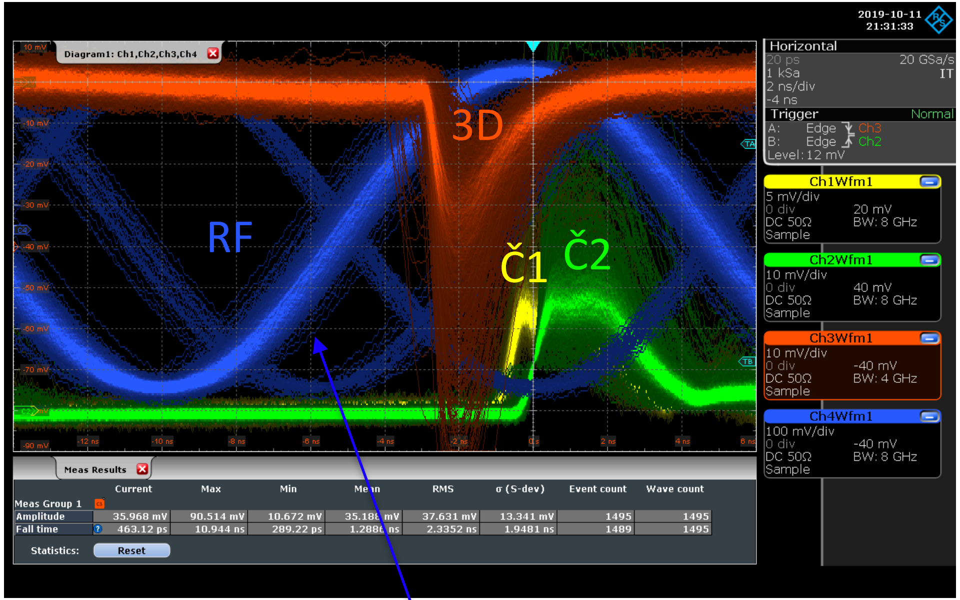
Analog signals travel on 10m low-loss coaxial ables

Thank you R&S for lending us this great oscilloscope!

The DAQ



The 4 acquired signals



2019-10-11
21:31:33

Horizontal
20 ps 20 GSa/s
1 kSa IT
2 ns/div
-4 ns

Trigger Normal
A: Edge Ch3
B: Edge Ch2
Level: 12 mV

Ch1Wfm1
5 mV/div
0 div 20 mV
DC 50Ω BW: 8 GHz
Sample

Ch2Wfm1
10 mV/div
0 div 40 mV
DC 50Ω BW: 8 GHz
Sample

Ch3Wfm1
10 mV/div
0 div -40 mV
DC 50Ω BW: 4 GHz
Sample

Ch4Wfm1
100 mV/div
0 div -40 mV
DC 50Ω BW: 8 GHz
Sample

Meas Results

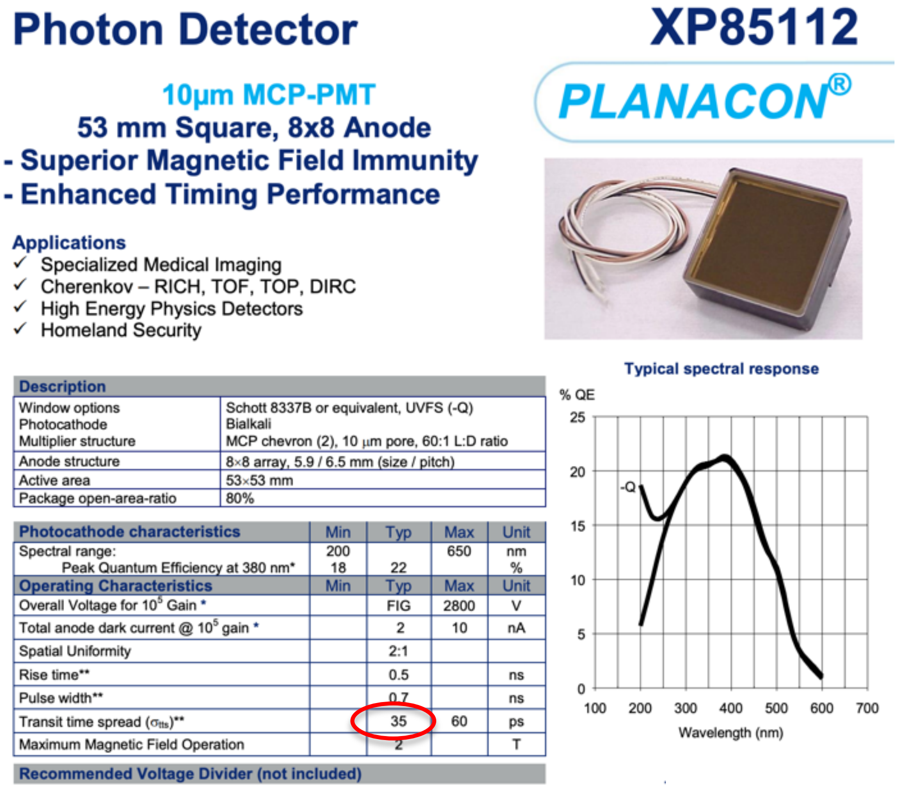
Meas Group 1	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Amplitude	35.968 mV	90.514 mV	10.672 mV	35.188 mV	37.631 mV	13.341 mV	1495	1495
Fall time	463.12 ps	10.944 ns	289.22 ps	1.2886 ns	2.3352 ns	1.9481 ns	1489	1495

Statistics: Reset

Signal from accelerator RF phase used for PID

- R&S RTP084 8 GHz Oscilloscope, 20 GSa/s
- 10m LLC200 low-loss cables to sensors and PMTs

Cherenkov Time Tagger



Photon Detector

XP85112

PLANACON®

10µm MCP-PMT
53 mm Square, 8x8 Anode
- Superior Magnetic Field Immunity
- Enhanced Timing Performance

Applications
- ✓ Specialized Medical Imaging
- ✓ Cherenkov – RICH, TOF, TOP, DIRC
- ✓ High Energy Physics Detectors
- ✓ Homeland Security

Description	
Window options Photocathode Multiplier structure	Schott 8337B or equivalent, UVFS (-Q) Bialkali MCP chevron (2), 10 µm pore, 60:1 L:D ratio
Anode structure	8×8 array, 5.9 / 6.5 mm (size / pitch)
Active area	53×53 mm
Package open-area-ratio	80%

