Performance of 3D-trench silicon sensors designed for high time resolution

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TimeSPOT
TIME and SPace real-time Operating Tracker

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TREDI2020: 15° Trento Workshop
17-19 February 2020 - Wien

Developments on future tracking/vertex detectors go in the direction of a full 4D approach …

Severe requirements for future detector:

- ☞ Space and time measuring capabilities at the single pixel level
  - space resolutions below 10 μm
  - time resolutions below 50 ps
- ☞ Sustain fluences greater than some 10^{16} n_{eq} cm^{-2}
- ☞ Very low material budget

HL-LHC
Future colliders

Several R&D studies of silicon sensors are ongoing

3D silicon pixel sensors: a very promising technology to be fully explored

3D succesfully used in current tracking systems and good candidates for HL-LHC tracker upgrades

→ Radiation hardness proved up to 10^{16} n_{eq} cm^{-2}

CMS-PPS

ATLAS-IBL

The TimeSPOT project

Main target:

Develop and realize a demonstrator consisting of a complete reduced size tracking system, integrating ~ 10^3 read-out pixel channels, satisfying the following requirements:

- Pixel pitch: ≤ 55 μm
- Radiation hardness: 10^{16} – 10^{17} n_{eq}/ cm^2 (sensors) – greater than 1 Grad (electronics)
- Time resolution: ≤ 50 ps per pixel
- Real time track reconstruction algorithms and fast read-out (data throughput > 1 TB/s)

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 with timing measurement
4. Design and implementation of real-time tracking algorithms
5. Design and implementation of high-speed readout boards
6. System integration and tests

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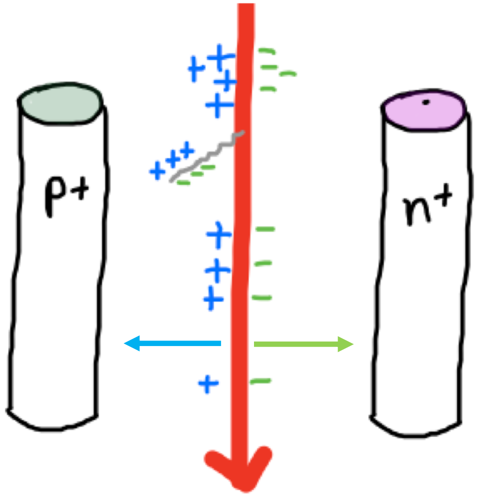
3 years work program + 1 year possible extension (2018-2021)

3D sensors for timing measurements

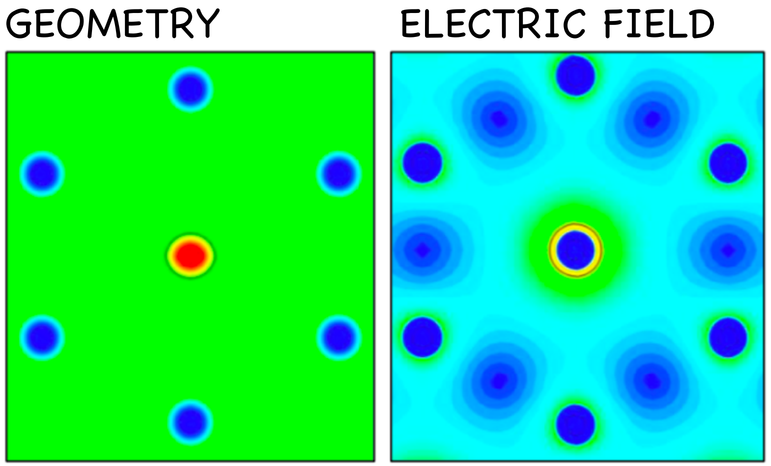


PROs

- ✓ Possibility to decouple sensor thickness and drift distance
  - → large signal amplitude & short collection time
- ✓ Lateral electric field and charge collection
  - → Signal concentrated in time
  - → Time uncertainties from non uniform ionization (Landau fluctuations) minimized

CONs

- Non-uniform electric field
- Electrodes are partially dead regions
- High capacitance
- Complicated fabrication technology (cost, yield)



Low-field regions in between electrodes of same type

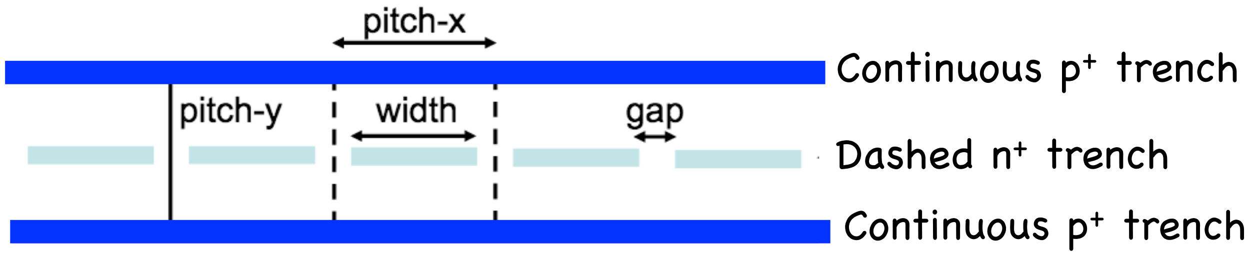
TimeSPOT: 3D pixel with trench electrodes

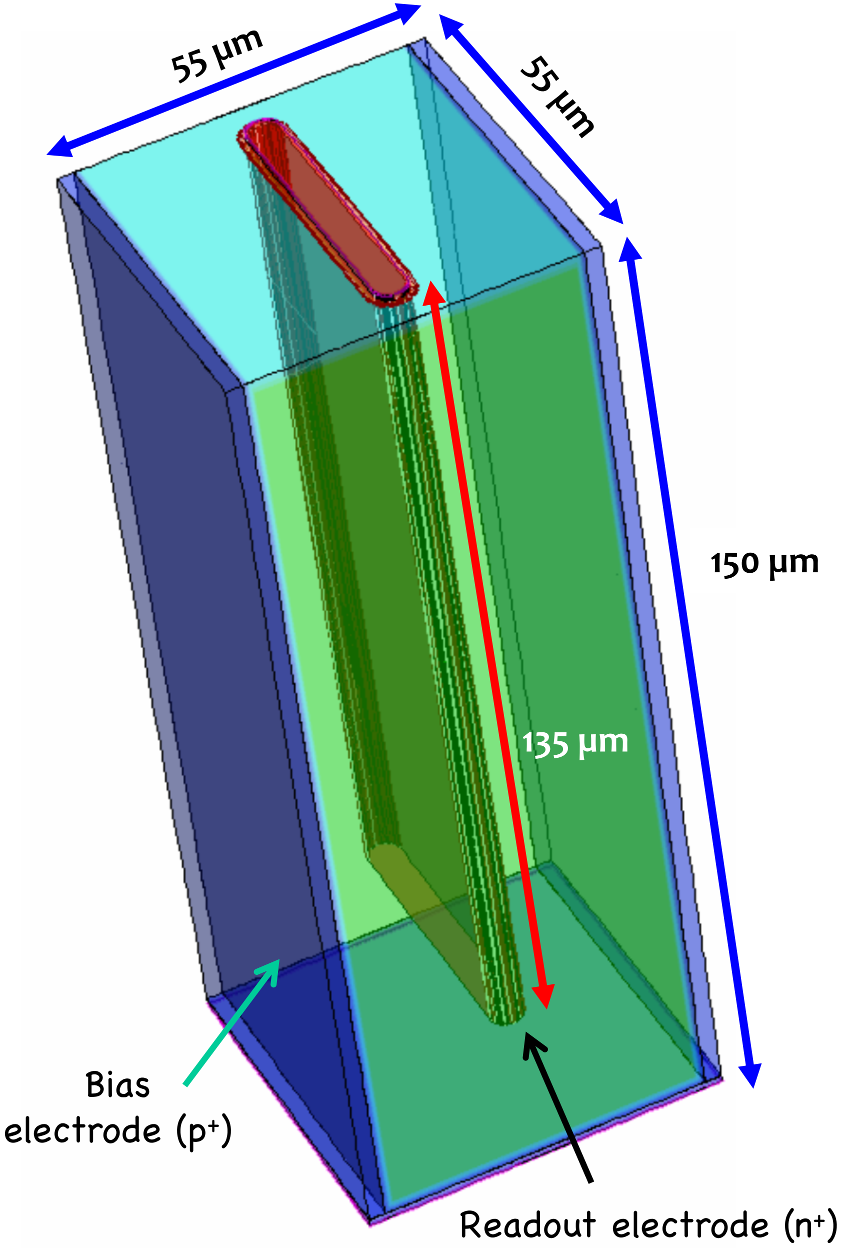
Different geometries based on hexagonal and square pixel with columnar and trench shaped electrodes designed and simulated (electric field, weighting field and carrier drift velocity, induced instant current).

