LGAD Sensors at FBK
(selected topics)

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Fondazione Bruno Kessler
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08.10.2022
Rare Pion Decay Workshop

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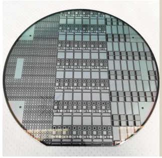
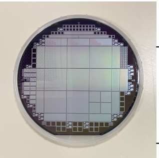
Fondazione Bruno Kessler

6 inch (150 mm)
Custom CMOS-like process

LGAD technologies:

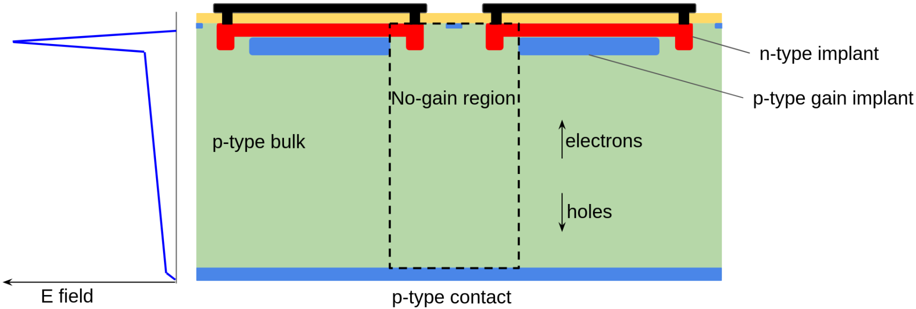
- Standard
- Double sided
- AC coupled (RSD)
- Trench isolated
- DC-RSD





Start	Batch
2015	UFSD1
2017	UFSD2
2018	UFSD3
2019	RSD1 HD0 UFSD3.2
2020	MOVEIT TI-LGAD RD50 PSI iLGAD HADES
2021	RSD2 UFSD4 Space LGADs
2022	ExFlu DC-RSD (planned) TI-LGAD AIDA (planned)

(Standard) Low Gain Avalanche Diodes

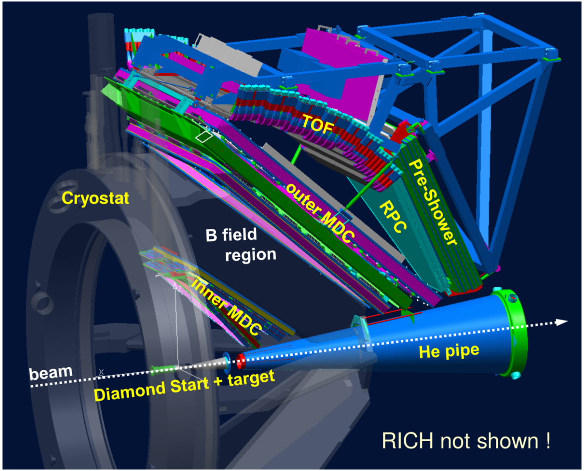


- Silicon detectors with charge multiplication
- Gain ≈ 10
- Gain layer provides high-field region
- No-gain region $\sim 30 - 80\ \mu$m
- Time resolution ~ 30 ps $\leftrightarrow$ thin $\sim 50\ \mu$m sensor

- **Improve SNR of the system**
  (When the sensor shot noise is not dominating)
- Noise and power consumption
  $\Rightarrow$ low gain

HADES Experiment

[R. Holzmann 54. Winter Meeting on Nuclear Physics]

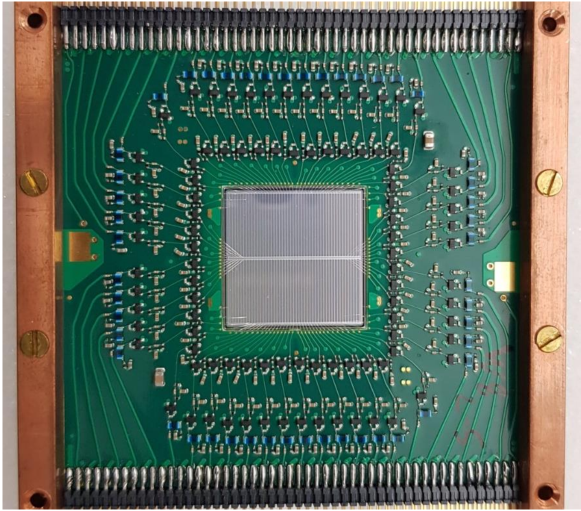


- Fixed target experiment at GSI
- TOF used for particle identification (among other methods)
- T_0 detector
  - Based on diamond detectors
  - Beam monitoring
  - TOF start
  - **Replace diamond with LGADs**

[J. Pietraszko et al. Eur. Phys. J. A 56 (2020) 183]

LGADs for HADES

[W. Krueger VCI 2022]



