

Concept of Low-Material-Budget 4D Tracking System Based on Double-Sided LGAD Sensors

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Outline:

- **Motivation:** High-precision 4D tracking with a minimal material budget
- **Applications:**
 - Reaction T0 determination in fixed-target experiments: in-beam detector vs. timing layer
 - Pion beam tracking stations at SIS18
 - Ion CT systems for medical applications
- **Detector Concept:**
 - Sensor Technologies: Thin (<100 μm), double-sided TI-LGADs or AC-LGADs for 2D position measurement and precise timing
 - Low-Mass Interconnects: Polyimide/Al micro-cables based on CBM STS technology or Hyperon–Nucleon Spectrometer (H-NS) tracker
 - Dedicated Front-End Electronics: LATIC ASIC – low-noise analog front-end, TDC, and data concentrator
- **Status & Outlook**

Fixed Target experiment - Precise T_0 determination

Timing layer (TL) instead of the first layer of the pixel tracker

Timing Layer (TL) vs. in-beam T_0 detector

- 1% target interaction probability $\rightarrow$ rates on TL are $\sim 100\times$ lower than on in-beam T_0
- Small distance to the target $\rightarrow$ all tracks give the same T_0
- Example: 4 particles (100 ps resolution each) $\rightarrow$ event $T_0 \approx 100 \text{ ps} / \sqrt{4} = 50 \text{ ps}$
- Large area with adequate segmentation $\rightarrow$ no pile-up
- Very clean event selection up to 10^9 beam particles/s $\rightarrow \sim 10 \text{ MHz}$ interaction rate
- Low momenta $\rightarrow$ requires a low-material-budget TL

Can we realize a low-mass 4D tracking layer around the target?

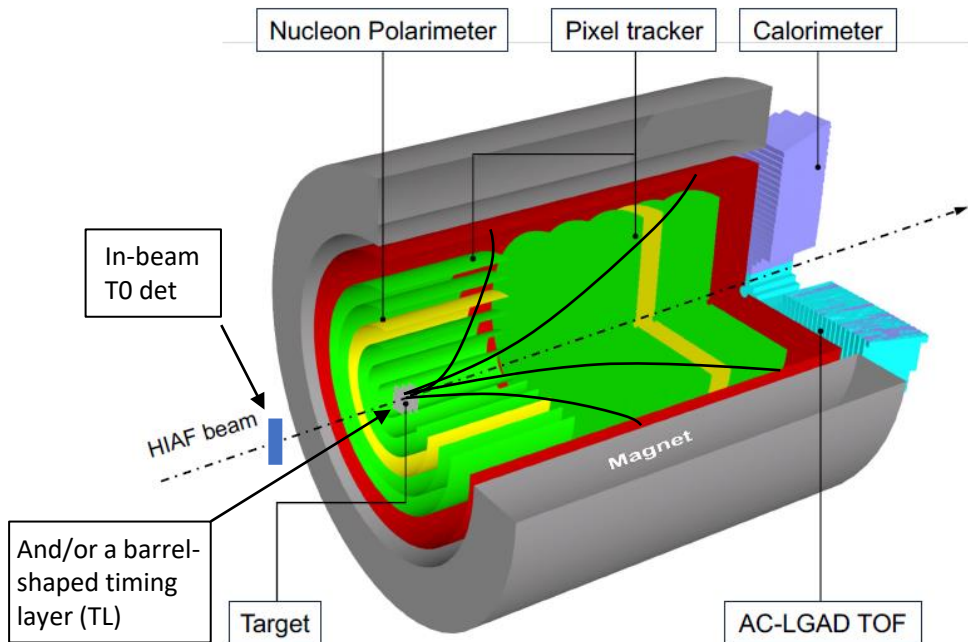
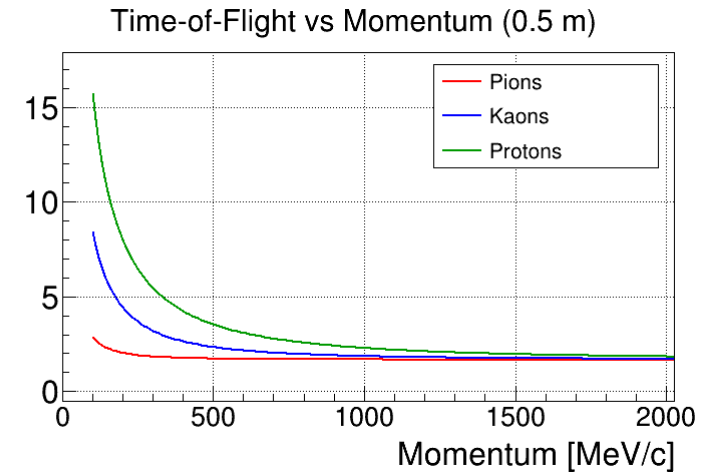
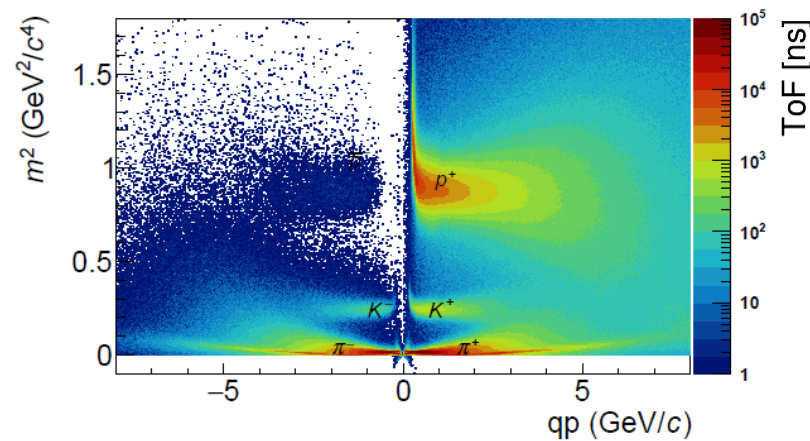


Figure 2.1: Concept of H-NS detector.



- Hyperon–Nucleon Spectrometer (H-NS) at the High-Intensity heavy-ion Accelerator Facility (HIAF).
- HADES at SIS18 (T_0 system and pion beam tracker)
- CBM at SIS100

LGAD-based TOF-iCT – Medical Application

Ion Computed Tomography allows determining the relative stopping power (RSP) distribution inside a patient directly

- Improves treatment planning accuracy
- Requires tracking and energy measurement

Meeting all clinical requirements at once is challenging

- RSP accuracy < 1%
- energy resolution < 1%
- DAQ rate > 10^6 - 10^7 Hz

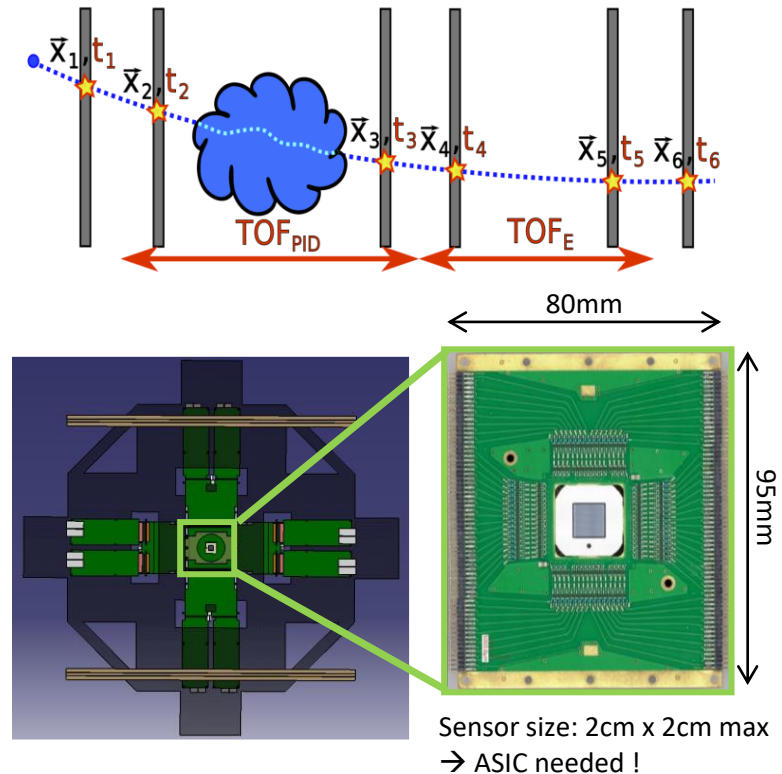
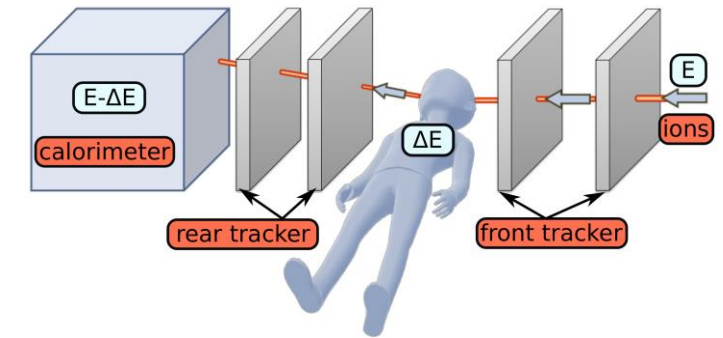
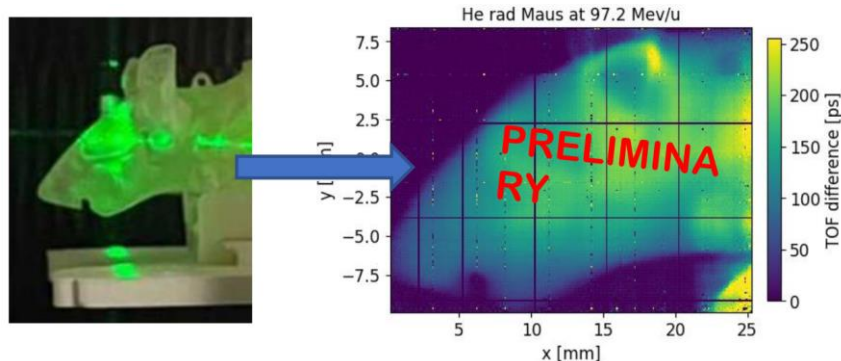
Low-Material-Budget 4D-tracking (LGAD-based) detectors would offer perfect solution

