LGAD at Collider Experiments

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First Annual EICC workshop 2026
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中国科学技术大学
University of Science and Technology of China

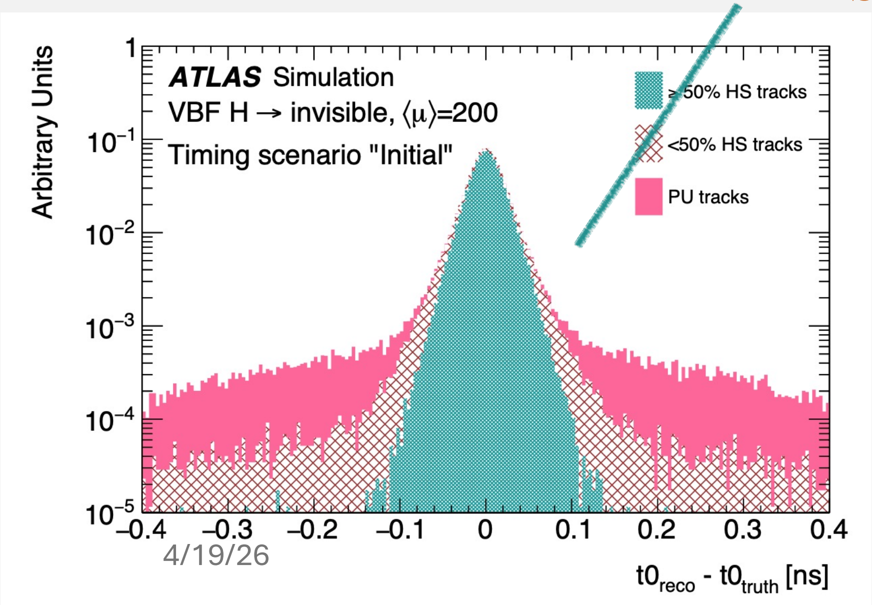
Outline

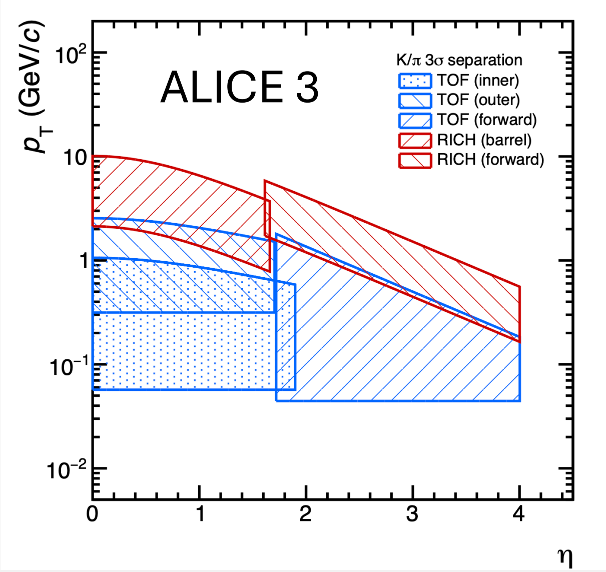
- Work principle of LGAD and early R&D
- Optimization for LHC phase 2 upgrade
- AC-LGAD for electron-ion colliders
- Trench-Isolated (TI) LGAD
- CMOS-LGAD

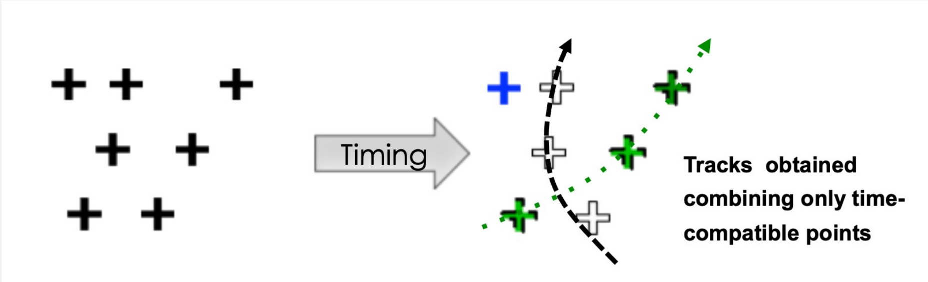
Applications of LGAD at collider experiments

- HL-LHC ATLAS/CMS: time information to tracks, vertices to mitigate pile-up (at peak luminosity, expect 200 pile-up per BX)
- EIC, ALICE 3 TOF for PID
- Future: 4D tracking

RMS = 22 ps



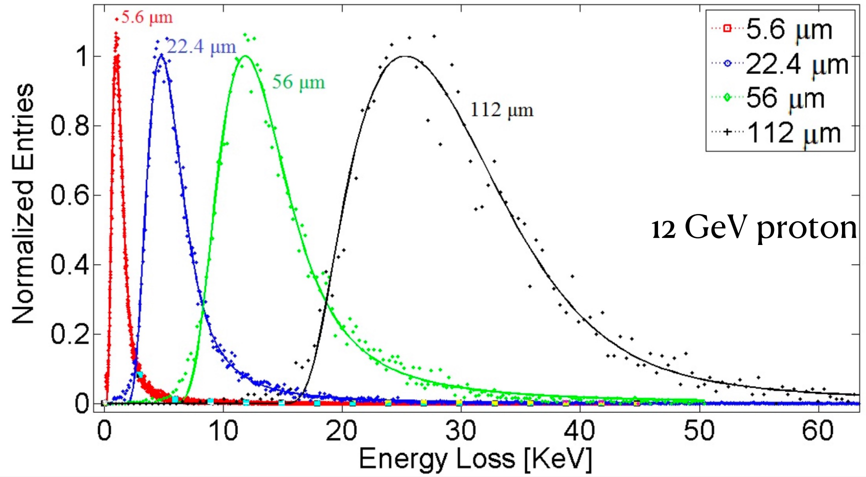


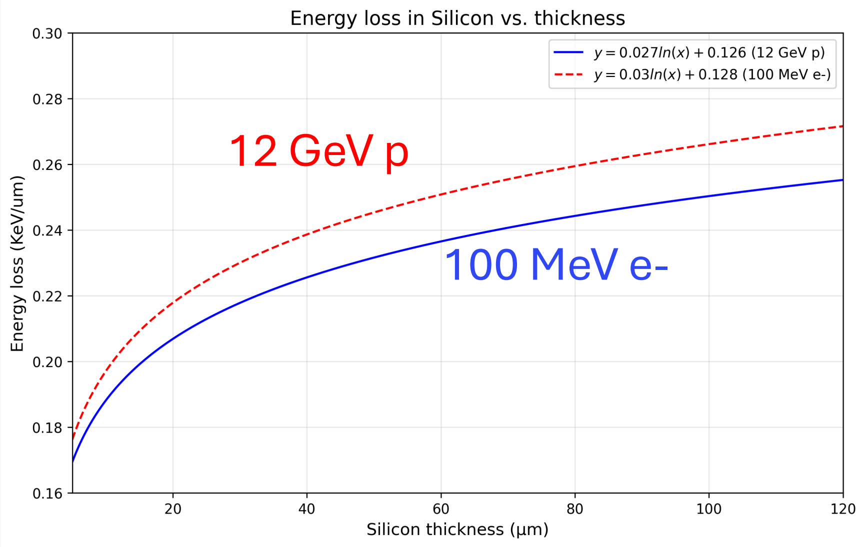


Some numbers about Silicon detectors

- MIP E loss : 0.23 keV/μm
  (MPV for 50 μm thick Si)
- Average ionizing energy: 3.68 eV
- If no gain, 50 μm → ~0.5 fC

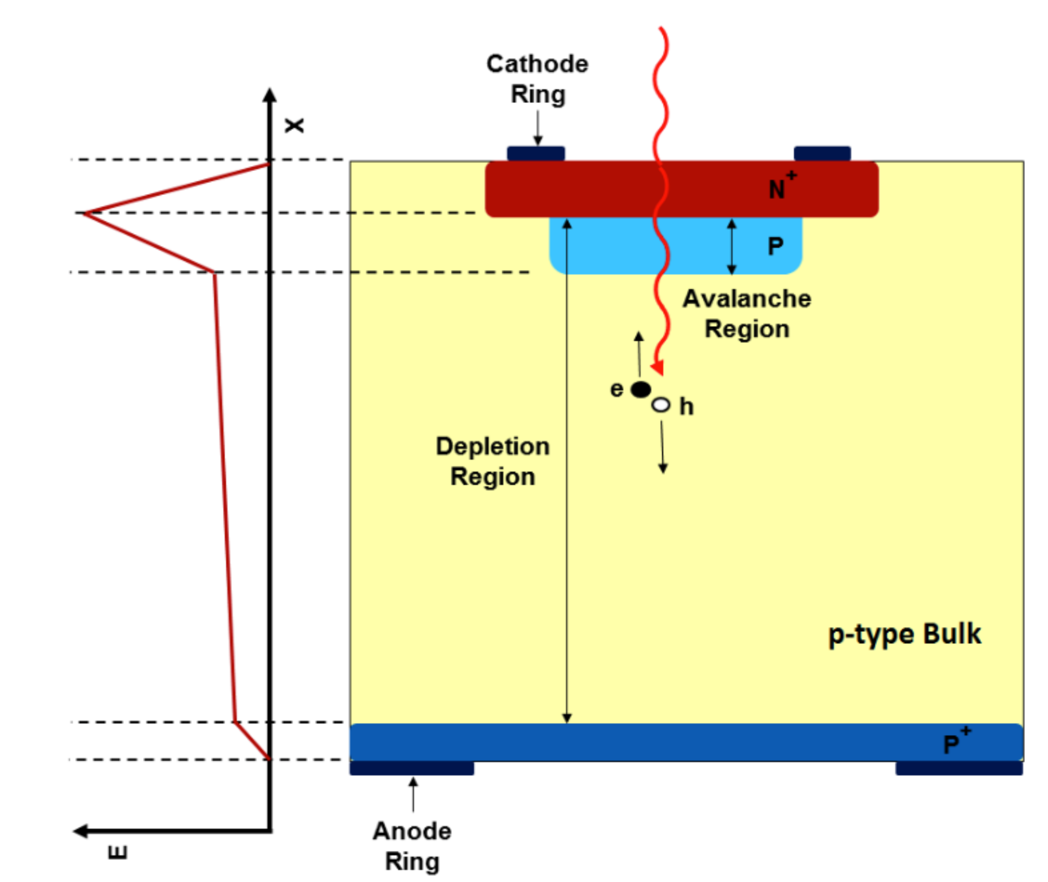
LGAD	Gain:5~20
APD	Gain: 50~1000
SiPM	Gain: 10^5~10^7

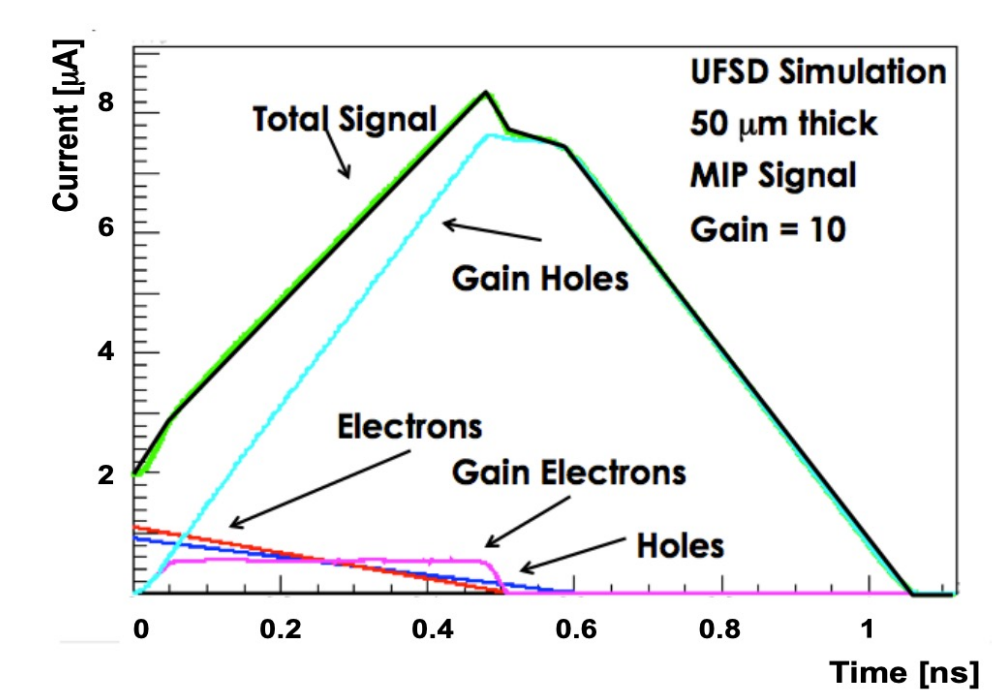




JINST 6 (2011) P06013

Work principle of Low Gain Avalanche Diode





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Invention of LGAD

- 21st RD50 WS **2012**:charge multiplication in irradiated silicon detectors [talk]
- 25th RD50 WS **2014**: Common project to investigate thin LGAD (talk at CB)

Radiation hard semiconductor devices for very high luminosity colliders

RD50

2004-2024 (evolved to DRD3)

RD50 - Common Projects

Template for funding request: Funding request to RD50 (Rules are given on bottom of this page)

2014.4

		Reference
August 2014	**Investigation of the properties of thin LGAD**; *Nicolo Cartiglia* *funding request* *approval*	2014-05
	RD50 Common Test beam at CERN; Marco Bomben (a financial support to students was granted 4 x 500 CHF)	2014-04
March 2014	**Production of thin active edge pixel sensors at ADVACAM**; Anna Macciolo funding request approval	2014-03
	Fabrication of 200um thick p and n- type pad detectors with enhanced multiplication effect; Giulio Pellegrini funding request approval	2014-02
	UBM for sensor wafers; Giulio Pellegrini (no cost to RD50 common fund)	2014-01

Status of CNM RD50 LGAD Project — 26th RD50 Workshop. Santander. 23th June, 2015

RD50 Samples Distribution 2015.6

1. CNM Barcelona, G. Pellegrini, Giulio.Pellegrini@cnm-imb.csic.es
2. CERN, M. Moll, Michael.Moll@cern.ch
3. UC Santa Cruz, Hartmut Sadrozinki, hartmut@ucsc.edu
4. LAL Orsay, Abdenour Lunis, lounis@lal.in2p3.fr
5. IFCA Santander, Ivan Vila, ivan.vila@csic.es
6. INFN Torino, N. Cartiglia <cartiglia@to.infn.it>
7. Jozef Stefan Institute , G. Kramberger, Gregor.Kramberger@ijs.si
8. IFAE Barcelona, S. Grinstein, sgrinstein@ifae.es

First paper on LGAD (2014.6)
300 μm thick!
Establsihed gain layer
No discussion about timing

Nuclear Instruments and Methods in Physics Research A 765 (2014) 12–16

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Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications

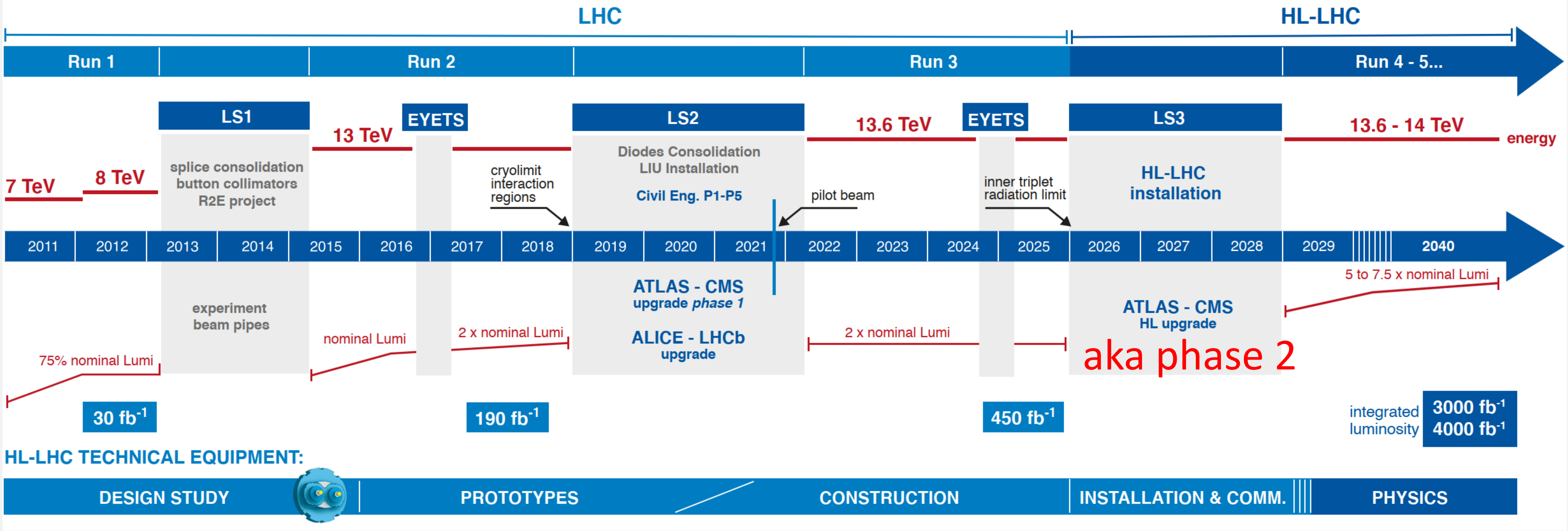
G. Pellegrini [a,*], P. Fernández-Martínez [a], M. Baselga [a], C. Fleta [a], D. Flores [a], V Greco [a], S. Hidalgo [a], I. Mandić [b], G. Kramberger [b], D. Quirion [a], M. Ullan [a]

[a] Centro Nacional de Microelectrónica, IMB-CNM-CSIC, Barcelona, Spain
[b] Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

High-luminosity LHC schedule

Phase 2 = 87% of LHC !

