DRD3 Hybrid Silicon Technologies for 4D Tracking

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on behalf of the DRD3 WG2 Collaboration

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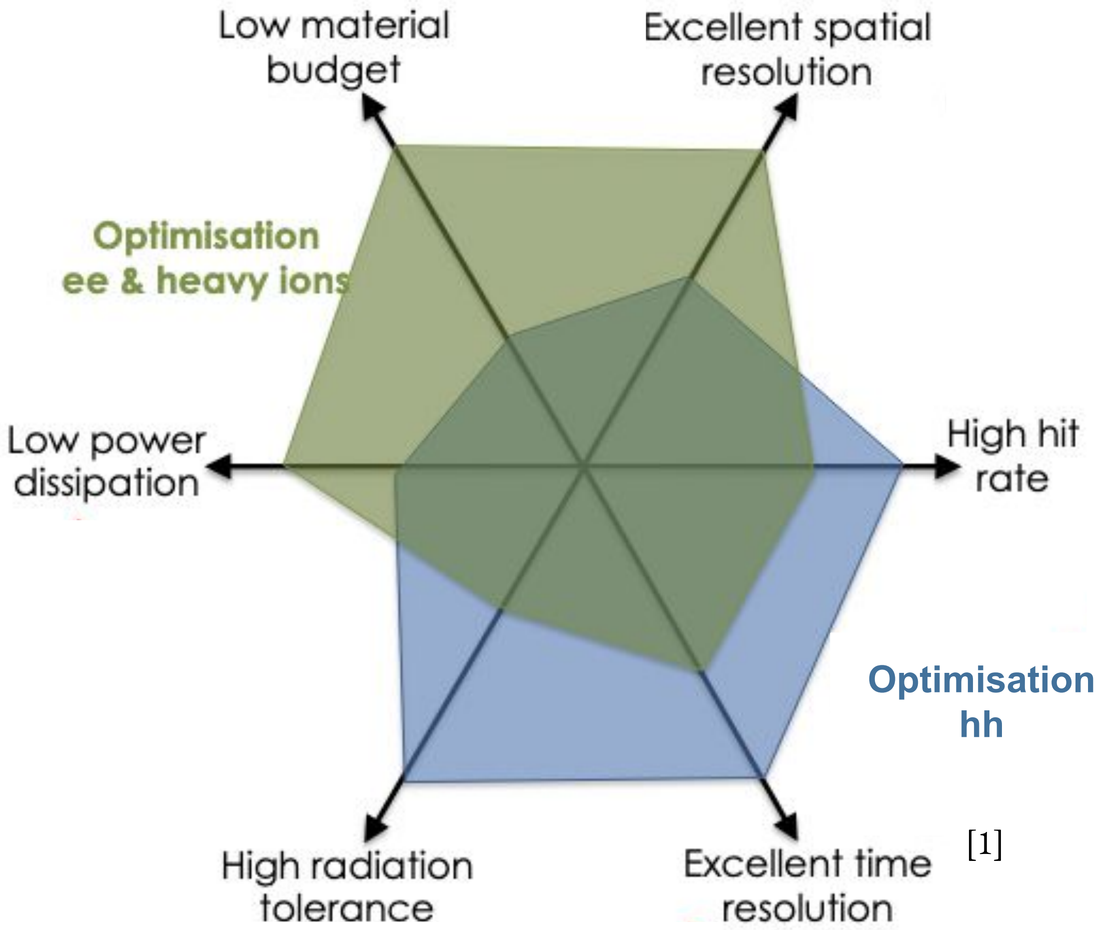
Future colliders - Requirements for detectors

- Detectors for future colliders like circular or linear e^+e^- colliders (CEPC, FCC-ee, iLC, CLIC), hadron colliders (FCC-hh, HE-LHC) or muon colliders need to fulfill many different requirements
- A lot of research ongoing to find the solutions to all challenges simultaneously
- Timing layers as planned for CMS, ATLAS and LHCb upgrades will be likely - LGADs are a key research topic
- Concerning hadron colliders, 3D sensors are an interesting research area
- Hybrid detectors offer many opportunities to tackle all challenges



[1]

[1] J. Baudot - Ongoing and future developments on CMOS-MAPS - IRFU/DPhN seminar, 23 January

DRD3 Working Group 2 - Hybrid Silicon Technologies

Broad scope:

- Sensors with 4D capabilities - from Time-of-Flight systems to large 4D trackers
- Two main technologies currently investigated: LGADs and 3D sensors

Challenges:

- Hadron colliders: High occupancy, extreme radiation levels
- Lepton colliders: Low material budget and power dissipation

WG2 research goals <2027	
	Description
RG 2.1	Reduction of pixel cell size for 3D sensors
RG 2.2	3D sensors for timing ($\leq 55 \times 55$ μm, < 50 ps)
RG 2.3	LGAD for 4D tracking < 10 μm, < 30 ps, wafer 6" and 8"
RG 2.4	LGAD for ToF (Large area, < 30 μm, < 30 ps)

Stay in touch:

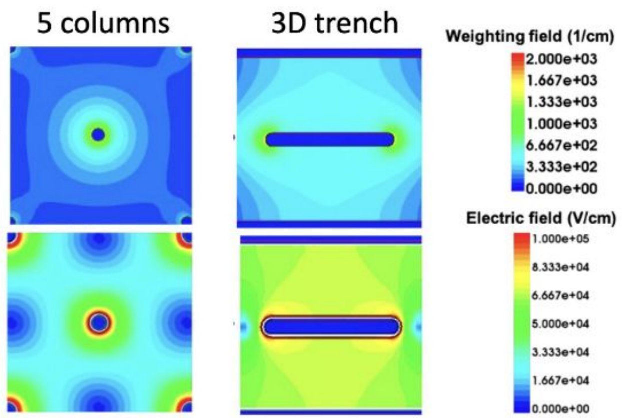
- Website: https://drd3.web.cern.ch/wg2
- Convenors (Anna Macchiolo, Martin van Beuzekom, Alessandro Tricoli): drd3-wg2-conveners@cern.ch
- Indico agendas for Meetings and Workshops - DRD3 and WG2
- Subscribe to WG2 e-group for general communications/announcements: drd3-wg2-hybrid@cern.ch

Find more details:

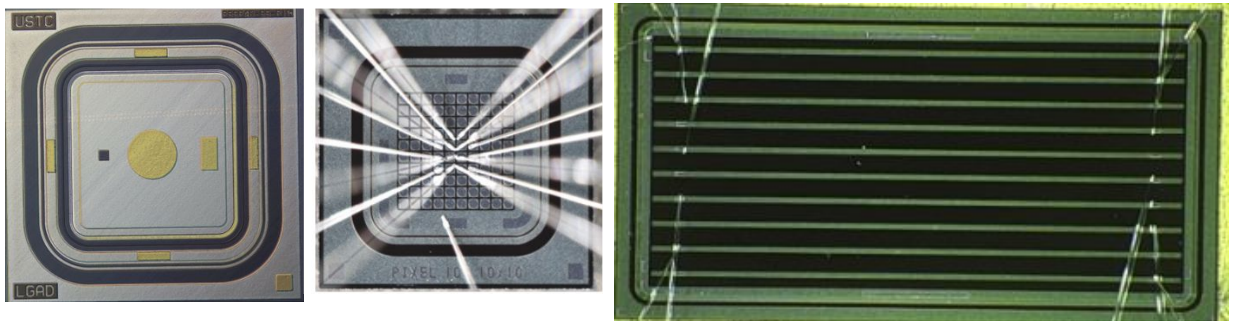
- DRD3 week in Amsterdam 2 weeks ago: Presentations on all ongoing research topics here

DRD3 WG2 - Research Goals and Activities

- **RG 2.1 Reduction of pixel cell size for 3D sensors.**
  - 2024-2025: 3D sensors test structures with pixel size smaller than the current $50 \times 50\ \mu m^2$ or $25 \times 100\ \mu m^2$
  - 2026-2028: Large size 3D sensors with reduced pixel size.
  - $\geq$ 2028: Expand the number of foundries capable of producing 3D sensors for HEP applications.
- **RG 2.2: 3D sensors with a temporal resolution better than 50 ps.**
  - 2024-2025: Production of a small matrix with pitch equal to or less than $55 \times 55\ \mu m^2$ to be connected with existing read-out ASICS
  - 2026-2028: Production of large-size sensors (using the selected geometry from the R&D runs) and interconnection with custom-made read-out ASIC



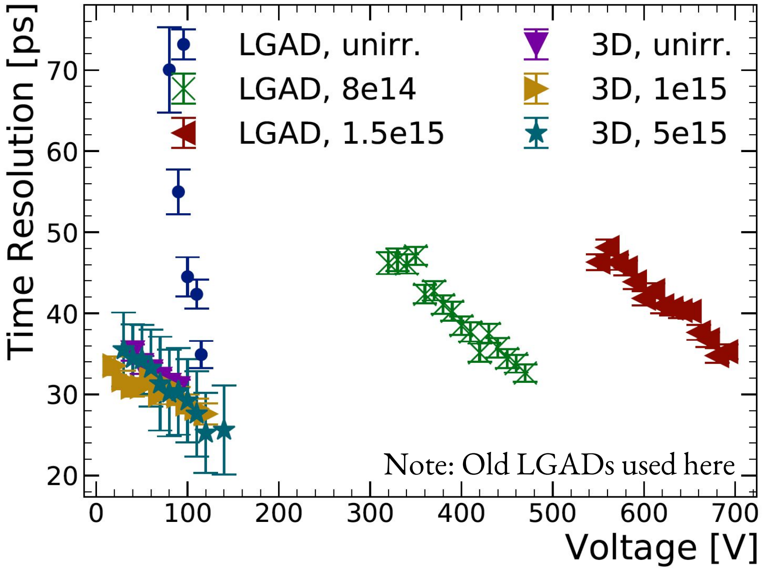
- **RG 2.3: LGAD Sensors with very high fill factor, and an excellent spatial and temporal resolution.**
  - 2024-2025: LGAD test structures of different technologies (TI-LGAD, iL-GAD, AC-LGAD/RSD, DJ-LGAD), matching existing read-out ASICs.
  - 2026-2028: Large LGAD sensors based on the best-performing technology.
  - 2025-2028: Investigation of radiation hardness of LGAD technology beyond $\sim 2.5 \cdot 10^{15}\ n_{eq}/cm^2$.
- **RG 2.4: LGAD sensors for Time-of-Flight applications**
  - 2024-2026: Production of LGAD sensors with large size for Tracking/Time-of-Flight applications to demonstrate yield and doping homogeneity. Study of spatial and temporal resolutions as a function of the pixel size.
  - 2026-2028: LGAD structures with 4D capabilities produced with vendors capable of large-area productions to demonstrate the industrialization of the process.