- Ulrich-Pur et al. 2022, <https://doi.org/10.1088/1361-6560/ac628b>
- Ulrich-Pur et al. 2023, <https://doi.org/10.1088/1748-0221/18/02/C02062>
- Ulrich-Pur et al. , https://indico.cern.ch/event/1455346/contributions/6323059/attachments/3009867/5306462/Ulrich-Pur_Felix_TOF-iCT_TREDI2025_250206_075654.pdf

TOF-iCT demonstrator - first experiments

First experimental TOF-based He radiography (TOF-HeRad) of a plastic mouse head

→ Larger active area urgently needed!



Sensor Technologies: Thin ($<100\text{ }\mu\text{m}$), Double-sided Strip TI-LGADs or AC-LGADs for 2D Position Measurement and Precise Timing

Advantages: Double-Sided LGAD Strips vs. Pixel Geometries

- Scaling: $2N$ channels (Strips) vs. N^2 (Pixels) for the same active area.
- Result: Drastic reduction in power consumption and front-end complexity.
- Ultrathin $50\text{-}100\text{ }\mu\text{m}$ Sensor Profile: reduced multiple scattering, critical for low-momentum ($100\text{ MeV}/c$) tracking.
- ASIC Thinning ($\leq 100\text{ }\mu\text{m}$): Readout chips can be thinned to match the sensor profile, maintaining a low X_0 .

Thermal Management:

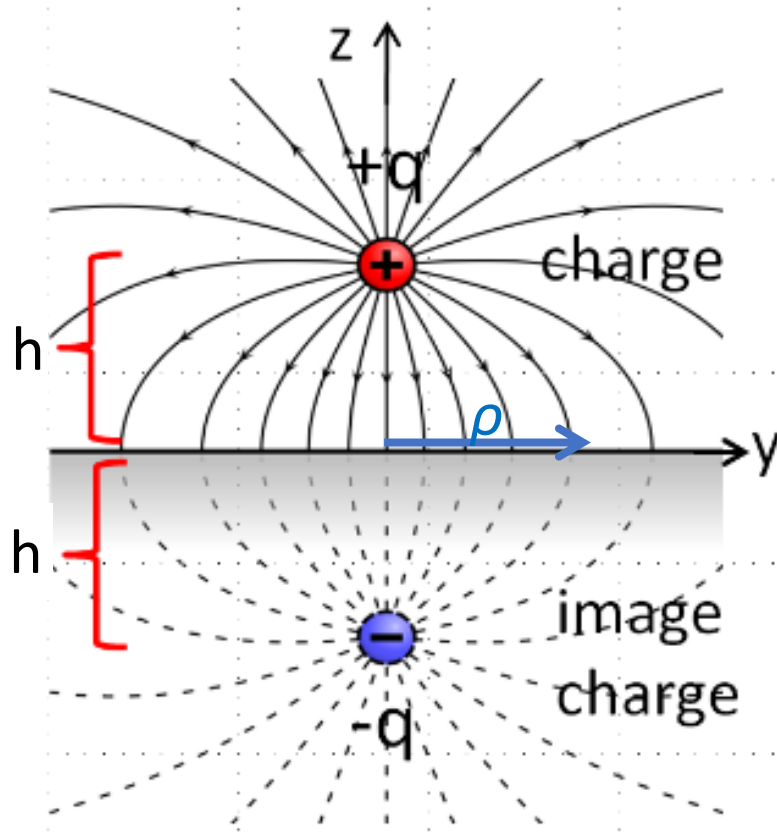
- Pixels: High power density directly on the sensor (LGAD/Silicon volume).
- Strips: Heat is dissipated through the peripheral cable/FEE, protecting sensor stability.

Pixel/DS Strip Performance:

- Equivalent spatial resolution to a pixel matrix (40,000 pixel equivalents for $200+200$ strips) in $2\text{cm} \times 2\text{cm}$ Sensor with $100\text{ }\mu\text{m}$ pitch
- Ambiguity Resolution: "Ghost hits" are mitigated via high-precision timing (TDC) information.

Double-Sided LGADs – The Principle of Operation

The classical electrostatic problem of *a point charge near an infinite conducting plane and its movement*



$$\sigma(\rho) = -\frac{Q}{2\pi} \frac{h}{(\rho^2 + h^2)^{3/2}} \quad \rho^2 = x^2 + y^2$$

Surface charge density **induced on an infinite conducting plane** by a point charge Q located at distance h above it.

ρ = radial distance along the surface from the point closest to the charge

As ρ increases, denominator $(\rho^2 + h^2)^{3/2}$ grows rapidly
→ σ becomes smaller in magnitude
→ σ falls approximately as $1/\rho^3$ for large ρ

If we connect the conductor to a PS (**constant potential**) and if the charge **moves from height h to h'** (even by a micron):

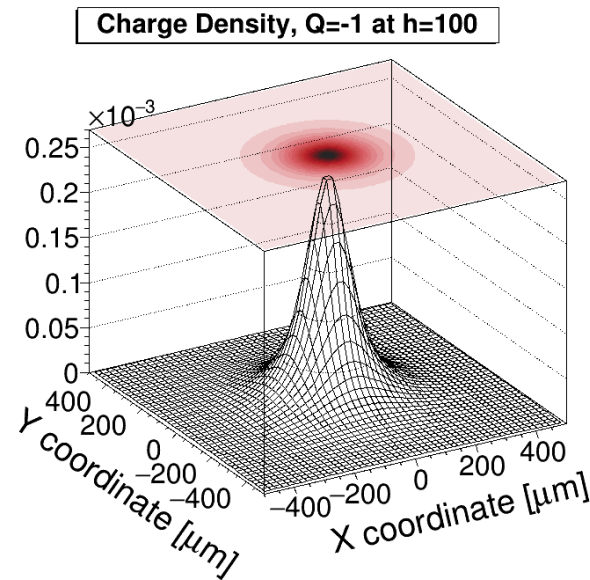
- The electric field in space changes.
- The surface charge density required on the conductor also changes.
- Because the conductor must stay at **exactly the same potential**, charges must flow to/from the power supply to *rearrange the surface charge*.

This flow of charge is a **measurable current** — this is our signal.

The same mechanism as in **Ramo's theorem** and **induced signals in detectors**.

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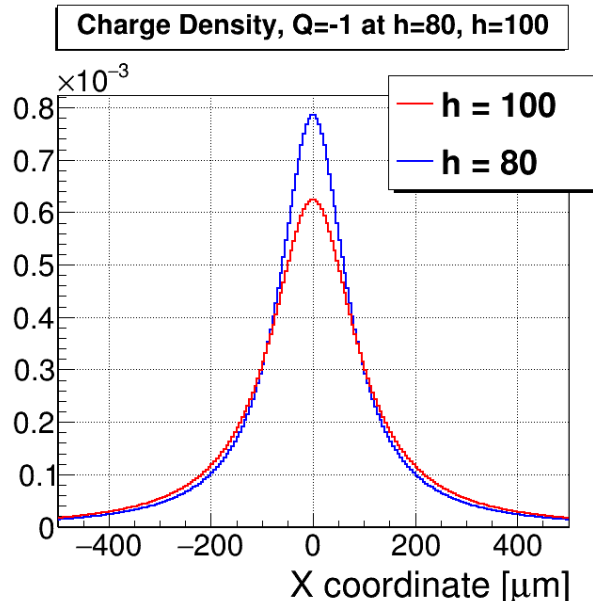
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→ **σ falls approximately as $1/\rho^3$ for large ρ**



Small charge displacement matters:

Shifting a charge by $20\text{ }\mu\text{m}$ causes a strong redistribution of induced surface charge at constant potential.

Signal formation:

The redistribution produces a transient current measured by the FEE.

