The LHCb U2 VELO: design, technologies and impact on physics

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Workshop Italiano sulla Fisica ad Alta Intensità

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Overview

- Technological requirements for tracking in HI experiments;
- Benefits of the HL-LHC programme for LHCb with new technologies;
- Challenges of LHCb-Run 5: VELO UII (Timing VELO, TV);
- TimeSPOT & IGNITE projects;
- Other application: High Intensity Neutrino tagging;
- Conclusions.

Technological requirements for tracking in HI experiments

Next generation High Energy Physics experiments
will starts the era of high intensity 4D-Tracking (**HI4DT**)

High rate of events → **Huge statistics** but ...

...the new detectors will have to cope with extreme environments:

- **TID > 1 Grad/ASIC;**
- **Fluence Φ > $1\text{x}10^{16}$ 1MeV n_{eq} /cm^2;**
- **Pileup <μ> ~ 200 (or above);**
- **Data rate > 100 Gbps/ASIC.**

orders of magnitude higher than current values !!!

Novel technological solutions are needed to match such requirements and enable High Intensity Physics.

INFN initiatives such as **TimeSPOT** (2018-2021) and **IGNITE** (2023-present) were born precisely with this aim in mind to offer a technological solution.

Benefits of the HL-LHC programme for LHCb with new technologies

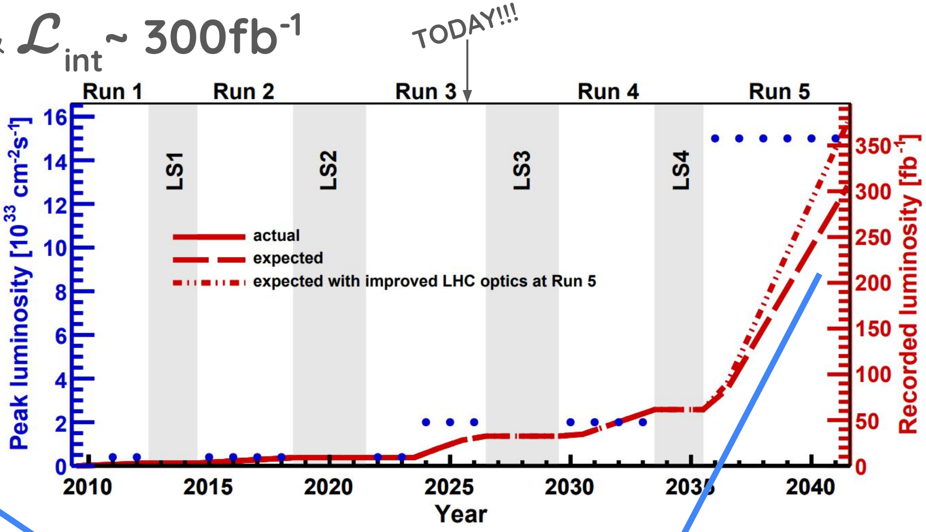
Delivered luminosity **$\mathcal{L}$ ~ 1.5x10^{34} cm^{-2} s^{-1}** & **$\mathcal{L}_{int}$ ~ 300fb^{-1}**

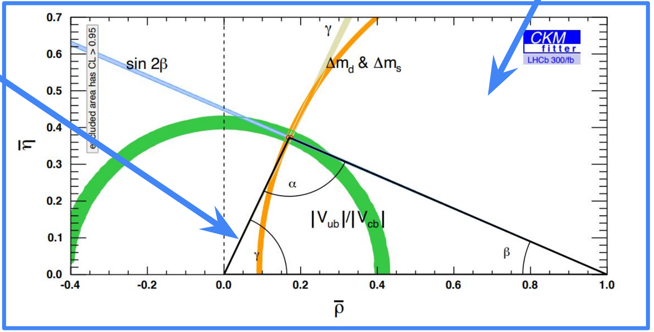
LHCb focuses on study b and c
in the **forward direction**

HL-LHC discovery potential @ LHCb:

- Searches for CP-violating NP;
- Determination of the CKM angle γ
- Matter-antimatter asymmetry;
- Enhanced sensitivity to rare decays;
- Heavy ion and fixed-target physics;
- Hadron spectroscopy;

And more ...





Images from LHCb Upgrade II Scoping Document

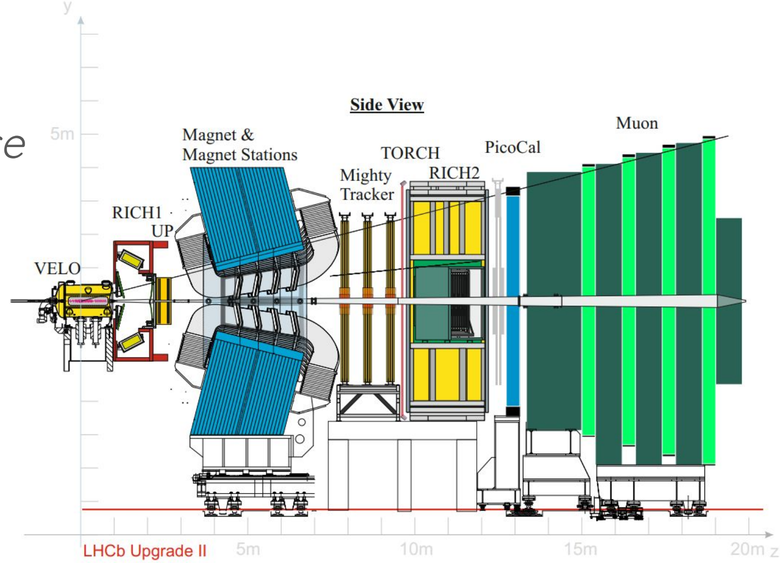
Challenges of LHCb-Run 5: VELO UII (Timing VELO, TV)

- Pile up **$<\mu_{RUN-5}>$ ~ 40** ($<\mu_{RUN-3}>$ ~ 5);
- Maximum radiation **Fluence Φ_{RUN-5} ~ 5×10^{16} 1MeV n_{eq} /cm^2**(Φ_{RUN-3}~ 5×10^{14});
- Data rate **DR_{RUN-5} > 100 MHz/mm^2** ($5 \times DR_{RUN-3}$);
- Material budget < 0.8% X_0.

Requirements to *maintain current detector performance* and *enable the HI program* under these conditions:

- Spatial resolution **σ_x ~ 10 μm**;
- Temporal resolution **σ_t<50 ps/hit** (sensor+FE).

