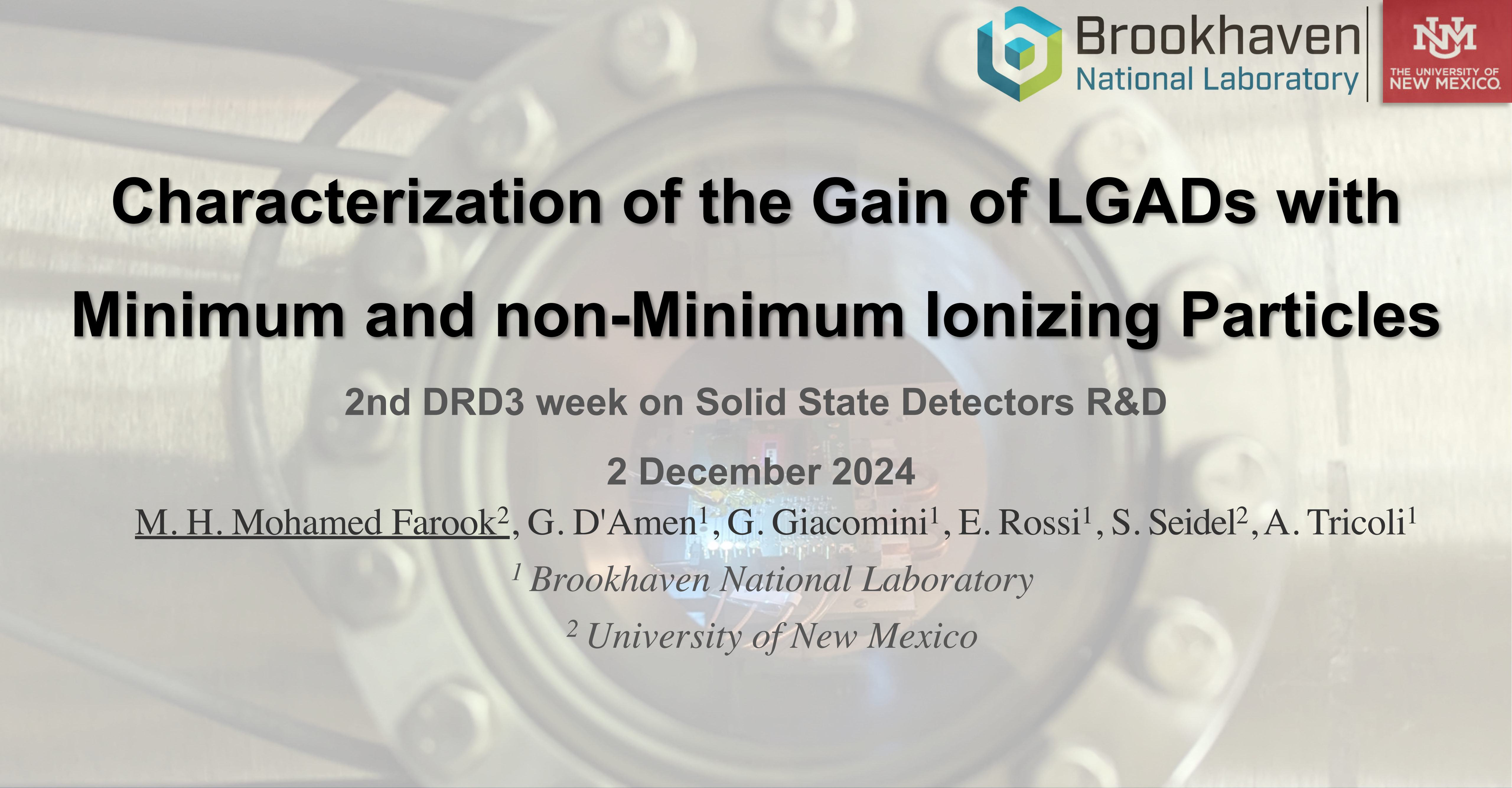


Characterization of the Gain of LGADs with Minimum and non-Minimum Ionizing Particles

2nd DRD3 week on Solid State Detectors R&D

2 December 2024

M. H. Mohamed Farook[2], G. D'Amen[1], G. Giacomini[1], E. Rossi[1], S. Seidel[2], A. Tricoli[1]

[1] *Brookhaven National Laboratory*

[2] *University of New Mexico*

Introduction

- **Low Gain Avalanche Detectors,** LGADs, are a new detector technology which can be used for **timing measurements** in a variety of applications, such as HEP, Nuclear Physics, medical imaging, and space experiments
- The characterization of LGAD performance has up till now focused primarily on the interaction of **minimum ionizing particles (MIPs)** for high energy physics applications
- This work expands the study to **highly-ionizing particles (non-MIPs)**, which are relevant for several future scientific applications.
- The **PIONEER experiment**, **micro-dosimetry for radiation therapy** and **high repetition rate experiments** are examples of applications of **LGADs in the non-MIP** regime

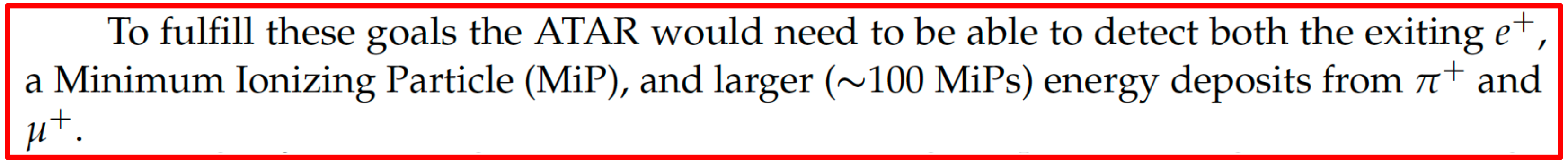
Motivations: Pioneer Experiment

$$R_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+ \nu(\gamma)\right)}{\Gamma(\pi^+ \to \mu^+ \nu(\gamma))}$$

- PIONEER experiment aims to measure the charged pion ratios to electron vs. muon and pion beta decay:

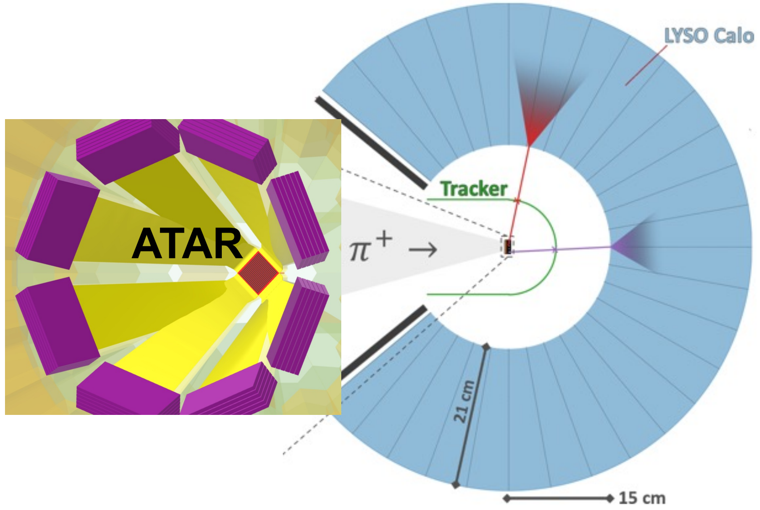
$\pi \to \mu \to e$ decay is four orders of magnitude more likely than $\pi \to e\nu$ decay

- An active target is used to suppress $\pi \to \mu \to e$ decays
- A highly segmented **A**ctive **TAR**get (**ATAR**) defines a fiducial pion stop which suppresses decay in flight.
- The **ATAR** would provide a high precision 4D tracking that would allow separating the energy deposits of the pion decay products in both position and time.



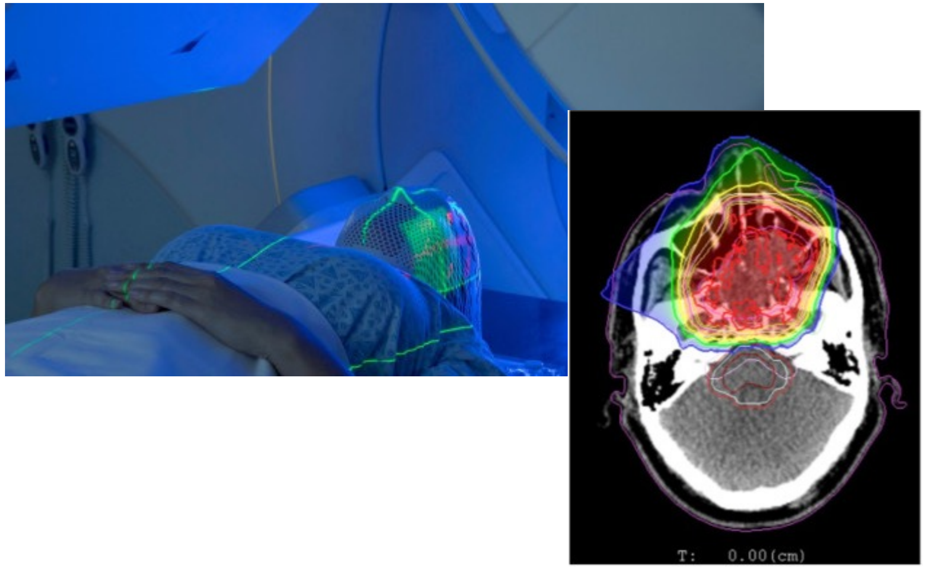
To fulfill these goals the ATAR would need to be able to detect both the exiting e^+, a Minimum Ionizing Particle (MiP), and larger (~100 MiPs) energy deposits from π^+ and μ^+.

PIONEER collaboration. (2021). An LGAD-Based Full Active Target for the PIONEER Experiment. *Instruments*, *5*(40), 2111-05375.

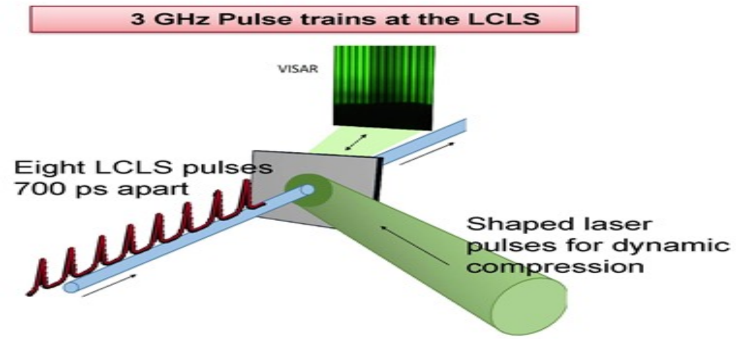


The chosen technology for **ATAR** is **LGAD**s, and this study focuses evaluating the **gain** performance of **LGAD** for **MIP and non-MIP**

Motivations: Medical, High repetition experiments



- **Radiation Therapy:**
  - Several ion species and different energy ranges used, e.g. protons (0-200 MeV), Carbon etc.
  - Micro-dosimetry is important to study damage to healthy cells
  - LGADs are considered to be used for micro-dosimeters

