Universität Hamburg
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DESY.

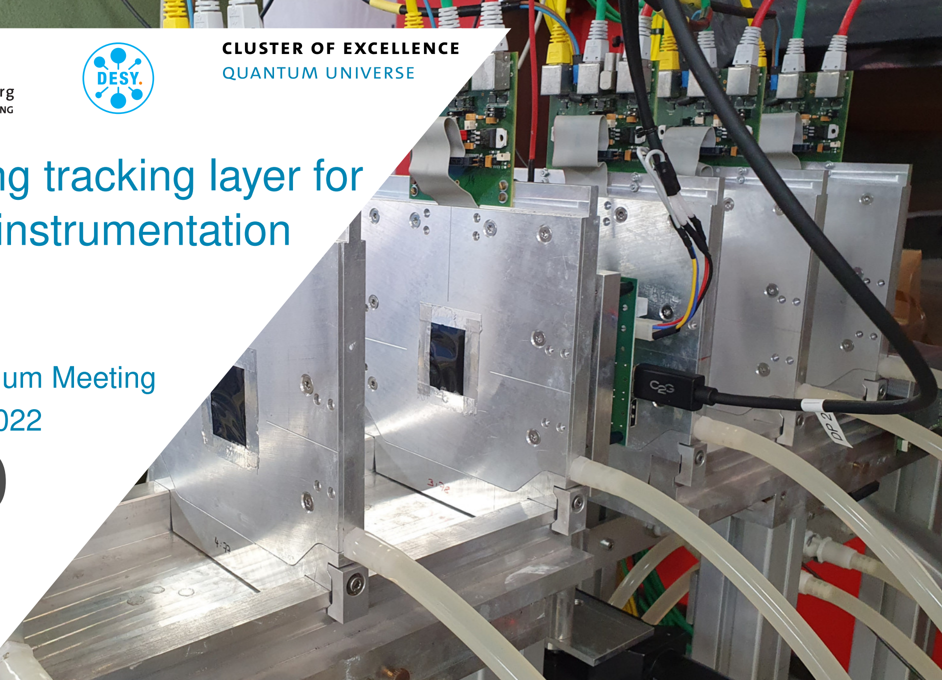
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

A fast timing tracking layer for test beam instrumentation

High-D Consortium Meeting
September 2, 2022

HIGH-D

Annika Vauth



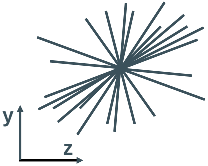
The need for new timing detectors

Experimental environments in HEP are evolving
$\rightarrow$ Include track timing to address new challenging conditions

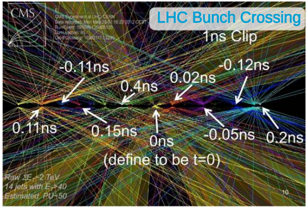
Time information complements spatial information:

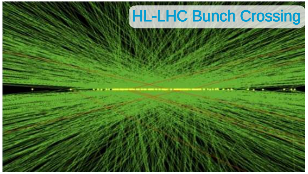
- "4D" tracking: timing at each point along the track
- Timing layer: timing in event reconstruction

Example



pileup tracks





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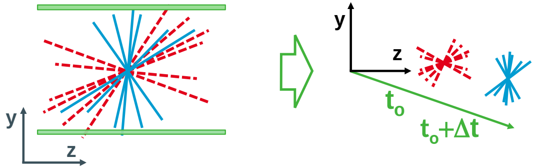
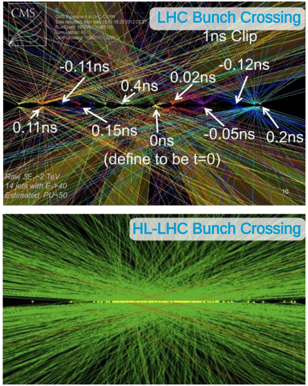
Example with timing info



