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

Coordinating Panel for Advanced Detectors (CPAD) Workshop
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Overview

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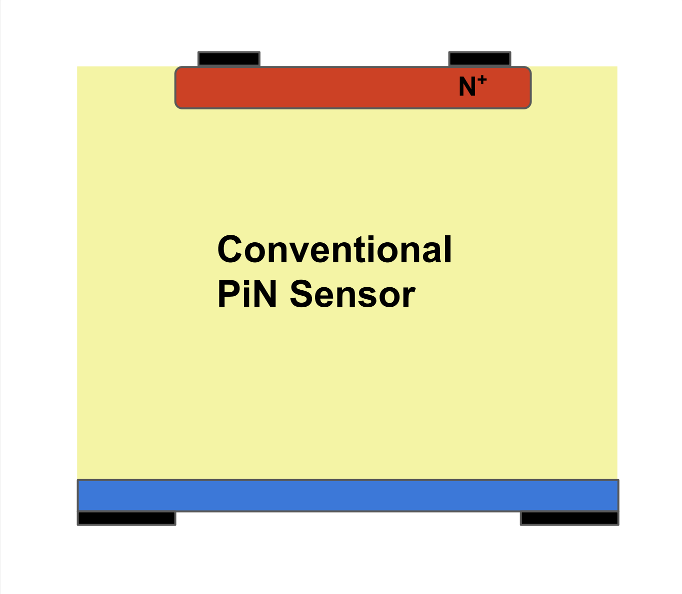
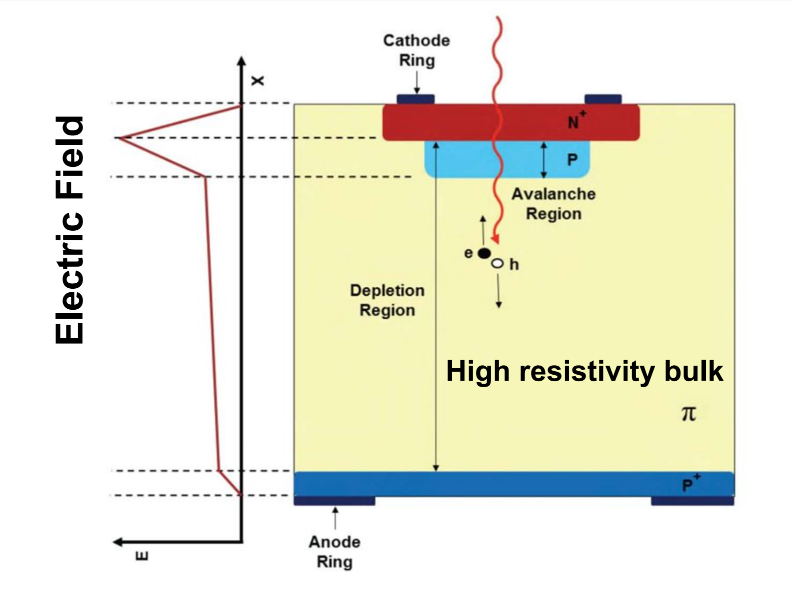
Introduction to LGAD

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:**
  - **A highly doped p+ avalanche region is implanted under the n+ layer.**
  - **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.**
  - **Exceptional timing resolution (20 ps or better) before high dose irradiation for MIPs.**





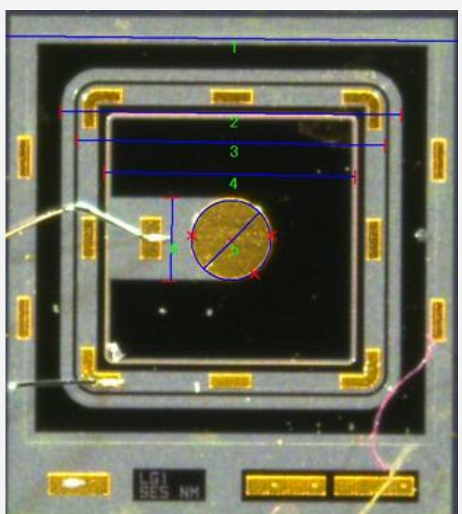
The SSRL Testbeam Setup

LGAD Tested Samples

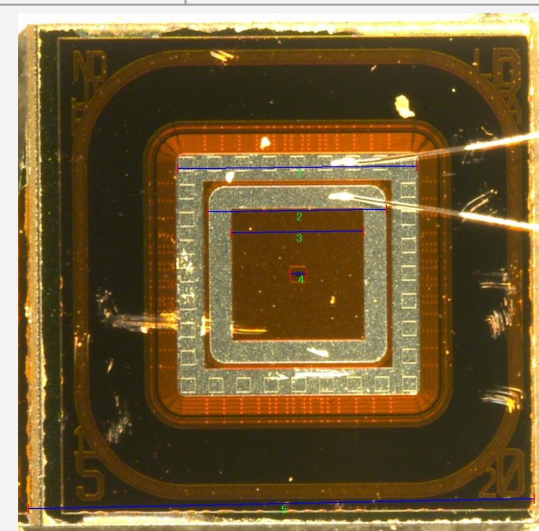
- **Tested 1 PiN device, 3 LGAD types.**
- **All Devices are single pad with active area of 1.3x1.3 mm^2.**
- **Two implant depths of the gain layer: shallow ~1um, deep ~2um.**

