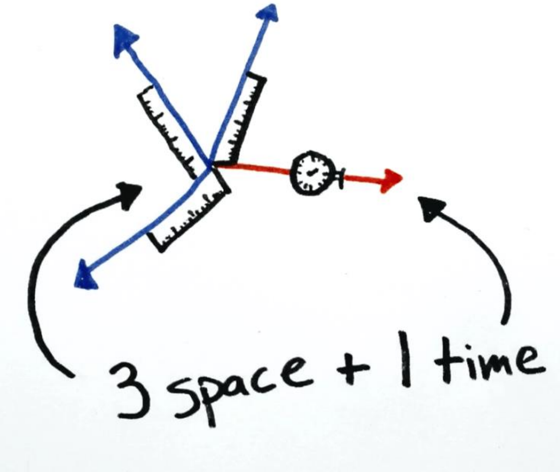
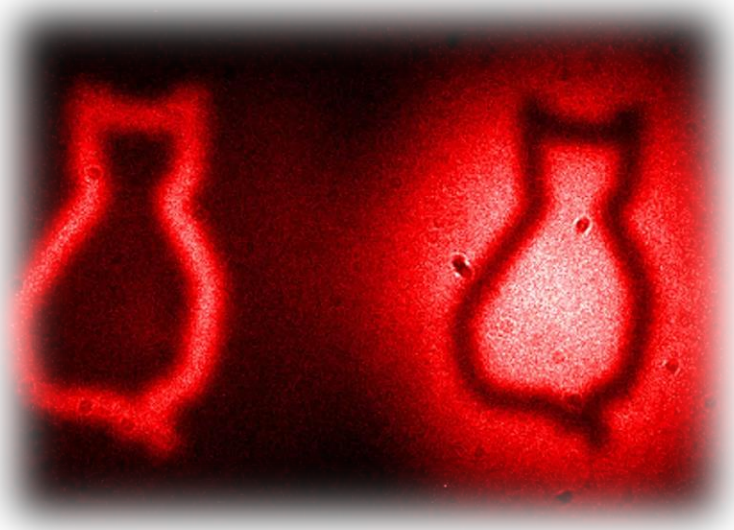
Activities at IFCA for Solid State detectors (DRD3)

Instrumentation for the future of particle, nuclear and astroparticle physics and medical applications in Spain

March 6th, 2023





Instituto de Física de Cantabria

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CSIC
Consejo Superior de Investigaciones Científicas
UC
Universidad de Cantabria

Outline

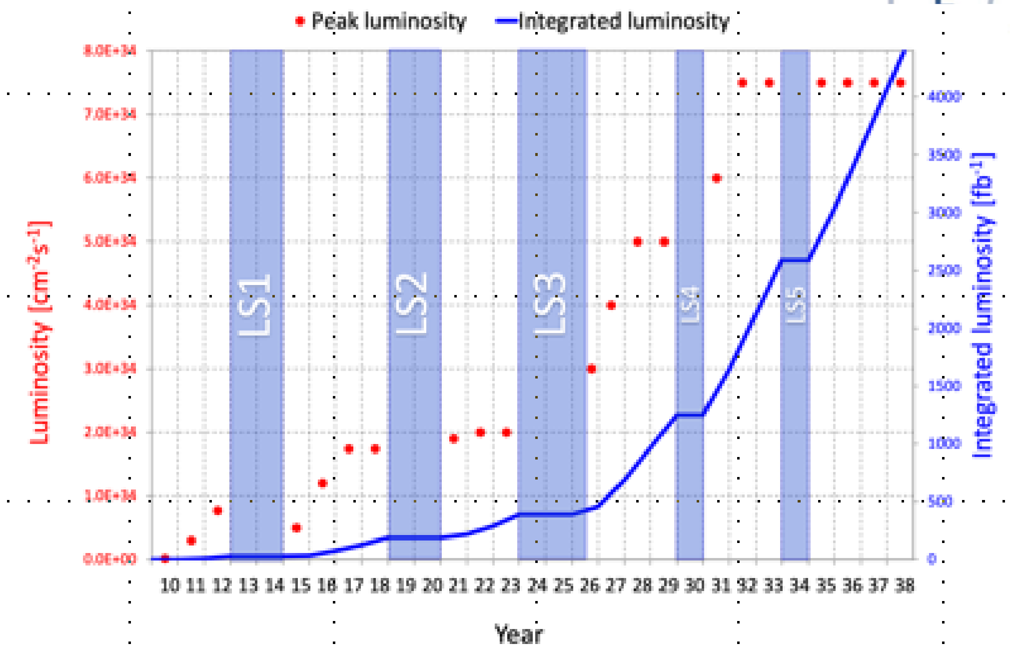
- **Group background: experiment-oriented R&D**
  - Inner Tracker and End Cap Timing layer subdetector at CMS.
- **Generic R&D activities**
  - Enabling technologies for 4D tracking
  - Advanced semiconductor characterization techniques.
  - Wide-bandgap semiconductors.
- **Generic R&D expected impacts (by fields)**
  - Nature of universe:
    - Detectors for future collider experiments.
    - Quantum imaging of dark matter (DRD5 connection)
  - Civil engineering:
    - Muon tomography for health structural monitory.
  - Radiation therapy:
    - In-vivo and High Rate Dosimetry.
- **Outlook**

Group background: experiment-oriented R&D

– Inner Tracker and End Cap Timing layer subdetector at CMS

High-Luminosity upgrade of the CMS experiment

- The high-luminosity phase of the LHC (2027-38) will increase up to a **factor of eight the original peak luminosity** of the LHC and will **multiply by ten the integrated luminosity** at the end of run 3.
- **Radiation tolerance** (2x1016 n/cm2 and 1 Grad) requires the installation of a new vertex detector (IT)
- **Disentangling the multiple collisions** (about 200) within a LHC bunch crossing requires precise time stamping of MIP particles (around 30 ps). A dedicated timing detector to be built (MTD)



- Manufacturing and qualification of 3D sensors for innermost layer of IT
- Design of power distribution system and EMC + grounding studies of IT
- HDI design and RD53 Readout ASIC power stage design and QA of IT
- Inner Tracker module assembly.
- **Inner Tracker sensor group convenorship since 2018**
- Manufacturing and qualification of LGAD sensors for Endcap Timing Layer
- ETL module assembly
- **Detector Physics Group convenorship since 2018**

Centro Nacional de Microelectrónica CSIC

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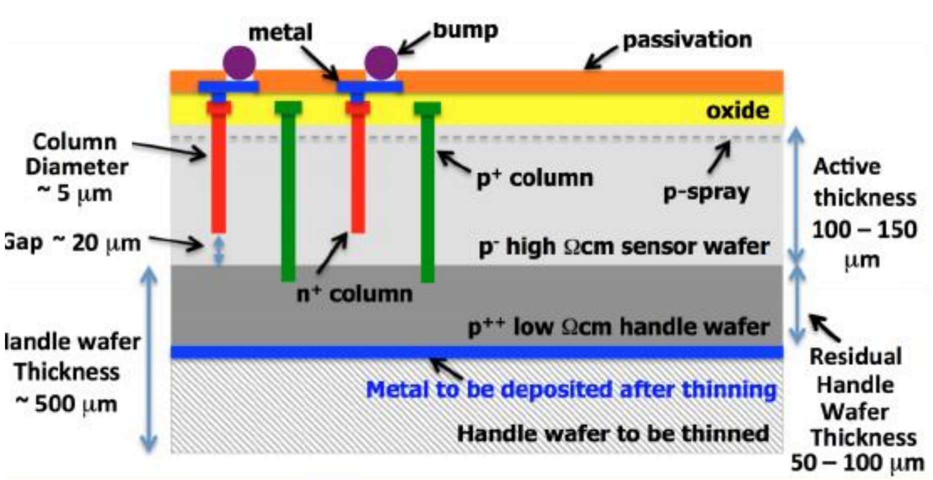
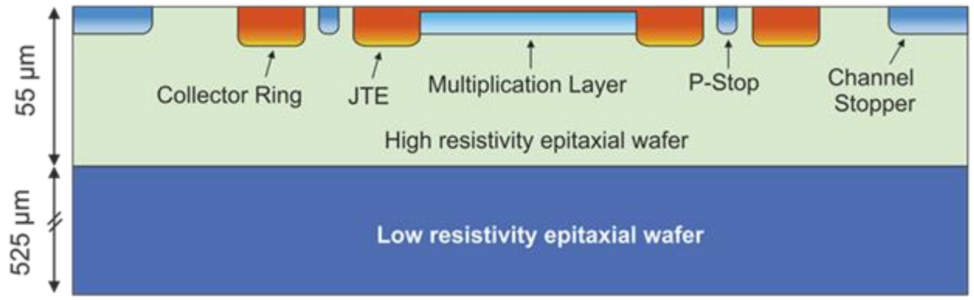
IFCA Instituto de Física de Cantabria

