Synchrotron Light Source X-ray Detection with Low-Gain Avalanche Diodes

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On behalf of the SCIPP and Sao Paulo group

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Overview

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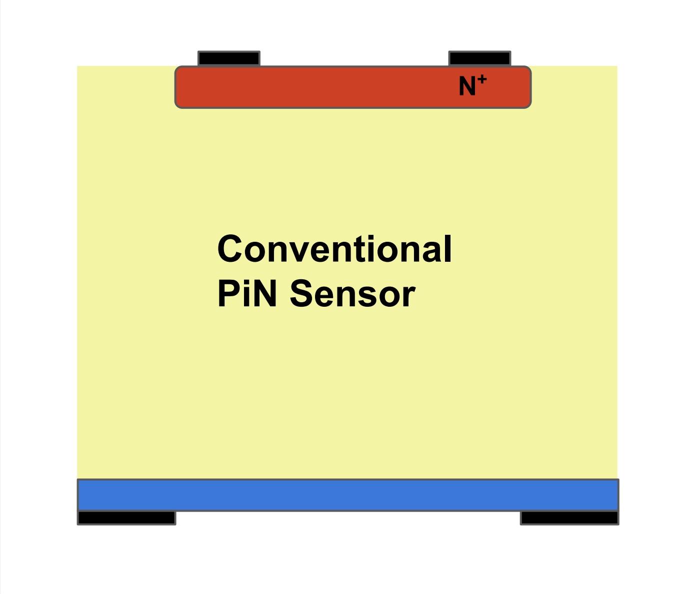
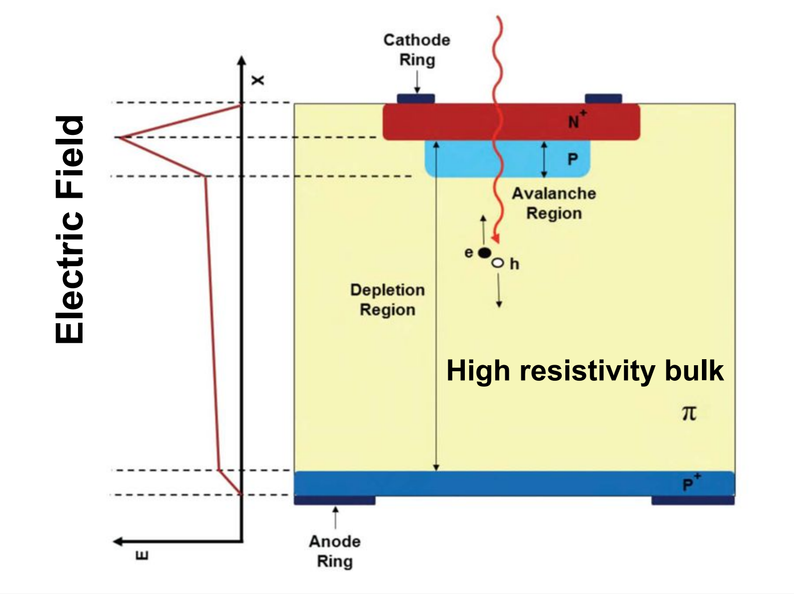
Introduction to LGAD

Low Gain Avalanche Diode

- **The low gain avalanche detector (LGAD) is the state-of-the-art technology in time measurement for charge particles, with the following features:**
  - **Provide moderate internal gain of 5 to 50 ⇒ can be used for small signal detector (low energy X-rays).**
  - **Active thickness of 20 to 50 um ⇒ fast collection time, high frame rate capability.**
  - **Timing resolution is 20 ps or better before high dose irradiation for MIPs.**





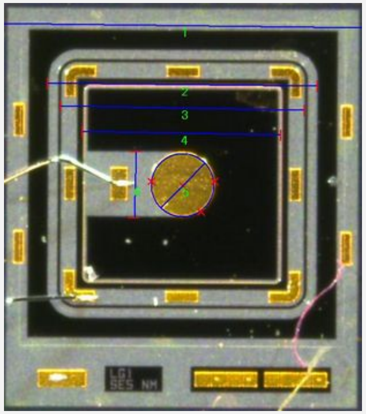
The SSRL Testbeam Setup

Tested LGAD Samples

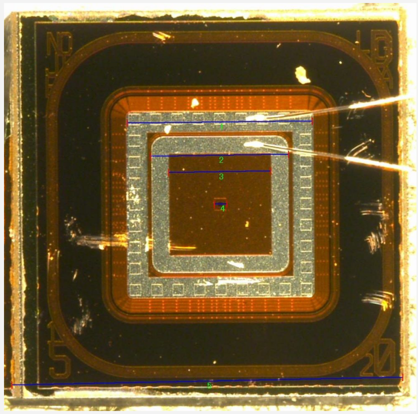
- **Tested 1 PiN device, 3 (DC) LGAD types:**
  - **All samples are single pad devices with active area of 1.3x1.3 mm^2**
  - **Two implant depths of the gain layer: shallow ~1um, deep ~2um.**
- **Tested 50um BNL strip AC-LGAD.** (very preliminary)

Device	Active Thickness [um]	Gain Layer	Breakdown [V]
HPK LGAD type 3.1	50	shallow	~230
HPK LGAD type 3.2	50	deep	~130
HPK PiN	50	No gain	~400
BNL LGAD	20	shallow	~100

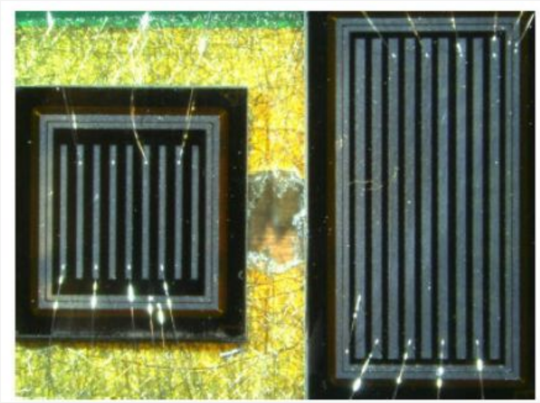
HPK Pad Device



BNL Pad Device

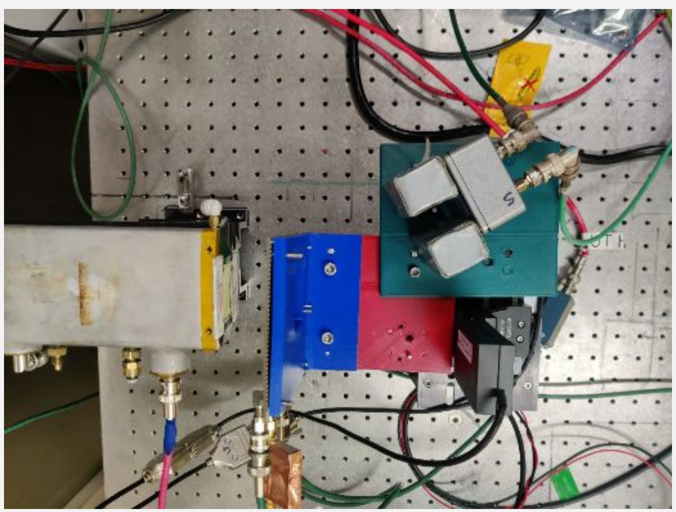


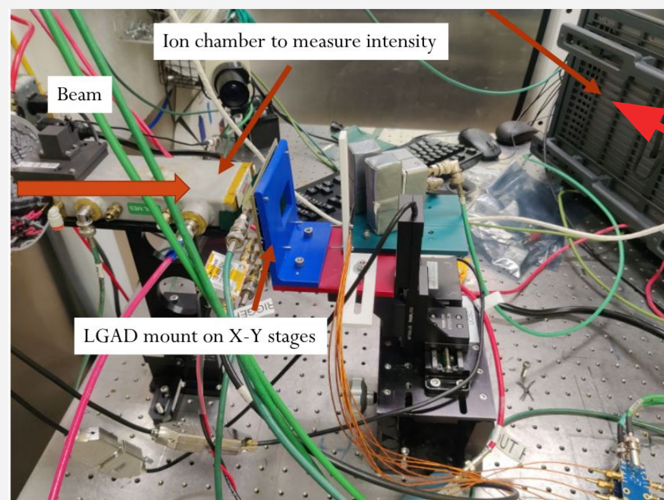
BNL AC-LGAD Strips Device



The SSRL Testbeam Setup

- **The Stanford Synchrotron Radiation Lightsource (SSRL) 11-2 beamline:**
  - **X-rays energy:**
    - 5 to 70 keV
    - Energy resolution of $\Delta E/E \approx 10^{-4}$
    - Monochromator to filter harmonics
  - **Beam structure:**
    - Spot size 25mm x 1mm
    - 4 groups of 70 bunches
      - 10 ps length (RMS)
      - Separated by 2.1 ns
- **All measurements were performed at room temperature.**