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 Device



BNL Device

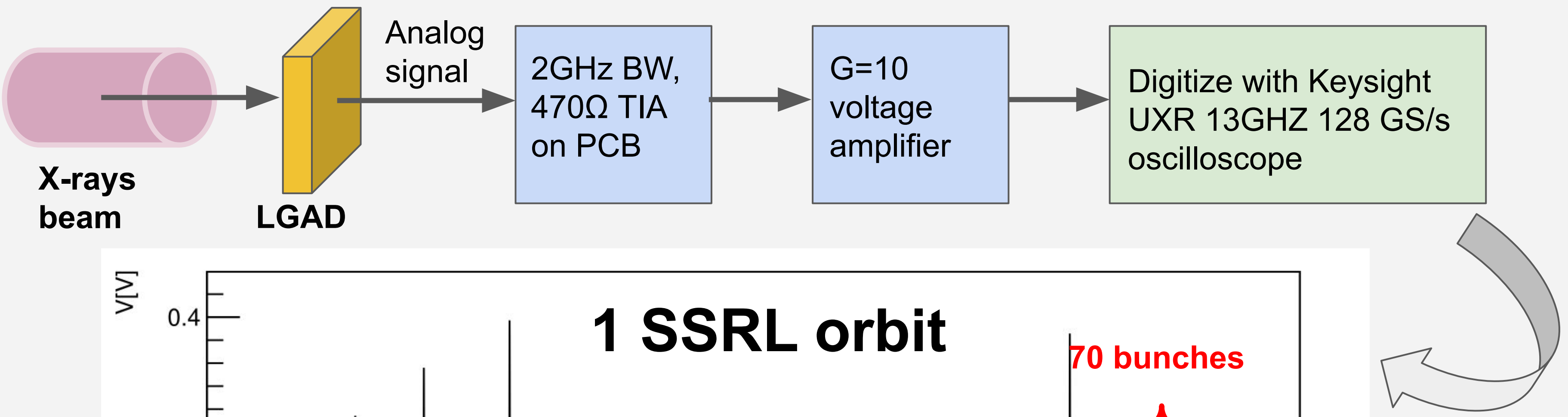


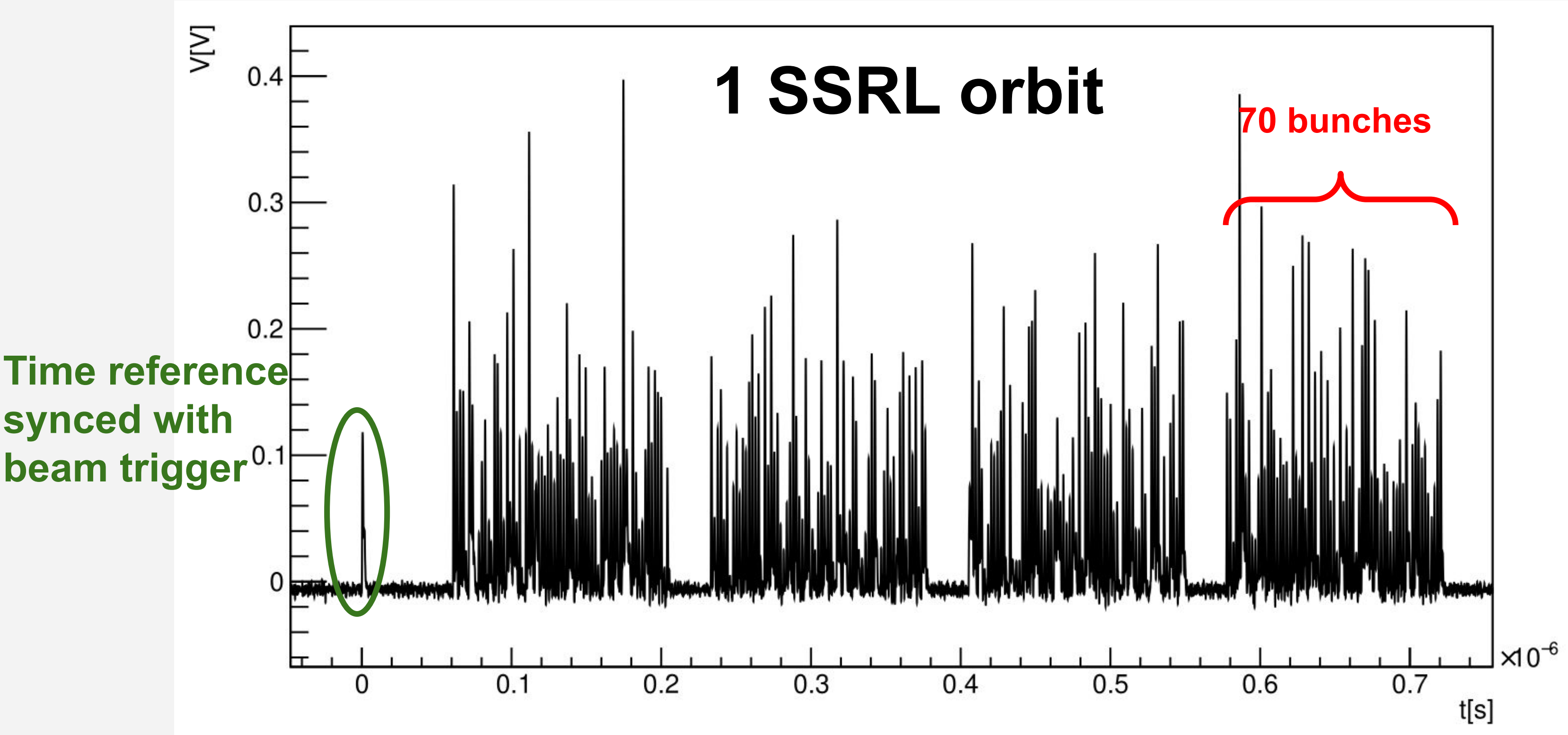
The SSRL Testbeam Setup

- **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.**

The SSRL Testbeam Setup

- **Data acquisition:**



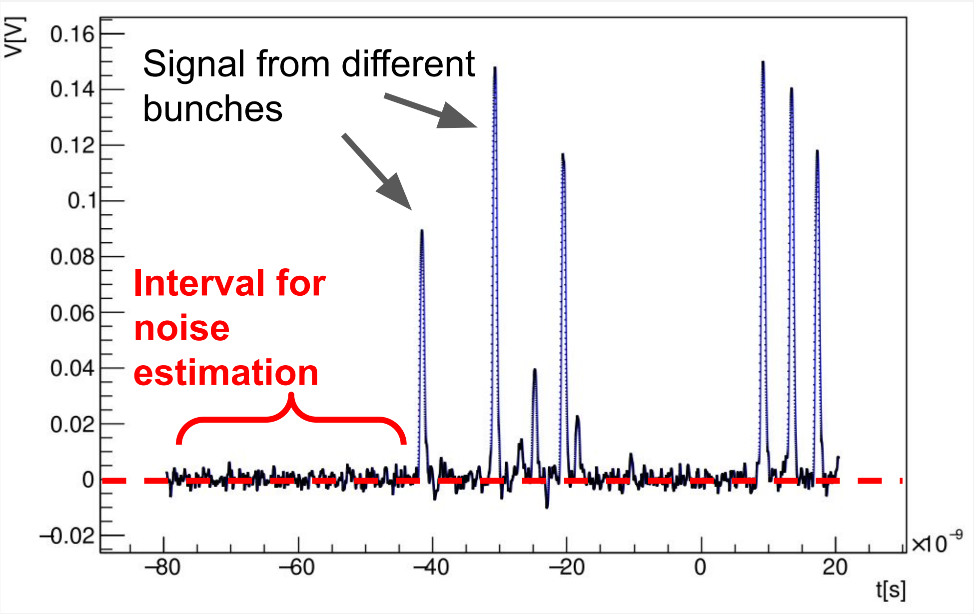


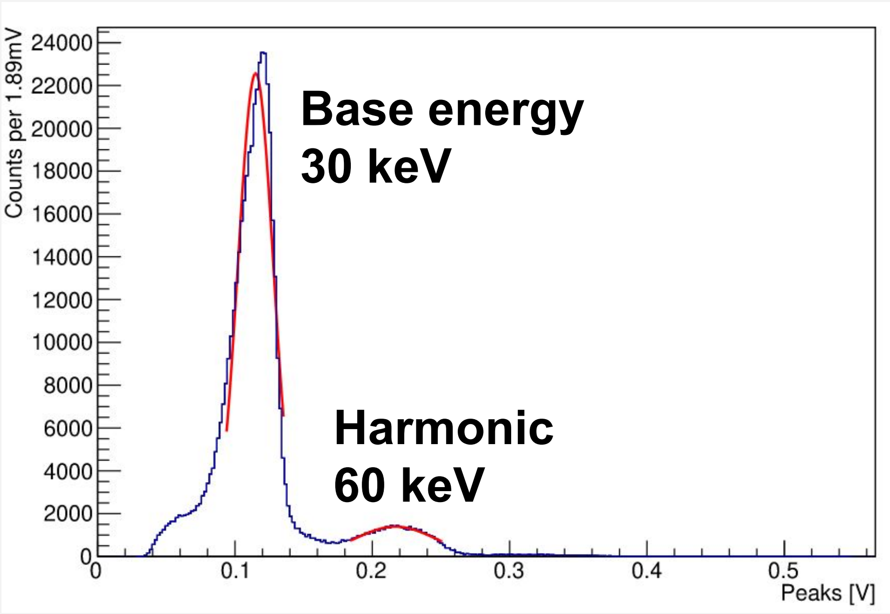
Energy Linearity & Resolution

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

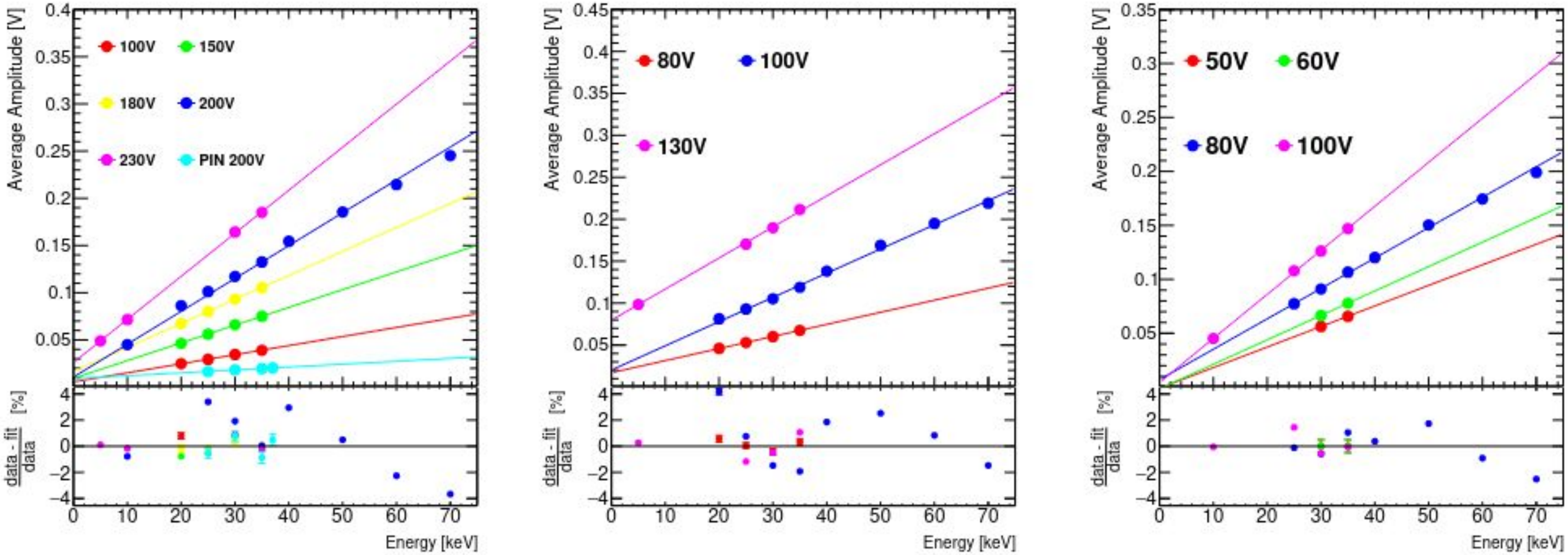
Example distribution for 30 keV X-rays
HPK 3.1 at 200V





X-rays Energy Linearity

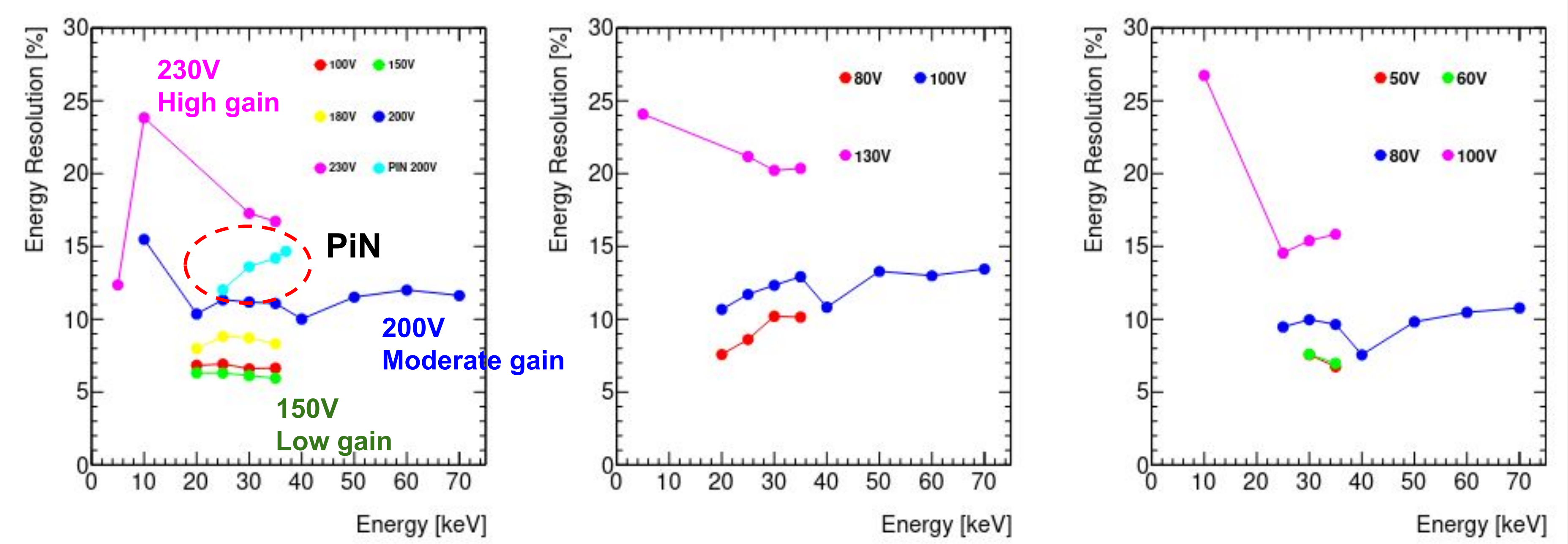
