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17–24 Jul 2024

Recent developments on 3D silicon sensors for 4D-tracking at extreme intensities

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Università di Cagliari

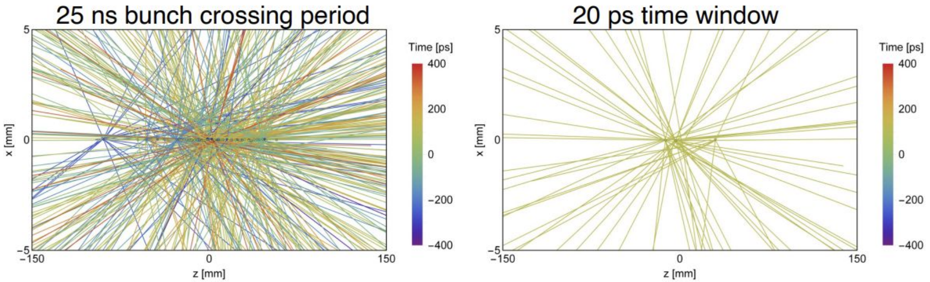
Outline

- Sensor and electronics requirements for 4D tracking in high luminosity
- TimeSPOT project
  - Selected old and new results
    on 3D-trench pixel sensors and electronics
- IGNITE project
  - Perspective for a 4D tracking system

Challenges in tracking - sensor requirements

- Future upgraded hadron colliders (HL-LHC/FCC-hh) will operate at extremely high instantaneous luminosity
  - Extreme radiation levels
  - Current tracking techniques will be inefficient

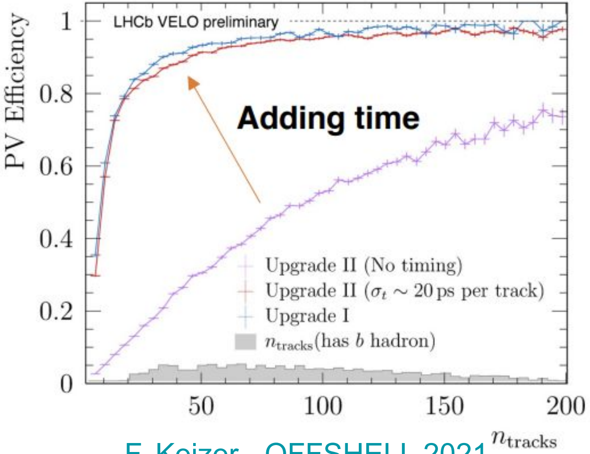
- Very good spatial resolution, excellent time resolution and radiation hardness are required at the same time



  - ATLAS & CMS Phase-II upgrades (2026): tracker + single timing layer
    $\sigma_t \sim 30$ ps, $\sigma_s \sim 100\text{–}300\,\mu$m, $F = 10^{15}\ 1MeVn_{eq}/cm^2$

  - LHCb Upgrade 2 (2033): pixels with timing information
    $\sigma_t < 50$ ps, $\sigma_s \sim 10\,\mu$m, $F = 10^{16}\text{–}10^{17}\ 1MeVn_{eq}/cm^2$

  - At FCC-hh the radiation fluence will be up to $10^{18}\ 1MeVn_{eq}/cm^2$



F. Keizer - OFFSHELL 2021

Challenges in tracking - system requirements

- **4D-tracking**: spatial inner tracking with additional temporal coordinate in single hit detection, by means of a precise measurement ($\sigma < 50$ ps per hit required)

- A number of strictly associated requirements
  - Small pixel pitch
  - High fluence dose
  - High data bandwidth

- Power budget one the most demanding electronics constraint against speed (fixed by state-of-the-art cooling system)

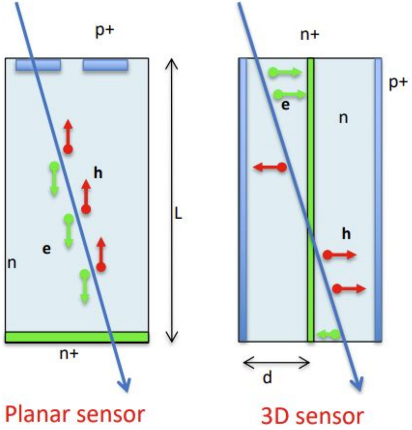
Target specifications

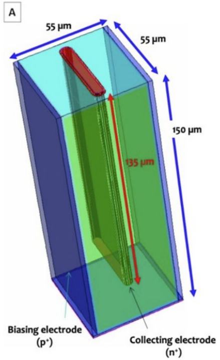
Space res	10 μm	Pitch, clustering
Time res	20 ps	Sensor only
	30 ps	Electronics (AFE+TDC)
	50 ps	**System (including clock jitter, IR-drop effects etc.)**
Power dens.	1.5 W/cm^2	Slightly increasable
Rate/pixel	50-300 kHz	Depending on pitch
Radiation	$\approx 5 \times 10^{16}$ 1 MeV n_{eq} cm^{-2}	sensor
	> 1Grad	electronics