Configuration with parallel trenches chosen

Column geometry

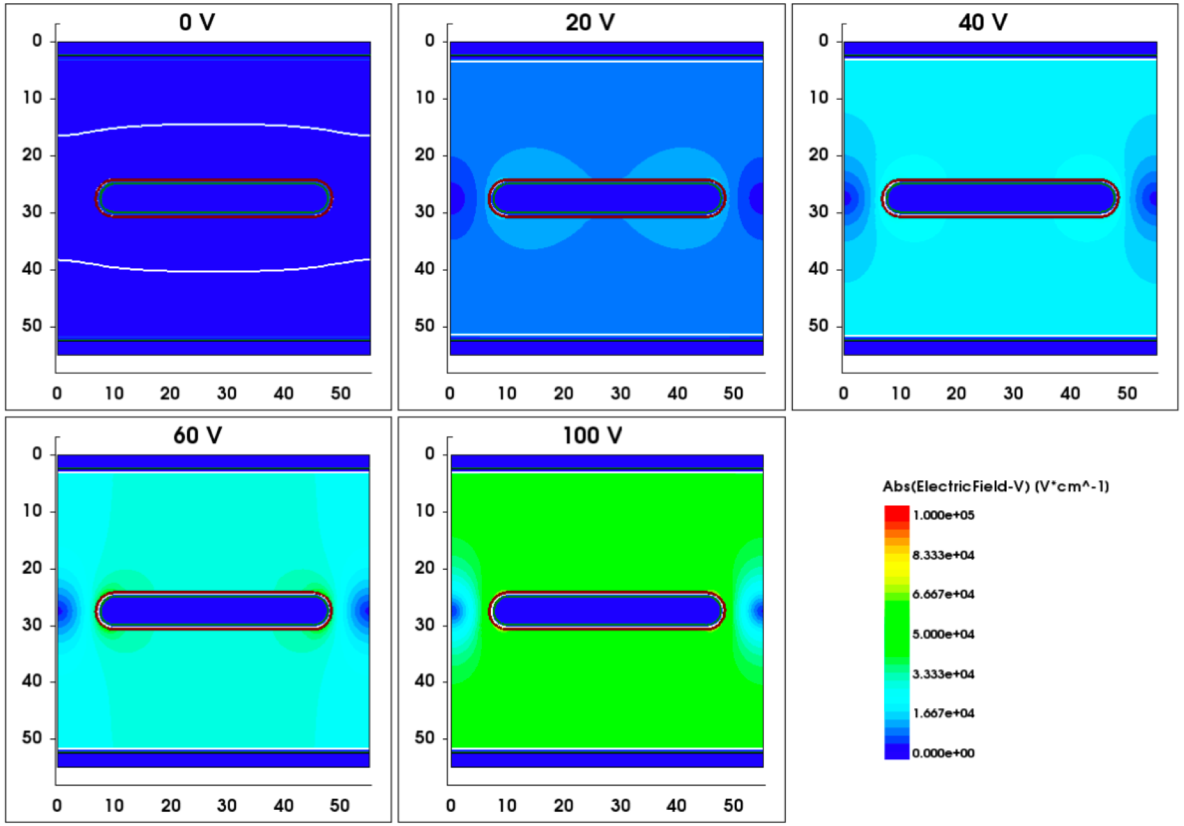
Trench geometry

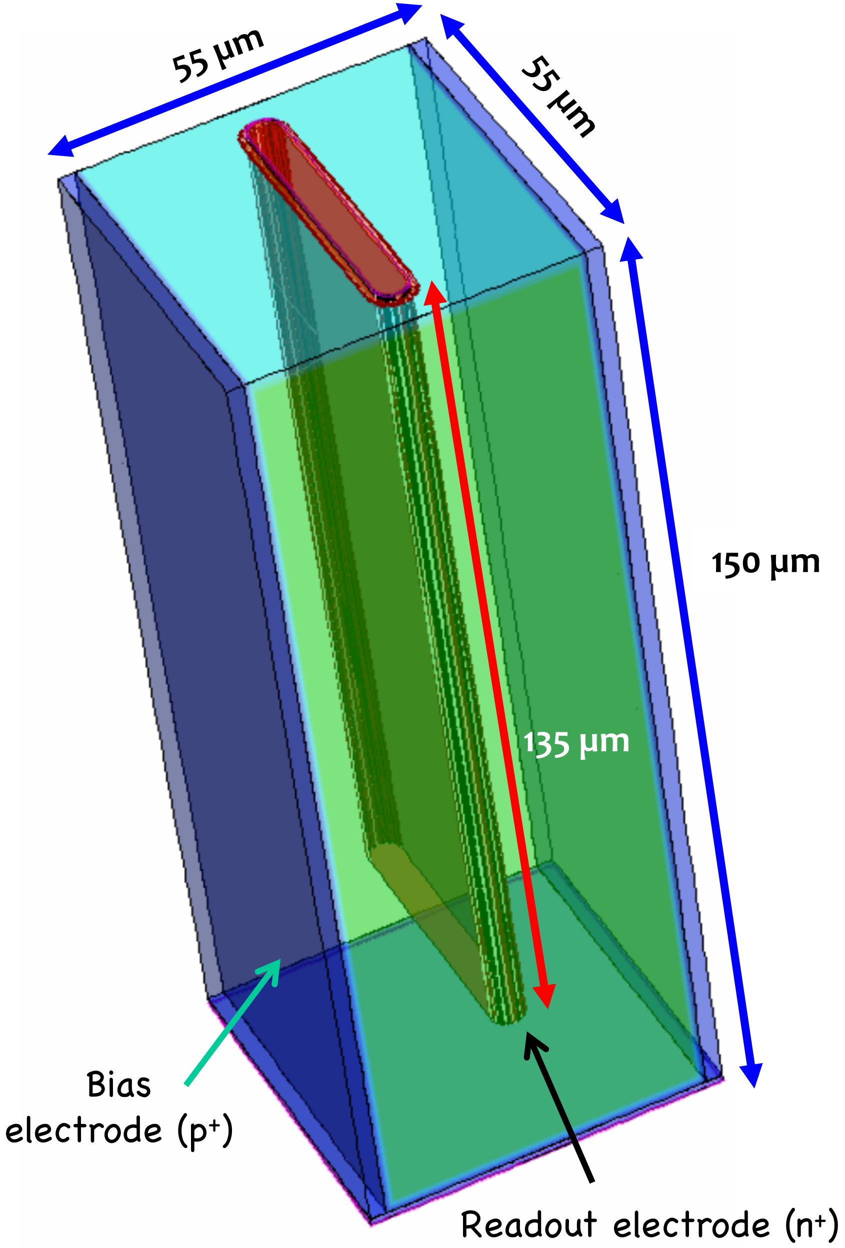




TimeSPOT 3D pixel simulation

Electric field map at different V_{bias}

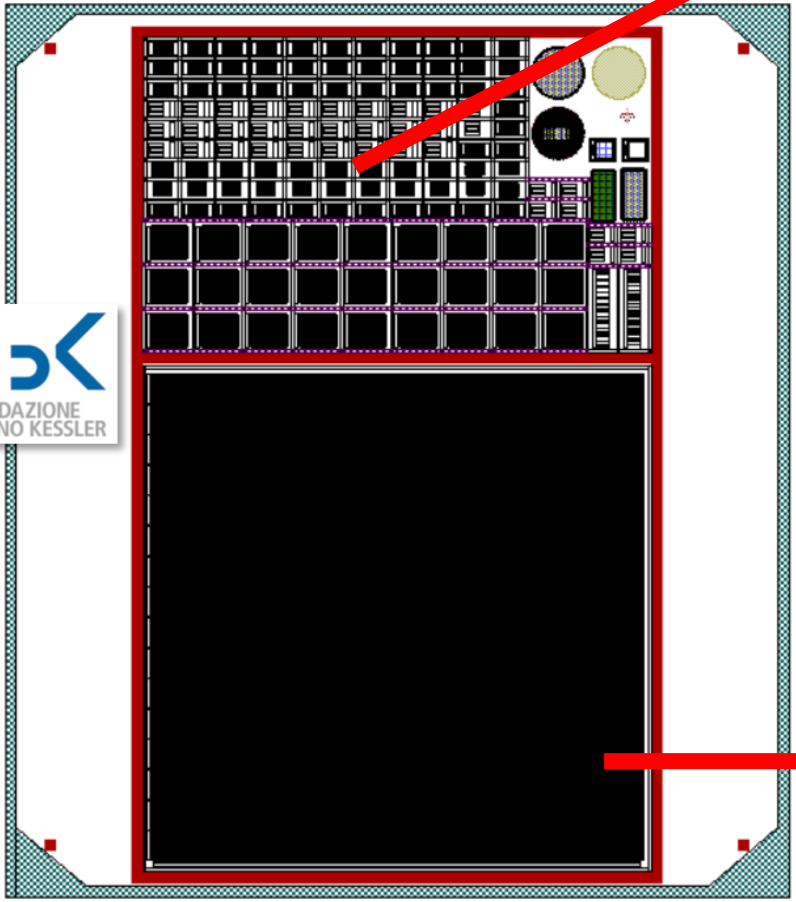




- Total charge deposit for MIP ≈ 2 fC
- Full depletion @ few volts, velocity saturation @ > 30 V
- Pixel capacitance (from simulation) ~110 fF

Study carried out using Synopsys Sentaurus TCAD

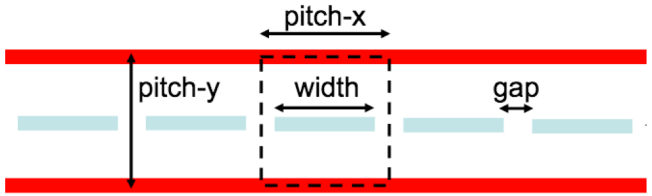
First 3D-trench batch



FONDAZIONE BRUNO KESSLER

3D Test structures

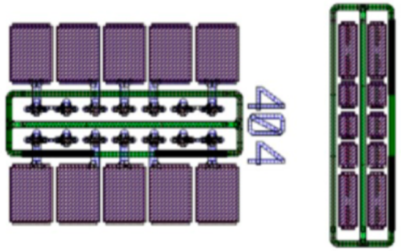
Schematic design



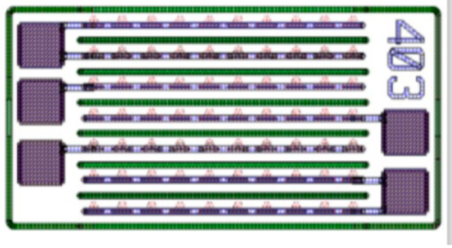
Continuous p⁺ trench

Dashed n⁺ trench

Two examples:

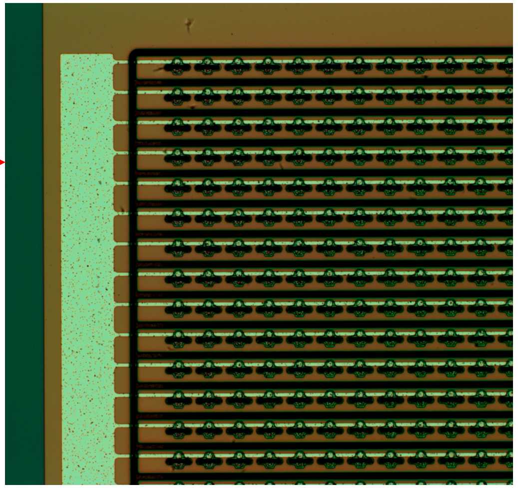


Single/double pixels



Pixel strips

Structures with different n⁺ trench width/gap size produced

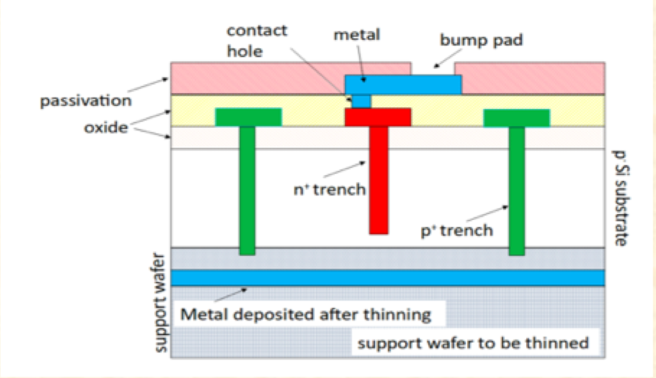


Timepix compatible device

- 256x256 pixels
- 55 μm pitch

First 3D-trench batch: fabrication technology

Single-Side production method

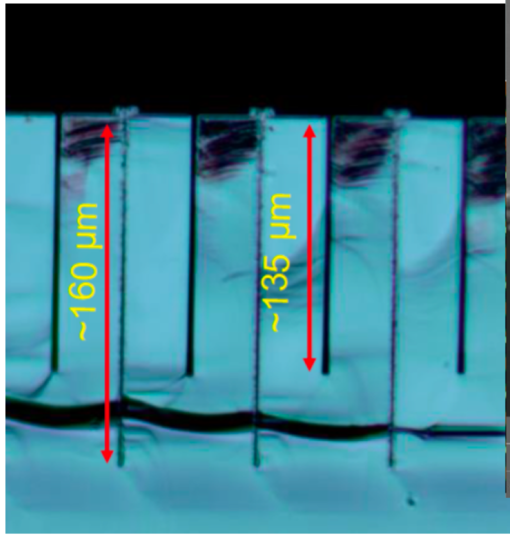


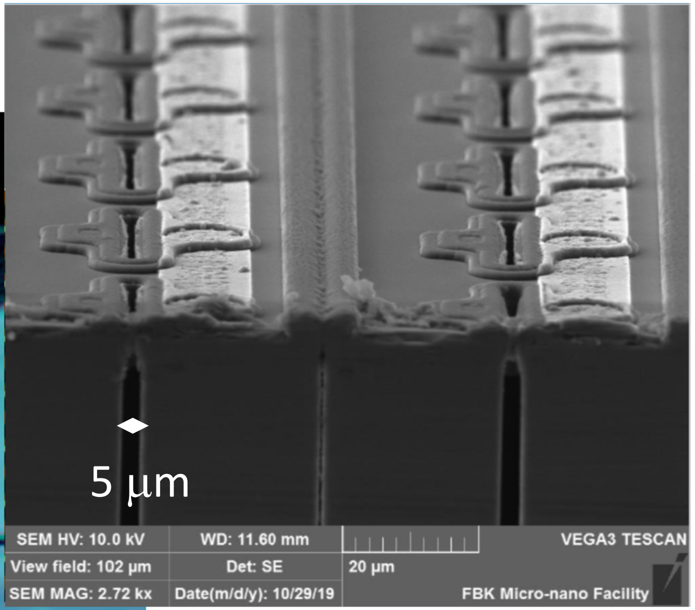
Sensitive volume:
- 150 µm
- HR Si (~ 5kΩ cm)

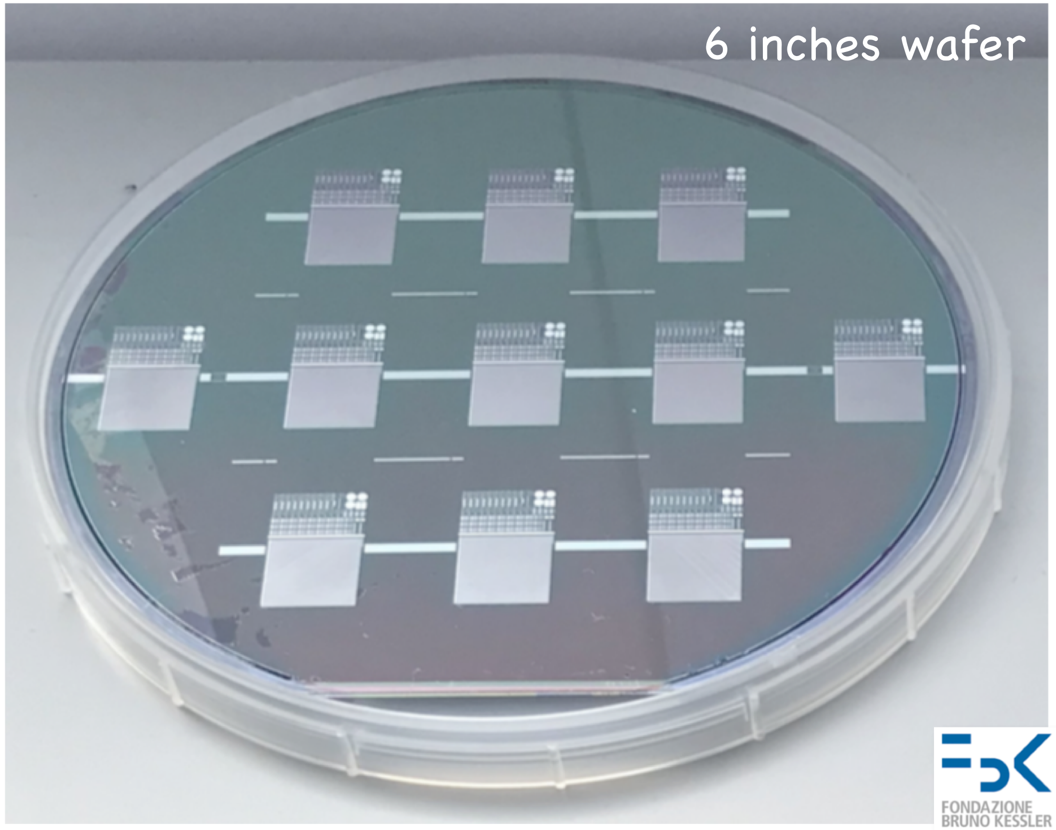
Support wafer:
- 500 µm
- LR Si (<Ω cm)

