VCI2025 - The 17th Vienna Conference on Instrumentation

Could we efficiently operate 3D silicon pixel-based tracking detectors irradiated with neutron fluences up to $1 \cdot 10^{18}$ 1 MeV $n_{eq} cm^{-2}$?

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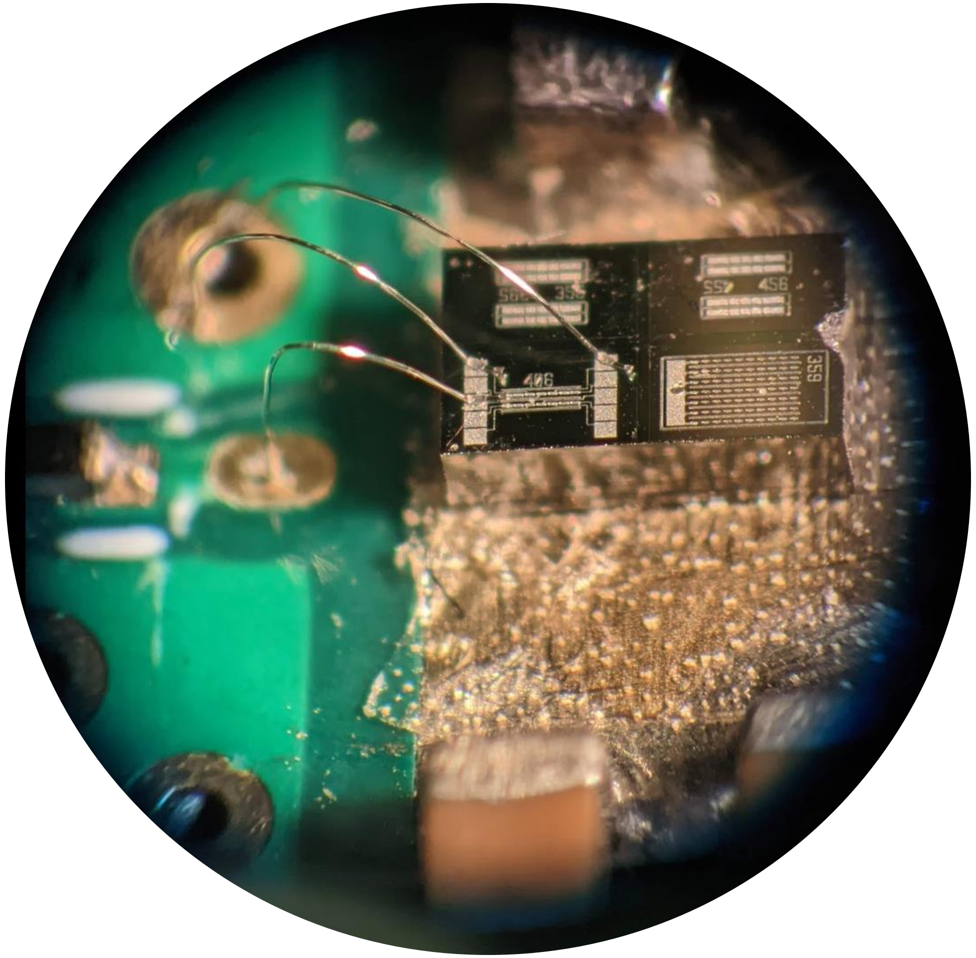
INFN Cagliari

And moreover:
M. Addison, A. Bellora, F. Borgato, M. Boscardin, D. Brundu, A. Cardini, G. M. Cossu, G. F. Dalla Betta, L. La Delfa, A. Lai, A. Lampis, A. Loi, M. M. Obertino, S. Ronchin, S. Vecchi, M. Verdoglia.

*sick with the flu(ence) ☹



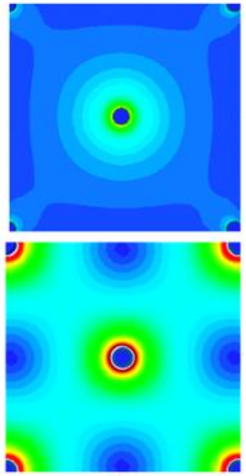
An optimized 3D sensor design for 4D-Tracking

Electrode shape optimisation to increase signals uniformity along the sensor volume

Current signal is defined as

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

5 columns

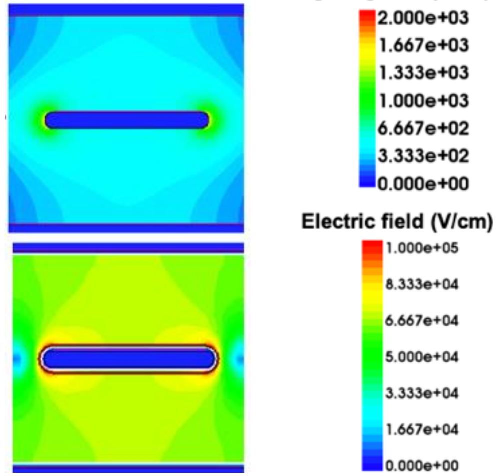


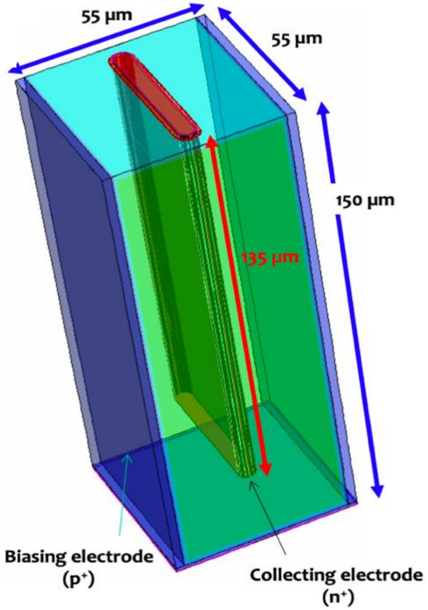
$\vec{E}_w$ uniform by design

Velocity saturation

TCAD Simulations Vbias = – 150 V

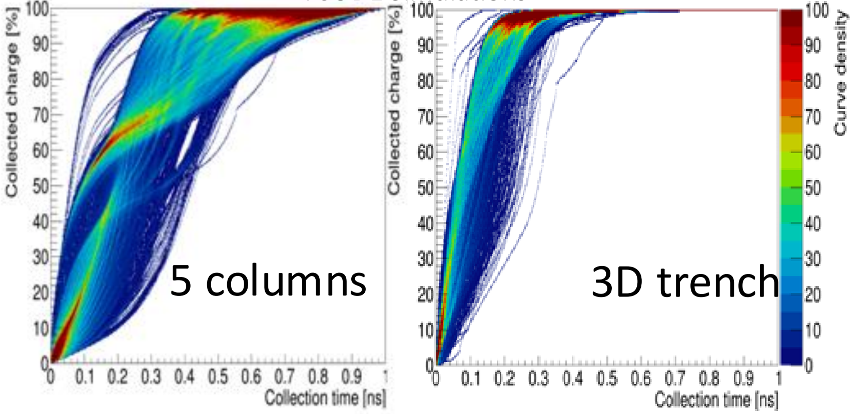
3D trench





Simulated charge collection curves for MIPs uniformly crossing a pixel over its active area

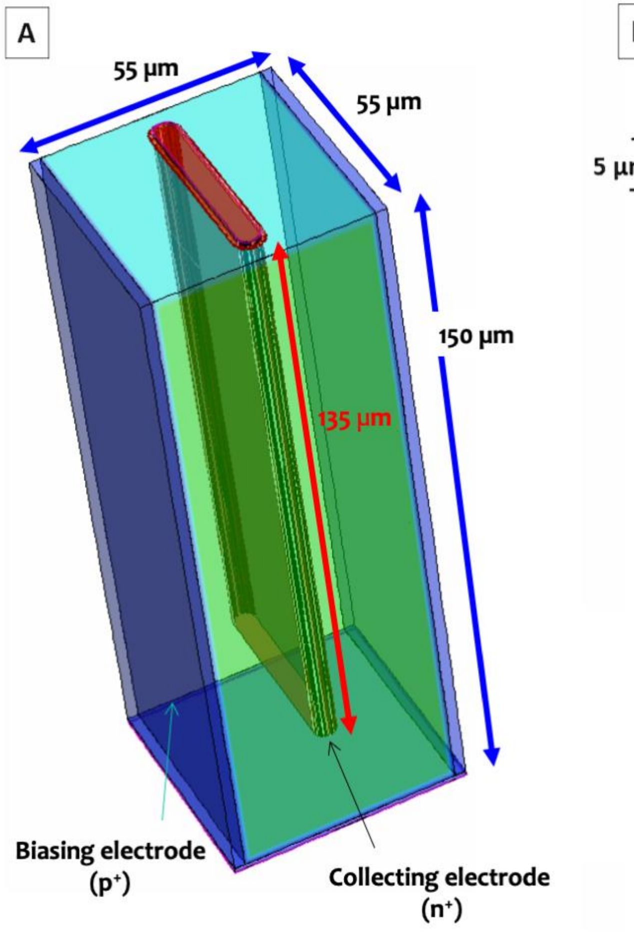
TCODE Simulations

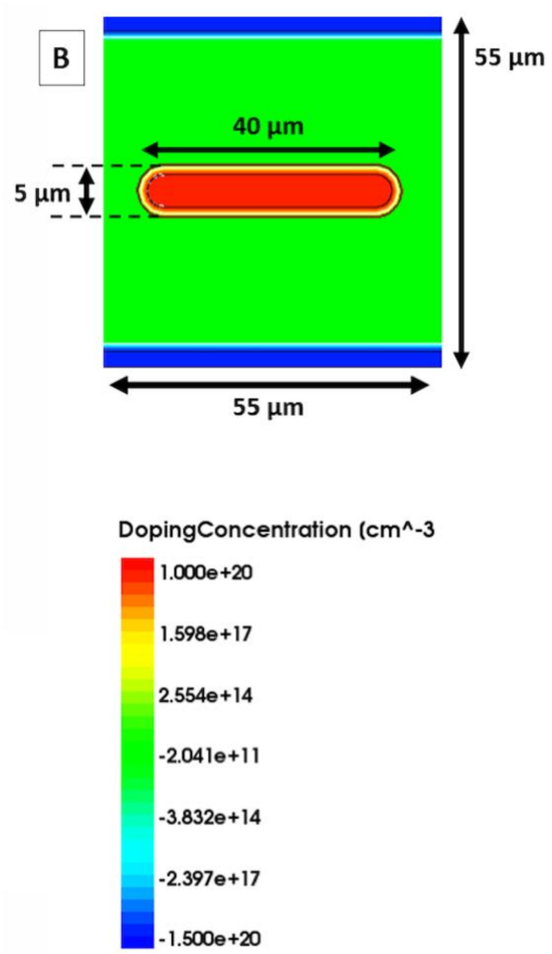


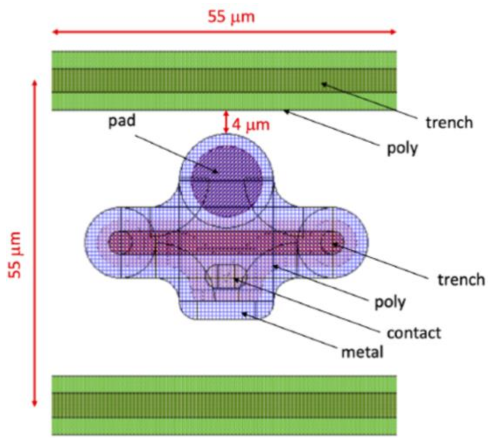
Shorter and much more uniform charge collection time for the 3D trench geometry

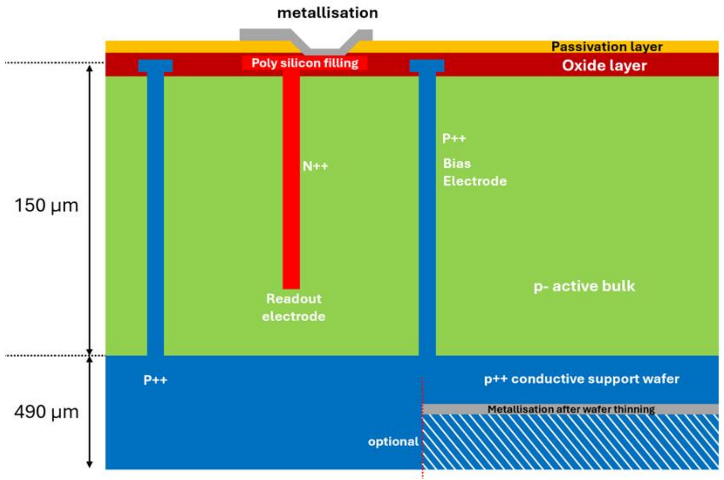
[A. Loi, Design and test of a timing optimized 3D silicon sensor…]

The trench-type TimeSPOT 3D pixels







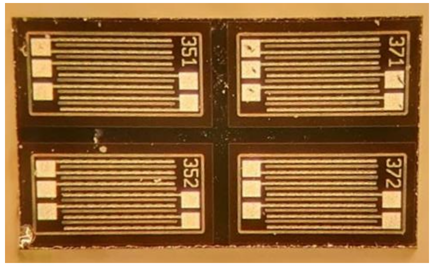


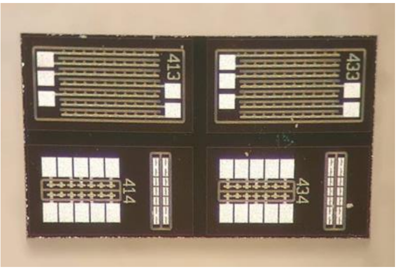
- 55µm x 55µm pixels (to be compatible with existing FEE, for example the Timepix family)
- In each pixel a 40µm long n++ trench is placed between continuous p++ trenches used for the bias
- 150µm-thick active thickness, on a 500 µm-thick support wafer
- The collection electrode is 135µm deep

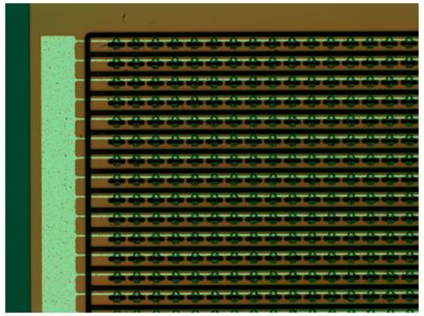
Sensor production

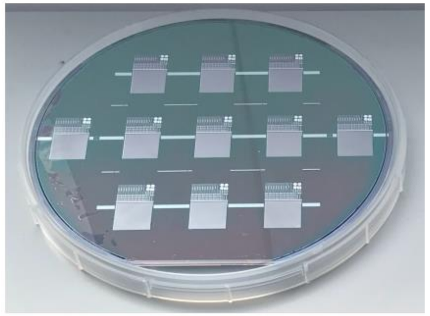
Two batches were produced in 2019 and 2021 at Fondazione Bruno Kessler (FBK, Trento, Italy) using the Deep Reactive Ion Etching Technique (DRIE) Bosch process, 6” wafers

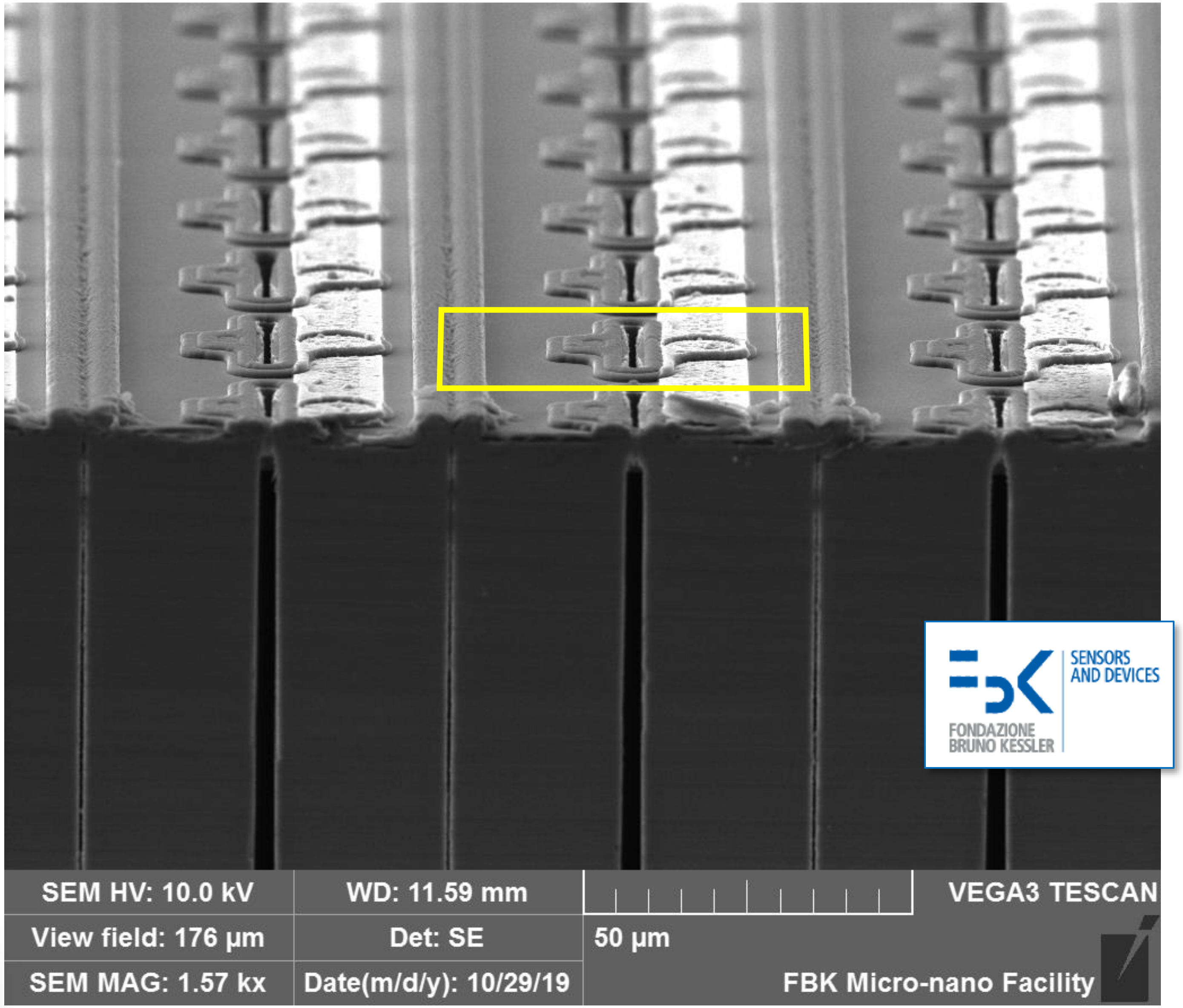
Many teest devices fabricated (single, double pixels, pixel-strips, 18x18 and pixel matrices: 32X32, 256X256)