Photocathode characteristics	Min	Typ	Max	Unit
Spectral range:	200		650	nm
Peak Quantum Efficiency at 380 nm*	18	22		%
Operating Characteristics	**Min**	**Typ**	**Max**	**Unit**
Overall Voltage for 10^5 Gain *		FIG	2800	V
Total anode dark current @ 10^5 gain *		2	10	nA
Spatial Uniformity		2:1		
Rise time**		0.5		ns
Pulse width**		0.7		ns
Transit time spread (σ_{tts})**		35	60	ps
Maximum Magnetic Field Operation		2		T

Recommended Voltage Divider (not included)

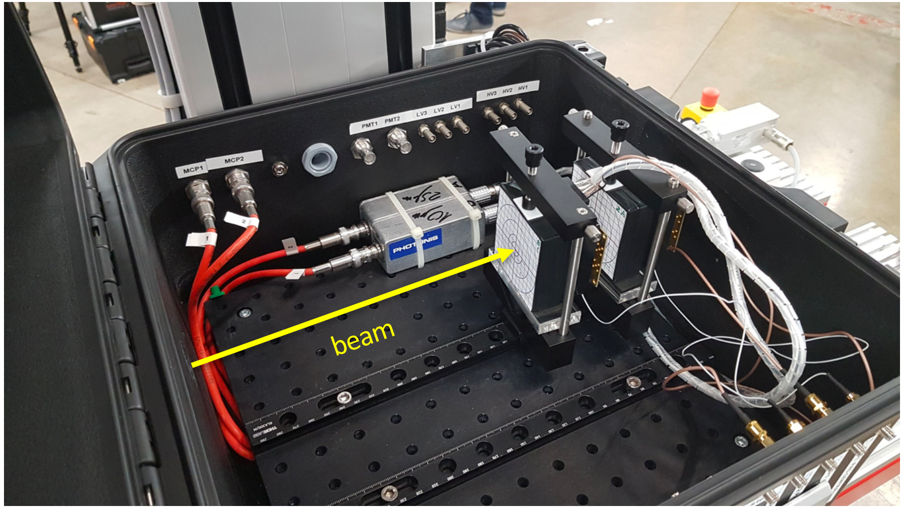
Typical spectral response

- Cherenkov detectors

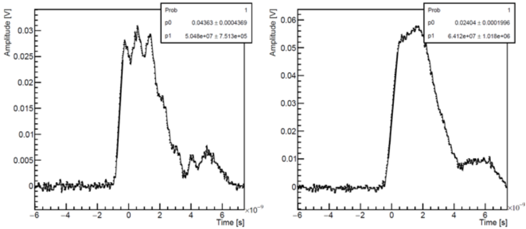
- Two Planacon MCP-PMTs, XP85112 (10µm pores) and XP85012 (6µm pores) *N.B.: not the optimal choice but we had those 2 PMTs in the lab. - thank you Richard Wigmans for lending us these two PMTs!*

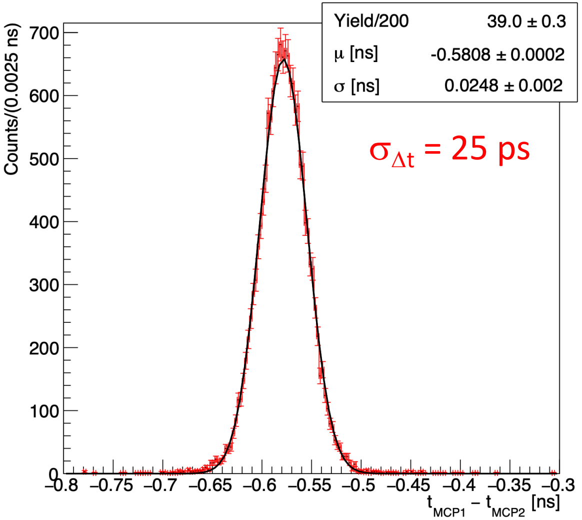
- Quartz radiators, 20mm thick

Time Tagger: performance with beam



Typical waveforms recorded from the two MCP-PMTs (common electrode)

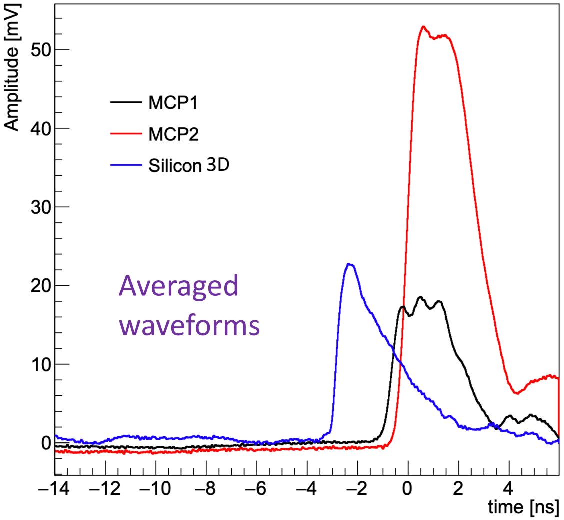




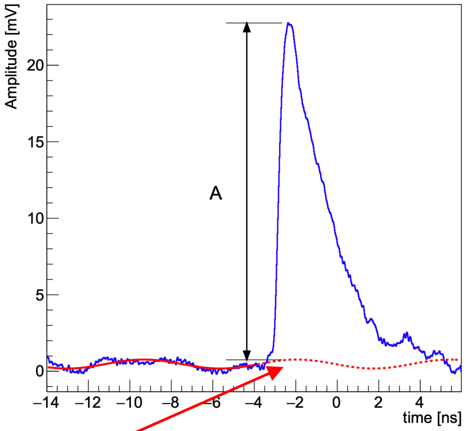
$\sigma_{\Delta t}$ = 25 ps

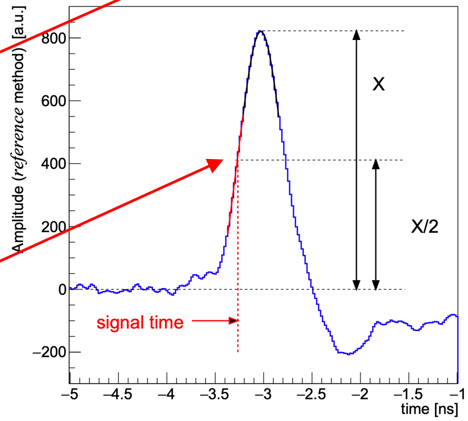
- Particle arrival time is estimated with a software constant-fraction method applied to the acquired waveforms
- The time difference between the two MCP-PMTs has a jitter of about 25 ps
- Since we will use both MCP-PMTs and evaluate the average time which we then use as reference, we estimate a time-tagger accuracy of ~12ps

