Development of LGADs for the 4D tracking of charged particles in Space Experiments

Ashish Bisht, G. Borghi, M. Boscardin, L. Cavazzini,
M. Centis Vignali, O. Hammad Ali, F. Ficorella. G. Paternoster

UNIVERSITY OF TRENTO

Astro Particle Physics - Laboratory

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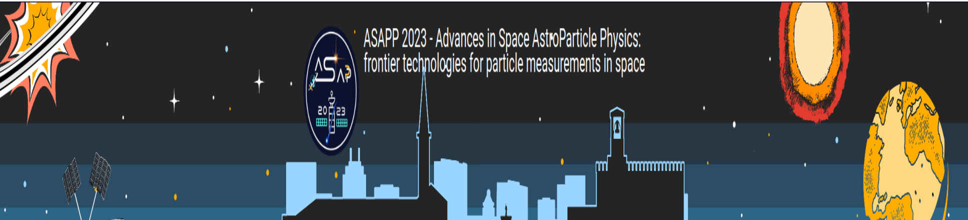
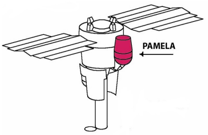
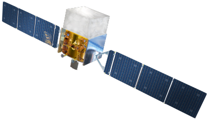
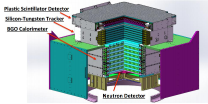








- Discrimination of charged particles
  → Magnetic spectrometers
- Tracking planes based on Silicon μ-strip detectors
- Magnetic field used to bend the trajectory
  → reconstruct momentum and particle charge

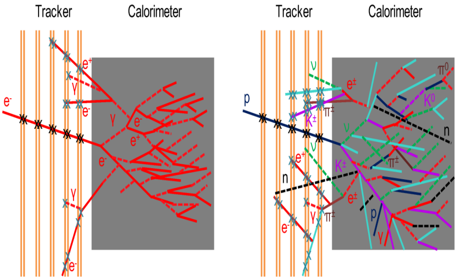
- γ-rays measurements
- High-density material is used for pair production
- Tracking planes are inserted between the conversion foils
- Tracking planes based on Silicon μ-strip detectors
  → reconstruct the vertex of the incoming photon and its direction.

Future missions → HERD, ALADINO, AMS-100

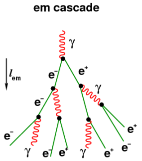
Objective → probe higher energy cosmic rays, improved sensitivity

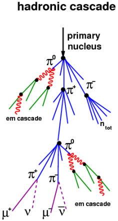
Time resolving tracking in space experiments

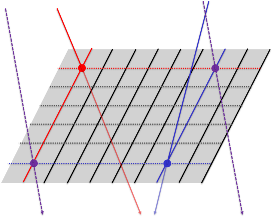
- Identification of back-scattered hits from calorimeters
- Ghost hits in “Si-MicroStrip” detectors
- Time-of-flight (ToF) measurement
- Improved e/p identification



$$\frac{\delta M}{M} = \frac{\delta p}{p} \bigoplus \gamma^2 \left(\frac{\delta\beta}{\beta}\right)$$





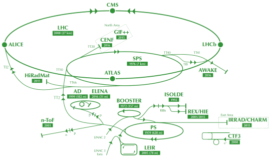


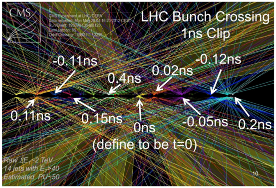
- d and anti-d
- ^{3}He/^{4}He

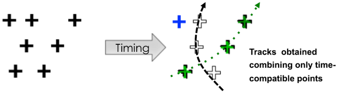
Matteo Duranti et al. Instruments 5.2 (2021)

4D tracking

4D tracking is referred to assigning a space and a time coordinate to a hit







H. Sadrozinski et al. Rept. Prog. Phys. 81 (2018) 026101

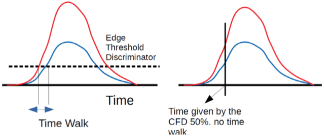
Timing for event reconstruction:

- Dedicated timing layer in a single point
- Timing at some points along the track
- Timing at each point along the track

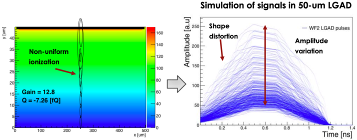
Is it possible to build a detector with excellent time and position resolution?
→ Spatial resolution [10's of μm] + timing resolution [∼ 10 ps]