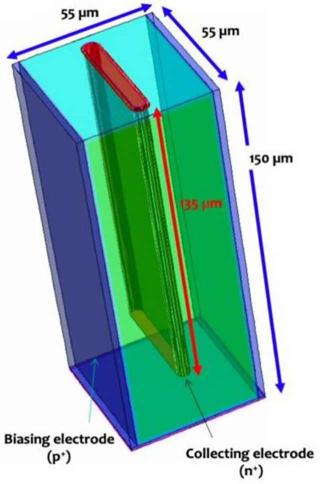
<u>Pileup can only be solved with 4D tracking;</u>



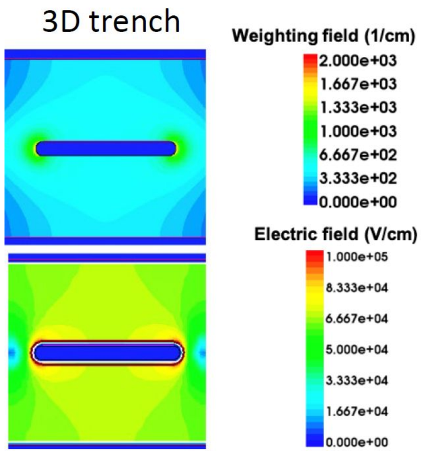
Images from [LHCb Upgrade II Scoping Document]

TimeSPOT & IGNITE projects: Current status

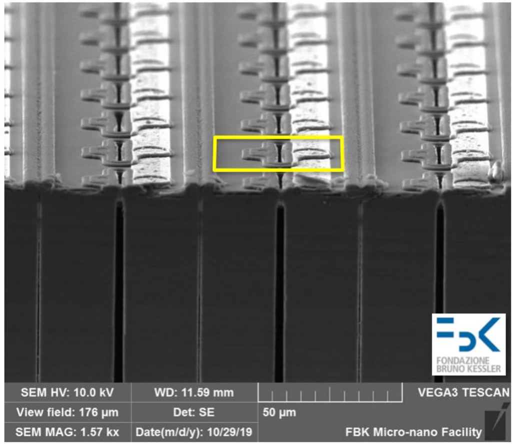
Designed to provide excellent timing performances and be radiation tolerant.



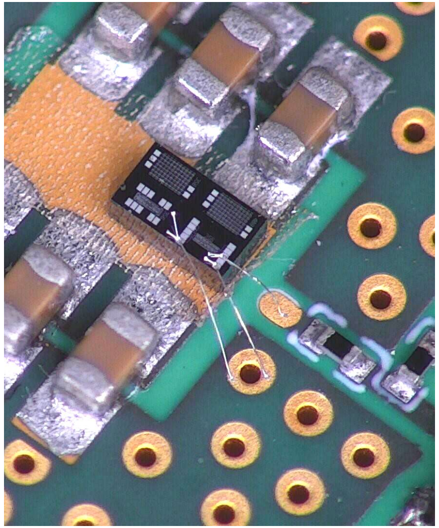
CAD design of a TimeSPOT 3D-Trench silicon Pixel, pitch 55µm



Weighting field and velocity map, from design and TCAD simulation it is possible to see uniformity and speed



FBK-TimeSPOT batch production

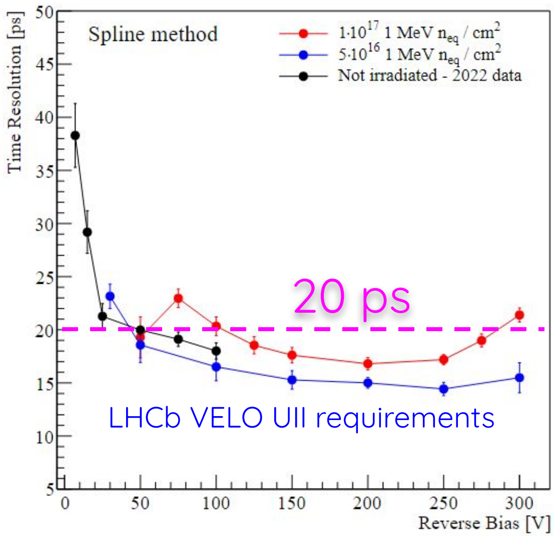


TimeSPOT test structure irradiated @ 5×10^{17} 1MeV n_{eq}/cm^2, wirebonded to the custom frontend electronics

Image from [Characterisation of highly irradiated 3D trench silicon pixel sensors for 4D tracking with 10 ps timing accuracy](#)

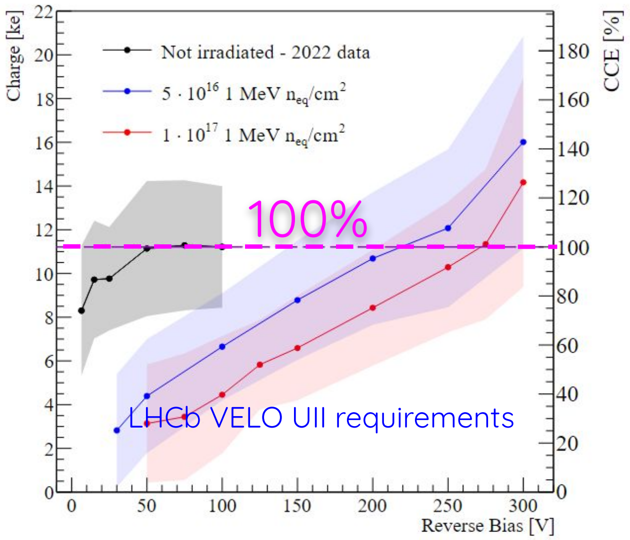
TimeSPOT: performances @ Fluence $\Phi = 1\times10^{17}$ 1MeV n_{eq} /cm^2

Temporal resolution σ_t



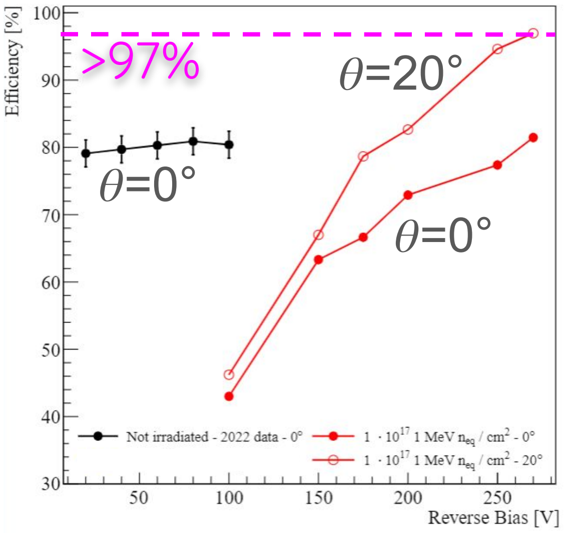
Time resolution (calculated with ARC method) less than 20 ps.