Baseline sensor for the Innermost layer of the IT & the End-Cap Timing layer





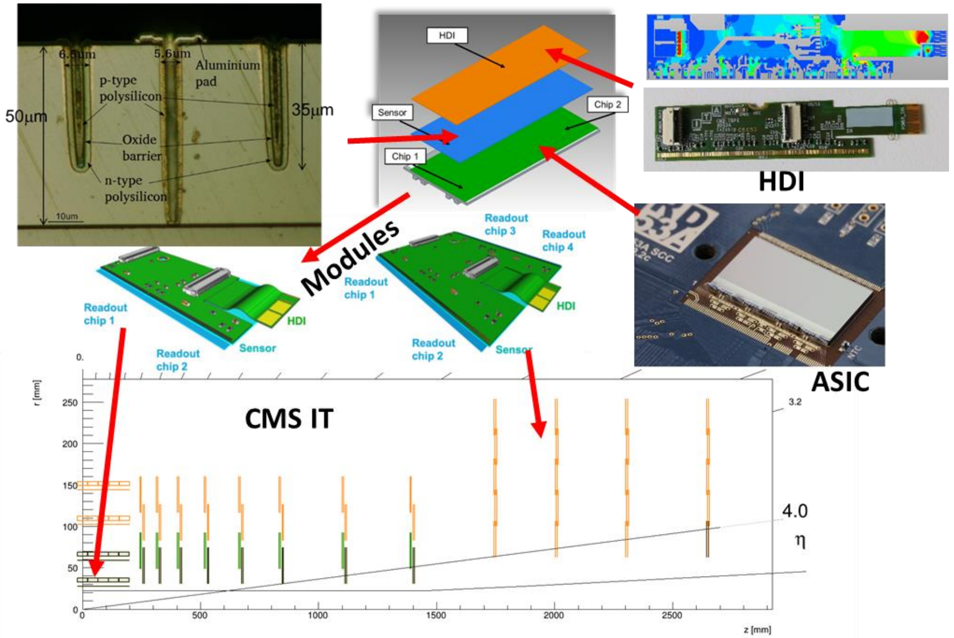
- Reduced distance between electrodes reduces the chances of carriers to get trapped in radiation-induced trap centers and allows for a much smaller bias voltaje to achieve a similar drift electric field, compared with conventoinal planar pixel sensors.
- Smaller bias implies smaller **power disipation**.
- No thermal runaway for 3D sensors after Runs 4 +5 in L1

- End Cap timing detector based on LGAD detector (8m^2)
- Punch-through avalanche diode architecture sensor with moderated gain (LGAD) provides 30 ps resolution per hit (before irradiation)

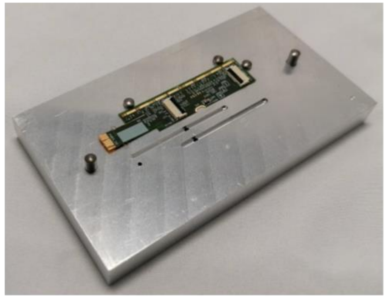
R&D on sensors is over: assembly of IT and ETL modules at IFCA

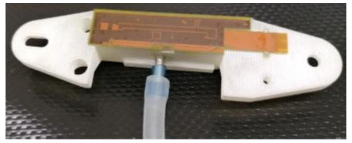
IFCA aims to assemble:

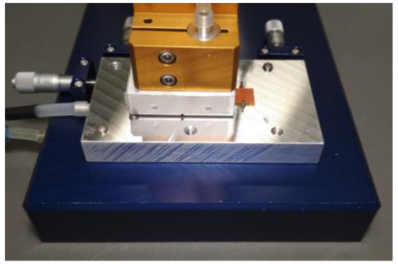
- **~ 50 TBPX L1 1x2 modules** (half of TBPX L1): ITAINNOVA 1x2 HDI with CNM and FBK 3D sensors
- **~ 300 TEPX 2x2 modules** (planar sensors)
- (TFPX mostly a USA project)

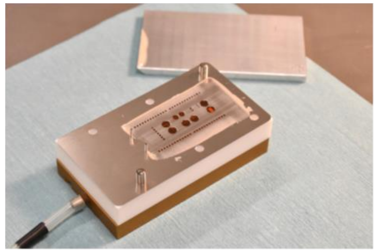


- **Duplicated size of IFCA clean room**
- **Acquired semi-automatic wire-bonding machine**
  - ~ 200/400 wire bonds between HDI and CROCs for double/quad modules
- **Precision mechanics and jigs fabricated**
- **Different glue deposition methods under study**
  - SMD stencil, glue stamp…
- **Starting to gain experience now**
  - Using RD53A-based double and quad modules
- **Robotized solution envisaged for**
  - Pick and place, alignment, glue deposition









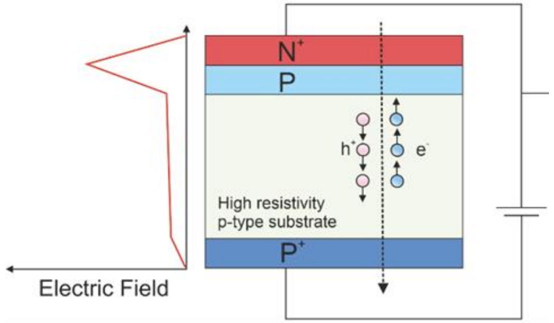
Generic R&D activities

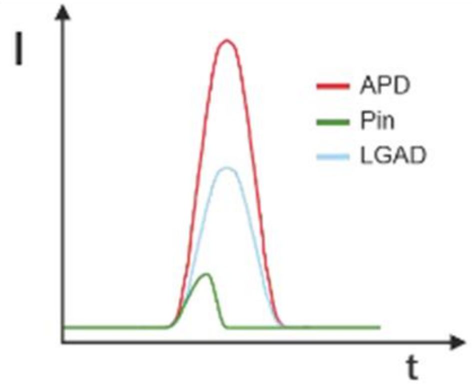
- Enabling technologies for 4D tracking
- Wide-bandgap semiconductors.
- Advanced semiconductor characterization techniques.

4D-tracking : timing with LGADs – State-of-the-art in a nutshell

- The Low Gain Avalanche Detectors (LGADs), introduced in HEP by the Institute of Microelectronics of Barcelona (IMB-CNM) about 10 years ago, is the most promising Time and Position-Sensitive Detector (TPSD) to implement the 4D tracking concept.
- LGAD is the baseline technology of the endcap MIP timing detector for the HL upgrade of Atlas and CMS experiments. Provide about 30ps MIP time stamping for disentangling between the different interaction vertices.
- Main challenges (and solutions)
  - **Radiation tolerance to (mostly) neutrons and protons:**
    - **Damage Mechanisms:** primary carriers trapping, acceptor deactivation, mean-free-path reduced, electric field modification,
    - **Solutions proposed:** Thin bulk, co-doping with Carbon, half-activated gain layer, compensated doping, deep multiplication layer.
    - **Current status:** radiation tolerance up to 2 e15 n/cm2 achieved (conservative bound).
  - **Long-term reliability:**
    - Damage mechanism: very rare highly ionizing events induce fatal diode breakdown (also in PINs @ very high HV)
    - Solution: limited average E field (< 12V/um).
    - Current status: fatal damage mechanism understood and implementation of maximum voltage bias.
  - Large scale **manufacturing yield (99.9% of good pads required).**
  - Increase **fill-factor and increase the granularity**

