Characterization of Large Area LGADs for Space Applications

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The Scientific Motivation

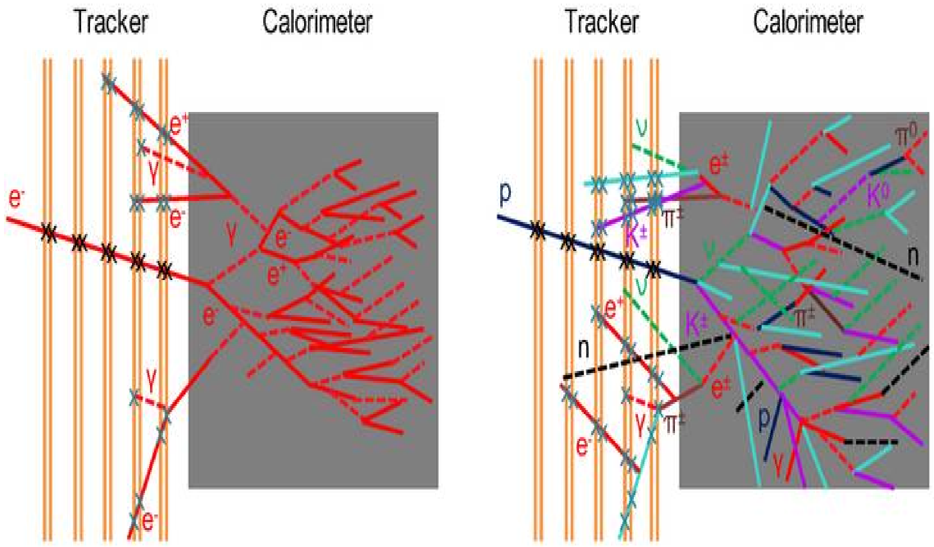
Improve the tracking capability for future space missions

4D-Tracking
Capability to reconstruct the incoming particle's trajectory together with the crossing time of each detecting layer

Advantages of Timing [1]

- Identification of back-scattered hits from calorimeters
- Time of Flight (ToF) measurements
- Improved e/p identification
- Reduction of "ghost" hits
- Timing resolution requirement O(100 ps)

Schematics of Space Instruments for Cosmic Rays



The Requirements

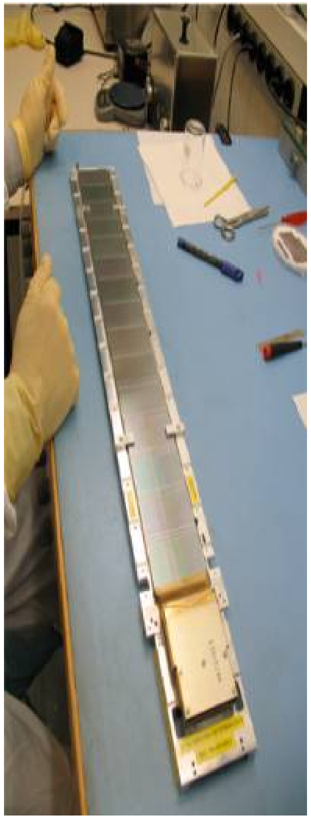
Requirements in Space

- Large Area to cover → Tens of m^2
- Power constraint → Reduce $N_{channels}$
- Small particle flux → Large channel size
- Radiation Tolerance

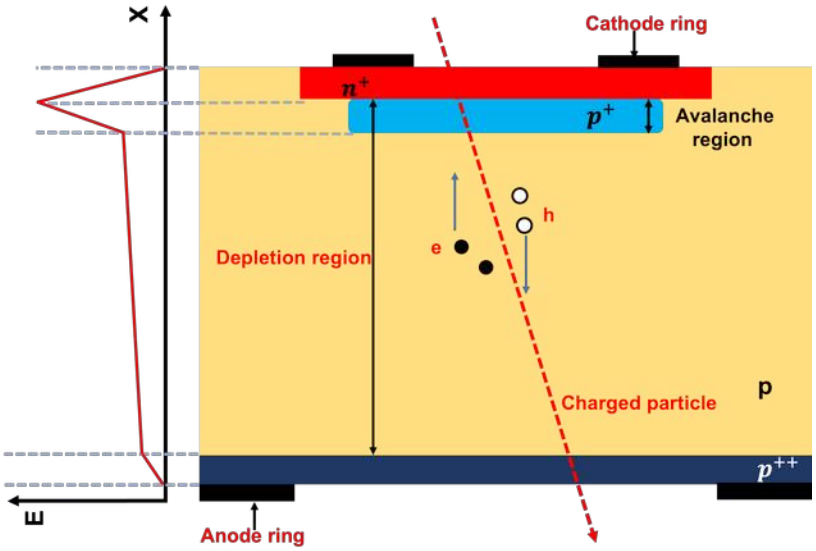
"Silicon ladder" (right)

- Strip geometry
- 60-100 cm long
- 100-200 um pitch

→ Channel size $O(1\ cm^2)$



Low Gain Avalanche Diode (LGAD)



Cross section of a LGAD with the electric field strength [3]

$$i_S = -\frac{dQ}{dt} = q\,\vec{E}_w\,\vec{v}$$

- Silicon detector with charge multiplication
- Gain layer provides high-field region O(10)
- Improved SNR
- Excellent radiation hardness > 10^{15} neq/cm^2
- Time resolution O(30 ps) [2]
- Typical channel area 1-2 mm^2 for High Energy Physics

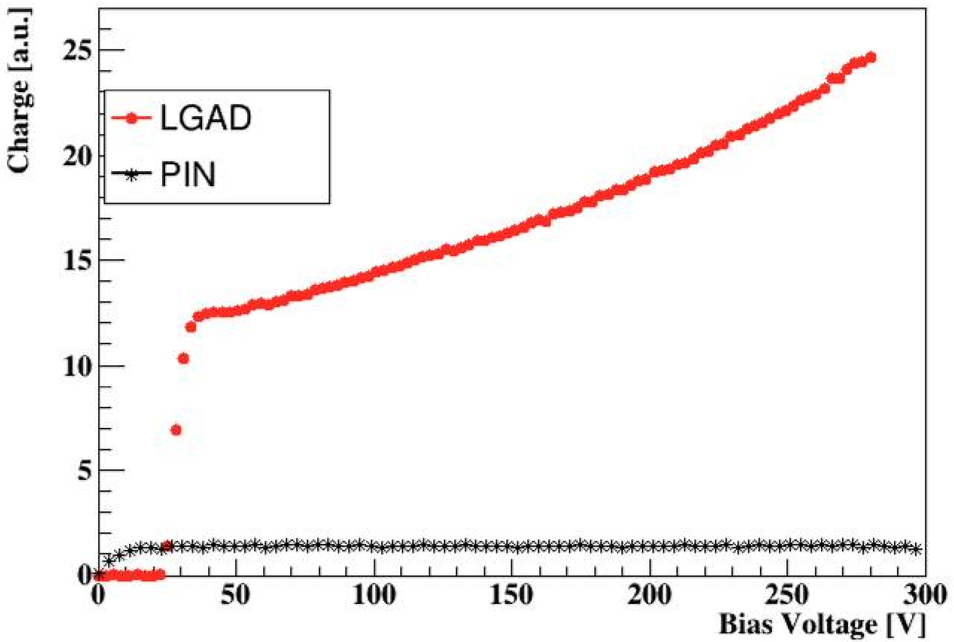
→ Are selected for the precision timing detectors of the ATLAS and CMS experiments during the High Luminosity phase of LHC