Photolithography with stepper

- 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

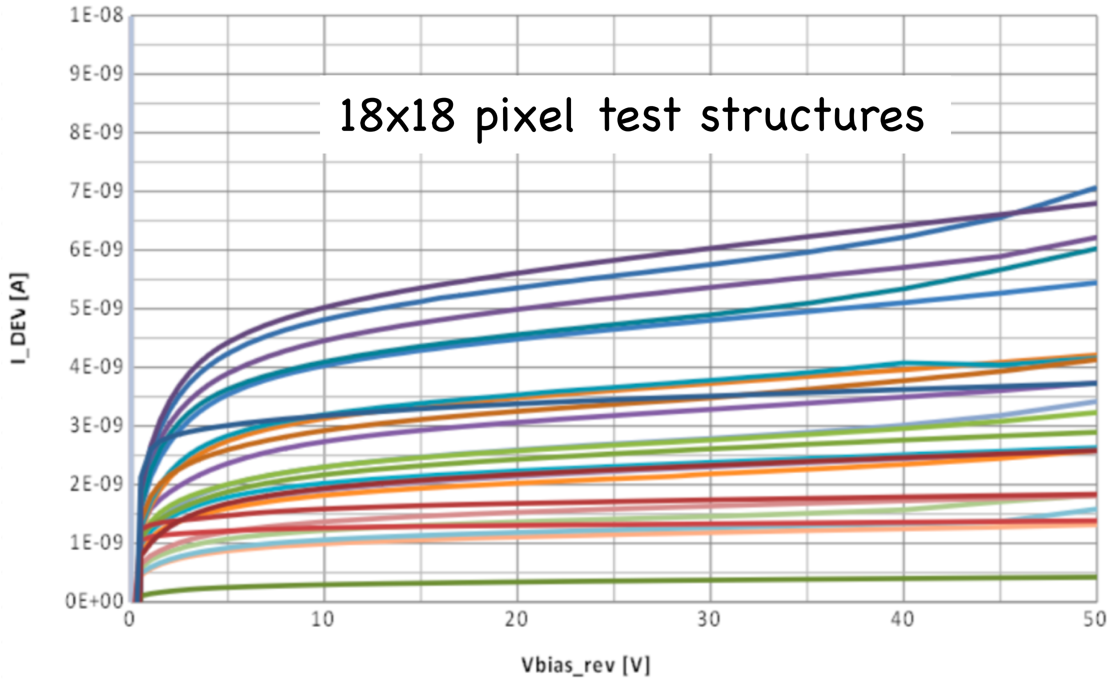




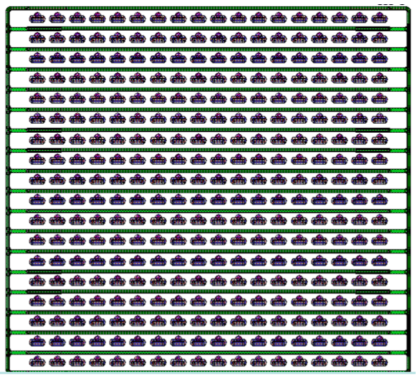


Delivered on June 2019

First 3D-trench batch: electrical measurements

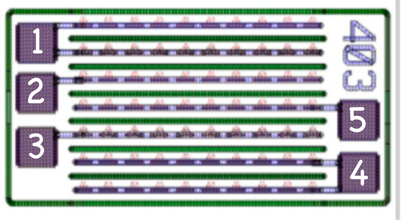


Measurements on wafer (FBK)

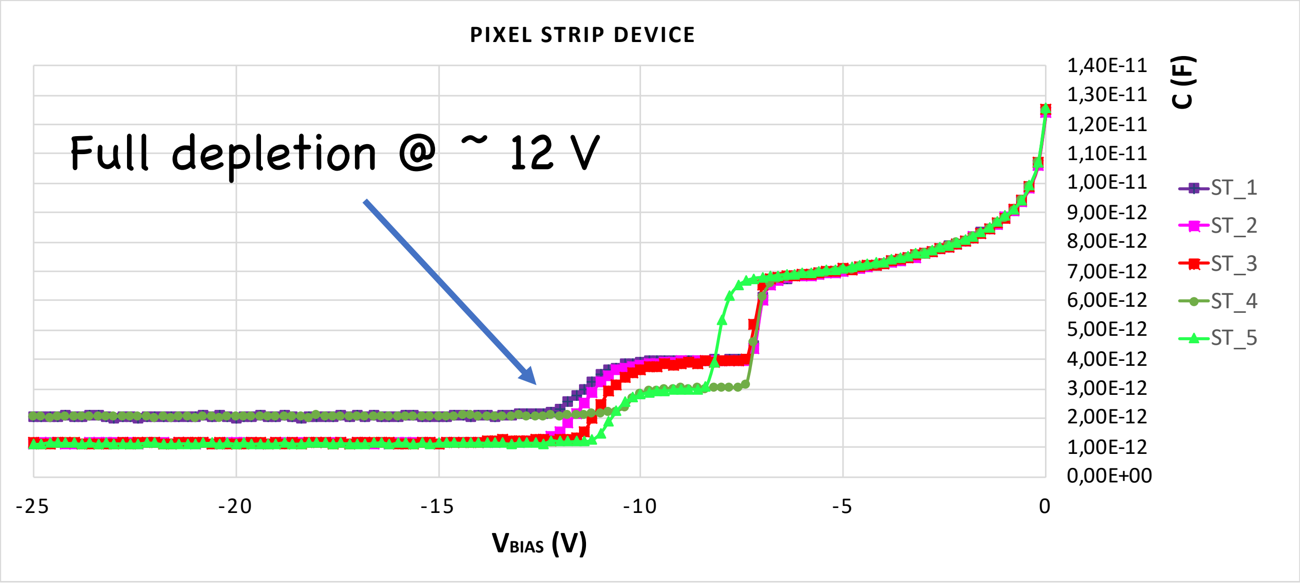


~10 pA/pixel on working devices

Measurements after dicing (Torino and Trento laboratory)



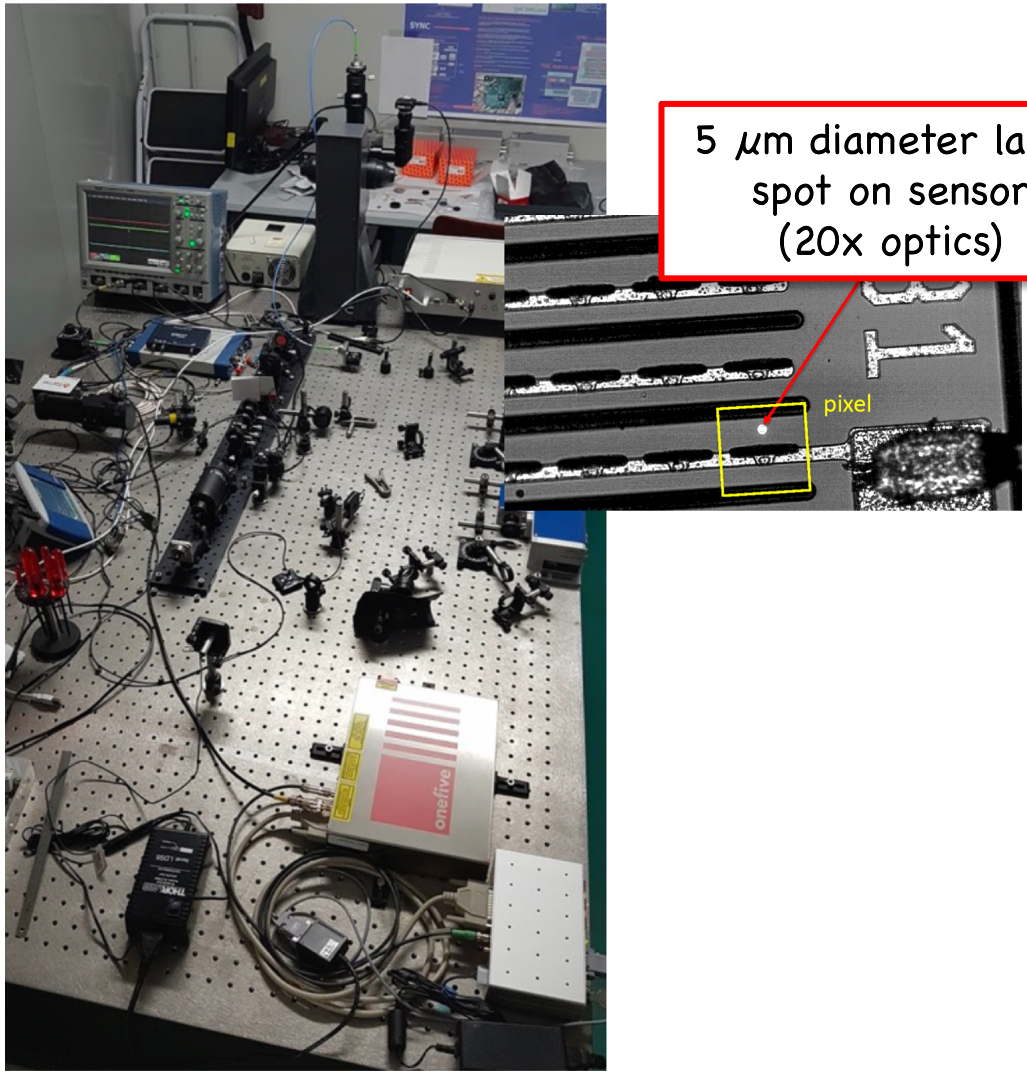
Measured capacitance ~110 fF/pixel
(in agreement with simulation)



Full depletion @ ~ 12 V

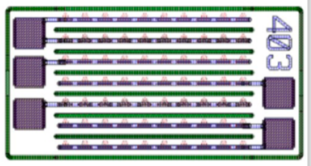
First 3D-trench batch: response to laser pulses

1030 nm, 200 fs, 40 MHz pulsed laser

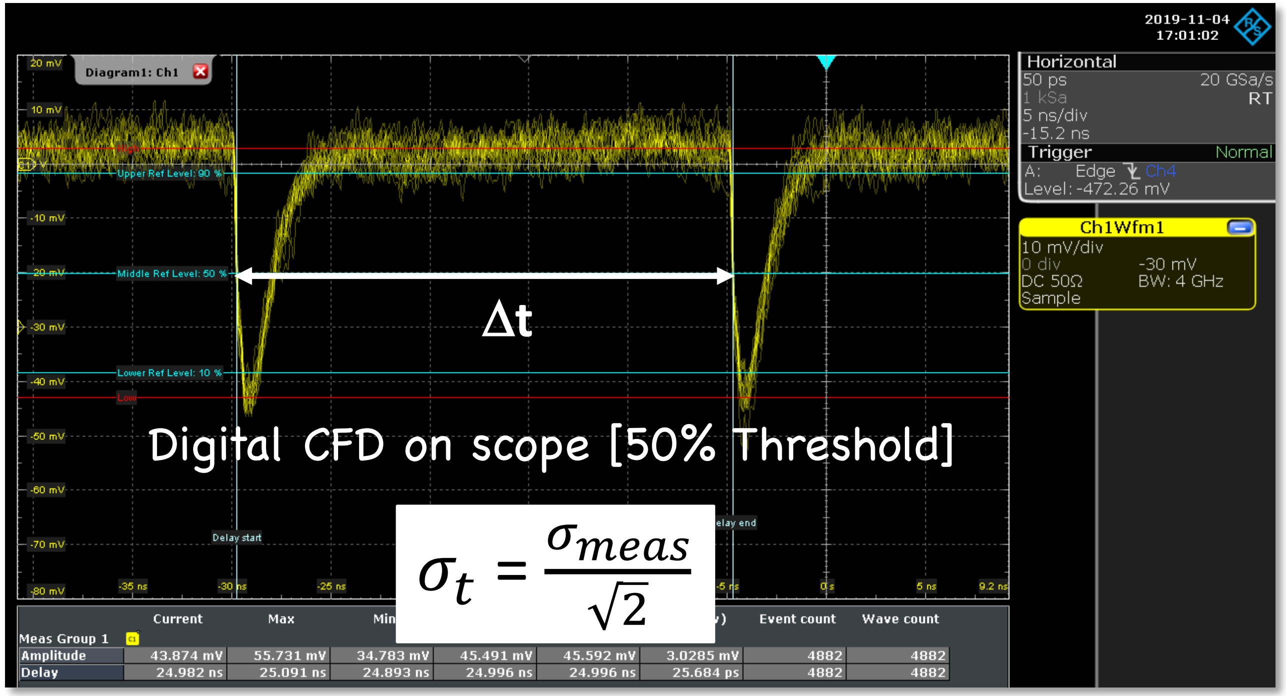


5 µm diameter laser spot on sensor (20x optics)

