Tests on radiation hardness of 3D-trench silicon sensors

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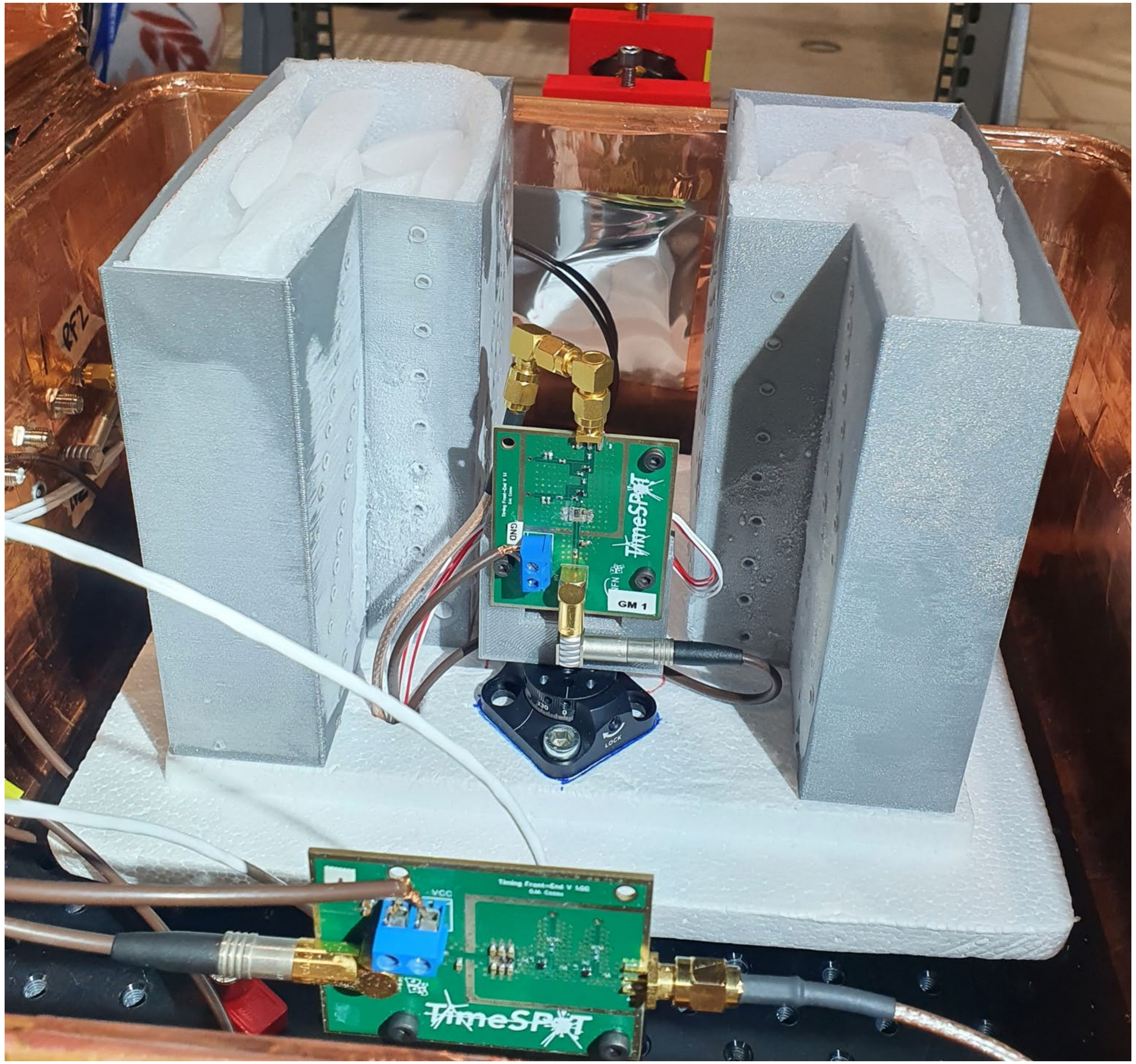
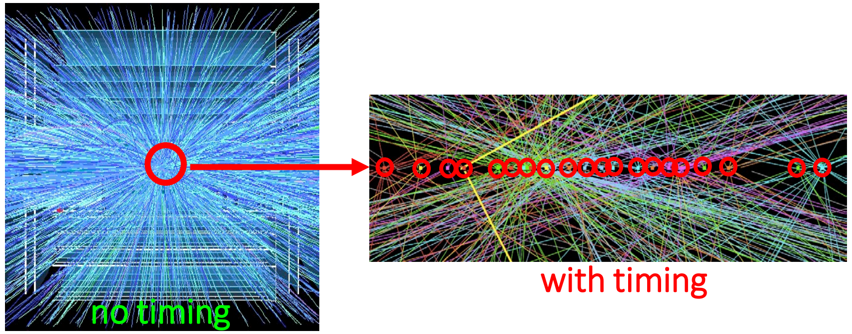


18th Trento Workshop on Advanced Silicon Radiation Detectors
1st March 2023

3D-trench silicon pixel sensors fo HEP experiments



To cope with the **very high instantaneous luminosity** in the current HEP experiments, detectors are required to have very good spatial resolution, time resolution and high radiation hardness **at the same time!**

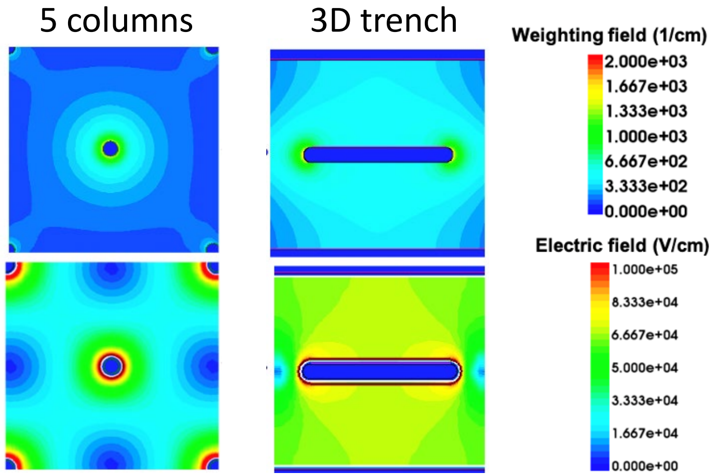
e. g. LHCb VELO requirements for Upgrade II:

- Radiation hardness 10^{16} - 10^{17} 1 MeV n_{eq}/cm^2
- $\sigma_t \approx 50$ ps per hit, $\mathcal{O}(20ps)$ per track
- $\sigma_s \approx 10$ μm

3D sensors are a very promising option to satisfy these requirements → TimeSPOT — TIME and SPace real-time Operating Tracker

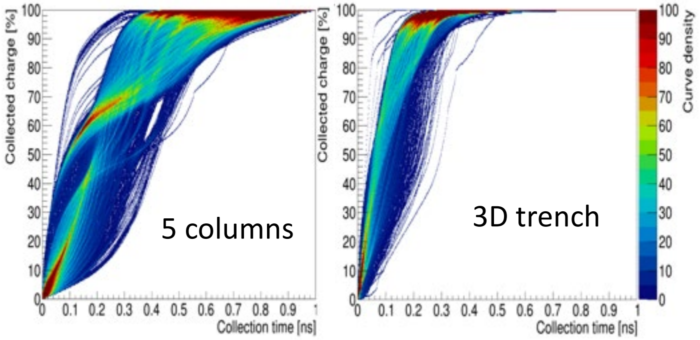
Optimization of the electrodes geometry **for timing**

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



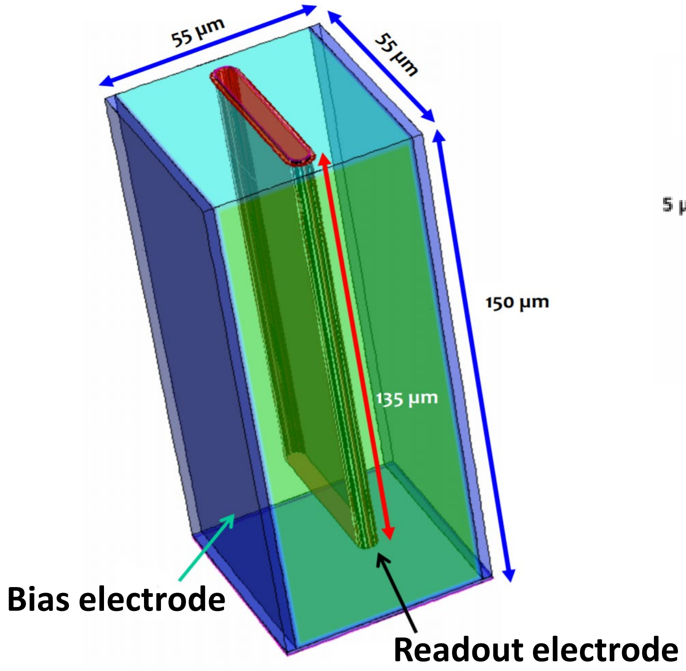
TCAD simulation, V_{bias} = -150V

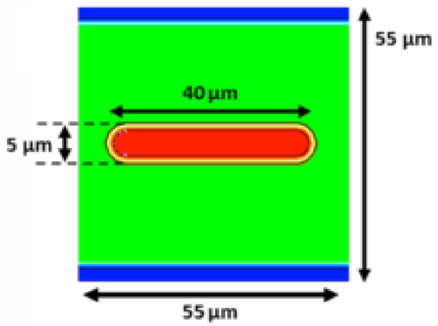
Electric and weighting field maps **much more uniform** in the **trench geometry** → **Faster and more uniform charge collection time in the 3D trench geometry**



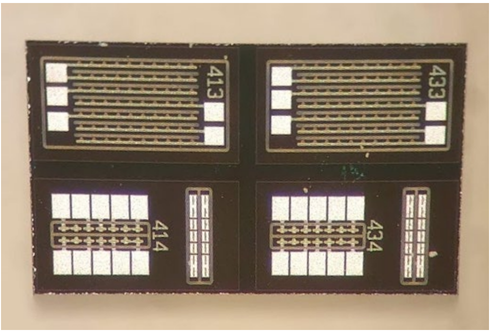
Simulated **charge collection curves** for MIPs uniformly crossing a pixel over its active area

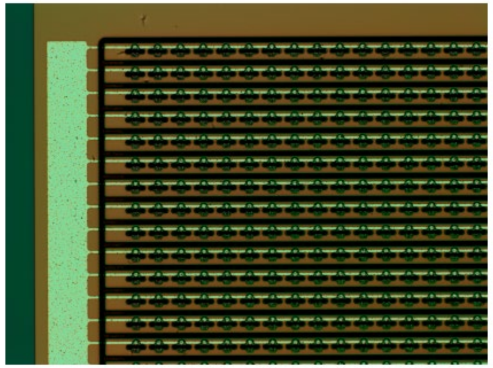
The TimeSPOT sensors

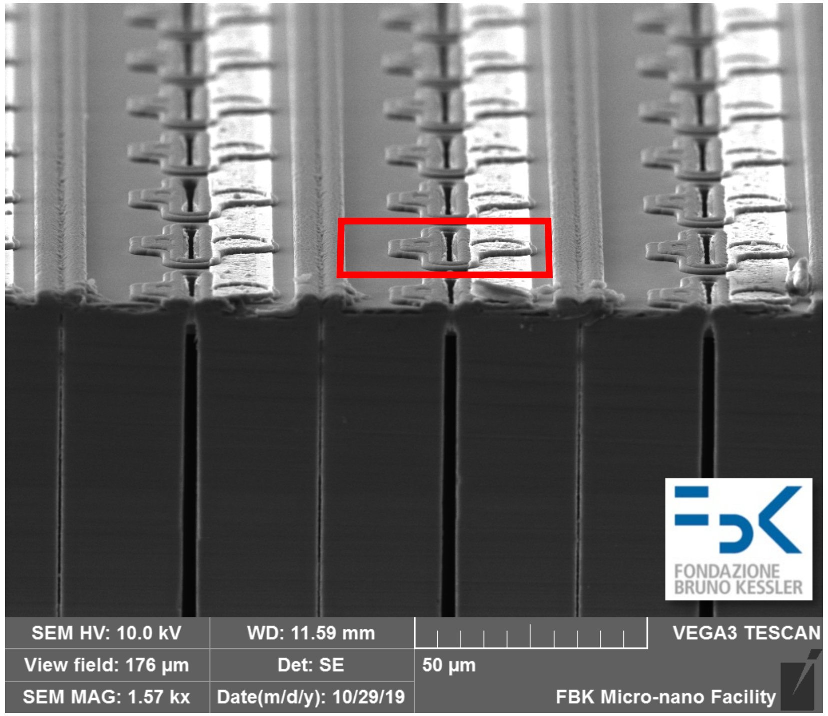




- 55x55 µm² pixels
- 40 µm long n++ trench placed between continuous p++ trenches used for the bias
- 150 µm active thickness
- Collection electrode 135 µm deep





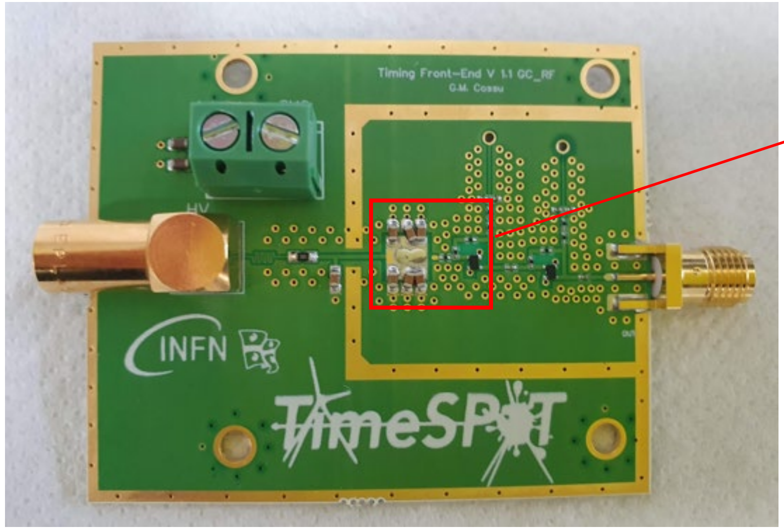


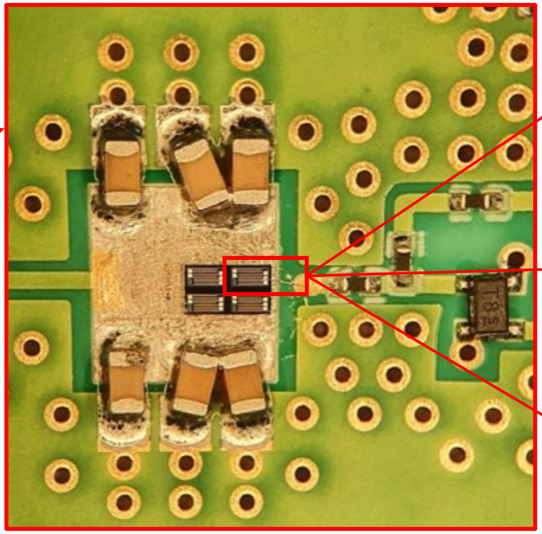
- Two batches of TimeSPOT sensors were produced in 2019 and 2021 at Fondazione Bruno Kessler (FBK, Trento, Italy)
- Several devices designed and fabricated (single and double pixels, 10 pixel-strips, various pixel matrices, etc.)

