Recent results on 3D diamond pixel detectors for 4D-tracking

L. Anderlini, on behalf of the Timespot Initiative

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TimeSPOT

INFN Istituto Nazionale di Fisica Nucleare

CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

lens European Laboratory for Non-Linear Spectroscopy

UNIVERSITÀ DEGLI STUDI FIRENZE

Tracking detectors for future experiments

Current tracking techniques will no longer be able to efficiently reconstruct the events at future high luminosity hadron colliders (HL-LHC/FCC-hh)

- The next generation of tracking detectors will be operating under extreme radiation levels:
  Sensors: O(10^{16}-10^{17}) 1 MeV n_{eq}/cm^2
  Electronics: 1 Grad
- They will be also processing a huge amount of information (~Tb/s) due to the very high number of primary vertices in the interactions

Radiation hardness

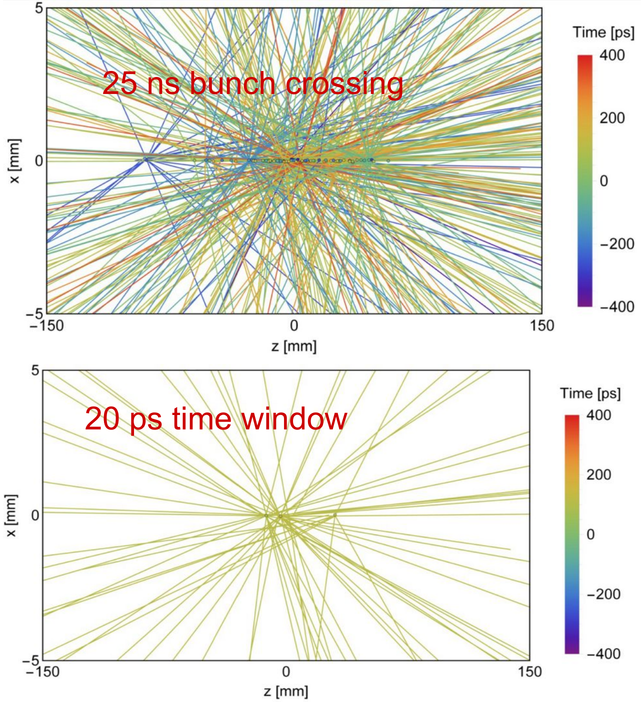
Revolutionary improvements on the performances of the vertex detectors are needed to match the requirements of future accelerators in terms of:

- Radiation hardness → 3D geometry
- Fast timing → ≈50 ps resolution
- High granularity → ≈50 µm pitch
- Front-end pre-processing of data

3D geometry + Time info

→ 4D Tracking

Example of vertex reconstruction @ LHCb Upgrade II



F. Keizer - OFFSHELL 2021

The TIMESPOT Project

The TIMESPOT (TIME and SPace real-time Operating Tracker) is an INFN funded R&D project aiming at the construction of a mini-tracker demonstrator with 4D capabilities

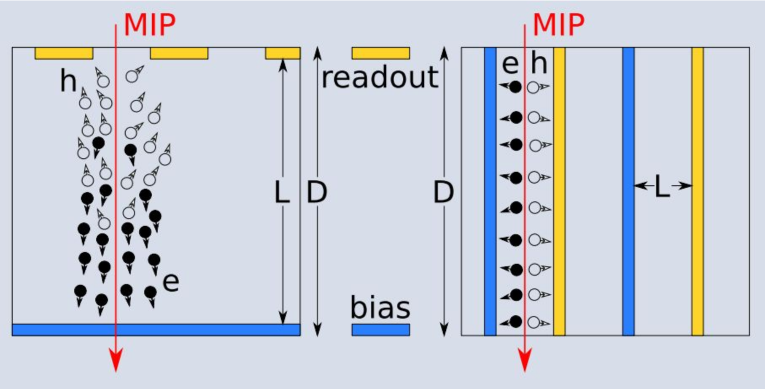
- Radiation hard 3D silicon trench and diamond pixel (55x55 μm^2) detectors optimized for timing
- Radiation hard (>1 Grad) 28 nm custom readout electronics with precise timing resolution
- Fast FPGA-based backend electronics for high data throughput
- Real time track reconstruction algorithms

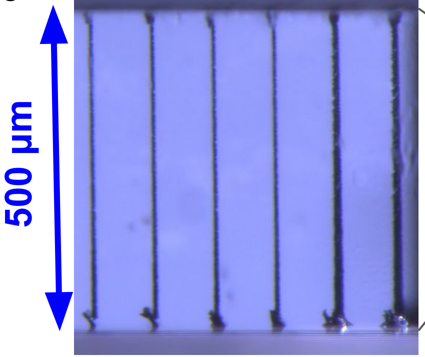
In this talk results from the activity on the development of diamond sensors

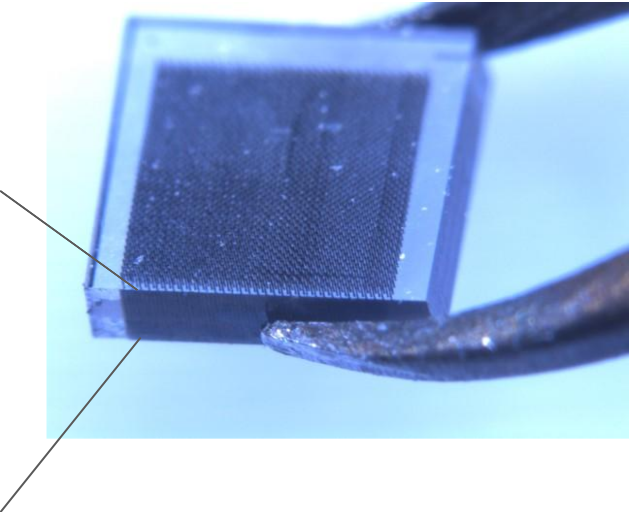
3D vs Planar geometry

- The 3D geometry is the most promising technology for high radiation environment
- Planar Configuration
  - Electrodes applied on the surface of the detector
  - Uniform electric field
  - Drift distance ~ Detector thickness
- 3D-geometry
  - Electrodes are located in the bulk of the detector
  - The electric field has radial symmetry around the electrode
  - Drift distance ~ Inter-electrode distance
  - ➔ Reduction of recombination of carriers in trapping centers with increase in radiation tolerance
  - ➔ Faster charge collection
  - ➔ Smaller operating voltage

L. Bäni - TIPP2021







Diamond sensors for particle detection (vs. Silicon)

- Insulator with negligible concentration of free carriers
  - Lower leakage current
  - Low noise at high temperature
  - Lower power consumption
  - No need for cooling
  - Blind to visible light ➔ No need of "black box"
- Higher mobility and v_{sat} ➔ Can generate faster signals
- Higher knock-off energy ➔ Better radiation resistance

PROS

- More Energy is requested to create charge
  - Partially compensated by higher density
  - Typical thickness 500 μm compared to 300 μm of Silicon
- Single crystal only available in small samples
  - Fabrication process can be very slow
  - Cost

CONS

Diamond for timing: the challenge

3D Diamond pros:

- Smaller capacitance than silicon pixels
- Higher mobility → Faster signal

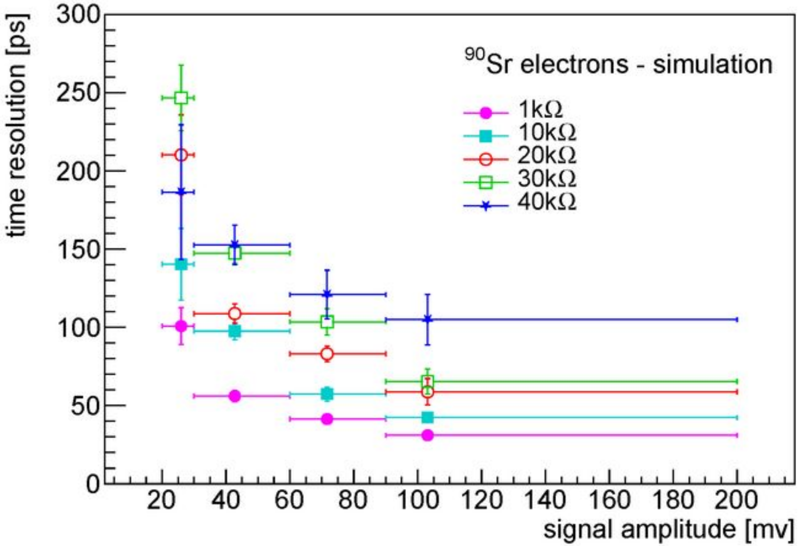
But:

high resistance of the electrodes → slower signals

The higher the resistance, the longer the leading edge, the worse the time resolution.

Big effort to reduce the electrode resistance by tuning the fabrication process.

Simulation obtained with Geant4, KDetSim and ROOT. Electronic noise was acquired and digitally superposed to the simulated signals. Instruments 5(4) 2021 39



Fabrication procedure

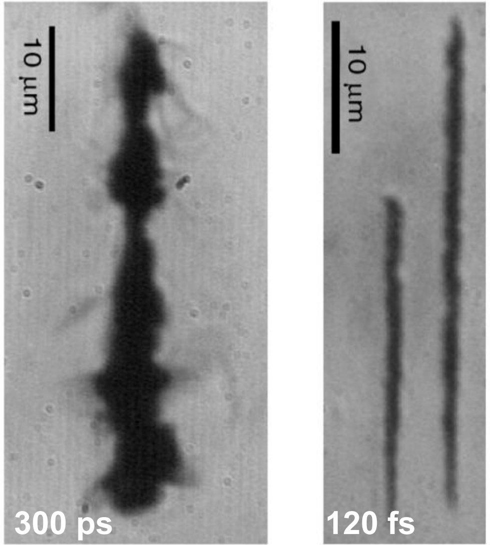
Electrodes are obtained by focussing a **high intensity laser** in the diamond bulk.