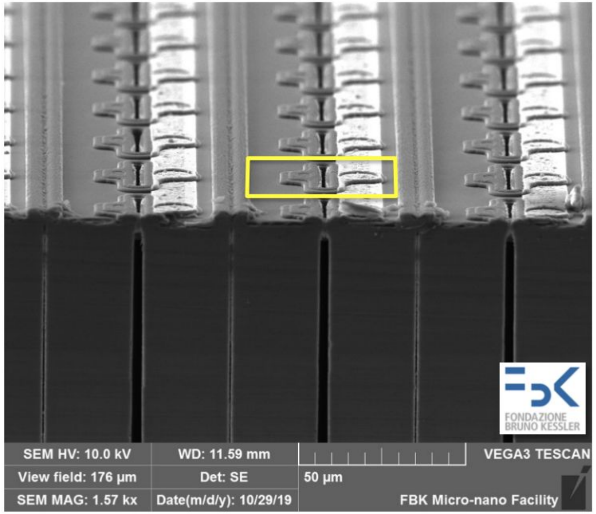
The TimeSPOT 3D silicon sensor

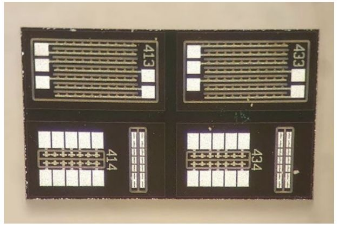
- **3D sensor**: electrodes parallel to the incident particle trajectory (S.Parker - 1997)
  - Very fast signals and high radiation hardness up to $> 10^{17}\ 1\mathrm{MeV}\ \mathrm{n_{eq}/cm^2}$ (NIMA, 979 (2020) 164458)

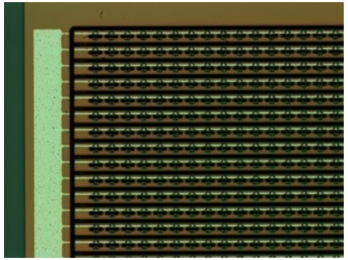
- The chosen TimeSPOT was the **3D-trench structure**:
  - weighting field more uniform, shorter charge collection time
  - signals largely independent on particle crossing point











- Two batches were produced in 2019 and 2021 at Fondazione Bruno Kessler (FBK, Trento, Italy) [G.T.Forcolin et al. - 2020]

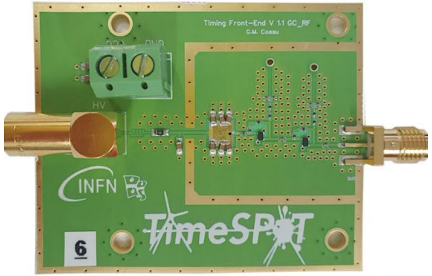
- Many devices fabricated (single, double pixels, 10 pixel-strips, various pixel matrices, etc.)

Selected results: intrinsic time resolution

F.Borgato et al., 2023

- Intrinsic sensor properties characterized in laboratory and in beam tests by using custom-made front-end electronics boards with a two-stage transimpedence amplifier (TIA) made with fast SiGe BJTs.

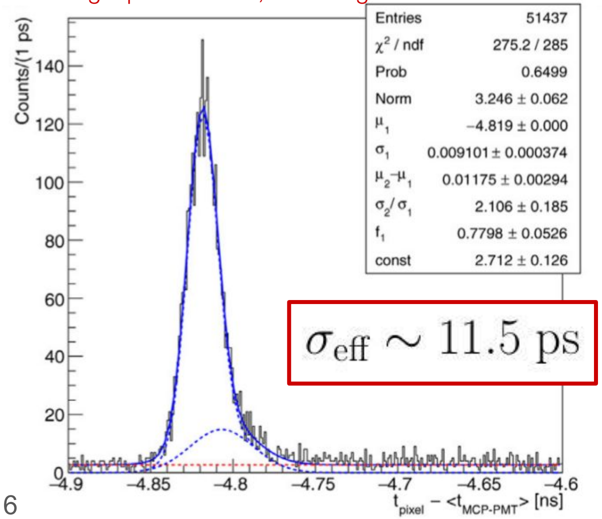
G.M. Cossu (Cagliari), 2023

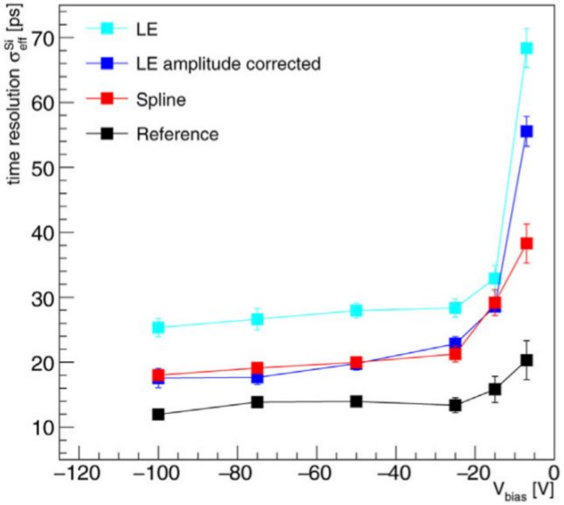


- 2022 SPS/H8 beam test using 180 GeV/C pion beam. Achieved excellent timing performances with CFD-based methods and leading edge.