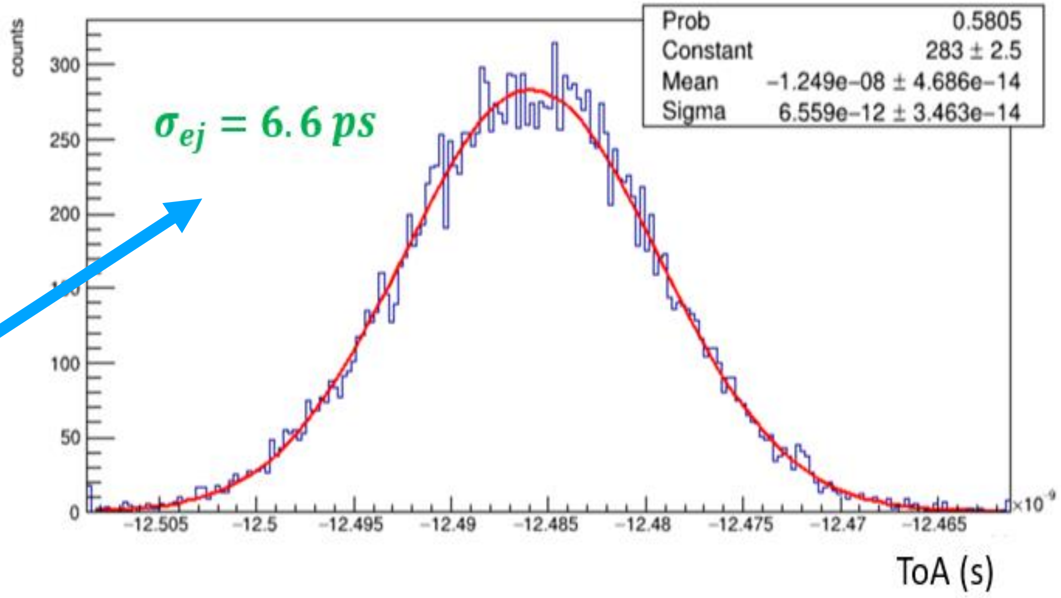
A third (more) optimized batch has been produced in 2024 by FBK within AIDAinnova (soon under test)

Fast Front-End amplifier

- Fast front end amplifiers, developed for the characterization of 3D trench pixels
- Custom-made front-end electronics boards featuring a two-stage transimpedance amplifier made with fast SiGe BJTs

Single channel board

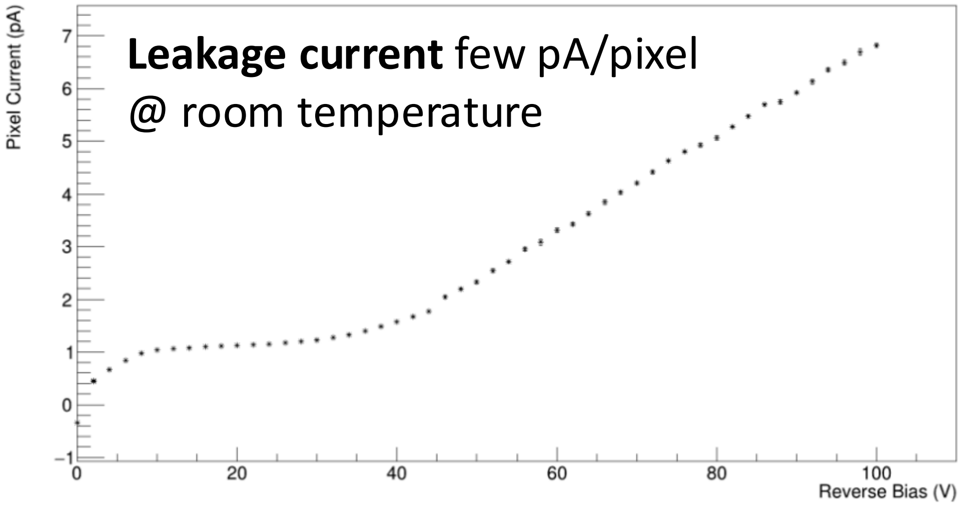
Timing performance of TimeSPOT amplifier board

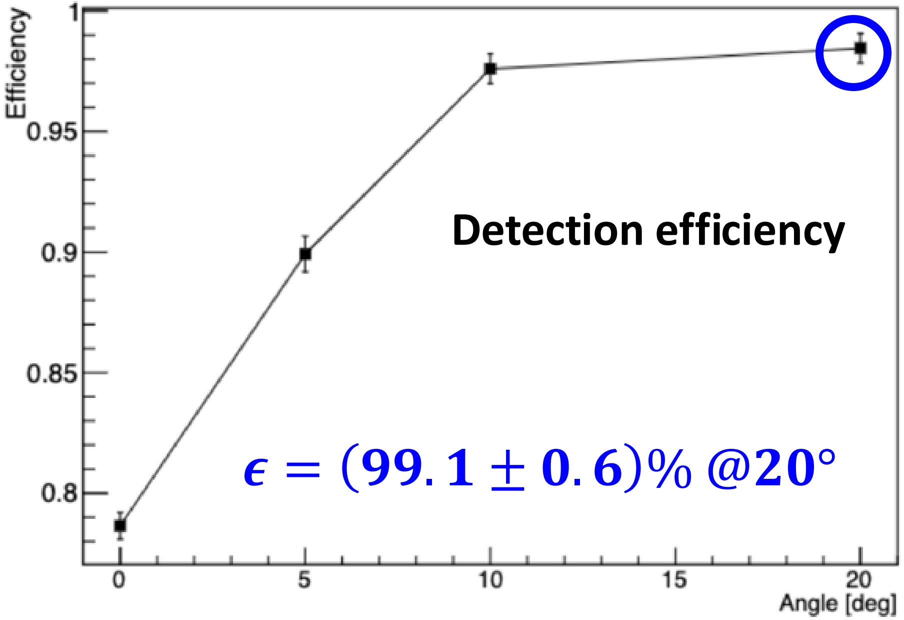


- Excellent tool to evaluate intrinsic sensors performance

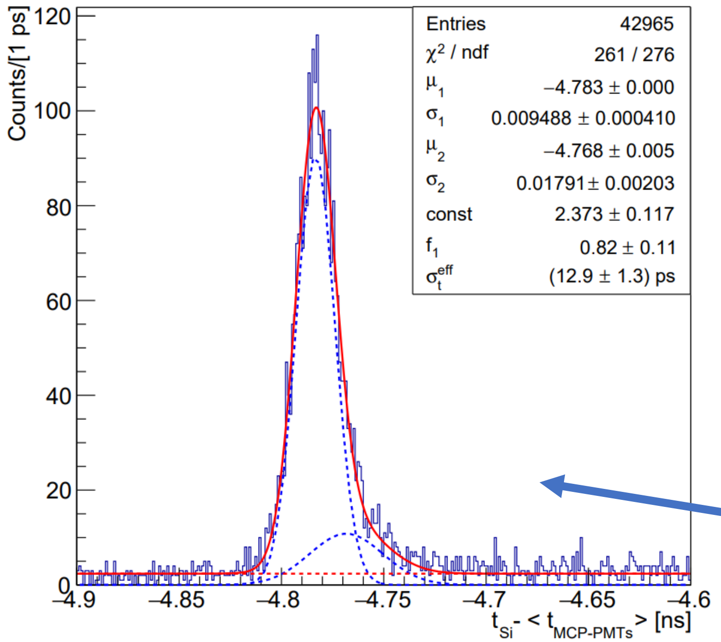
All details in: GM Cossu, A. Lai, *Front-end Electronics for Timing with pico-second precision using 3D Trench Silicon Sensors*, 2023 JINST 18 P01039

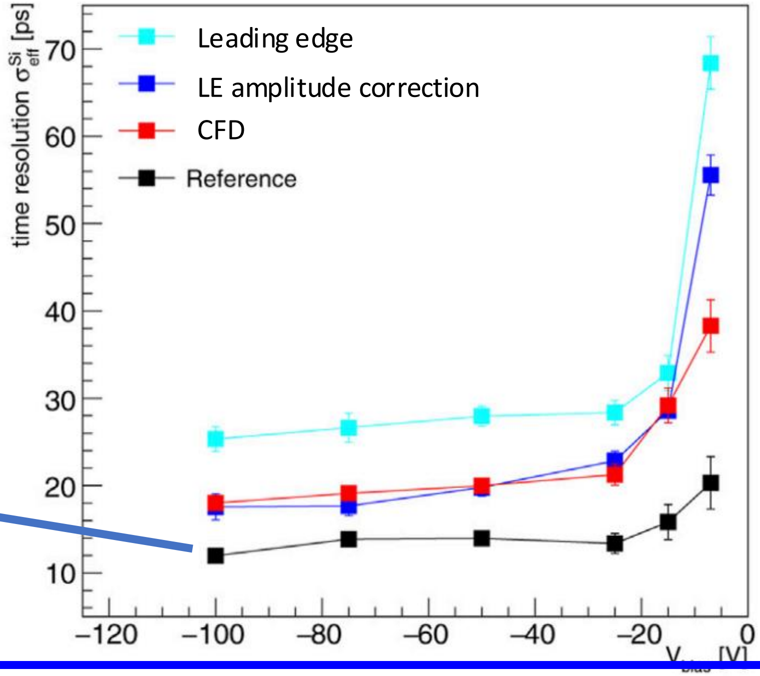
3D trench before irradiation





Time resolution





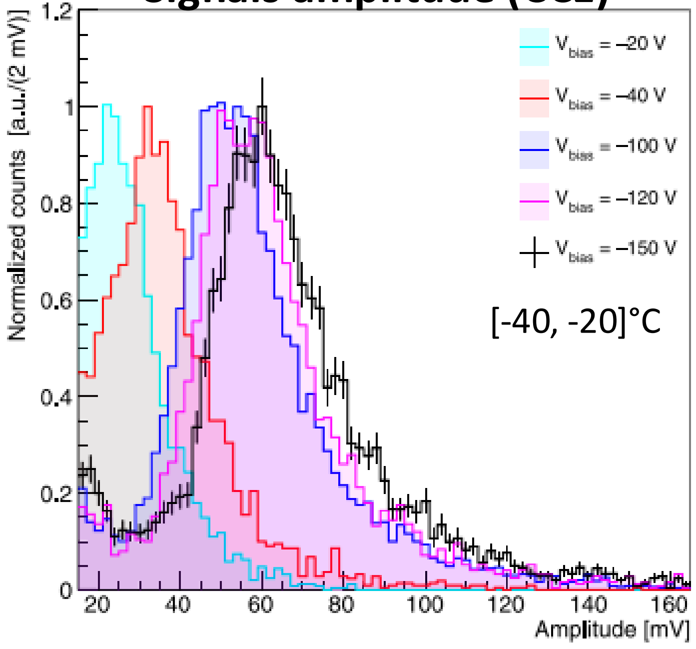
- **Leakage current** under control
- **Time resolution** ~10 ps (25 ps leading edge w/o Time Walk correction)
- 99% **detection efficiency** when operated tilted

[Frontiers in Physics, Charged-particle timing with 10 ps accuracy..]

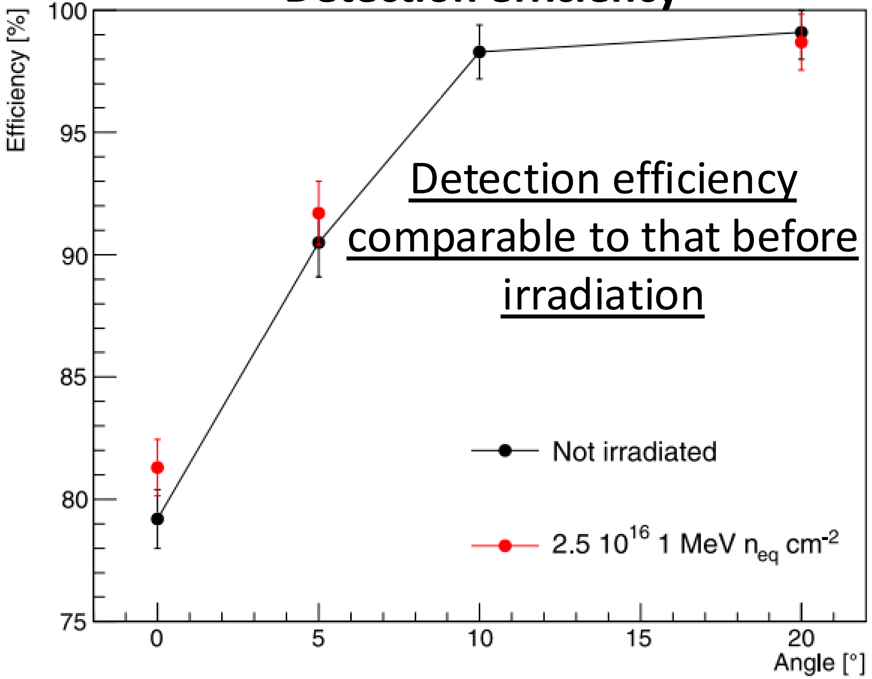
Results after first irradiation

- First irradiation campaign with neutrons at the Triga Mark II Reactor in Lubjana (JSI) up to $\mathbf{2.5 \cdot 10^{16}\ 1\ \mathit{MeV}\ \mathit{n}_{eq}\mathit{cm}^{-2}}$
- **Beam test characterization** with MIPs at the SPS in 2022

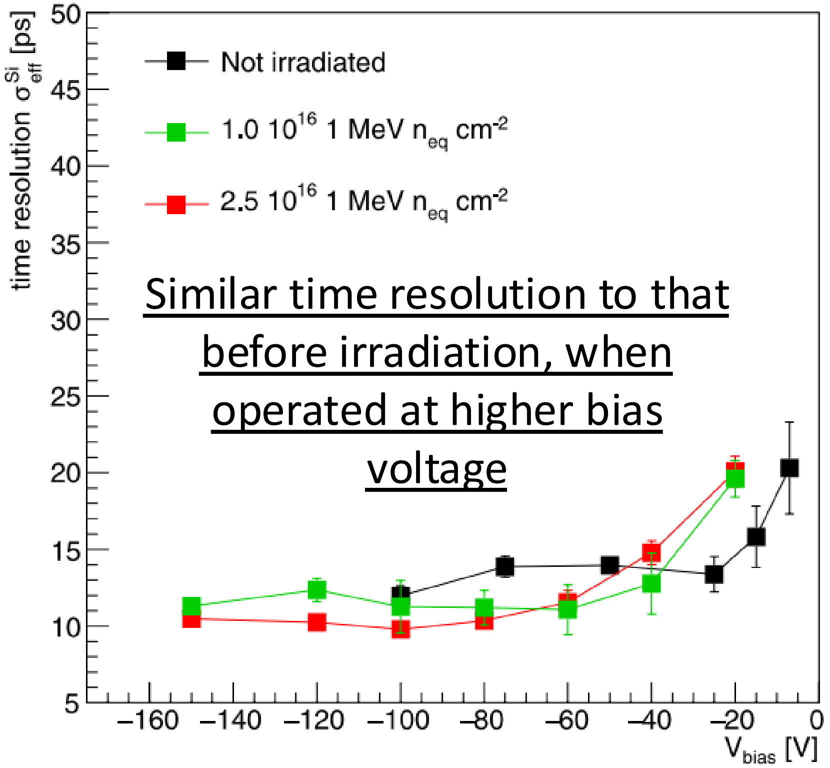
Signals amplitude (CCE)



Detection efficiency



Time resolution



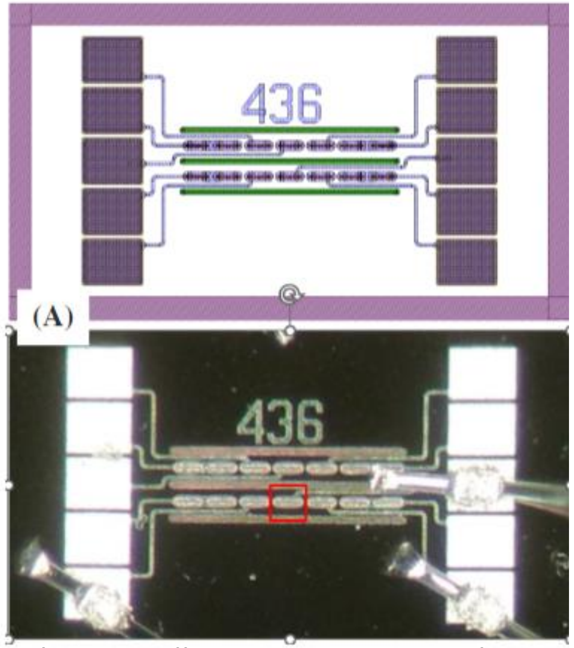
- **Recovery of charge collection if bias voltage is increased by about 50 V**
- **Similar timing and efficiency performance to those before irradiation, obtained with a slight increase of the bias voltages**

Ref: Characterisation of highly irradiated 3D trench silicon pixel sensors for 4D tracking with 10 ps timing accuracy , Frontiers in Phys. 12 (2024)

Second irradiation up to $1 \cdot 10^{17}\ 1\ MeV\ n_{eq}\ cm^{-2}$

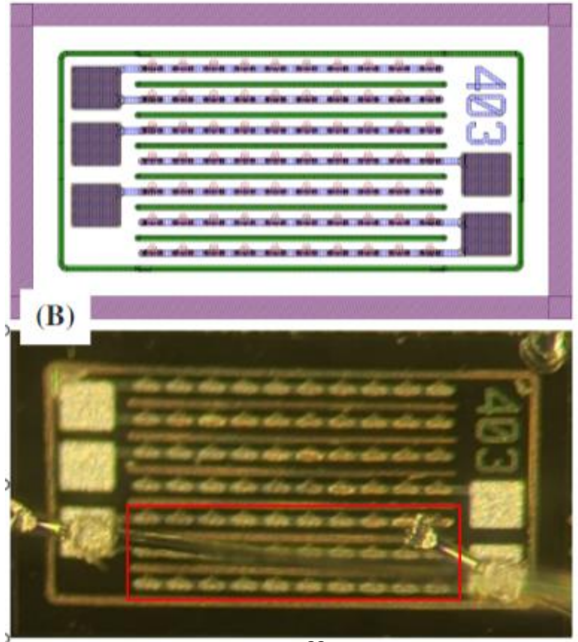
- 3D trench test structures (single pixels and triple strip) irradiated at the Triga Mark II Reactor with neutrons
- Two irradiation fluences $5 \cdot 10^{16}\ 1\ MeV\ n_{eq}\ cm^{-2}$ and $\mathbf{1 \cdot 10^{17}\ 1\ MeV\ n_{eq}\ cm^{-2}}$

Single pixel structure



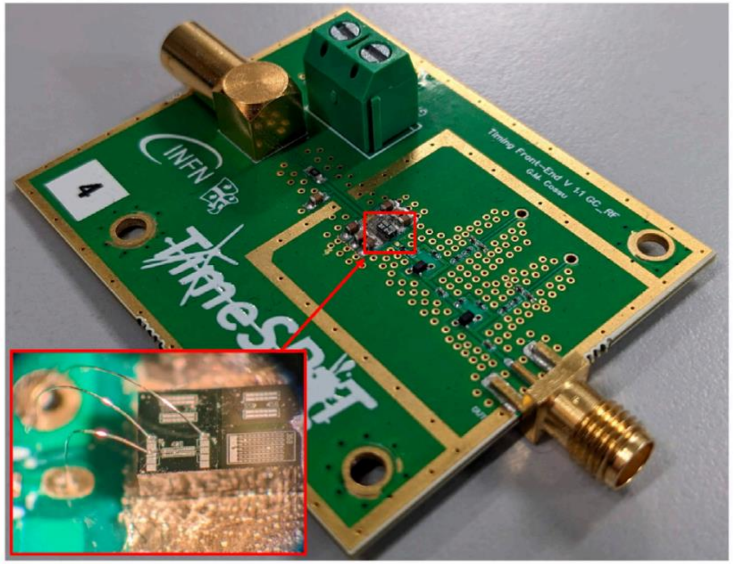
Charge Collection & Time resolution

Triple strip structure



Detection efficiency

Structures wire bonded to the TimeSPOT amplifier and stored back at -20°C

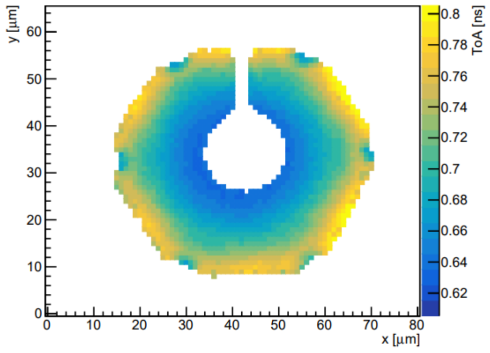


Preliminary measurements with a new TCT-Red cold setup to estimate charge collection efficiency before a beam test