Multi-photon absorption induces a phase transition of carbon from diamond (semiconductor) to a mixed phase including graphite (conductor).

Larger waist → Larger area interested → Cracks

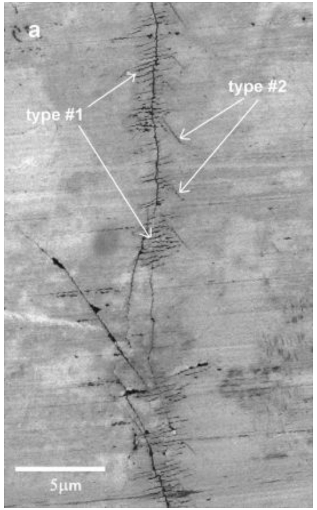
Graphite is not transparent: adsorb much more energy → phase transition to amorphous carbon (insulator). **Keep pulses short!**

Diam. Relat. Mater 18 (2009) 196

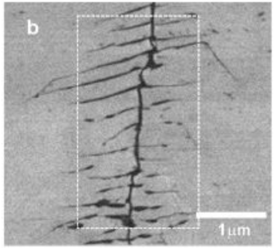


Effect of longer laser pulses

Carbon 102 (2016) 383



SEM images of laser induced graphitization



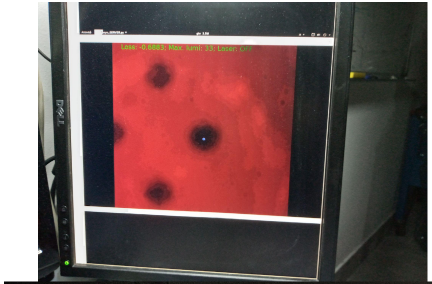
Shopping List

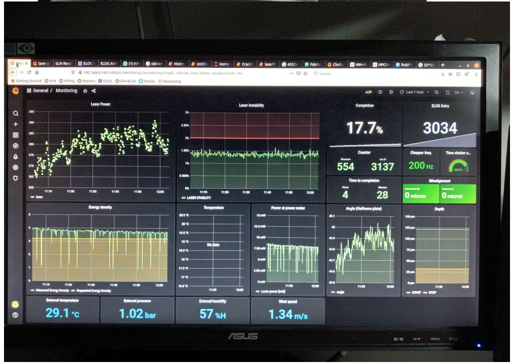
- *High laser intensity* ☐
- *Excellent laser focus* ☐
- *Shortest laser pulses* ☐
- ☐

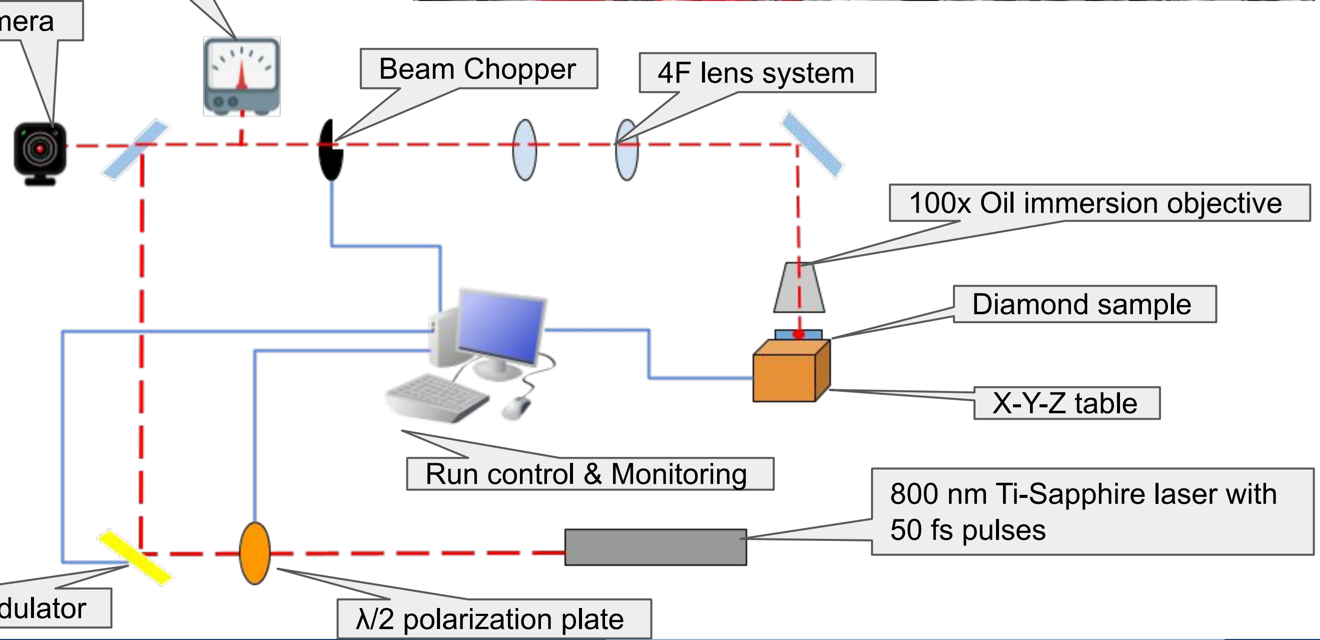
Fabrication of 3D diamond sensors in Firenze

➔ Front. Phys 08 (2020) 589844

- Polarization plate & chopper to control laser power
- Space light modulator to correct aberration
- Fully automatized procedure







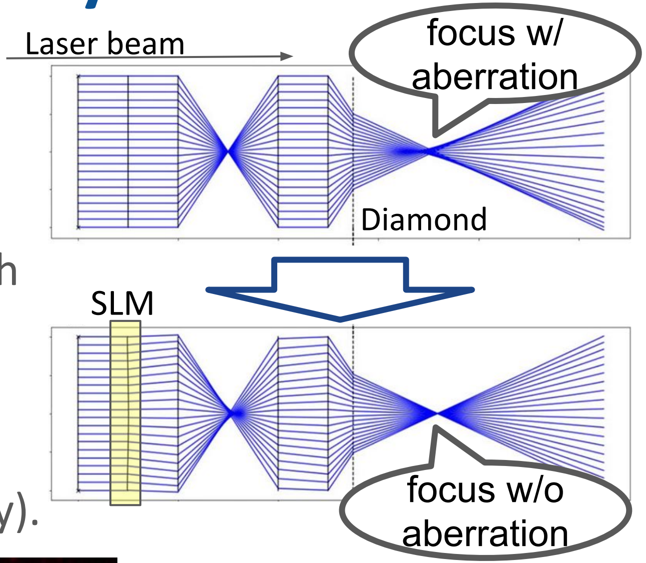
Salter & Booth, “Adaptive optics in laser processing, Light: Science & Applications, 8 (2019) 110

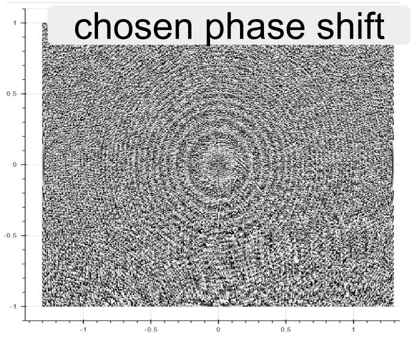
(Liquid Crystal on Silicon - Space Light Modulator)

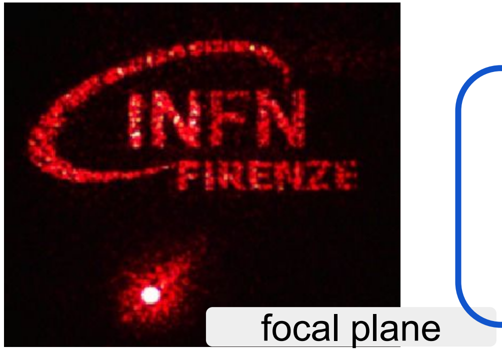
Improving the focus quality with LCoS-SLM

The high refractive index of diamond introduces an **important spherical aberration** that depends on the depth of the focus. Need adaptive optics to introduce a correction.

Using SLM (often used for holography).







Quality of the correction assessed engraving serpentines with and without corrections.

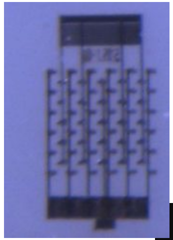
Mini sensors

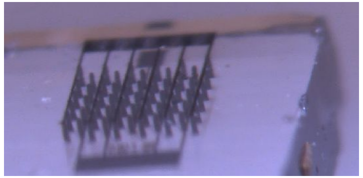
Three sensor prototypes were fabricated with slightly different fabrication tunings.

Surface graphitization was used for short-circuiting multiple pixels into test structures (strips and combs).

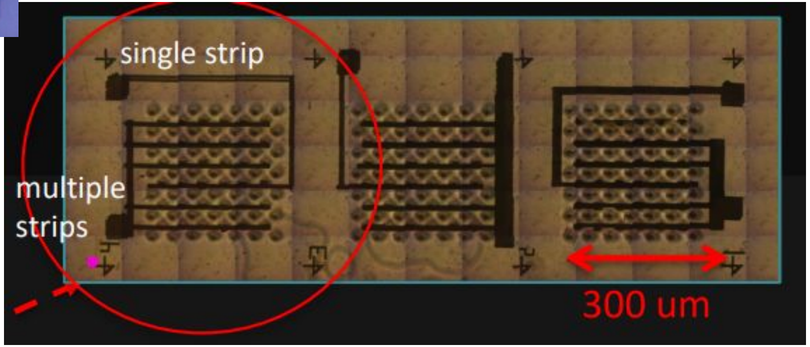
Discrete fast electronics was connected with 25 µm wedge wire-bonding.

