LGAD Development within RD50

Centro Nacional de Microelectrónica IMB

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Vertex 2021

30th September 2021

Neil Moffat on behalf of the RD50 collaboration

Outline

- RD50 Collaboration
- LGAD Technology
- LGAD Technologies @ CNM
- Experimental Procedures
- Gain Suppression
    - TPA-TCT
    - TCT
    - IBIC
- Timing Performance
- LGAD outside HEP

The RD50 Collaboration

- RD50: *64 institutes and 410 members*

51 European institutes

Austria (HEPHY), **Belarus** (Minsk), **Czech Republic** (Prague (3x)), **Finland** (Helsinki, Lappeenranta), **France** (Marseille, Paris, Orsay), **Germany** (Bonn, Dortmund, Freiburg, Göttingen, Hamburg (Uni & DESY), Karlsruhe, Munich (MPI & MPG HLL)), **Greece** (Demokritos), **Italy** (Bari, Perugia, Pisa, Trento, Torino), **Croatia** (Zagreb), **Lithuania** (Vilnius), **Montenegro** (Montenegro), **Netherlands** (NIKHEF), **Poland** (Krakow), **Romania** (Bucharest), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona(3x), Santander, Sevilla (2x), Valencia), **Switzerland** (CERN, PSI, Zurich), **United Kingdom** (Birmingham, Glasgow, Lancaster, Liverpool, Oxford, Manchester, RAL)

Full member list: www.cern.ch/rd50

8 North-American institutes

Canada (Ottawa), **USA** (BNL, Brown Uni, Fermilab, LBNL, New Mexico, Santa Cruz, Syracuse)

1 Middle East institute

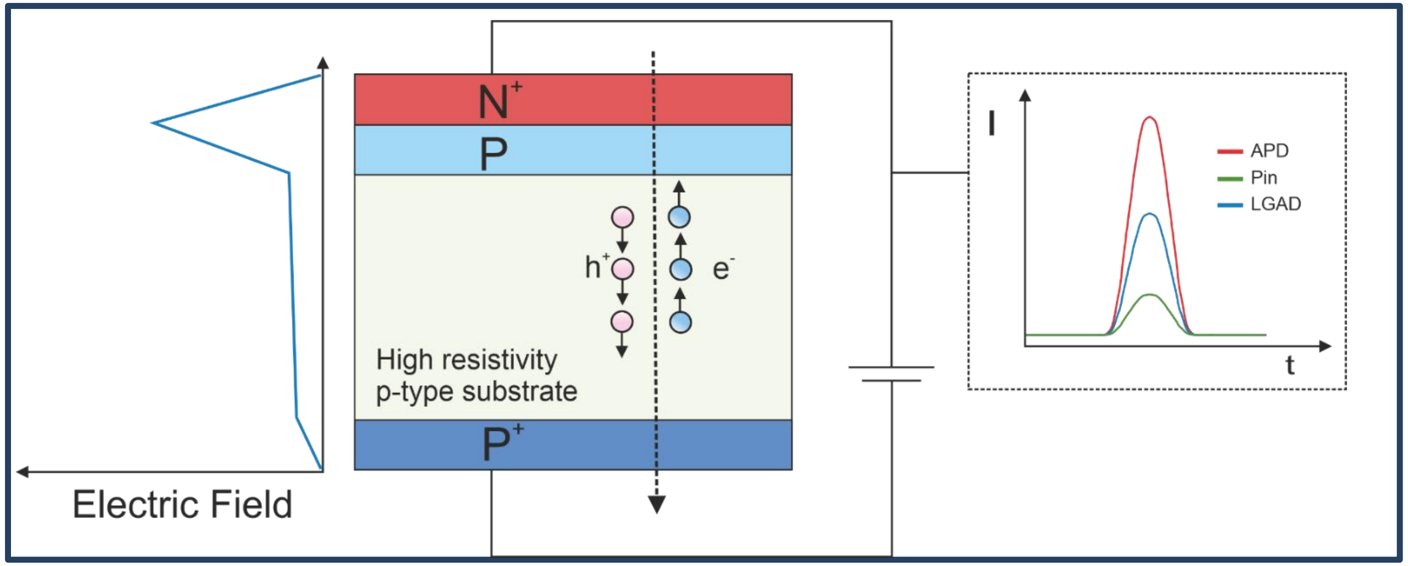
Israel (Tel Aviv)

4 Asian institutes

China (Beijing-IHEP, Hefei, Jilin), **India** (Delhi)

Introduction: Low Gain Avalanche Detector (LGAD) Technology

Low Gain Avalanche Detector (LGAD)



- **LGAD** technology is based on the APD concept.
- Multiplication layer less doped to reach a **linear** and **moderate gain** (10-30) in a high operating voltage regime.
- **Low** signal to noise ratio **(S/N)**.

$$G = \frac{\int_{t_0}^{t_f} I_{LGAD}\, dt}{\int_{t_0}^{t_f} I_{PIN}\, dt}$$

LGAD is the baseline technology of the timing detectors for the high-luminosity upgrade of the **ATLAS (HGTD)** and **CMS (ETL)** experiments.

Introduction: Low Gain Avalanche Detector (LGAD) Technology

Clean Rooms that develop LGAD technology

2013
- Centro Nacional de Microelectrónica CSIC

2016
- Centro Nacional de Microelectrónica CSIC
- Fondazione Bruno Kessler

2017
- Centro Nacional de Microelectrónica CSIC
- Fondazione Bruno Kessler
- HAMAMATSU

2018
- Centro Nacional de Microelectrónica CSIC
- Fondazione Bruno Kessler
- HAMAMATSU
- Micron Semiconductor Limited
- Brookhaven National Laboratory

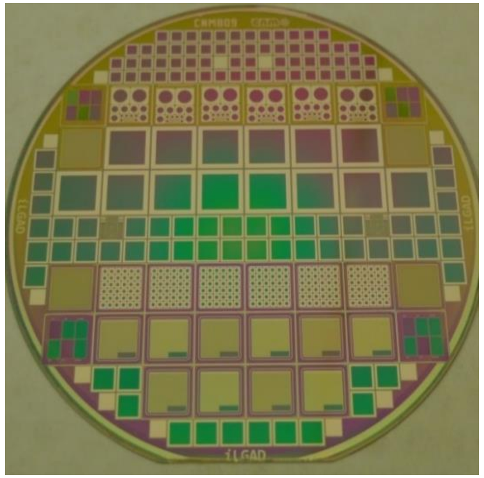
2021
- Centro Nacional de Microelectrónica CSIC
- Fondazione Bruno Kessler
- HAMAMATSU
- Micron Semiconductor Limited
- Brookhaven National Laboratory
- Institute of Microelectronics of the Chinese Academy of Sciences
- CiS Forschungsinstitut für Mikrosensorik GmbH

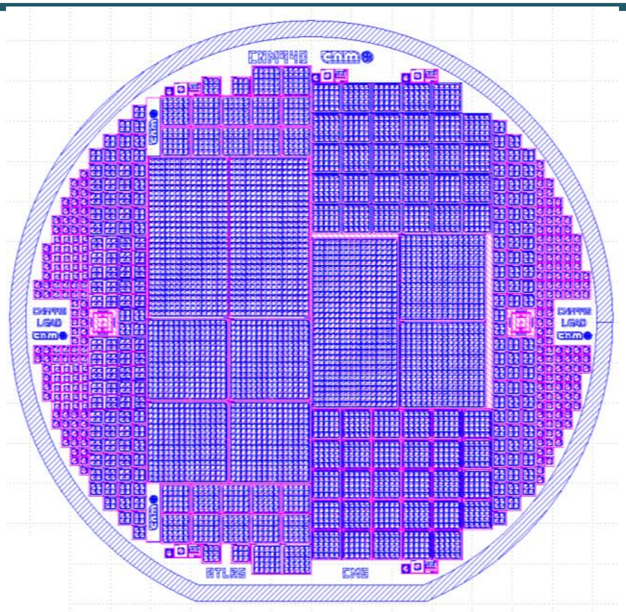
RD50

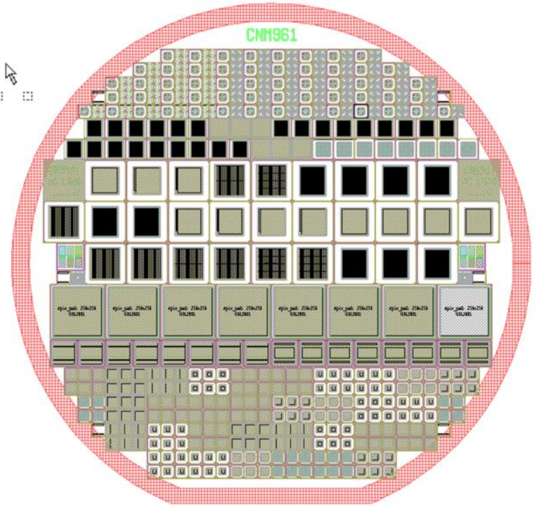
Development and study of new sensors for the HL-LHC

LGAD Technologies @ CNM

- LGAD
- Epitaxial LGAD
- AC-LGAD
- iLGAD
- Trench iLGAD
- p-LGAD





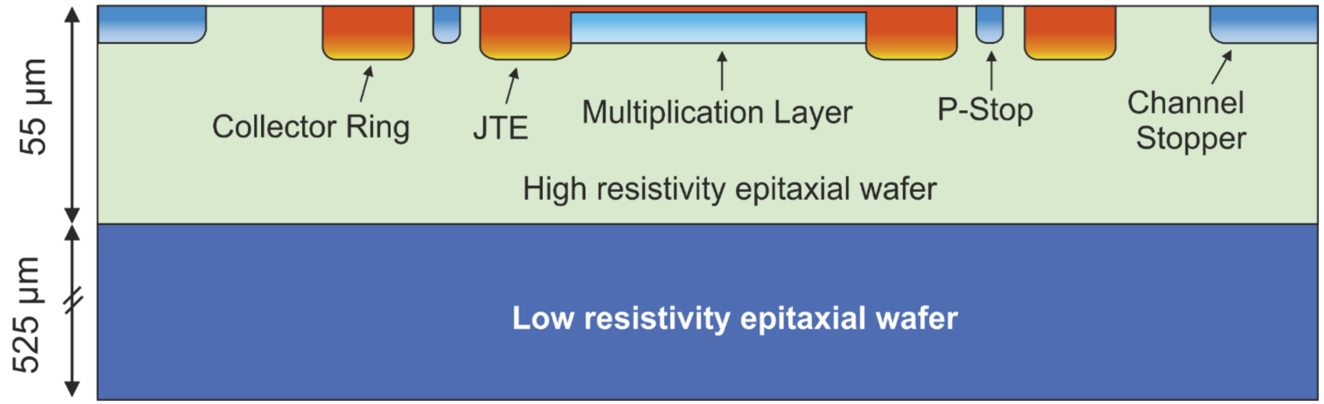


Disclaimer: Talk focused on CNM LGADs,
Previous talks focus on BNL,HPK,KEK and FBK

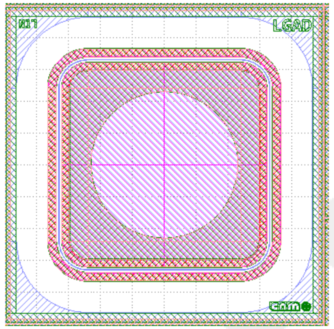
Run 13002: 6-inch LGAD in Epitaxial Wafers

- **4 wafers (3 LGAD + 1 PiN).**
- 6-inch 55/525 µm **epitaxial** wafers.
  - ➢ Handle wafer resistivity = 0.001-1 Ohm-cm
  - ➢ Substrate resistivity ~ 1-10 kOhm-cm
- Same mask as Run 11486.