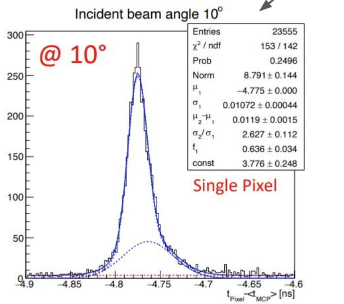
F. Borgato, D. Brundu, A. Cardini, G. M. Cossu, G. F. Dalla Betta ,M. Garau, L. La Delfa, A. Lai, A. Lampis, A. Loi, M. M. Obertino, G. Simi, S. Vecchi

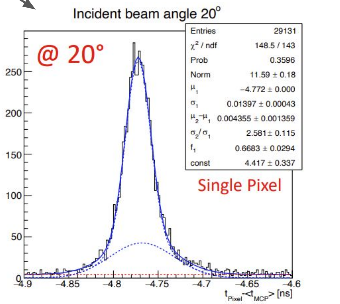
Single-pixel @ 100V, 0° tilt angle





- More uniform time distribution at tilted angles, comparable time resolution





Selected results: radiation hardness

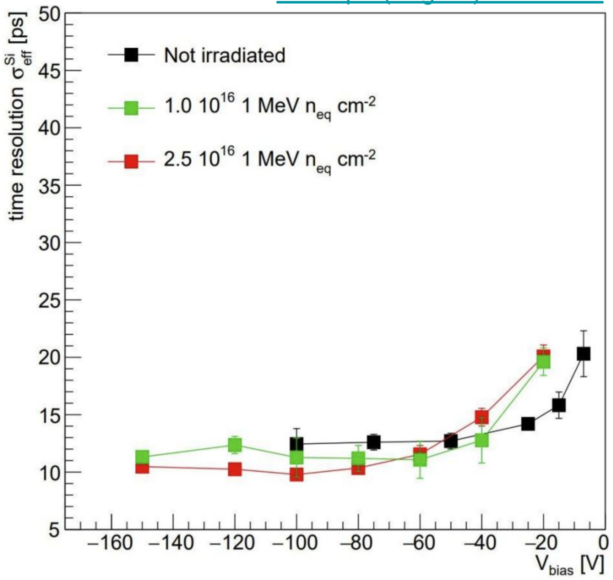
[F.Borgato et al., 2024]

- 3D sensors irradiated the Triga Mark II reactor (Jožef Stefan Institute, Lubjiana), up to $2.5 \cdot 10^{16}\ 1\mathrm{MeV}\ \mathrm{n_{eq}}/\mathrm{cm}^2$
  Irradiated sensors show excellent timing performance, compatible with pre-irradiation

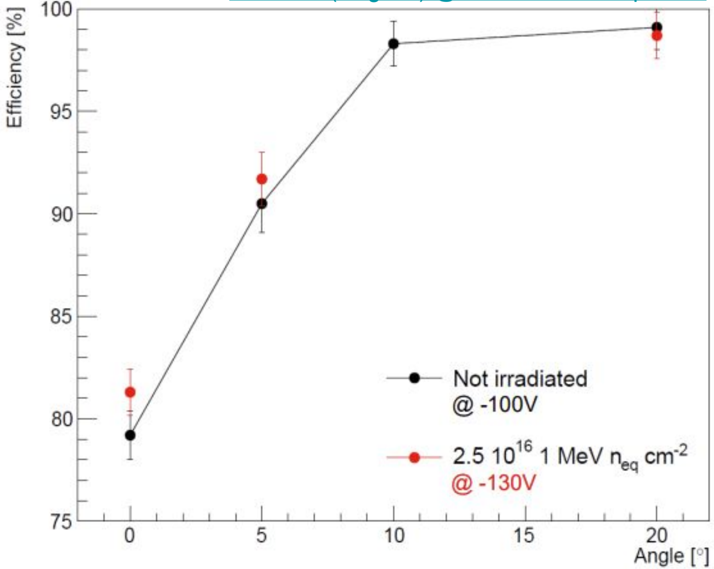
- Performed rotation around the trench axis: the inefficiency at 0° due to trenches dead-area is recovered by tilting the sensors around the trench axis. This is true also for irradiated sensors.

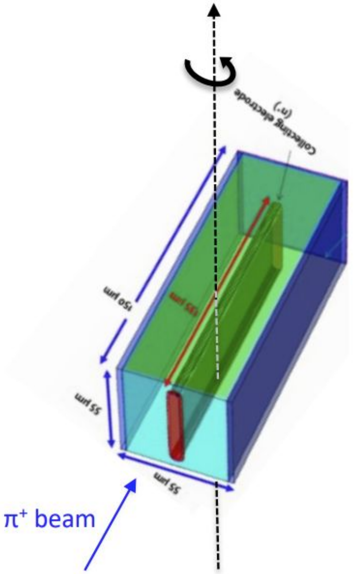
F. Borgato, A. Cardini, G. M. Cossu, G. F. Dalla Betta, M. Garau, L. La Delfa, A. Lai, A. Lampis, A. Loi, M. M. Obertino, G. Simi, S. Vecchi