added timing layer



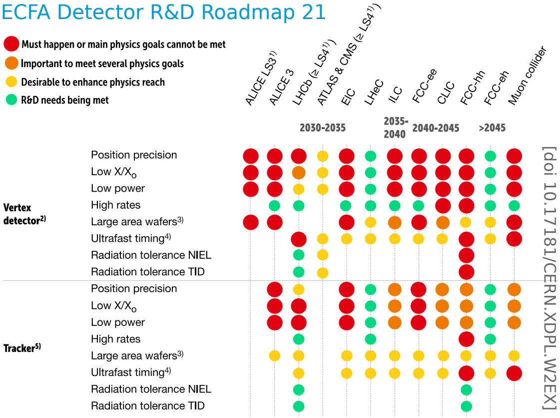
Future detectors

Particle physics at high energy frontier:
What comes beyond HL-LHC?

Future hadron colliders:
Very high luminosity operation

→ Challenges from extreme pile-up, track density, radiation load and data

R&D in many areas necessary
Radiation hardness, power consumption, spatial and timing resolution, ...



Test beam

HEP detector R&D: dedicated beam tests for
conceptual / technical design, calibrations, commissioning, ...

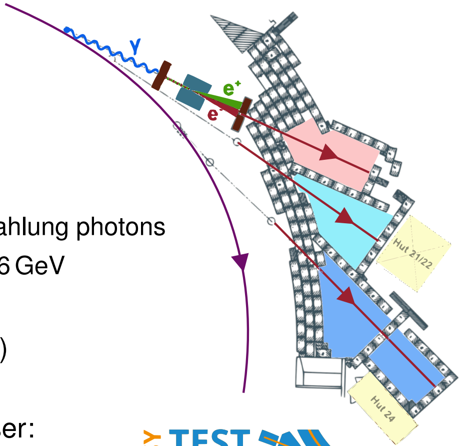
- Measurements of efficiency, resolution, ...
- Irradiation studies
- Integration tests with multiple detectors

Studies with Minimum Ionising Particles $\rightarrow$ e.g. at DESY II Testbeam Faciliy

DESY II facitily

Testbeam parasitically fed by DESY II synchrotron (PETRA III injector)

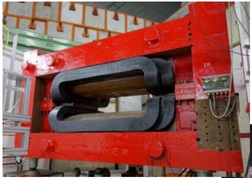
- Very high availability ($\sim$99% uptime)
- Test beam generation:
  - Primary carbon fiber targets generate bremsstrahlung photons
  - Conversion at secondary target to e^+/e^- up to 6 GeV
  - Energy selected with dipole / collimator
- Single electrons, rates $\mathcal{O}$(10k particles $s-1s-2$) depending on beam line settings
- Three individual beam lines, controlled by the user: shutter, area interlock, converter, momentum + collimation

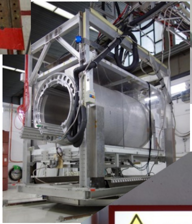


DESY TEST BEAM.

Test beam infrastructure

- Movable stages, hall crane
- Magnet (dipole, solenoid)
- Dry nitrogen, cooling water
- Gas cabinets
- Laser alignment, weather station, cameras
- Beam telescopes:
  - Common infrastructure to study prototype detectors
  - Used to precisely define particle track in test beam
  - Resolution should be better than intrinsic resolution of DUT (device under test)



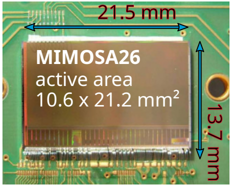


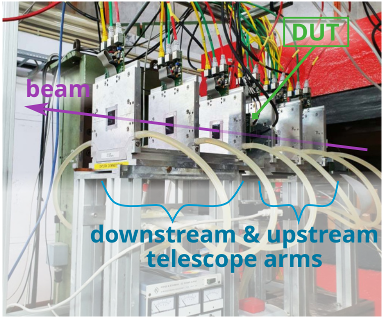
→ EUDET-type telescopes (copies at DESY, CERN, Bonn, SLAC)