- **The μ is extracted for each energy, bias voltage, and sensor type.**
- **The relation of μ to X-rays energy is shown below:**



(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 energy range.**
  - **The energy resolution degrades at higher gains.**



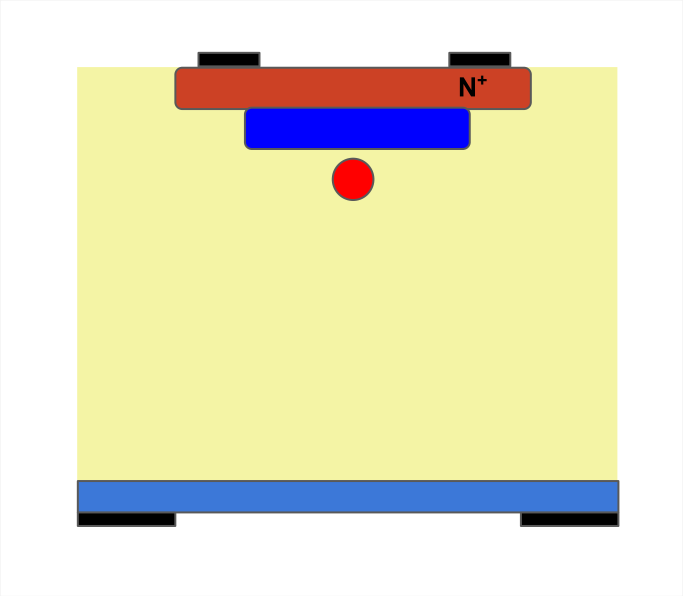
(a) HPK PIN and type 3.1 LGAD (b) HPK type 3.2 LGAD (c) BNL 20um LGAD

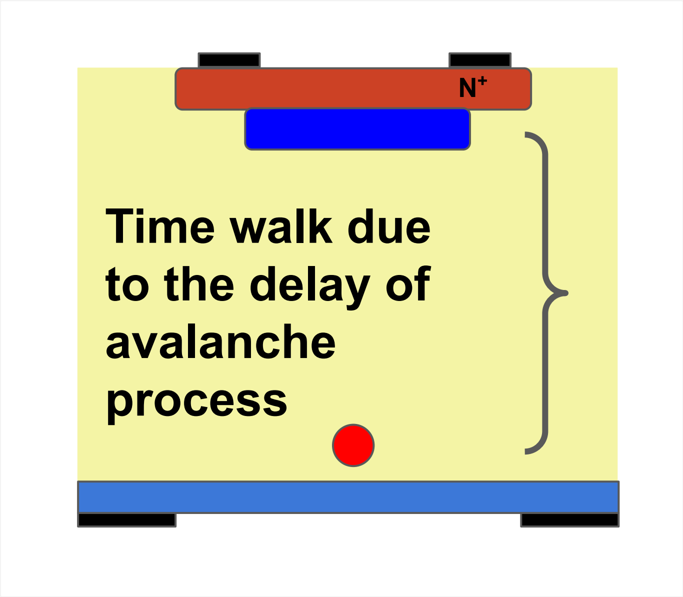
Timing Performance

Time Resolution

- The major timewalk effect from photon absorption at different depth inside the sensor contributes to the time 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.