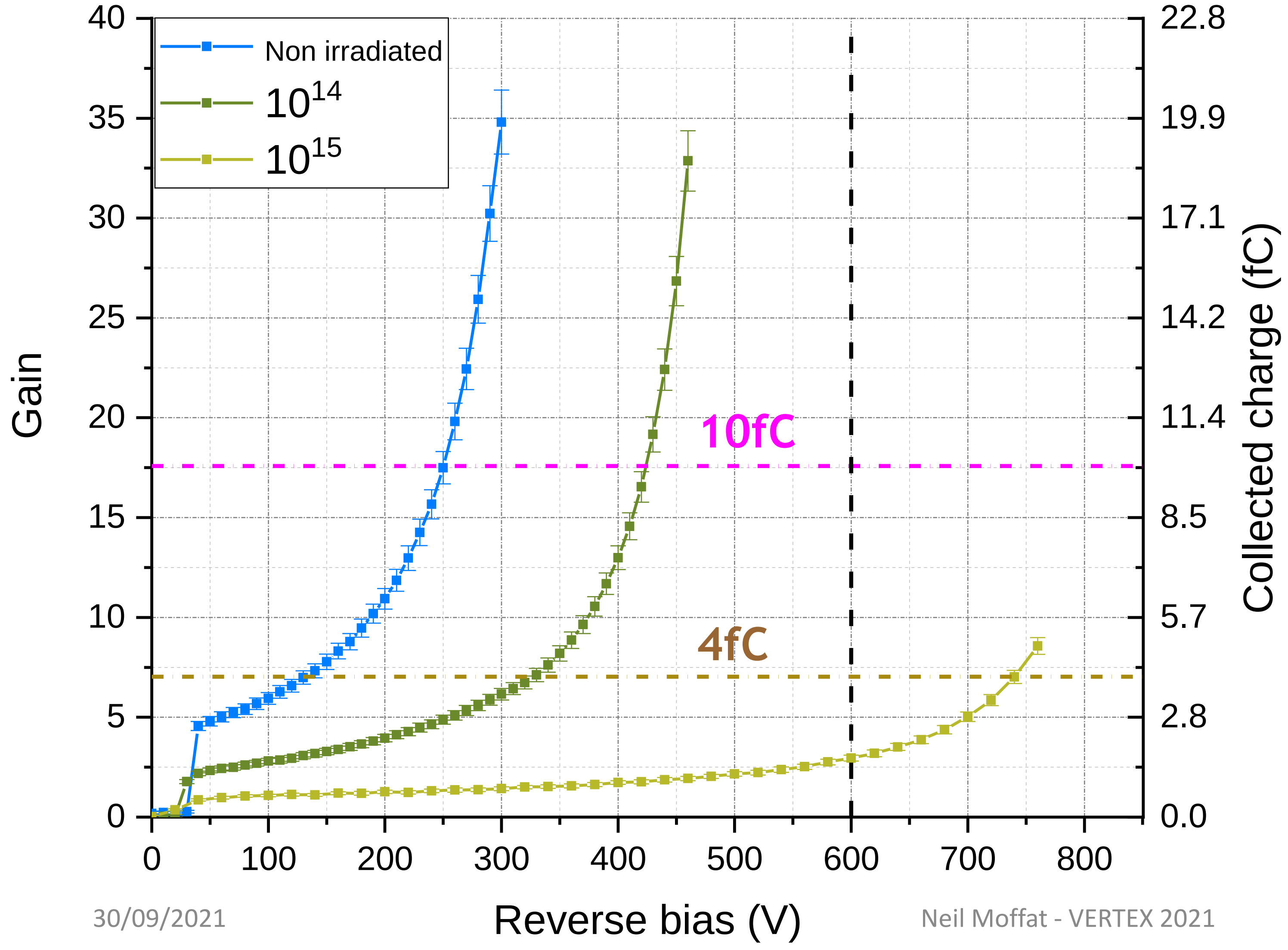
Wafer	Dose (at/cm²)	Energy (keV)
1	-	-
2	D1	E1
3	D2	E1
4	D3	E1



Pad diodes



TCT measurements : gain and collected charge for a MIP (-20ºC)



Device	Φ_{eq} (1/cm²)	Breakdown voltage (V)
W4_N18.6	-	325
W4_N09.4	10^{14}	500
W4_N09.3	10^{15}	>800

Gain=Q(LGAD)/Q(PiN)

Infrared laser (1064nm)
Laser pulse width : 1.52ns
40µm FWHM & ~15MIPs

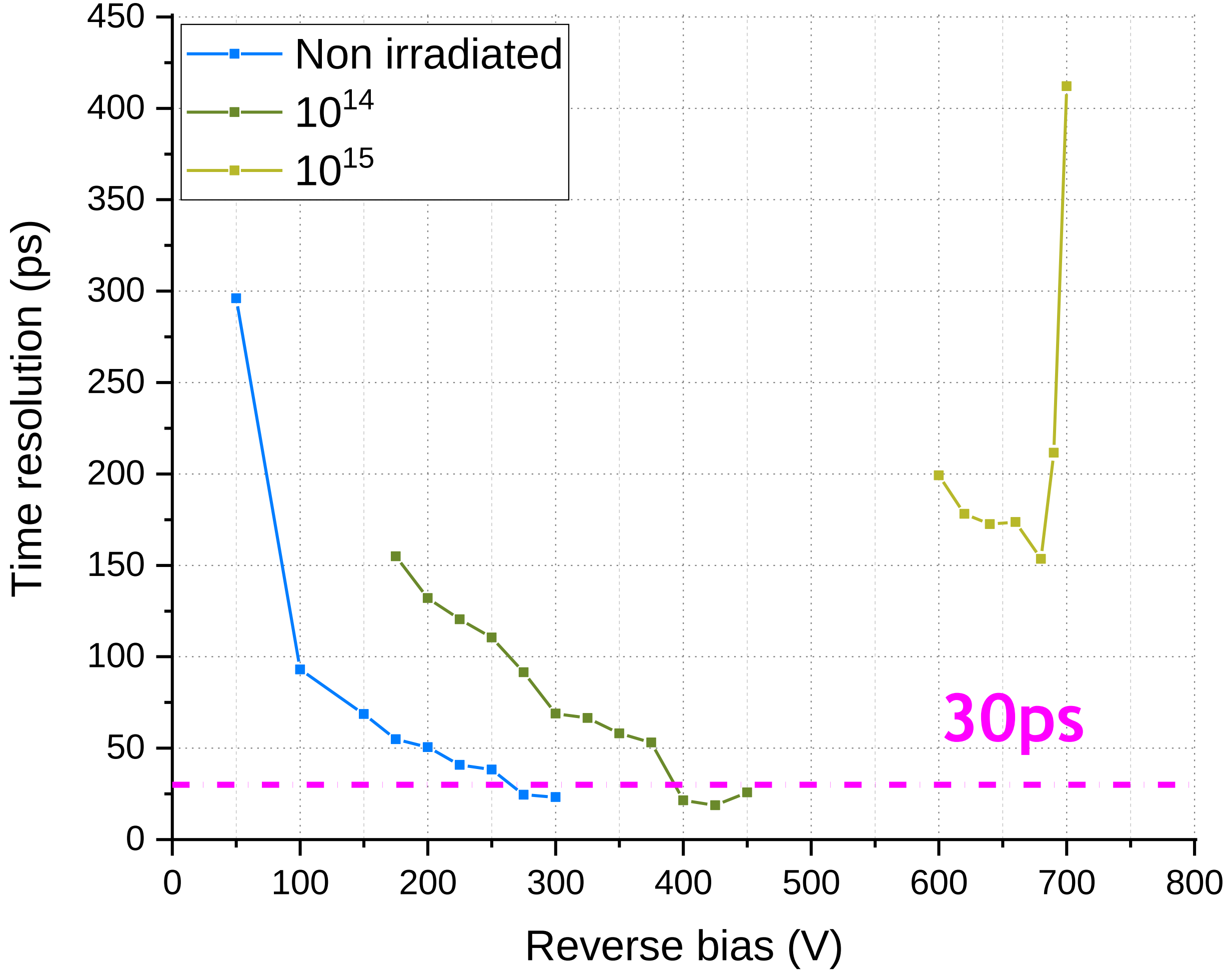
CMS : 10fC at $1.5 \cdot 10^{15}$ /cm² at (max) 600V
ATLAS : 4fC at $2.5 \cdot 10^{15}$ /cm² at (max) 600V

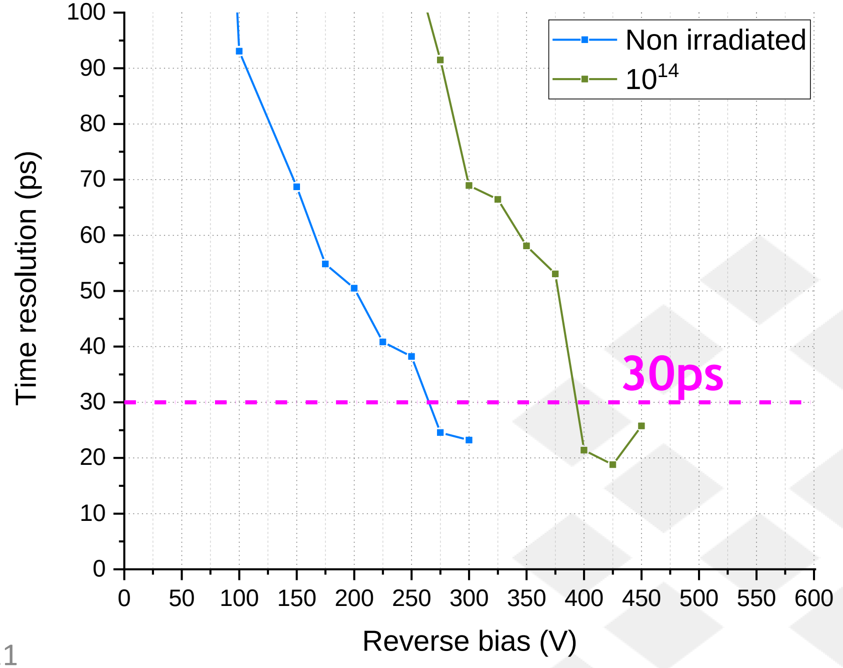
Gain 1 = 0.569fC (MIP → 67e/h pairs per µm in silicon low doped x 53 µm)

TCT measurements : Time resolution for ~ 1MIP (-20ºC)

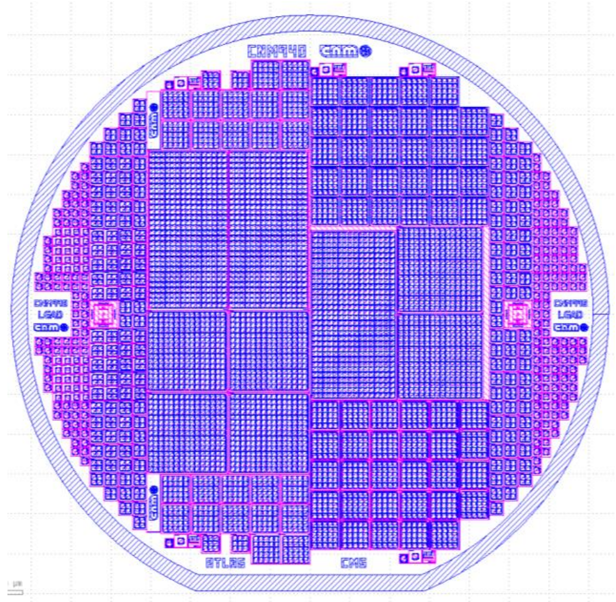
Device	Φ_{eq} (1/cm²)	Breakdown voltage (V)
W4_N18.6	-	325
W4_N09.4	10^{14}	500
W4_N09.3	10^{15}	>800
W4_N09.6	$5\cdot10^{15}$	>800

W4_N09.6 couldn't be tested (signal ~ noise)

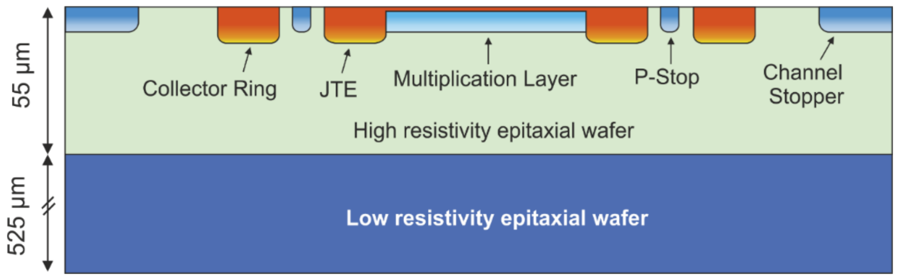




Run 13840: 6” ATLAS-CMS Common Run (6LG3)



- **10 wafers (9 LGAD + 1 PiN).**
- 6-inch 55/525 µm **epitaxial** wafers.
  - ➢ Handle wafer resistivity = 0.001-1 Ohm-cm
  - ➢ Substrate resistivity > 200 Ohm-cm
- Same technological process as Run 13002. 6LG3
- **50/97** steps done (**Multiplication** Well Implantation)
- Calibration of the new Diffusion Furnaces
- Higher diffusion processes quality and uniformity
  - ➢ Higher Vbr and Gain uniformity

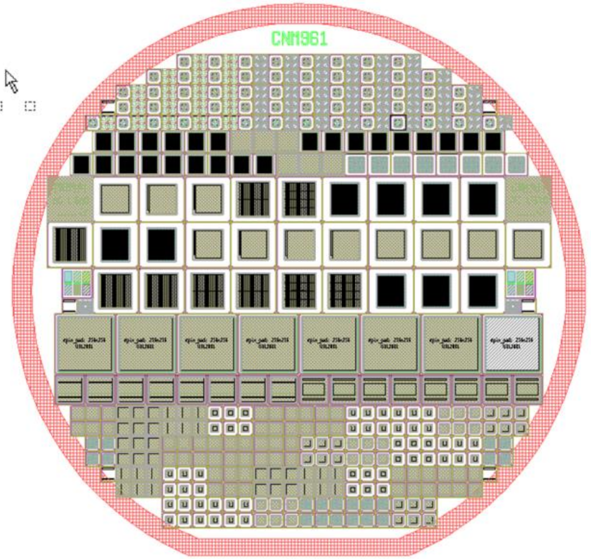


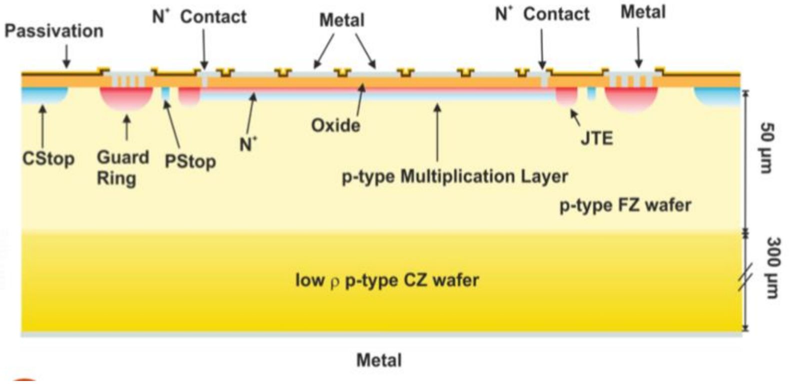
Wafer	Dose (at/cm^2)	Energy (keV)
1	-	-
2,5,8	Medium	Medium
3,6,9	Med-High	Medium
4,7,10	High	Medium

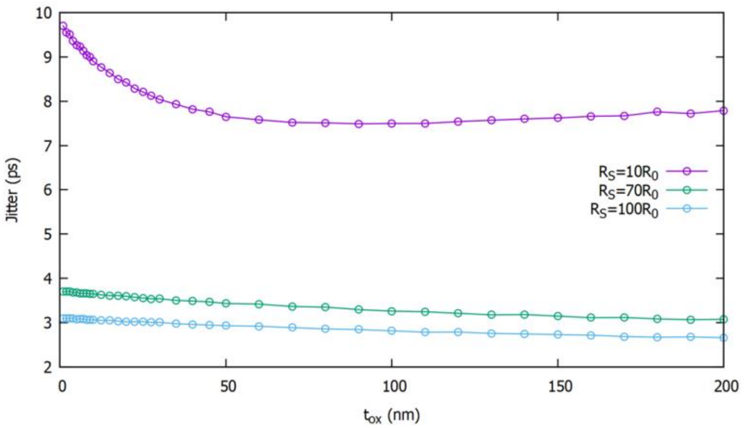
New run with Si-Si wafers will start this week, some wafers will have carbon implantation.

