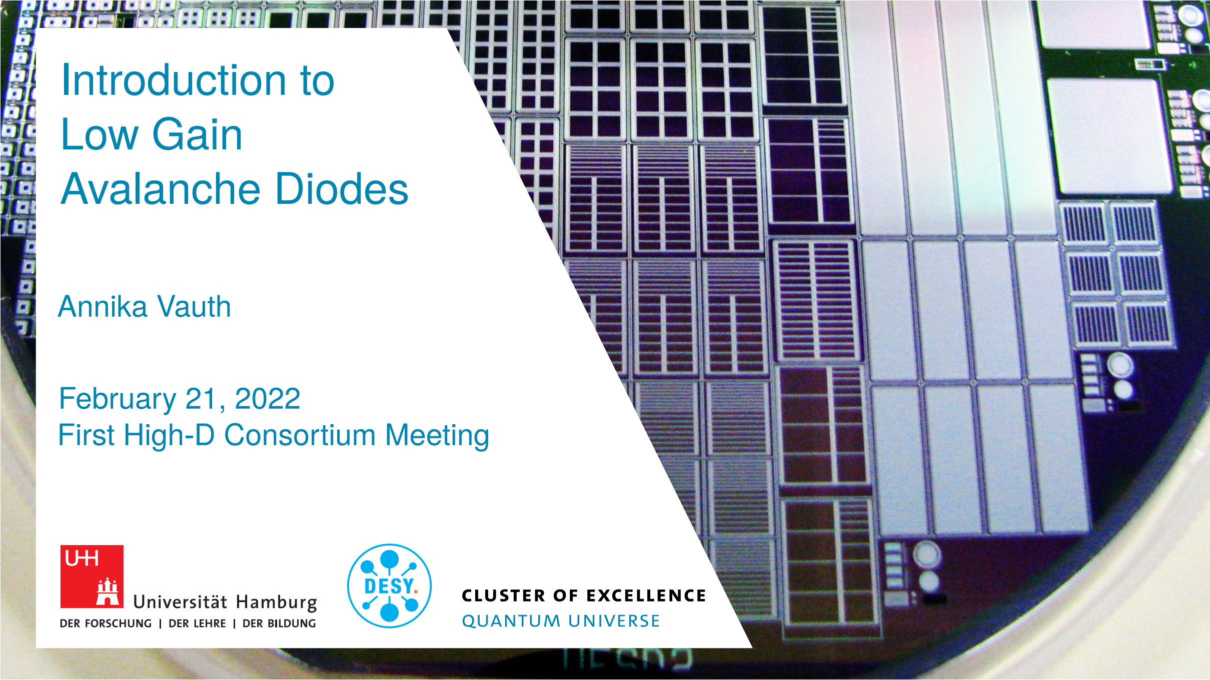
Introduction to Low Gain Avalanche Diodes

Annika Vauth

February 21, 2022
First High-D Consortium Meeting



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Motivation

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

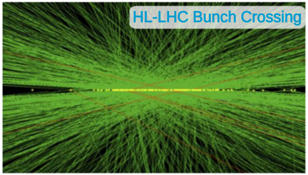
Future hadron colliders:
Challenges from very high luminosity operation
$\rightarrow$ extreme pile-up, track density, irradiation, data load

Central tracker requirements

Parameter \ Facility	HL-LHC	SPS	FCC-hh	FCC-ee	CLIC
Fluence $[n_{eq}/\mathrm{cm}^2/y]$	10^{16}	10^{17}	10^{17}	$< 10^{10}$	$< 10^{11}$
Inn. tracker $[\mathrm{m}^2]$	10	0.2	15	1	1
Out. tracker $[\mathrm{m}^2]$	200	–	400	200	140
Pixel size $[\mu\mathrm{m}^2]$	50×50	50×50	25×50	25×25	25×25
Time res [ps]	50	40	10	1k	5k

[doi.org/10.1016/j.nima.2020.164383]

The need for new timing detectors



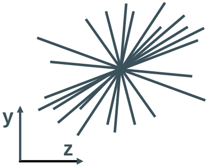
Experimental environments are evolving
$\rightarrow$ Include track timing to address new challenging conditions

Many use cases for fast timing detectors:
Pileup-reduction at HL-LHC,
ToF PID in Higgs factories,
Fast X-ray detection, ...