Towards a 4-D tracker system



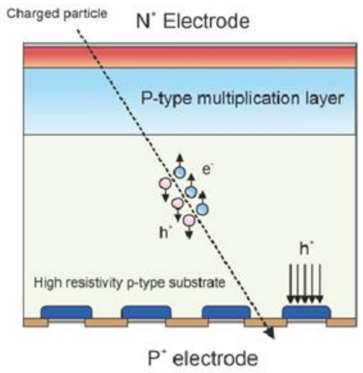


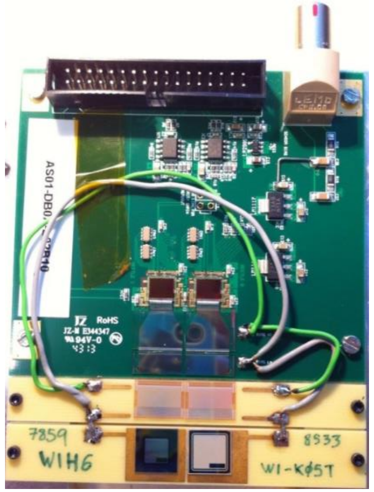
Enabling Technologies Towards a LGAD-based 4D tracker

- Inverse Low Gain Avalanche Detectors (**ILGAD**) manufactured by IMB-CNM and FBK.
- Resistive AC-Coupled LGADs (**AC-LGADs**) manufactured by IMB-CNM, FBK, IME-IHEP, BNL, HPK,…)
- Trench-isolated LGADs (**TI-LGAD**) Manufactured by FBK.
- Deep Junction Low Gain Avalanche detectors (**DJ-LGAD**) manufactured at BNL
- **Thin Inverse Low Gain Avalanche detectors (Trench-iLGAD) by IMB-CNM** ⇐ Our Interest

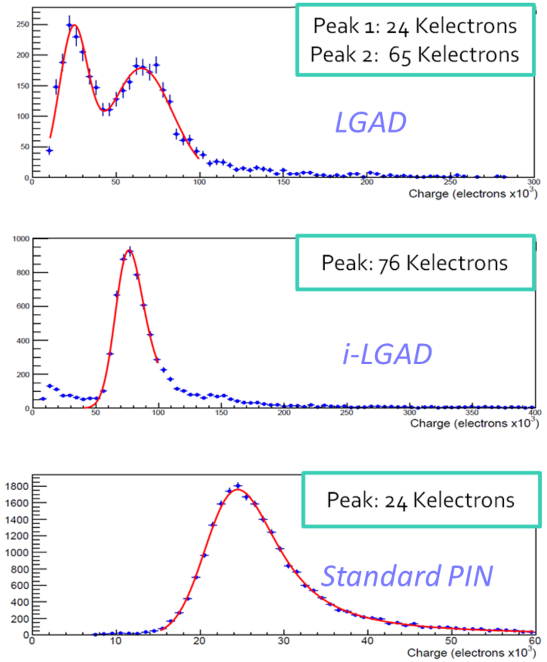
Inverse LGAD (iLGAD) – State-of-the-Art

- Continuous multiplication layer (100% fill factor), segmented ohmic contact, hole recollation.
- 2018 proof-of-concept 80 μm strip prototype (IMB-CNM) demostrated by IFCA **for MIPs** (no time readout).
- 2023 25x25 μm^2 pixel sensor prototype (FBK) demonstrated by PSI for **soft X-rays** detection (no time readout).
- No other candidate sensor tehcnology for 4D tracking has achieved this level of maturity.

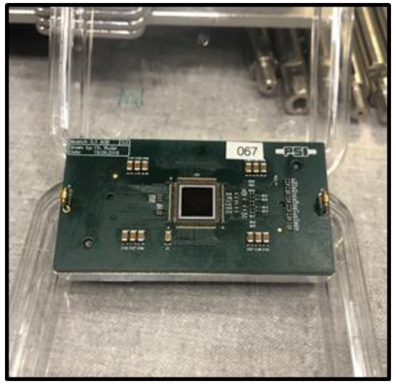




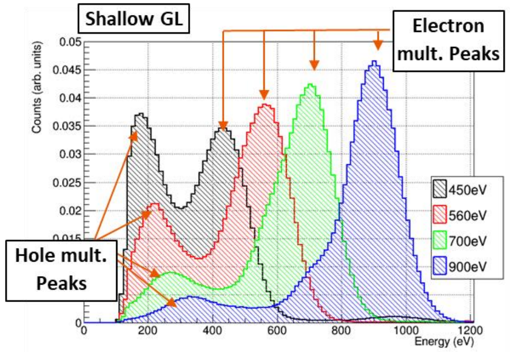
I. Vila, 13th Trento Workshop, February 2018



Gain Spatial Uniformity: Collected Charge



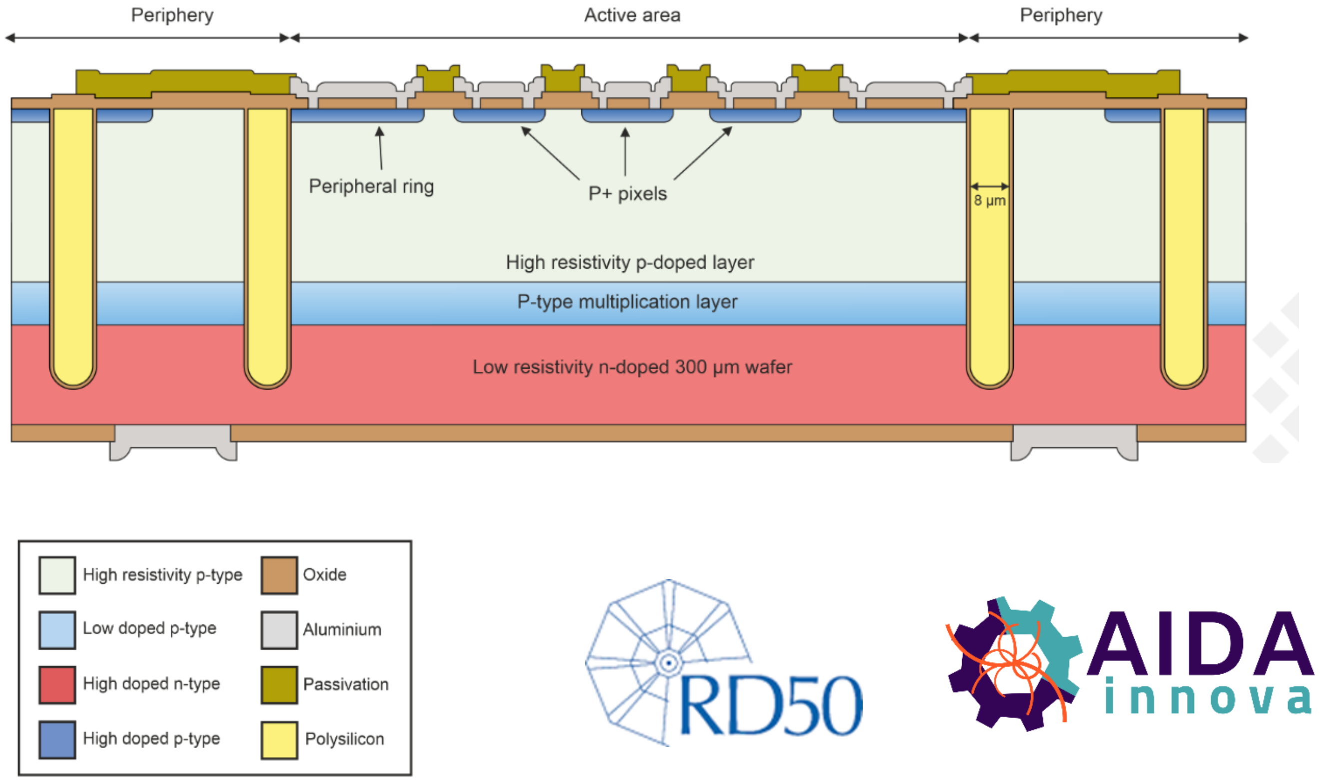
Pixelated iLGADs ($25\mu m$ pitch) charge integrating Mönch readout