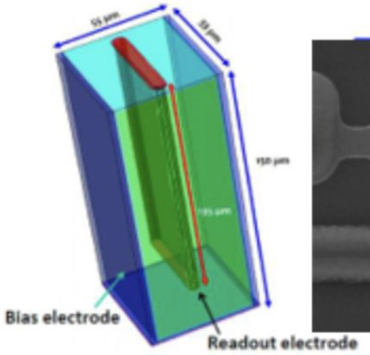


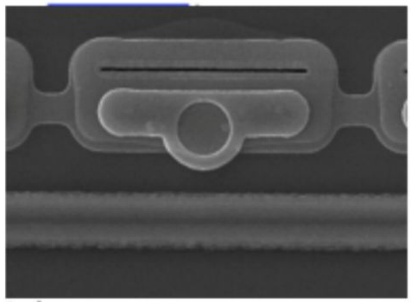
Thriving field of research for 4D detectors: LGAD pixels or strips with various processes

DRD3 WG2 - 3D sensors

- Charge collection distance decoupled from sensor thickness
- 3D sensors proven more radiation hard than planar silicon
  - Less affected by signal trapping
  - Partial depletion possible
- Currently also under investigation as timing detectors
  - Initial measurements have shown promising timing capabilities before and after irradiation
- Different collaboration projects starting
  - [Novel 3D-trench detectors produced on 8” wafers using CMOS processes]
  - [Very small pitch, ultra rad-hard 3D sensors for tracking & timing at FBK]

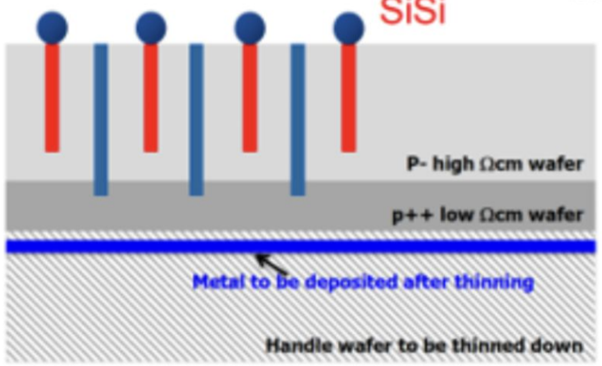




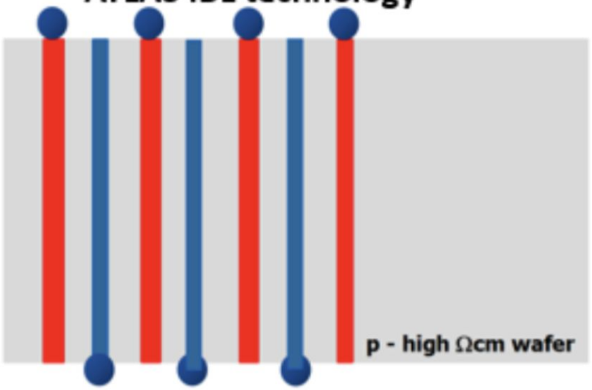


Trenched detectors for timing applications

150 µm thick
Single sided
ATLAS and CMS Phase-2 technology



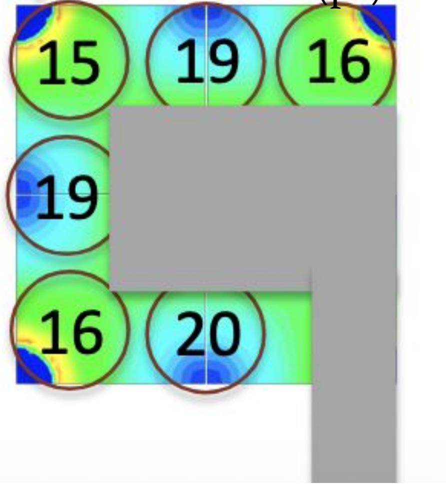
285 µm thick
Double sided
ATLAS IBL technology



