Detector R&D: 4D tracking - LGAD (DRD3)

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CSN5-4DSHARE

Tracker design
sensors requirements – Space-Time tracking

Sensor requirements for spatial and temporal tracking in a 10 TeV Detector

	Vertex Detector	Inner Tracker	Outer Tracker
Sensor type	pixels	macro-pixels	macro-pixels
Barrel Layers	4	3	3
Endcap Layers (per side)	4	7	4
Cell Size	$25\,\mu m \times 25\,\mu m$	$50\,\mu m \times 1\,mm$	$50\,\mu m \times 10\,mm$
Sensor Thickness	$50\,\mu m$	$100\,\mu m$	$100\,\mu m$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\,\mu m \times 5\,\mu m$	$7\,\mu m \times 90\,\mu m$	$7\,\mu m \times 90\,\mu m$

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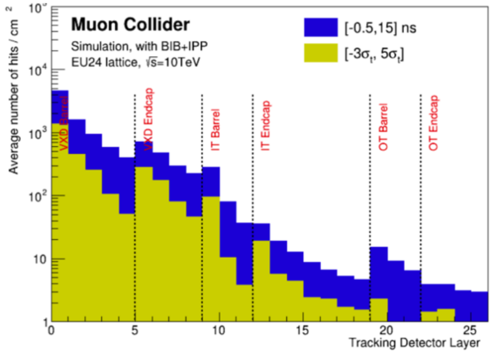
Occupancy plots in tracking detectors

MUSIC tracking Detector



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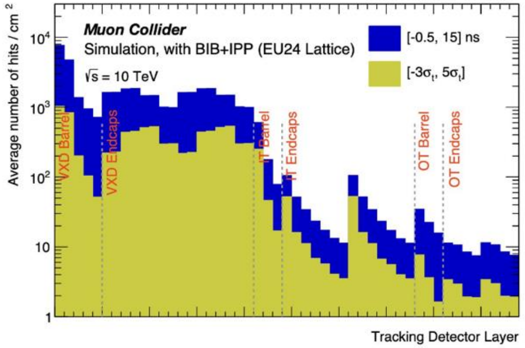
MAIA tracking Detector



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Occupancy in the tracking system is partially reduced by **timing requirements**
(**30 ps and 60 ps time resolutions** are assumed in Vertex and IT+OT respectively)

Tracker design
sensors requirements – Radiation Damage

Sensor requirements for spatial and temporal tracking in a 10 TeV Detector

	Vertex Detector	Inner Tracker	Outer Tracker
Sensor type	pixels	macro-pixels	macro-pixels
Barrel Layers	4	3	3
Endcap Layers (per side)	4	7	4
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

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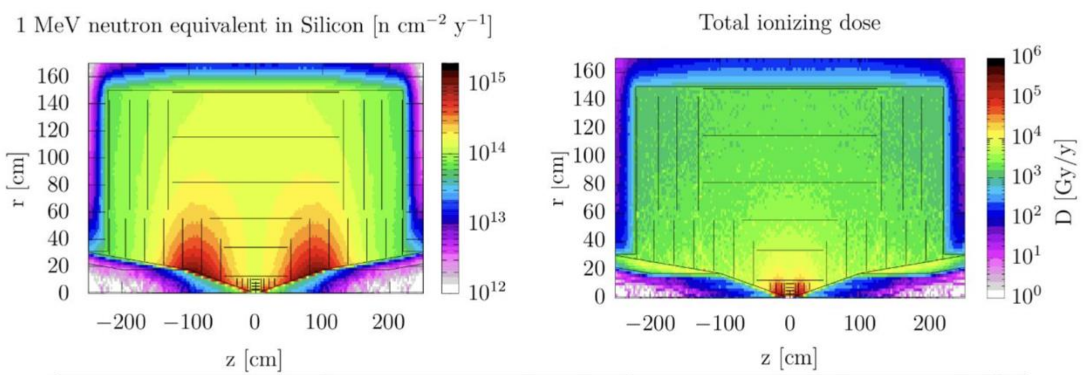
Radiation hardness requirements @ 10 TeV comparable to HL-LHC level



	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

[MuCol annual meeting 2025]

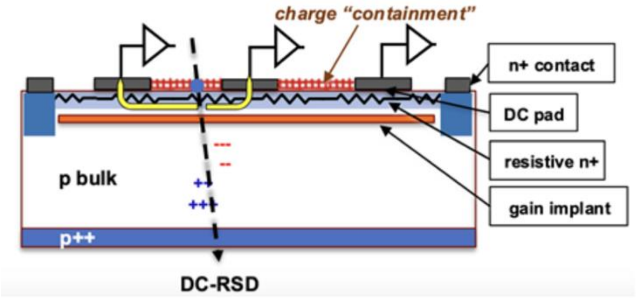
Low Gain Avalanche Diode (LGAD) developments - Contributions on Turin