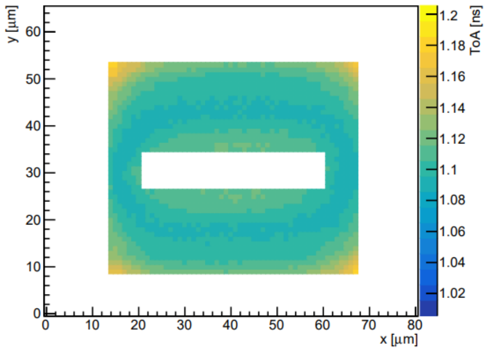
Sensor characterization

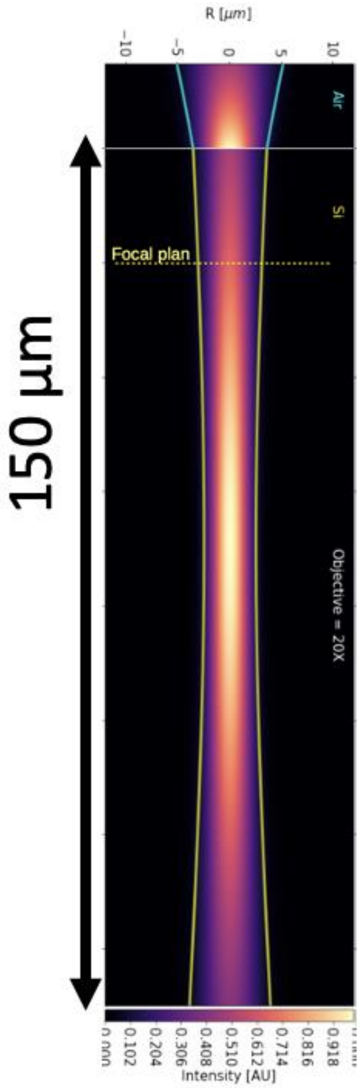
- Sensor characterization campaigns to prove the performance
- A total of 5 beam tests have been conducted at the PSI and SPS north area beam facilities
- We built in the INFN Cagliari Labs dedicated TCT setups to evaluate sensor response at sub-pixel level, with < 1 ps timing accuracy, by using infrared and red lasers → very useful tools for sensor characterization before test beams

Column, hexagon, 60 µm

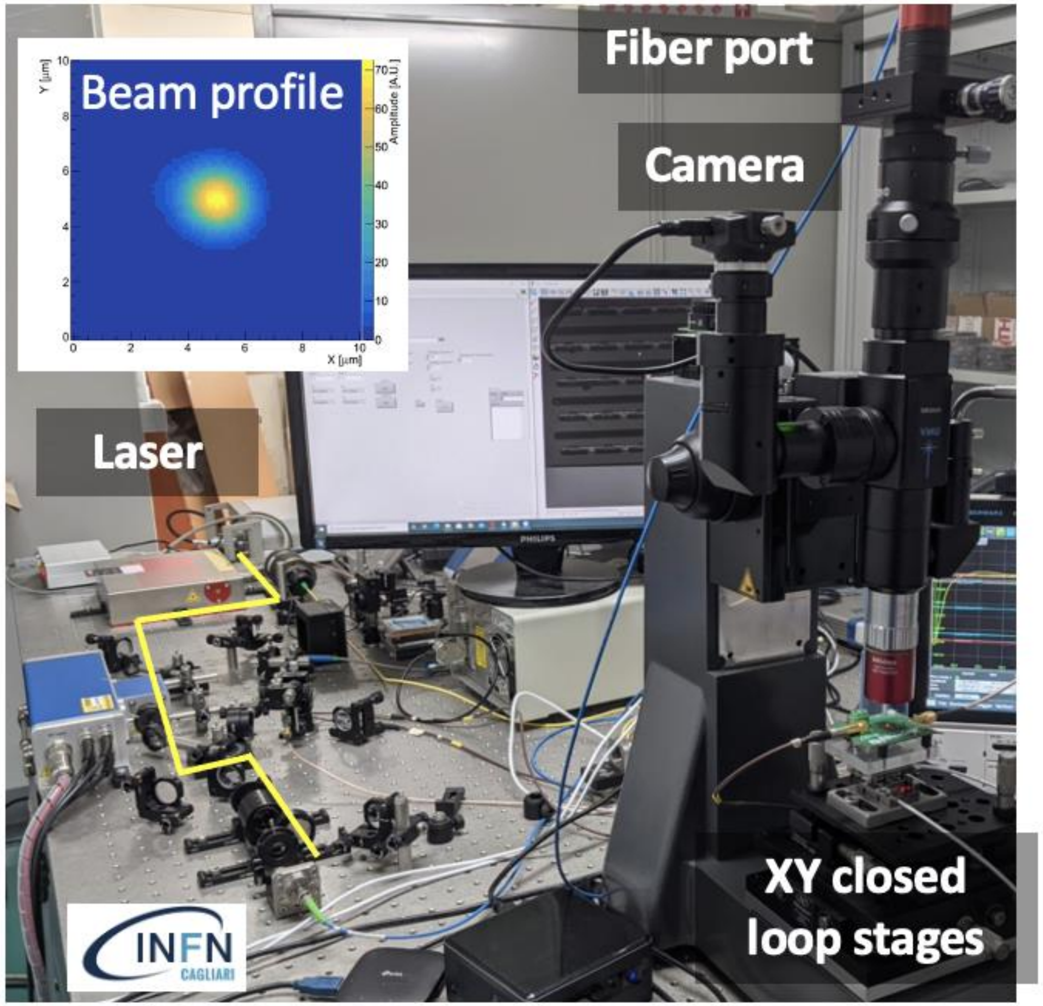


Trench, square, 55 µm



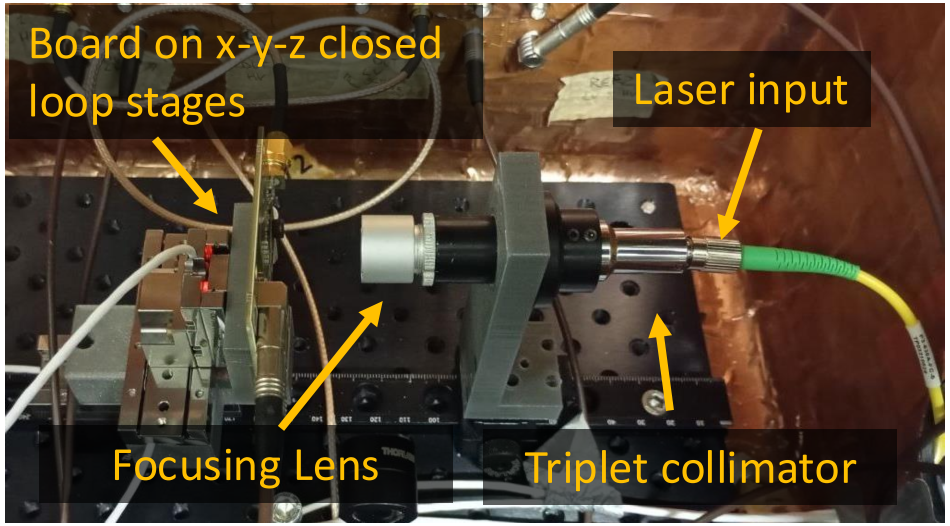


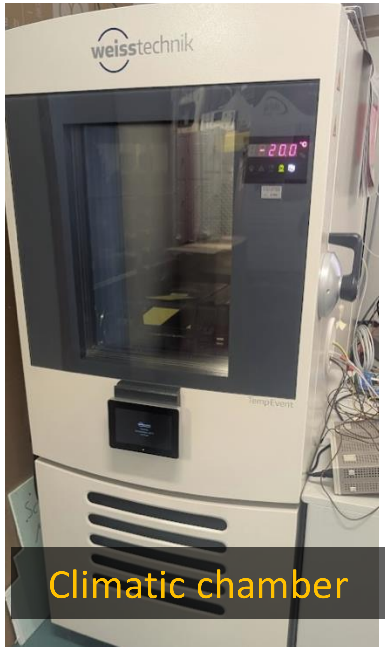
INFN Cagliari TCT setup

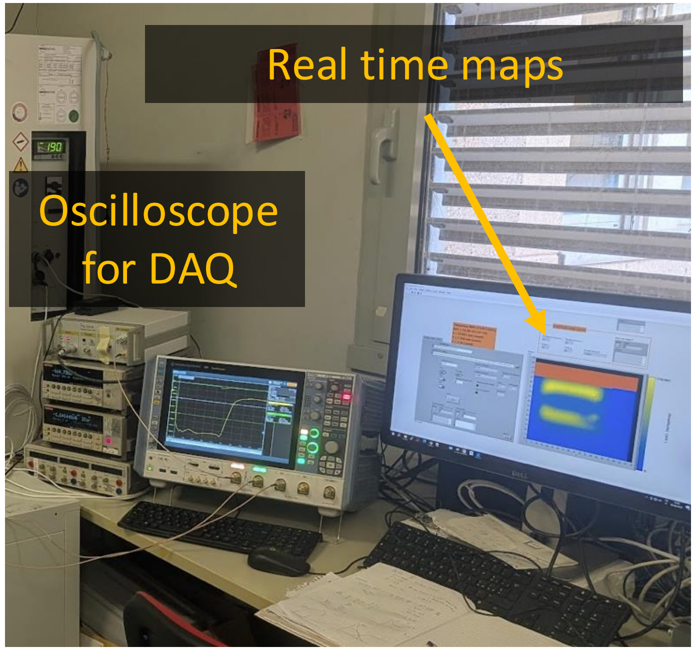


Laboratory characterization of innovative..

Cold TCT-Red setup for irradiated sensors

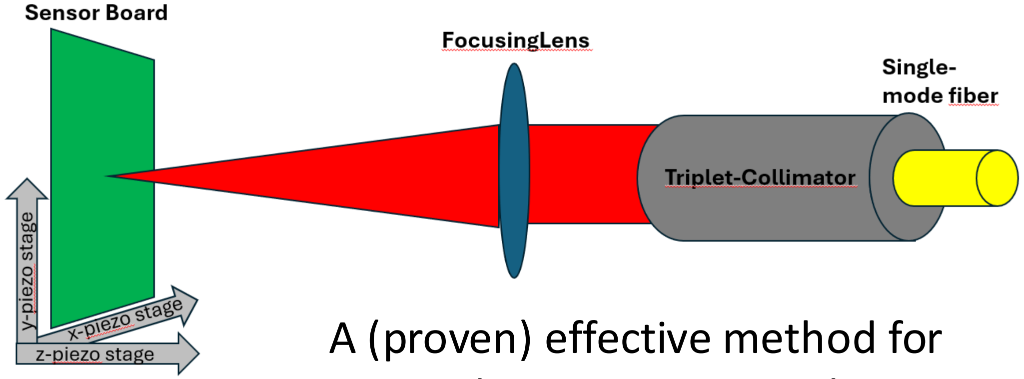






- Pulsed red laser: 650 nm with 50 ps pulse duration: **surface charge deposition**
- Simple optic system allows to have **3-4 μm laser waist** focused on sensor surface
- Stages to perform sensor scan and focus the laser on the sensor

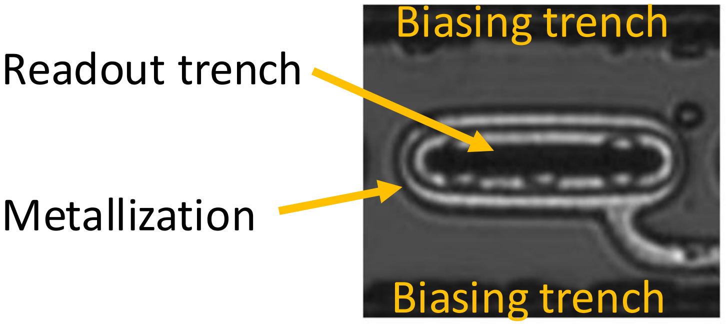
Laser scans to evaluate charge collection efficiency at a subpixel level



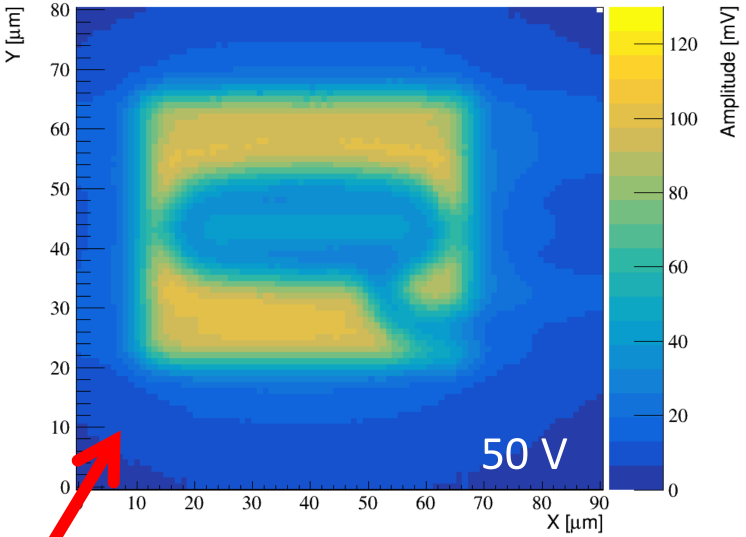
A (proven) effective method for pre-characterization at low temperature

CCE maps

Single pixel

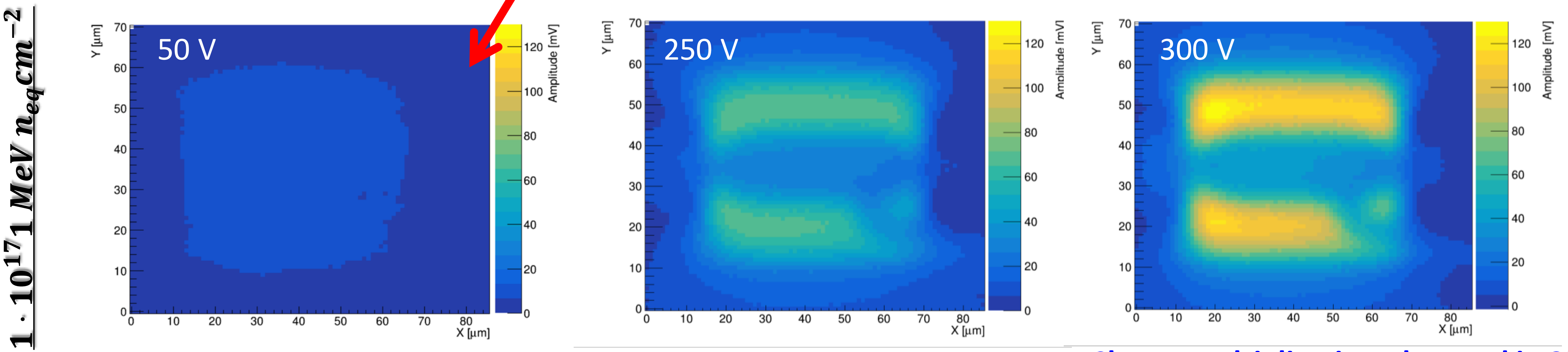


Not-irradiated



Sensors at -20°C

- Laser intensity tuned to have 100 mV on not irradiated sensor, used as a reference
- Maps of Signal Amplitude -> Proportional to collected charge
- CCE maps on irradiated sensor vs bias voltage