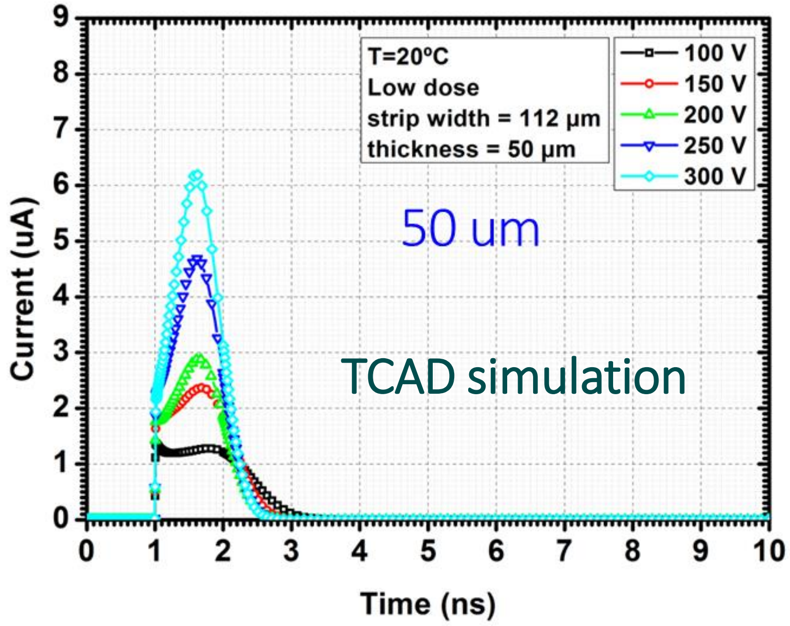


Antonio Liguori , 18th Trento Workshop, February 2023

iLGAD for timing: Trench - Inverse LGAD (T-iLGAD)

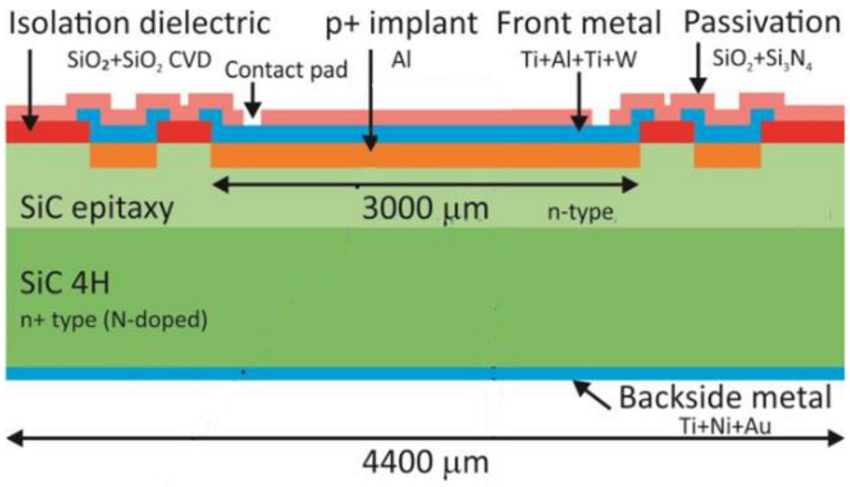
- Thin active region in a single-sided process, currenlty under production at IMB-CNM.
- Timepix3 (RD50) and Timepix4 (AIDAInnova) layouts.

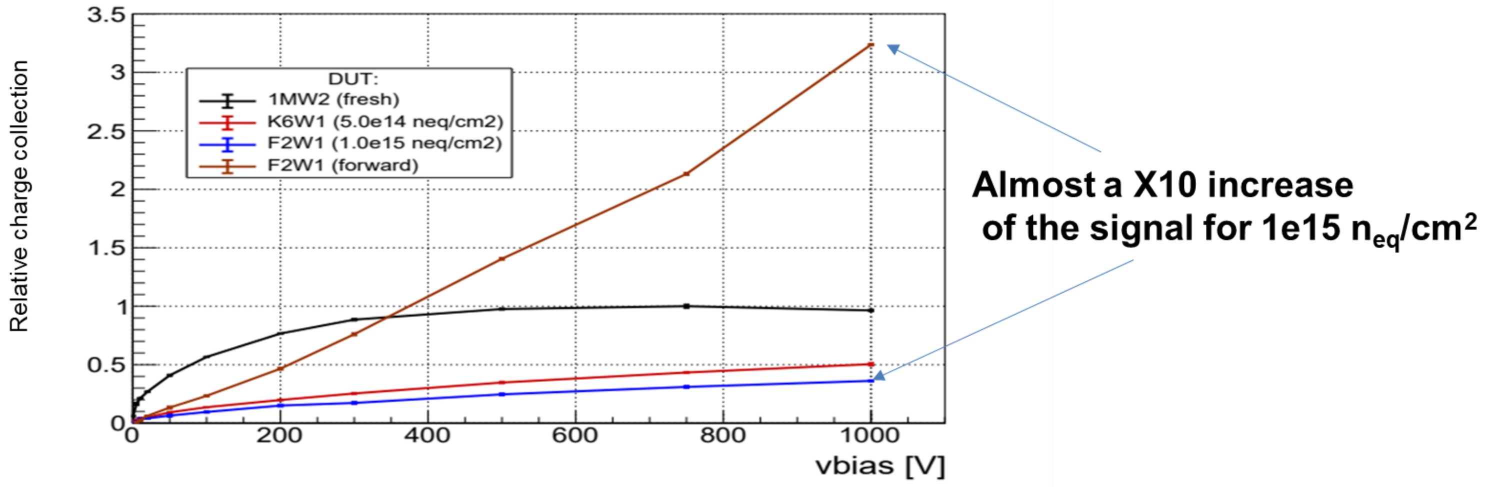




Wide bandgap semiconductors (SiC)

- Wide-bandgap semiconductors insensitive to temperature (no termal generated current).
- High irradiated diodes can be operated without cooling.
- SiC becoming a mainstream semiconductor material.
- Dedicated irradiation study with p-in-n diode manufactured at IMB-CNM.



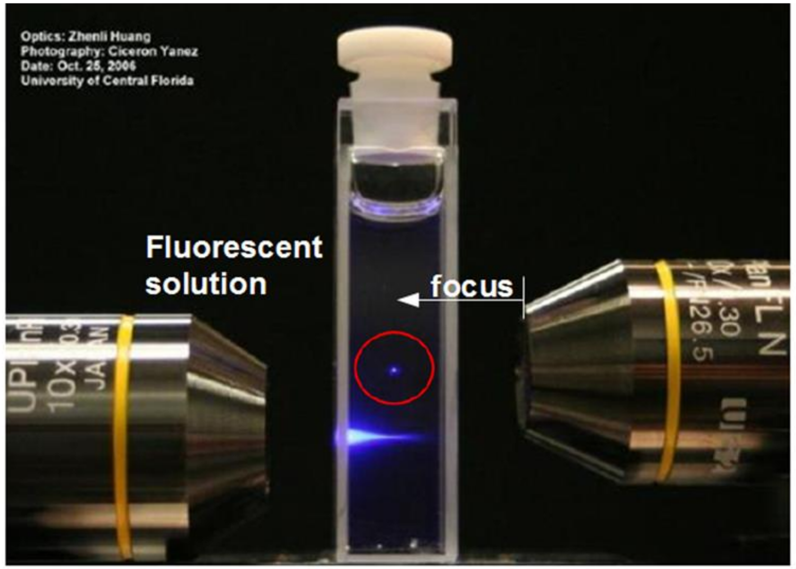


Advanced Semiconductor characterization techniques: TPA-TCT

The TPA electron excitation is more likely in high irradiance regions (near the laser focus). Enabling the localized photo-generation of free carriers

Single Photon Absorption

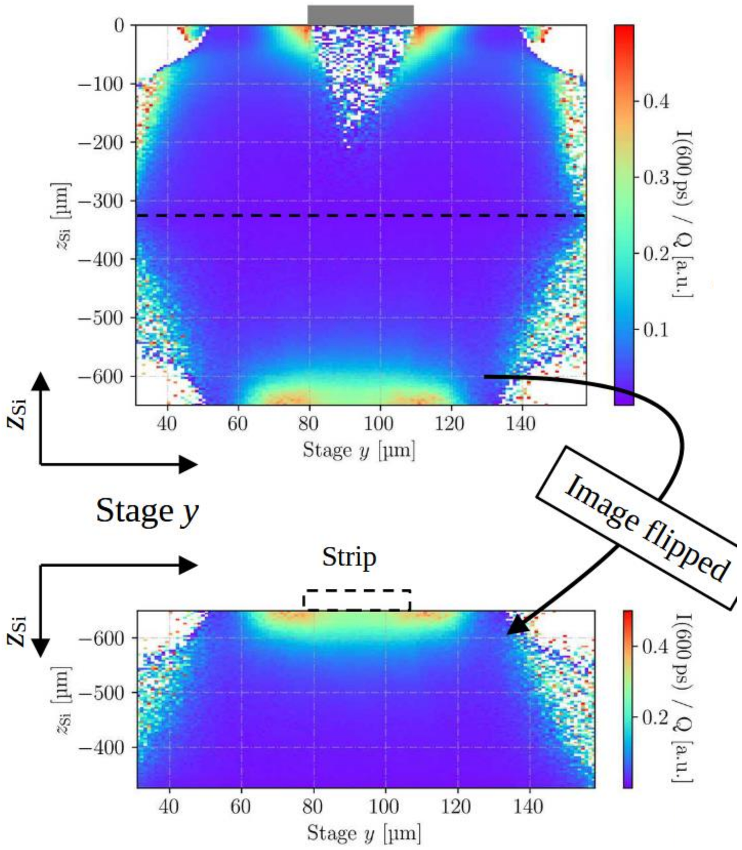
Continuous energy deposition



Two Photon Absorption

Energy confinement
Two photons from left objective

TPA-TCT is a way to **generate very localized electron-hole pairs** in semiconductor devices (microscale volume).