LASER SETUP @INFN CAGLIARI



10-pixel strip + amplifier board with discrete components (KU board), not optimized for our sensors



Horizontal
50 ps 20 GSa/s
1 kSa RT
5 ns/div
-15.2 ns
Trigger Normal
A: Edge Ch4
Level: -472.26 mV

Ch1Wfm1
10 mV/div
0 div -30 mV
DC 50Ω BW: 4 GHz
Sample

Digital CFD on scope [50% Threshold]

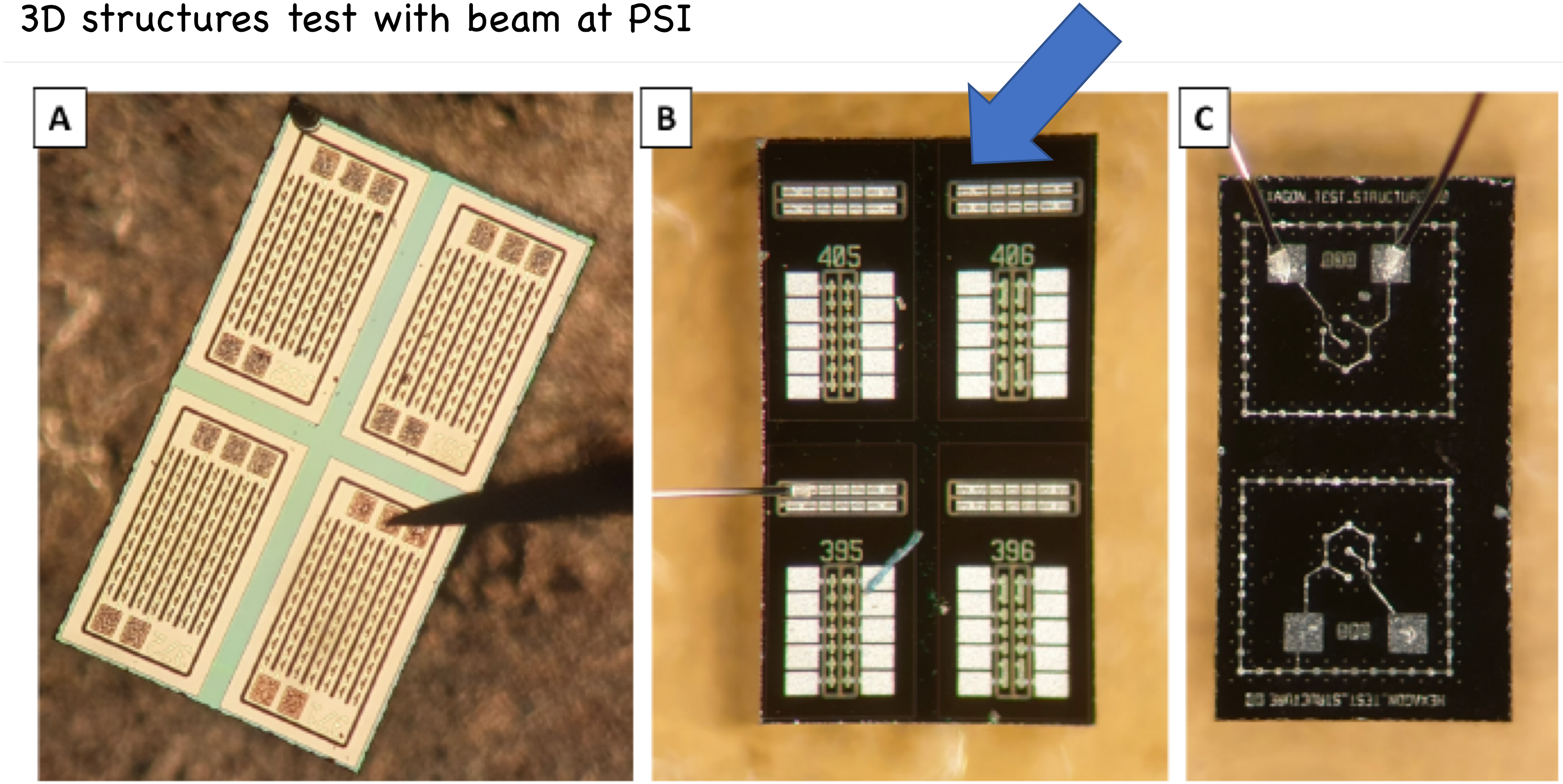
$$\sigma_t = \frac{\sigma_{meas}}{\sqrt{2}}$$

Meas Group 1	Current	Max	Min			v)	Event count	Wave count
Amplitude	43.874 mV	55.731 mV	34.783 mV	45.491 mV	45.592 mV	3.0285 mV	4882	4882
Delay	24.982 ns	25.091 ns	24.893 ns	24.996 ns	24.996 ns	25.684 ps	4882	4882

σ_t ~ 20 ps @ MIP equivalent laser signal

First 3D-trench batch: test beam

Several 3D structures test with beam at PSI



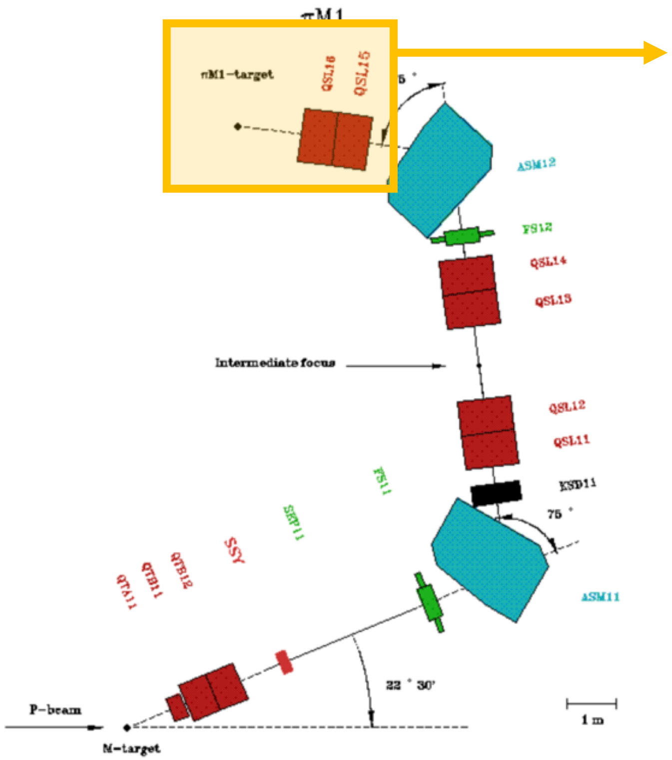
(A) Pixel-strip (10 pixels connected on the same read-out pad)
(B) Single and double pixel
(C) Hexagonal (column) pixel device, based on FBK 3D Single Sided Technology

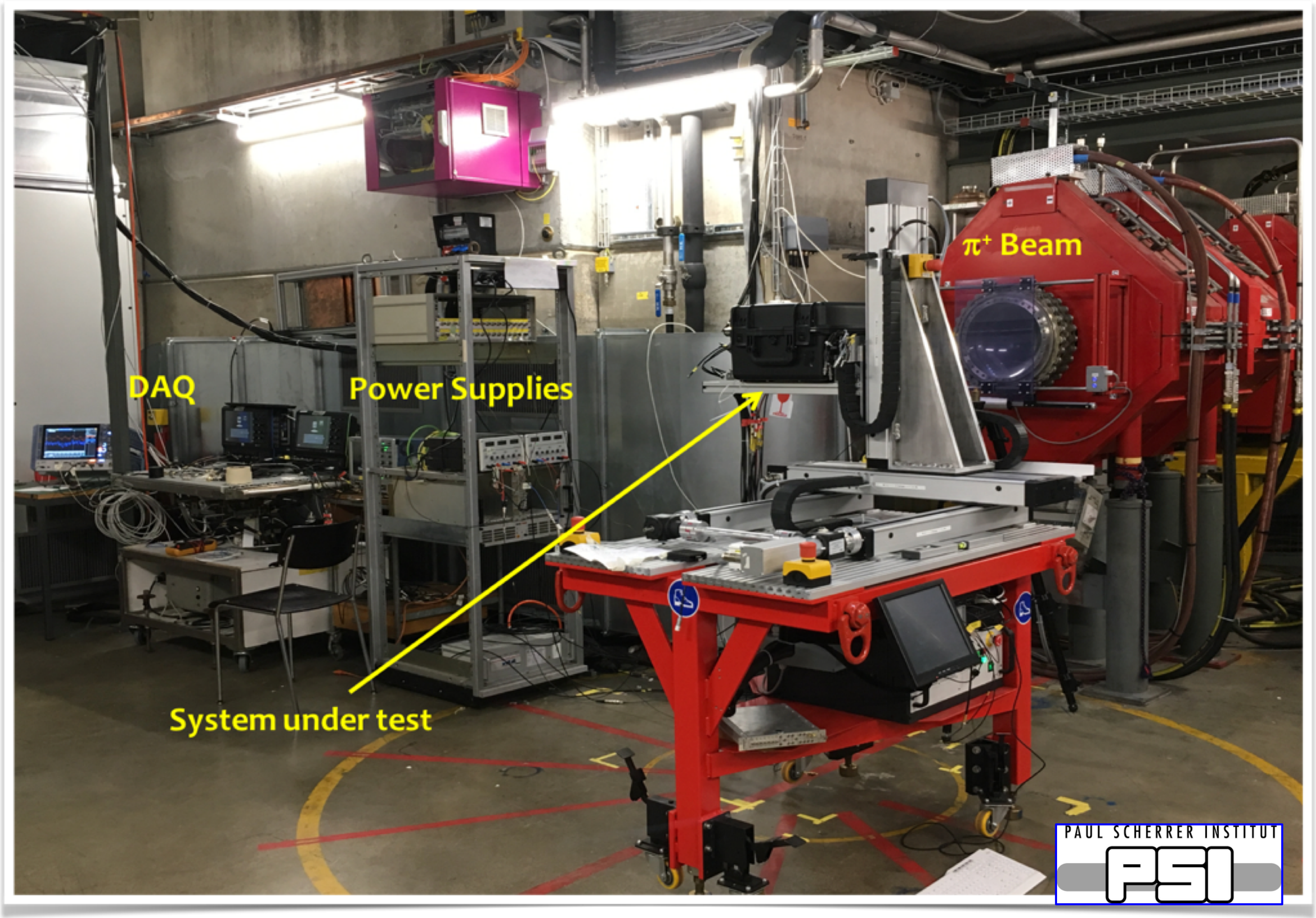
Devices connected to electronics by wire bonding (Al, 25 μm diameter, ~ 5 mm length)

Test beam setup

πM1 beam line

- π+ beam (negligible e+ contamination)
- Momentum: 270 MeV/c
- Radius on the spot: σ ~ 1.5 cm

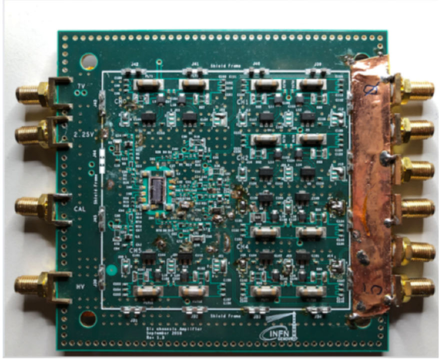




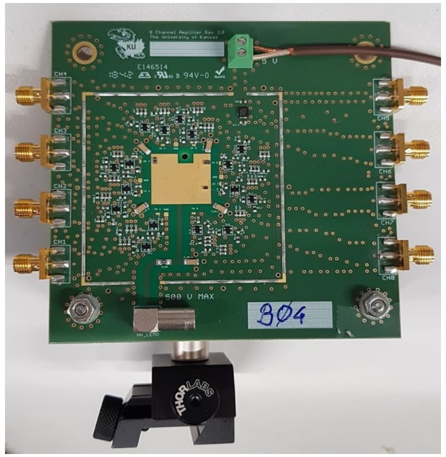
Test beam setup: system inside the "black box"