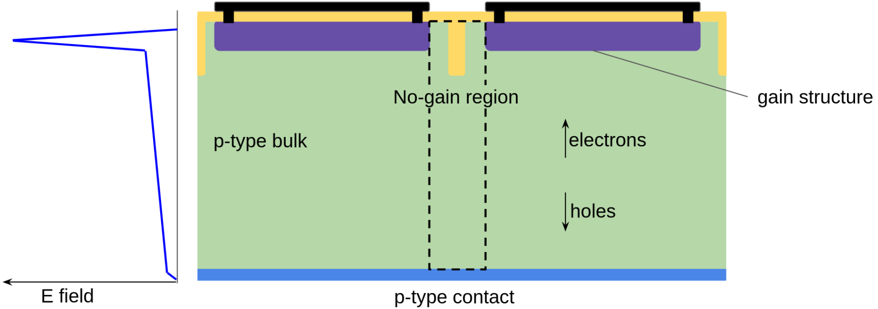
- Strip geometries
- Sensor dimension up to $\sim 2 \times 2$ cm^2
- Strip up to 0.387×9.28 mm^2
- Wafers thinned down to 200 μm total
- Dicing after thinning

MIP time resolution (largest strips):

[W. Krueger et al. NIMA 1039 (2022) 167046]

- $\sim$ 85 ps in full system tests
- $\sim$ 130 ps in the experiment (discrepancy under investigation)

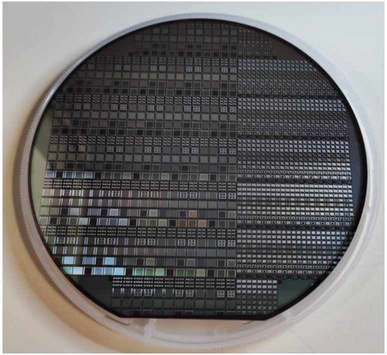
Trench Isolated LGADs

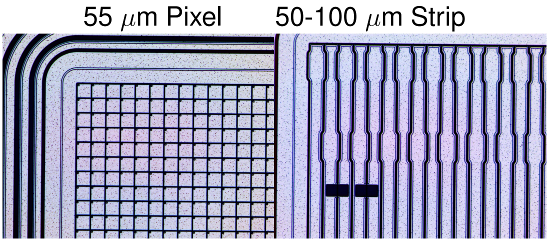


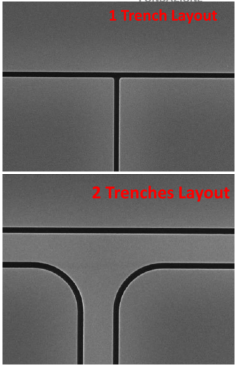
- Trenches substitute the isolation structures
- Trench width about 1 μm $\Rightarrow$ fill factor close to 100%

[G. Paternoster et al. IEEE EDL Vol 41 Issue 6 (2020) 884-887]

TI-LGADs RD50



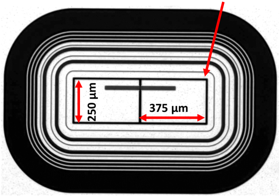


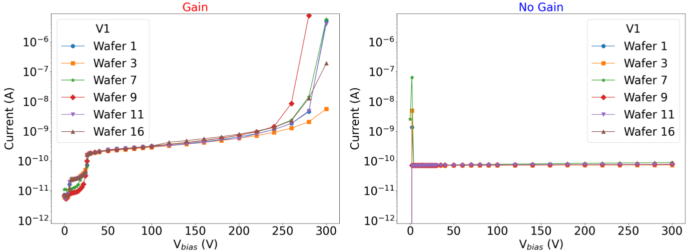


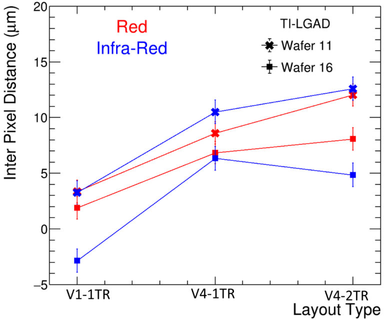
- Second TI-LGAD run
- Project within the RD50 collaboration
- Several pixel and strip geometries
- Different gain structure layouts
- Variations in trench depth and fabrication process

TI-LGAD RD50 Characterization

[A. Bisht Picosecond Workshop 2021]

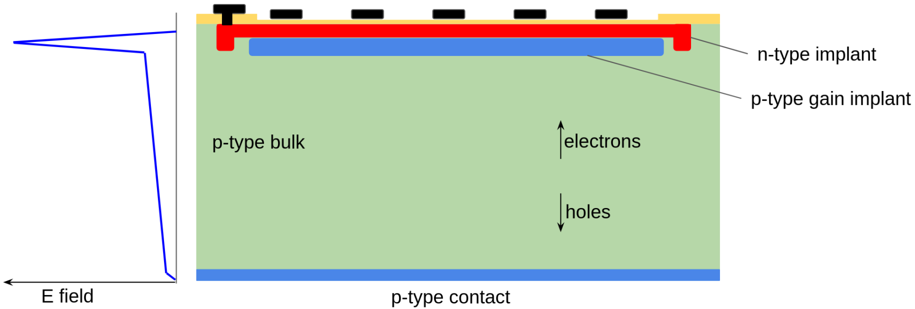






- Stable trench structures
- Breakdown due to gain layer
- Interpad 3-10 μm with laser [A. Bisht Picosecond Workshop 2021]
- $\sim 10\times$ improvement from STD LGAD
- Same radiation hardness and time resolution as standard LGADs [M. Senger et al. NIMA 1039 (2022) 167030]
  (this batch was without carbon coimplantation)