Time resolution of time tagging detectors

$$\sigma_t^2 = \sigma_{\text{timewalk}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Jitter}}^2$$

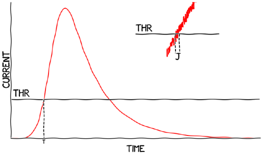


- **Time walk:**
  → minimized by using Constant Fraction Discriminator (CFD) for time reference



N. Cartiglia et al. PSD12 (2021)

- **Landau noise:** non-uniformity in the energy deposited per unit length
  → reduced for **thinner sensors** (50, 35 µm)

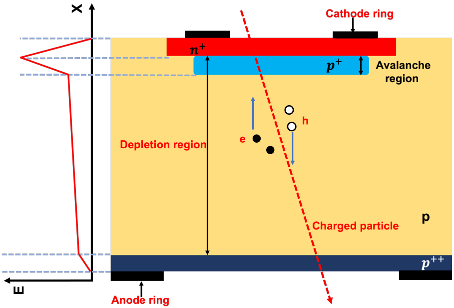


- **TDC:** resolution of the TDC (bin/$\sqrt{12}$)

- **Jitter:** proportional to $\sigma_N / \frac{dV}{dt}$
  → reduced by increasing SNR with gain.

$$\sigma_j = \sigma_n / \frac{dI}{dt}$$

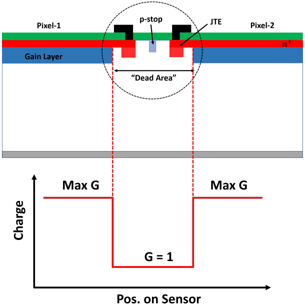
Low Gain Avalanche Detector (LGAD)



- Silicon detectors with charge multiplication
- Gain layer provides a high-field region
- Radiation hard (10^{15} neq/cm^2)
- Low Noise (low shot noise)

- Improved SNR: 5-10 times better than current PIN detectors
- Good timing resolution:
  $\sigma_t = 30$ ps $\rightarrow$ 50 μm thick LGADs (1.3×1.3 mm^2)
- No-gain region $\sim$ 30-80 μm
  A. Bisht et. el., Characterization of Novel trench-isolated LGADs for 4D tracking
  $\rightarrow$ No-gain region $\sim$ 3 μm

LGADs: segmentation issue



- Segmentation in LGADs:
  - Junction Termination Extensions (JTEs)
  - p-Stop, and virtual Guard-Rings
- Pixel border is a dead region.
- The no-gain width depends on:
  - technology (photolithography) constraints
  - physical limits (maximum E fields) to fulfill operational requirements (VBD)
- Intrinsic limit in reducing the inter-pad region (*Early edge breakdown*).

$$\text{Standard LGADs} \rightarrow \begin{cases} \text{Good timing resolution} \\ \text{Poor spatial resolution} \end{cases}$$

LGADs: Fill Factor

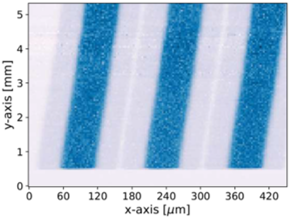
$$\text{Fill Factor} = \text{Area}_{\text{gain}} / \text{Area}_{\text{total}}$$

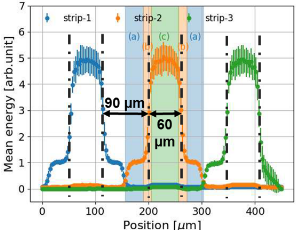
Measurements with a micro-focused X-ray beam (width $\sim 2\ \mu m$, 20 keV)

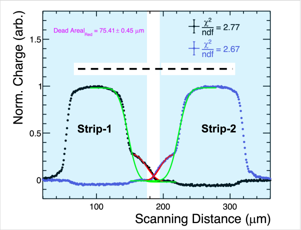
- LGAD μ-strip sensor (146 μm pitch)
- Nominal gain region: 80 $\mu m \rightarrow$ Nominal FF: 55%
- Measured FF: 40%

Measurements with a pulsed laser.

- 180 μm pitch
- Nominal FF: 63%
- Measured FF: 58%

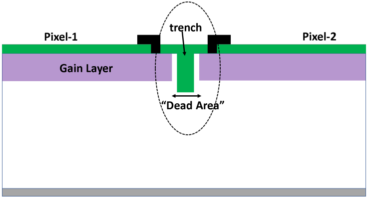


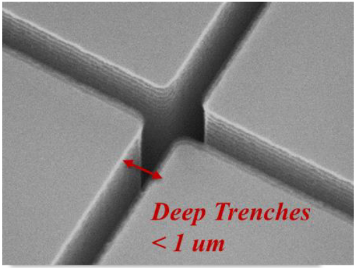




M. Andrä et al., "Development of low-energy X-ray detectors using LGAD sensors"

Fill Factor: solution?