X-rays absorption front vs back





Time Resolution

- The major timewalk effect from photon absorption at different depth inside the sensor contributes to the time resolution.
- Constant fraction discriminator (CFD) at 20% is used for timing.
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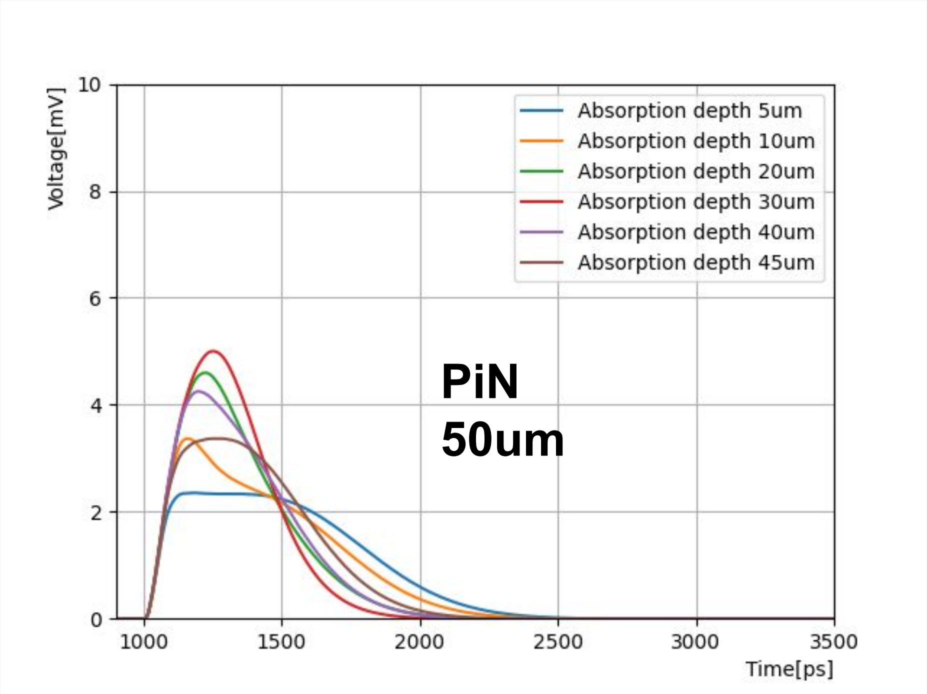
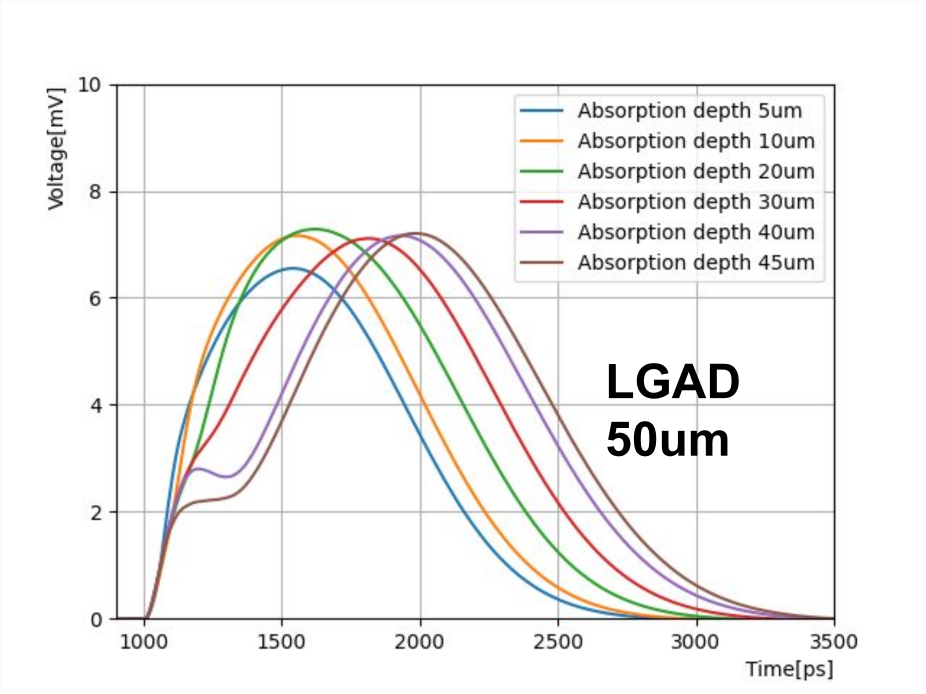
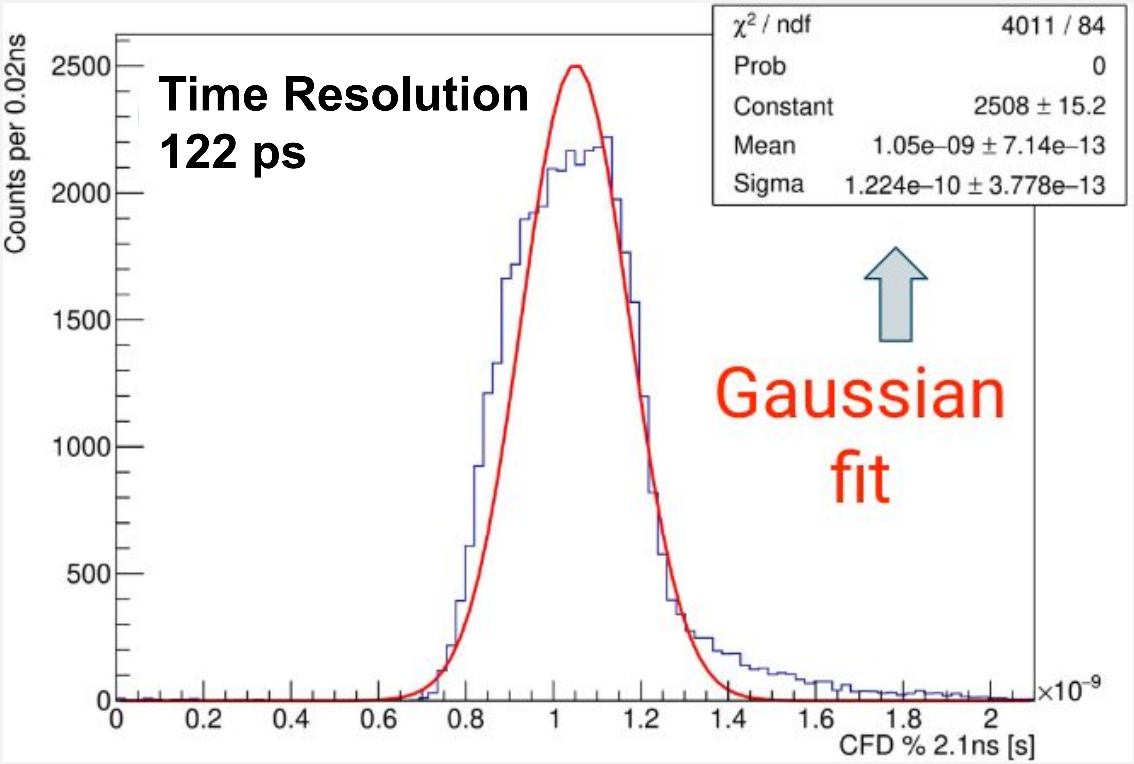
TCAD Simulation of PiN and LGAD Signal for different absorption depth. E = 20keV