Current LS3 schedule: Jul 2026 ~ Jun 2030



Rept.Prog.Phys. 81 (2018) 2, 026101

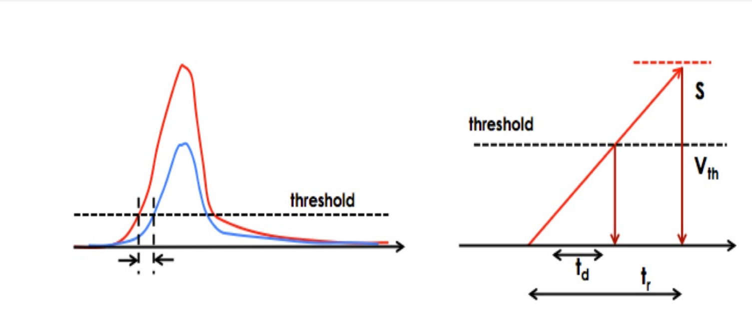
Key points for timing: low gain and thin!

- Time resolution decomposition

$$\sigma_t^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TimeWalk}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{clock}}^2$$

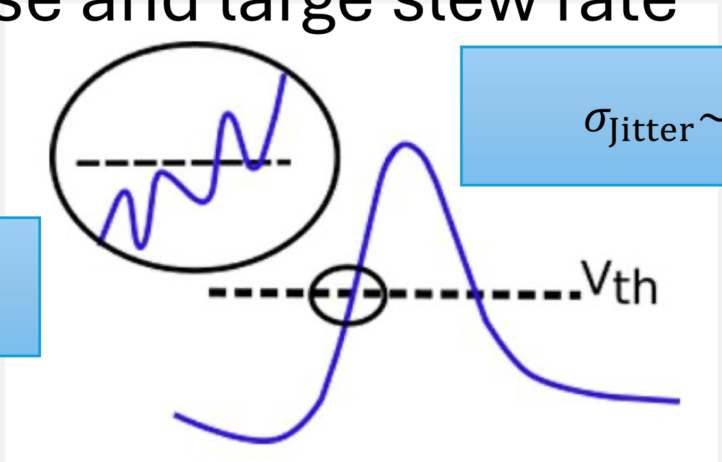
Often negligible

- Landau: fluctuation of energy deposition
  - Mitigation: thin sensors
- Distortion: non-uniformity of drift velocity and weighting field
  - Mitigation: planar and thin sensor, high E-field to saturate drift velocity
- Time-walk and jitter minimized by low noise and large slew rate



$$t_d = \frac{V_{th}}{S} t_{\text{rise}} \propto \frac{\text{Noise}}{S/t_{\text{rise}}}$$

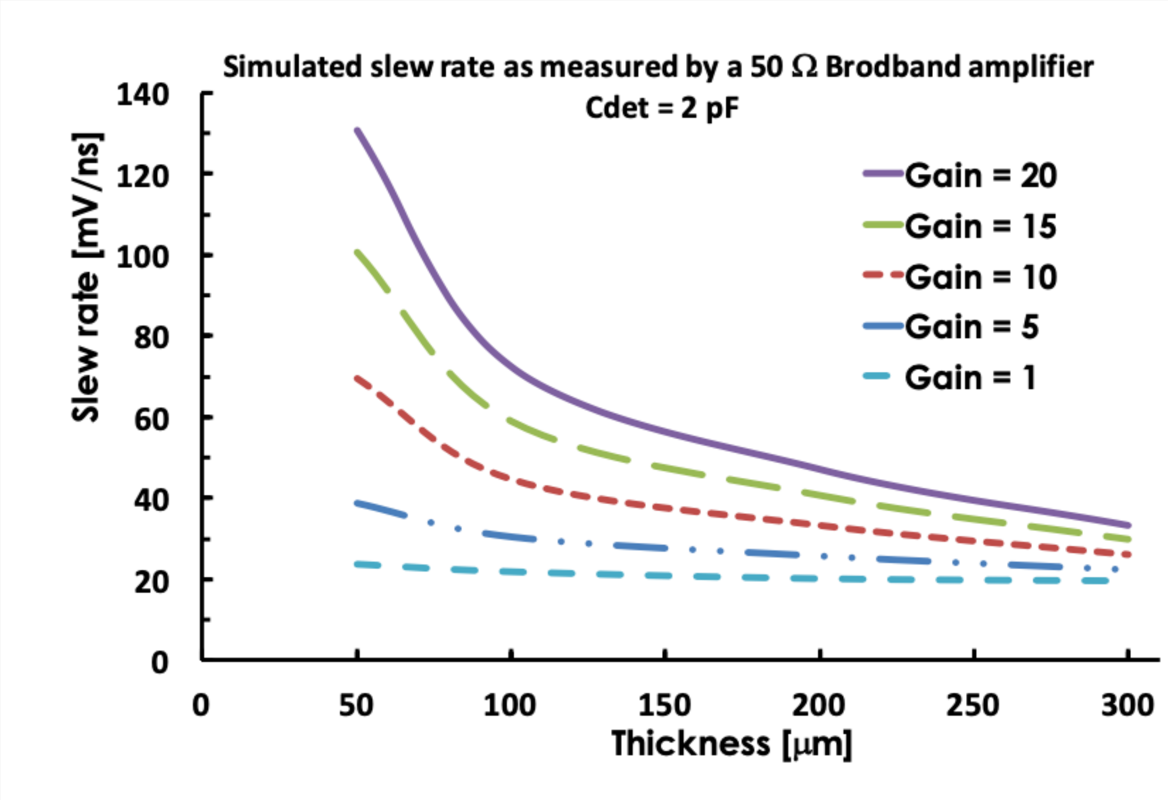
$$\sigma_{\text{TimeWalk}} \sim \text{RMS}[t_d] \sim \text{RMS}[\frac{\text{Noise}}{S/t_{\text{rise}}}]$$

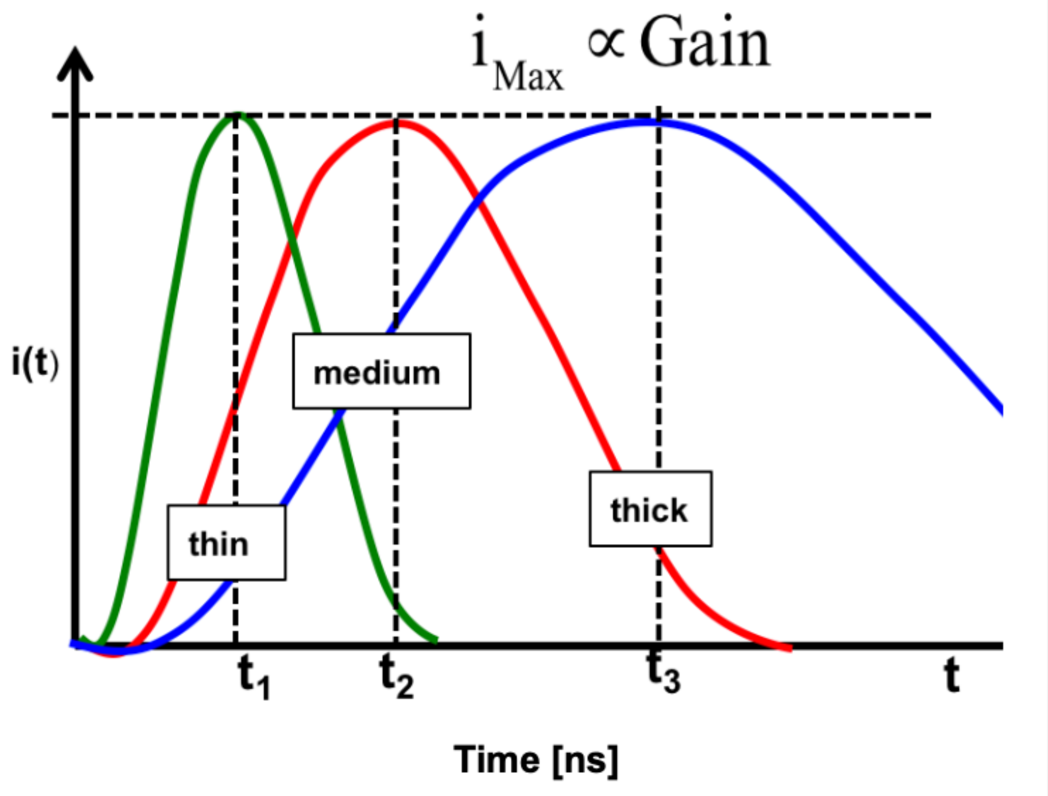


$$\sigma_{\text{Jitter}} \sim \frac{\text{Noise}}{S/t_{\text{rise}}}$$

Slew rate vs. thickness

$i_{\max}$ independent of thickness
Thinner sensor => higher slew rate





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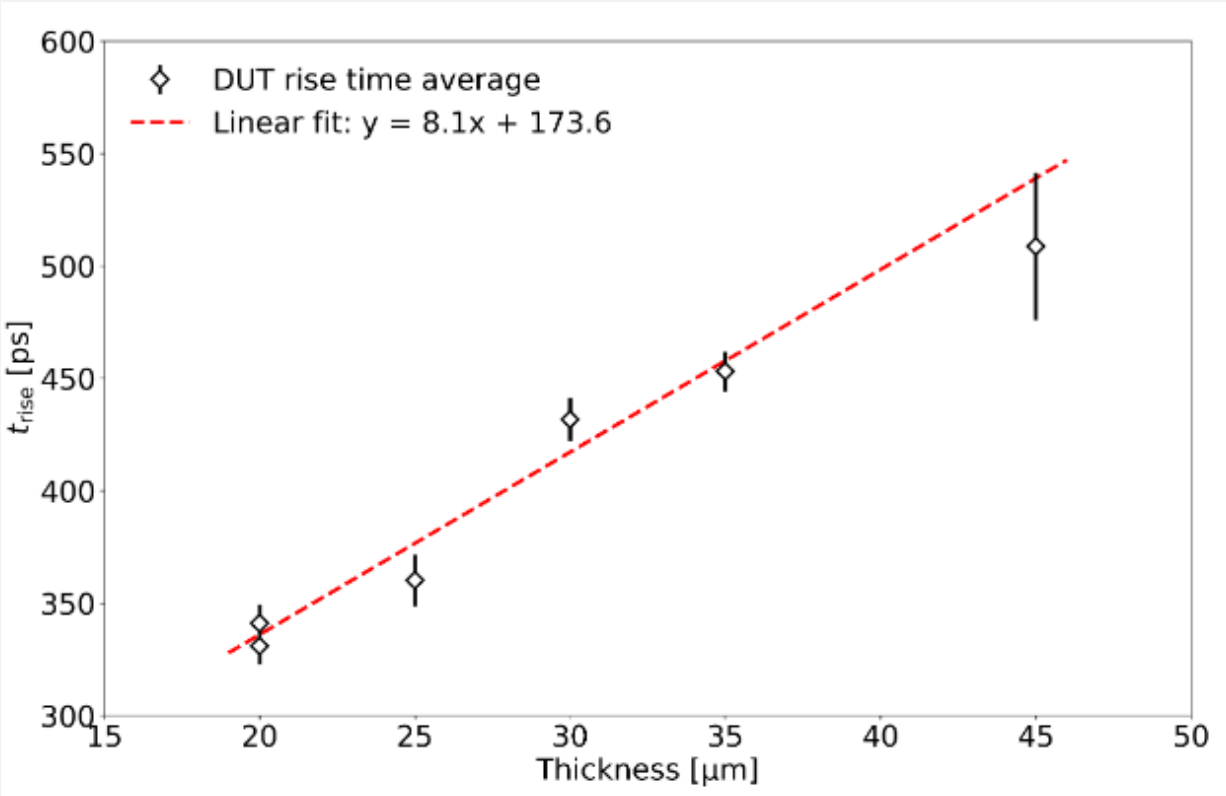
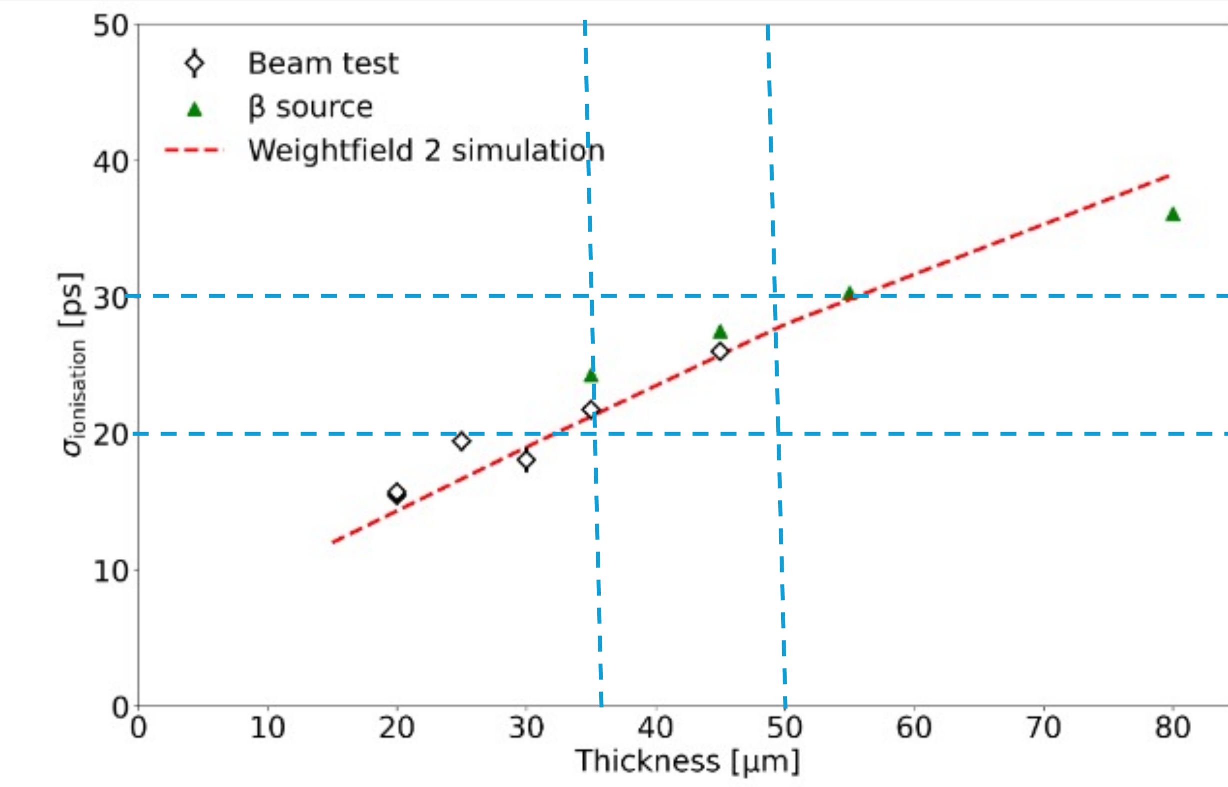
arXiv:2511.22308