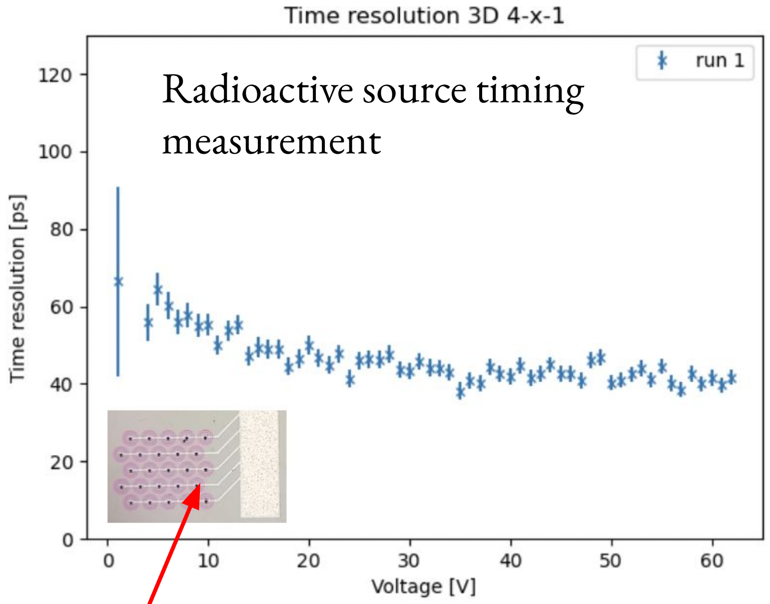
DRD3 WG2 - 3D sensors for timing

- Ongoing DRD3 project to investigate different 3D sensor layouts for timing purposes
- First batches have been manufactured and are currently measured
- Promising results - time resolutions down to 40ps for arrays
- Below 20ps time resolution in position dependent TCT measurements - average below 30ps
- First irradiation rounds planned

Position dependent time resolution (ps)

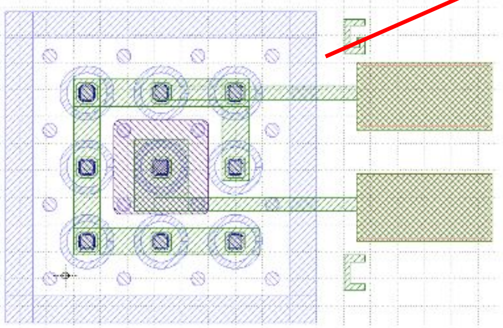


Bias Voltage: -30 V
Laser Source: IR, 50 KHz
Z Position: -1000 μm
Average Timing Resolution: 27.5 ps

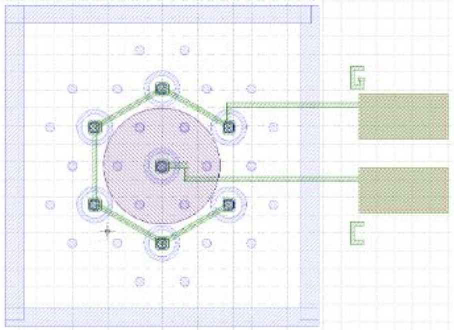


[Fabian Lex - Timing of double sided CNM 3D sensors]
[Stefano Terzo- TCT results of double sided CNM 3D sensors]

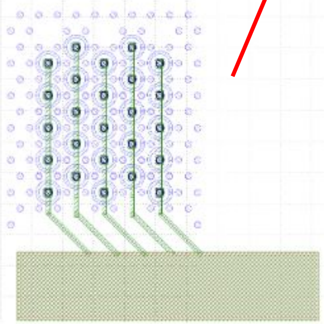
1-x



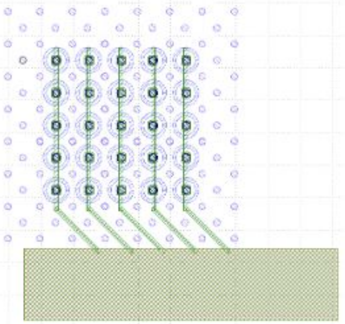
2-x



4-x



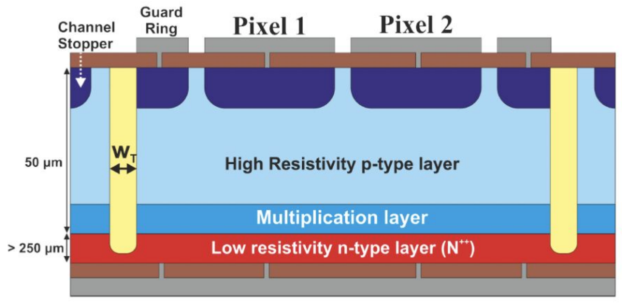
5-x



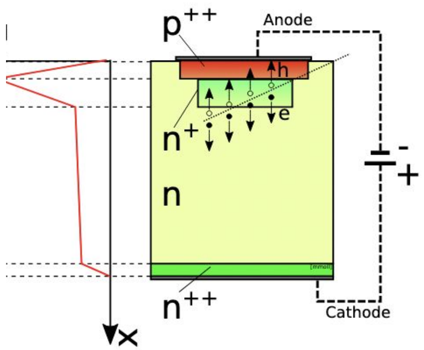
DRD3 WG2 - LGADs

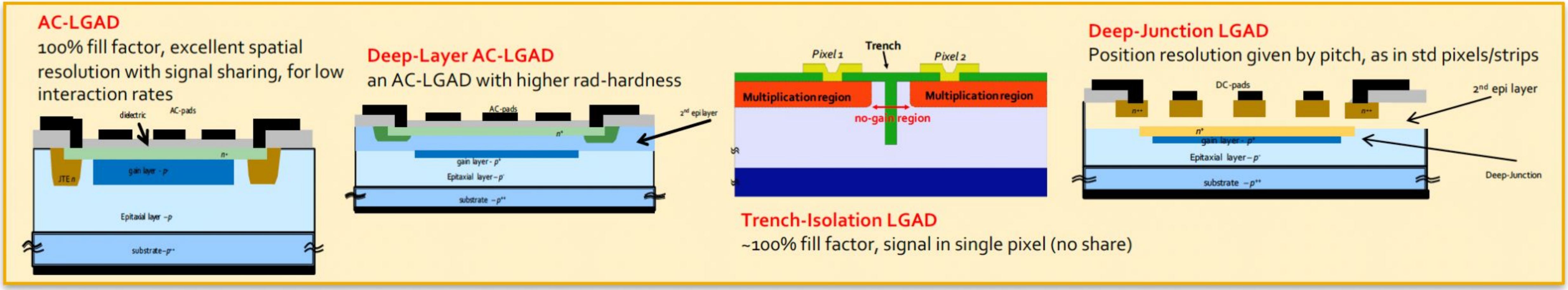
- Many different LGAD technologies are investigated
- Focusing on different challenges: Radiation hardness, fill factor, timing, large size detectors
- Several foundries in China, Europe, US and Japan
- Collaborative projects starting within the DRD3:
  - [Development of TI-LGADs]
  - [Development of Ultra-Fast-Time Low Mass Tracking Detectors]
  - [LGAD based Timing Tracker Development]