AC Coupled LGADs (RSD)

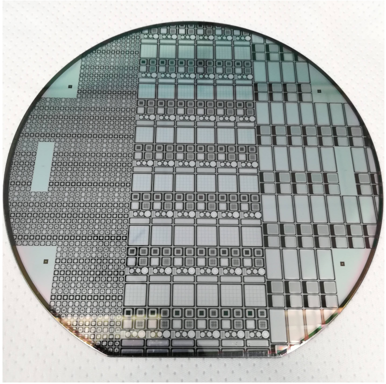


- Continuous gain area in the active region $\Rightarrow$ 100% fill factor
- Readout channels capacitively coupled and resistive layer to limit signal spreading
- No restrictions on channel dimension

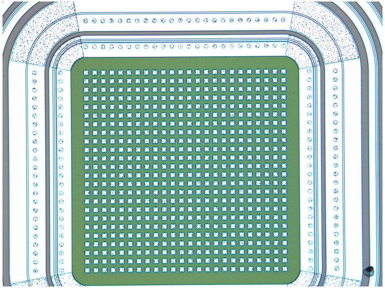
[M. Mandurrino et al. IEEE EDL Vol 40 Issue 11 (2019) 1780-1783]

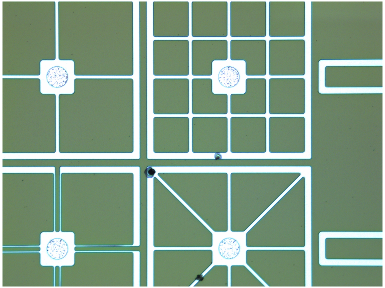
RSD Productions

RSD1



RSD2

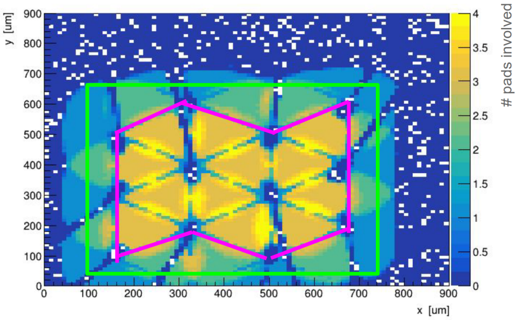




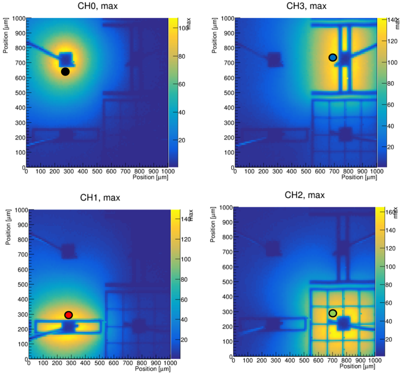
- Several pixel and strip geometries
- Electrode geometries to exploit signal propagation
- Variations of resistive layer
- Variations of coupling dielectrics

RSD Characterization

[F. Siviero VCI 2022]

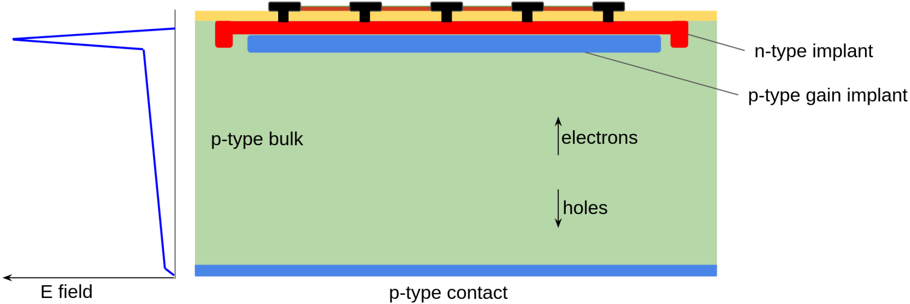


[S. Mazza 40th RD50 workshop 2022]



- $\sim 6\ \mu$m resolution with 200 μm pitch (laser) [F. Siviero et al. NIMA 1041 (2022) 167313] [S. Mazza 40th RD50 workshop 2022]
- Time resolution $\sim$ 44 ps with 200 μm pitch (MIPs) [M. Tornago et al. 2020 IEEE NSS/MIC (2020) 1]

DC-Coupled Resistive Silicon Detectors (DC-RSD)