CCE



Charge collection can be restored by acting on the reverse voltage. Observation of charge “multiplication” effects.

Detection efficiency



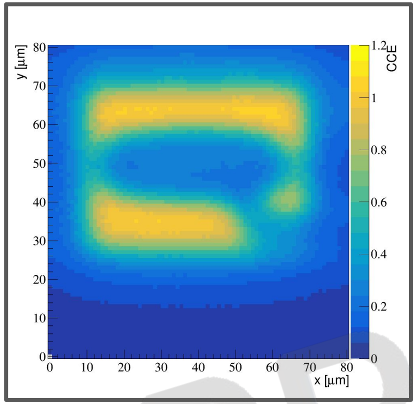
Efficiency as a function of applied reverse bias voltage and tilt angle.

Characterisation of 3D trench silicon pixel sensors irradiated at 1x10^{17} 1 MeV n_{eq} /cm^2

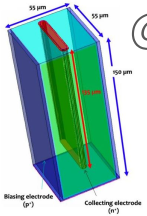
TimeSPOT: push the limits @ Fluence $\Phi = 10^{18}$ 1MeV n_{eq} /cm^2

Cold-TCT infrared (λ=1030nm) laser setup used to study sub-pixel performances

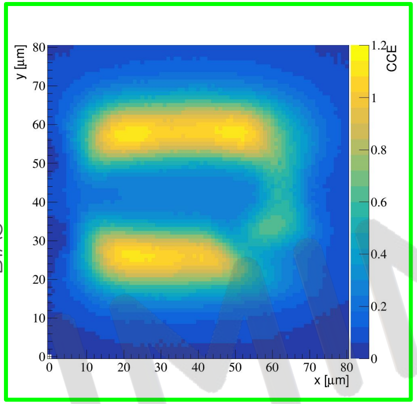
T=-20°C



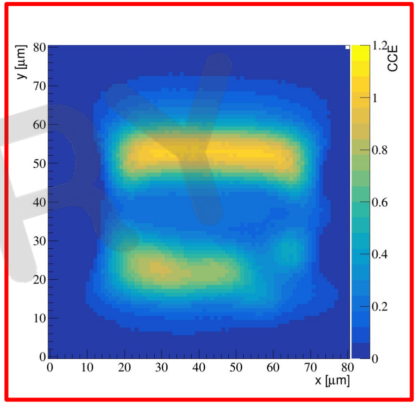
Not irradiated @ 50V$_{BIAS}$



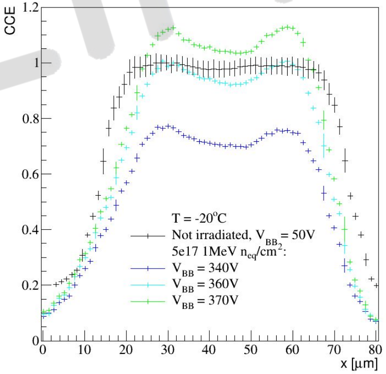
5x10^{17} 1 MeV n_{eq} /cm^2 @ 370V$_{BIAS}$

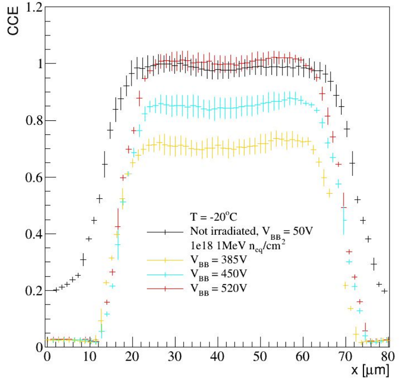


10^{18} 1 MeV n_{eq} /cm^2 @ 520V$_{BIAS}$



Profiles





3D trench pixels, a sensor solution for 4D tracking in HL-LHC experiments and beyond

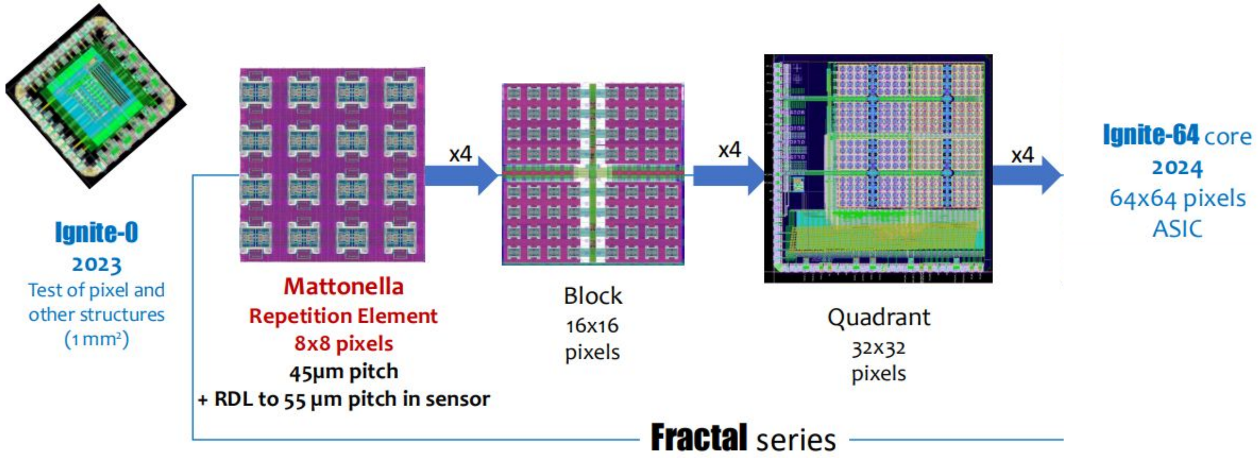
IGNITE Application specific integrated circuit

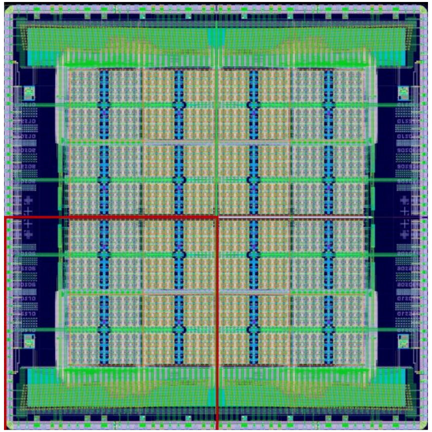
Idea of Fractal Design to build the Large Area ASICs:

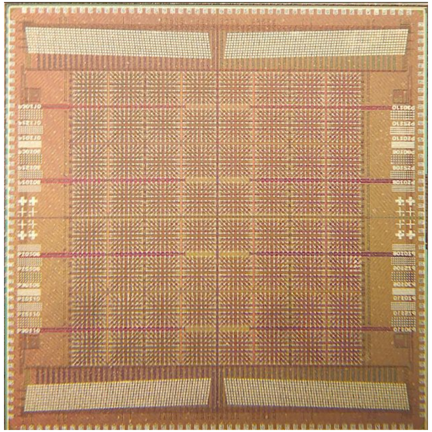
- 28 nm CMOS;
- Pixel pitch 55 µm.