Time information can be used
to complement spatial information:

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

Example



pileup tracks

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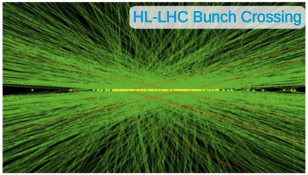

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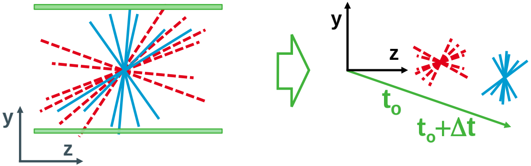
Example with timing info



added timing layer

The need for new timing detectors

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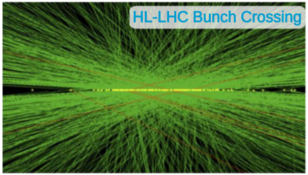
→ Include track timing to address new challenging conditions



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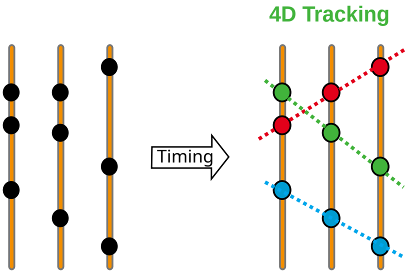
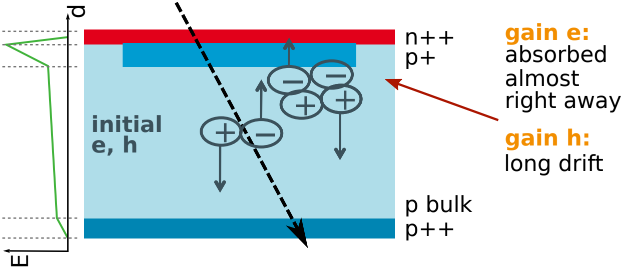


LGAD

Low Gain Avalanche Diodes

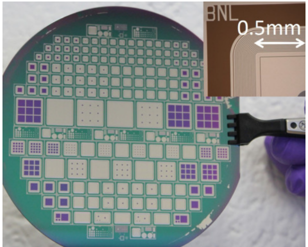
Ultra Fast Silicon Detectors
optimised for timing measurements:

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)

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



arXiv:1811.04152

LGADs for Timing

Time resolution is affected by:

- Each step in the read-out process
- Anything that changes the shape of the signal

$$\sigma_t^2 = \sigma_{\mathrm{TimeWalk}}^2 + \sigma_{\mathrm{LandauNoise}}^2 + \sigma_{\mathrm{Distortion}}^2 + \sigma_{\mathrm{Jitter}}^2 + \sigma_{\mathrm{TDC}}^2$$

arXiv:1704.08666

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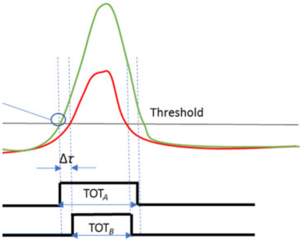
arXiv:1704.08666

Variation in time of arrival
due to different signal amplitudes

Compensation:
Constant Fraction Triggering
or amplitude-based correction (TOT)



Time walk effect OE 56(3), 031224 (2017)

LGADs for Timing

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arXiv:1704.08666

Caused by inhomogenities in drift velocity & weighting field

Compensation:
saturated drift velocity
& optimised geometry ("parallel plate")

Time-to-digital converter contribution $\Delta T/\sqrt{12}$ (bin width)

in most cases small contribution

LGADs for Timing

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$$\sigma_t^2 = \sigma_{\mathrm{TimeWalk}}^2 + \boxed{\sigma_{\mathrm{LandauNoise}}^2} + \sigma_{\mathrm{Distortion}}^2 + \boxed{\sigma_{\mathrm{Jitter}}^2} + \sigma_{\mathrm{TDC}}^2$$

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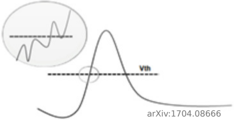
Energy deposit
Current fluctuations due to signal shape variations for MIP ionization

Time-Of-Arrival variations due to noise
- sensor noise
- electronics noise
- slew rates (dV/dt)

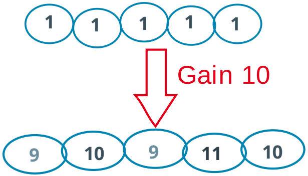


= the main contributors → **low gain, thin detectors**

Typical numbers: 20-30 ps time resolution

Why Low Gain?

High gain has many drawbacks:
risk of breakdown, power consumption, higher noise



"Excess Noise Factor" (F): additional noise induced by the multiplication mechanism

(gain not constant $\rightarrow$ additional fluctuations in current)

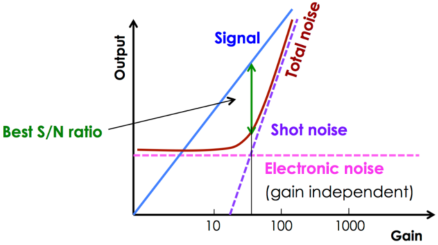
$F \sim G^x$

signal after multiplication: multiplied by G

current noise increases with $\sqrt{F}$

$\rightarrow$ S/N ratio deteriorates at higher gain

For a given ENF, there is an optimum gain (10 $\sim$ 30)



JINST (2017) 12 C02072

Why thin sensors?