Status: MIMOSA telescopes

6 layers of MIMOSA26 pixel sensors

- 1152 $\times$ 576 pixels, pitch: 18.4 µm, i.e. $\sim$2 cm $\times$ 1 cm area
- Measured intrinsic sensor resolution: $\sigma \cong 3\,\mu m$
- Rolling shutter readout, readout cycle 115 µs
- A decade of successful operation!
  telescope requested for $\sim$90% of DESY TB weeks





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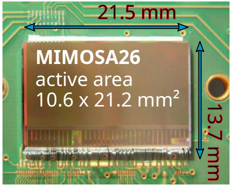
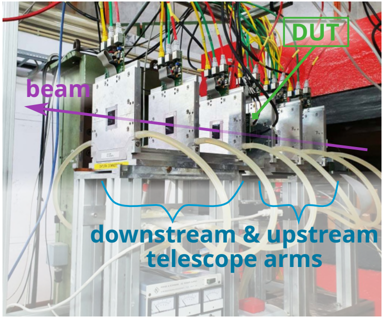


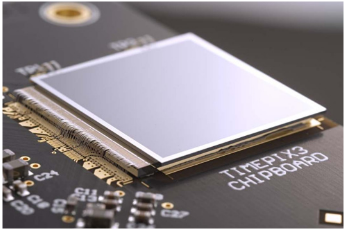
“No“ time resolution → upgrade needed
to meet requirements of future detector test campaigns



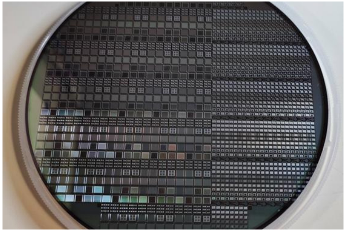
Add faster device for time stamping the tracks
→ Timing layer

Upgrade Plans

- Short term: existing sensor as intermediate solution
  - Timepix3
  - Already existing and functional
  - Timestamps $\mathcal{O}(1\,\text{ns})$
- Long term: develop next-generation timing layer
  - LGAD
  - Allow for picosecond-timing
  - Requires R&D
  - Dedicated ROC?
    Start with Timepix3(/4) for first prototypes



[CERN-PHOTO-201702-048-4]

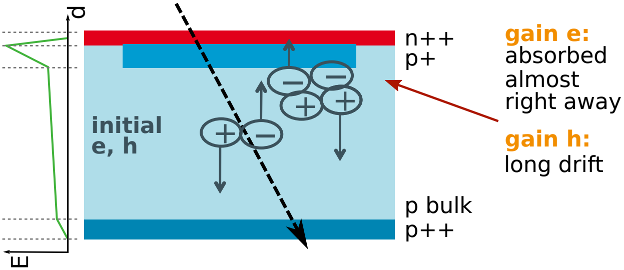

[FBK RD50 TI-LGAD wafer]

LGAD

Low Gain Avalanche Diodes

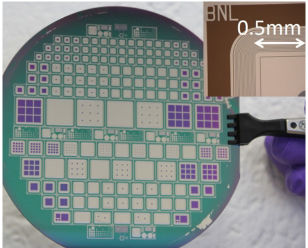
Ultra Fast Silicon Detectors optimised for timing measurements:

Thin multiplication layer
→ High field
→ Increase signal by factor ∼10



LGADs are routinely produced in various sizes and pad numbers
(e.g. by CNM, FBK, HPK)

$\mathcal{O}$(30 ps) time resolution possible



arXiv:1811.04152

LGAD timing layer - technology options

Low Gain Avalanche Diodes suitable to measure both time and space

- Preferred for timing: 30-50 µm thickness, gain $\mathcal{O}(10)$
- Segmentation to improve spatial resolution
- Interpad regions with no gain $\mathcal{O}(\approx 30\,\mu m$ to $70\,\mu m)$

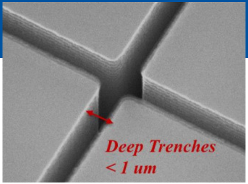
$\rightarrow$ R&D challenge: finer segmentation, with improved fill factor

Several technology options:

- Trench-isolated LGAD
- Inverse LGAD
- Resistive AC-Coupled LGAD

} Options for first timing layer prototypes
55 µm pitch, read out with Timepix3

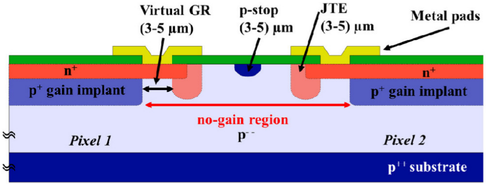
TI-LGAD



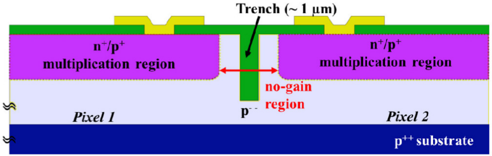
Trench isolation:

- Barrier structures replaced by trenches to isolate the pixels
- Filled with SiO_2, Si_3N_4, Polysilicon
- Typical trench width $< 1\,\mu m$, much smaller than conventional segmentation
  $\rightarrow$ smaller no-gain region
  $\mathcal{O}(\approx 4\,\mu m \text{ to } 7\,\mu m)$

a) Standard segmentation

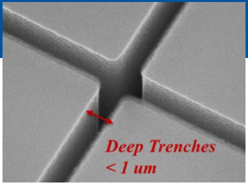


b) Trench-isolated LGAD



[doi: 10.1109/LED.2020.2991351]

TI-LGAD



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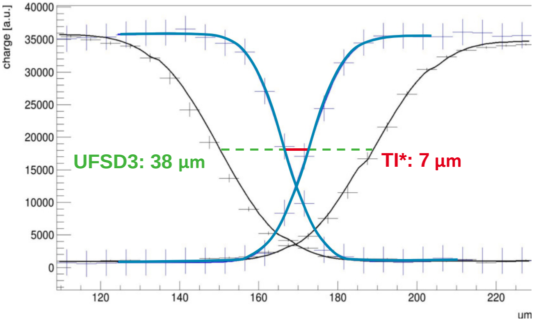
Comparison of FBK productions: UFSD3 vs Trench-Isolated



[F. Siviero, 35th RD50 workshop, Nov 2019]

First LGAD samples

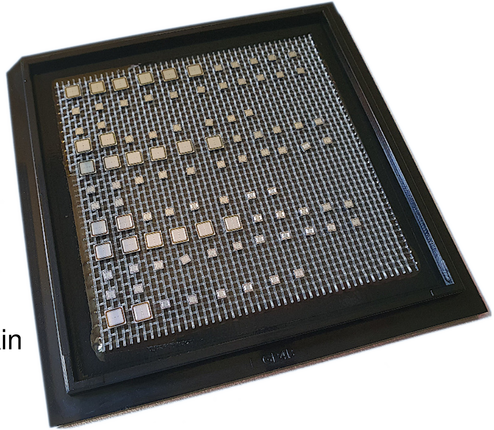
FBK, trench isolated: received first test structures

General properties: 45 µm substrate, trench depth “D2“, no carbon

Samples from three different wafers
(low/high diffusion, different trench processes)

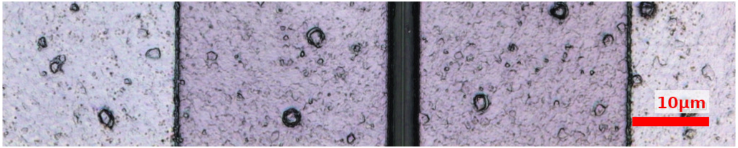
➤ The “big ones“:
4 mm x 4 mm, pixels 2x2 (1300 µm x 1300 µm)
all single trench, 18 with (6 without) gain