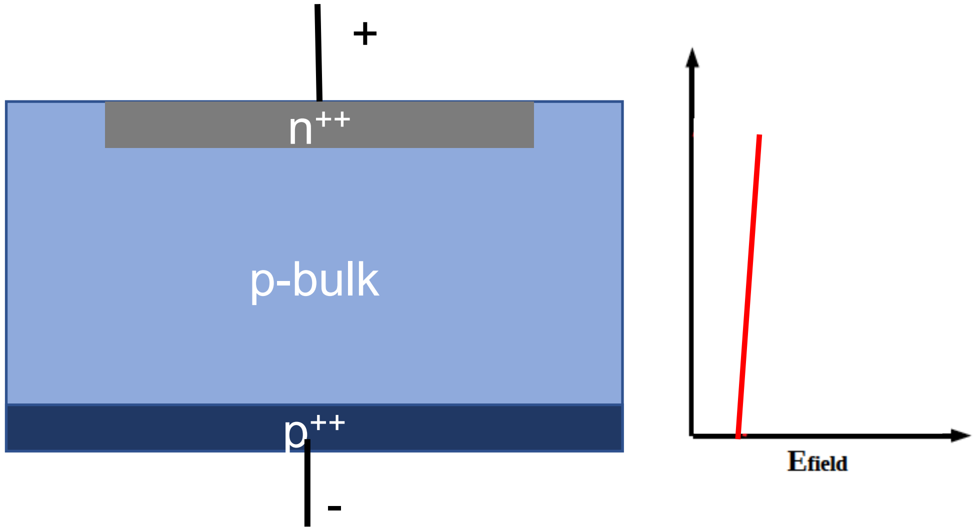


X-ray Detection: speed is the goal

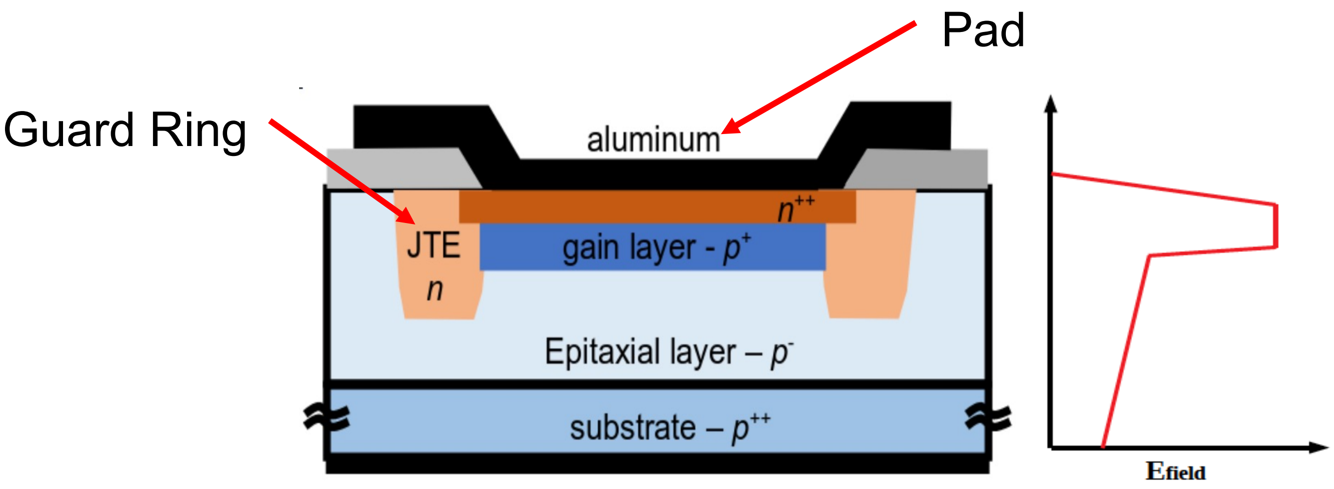
- **High Repetition Rate experiments:**
  - sub-ns timing allows to study fast evolving samples
  - Light-sources may have high repetition rates, sub-ns

Introduction: Low Gain Avalanche Diode (LGAD)

- The LGAD is silicon-based and characterized by an **intrinsic gain** due to a p+-doped layer that allows the production of a controlled avalanche of carriers



Standard Silicon Diode
Gain = 1
Signal/Noise Ratio is low

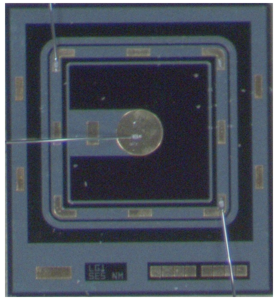


Low Gain Avalanche Diode/Detector LGAD
Gain ~ 10 – 100
Signal/Noise Ratio is very high
Timing resolution ~ 30 ps

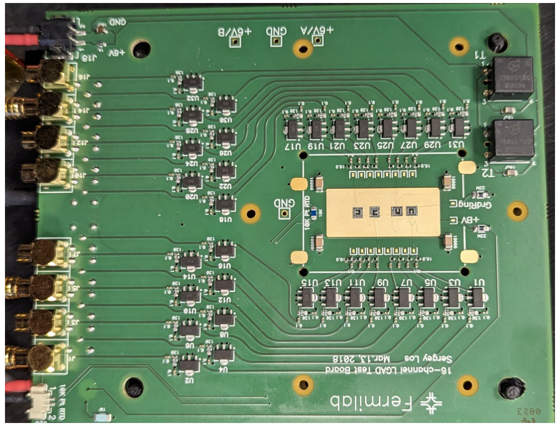
The **high timing** resolution and **precise tracking** ability of LGADs and the variants of this technology have made them a good candidate for **4-dimensional detectors**

Experimental Setup

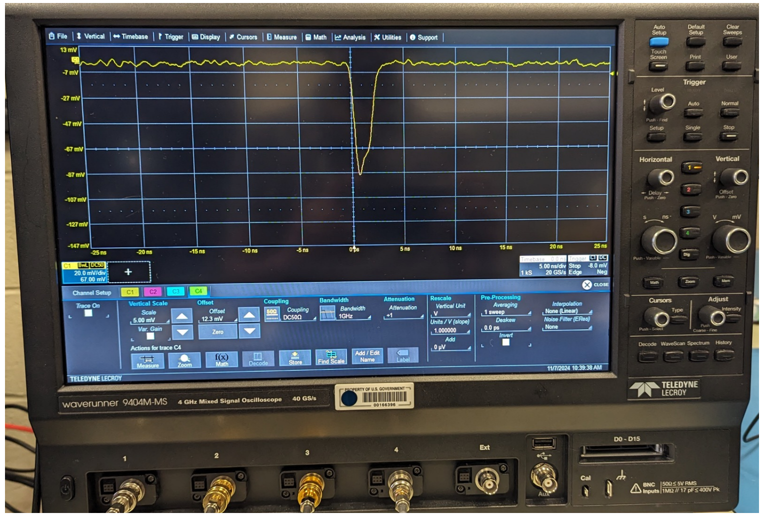
- In this study **35 µm thickness** pixel sensors manufactured by **HPK** were tested.
- Two **LGAD**s and Two **diode**s were wire bonded to the **FNAL Signal Readout board**.
- A **Waverunner 9404M-MS** 4 GHz Mixed Signal **Oscilloscope** was used to record the signal output.
- All test were done at room temperature.



HPK 3.1 LGAD



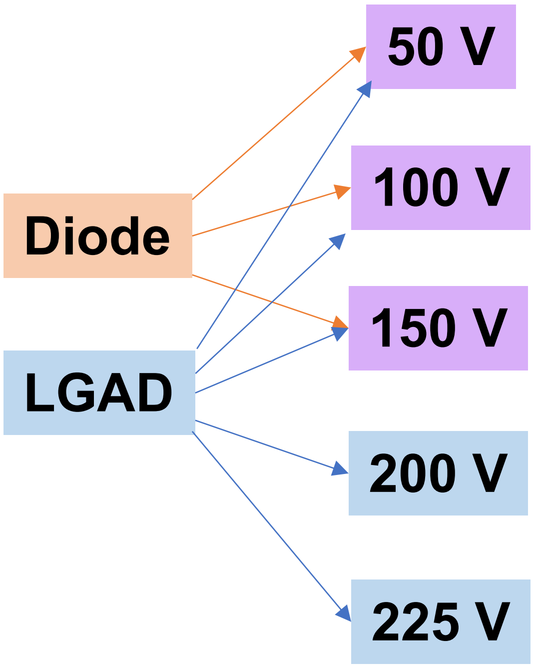
Fermilab 16 – channel LGAD Test Board



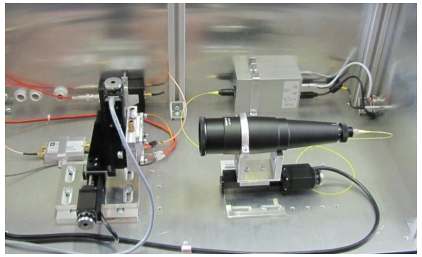
Waverunner 9404M-MS

Experiment

- Tests were performed with a beam of **28 MeV protons (non-MIP)** and **beta-particles** (**MIP**) from a **^{90}Sr source** as well as an **infrared laser** (**MIP to non-MIP range**) to **characterize the gain of the LGAD as a function of bias voltage and injected charge**.

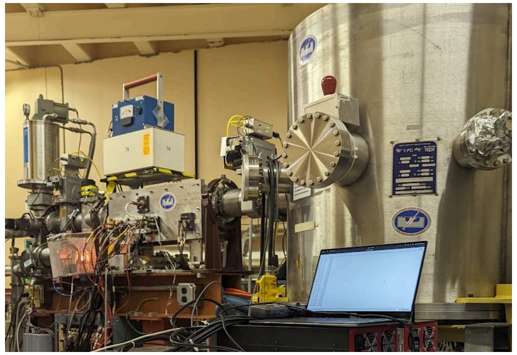


TCT



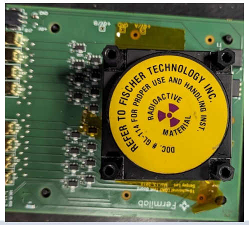
Transient Current Technique for Laser Test

28 MeV Proton



28 MeV protons from BNL Tandem Van de Graaff facility

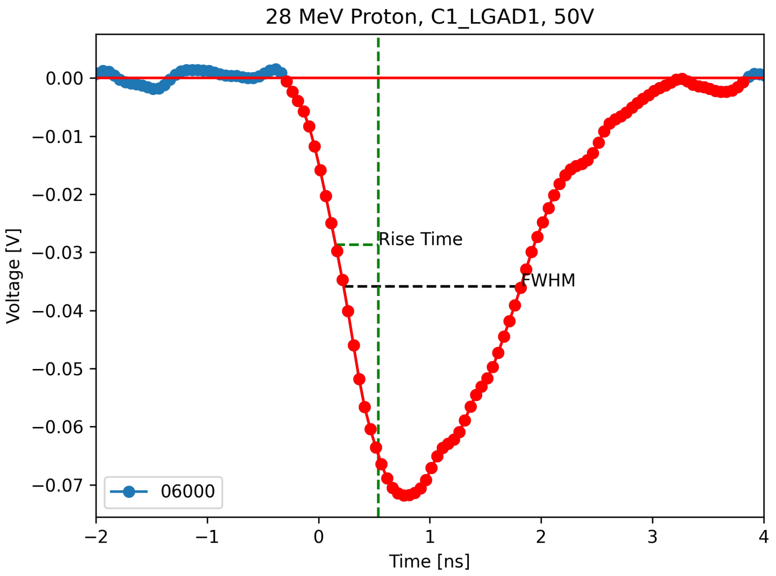
^{90}Sr-Beta

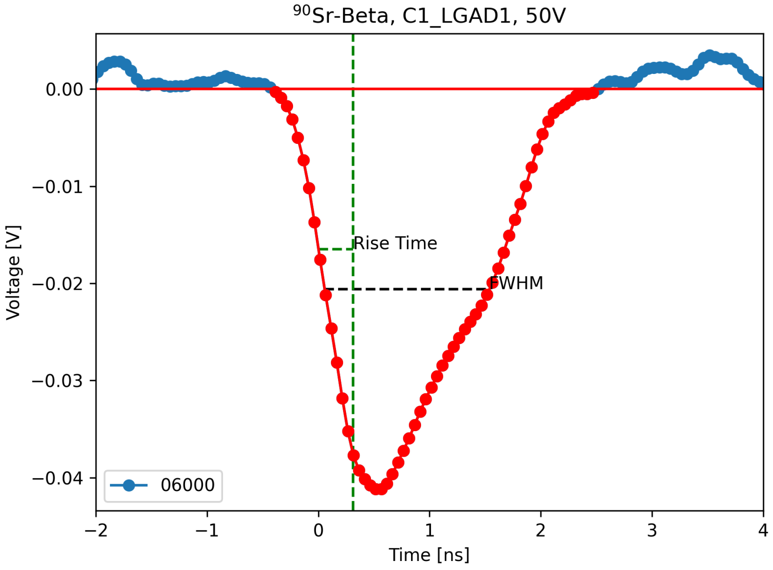


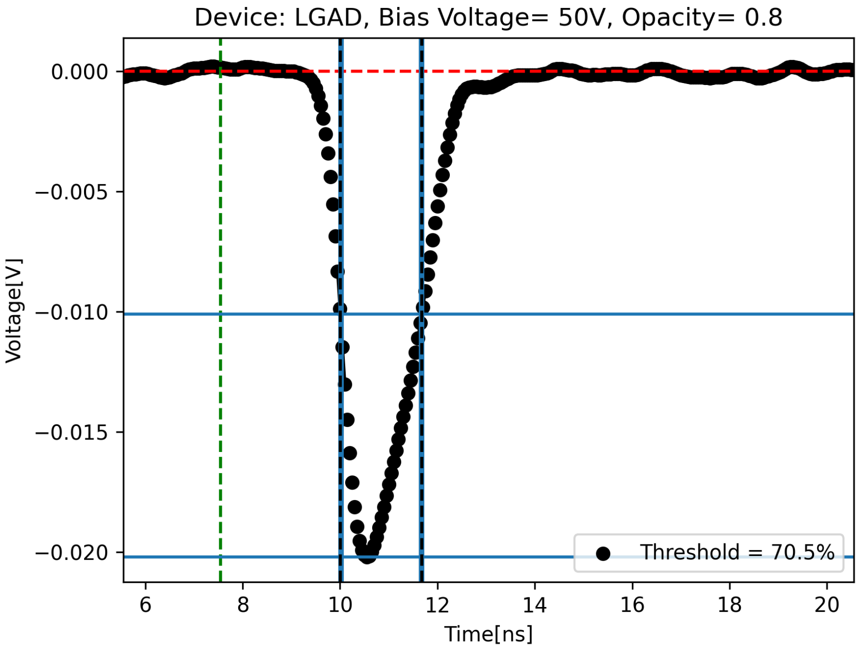
Sensor under ^{90}Sr-beta source
1 mm absorber of Al was used to absorb low energy beta particles

Waveform and Signal Parameters

- Signal parameters such as Amplitude, Full Width Half Maximum (FWHM) and Rise Time were calculated for each waveforms.
- Rise Time was estimated between 40% - 90% of the maximum amplitude.