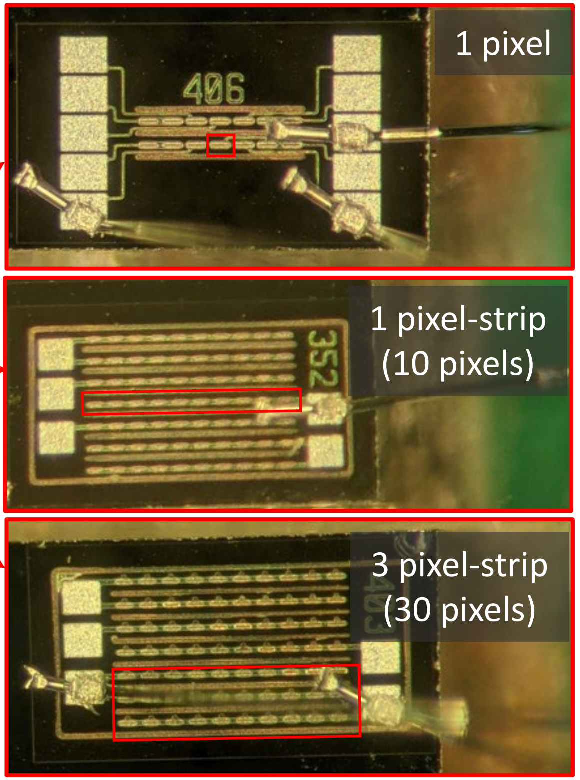
3D-trench sensors characterization

- **Different test structures** characterized: single pixels, pixel-strips (10 or 30 pixels)

- Single-channel custom-made Front-End Electronics boards featuring a two-stage transimpedence amplifier made with fast SiGe BJTs



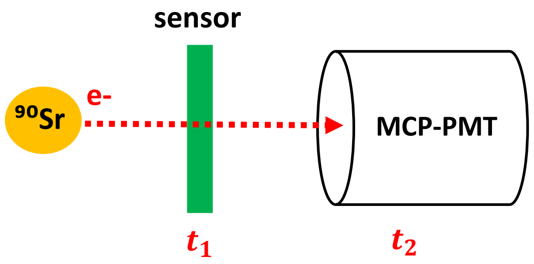




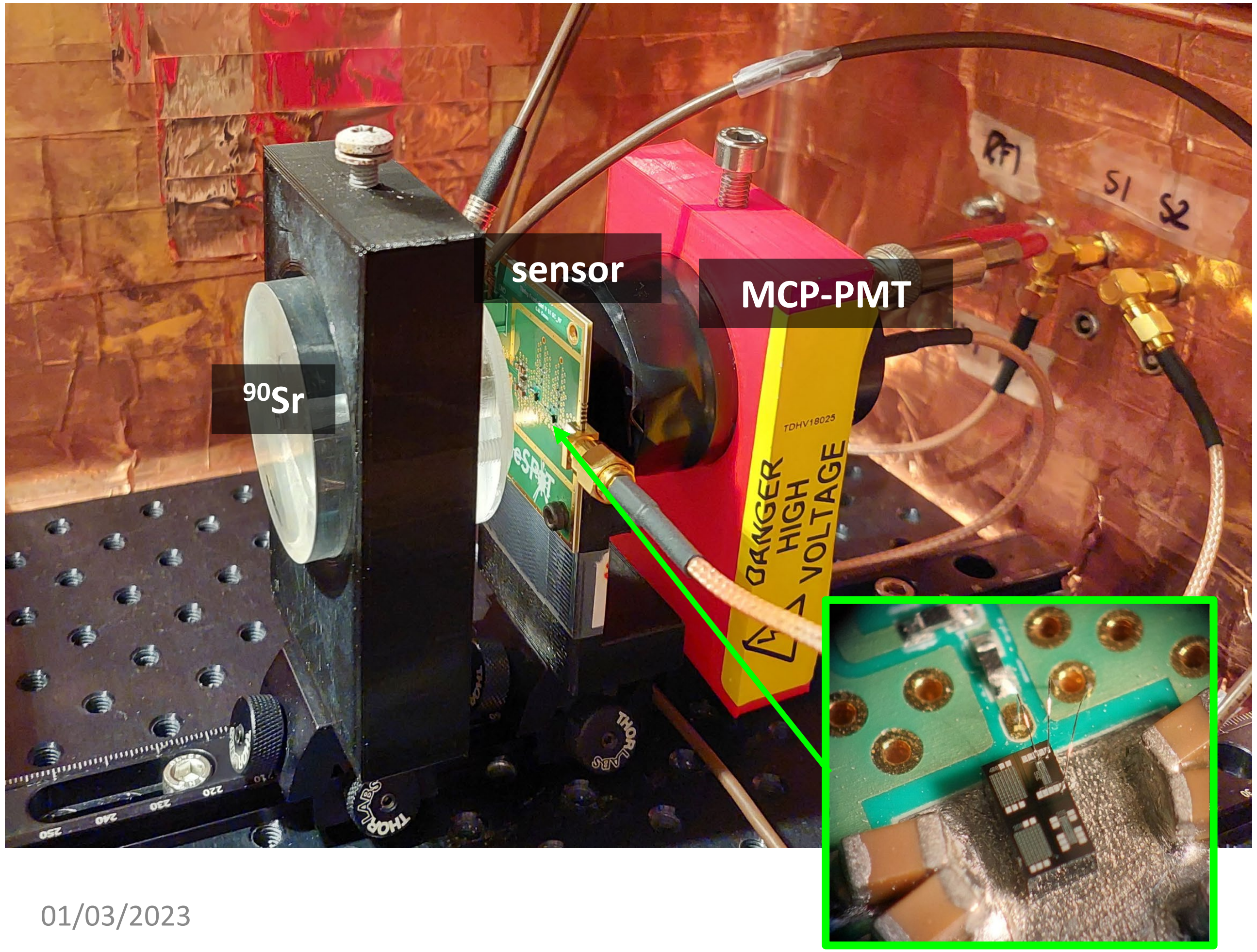
- In this talk I will focus on **highly irradiated TimeSPOT sensors** characterization, comparing the results with those obtained for non-irradiated sensors

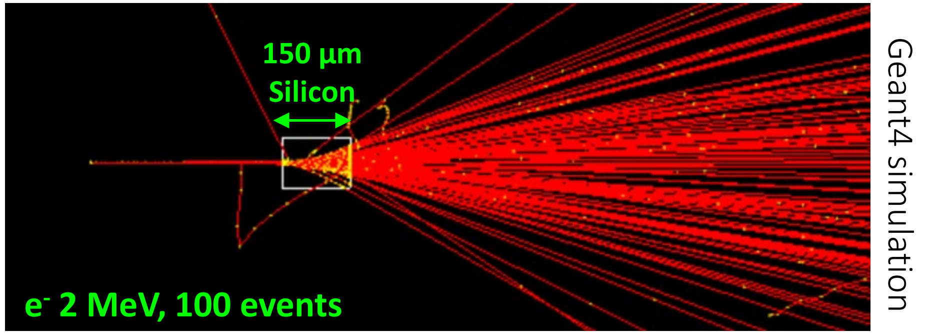
- Laboratory and beam tests characterizations

Laboratory setup with ^{90}Sr source



^{90}**Sr β^{-}** radioactive **source**, emitting electrons with energy in the range **(0.5-2.2) MeV**





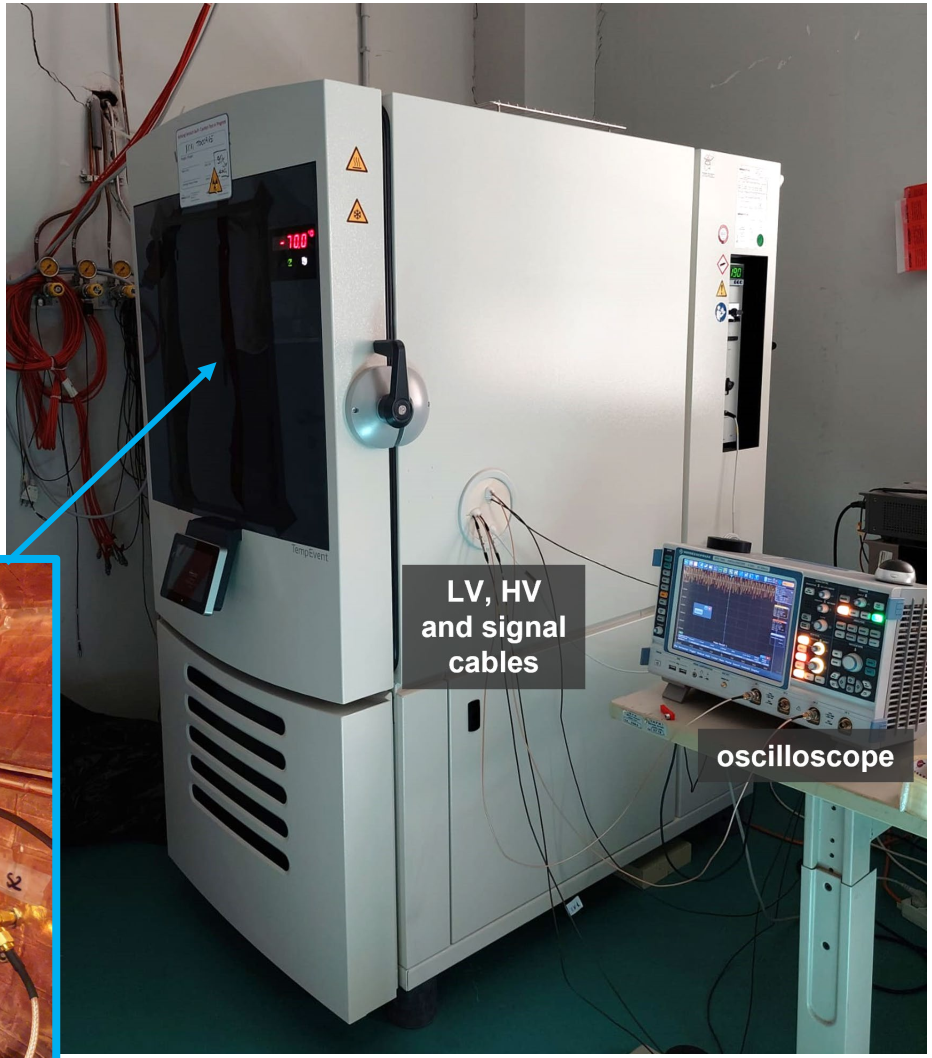
The **multiple scattering** in silicon at these energies is an important effect

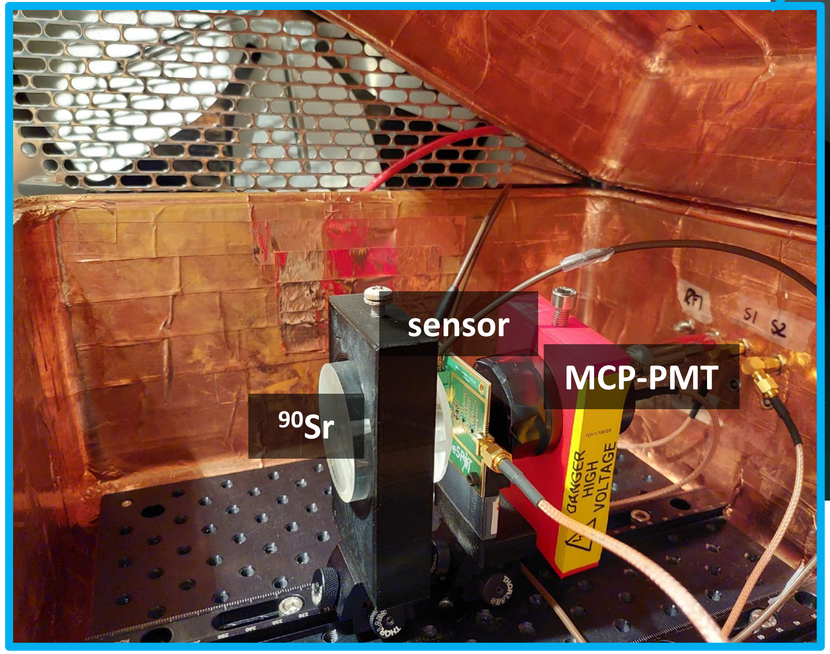
⇩

- **This setup** with the ^{90}Sr source allows to measure only an **upper limit** of the **time resolution** - about twice that one measured at the test beam
- However, it allows to make **preliminary tests** in **laboratory** and to compare different test structures performance