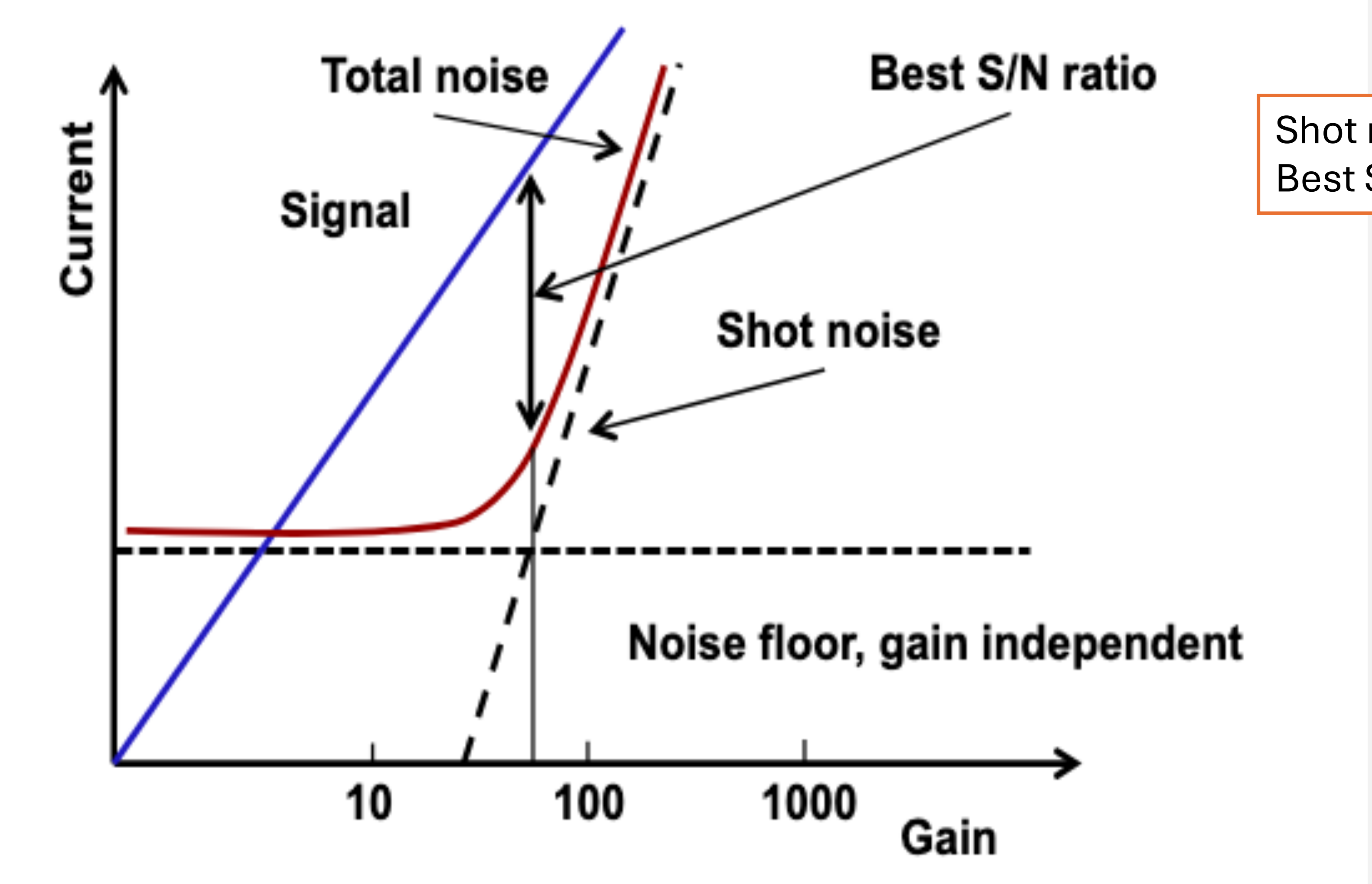
Systematic experimental verification (2025)





50 μm → ~ 30 ps
35 μm → ~ 22 ps

Gain optimization

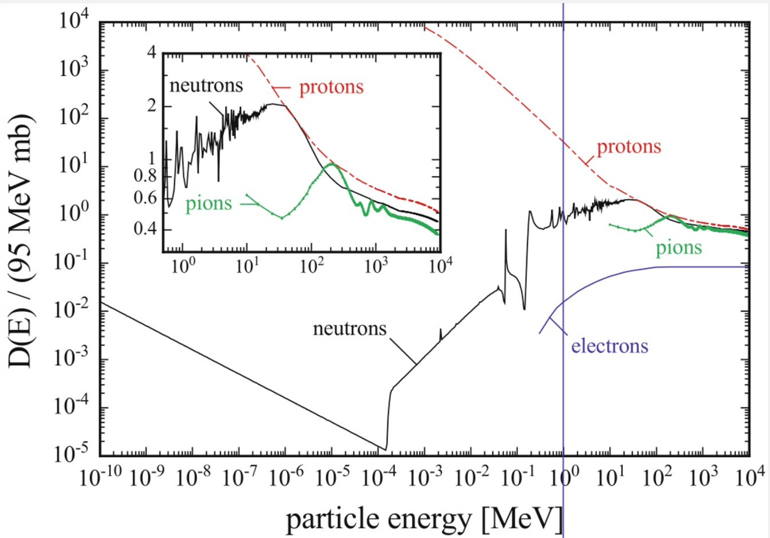


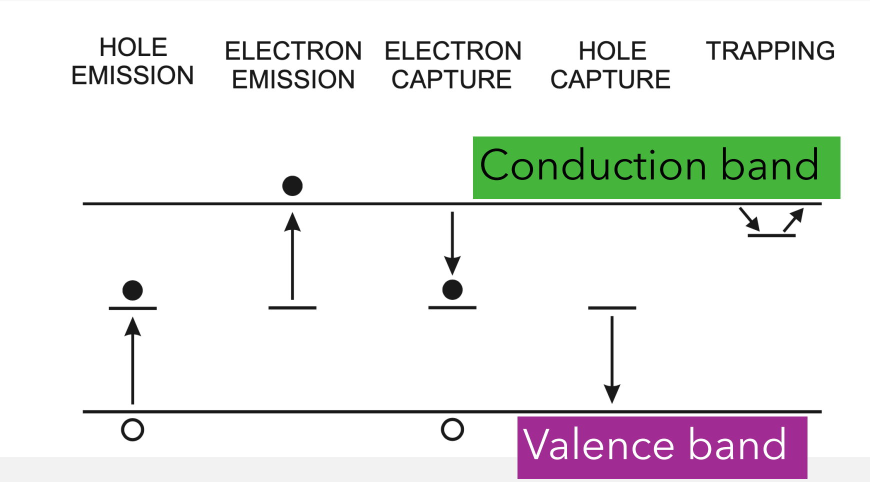
Shot noise increase with bulk leakage current
Best S/N achieved at gain of few 10s

Radiation damages to LGAD

- **Ionizing damage**: energy absorbed by ionizing(1 Gy = 1 J/kg = 100 rad) in insulating layers, liberates charge carriers (less relevant for sensors)
- **Displacement damage**(displaces silicon atoms from their lattice sites)
  - Formation of mid-gap states => increase of leakage current
  - states close to band edges => trapping(decrease charge collection efficiency)
  - Inactivation of Boron doping(Acceptor removal)
  - Energy and particle type dependent (measured in 1 MeV neutron equivalent / cm^2)

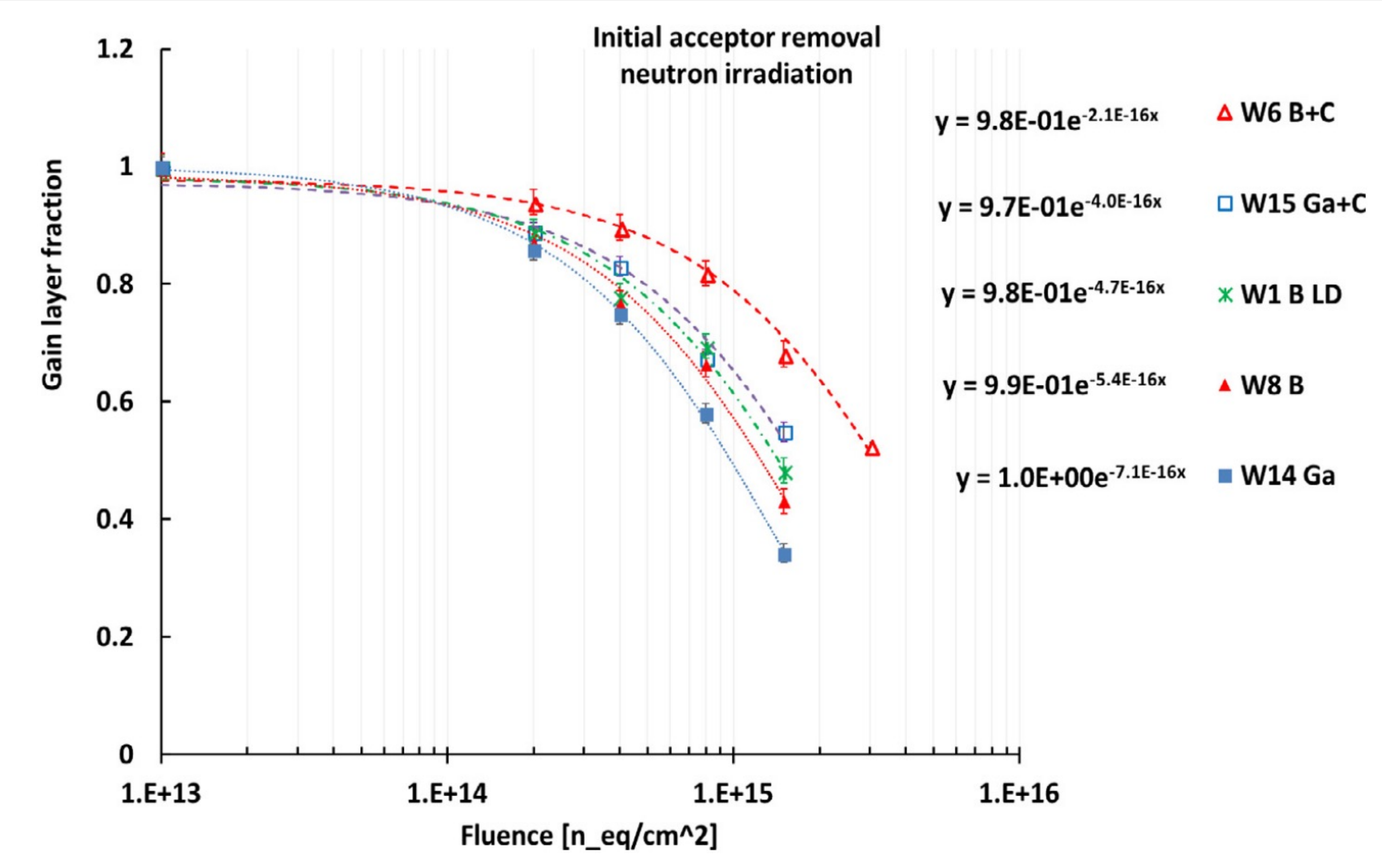
$$D(E) = \sum_{\nu} \sigma_{\nu}(E) \int_0^{E_R^{max}} f_{\nu}(E, E_R) P(E_R) \mathrm{d}E_R$$