Polarity flip:

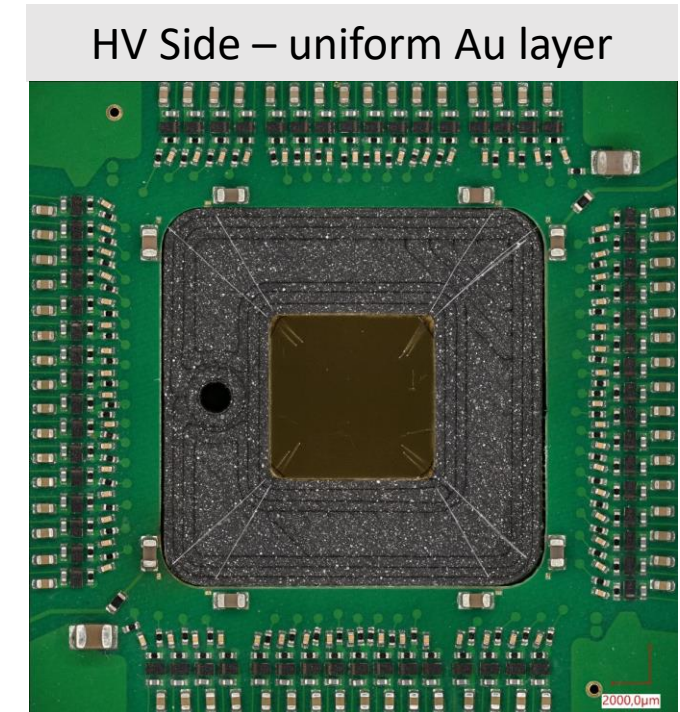
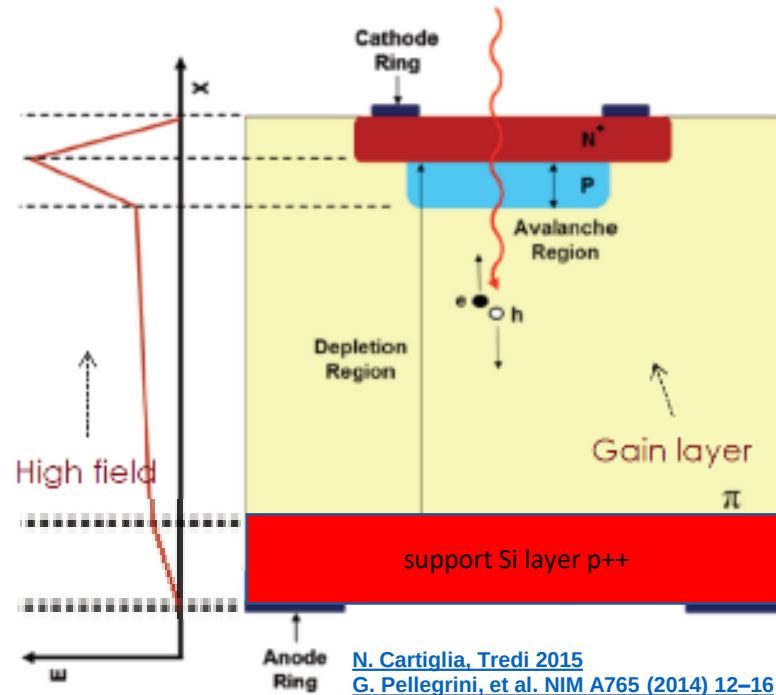
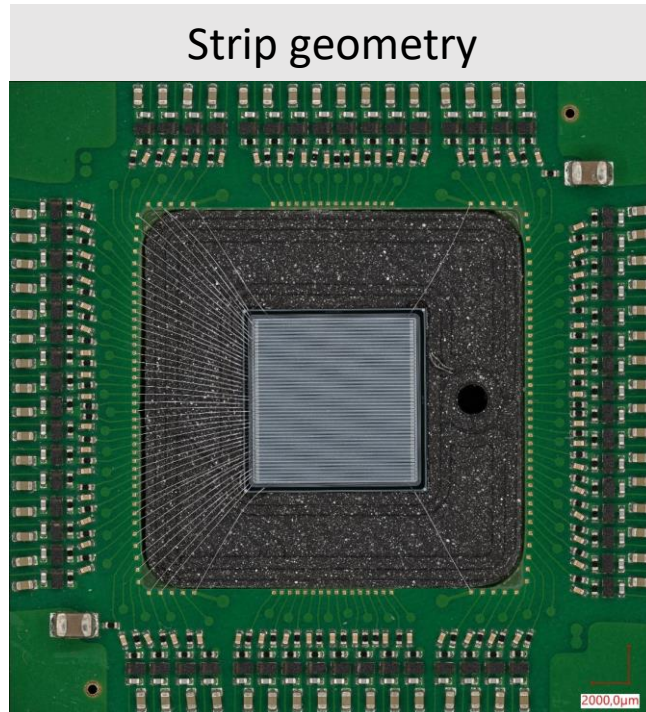
Electrodes above and below the charge see signals of opposite sign.

Constant charge used for illustration; real detector signals involve time-dependent charge.

Double-Sided LGADs – From Single-Sided to Double-Sided

Sensors used for this prototyping: HADES LGAD sensors produced by FBK

200 μm total thickness / 85 μm active thickness; 100 μm pitch, size of 1cm x 1cm.



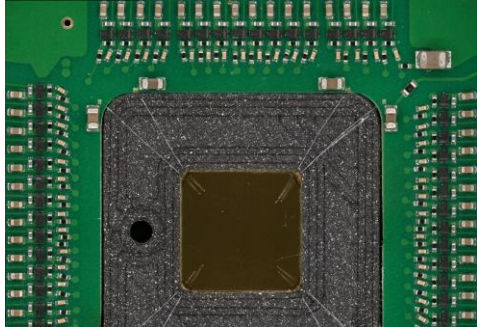
- Strip geometry: Segmented strip implants on top of segmented Gain Layer
- Active Volume: Drift Region: **high-resistivity bulk**: lightly doped silicon.
- Mechanical & Electrical support layer: **low-resistivity**, acting as the anode.
- Au Metallization: Uniform metal deposition on the backside, biasing
- For **double-sided** LGADs, **segmentation** on the HV **backplane** is essential.

Nomenclature: *Al side* (gain-layer Al strips) and *Au side* (HV-side Au metallization).

Double-Sided LGADs – The Principle of Operation - Segmentation

Sensors used for this prototyping: HADES LGAD sensors produced by FBK

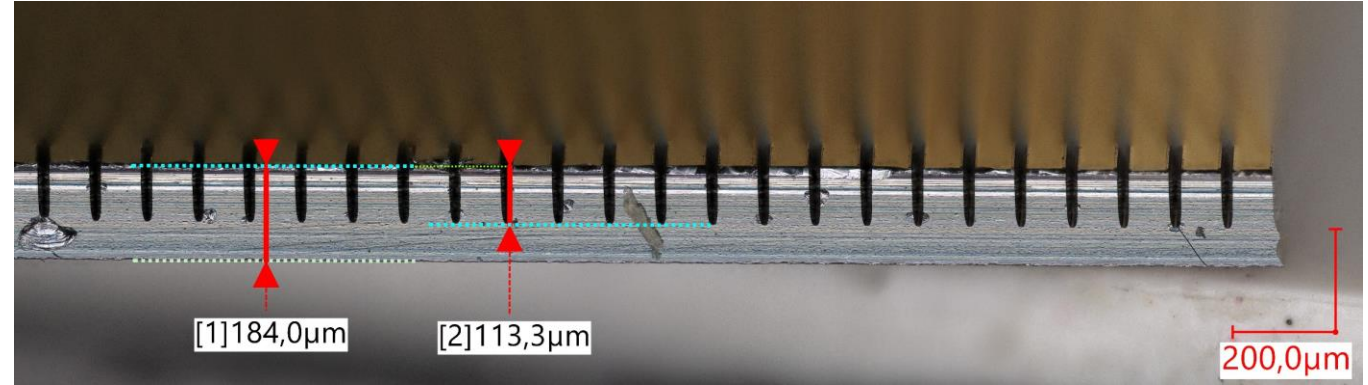
200 μm total thickness / 85 μm active thickness; 100 μm pitch, size of 1cm x 1cm.



HV Side
uniform Au layer



Trenches on HV side



Trenches on HV side – Side view

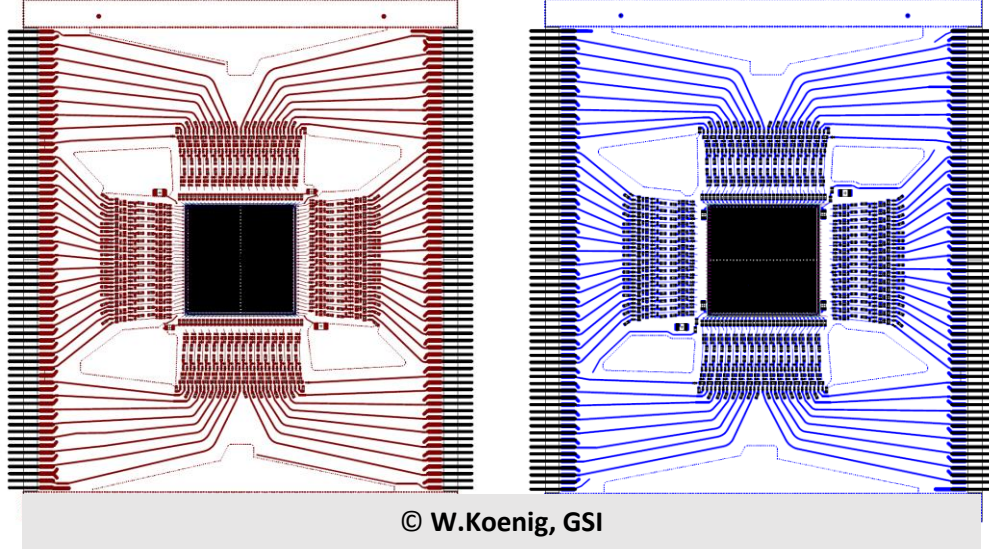
- Conductive sensor surface on **Au side** is divided into **parallel strips** using insulating trenches
(**machined at Hahn-Schickard Gesellschaft** Villingen-Schwenningen, Germany)
- Each strip is biased to the same HV via an individual **high-ohmic resistor**.
- Additional **high-ohmic resistance** between strips ensures controlled potential equalization.
- Local charge deposition stays confined to individual strips → **good position resolution**, see previous slide
- Each strip is **AC-coupled to its amplifier** through a capacitor on PCB (HV is blocked).
- Readout electronics see **only the fast signal**, not the high-voltage bias.
- Result: Clean segmentation and precise position sensitivity; however, **high dark current** (100 μA @ 100 V). **Trench machining requires optimization.**