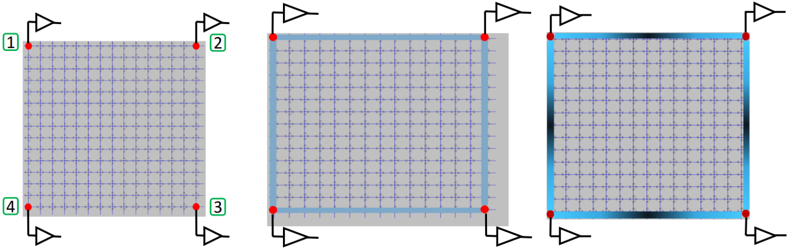


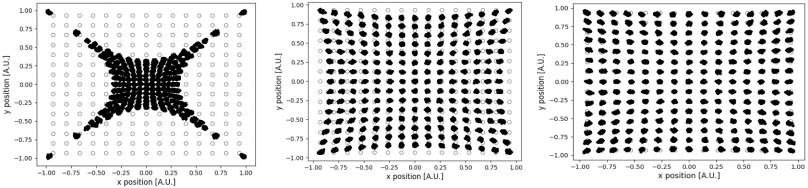
- Continuous gain area in the active region $\Rightarrow$ 100% fill factor
- Resistive charge division
- Resistors between readout pads to improve reconstruction

[N. Cartiglia 39th RD50 Workshop 2021]

DC-RSD Reconstruction Improvement

[L. Menzio VCI 2022]





Empty circles → input
Full circles → reco

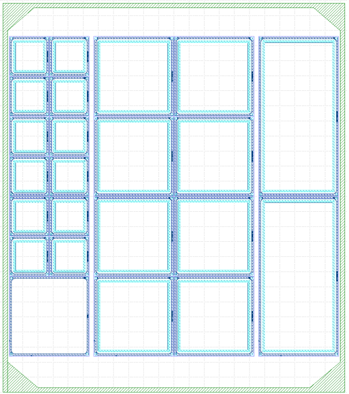
More details: L. Menzio et al. NIMA 1041 (2022) 167374

First batch planned for end of the year

Plans for RSD (AC/DC) and TI-LGADs

2022

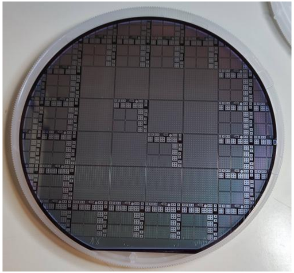
- DC-RSD
  - first demonstrator for the technology
  - fabrication tests and design ongoing
- TI-LGADs AIDA
  - evolution from RD50 batch
  - larger devices, up to $\sim 1 \times 1$ cm^2
  - carbon coimplantation
  - design ongoing

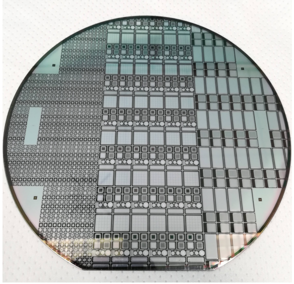


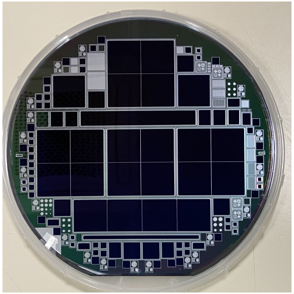
2023

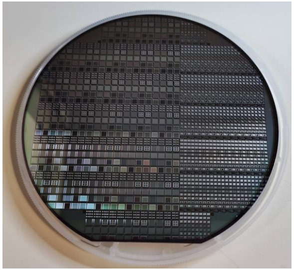
- TI-LGADs GSI,HEPHY,TU-Wien
  - HADES and medical applications
  - strip geometries, sensors up to $\sim 2 \times 2$ cm^2
  - wafer thinning

Thank you for your attention



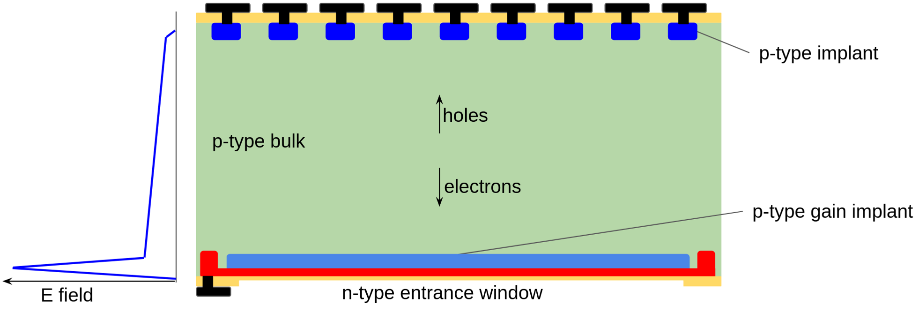






Backup Material

Double Sided (Inverted) LGADs

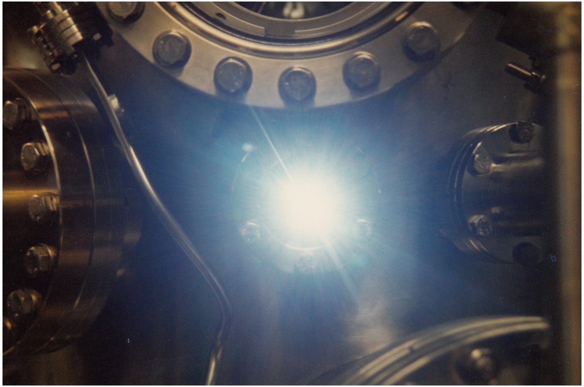


- Continuous gain area in the active region ⇒ 100% fill factor
- Double sided process → active thickness is the wafer thickness ⇒ not optimal for timing
- Readout side is ohmic
- Readout side separated from LGAD side ⇒ no restrictions on channel dimensions