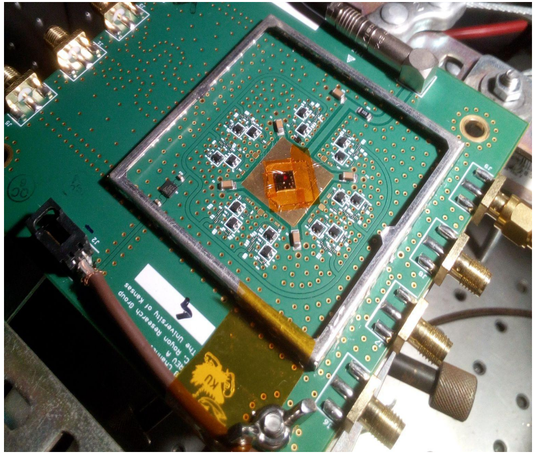
Read-out with high-end 20 GSps R&S oscilloscope (8 GHz bandwidth).





Instruments 5(4) 2021 39





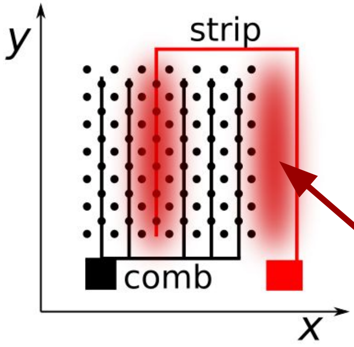
Many thanks to Kansas University Team and in particular to Nicola Minafra for developing and providing the boards and for the valuable support.

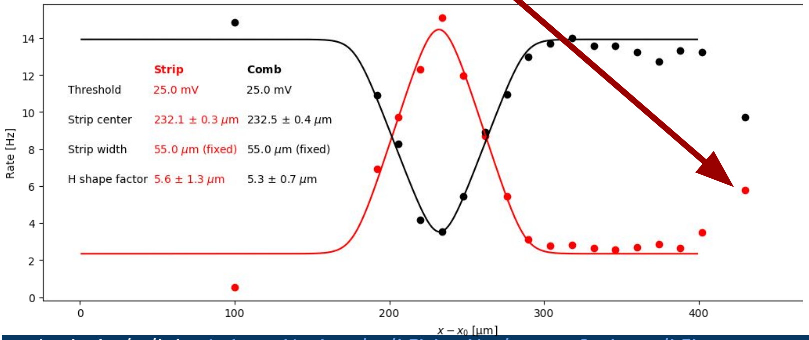
Minisensor test @ CERN SPS H8

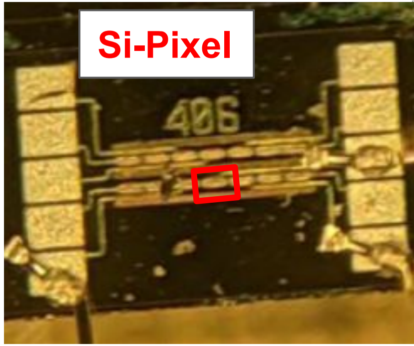
Beam test with 180 GeV hadrons from SPS

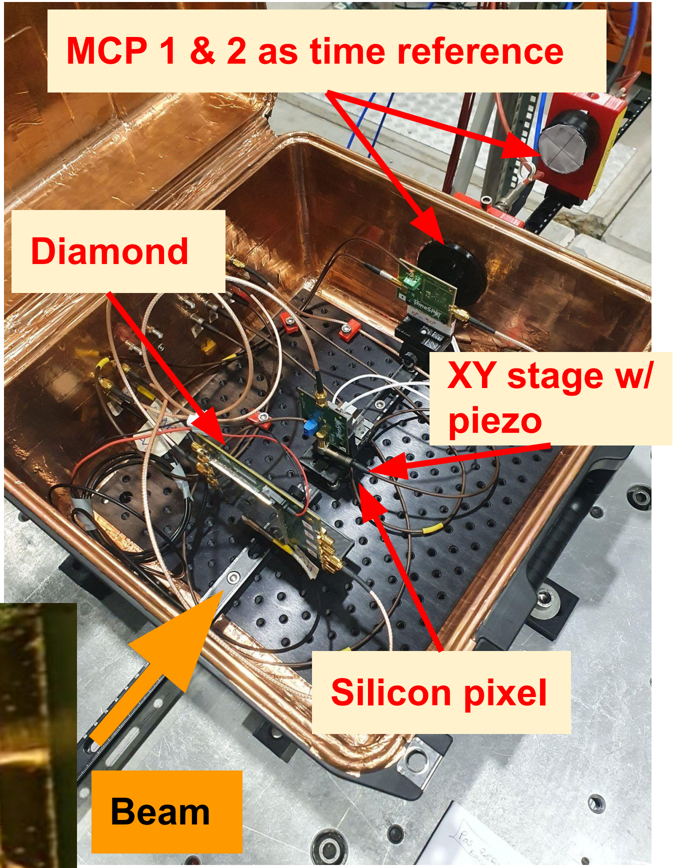
A 55 × 55 μm^2 silicon pixel was used to "select" signals from geometrical portions of the sensor, by requiring coincidences.

This also discards signals from outside the pixelated area.



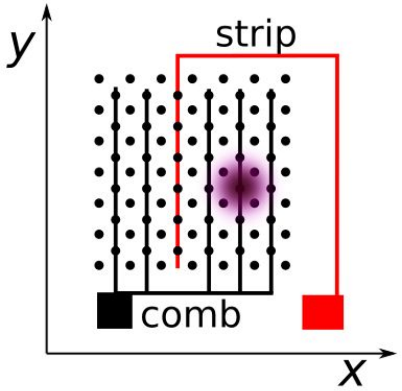


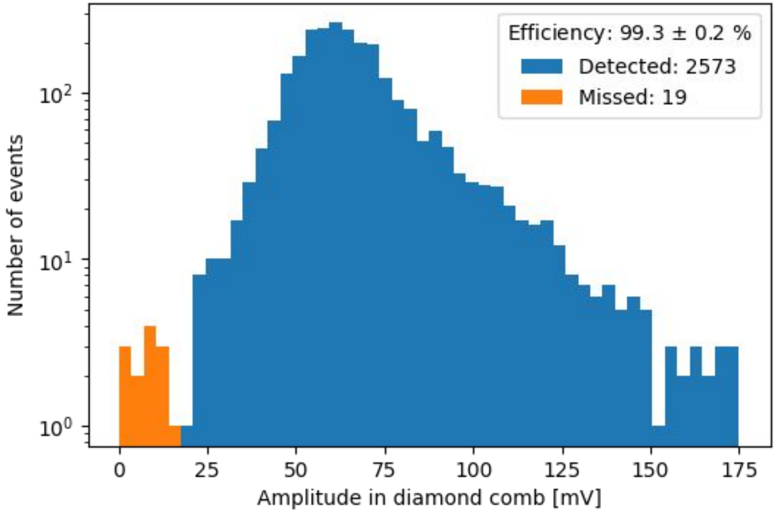




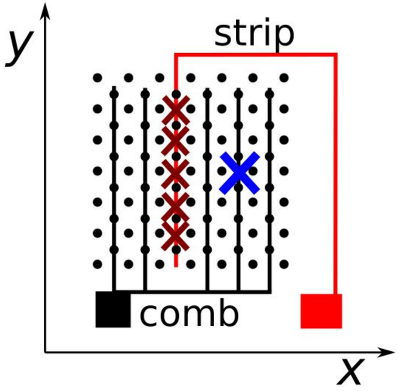
Sensor efficiency

- Using as trigger the silicon pixel we can determine with a precision of few µm the position of the diamond structures
- Select a region well inside the Comb sensitive area
- Use as trigger the **Silicon pixel and the MCP selecting coincidence events with amplitudes compatible to those of MIPs**
- Signal from Comb, no signal from Strip
- $\varepsilon_{comb} = (99.3 \pm 0.2)\%$