- New LGAD technology :
  - **JTE and p-stop → trench**
  - Trenches → drift/diffusion barrier
- Dead region is significantly reduced
- The trenches are < 1 µm wide and few microns deep.
- Trenches are filled with SiO_2

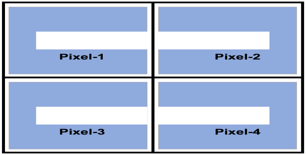
$$\mathrm{TI-LGADs} \rightarrow \begin{cases} \text{Good timing resolution} \\ \text{Smaller gain -- loss region} \\ \text{Improved spatial resolution} \end{cases}$$

New batch fabricated under the RD50 collaboration

G. Paternoster et al., "Trench-Isolated Low Gain Avalanche Diodes"

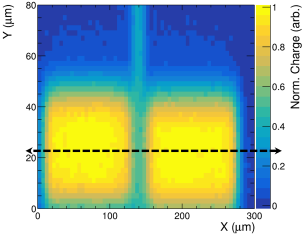
TI-LGADs: no-gain region width

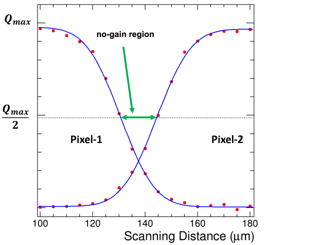
250 × 375 µm, 1 trench



250 × 375 µm, 2 trenches

charge map @ -200 V



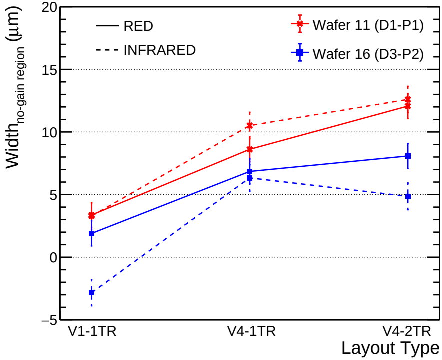


$$f(x) = \left[Erf\left(\pm\frac{x - c_1}{c_2}\right) + 1\right] \times c_3 + c_4,$$

$$Erf(x) = \frac{2}{\sqrt{\pi}} \times \int_0^x e^{-t^2} dt$$

V1-1TR, V4-1TR, V4-2TR

TI-LGADs: no-gain region width

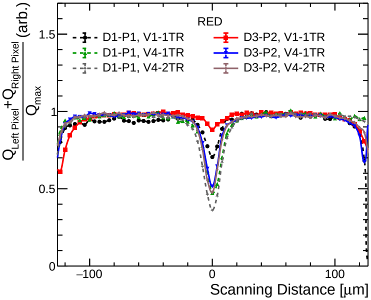


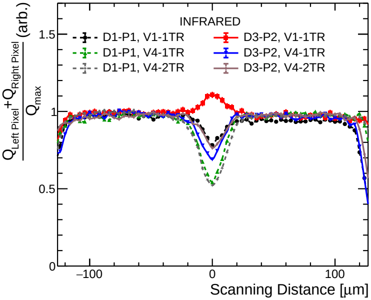
40 μm → 3 μm

- No-gain region width < 15 μm
  → Better compared to all standard LGADs
- Width of no-gain region for V1-1TR layout is less than 5 μm for both wafers
  V1-1TR → Highest Fill-Factor
- Wafer 16 has lower no-gain region width compared to wafer 11
- Red laser does not account for the change in field in the bulk due to trench

- Negative width of no-gain region is measured in W16, V1-1TR layout (See next Slide)
- Wafer 16, V4-2TR → significant reduction of no-gain region width

TI-LGADs: sum of pixel charge





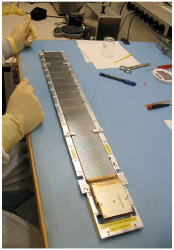
- IR Laser → W16: charge enhancement close to the trench region (higher gain) for V1-1TR, V4-2TR.
- Higher gain in trench region artificially reduces width of the no-gain region.

TI-LGADs → to achieve high FF.

Large strip sensors using TI-LGADs.