Trench-isolated inverse LGAD



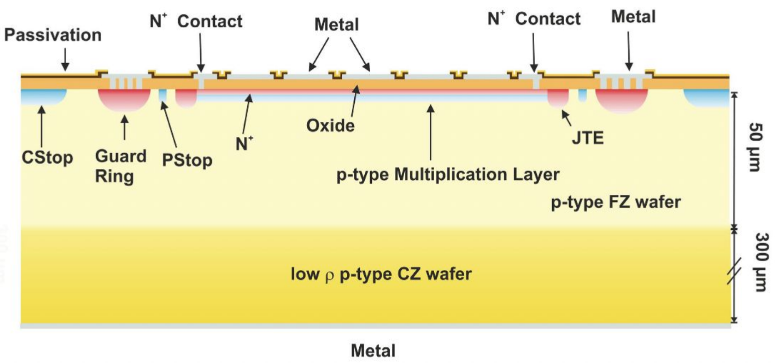
n-LGAD



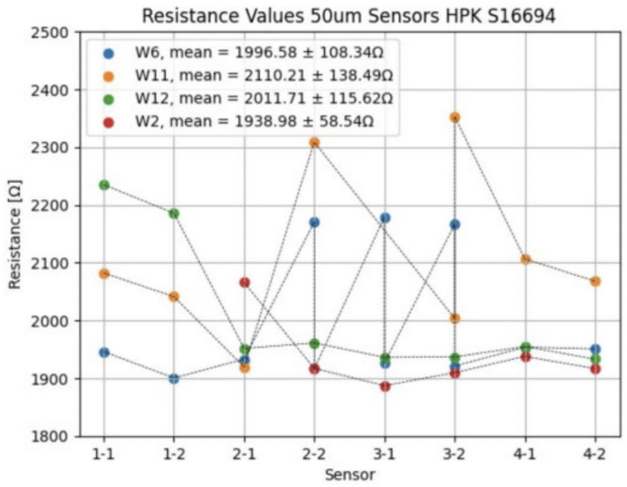


DRD3 WG2 - AC-LGADs

- Readout pads are AC-coupled, insulator layer between N+ and pads
- Continuous multiplication layer coupled with resistive N+ layer
- First large-scale AC-LGAD production from HPK
- First TCT measurements show good results - small gain variations, expected 600-700ps rise times
- Gain test show <1% variation for both 30um and 50um thick sensors
- N+ resistivity in line with HPK specs (~2kOhm)

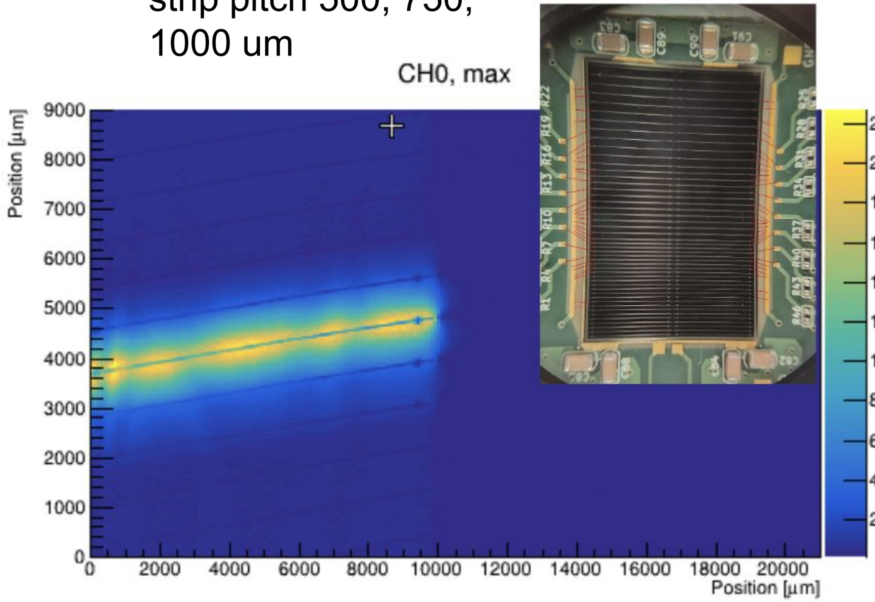


Nominal size:
3.2x2.2 cm, 1cm strip 'segments'
Strip width: 50um,
strip pitch 500, 750, 1000 um