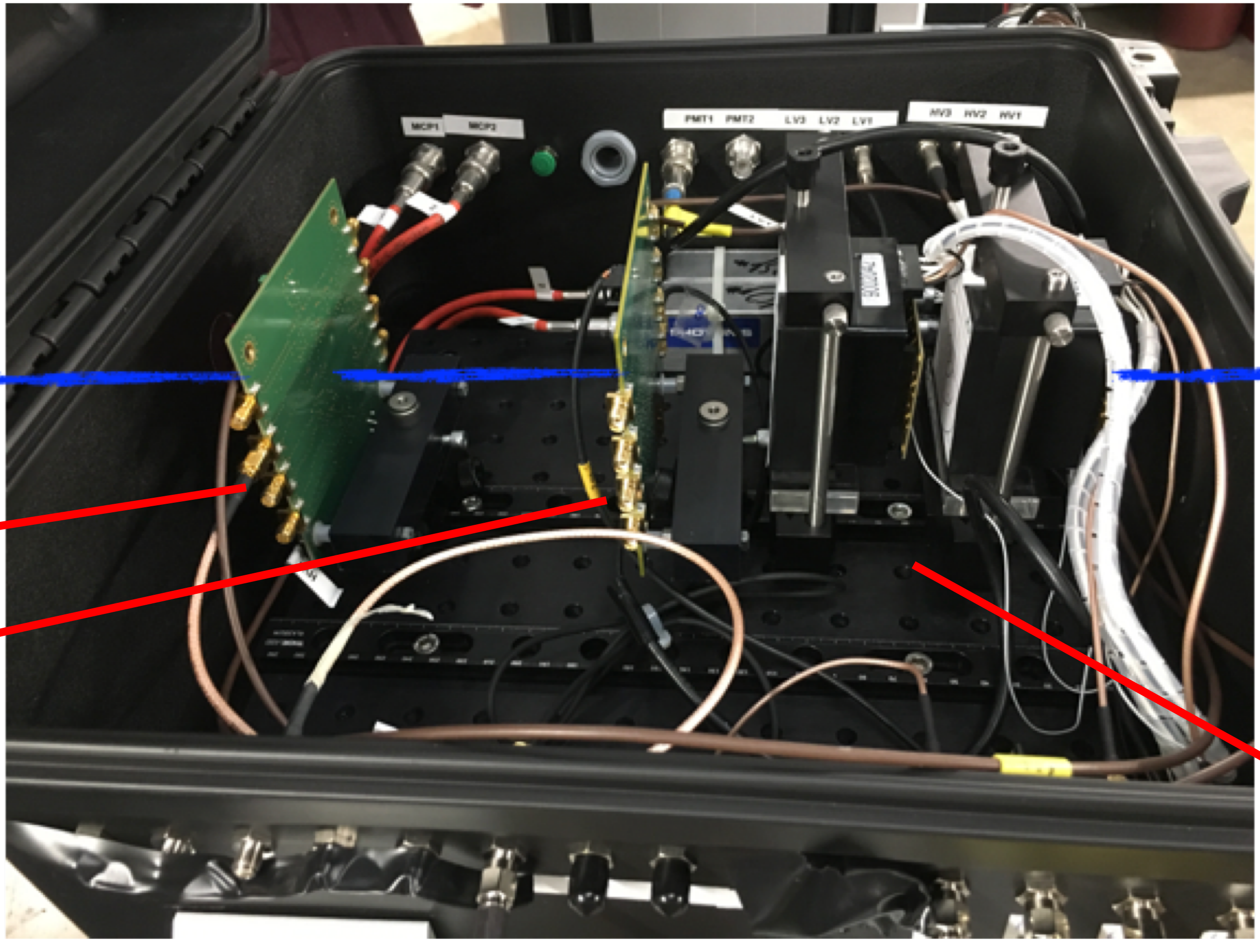
DUT front end:
broadband amplifier board with discrete components

INFN-Ge Front End

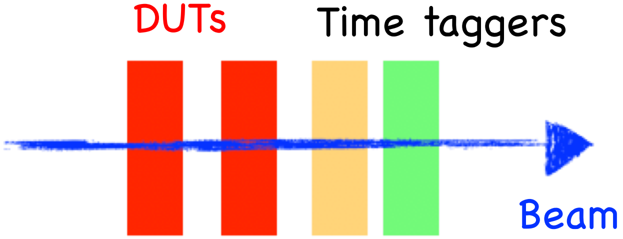


KU Front End





Beam

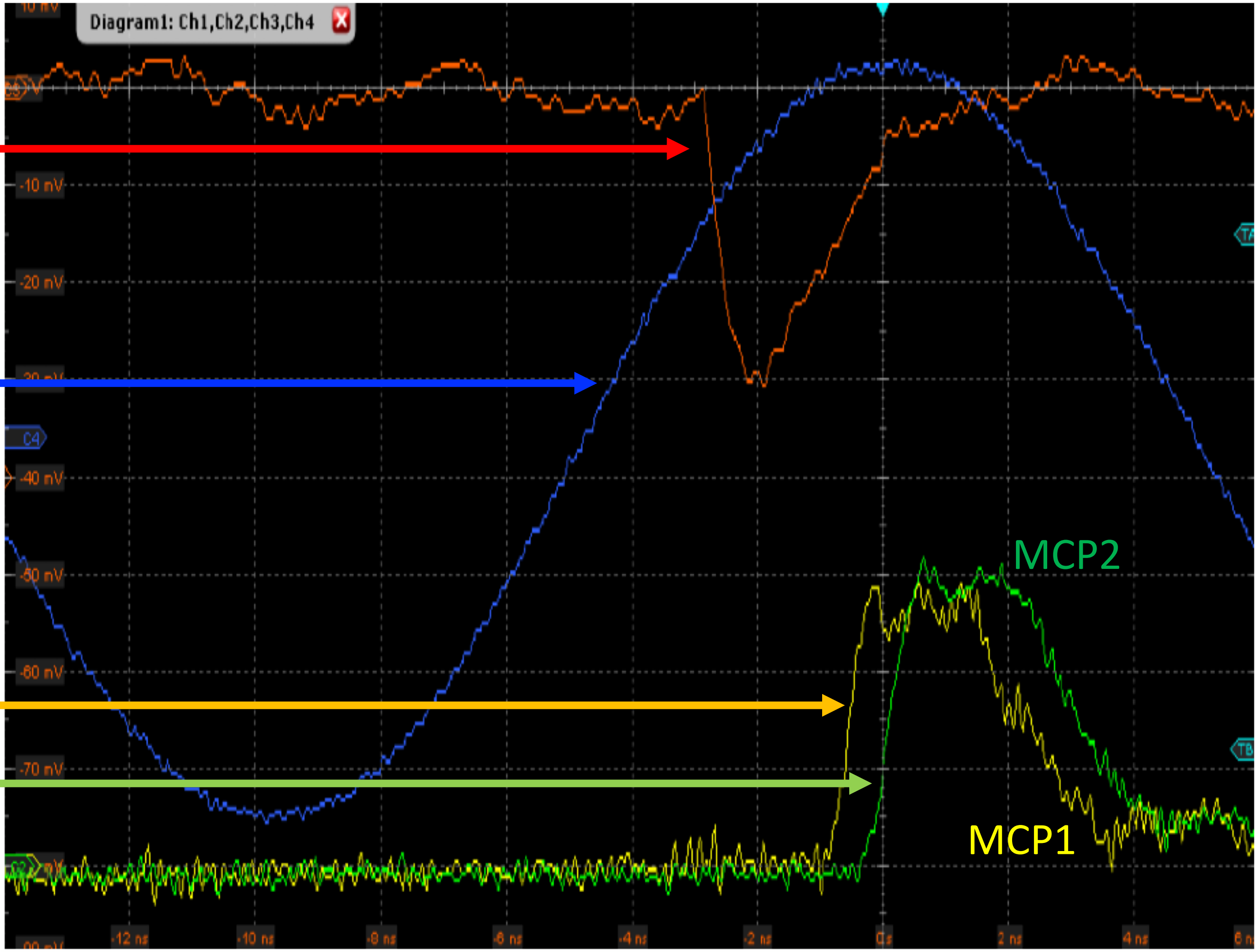


Time Taggers:

- Quarz Cherenkov radiator + MCP
- Area: 5x5 cm^2
- σ_t ~ 15 ps

Test beam setup: trigger & DAQ

DAQ: Oscilloscope Rohde&Shwarz RTP084 - Samplig frequency: 20 Gsample/s - Bandwidth: 4 GHz (or 8 GHz)



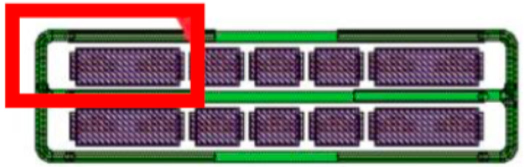
Silicon sensor

Beam RF signal
(50 MHz)

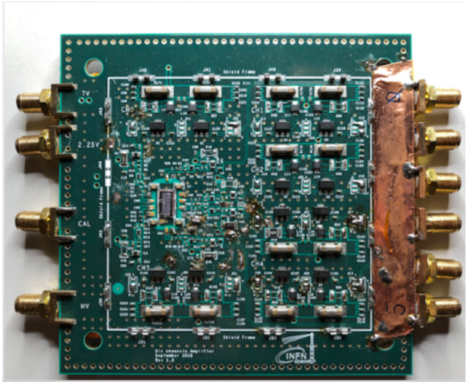
MCP 1 & 2
(time taggers)

Trigger: Coincidence of MCP2 and Si sensor

First 3D-trench batch: test beam results



DUT: Double pixel



INFN-Ge Front End Board

(1 amplification stage, G~30

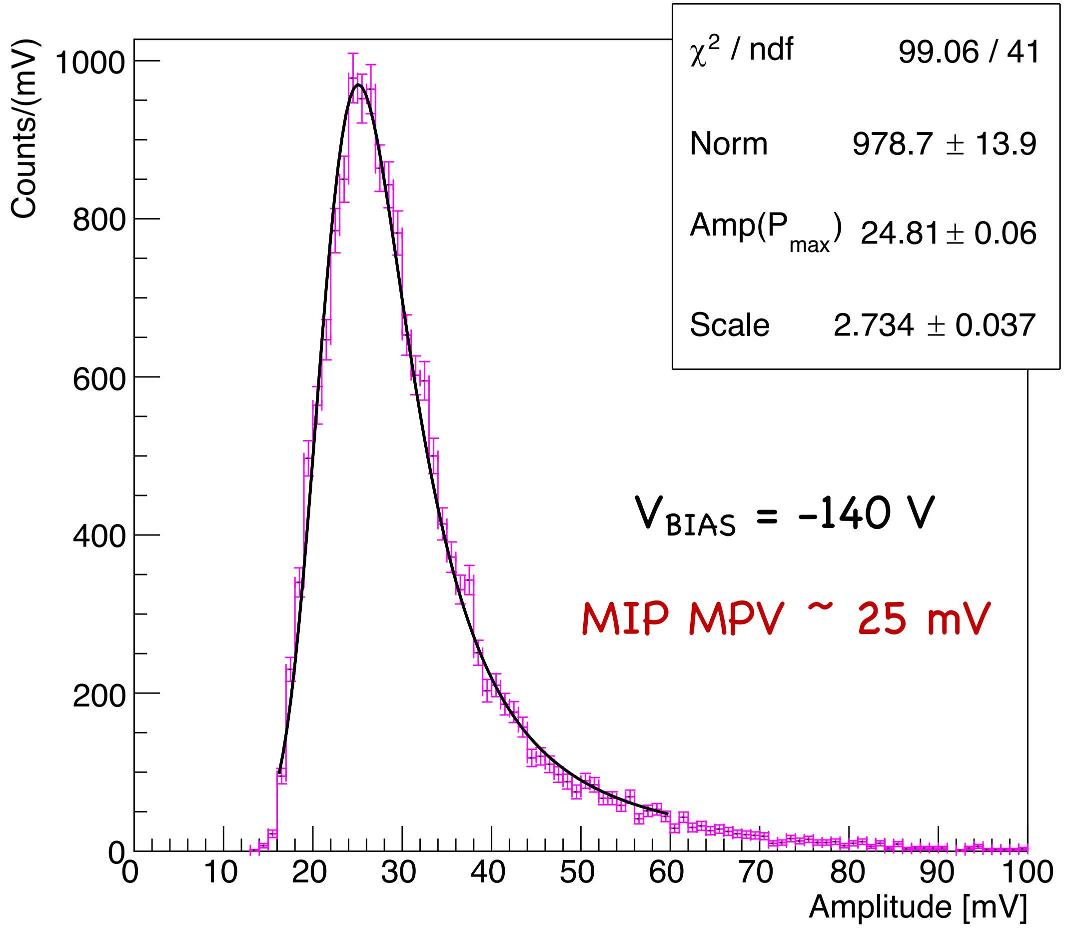
2 GHz bandwidth)