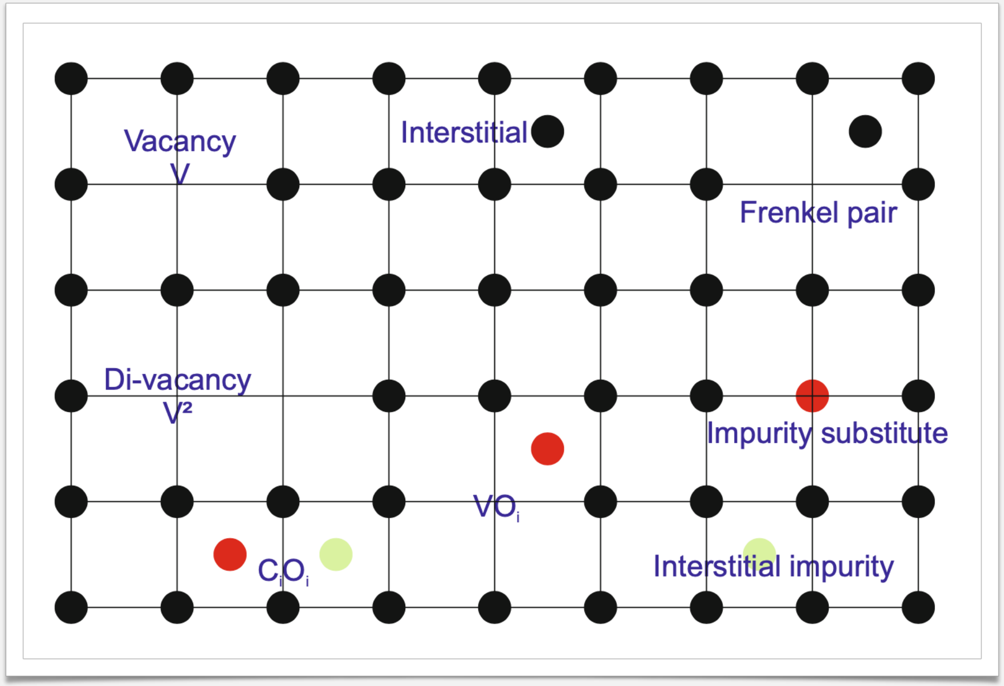
NIMA 910(2019)16

Co-implantation of gain layer

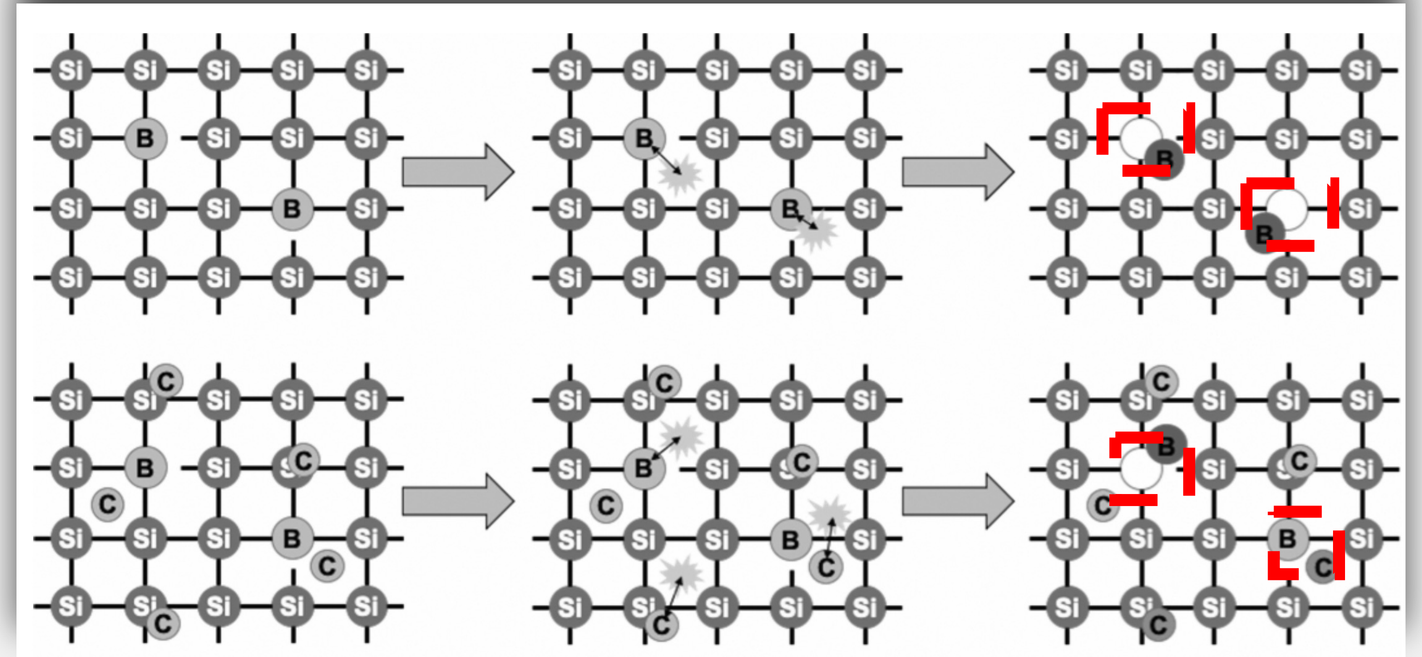


Effects of Carbon in gain layer (conjecture)

Defects in Silicon lattice



Carbon competes with Boron to form ion-defect states



Carbon implantation at gain layer:

1) replace Boron in ion-defect complex formation
2) substitutional carbon pair with interstitial Boron to form centers with energy of 80% acceptor energy level

Snapshot of sensor status in 2021

Recent productions (>2020)

Manufacturer	Name	D [μm]	GL [μm]	V_{gl} [V]	Dopant/C	SE [μm]	IP [μm]	Max. Array Size
HPK (HPK-P2) (6”)	P2 (4 splits)	~50	~2.2	50.5-54.5	B/NO	300-500	30-70	Single,2x2,3x3,5x5,15x15,15x30
FBK (6”)	UFSD 3.2	~45,55	~1-2	25-50	B/YES	500	28-49	Single, 2x2,5x5
NDL (6”)	V3, V4	~50	~1	~29	B/NO			2x2
IHEP-IME (8”)	V1, V2	~50	~1	~25	B/YES			Single, 2x2, 5x5
USTC-IME (8”)	V1.1, V2.0, V2.1	~50	~2	30-40	B/YES		30-90	Single,2x2,5x5,15x15
CNM (6”)	R12916 (AIDAv2)	~50	~1	~40	B/NO			Single, 2x2, 5x5

HPK serves as “gold standard” to which others are compared – the key results will be shown HPK

Mains specifications are in the TDRs.

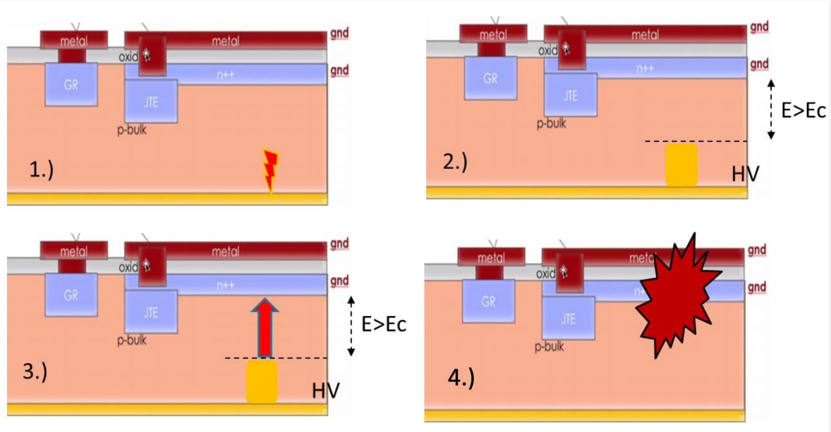
The key property is collection of **4 (ATLAS) /5 (CMS) fC** (G~8/10) at **safe operation voltage** over the entire lifetime of the experiments (2.5e15 cm^{-2})

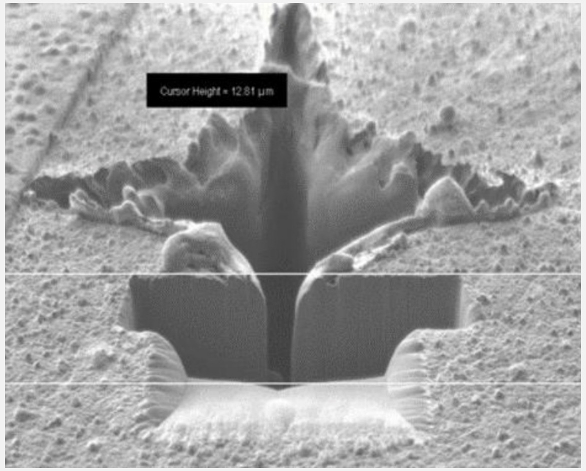
It was shown with discrete electronics that the required time resolution and efficiency can be achieved with >4 fC and also for expected ASICs performance <70 ps for single hit resolution.

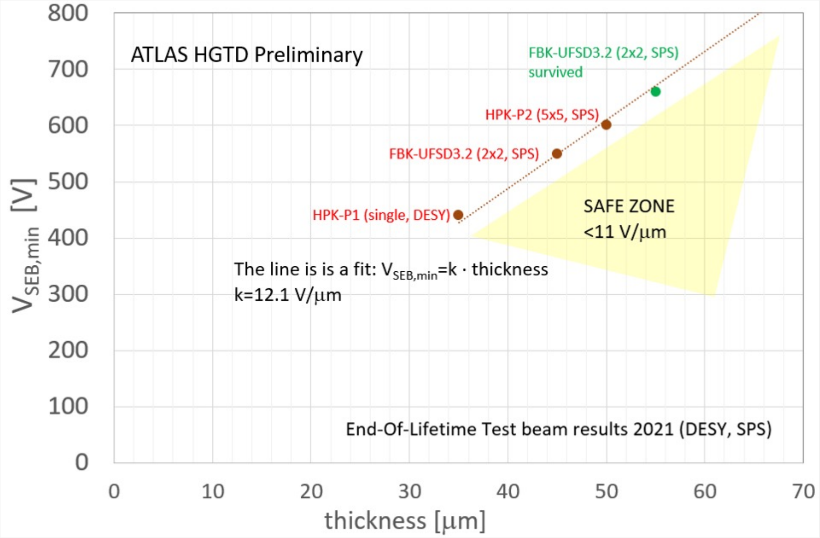
NIMA 1041(2022)167321

Sensor mortality

Large energy deposition →large amount of charge carriers → conductive path
→ localized high E-field (above critical E-field) → irreversible breakdown

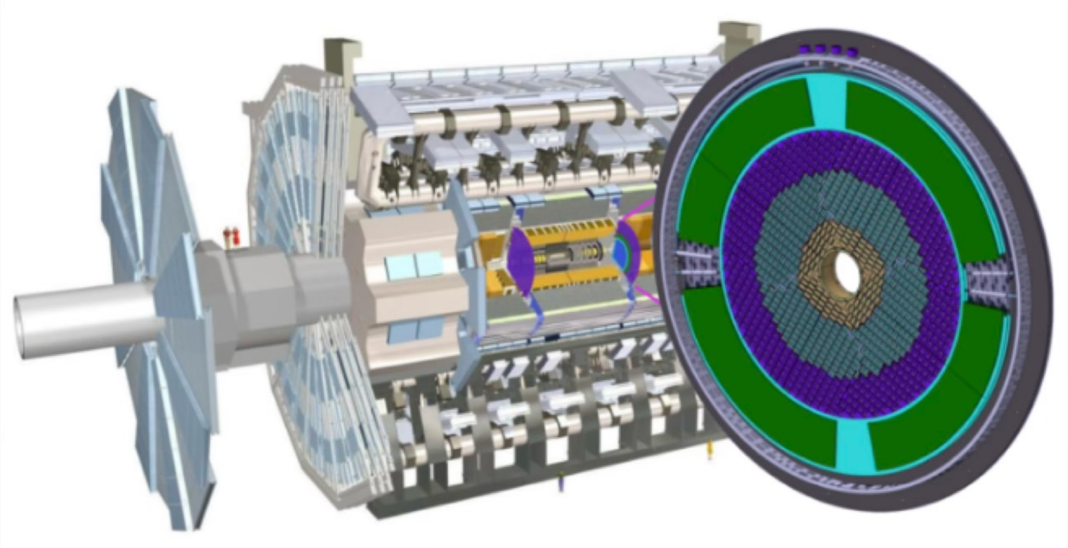




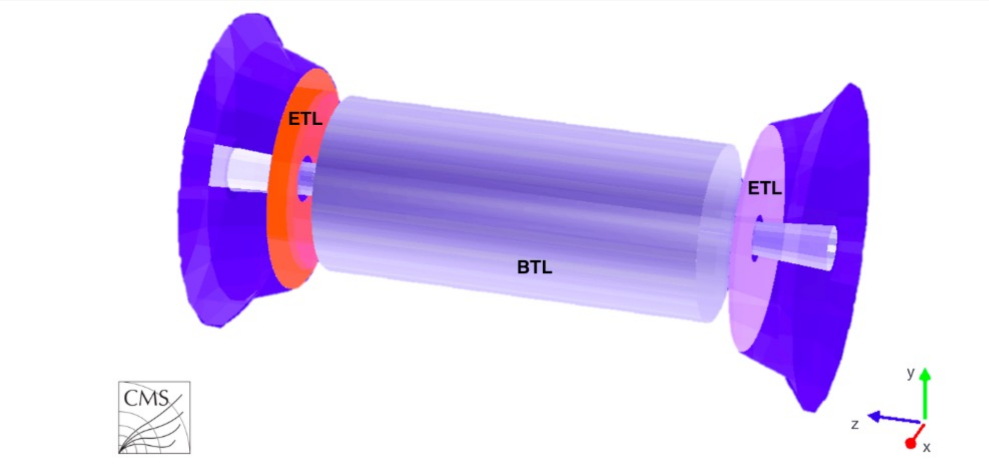


- Unrecoverable breakdown of irradiated sensors observed at proton/electron/laser beam
- “Crater” burn mark at the hit position of the beam particle
- Collaborative investigations at FNAL/DESY/ELI-Prague:
  reproduceable mortality with localized large energy deposition
- Safe bias V < 550 GeV for 50 um sensor

LGAD for ATLAS and CMS



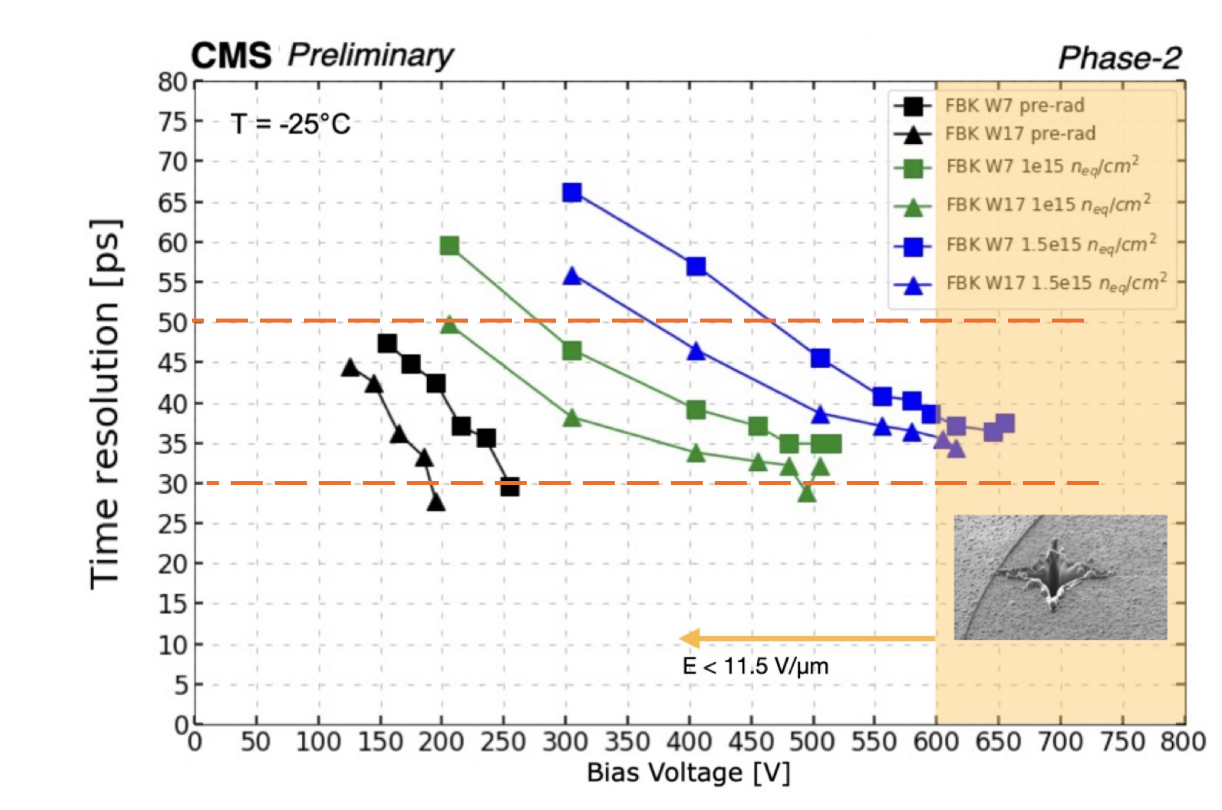
ATLAS HGTD LGAD:15x15 array of 1.3 mm x 1.3 mm
total active area 6.4 m^2
~3.6 M channels
Suppliers: IHEP-IME, USTC-IME