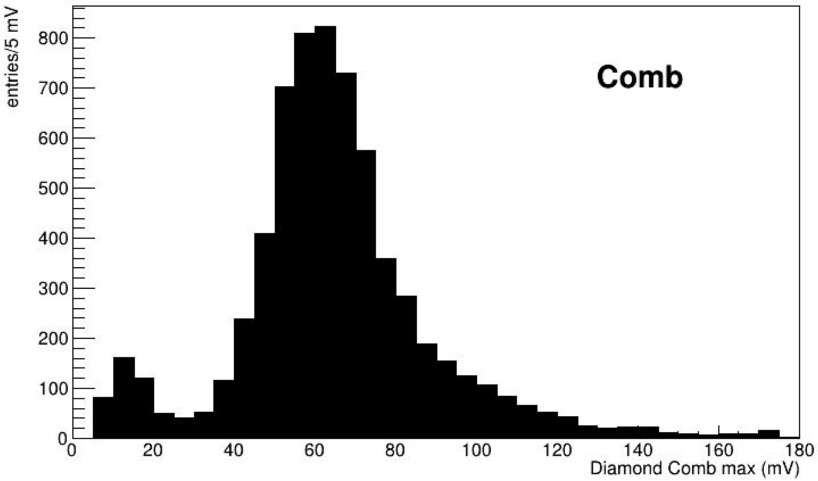


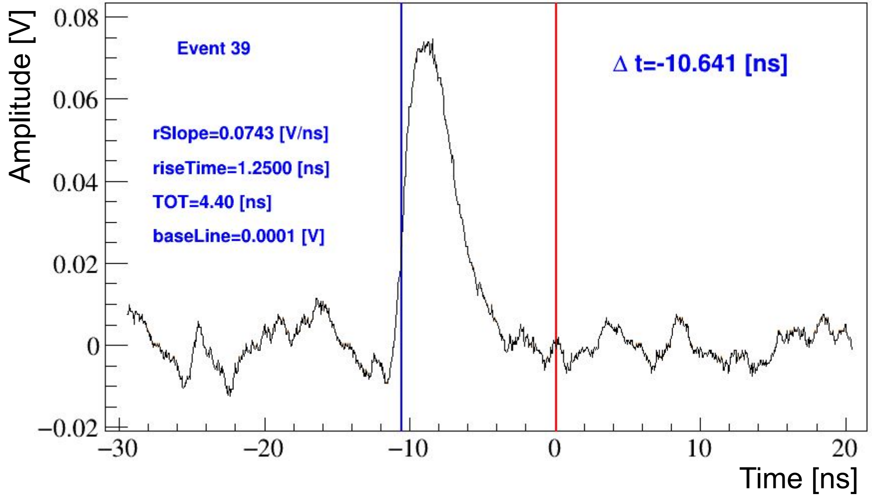


Test @ CERN SPS H8 beam: Comb amplitude spectrum



- Select the Comb center (**X**) ➔ Proxy for a cluster of pixels
- Landau peak for the amplitude distribution (MPV ~ 60 mV)
- **S/N = 12**

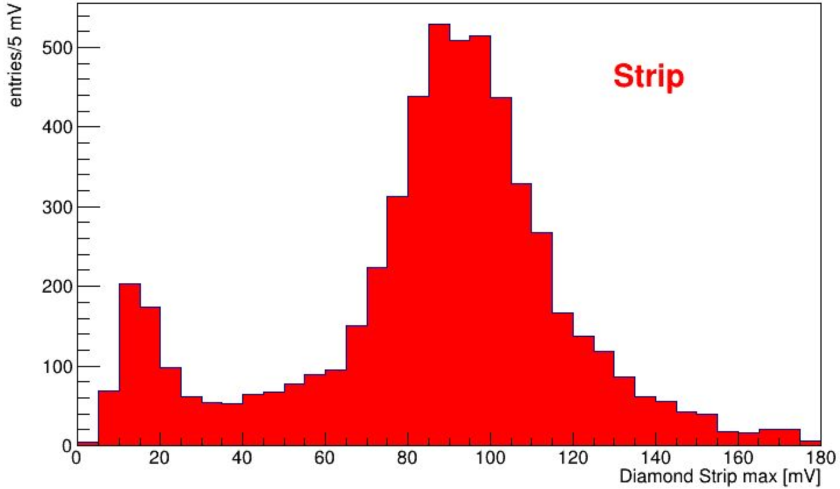


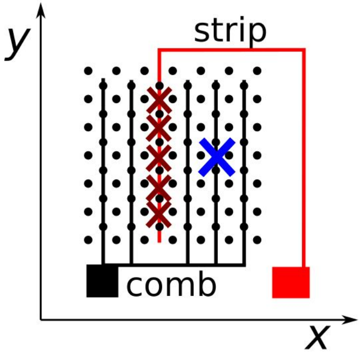


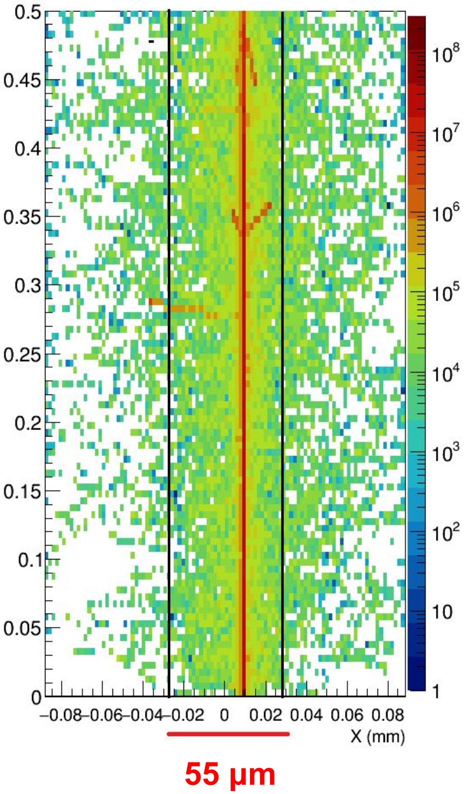
Test @ CERN SPS H8 beam: Strip amplitude spectrum

- Scan in vertical direction along the Strip (**X**) ➔ Proxy for a single pixel
- No difference between different positions ➔ Merge the datasets
- Again Landau peak well visible (MPV ~ 90 mV)
- **S/N = 18**
- Better S/N with respect to Comb

  ➔ Less columns in parallel, smaller capacitance



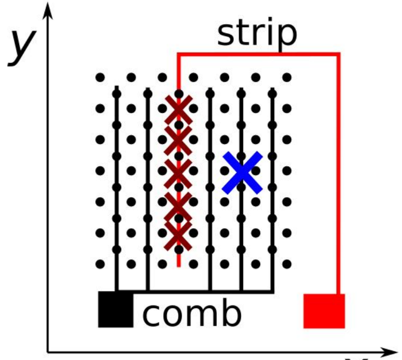


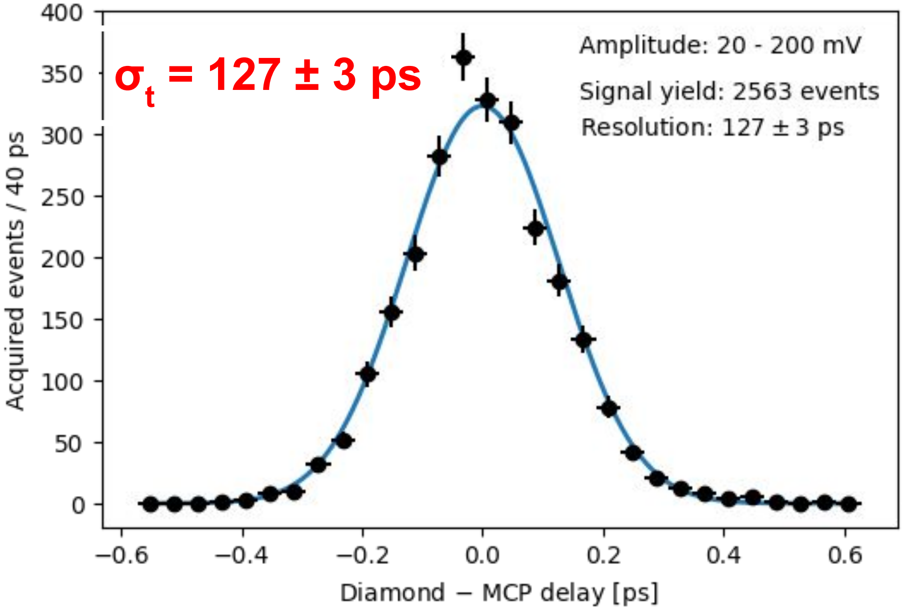


GEANT4 simulation of the deposited energy (z-x) profile inside the detector of a 180 GeV pion beam

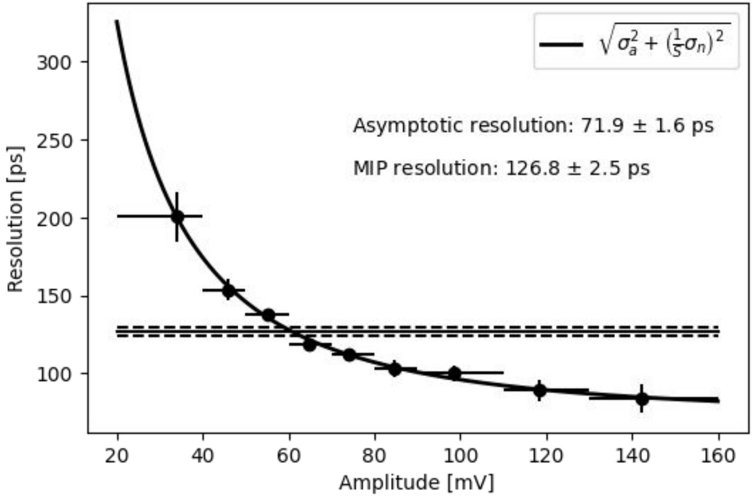
Test @ CERN SPS H8 beam: time resolution for Comb

- Time resolution from the difference between MCP (σ_t ~ 20 ps) and diamond time
- Threshold in Comb @ 20 mV; no signal in strip
- Δt distribution is symmetric ➔ Gaussian fit