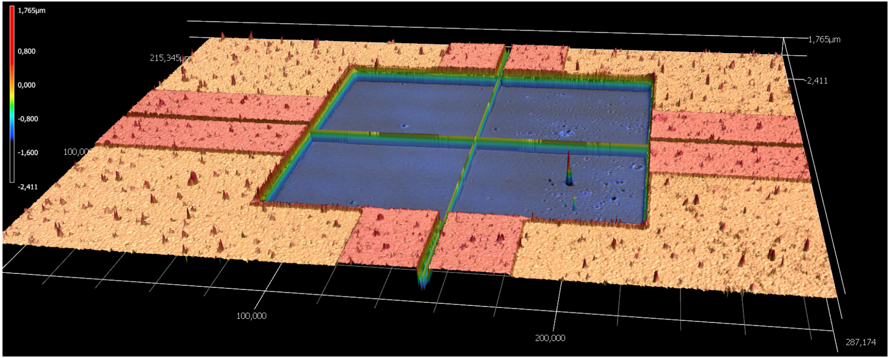
➤ The “small ones“:
2 mm x 2 mm, pixels 4x4 (250 µm x 250 µm)
some single/double trench, 54 with (18 without) gain



First LGAD samples (2)

First look with the laser microscope:

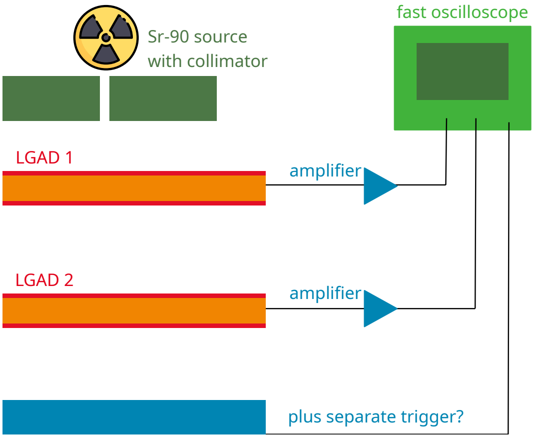




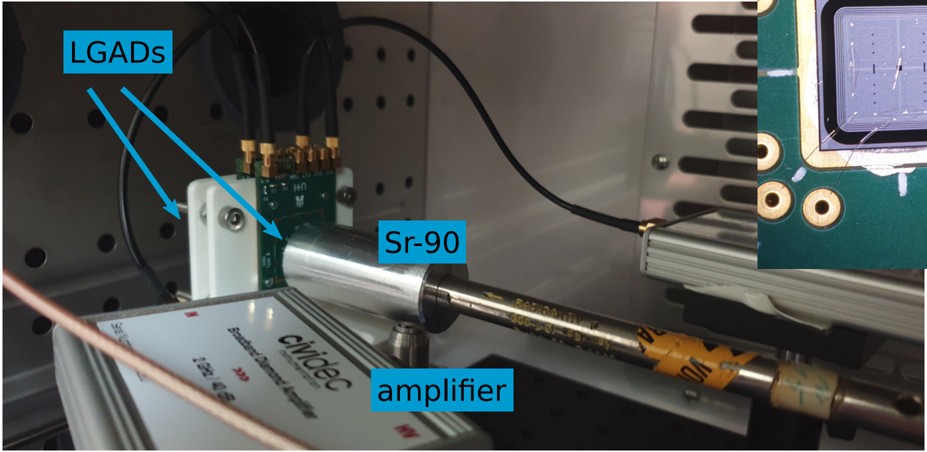
Time resolution measurement

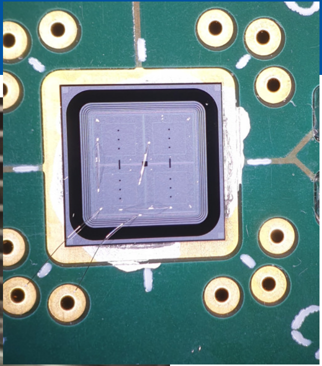
Beta setup for timing measurements under construction:

- Two LGADs (parallel to each other)
- Beta source with collimator in front
- Each detector connected to an amplifier
- Signals fed into oscilloscope, triggers on signal in both
- Measure Δt distribution, Combinations of three LGADs $\rightarrow$ time resolution