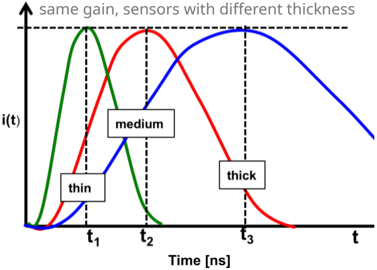
Current fluctuations are due to statistics of MIP ionization

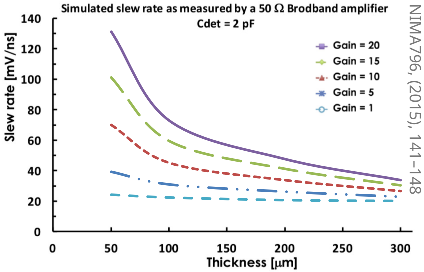
- For a fixed gain: amplitude of the signal independent of thickness d:

$$I_{max} \sim n_{eh-initial}\, G\, q\, v_{sat}$$

arXiv:1704.08666

- Slew rate (dV/dt): increases with $\frac{G}{d}$





NIMA796, (2015), 141–148

→ Thin detectors improve time resolution (35-50 µm available)

R&D Challenge: Fill Factor

Segmentation to improve spatial resolution

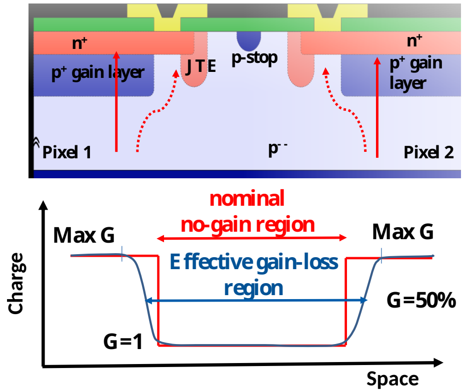
- Inter-pixel region:
  isolation and termination structures
  (p-stop, Junction Termination Extension, virtual GR)
- Carriers generated in this area not multiplied
- Interpad regions with no gain $\mathcal{O}(\approx 30\,\mu\text{m to } 70\,\mu\text{m})$

$\rightarrow$ R&D challenge:
Segmentation with improved fill factor

Several technology options:

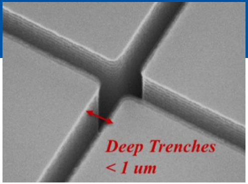
- Trench-isolated LGAD
- Inverse LGAD
- Resistive AC-Coupled LGAD

Standard segmentation



[G. Paternoster , 35th RD50 workshop, Nov 2019]

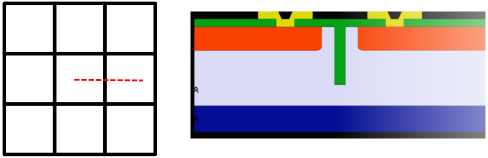
TI-LGAD



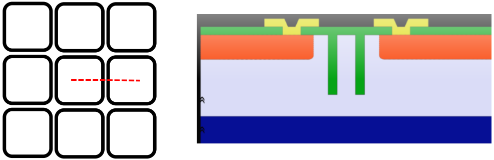
Trench isolation:

- JTE and p-stop replaced by trench to isolate the pixels
- Filled with Silicon Oxide
- Typical trench width $< 1\,\mu m$
  much smaller wrt. JTE and p-stop
  $\rightarrow$ smaller no-gain region

1 Trench Layout (trench grid)



2 Trenches Layout



[G. Paternoster , 35th RD50 workshop, Nov 2019]

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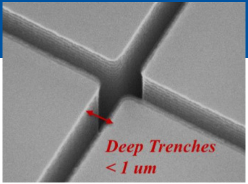

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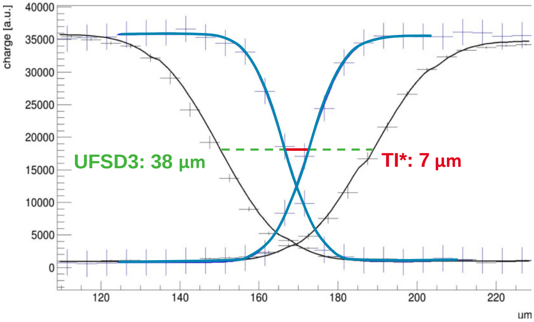
Layout	Nominal no-gain	Effective gain-loss
1 Trench	~ 4 um	~6 um
2 Trenches	~ 6 um	~3 um

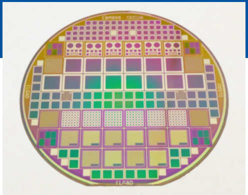
[G. Paternoster , 35th RD50 workshop, Nov 2019]