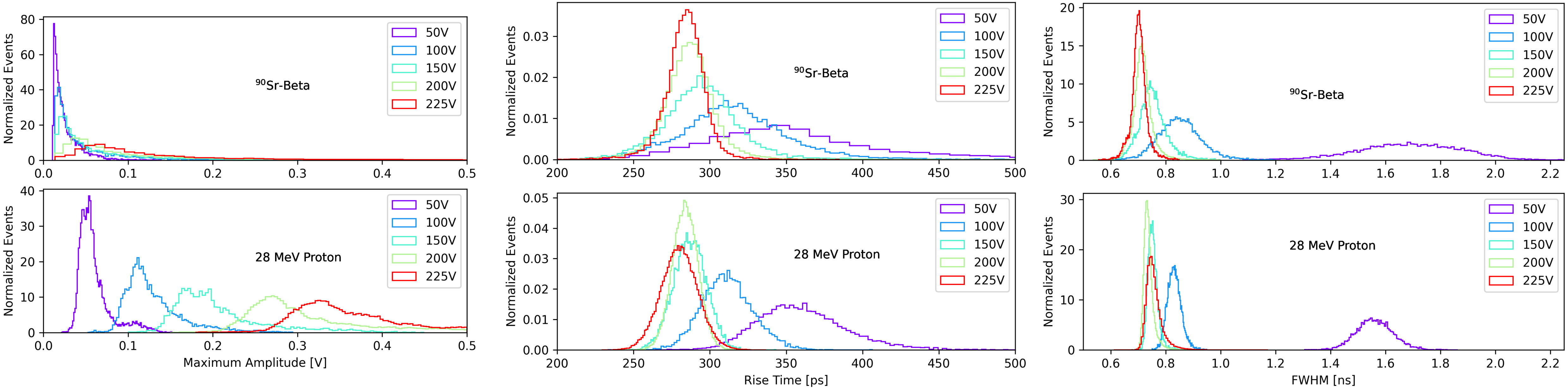


Results: 28 MeV Proton and ^{90}Sr –Beta

- Signal parameters were measured for non-MIP and MIP particles of 28 MeV proton and ^{90}Sr-beta particles respectively.

Particle	Energy [MeV]	Stopping Power [MeV cm²/g]	Particle Type
Proton	28	15.51	non-MIP
Electron (Beta)	2.3	1.59	MIP

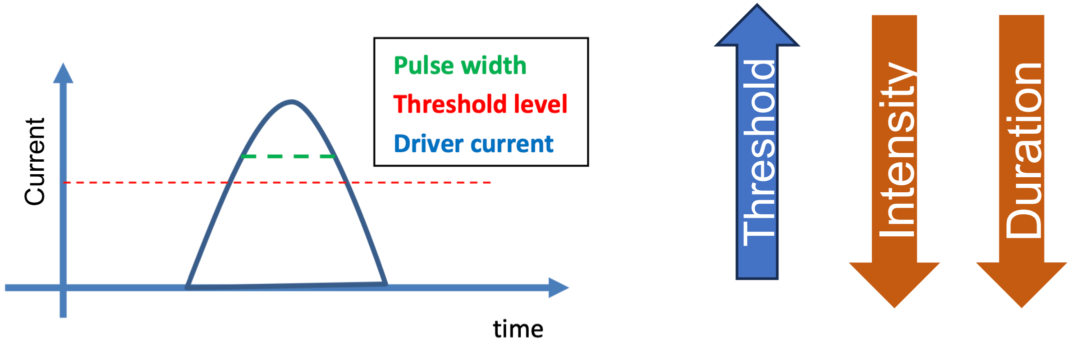
	Bias Voltage	Stopping Power
Amplitude	Dependent	Dependent
Rise Time	Dependent	Independent
FWHM	Dependent	Independent



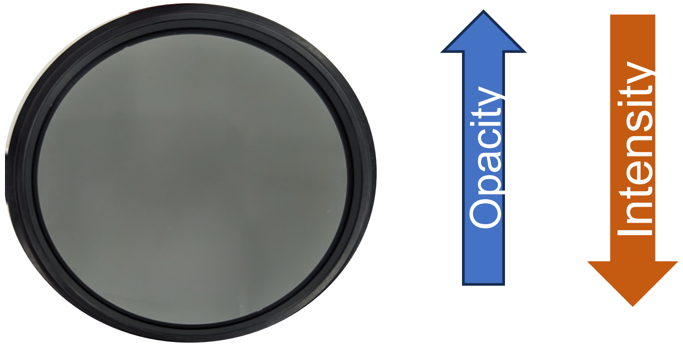
For a specific bias voltage of LGAD sensor, amplitude is higher for non-MIPs than MIPs

Laser Test using Transient Current Technique (TCT)

- To understand the response of LGADs to **MIP** and **non-MIP particles**, we emulate the sensor response to different types of particles using the **Transient Current Technique** (**TCT**):
- **Infra-red Laser pulse power** is controlled by **changing the threshold** of the pulses and using an **optical filter**.

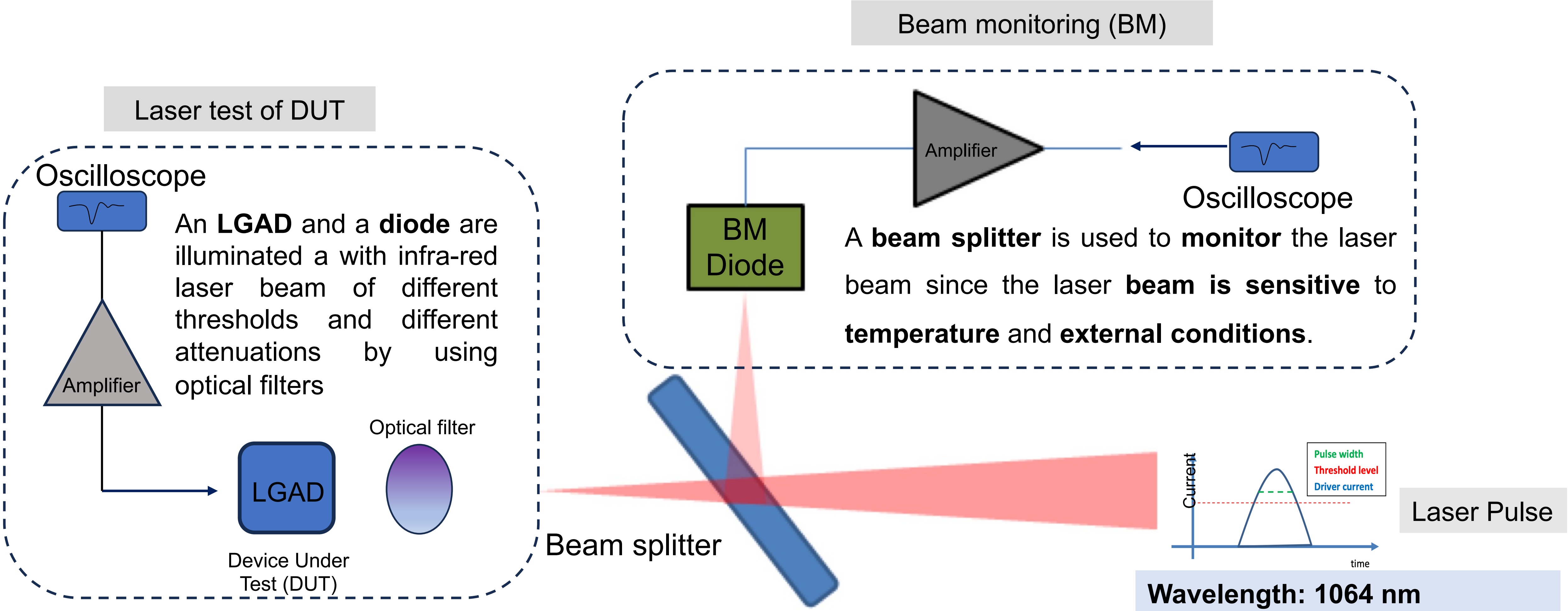


By changing the threshold of laser beam, both **intensity** and **duration** of the **beam** are **changed**



By **changing** the **opacity** of the filter only the **intensity** of the beam is **changed**

Transient Current Technique (TCT) Setup



An **LGAD** and a **diode** are illuminated a with infra-red laser beam of different thresholds and different attenuations by using optical filters

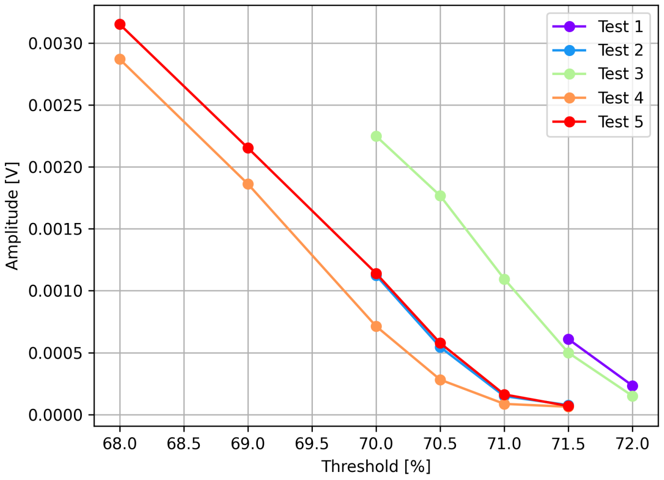
A **beam splitter** is used to **monitor** the laser beam since the laser **beam is sensitive** to **temperature** and **external conditions**.

Wavelength: 1064 nm
Frequency: 1 KHz
Pulse Width: 350 ps – 4000 ps

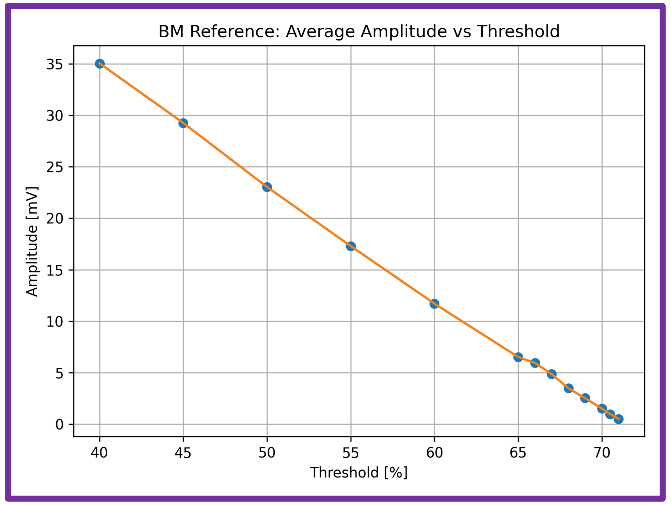
Beam Monitoring (BM)

- Following plot shows amplitude of Beam Monitoring signal for different tests.
- Ideally for all the tests, amplitude corresponding to a particular threshold level should be the same.
- But we observe deviations due to temperature fluctuations and possible external factors influencing the laser beam intensity
- This fluctuation is corrected by scaling the amplitude using a reference amplitude.