Figures of Merit: Gain

Gain: is the ratio of charge obtained from a LGAD with respect to an equivalent PIN diode

$$Gain = \frac{Ch_{LGAD}[fC]}{Ch_{PIN}[fC]}$$

We want to detect a signal and process it with electronics



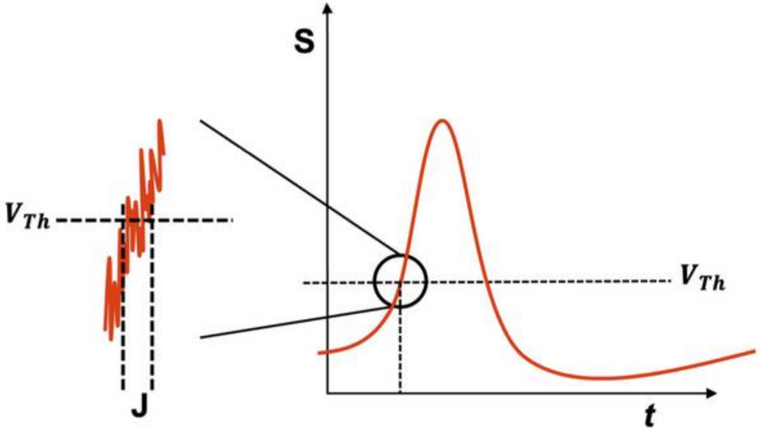
Figures of Merit: Time Resolution

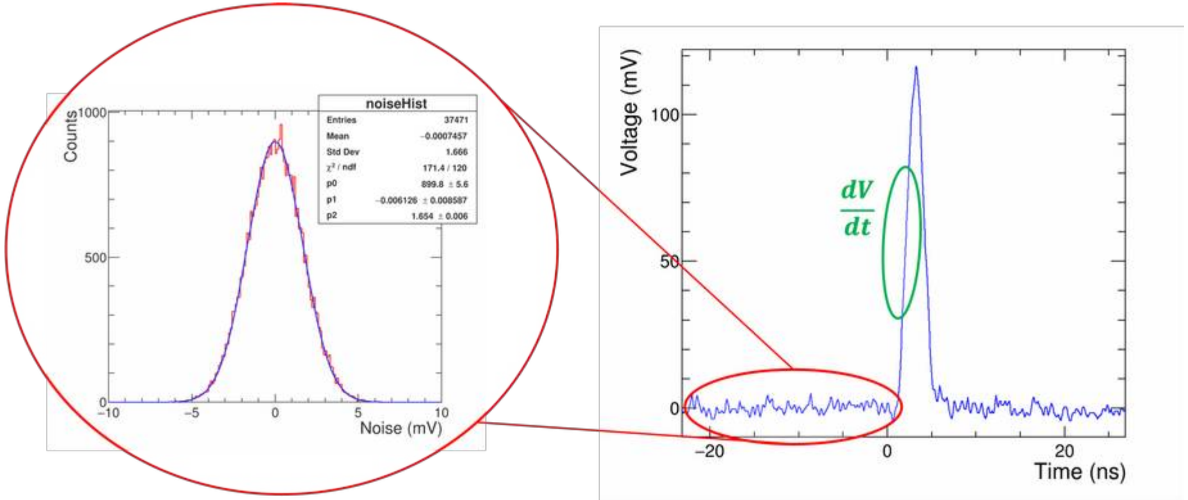
$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{jitter}^2 + \sigma_{timewalk}^2$$

$$\sigma_{jitter} = \frac{N}{dV/dt} = \frac{t_{rise}}{(S/N)}$$

$$\sigma_{timewalk} = [\frac{V_{th}}{S/t_{rise}}]_{RMS} \propto [\frac{N}{dV/dt}]_{RMS}$$

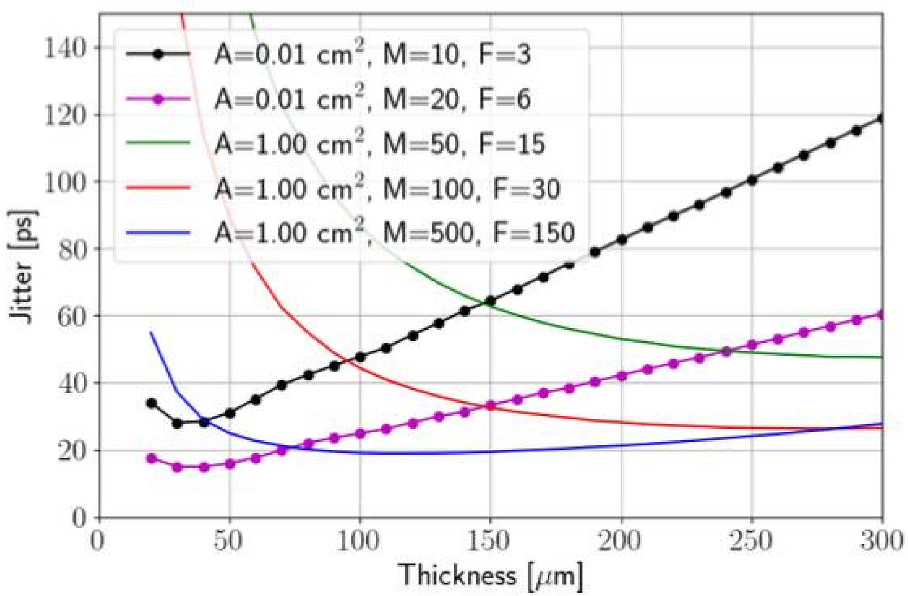
S = Signal
N = Noise
dV/dt = Slew Rate
t_{rise} = RiseTime of signal
V_{th} = Threshold voltage to determine the Time of Arrival





Time-walk may be corrected with some clever signal analysis.
Landau contribution is present only with real Minimum Ionizing Particles
Jitter must be evaluated

Signal formation simulations in LGADs



Working point is set between 100 and 150 um, aiming for a gain of 100

Assumptions [4]:

- The initial ionization is assumed to be uniform along the sensor thickness and it is given by the deposited charge of a MIP.
- The deposited charge increases with the thickness.
- Saturated drift velocity for the carriers.
- The excess noise factor (F) scales with the gain (M).
- Noise contribution from the sensor is restricted to shot noise
- Noise of the electronics is constant.
- Signal is shaped by the e RC of capacitance of the sensor and the resistance of the readout.
- Jitter calculated as noise over slew rate.

Black and **pink** markers are for the go-to technology in High Energy Physics experiments

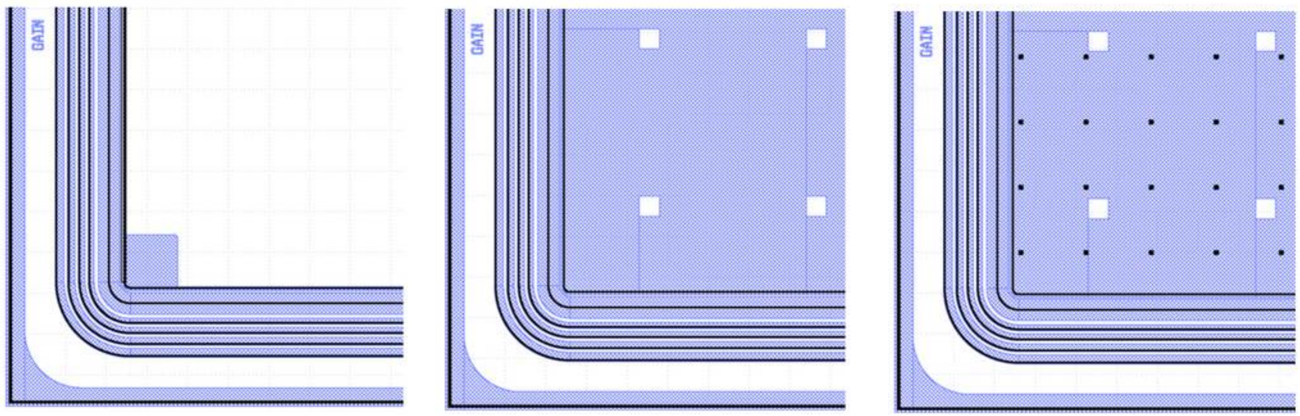
SLAPP: Space LGADs for AstroParticle Physics