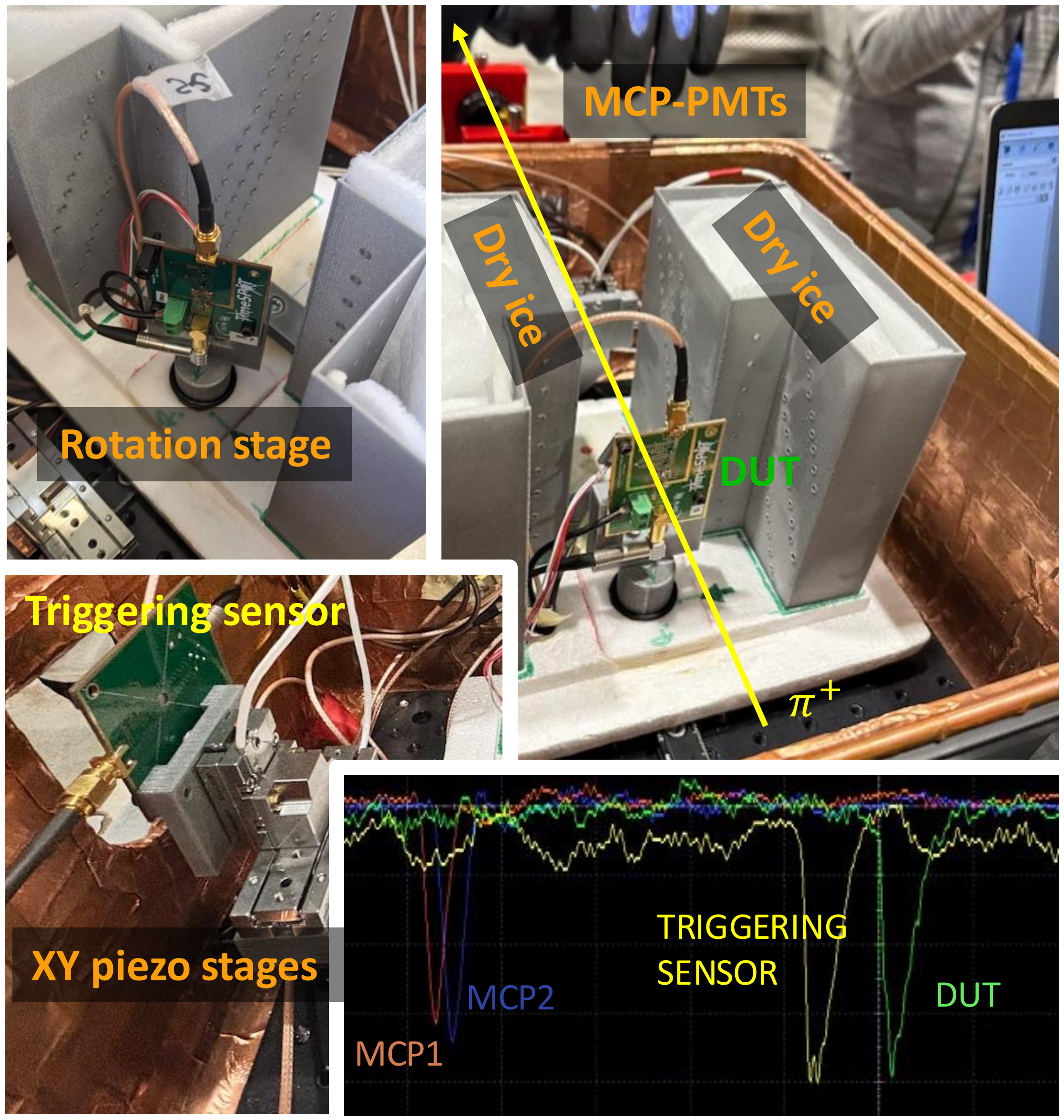


Recovery of collected charge at bias voltages >250 V

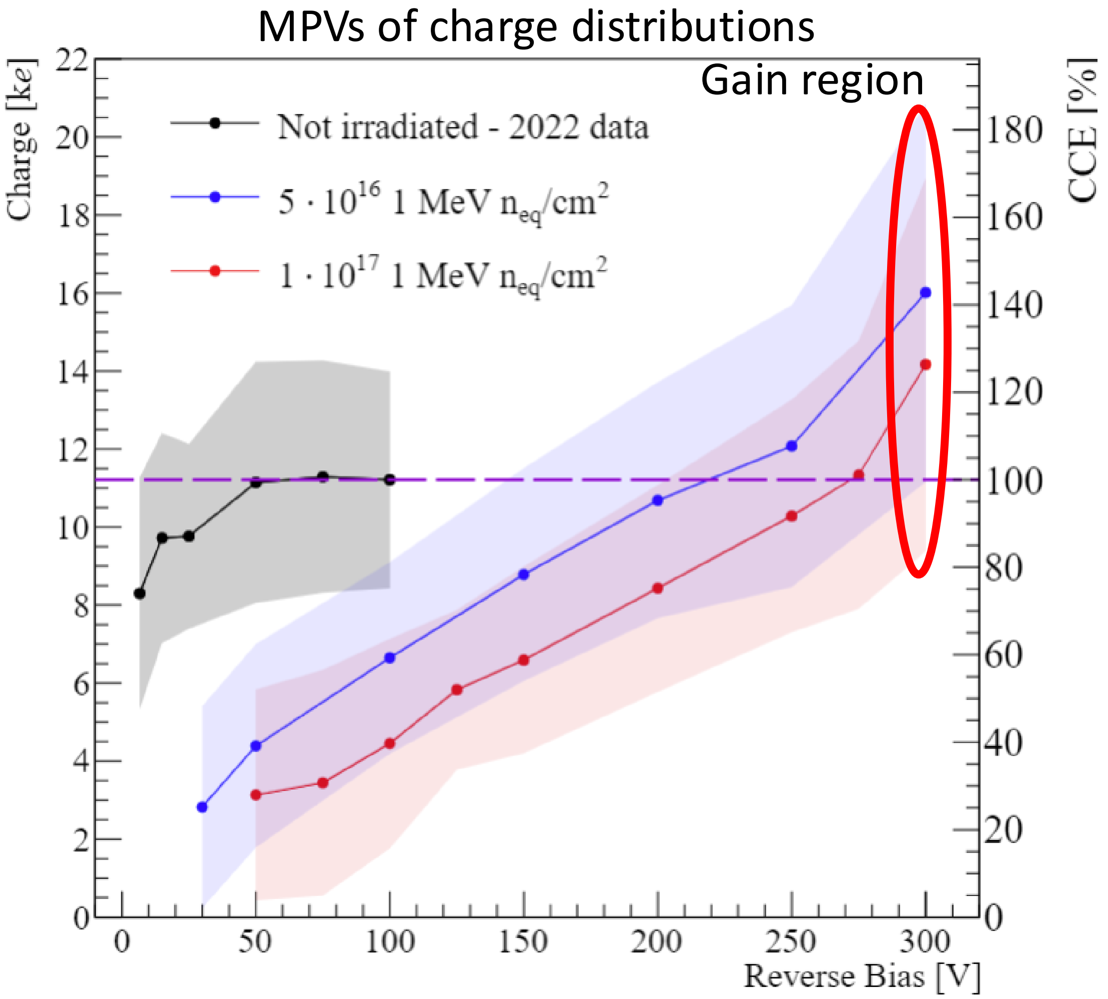
Charge multiplication observed in 3D trench sensors

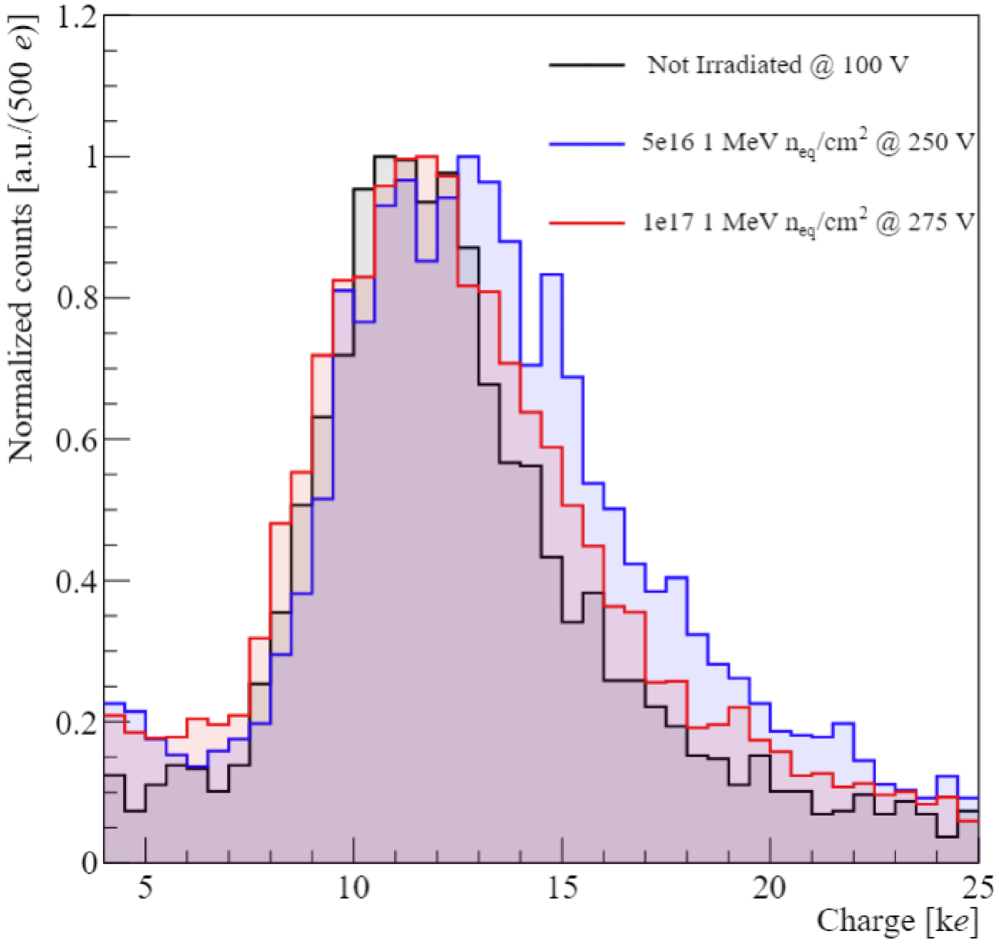
Test beam characterization

- 180 GeV/c π+ beam at the SPS H8 beam line
- Irradiated sensor station thermally isolated, cooled with dry ice [-40,-20]°C.
- Rotational stage to **<u>change DUT tilt angle</u>** with respect to beam direction
- Up to two **MCP-PMTs** to have an accurate reference for particles arrival time with 3-4 ps accuracy
- **Trigger sensors** for the DAQ mounted on XY closed loop translational stages aligned to the DUT to **avoid trigger condition imposed to DUT signals**
- Readout with 8 GHz bandwidth 20 GSa/s oscilloscope, digitization of analogue waveforms to perform **offline analysis**



Results: Charge Collection Efficiency



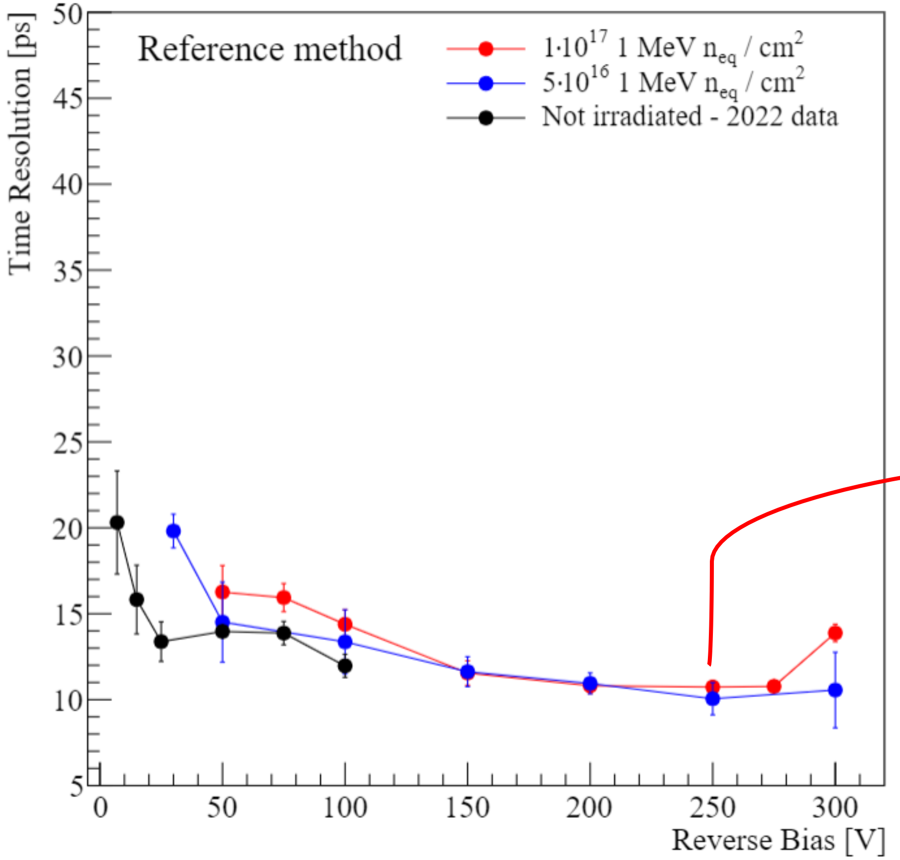


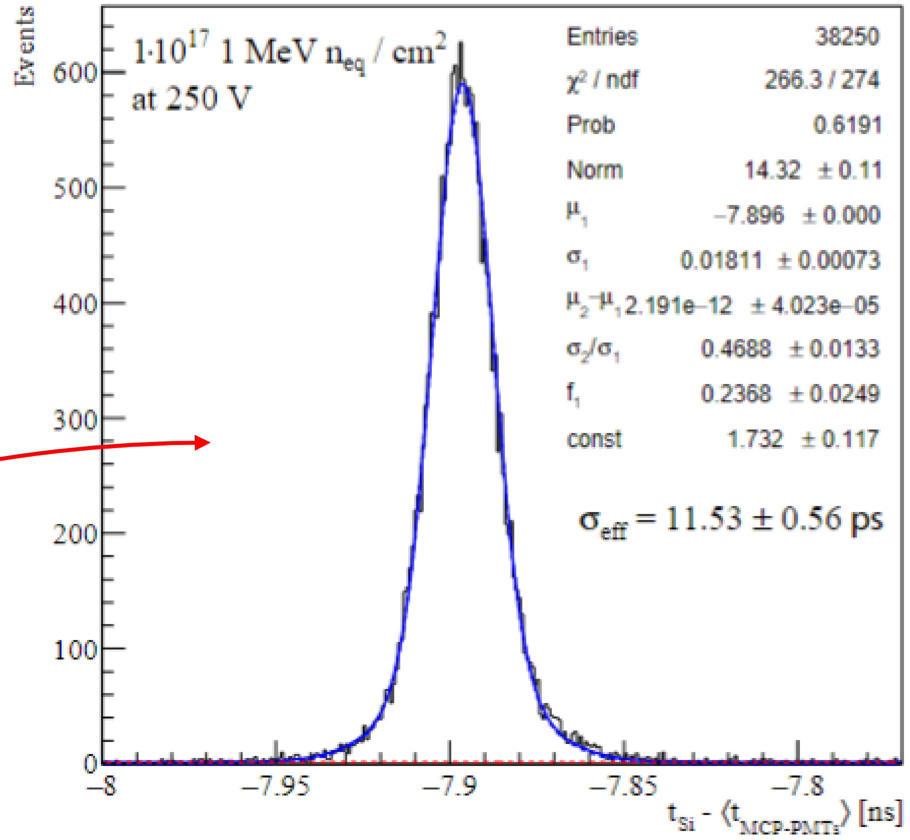
- Results confirmed TCT measurements

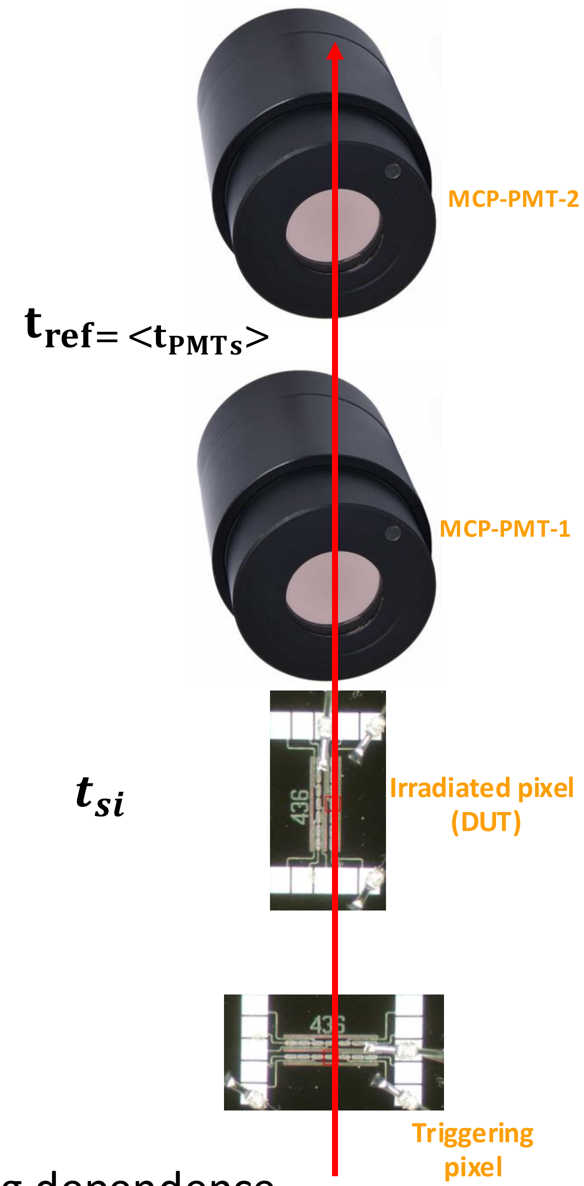
Full recovery of CCE:

- 250 V for the $5 \cdot 10^{16}$ $1\ MeV\ n_{eq}cm^{-2}$
- 275 V for the $1 \cdot 10^{17}$ $1\ MeV\ n_{eq}cm^{-2}$

Results: time resolution

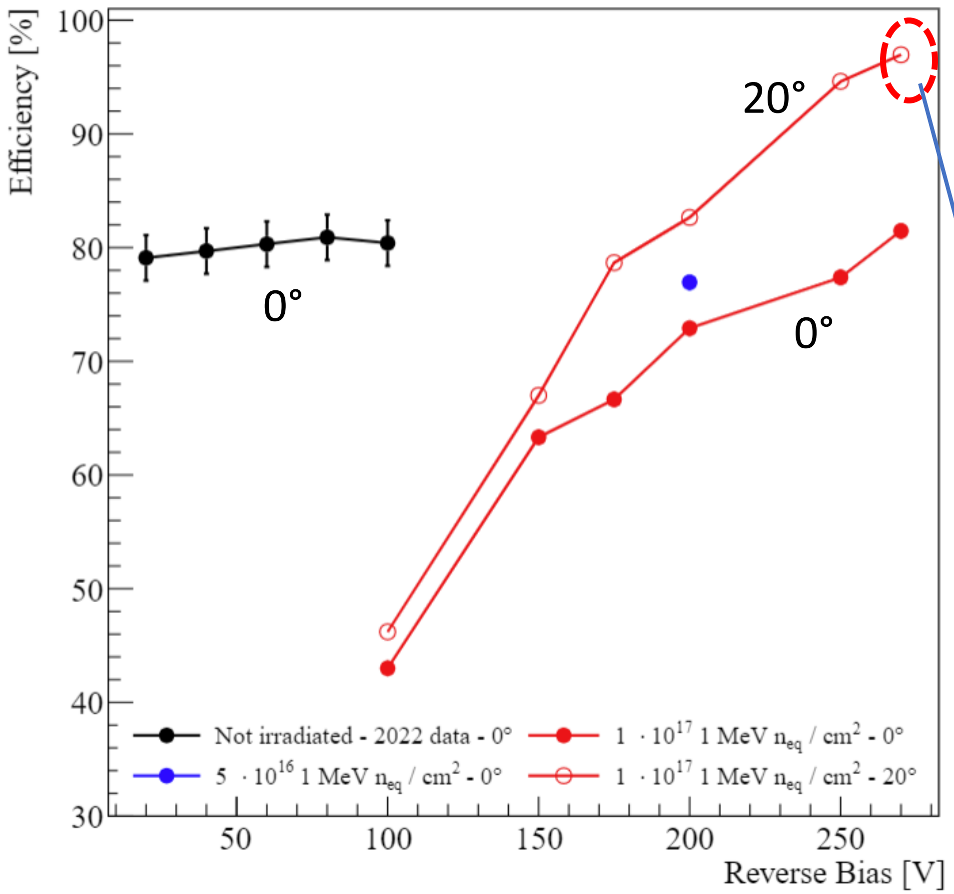


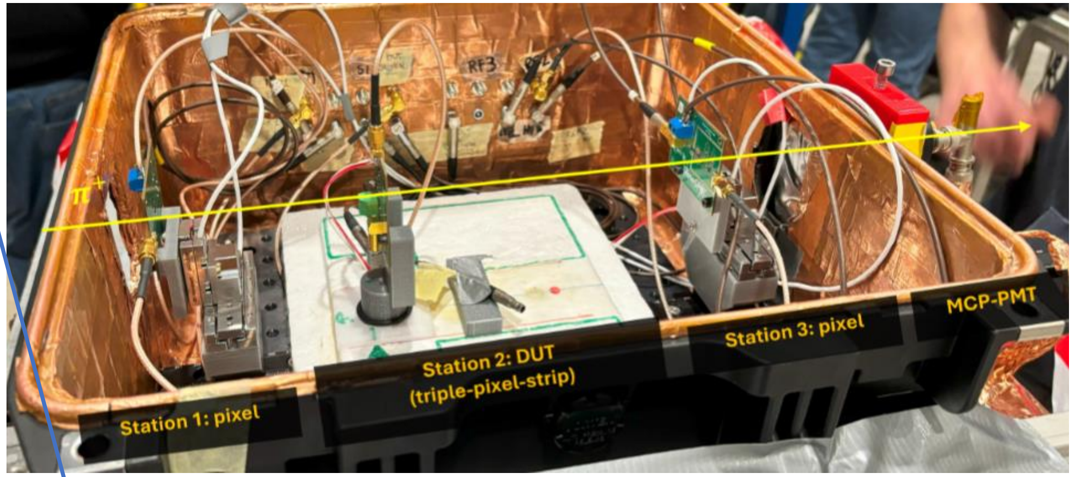


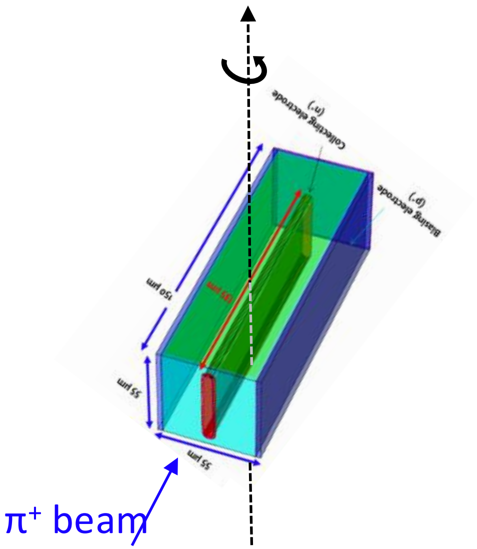


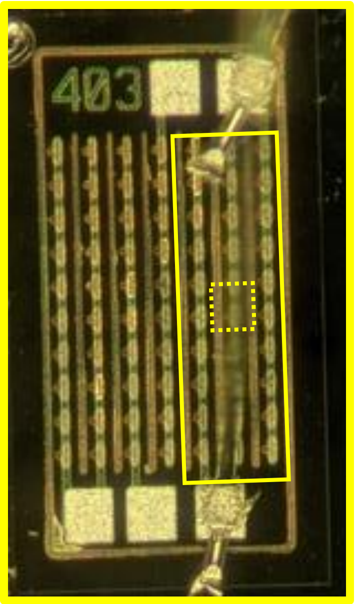
- **Irradiated 3D trench sensors maintain excellent timing performance even after irradiation**
- Higher irradiated sensors requires higher bias voltage to minimize time resolution, but no strong dependence