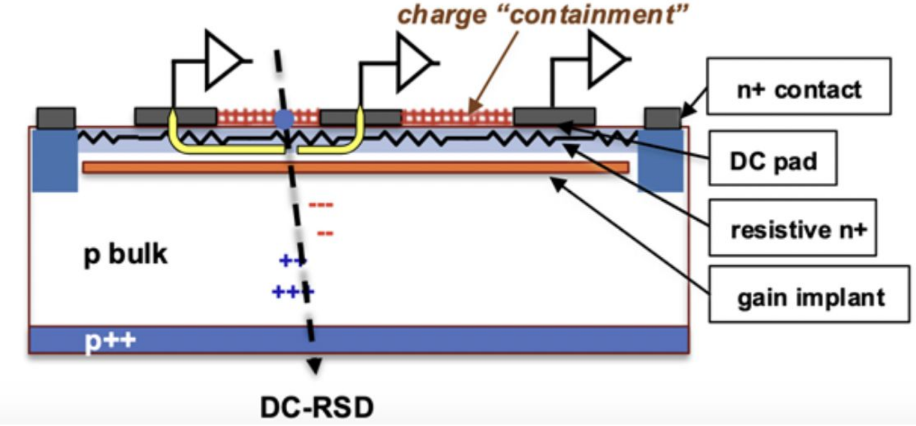
Test beam planned this year (Jlab/KEK) for full-size sensor testing and readout electronic testing

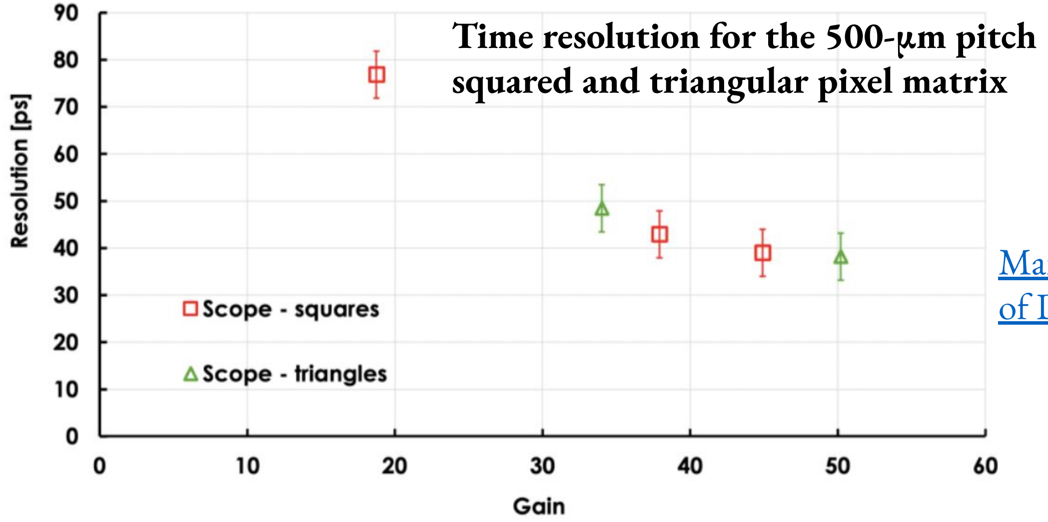
[Simone Mazza- First full-size AC-LGAD production for the ePIC detector]



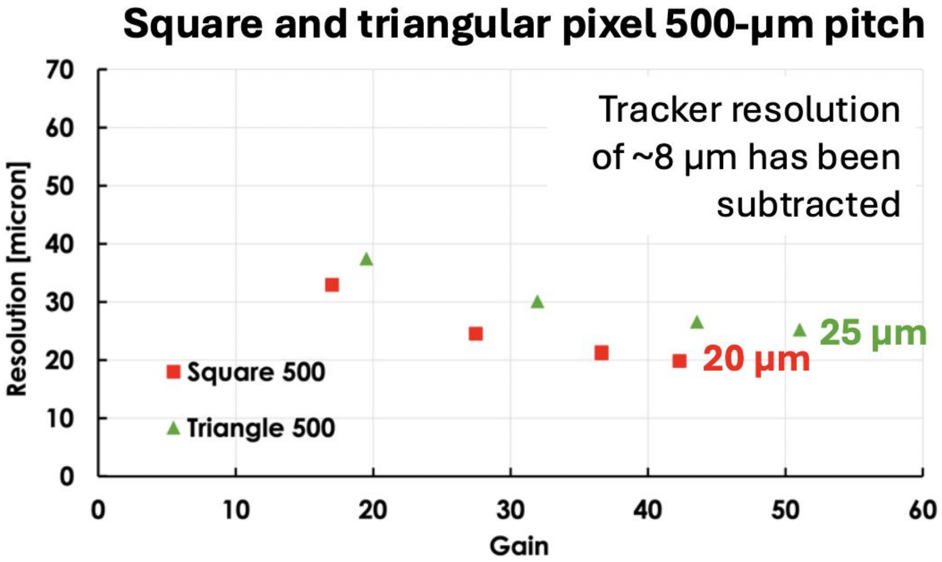
DRD3 WG2 - DC-LGADs

- DC-Resistive Silicon Detector technology is the evolution of RSD (AC-LGAD) to improve some not-ideal features like signal spread, baseline fluctuations and bipolar signals
  - Signal confined through containment structures and low resistivity paths
  - No-bipolar signal: of 1-2 ns of duration as in standard LGADs
- Trench Isolation to confine the charge sharing inside a single pixel
- Testbeam: ~99% fill factor, space resolution below 5% of the pitch
- Time resolution achieved is around 40ps