→

- TID > 1 Grad;
- Ultra-fast timing < 50 ps.



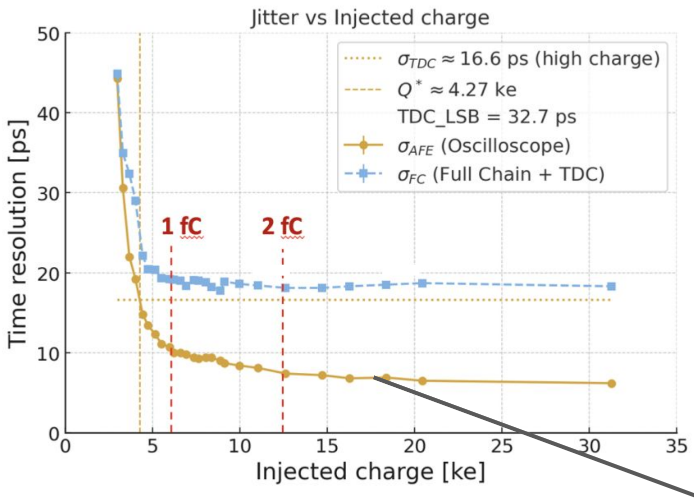


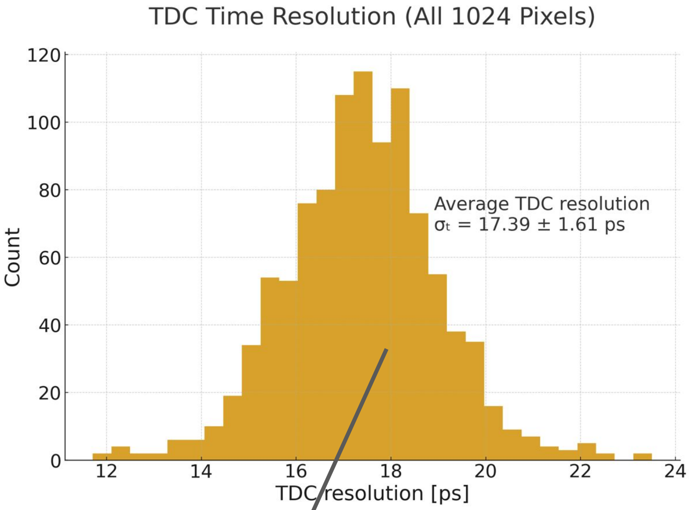


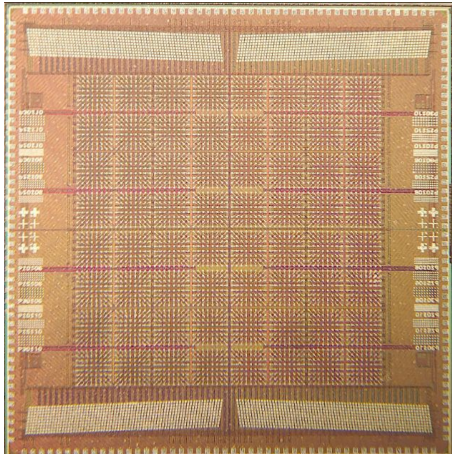
Timing VELO developments for U2

IGNITE: Some Results

Temporal resolution performances σ_t^{FE} ~ 20 ps (**without sensor**) @ 1fC.







$$\text{Total } \sigma_t = \sigma_{sensor} \oplus \sigma_{AFE} \oplus \sigma_{TDC} \oplus \sigma_{LHC\text{-}CLK} \lesssim 30\text{ps}$$

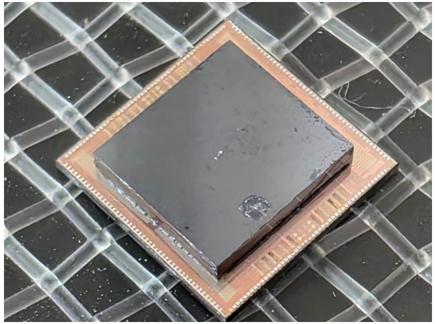
$\sigma_{TimeSPOT}$ < 20ps

10ps (estimate)

Characterization of the Ignite32-64 ASICs in CMOS 28-nm technology for 4D-tracking

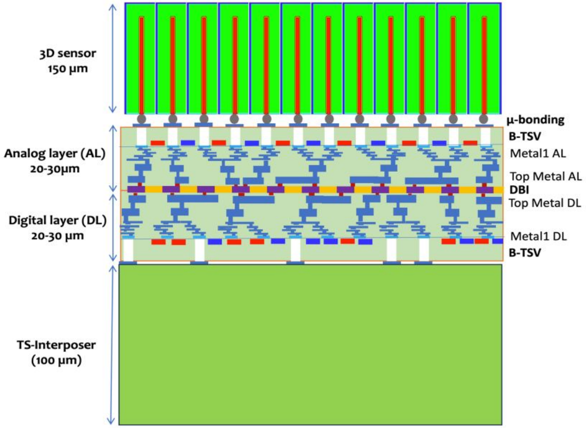
IGNITE: Next developments steps

- 2025-2026 - Tests with sensors will start very soon:
  - ^{90}Sr source;
  - TCT Laser studies;
  - and Test Beam (4D-telescope tests in Apr.2026);



- 2026 -Engineering Run:
  - 320x256 pixels ASIC (IGNITE-ER);
  - 45 µm pitch.

- Late 2026 - Validate Vertical Integration technique.



Other application: High Intensity Neutrino tagging

NuSCOPE is an international proto-collaboration aimed at building the first monitored and tagged neutrino beam at CERN SPS.

Physics reach potential:

- Determination of ν_μ/ν_e *cross-sections* in the 1-10 GeV range with 1% accuracy (to solve systematic limitation in DUNE and HK);
- PNMS parameter determination and search for leptonic CP-Violation.