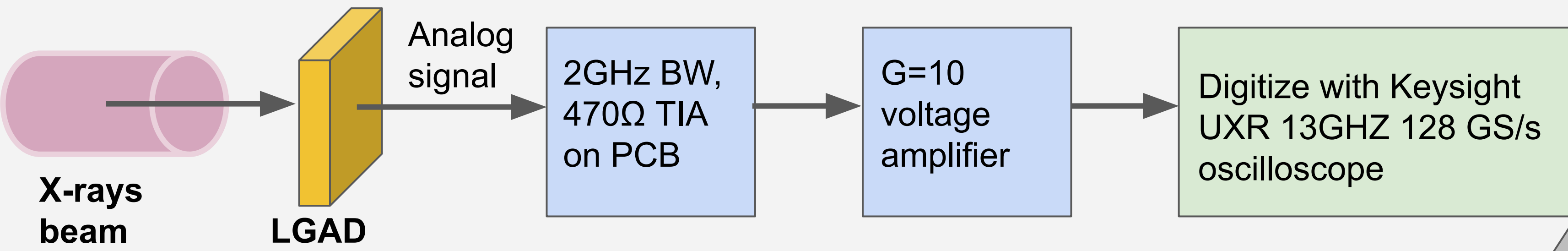


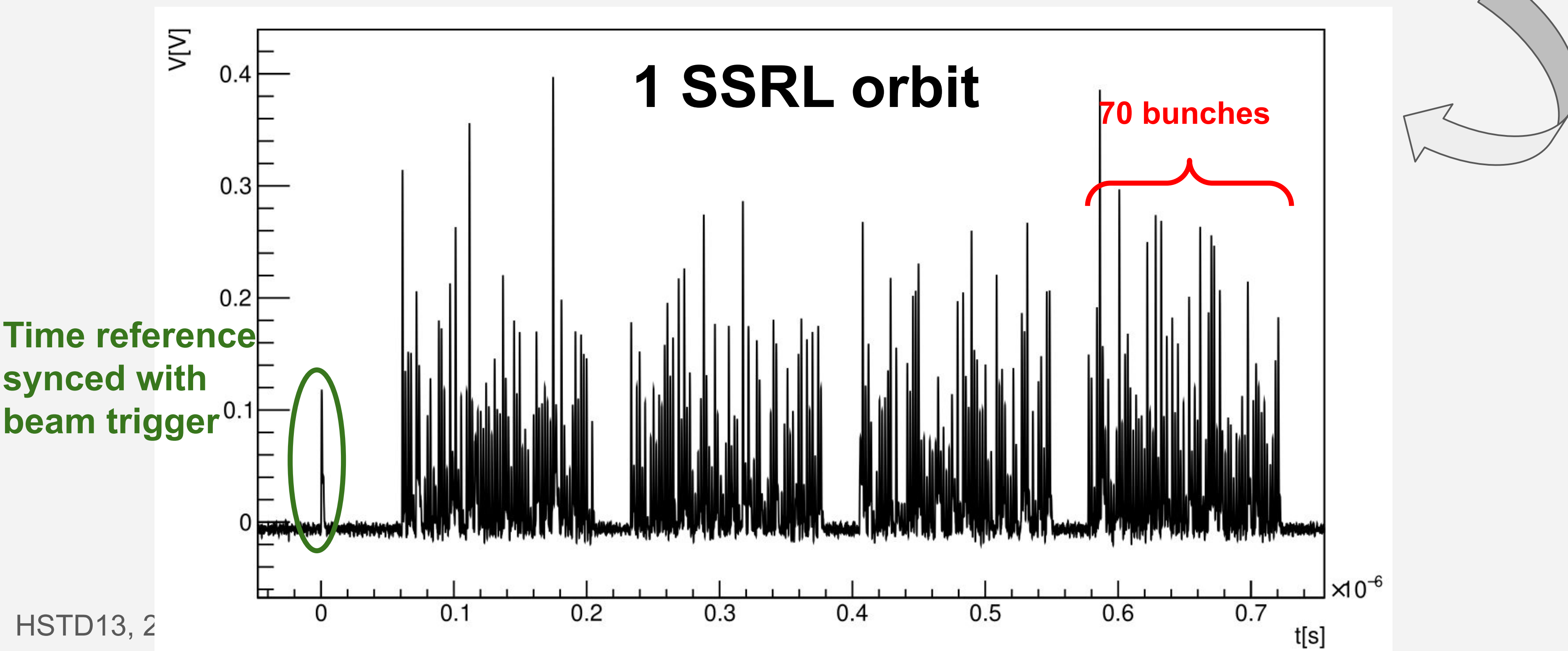


Digitize with Keysight UXR 13GHZ 128 GS/s oscilloscope

The SSRL Testbeam Setup

- **Data acquisition:**

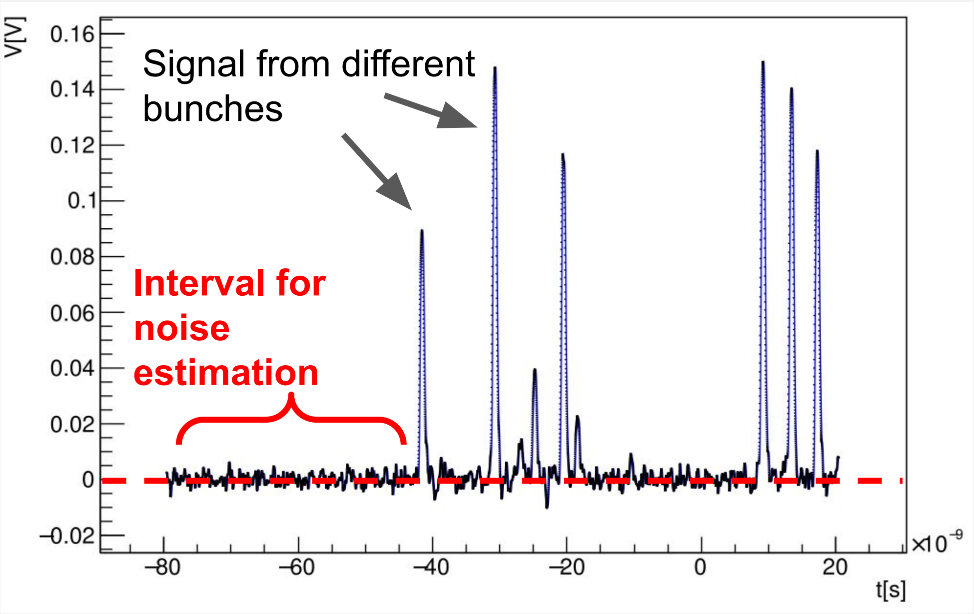




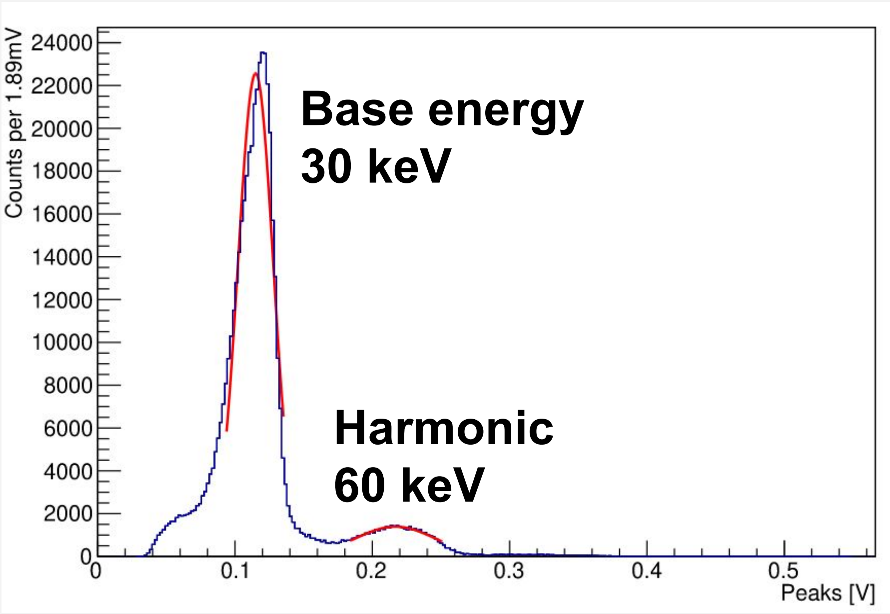
Energy Linearity & Resolution

X-rays Energy Estimation

- **The signal maximum (peak) is used as estimator for X-rays energy.**
  - Baseline correction from [1] is applied to reduce fluctuation from amplification circuit.
  - Signal peak at least > $7\sigma_{noise}$
  - Time separation between adjacent peaks at least 2.1 ns
- Using mean(μ) and width(σ) of the Gaussian fit to the peaks distribution:
  - **Energy :** μ
  - **Resolution:** σ/μ