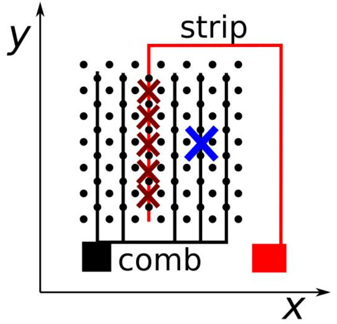

σ_t = 127 ± 3 ps

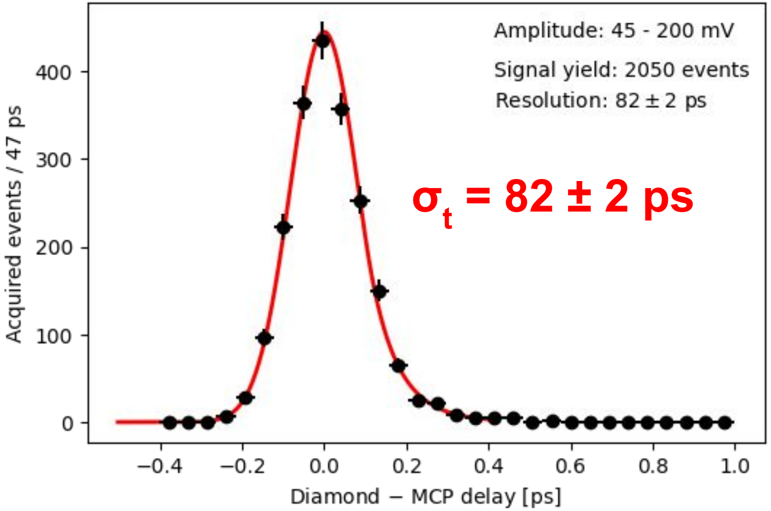
Time resolution in bins of signal amplitude ➔ σ_{asy} ~ 72 ps



Test @ CERN SPS H8 beam: time resolution for Strip

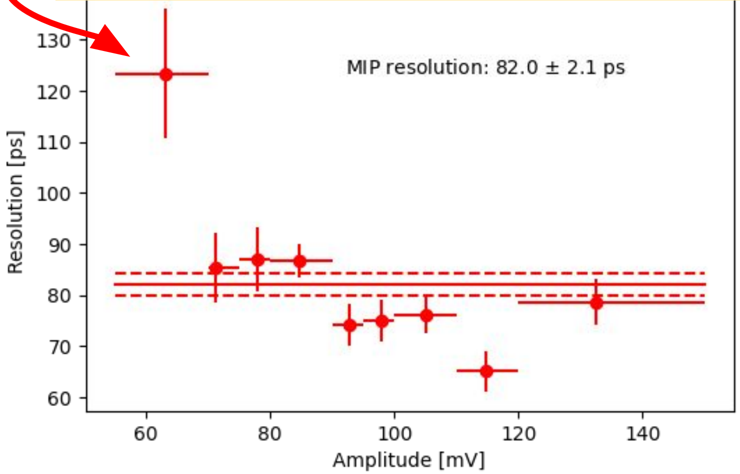
- Request no charge sharing in Comb
- Threshold in Strip @ 45 mV exploiting better S/N
- Δt distribution shows a moderate tail ➔ Crystal Ball fit
- The right tail indicates the presence of additional, slower, contributions





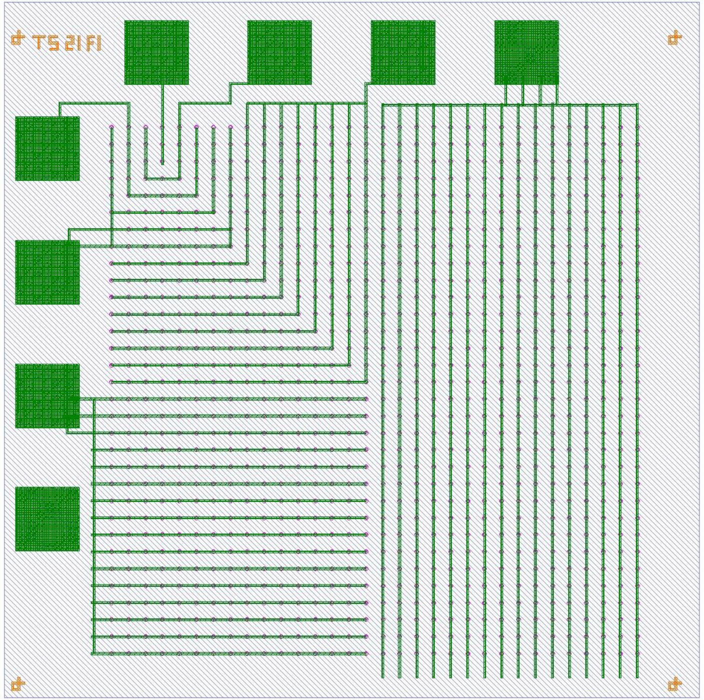
σ_t = 82 ± 2 ps

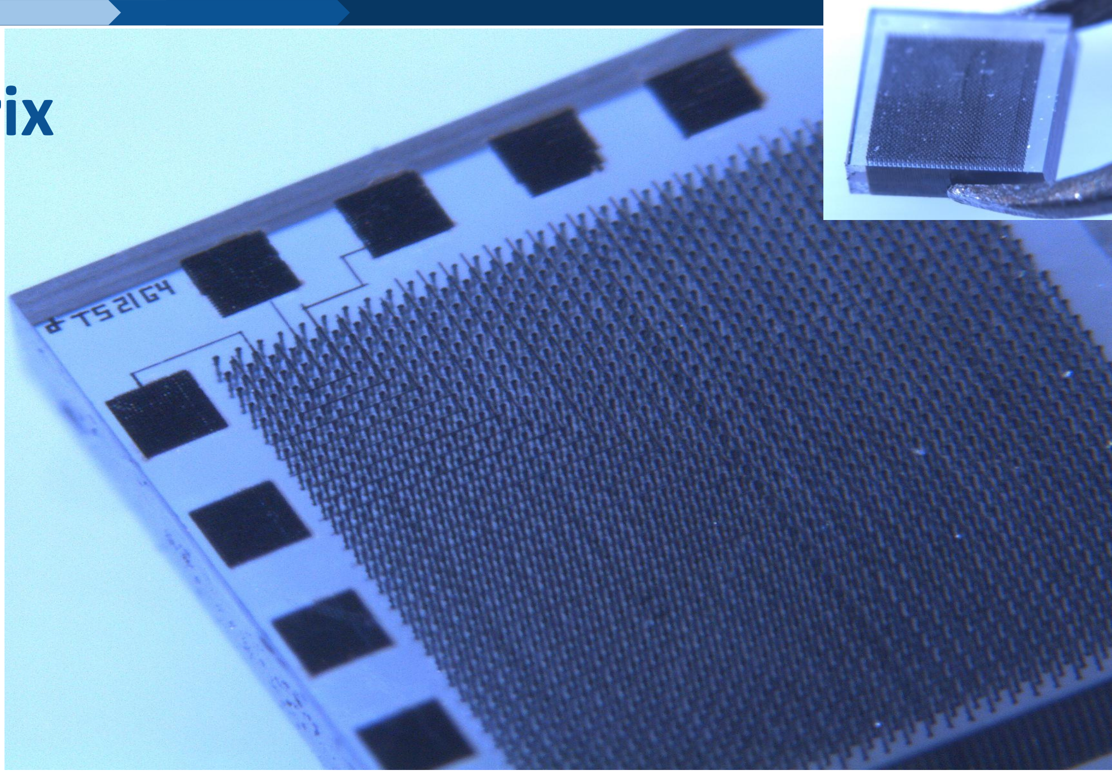
This point is inconsistent with jitter noise ➔ Probably includes contributions from regions outside the fiducial area



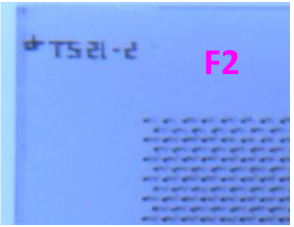
Scaling up: 32 × 32 matrix

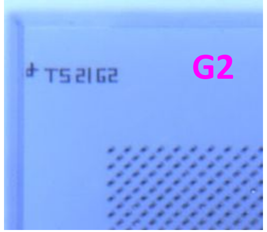
Fabrication system reading GDS files drawn with kLayout

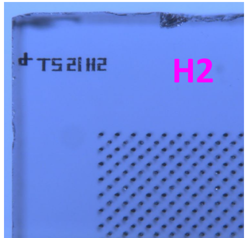




Engraved 12 sensors in 3 batches: F, G, H (while optimizing the procedure)