Space experiment requirements

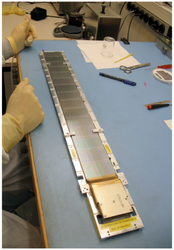
- Large area to cover $\rightarrow$ O(m^2)
- Low Earth Orbit Experiments
  $\rightarrow$ *Radiation is not an issue*
- Rate is not as high as in HEP
- Power constraint
  $\rightarrow$ *Reduce the number of channels*
- **Timing ($\sim$ 50-100 ps) is desired**



- "Typical" Silicon sensor
  $\rightarrow$ Strips (100 μm pitch)
  $\rightarrow$ 60-100 cm long
  $\rightarrow$ $\sim$ 1 cm^2

Space experiment requirements

- Large area to cover → $O(m^2)$
- Low Earth Orbit Experiments
  → *Radiation is not an issue*
- Rate is not as high as in HEP
- Power constraint
  → *Reduce the number of channels*
- **Timing (∼ 50-100 ps) is desired**



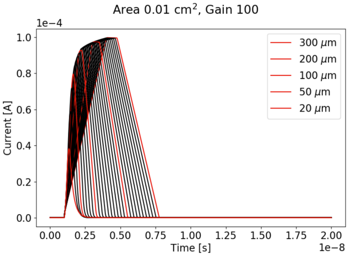
- "Typical" Silicon sensor
  → Strips (100 μm pitch)
  → 60-100 cm long
  → ∼ 1 cm^2

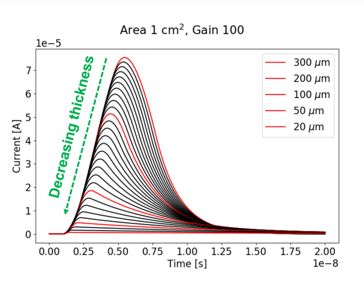
Scaling LGAD channel size to 1 cm^2

Capacitance?
Time resolution?

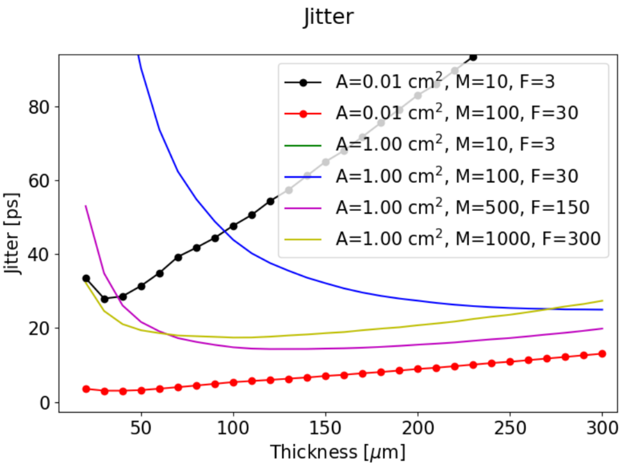
Thickness and Gain Optimization

- LTspice simulation
- Sensor capacitance
- No Landau fluctuations (uniform charge deposition)
- Saturated velocities
- Total Noise = Amplifier ⊕ Sensor





[M. Centis Vignali et al. VCI (2022)]



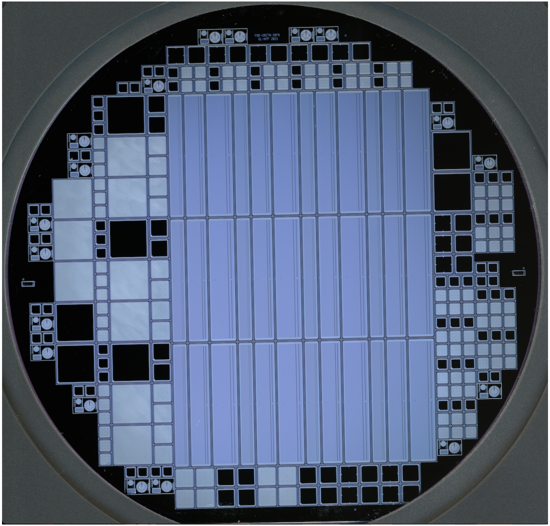
[M. Centis Vignali et al. VCI (2022)]

LGAD thickness $> 100\ \mu m$ and gain ≈ 100

Space LGADs

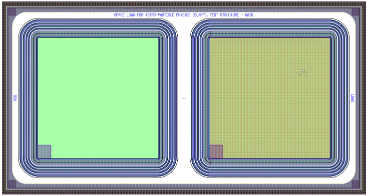
Production of new LGAD sensors under INFN project