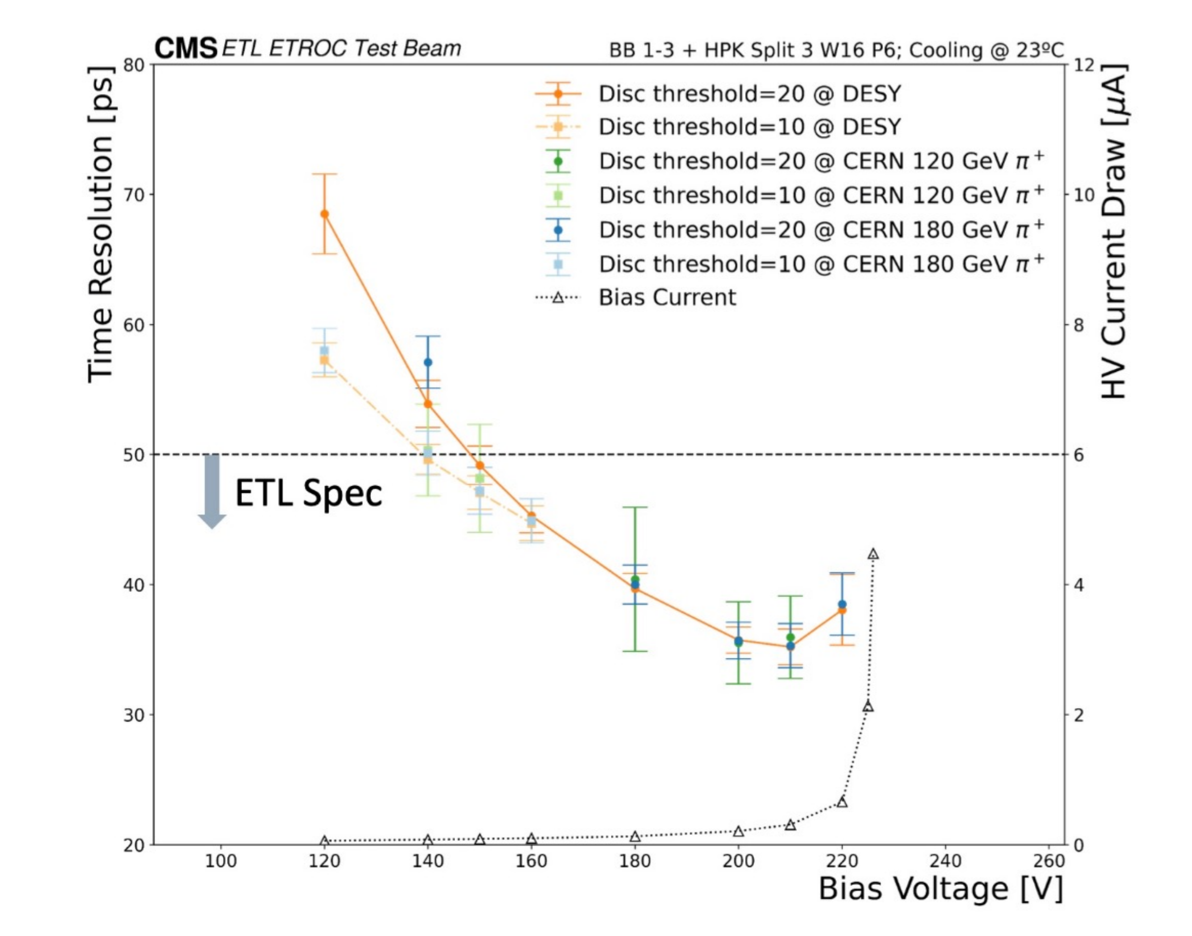
CMS ETL LGAD: 16x16 array of 1.3 mm x 1.3 mm
total active area 14.4 m^2
~8.5 M channels
Suppliers: FBK (LFoundtry), HPK

Some test results of production LGAD (CMS)

EPS HEP 2025

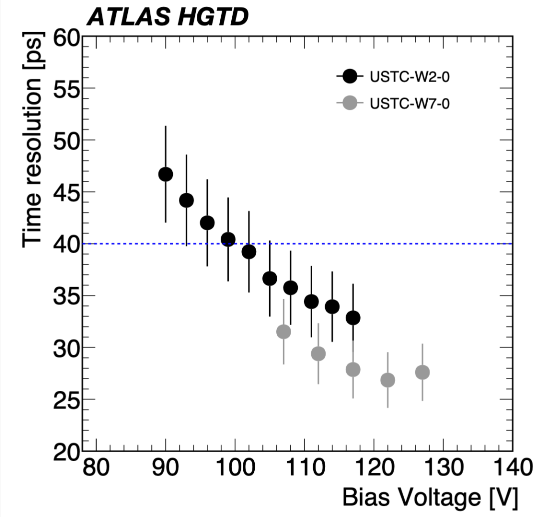


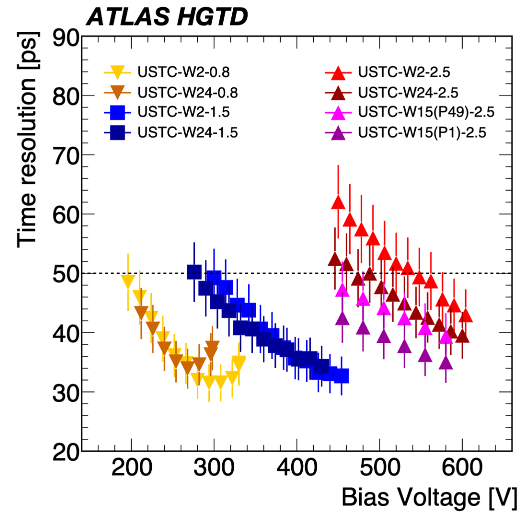
LP 2025 conference report

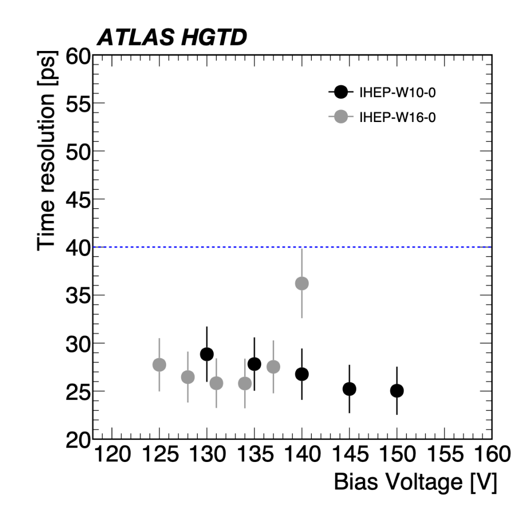


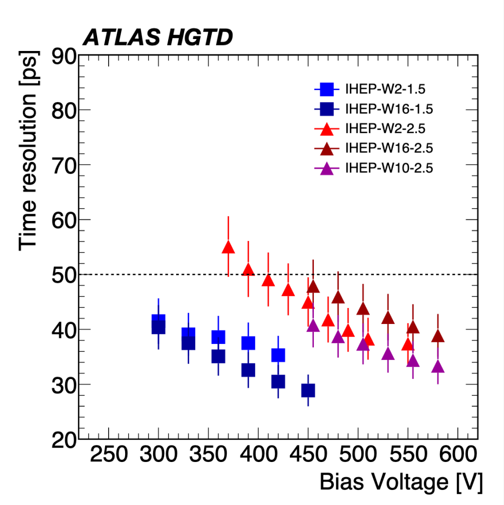
JINST 21(2026)P03021

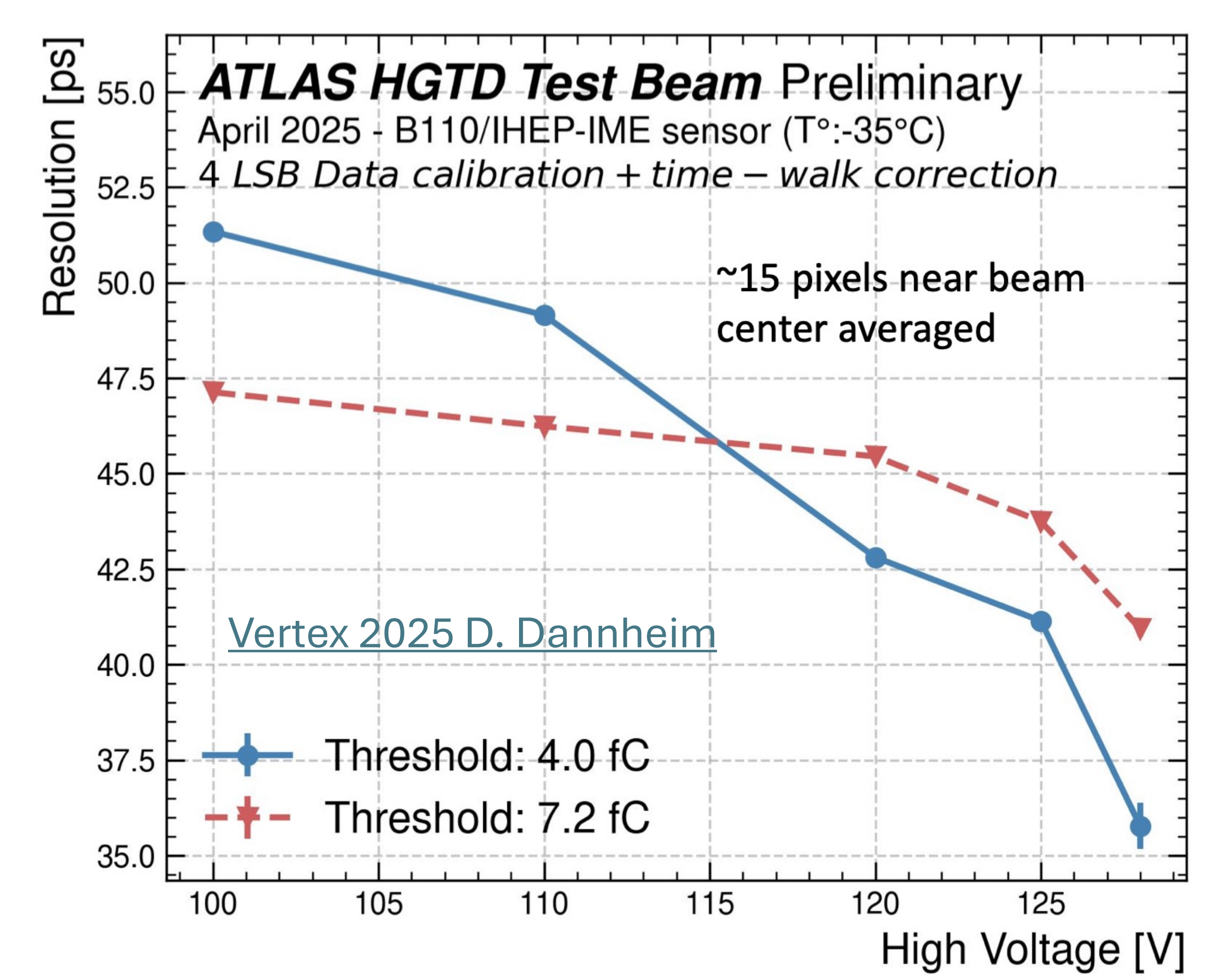
Some test results of production LGAD (ATLAS)











Vertex 2025 D. Dannheim

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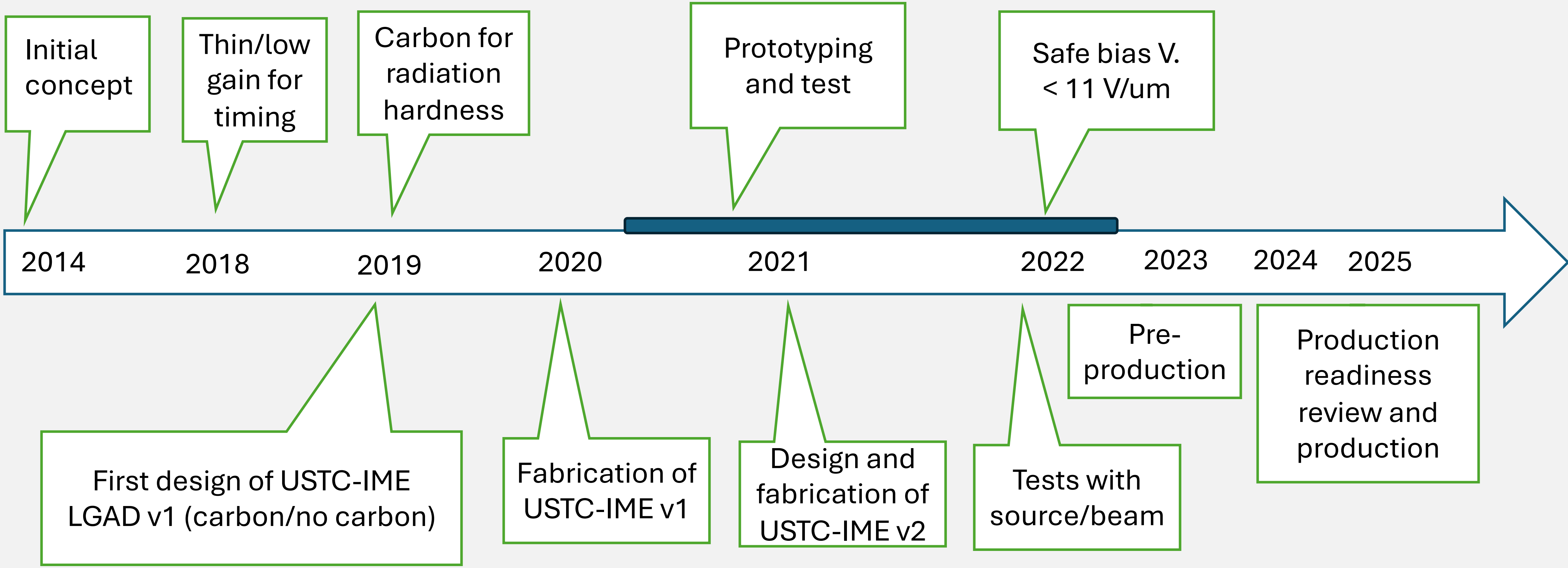
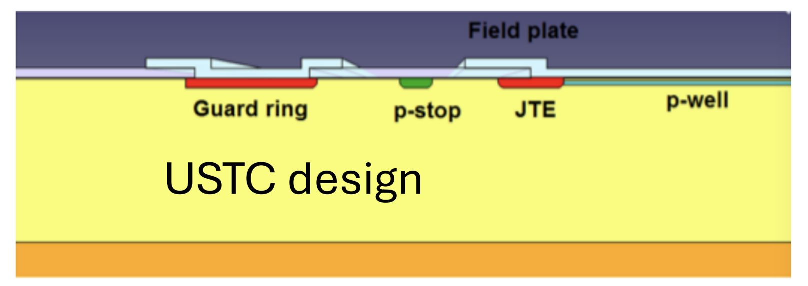
Recap of the LGAD RD for ATLAS/CMS