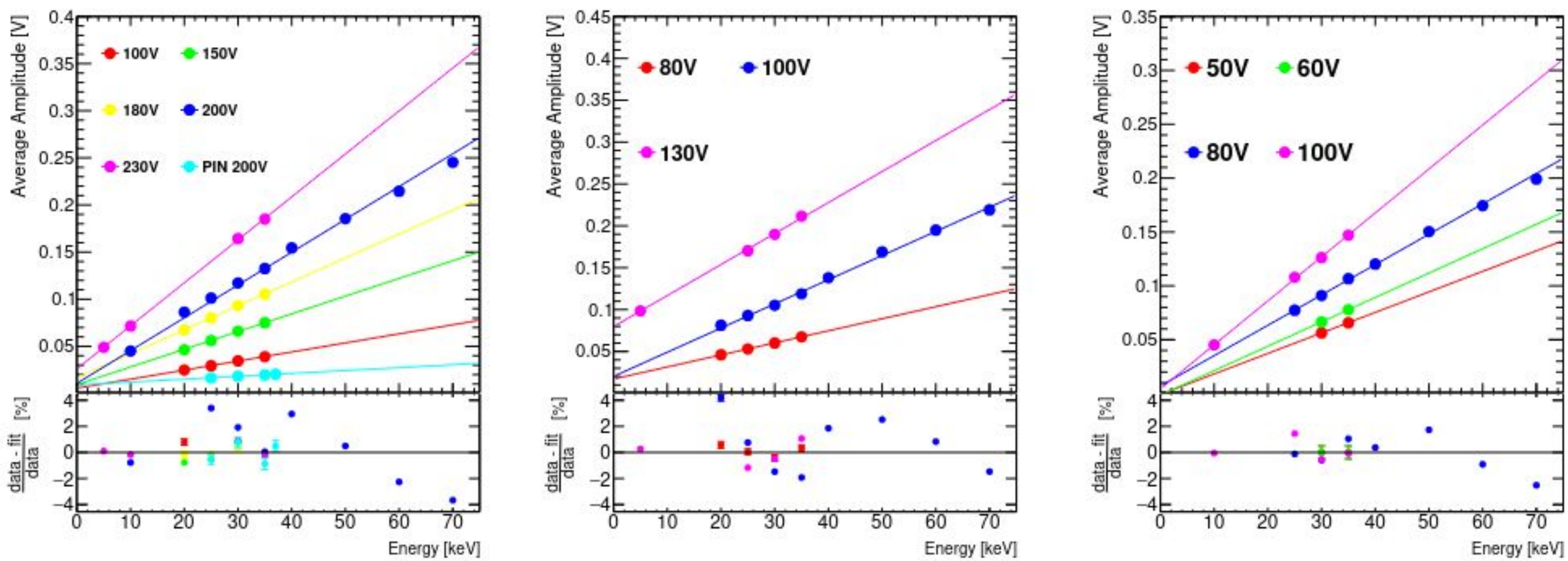


Example distribution for 30 keV X-rays
HPK 3.1 at 200V



X-rays Energy Linearity

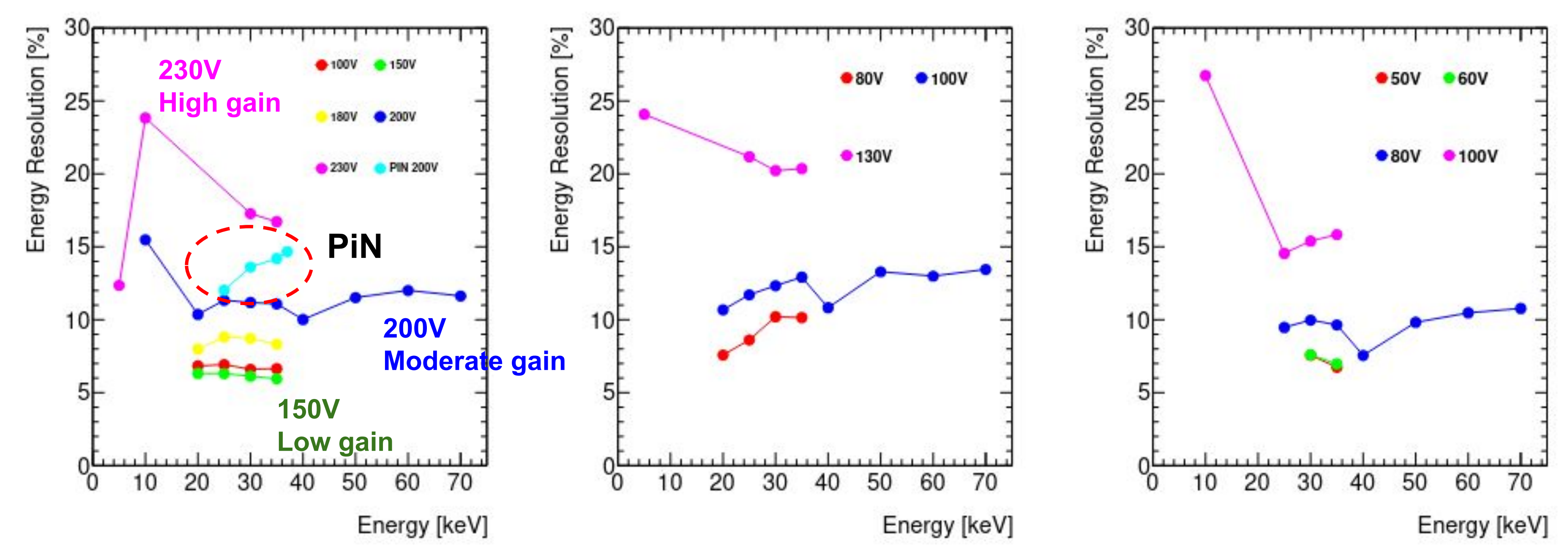
- **The μ is extracted for each energy, bias voltage, and sensor type.**
- **The relation of μ to X-rays energy is shown below:**



(a) HPK PIN and type 3.1 LGAD (b) HPK type 3.2 LGAD (c) BNL 20um LGAD

X-rays Energy Resolution

- The energy resolution (σ/μ) of LGADs for each of the tested X-rays energies are shown:
  - **The energy resolution is approximately constant over the tested energy range.**
  - **The energy resolution degrades at higher gains.**

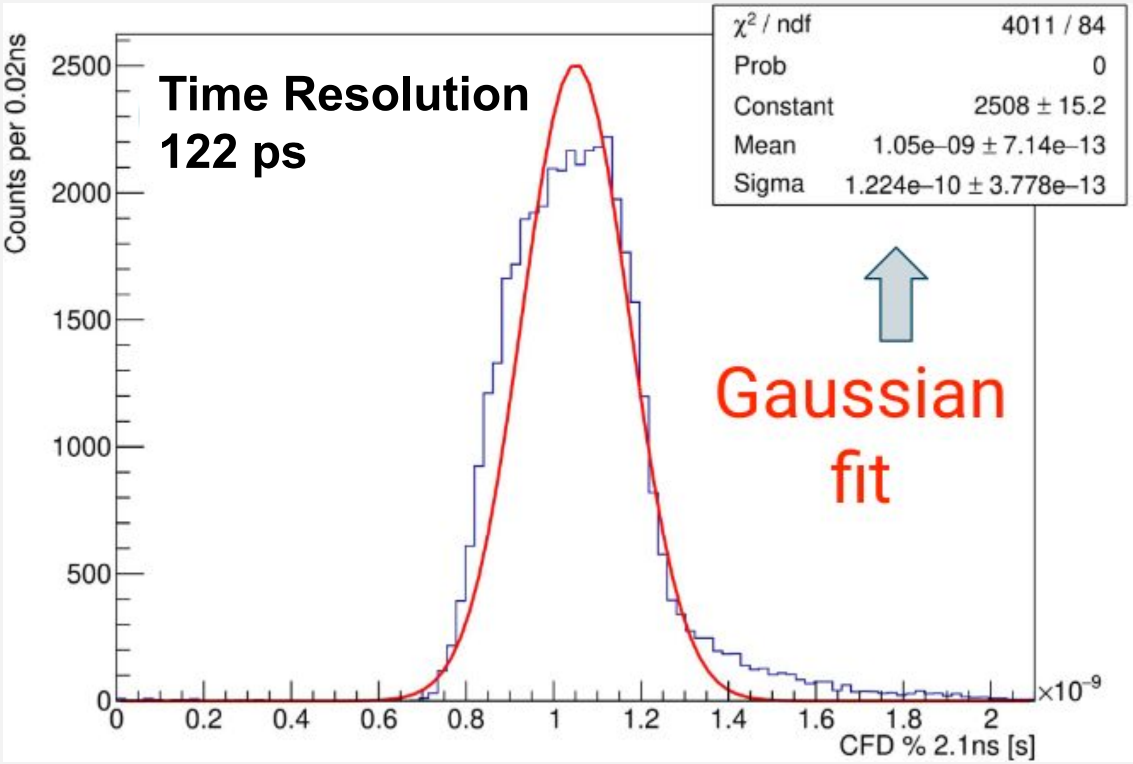


(a) HPK PIN and type 3.1 LGAD (b) HPK type 3.2 LGAD (c) BNL 20um LGAD

Timing Performance

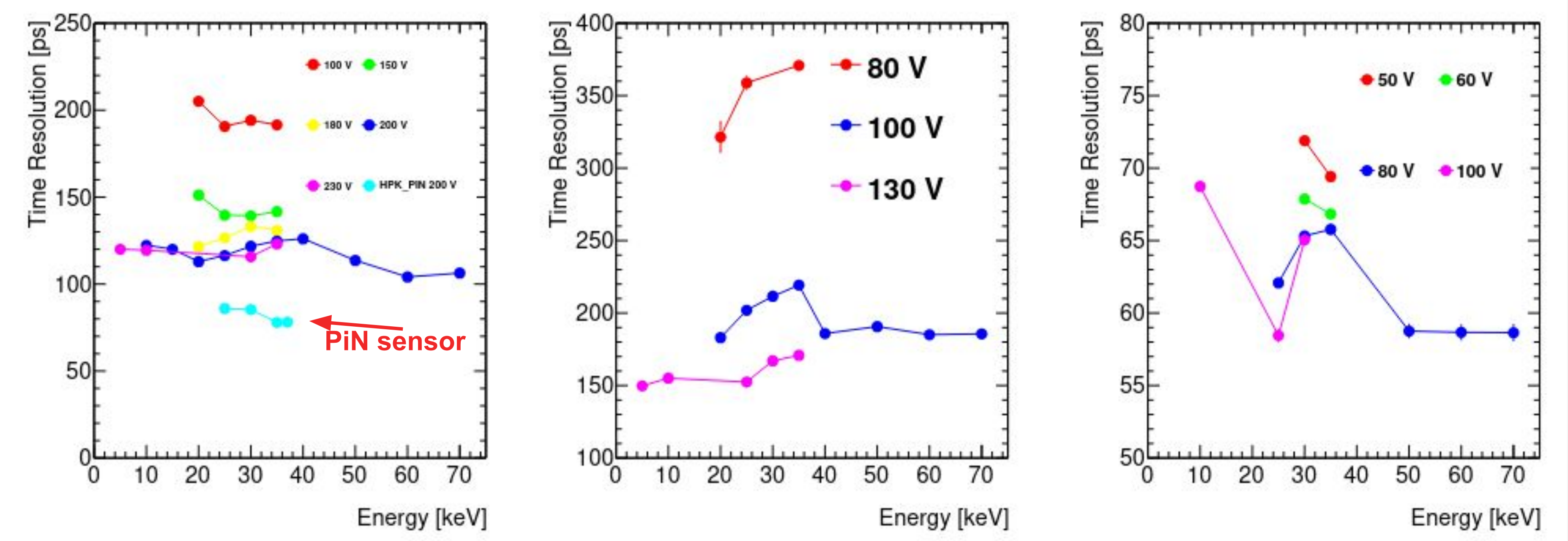
Extracting the Timing Resolution

- **Constant fraction discriminator (CFD) at 20% is used for timing.**
  - The fast rising edge of the initial carrier drift is more stable and precise.
- **Time difference with respect to the reference time is calculated for each bunch**
  - The bunch separation of 2.1 ns is accounted.
  - Distribution is fitted with a Gaussian, the sigma is the timing resolution.



Timing Resolution for X-rays

- The timing resolution is consistent for the tested X-rays energy range.
- Thinner sensors (20 vs 50 um) have better timing performance as expected.
- However:
  - The timing performance for X-rays is worse comparing to MiPs (< 50 ps)
  - In the case of 50um sensors, PiN provides better timing.
- Why are we seeing bad timing resolution?