Resistive silicon detector (AC- or DC-RSD)

One of the candidate technology for the major part of the tracker

The operation principle is based on signal sharing between read-out electrodes, through a resistive read-out

- ➢ Fill factor close to 100%
- ➢ Space resolution: ~ 3-5% of the pitch
- ➢ Timing resolution of 30-40 ps



RSD is a technology suitable for:

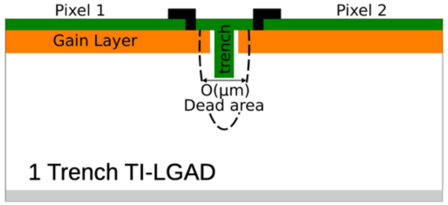
- ➢ low density, low power read-out architectures (approximately x100 fewer channels than standard pixel sensors)
- ➢ Environment with low-medium event rate

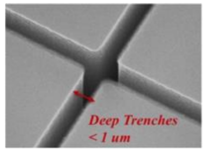
Trench-isolated LGADs (TI-LGADs)

The traditional JTE and p-stop are replaced by trench etched into the silicon sensor

- ➢ Smaller dead area: trench width ~1µm
- ➢ Small pixels (down to 50 µm) with high fill factor

R&D ongoing in DRD3 collaboration

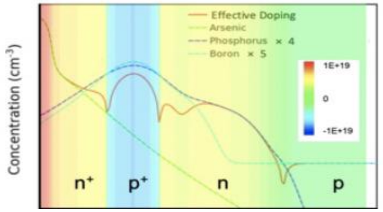




Radiation hardness and Extreme fluence

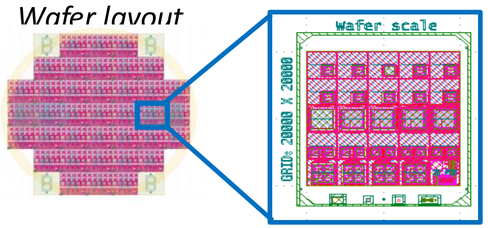
➢ Compensated-LGAD

Improvement of the multiplication layer design to cope with fluences exceeding $10^{16}\ n_{eq}/cm^2$



➢ *p-in-n* LGAD

Study of donor removal mechanism.
Propaedeutic for Compensated-LGADs



Batch is releasing in September

Projects

Projects oriented to improve the radiation hardness of LGAD technology

- **eXFlu-Innova** (AIDAinnova project from 2022 to 2025) and **ComonSens** (PRIN2022 - from 2023 to 2025):
  - → Funding *p-in-n* LGAD, propaedeutic to the design of compensated-LGAD
  - → *p-in-n* LGAD is releasing in September
- **CompleX** (ERC - from 2024 to 2029):
  - → Funding of 3 productions of Compensated LGAD for extreme fluences
  - → First batch of compensated LGAD will be released in 2026
- **Partial Activated Boron LGAD (PAB-LGAD)** (RD50/DRD3 common project - from 2024)
- **SiC-4Gain** (INFN CSN5 project 2026 to 2028): Silicon Carbide 4D-tracking detector

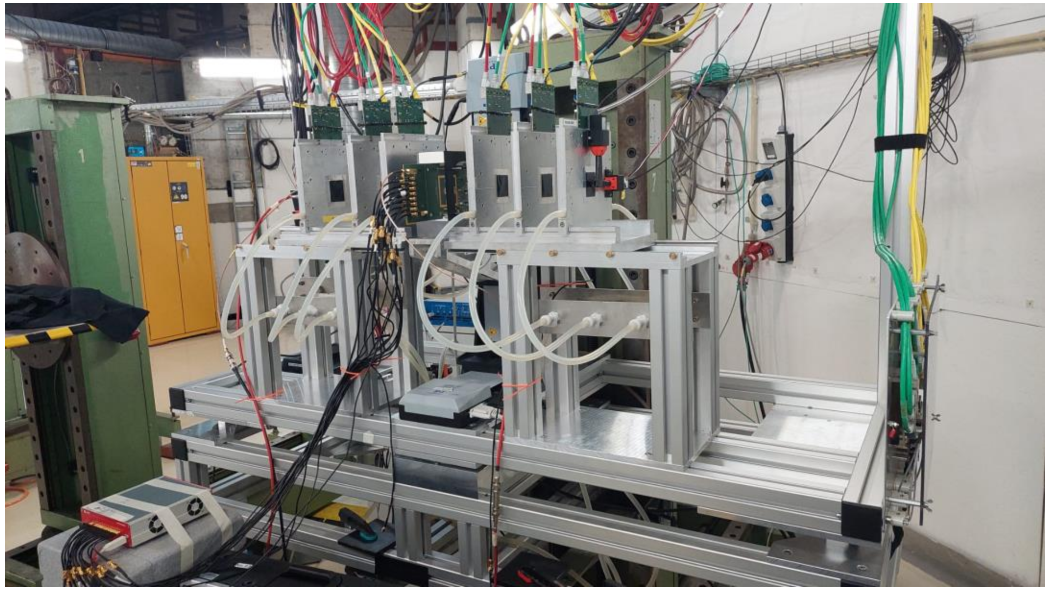
Projects involved RSD technology development:

- **4D_Share** (INFN CSN5 project 2023 to 2025) and **4D_Share** (PRIN2022 - from 2023 to February 2026):
  - → Funding 2 productions of DC-RSD sensors
  - → The second production of DC-RSD is scheduled for the end/beginning of 2025/2026
- **RadHard AC-LGAD** (RD50/DRD3 common project - from 2024):
  - → An AC-LGAD production with the purpose of investigating and extending the radiation hardness of the RSD technology
- **FAST3-Amplifier** (RD50/DRD3 common project - from 2024):
  - → Development of a multichannel amplification boards based on FAST3 ASIC, optimized to readout multi-channel LGAD prototypes (suitable for sensor R&D in laboratory and test beam activities).

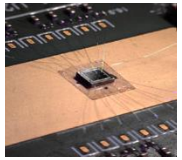
Beam test activities ad funding request

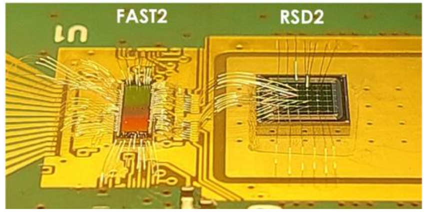
Beam tests activities are crucial in order to evaluate the performance of devices

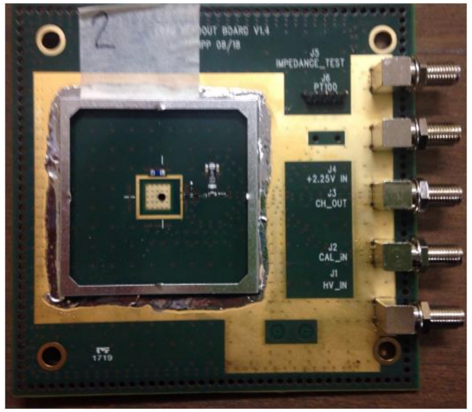
Beam test on DC and AC-RSD



DESY beam line

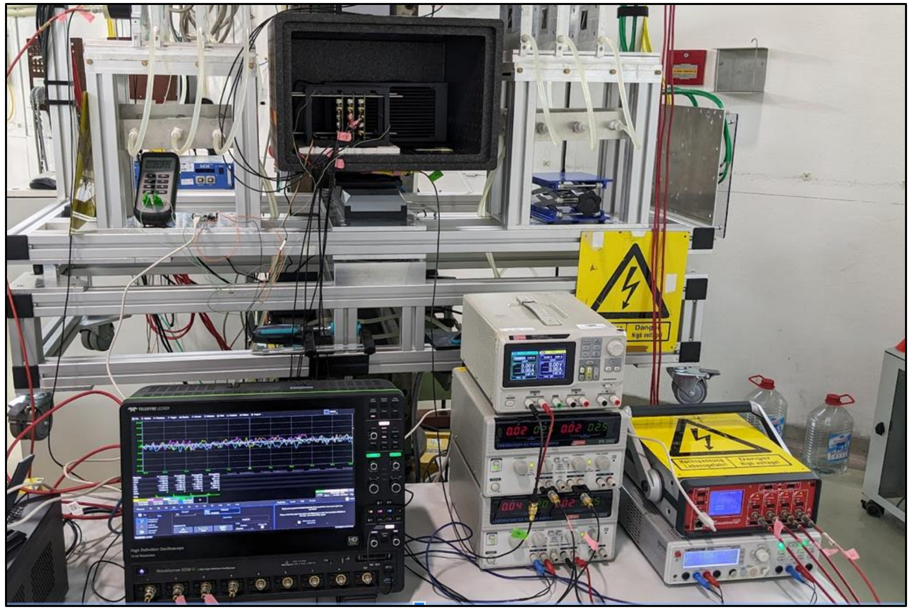






Single channel Read-out board

Beam test on thin LGAD



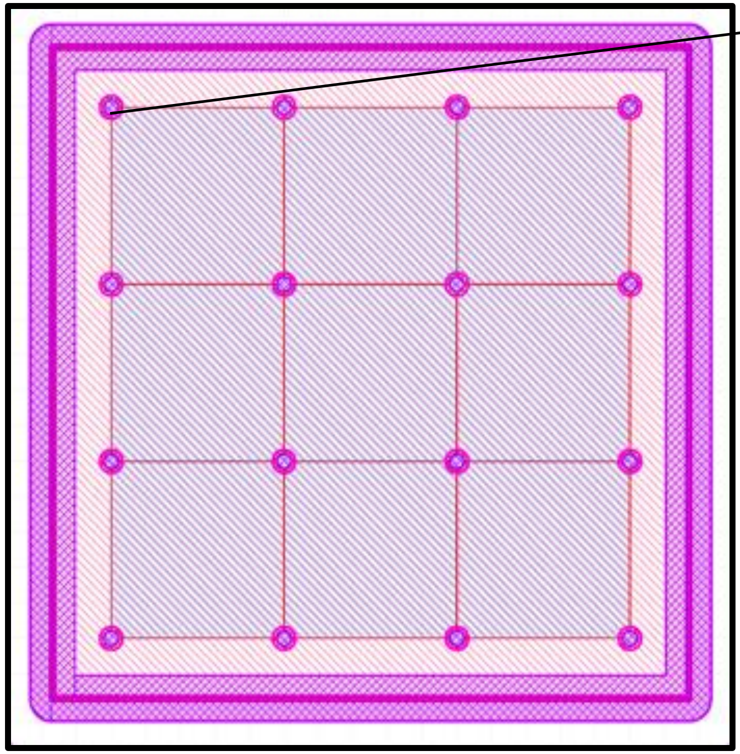
DESY beam line

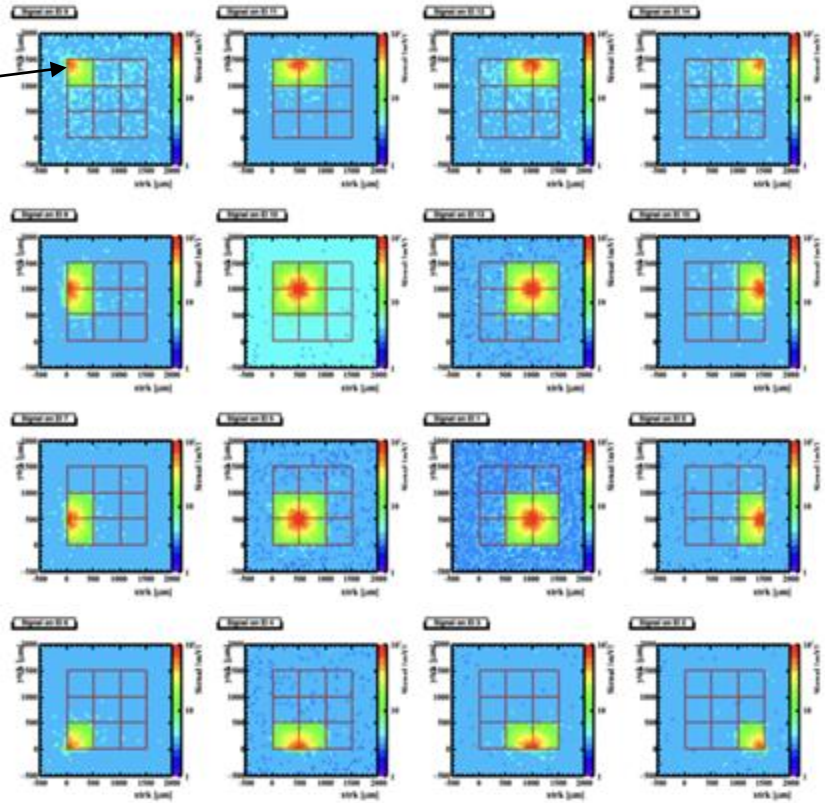
Funding request:

- Beam test: **10 k€**
- Single channel Read-out board (optimal for timing): **5 k€**

State of the art of LGAD for space tracking
LGAD based on resistive readout (DC-RSD)

Average signal amplitude seen by each electrode as a function of the $(X,Y)_{TRACKER}$





Data acquired during beam test

State of the art of LGAD for space tracking
LGAD based on resistive readout (DC-RSD)

