INFN

The Pentadimensional Tracking Space Detector project, R&D for space-borne LGAD Si-microstrip tracking detectors

M. Barbanera[2] (INFN - Perugia)
on behalf of the PTSD team
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1) Italian Space Agency
2) INFN
3) Università degli Studi di Perugia
+ many thanks to L. Pacini (INFN) and F. Moscatelli (CNR and INFN)

Pentadimensional Tracking Space Detector (PTSD)
is a project funded by NextGenerationEU and Italian Ministry of University and Research
PNRR M4.C2.1.1, PRIN 2022, n. 2022JNF3M4, CUP I53D23001190006

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
ASI Agenzia Spaziale Italiana
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The Pentadimensional Tracking Space Detector project, R&D for space-borne LGAD Si-microstrip tracking detectors

1. Scientific context
2. Reasons for 5D tracking in space
3. The PTSD project: space-driven R&D of LGAD-µstrips detectors
4. PTSD first prototypes and measurements
5. Design of a PTSD CubeSat with ASI-CEF

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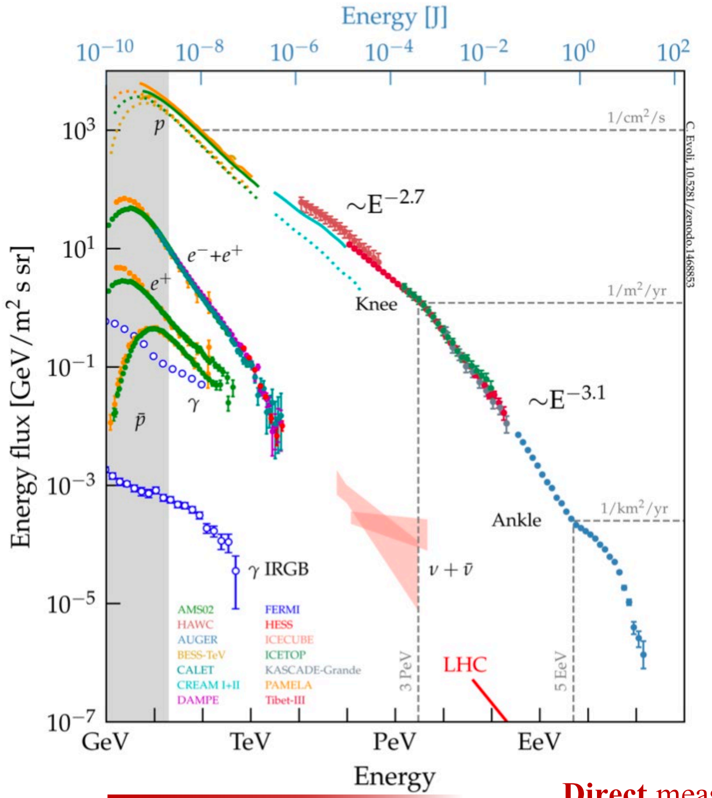
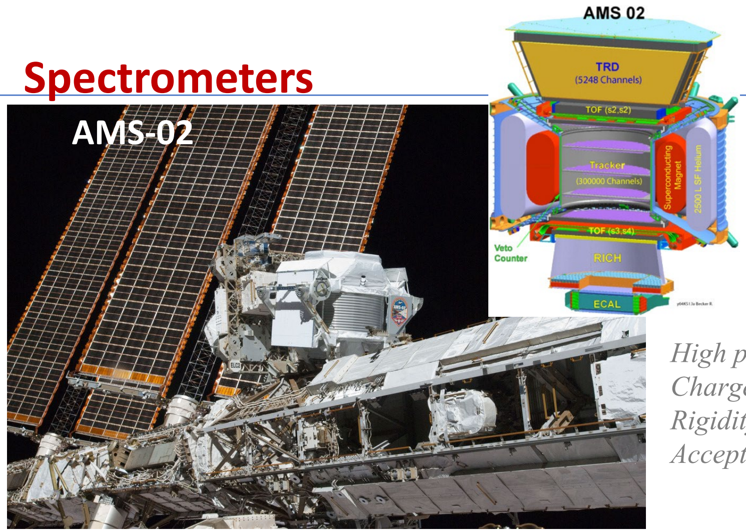
Charged CRs: state of the art