Results: detection efficiency









(96.8±0.6)% vs (99.1 ± 0.6)%

$1 \cdot 10^{17}\ 1\ MeV\ n_{eq}cm^{-2}$

Not irradiated

Only 2% degradation after irradiation

The beam test confirmed the preliminary measurements, proving that 3D trench sensors maintain the performance up to fluences of $10^{17}\ 1\ MeV\ n_{eq}cm^{-2}$

Characterisation of 3D trench silicon pixel sensors irradiated at 1·1017 1 MeV n_{eq} cm-2, Frontiers in Physics 12-2024

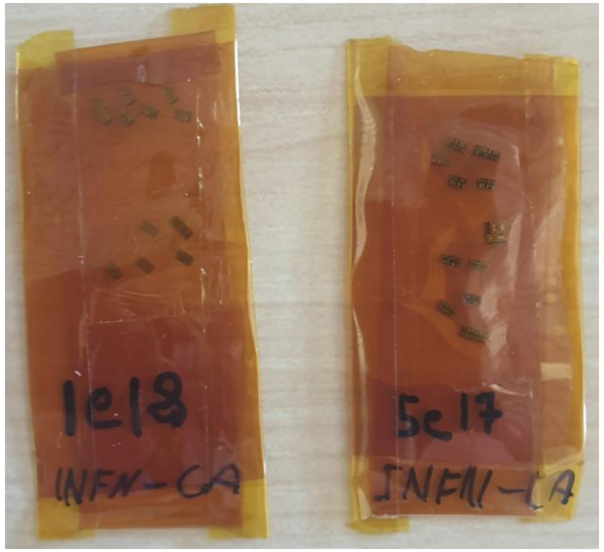
Third irradiation up to $1 \cdot 10^{18}\ 1\ MeV\ n_{eq}\ cm^{-2}$

Irradiation founded by European Union
Grant Agreement No. 101057511

- Irradiation at the JSI in Lubjana, Triga Mark II Reactor, fluences up to $5 \cdot 10^{17}\ 1\ MeV\ n_{eq}\ cm^{-2}$ and $\mathbf{1 \cdot 10^{18}\ 1\ MeV\ n_{eq}\ cm^{-2}}$
- One of the first attempt to irradiate silicon sensors to these unreached fluences
- 40 hours nearby the reactor at full power, maximum temperature of the samples during irradiation ~ 100°C

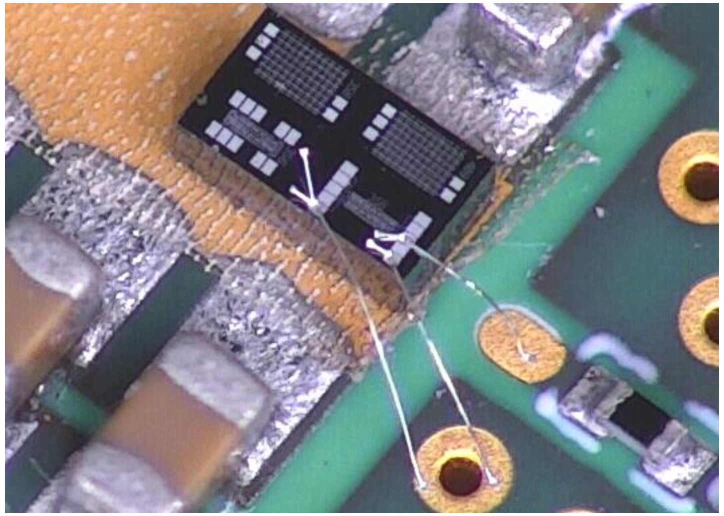
many thanks to Igor Mandic (JSI) for taking care of the irradiation

Sensors prepared for irradiation



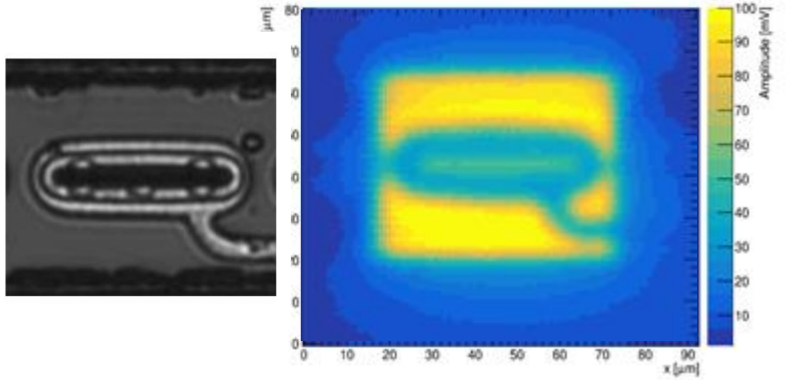
Samples after irradiation

Sensors wire bonded and stored back @ -20°C



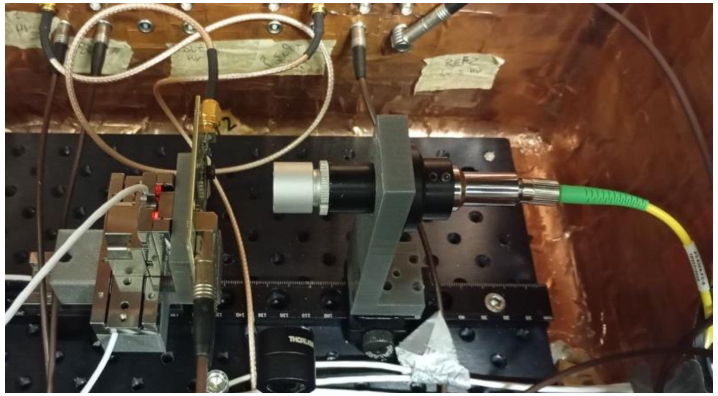
TCT scans CCE

Not-irradiated @ 50 V



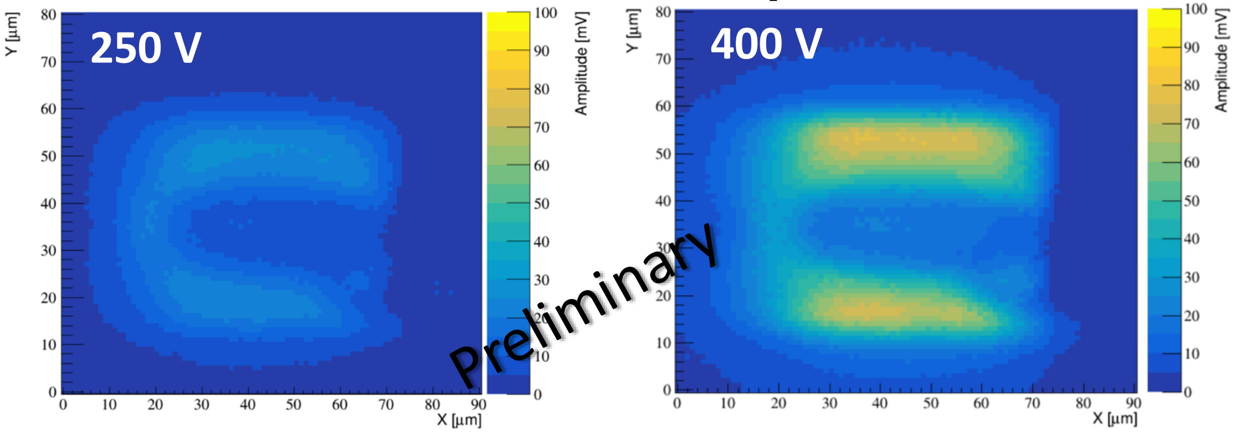
- Laser intensity tuned to have 100 mV on not irradiated sensor, used as a reference
- CCE evaluated as fraction of amplitude with respect to reference sensor

Sensors tested at -20°C



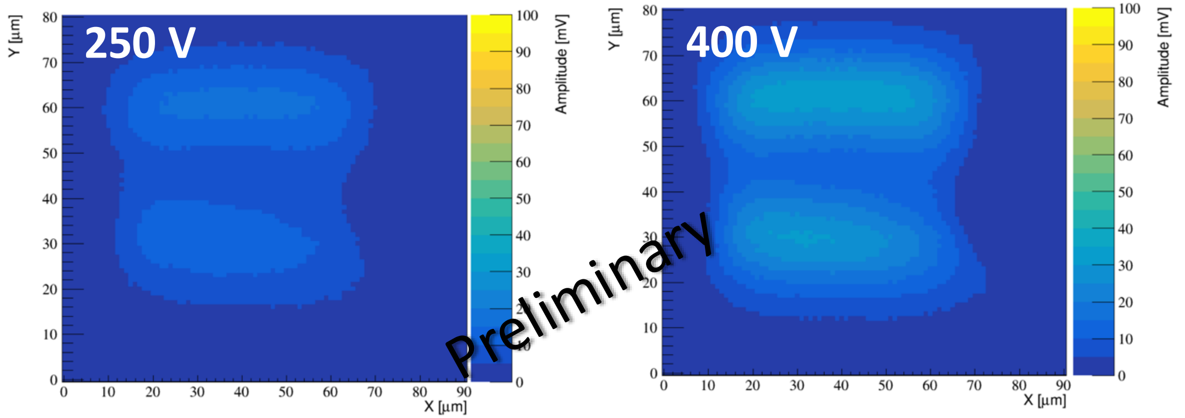
Our F/E TimeSPOT card could not be operated beyond 400 V.   Thee PCB will be soon modified for that

$5 \cdot 10^{17} 1\ MeV\ n_{eq} cm^{-2}$



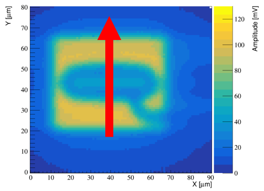
- Recovers charge collection efficiency >70% at 400 V

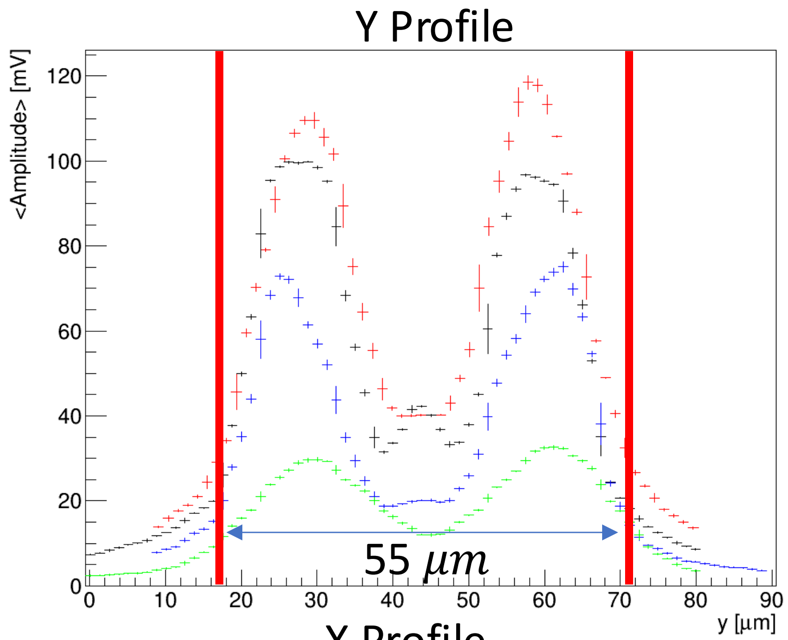
$1 \cdot 10^{18}\ 1\ MeV\ n_{eq} cm^{-2}$

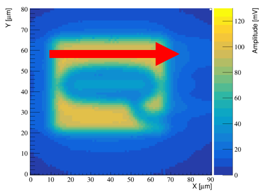


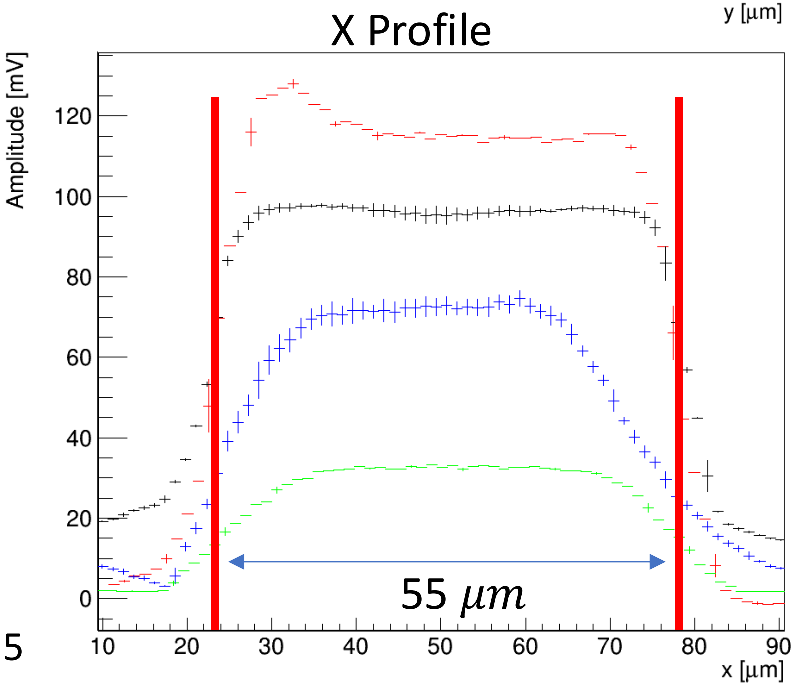
- Still very low charge collection efficiency at 400 V

TCT CCE

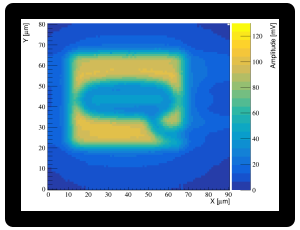


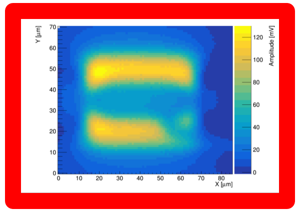


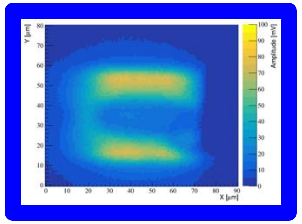


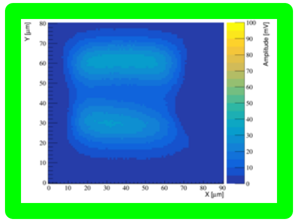


- Not-irradiated @ 50 V
- $1 \cdot 10^{17} 1\ MeV\ n_{eq} cm^{-2}$ @ 300 V
- $5 \cdot 10^{17} 1\ MeV\ n_{eq} cm^{-2}$ @ $400\ V$
- $1 \cdot 10^{18} 1\ MeV\ n_{eq} cm^{-2}$ @ $400\ V$









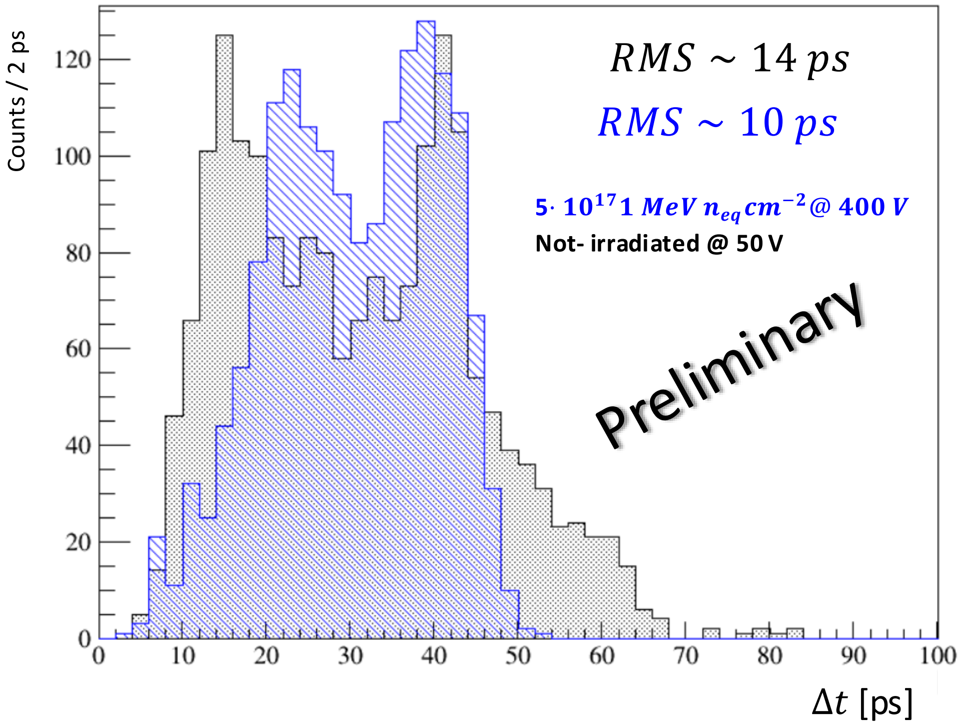
- 10^{17} fully depleted, up to 20% charge multiplication observed
- $5 \cdot 10^{17}$ up to 70% recovery of CCE, already not fully depleted at 400 V
- $1 \cdot 10^{18}$ low CCE observed at 400 V $< 30\%$

Breakdown voltage not reached yet, TimeSPOT board not suited for voltages > 400 V → **margin for improvement**