Position resolution $(X, Y)_{DC\text{-}RSD}$ - $(X, Y)_{Tracker}$

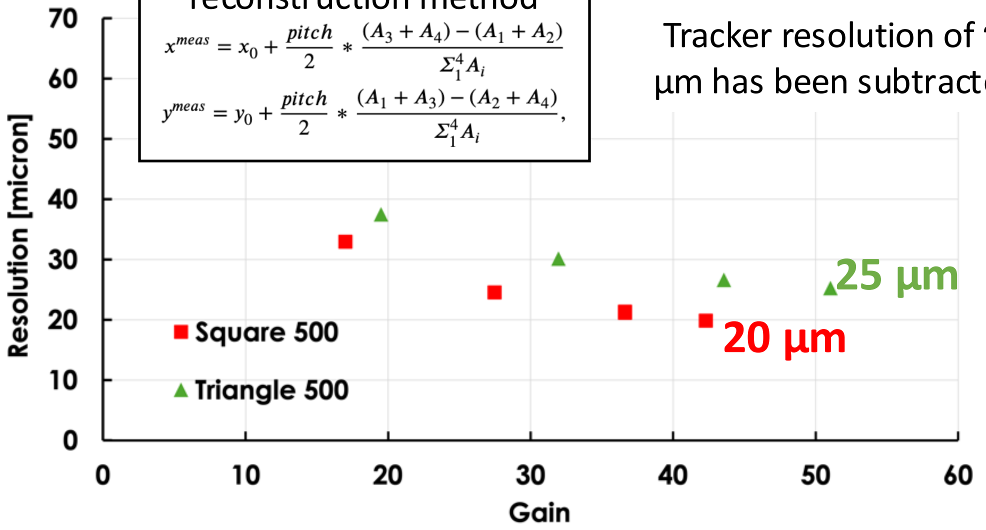
Square and triangular pixel 500-µm pitch

Charge imbalance as reconstruction method

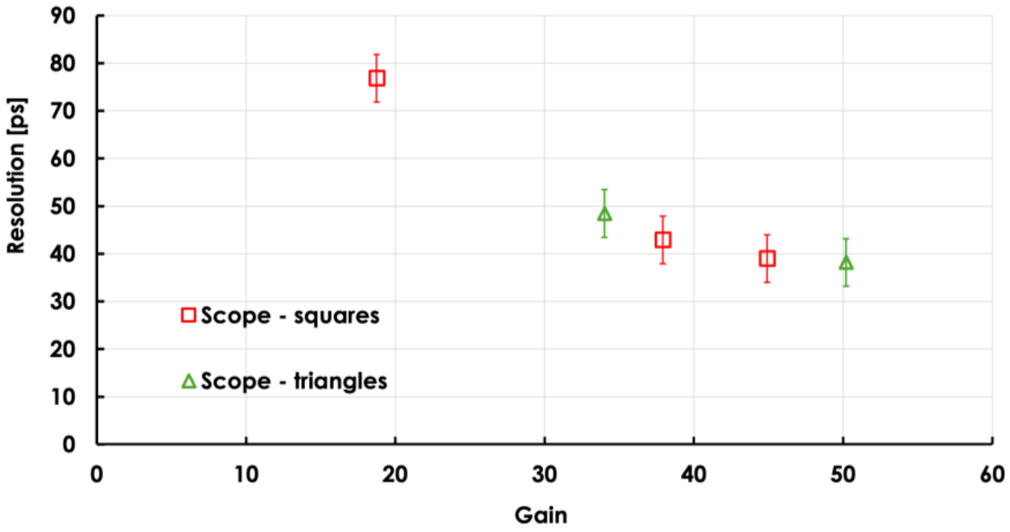
$$x^{meas} = x_0 + \frac{pitch}{2} * \frac{(A_3 + A_4) - (A_1 + A_2)}{\Sigma_1^4 A_i}$$

$$y^{meas} = y_0 + \frac{pitch}{2} * \frac{(A_1 + A_3) - (A_2 + A_4)}{\Sigma_1^4 A_i},$$