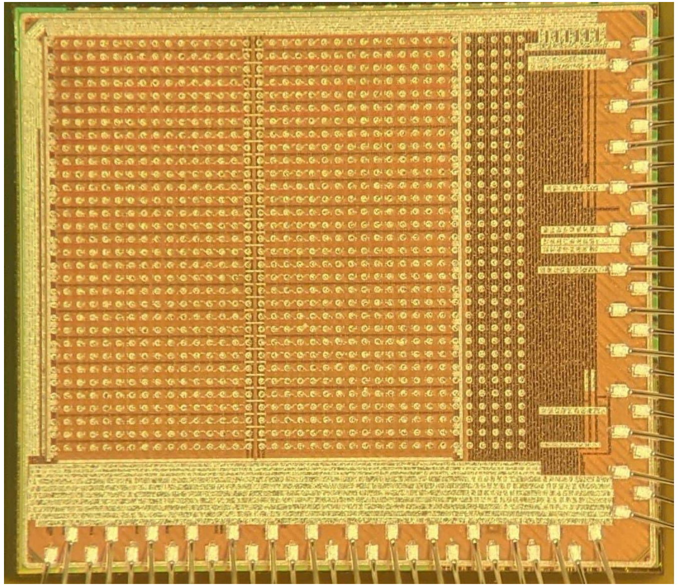




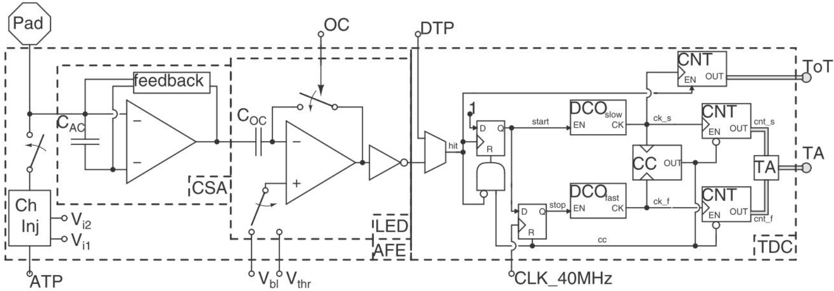


TIMESPOT 1 Front End ASIC

- Designed in 28 nm CMOS commercial technology
- Dimensions: 2.6 mm X 2.3 mm
- 32x32 Channels pixel matrix with pixel pitch of 55 µm
- Bump bondable to the sensors
- Time resolution 50 ps per hit
- Event rate of 3 MHz/channel
- Low power consumption (below 1.5 W/cm^2)
- 4 readout trees (slow out for demo test purpose)
- Every pixel in the detector is connected to:
  - **Analog chain:** made by a charge sensitive amplifier and a leading edge discriminator
  - **Digital chain:** with a TDC providing the time of arrival (TA) and the time over threshold
  - Each channel generates a 24 bit word which is transmitted serially at 160 MHz



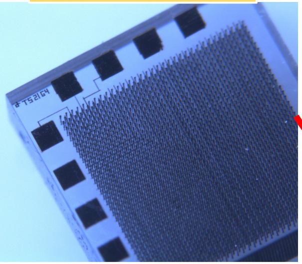
L. Piccolo et al., JINST 17 (2022) C03022



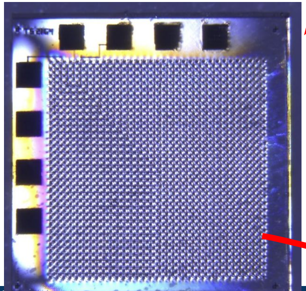
Hybridization of the diamond sensor

- After the successful test of prototypes we proceeded to the hybridization of the final sensors with the dedicated TIMESPOT ASIC
- 8 diamond pixel sensors of 32 × 32 channels and 2.2 × 2.2 mm^2 size, were successfully paired to the ASIC through bump-bonding at Fraunhofer IZM

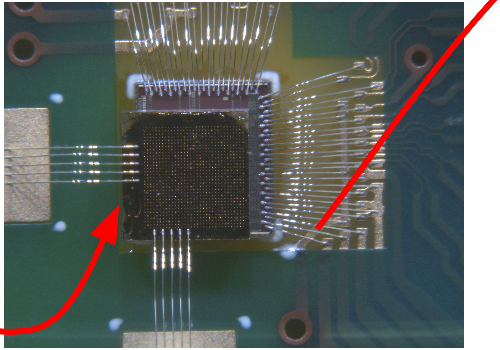
Raw sensor

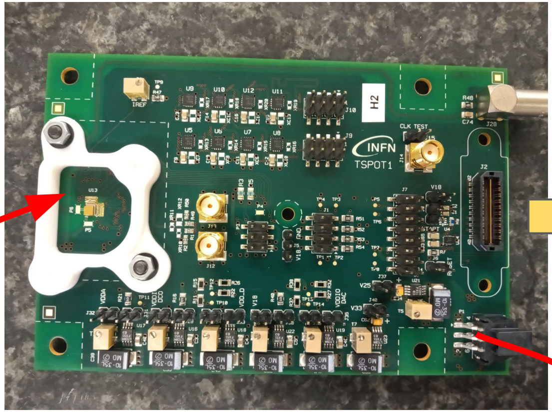


Gold sputtering on the HV side



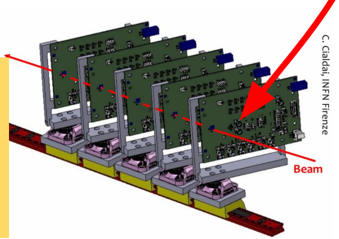
Bump-bonding to the ASIC





To mezzanine and FPGA

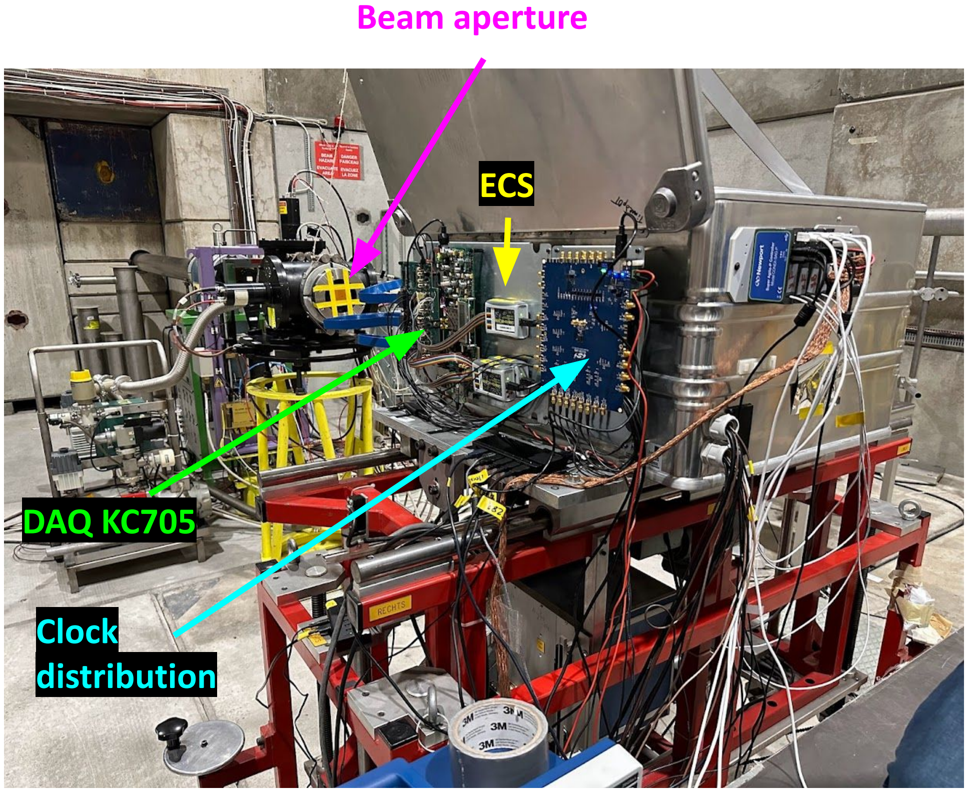
The test bench PCB (TSPOT1) operates also as tracking station in the Si/Diamond demonstrator