Comparison of FBK productions: UFSD3 vs Trench-Isolated



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

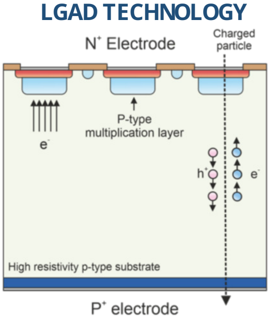
iLGAD

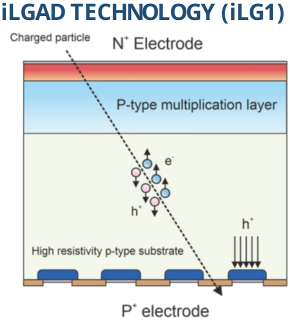


[D. Flores, SIMDET '16, Sep 2016]

Inverse LGADs:

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





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

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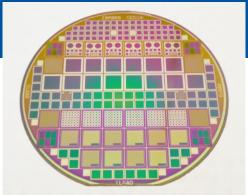
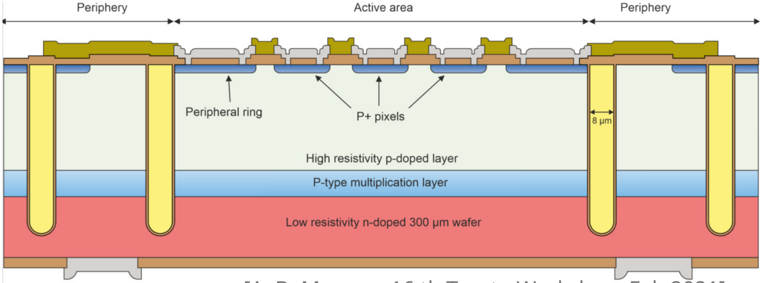


[D. Flores, SIMDET '16, Sep 2016]

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)



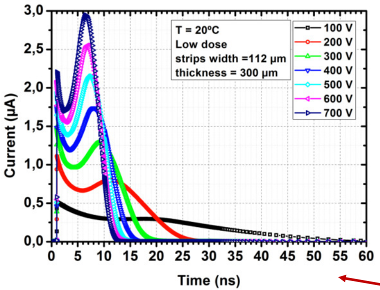
[A. D. Moreno, 16 th Trento Workshop, Feb 2021]

iLGAD for Timing

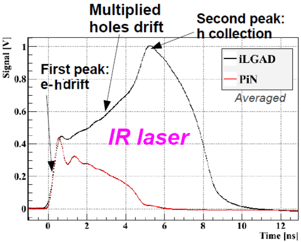
To use iLGADs for timing applications → Reduce the thickness of the detector
CNM: fabrication with two different approache

1. Epitaxial wafer + epitaxial multiplication
2. Si-Si wafers + implanted multiplication

TCAD Simulation 300 µm thick iLGAD



Experimental 300 µm thick iLGAD



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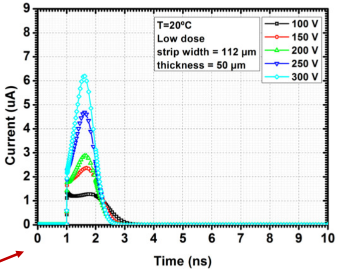
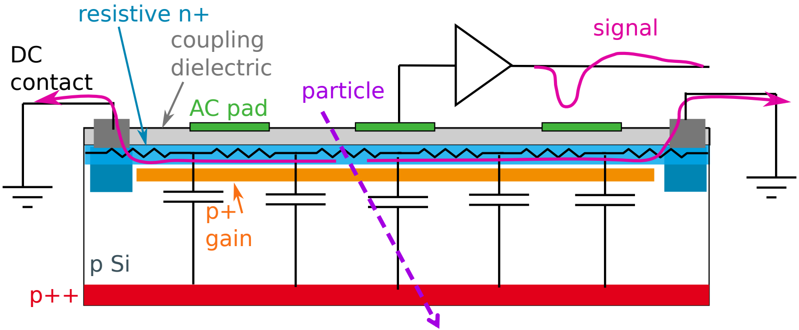


Different scale!