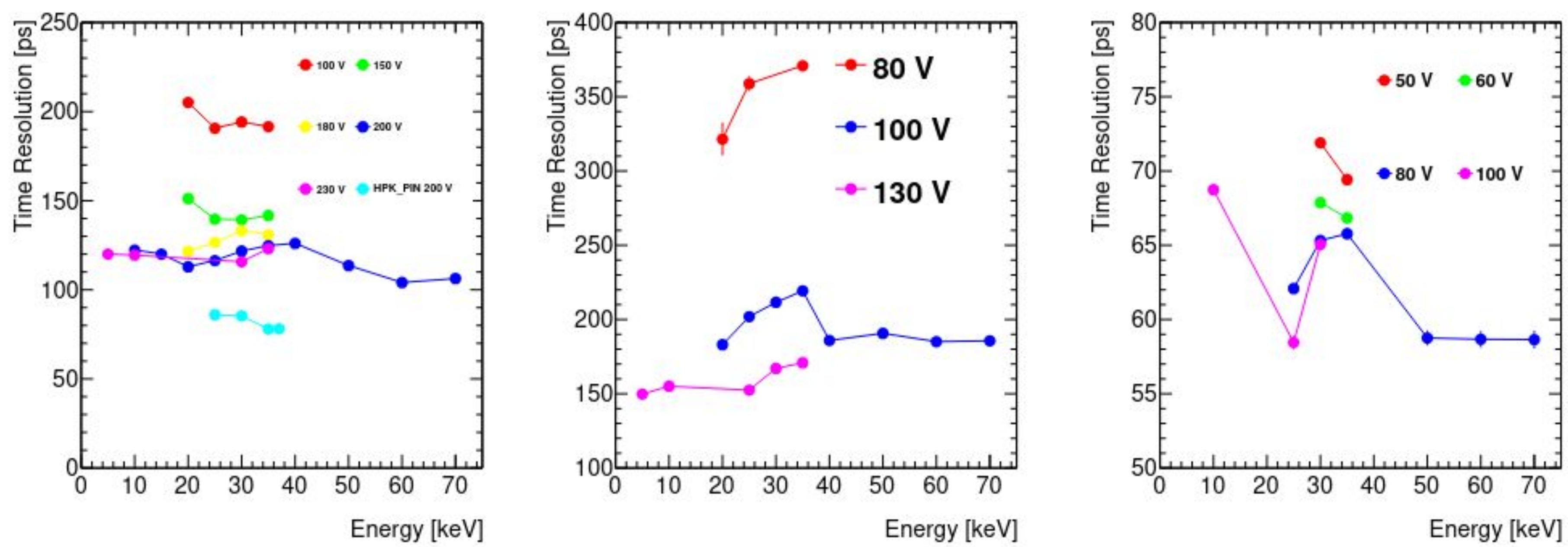
Time Resolution

- **The major timewalk effect from photon absorption at different depth inside the sensor contributes to the time 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.



X-rays Energy Resolution

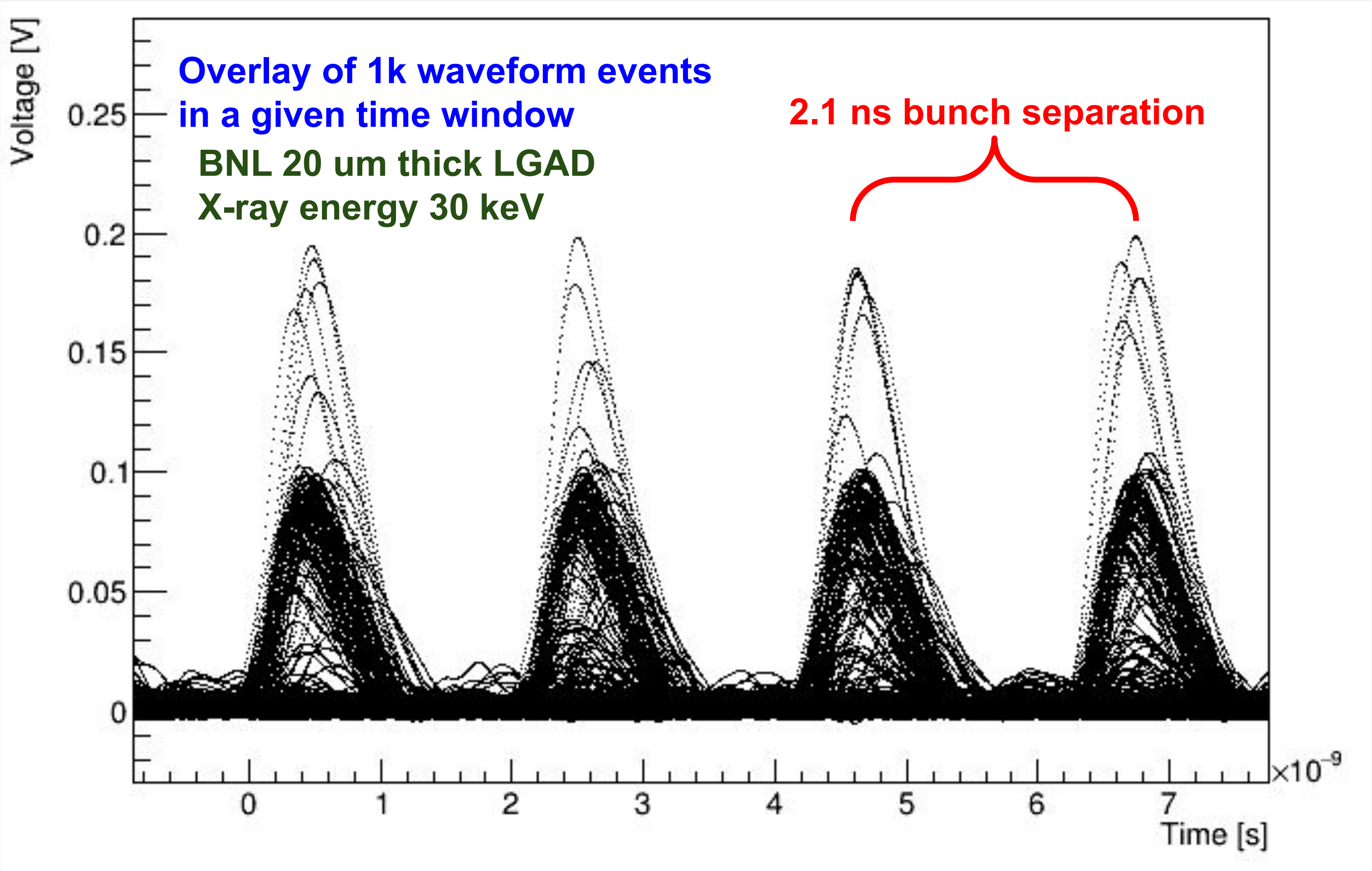
- **LGAD bulk E-field is usually high enough to saturated the carrier drift velocity (1×10^{7} cm/s).**
- **Assuming photon absorption is approximately equally probable, the time resolution due to timewalk is :**
  - **50um is ~125 ps, 20um is ~50 ps**