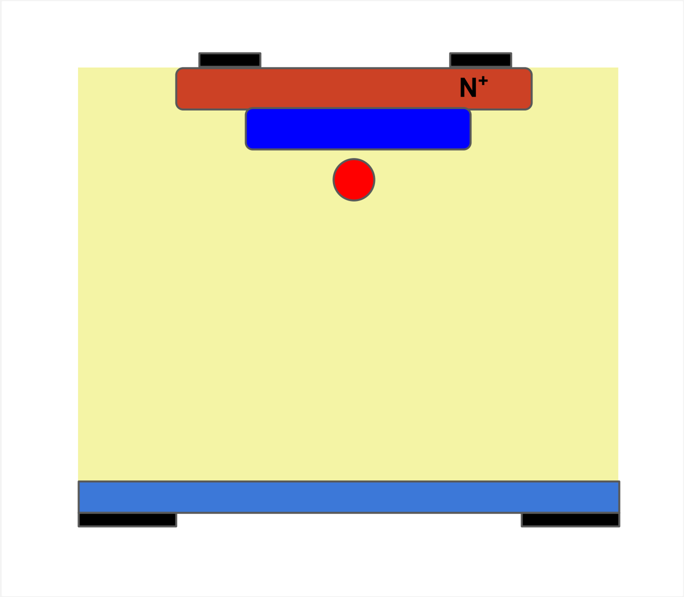


(a) HPK PIN and type 3.1 LGAD (b) HPK type 3.2 LGAD (c) BNL 20um LGAD

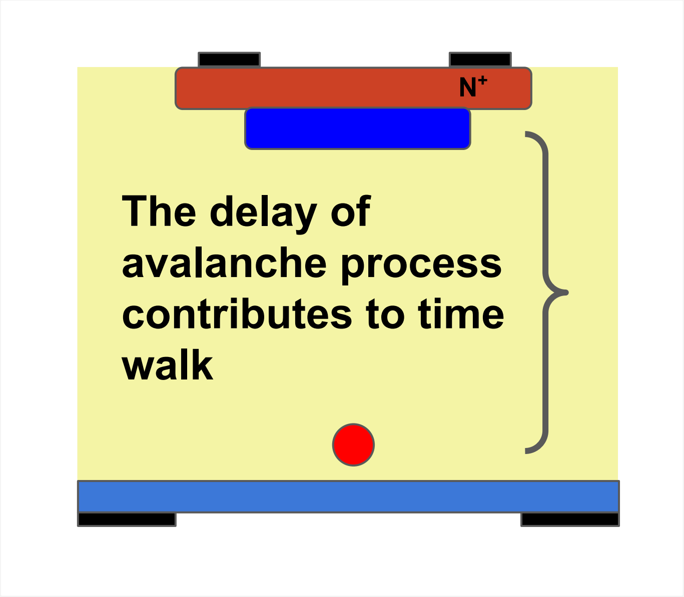
Time Walk Due to X-rays Conversion

- **The absorption of X-rays photons at different depth inside the sensor introduces time delay in the avalanche process.**
- **The time delay in the avalanche process will affect the signal formation shape and contributes to the timing performance.**

X-rays absorption near surface



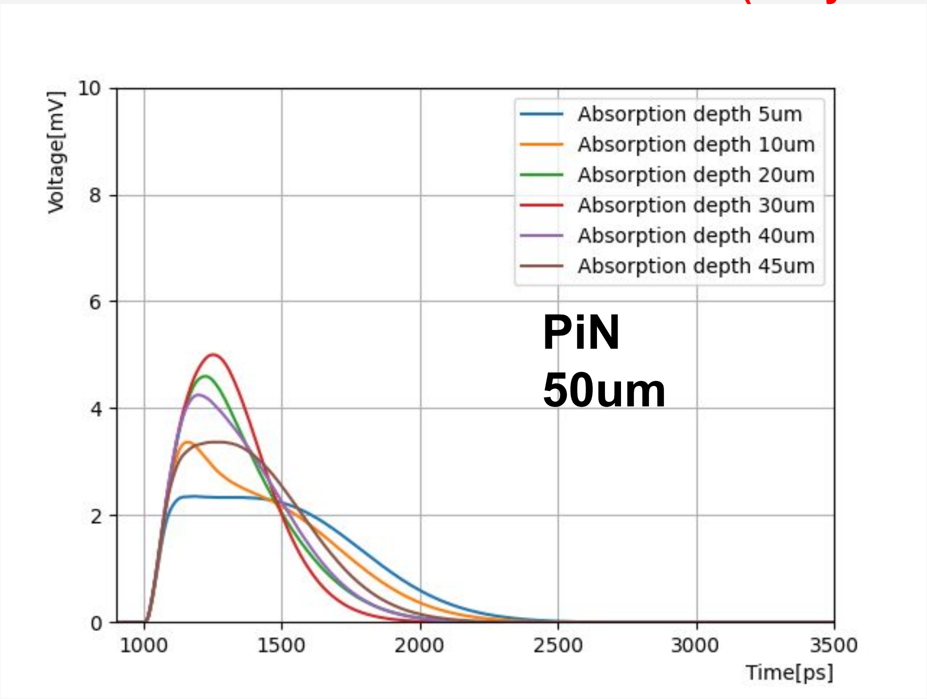
X-rays absorption near backside

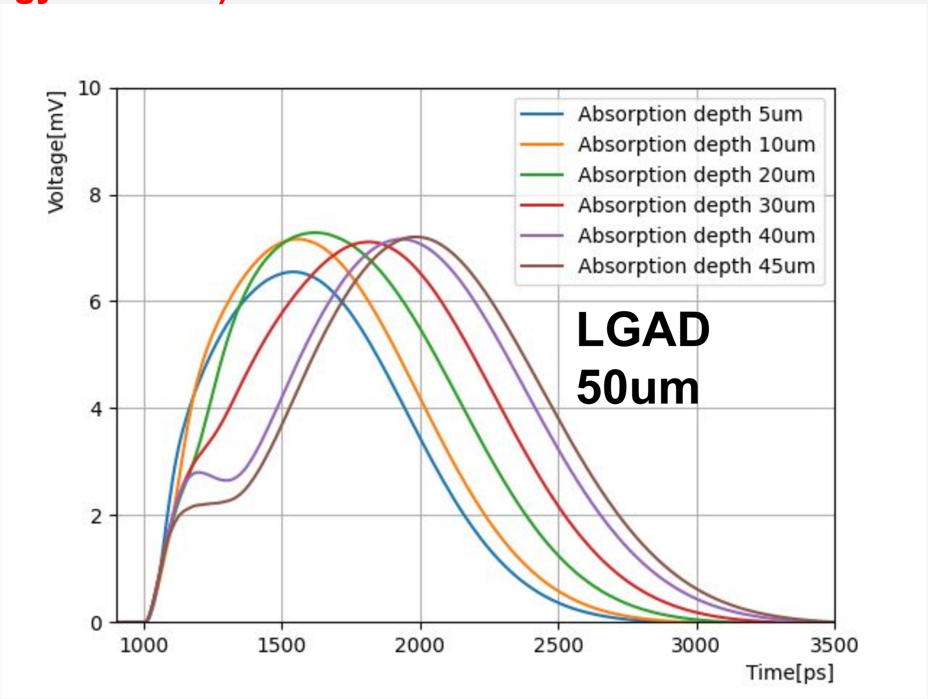


Time Walk Due to X-rays Conversion

- **In the case of PiN (no gain), the rising edge not affected by the delay.**
  - The variation in the peak and width is due to the collection of electrons vs holes.
- **The rising edge and the peak of LGADs is sensitive to the X-rays absorption depth:**
  - Using CFD 20% reduces the time walk effect but doesn't remove it completely.
  - **Absorption on the back has more gain (charge cloud expansion & gain suppression)**

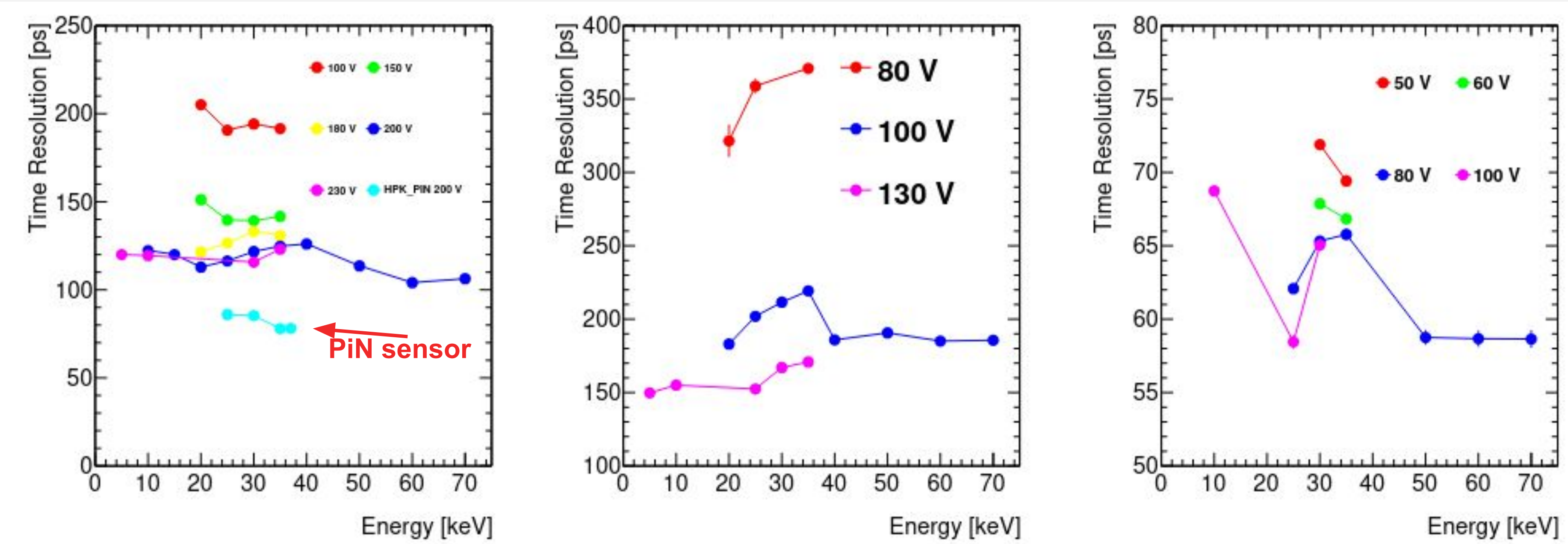
TCAD simulated signal of PiN and LGAD at different absorption depth.
(X-rays energy = 20 keV)





Timing Resolution for X-rays

- **LGAD bulk E-field is usually high enough to saturated the carrier drift velocity (1x10^{7} cm/s).**
- **Assuming X-rays photon absorption depth is approximately equally probable** (which is not true and it depends on the X-rays energy)**, the time resolution due to avalanche process delay is approximately: 50um is ~125 ps, 20um is ~50 ps**
- **Although PiN devices have better timing resolution, LGADs have advantage on signal amplification. Also, thinner LGADs will improve the timing resolution for X-rays.**