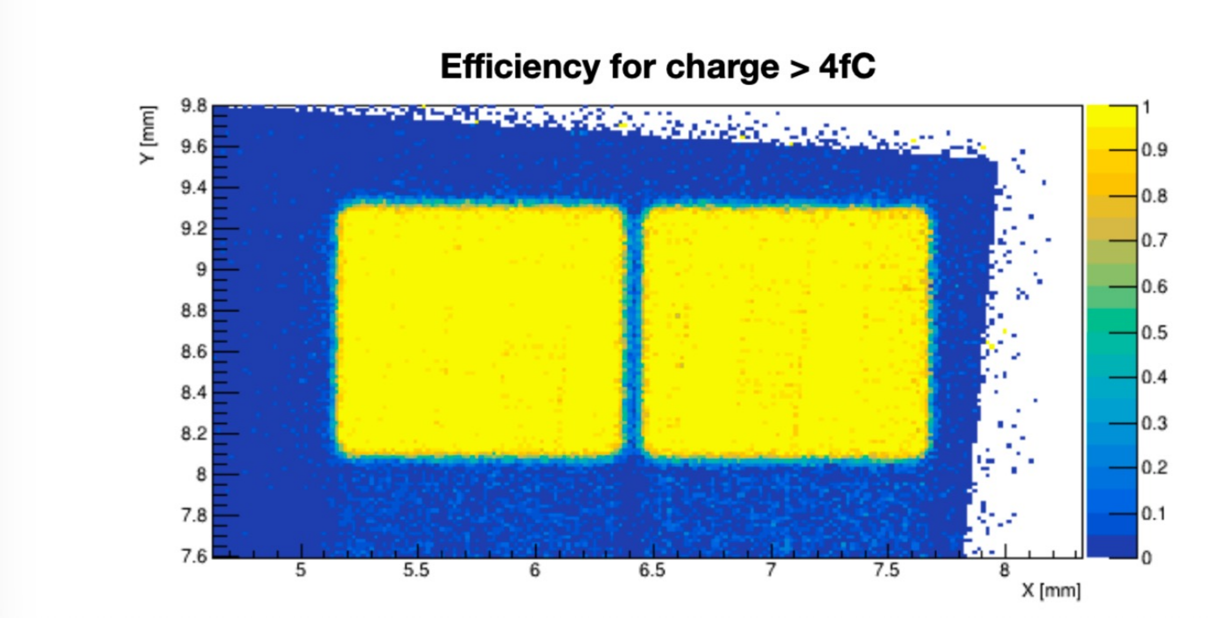


CMS ETL TDR: CERN-LHCC-2019-003
ATLAS HGTD TDR: CERN-LHCC-2020-007

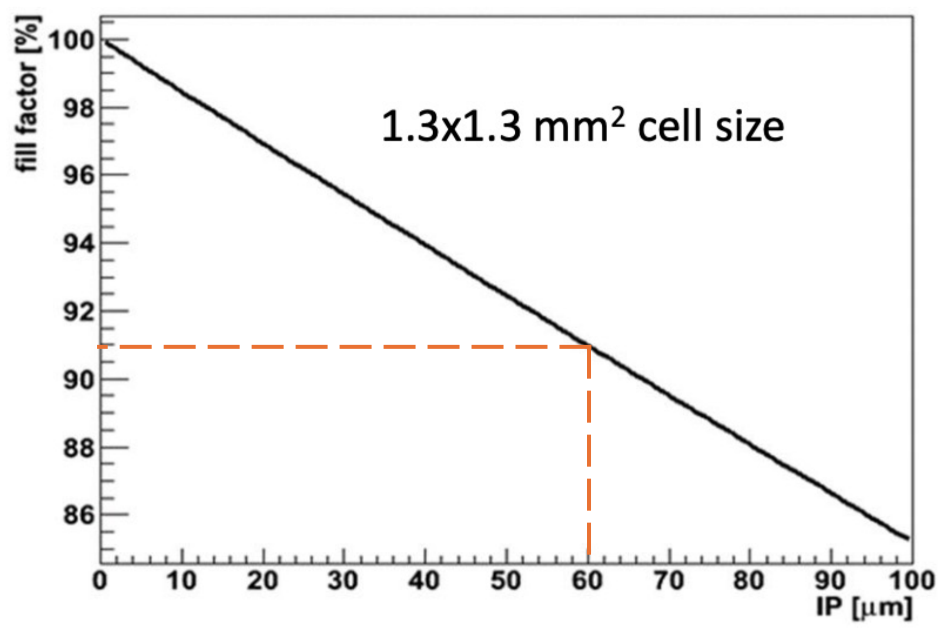
Fill-factor of LGAD

- Structures at peripheral region
  - Isolation, protection and field adj. at edge
- Fill-factor = [area w. gain]/[total area]
- Limiting the pitch size of LGAD





USTC-IME v2 W17-2x2 IP3:
inter-pad width = 62 um



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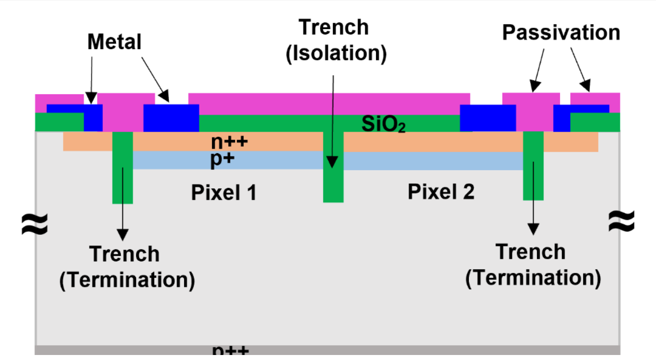
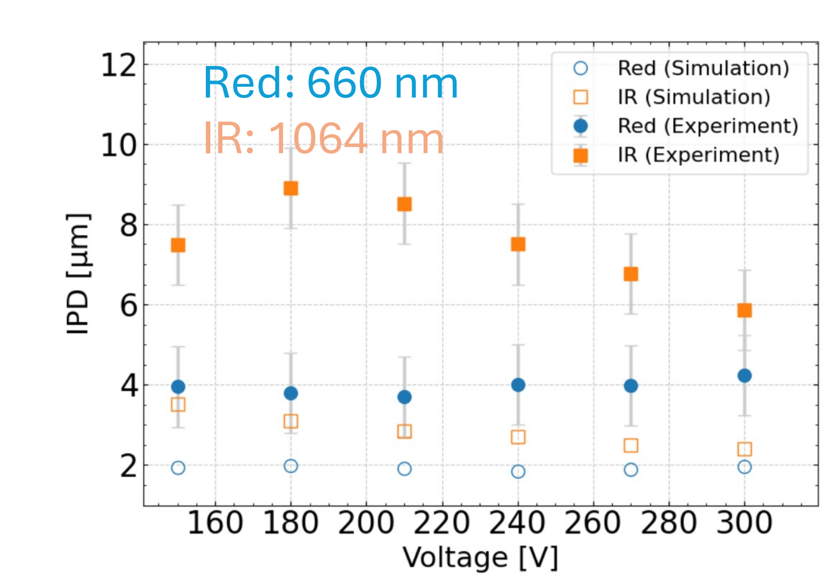
Trench-Isolated LGAD (TI-LGAD)

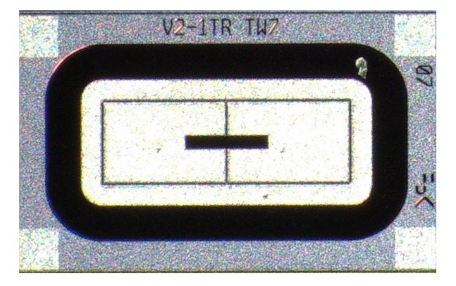
A. Carrera @ Trento 2026

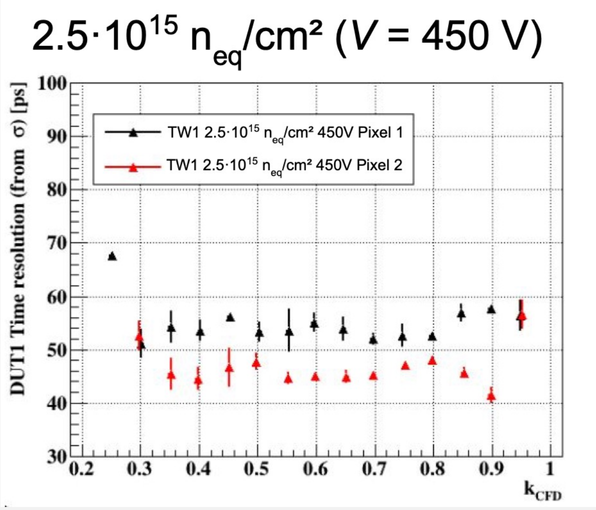
Micron Semiconductor Ltd.

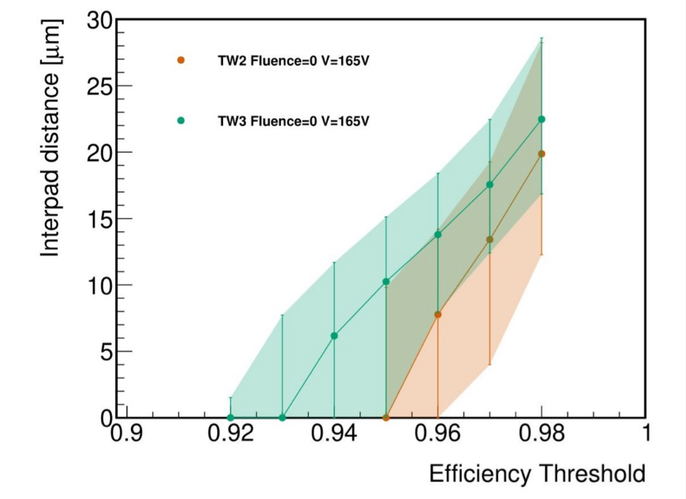




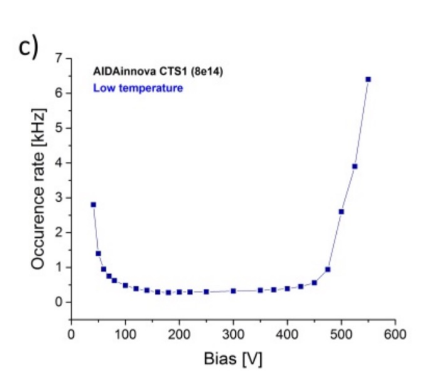
FBK AIDAInnova

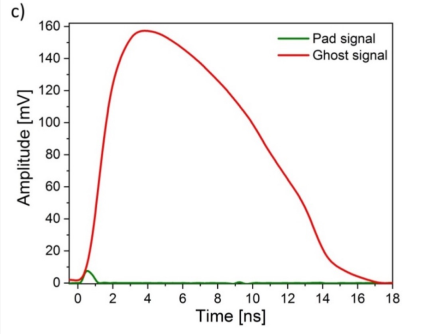






Self induced signal after irradiation





2025 JINST 20 P07037

2025 JINST 20 C07015

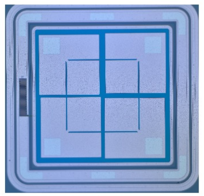
AC-LGAD

- Continuous gain layer, segmented electrodes
  - Solve the fill factor issue
  - Flexibilities in sensor design
  - Capacitively coupled readout:charge sharing

EIC requirement

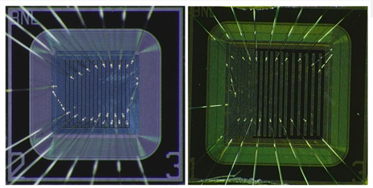
Subsystem	Timing	Spatial	Geometry
Barrel TOF	~30 ps	~30 μm	1 cm strip,500-1000 μm pitch
Forward TOF	~25 ps	~30 μm	500 x 500 μm^2 pixels

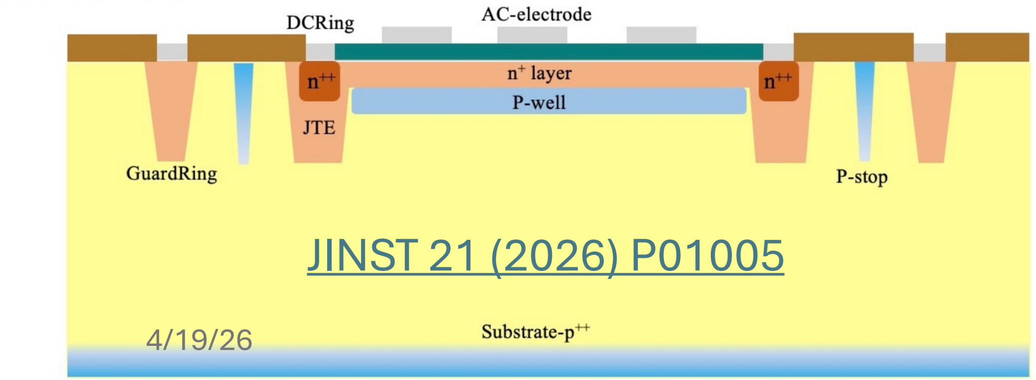
HPK: Pad size 500 μm x 500 μm
inter-pad gap: 20,30,40,50 μm
Thickness 50 μm



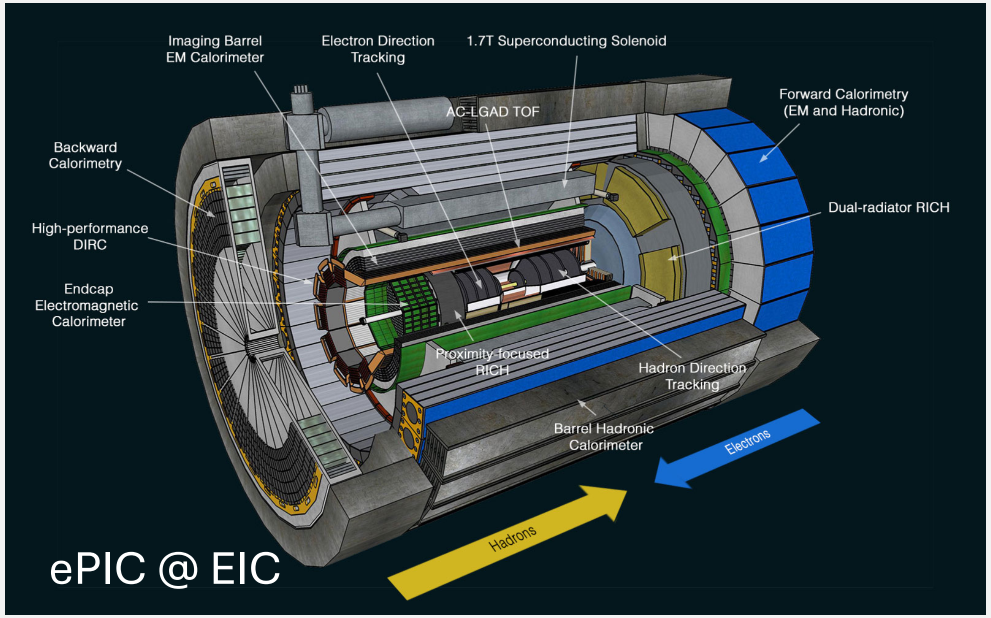
BNL: Pitch:100/150/200 μm, strip: 80 μm x 1.7 mm
thickness: 50 μm