A.Lampis (Cagliari) PhD thesis



M.Garau (Cagliari) @ Trento Workshop 2023

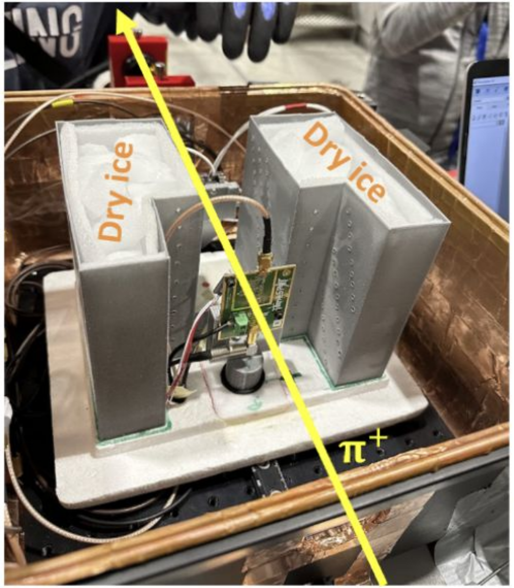


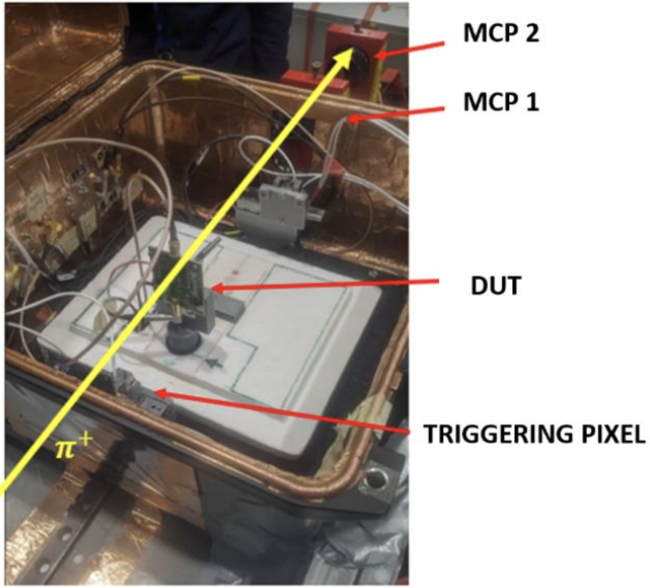


NEW results: radiation hardness and efficiency

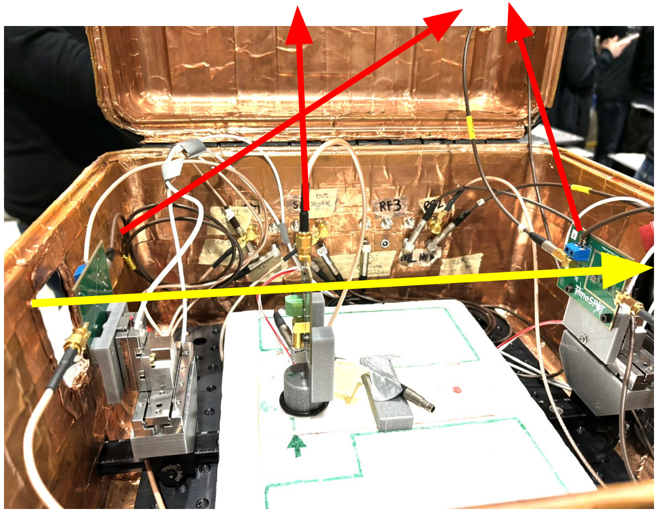
- 3D sensors irradiated **further** at the Triga Mark II reactor up to **10^{17} 1-MeV n_{eq} / cm^2**
- New test beam in May 2024 at SPS/H8, with an improved setup.
- Structures under test: irradiated single pixel and 3-strips.