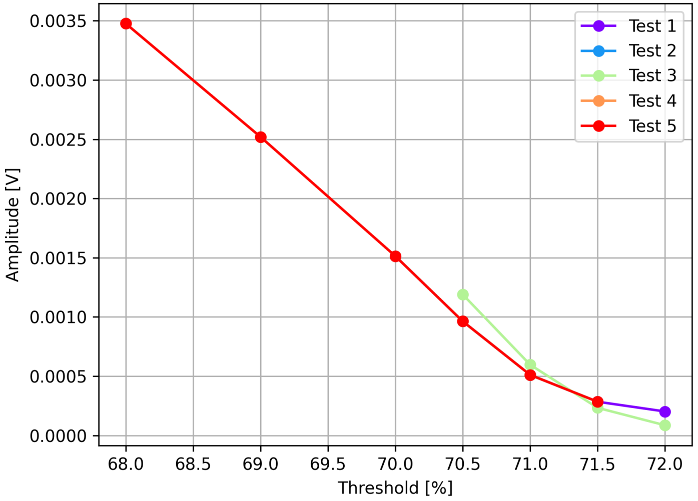
Beam Monitoring



Reference Amplitude

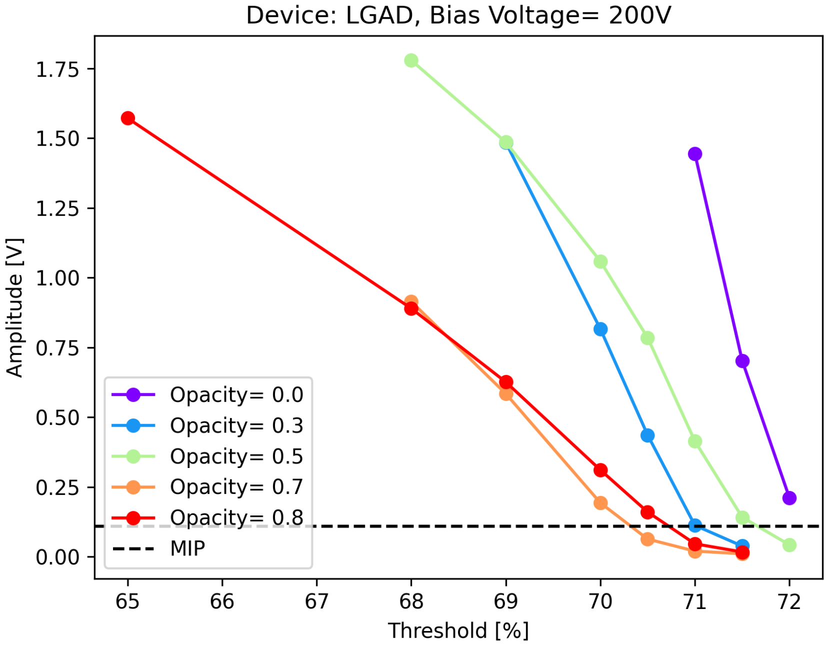


Beam Monitoring after scaling

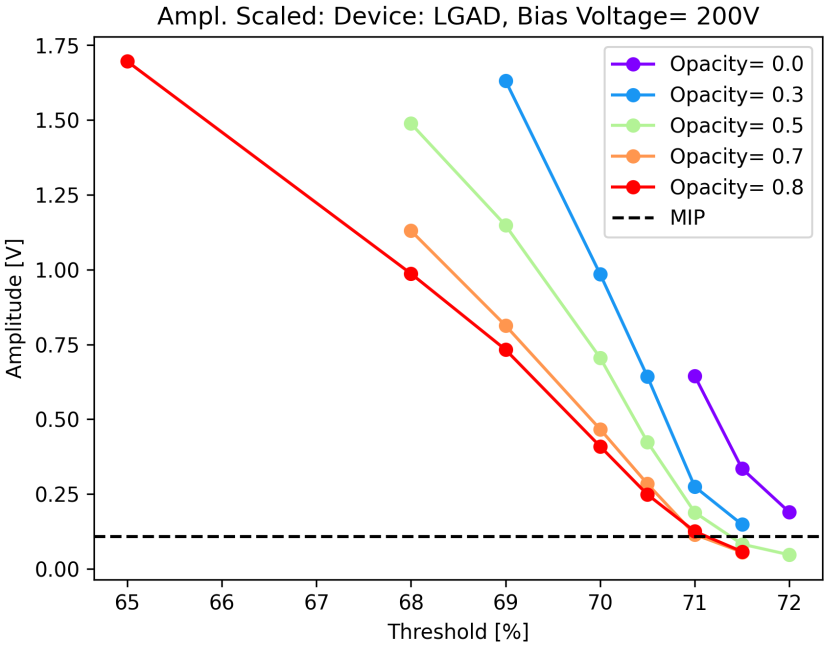


Laser Pulse Scaling

- Scale factor calculated from BM is applied on the corresponding laser test of DUT (LGAD) signal

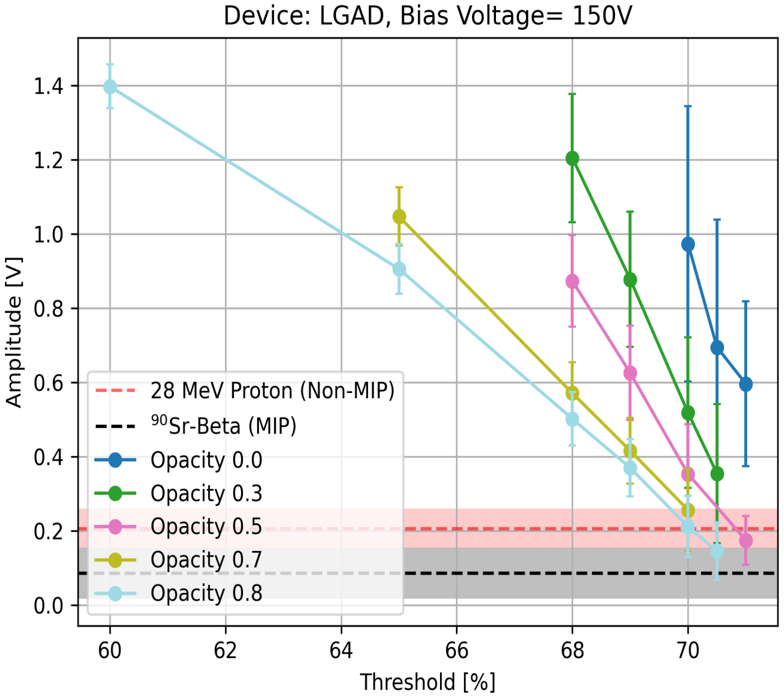


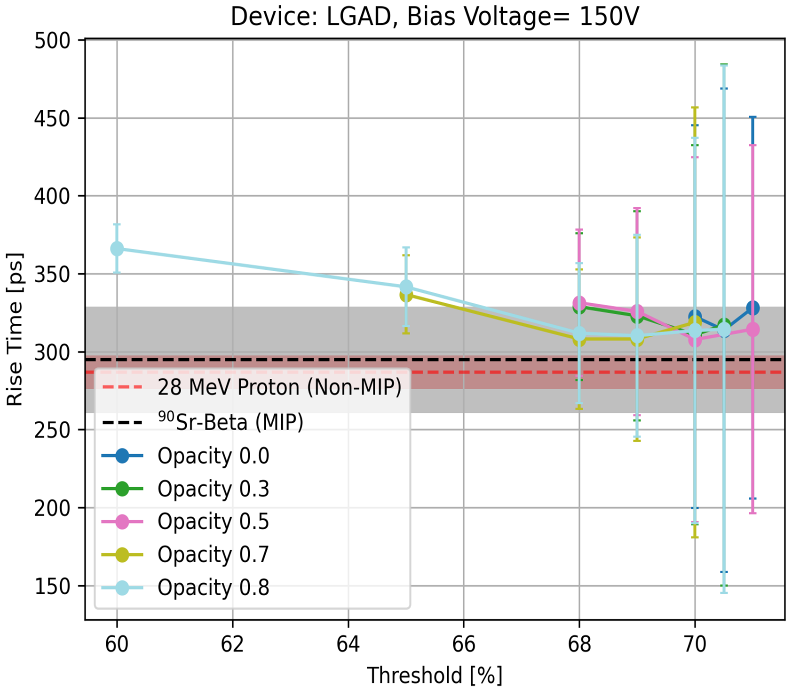
Scale factors are applied in an event-by-event basis to the DUT pulse

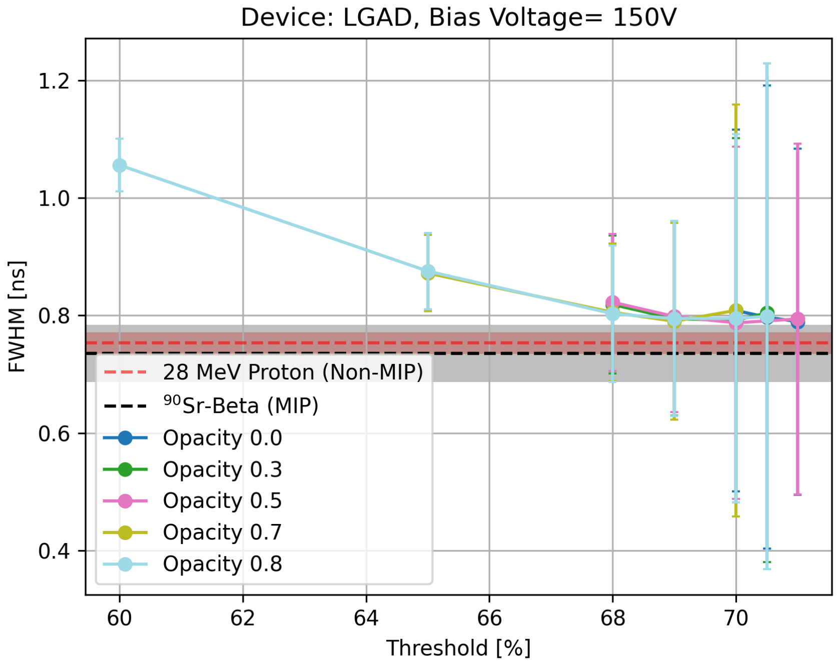


Results: Laser Tests

- Signal parameters were calculated for different thresholds and with different opacities of infra-red laser pulse:



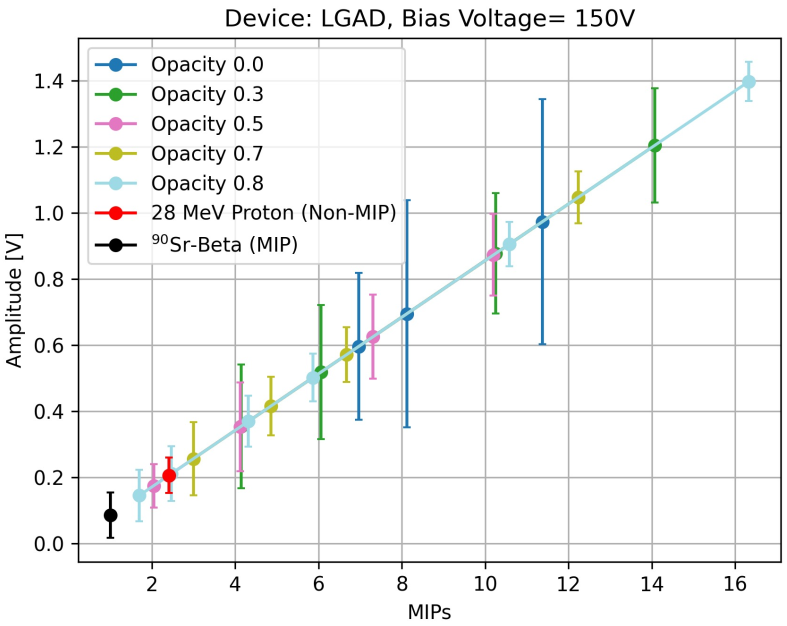


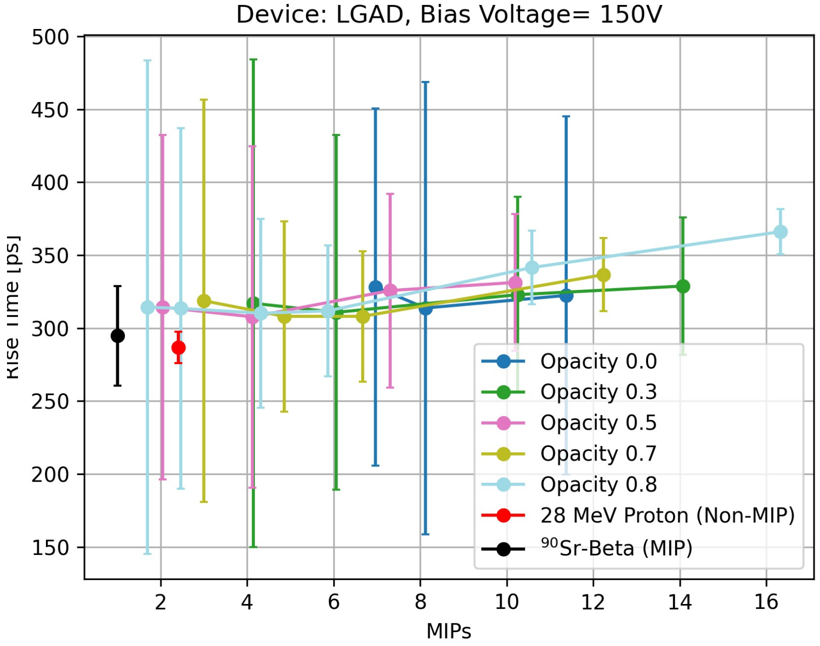


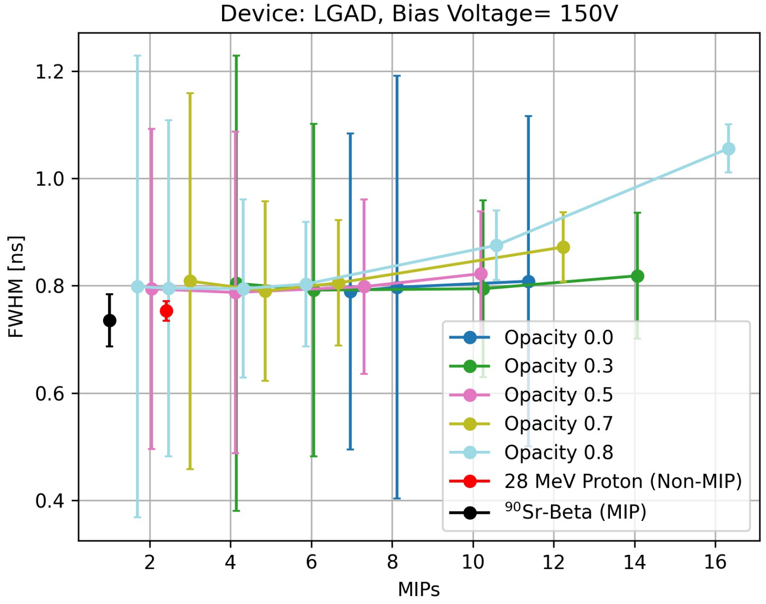
	Threshold	**Opacity**
Amplitude	Dependent	Dependent
Rise Time	**Saturates after 68%**	Independent
FWHM	**Saturates after 68%**	Independent

Results: Laser Tests

- Following plots have been rescaled to interpret the threshold values as MIPs
- Amplitude of the laser beam has been divided by the MIP amplitude to rescale to no. of MIPs each combination of opacity and threshold represents:

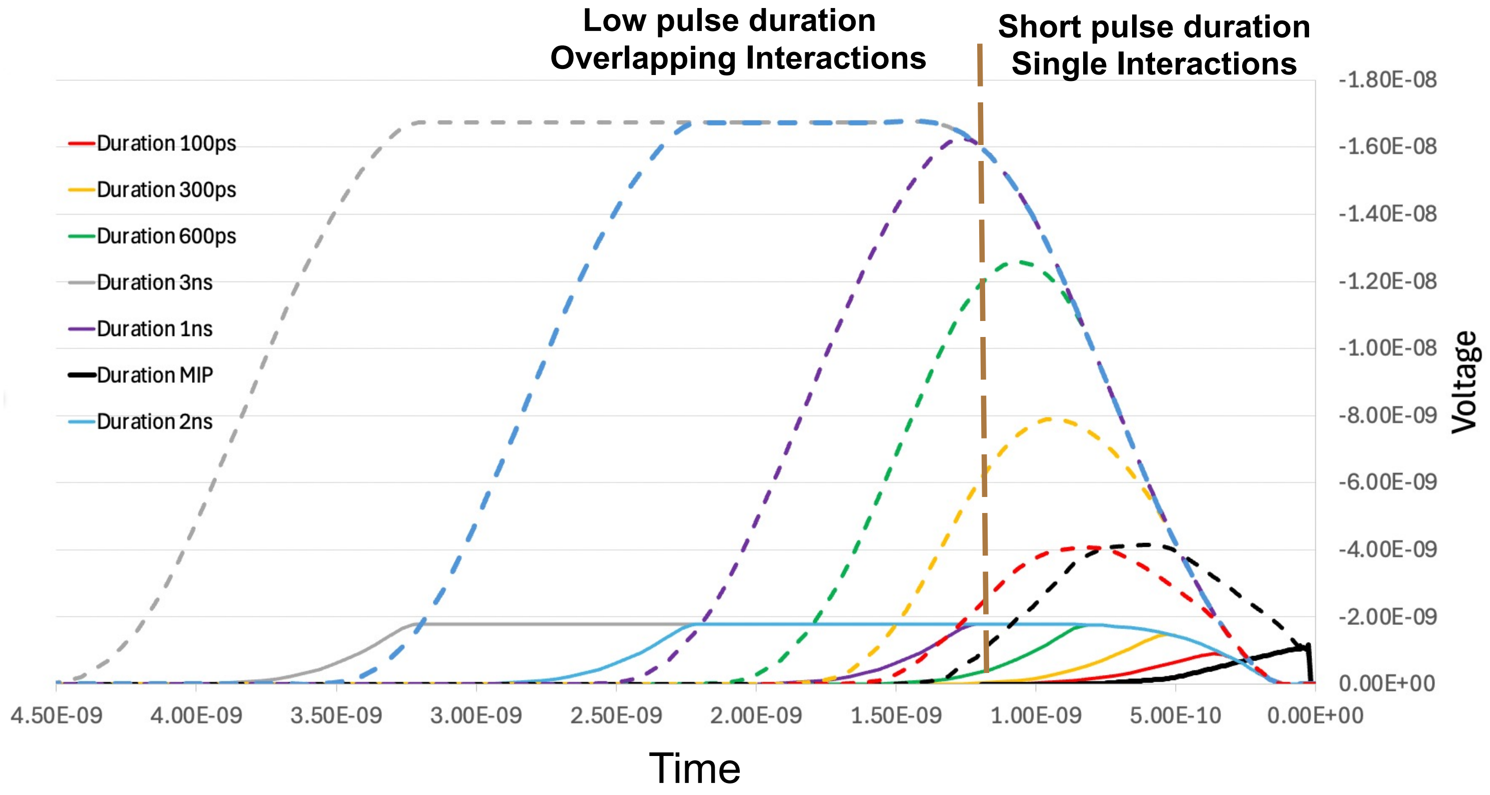


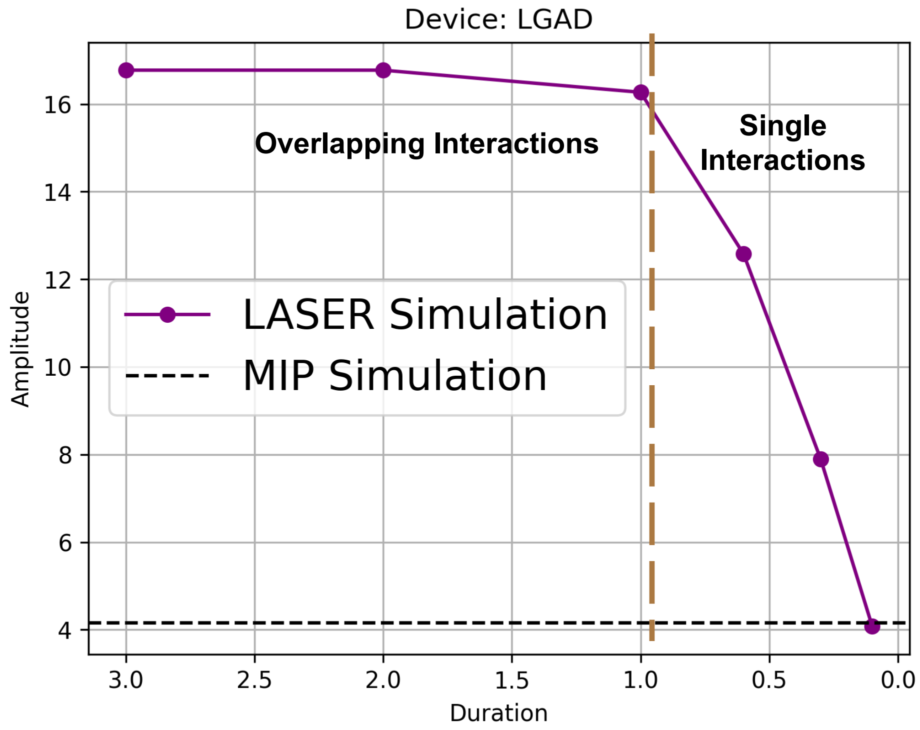




TCAD Simulation of TCT Response

- To understand the LGAD response to infra-red laser beam in TCT, **TCAD** was used to **simulate fully depleted LGAD signals** for **different threshold levels of laser pulse**.
- Two distinct interaction regions can be demarcated:





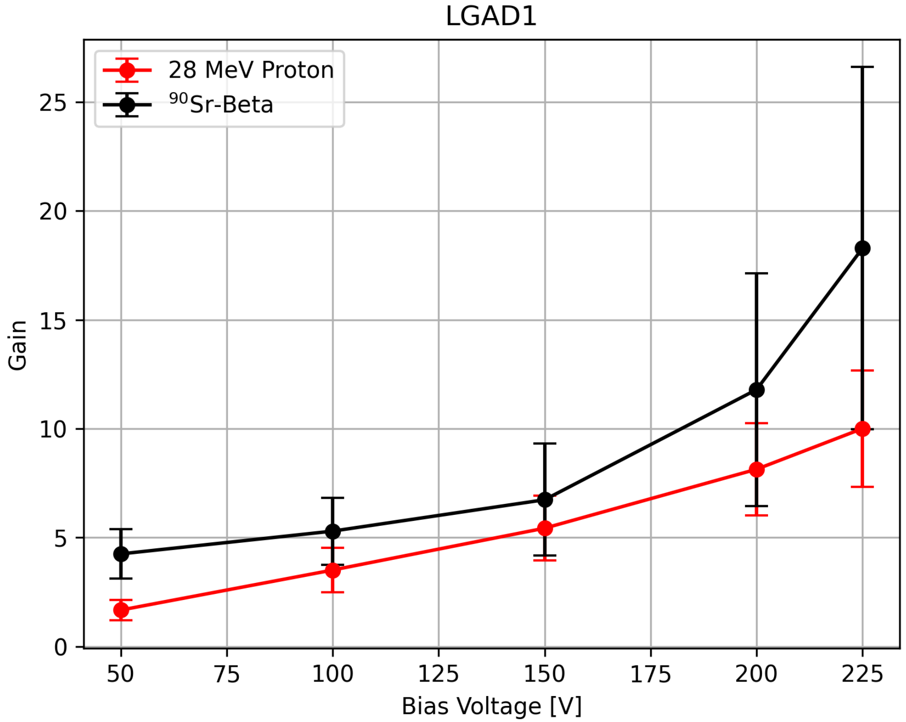
Results: Gain

- Gain of LGAD is calculated using the amplitude:
- Single and overlapping interactions in laser test are distinguished as follows:

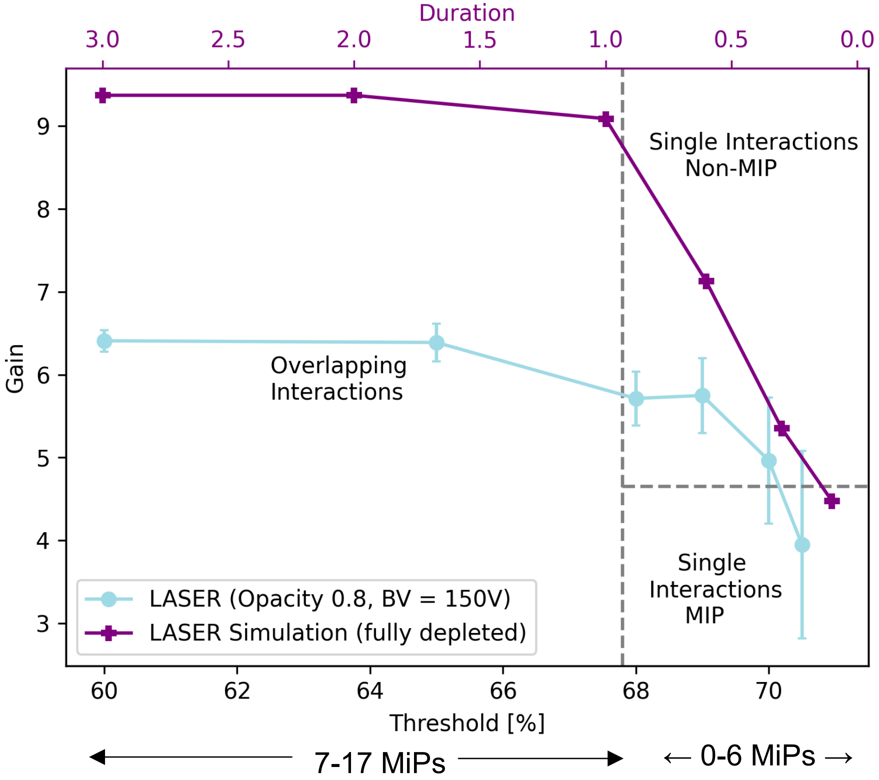
$$\text{Gain} = \frac{\text{Amplitude of LGAD}}{\text{Amplitude of Diode}}$$

Diode amplitude of ^{90}Sr-beta particles is calculated

High Threshold (>68%) → Single Interactions
Low Threshold (<68%) → Overlapping Interactions



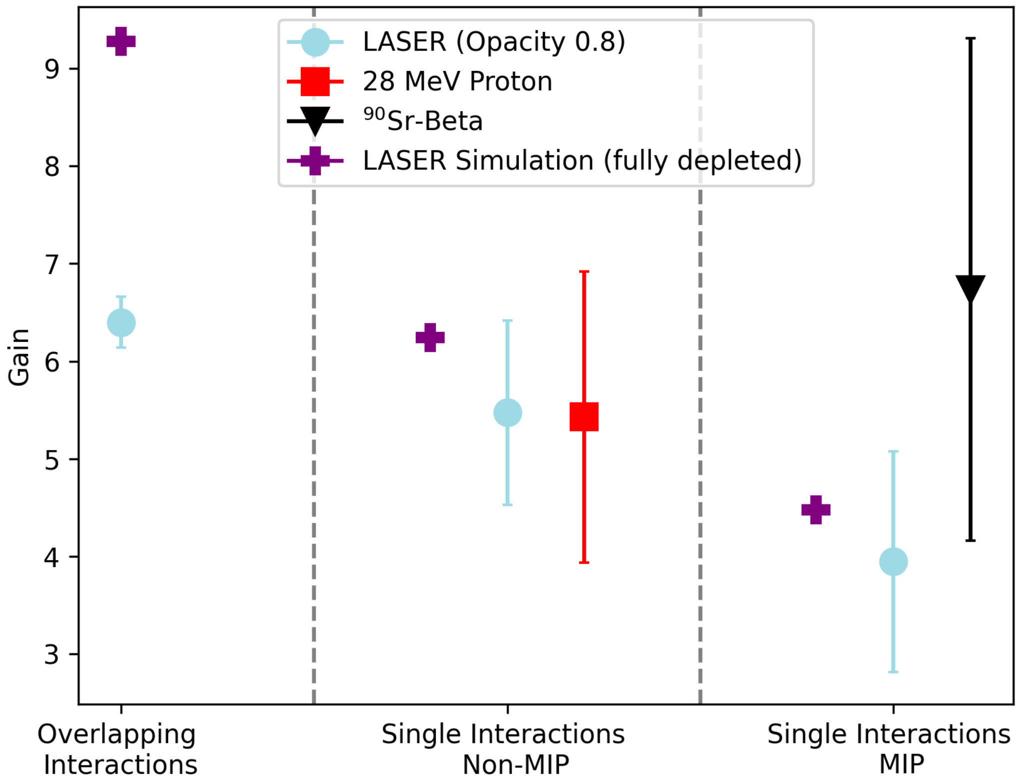
Gain results of the two LGADs we tested follow similar trend



Conclusion

- **Laser simulation agrees** with **laser data**
- **28 MeV proton** gain and **^{90}Sr-beta** gain correspond to the **single interaction region**
- The **amplitudes** and **gain** are **comparable between single non-MIP** and **MIP** charged particles.
- The **amplitudes** and **gain increase** if the **particle flux is sufficiently intense** to cause **overlapping particle interactions** in silicon

Gain of LGAD at 150V



The results show that the LGAD amplitudes and gain depend on the particle beam and the interacting conditions.

Outlook

- Currently working on calculating the **gain** using the **deposited charge** to complement our results.
- We will work on reproducing simulation for charged particles (Proton and Beta).
- We are hoping to test the sensors with **332 MeV ^{197}Au** and possibly **other kinds of particles** and **low energy protons** from **Tandem Van De Graff facility at BNL**.

Acknowledgement

The authors wish to thank their colleagues at Brookhaven National Laboratory: Ron Angona and Sean Robinson for sensor fabrication; Don Pinelli, Antonio Verderosa, Joe Pinz and Tim Kersten for sensor mounting. This material is based upon work supported by the U.S. Department of Energy under grant DE-SC0012704. This research used resources of the Center for Functional Nanomaterials, which is a U.S. DOE Office of Science Facility, at Brookhaven National Laboratory under Contract No. DE-SC0012704.

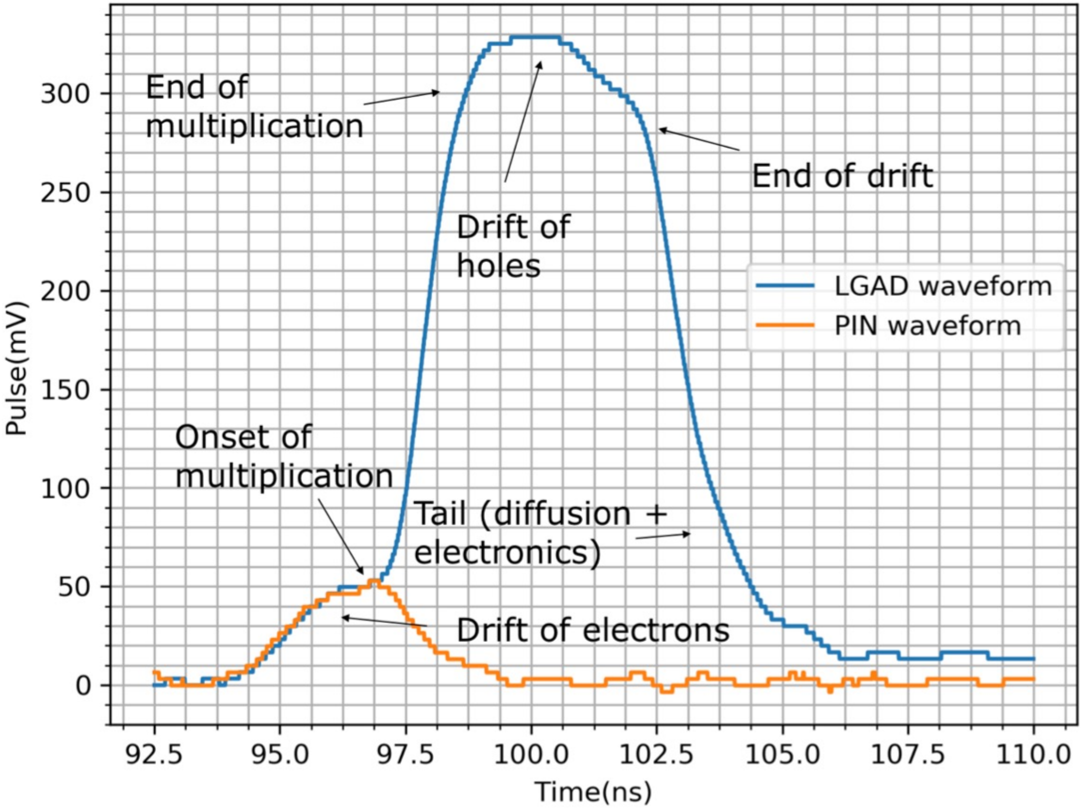
US ATLAS

U.S. DEPARTMENT OF ENERGY

US ATLAS - ATC

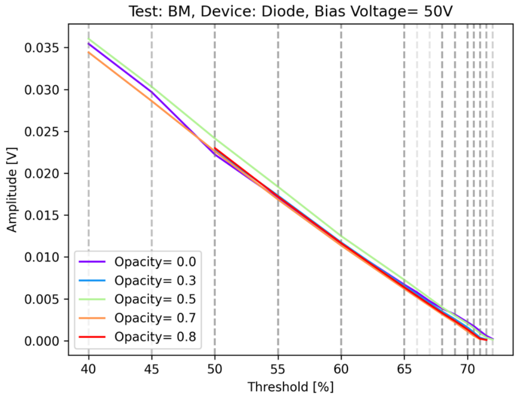
Back-up

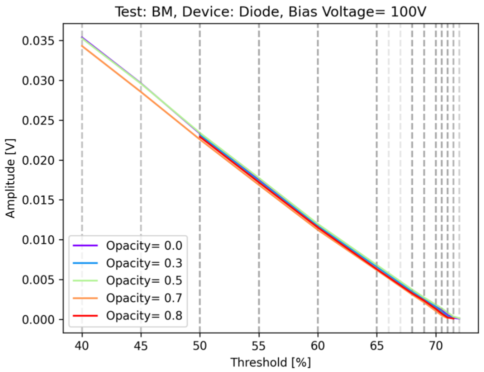
Diode Vs LGAD Pulse

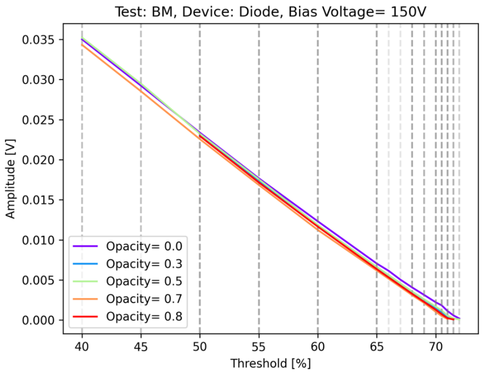


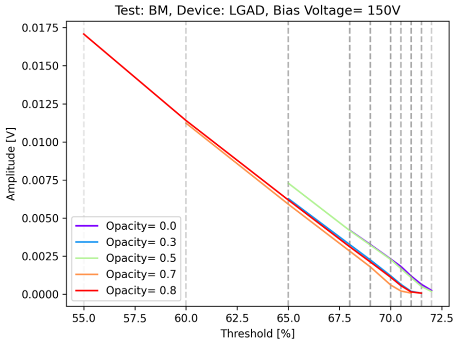
Laser Tst: Beam Monitoring

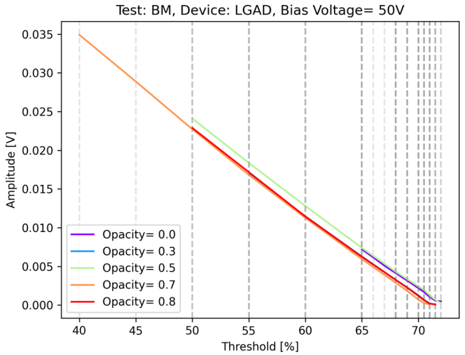
- Following plots show amplitude of BM for different thresholds during different tests