Highly irradiated TimeSPOT sensors

- **Irradiation** of TimeSPOT sensors (1st and 2nd batch) with **neutrons** in the TRIGA Mark II reactor of Institut Jožef Stefan in **Ljubljana** (Slovenia)
- **Up to a fluence of** $\mathbf{2.5 \cdot 10^{16}\ \ 1\ MeV\ n_{eq}/cm^2}$ (max irradiation fluence of the VELO Upgrade 2 detector $6 \cdot 10^{16}\ \ 1\ \mathrm{MeV\ n_{eq}/cm^2}$ without modules replacement every year)
- It is necessary to operate irradiated sensors at **low temperature** to reduce the leakage current
- **Preliminary characterizations** in the **laboratory**

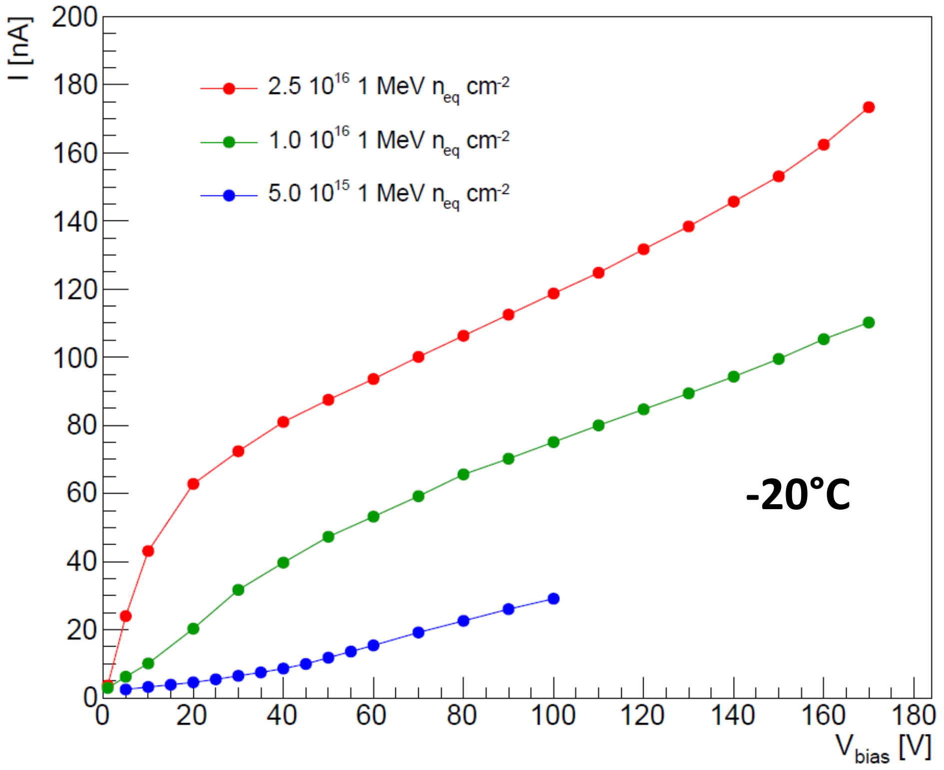




^{90}Sr source setup inside a **climatic chamber** to cool down the irradiated sensors and reduce, in this way, the leakage current

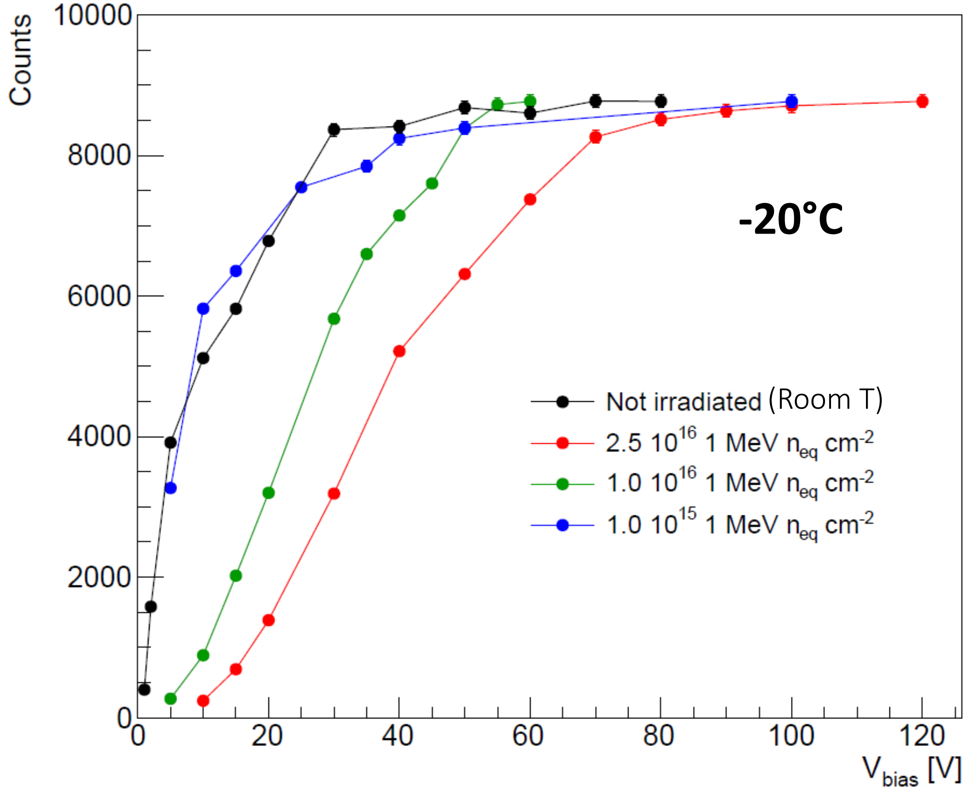
Laboratory characterization of irradiated TimeSPOT sensors

IV curves (single-pixels)



Leakage current increases with the irradiation fluence

Events rate VS bias voltage (pixel-strips)



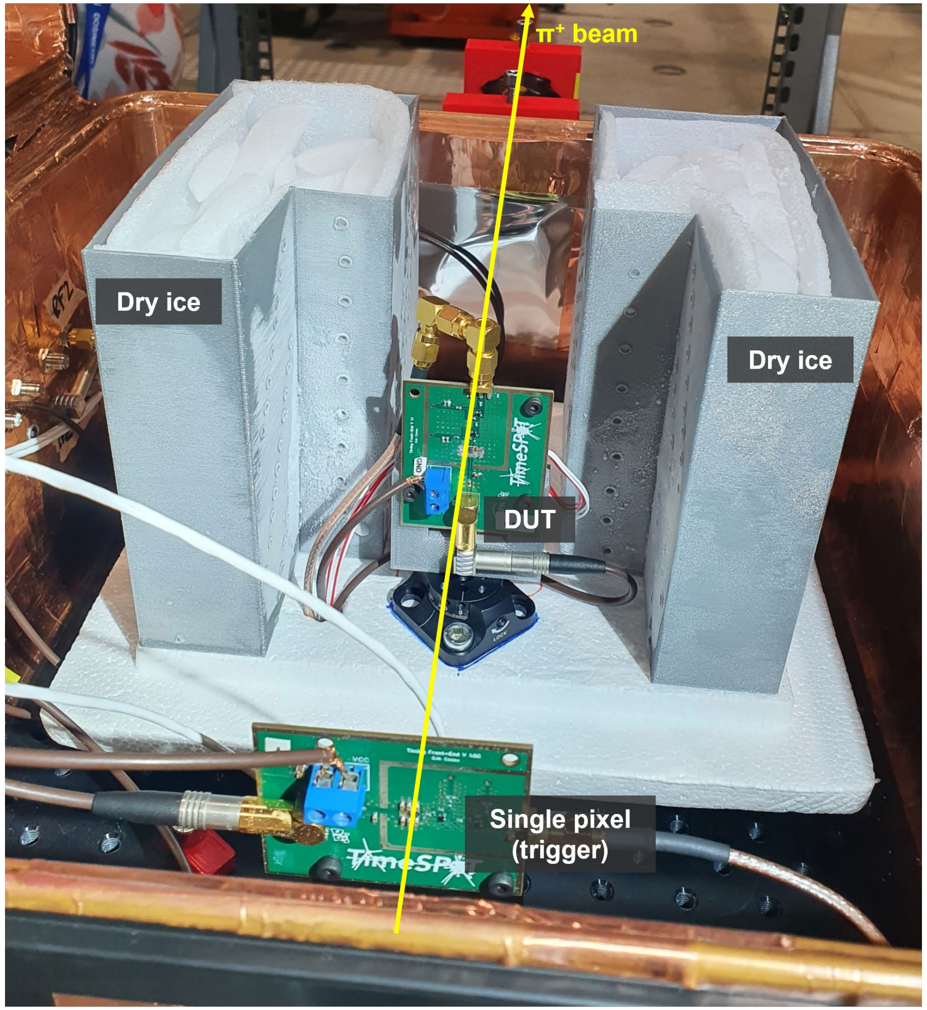
Trigger at fixed threshold, slightly above the noise, and **events count** in a 30s time interval.

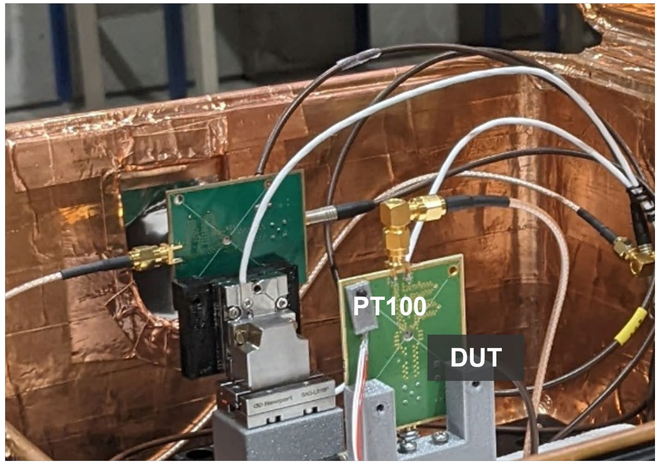
First indication that it is necessary to increase the bias voltage (few tens of volts) applied to irradiated sensors to recover the performance before irradiation – because of the depletion voltage increase

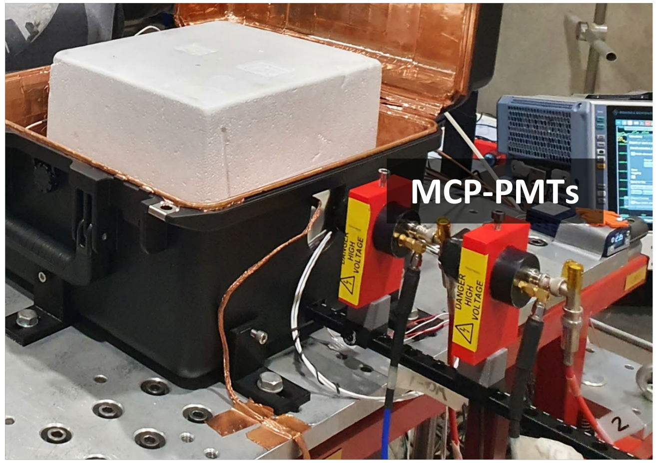
Test beam of irradiated sensors

Test beam made in **May 2022** at CERN **SPS/H8** beamline, **180 GeV/c positive pions beam**

- **DUT outside the trigger** and can be rotated
- **Piezoelectric stages to precisely align** the two 3D structures with beam, all mounted in a RF-shielded box
- **Dry ice**, allows to keep the irradiated sensor under test in the range of temperature **(-40,-20)°C,** monitoring with a PT100 sensor
- **2 MCP-PMTs** as time reference of the setup with a measured accuracy of **3-4 ps**
- **DAQ** with an **8 GHz bandwidth 20 GSa/s oscilloscope**
- **Time resolution** and **efficiency** measurements



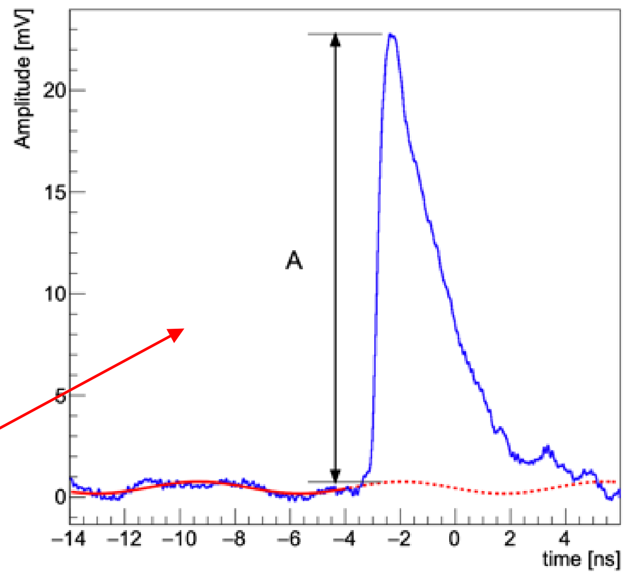


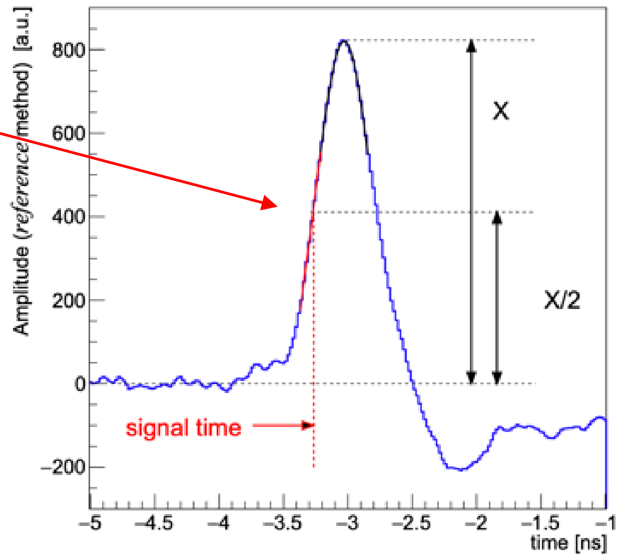


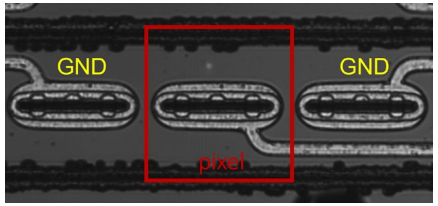
Waveforms analysis

For each sensor's waveform – in both laboratory and test beam data analysis:

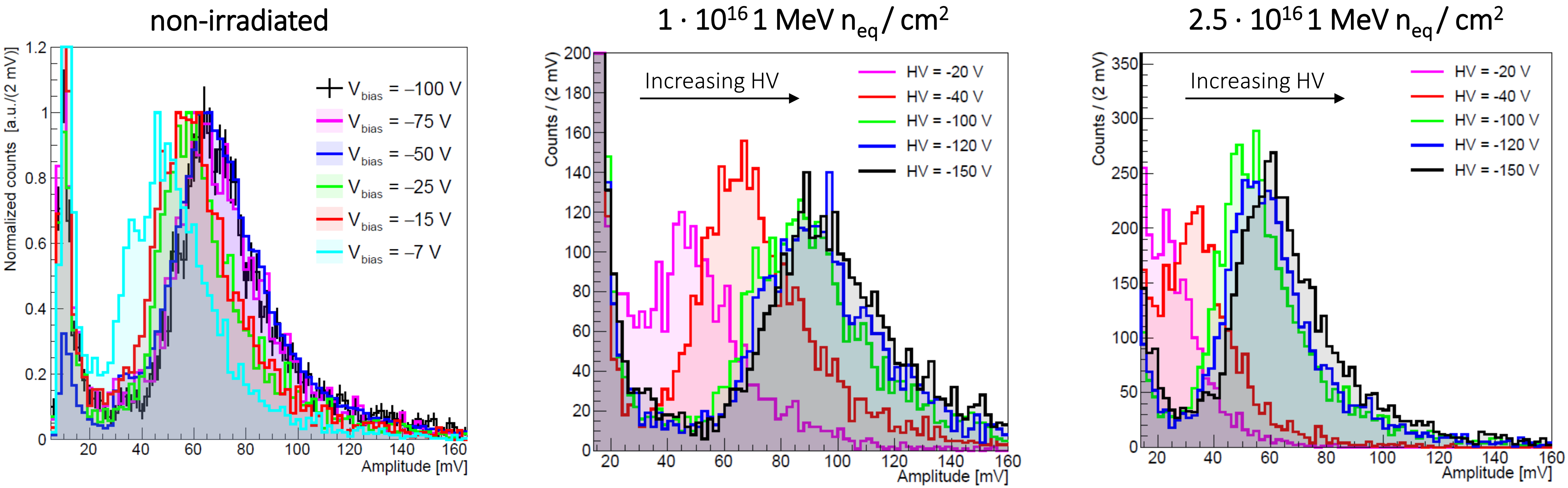
- Signal baseline (red-dashed line) is evaluated on an event-by-event basis
- The **signal amplitude** A is measured (w.r.t. to the event baseline)
- **Signal time of arrival** evaluated with a costant fraction algorithm, the ***Reference** method*: subtract each waveform from a delayed (by about half of the signal rise time) copy of itself, then on the resulting signal we trigger at X/2 height







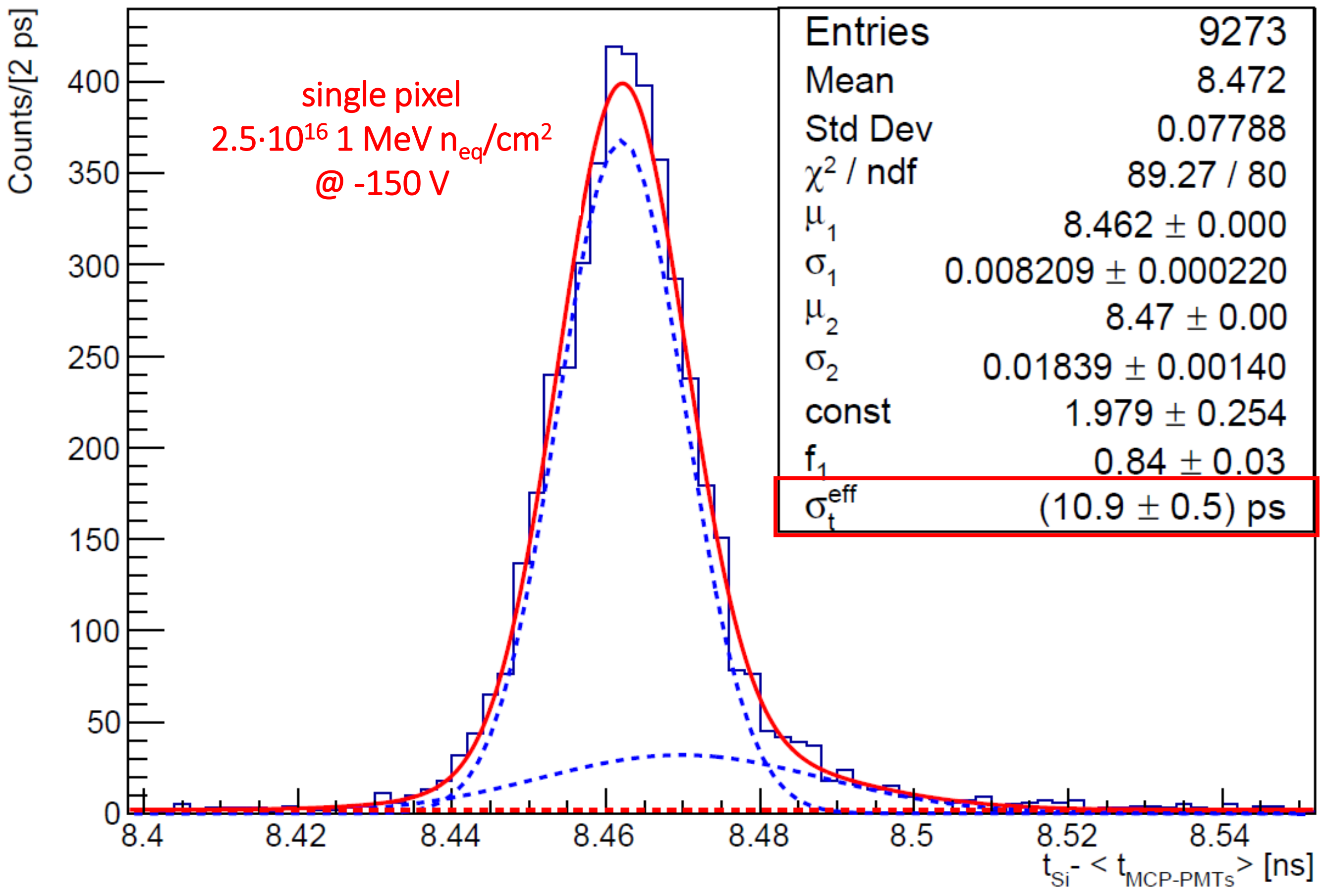
Single pixel – amplitude distributions



- Very good performance of the **non-irradiated** sensor even at low V_{bias}
- A **slightly larger bias voltage** is required to recover the signal amplitude for **irradiated sensors** – indication of good functioning also after high radiation fluence exposition

Irradiated single pixels – time resolution

$\Delta t = t_{single-pixel} - < t_{MCP-PMTs} >$



Two Gaussian fit of the time distribution to include late signals contributions + a constant modelling the background

σ_{eff} is the standard deviation of the mixture distribution of the two Gaussians

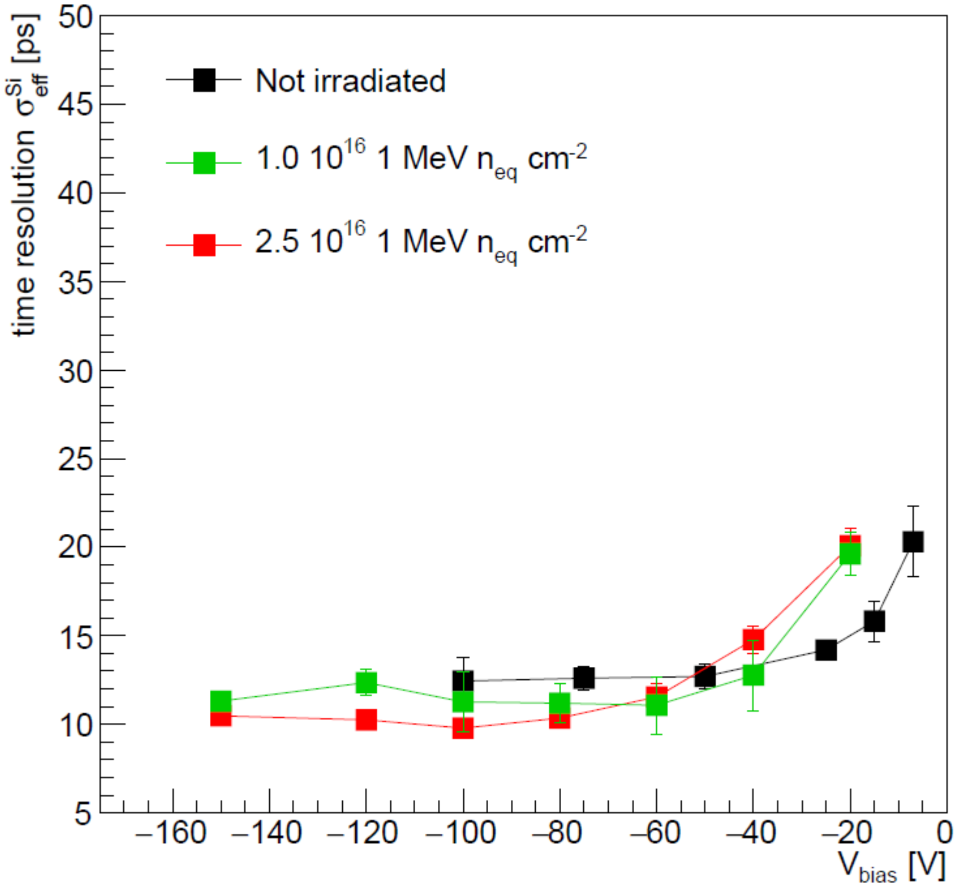
$$(\sigma_t^{\text{eff}})^2 = f_1(\sigma_1^2 + \mu_1^2) + (1 - f_1) \cdot (\sigma_2^2 + \mu_2^2) - \mu^2$$

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

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

Irradiated single pixels – time resolution

Results obtained with a constant fraction based algorithm - *Reference* method



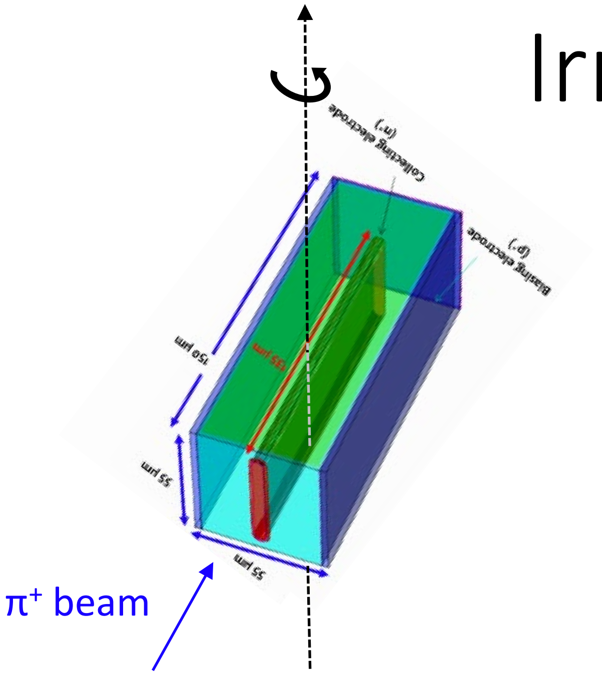
- **Excellent time resolution measured also on irradiated single pixels**
- Slightly better results on irradiated sensors w.r.t. non-irradiated one (also in laboratory measurements)

Possible explanations:

1) At lower temperatures the timing performance improves (transistor gain) – verified by measuring the non-irradiated pixel performance at low temperature
2) The FEE boards have a slightly different gain

First time resolution measurements of irradiated TimeSPOT sensors have shown an excellent time resolution up to a fluence of $2.5 \cdot 10^{16}$ 1 MeV n_{eq} / cm^2