Beta setup in Hamburg

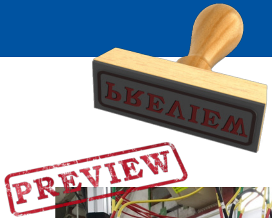




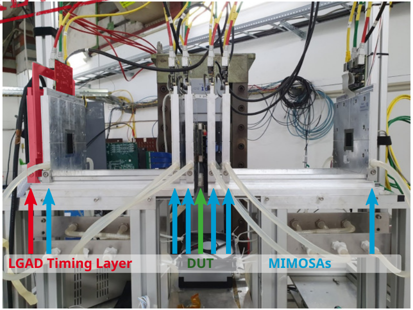
2x2 LGAD (pads bonded together)

New UHH Beta setup in commissioning right now

Summary & Outlook



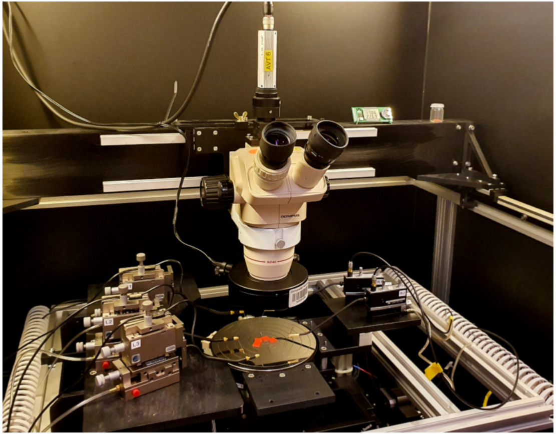
- Test beams: tool for detector development
- TB infrastructure: EUDET beam telesopes
- More and more R&D on fast timing detectors
  $\rightarrow$ growing need for timing layer to test them
- Short term:
  Timepix3 plane for improved timing $\mathcal{O}(1\,\text{ns})$
- Long term:
  LGAD+TP3(TP4?) layer for $\mathcal{O}(\text{tens}\,\text{ps})$ timing
- First test structures available
- Setup of LGAD characterisation tools in progress
- Next step: 55 µm pitch structures

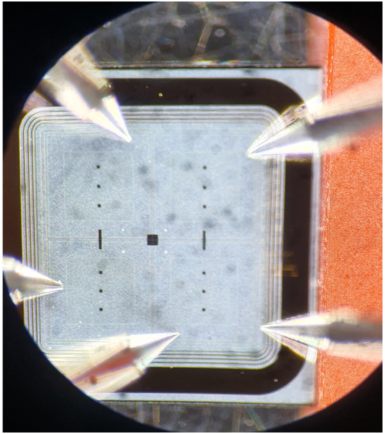


Backup Slides

LGAD characterisation

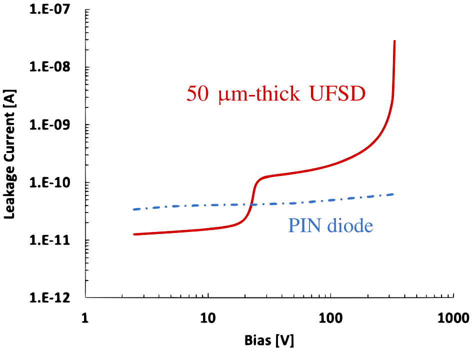
Setup for IV and CV measurements:



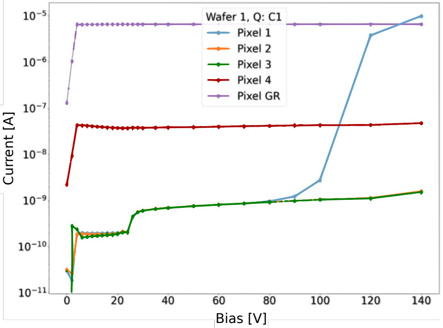


Current-Voltage measurement

IV-curves (textbook and reality)



[M. Ferrero, R. Arcidiacono, M. Mandurrino, V. Sola, N. Cartiglia, 2021 "An Introduction to Ultra-Fast Silicon Detectors", ISBN 9780367646295]