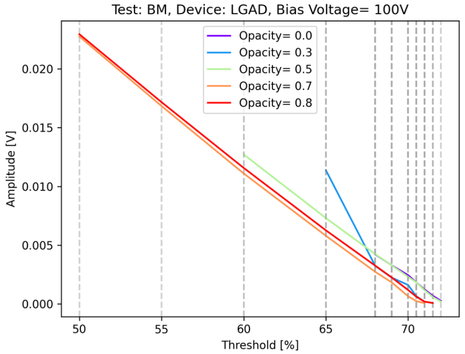

Test: BM, Device: Diode, Bias Voltage= 50V

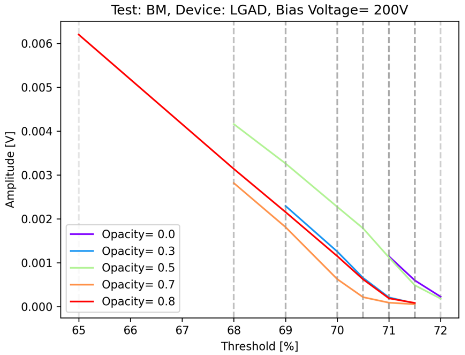

Test: BM, Device: Diode, Bias Voltage= 100V

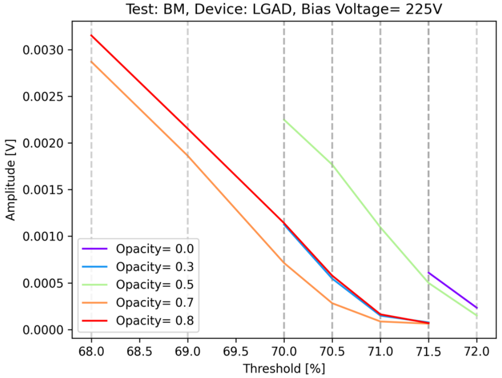

Test: BM, Device: Diode, Bias Voltage= 150V


Test: BM, Device: LGAD, Bias Voltage= 150V


Test: BM, Device: LGAD, Bias Voltage= 50V

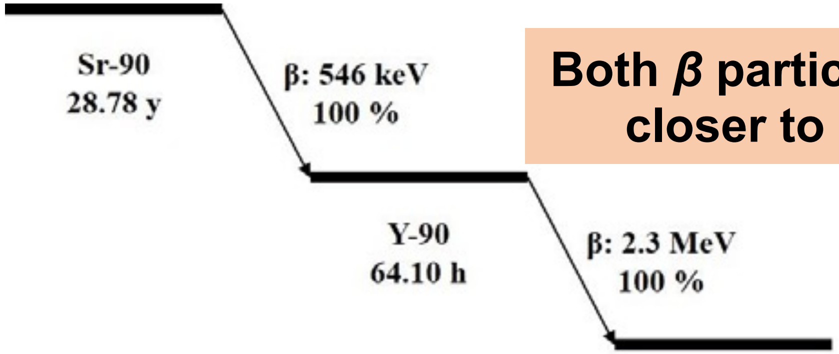

Test: BM, Device: LGAD, Bias Voltage= 100V


Test: BM, Device: LGAD, Bias Voltage= 200V


Test: BM, Device: LGAD, Bias Voltage= 225V

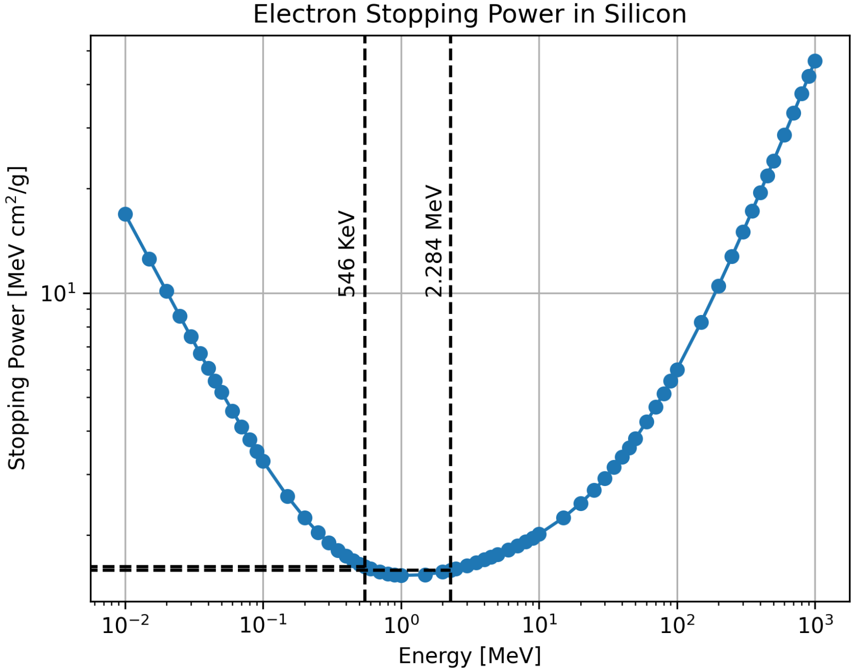
Optical Filters used in this study:
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5011

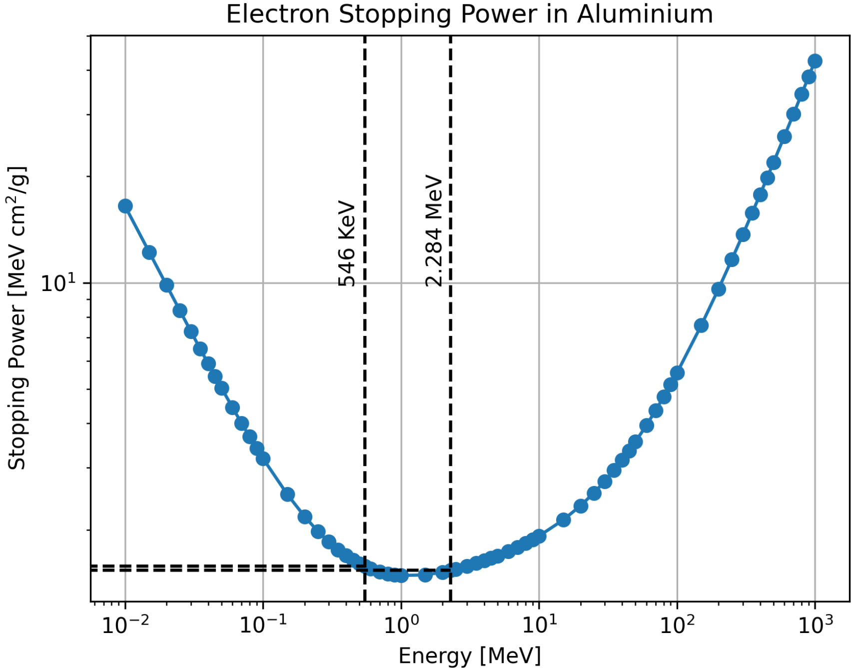
Decay Scheme of ^{90}Sr



Both β particles are closer to MIP

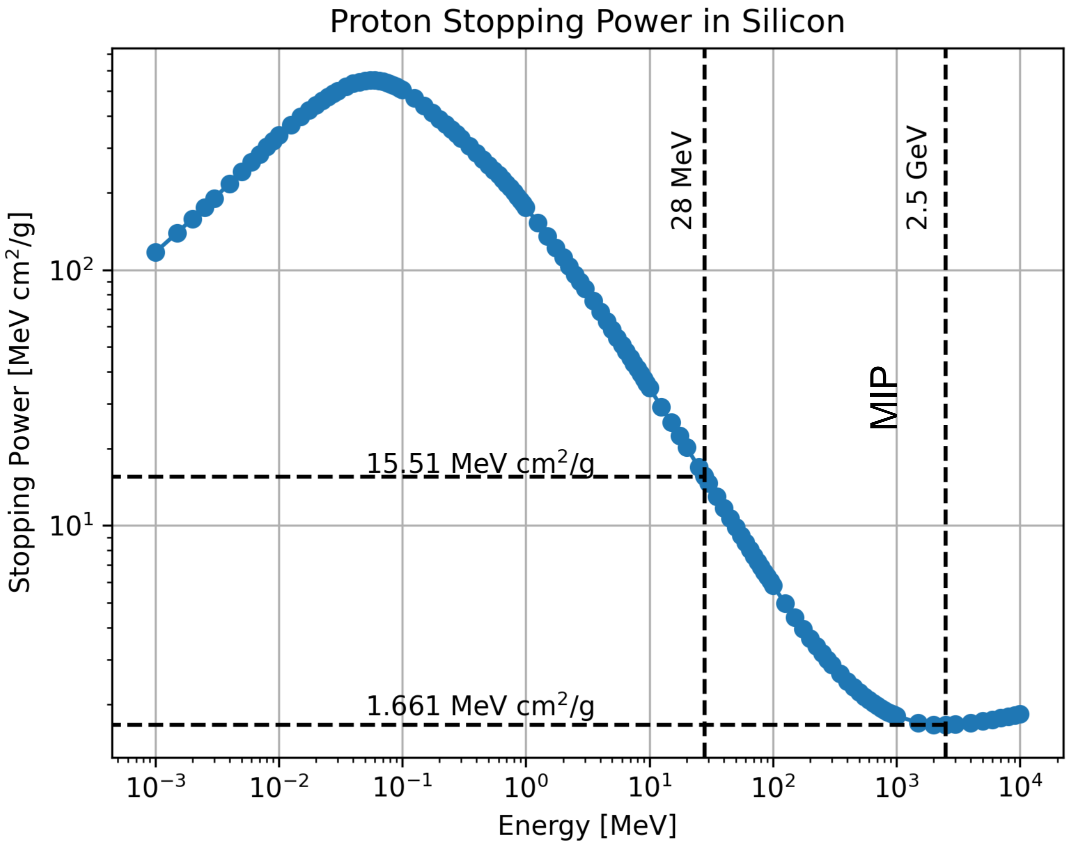
To avoid overlapping of signals from both particles, an Aluminium shielding of ~1 mm was used to absorb low energy β particles


Electron Stopping Power in Silicon


Electron Stopping Power in Aluminium

28 MeV Proton signal Amplification on LGAD

MIP creates $\mathbf{80}\ \boldsymbol{e/h\ \mu m^{-1}}$ in Silicon



Energy [MeV]	**Stopping Power [MeV cm²/g]**	$\boldsymbol{e/h\ \mu m^{-1}}$
2500	1.661	80
28	15.51	$x = 747.02$

$$\frac{15.51}{1.661} = \frac{x}{80}$$

$$x = \frac{15.51}{1.661} \times 80$$

$$= 747.02\ e/h\ \mu m^{-1}$$

Above plot is plotted using data from:
https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

28 MeV proton creates $\mathbf{747.02}\ \boldsymbol{e/h\ \mu m^{-1}}$ in Silicon

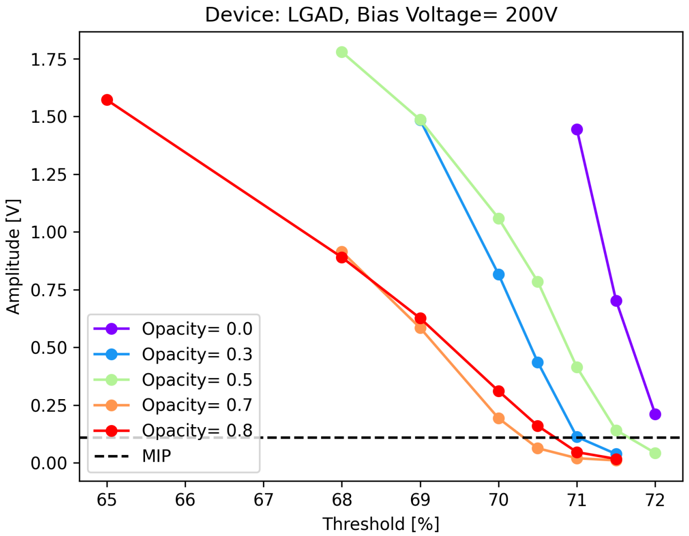
Laser Pulse Scaling

- To correct for the fluctuations in laser pulse, amplitude of the signal waveforms are scaled according to BM.