Tracker resolution of ~8 µm has been subtracted

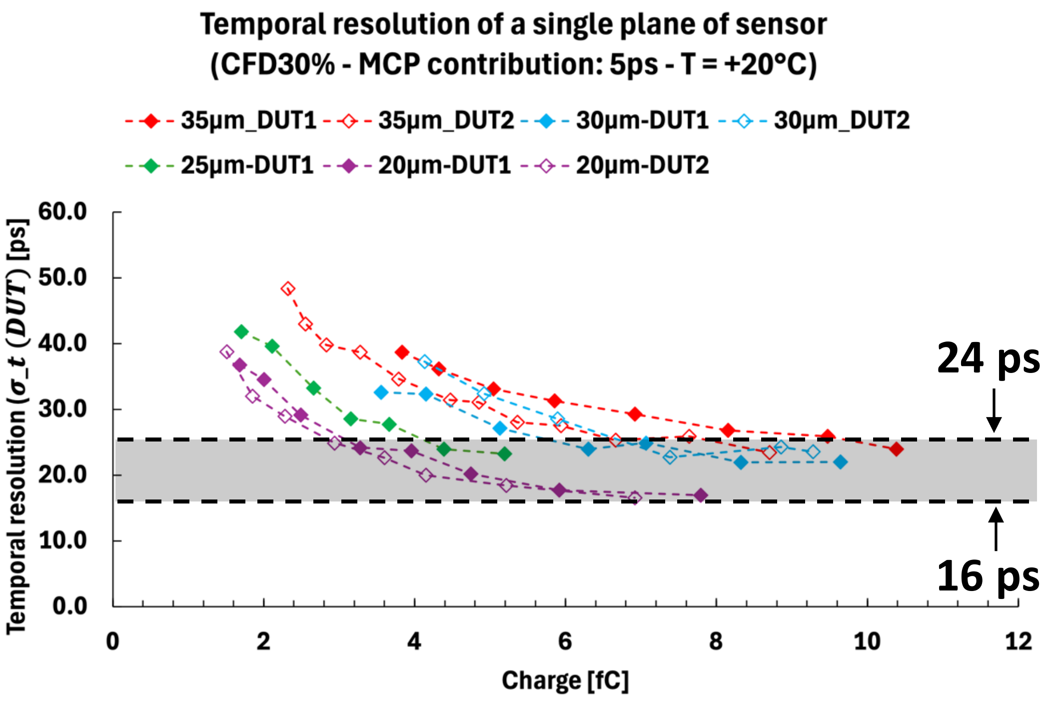


Time resolution for the 500-µm pitch squared and triangular pixel matrix

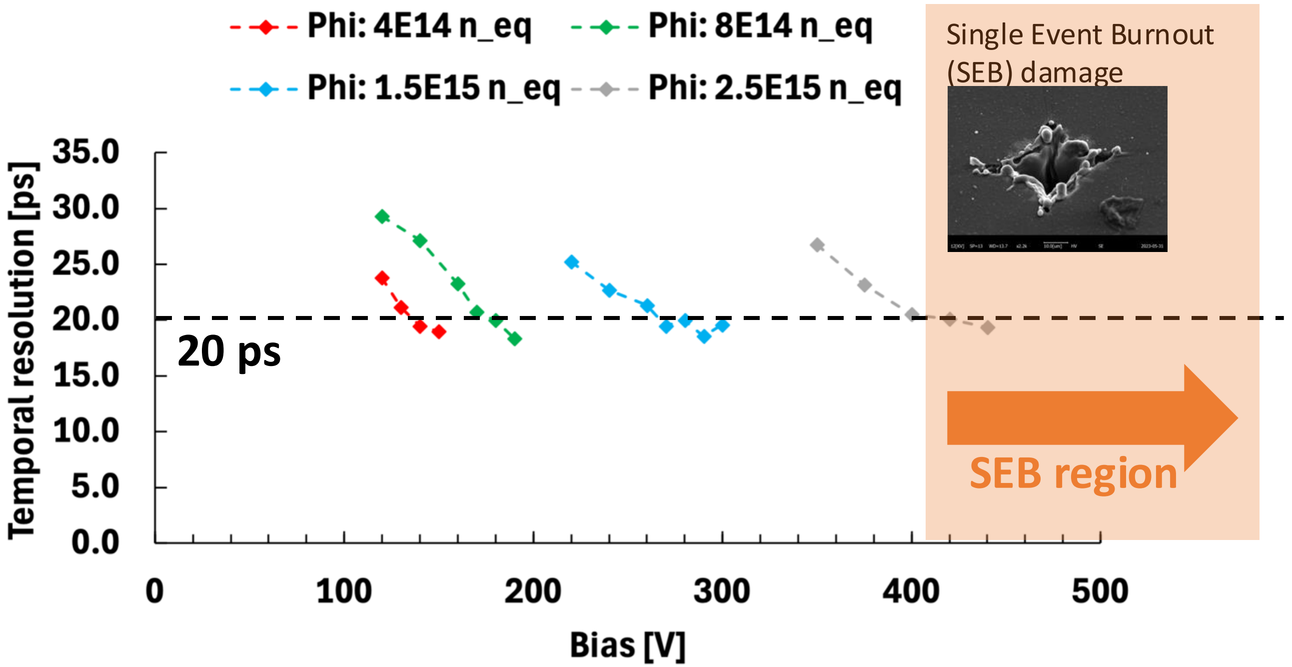


- ➢ All sensors achieve a space resolution **below 5% of the pitch**
- ➢ **Square pixels** yield a slightly better spatial resolution

State of the art of LGAD for time tracking



Time resolution between **16 ps** and **24 ps** measure with **20-35µm** thick LGAD UnIrradiated



Time resolution of **20 ps** achieved by **30 µm**-thick LGAD irradiated up to **$2.5 \cdot 10^{15}$ n_{eq}/cm^2**