SPS can provide p^+ of 400 GeV/c colliding on a graphite target producing:

- $K^+ / \pi^+ \rightarrow \mu^+ \nu_\mu$ (Two-body decay !!!)
- $K^+ \rightarrow \pi^0 e^+ \nu_e$

→ 4D tracking is necessary for accurate measurement of ν_μ/ν_e flux

SBN@CERN A short-baseline neutrino beam at CERN for high-precision cross-section measurements

Neutrino tagging: Tracking technology requirements

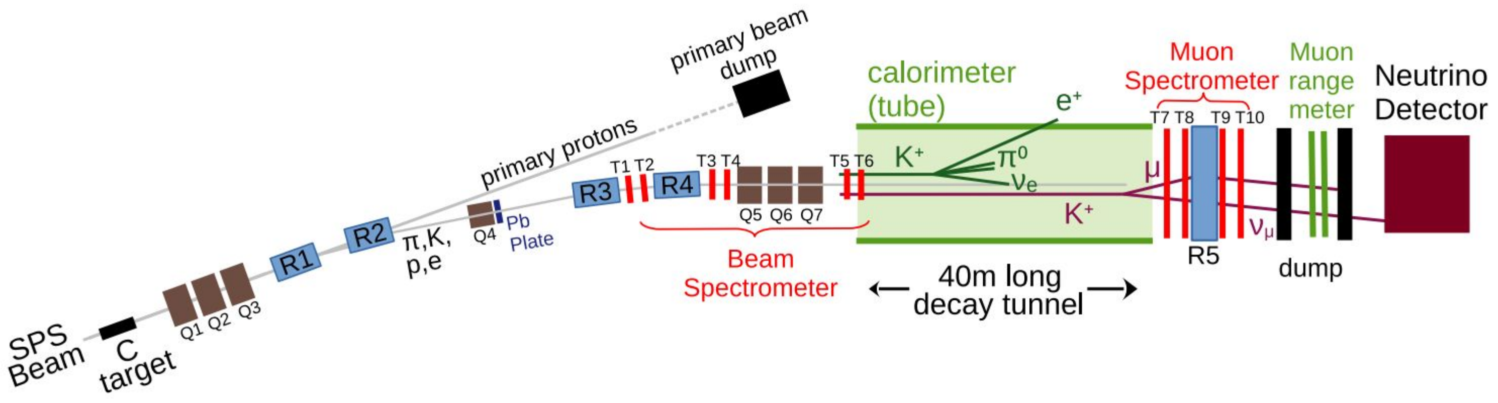


Image from SBN@CERN A short-baseline neutrino beam at CERN for high-precision cross-section measurements

The technological requirements for 4D-tracking (temporal correlation between decay products and detected ν_μ/ν_e) are very similar to those needed for the LHCb TV:

- Radiation tolerance **Fluence Φ ~ $1\text{x}10^{16}$ 1MeV n_{eq} /cm^2**;
- Temporal resolution **σ_t< 40 ps**;
- Data rate **~ 20 MHz/mm^2**;
- Material budget **< 1% X_0**.

TimeSPOT Sensors: legacy and future projects

	LHCb VELO UII	NuSCOPE	TimeSPOT
Fluence Φ [1MeV n_{eq} /cm^2]	5×10^{16}	1×10^{16}	$>1\times10^{17}$
Temporal res. σ_t[ps]	<50	<40	<20

- 3D sensors are the favourite option for the LHCb VELO UII.

LHCb Upgrade II Scoping Document

Next developments steps:

- Validate irradiated sensor @ Fluence $\Phi = 10^{18}$ 1MeV n_{eq}/cm^2 at a test beam;
- Improve the fabrication yield and produce large matrices (>64x64 pixels);
- Explore column-like geometries (improve yield);
- Explore stitching techniques, to produce very large matrices (of importance for NuSCOPE).

Conclusions

- <u>Enable HI experiments require new technologies:</u>
  - 4D tracking;
  - High radiation tolerance.

- INFN TimeSPOT & IGNITE projects:
  - Aim to provide a technological solution;
  - Timespot sensors met already the requirements;
  - IGNITE ASIC preliminary results very promising.

$$\textbf{Expected Total } \sigma_t = \sigma_{sensor} \oplus \sigma_{AFE} \oplus \sigma_{TDC} \oplus \sigma_{LHC\text{-}CLK} \lesssim 30\text{ps}$$

- Next developments steps:
  - IGNITE: Study of 64x64 pixel matrices (Lab and Test-Beam);
  - IGNITE: Validate the Vertical Integration;

THANKS !!!

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BACKUP SLIDES

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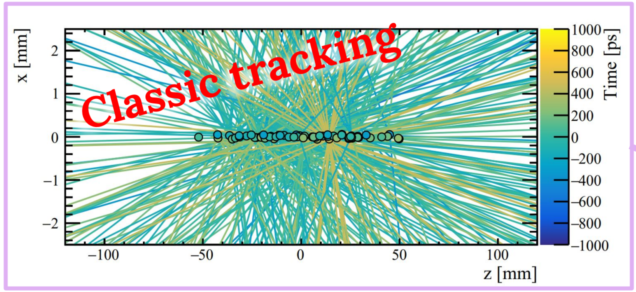
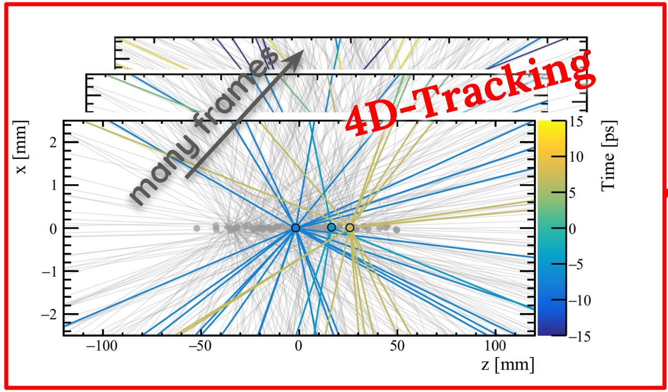
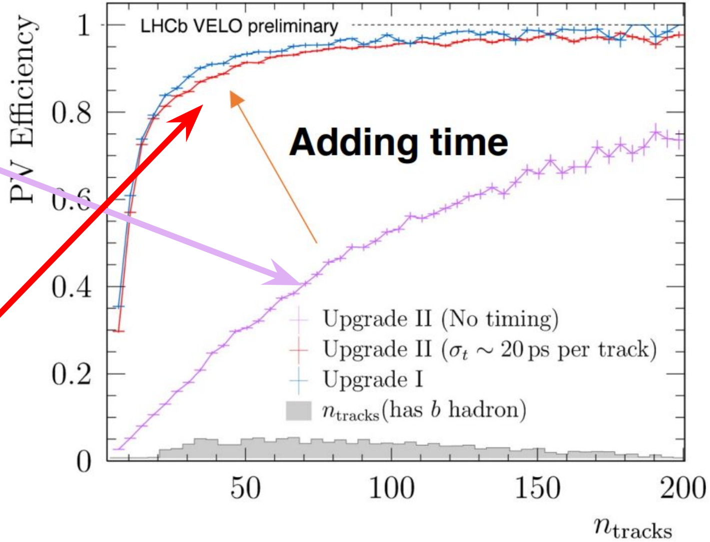
VeLo UII: WHY 4D TRACKING ?