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

Resistive AC-Coupled LGAD

- Continuous resistive n+ implant
- Readout: AC-coupling through a dielectric layer
- Segmentation obtained by postion of the AC pads
  $\rightarrow$ 100% fill factor design

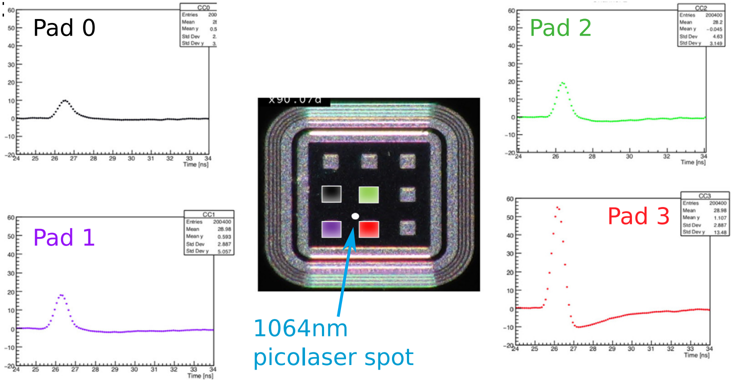


Resistive AC-Coupled LGAD (2)

Naturally leads to signal-sharing among the pads

$\rightarrow$ High position resolution even with “larger“ pitch e.g. $\sim 5\,\mu m$ resolution with $200\,\mu m$ pitch

Charge sharing optimisation:
Arrays (regular/staggered),
Pad shape designs



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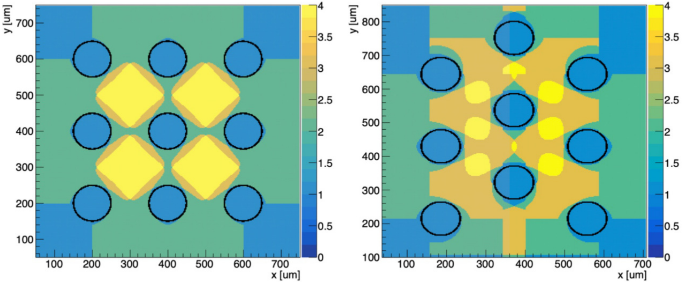

[doi.org/10.1016/j.nima.2021.165319]

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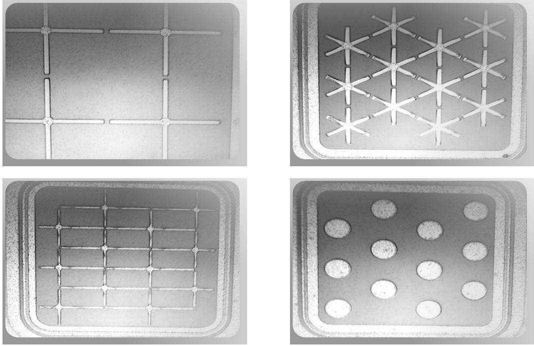
Naturally leads to signal-sharing among the pads

→ High position resolution even with “larger“ pitch e.g. $\sim$ 5 µm resolution with 200 µm pitch

Charge sharing optimisation:
Arrays (regular/staggered),
Pad shape designs

Hit on pads: charge sharing
only 10-20 µm from metal edge

Example: FBK RSD2 designs



INFN-FBK design patent submitted to the *Italian Ministry of Economic Development* (MISE), application number **102021000011444**, May 2021

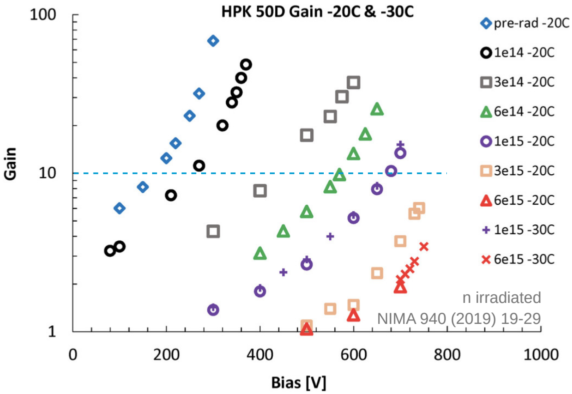
[M. Mandurrino, 39th RD50 workshop]

R&D Challenge: Radiation Tolerance

Irradiation causes three main effects:

- Decreased charge collection efficiency
- Increased leakage current
- Change of doping profile

Deactivation of p-doping by Boron removal
→ Gain reduction due to irradiation



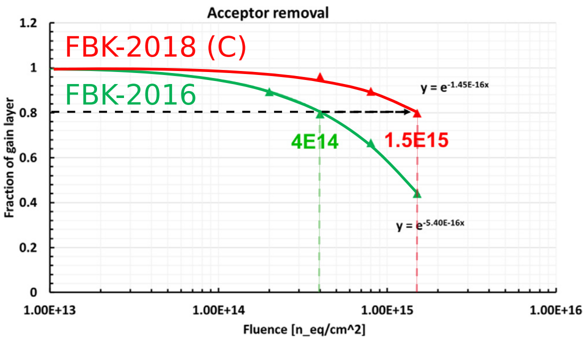
R&D Challenge: Radiation Tolerance (2)

Lots of R&D ongoing, different doping profiles and ion implants:

Defect Engineering of the gain implant
- Carbon co-implantation in gain layer volume
- Boron as gain layer implant