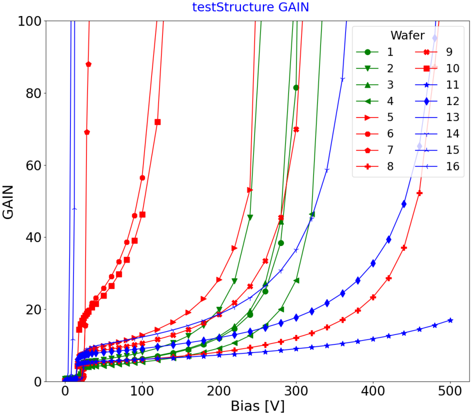
- Optimized for large areas
- Pad and strip sensors
- Strips: 100 μm, 150 μm, 200 μm pitch
- Active thickness: 50 μm, 100 μm, 150 μm thick
- Gain implant dose and energy optimized for high gain using TCAD
- Signal propagation



Gain: using IR LED

- $T = 24^{\circ}$ with illumination.
- 50 μm
- 100 μm
- 150 μm



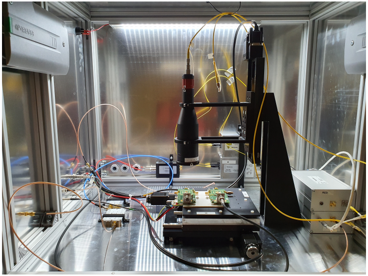


- value of gain highly depends on the dose and energy of the implant
- less steep curves for better operating voltage

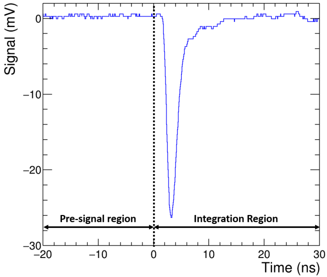
Particulars TCT setup:

- Infra-Red (1060 nm) and Red (600 nm) pulsed Laser
  → 10-15 μm spot
- X/Y translation stage (0.8 μm precision)
  → precise inter-pixel scan and DUT maps
- DAQ: 2.5 GHz, 20 GS/s
- Beam Monitor: normalization
- Collected charge is given as:

$$Q = \int_{t_0}^{t_f} I(t)dt$$



Waveform @ -200V

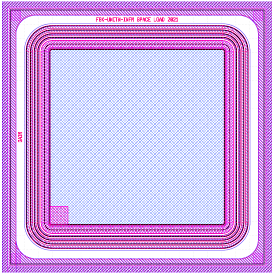


Samples investigated

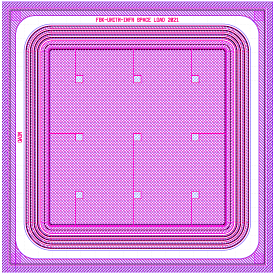
- Pad active area:
  - A (6.25 mm^2)
  - B (25 mm^2)
  - C (100 mm^2)

- Pad types:
  - **Type-0**: Metal frame
  - **Type-1**: Fully Metallized, Contacts at the edge of the active area
  - **Type-2**: Fully Metallized, Contacts covers all active area