\+ external broadband amplifiier

(G=10, 2 GHz bandwidth)

Measurements perfomed at different V_{BIAS}

V_{BIAS} (V)	Nevent
-20	20k
-50	20k
-80	3k
-110	20k
-140	20k



V_{BIAS} = -140 V

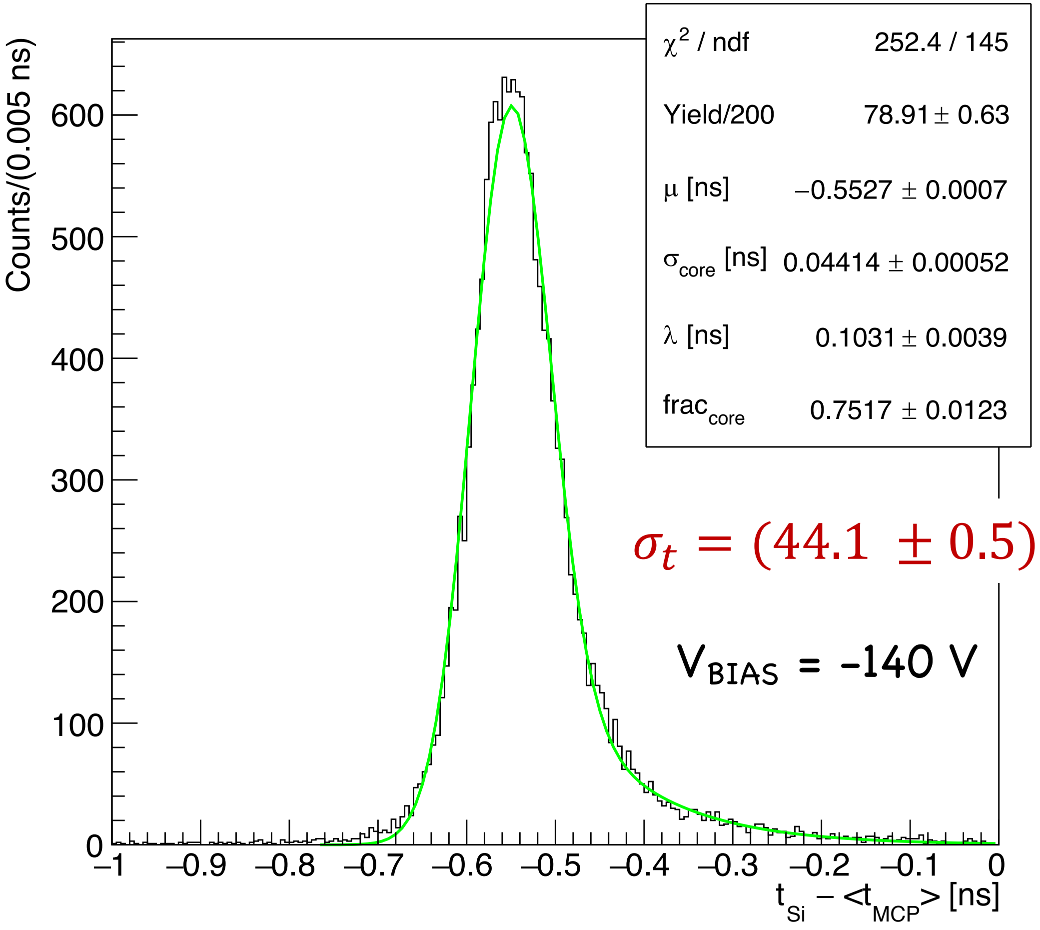
MIP MPV ~ 25 mV

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

First 3D-trench batch: time resolution (I)

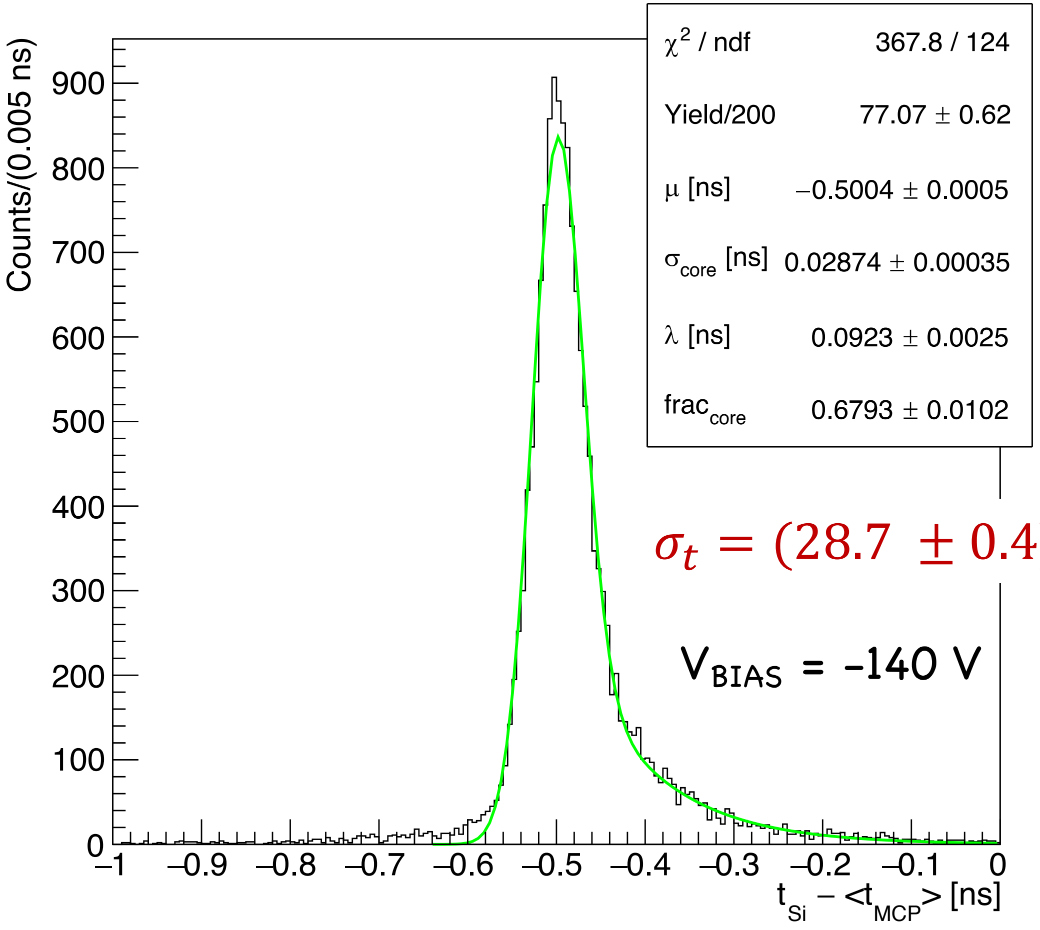
- ToA: numerical leading edge discriminator with a fixed threshold Th=5mV (no TOT correction)