Modification of gain layer profile
- Narrower doping layer
  with higher initial doping

More on radiation damage:
See talk by Chuan Liao
tomorrow afternoon

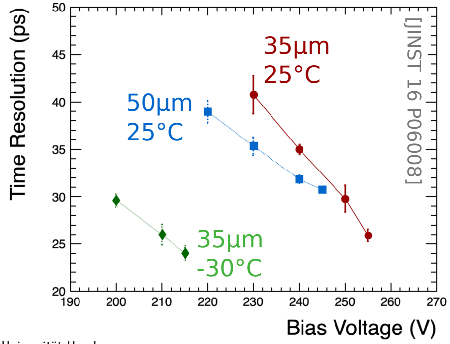


[doi 10.1016/j.nima.2020.164383]

Ultra-fast silicon detectors - performance

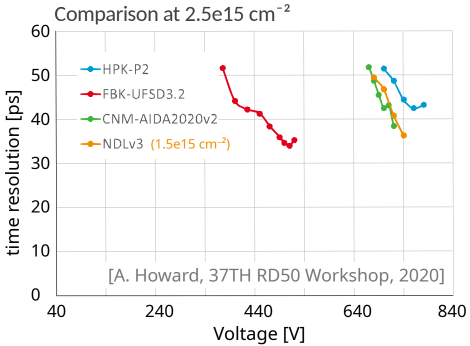
Example: Study for TOPSiDE

- HPK LGADs with 35 / 50 µm thickness
- Time res up to ∼25 ps
- With 3 layers: 14.3±1.5 ps



Example: Irradiation study for HGTD

- LGAD with 45 – 55 µm thickness
- Different vendors/implantations
- ∼40 ps time resolution after irradiation



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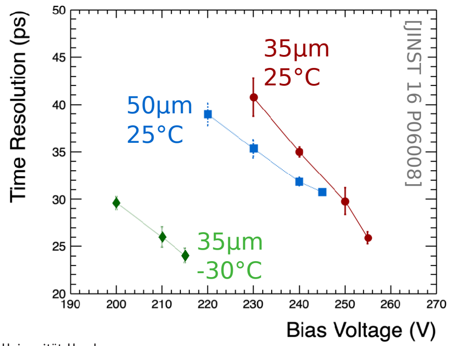

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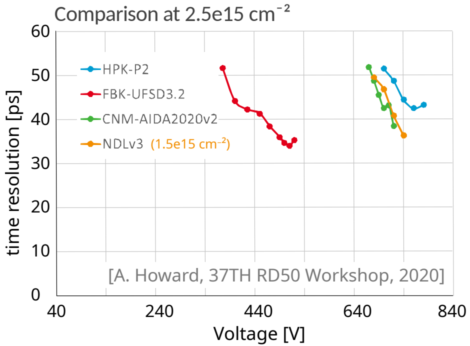


Hamburg University LGAD projects (1)

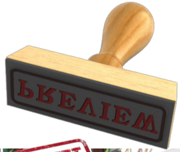
HEP detector R&D: dedicated beam tests for conceptual / technical design, calibrations, commissioning, ...

$\rightarrow$ DESY II Testbeam Faciliy

Integral part of test beam infrastructure: Beam Telescopes
Current EUDET-type telescopes:
Six planes of MIMOSA26 sensors
Intrinsic sensor resolution: $\sigma \cong 3\,\mu\text{m}$

Rolling shutter readout, readout cycle $115\,\mu\text{s}$

Add faster device for time stamping the tracks
$\rightarrow$ LGAD timing layer

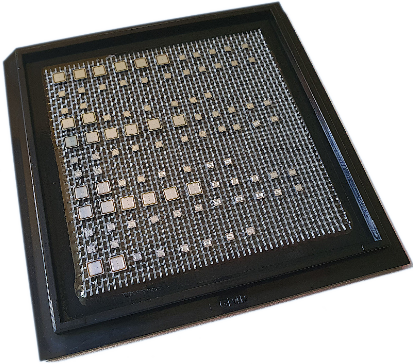


Hamburg University LGAD projects (2)

LGAD prototypes expected:

- TI-LGADs from FBK(*)
- i-LGADs from CMN

(*)received first test structures



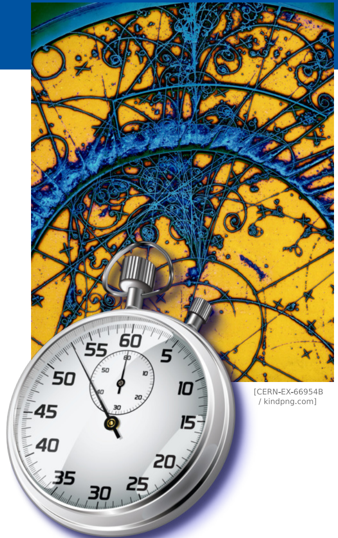
Setups for characterisation existing / in preparation

- CV-IV measurements
- Beta-source setup for timing measurements
- TCT setup
- ...