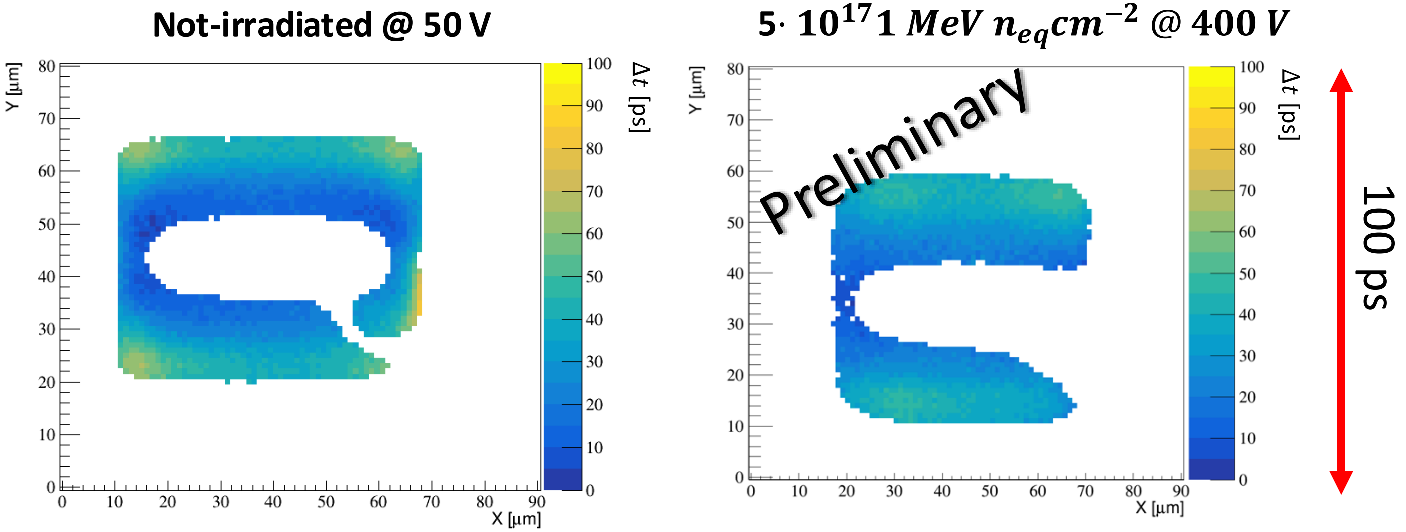
Timing characterizations

- Evaluation of **timing spread** across the pixels (amplitude selection to avoid metallization)

Time distributions



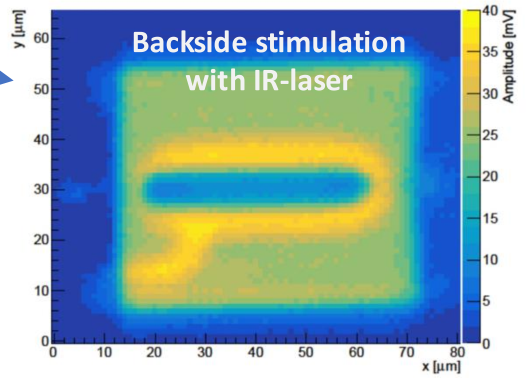
Timing maps

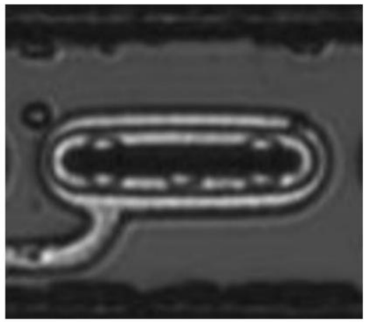


Irradiated sensor seems to have a better timing.. but just because is less efficient

Timing can't be evaluated without considering sensor efficiency

- Setup improvement with infrared laser, to inspect all the sensors active area





Preliminary measurements show no degradation of time uniformity up to $5 \cdot 10^{17} 1\ MeV\ n_{eq} cm^{-2}$

Conclusions

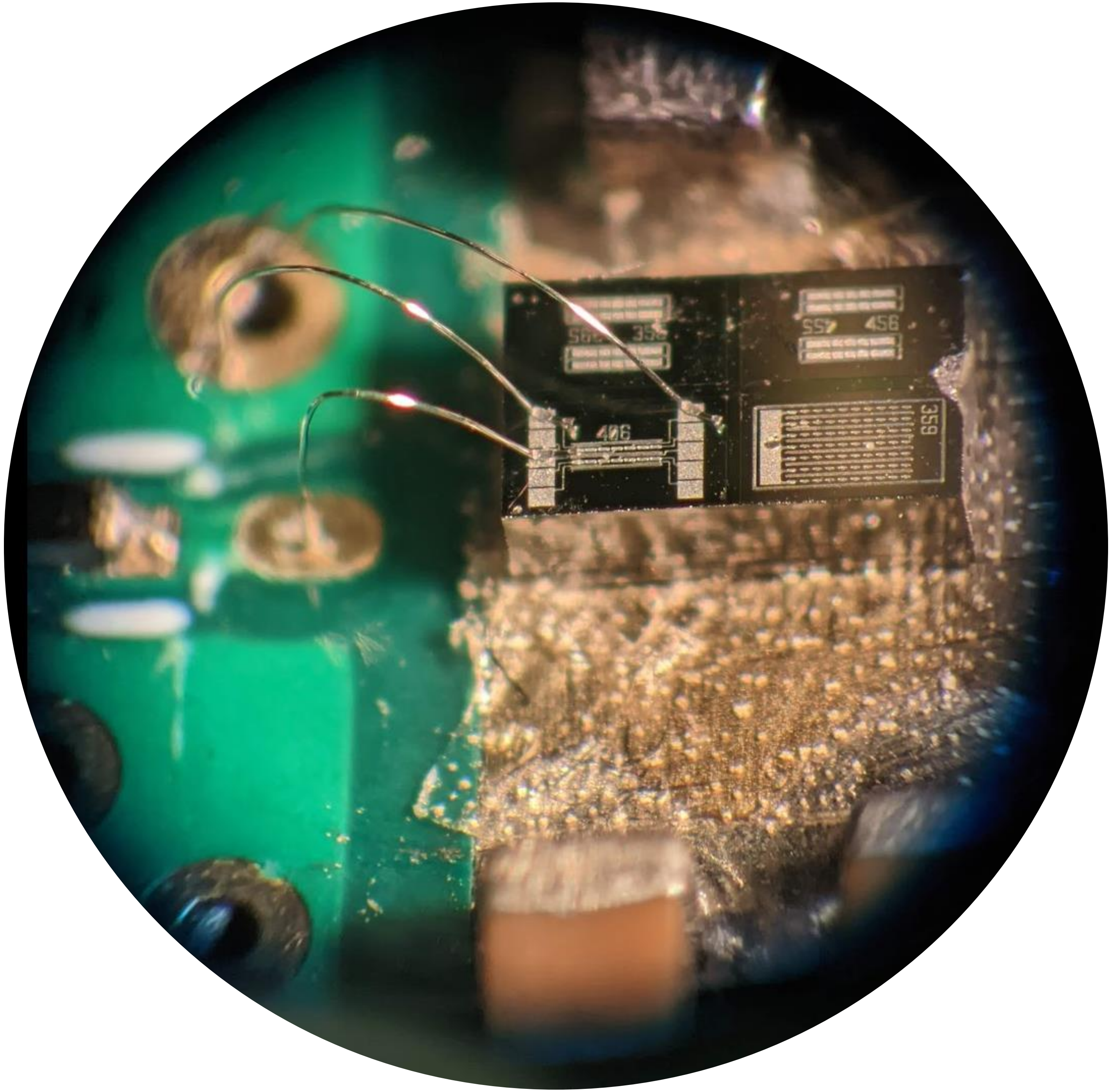
- We proved that 3D trench sensors withstand neutron fluences of $\mathbf{1.0 \cdot 10^{17} 1\ MeV\ n_{eq} cm^{-2}}$ having similar performance to the non-irradiated sensors, obtained by increasing the operation voltage from about 50 V to less than 300 V

- A new irradiation up to unprecedent fluences have shown significant decrease of CCE, with the $5 \cdot 10^{17}$ reaching 70% and the $1 \cdot 10^{18}\ 1\ MeV\ n_{eq} cm^{-2}$ only 30% of the charge before irradiation. Maximum bias voltage tested 400 V, still **margin for CCE recovery at higher bias voltages**.

- A new TCT setup have been developed in the INFN Cagliari Labs to characterize highly irradiated sensors, which allows to study irradiated sensor's response at a sub-pixel level, and proven valid to predict beam test results.

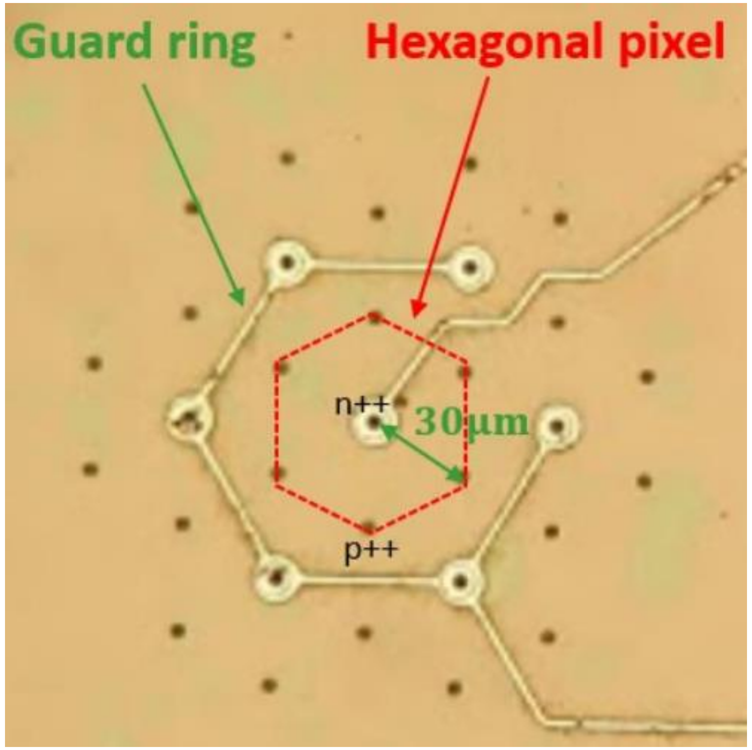
- Preliminary measurements show **no degradation of time uniformity up to $5 \cdot 10^{17} 1\ MeV\ n_{eq} cm^{-2}$** but more detailed studies will come with the improved TCT setup. Full characterization @ 10^{18} n_{eq}/cm^2 is to be completed, probing the device at |Vbias| > 400 V

BACKUP

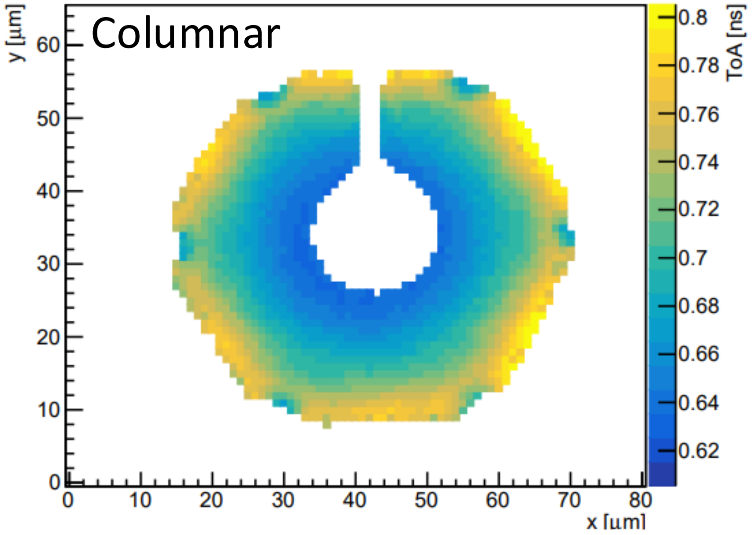


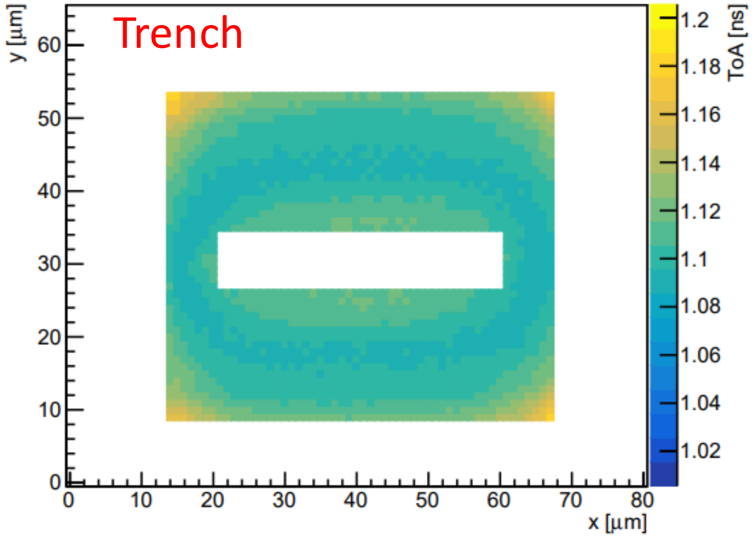
Trench vs Column

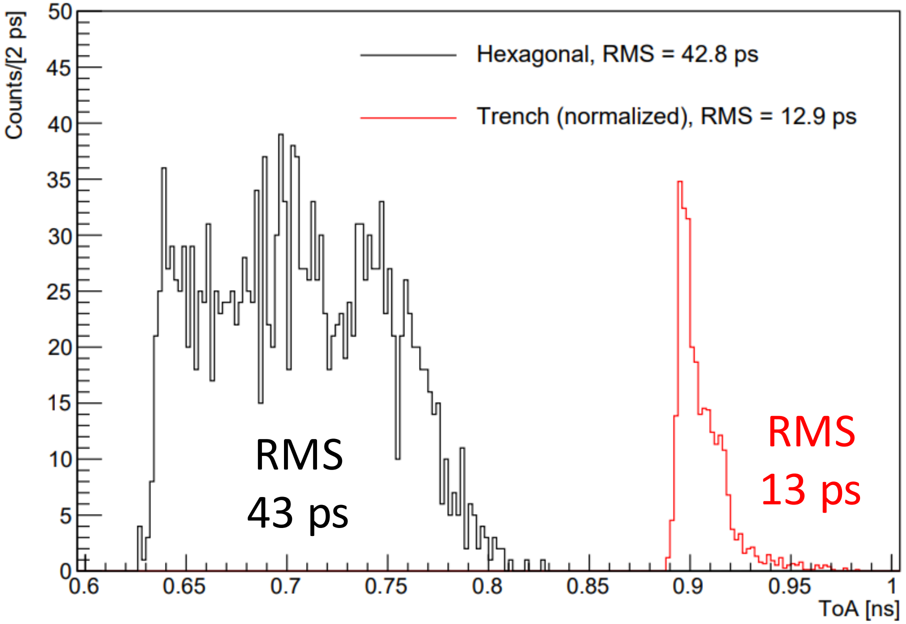
- Timing non-uniformity evaluated with TCT setup for columnar and trench sensor (both 100 V bias, 50% CFD)



[Sultan, D M S. (2017). Development of Small-Pitch, Thin 3D Sensors for Pixel Detector Upgrades at HL-LHC. DOI: 10.13140/RG.2.2.36253.82403/1]







3D trench 3 times better time uniformity than standard 3D column pixel

[A. Lampis Innovative silicon sensors for a 4D VErtex LOcator detector…]

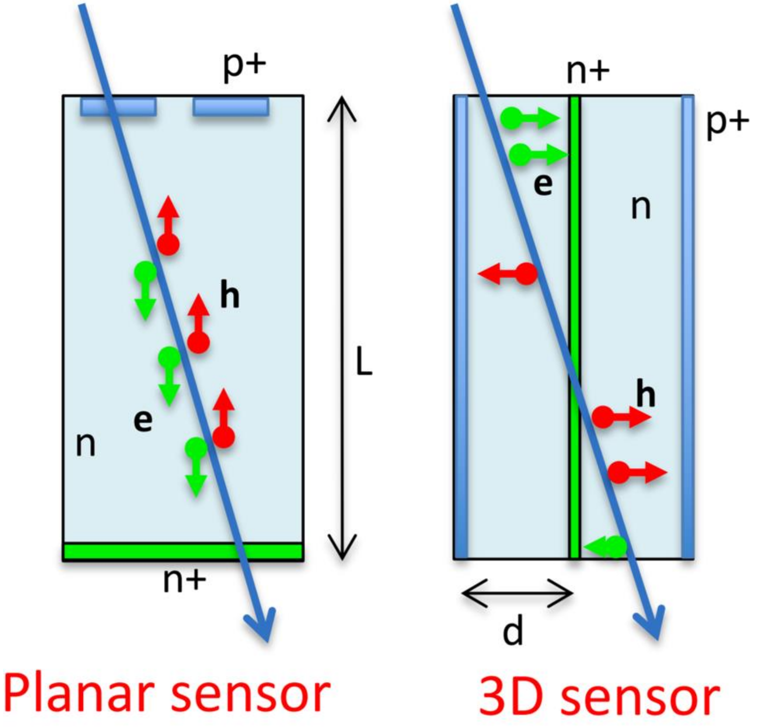
3D sensors

A sensor for the high luminosity VELO **must have**:

Framework TDR for the LHCb Upgrade II

Requirement	scenario S_A	scenario S_B
Pixel pitch [µm]	$\leq$55	$\leq$42
Lifetime fluence [1×10^{16} 1 MeV n_{eq}/cm^2]	>6	>1
TID lifetime [MGy]	>28	>5
Sensor Timestamp per hit [ps]	≤ 35	≤ 35
ASIC Timestamp per hit [ps]	≤ 35	≤ 35
Hit Efficiency [%]	≥ 99	≥ 99
Power per pixel [µW]	≤ 23	≤ 14
Pixel rate hottest pixel [kHz]	>350	>40
Max discharge time [ns]	<29	<250
Bandwidth per ASIC of 2 cm^2 [Gb/s]	>250	>94