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

V_{BIAS} = -140 V

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

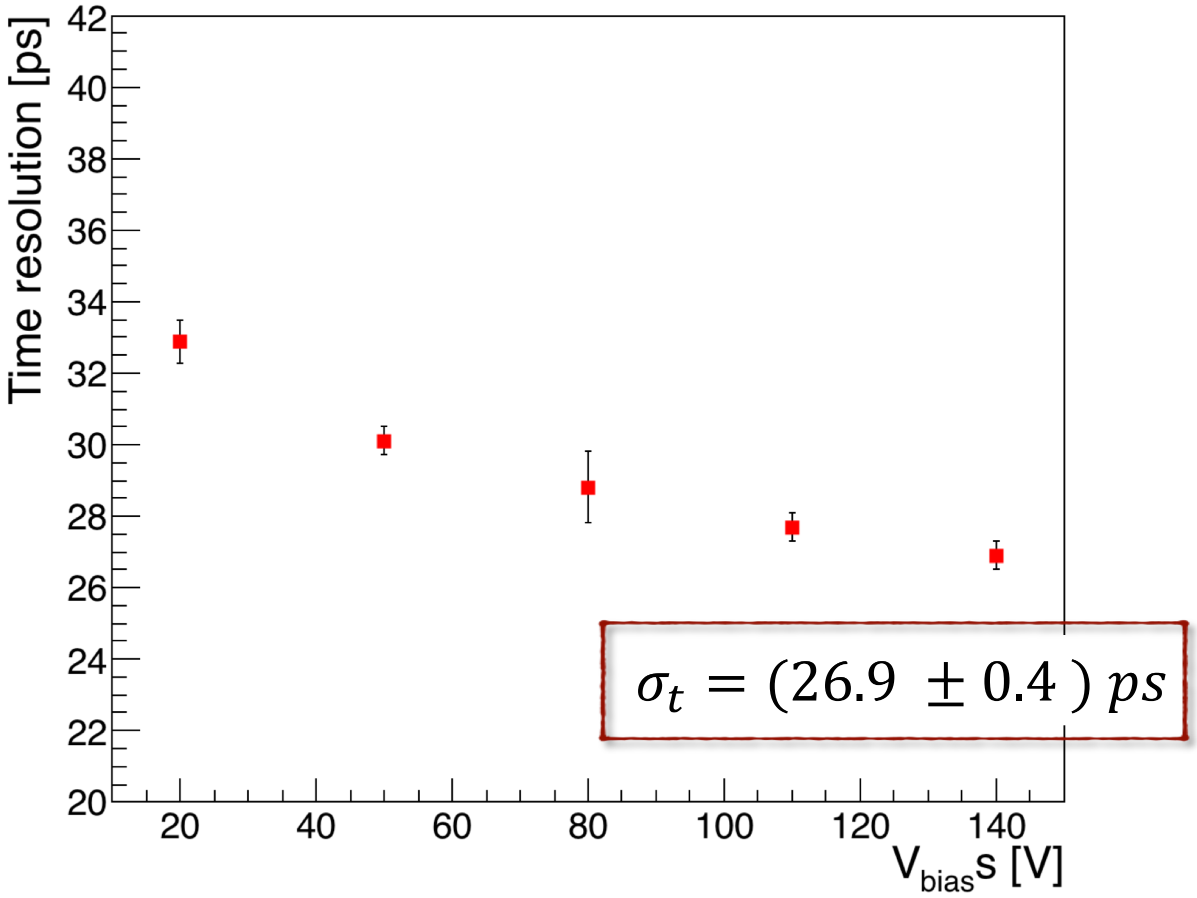


$\sigma_t = (28.7\ \pm 0.4)\ ps$

V_{BIAS} = -140 V

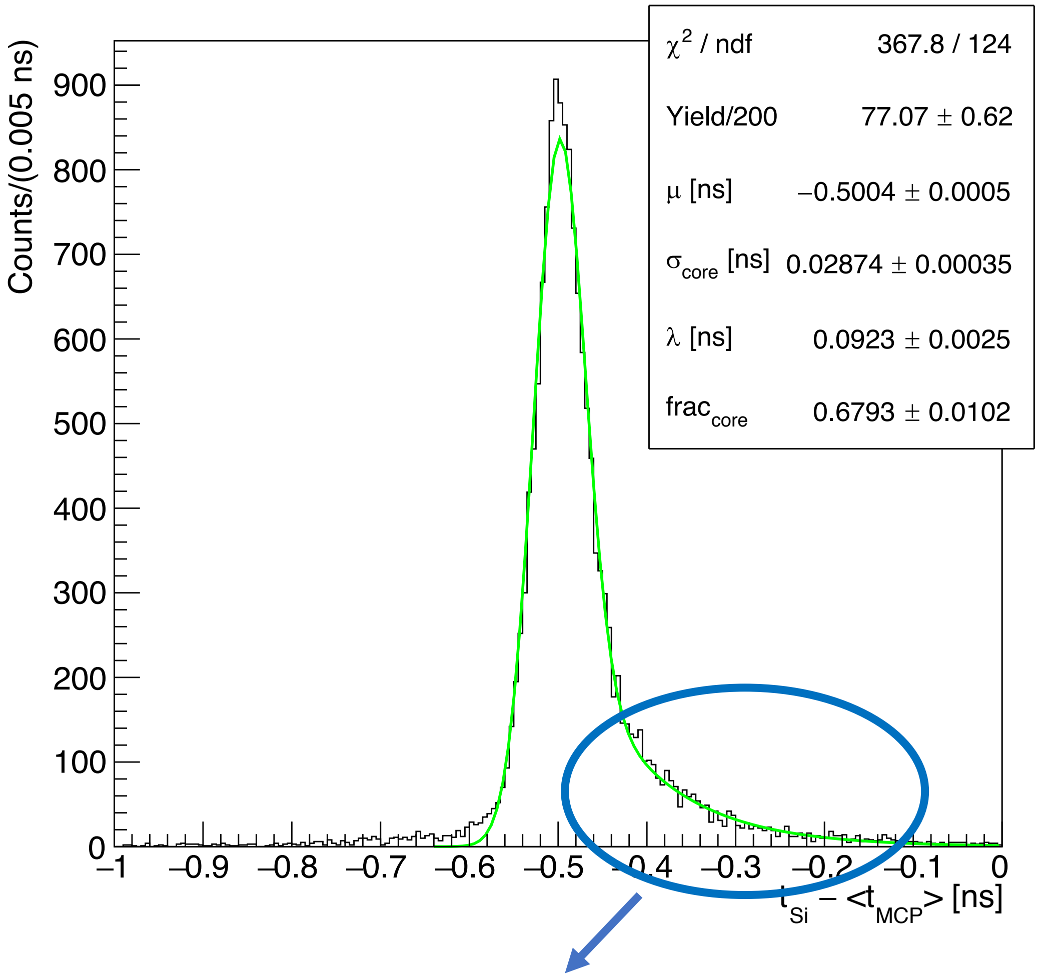
FIT: $f \cdot Gaus(\mu,\sigma) + (1-f)\exp(\lambda) \otimes Gaus(\mu,\sigma)$

First 3D-trench batch: time resolution (II)



$$\sigma_t = (26.9 \pm 0.4)\ ps$$

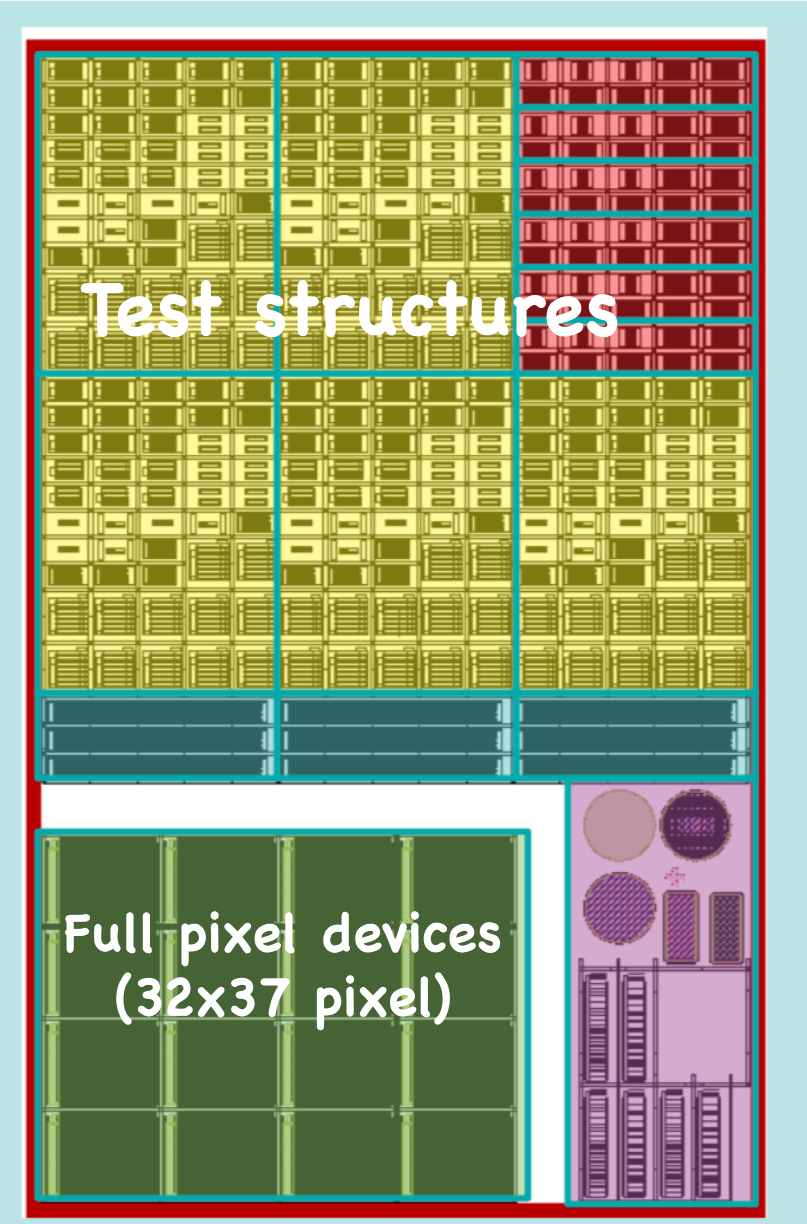
Si-sensor time resolution after deconvolving the MCP time resolution



Combination of 3 main effects:

- Spurious signals (algorithm and in-time EMI noise)
- Partial charge deposit (neighbour un-read pixels)
- Weak field spots

Future production



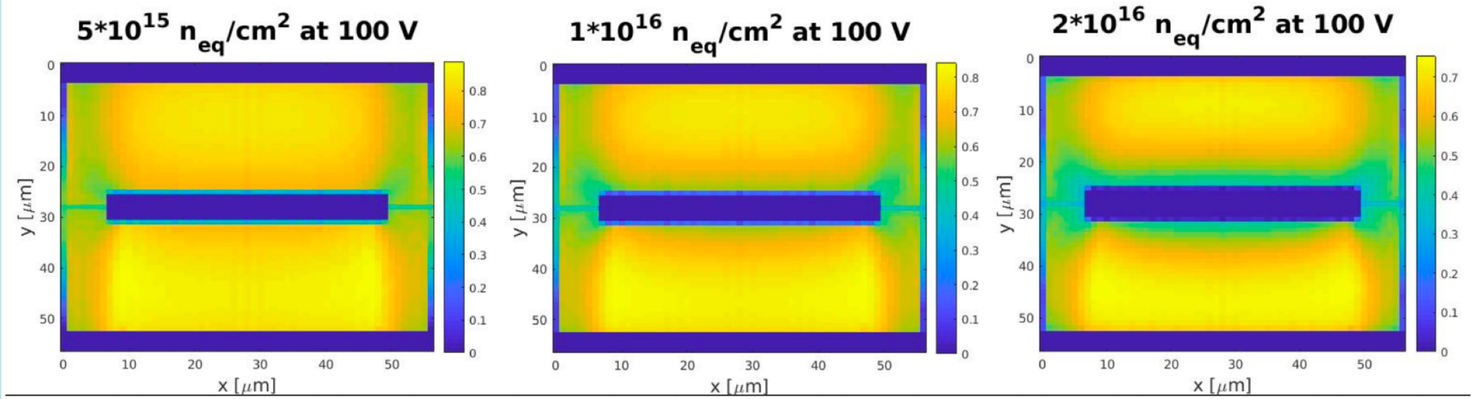
New 3D-trench batch:

- design completed
- production at FBK almost ready to start
- foreseen delivery: second half of 2020

☞ New (and old) devices will be extensively tested in laboratory (with laser and β-source)

☞ Test beam @ PSI in December 2020

☞ Irradiation campaign will be carried out in 2020



Simulated Charge Collection Efficiency

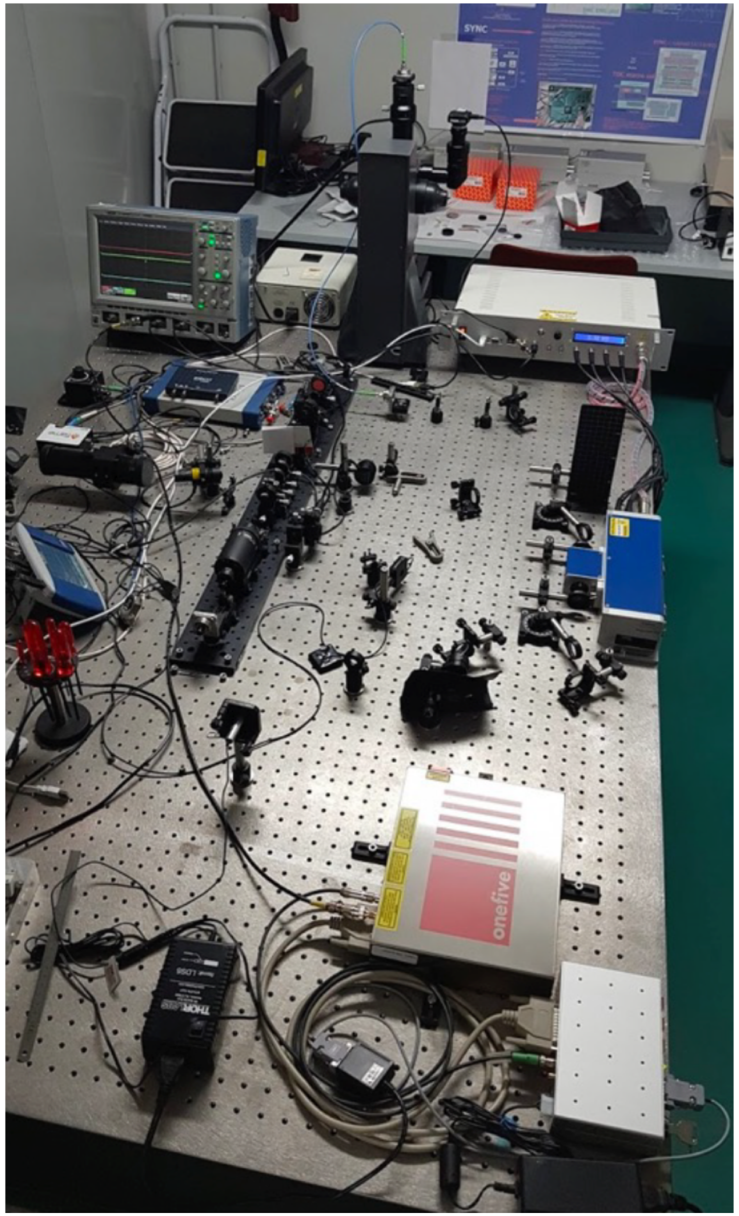
R. Mendicino, '3D trenched-electrode sensors for charged particle tracking and timing' NIMA 927 (2019)

Conclusion

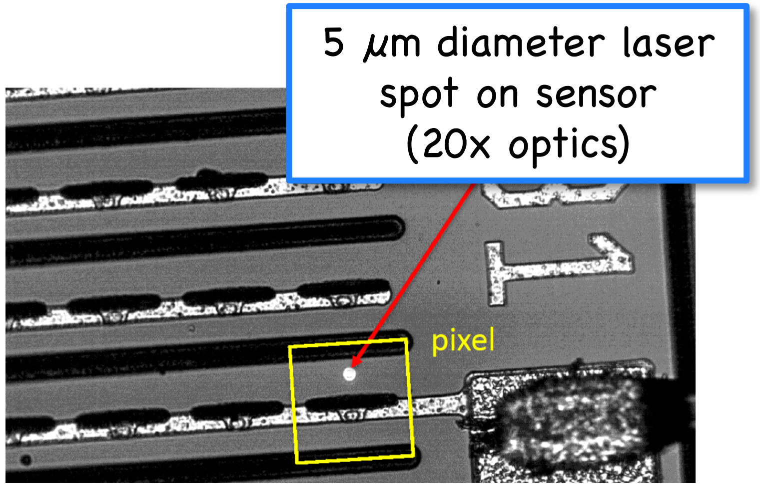
- First measurement of timing perfomance of 3D Silicon pixel sensors based on parallel trench electodes: time resolution below 30 ps
  - Measurement still limited by the front-end electronics
  - New trench electrode design represents a significant step forward towards the optimization of the timing performance of 3D silicon sensors
- Design of the second batch of 3D sensor complete; delivery foreseen in 2020
- Improved dedicated electronics (both discrete components and 28-nm CMOS ASIC) under development