[G.F. Dalla Betta et al. NIM A 796 (2015) 154]

X-ray Detection

[Wikipedia CC BY-SA 2.0]



Advantages of LGADs demonstrated in:
[Andrae et al. J.Synchrotron Rad. 26 (2019) 1226-1237]

Development in collaboration with PSI

PAUL SCHERRER INSTITUT

PSI

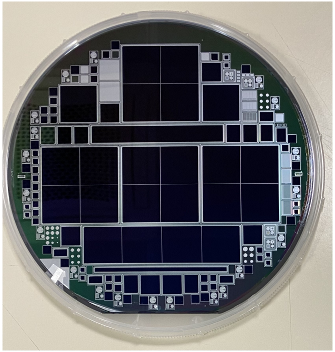
Detection of soft X-rays: 250 eV - 2 keV

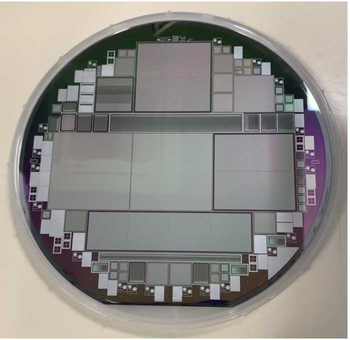
- K-edges of bio elements
  $\rightarrow$ pharmaceuticals, cell imaging
- L-edges of 3d-transition metals
  $\rightarrow$ magnets, superconductors, quantum materials ...

Use LGADs:

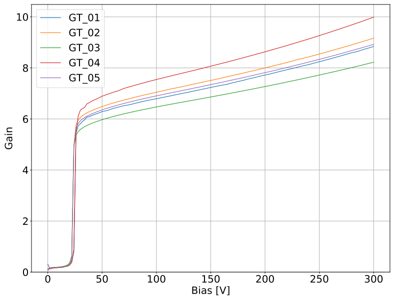
- Gain to lower the detection limit of photon counting detectors
- Gain to improve SNR of integrating detectors
- Thin entrance window and gain structure must be developed

Double Sided LGADs for PSI



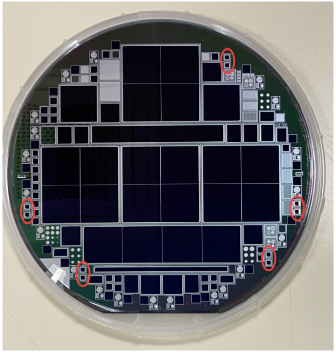


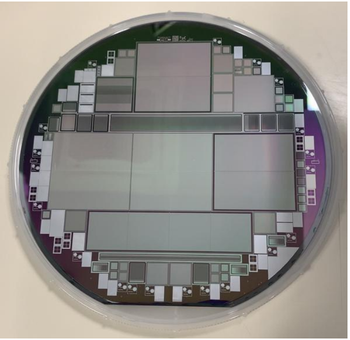
Gain with LED (STD gain structure)



- Several pixel and strip geometries
- Thin entrance window
- Several gain structure designs → make as thin as possible
- Thickness 275 μm
- First results with x-rays at TREDI next week

Double Sided LGADs for PSI





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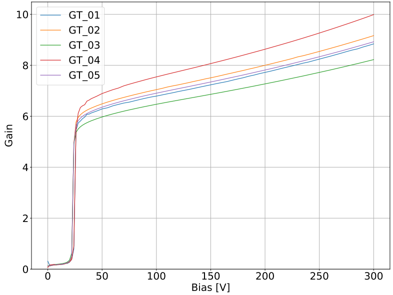

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- Thin entrance window
- Several gain structure designs $\rightarrow$ make as thin as possible
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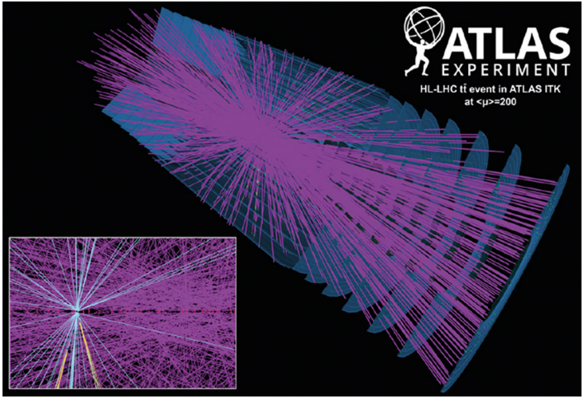
High Luminosity LHC