Electric field mapping of a microstrip detector

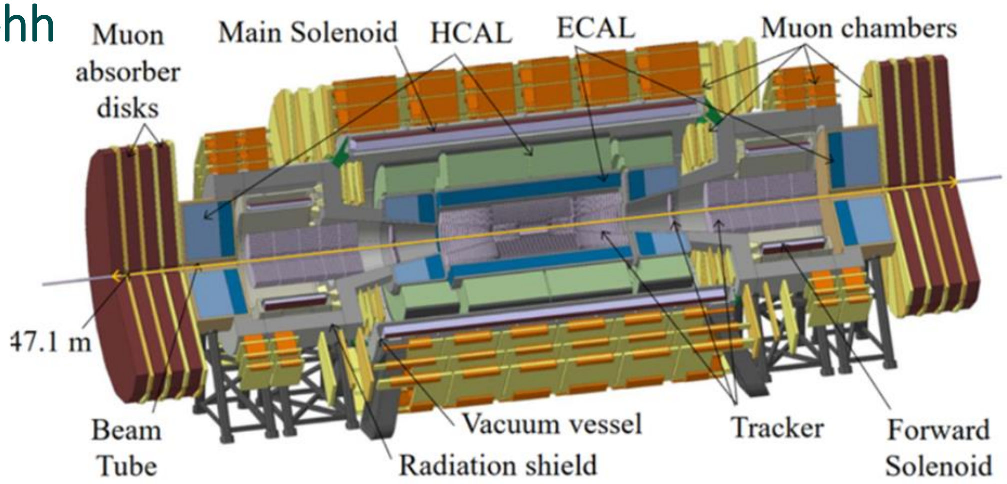
Generic R&D Impacts (by fields)

- Nature of universe:
  - Detectors for future collider experiments.
  - Quantum imaging of dark matter (DRD5 connection)
- Civil engineering:
  - Muon tomography for health structural monitory.
- Radiation therapy:
  - In-vivo and High Rate Dosimetry.

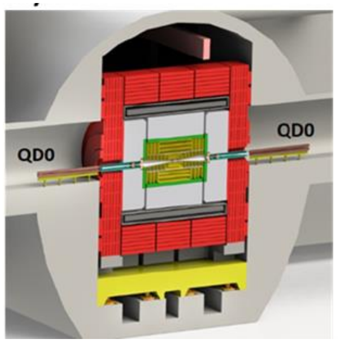
R&D Impact: Advancing scientific knowledge

Future collider experiments

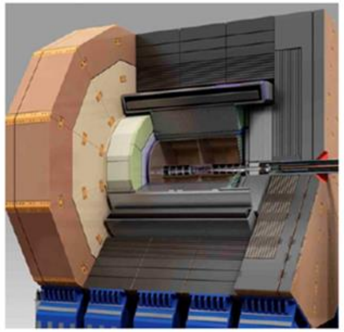
FCC-hh



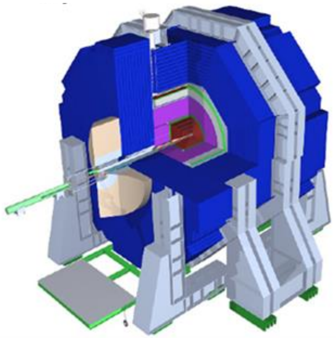
CLIC



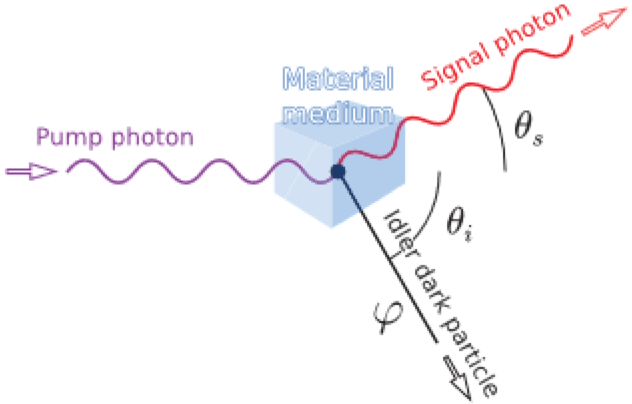
ILD

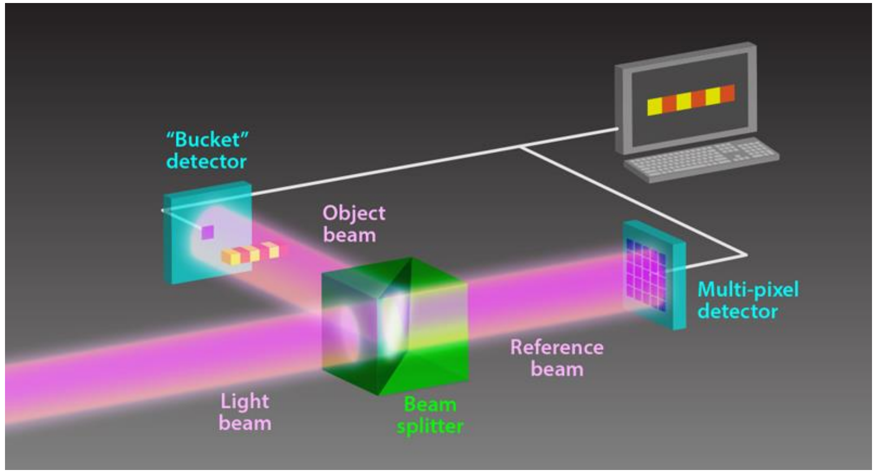


SiD



Quantum imaging of dark matter





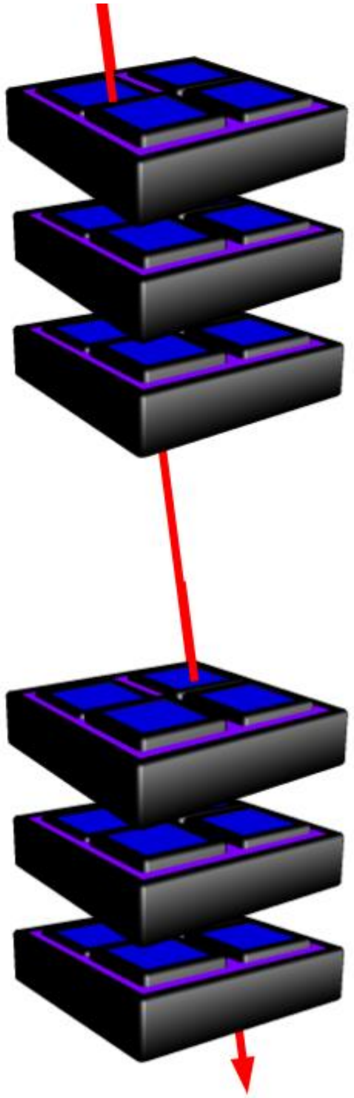
R&D Impact: civil society

Muon Tomography (LGAD)