Matching LGAD capabilities to muColl request

			cell size	sensor thickness	time resolution	spatial resolution	LGAD technology
Vertex Detector	VXD	B	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	TI-LGAD
		E	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	
Inner tracker Detector	IT	B	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	RSD
		E	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	
Outer tracker Detector	OT	B	50 µm × 10 mm microstrips	100 µm	60 ps	7 µm × 90 µm	RSD
		E	50 µm × 10 mm microstrips	100 µm	60 ps	7 µm × 90 µm	

- High occupancy and radiation level
- R&D in radiation hardness will cover the radiation requirements

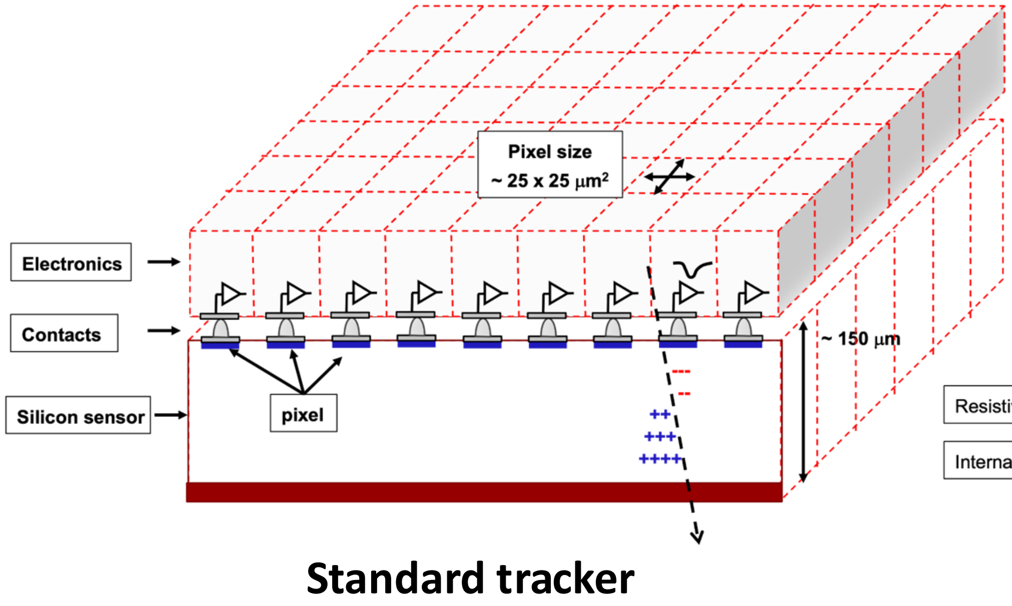
- Low occupancy and radiation level
- Pixel size, spatial and temporal resolution are a perfect fit for present RSD technology
- **RSD** will strongly reduce the number of pixels
- **RSD macro pads** are probably better than strips in term of spatial and temporal resolution

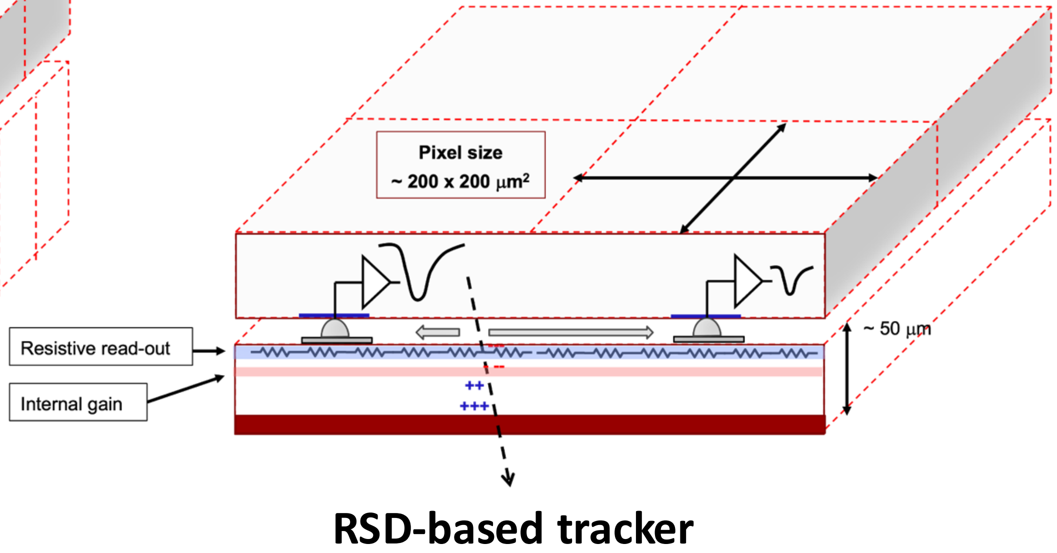
Backup

A completely new tracker based on RSD (AC or DC couple)