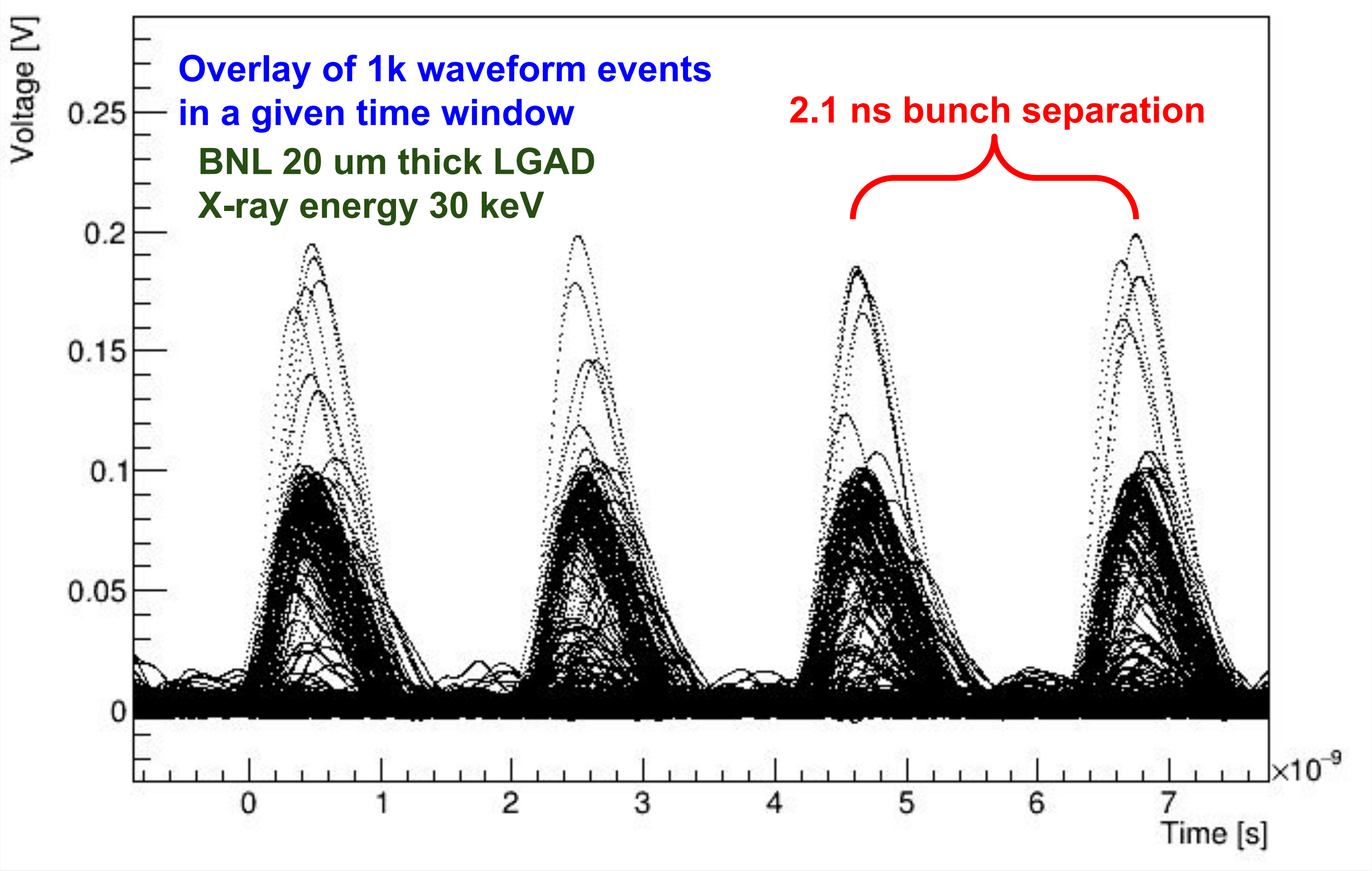


(a) HPK PIN and type 3.1 LGAD (b) HPK type 3.2 LGAD (c) BNL 20um LGAD

Timing Performance:
High Frame Rate Capability

High Repetition Rate Capability

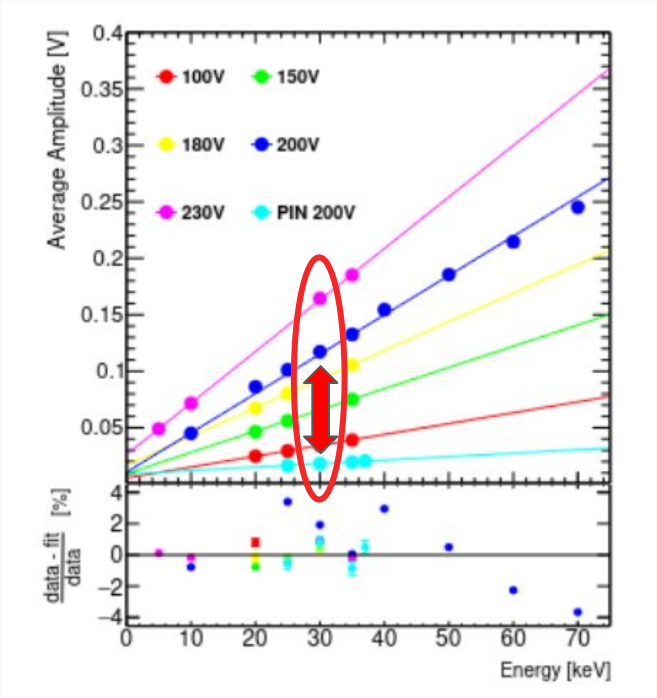
- **The LGAD charge collection time is fast due to very thin active thickness and saturated carrier drift velocity.**
- **LGADs is able to resolve 500 MHz repetition rate (with capability up to 1GHz).**



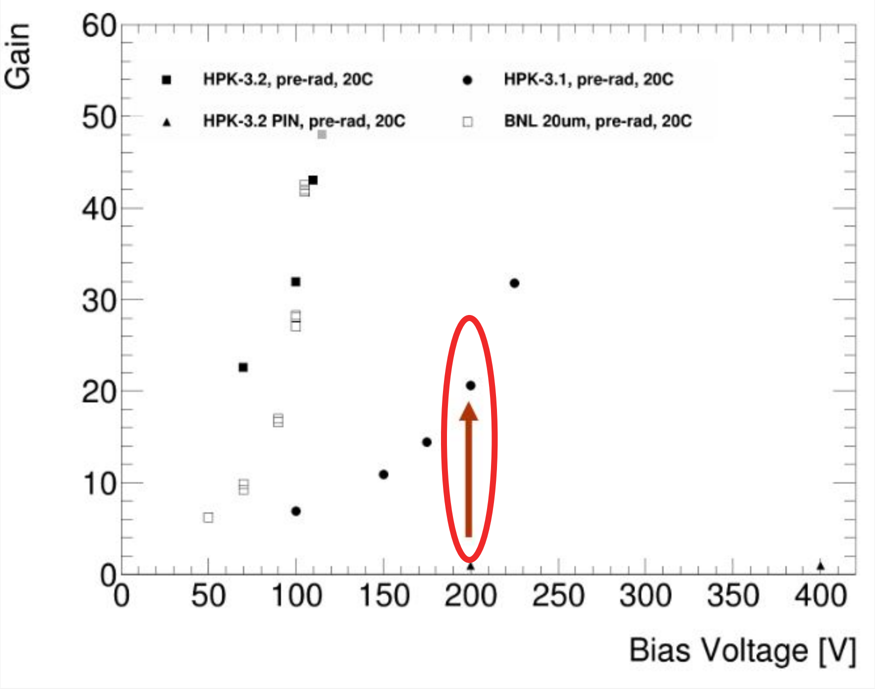
Gain Suppression

Why is the Gain Different?

- **The gain of LGAD is measured in reference to the PiN device in the laboratory.**
- **The gain of LGAD for conventional MIP like charge particles is different from X-rays. In the case of HPK 3.1 at 200V:**
  - **The gain for MIPs is ~20.**
  - **The gain for 30 keV X-rays is ~10**