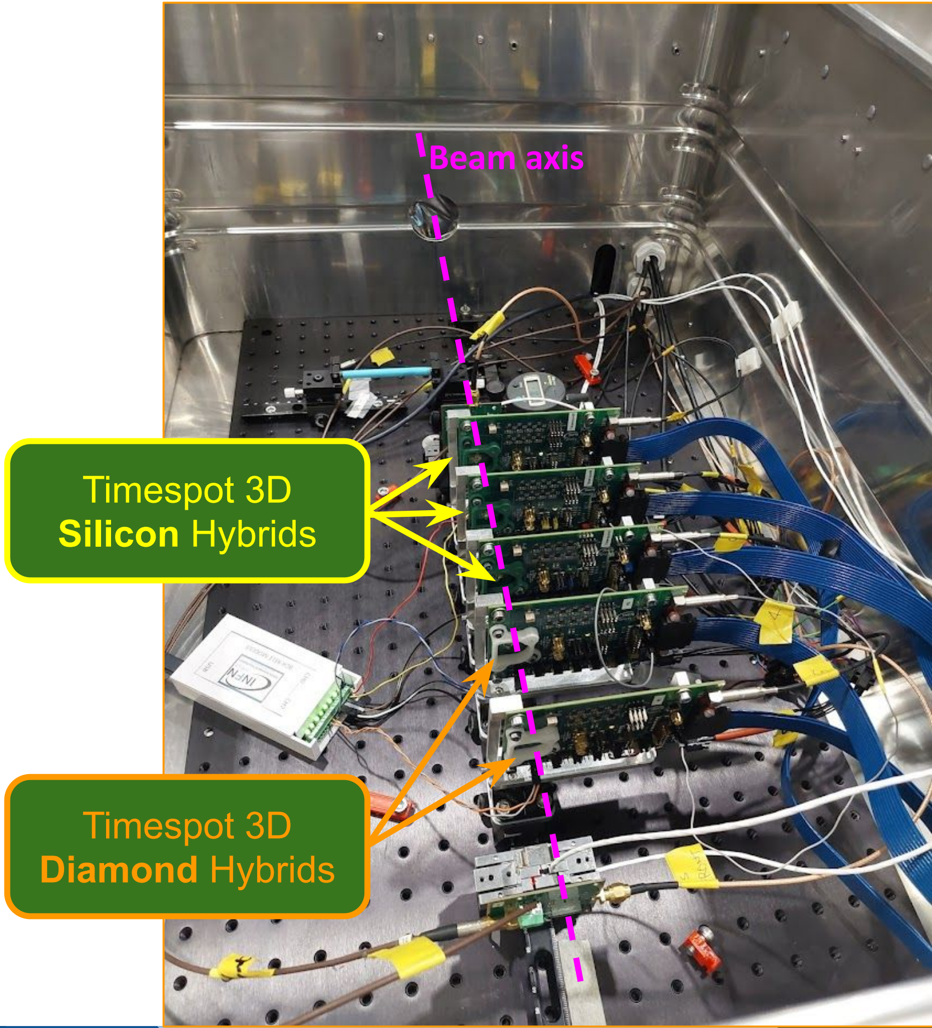


C. Cialdai, INFN Firenze

Beam Test at CERN SPS – H8

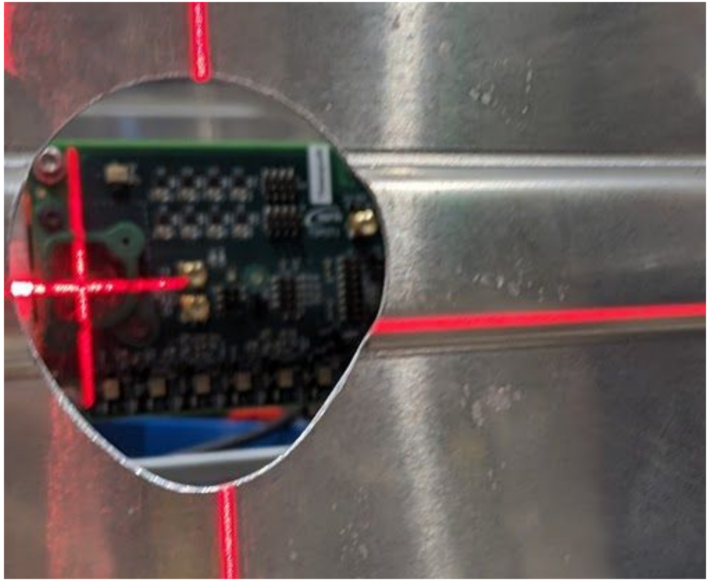
April 2023





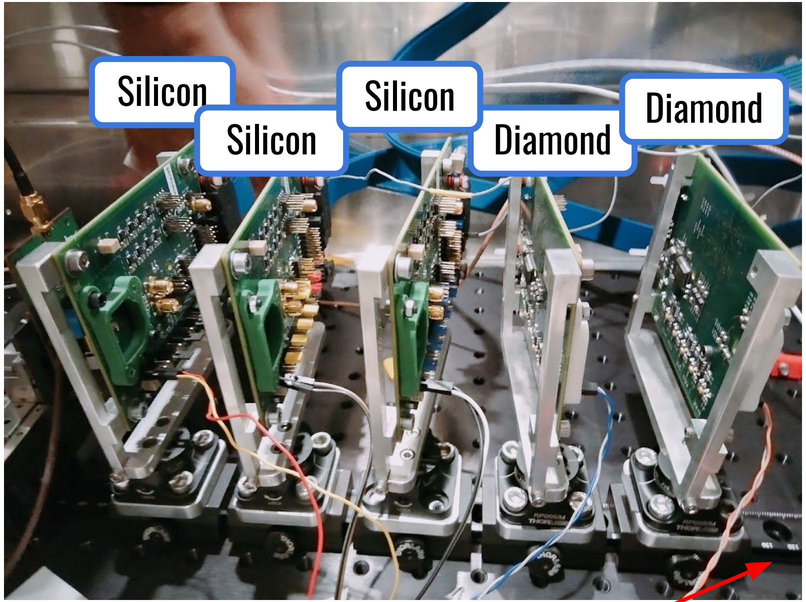
Coarse alignment

1. Sensors aligned to the rail, by optical alignment
2. Rail aligned to the beam with a laser-line level



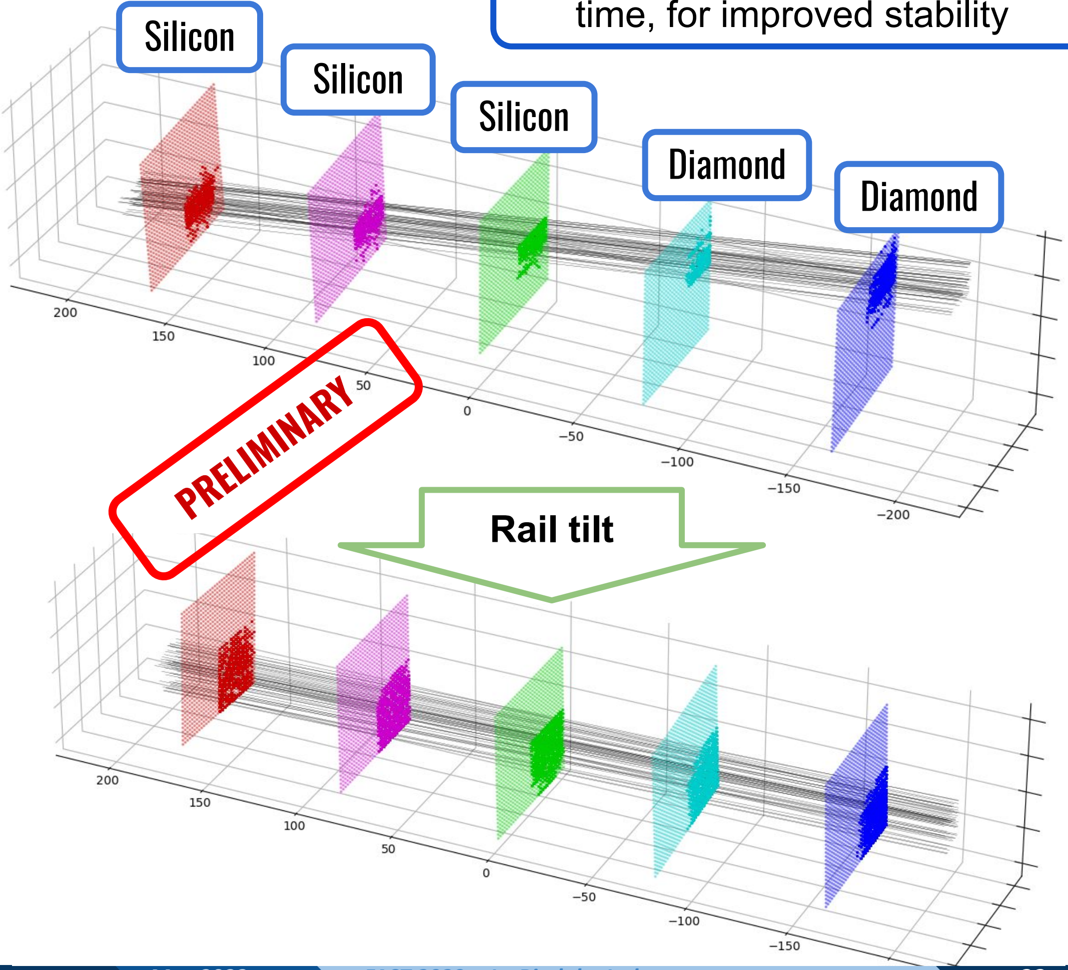
Fine Alignment

3. Alignment refined by reconstructing the beam



Orientable rail

Operating one quadrant at the time, for improved stability

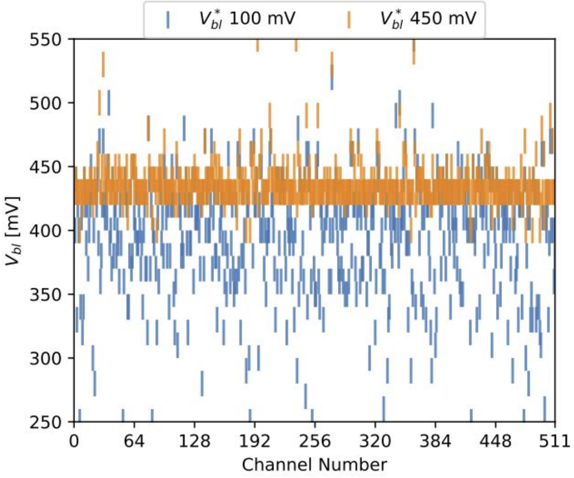


Offset compensation and Time Over Threshold

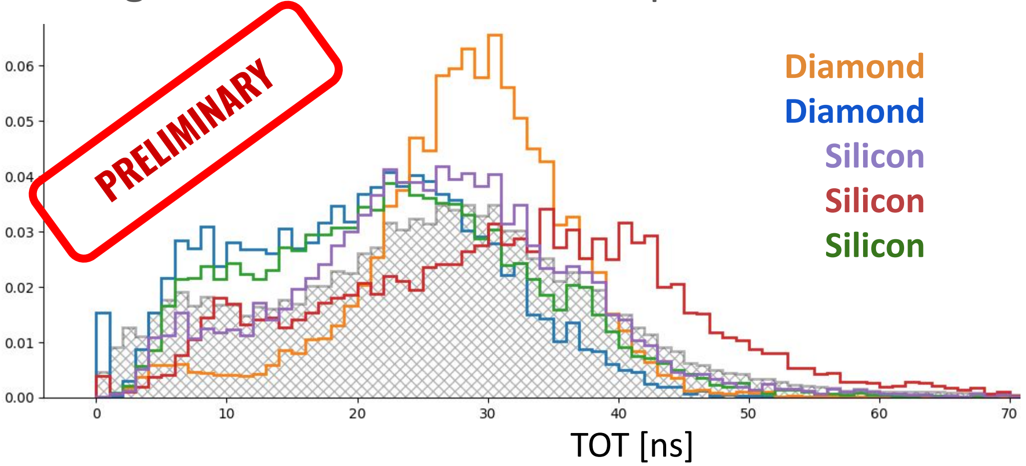
Timespot1 does not provide a direct measurement of the amplitude, but measures the "Time over threshold" of the analog signal.