M. Ferrero , INFN Torino, MuCol -25 July 2024

One of the candidate technology for the major part of the tracker

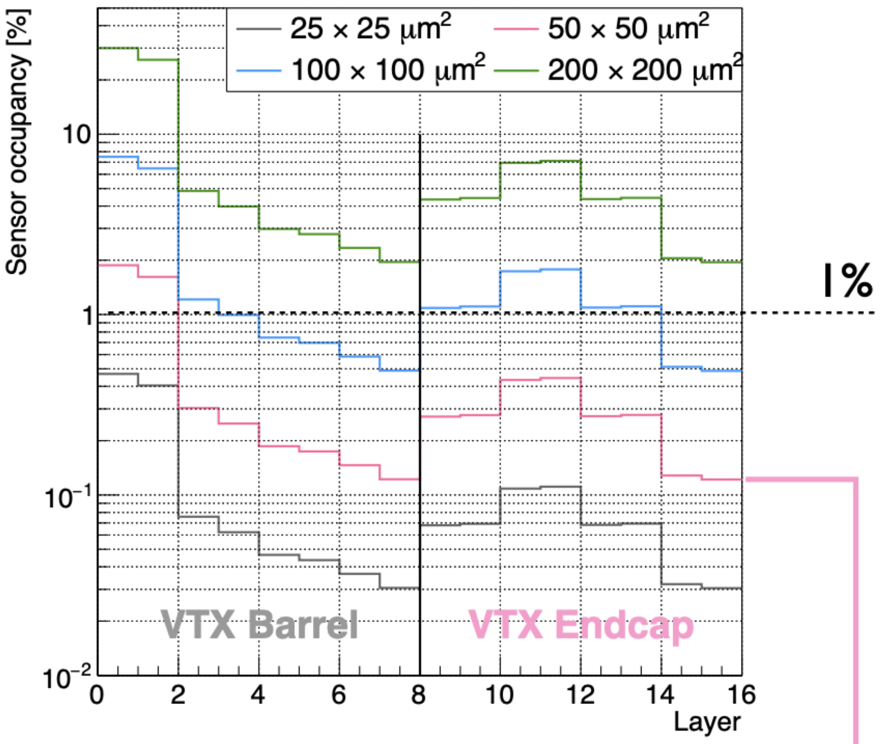




The design of a tracker based on RSD is truly innovative:

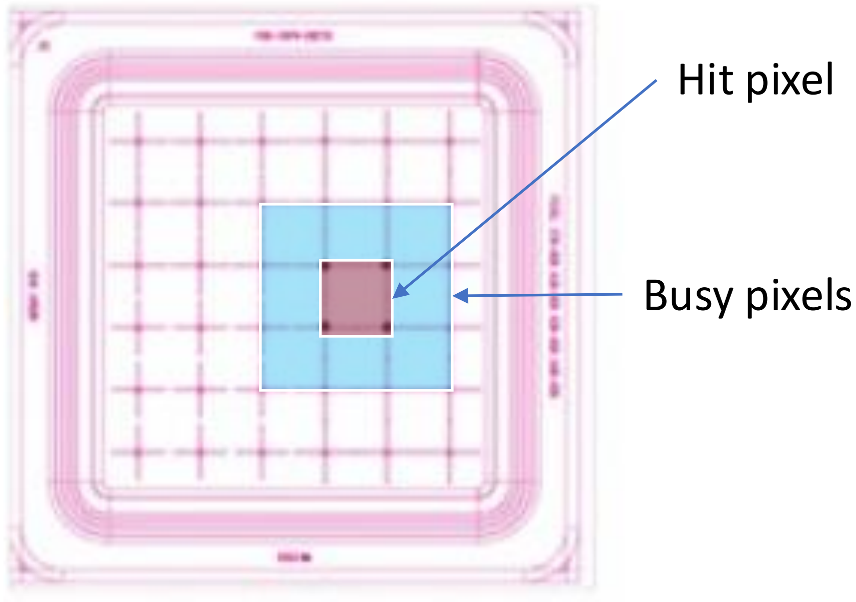
- It delivers ~ 20 -30 ps temporal resolution
- For the same spatial resolution, the number of pixel is reduced by 50-100
- The electronic circuitry can be easily accomodated
- The power consumption is much lower, it might even be air cooled (~ 0.1-0.2 W/cm^2)
- The sensors can be really thin

Occupancy



Low Occupancy must be ensured to avoid pile-up effects
50x50 μm pads would be sufficient for most of the VTX

Effective area for read out of a single hit is 3x3 pixels



Traditional trench-isolated LGADs could be more suitable mere suitable for VTX

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