2022 JINST 17 P05001





JINST 21 (2026) P01005



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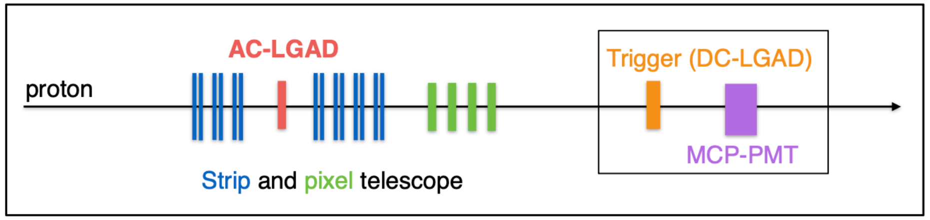
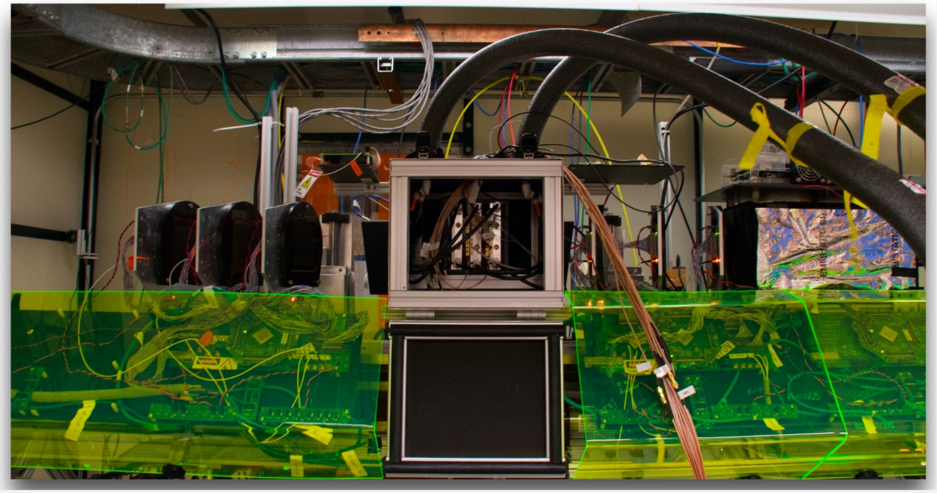
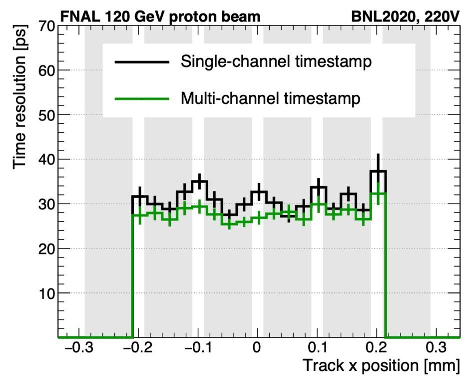
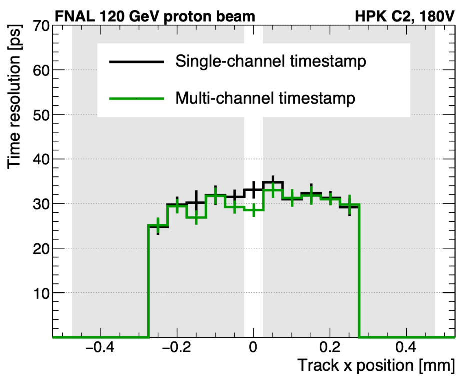
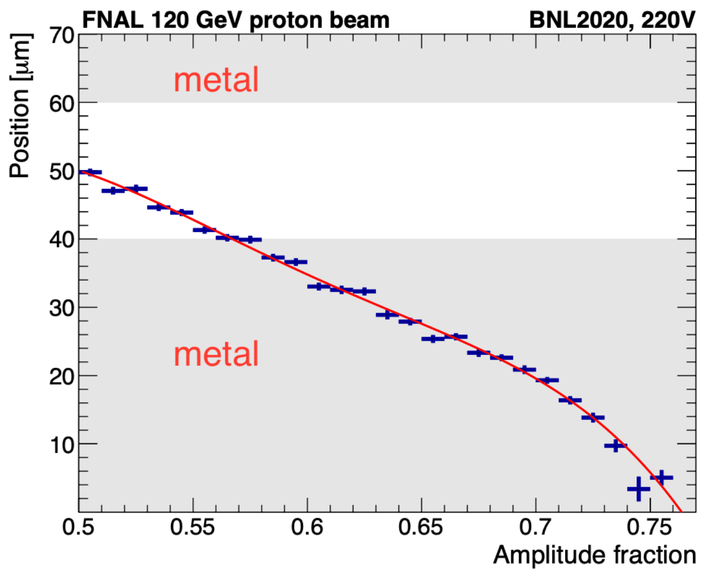
Performance from test beam(prototypes)

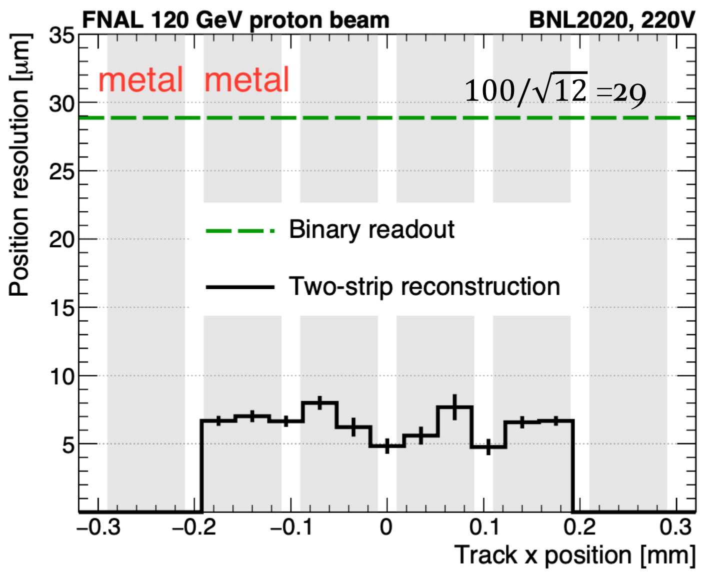


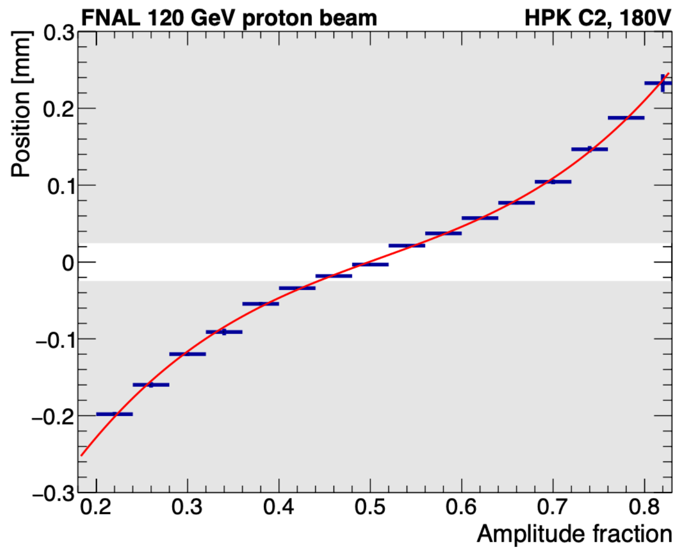


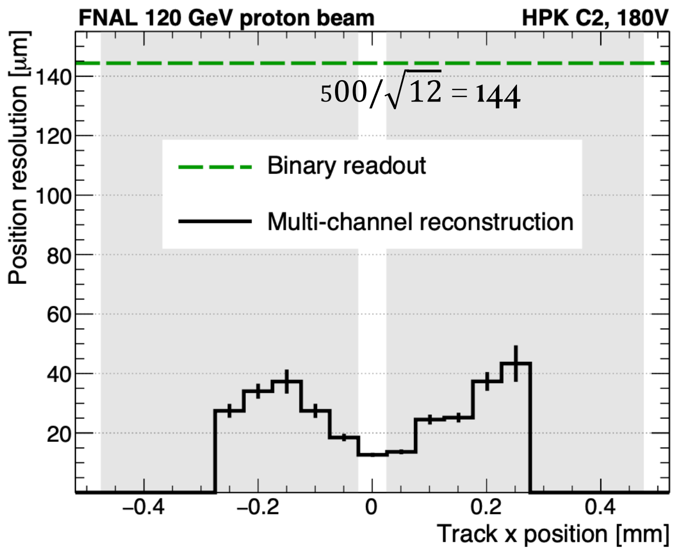












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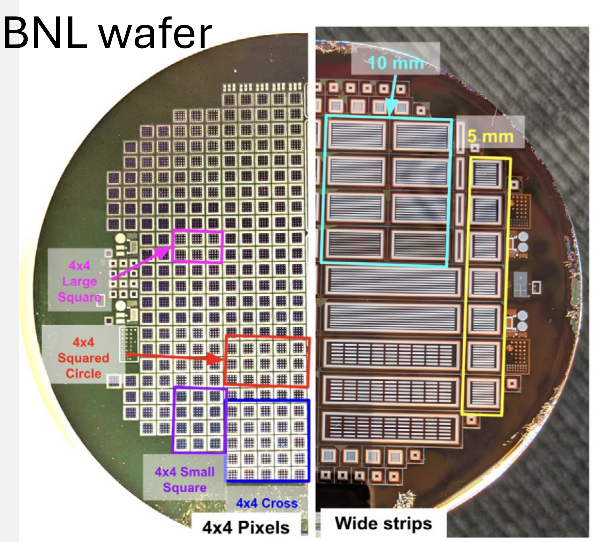
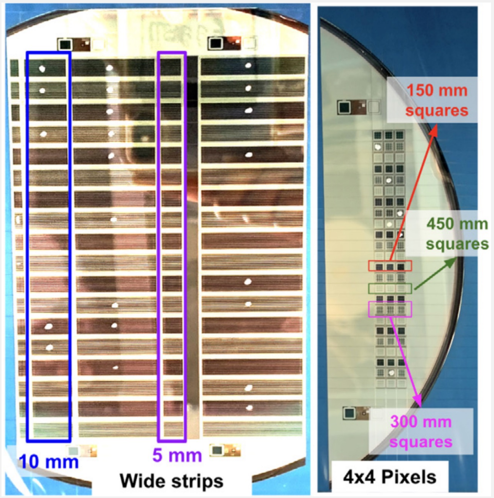
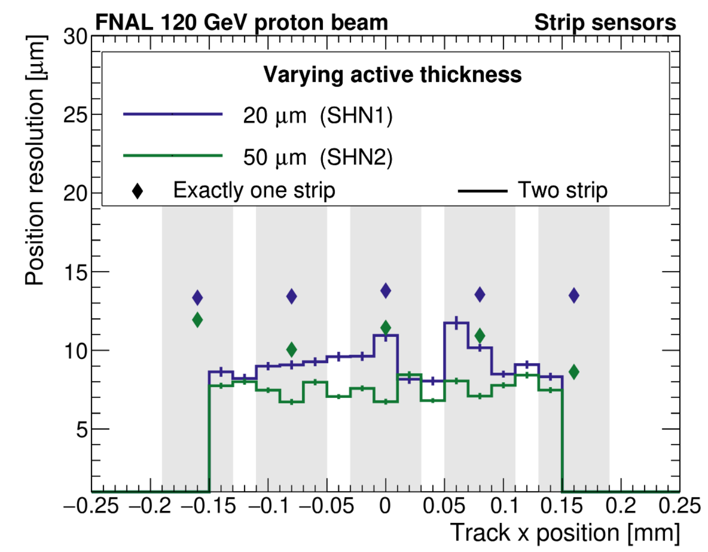
Test results of cm-scale AC-LGAD for ePIC

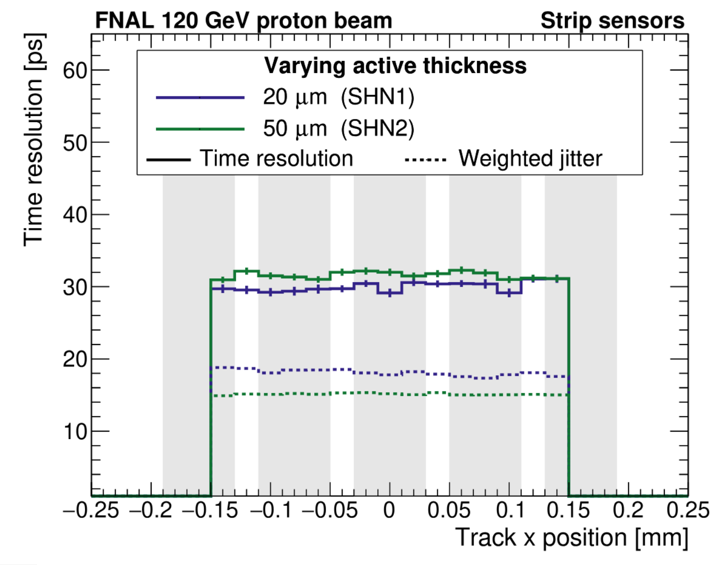
BNL wafer

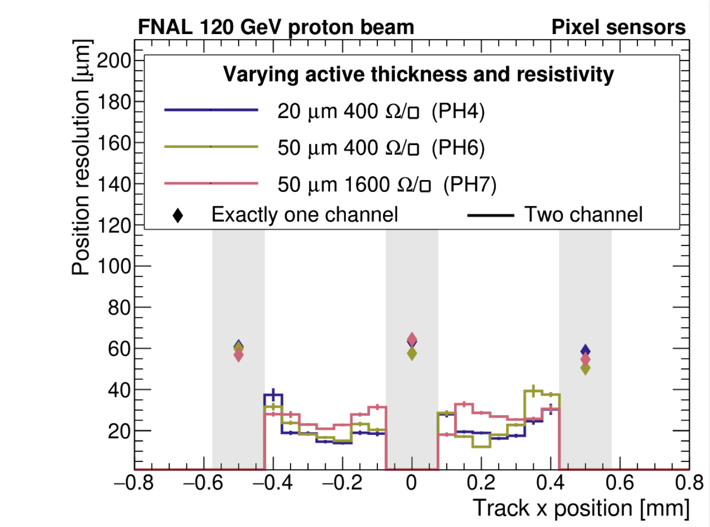


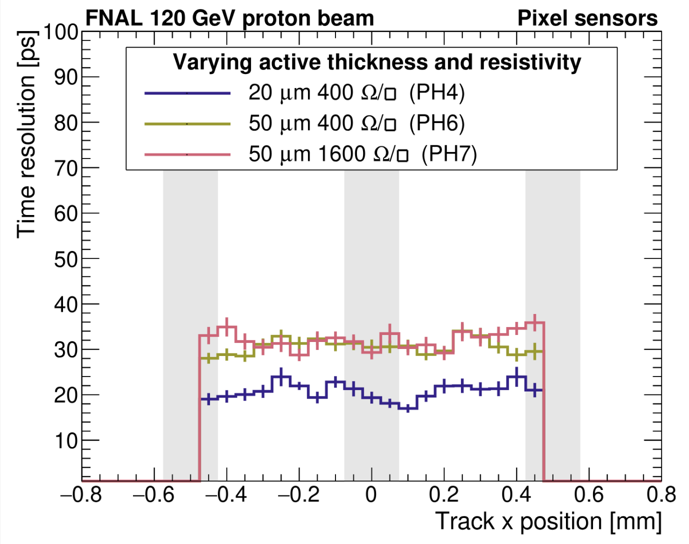
HPK wafer











R&D mostly completed. Large-scale production and testing on-going

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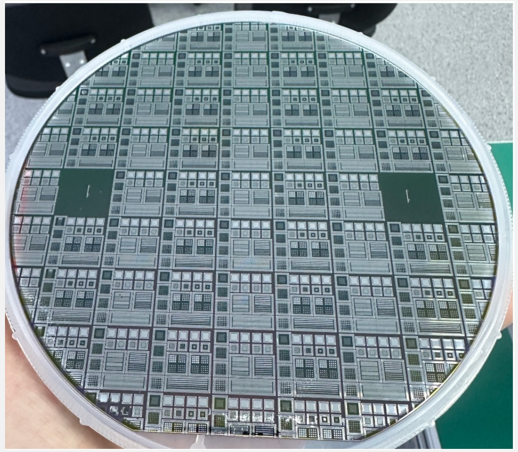
AC-LGAD R&D at USTC

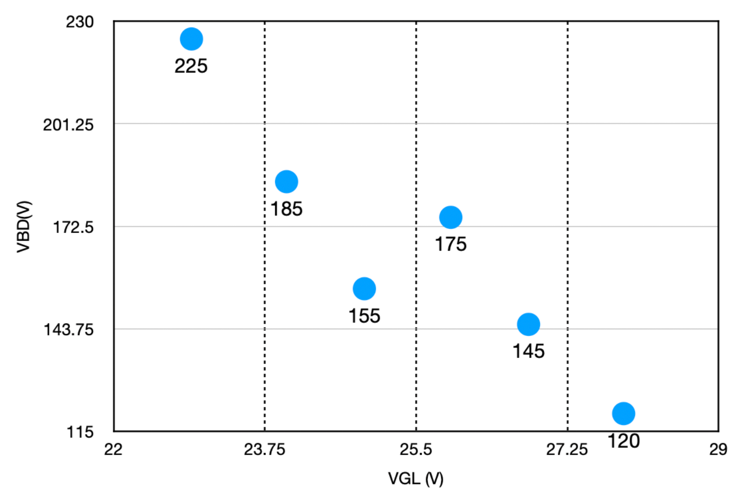
- USTC made some AC-LGAD in house during the R&D for ATLAS HGTD
- Finished characterization and started developing AC-LGAD for EICC