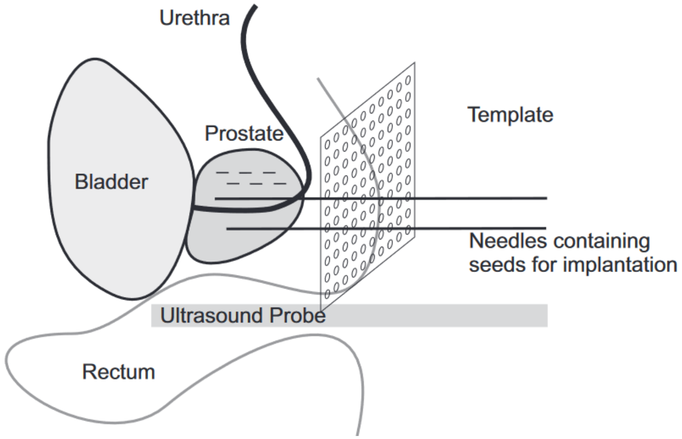
Optimization and fabrication of LGAD sensors for technology demonstrator of the Timing Muon Tomography Concept

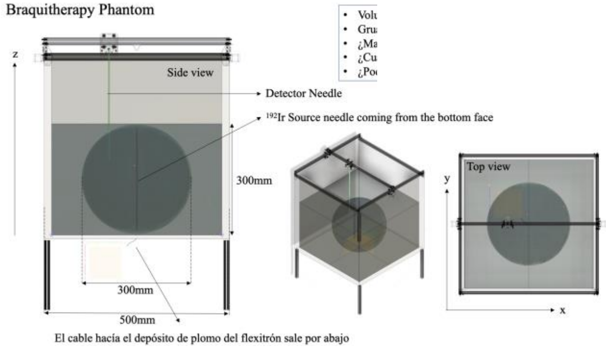
Integration and experimental validation of a technology demonstrator of the Timing Tomography Concept

Distributed Clock network and power distribution system design for the technology demonstrator othe Timing Muon Tomography Concept



High-dose rate Braquytherapy and prototherapy (SiC diodes)





IFCA Spanish DRD network

See G. Rius tomorow's talk

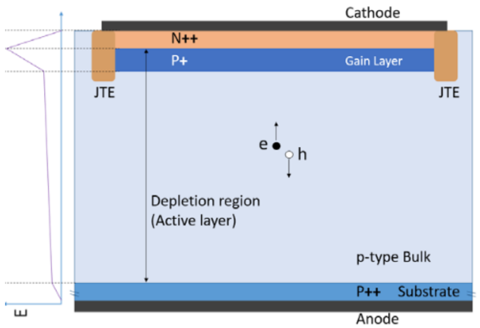
Outlook

- IFCA researchers shaping the new DRD3 collaboration (as members of the RDR3 preparatory team). Aiming to keep the good thing of previous RD50 collaboration avoiding too much administrative overhead.
- Under preparation, less defined, contribution to the DRD5 quantum workshop.
- My whish list, in a local perspective and within the reach of the community without changing the current administrative framework:
  - A Spanish network on detector R&D will enhance the impact of the groups activities (à la CPAD in USA).
  - Collaborative projects focused on specific R&D topics (Ex. TimeSpot type of projects by INFN).

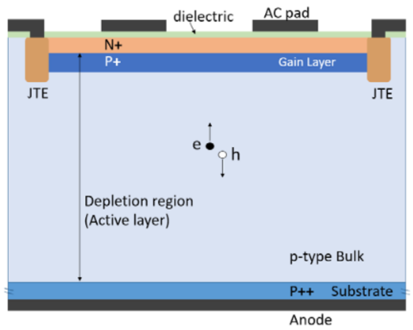
THANK YOU FOR YOUR ATTENTION

Resistive AC-Coupled Silicon Detectors

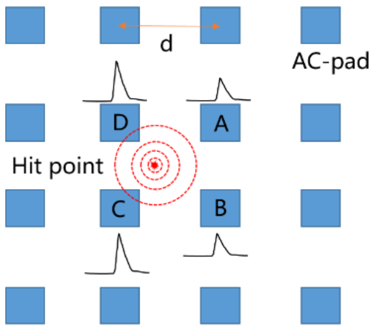
- Resistive readout of Si strip detectors first proposed by Radeka in 1974 (IEEE Transaction on Nuclear Science NS-21 (1974) 51)
- Feasibility studies on the Resistive DC readout for a **linear collider** tracker were carried out by J. K. Carman, et al in 2011 (NIM A 646 (2011) 118)
- 1D Resistive AC coupled microstrip as tracking sensors for the **linear collider** were introduced by IMB-CNM (D. Bassignana et al., 2012 JINST 7 P02005)
- 2D Resistive AC coupled readout in LGAD introduced by FBK (M. Mandurrino et al., IEEE Electron Device Lett. 40(11) (2019) pp.1780-1783.):
  - Non-segmented LGAD gain layer; segmented electrode on top of a dielectric layer .



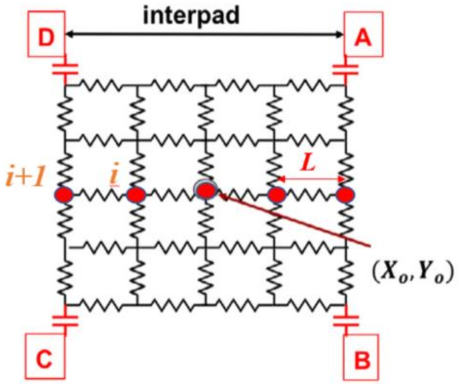
LGAD (Low-Gain Avalanche Diode)



AC-LGAD (AC-coupled LGAD)



AC-pad layout scheme

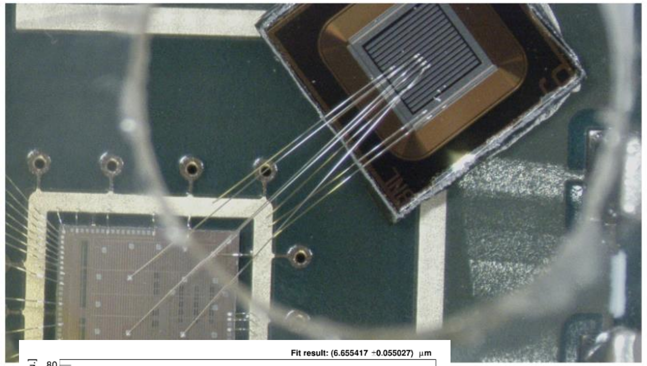


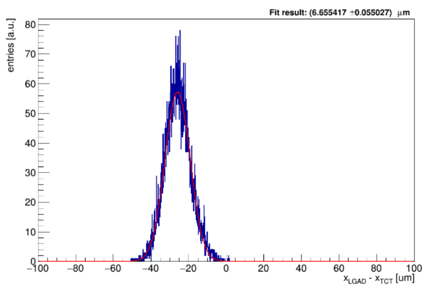
Mengzhao Li, 39th RD50 Workshop, Nov 2021

- Hit position reconstruction algorithm based on charge sharing among the electrodes (Smarter ML algorithms possible) achieve sub-pitch hit resolution figures.
- Timing resolution improved by multiple electron readout. Not as simple as sqrt of # of electrodes improvement due to correlations)
- Advantages:
  - 100% fill factor
  - high spatial resolution for large pitch devices.
- Limitations:
  - Hits on top of the electrode with do not have charge sharing (resolution degraded to the electrode size).
  - Maximum hit occupancy one hit / electrode pitch.