[ATLAS simulation]



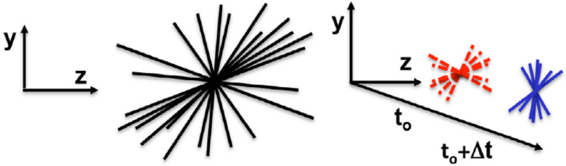
Application described in:
Daniel Spitzbart talk on Wednesday
Frank Filthaut talk on Wednesday

Development within the UFSD project

Use time coordinate to mitigate pile-up

- Track time resolution $\approx$ 30 ps
- Radiation resistance to few 10^{15} n_{eq}/cm^2
- Hit time resolution at end of life $\approx$ 50 ps

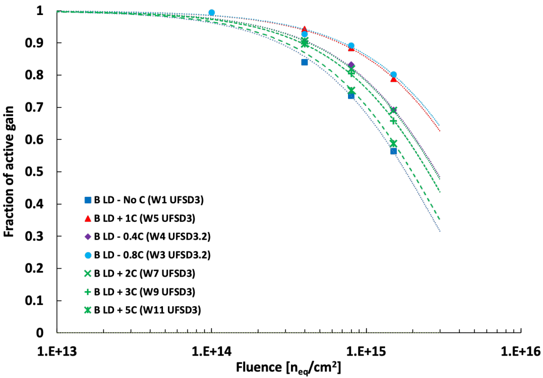
[H. Sadrozinski et al. Rept. Prog. Phys. 81 (2018) 026101]



Radiation Hardening of LGADs

Gain layer doping

[M. Ferrero TREDI2021]



$$N_B(\phi_{eq}) = N_B(0) \exp\{-c\phi_{eq}\}$$
$$c = c(N_B(0))$$

[M. Moll PoS Vertex2019 (2020) 027]

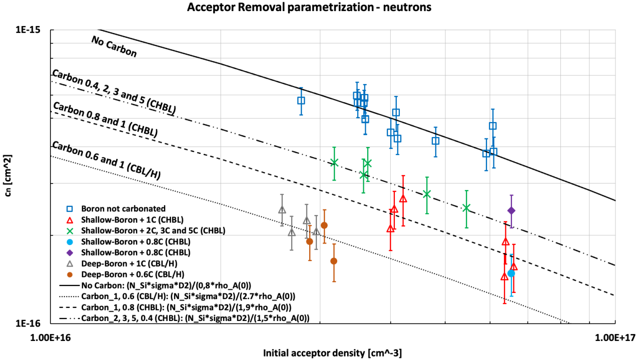
- Acceptor removal:
  $Si_i + B_s \rightarrow B_i$
  $B_i + O_i \rightarrow B_iO_i$ (donor level)
- Carbon $\Rightarrow$ Competing reaction:
  $Si_i + C_s \rightarrow C_i$
  $C_i + O_i \rightarrow C_iO_i$ (neutral)

- Initial B concentration
  $\rightarrow$ higher concentration favored
  $\rightarrow$ narrower B distribution
- Carbon coimplantation
  $\rightarrow$ optimized dose found

Radiation Hardening of LGADs

Removal constant

[M. Ferrero TREDI2021]



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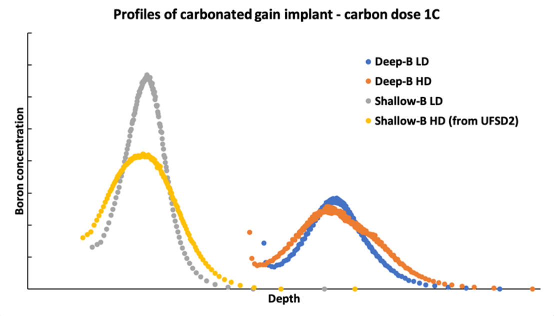
Radiation Hardening of LGADs

[G. Paternoster VERTEX2021]



Gain layer position:

- "shallow" $\rightarrow$ higher B concentration
- "deep" $\rightarrow$ easier compensation of B loss by increasing bias

[M. Moll PoS Vertex2019 (2020) 027]

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  $Si_i + B_s \rightarrow B_i$
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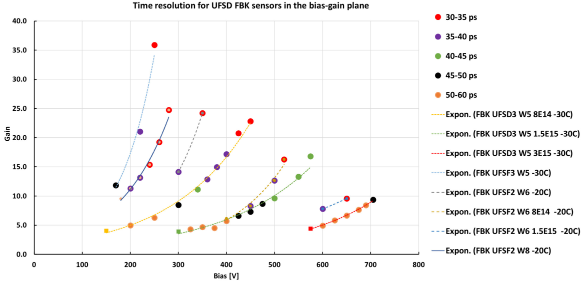
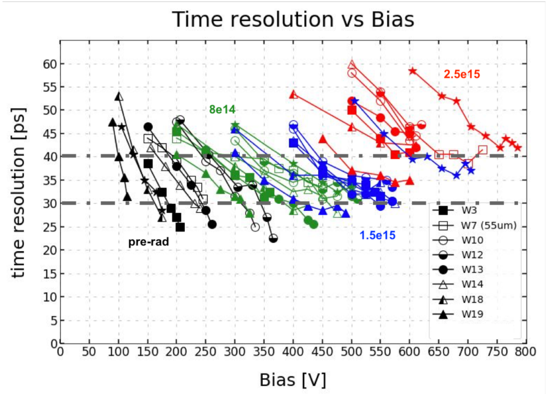
Radiation Hardness Results