Double-Sided LGADs – A Dedicated FEE

The front-end electronics must provide three key functions:

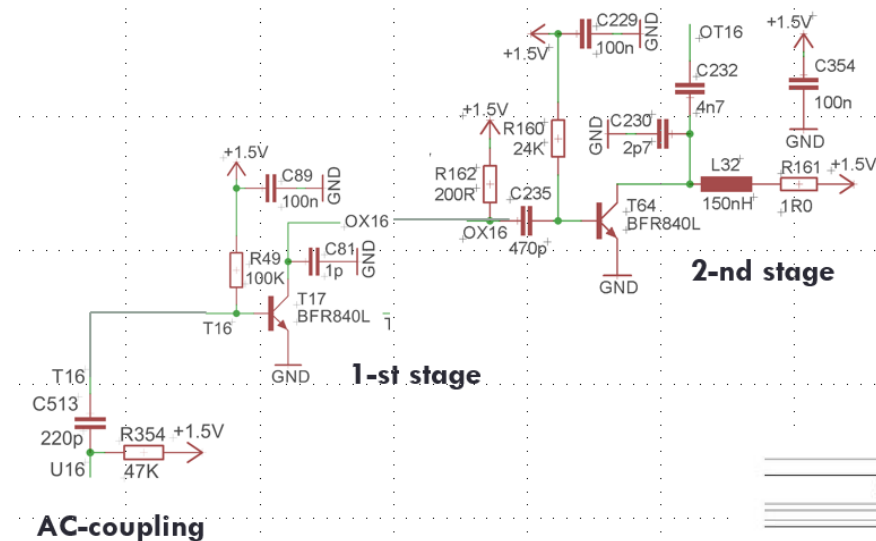
- signal amplification,
- **stable high-voltage biasing**, -> can be done on sensor (CMS/CBM)
- **reliable decoupling of the sensor signals** -> can be done on sensor, AC coupling (CMS/CBM)

Jerzy Pietraszko et al 2025 JINST 20 C08007, <https://doi.org/10.1088/1748-0221/20/08/C08007>



Amplifiers (128 channels / 64 on each side)

- AC coupled
- Single/Double sided (X/Y) measurement in one sensor possible (LGAD/Diamond)
- 50-60ps for MIPs
- 30ps for C ions
- Voltage gain: up to 400



- + HV biasing
- + AC signal decoupling

-> Can be done on the sensor (CMS/CBM)

[M. Krammer et al., "The silicon sensors for the CMS tracker" Nucl. Instrum. Methods Phys. Res., A 531 \(2004\) 238-245](#)

Resistor: Polysilicon Bias Resistor (The "Snake")

AC Coupling: Dielectric material (typically thermal **Silicon Dioxide**, SiO₂, combined with Silicon Nitride, Si₃N₄) and Al strip on top

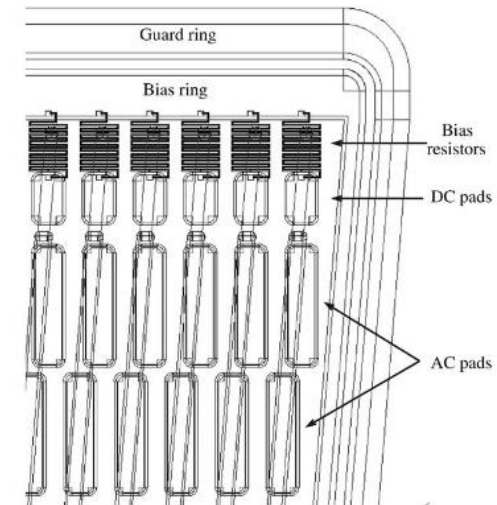
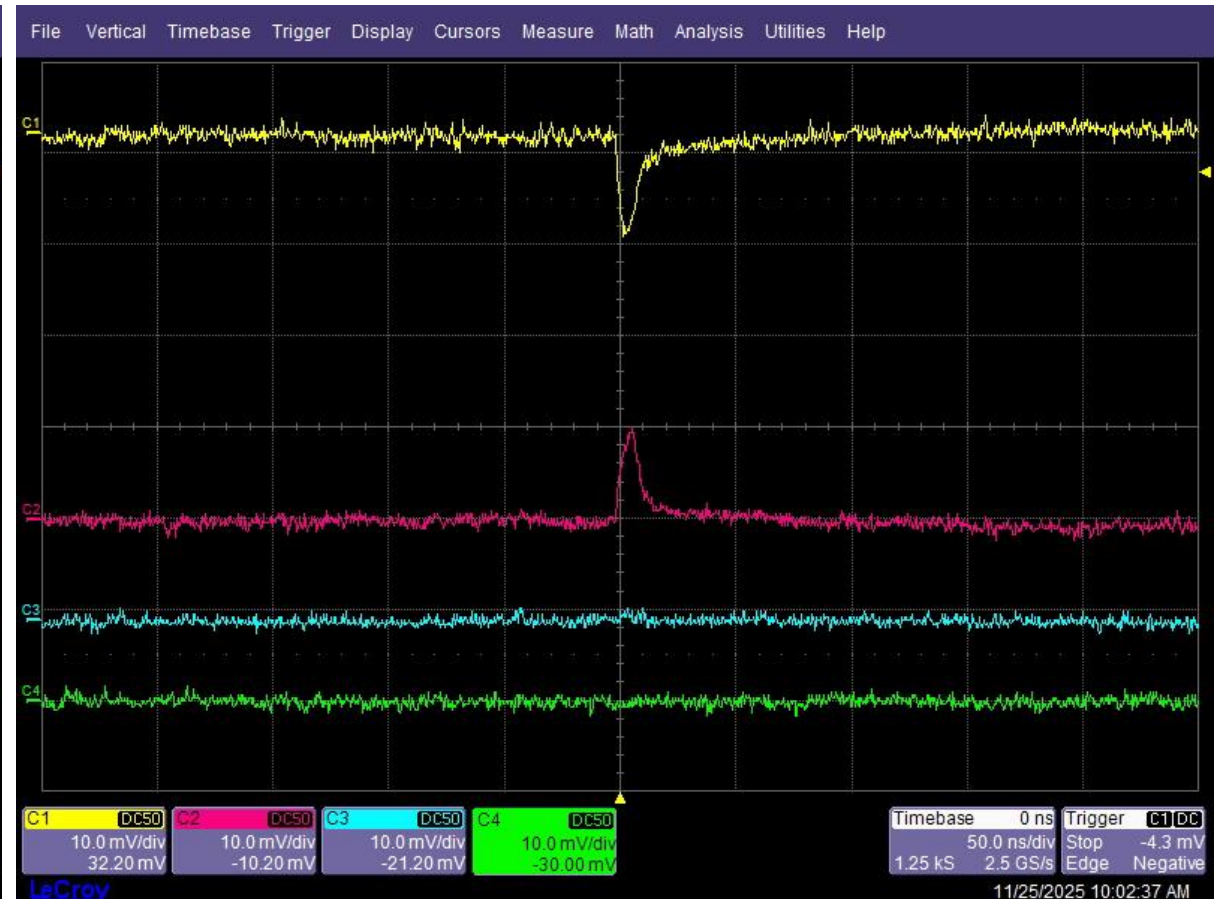
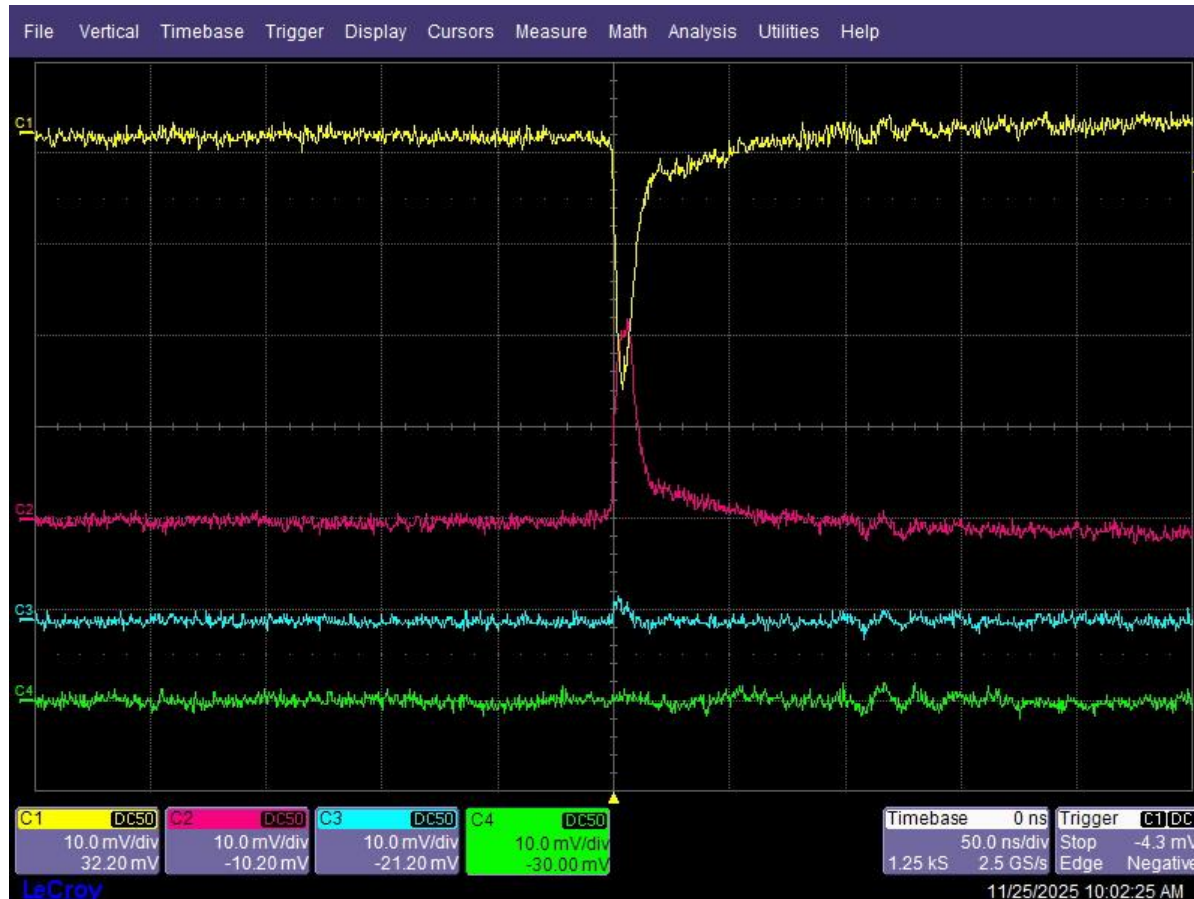