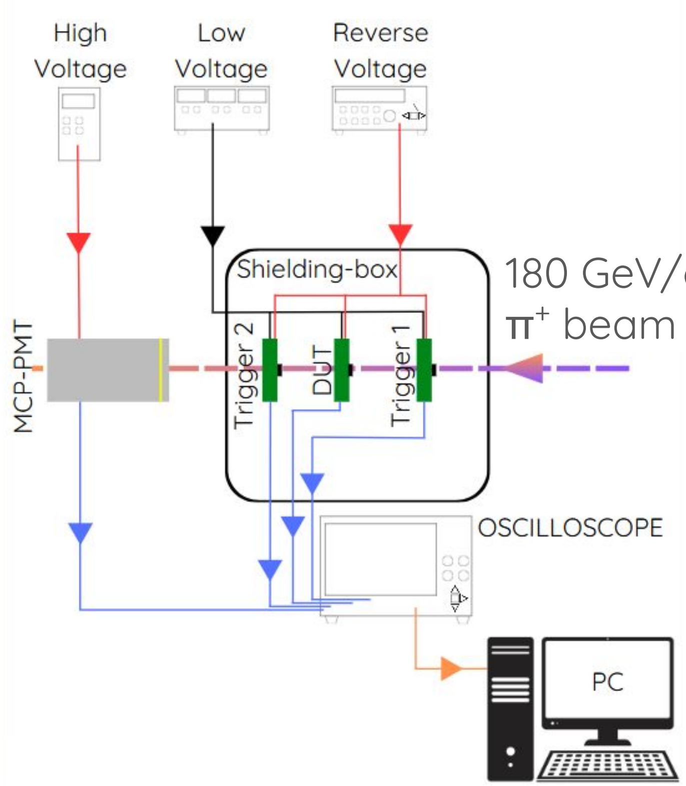


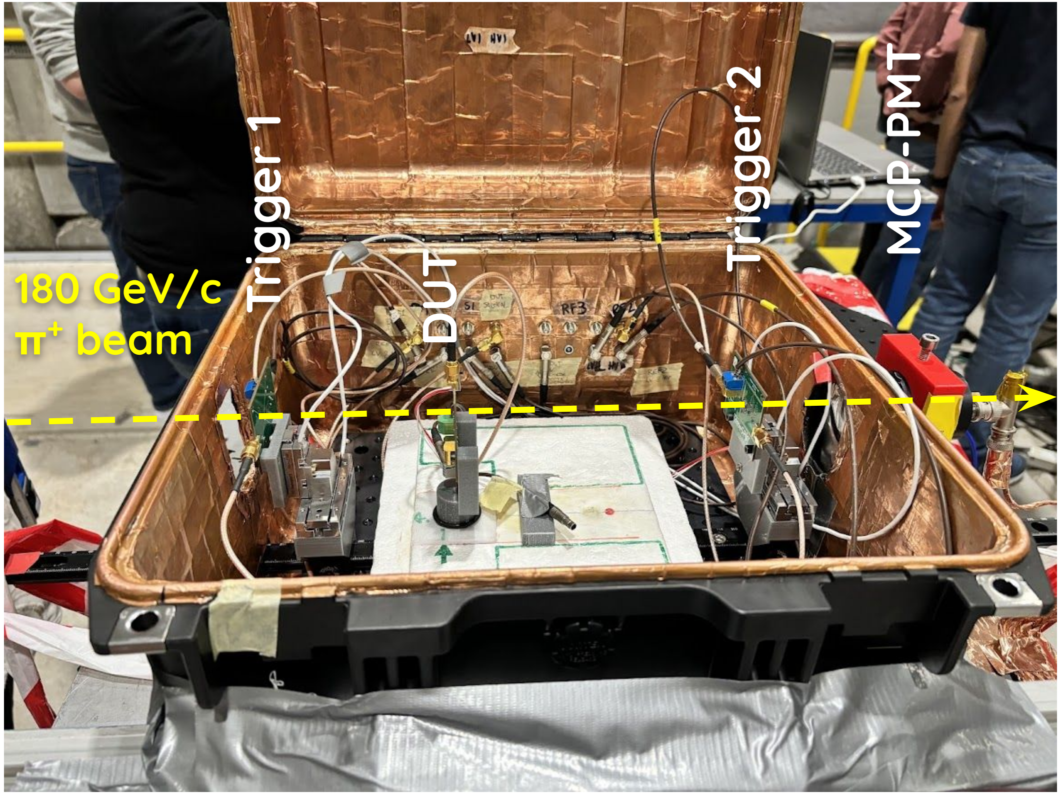


Images from LHCb Upgrade II Scoping Document

TimeSPOT: Test Beam setup

Efficiency setup

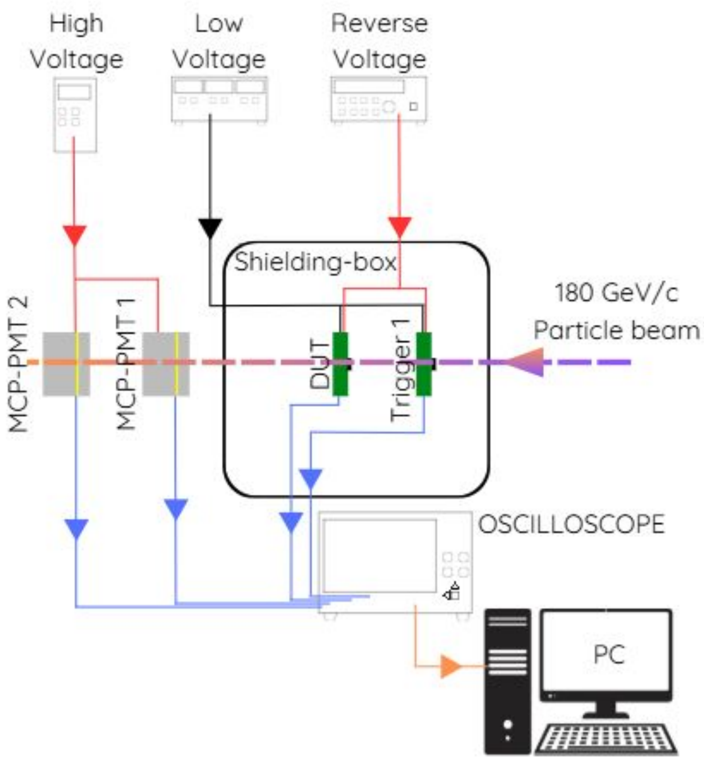


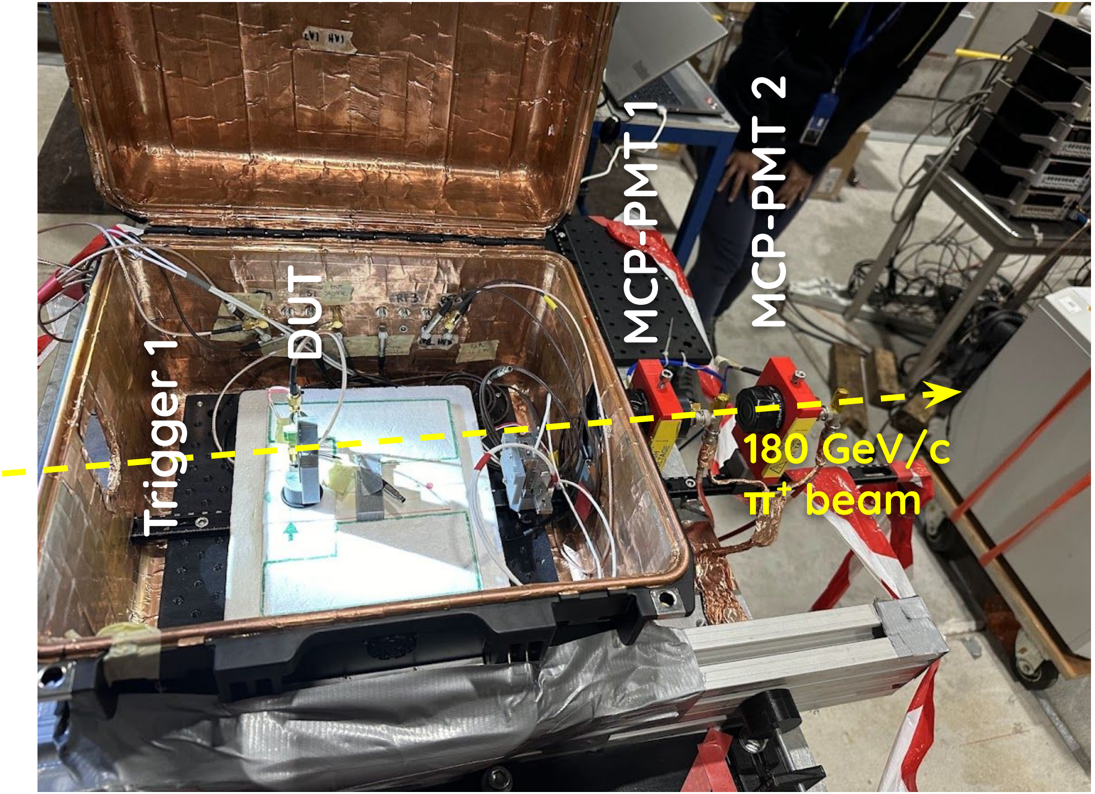


[Characterisation of 3D trench silicon pixel sensors irradiated at 1×10^{17} 1 MeV n_{eq}/cm^2]