Backup slides

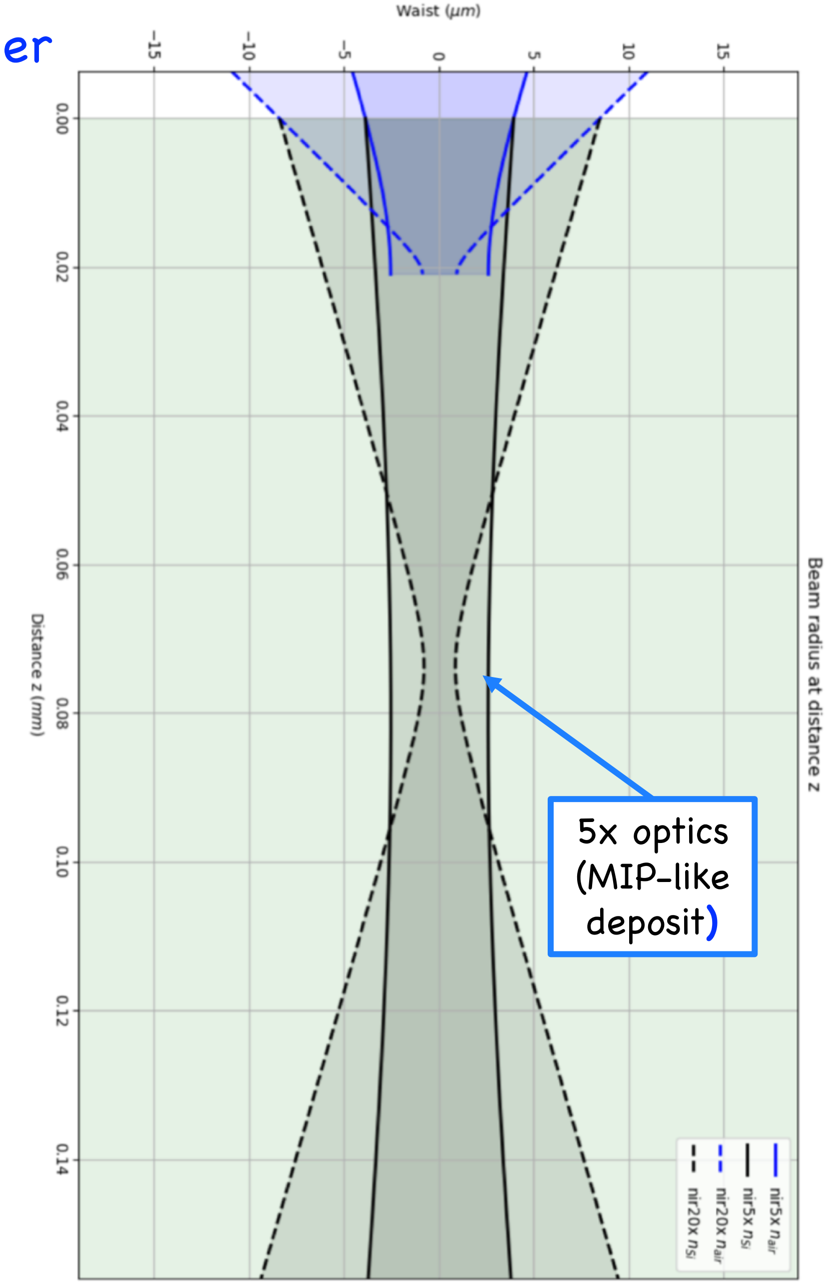
Laser setup @INFN Cagliari



- 1030 nm, 200 fs, 40 MHz pulsed laser
- Pulse-picker to select pulses from 40 MHz to 1MHz
- Monomode fiber to microscope
- 5x and 20x optics
- Optical filters for light intensity attenuation
- Microscope with IR camera

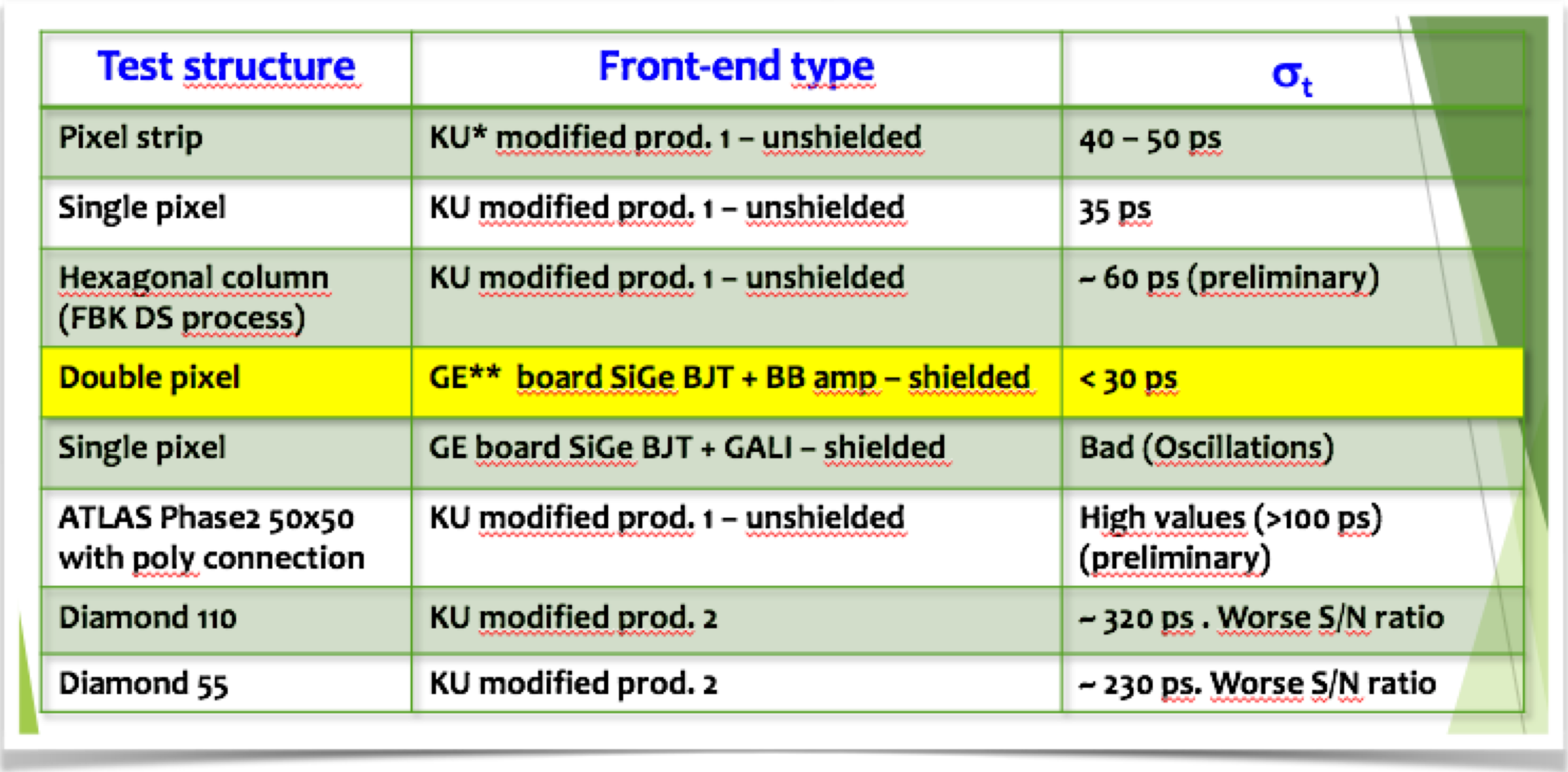


5 μm diameter laser spot on sensor (20x optics)



5x optics (MIP-like deposit)

First 3D-trench batch: test beam "online" results



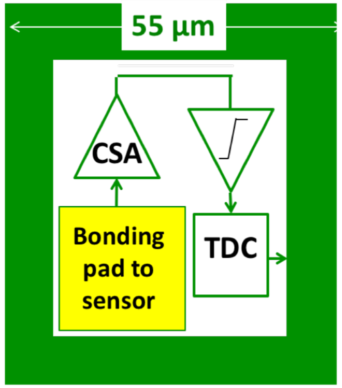
Test structure	Front-end type	σ_t
Pixel strip	KU* modified prod. 1 – unshielded	40 – 50 ps
Single pixel	KU modified prod. 1 – unshielded	35 ps
Hexagonal column (FBK DS process)	KU modified prod. 1 – unshielded	~ 60 ps (preliminary)
Double pixel	GE** board SiGe BJT + BB amp – shielded	< 30 ps
Single pixel	GE board SiGe BJT + GALI – shielded	Bad (Oscillations)
ATLAS Phase2 50x50 with poly connection	KU modified prod. 1 – unshielded	High values (>100 ps) (preliminary)
Diamond 110	KU modified prod. 2	~ 320 ps . Worse S/N ratio
Diamond 55	KU modified prod. 2	~ 230 ps. Worse S/N ratio

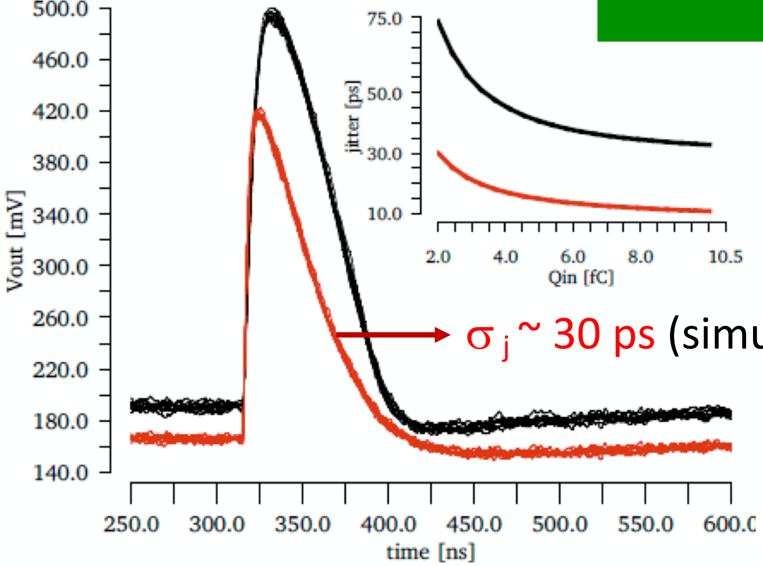
A. Lai – HSTD12 (Hiroshima) – Dec2019

TimeSPOT readout chip

Front-End ASIC prototype on 28nm CMOS technology with full pixel readout chain.

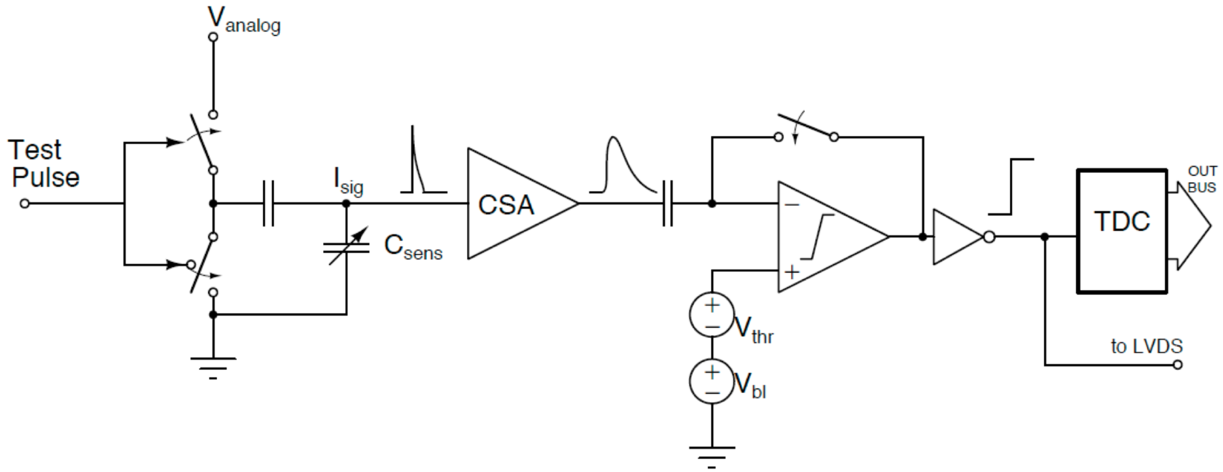
55-pitch pixel integrating CSA+Disc+TDC





σ_j ~ 30 ps (simulation)

«High» power (7.2 µA)
«Low» power (4.1 µA)



- Input stage → Charge Sensitive Amplifier (CSA) with sensor leakage current compensation
- Discriminator → Leading Edge with discrete-time offset compensation
- 1 TDC per channel based on all-digital architecture

☞ First prototype produced with the mini@sic approach (1.5x1.5 μm^2 chip): 3 TDC, 8 CSA+Leading Edge Discriminator, 1 DAC

☞ Measured jitter ~60 ps

☞ A second modified version will be submitted in mid 2020