Resistive AC-Coupled Silicon Detectors (2)

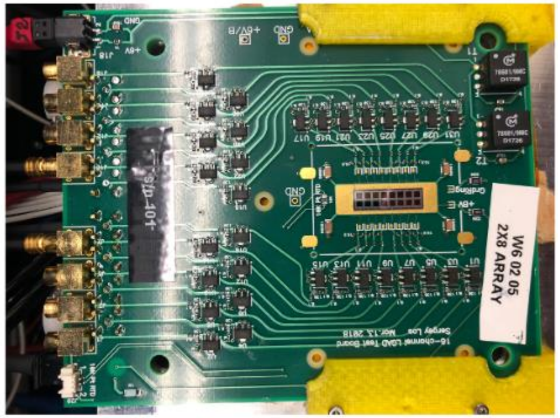
- Beyond the proof-of-concept limitations.
- 16 strips, pitch 100 µm, gap 44 µm
- Central and neighbouring strips wire bonded to the four input channels on the ALTIROC ASIC (Atlas HGTD ROC)
- Strips chosen to be far from the device guard-ring to minimize border effects Lateral strips on their left and right are wire-bonded to the same ground as the ASIC
- Second prototype bonded to dedicated discrete front-end amplifier board from Fermilab + fast digitizer.
- **Test beam studies** of second prototype



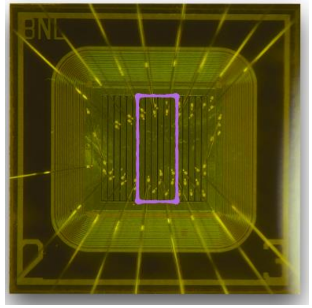


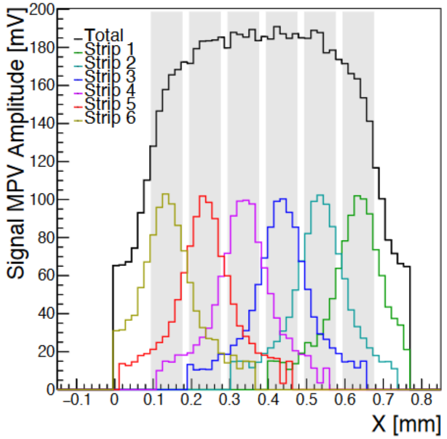
G. D'Amen, C. Madrid, 39th RD50 Workshop, Nov 2021

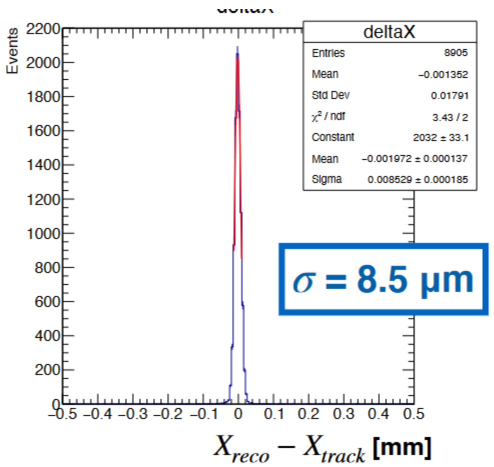
Interstrip spatial resolution estimated with laser TCT setup. Estimated resolution of 6 um.



16-ch sensor LGAD on Fermilab readout board







Timing resolution between 30 and 40 ps

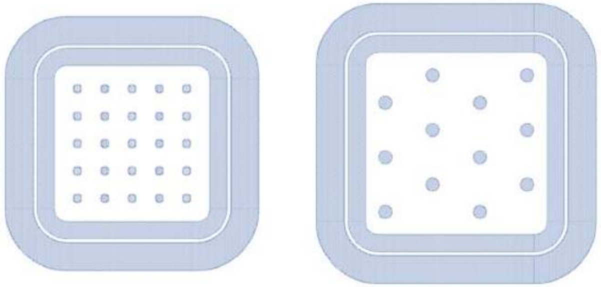
Discontinuities are observed where the relative fraction is large or when we get direct hits to the strip

Resistive AC-Coupled Silicon Detectors (3)

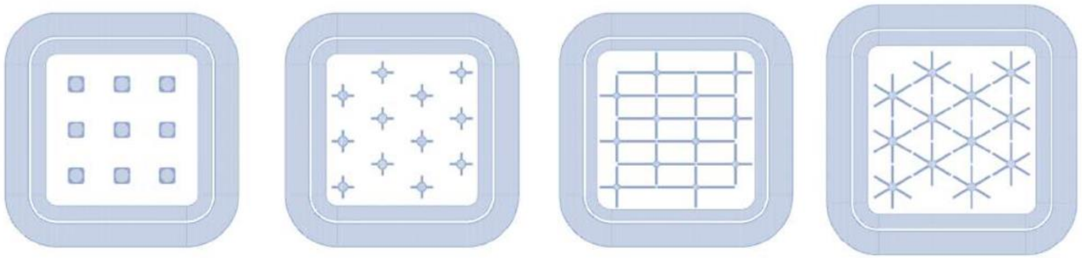
– Moving beyond the current technology limitations: trade off between signal detection efficiency and electrode area.

M. Mandurrino, 39th RD50 Workshop, Nov 2021

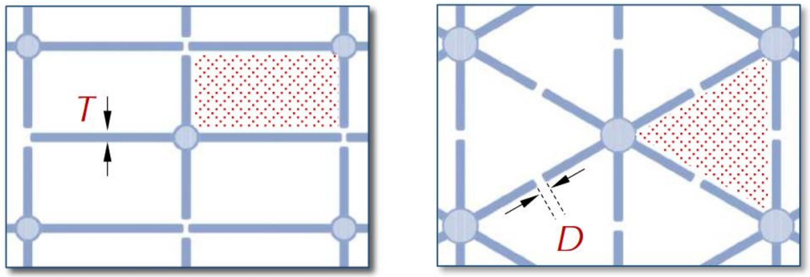
- Two different **array configurations**: *regular* and *staggered*



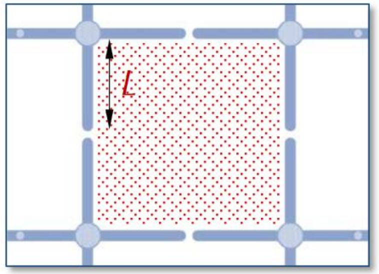
- Several **pad geometries**: *squares*, *circles*, *crosses*, *stars*, etc...



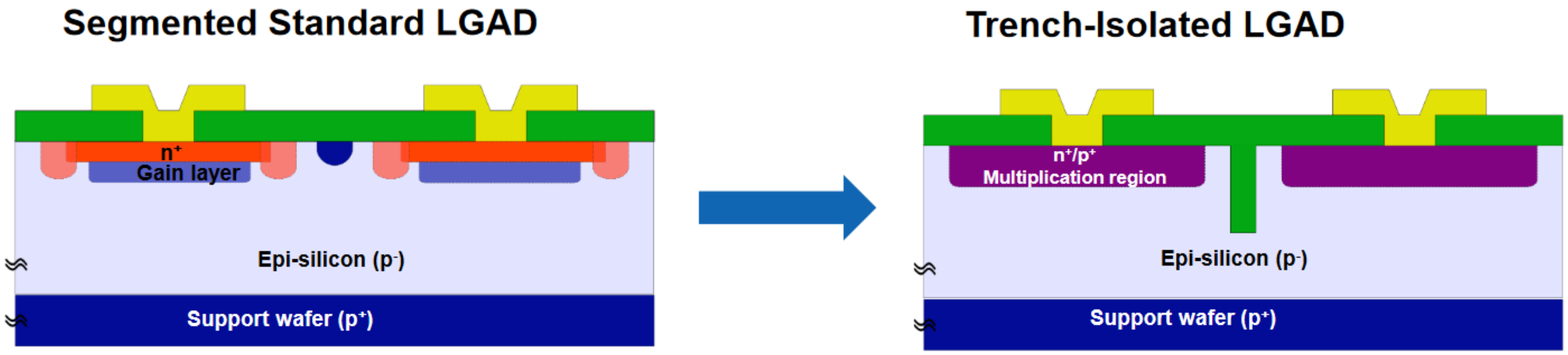
- **Signal confinement** with *cross* or *star* AC-pads in the **staggered arrays**:

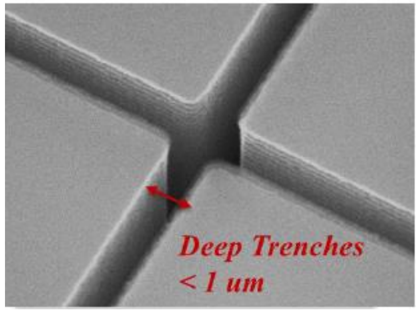


- and in the **regular arrays**:



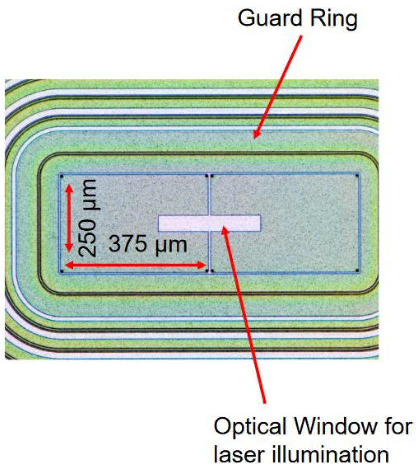
Trench-isolated Low Gain Avalanche detectors (**TI-LGAD**)