FBK measurement with automatic probe (before dicing)

Solving for LGAD time resolution

Use three LGADs measured in three combinations to compute individual time resolutions

$$\sigma_{12}^2 = \sigma_1^2 + \sigma_2^2, \sigma_{13}^2 = \sigma_1^2 + \sigma_3^2, \sigma_{23}^2 = \sigma_2^2 + \sigma_3^2$$

$$\sigma_{12}^2 - \sigma_1^2 = \sigma_2^2 = \sigma_{23}^2 - \sigma_3^2, \sigma_3^2 = \sigma_{13}^2 - \sigma_1^2$$

$$\sigma_{12}^2 - \sigma_1^2 = \sigma_{23}^2 - \sigma_{13}^2 + \sigma_1^2$$

$$\sigma_1^2 = \frac{1}{2}\left(\sigma_{12}^2 + \sigma_{13}^2 - \sigma_{23}^2\right)$$

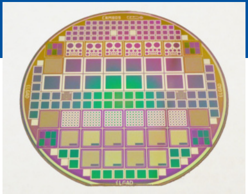
(and equivalent for the other two)

to **can determine time resolution of all three LGADs**

iLGAD

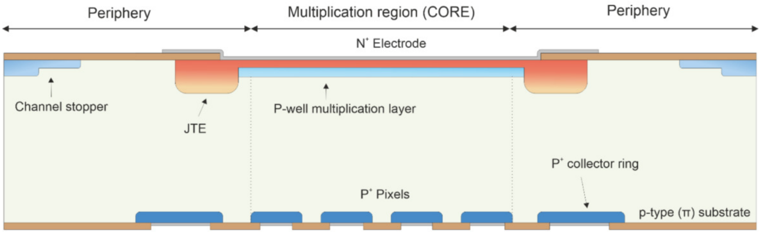
Inverse LGADs:

- No segmentation of the multiplication layer
- Hole collection
- Complex double side process (first generation)



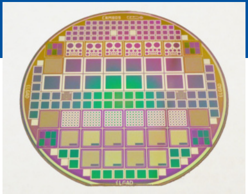
[D. Flores, SIMDET '16, Sep 2016]

inverse LGAD (CNM first generation)



[A. D. Moreno, 16 th Trento Workshop, Feb 2021]

iLGAD

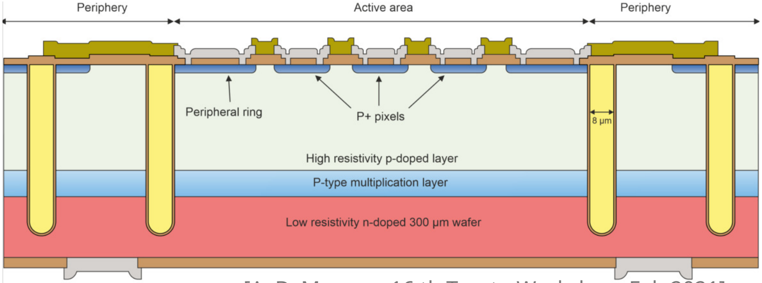


[D. Flores, SIMDET '16, Sep 2016]

Inverse LGADs:

- No segmentation of the multiplication layer
- Hole collection
- Trenches to isolate the active area (third generation)
- Single-side process

inverse LGAD (third generation)



[A. D. Moreno, 16 th Trento Workshop, Feb 2021]

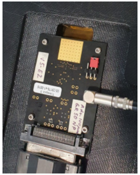
Beam tests with Timepix3

Testbeam time 2021:

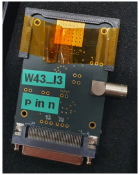
- No LGADs, but three different Timepix3 assemblies
- Test readout, DAQ and reconstruction chain

→ Two weeks (plus some bonus time) in area 21

W5_E2 (TB 1)
100um Si, n-in-p



W43_I3 (TB 1)
300um Si, p-in-n, ACF



W19_K6 (TB 2)
500um Si, n-in-p