Direct measurements
in **space**

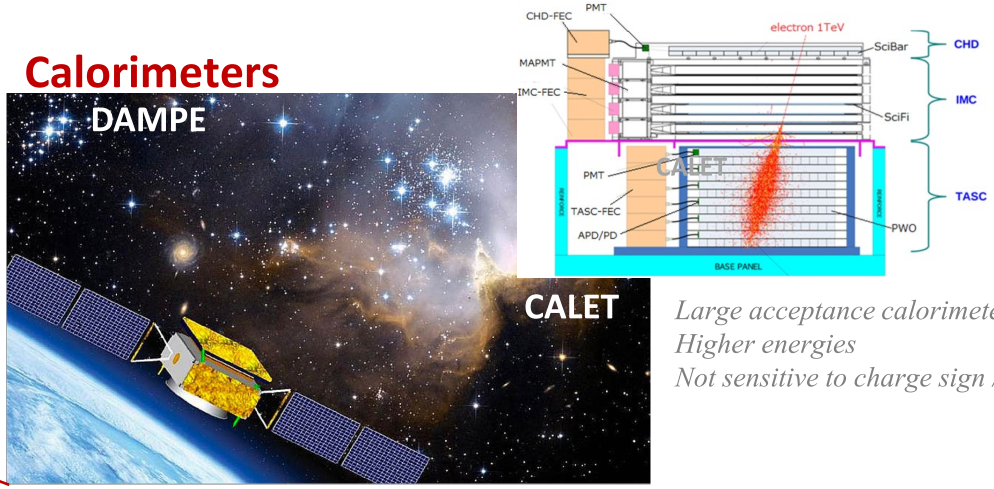
Indirect measurements
from **ground**

Spectrometers



High precision particle ID (e.g., mass)
Charge-sign discrimination
Rigidity/energy cross-calibration
Acceptance constrained by magnet

Calorimeters



Large acceptance calorimeters
Higher energies
Not sensitive to charge sign / mass

Large acceptance missions remain the most promising approach to new discoveries and high-accuracy space measurements

Si-µstrip detectors are the preferred solution to instrument **large area detectors** with larger number of electronics channels coping with the **limitations on power consumption in space**

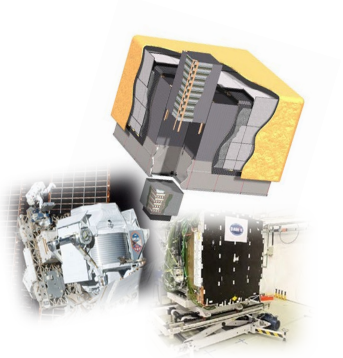
Large area Si-microstrip detectors in space

M. Duranti et al., *Instruments* 2021, 5(2), 20

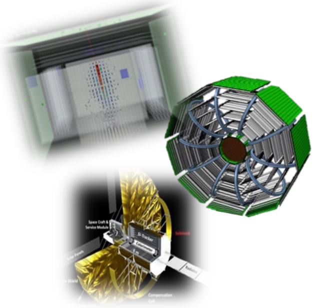
Most space detectors for charged cosmic ray and γ-ray measurements require **solid state tracking systems based on Si-µstrip sensors**.

Si-µstrip detectors are the preferred solution to instrument

- large area detectors
- large number of electronics channels
- copying with the **power consumption limitations in space**



Operating Missions						
	Mission Start	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
Fermi-LAT	2008	$\sim 74\,m^2$	38 cm	$\sim 880 \cdot 10^3$	228 μm	$\sim 66\,\mu m$
AMS-02	2011	$\sim 7\,m^2$	29–62 cm	$\sim 200 \cdot 10^3$	110 μm	$\sim 7\,\mu m$
DAMPE	2015	$\sim 7\,m^2$	38 cm	$\sim 70 \cdot 10^3$	242 μm	$\sim 40\,\mu m$



Future Missions						
	Planned operations	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
HERD	2030	$\sim 35\,m^2$	48–67 cm	$\sim 350 \cdot 10^3$	$\sim 242\,\mu m$	$\sim 40\,\mu m$
ALADInO	2050	$\sim$ 80-100 m^2	19–67 cm	$\sim 2.5 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$
AMS-100	2050	$\sim$ 180-200 m^2	$\sim$ 100 cm	$\sim 8 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$