Run 13911: 6” AC-LGAD

- AC-LGAD replaces the segmentation of the pad implants into continuous sheets of multiplication layer and n+ layer and only segments the metal connected to the readout
- The signal is AC-coupled into the metal pads by another continuous sheet of coupling oxide.
- Technological parameters (capacitance, resistance, pitch, etc..) optimized with TCAD and PSPICE.
- Status: in fabrication 23 of 116
- Medipix and other structures (strips, pixels, etc9)





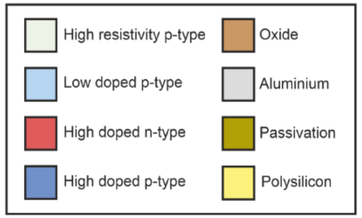


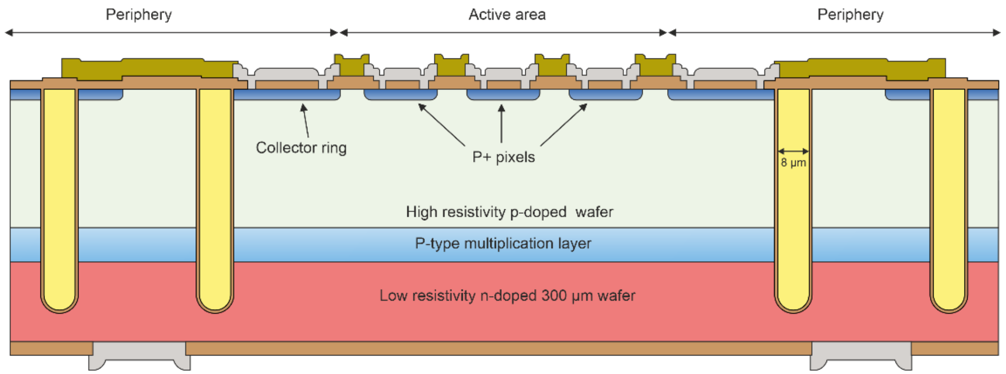
Has been shown by FBK and BNL to have excellent time and position resolution, 30ps and 5um respectively.

iLGAD Third Generation (iLG3): Trench iLGAD Concept

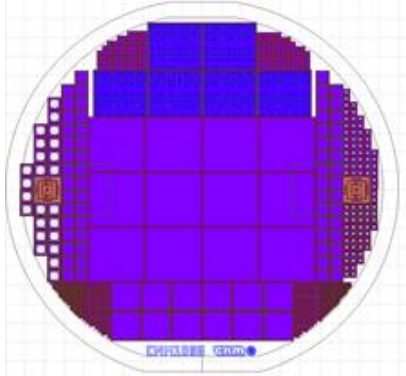
In the iLG3 we are going to use trenches to isolate the active area.

- ✓ **Multiplication region** is fully **isolated**.
- ✓ **Simpler single-side** and **50% less** fabrication steps.
- ✓ Devices are able to sustain **higher voltages.**
- ✓ **Slim-edge technology.**
- ✓ Optimization of the **multiplication layer is independent of charge collection and cross-talk at the electrodes.**





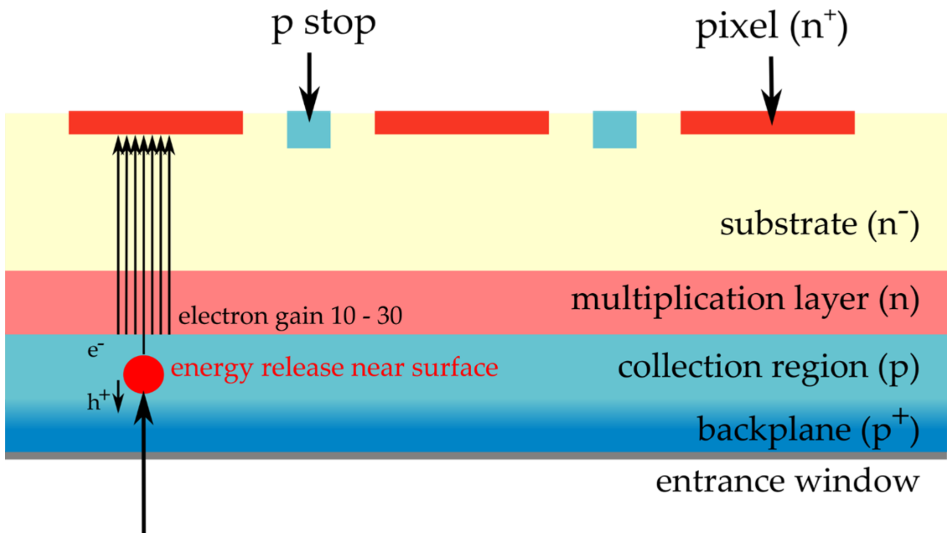
- **TimePix3.** 55x55 µm pitch, 256x256 pixels: 12
- **TDCPix.** 300x300 µm pitch, 40x45 pixels: 8
- **UZH-PSI.** 100x100 µm pitch, 30x30 pixels: 36
- **iStrip.** 80 µm pitch, 20 strips: 40



Status: Mask set just arrived

Two fabrications: Si-Si wafers and Epitaxial wafers

p-LGAD for low penetrating particles



Low energy X-rays or protons

Not radiation hard but interesting for many other applications

EU Patent 20382836.3-1230

- Polarity is chosen so electrons drift to the readout side after crossing the multiplication layer,
- Thick substrate to reduce noise.
- Uniform gain and pixelated geometry possible.

W. Khalid et al., pLGAD: A New Sensor Concept for Low Penetrating Particles, https://indico.cern.ch/event/813597/contributions/3727804/

Vendors Overview

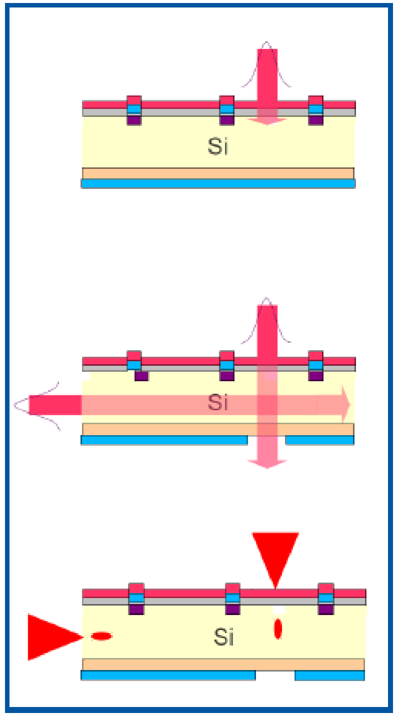
Vendor	LGAD	iLGAD	AC-LGAD	TI-LGAD	p-LGAD
IMB-CNM (Spain)*+	✓	✓	✓		✓
FBK (Italy)*+	✓		✓	✓	
Micron Semiconductor Ltd (UK)°	✓	✓		✓	
HPK (Japan)°	✓		✓		
BNL (USA)*+	✓		✓		
NDL (China)*+	✓				
IME (China)*+	✓				

* RD50 Member
+ RTO (Research and Technical Organisation)
° Commercial Manufacturer

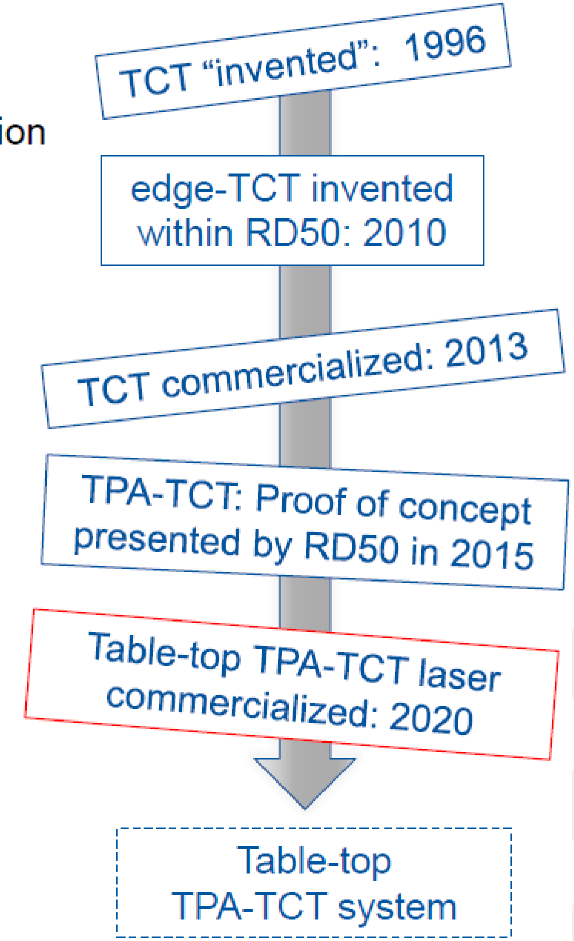
Experimental Procedures

Experimental Procedures TPA-TCT

- Pulsed laser induced generation of charge carriers inside detector
  - Study of: electric field in sensor, charge collection efficiency, homogeneity,..
  - Benchmark simulation tools, measure physics parameters from mobility to impact ionization
- New TCT technology: TPA-TCT – Two Photon Absorption TCT

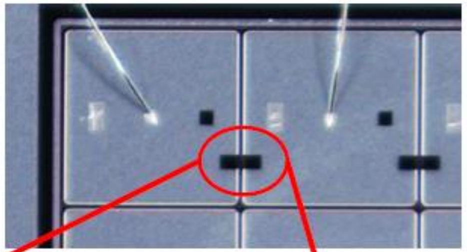


- **TCT (red laser)**
  - short penetration length (650nm = 1.9eV)
  - carriers deposited in a few μm from surface
  - front and back TCT: study electron and hole drift separately
  - 2D spatial resolution (5-10μm)
- **TCT (infrared laser)**
  - long penetration (1064nm = 1.17 eV)
  - similar to MIPs (though different dE/dx)
  - top and edge-TCT
  - 2D spatial resolution (5-10μm)
- **TPA-TCT (far infrared)**
  - No single photon absorption in silicon
  - 2 photons produce one electron-hole pair
  - Point-like energy deposition in focal point
  - **3D** spatial resolution (1 x 1 x 10 μm^3)

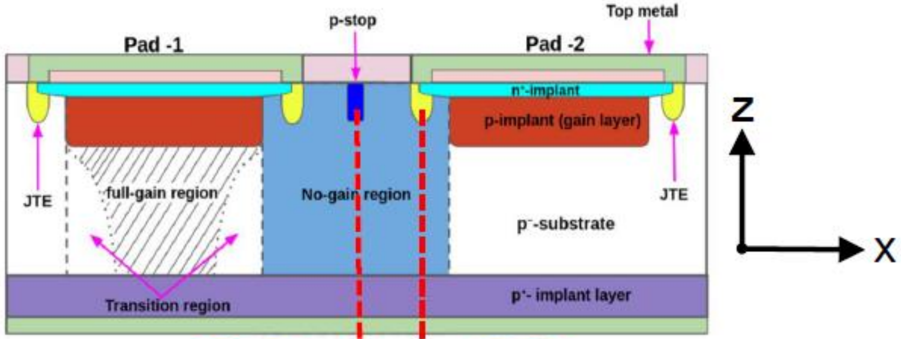


Experimental Procedures TPA-TCT

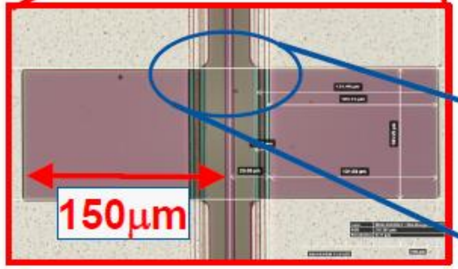
- **top-TPA-TCT** on the inter-pad region of an HPK2-LGAD matrix