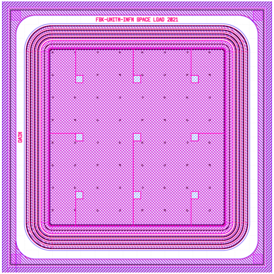
Type-0



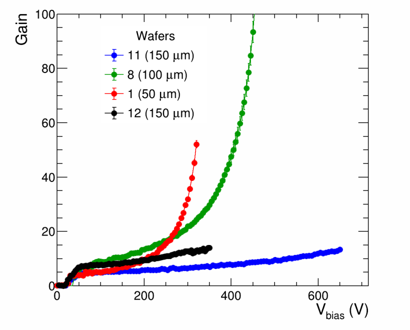
Type-1

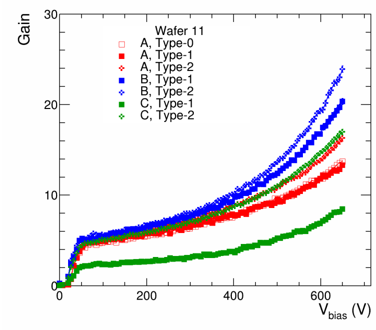


Type-2



Gain: using TCT setup





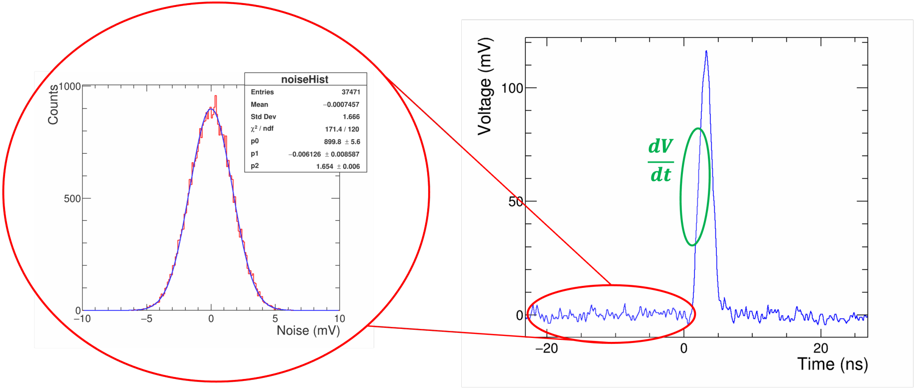
$$Gain = \frac{Charge_{LGAD}}{Charge_{PIN}}$$

- Laser Intensity: 1 MIP
- Low bias voltage: gain value is similar
- High bias voltage: gain value has a spread of about 20%
- One device show low gain values compared to others

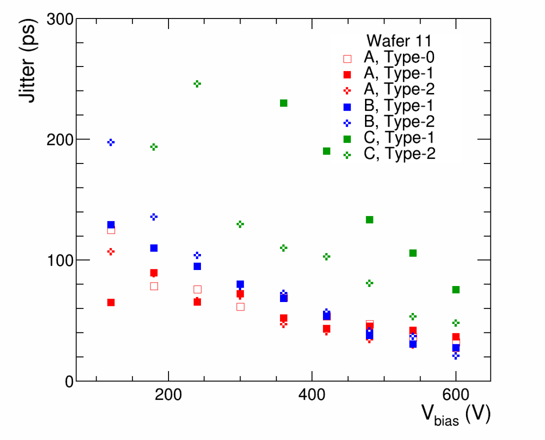
Jitter Measurements

$$\sigma_{jitter} = \frac{Noise\ (N)}{Slew\ \ rate\ (dV/dt)}$$

- Measurement (no averaging in Oscilloscope) → Noise estimation
- Measurement (256 averages in Oscilloscope) → Slew rate estimation



First Jitter measurements of 1 cm^2 LGADs



- Laser intensity: 1 MIP
- substrate thickness: 150 μm
- pad sizes:
  - A (6.25 mm^2)
  - B (25 mm^2)
  - C (100 mm^2)
- Metallization:
  - □ metal frame
  - ■ fully metallized
  - fully metallized + contact openings

σ_{Jitter} < **50 ps for an LGAD 1 cm^2 @ 600 V**

Summary

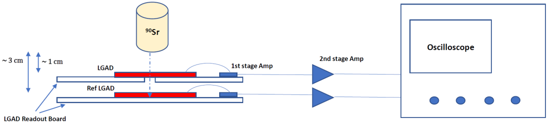
- Include timing measurement for each hit/track in the silicon tracker
- LGADs $\rightarrow$ suitable candidate based on the timing performance for HEP experiments
- TI-LGADs show a no-gain region less than 5 µm (high Fill Factor).
- Increase active area of the LGADs $\rightarrow$ Gain $\sim \mathcal{O}(100)$ and Thickness ($>$100 µm
- Increase the gain to about 100 for reduced Jitter values
- Space LGADs production optimized to study large area LGADs
- $\sigma_{Jitter} < 50$ ps $\rightarrow$ 100 mm^2 active area
- $\sigma_{Jitter} \sim 20$ ps $\rightarrow$ 6 mm^2 active area.

Current Status and Outlook

- Ongoing characterization of space LGADs → timing resolutions
- Possible beam test in future
- Space qualification test

Two new projects with LGADs for space applications

- INFN-FBK: ADA-5D
- PRIN: Pentadimensional Tracking Space Detector -PTSD
- PNRR: LGADs for TOF measurements



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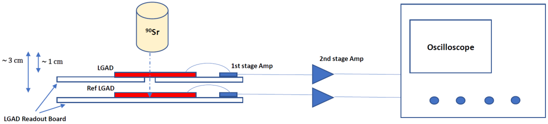

Thank you for your attention