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





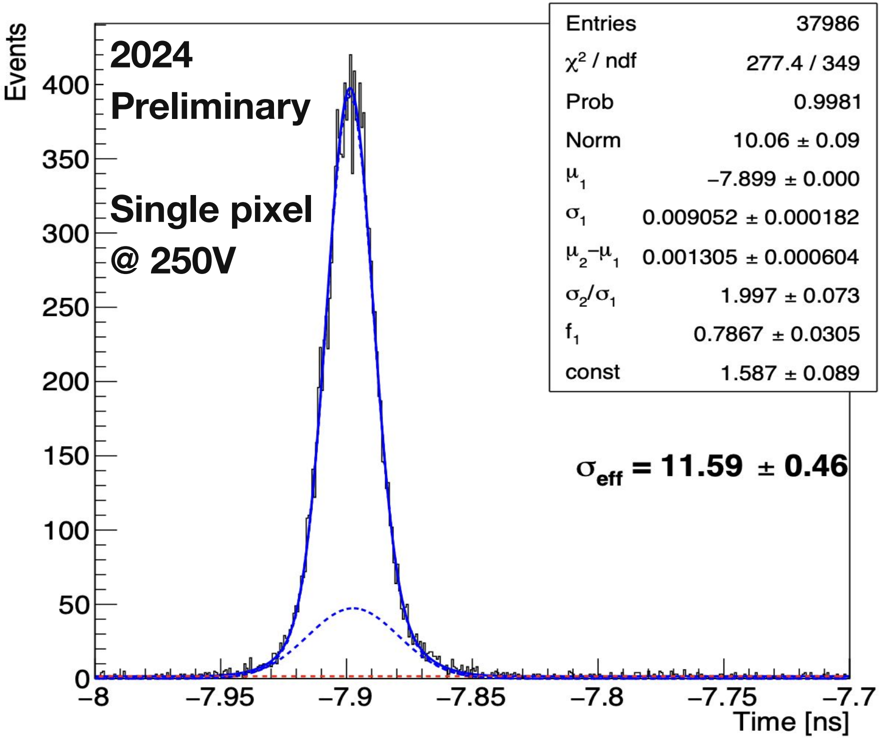
Telescope with DUT + two single-pixels

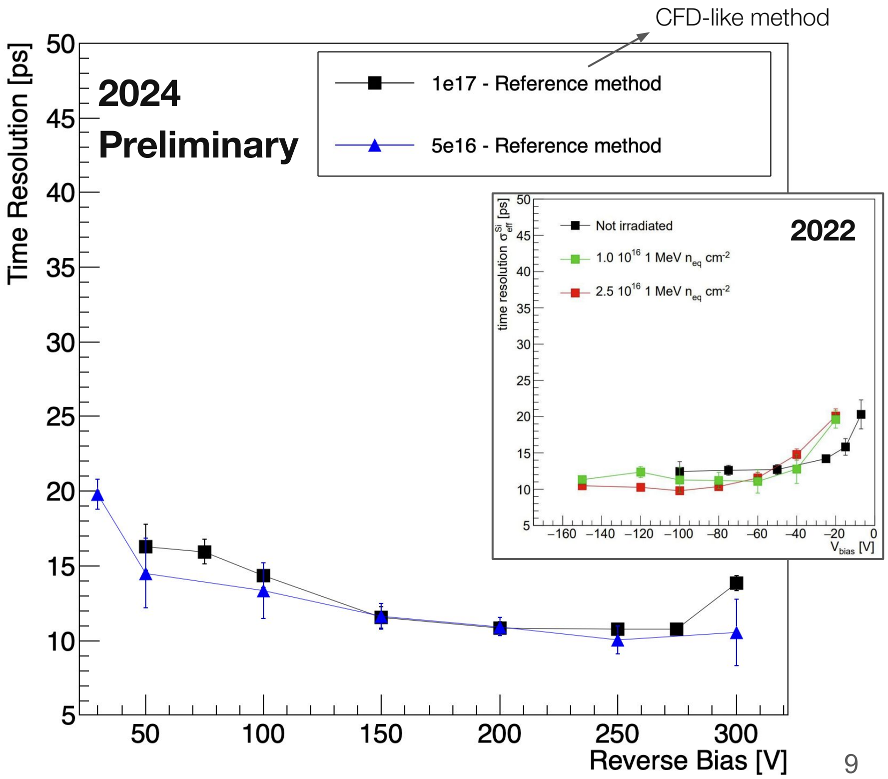


[A.Lampis @ PM2024]

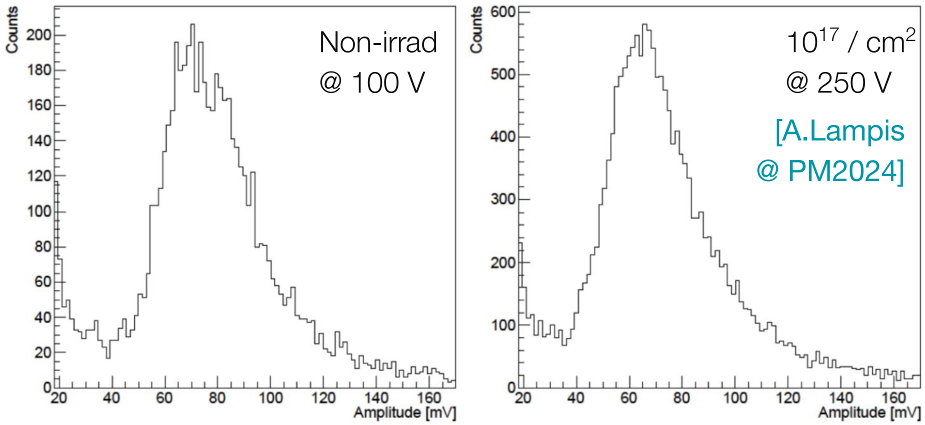
NEW results: radiation hardness and efficiency

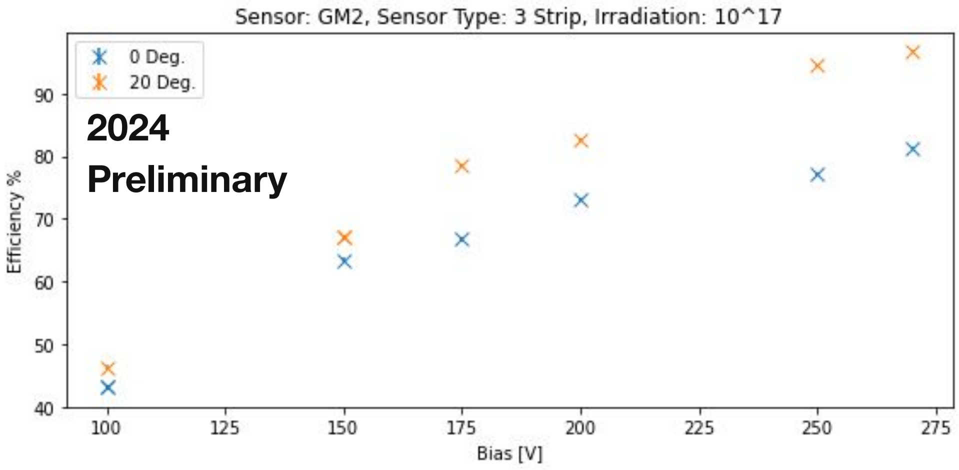
- Highly irradiated sensors show excellent timing performance, compatible with pre-irradiation.