	State of the art LGAD technology	Space-LGADs' goal
Area	1 mm^2	$\leq$ 100 mm^2
Time Resolution	O(10 ps)	< 100 ps
Gain	~20	~100

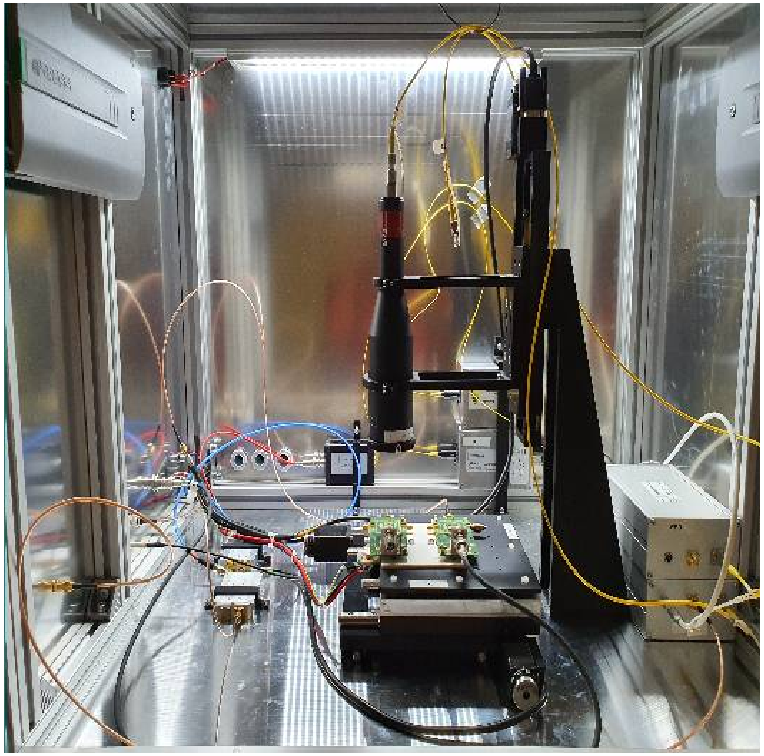
Scaling up the LGADs is the first step

Pad Types

- **Type 1**: Metal Frame (left)
- **Type 2**: Fully Metallized, Contacts at the edge of the active area (center)
- **Type 3**: Fully Metallized, Contacts covers all active area (right)



Experimental Methods: Transient Current Technique (TCT)



Particulars Large Scanning TCT setup [5]

- Infra-Red (1060 nm)pulsed laser (1 kHz)
- X/Y translation stage 0.8 um precision)
- Calibration of the laser power at 1 Minimum Ionizing Particle (MIP)
- Sensor can be biased both from the top and from the bottom
- 16-ch Fermilab Board [6]

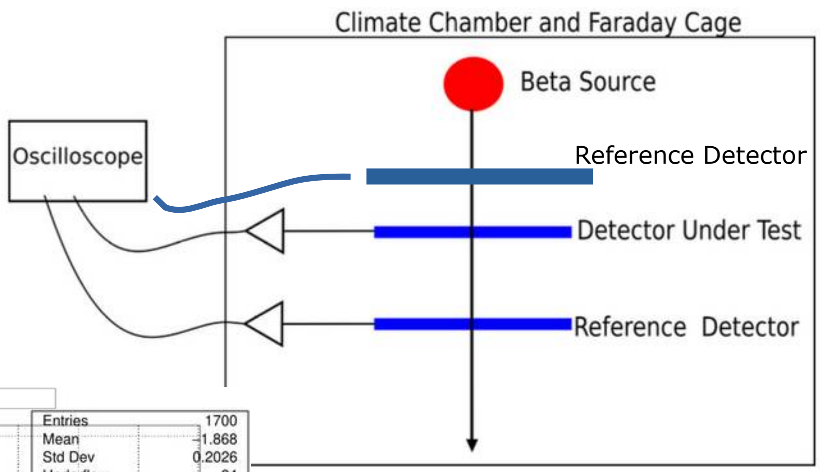
Experimental Methods: Radioactive Source

Radioactive Source: 90Sr

DUT is mounted on a passive PCB

The trigger is given by the coincidence of the two Reference Detectors.

Temperature = 20 C

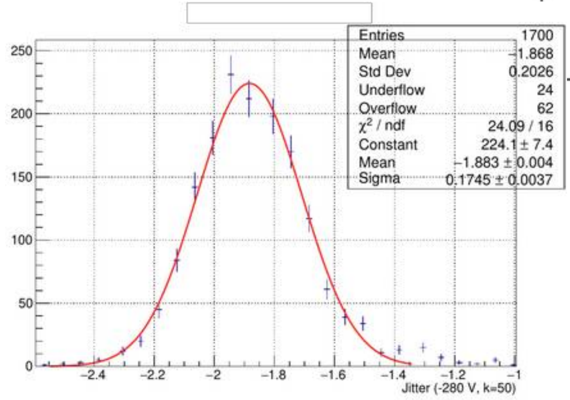


Time resolution of the detectors [7]

$$\sigma_1 = \left(\frac{1}{2}\left(\sigma_{21}^2 + \sigma_{13}^2 - \sigma_{32}^2\right)\right)^{\frac{1}{2}}, \quad \sigma_2 = \left(\frac{1}{2}\left(\sigma_{21}^2 - \sigma_{13}^2 + \sigma_{32}^2\right)\right)^{\frac{1}{2}},$$

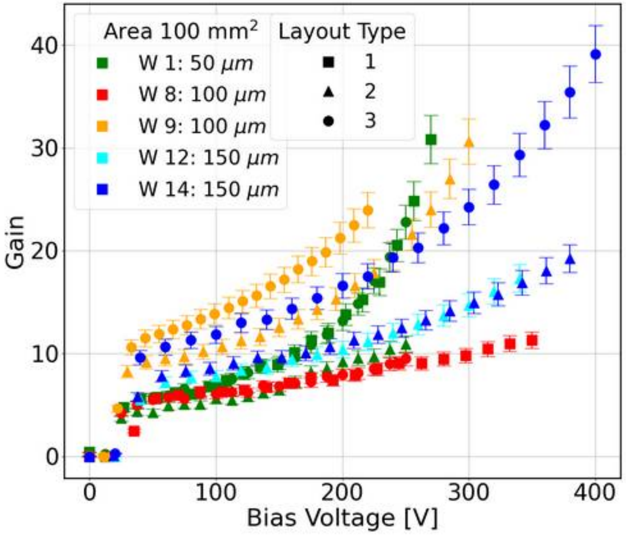
$$\sigma_3 = \left(\frac{1}{2}\left(-\sigma_{21}^2 + \sigma_{13}^2 + \sigma_{32}^2\right)\right)^{\frac{1}{2}}$$

σ_{ij} = Standard deviation of the gaussian fitting at best the time difference between two signals