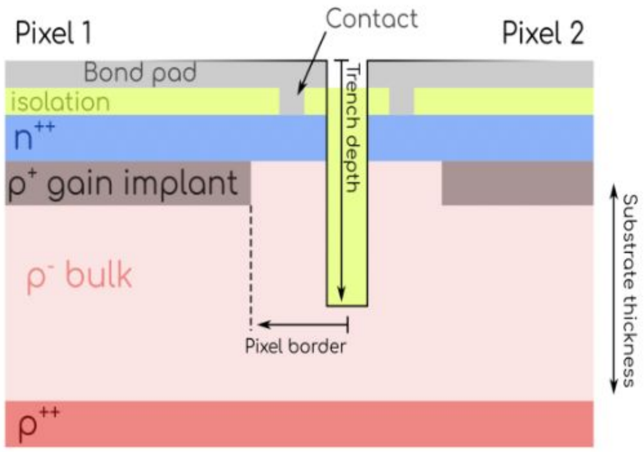


[Marco Ferrero - First production of DC-coupled RSDs]()



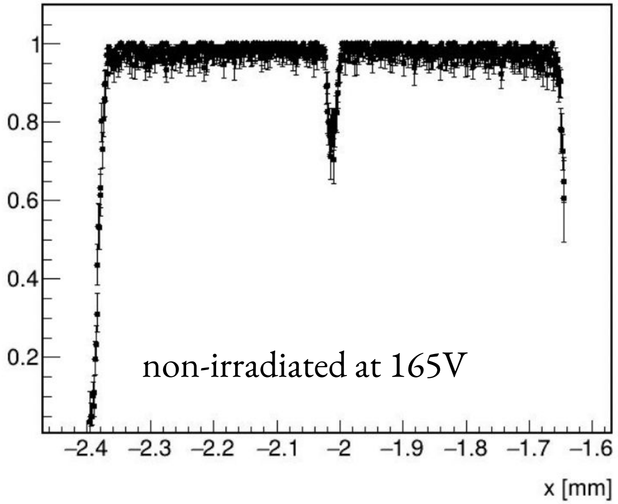
DRD3 WG2 - Trench-Isolated-LGADs

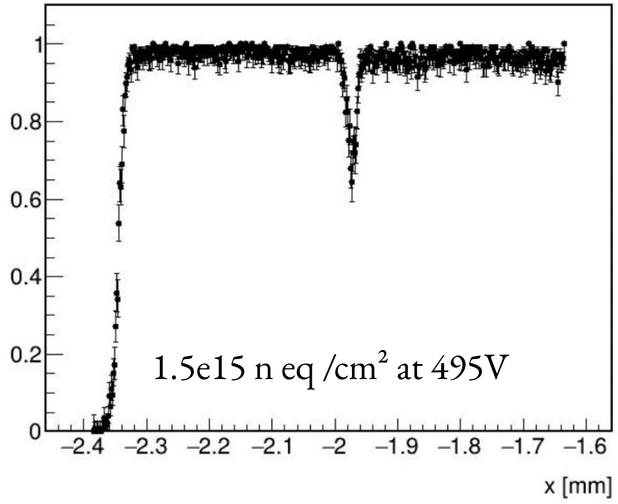
- Collaboration project among 19 institutes
- Two productions completed at FBK
- Variations of trenches (1 or 2), trench depths, carbon co-implantation and pixel border tested
- Goals:
  - Inter-Pixel distance of a few microns (<5 μm)
  - Radiation hardness of TI-LGADs up to a level of 3×1015 neq/cm2
  - Time resolution per hit around 30-40 ps
  - Industrialisation of the process



- Test beam shows a mean tracking efficiency of
  - (98.61 ± 0.06)% (stat only) before irrad.
  - (97.68 ± 0.08)% (stat only) after irrad.

Single trench, pixel size of 375μm x 250μm, 45μm thickness

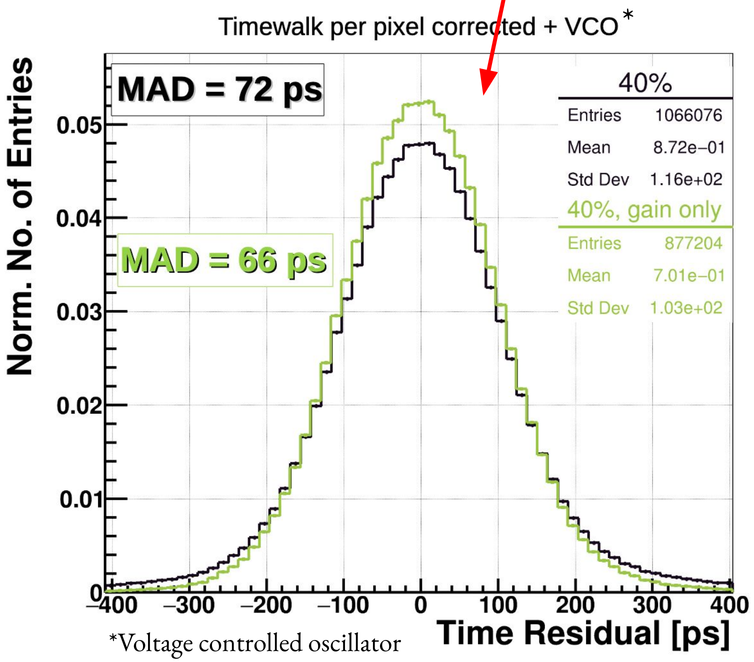




[Antonio Gómez Carrera - Performance of irradiated TI-LGADs]