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

High Repetition Rate Capability

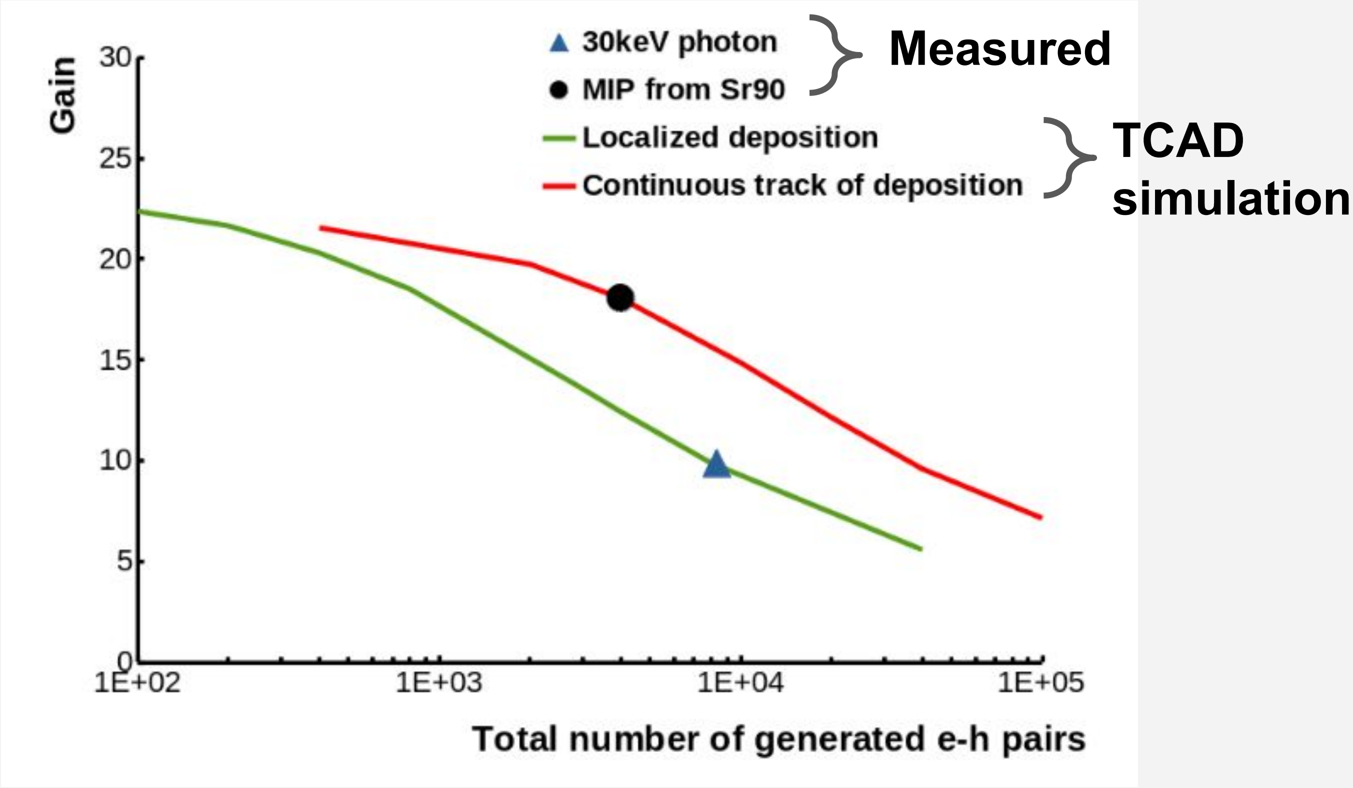
- **The LGAD charge collection time is extremely fast due to thick active thickness and saturated carrier drift velocity.**
- **resolve 500 MHz repetition rate (with capability up to 1GHz).**



Gain Suppression

Gain Suppression

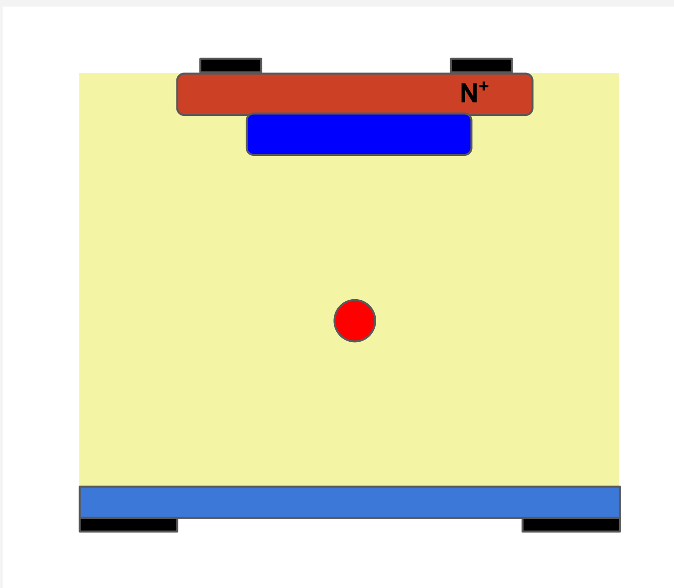
- The gain of LGAD for conventional MiP like charge particles is different in the case of X-rays.
- The gain of LGAD is measured in reference to the PiN device in the laboratory.
- TCAD simulation is used to study the MiP-like vs X-rays-like deposition.
- Same device and operation voltage is used.