Fig. 4. View of the corner region of a wedge-type sensor.

^{90}Sr radioactive source test

Oscilloscope connection scheme:

- **C1**: negative signal, from the original strips (on the gain layer side – **Al side**)
- **C2, C3, C4**: positive signals from the strips on the HV side – **Au side**; the **strips on both sides are parallel to each other**
- The strips connected to **C1** and **C2** are positioned directly on top of each other.

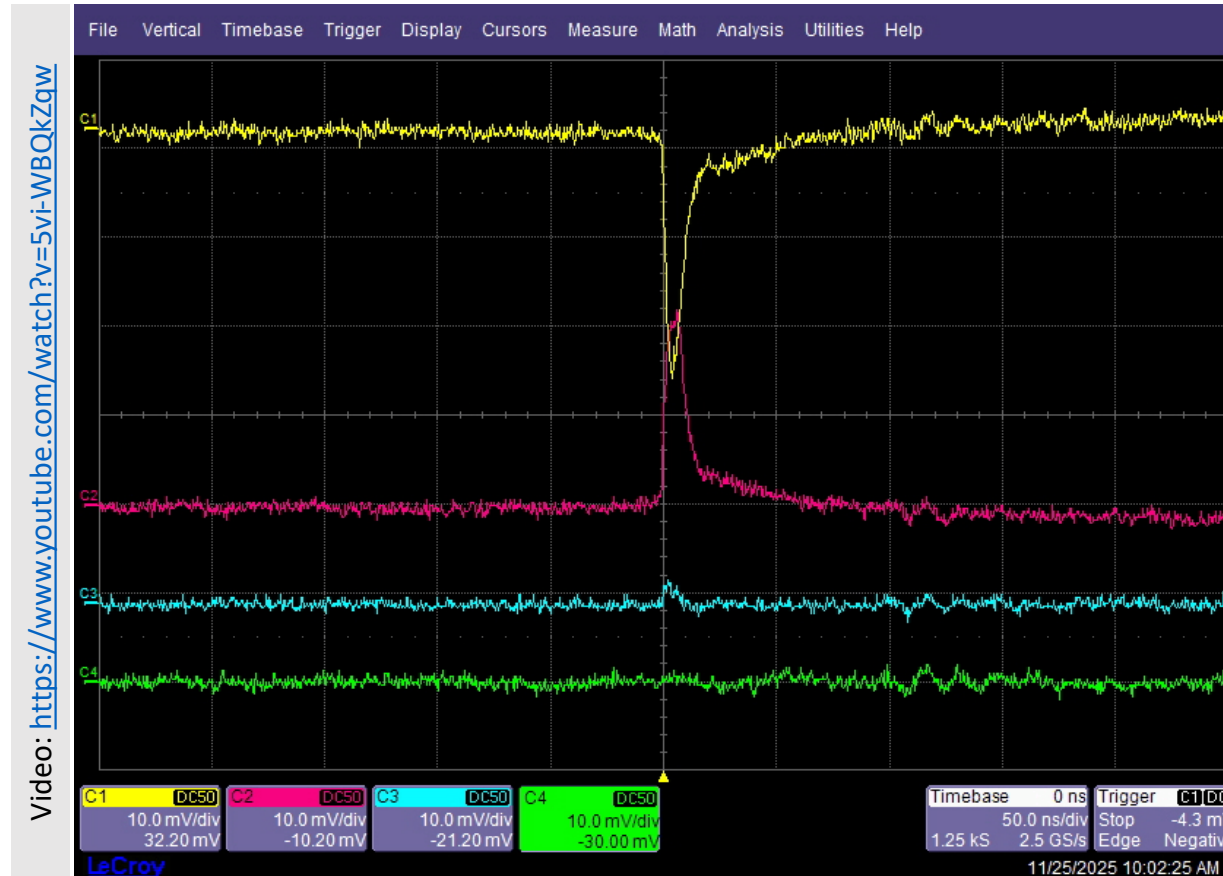


Signal amplitudes of C1 and C2 clearly correlated

^{90}Sr radioactive source test

Oscilloscope connection scheme:

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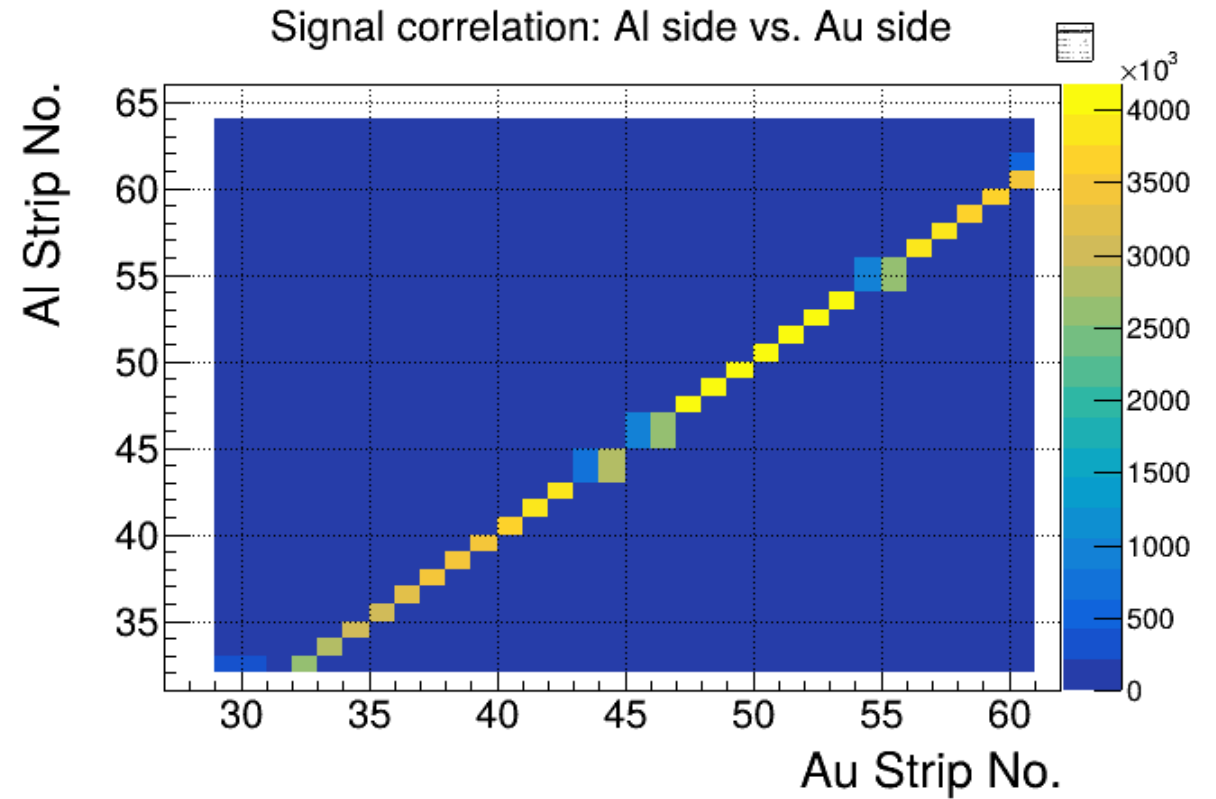
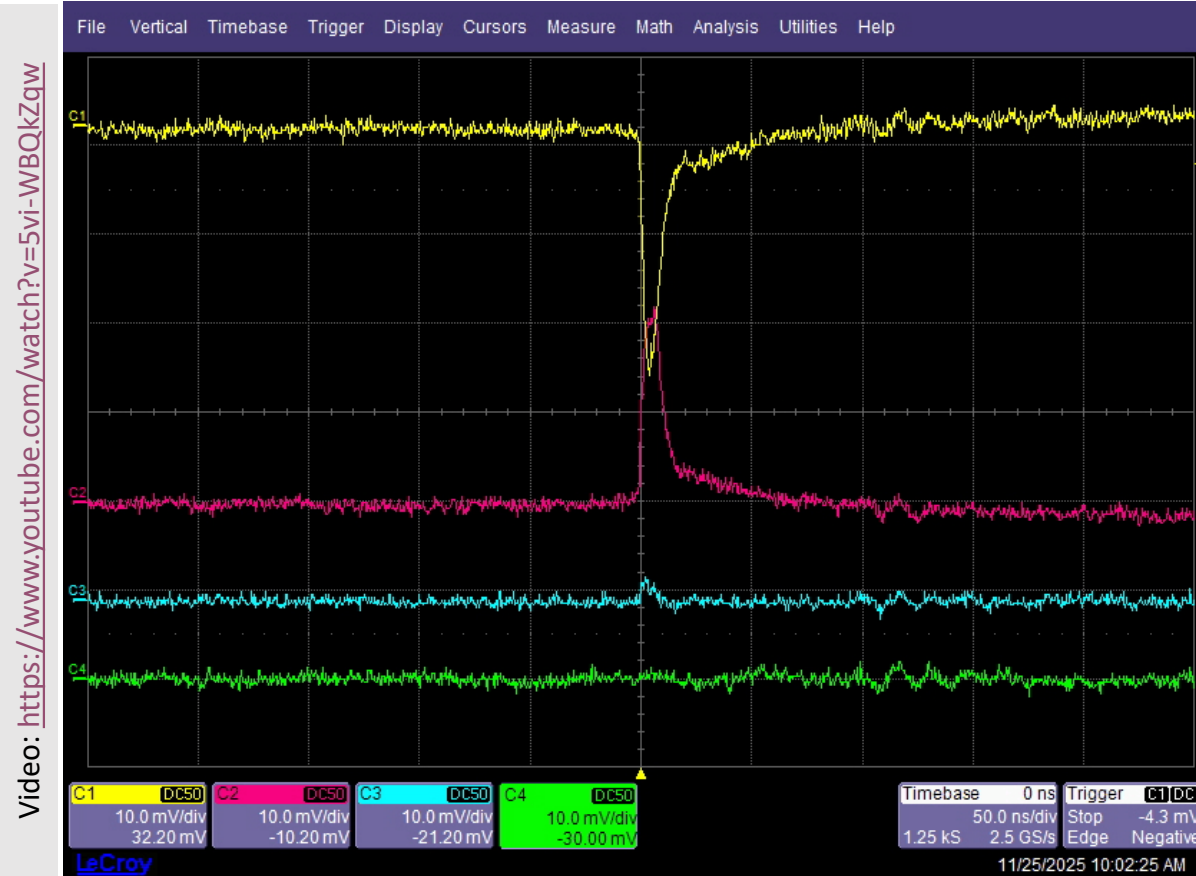


Trigger on C1 → A corresponding signal is always visible on C2.

^{90}Sr radioactive source test

Full sensor test analysis:

- Identify **local maxima on the Al side** and determine the channel number.
- Search for clusters in the **corresponding Au-side strip region**.
- Compute the **Au-side cluster size, find local maxima**
- Plot the **correlation of local maximum positions**: Al side vs. Au side



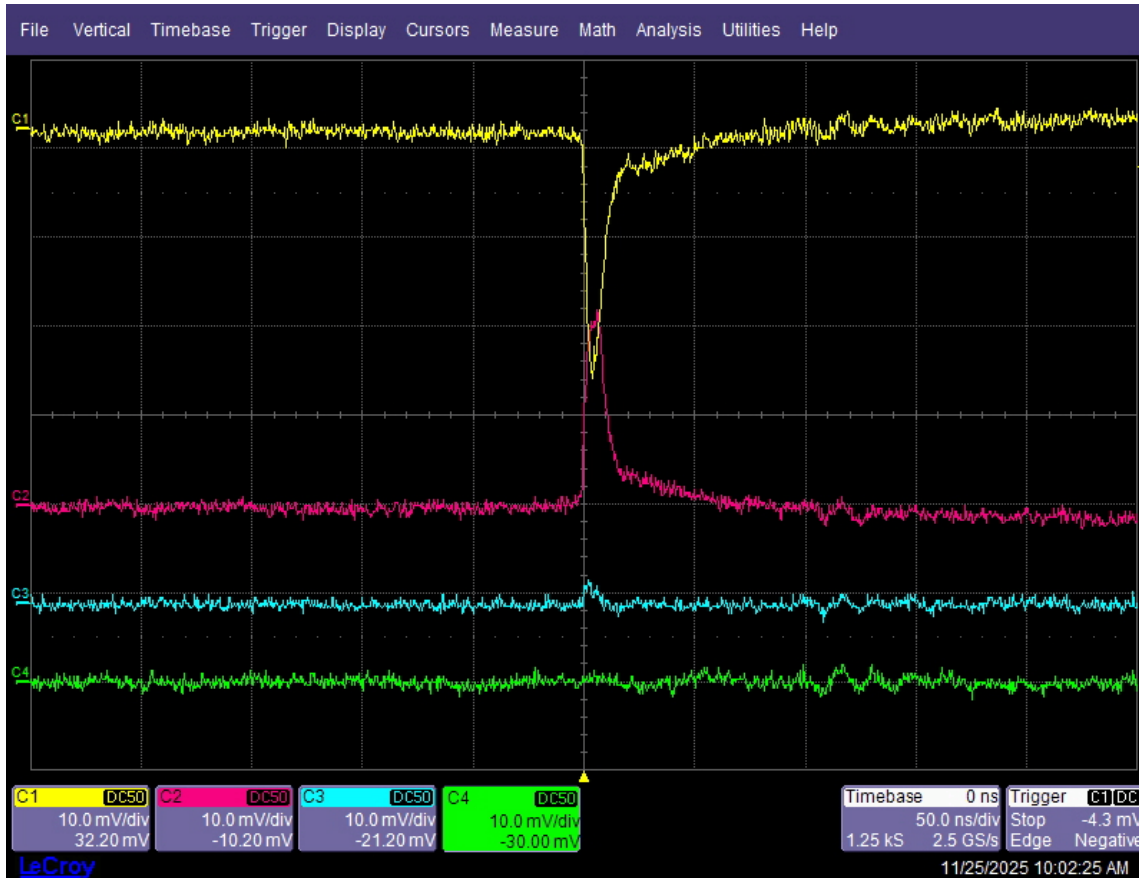
Strong linear correlation → excellent localization.

Trigger on C1 → A corresponding signal is always visible on C2.