TimeSPOT: Test Beam setup

Temporal resolution % CCE setup

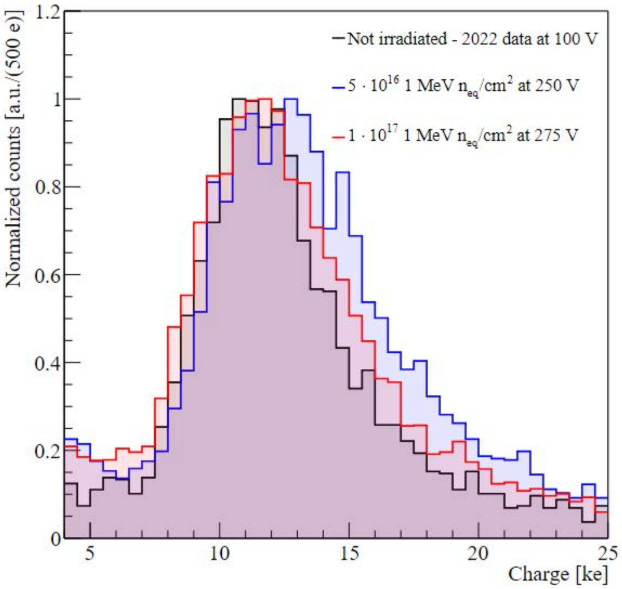




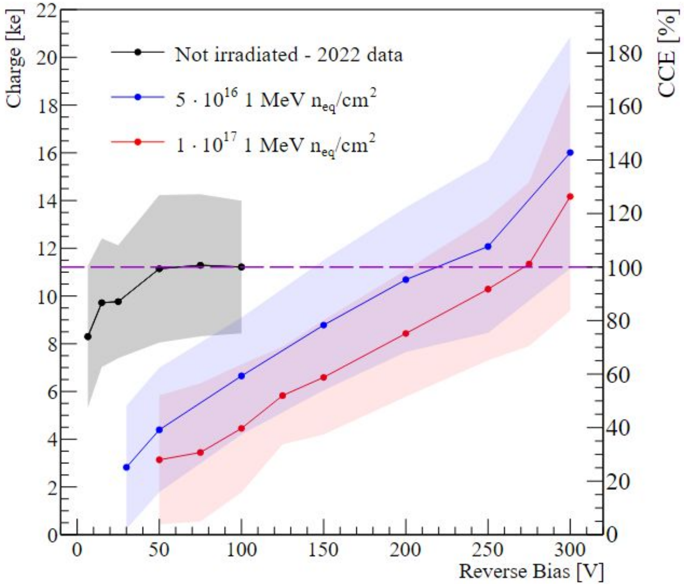
Characterisation of 3D trench silicon pixel sensors irradiated at 1×10^{17} 1 MeV n_{eq}/cm^2

TimeSPOT: Test Beam details

CCE



Amplitude distribution in electrons.
3 fluences are compared at different bias voltage.