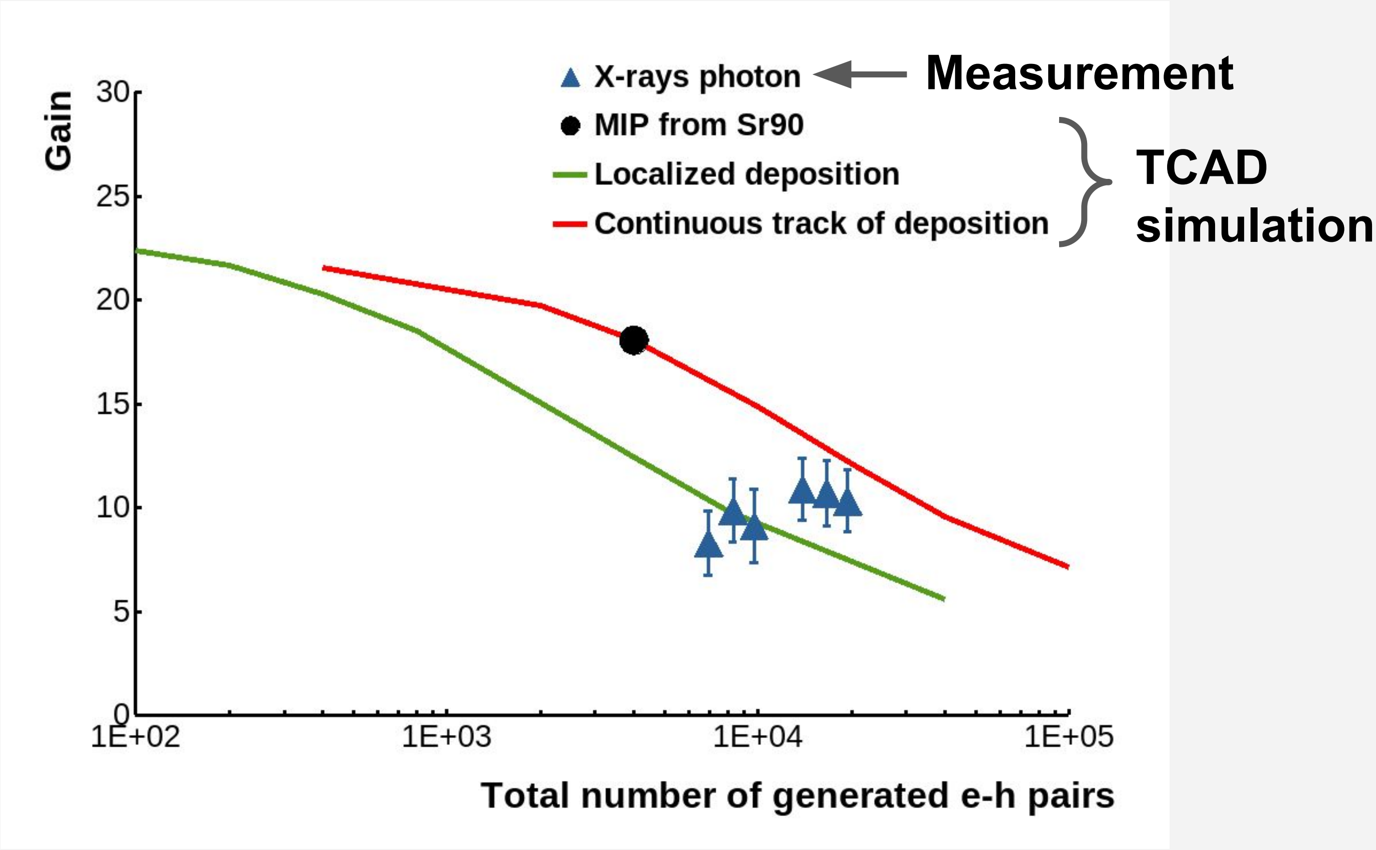


(a) HPK PIN and type 3.1 LGAD



Gain Suppression

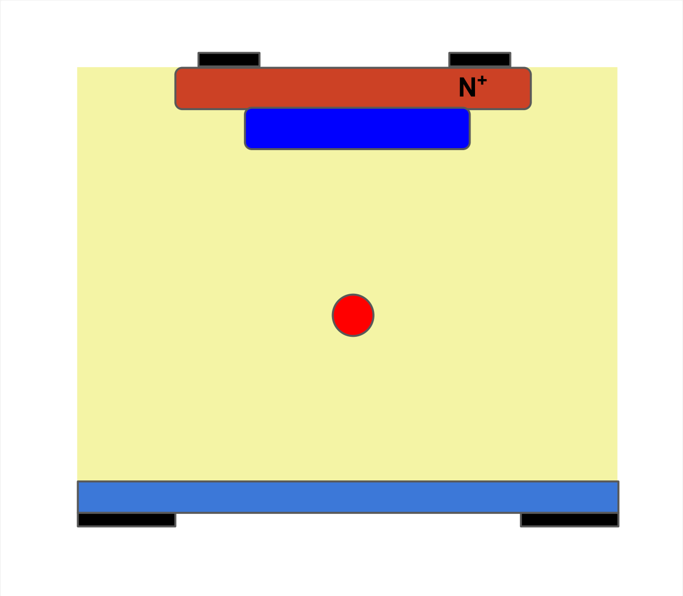
- **TCAD simulation is used to study the MiP-like vs X-rays-like deposition.**
  - **Localized deposition is used to approximate X-rays deposition.**
  - **Continuous track is used to approximate MIP deposition.**



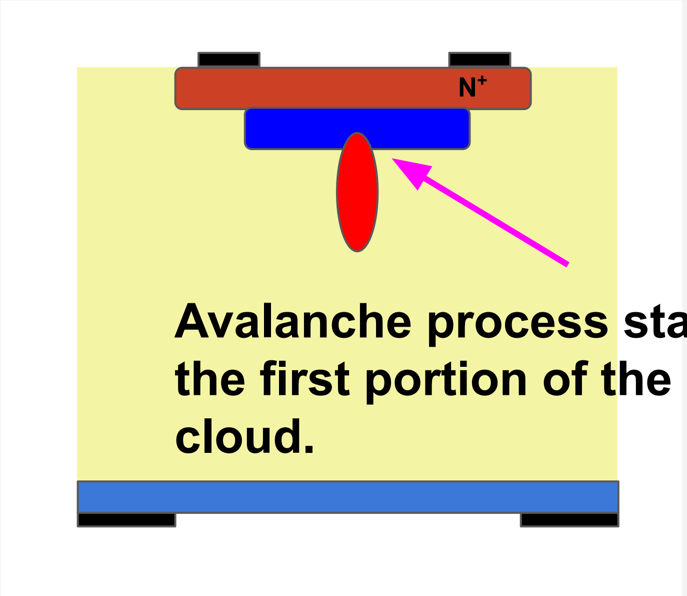
Gain Suppression

- **One possible explanation to gain suppression is related to the generated e-h density and the gain layer E-field relaxation process.**

Initial Deposition from X-rays



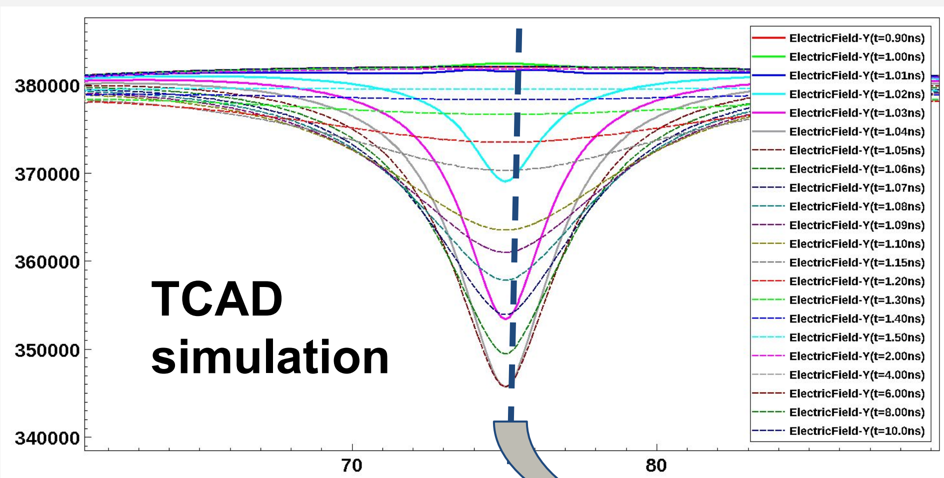
Charge cloud drift toward gain layer. Shape expand due to diffusion

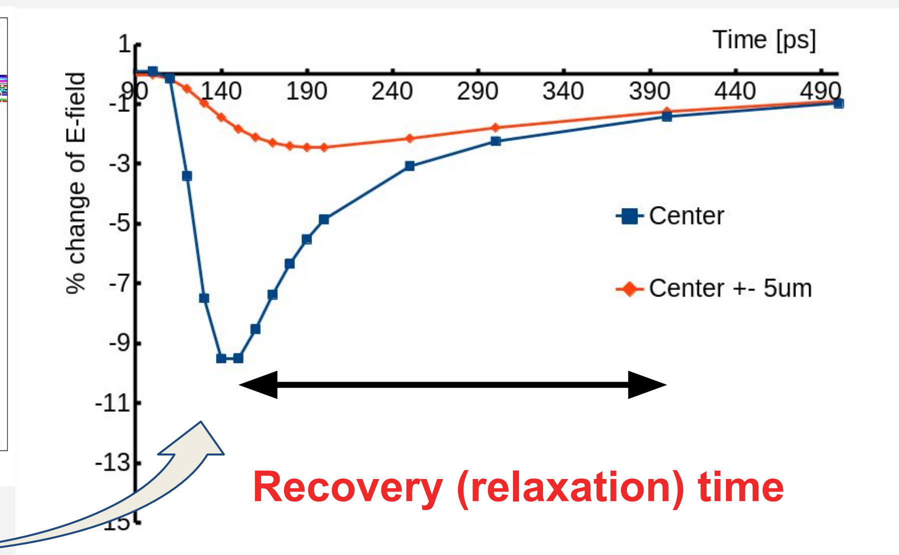


Avalanche process starts for the first portion of the charge cloud.

Gain Suppression

- **One possible explanation to gain suppression is related to the generated e-h density and the gain layer E-field relaxation process.**
- **This variation of E-field depends on the generated e-h paris density per unit distance.**
- **MiP generates less e-h paris per unit distance comparing to point-like X-rays deposition.**





Snapshot of the electric field within the gain layer at different time for localized input charge.

Note: the impact ionization has exponential dependence on the field.

Gain Suppression

- One possible explanation to this is related to the generated e-h density and

Gain suppression studied by other groups: e.g. “Hunting for Sharks with TCAD (Simulation of TPA-TCT measurements on LGAD Gain Suppression)”

https://indico.cern.ch/event/1334364/contributions/5672074/

Gain suppression with larger dynamic range (e.g. non MIP particles with bragg-peak in energy deposition):

See Jennifer Ott’s talk on the PIONEER experiment:

https://indico.cern.ch/event/1184921/contributions/5574780/

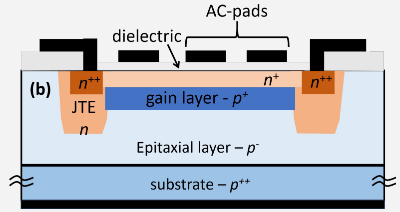
380000
370000
360000
350000
340000

Sna… withi… time for localized input charge.

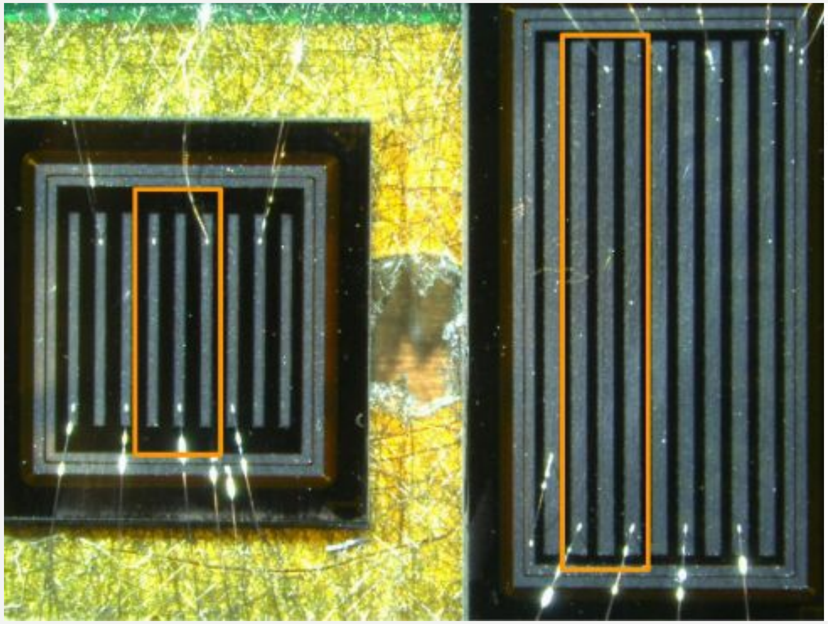
…field.

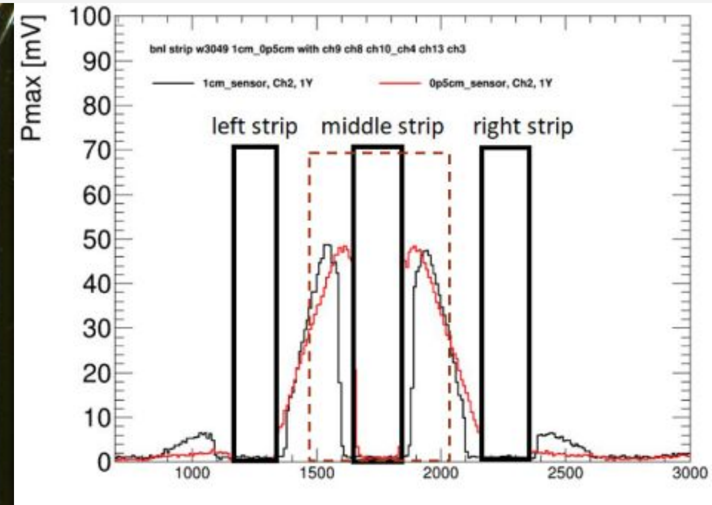
How about AC-LGAD?