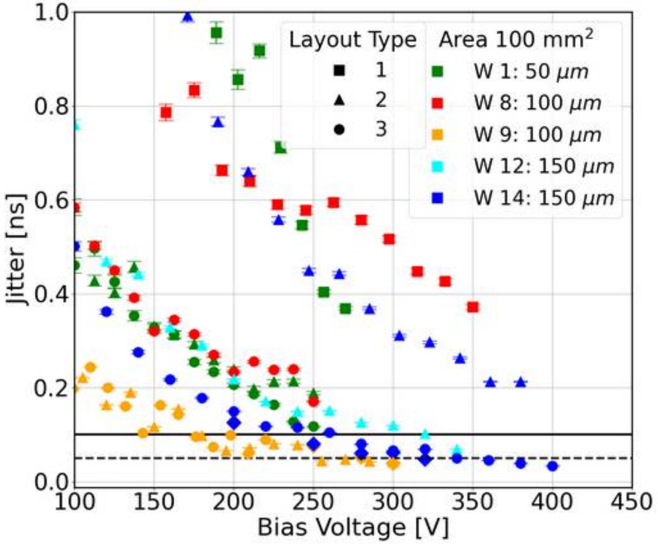


the EP-DT-SSD laboratories at CERN

SLAPP Performances: TCT



Gain between 20 and 30



Black solid and dashed line represent 100 and 50 ps threshold respectively

[4] Laser power tuned to produce 1 MIP equivalent charge

Type 1: Metal Frame

Type 2: Fully Metallized, Contacts at the edge of the active area

Type 3: Fully Metallized, Contacts covers all active area

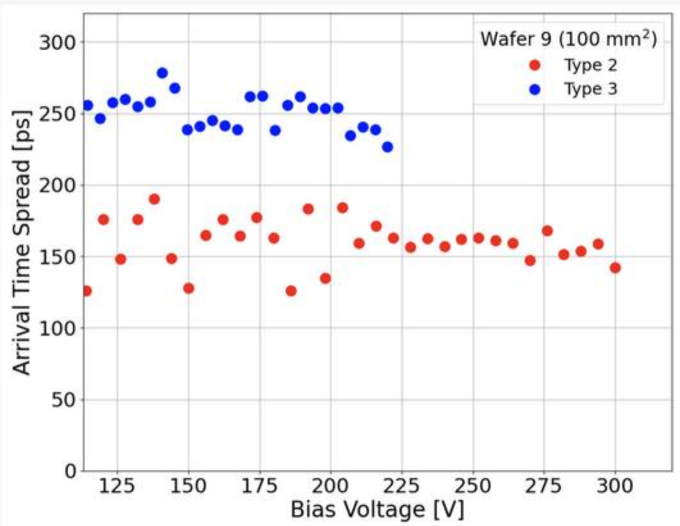
Wafer 9 and **Wafer 14** display a comparable jitter albeit at different bias voltage

☺ Jitter ~ 40 ps for 1 cm² sensor

SLAPP Performances: Uniformity

Goal: quantify the uniformity of the signal response related to the difference in the propagation time.

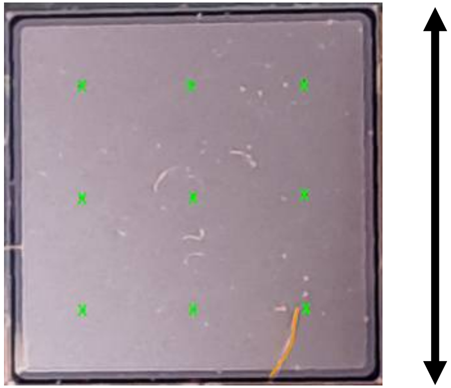
Plot of the maximum dispersion of the arrival time for two sensors of same area and thickness [4].



Type 2: Fully Metallized, Contacts at the edge of the active area

Type 3: Fully Metallized, Contacts covers all active area

Laser illuminates the sample through the different apertures.



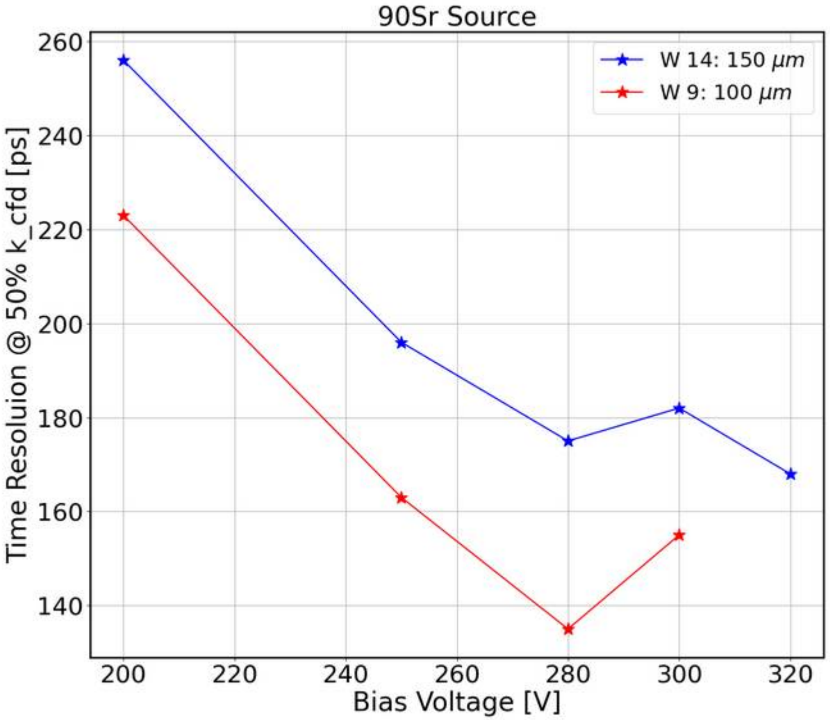
1.1 cm

Supposing a uniform distribution of events on the sensor

$\sigma_{uniformity} = 153/\sqrt{12}$ ps = 44 ps

$\boldsymbol{\sigma_{laser} = \sqrt{(\sigma_{uniformity}^2 + \sigma_{jitter}^2)} \sim 60}$ **ps**

SLAPP Performances: Radioactive source



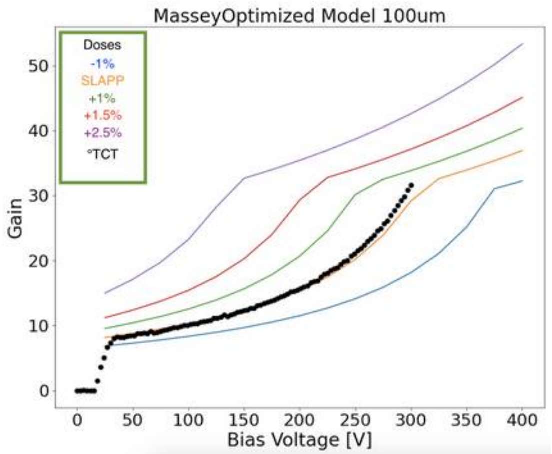
Different electronics compared to previous results. Might lead to a worsening of the time resolution.

Landau contribution

Contribution of the $\sigma_{uniformity}$

Work in progress to disentangle the various contributions

What is next?   SLAPP-2

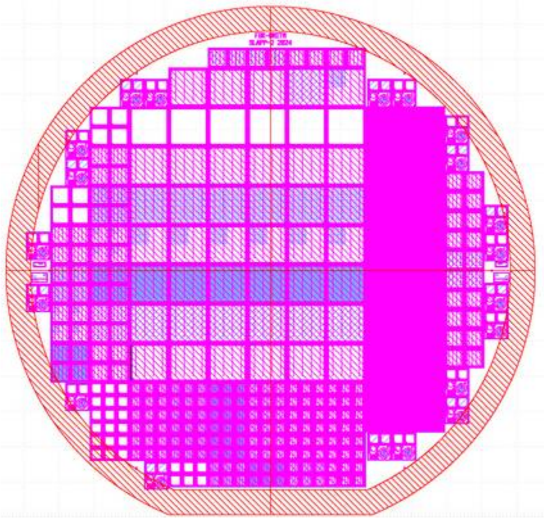


Simulations of the performance of the new batch: gain layer dose variation to improve the gain of the production

Design of the SLAPP-2 batch.

Objectives:

- Improve the gain of the large area LGAD
- Study the signal propagation within the detectors’ layers
- Improve the overall timing capabilities



Wafer Number	Thickness [um]
1-8	100
9-16	150

Production ongoing in FBK, soon available for testing

Summary

Objective:
Demonstrate that it is possible to have LGADs with active area in O(1 cm^2) and time resolution smaller than 100 ps .