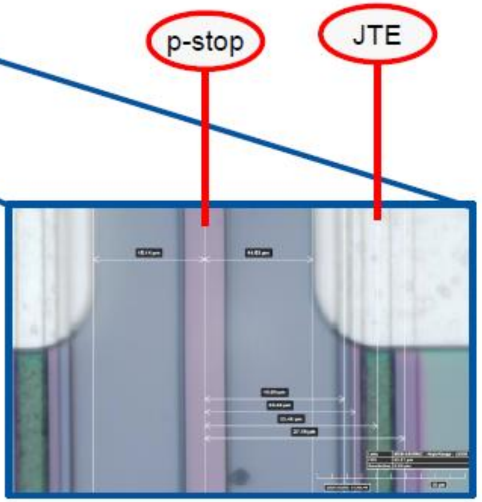


schematic cut through device



Drawing: S. Bharthuar et.al. https://doi.org/10.1016/j.nima.2020.164494

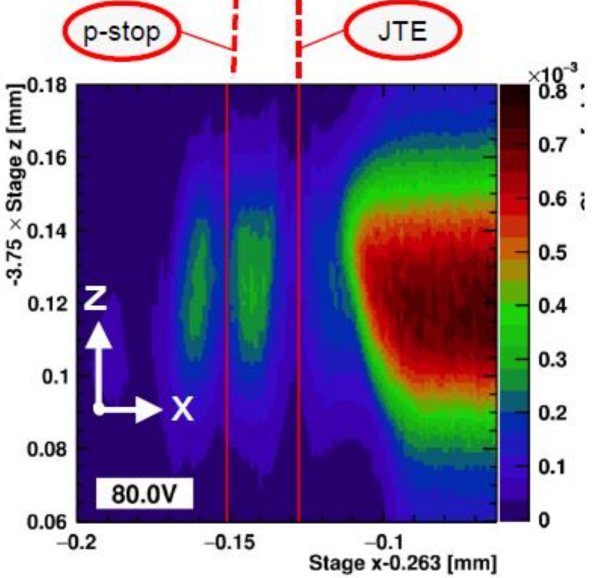




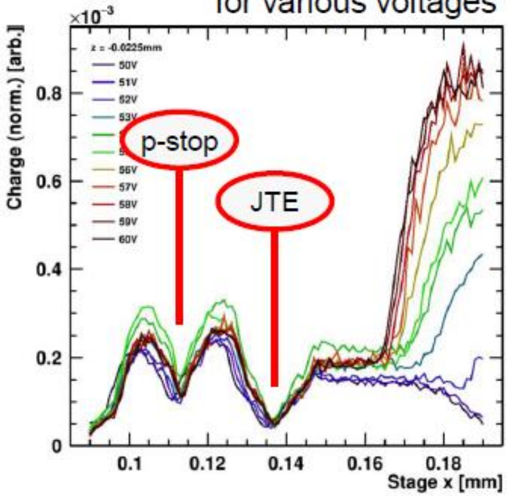
Images with Hirox microscope taken at CERN EP-DT QART lab

HPK2-W28-S1-LGAD-P14

LG 5x5-SE3-IP5-UBM



x scan at fixed depth for various voltages



https://indico.cern.ch/event/1029124/contributions/4411336/attachments/2269311/3853596/2021_06_23_RD50_Pape.pdf

Gain Suppression TPA-TCT

Gain suppression mechanism in LGADs

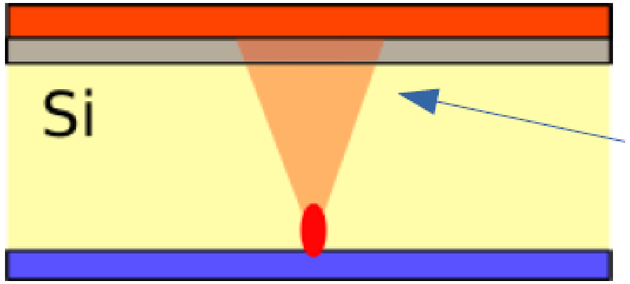
Sebastian Pape
technische universität dortmund

1.) Low charge density in the GL will lead to a higher gain: there will be a negligible gain suppression.

2.) High charge density in the GL will lead to a reduction in the gain: drop in the GL E-field (less amplification).

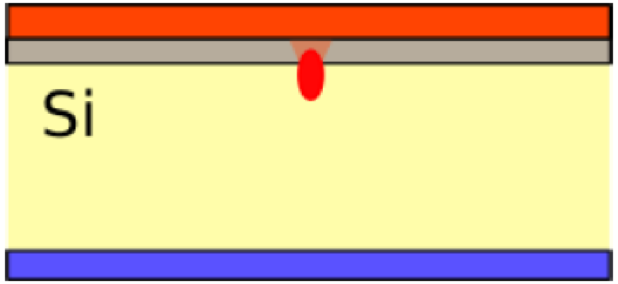
E. Currás - 38th RD50 Workshop

1.)



Shaded red: *schematic evolution of the charge density*

2.)



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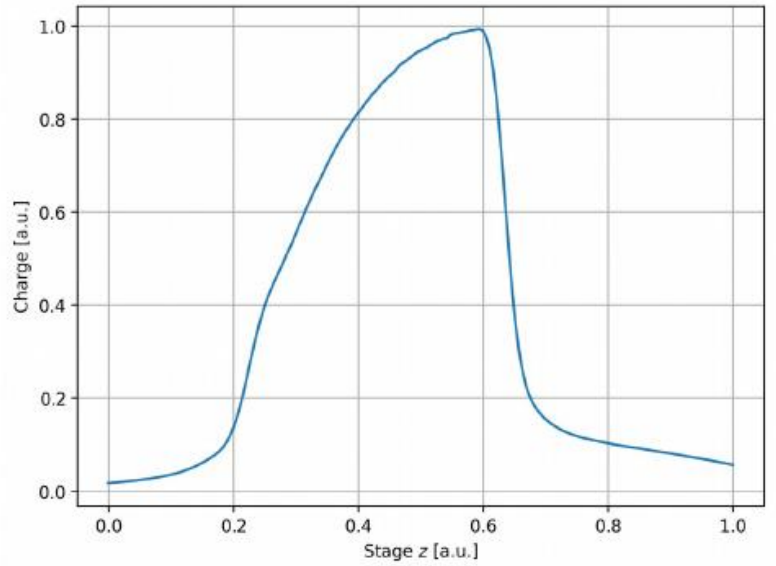
CSIC Consejo Superior de Investigaciones Científicas

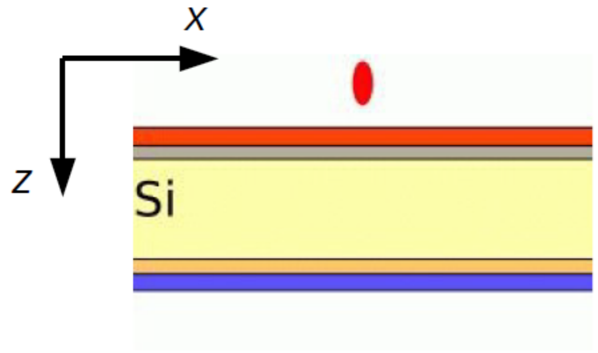
Study of the gain suppression mechanism with TPA-TCT

Sebastian Pape
technische universität dortmund

- Investigate gain suppression using TPA-TCT
- Expectation: significant amount of charge is generated in or close to the gain layer leading to:
    - Suppressed gain
    - Less charge is collected at the front side
    - Shark fin plot



Schematic expected charge collection ("shark fin" plot)



Study of the gain suppression mechanism with TPA-TCT

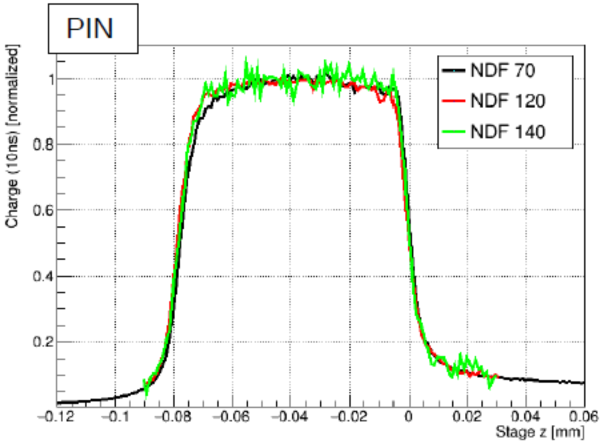
Sebastian Pape
technische universität dortmund

Samples:

PIN_8622_W5_J6_2

CNM, **~280µm physical thickness**
Unirradiated

Objective: NA0.7



Study of the gain suppression mechanism with TPA-TCT

Sebastian Pape
technische universität dortmund

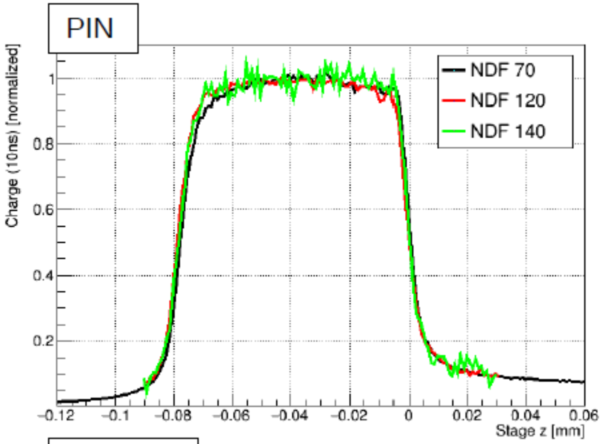
Samples:

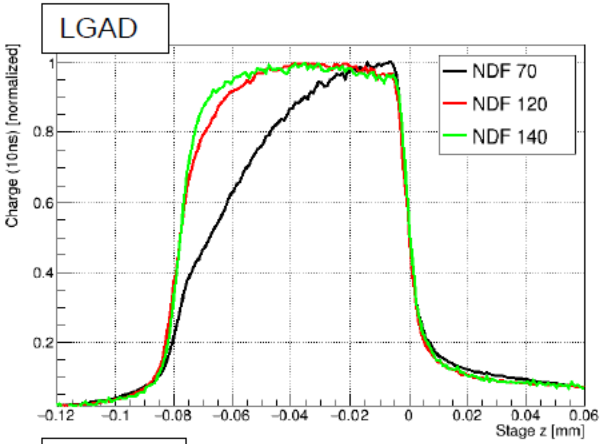
PIN_8622_W5_J6_2
LGAD_8622_W5_D8_2

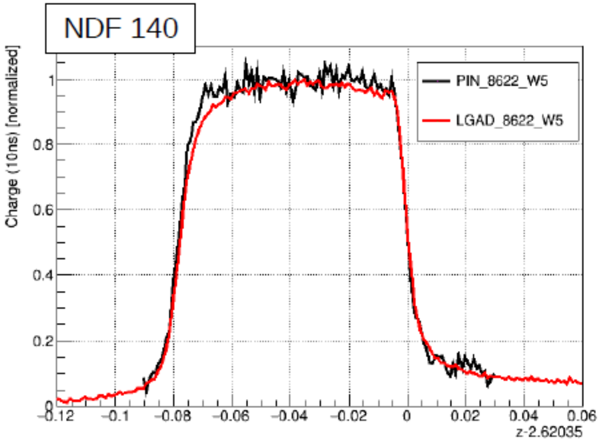
CNM, **~280µm physical thickness**
Unirradiated