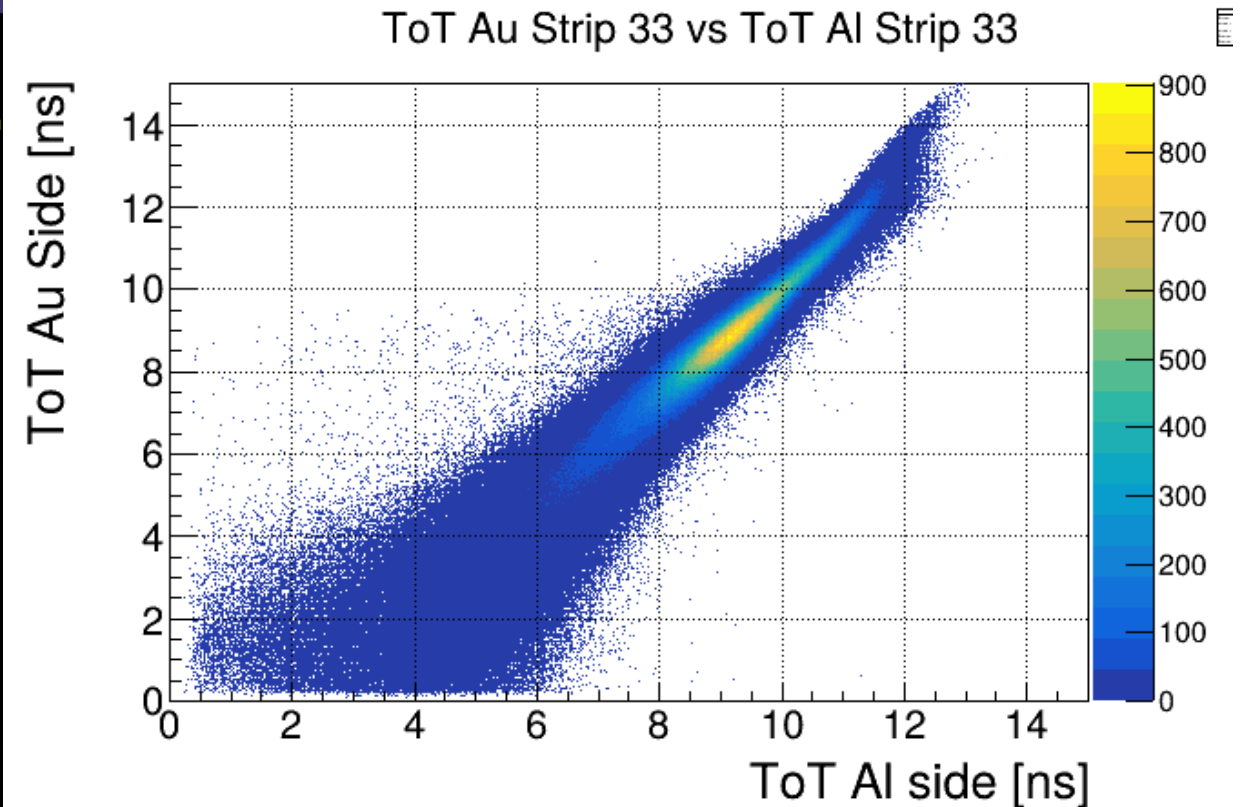
^{90}Sr radioactive source test

Full sensor test analysis:

- Identify **local maxima on the Al side** and determine the channel number.
- Search for clusters in the **corresponding Au-side strip region**.
- Compute the **Au-side cluster size**, find local maxima
- Plot the **correlation of the local-maximum ToT: Al side vs. Au side**



Trigger on C1 → A corresponding signal is always visible on C2.



Strong amplitude (ToT) correlation between Al and Au sides.

^{90}Sr radioactive source test

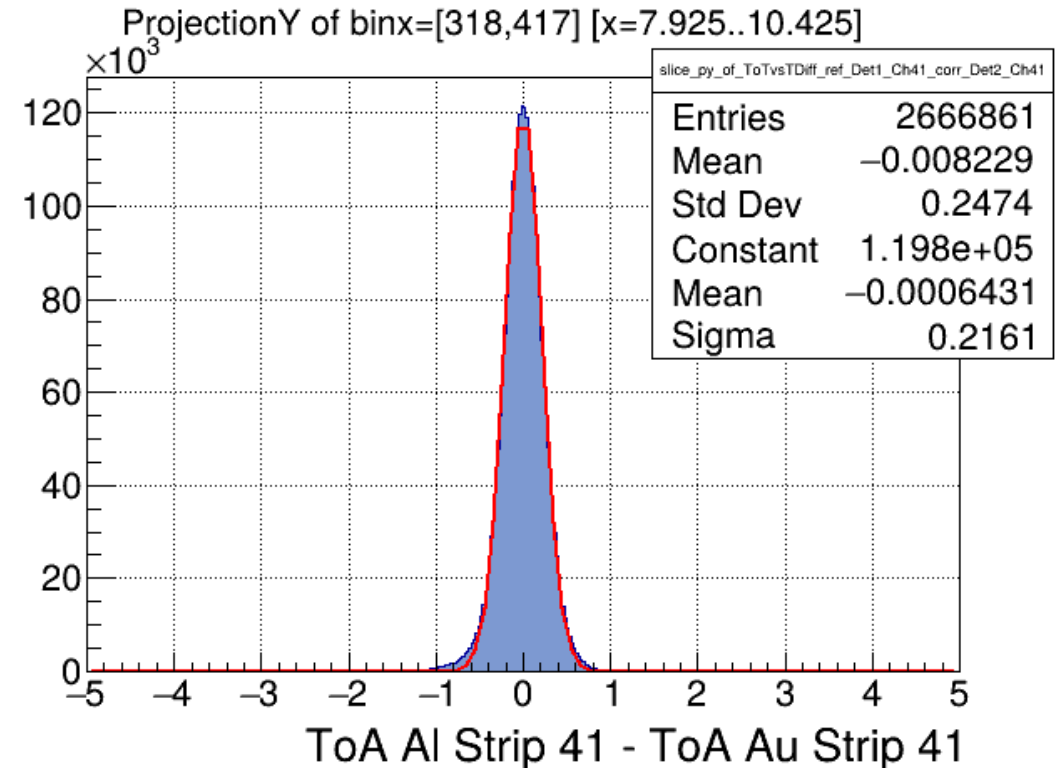
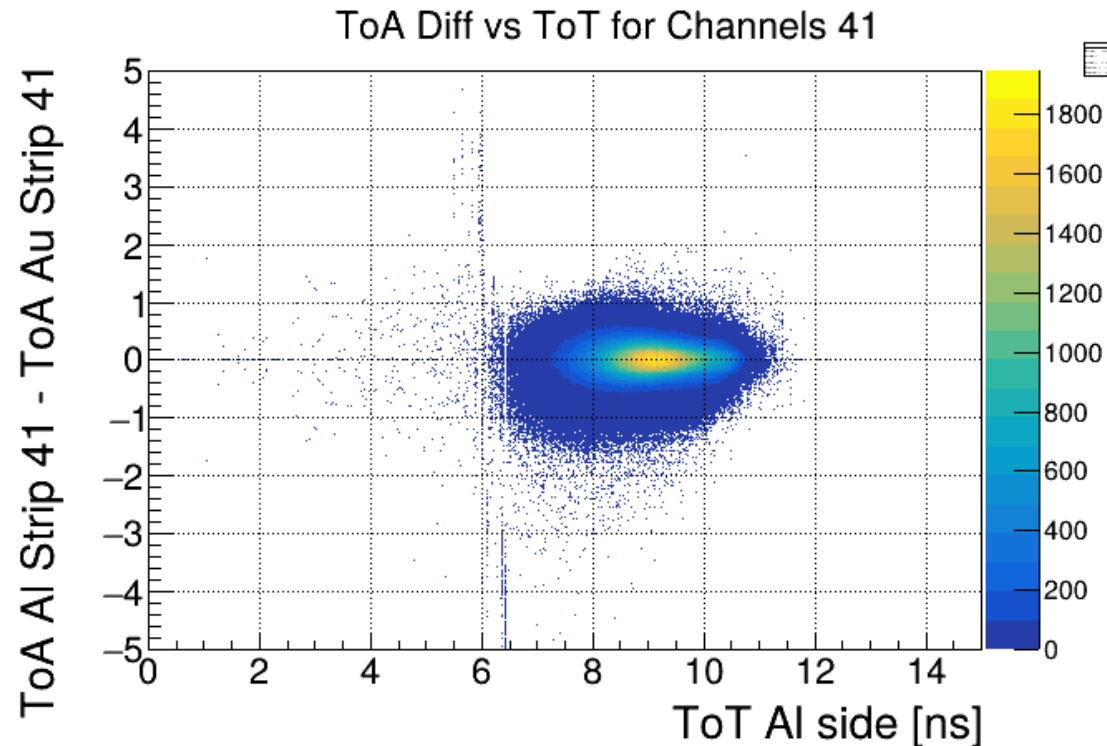
Full sensor test:

Match Al and Au signals event-by-event.

Compute Δt (Al – Au).

Apply offset and time-walk corrections.

Plot corrected Δt vs. Al-side ToT (example channel pairs 44).



- Timing precision extracted from the Y-projection of Δt .
- **Too low bias voltage and propagation effects along the strips broaden the distribution**, as the strips are not bonded on the same side!

Dedicated Front-End Electronics: LATIC ASIC – low-noise analog front-end, TDC, and data concentrator

LATIC ASIC

- Designed and produced by **University of Science and Technology of China (USTC), Hefei, 230026, China**
- Current version: pad structure, 5 x 5 pads, 1.3mm pitch.
- Performance comparable to ALTIROC (ATLAS) and ETROC (CMS)

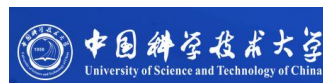


Design of high-precision time measurement prototype ASIC for the LGAD readout

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H. Chen et al.

Nuclear Inst. and Methods in Physics Research, A 1064 (2024) 169302

Table 2
key design parameters of LGAD readout ASICs.