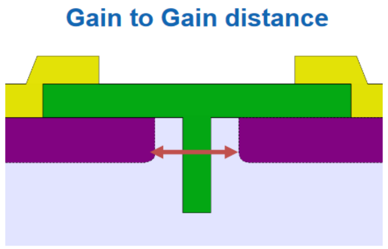




G. Paternoster, 39th RD50 Workshop, Nov 2021

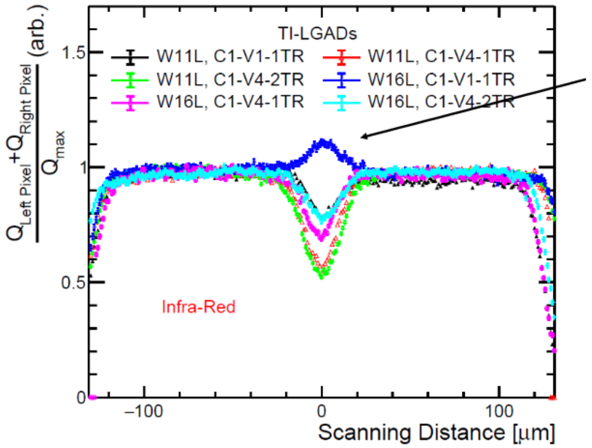
- Pixel border region hosts structures to control E field (JTE, p-stop, etc..)
- Trench isolation could drastically reduce inter-pixel border region down to few µm
  - Typical trench width < 1 µm (max aspect ratio: 1:20)
  - Trench filling with: SiO2, Si3N4, Polysilicon





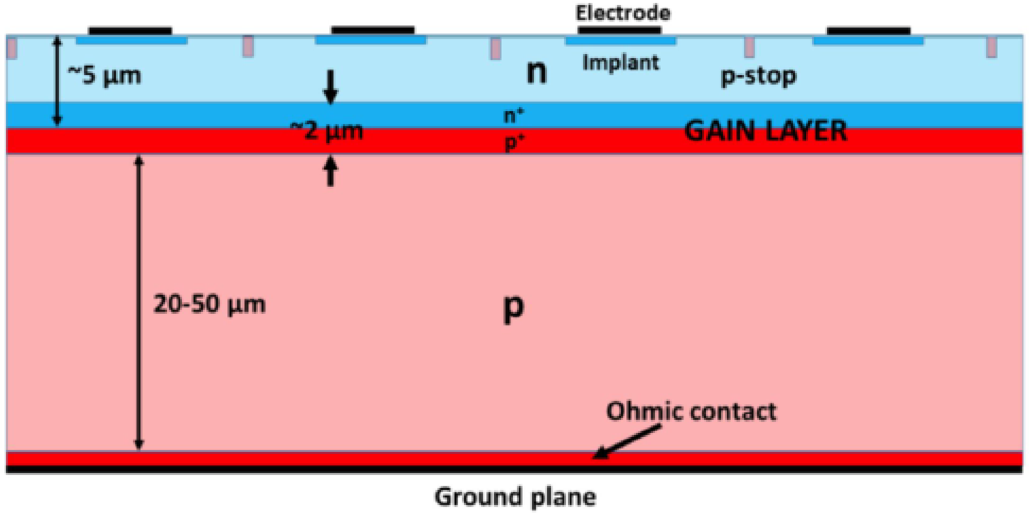
Nominal no-gain width

- V1 < 1um
- V2 < 3um
- V3 < 4um
- V4 < 5 um

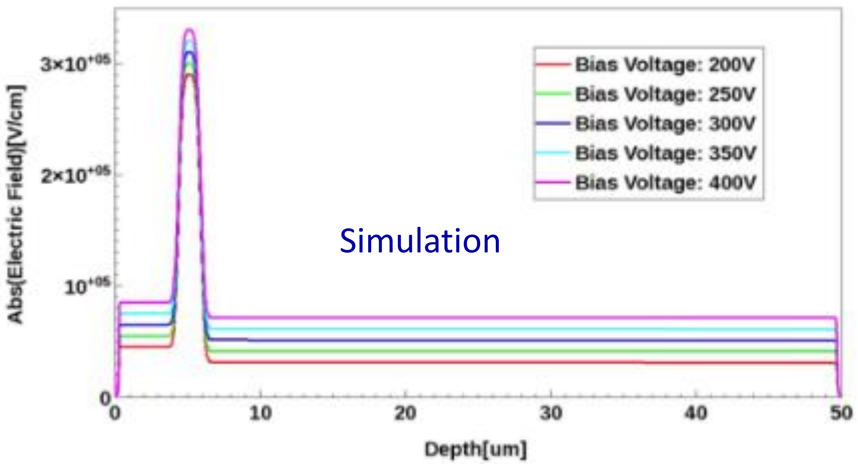


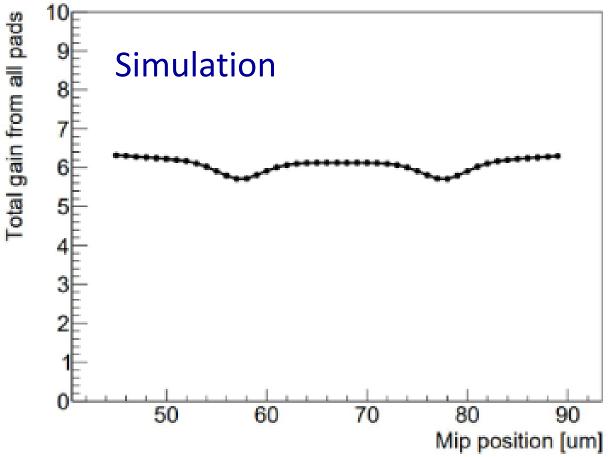
Deep Junction - LGAD

C. Gee, 39th RD50 Workshop, Nov 2021



- Advantageous to bury high p-n junction several um below the surface of the sensor so fields low at surface, allowing conventional granularization
- Electric field in p-n junction is high enough to maintain drift-velocity saturation
- Maintains fine granularity on order of tens of microns
- Preserves direct coupling of signal charge to readout electrodes
- Initial prototype manufacturing at BNL





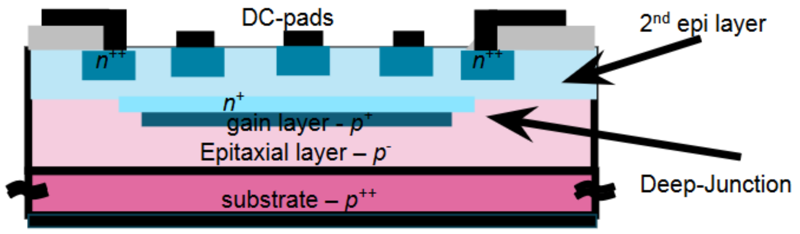


Diagram credit: BNL

Take home messages

- LGAD (HEP jargon for an APD with moderate gain) is the solution towards:
  - larger SNR (decoupled from the material) for O(10ps) hit resolution
  - O(10um) spatial resolution with fine electrode segmentation and AC coupling
- Many 4D LGAD architectures are under intense R&D.
- The next stepping stone in the development of a true 4D tracking sensor will be based on a hybrid sensor design with LGAD interconnected to timepix4 ASIC (AIDAInnova WP6)
- The technology is maturing and attracting the interest of major manufacturing companies BUT still a long way to go:
  - Complete proof-of-concept studies.
  - Reliability (long term stability, noise and destructive breakdown)
  - Manufacturing yield?
  - Scalability (larger area sensors) ?
  - Uniformity ?
  - Radiation tolerance fine pitch devices?
- Other strategies for the implementation of a 4D tracking should be also considered: PIN diodes with special junction geometries (TimeSPOT project) or monolithic CMOS based.

Final (personal) remark: The elephant in the room

- I do not see any technical showstopper for the LGAD sensors as true 4D sensing technology.
- Quite confident that LGAD sensor can become the baseline technology for the next generation of large 4D tracker systems.
- But LGAD are hybrid sensors interconnected to a dedicated readout ASIC:

The feasibilty of a front-end readout electronics with a relatively high density of readout channels is still to be proven; the power consumption and the corresponding heat disipation could become the showstopper.