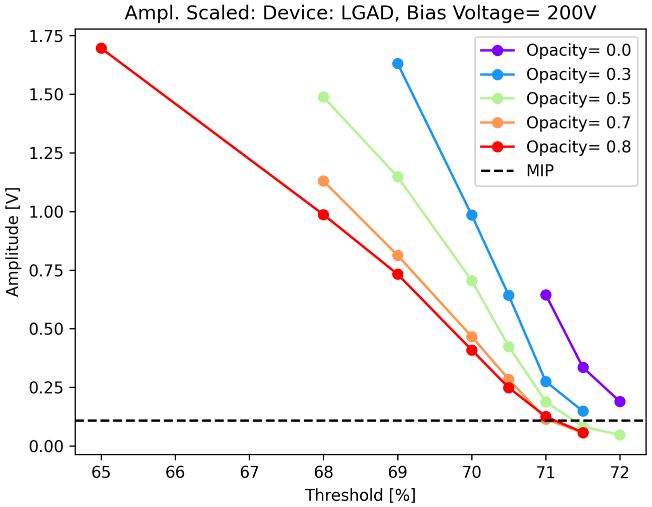
$$Reference\ Amplitude(Th = l) = Amplitude\ of\ BM\ for\ average\ of\ (Sensor = all, BV = all, Opacity = all, Th = l)$$

$$Scale\ Factor:\ W_{i,j,k,l} = \frac{Amplitude\ of BM(Sensor = i, BV = j, Opacity = k, Th = l)}{Reference\ Amplitude(Th = l)}$$

$$Scaled\ Amplitude_{i,j,k,l} = \frac{Amplitude\ Observed\ in\ Laser\ Test(Sensor = i, BV = j, Opacity = k, Th = l)}{W_{i,j,k,l}}$$

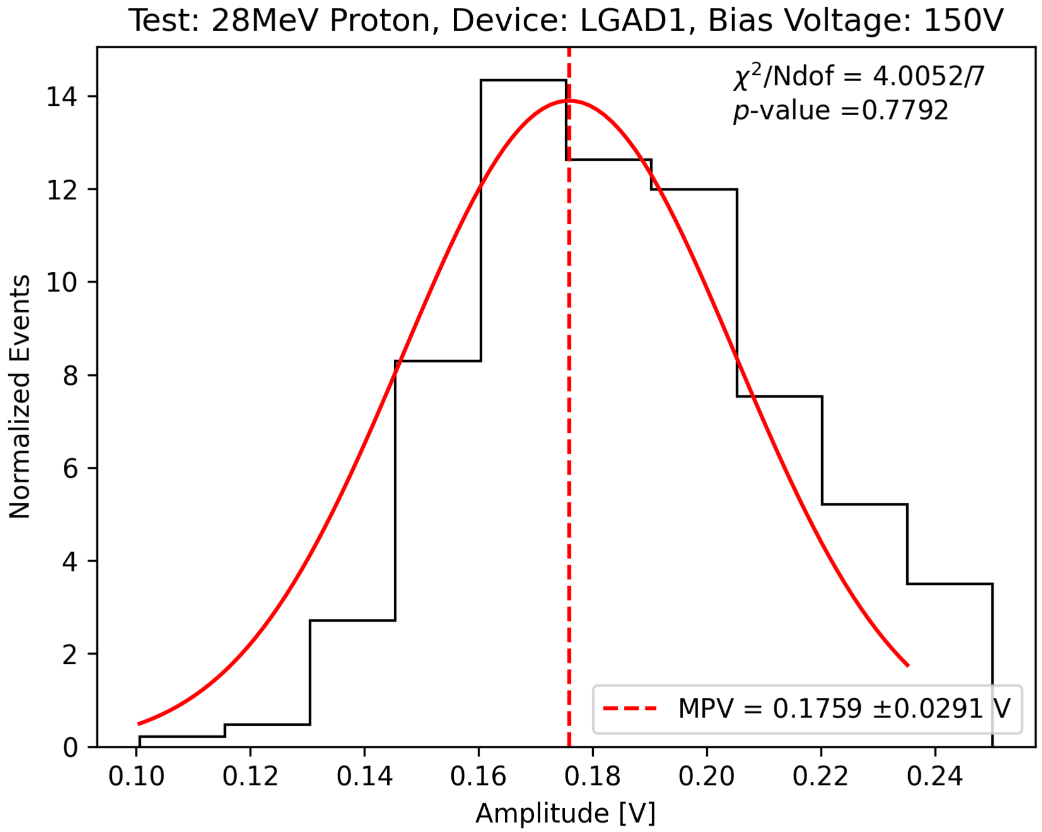


After Scaling

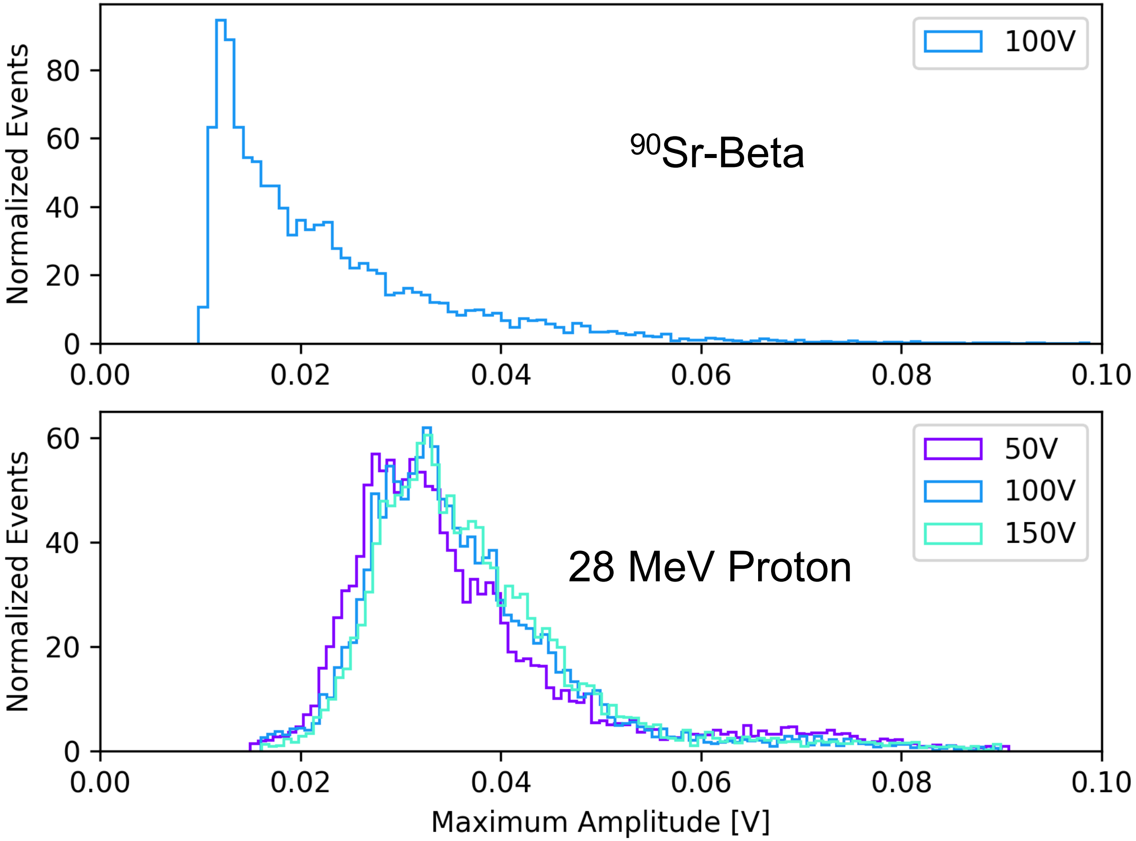


Error estimation of Amplitude

- A gaussian function is fit to amplitude distribution of Proton beam tested Diode and LGAD, and ^{90}Sr-Beta tested LGAD .
- Mean and sigma of the gaussian the distribution are taken as central value and error respectively.



Diode: Amplitudes



When we use a lower threshold for Diode data taking with ^{90}Sr-Beta source, we trigger mostly on noise

By using a higher threshold, we cut the diode peak of amplitude spectrum

Area and Amplitude of Diode signals for ^{90}Sr-Beta particles

Thickness of sensor = 35 μm
MPV of e/h pairs created by MIP of ^{90}Sr-Beta in silicon = 80 e/h μm^{-1}
Bias Voltage = 100 V

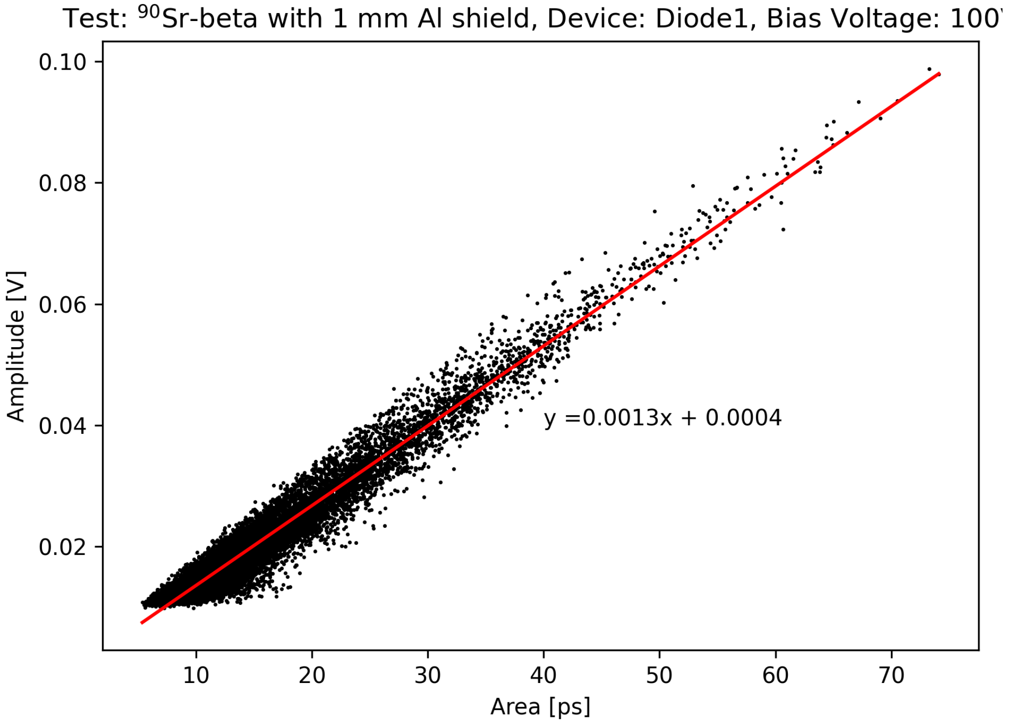
$$Area = \int dtV = \int dt\, IR \times A^2 = Q\; R\; A^2$$

$$= 80\; e/h\;\; \mu m^{-1} \times 50\; \mu m \times 50\; \Omega \times 10^2$$

$$= 80\; \times 1.602 \times 10^{-19}\; C\; \mu m^{-1} \times 35\; \mu m \times 50\; \Omega \times 10^2$$

$$= 2.2428 \times 10^{-12}\; Vs$$

$$Diode\; Amplitude = 0.0013 \times 2.2428 + 0.0004 = 0.00338\; V$$



^{90}Sr-Beta: Calculating Diode Amplitude and Estimating Error

Amplitude = 0.0033811213714801604 V

Error propagation:

$$y = ax + b$$

a = 1316112625.3761208 ± 2876868.397177739

b = 0.0004293439752865967 ± 5.473657830733507e-05

x = area calculated = $2.2428 \times 10^{-12}\ Vs$

y = Amplitude = 0.0033811213714801604

$$\Delta y = \sqrt{(x\ \Delta a)^2 + (a\ \Delta x)^2 + (\Delta b)^2}$$

$$\Delta y = 5.51 \times 10^{-5}$$

Diode amplitude $y = (3.38\ \pm 0.05)\ \mathrm{mV}$