[R. Arcidiacono et al. NIMA 978 (2020) 164375]



[M. Ferrero Vertex2021]

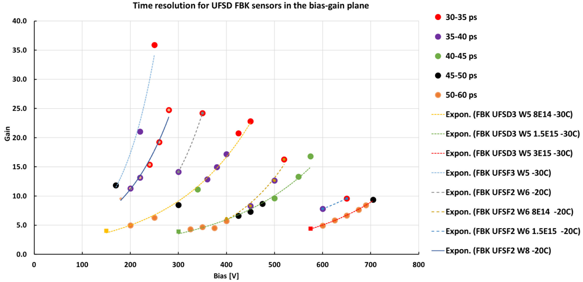


- Time resolution < 40 ps for $2.5 \cdot 10^{15}\ n_{eq}cm^{-2}$
- Time resolution < 50 ps for $3 \cdot 10^{15}\ n_{eq}cm^{-2}$

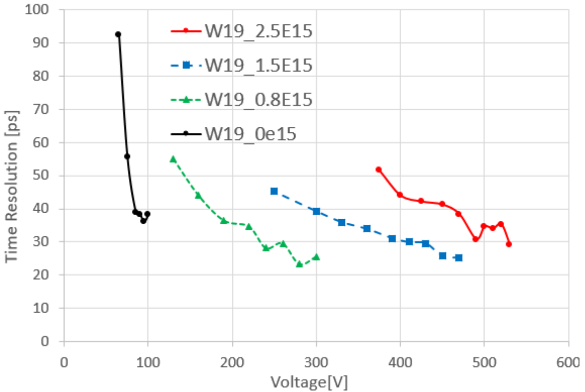
Demonstrated radiation resistance and time resolution for HL-LHC

Radiation Hardness Results

[R. Arcidiacono et al. NIMA 978 (2020) 164375]



[A. Howard 37th RD50 Workshop]



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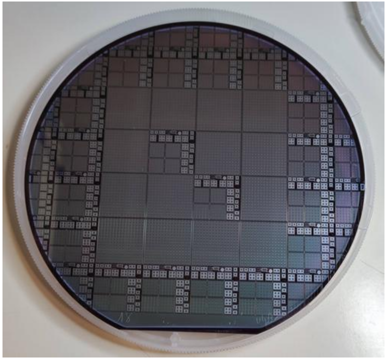
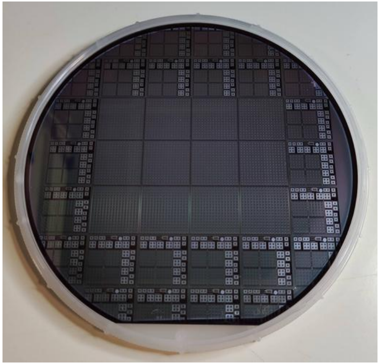
Demonstrated radiation resistance and time resolution for HL-LHC

UFSD4

ATLAS



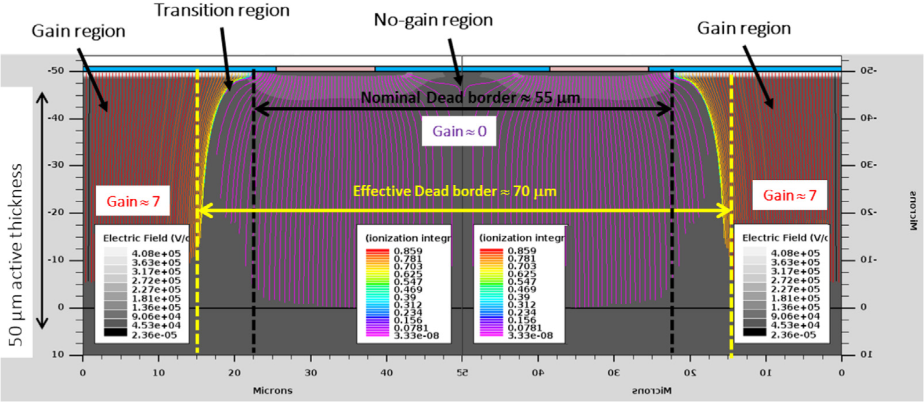
CMS



- Both “shallow” and “deep” gain layers
- Different pad layouts
- Sensors up to $\sim 2 \times 2$ cm^2