How about AC-LGAD?



- **Very preliminary test of AC-LGAD strip sensors using the same beam line:**
  - Readout all strips with 16 channels FNAL board and CAEN DT5742 digitizer.
  - Unfortunately, beam spot is broad so no information on position.
- **Base on the TCT studies on the same devices, the charge sharing mostly contained in 3 strips:**
  - Search for events with highest response in the middle strip and lower response in the two neighbors, and response from the remaining strips.
  - Sum the three strips signals to estimated the total energy.

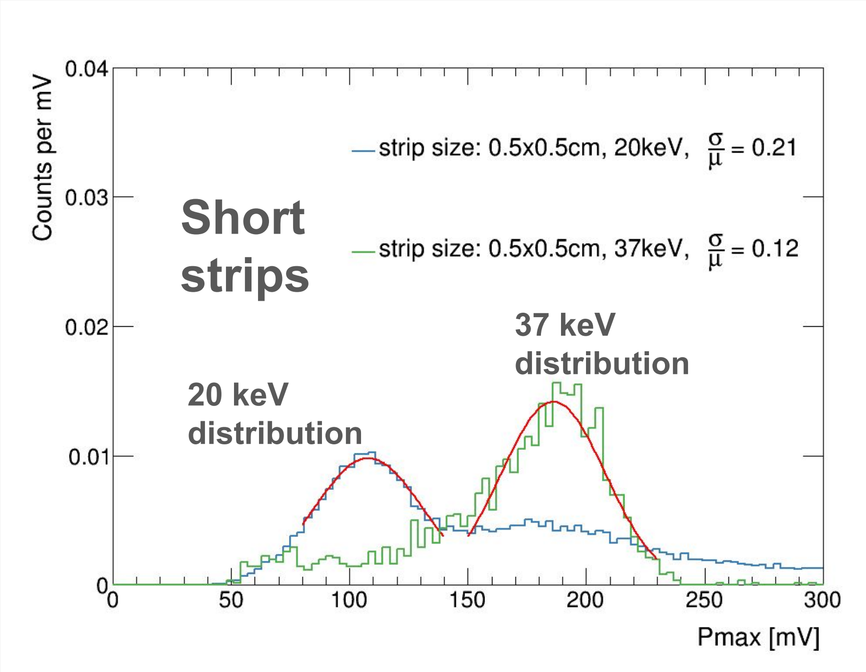


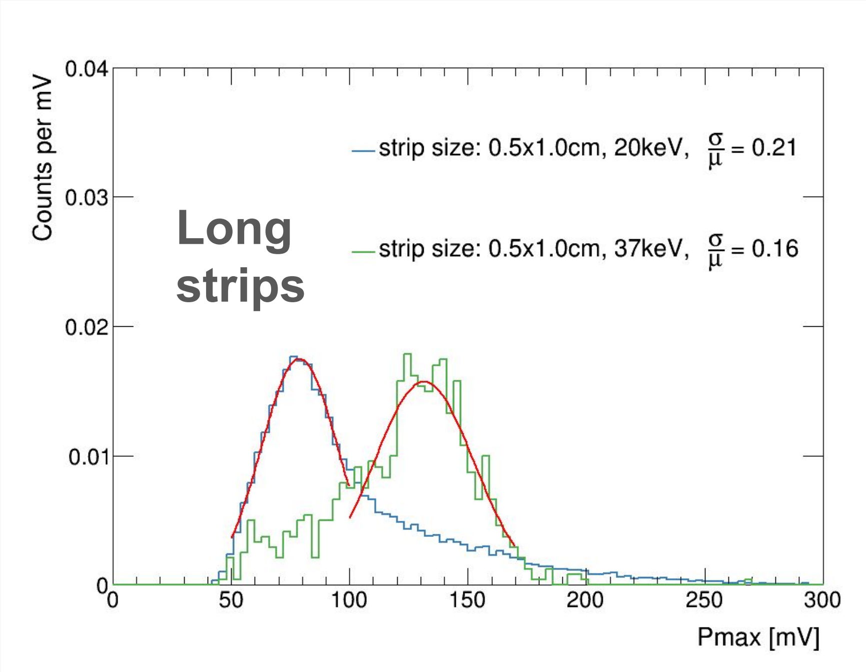


Laser TCT response
Selected event in the dashed box

How about AC-LGAD?

- **The energy response is roughly linear as expected.**
- **The energy resolution is between 12% to 21%. It's slightly worse than DC devices probably due to charge sharing.**
- **The shorter strip device has slight better energy resolution at high energy due to smaller sharing.**





Summary

Summary

- **The SSRL testbeam results for LGADs were shown:**
  - **Energy resolution is between 6% to 20%, and out performing conventional PiN devices (and better SNR).**
  - **Time resolution is between 50 to 200 ps. (depends on thickness)**
  - **Easily resolve 500 MHz repetition rate of the X-rays beam line.**
- **The gain of LGADs depends on the type of energy deposition. The gain is lower for X-rays in comparison to MiP.**

35 keV X-rays

	HPK PIN	HPK3.1		HPK3.2		BNL 20um	
Bias V	200 V	150 V	230 V	80 V	130 V	50 V	100 V
Energy Resolution	14 %	6 %	17 %	10 %	20 %	6 %	16 %
Energy Response	19 mV	75 mV	185 mV	68 mV	211 mV	66 mV	147 mV
σ_t CFD	78 ps	141 ps	123 ps	371 ps	171 ps	69 ps	65 ps

Future Developments

- **Next test beam scheduled for February 2024:**
  - **Beam line 7-2 with focused beam of spot size 50x100um**
  - **Allows for better study of standard LGADs with X-rays always contains in the active region with gain.**
  - **Test of LGAD and AC-LGAD array with position information.**
- **Looking for Compton response using SiPM trigger/tag.**
- **Extend the energy range down to sub-KeV.**

Backup

Reference

- [1] S.-J. Baek, A. Park, Y.-J. Ahn and J. Choo, Baseline correction using asymmetrically reweighted penalized least squares smoothing, Analyst 140 (2015) 250–257.

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Funding & Acknowledgement

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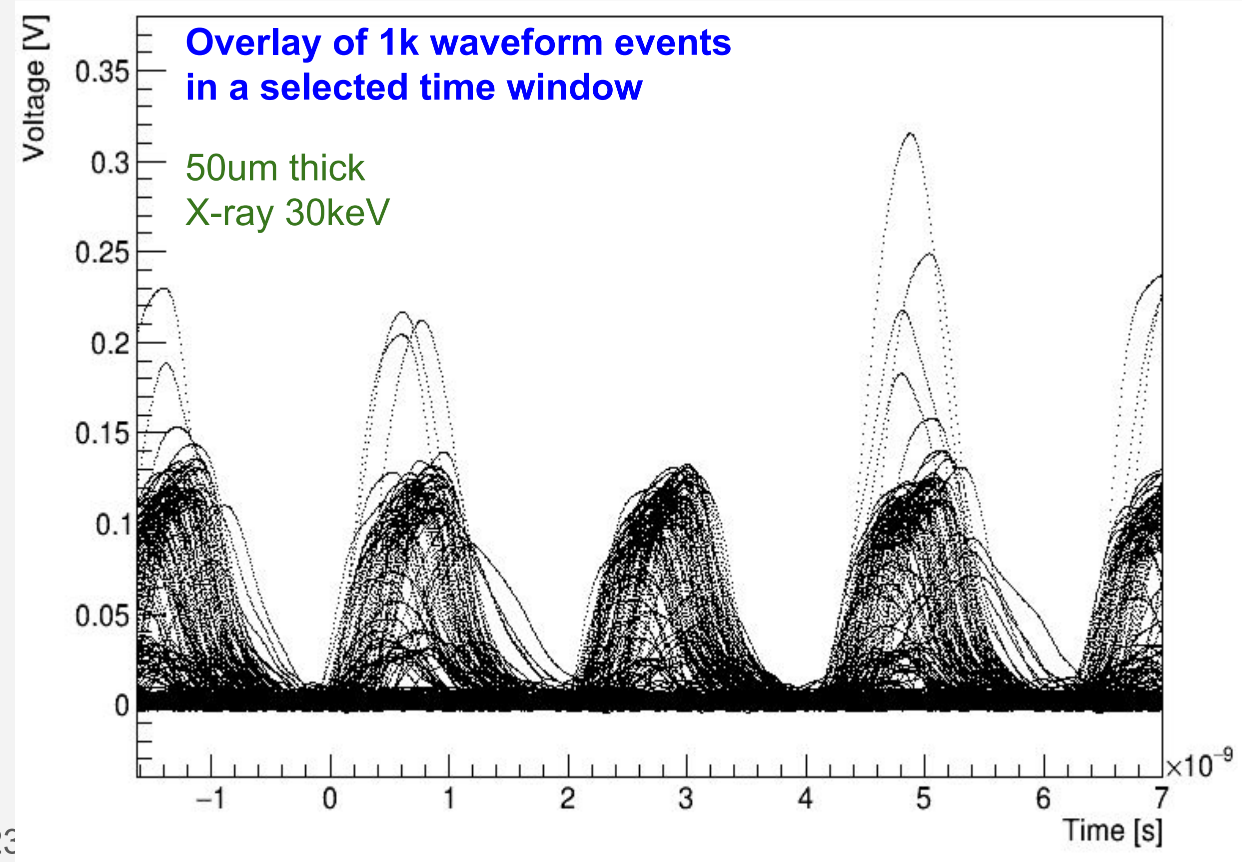
- The group from USP acknowledges support from FAPESP (grant 2020/04867-2) and CAPES.