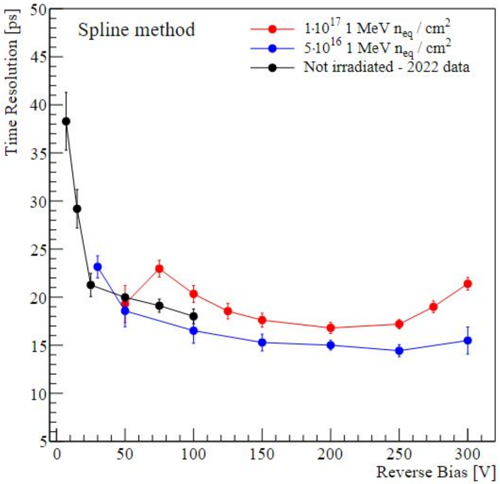


Dots are the Landau distribution MPV, the shaded areas represents the corresponding FWHM.

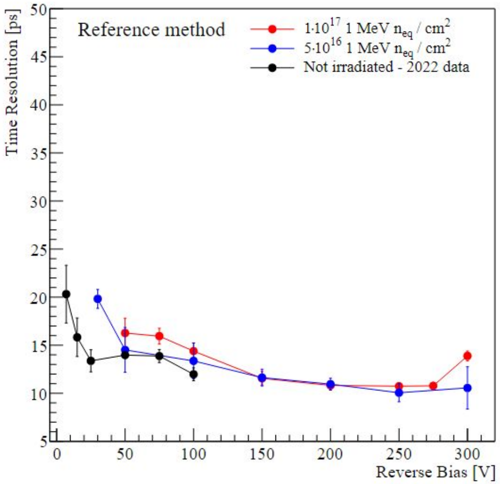
Characterisation of 3D trench silicon pixel sensors irradiated at $1x10^{17}$ 1 MeV n_{eq}/cm^2

TimeSPOT: Test Beam details

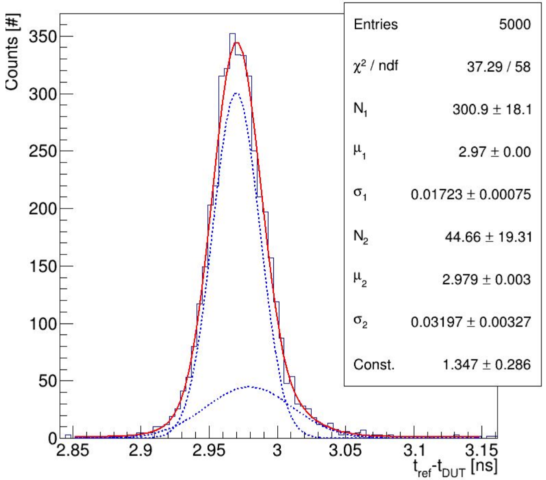
Temporal resolution



ARC method

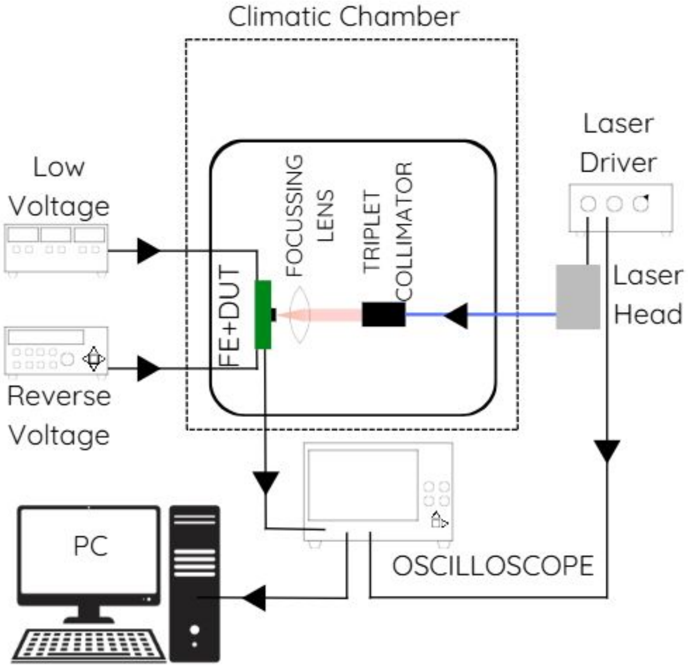


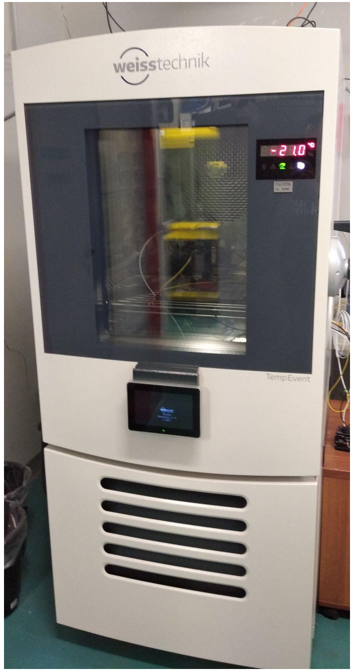
CFD method



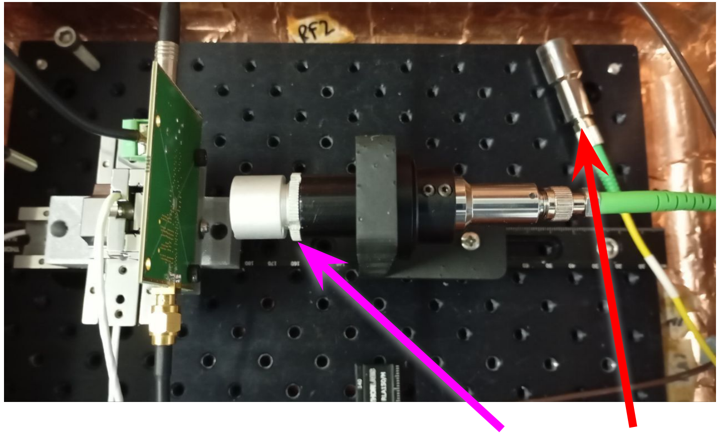
ToA distribution, fast and “peripheral” contributions can be separated.

TimeSPOT: Cold-TCT setup





Climatic Chamber



Motion and optical systems (1030 and 650 nm lasers available)

TimeSPOT: Cold-TCT setup

Temporal resolution of a 5e17 1 Mev n_{eq} $/cm^2$ irradiated sensor

- N.I. ref
  @ HV = 50 V
  σ_t = 14.4 ps

- 5e17 1 Mev n_{eq} $/cm^2$
  @ HV = 400 V
  σ_t = 9.9 ps