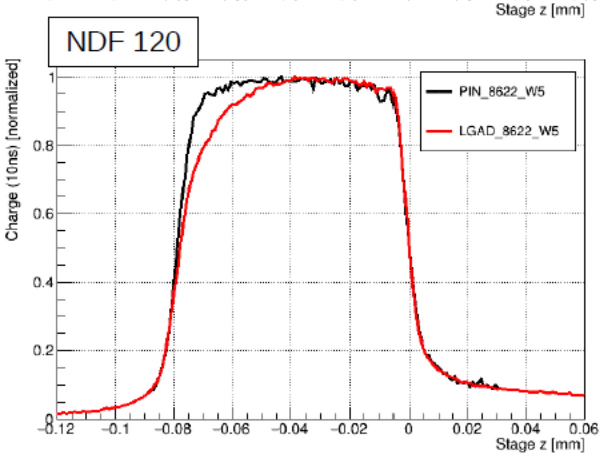
LGAD Gain: around 10

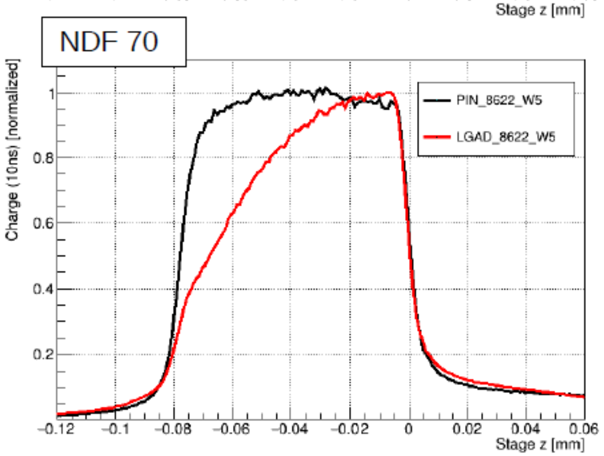
Objective: NA0.5











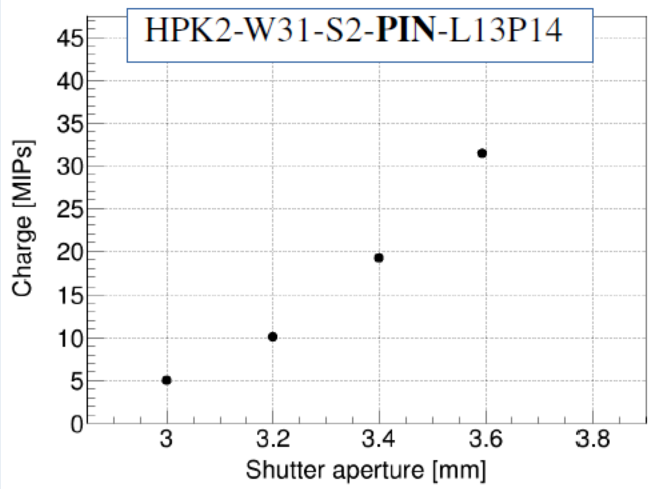
Gain Suppression TCT

Study of the gain suppression mechanism with TCT IR-laser

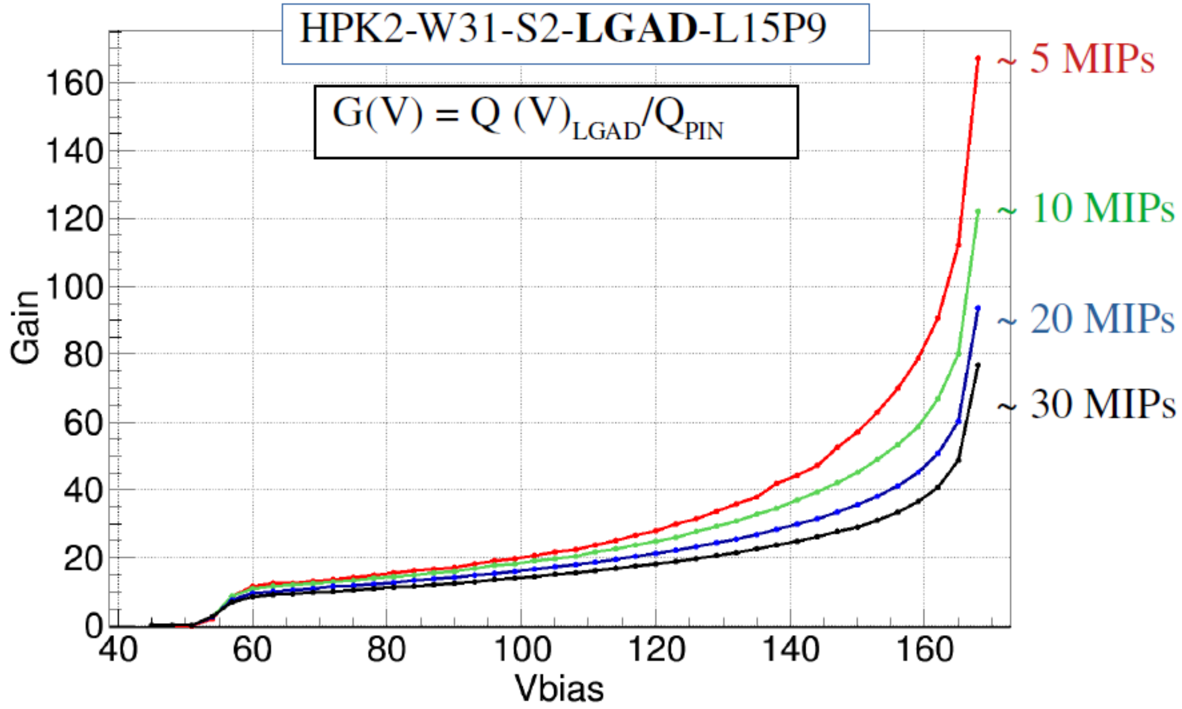
Increasing laser intensity in TCT:

EP R&D

T: +20 ^{O}C
Averaging: 1024
No amplifier
IR shutter aperture:
- 3.0 (~ 5 MIPs)
- 3.2 (~10 MIPs)
- 3.4 (~20 MIPs)
- 3.6 (~30 MIPs)



IR laser intensity (Charge density) ↑ Gain ↓



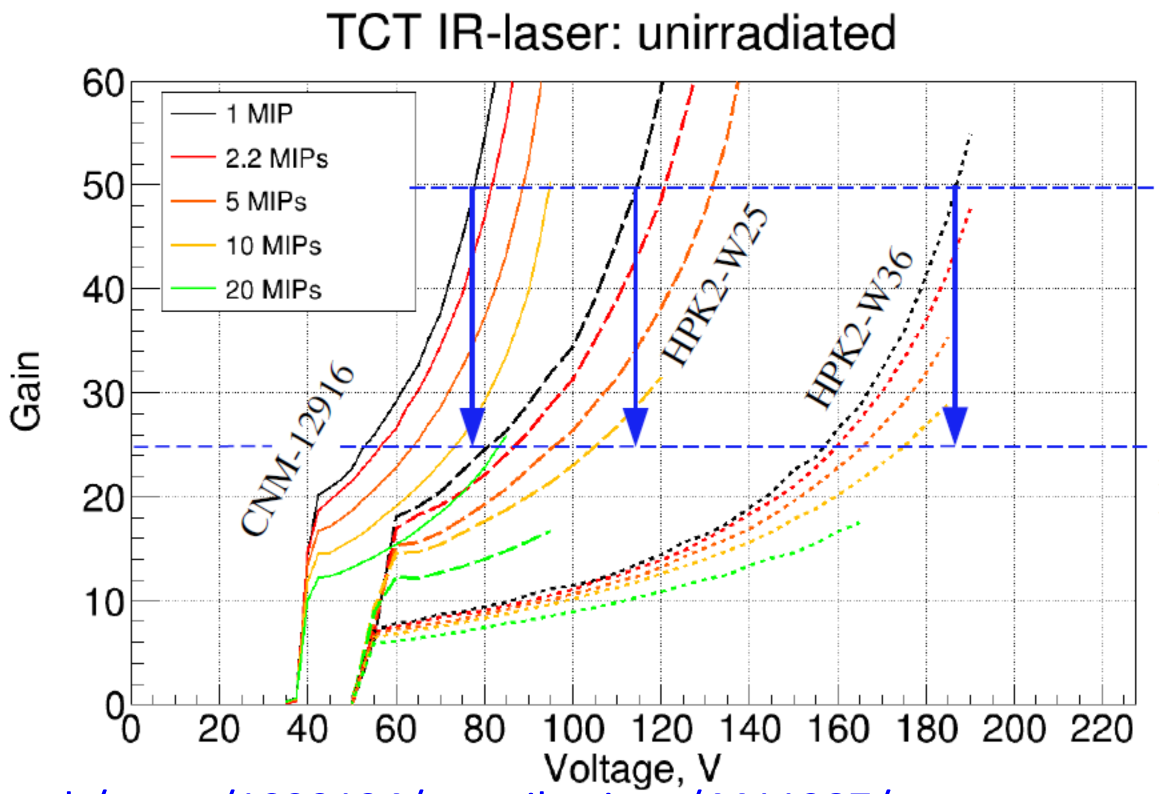
https://indico.cern.ch/event/1029124/contributions/4411287/

https://arxiv.org/abs/2107.10022

Study of the gain suppression mechanism with TCT IR-laser

Different types of unirradiated LGADs

EP R&D



Measurements done at +20C

Gain suppression effect observed for all the 50 um LGADs that we studied.

We observe a higher suppression for the LGADs with a higher nominal gain.

For all the samples: the higher the gain the higher the suppression, e.g:

- For a gain of 50 at 1 MIP the gain drops more than 50% for 20 MIPs.

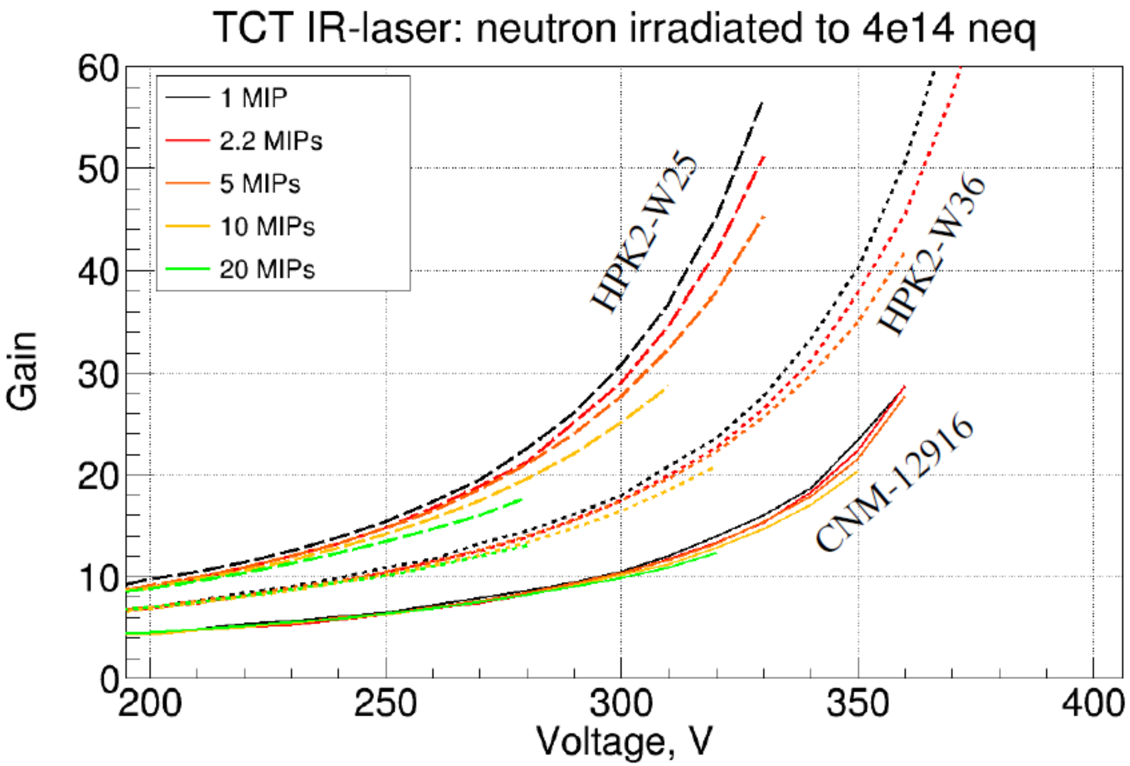
https://indico.cern.ch/event/1029124/contributions/4411287/

https://arxiv.org/abs/2107.10022

Study of the gain suppression mechanism with TCT IR-laser

Different types of irradiated LGADs: $4x10^{14}$ n_{eq}/cm^2

EP R&D



Measurements done at -20C

Gain suppression effect observed for all the 50 um irradiated LGADs to 4e14 n_{eq}.

The gain suppression is reduced with irradiation for all these devices.

For all the samples: the higher the gain the higher the suppression. But the effect is reduced w.r.t the non-irradiated ones.

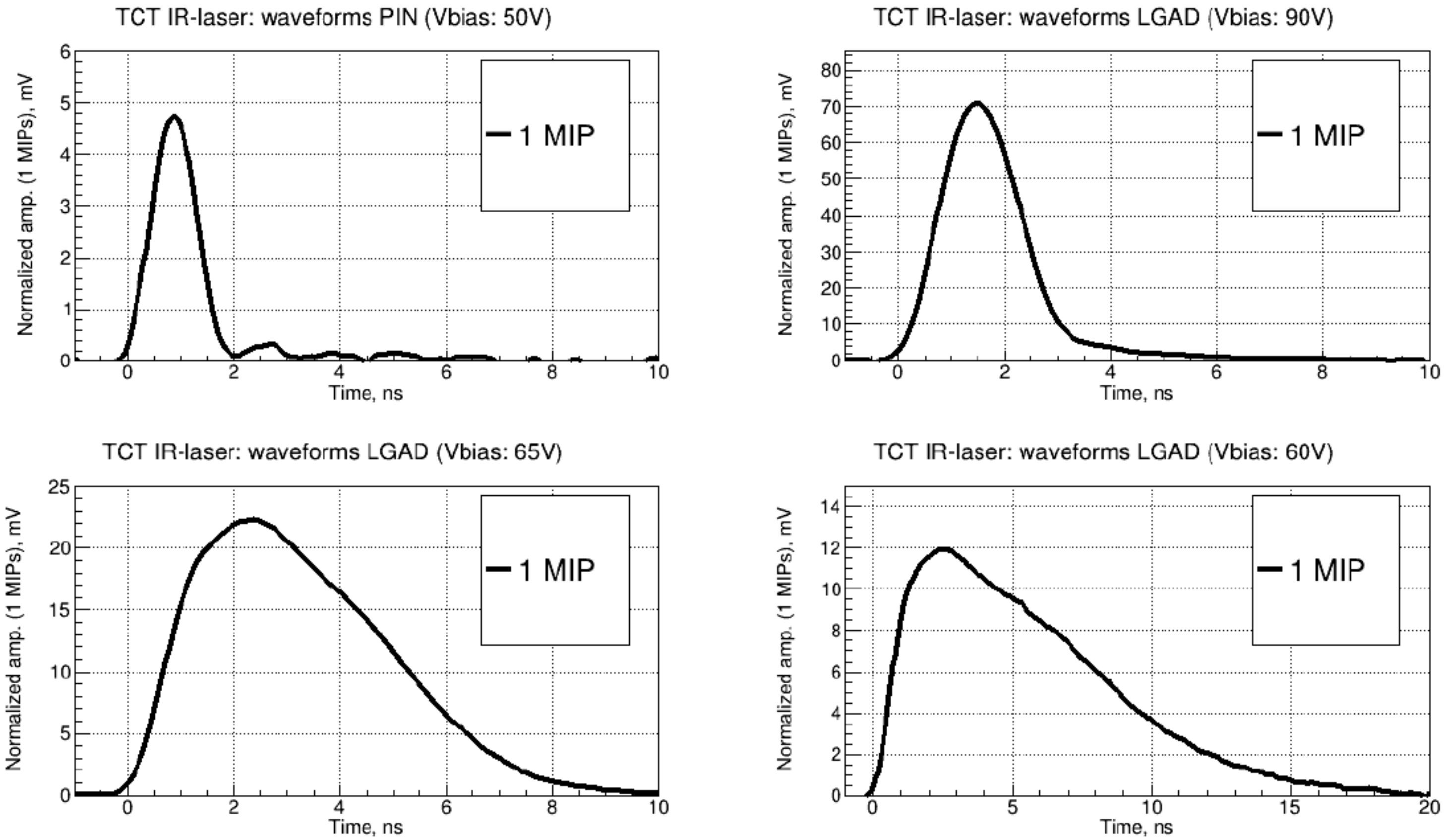
https://indico.cern.ch/event/1029124/contributions/4411287/