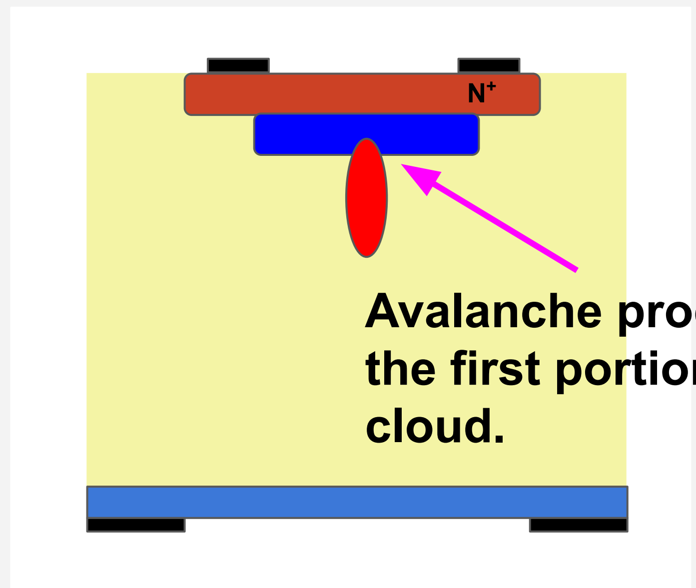
Gain Suppression

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

Initial Deposition from X-rays



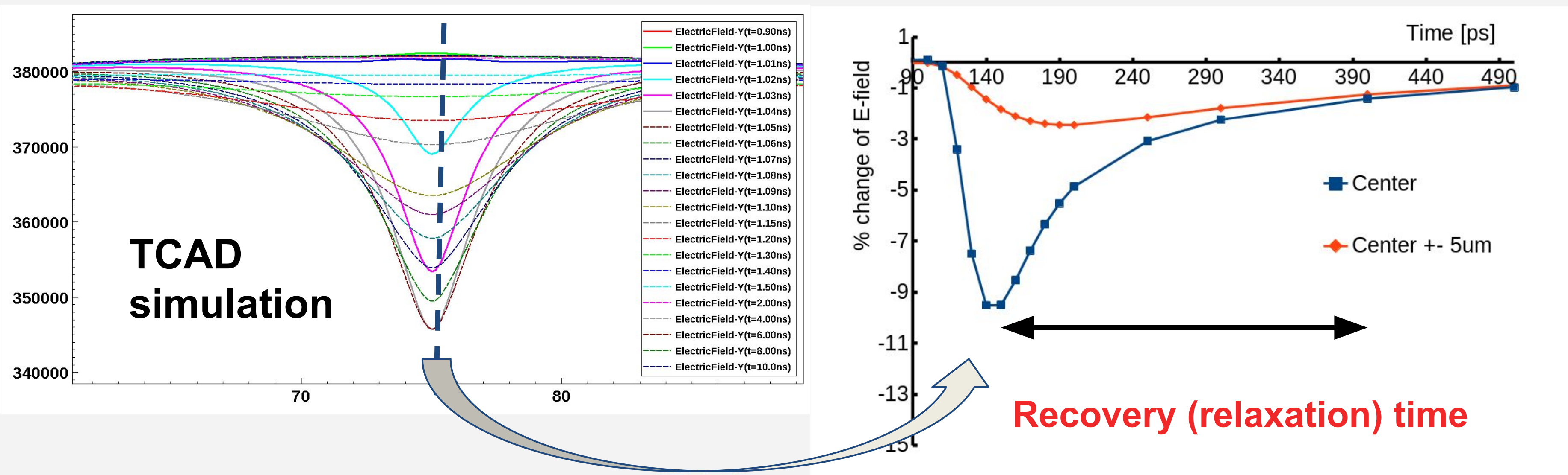
Charge cloud drift toward gain layer. Shape expand due to diffusion



Avalanche process starts the first portion of the cha cloud.

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.**



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.

Summary

Summary

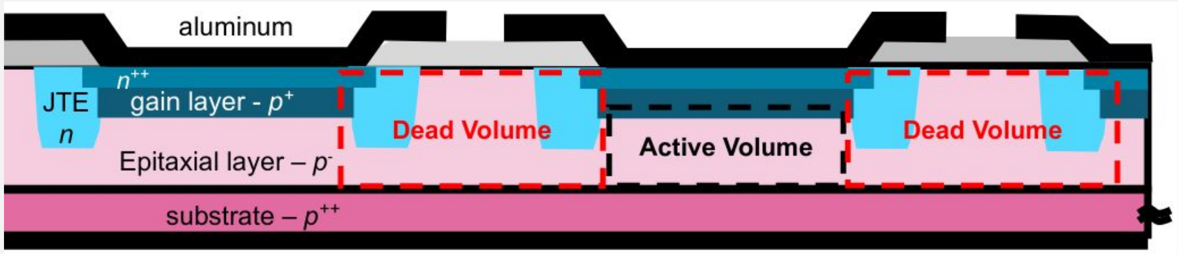
- The SSRL testbeam results for LGADs were shown:
  - Energy resolution is between 6% to 20%, and out performing conventional PiN devices (and better SNR).
  - Time resolution is between 50 to 200 ps. (depends on thickness)
  - Easily resolve 500 MHz repetition rate of the X-rays beam line.
- The gain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

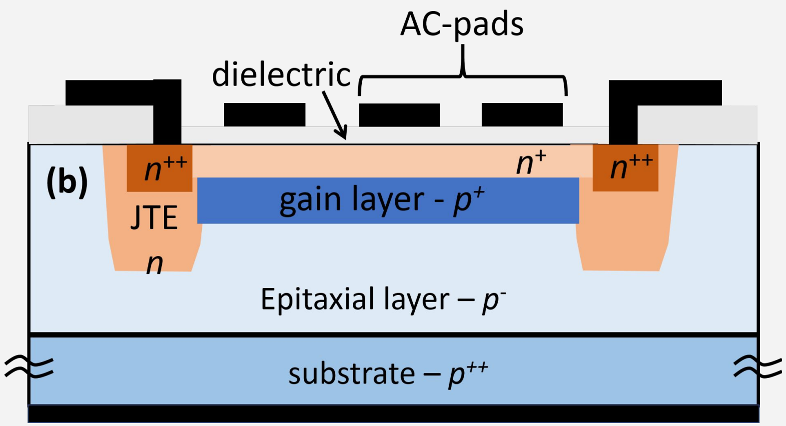
Future Developments

- **Standard LGAD has several known limitations, one of which is the granularity which is limited to mm scale.**
- **X-rays imaging application requires um level spatial resolution.**

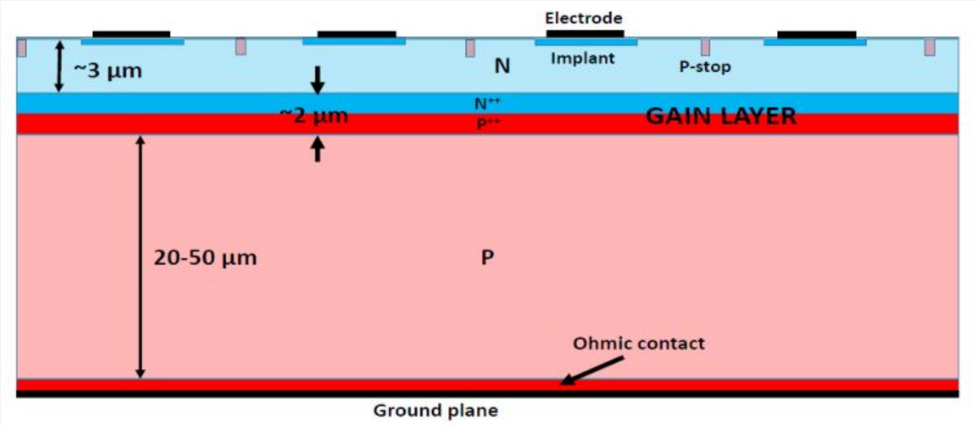


Possible solution with improved LGAD design:

AC-coupled (RSD) LGAD



Deep junction LGAD (DJ-LGAD)