3D sensor are a strong candidate

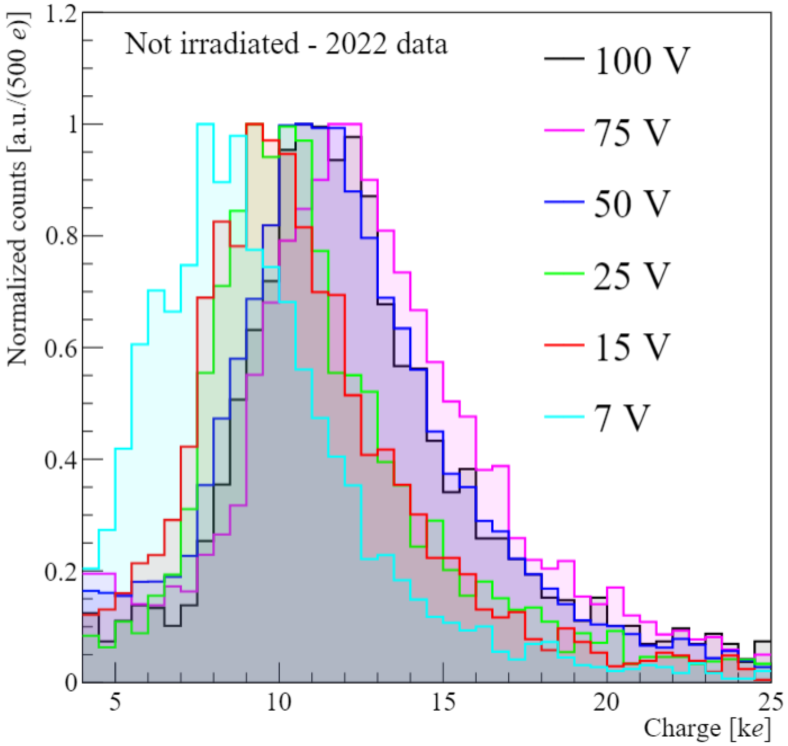


Key points

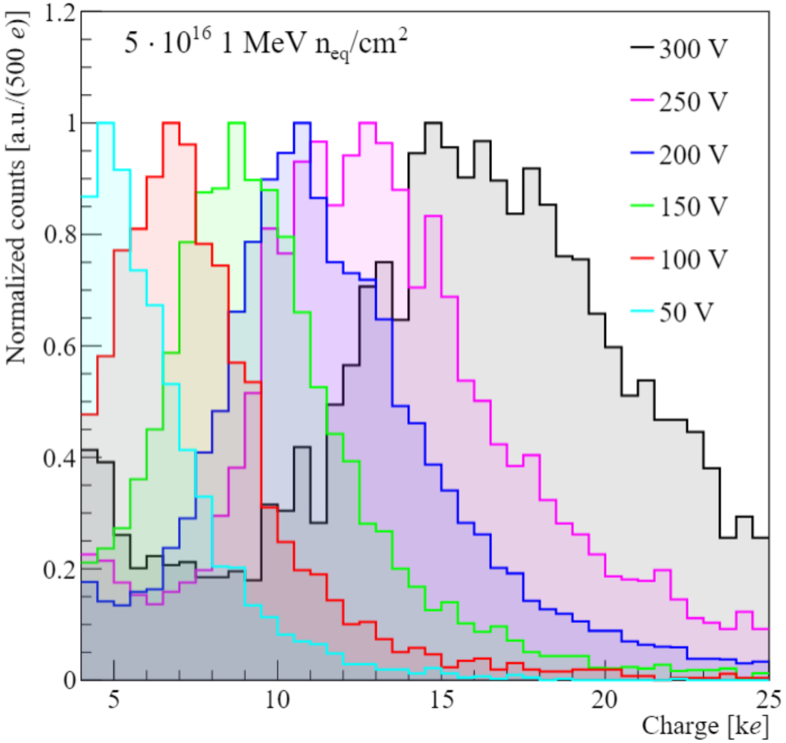
- Short inter-electrode drift distance (tens of µm) give rise to extremely fast signals (d<<L)
- Unmatched radiation hardness (> 10^{17} 1MeV n_{eq}/cm^2, NIMA, 979 (2020) 164458)
- 3D columnar geometry is a production-ready technology (ATLAS IBL, ATLAS-P2)
- Electrode shape can be designed for maximum performance

Results: Charge distributions

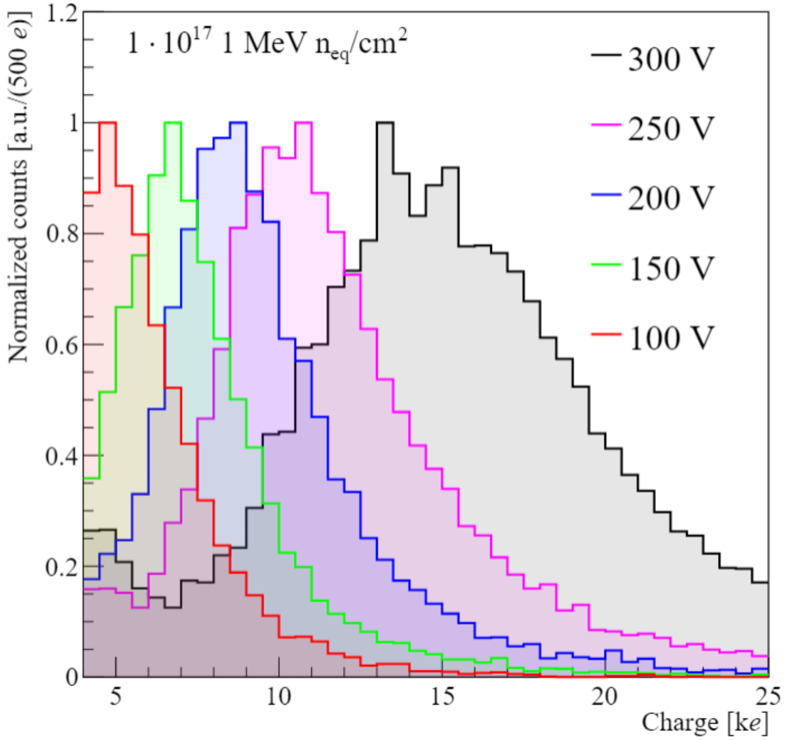
Not irradiated



$5 \cdot 10^{16}\ 1\ MeV\ n_{eq}cm\text{^} - 2$



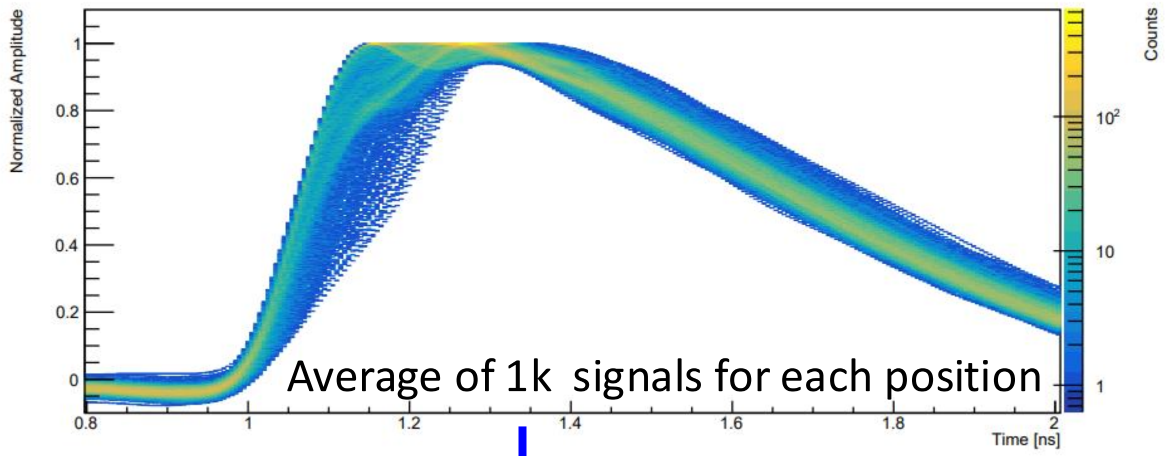
$1 \cdot 10^{17}\ 1\ MeV\ n_{eq}cm\text{^} - 2$



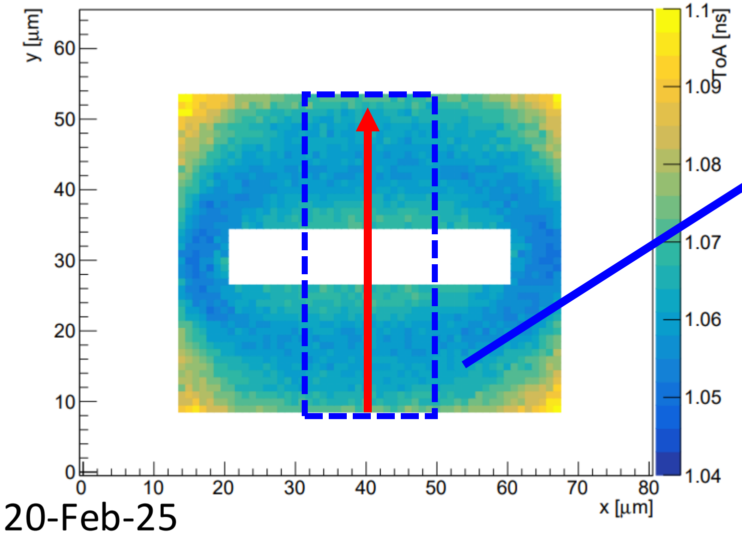
- Decrease in collected charge for irradiated sensor at **100 V** bias after irradiation
- Collected charge recover at a similar level by increasing the bias voltage
- Hints of multiplication in 3D trench at extreme bias voltages around 300 V

Sensor timing non-uniformity σ_{un}

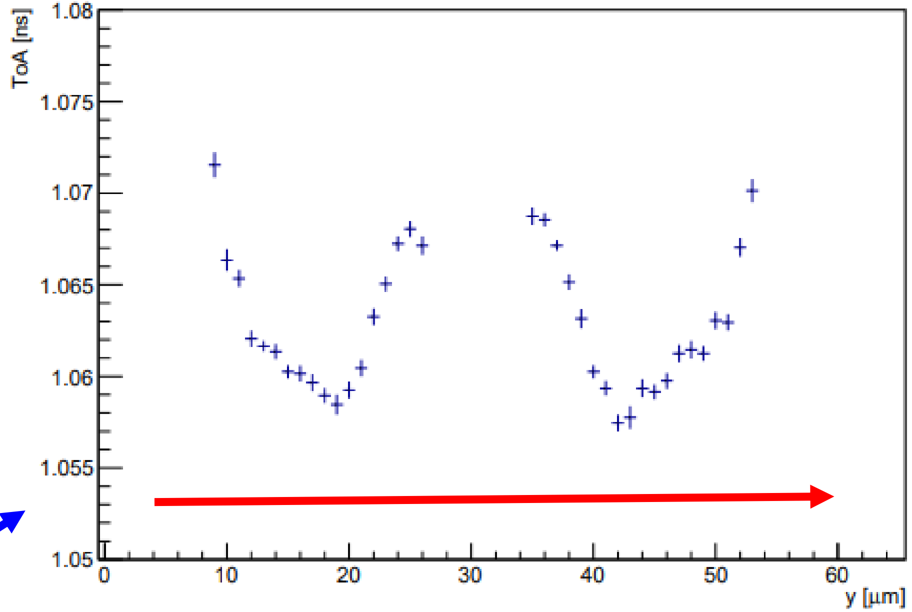
Different signals shape depending on the excitation position

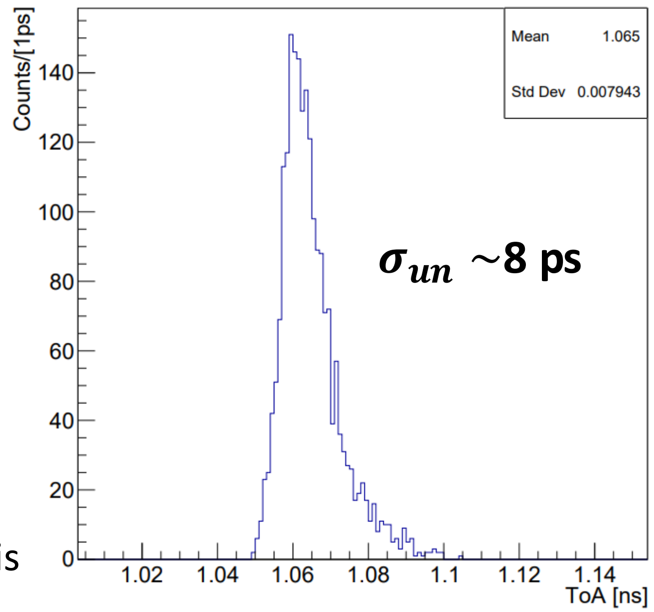


ToA variation depending on the excitation position



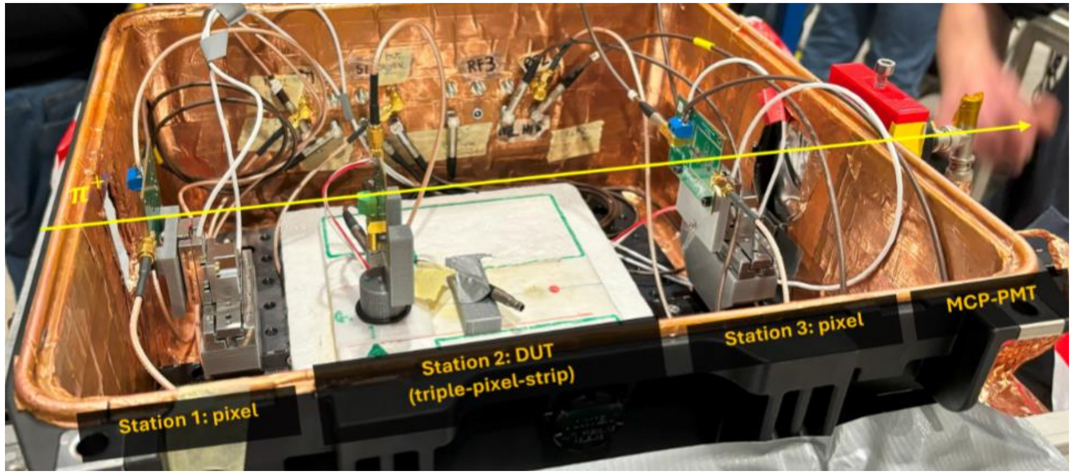
CFD @ 20%

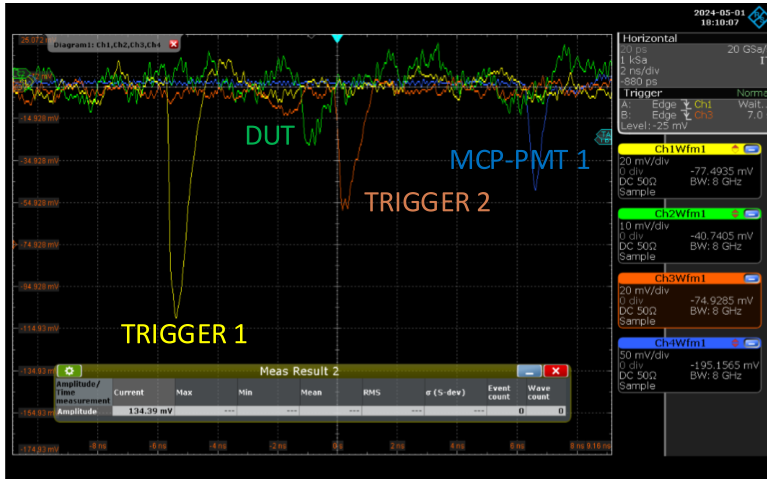


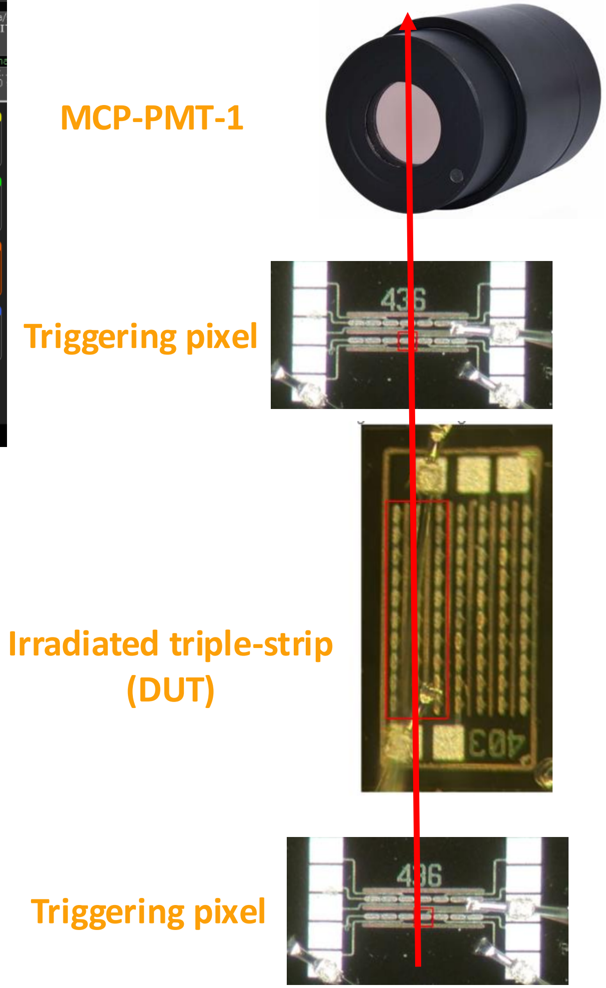


<u>Intrinsic time resolution of 3D-trench pixels about 8 ps</u>

Detection Efficiency setup



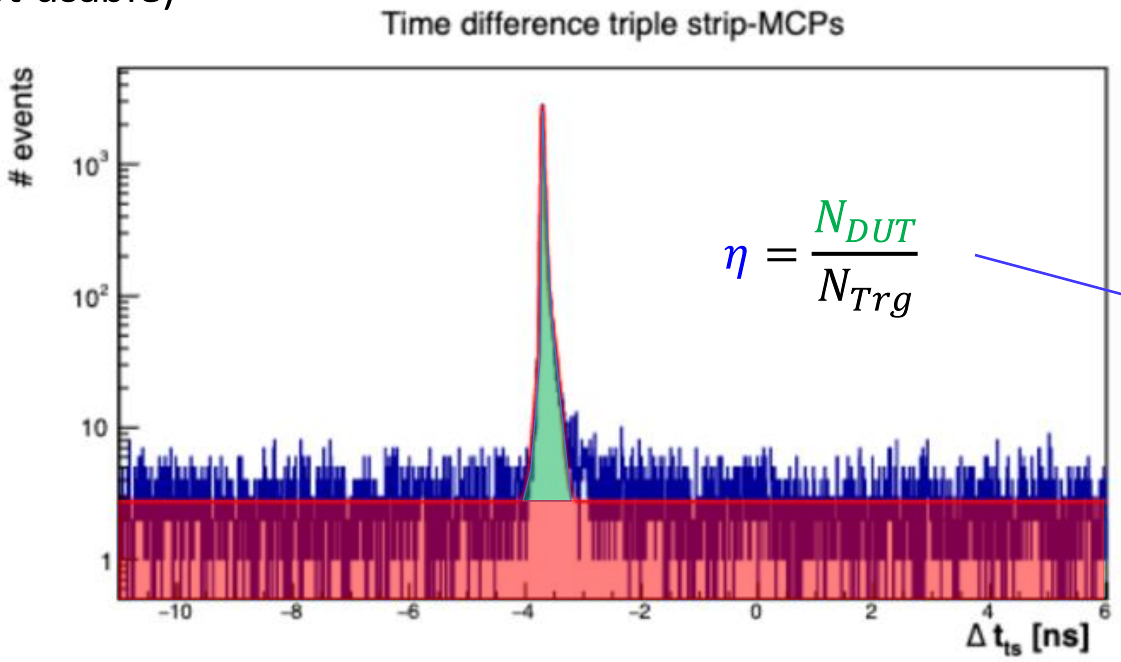




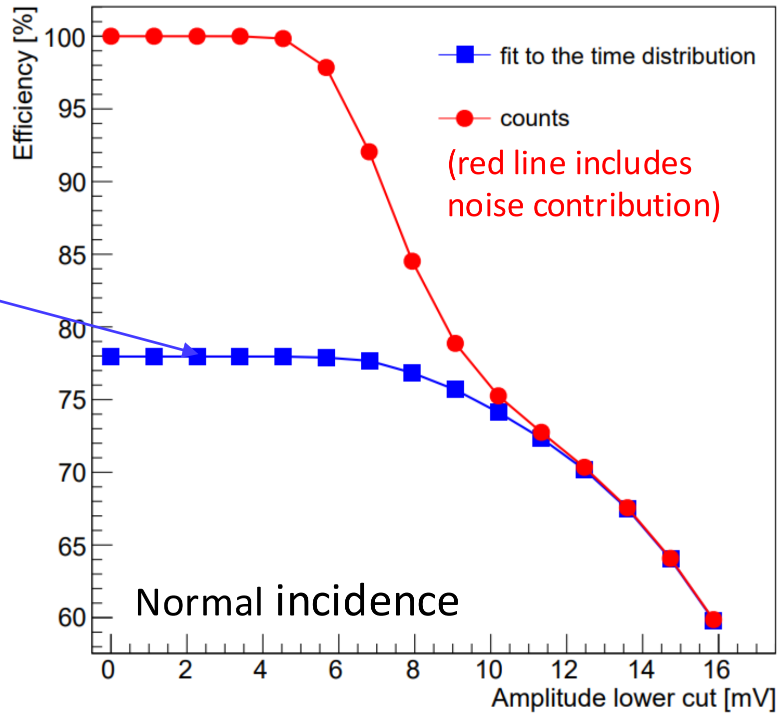
- DUTs: irradiated triple-strip at different fluences
- DAQ Trigger: coincidence in a 20 ns time window of two single pixels, one upstream and the second downstream of the DUT
- Acquisition scans at different tilt angle and bias voltages
- Efficiency evaluated as $\eta = \frac{N_{DUT}}{N_{Trg}}$