Future plans: testbeam campaigns and irradiation studies

Summary & Outlook

- Low Gain Avalanche Diodes to measure both time and space - with improved signal-to-noise ratio
- For timing: 30-50 μm thickness, gain $(O)(10)$
- LGAD design: R&D ongoing on
  - radiation hardness (doping profile, ion implantats)
  - segmentation (Trench / Resistive AC / i-LGAD)
  - and more (uniformity, electronics, ...)
- Current University of Hamburg projects: beam telescope timing layer & radiation hardness studies



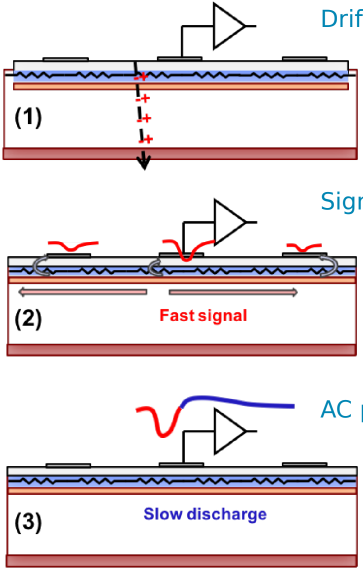
[CERN-EX-66954B / kindpng.com]

The future of timing:
LGADs will find more and more applications in 4D-tracking

Backup Slides

AC LGAD Signal Formation

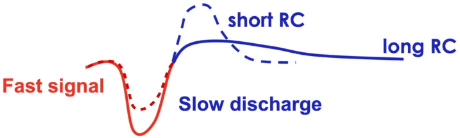
[doi.org/10.1016/j.nima.2021.165319]



Drifting e/h pairs induce charge on n+ implant

Signal spreads along n+ layer

AC pads discharge



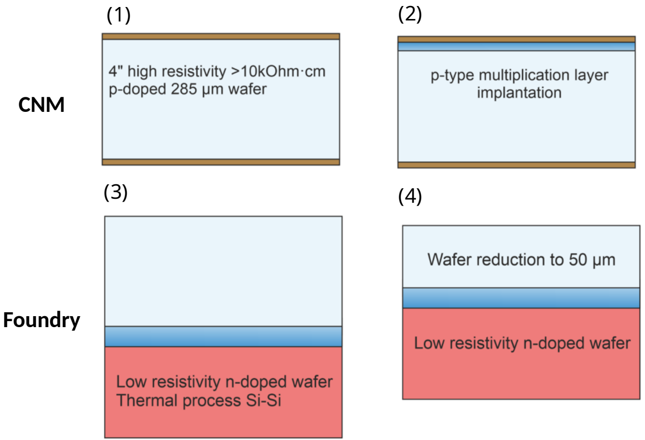
R → n+ sheet resistance

C → bulk thickness, metal pad capacitance

iLGAD Third Generation (iLG3): Fabrication Process

We are planning to carry out this fabrication with two different approaches:

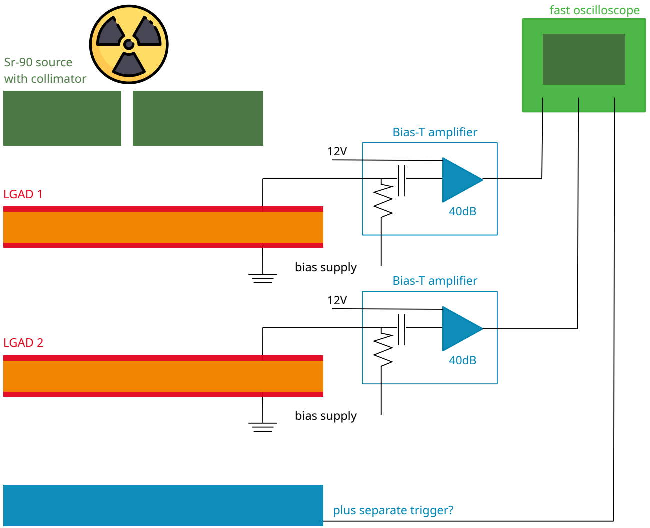
1. Epitaxial wafer + epitaxial multiplication
2. **Si-Si wafers + implanted multiplication**



Dose/energy multiplication layer is adapted to the Si-Si thermal process

After (4), the profile is the same as standard LGAD runs. This is the starting point for the fabrication.