DRD3 WG2 - Trench-Isolated-LGADs

- No dedicated timing measurement run yet - still achieved resolutions below 40ps after a fluence of 1.5 n_{eq}/cm^2 in testbeam
- Second testbeam campaign with the Timepix4 readout ASIC to measure time resolution including a readout chip



*Voltage controlled oscillator

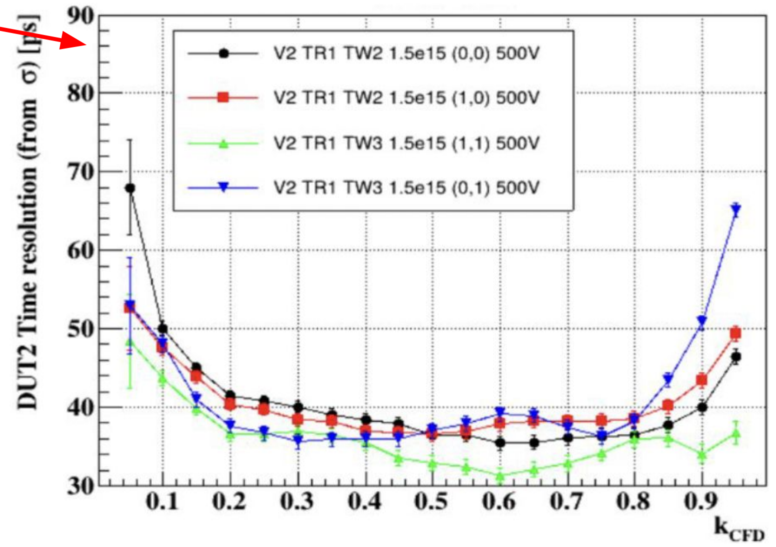
Contributions to the achieved 98 ps time resolution:

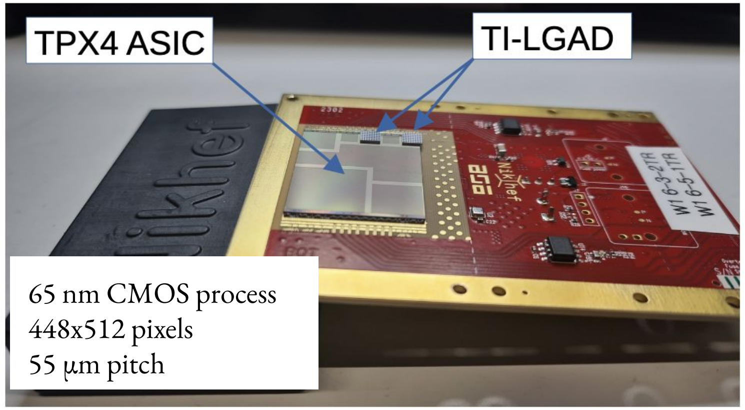
- Time to digital converter
- Clock distribution
- Analog-Front-End
- Sensor

Improving the readout electronics is a major factor to achieve ps timing

$$\mathrm{MAD} = \mathrm{median}(|X_i - \bar{X}|) \xrightarrow{\text{Gaussian distribution}} \sigma = 1.4826 \cdot \mathrm{MAD}$$

Fluence = 1.5e15 (V=500V)





65 nm CMOS process
448x512 pixels
55 µm pitch

[Uwe Kreamer - TI-LGADs on Timepix4]

DRD3 WG2 - Readout challenges

- ASICs for HL-LHC Timing detector (pitch of 1.3 mm x 1.3 mm):
  - ATLAS HGTD ALTIROC chip in 130 nm CMOS
  - CMS ETL ETROC chip in 65 nm CMOS

- From the ECFA Roadmap: Technology Choice
  - Adopting the 28 nm CMOS technology as a “mainstream” process will help with the developments of future experiments
  - A few chips are being developed at the moment for 4D tracking:
    - Ignite and PicoPix, focused on LHCbVELO upgrade in 28 nm CMOS
    - EICROC for ePIC detector at EIC in 130 nm CMOS
    - Fermilab’s FCFD for 4D trackers in 65 nm CMOS Etc.
- Collaboration with other DRD3 working groups to contribute to collect requirements for future ASICs

Conclusions

- Broad scope of research towards 4D tracking detectors for future colliders
  - Newly starting projects as well as established research campaigns as presented

- Collaborative efforts to maximise the available resources, equipments and capabilities
  - Including shared irradiation runs, testbeam campaigns and readout chip development

- The DRD3 WG2 studies many variations of LGADs - both for 4D tracking as well as ToF detectors, as well as 3D sensors for timing purposes and precise tracking in high radiation environments

- WG2: 46 institutes from 15 countries and 3 continents (Europe, US, Asia and South America)

  - We welcome more - contact us to join!
  - Expression of interest:
    https://drive.google.com/drive/folders/1vQMFIwzgQ33M7aJ1KxKt9Ye4B5Lz1Xj8?usp=sharing