3D trench efficiency: method

- Triple strip structure has 30 pixels shorted together → very low S/N (standard efficiency method based on amplitude cut not usable)



$$\eta = \frac{N_{DUT}}{N_{Trg}}$$



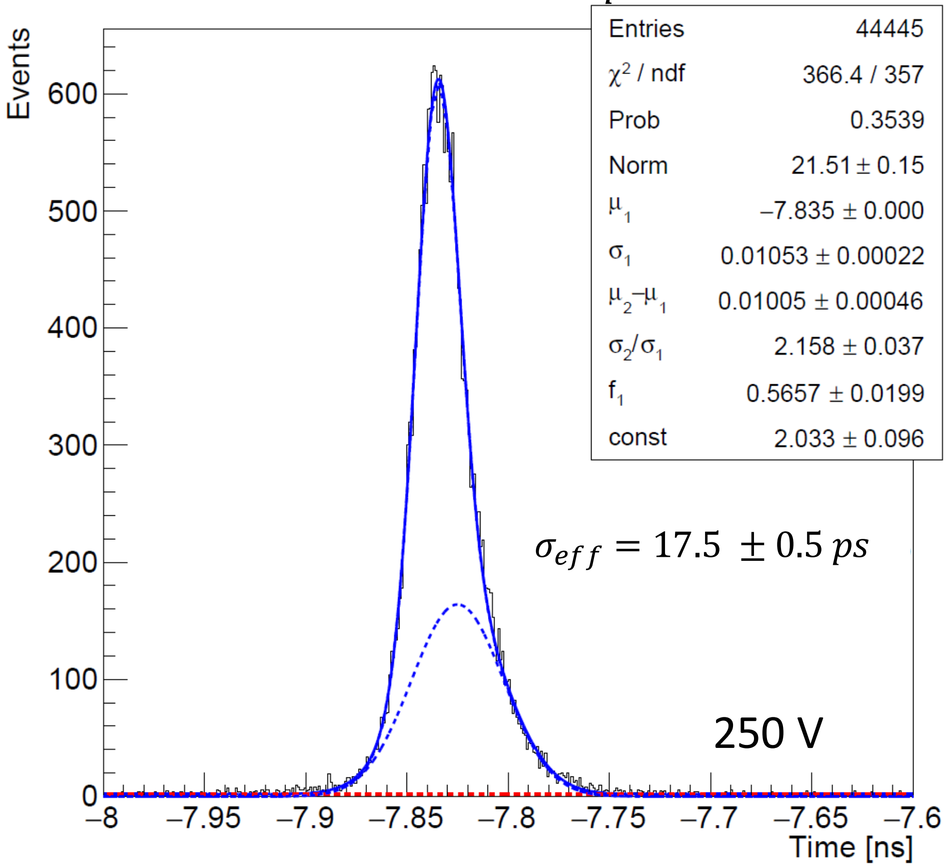
- Time distribution of **all triple-strip signals** w.r.t. MCP-PMT and count as 'seen' the ones under the peak

- Detection efficiency at normal incidence is in agreement with calculated fraction of active area

Results: time distributions

- Distribution of DUT time with respect to MCP-PMTs average time to evaluate time resolution

$1 \cdot 10^{17} 1\ MeV\ n_{eq} cm\text{^} - 2$



$\sigma_{eff} = 17.5 \ \pm 0.5\ ps$

- Narrow peak, with a small tail due to late signals, similar to non-irradiated pixels
- **Two gaussian fit to evaluate the time resolution** (σ_t^{eff}) with the mixture distribution

$$(\sigma_t^{\text{eff}})^2 = f_1(\sigma_1^2 + \mu_1^2) + (1 - f_1) \cdot (\sigma_2^2 + \mu_2^2) - \mu^2$$

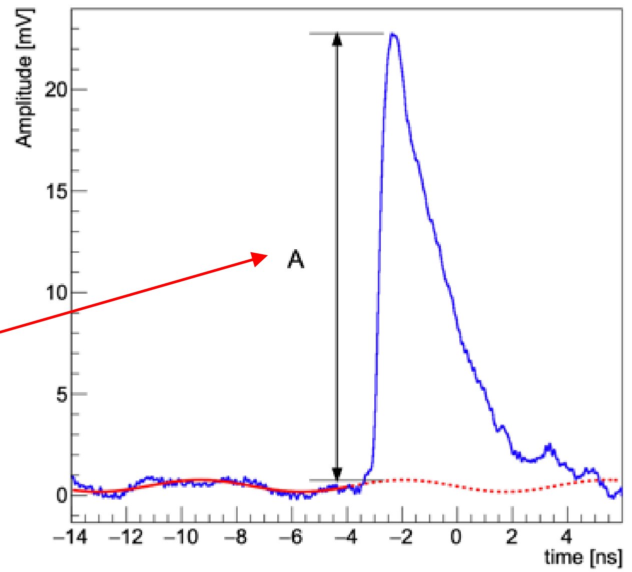
where f_1 is the fraction of the Gaussian core and μ is defined as

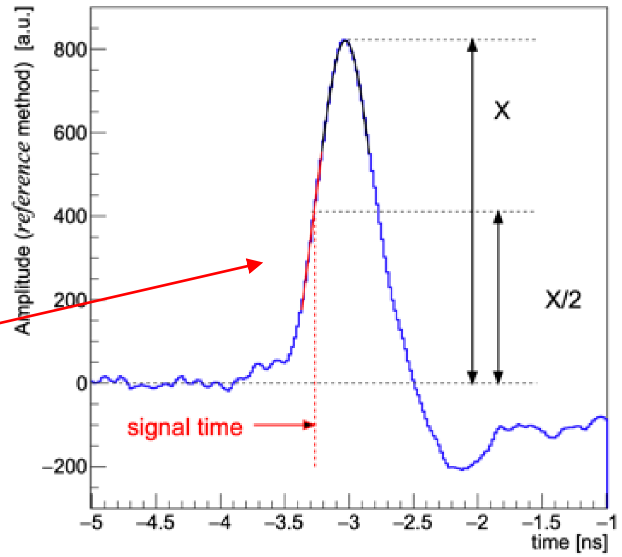
$$\mu = f_1 \mu_1 + (1 - f_1) \cdot \mu_2$$

- Time resolution obtained by subtracting to σ_t^{eff} the time reference contribution

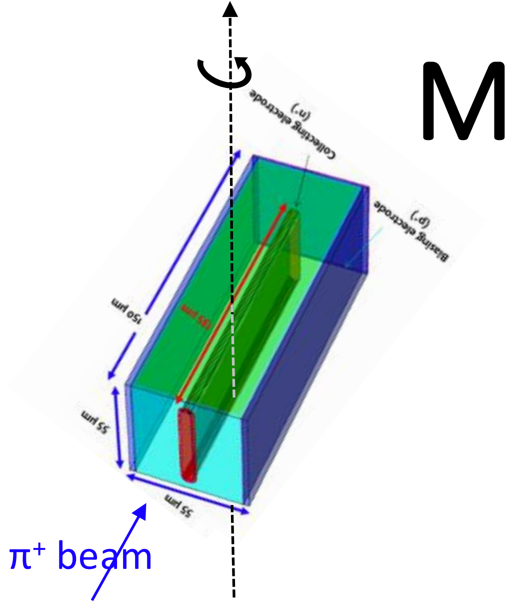
Waveforms analysis

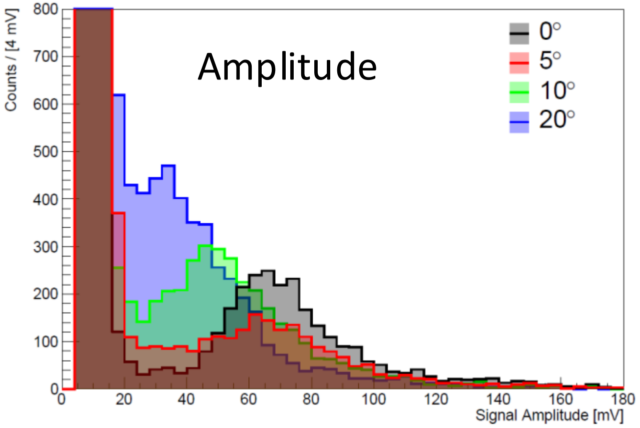
- <u>For each sensor's waveform:</u>
  - Signal baseline (red-dashed line) is evaluated on an event-by-event basis
  - The signal amplitude A is measured (w.r.t. to the event baseline)
  - Signal amplitude is scaled by the amplifier sensitivity to compute the **collected charge** (non-irradiated sensors data have been used to evaluate amplifier sensitivity)
  - **Signal time of arrival (ToA)** evaluated with various methods:
    - <u>Spline</u>: a CFD at 20% with rising edge interpolated with a spline
    - <u>*Reference*</u>: subtract each waveform from a delayed (by about half of the signal rise time) copy of itself, then on the resulting signal we trigger at X/2 height





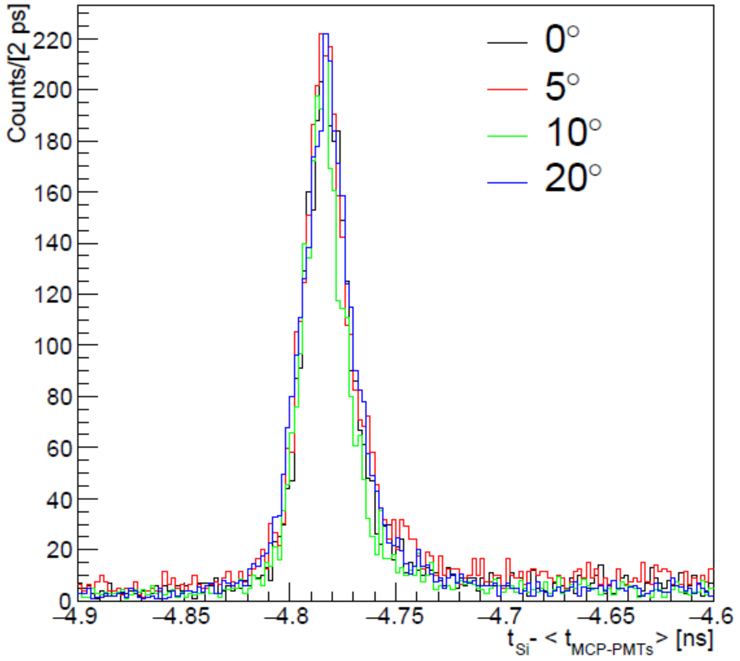
Main results before irradiation (3)



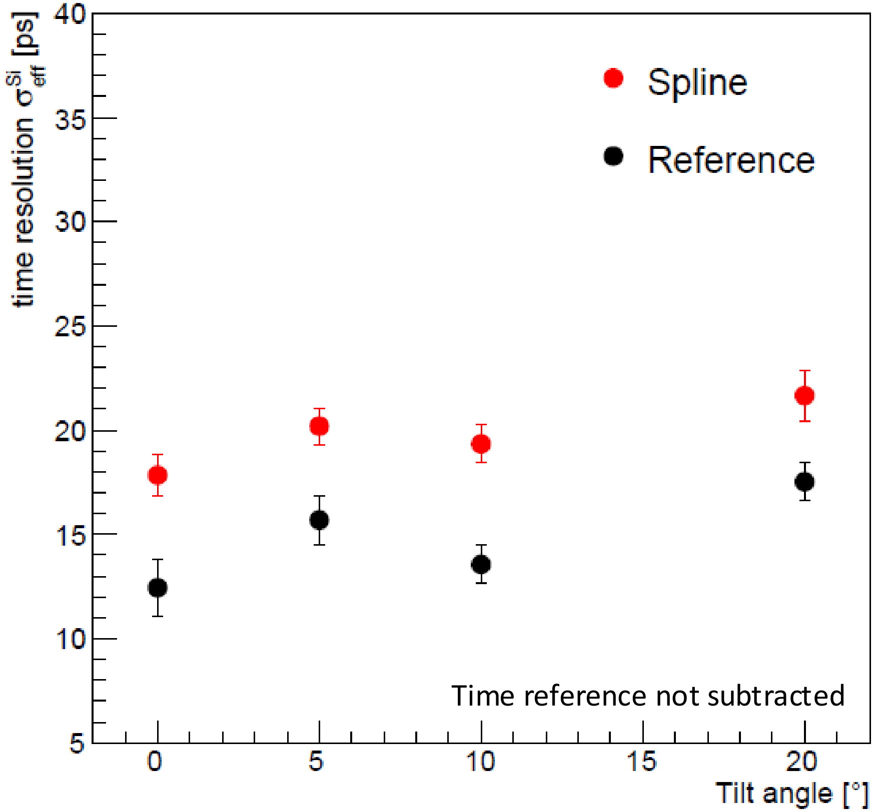


- Tilted operation performance

Time distributions



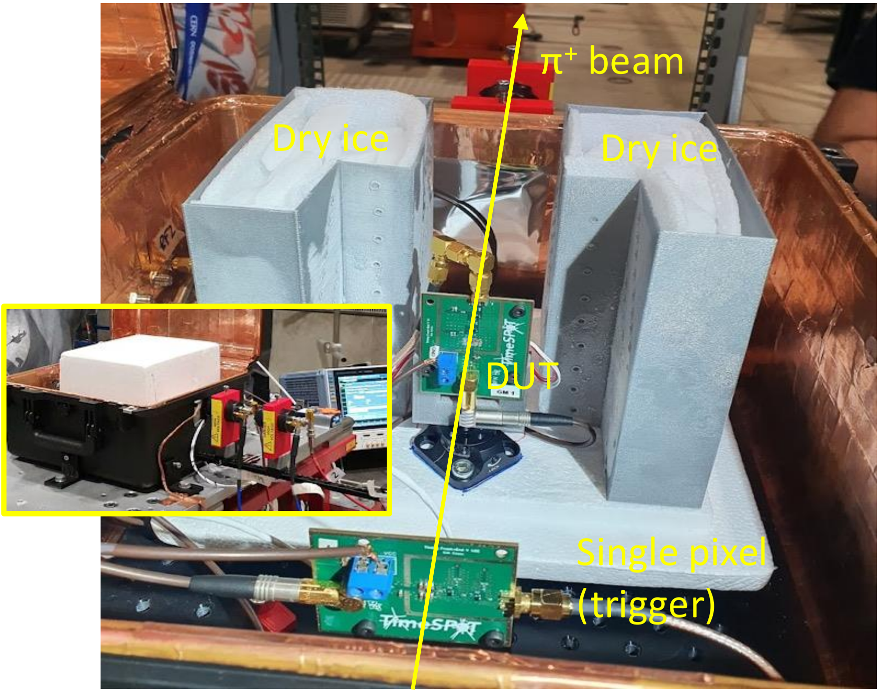
Time resolution



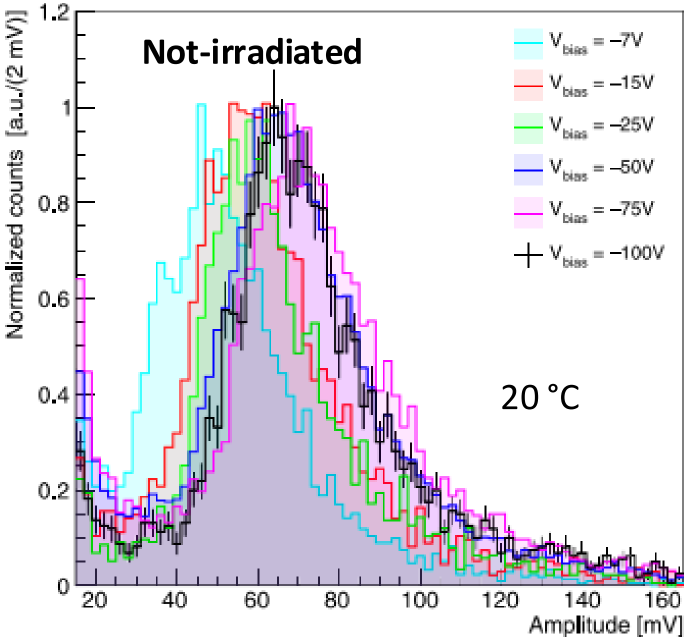
- Charge is shared between adjacent pixels (lower most probable signal amplitude to each pixel)
- **Very low impact in timing performance** → more uniform sensor response when tilted

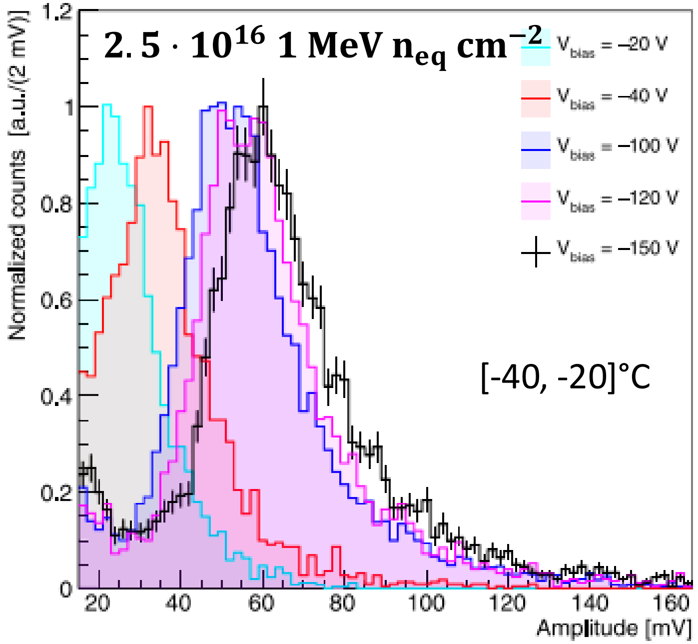
First irradiation campaign

- First irradiation campaign to evaluate radiation hardness of 3D trench
- Sensors irradiated with neutrons at the Triga Mark II Reactor in Lubjana (Slovenia) at a fluence of $1 \cdot 10^{16}$ $1\ MeV\ n_{eq}cm^{-2}$ and $\mathbf{2.5 \cdot 10^{16}\ 1\ MeV\ n_{eq}cm^{-2}}$
- Beam test characterization at the SPS



Signal Amplitude studies (Charge collection)





- Irradiated sensor exhibits lower amplitude if operated at the same bias voltage
- **<u>Recovery of charge collection if bias voltage is increased by about 50 V</u>**