Irradiated sensors – efficiency

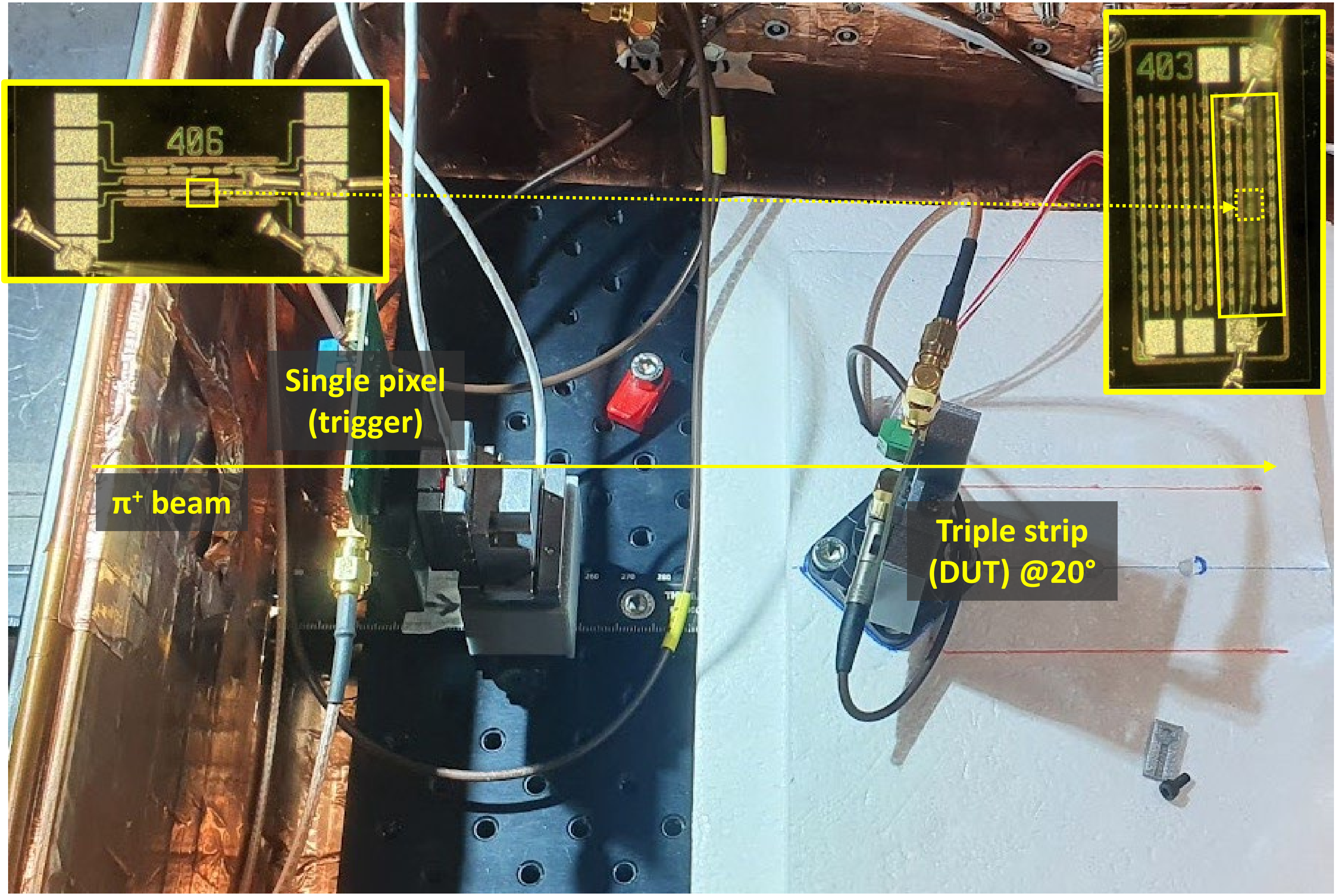


- **Trenches** (5 µm wide) are **non-active** volumes, channeled particles will not be detected

- **Tilt the sensors** with respect to normal incidence should allow **to recover geometrical efficiency**

- **Trigger on one pixel** (55 µm x 55 µm, on piezos) centered on a triple strip (165 µm x 550 µm, DUT) and **counting the fraction of signals seen in the triple strip** (on a single FE channel)

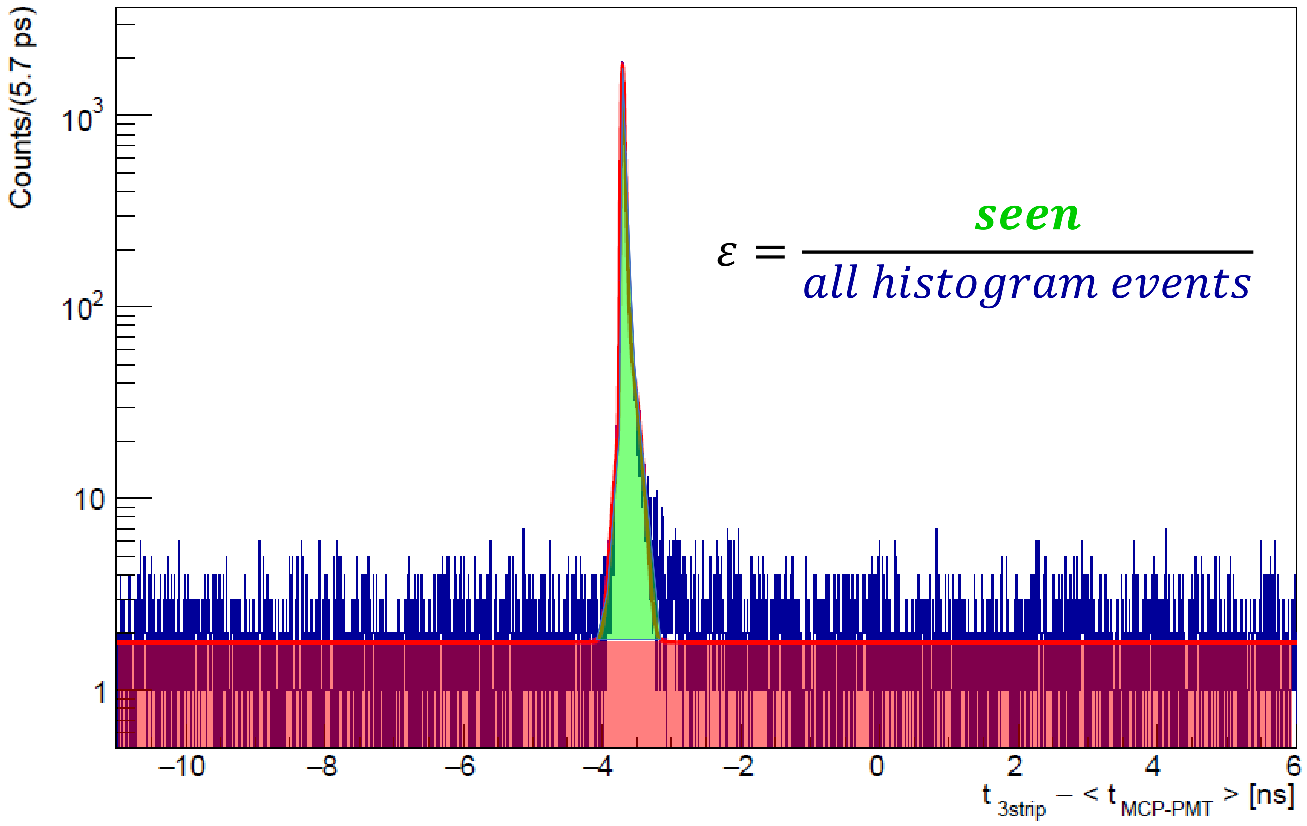
- Rotate the DUT around the trench direction



Irradiated sensors – efficiency

Geometrical efficiency measurement method:

Time distribution of the triple-strip signals w.r.t. the time reference

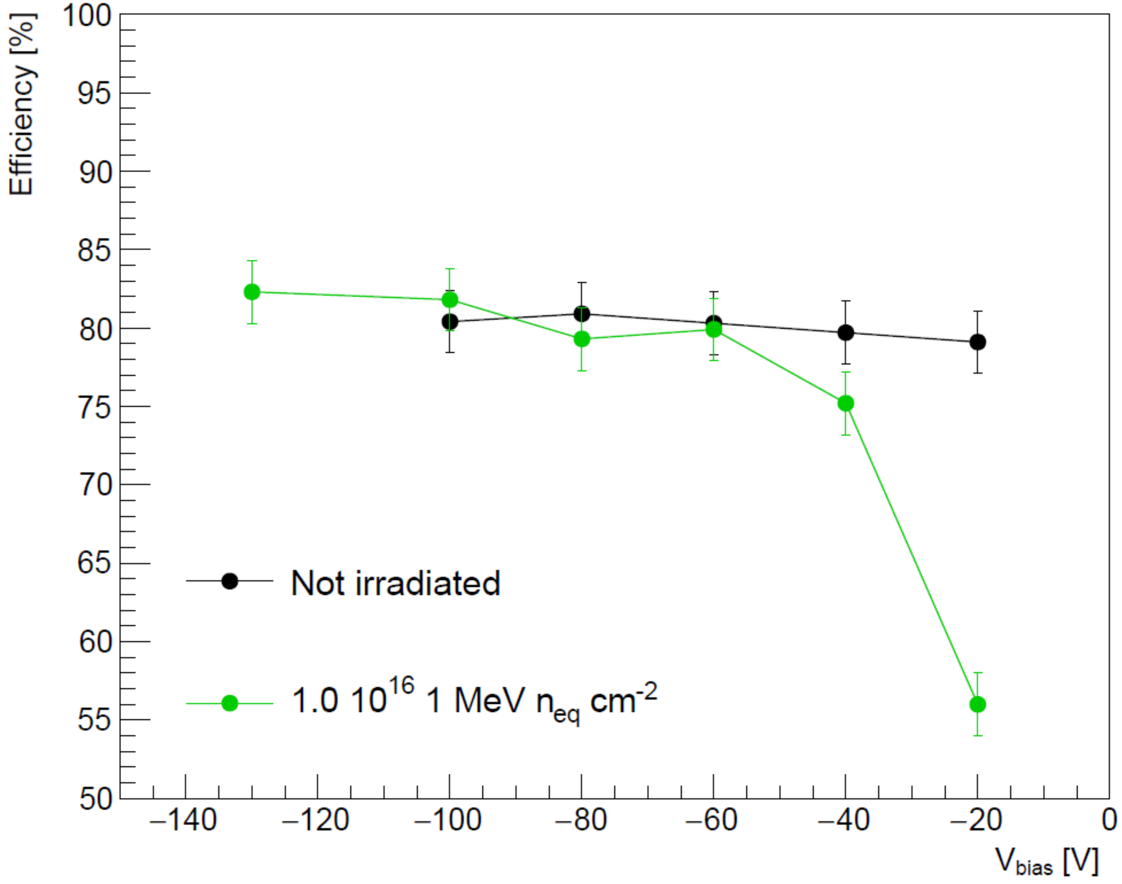


$$\varepsilon = \frac{seen}{all\ histogram\ events}$$

- Fit of the **peak** + the **background**
- The events under the peak are the events seen by the triple-strip
- The flat background corresponds to undetected particles
- The *seen* events are calculated by subtracting the background events from the total histogram events

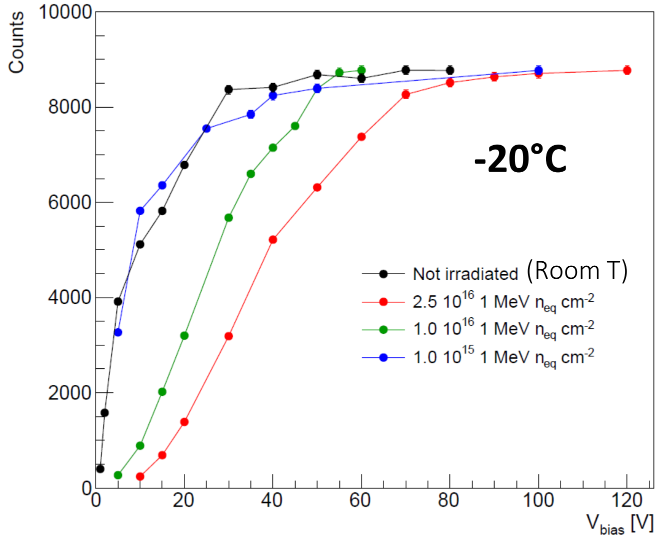
Irradiated sensors – efficiency

Efficiency VS bias voltage at perpendicular beam incidence (0°)



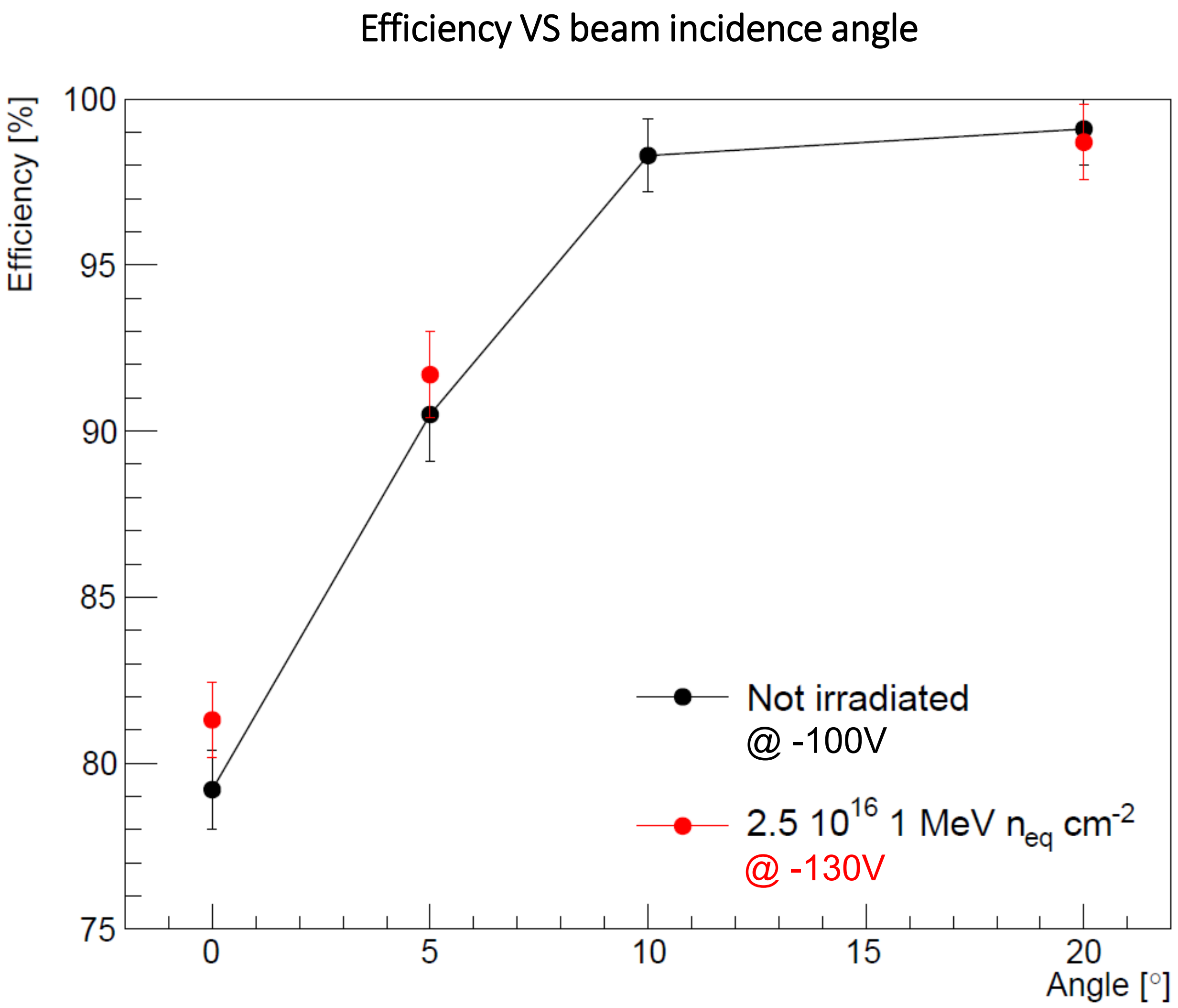
- **Non-irradiated sensor** already efficient at -20 V
- **$1 \cdot 10^{16}$ 1 MeV n_{eq} / cm^2** triple strip shows an about 30% smaller efficiency at -20 V w.r.t. the non-irradiated one
- Irradiated sensor **efficiency recovery** by increasing the bias voltage