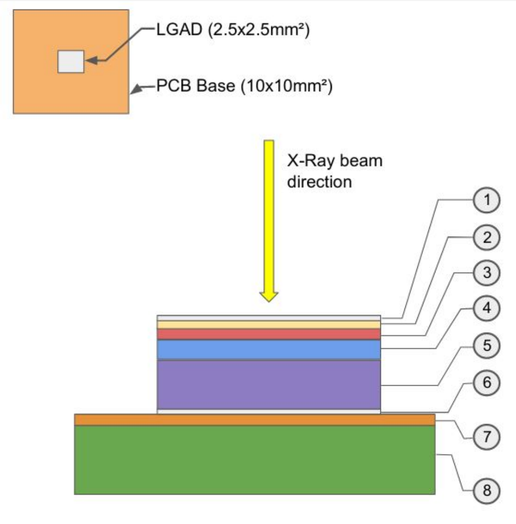
High Repetition Rate

- **Frame rate capability is lower for thicker LGAD (50um)**
- **It's still capable to fully resolve 500MHz frame rate.**



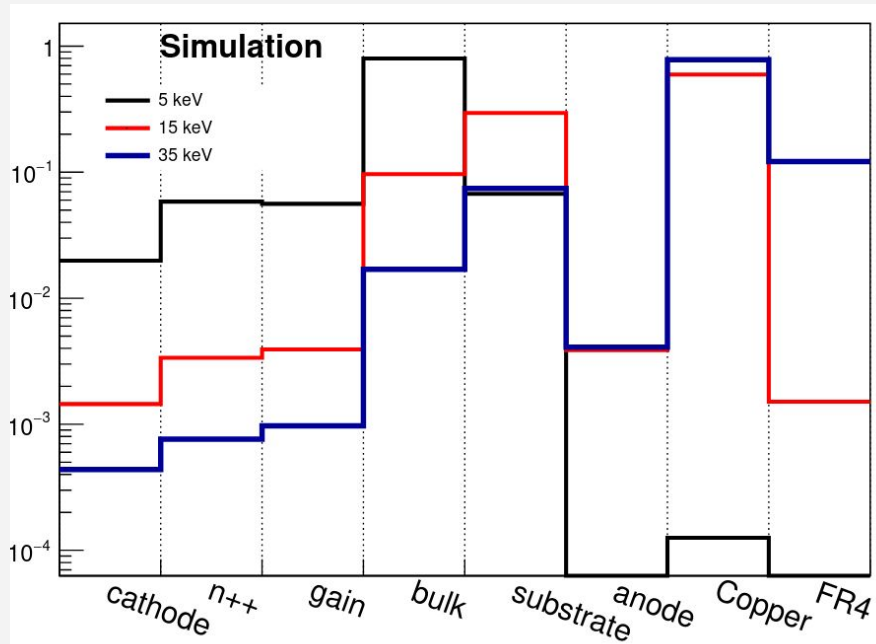
GEANT4 Simulation of X-rays Absorption Location

- **GEANT4 simulation of the X-rays absorption location.**



	LGAD layer	Thickness (μm)
1	Al cathode Contact	0.3
2	n++	1.0
3	gain (p+)	1.0
4	bulk active	45.0
5	p++ substrate	150.0
6	Al anode contact	0.3

	PCB Base layer	Thickness (μm)
7	Copper Laminate	100
8	FR4	1600

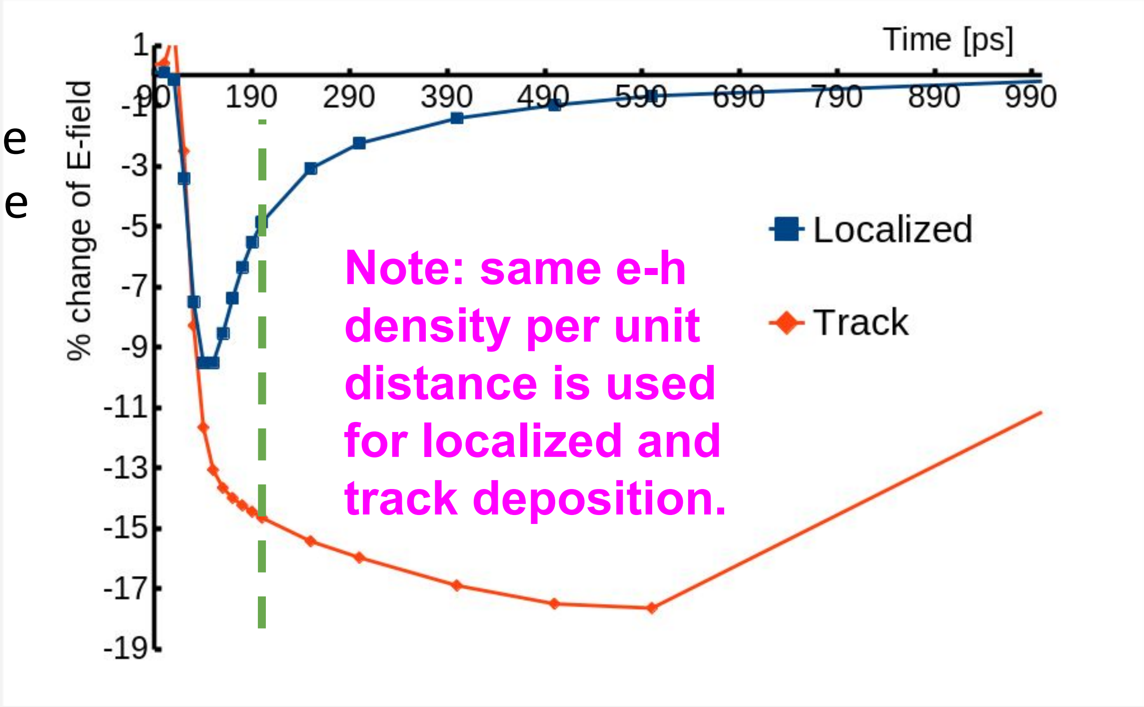


Gain Suppression

- **One possible explanation to this is related to the generated e-h density and the gain layer E-field relaxation process.**
- **This variation of E-field depends on the generated e-h paris density per unit distance.**
- **MiP generates less e-h paris per unit distance comparing to point-like X-rays deposition.**

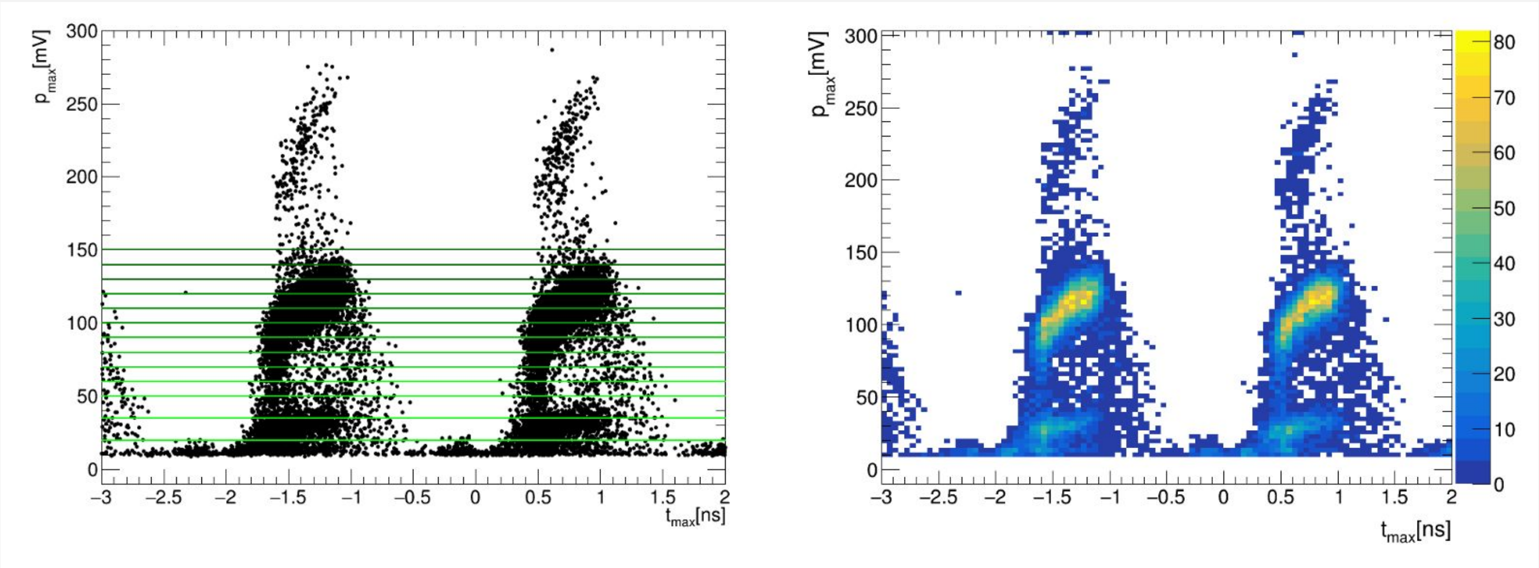
1) charge arrived at the gain layer at later time see a relatively lower field due to the previous impact ionization process.
–> gain suppression

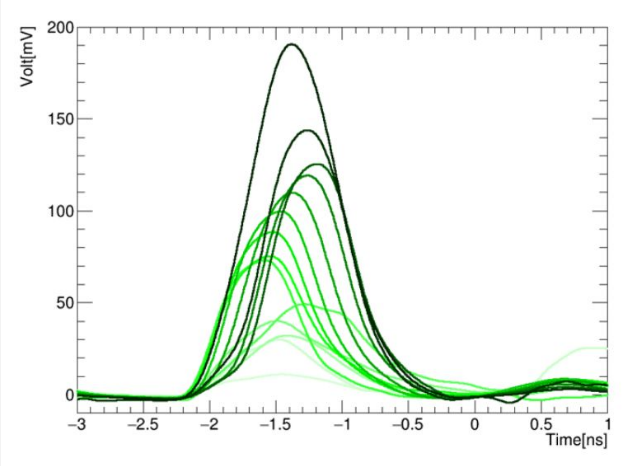
2) **Faster recovery time should reduce the gain suppression effects.**

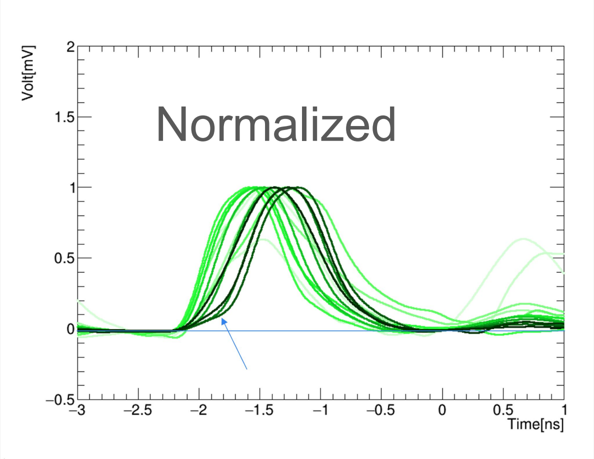


Tmax vs Pmax & Averaged Waveform

- **Correlation plots of the Tmax vs Pmax**







Gain Suppression & Absorption Depth

- **Absorption on the back has more gain for LGADs due to charge cloud expansion**