3D pixel waveforms data analysis

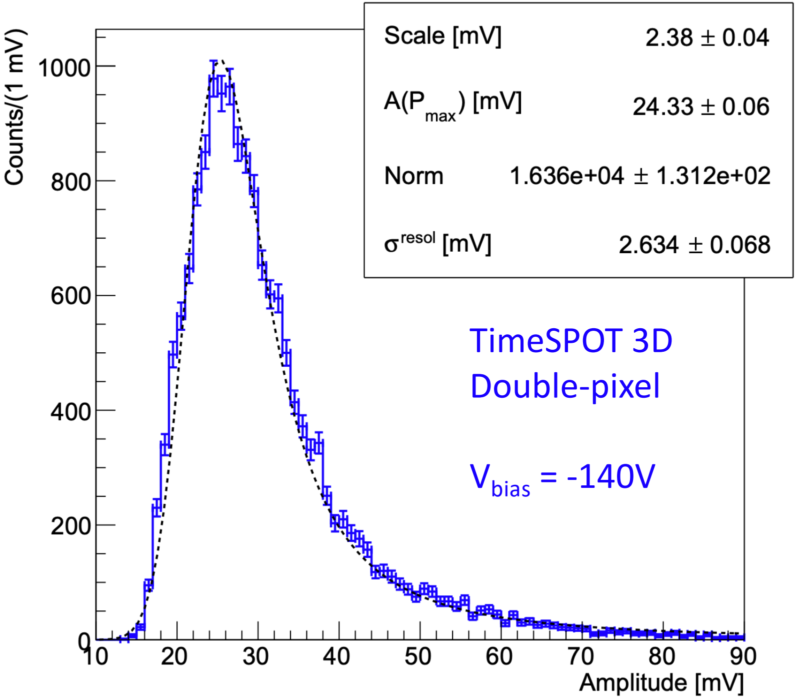


Averaged waveforms



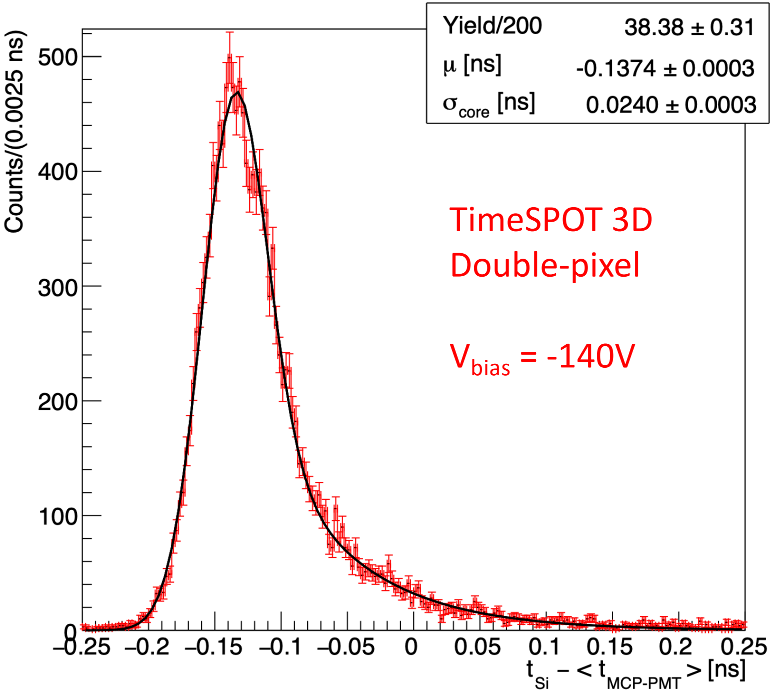


- <u>For each sensor's waveform:</u>
  - Signal baseline (red-dashed line) is evaluated on an event-by-event basis
  - The signal amplitude A is measured (w.r.t. to the baseline of every event)
  - *<u>Reference method</u>*: subtract each waveform from a delayed (by ~½ of the signal rise time) copy of itself, then on the resulting signal we trigger at X/2 height



Amplitude distribution

- Fit with Landau + gaussian noise
- No losses at small amplitudes due to trigger conditions
- Landau shape is in agreement with what is expected for a 150µm-thick Si sensor

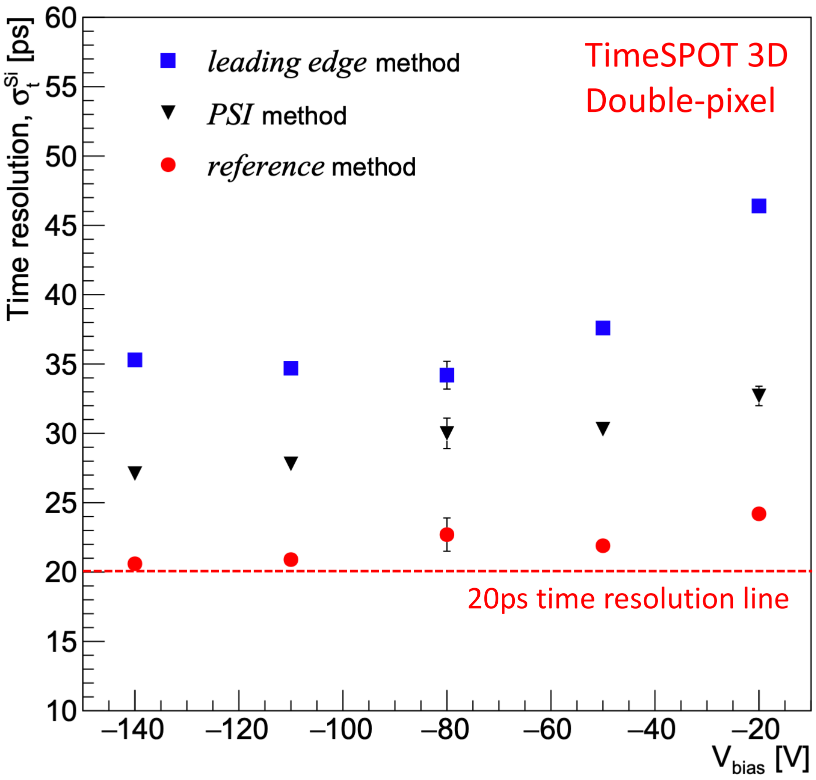


3D sensor signal delay w.r.t to time-tagger time

- Fit with gaussian core + exponential tail (*a tail of late signals is indeed expected from simulation*)
- Gaussian core: $\boxed{\sigma_t = 24.0 \pm 0.3\ ps}$