This result is in agreement with the study made with the ^{90}Sr source



Events rate VS bias voltage

Irradiated sensors – efficiency



Compatible results obtained for the **non-irradiated** and the **$2.5 \cdot 10^{16}$ 1 MeV n_{eq} / cm^2** sensors by increasing the bias voltage of the second by only 30 V w.r.t. the non-irradiated

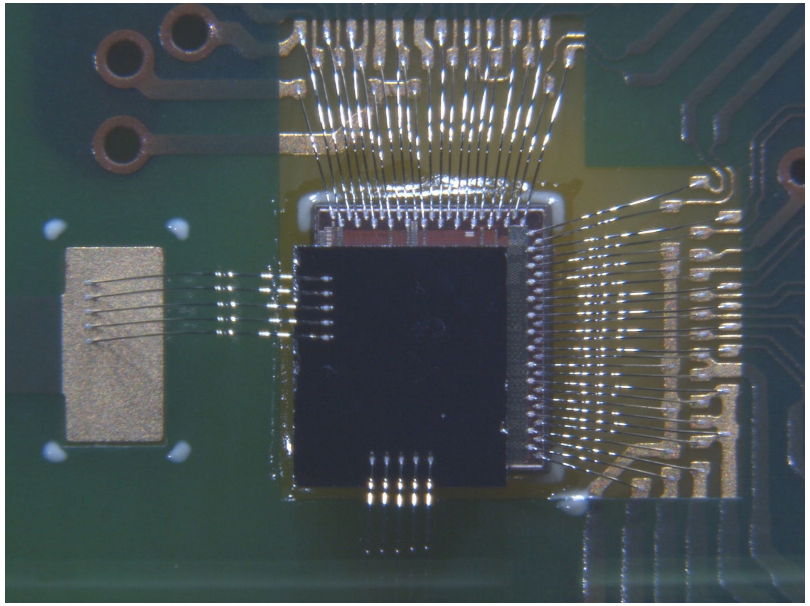
Almost fully efficient at 20°

$$\varepsilon = 99.1 \pm 1.2\ \%$$
$$\varepsilon = 98.7 \pm 1.1\ \%$$

This result, together with the timing measurements, proves for the first time the **good performance of TimeSPOT sensors** also when they are exposed to **high radiation fluences**

Conclusions

- Characterization of highly irradiated TimeSPOT silicon sensors both in the laboratory and at the test beam
- **Excellent timing performance of irradiated sensors**, compatible with those of non-irradiated sensors, showing a time resolution of **10-12 ps** at **-100V**
- **Efficiency** of **irradiated sensors** compatible to non-irradiated one, by slightly increasing the bias voltage. At **20°** beam incidence angle about **99% efficiency**
- Radiation tolerance limit not reached yet
- Tests on the Timespot1 ASIC are ongoing (see A. Loi talk)

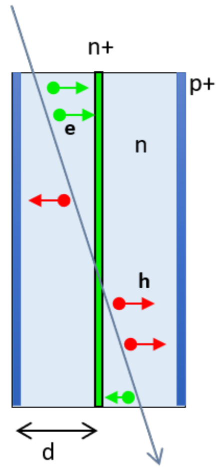


Additional material

Time resolution contributions

At a first order simplified analysis, the time resolution of a system sensor + read-out electronics is

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



~~$\boldsymbol{\sigma_{tw}}$~~: signal amplitude fluctuation event by event → time-walk jitter ⟶ constant fraction discriminator

~~$\boldsymbol{\sigma_{dr}}$~~: delta rays → signal amplitude and shape variations ⟶ negligible in a 3D sensor

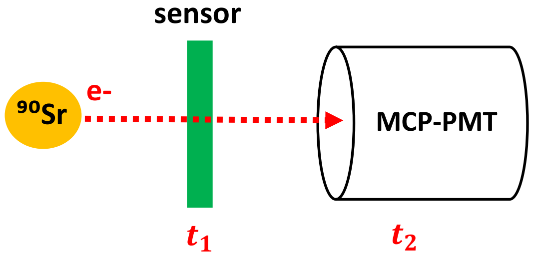
$\boldsymbol{\sigma_{un}}$: non-uniformities in the charge collecting field and carrier velocities → different signal shape

$\boldsymbol{\sigma_{ej}}$: noise of the preamplifier used to readout the sensor

~~$\boldsymbol{\sigma_{TDC}}$~~: digital resolution of the electronics used to measure the signal ⟶ adequate TDC

For a 3D sensor ⇒ $\sigma_t \cong \sqrt{\sigma_{un}^2 + \sigma_{ej}^2}$

Laboratory setup with ^{90}Sr source (2)



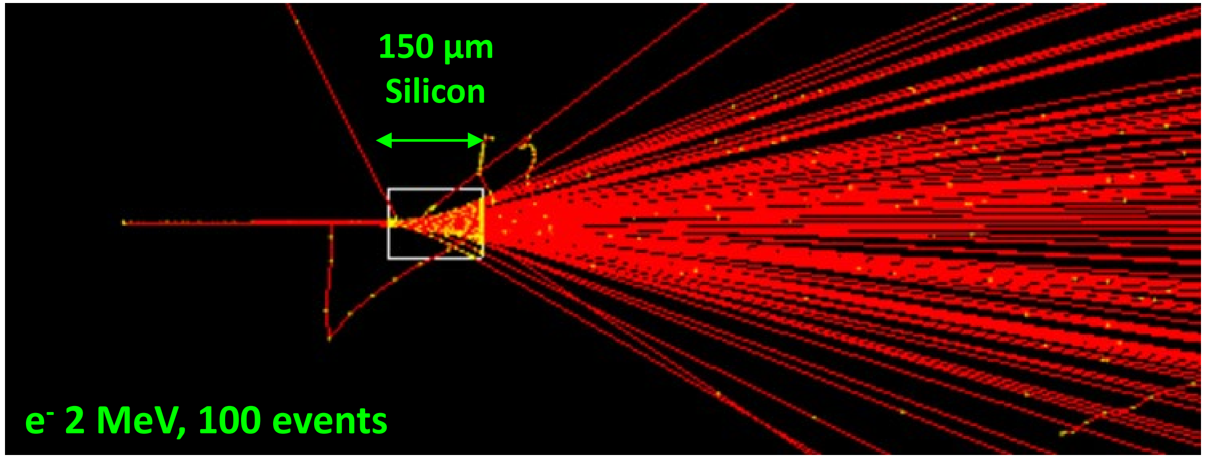
^{90}Sr: e^- (0.5-2.2) MeV

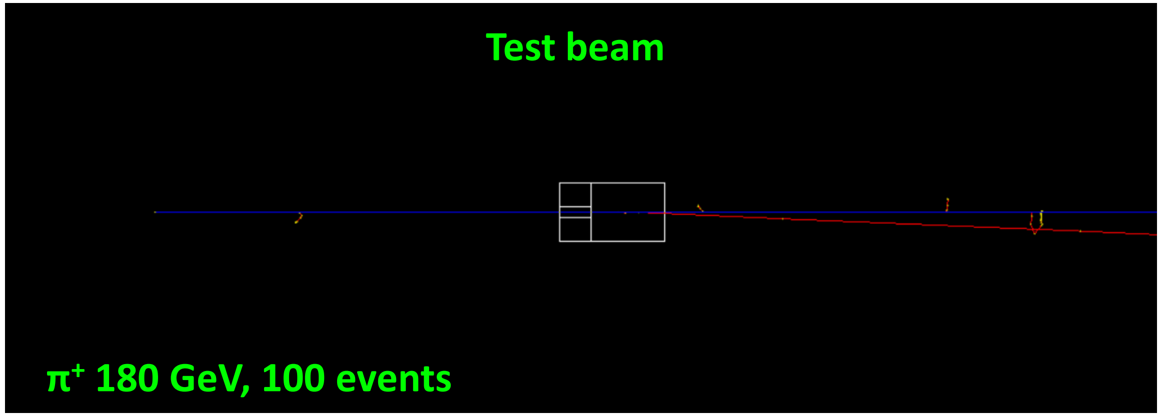
The multiple scattering in silicon at these energies is an important effect to be taken into account –> **simulation**

The **MCP-PMT** is used both to:

- have an accurate time reference
- select more energetic electrons → Cherenkov threshold in the 5.5 mm thick quartz input window $E_{th} \sim 0.7\ MeV$

Geant4 simulation

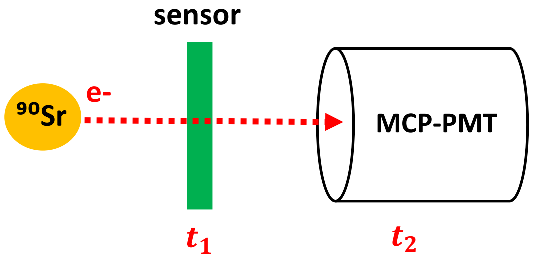




Beam at CERN SPS/H8 beamline where we made TimeSPOT beam tests in 2021 and 2022

Laboratory setup with ^{90}Sr source

^{90}Sr: e^- (0.5-2.2) MeV



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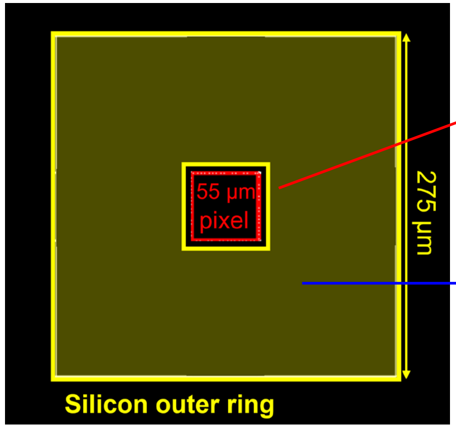
- have an accurate time reference
- select more energetic electrons → Cherenkov threshold in the 5.5 mm thick quartz input window $E_{th} \sim 0.7$ MeV

The **multiple scattering** in silicon at these energies is an important effect to be taken into account and it is a critical aspect of this setup

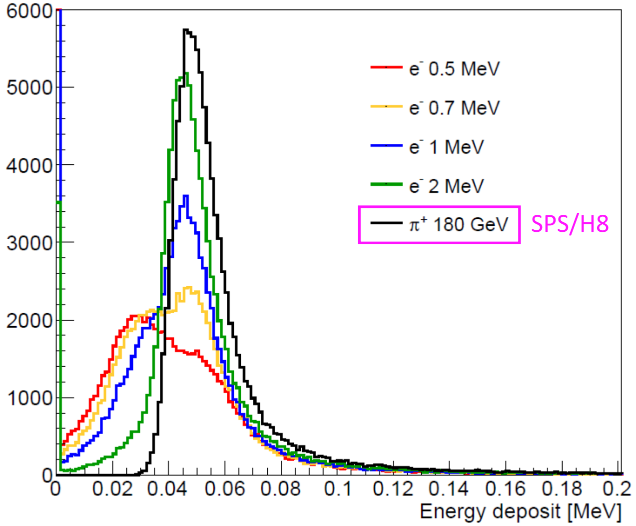
Geant4 simulated geometry



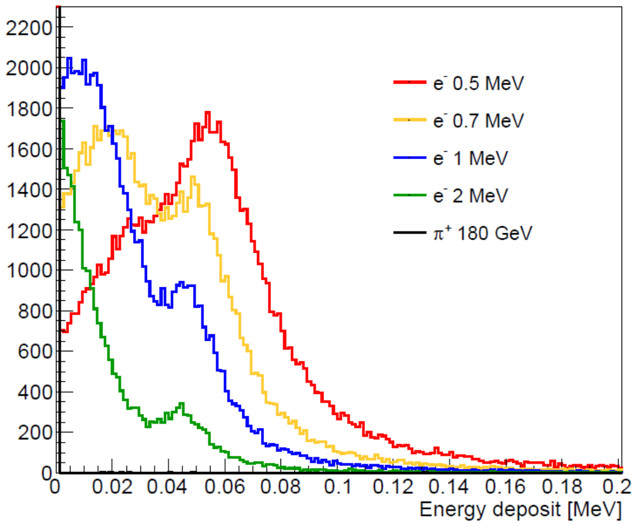
55 x 55 x 150 µm^3 Silicon block – representing a TimeSPOT pixel

Outer Silicon ring 275 x 275 x 150 µm^3

Energy deposit in the **pixel**



Energy deposit in the **outer ring**

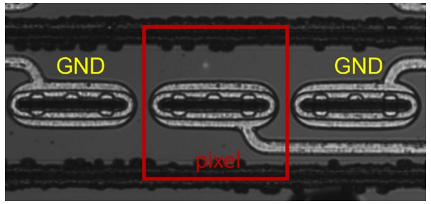


For electrons 0.5-2 MeV a large amount of charge deposited outside the pixel ⇒ lower deposit ⇒ higher time jitter $\left(\sigma_{ej} \approx \frac{t_r}{S/N}\right)$