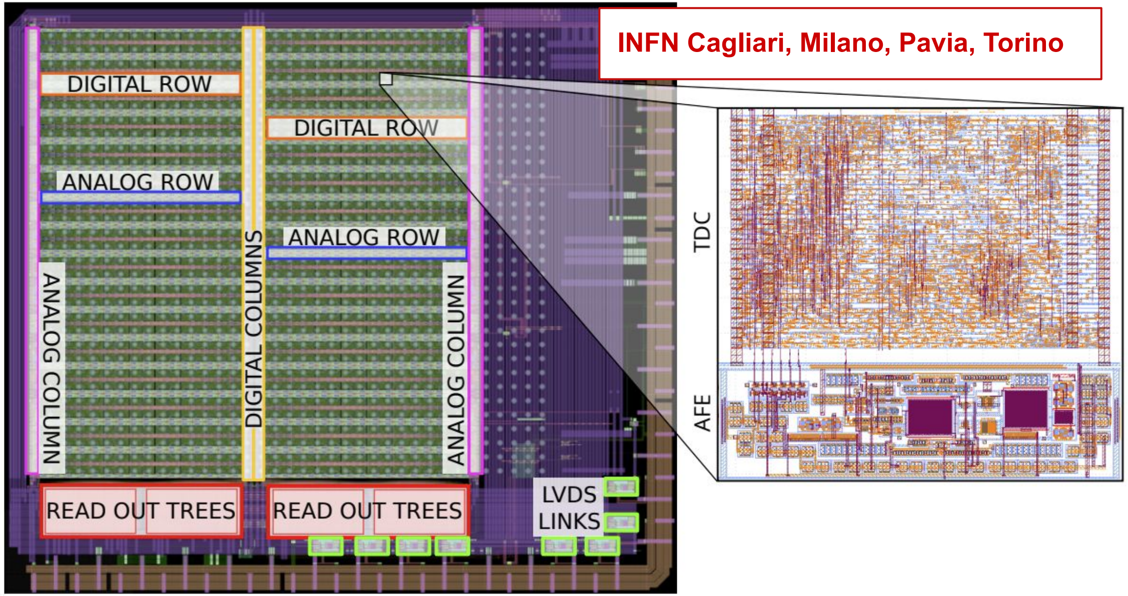
NEW results: radiation hardness and efficiency





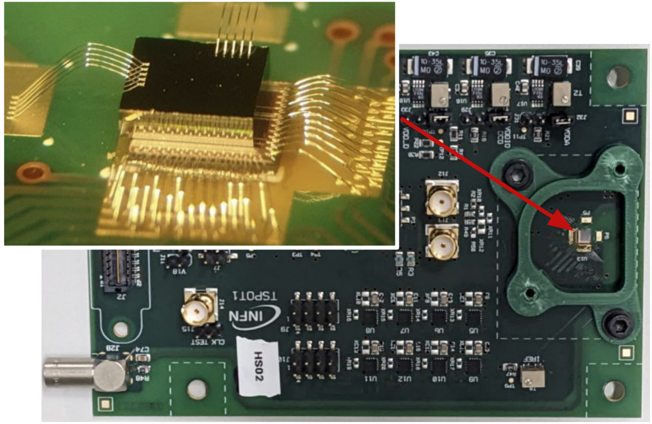
- Charge collection efficiency of the irradiated sensor is restored at the bias voltage of 250 V.
- The efficiency of the triple-pixel-strip was evaluated by using two single-pixels as trigger reference. Results show the irradiated sensor achieves 95% efficiency at 20 degrees, compared to 99% for the non-irradiated structure [F.Borgato et al., 2023]

Front-end electronics: the TimeSPOT1 ASIC



INFN Cagliari, Milano, Pavia, Torino

- ASIC developed in 2020 in CMOS 28-nm, 1024 pixels with pitch of 55 µm, one TDC per pixel
- TSPOT1 test board, used for in-laboratory tests and beam tests. Sensors bump-bonded by IZM
- A.Lai @ Pixel2022, A.Loi @ Trento Workshop 2023 [S.Cadeddu et al. - 2023]



- TDC has a time resolution of ~20 ps, limited by clock jitter
- Analog Front-End time resolution is typical 43 ps without sensor. In the best cases it is < 20 ps as expected by simulation
- The hybrid achieves a time resolution of 60-75 ps and a power consumption of 40 µW per channel

Beyond TimeSPOT: the IGNITE project

- From TimeSPOT results we learned that:
  - Best timing performance of TimeSPOT ASIC around 20 ps, at a reasonable low power consumption
  - Limitations due to amendable bugs and to global issues, such as clock jitter and power distribution

IGNITE
INFN Istituto Nazionale di Fisica Nucleare
INFN Ground-up iNITiative for µElectronics developments

- The project aims to develop a full 4D tracking system. The requirements practically forces the use of **28-nm CMOS** technology
  - the most advanced technology node adequately studied and characterized against TID
  - higher dependence on parasitics and IR-drop effects (critical lines: power and clock)

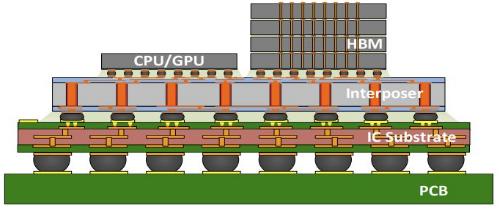
IGNITE is a national initiative funded by INFN, involving 14 INFN institutes (physicist and engineers), P.I. Adriano Lai (INFN Cagliari).

- Main features and challenges:
  - Time resolution < 50 ps per pixel with power budget constraints,
  - Large scale matrix with adequate power distribution,
  - Data transmission at high bandwidth towards the readout.