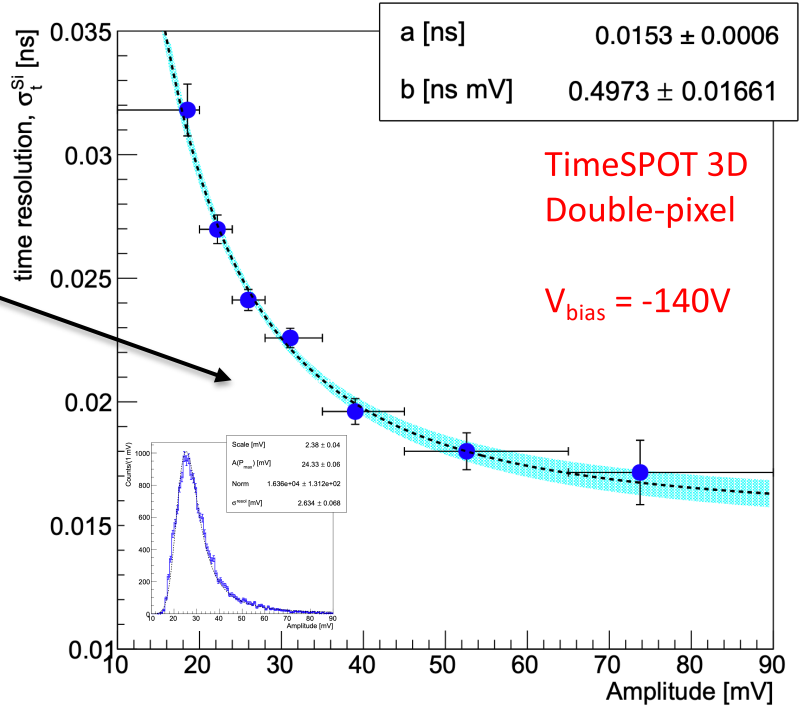
Summary of time resolution measurements

- The 3D pixel time resolution is measured at various sensor's biases by *subtracting (in quadrature) the time-tagger jitter:*
  - Best results with the previously described method (*Reference*)
  - Traditional Constant Fraction Discriminator @ 35% (called *PSI* in the plot) gives slightly worse results
  - A simple *leading-edge* triggering, with no correction for the time-walk, gives, somehow unexpectedly, *surprisingly good results*

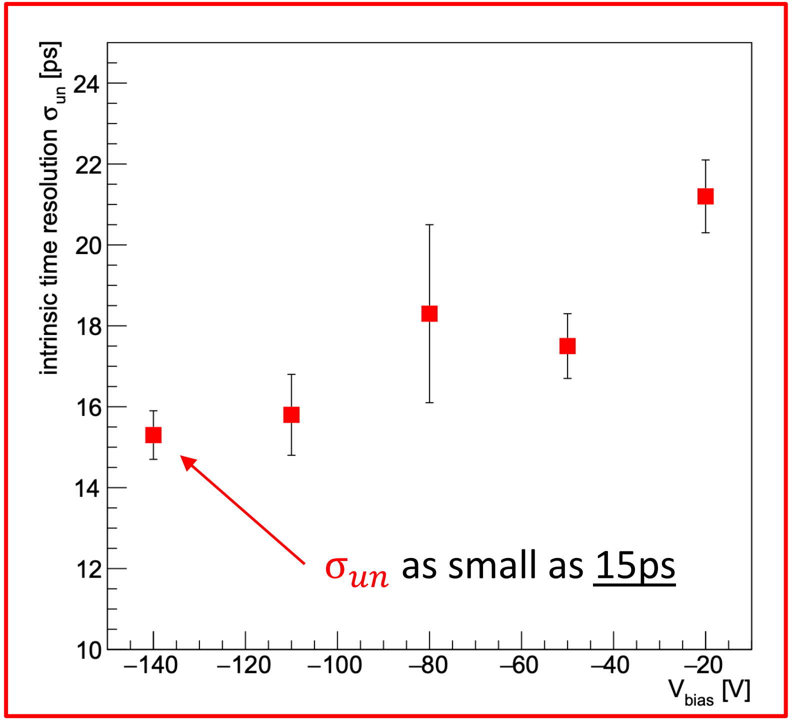


Intrinsic sensor’s time resolution

- Measured time resolution vs. signal amplitude
- Scales as $\sigma_t = \sqrt{(a^2 + \frac{b^2}{Amplitude^2})}$
- This is in agreement with what we discussed at the beginning: $\sigma_t \cong \sqrt{\sigma_{un}^2 + \underbrace{\alpha \cdot \sigma_{noise}^2/Amplitude^2}_{\sigma_{ej}^2}}$
- Following this approach:
  - a represents σ_{un}, the intrinsic limit to sensor’s timing performances
  - b/Amplitude is σ_{ej}, the contribution of the electronics noise to the time resolution