ASIC	ALTIROC0	ALTIROC1	ETROC0	ETROC1	LATIC0	LATIC1
Technology	130 nm	130 nm	65 nm	65 nm	180 nm	130 nm
LGAD pad size	1.3 × 1.3 mm ²	1.3 × 1.3 mm ²	1.3 × 1.3 mm ²	1.3 × 1.3 mm ²	1.3 × 1.3 mm ²	1.3 × 1.3 mm ²
Channel number	8	5 × 5	1	5 × 5 (4 × 4 with full chain)	8	5 × 5
Integrated TDC	no	yes	no	yes	no	yes
σ _{TOA} @	27 ps	<25 ps	<16 ps	−42 ps beam test with sensor	<20 ps	<20 ps
Charge	10 fC	10 fC	15 fC sensor cap.		10 fC	10 fC
Capacitance	3.3 pF	4 pF			6 pF	4 pF

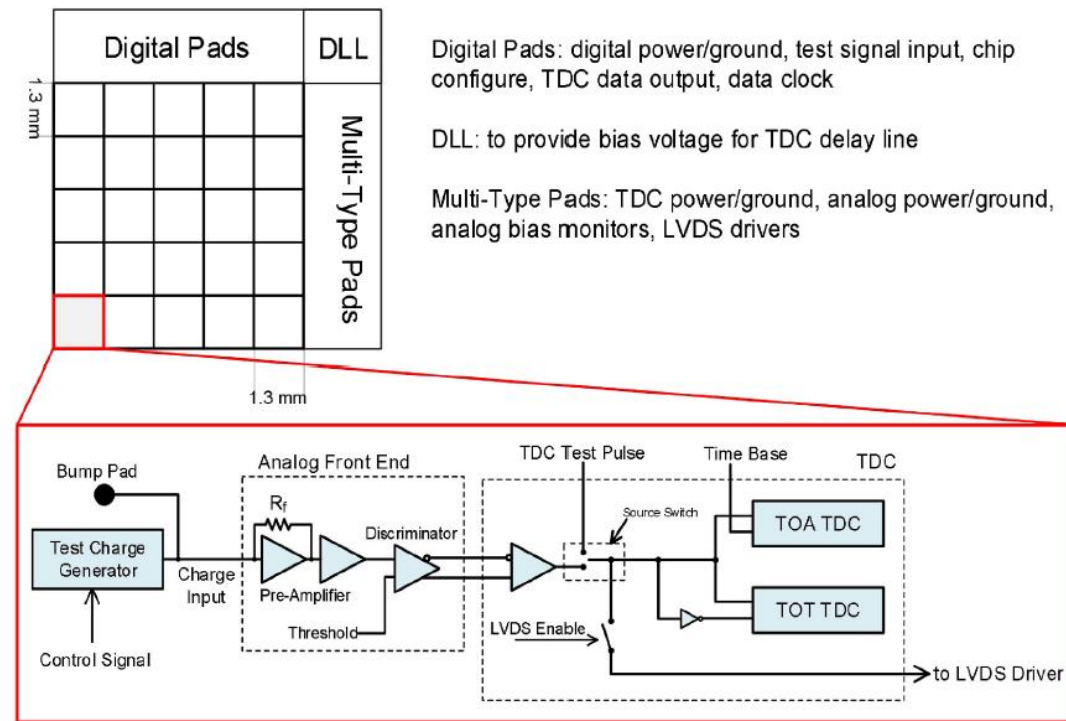
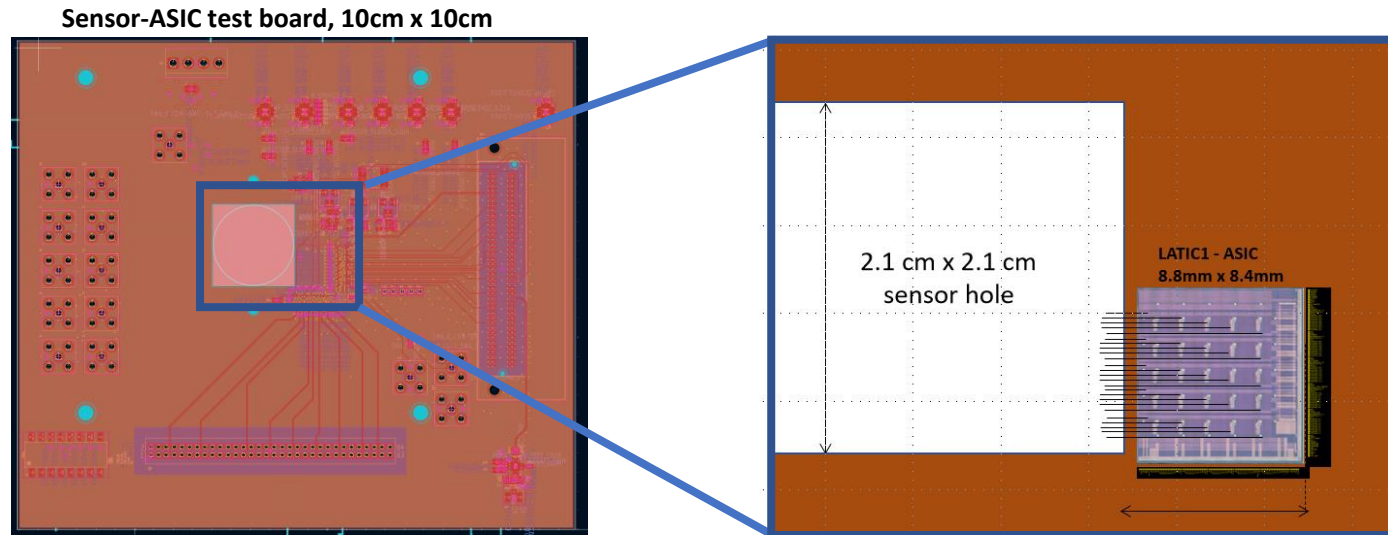


Fig. 1. The overall (upper image part) and one-channel (lower image part) structure of the LATIC1.

LATIC ASIC – Short- and Long-Term Plans

- Designed and fabricated by the **University of Science and Technology of China (USTC), Hefei**
- Current version: pad structure, 5 x 5 pads, 1.3mm pitch.
- Test PCB board designed, should be ready in 1-2 months (USTC)
- Tests with LGADs in preparation



Next-Generation LATIC ASIC – Strip Readout Concept Under Discussion

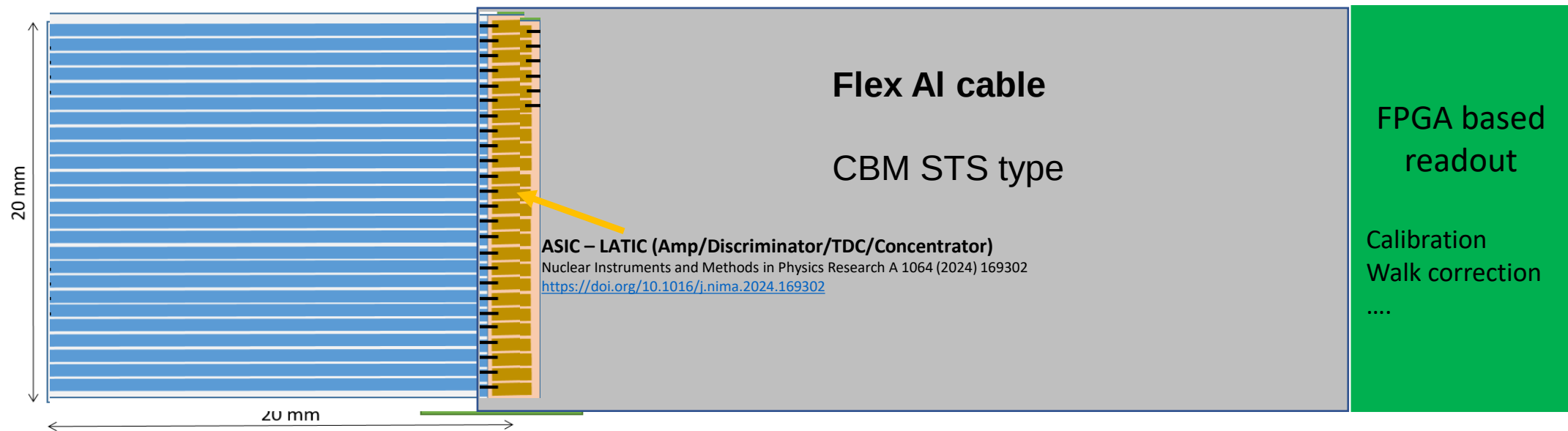
- ASIC redesign for double-sided strip LGAD sensors
- Target strip pitch: 180–200 μm
- Compact channel layout: 10 channels within 2 mm or 25 channels within 5 mm at 200 μm pitch
- Next step: Define the channel layout and prepare the next ASIC version

Timing Layer – Single-Module Integration Concept

- Strip LGAD sensor mounted on a low-mass Al/polyimide flex cable
- LATIC ASIC mounted directly onto the flex cable
- Direct wire bonding between LGAD strips and ASIC inputs
- Thermal management: ASIC heat dissipated through the flex cable rather than the LGAD sensor
- Digital readout: TDC data transmitted via low-mass flex interconnects
- Modular design: Compact, low-material-budget building block for a scalable 4D timing layer

Prototyping and R&D Scenario

ASIC (amplifier, discriminator, TDC) with a concentrator mounted on a flexible Al cable
→ Heat dissipation directed to the cable rather than the Si sensor



Concept of Low-Material-Budget TL Based on Double-Sided LGAD Strip Sensors

– Summary and Outlook

Summary

- **Thin, double-sided LGAD concept** potentially extendable to AC-LGAD and SiC sensors
- **Low-mass 4D Timing Layer concept** developed, with excellent expected timing and spatial performance
- **Tracking performance** potentially comparable to that of pixel detectors, with significantly reduced readout complexity

Outlook

- **Thin double-sided strip LGADs:** Evaluate and establish mass-production capabilities
- **LATIC ASIC:** Test the current version with strip LGAD sensors
- **Next-generation LATIC:** Develop a dedicated strip-readout architecture
- **Low-mass interconnects:** Design and manufacture Al/polyimide flex cables
- **Mechanical integration:** Develop the module support and assembly concept
- **Thermal management:** Develop and validate the ASIC cooling concept

THANK YOU