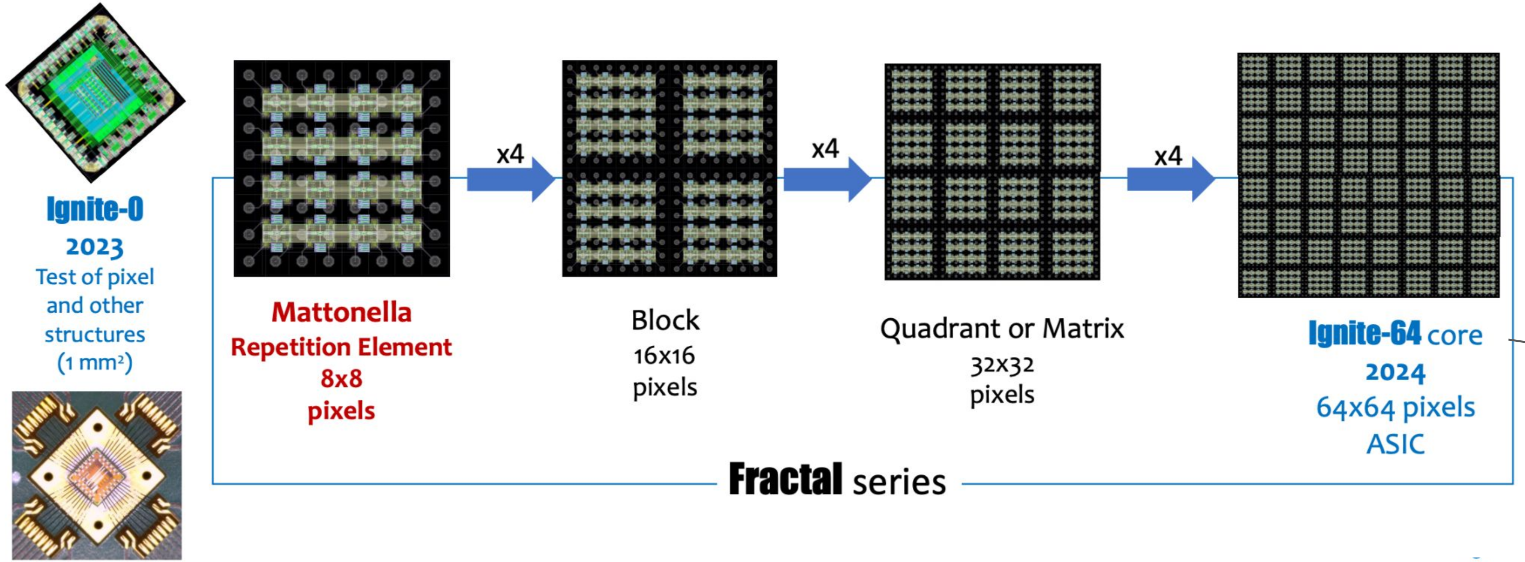
IGNITE project: general ideas

- The main idea is to develop a Large Area Asic (~1cm^2), as repetition of a small structure, small enough to be fully simulated, produced, and tested in a reliable way (**FractalDesign** ©)

- The full potential of **FractalDesign** is exploited by the use of vertical **3D μ-integration** to facilitate vertical interconnection between active layers (consolidated in industrial developments)



Example of high-density micro-integration, taken from [T.Fritzsch @ Pixel2022]

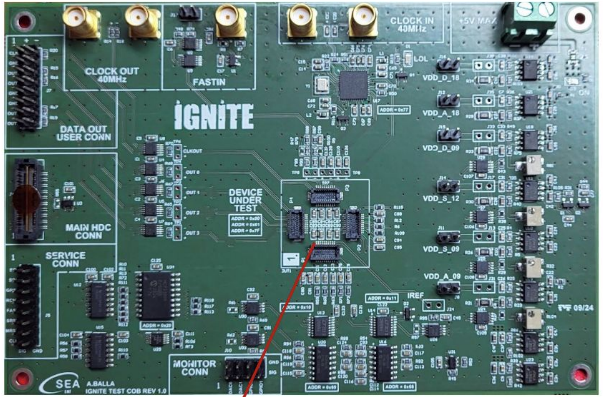


Submission foreseen in October 2024

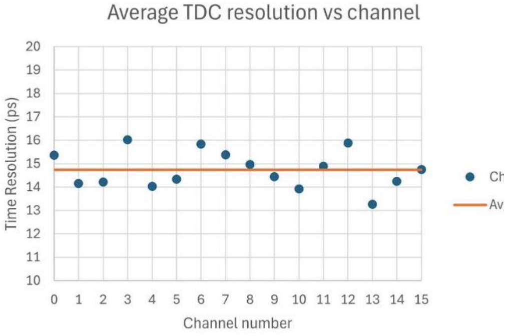
IGNITE0: test chip

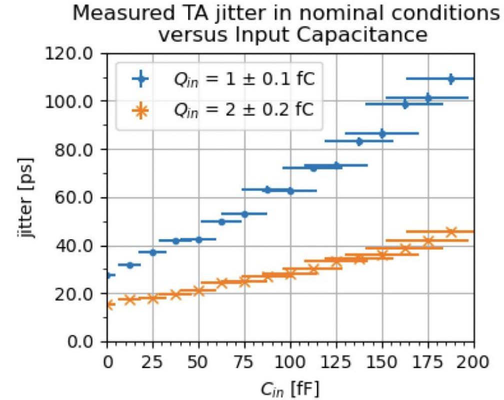
INFN Cagliari, Milano, Firenze, Lab. Frascati

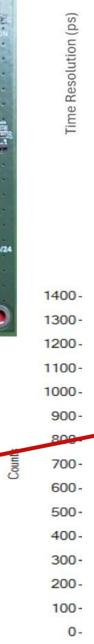
- To test the components of **FractalDesign** a first chip has been submitted in July 2023 and received in March 2024, with a half version of the 8x8 matrix to perform internal node testing.