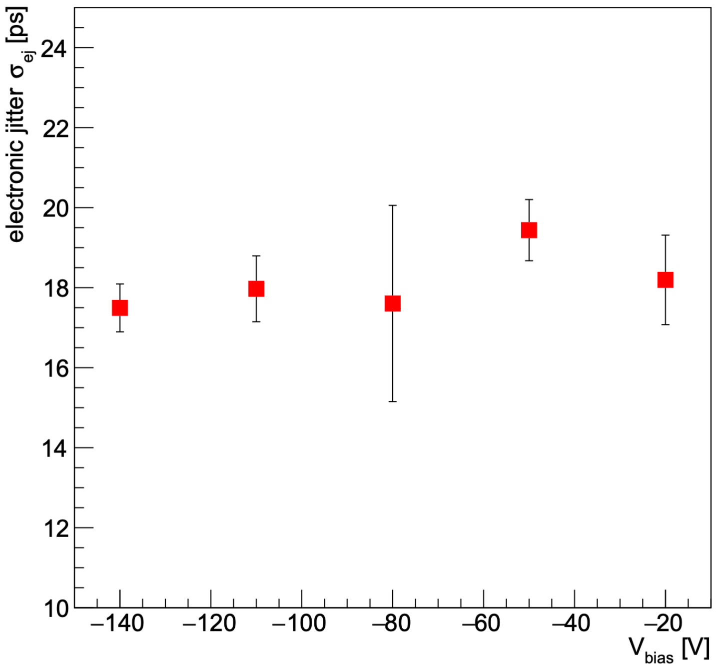


Intrinsic sensor’s time resolution



σ_{un} as small as 15ps

σ_{un} decreases with V_{bias} as expected from simulations

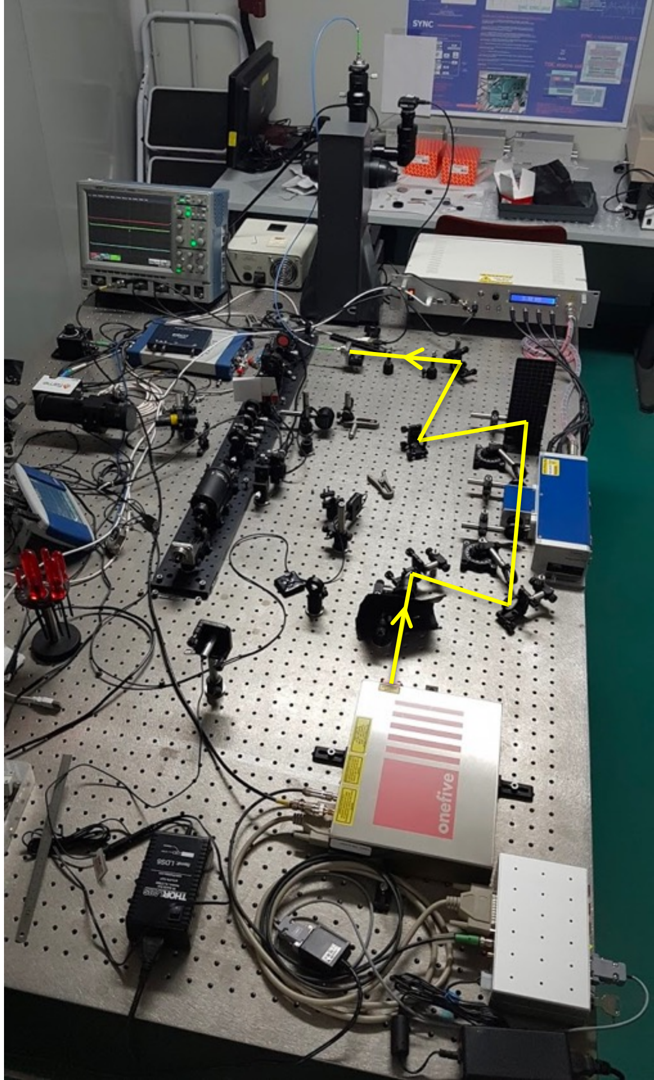


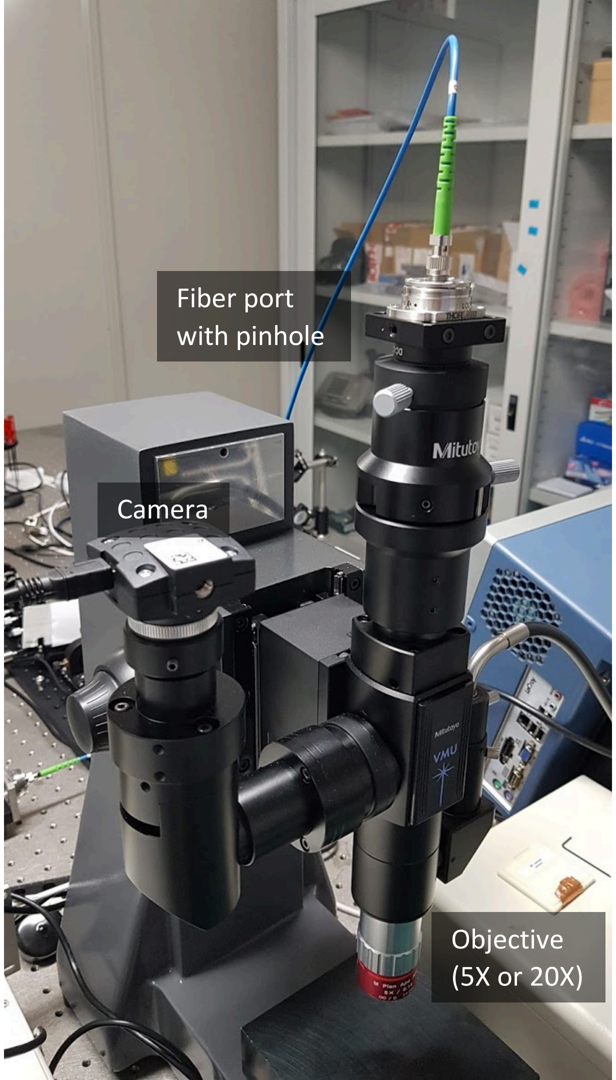
σ_{ej}, the electronic noise contribution to the time resolution, does not depend on V_{bias}

The laboratory test setup

- The complete characterization of these very high-performance sensors also needs to be performed in the laboratory with a dedicated setup