Results:

- LGADs with area 1 cm^2 and thickness 50 um, 100 um, 150 um were produced.
- Sensors present a gain up to 40.
- Sensors display a time resolution σ ~ 60 ps when illuminated with a laser.
- Sensors have a time resolution that goes below 150 ps for MIPs.

Next step:
1) More sensors with large area will be tested with the new production.
2) LGAD Strips?

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[1] Duranti, M.; Vagelli, V.; Ambrosi, G.; Barbanera, M.; Bertucci, B.; Catanzani, E.; Donnini, F.; Faldi, F.; Formato, V.; Graziani, M.; et al. Advantages and Requirements in Time Resolving Tracking for Astroparticle Experiments in Space. Instruments 2021, 5, 20. http://dx.doi.org/10.3390/instruments5020020

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[3] Kramberger, G.; Carulla, M.; Cavallaro, E.; Cindro, V.; Flores, D.; Galloway, Z.; Grinstein, S.; Hidalgo, S.; Fadeyev, V.; Lange, J.; et al. Radiation hardness of thin Low Gain Avalanche Detectors. Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 2018, 891, 68–77. http://dx.doi.org/10.1016/j.nima.2018.02.018

[4] Bisht, A.; Cavazzini, L.; Centis Vignali, M.; Caso, F.; Hammad Ali, O.; Ficorella, F.; Boscardin, M.; Paternoster, G. Jitter Measurements of 1 cm^2 LGADs for Space Experiments. Instruments 2024, 8, 27. https://doi.org/10.3390/instruments8020027

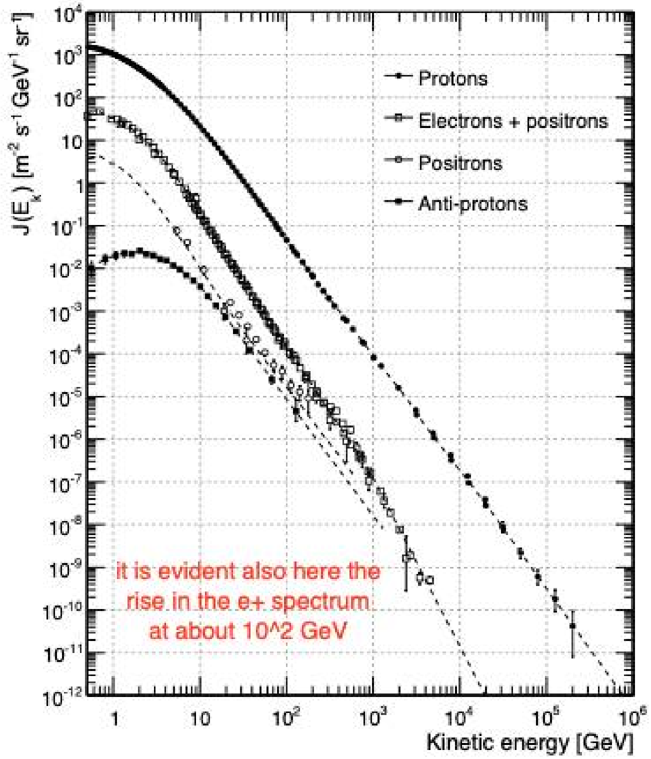
[5] Large Scanning TCT Setup, Particulars. Available online: http://particulars.si/index.php

[6] Heller, R.; Abreu, A.; Apresyan, A.; Arcidiacono, R.; Cartiglia, N.; DiPetrillo, K.; Ferrero, M.; Hussain, M.; Lazarovitz, M.; Lee, H.; et al. Combined analysis of HPK 3.1 LGADs using a proton beam, beta source, and probe station towards establishing high volume quality control. NIMA 2021, 1018, 165828. http://dx.doi.org/10.1016/j.nima.2021.165828

[7] McKarris, P.; Centis Vignali, M.; and Wiehe, M.; Commissioning of a Beta Setup for Time Resolution Measurements. https://cds.cern.ch/record/2688012/files/commissioning_of_a_beta_setup_for_time_resolution_measurements_Paul_McKarris.pdf

EXTRAS

Objectives of the Research: Cosmic Rays



Baldini L. https://doi.org/10.48550/arXiv.1407.7631

General
Cosmic Rays (CR) are extraterrestrial ionizing radiation whose energy spans over 12 orders of magnitude

Due to small flux above that energy, the CRs in space are studied up to 10^6 GeV

Even though they were discovered 100 yrs ago, CRs’ science is not solved

Properties

- Can be charged (CCRs)
- Protons are the most abundant particles in the spectrum
- Extra Galactic Background
- Further complications due to the Earth-Sun environment

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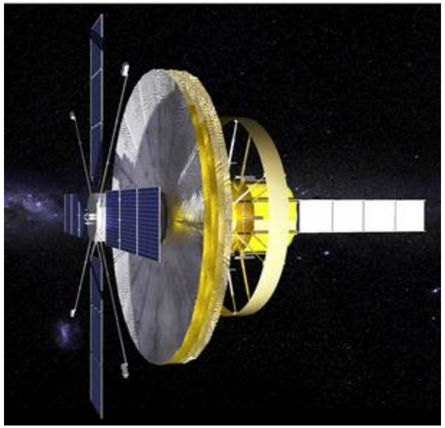
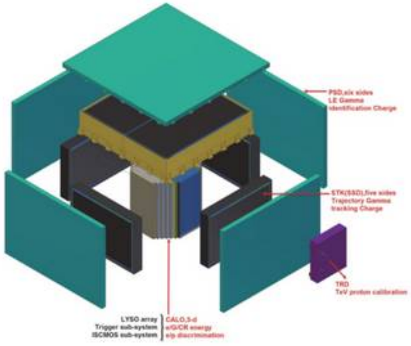
Context: The Missions

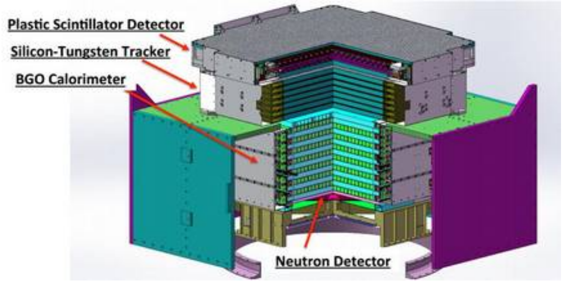
AMS-100



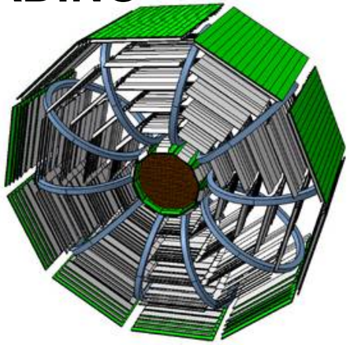
HERD



DAMPE



ALADINO



Cosmic Rays Science in Space:

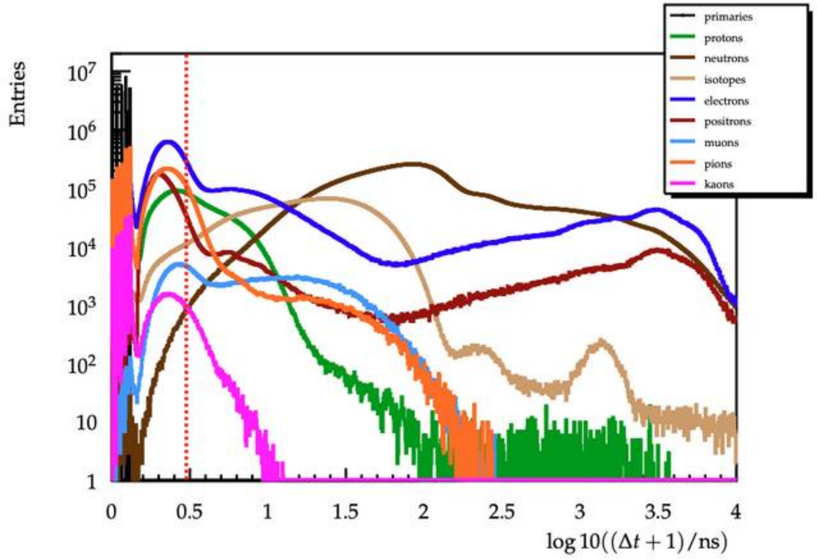
- Fundamental Physics
- Matter-antimatter Symmetry
- Dark Matter