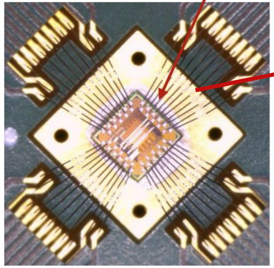


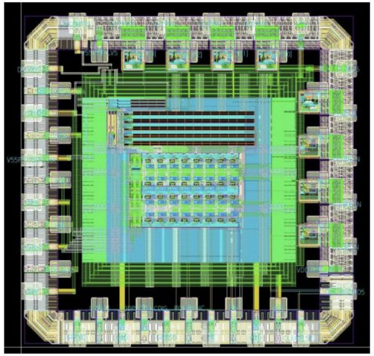
Ignite-0 test PCB (15x10 cm^2), LNF
Bonding by Firenze









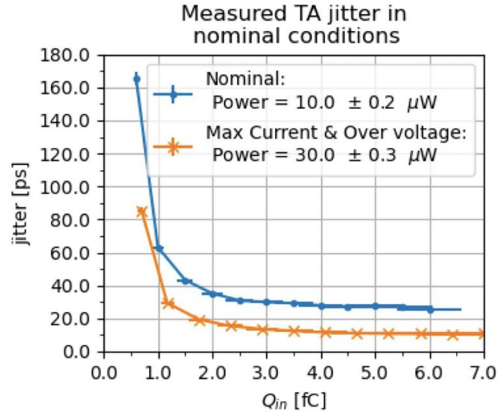


TDC average σ_t < 15ps

AFE average

σ_t < 30 ps @ 100 fF

σ_t < 20 ps (max pwr, 2 fC)



Concluding remarks

- 4D techniques are essential for next-generation inner trackers.

- Main issues in 4D tracking are **system related:**
  - exploit 3D high-density integration
  - cooling techniques to allow higher power budget while minimizing material budget
  - High-bandwidth communication (Silicon photonics)
  - Verification techniques at system level and scalable prototypes (like IGNITE0, IGNITE64, ...)

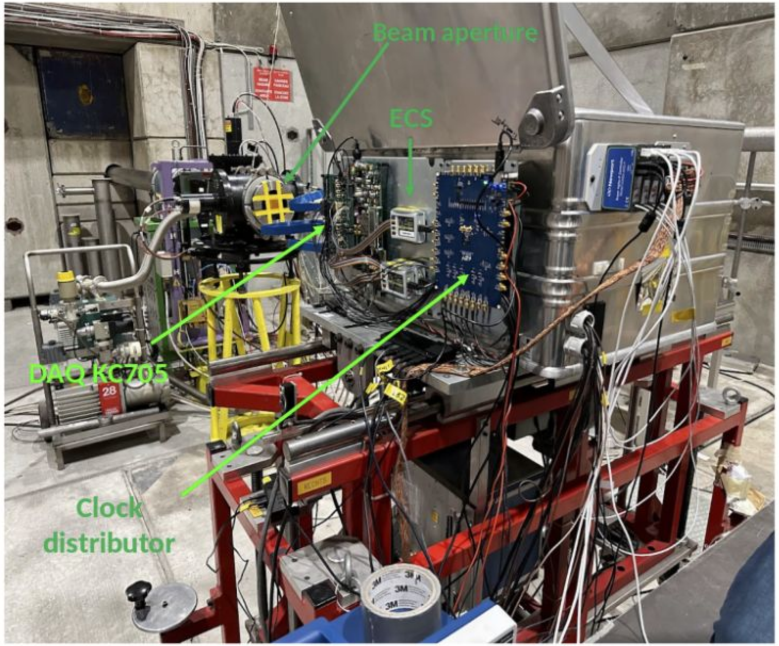
- From TimeSPOT experience, **3D-trench silicon sensors are able to address the 4D tracking requirements** in terms of time resolution, efficiency and radiation hardness

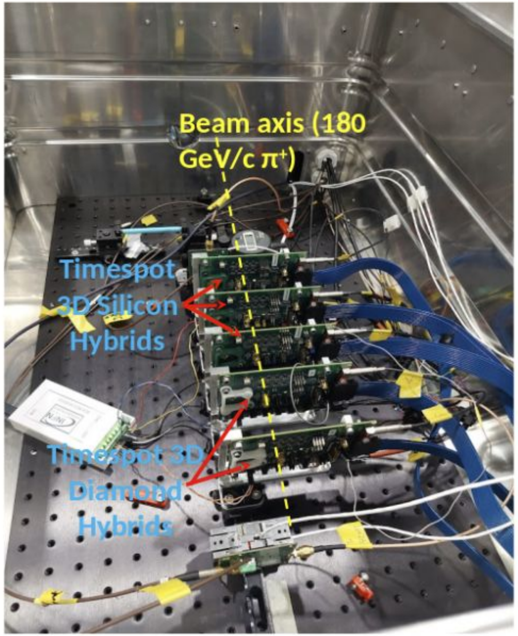
- The IGNITE project aims at addressing the full requirements for 4D tracking. Many “users” possibly interested.

Backup

2023 SPS/H8 beam test - demonstrator

- Beam test in April-May 2023 at SPS/H8 (180 GeV/c pions)
- Complete demonstrator with 5 stations (3 with silicon, 2 with diamond sensors)
- DAQ in-laboratory assembled and fully tested with FPGA-based readout and custom DAQ/control software
- Optical alignment of sensors and rail to the beam, also refined by track reconstruction





2023 SPS/H8 beam test - demonstrator

- A main limitation of the test was a strong leakage located near some dummy structures inserted for mechanical strength → not possible to provide a meaningful bias voltage. This is currency under investigation

- **Mini-tracker DAQ operations and track reconstruction were successful**, but the time resolution measured per pixel was affected (~200 ps)

- The same results have been replicated in laboratory by a laser setup and a single channel board (modified to get CSA behaviour) and by using 1 V bias. The time resolution worsen by a factor 10, reaching ~200 ps.

Further details in [L. Anderlini (Firenze) @ FAST 2023]