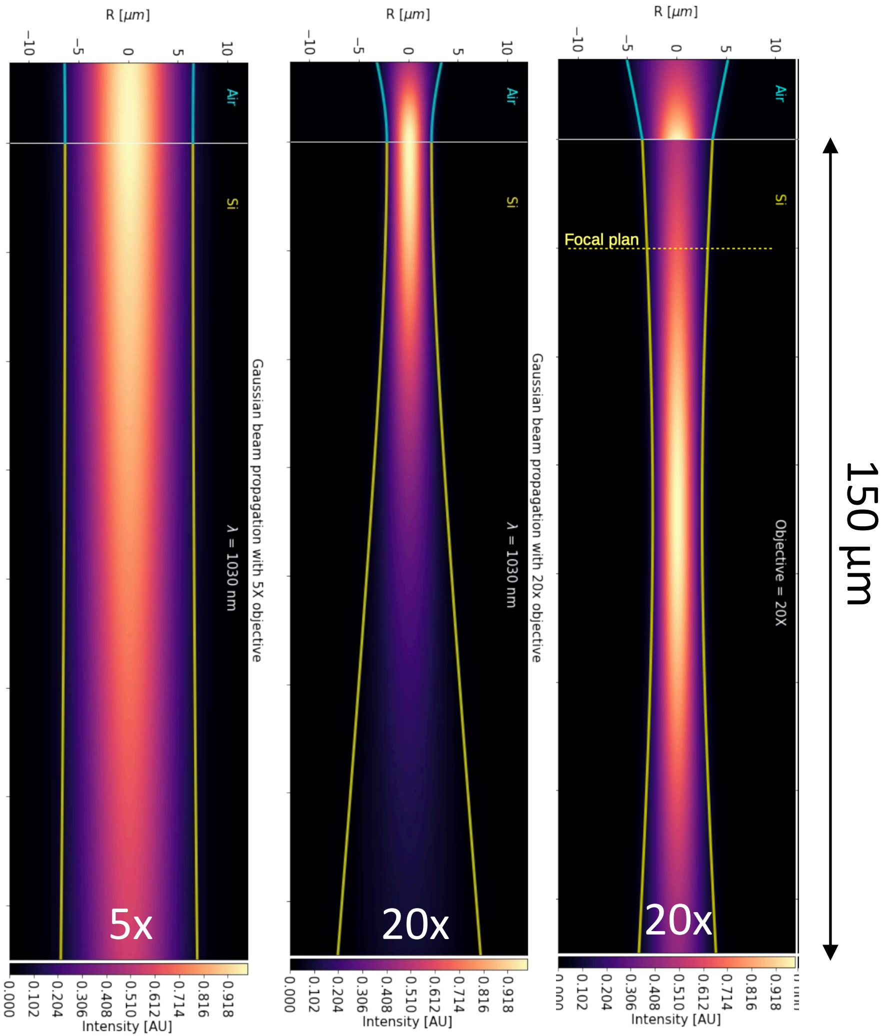
- At INFN Cagliari we developed a new testing station
  - 1030nm, 100fs, 2nJ per pulse, 40MHz laser
  - Pulse-picker to select pulses in the pulse train down to O(1 kHz)
  - Mono-mode fiber to the microscope laser port
  - Pin-hole to collimate laser spot on microscope image plane
  - IR camera
  - XY 3D sensor automated moving system (coming soon)





Both optics provide an almost cilindrical energy deposit in the sensor; this emulates a MIP crossing the sensor

At 1030nm, ~1/3 of the laser pulse energy is absorbed in 150µm of Silicon

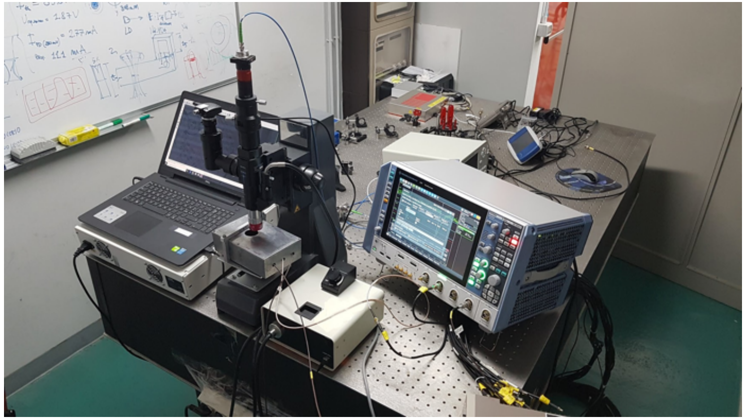


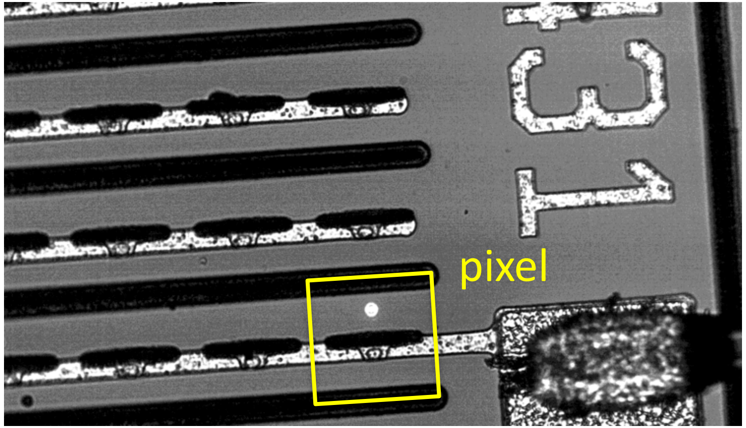
Measurements with IR laser

- We can measure, over the pixel active area:
  - Timing performances
  - Signal response

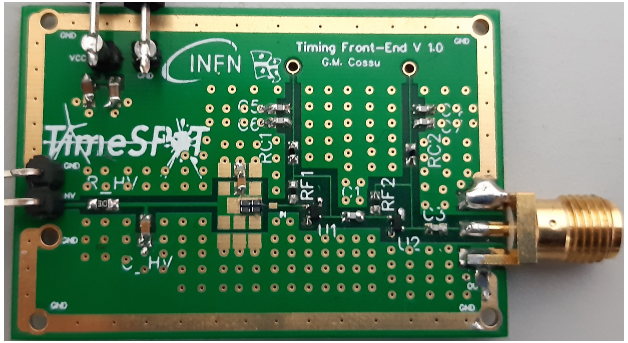
- Calibration of deposited energy
  - Using 3D silicon sensor connected to a charge-sensitive amplifier and using radioactive sources
  - Cross-checked with test beam data

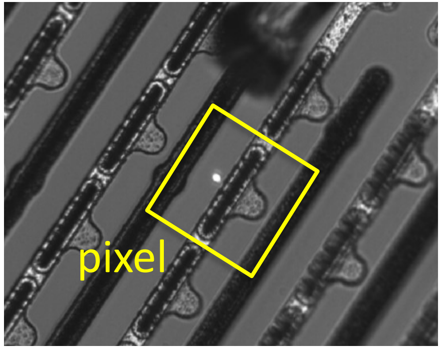
- Sensor's signal time reference:
  1) Use previous laser pulse (note that laser jitters <1ps and the laser amplitude pulse-by-pulse is extremely stable)
  2) Use same pulse but seen by another 3D trench-type sensor (strongly) illuminated by a reflection of the laser in an optical element