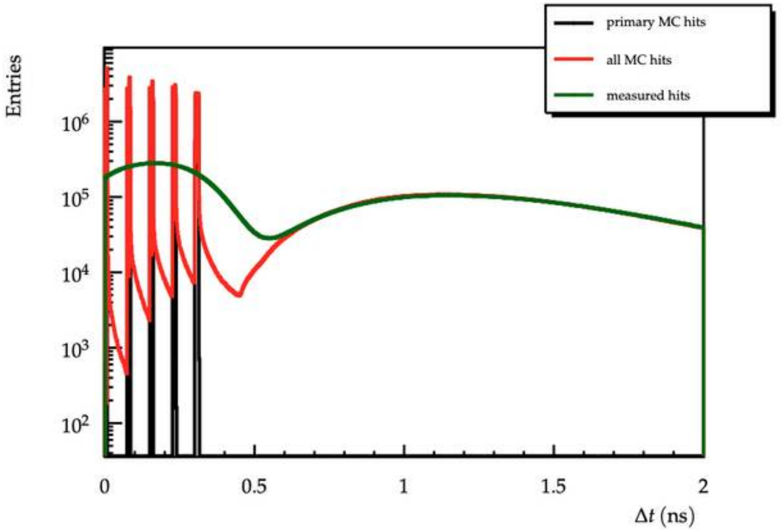
Spectrometric experiments to measure the rigidity of the particles (AMS, PAMELA)

Calorimetric experiments to measure the energy (HERD, DAMPE)

Improve the tracking capability for future missions

Observation simulations

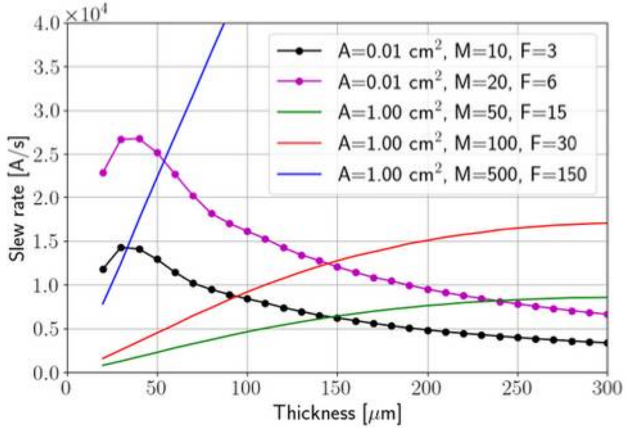


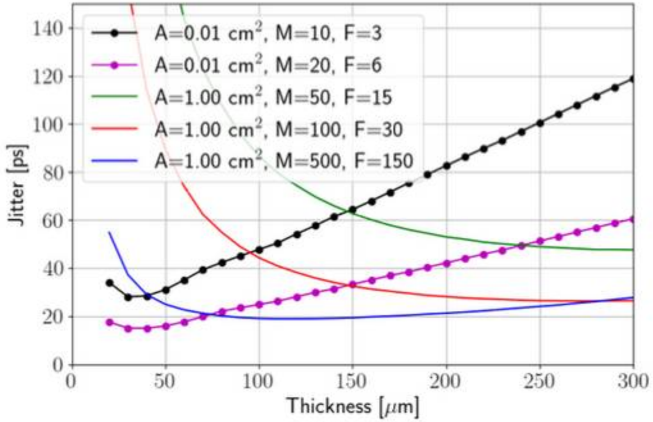


[Matteo Duranti et al. Instruments 5.2 (2021)]

Figure 3. (Left): Distributions of the true arrival time in the tracker sensors of primary 1 TeV protons (black) and of the secondary particles generated by interactions of the primary protons with the detector materials. Each entry represents the timing information associated to one hit in the tracker. A dashed vertical red line indicates a delay, from the first primary hit, of 2 ns, that is the time range in the figure on the right. (Right): for the same events, the inclusive distribution of true arrival times (red) with the superimposed distribution of measurements assuming a timing resolution of ~100 ps (green). The distributions are obtained out of ~5 million generated events. In the distributions, we consider “hits” all the energy depositions in the sensitive volumes above a certain threshold (~10 keV, that represents the amount of ionization energy deposit resulting in a readout signal comparable to the typical FEE noise), also including energy depositions different from ionization.

Timing simulations



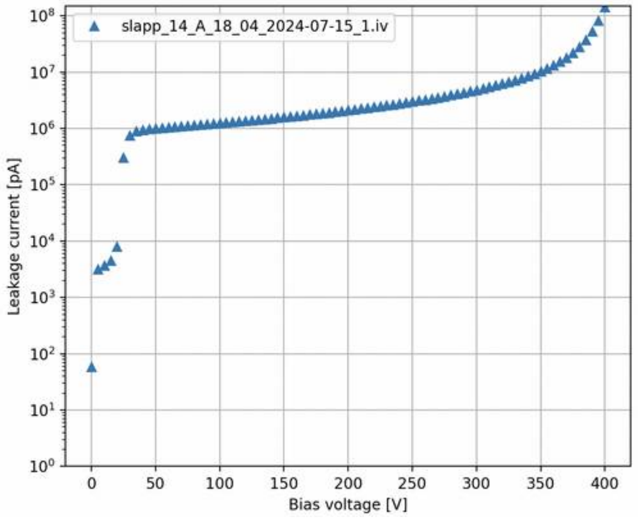


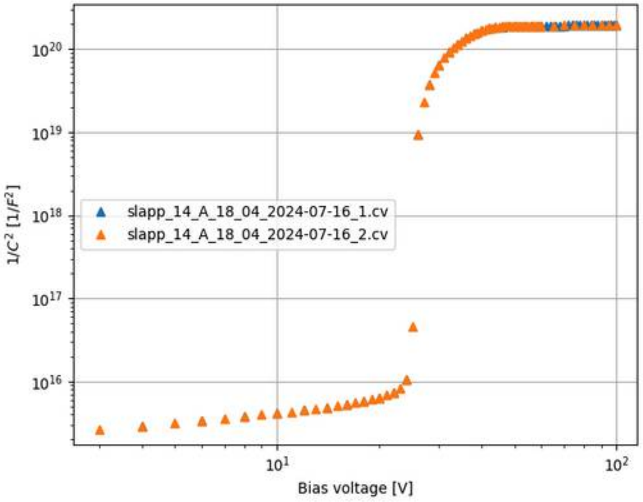
Simulations are assuming the drift velocity of the carriers to be saturated.
As a consequence the higher the thickness the higher the required bias voltage

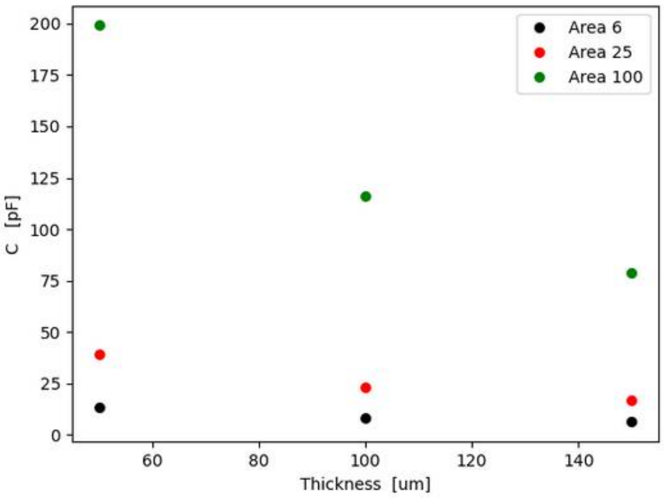
After a certain point, see the blue line in figure, the gain (M) leads to a decrement of the jitter because of the excess noise (F).