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 and Acknowledgement

Funding & Acknowledgement

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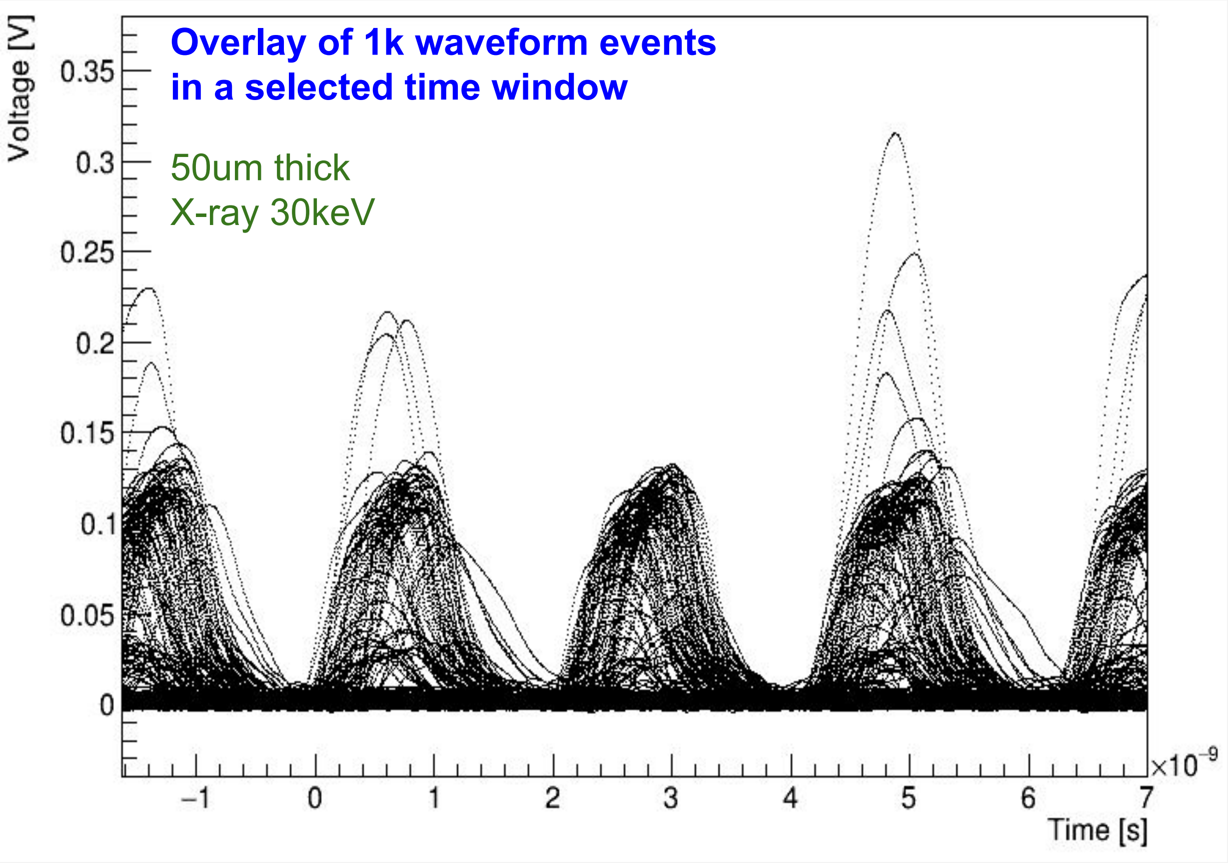
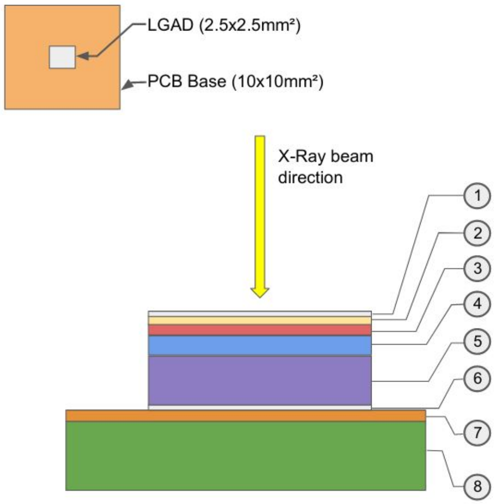
High Repetition Rate

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



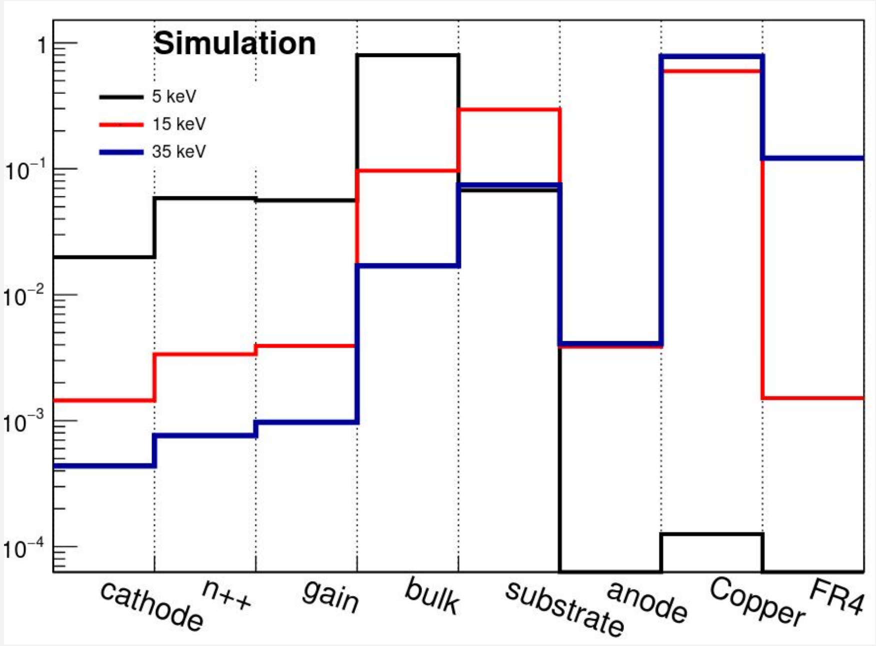
GEANT4 Simulation of X-rays Absorption Location

- **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

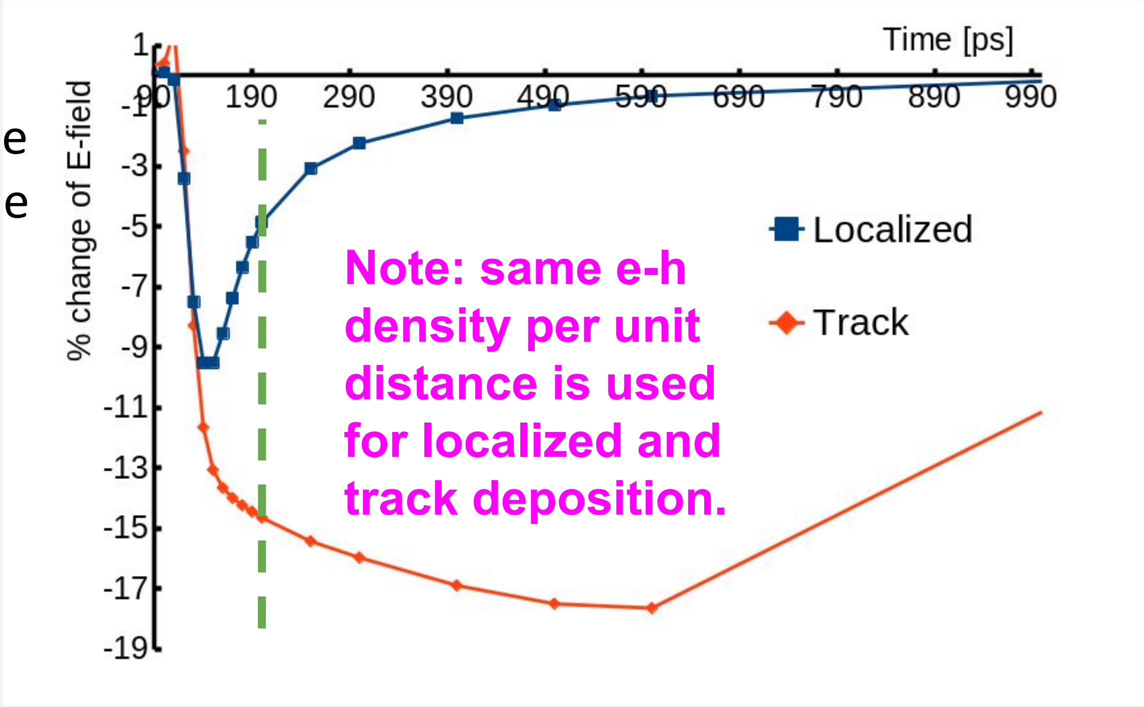


Gain Suppression

- **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**