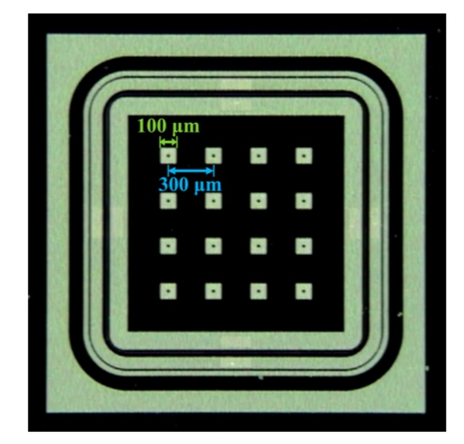
V1: thickness = 50 μm JINST 21(2026)P01005

V2: thickness = 35 μm
Characterization on-going



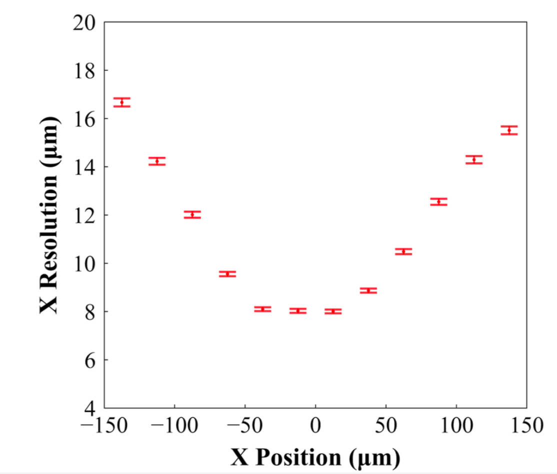
6 splits, very good correlation of VBD~VGL



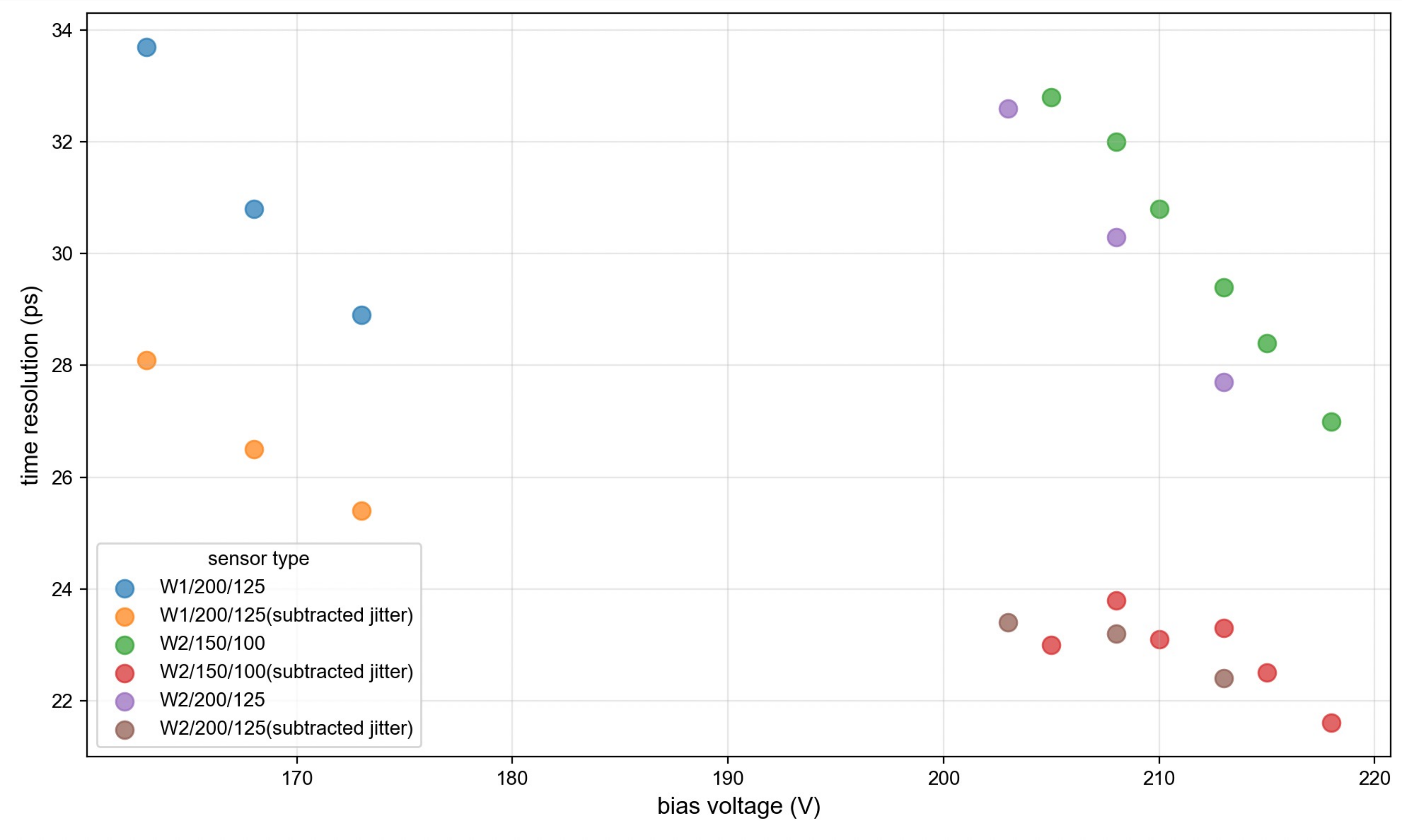


ChinaXiv:202602.00195V1

ML on waveform



Very Preliminary Results on time resolution



1.2 mm strips

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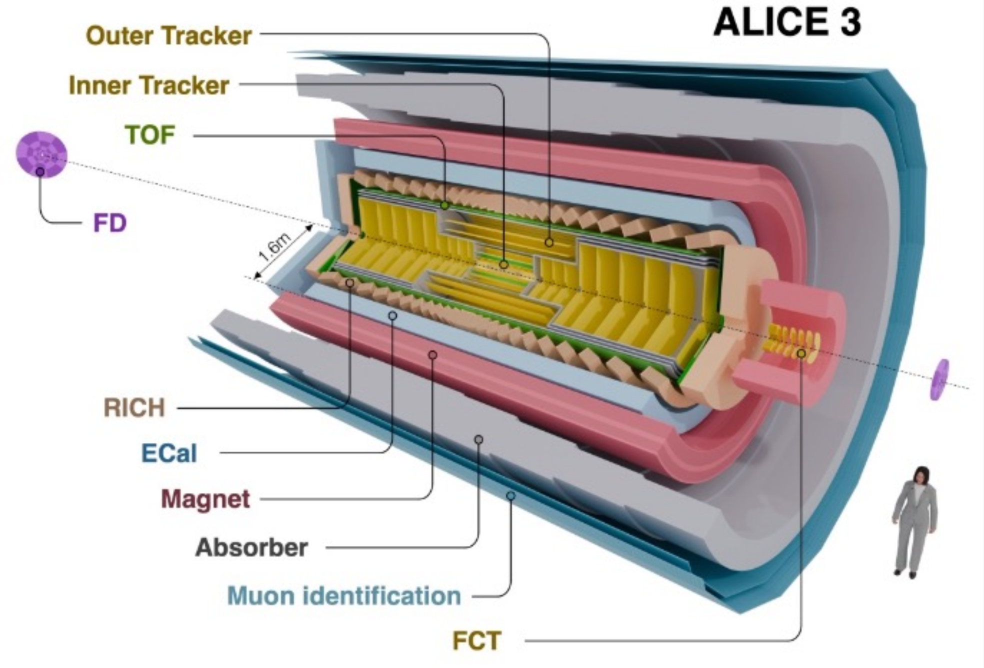
Readout ASIC chips for LGAD

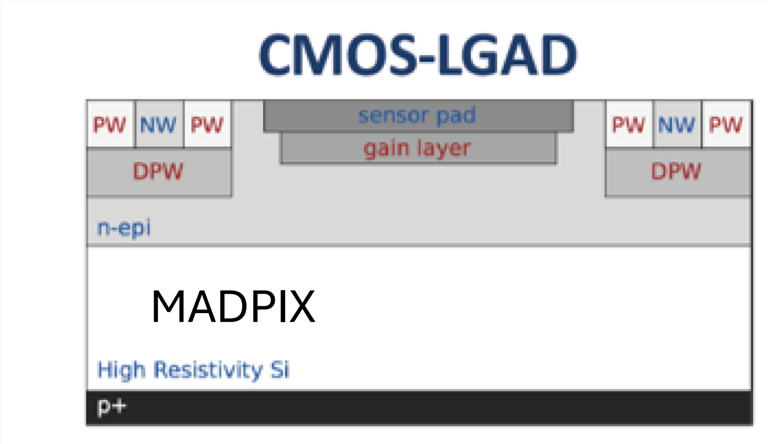
ASIC	Process	Electronics jitter	Sensor type	Application
ETROC	65 nm	~25 ps	LGAD	CMS MTD ETL
ALTIROC	130 nm	~30 ps	LGAD	ATLAS HGTD
TOFHIR2	130 nm	30–60 ps	SiPM + Crystal	CMS MTD BTL
EICROC	130 nm	~30 ps	AC-LGAD	EIC ePIC TOF
FCFD	65 nm	~10 ps	LGAD / AC-LGAD	EIC ePIC TOF
TIMESPOT1	28 nm	~7 ps	3D Trench / LGAD	Demonstrator
PICOPIX	28 nm	~20 ps	3D Trench / LGAD	LHCb VELO II
SAMPIC/ASOC	130–65 nm	<10 ps	MCP-PMT / SiPM	TORCH, small systems

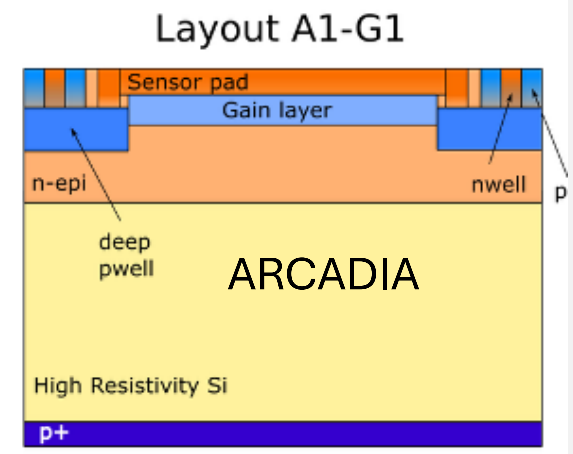
Development of ASIC in China
LATRIC (IHEP)
LATIC (USTC)
ALGROC (NWPU)
...

CMOS-LGAD / Monolithic LGAD

- Implement both sensor and IC on a same silicon wafer
- Application for ALICE LS4 upgrade (2034 ~ 2035)
  - Requirements: $\sigma_t \leq 20\ \mathrm{ps}$,power consumption: 50 mW/cm^2







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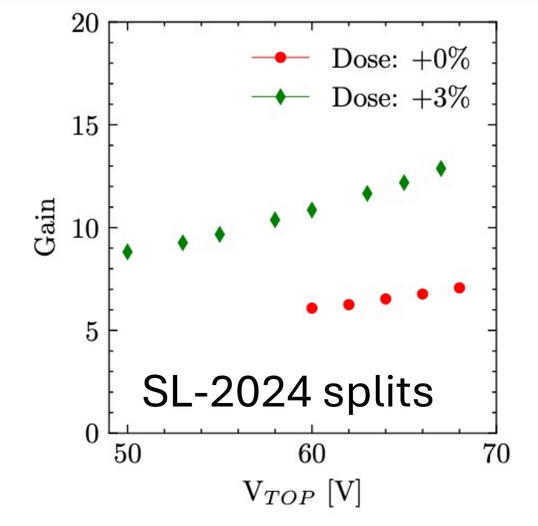
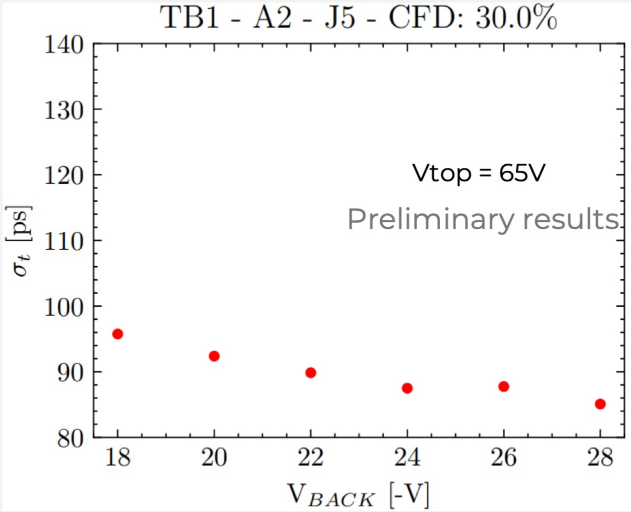
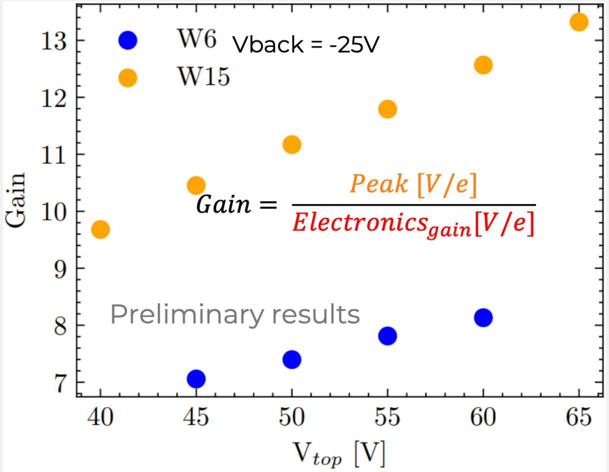
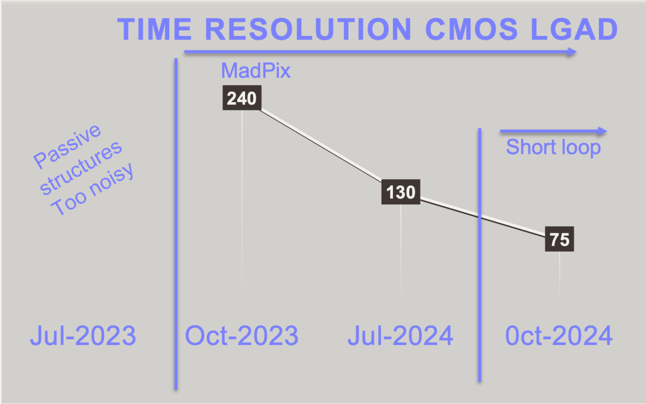
Status of MadPix for ALICE 3

- ER-2023: σ_t = 120 ps, power consumption 0.17 mW/ch gain ~ 3, 48 μm
- SL-2024: calibrated the gain to 10-20 σ_t=75 ps(subtracted jitter)
- SL-2025: thickness = 15 μm, expect ~30 ps time resolution
- ER-2027: full-size chip, optimal pitch to achieve 20 ps
- Backup solution: hybrid LGAD being developed at USTC









U. Follo talk at Trento 2025

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Summary

- Very intensive R&D of LGAD technology in the past 10+ years
- Extremely good progress (excellent teamwork of the community!)
- DC-LGAD ➔ AC-LGAD ➔ CMOS LGAD
- Current state-of-art resolutions: 20 ~ 40 ps / ~10 μm
- Applications at Collider experiments
  - LHC-LHC (pile-up mitigation)
  - EIC (TOF for PID)
  - Future (4D –tracking)