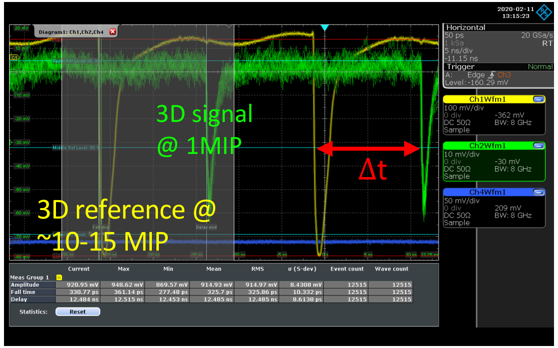




Preliminary results with IR laser







2020-02-11
13:15:23

Horizontal
50 ps 20 GSa/s
1 kSa RT
5 ns/div
-11.15 ns

Trigger Normal
A: Edge Ch3
Level: -160.29 mV

Ch1Wfm1
100 mV/div
0 div -362 mV
DC 50Ω BW: 8 GHz
Sample

Ch2Wfm1
10 mV/div
0 div -30 mV
DC 50Ω BW: 8 GHz
Sample

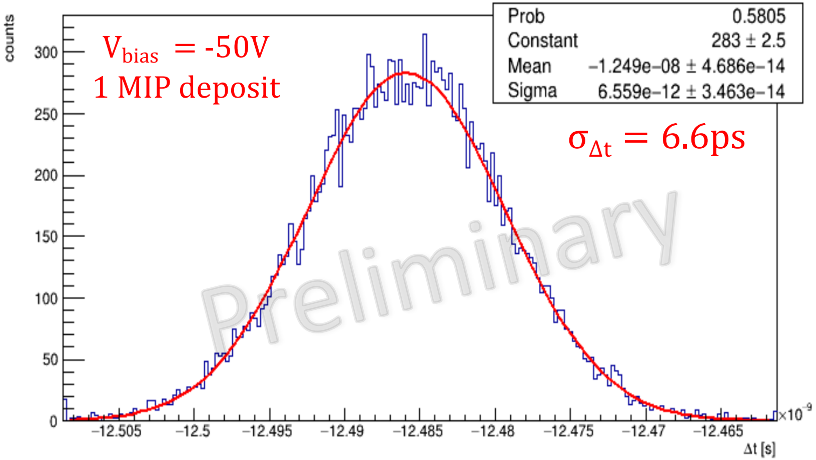
Ch4Wfm1
50 mV/div
0 div 209 mV
DC 50Ω BW: 8 GHz
Sample

Meas Group 1

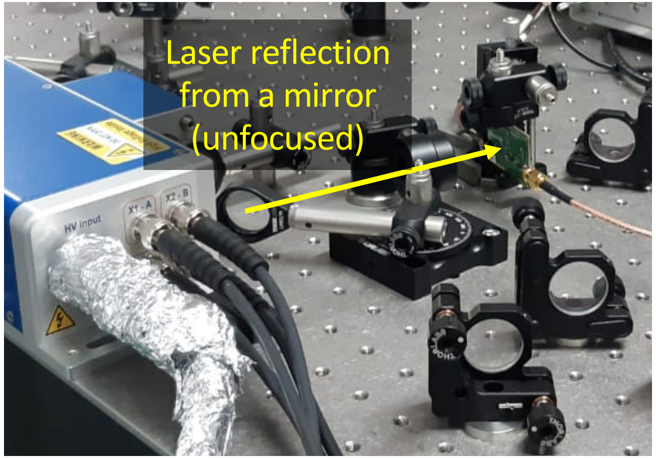
	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Amplitude	920.95 mV	948.62 mV	869.57 mV	914.93 mV	914.97 mV	8.4308 mV	12515	12515
Fall time	330.77 ps	361.14 ps	277.48 ps	325.7 ps	325.86 ps	10.332 ps	12515	12515
Delay	12.484 ns	12.515 ns	12.453 ns	12.485 ns	12.485 ns	8.6138 ps	12515	12515

Statistics: Reset

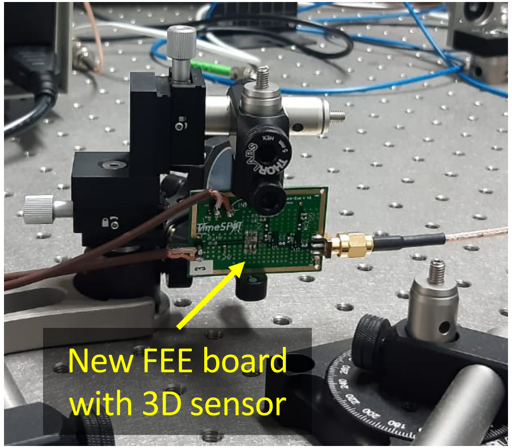
- A new transimpedance FEE with 2-stage SiGe BJTs, single-channel, for sensor's testing, designed and produced in 2020
- TIMESPOT 3D pixel-strip sensor
- Another 3D pixel-strip sensor is used as time reference (more light ➔ better time resolution)
- 20Gs/s, waveform interpolation, software CFD @35%
- Excellent time accuracy to allow a precise sensor characterization
  - Not taking into account the effect of non-uniformities inside the 3D pixels (σ_{un}) ➔ a convolution of signals from a laser scan over the full pixel active area is needed
  - This result is limited in practice only by the FEE noise σ_{ej}



Time reference outstanding accuracy

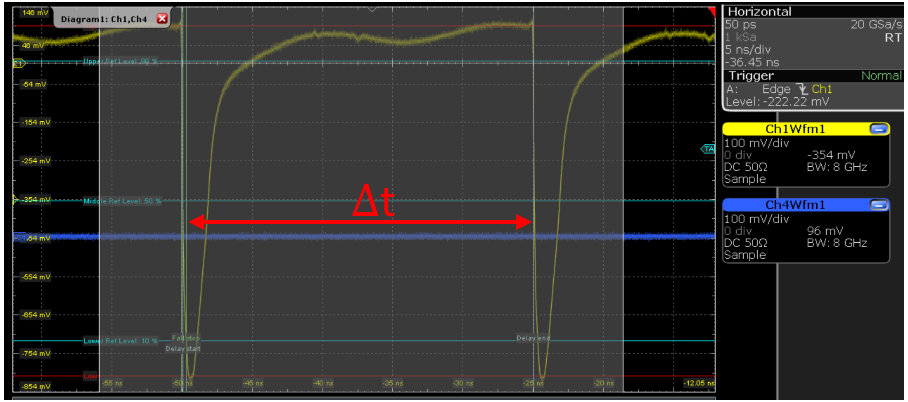


Laser reflection from a mirror (unfocused)