Black and **pink** dots are for the go-to technology in High Energy Physics experiments

Electrical Characterization







Operational parameters
Breakdown voltage

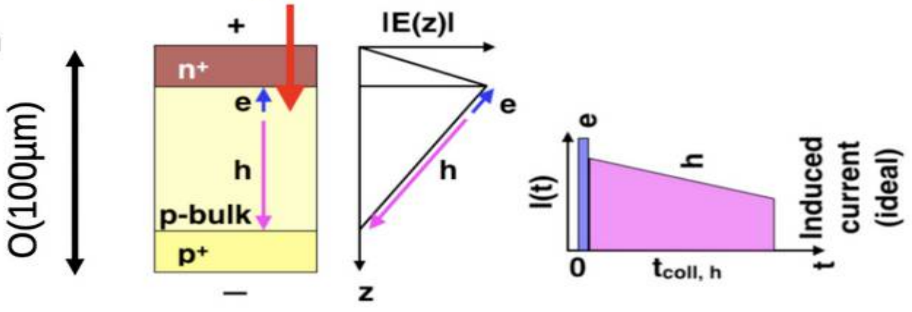
Gain Layer depletion voltage is 24.6 V
Full depletion voltage is 47.2 V
Capacitance at full depletion 85 pF

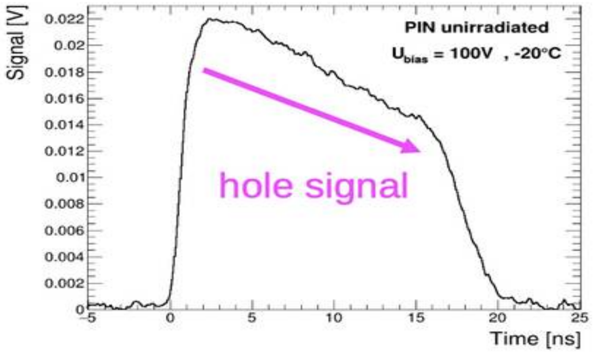
C ≈ Area/Thickness

It will shape the output signal

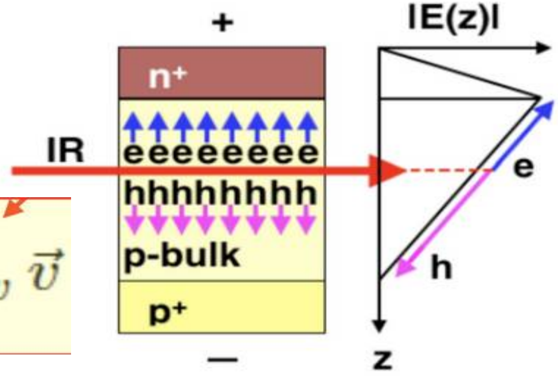
Methods: Transient Current Technique (TCT)

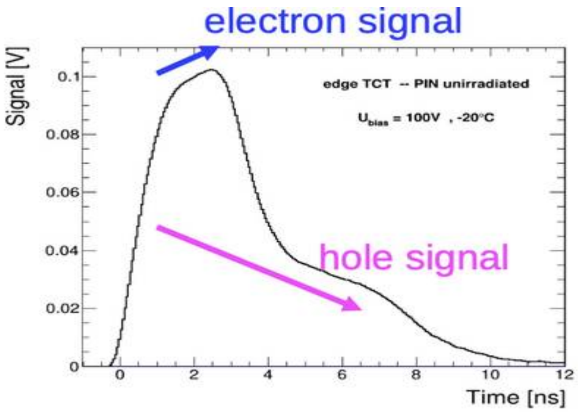
Red 660nm





Near IR 1064nm
edge-TCT

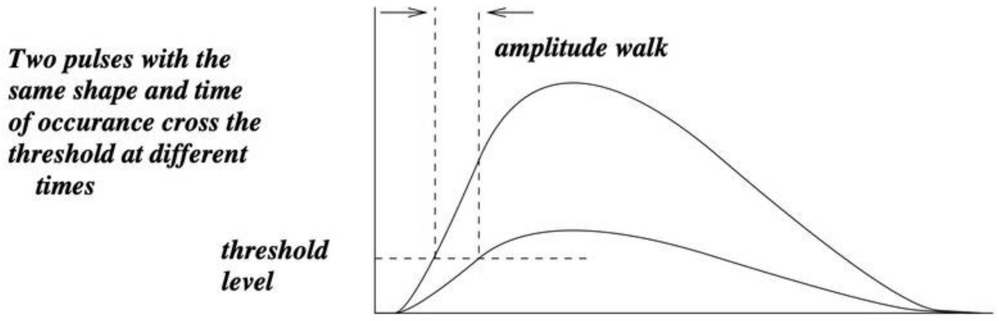




$$i_S = -\frac{dQ}{dt} = q\,\vec{E}_w\,\vec{v}$$

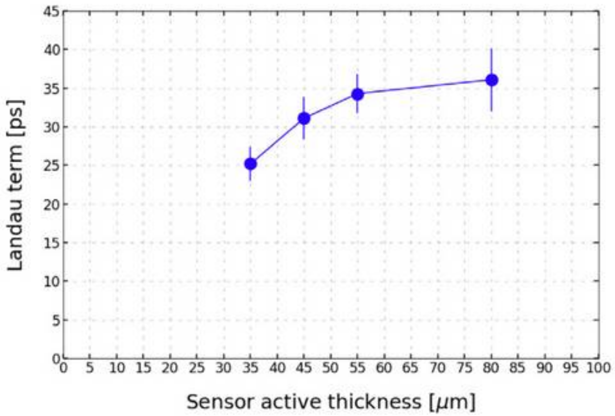
DT seminar: M. Fernández, The Transient Current Technique: laser characterization of silicon detectors
C. Gallrapp, The TCT+ setup - a system for TCT, eTCT and timing measurements, 1st TCT Workshop (2015)

Figures of Merit: Time Resolution



At the same time, a different shaping results in the same delay.
A Constant Fraction Discrimination imposes a “dynamic” threshold that removes this effect.

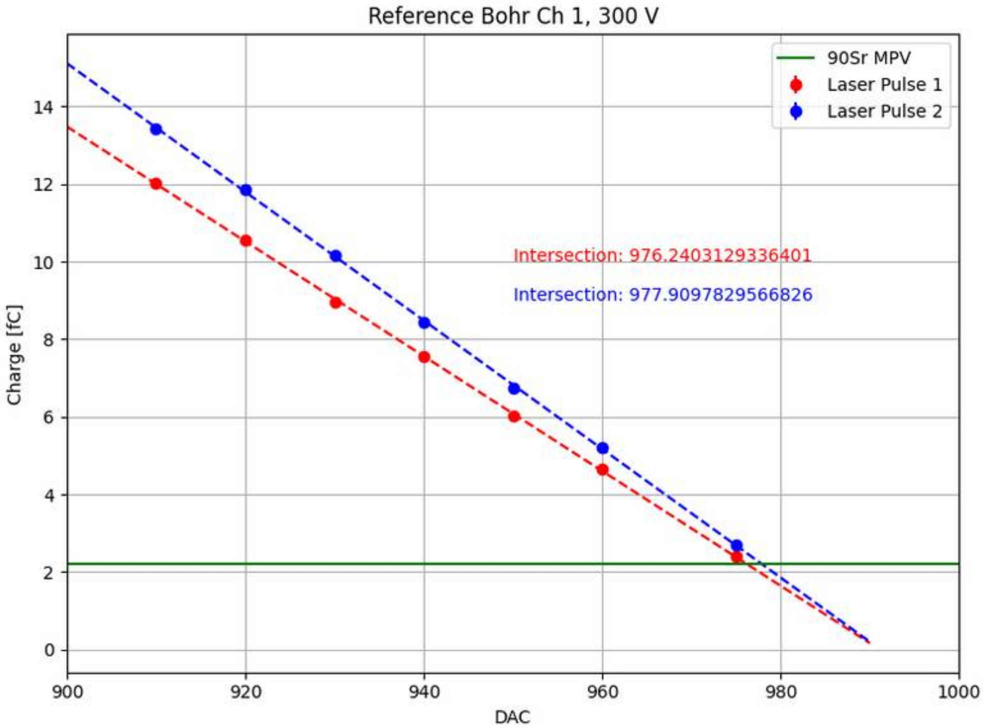
The non-uniform energy deposition generated by an impinging MIP, amplified by the gain, creates variations of the signal shape on an event-to-event basis



https://doi.org/10.1016/j.nima.2022.166739000

Calibration of the Laser Power

The same sample is analyzed with the radioactive source and with the laser.
The laser power is modulated with the DAC.
Comparing the collected charge is obtained the value of DAC that results in a laser power equivalent to 1 MIP