Beta Timing Setup



ATLAS

High-Granularity Timing Detector for phase 2 upgrade

Two endcap disks at $z=\pm 3.5\,\mathrm{m}$

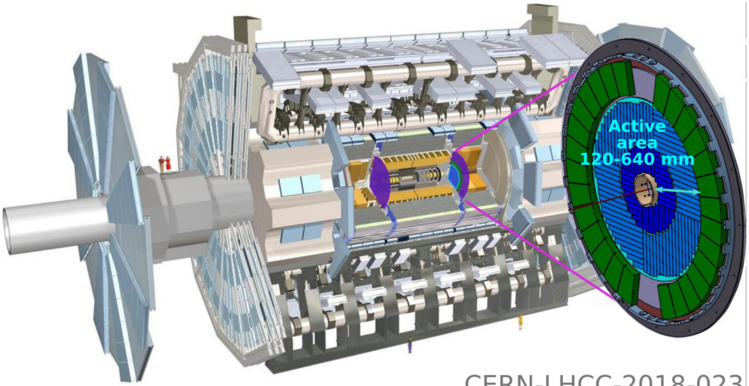
2 double-sided layers

30 ps TOF resolution for charged particles,,

$1.3\times 1.3\,\mathrm{mm}^2$ pixels

for occupancy $<10\%$

$6.3\,\mathrm{m}^2$ active area



CERN-LHCC-2018-023

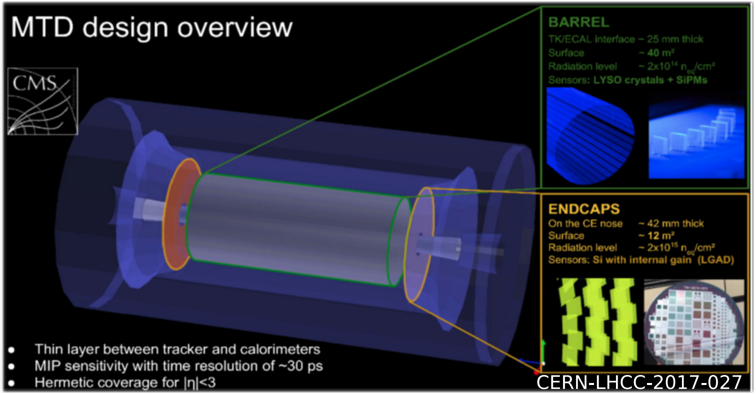
CMS

MIP Timing Detector timing layer between tracker and calorimeter

- Barrel Timing Layer:
  thin crystal (LYSO) + SiPM
- Endcap Timing Layer
  in front of HGCal: LGAD

30 ps TOF resolution for charged particles
($p_T > 0.7 GeV$)

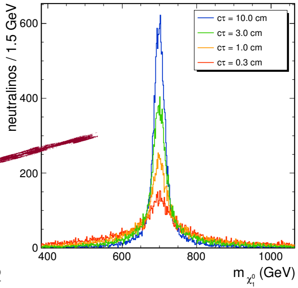
7.9 m^2 sensor area/side



Benefits of 30ps Timing to CMS Physics

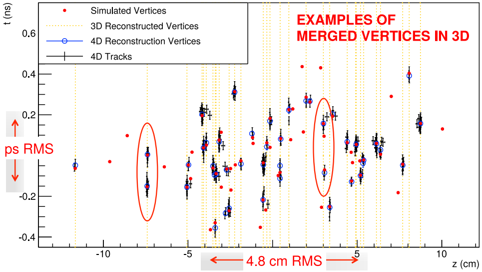
Signal	30ps Timing Benefits	**Physics Impact**
$H \to \gamma\gamma$ **(*)**	Photon isolation, vertex choice	+25% precision on cross-section
VBF + $H \to \tau\tau$	Isolation, VBF tagging, ME_T resolution	+20% precision on cross-section
HH	Isolation, b-tagging	+20% signal efficiency
SUSY	Reduce MET tails	-40% irreducible BG

- Benefits across **many** physics channels
  - Overall: +20-40% **effective** integrated lumi
- **New** physics opportunities
  - Reconstruct **mass of tracks** (LLP, HSCP)
  - TOF PID: **exclusive flavour** physics in Pb-Pb

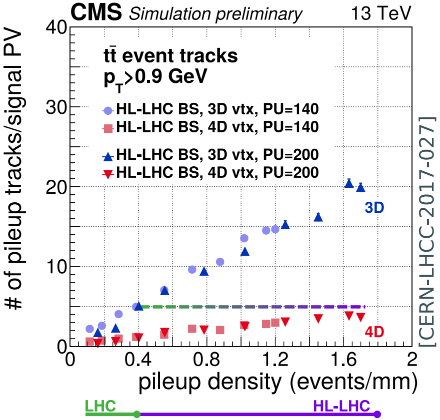


Example of time-aware vertexing

- **Event with 50 pileup collisions to ease eye analysis**



- 4D reconstruction with track time information: σ~25 ps



[slide Tommaso Tabarelli-de-Fatis , Scint 2017