New FEE board with 3D sensor

Sub-ps timing accuracy can be obtained with 3D sensors when the energy deposit is ~10 MIPs



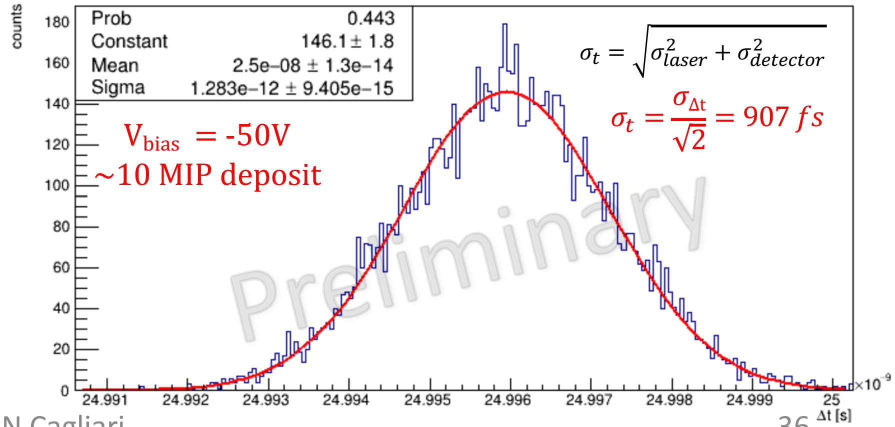
Horizontal
50 ps 20 GSa/s
1 kSa RT
5 ns/div
-36.45 ns

Trigger Normal
A: Edge Ch1
Level: -222.22 mV

Ch1Wfm1
100 mV/div
0 div -354 mV
DC 50Ω BW: 8 GHz
Sample

Ch4Wfm1
100 mV/div
0 div 96 mV
DC 50Ω BW: 8 GHz
Sample

Δt



$V_{\text{bias}} = \text{-50V}$

~10 MIP deposit

$$\sigma_t = \sqrt{\sigma_{laser}^2 + \sigma_{detector}^2}$$

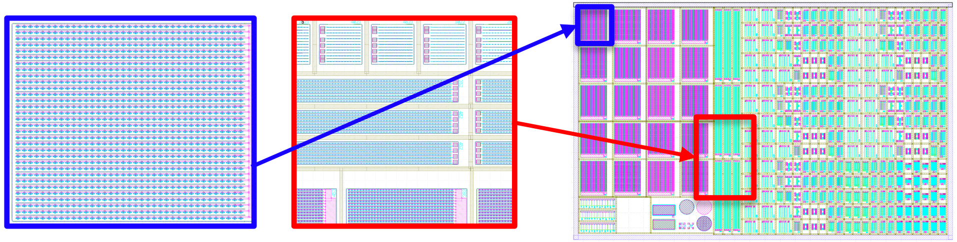
$$\sigma_t = \frac{\sigma_{\Delta t}}{\sqrt{2}} = 907\ fs$$

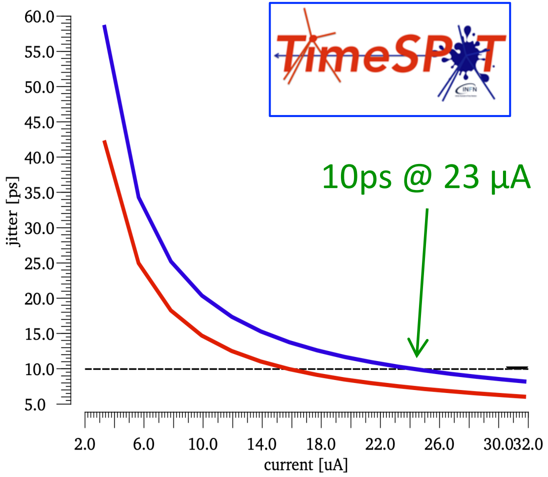
Conclusions

- Unprecedented results on trench 3D Si pixels timing have been presented
- The time resolution of a double-pixel sensor was measured with a 270 MeV/c π^+ (MIP) beam and found to be of about 20ps @ V_{bias} = – 140V (sensor intrinsic + FEE noise)
- Note that results were obtained on wire-bonded sensors (x10 of nominal pixel capacitance)
- The studies to understand the origin of the O(6%) tail in the time distribution are ongoing, but we know that this tail arises from the presence of lower field regions in the pixel active area. A dedicated signal processing will allow to reduce the tail. However, in a (multi-layer) tracking system, its effect will be practically negligible
- 3D devices confirm their theoretical excellent performance in timing, and the trench geometry appears to be the right direction to go
- Up to now, the front-end electronics is the limiting factor to sensor and system performance

… and Outlook

- The TIMESPOT collaboration is developing an optimized VLSI electronics (CMOS 28nm) able to read a small pixel matrix, possibly improving the timing performances already seen in small test structures
- New sensors are currently in production at FBK
  - New pixel matrix, usable with our VLSI FEE
  - New test structures, to continue the characterization of these innovative 3D pixels





Time jitter vs. current consumption of the CSA stage:

- Schematic simulation
- Post-layout simulation including parasitics

More news on TimeSPOT activities and results at the next Conferences!

Thank you very much!

Publications by the TimeSPOT Collaboration

- 3D trenched-electrode sensors for charged particle tracking and timing, NIM A, (2019)
- Simulation of 3D-Silicon sensors for the TIMESPOT project NIM A, 936-, (2019)
- Development of 3D trenched-electrode pixel sensors with improved timing performance JINST, 14-, C07011 (2019)
- Sensors, electronics and algorithms for tracking at the next generation of colliders NIM A, 927-, (2019)
- Combined TCAD and Geant4 simulations of diamond detectors for timing applications NIM A, 936-, (2019)
- A Timing Pixel Front-End Design for HEP Experiments in 28 nm CMOS Technology, 15th Conference on Ph.D. Research in Microelectronics and Electronics, 2019
- First results of the TIMESPOT project on developments on fast sensors for future vertex detectors, to appear in NIM A, 2020
- Timing characterisation of 3D-trench silicon sensors, to appear in JINST, 2020
- Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection, arXiv:2004.10881, to appear in JINST, 2020
- High-resolution timing electronics for fast pixel sensors, arXiv:2008.09867, to appear in JINST