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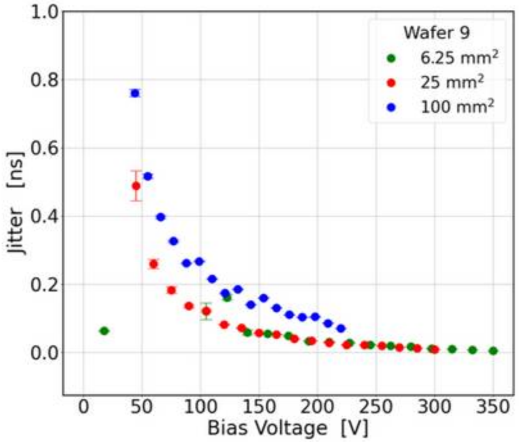
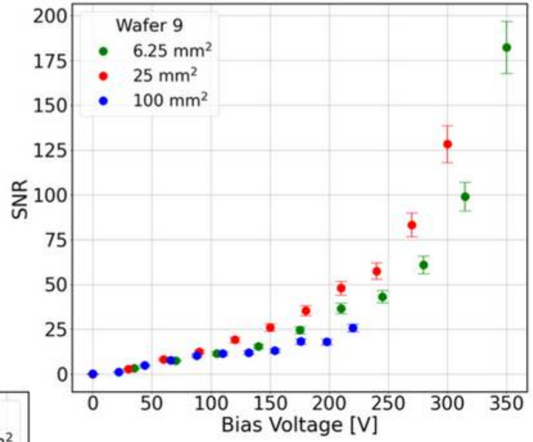
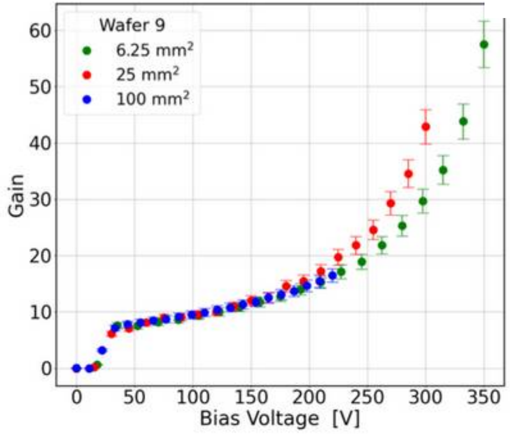
SLAPP Performances: TCT

Testing
smaller areas

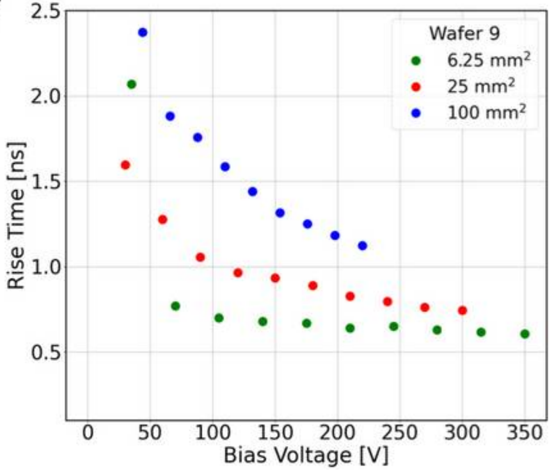
Gain < 60
for an LGAD
6.25 mm²





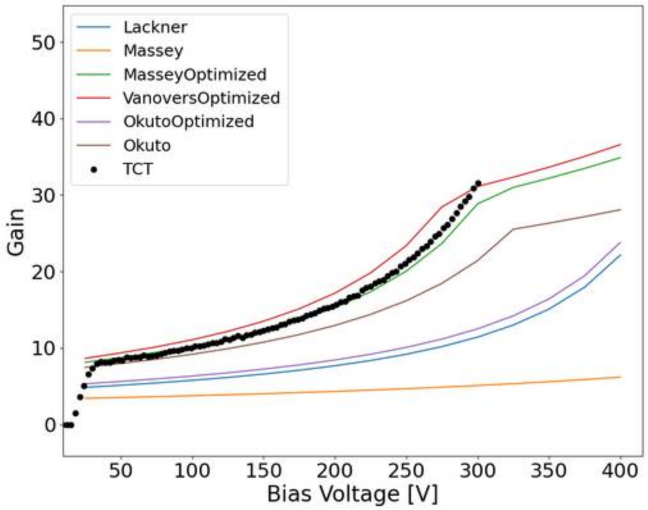


$\sigma_{Jitter} \approx$ 20 ps
for an LGAD
6.25 mm²

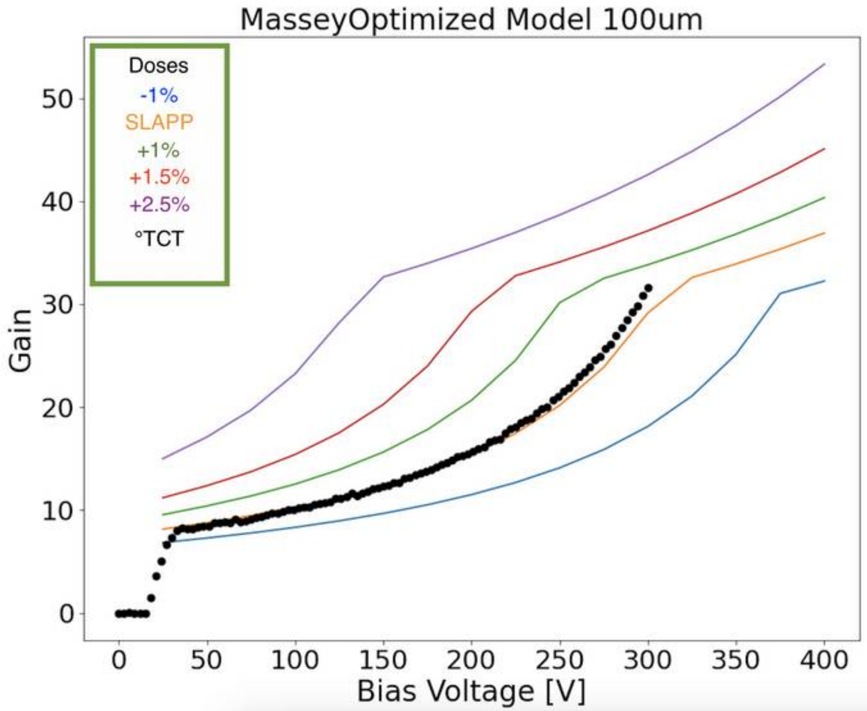


The next step: SLAPP-2 Simulation

Use of Tcad to construct 1D model of a LGAD and test different impact ionization models to match the measurements



Gain layer dose variation to improve the gain of the production



The next step: SLAPP-2 Simulation