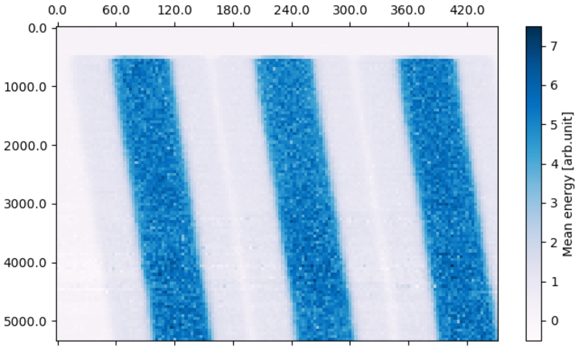
Wafers and sensors for qualification for ATLAS and CMS timing detectors

[G. Paternoster et al. NIMA 987 (2021) 164840]

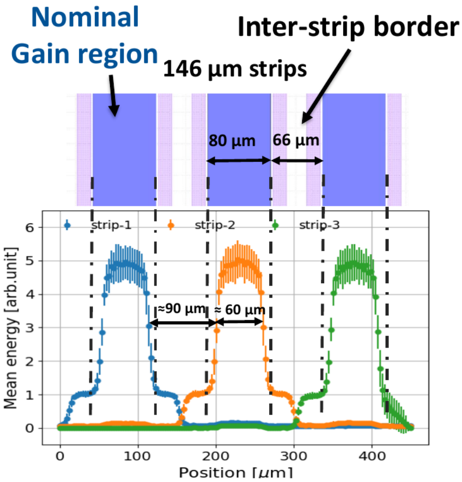


Segmentation: Fill Factor

Focused 20 keV x-ray beam



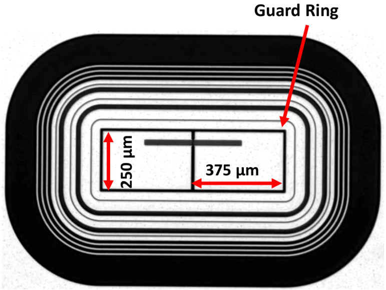
- Measured FF: ≈ 40%
- Impact on detection efficiency

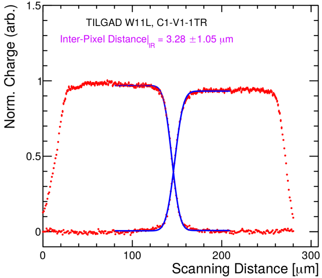


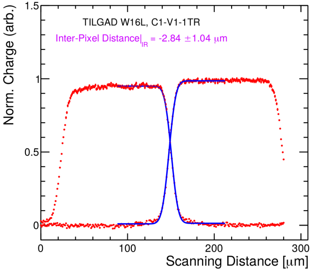
Signal vs position for 3 strips

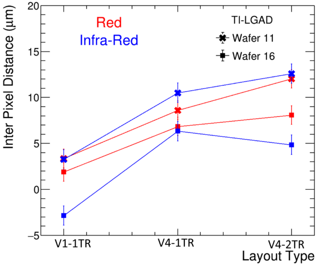
[M. Andrae, J. Zhang, et al. J. Synchrotron Rad. (2019)]

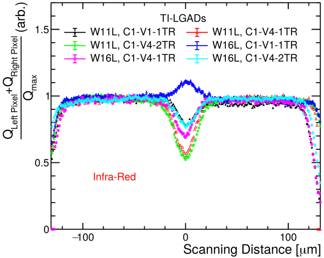
Interpad Distance TI-LGADs









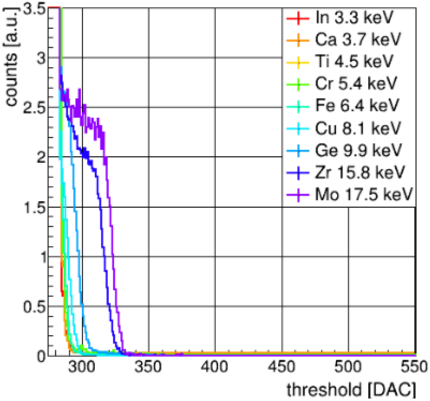


[A. Bisht Picosecond Workshop 2021]

Low Energy X-ray Detection

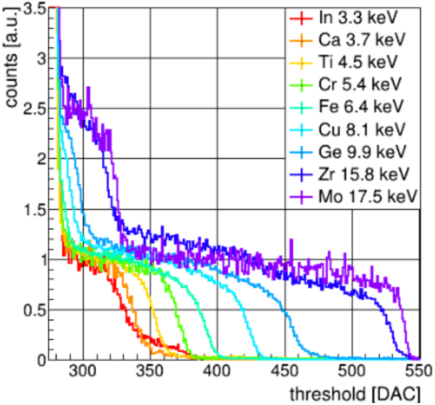
Photon counting strip detectors, fluorescence X-rays

PiN sensor



E > 8 keV visible

LGAD sensor



E < 3.3 keV visible

Improvement in detection threshold

[A. Bergamaschi TREDI2019]
[M. Andrae, J. Zhang, et al. J. Synchrotron Rad. (2019)]