https://arxiv.org/abs/2107.10022

Study of the gain suppression mechanism with TCT IR-laser

TCT waveforms: non-irradiated LGAD-HPK2-W25

EP R&D



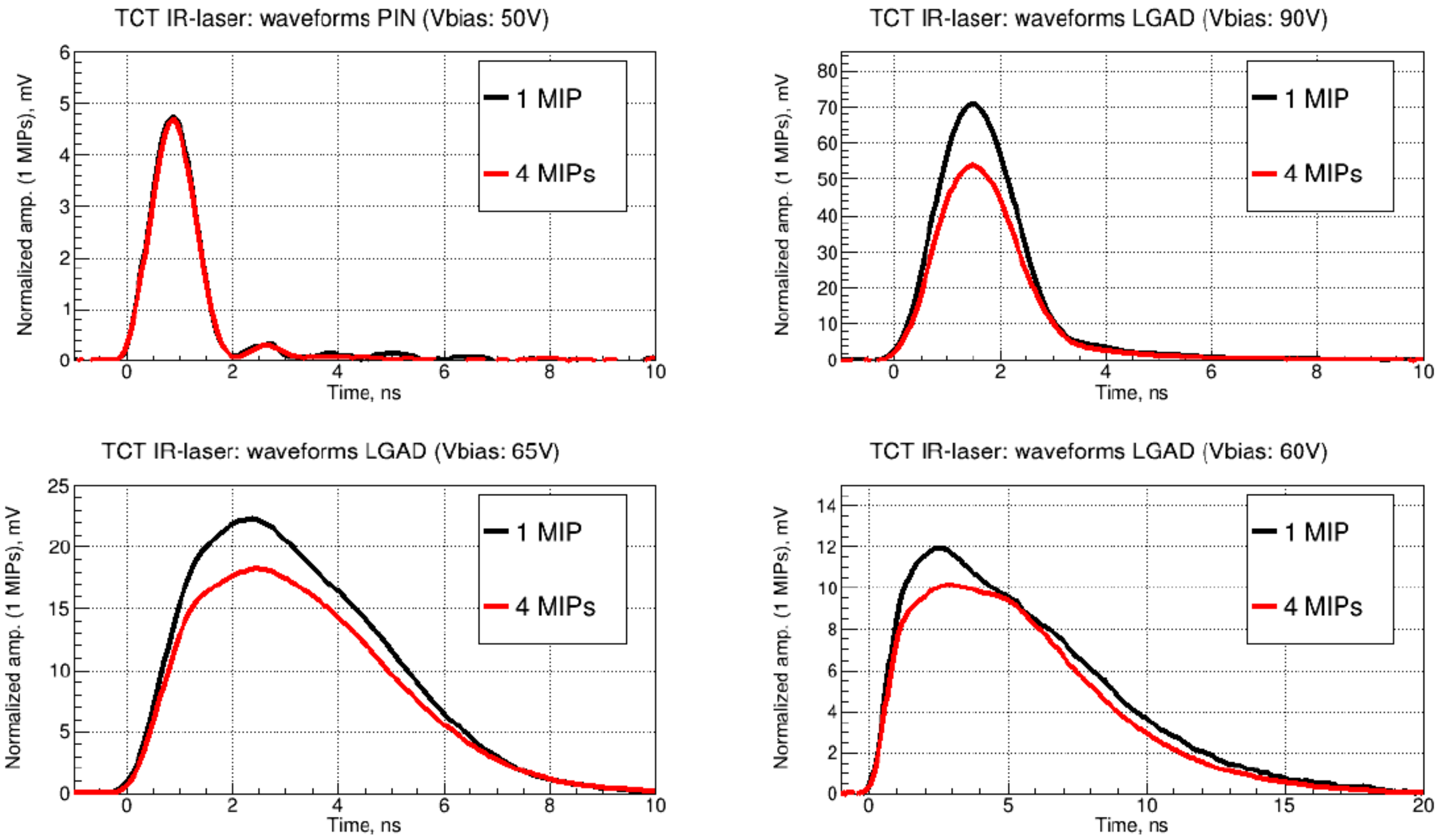
https://indico.cern.ch/event/1029124/contributions/4411287/

https://arxiv.org/abs/2107.10022

Study of the gain suppression mechanism with TCT IR-laser

TCT waveforms: non-irradiated LGAD-HPK2-W25

EP R&D



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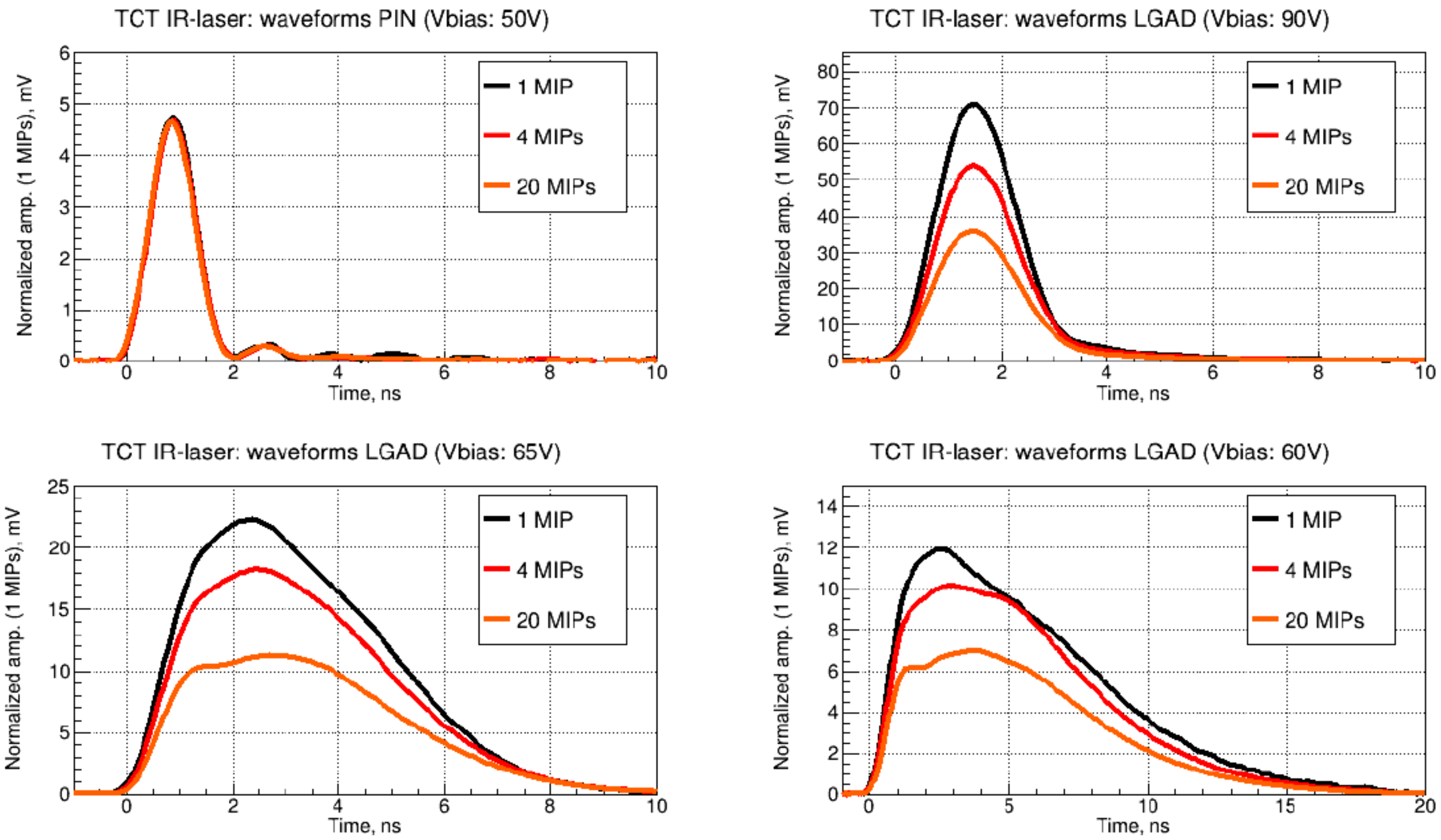

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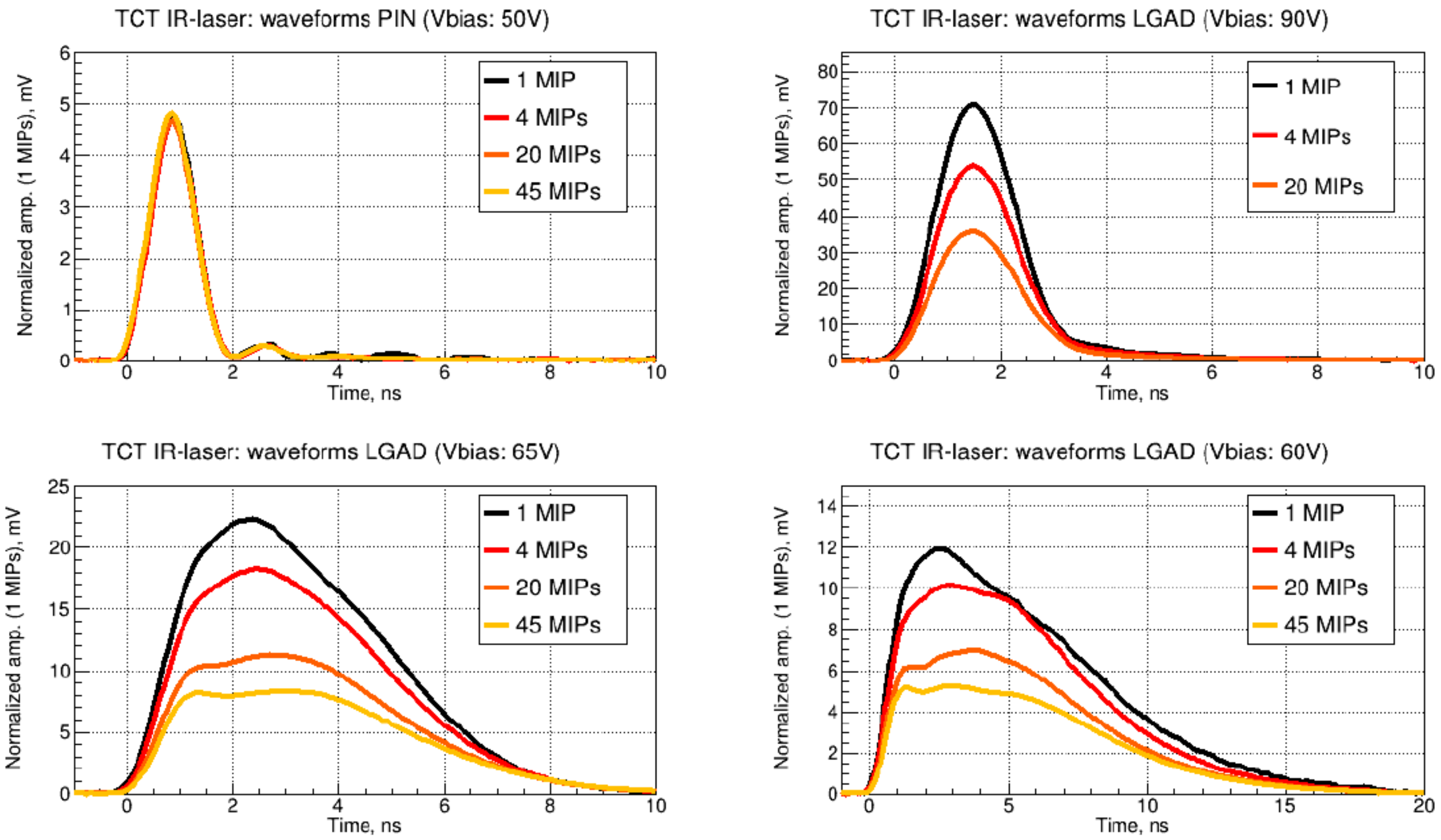
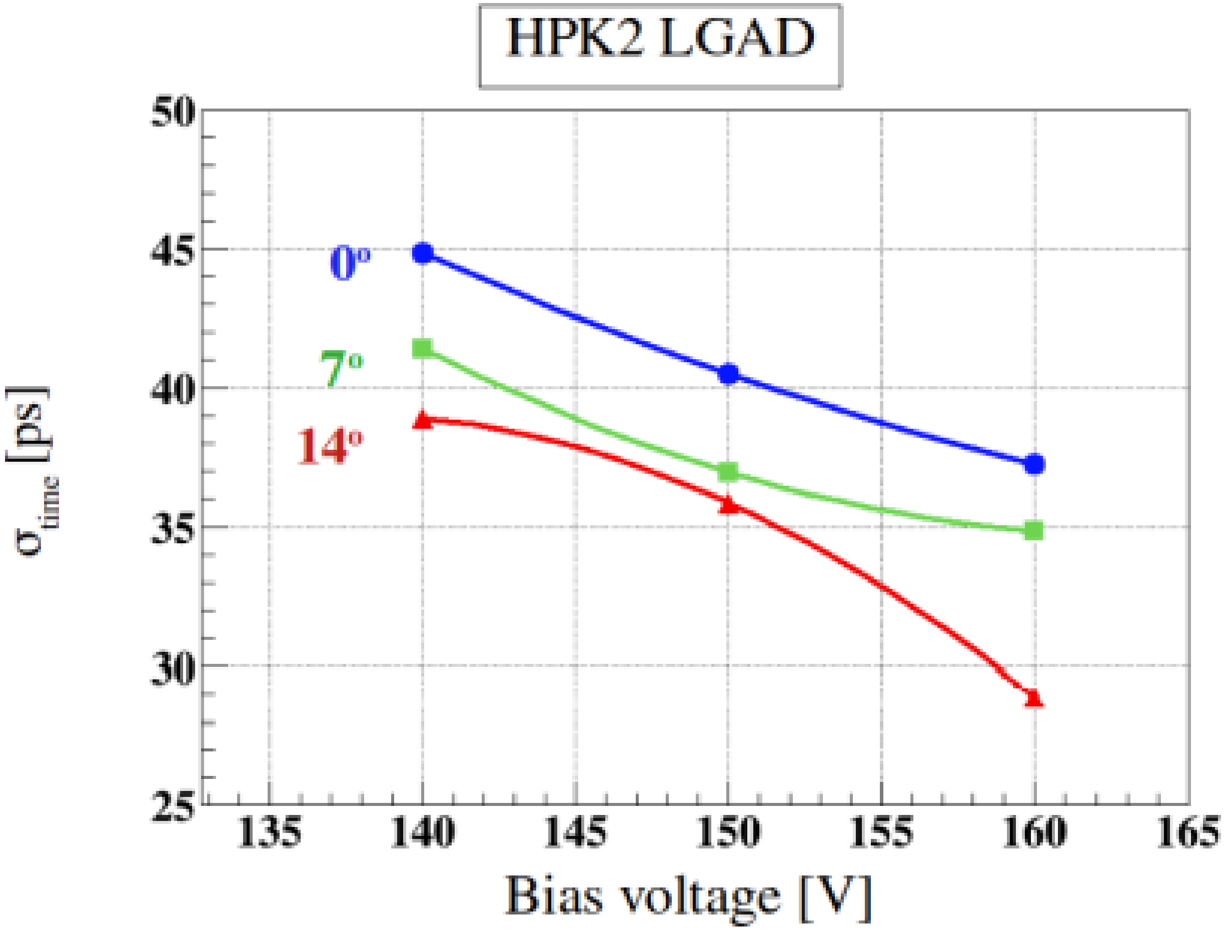