→ Conceived to correct for time walk effects

Significant difference from a pixel to another.



L. Piccolo et al., JINST 17 (2022) C03022



Expected TOT from a MIP
(from calibrated-laser pulses)

TOT ≃ 50 ns

Measured is ≃ 30 ns

A. Loi, TREDI 2023

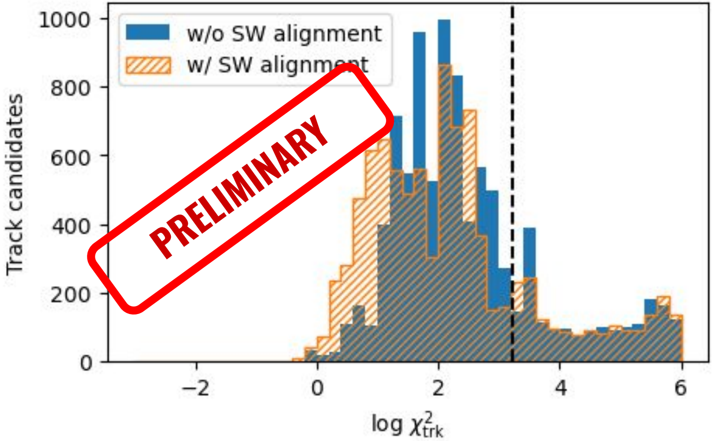
Sensor efficiency

Sensor efficiency of each pixel:

$$\varepsilon_{\text{pixel}} = \frac{N_{\text{hits}}}{N_{\text{trk}}}$$

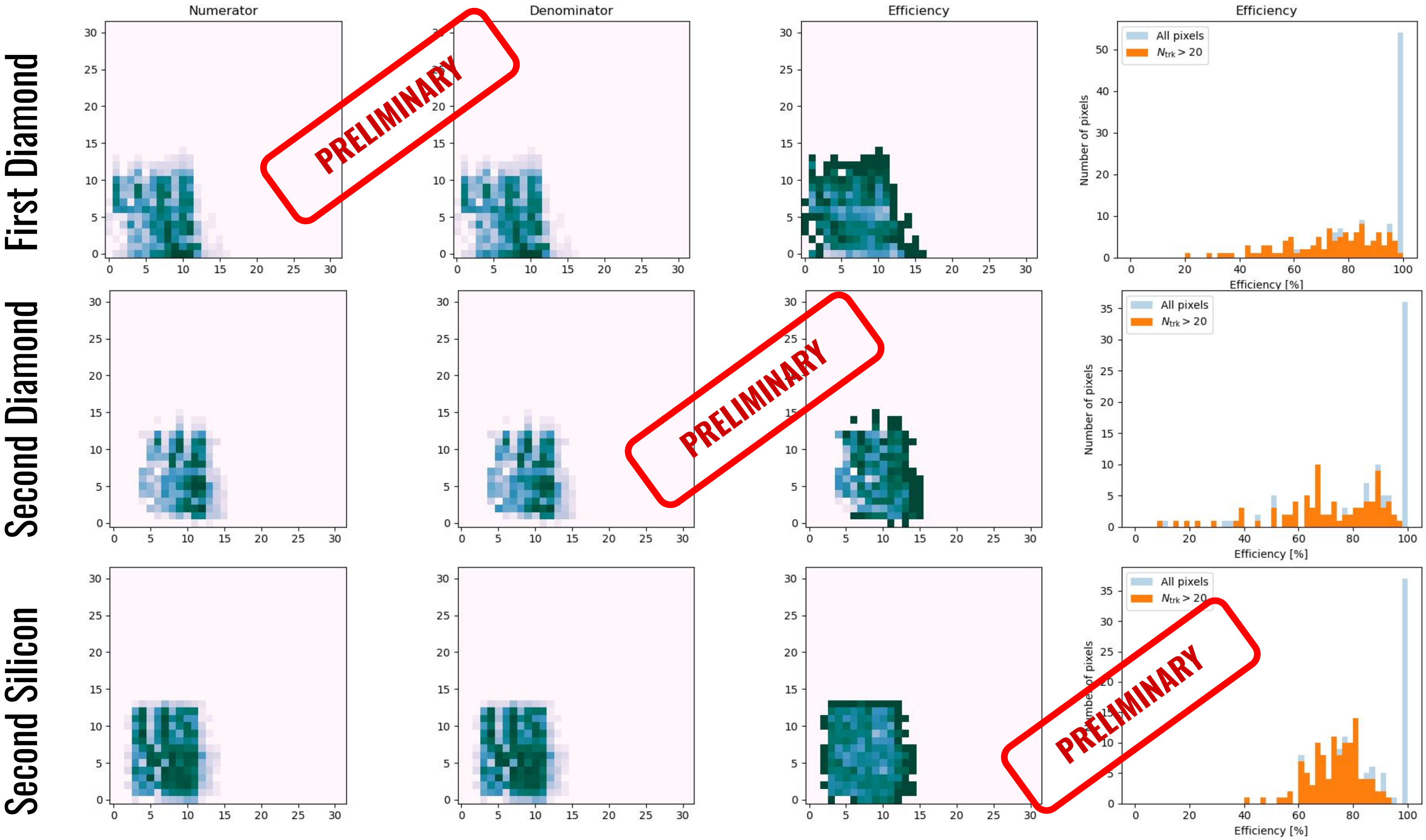
N_{trk} Number of tracks well reconstructed (at least three stations, $\chi^2 < 25$) independently of the station under test passing in the active area of the pixel.

N_{hits} Number of those tracks also featuring a hit, in the pixel or in an adjacent pixel, with loosely consistent timestamp.



The results shown below were obtained with a 2h data taking, corresponding to **35×10^6 hits**, split in **12.4×10^6** independent "events".
Out of these, **5×10^6** involve at least 3 stations.

Efficiency maps (*preliminary*)



Efficiency maps (*preliminary*)

First Diamond

Second Diamond

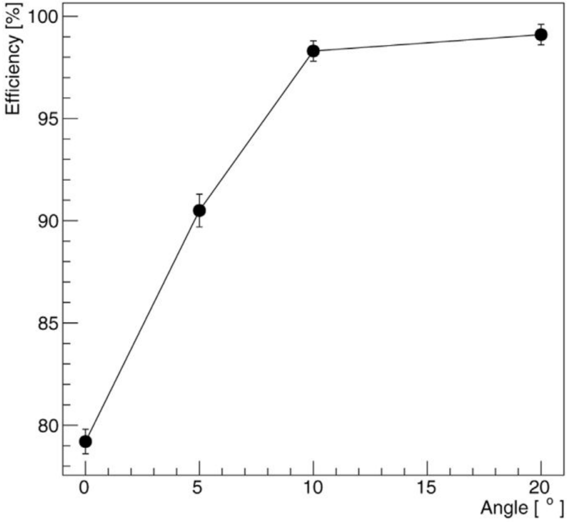
Second Silicon

Diamond.

From single-pixel tests, we expect efficiency above 99% [Front. Phys. 8:589844].

Lower efficiency might be due to suboptimal thresholds (electronics), or too high resistance of some of the electrodes (fabrication).

Front. Phys. 11:1117575

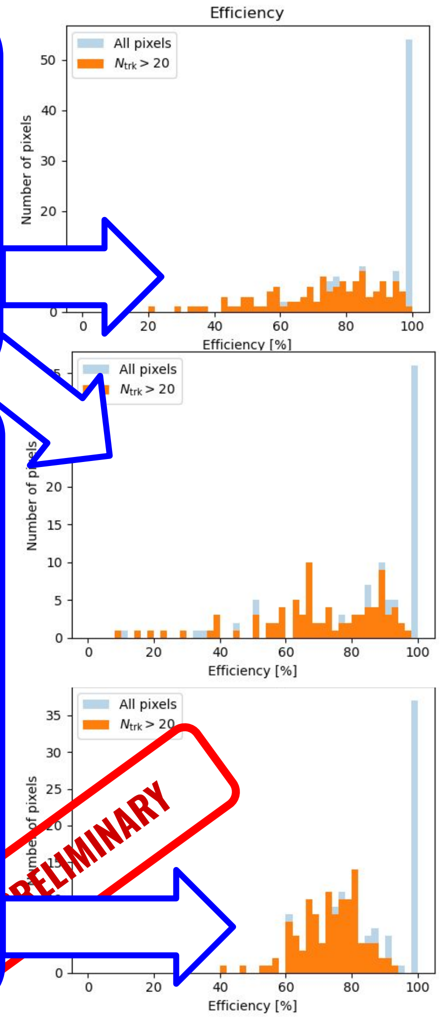


Silicon.

The geometrical efficiency of the trenches, installed orthogonally to the beam was measured in single-pixel configuration.

The ASIC may reduce it further.

The statistical uncertainty smears the results.



Conclusion

1. 1024 pixel, 55 µm-pitch **3D Diamond sensors** were fabricated via laser graphitization and characterized electrically, with beta sources and with high energy hadrons;
2. With discrete electronics, we expect a **time resolution of 80 ps**, still largely dominated by large resistance of the electrodes;
3. Bump-bonding the diamond sensors to Timespot ASIC we have built a first prototype of **fast timing, diamond pixel hybrid,** which has been studied with high energy hadrons in a recent test beam;
4. **First results on the efficiency measurement were presented;**
5. **Diamond efficiency results are encouraging**. Known issues with offset compensation, clock and power distribution tend to dominate the performance making it suboptimal;
6. The analysis of the timing performance is ongoing and may require a next-gen ASIC.