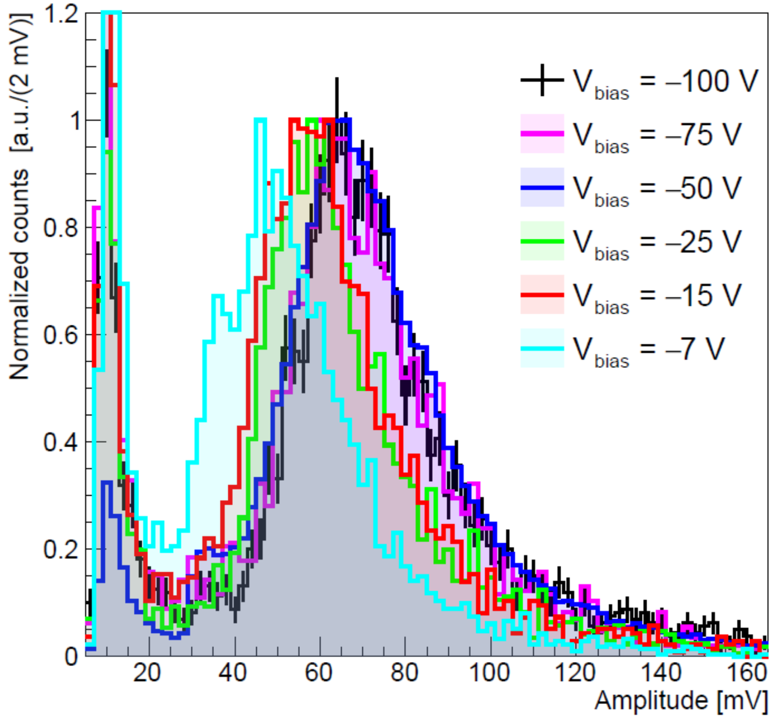
This setup with the ^{90}Sr source allows to measure only an **upper limit** of the **time resolution** (about twice), but it allows to make **preliminary tests** in **laboratory** and to compare different test structures performance

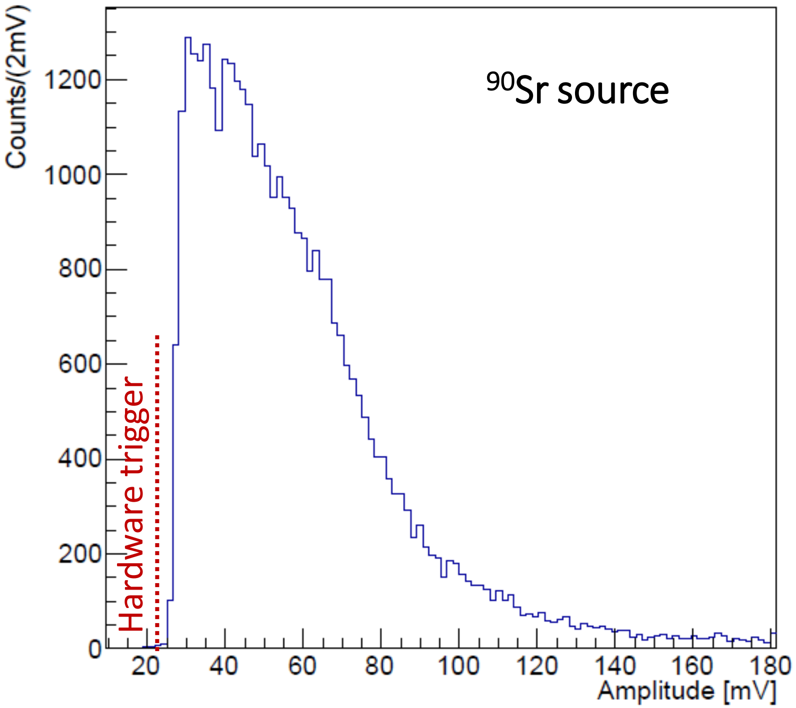
Not-irradiated sensors characterization with ^{90}Sr setup

Measured amplitude distributions



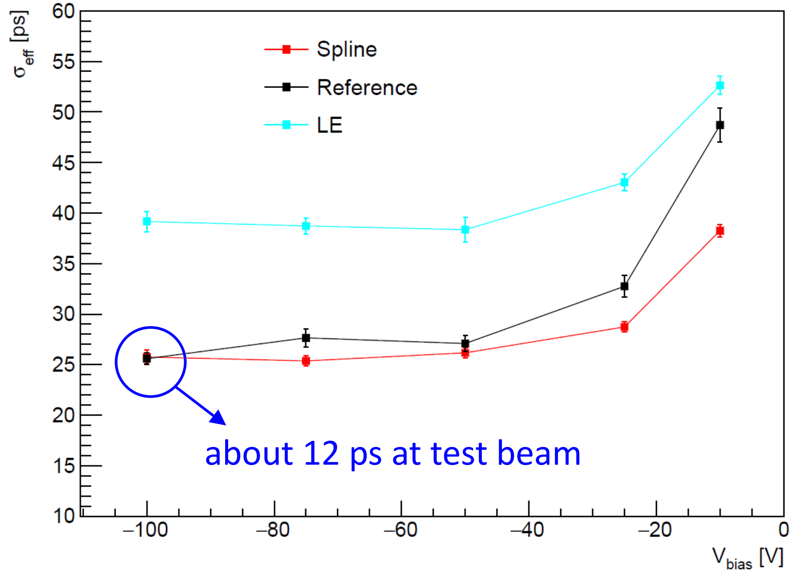
π^+ 180 GeV/c test beam SPS/H8





Lower deposit = higher time jitter

$$\sigma_{ej} \approx \frac{t_r}{S/N}$$

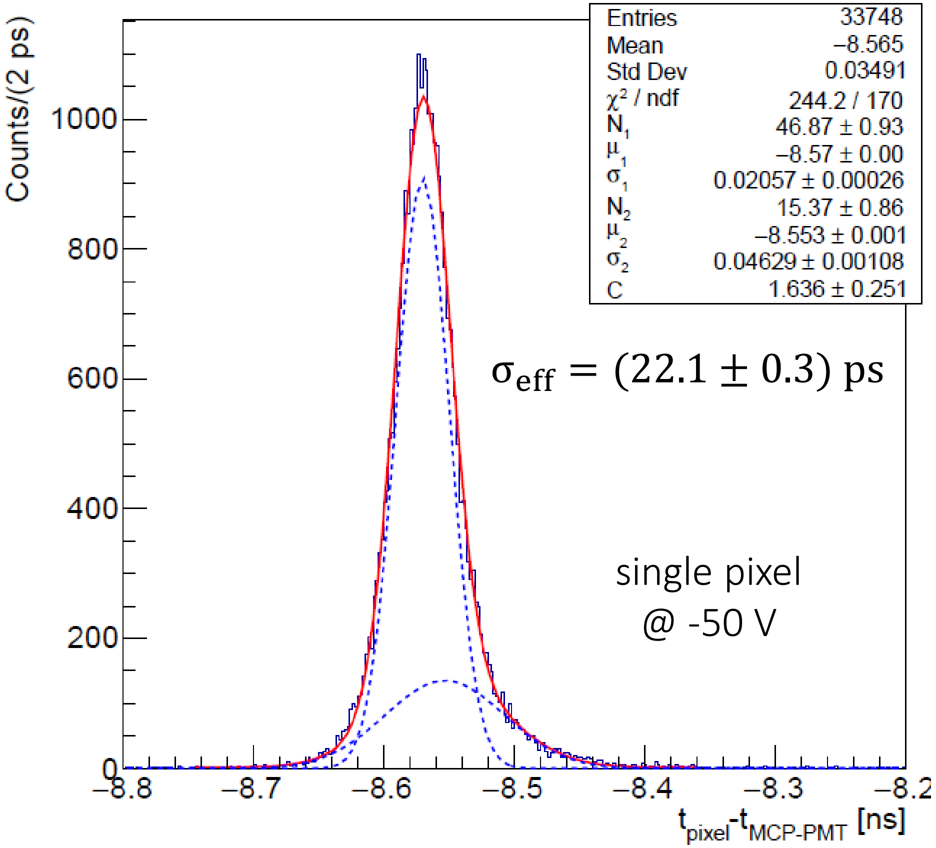


MCP-PMT time jitter contribution subtracted on the basis of laser characterization made in laboratory

This setup with the ^{90}Sr source allows to measure only an **upper limit** of the **time resolution** (about twice), but it allows to make **preliminary tests** in **laboratory** and to compare different test structures performance

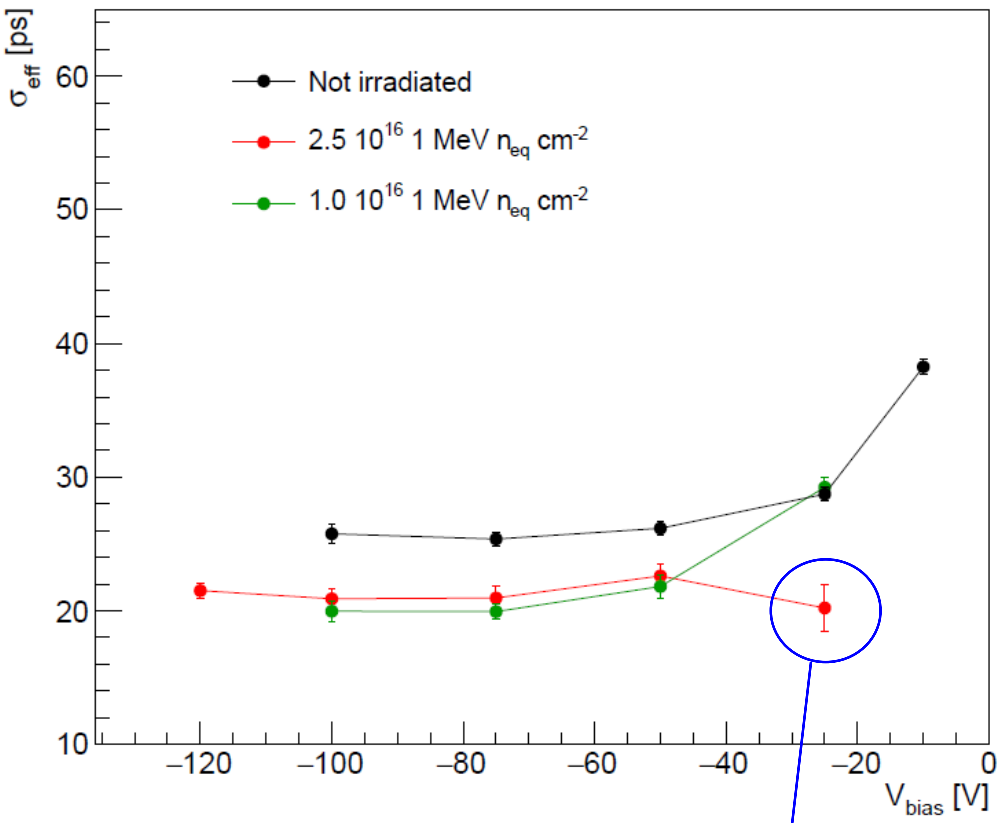
Laboratory characterization of irradiated TimeSPOT sensors

$$\Delta t = t_{single-pixel} - t_{MCP-PMT}$$



Two Gaussian fit of the time distribution to include late signals contributions + a constant modelling the background
→ **mixture distribution** with std dev $\boldsymbol{\sigma_{eff}}$

Effective time resolution VS bias voltage



Spline method

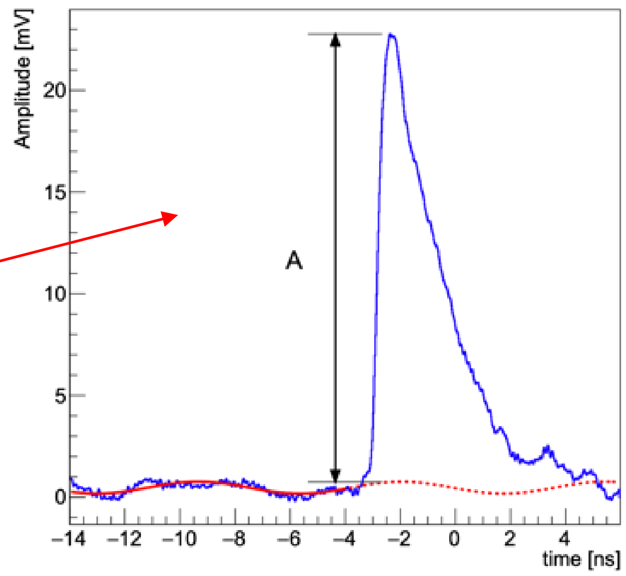
The irradiated sensors time resolution is not degraded after irradiation, they show an **even better $\boldsymbol{\sigma_{eff}}$ w.r.t. non-irr. one** → possible explanations later

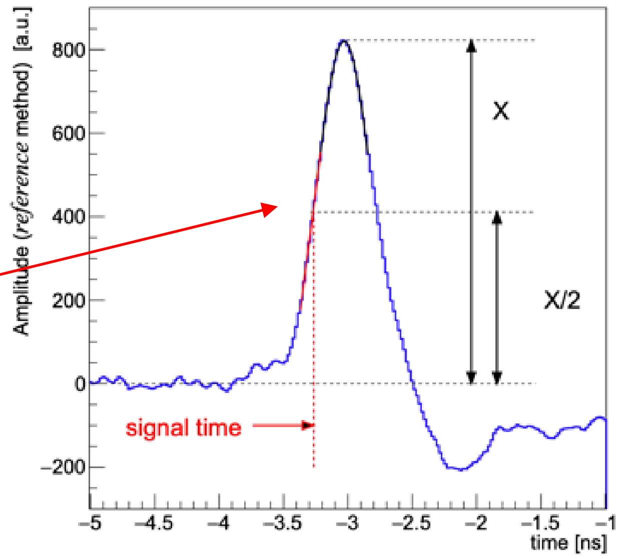
Apparently better result at -25 V, probably due to the rejection of small signals by the trigger coincidence condition → following test beam results confirm this hypotesis

Waveforms analysis

For each sensor’s waveform – in both laboratory and test beam data analysis:

- 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 time of arrival** evaluated with a costant fraction algorithm:
    - ***Reference***: 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
    - **Leading-edge**: time at 15 mV signal amplitude, linear interpolation around threshold (time-walk effect is present)
    - **LE corrected for the amplitude** to suppress the time-walk effect
    - **Spline**: a classic CFD at 20% with rising edge interpolated with a spline

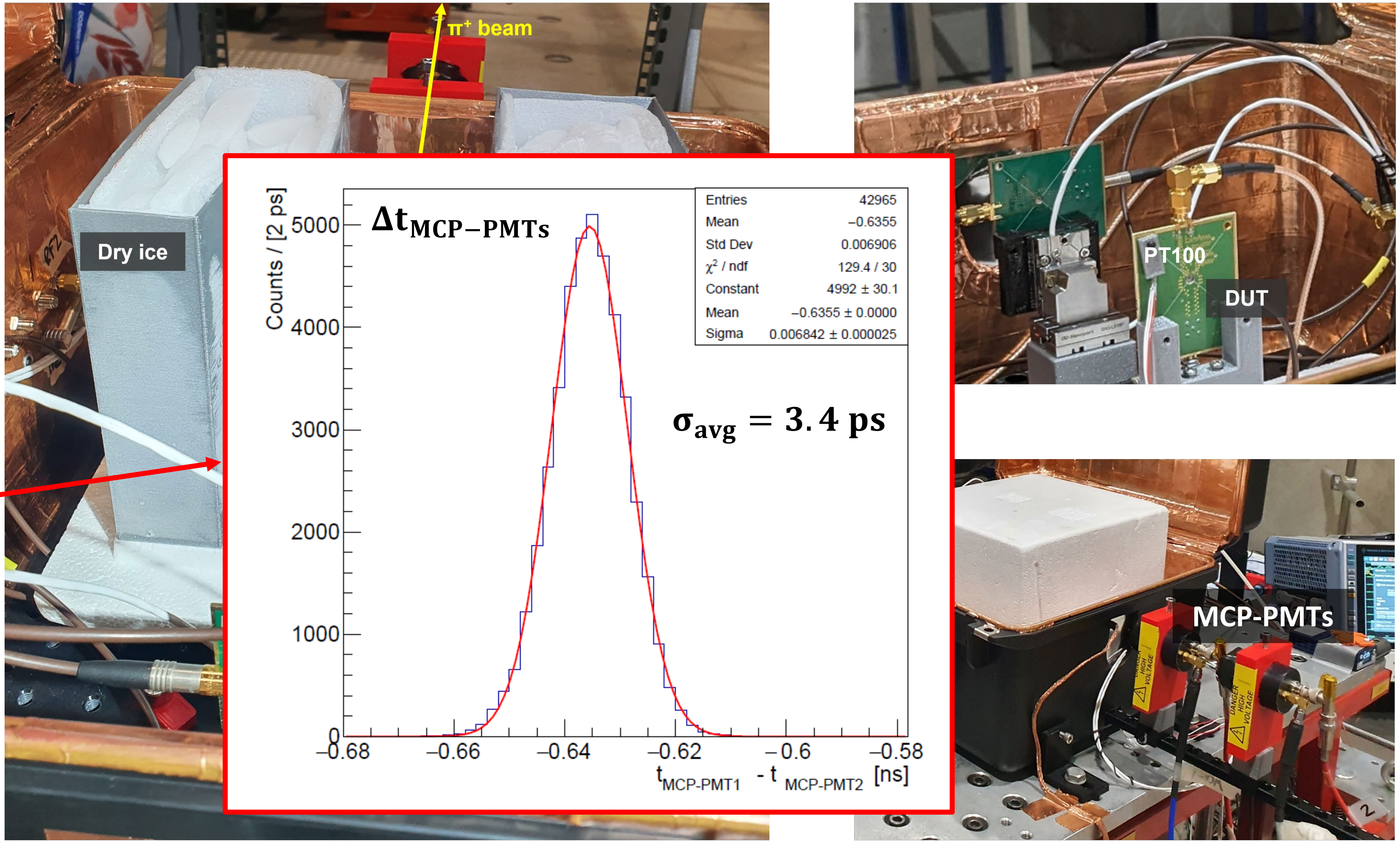




Test beam of irradiated sensors

Test beam made in **May 2022** at CERN **SPS/H8** beamline, **180 GeV/c positive pions beam**

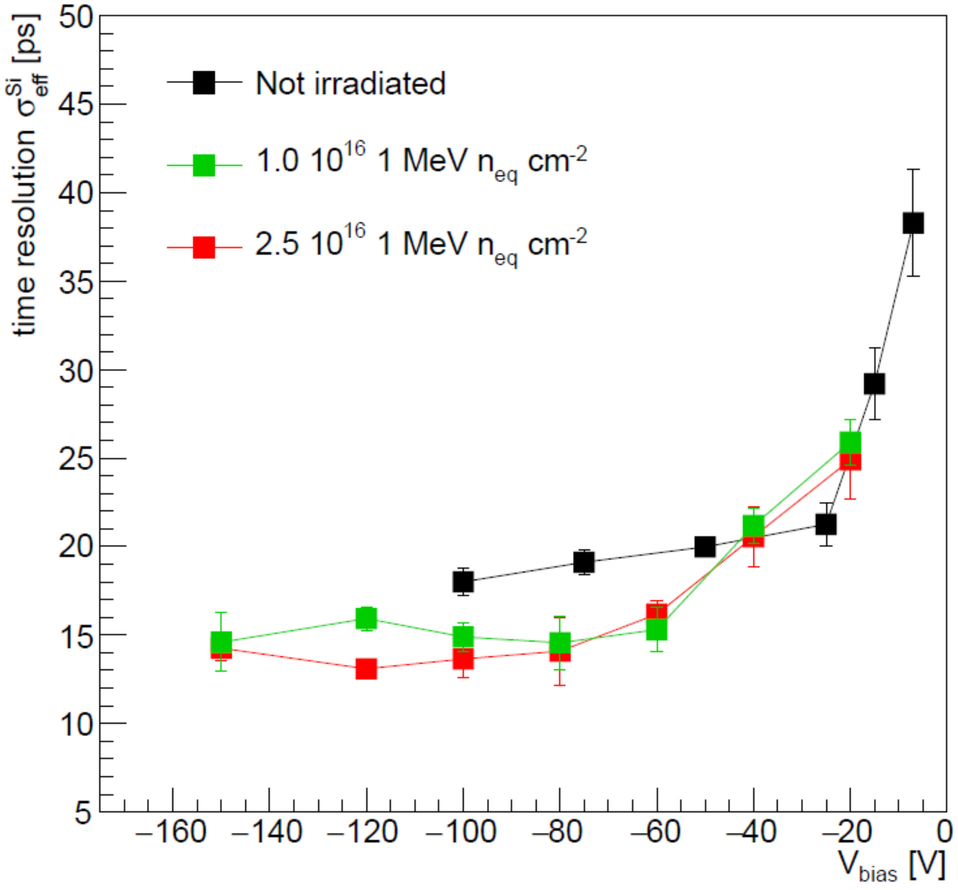
- **DUT outside the trigger** and can be rotated
- **Piezoelectric stages to precisely align** the two 3D structures with beam, all mounted in a RF-shielded box
- **Dry ice**, allows to keep the irradiated sensor under test in the range of temperature **(-40,-20)°C,** monitoring with a PT100 sensor
- **2 MCP-PMTs** as time reference of the setup with a measured accuracy of **3-4 ps**
- **DAQ** with an **8 GHz bandwidth 20 GSa/s oscilloscope**
- **Time resolution** and **efficiency** measurements



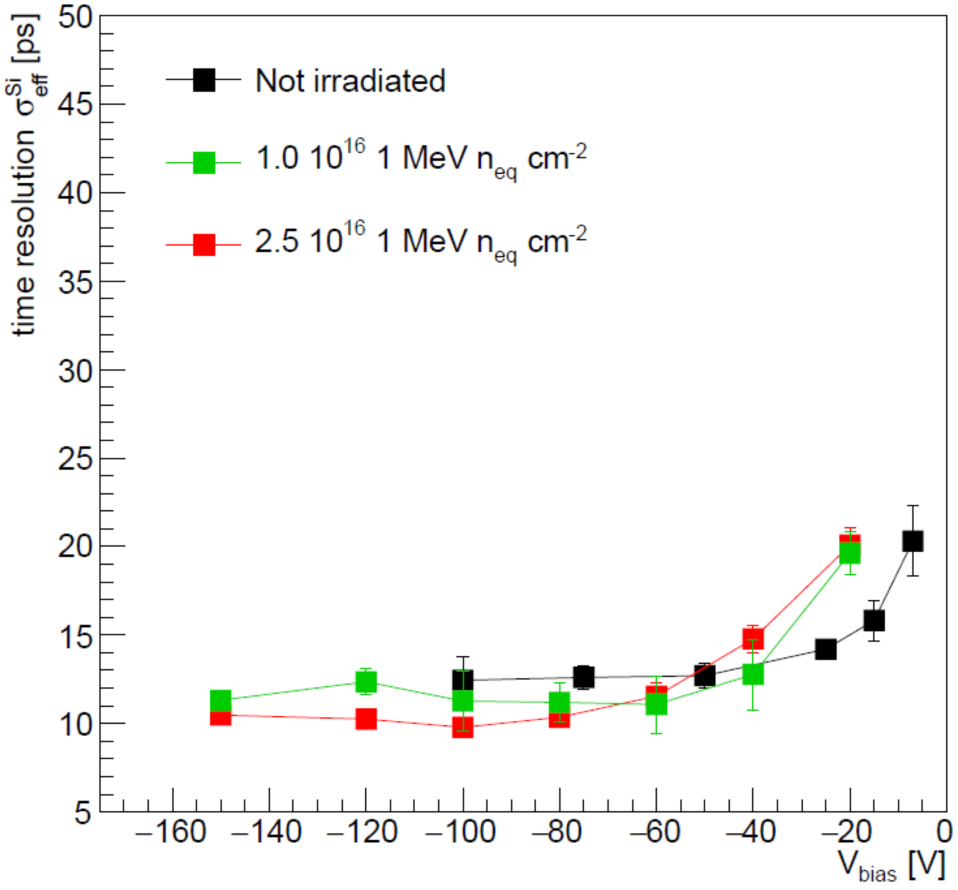
Irradiated single pixels – time resolution

Single pixel time resolution measured with the two constant fraction based algorithms *Spline* and *Reference*

Spline method

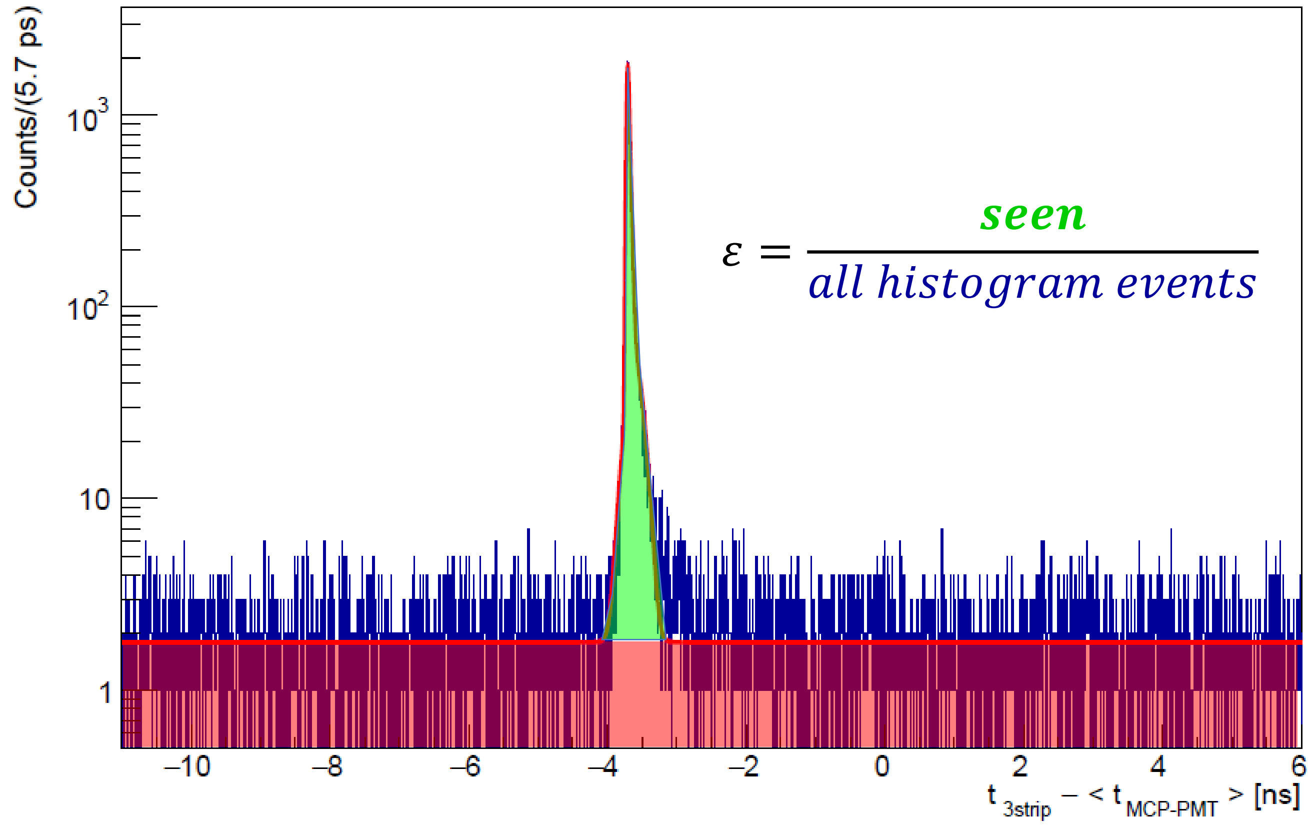


Reference method



Efficiency measurement

Time distribution of the triple-strip signals w.r.t. the time reference



$$\varepsilon = \frac{seen}{all\ histogram\ events}$$