https://indico.cern.ch/event/1029124/contributions/4411287/

https://arxiv.org/abs/2107.10022

Gain suppression effect on Timing Performance



Tilt angle increases

↓

Gain increases

↓

Time resolution improves

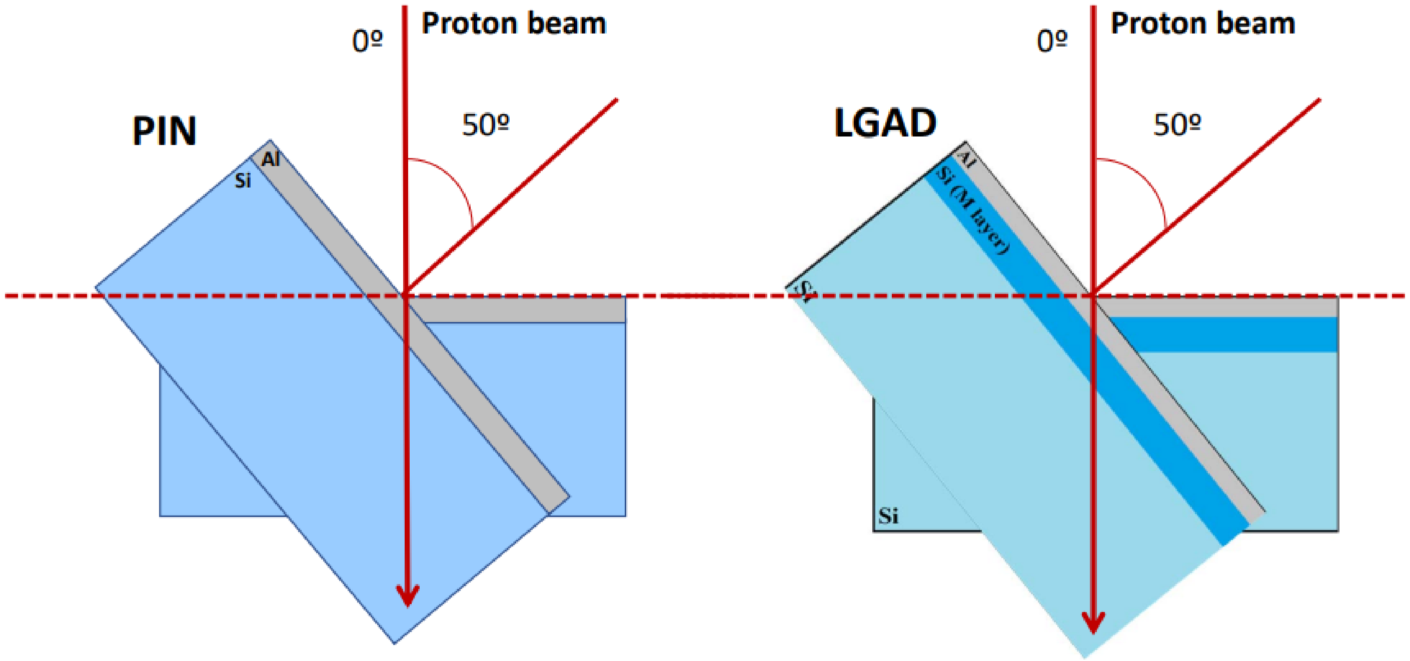
https://arxiv.org/abs/2107.10022

Gain Suppression IBIC

Study of the gain suppression mechanism with IBIC

IBIC – Ion Beam Induced Charge

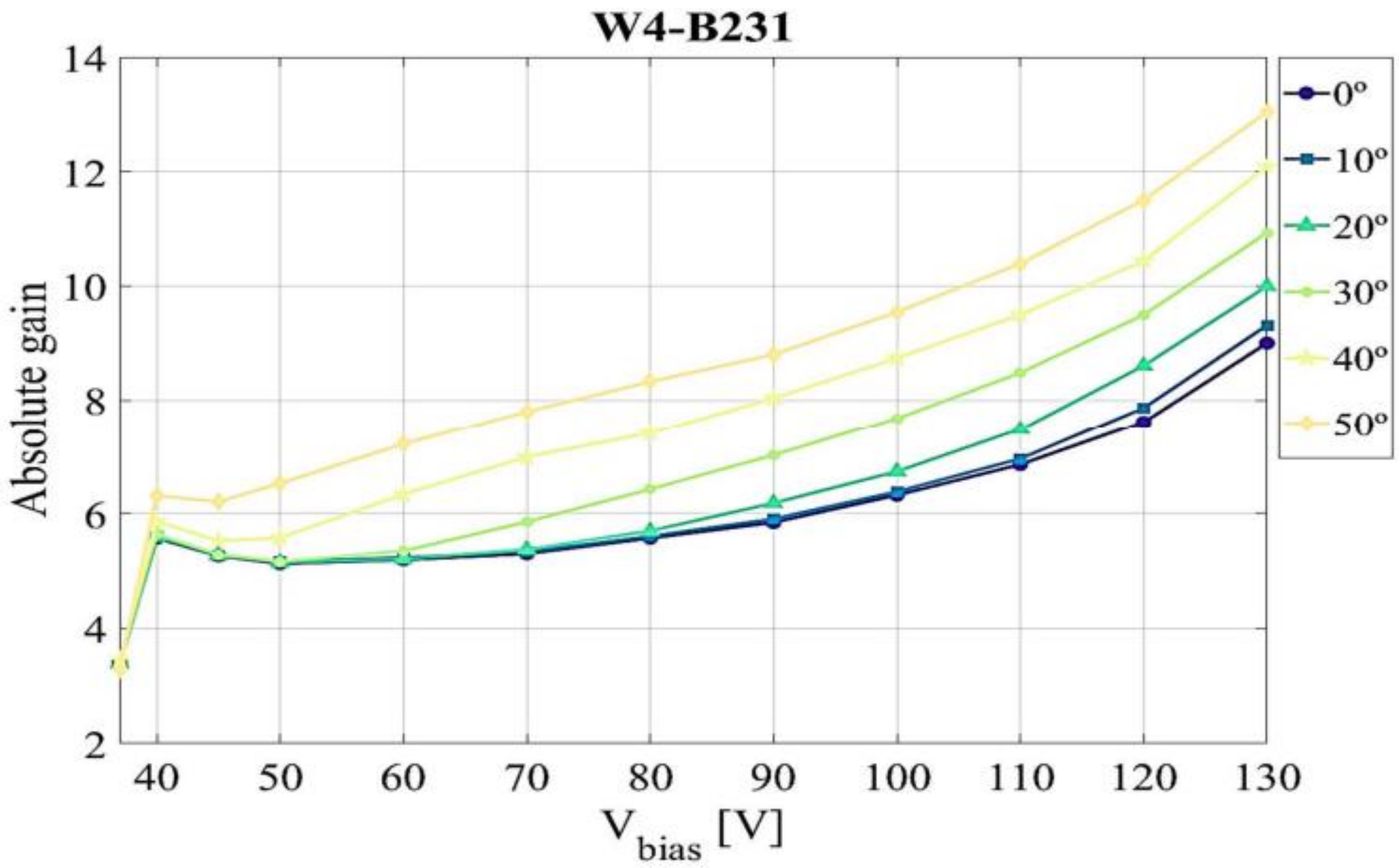
Gain definition: $G(V) = E(V)_{LGAD}/E_{PIN}$ For all θ

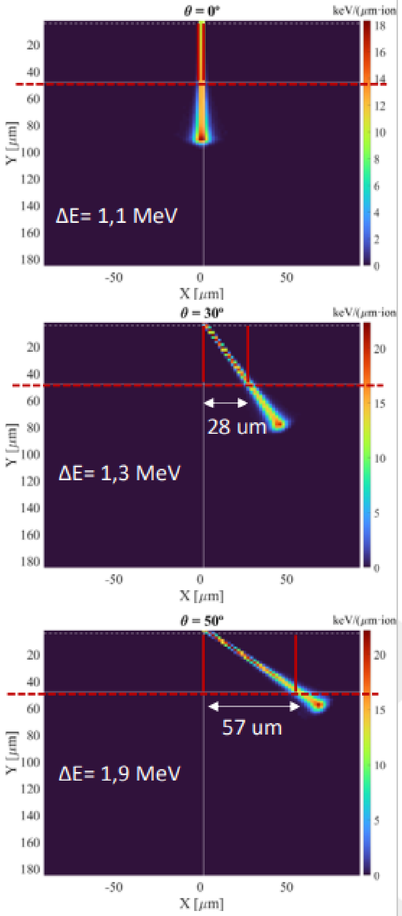


All geometrical effects are well determined and are corrected by normalizing by the PIN.

https://indico.cern.ch/event/1029124/contributions/4410381/

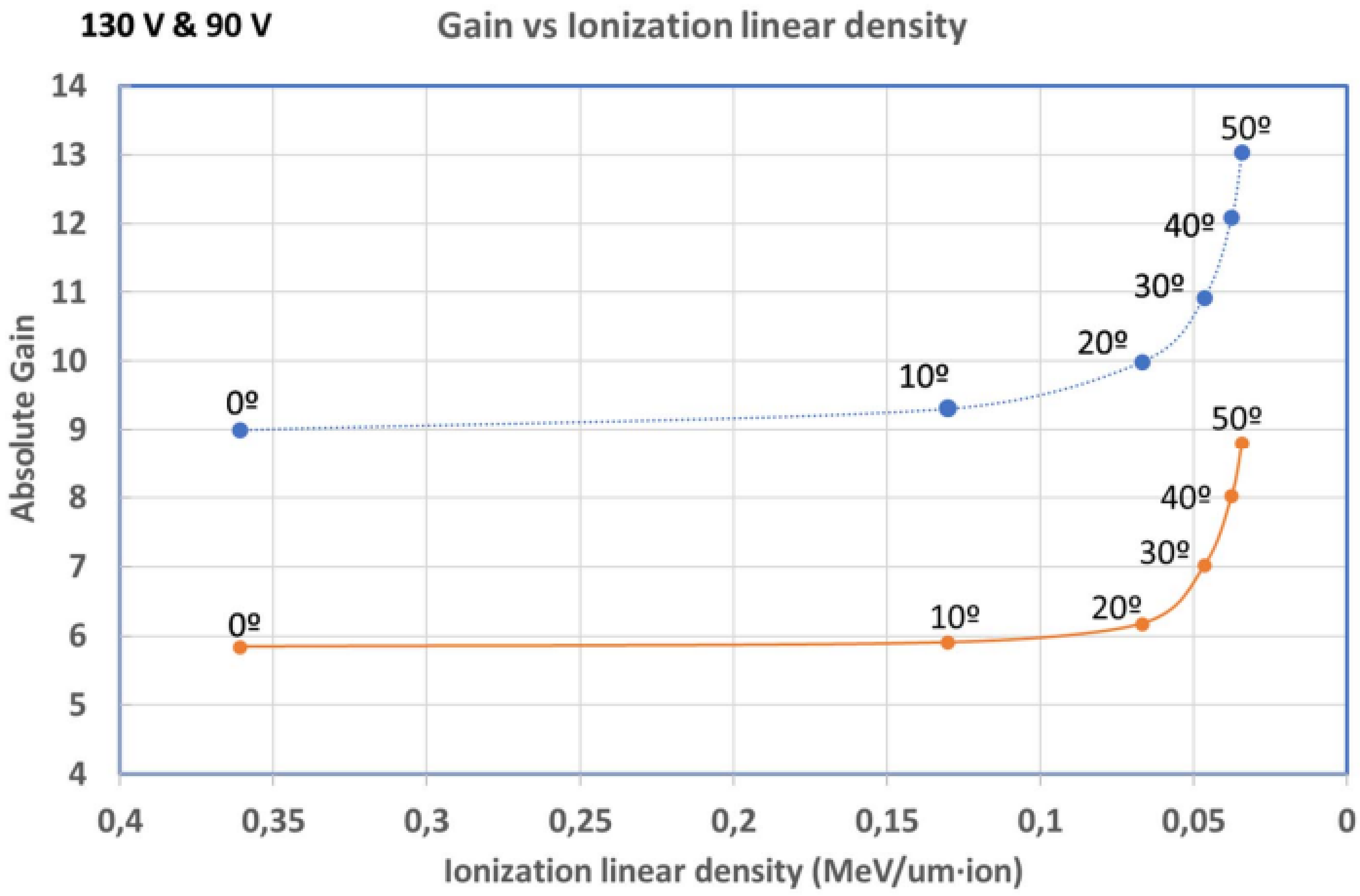
Study of the gain suppression mechanism with IBIC





https://indico.cern.ch/event/1029124/contributions/4410381/

Study of the gain suppression mechanism with IBIC



The mean ionization density projected on the multiplication layer decreases up 50º while gain increases with tilt angle.

↑ Tilt Angle

↓

↑ Gain ↓ Ionz. Lineal Dens.

https://indico.cern.ch/event/1029124/contributions/4410381/

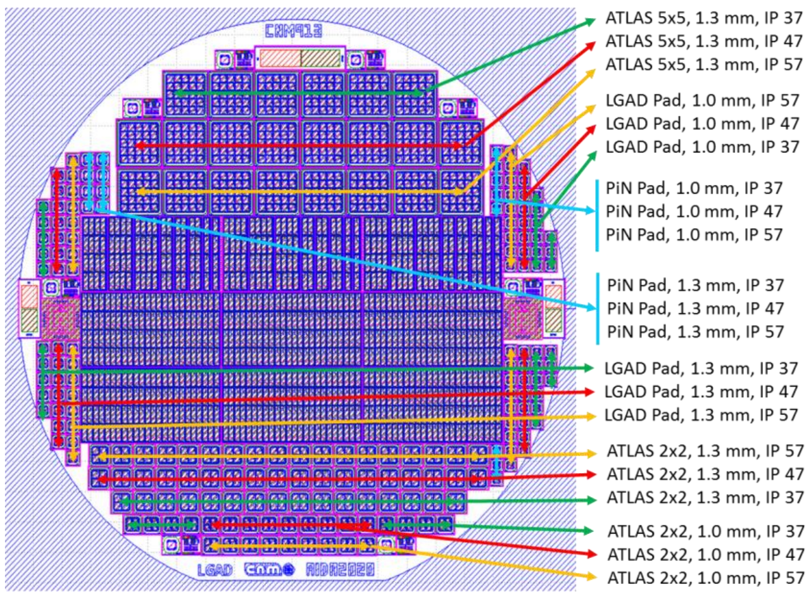
Timing Performance of Irradiated LGADs

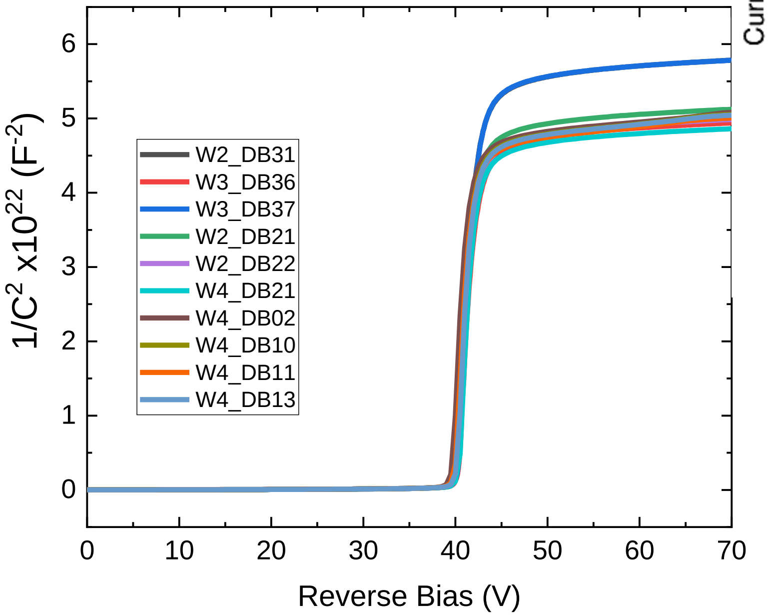
CNM AIDA 2020 Run 12916

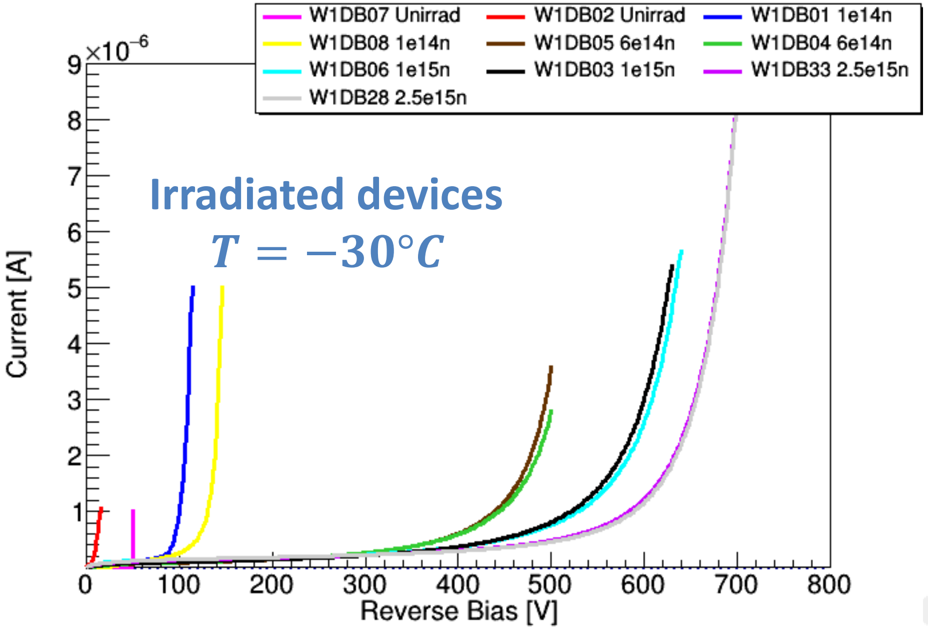
- 4 wafers
- 50 µm active layer, **Si-on-Si** wafers
- $V_{gl} \sim 38V, V_{fd} \sim 42V, V_{bd} \sim 85V$ at room temperature

https://indico.cern.ch/event/797047/contributions/4455198/attachments/2307696/3928110/OverviewCNM_CGrieco_PSD12.pdf

Wafer	Thickness (µm)	Dose (at/cm^2)	Energy (keV)
1-4	50	1,8E13	100



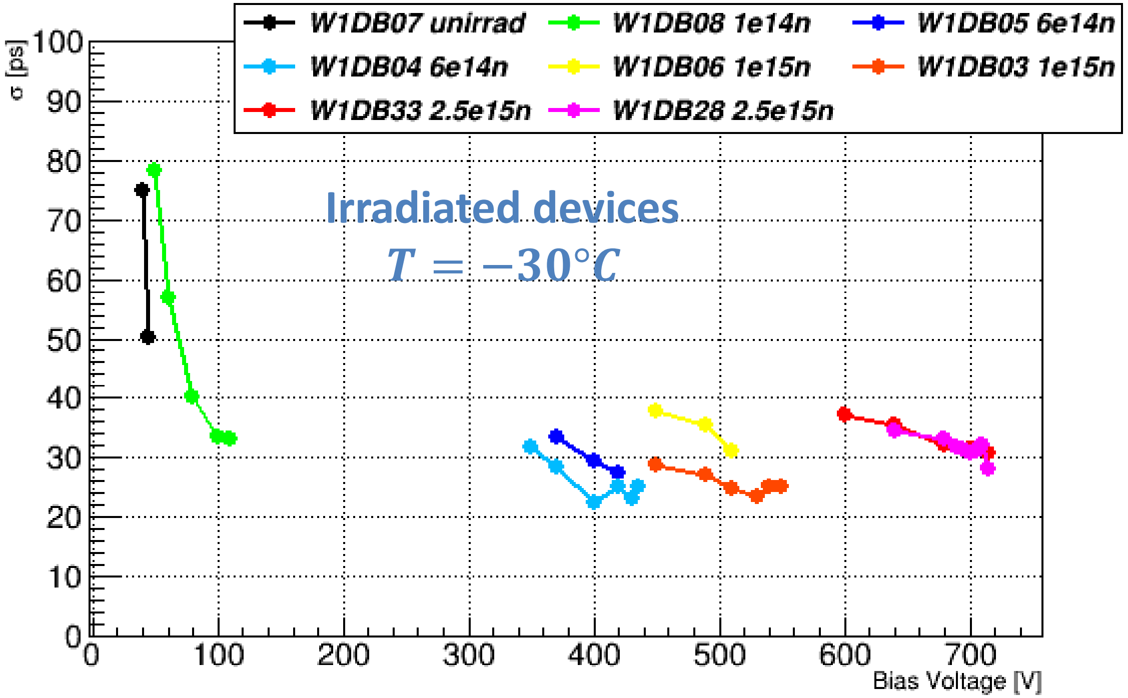




CNM AIDA 2020 Run 12916

https://indico.cern.ch/event/797047/contributions/4455198/attachments/2307696/3928110/OverviewCNM_CGrieco_PSD12.pdf

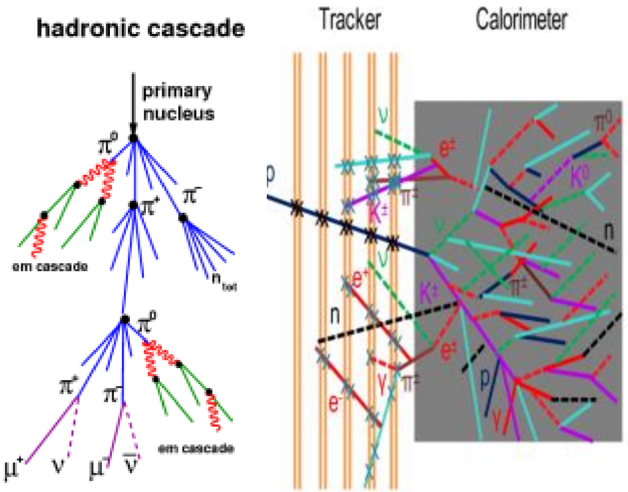
- Unirradiated sensor cannot be operate at higher voltage due to auto-triggering, marginal performances in timing
- Irradiated sensors present a time resolution lower than 40 ps at all level of neutron irradiation.
- Unirradiated devices do not have enough room to operate at cold temperature due to early breakdown



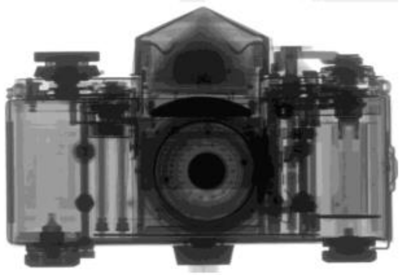
LGAD and timing beyond HEP

Synchrotron Applications
(LGAD tailored for X-ray detection)

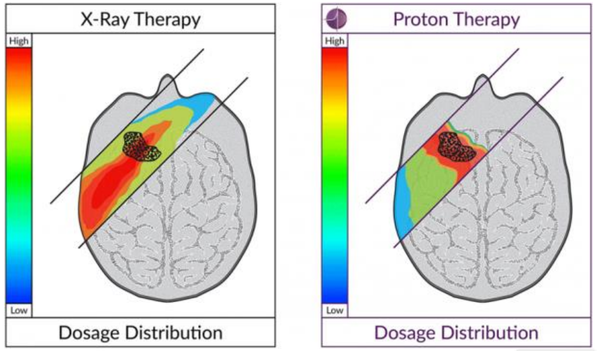
Space Applications
(Time resolved tracking)



Neutron Imaging
(Combining timing LGAD with a conversion layer)



Medical Physics
(4D tracking, X-ray detection...)



Check a full dedicated session at the [38th RD50 Workshop]

Thanks for your attention!