[1] HERD Collaboration. *HERD Proposal, 2018* https://indico.ihep.ac.cn/event/8164/material/1/0.pdf
[2] Battiston, R.; Bertucci, B.; *et al. High precision particle astrophysics as a new window on the universe with an Antimatter Large Acceptance Detector In Orbit (ALADInO)*. Experimental Astronomy 2021. https://doi.org/10.1007/s10686-021-09708-w
[3] Schael, S.; *et al. AMS-100: The next generation magnetic spectrometer in space – An international science platform for physics and astrophysics at Lagrange point 2*. NIM-A 2019, 944, 162561. https://doi.org/10.1016/j.nima.2019.162561

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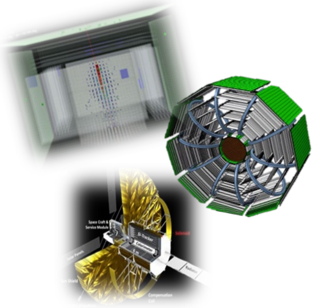

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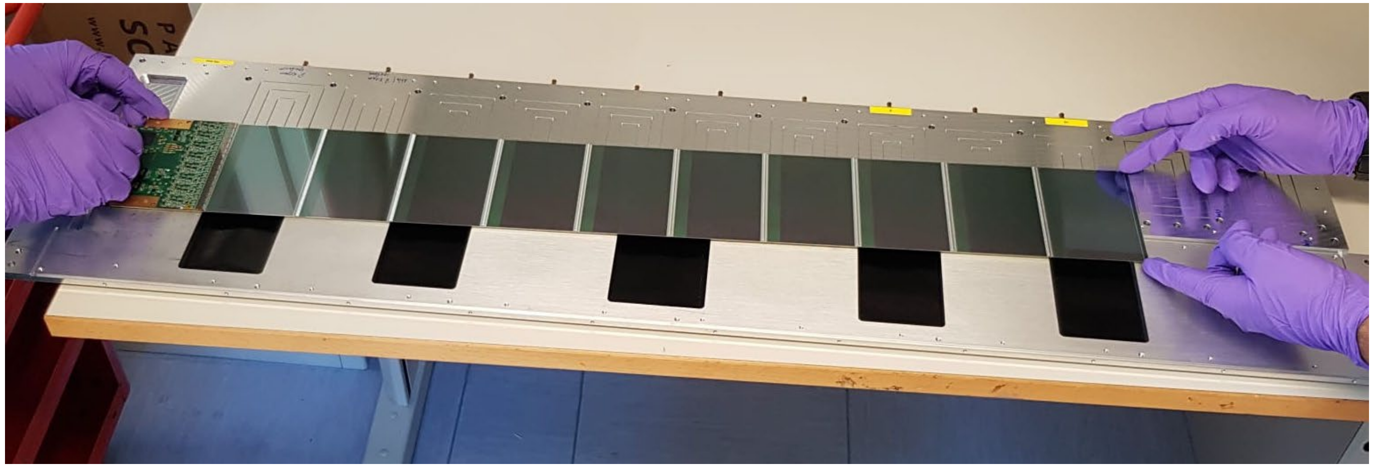
Capacitance and daisy-chain: example of AMS-L0 upgrade

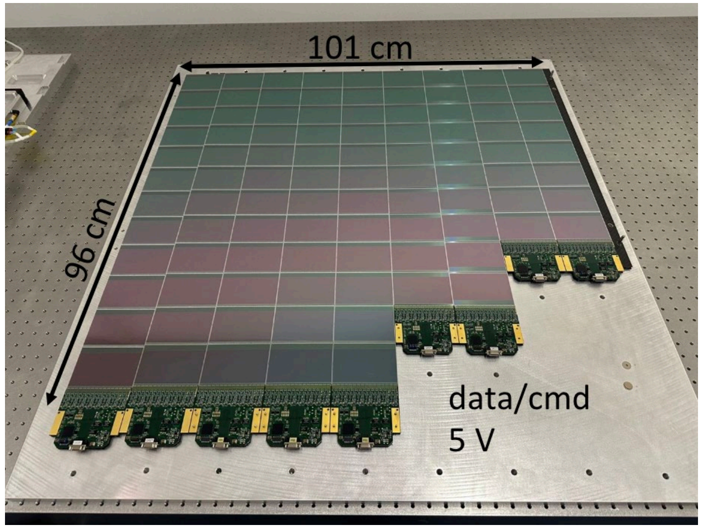
At production level the strips cannot be so long:

- they must be at least shorter than the wafer diagonal (i.e. 6'' – some margin)
- Typically, is at most ~ 10 cm long

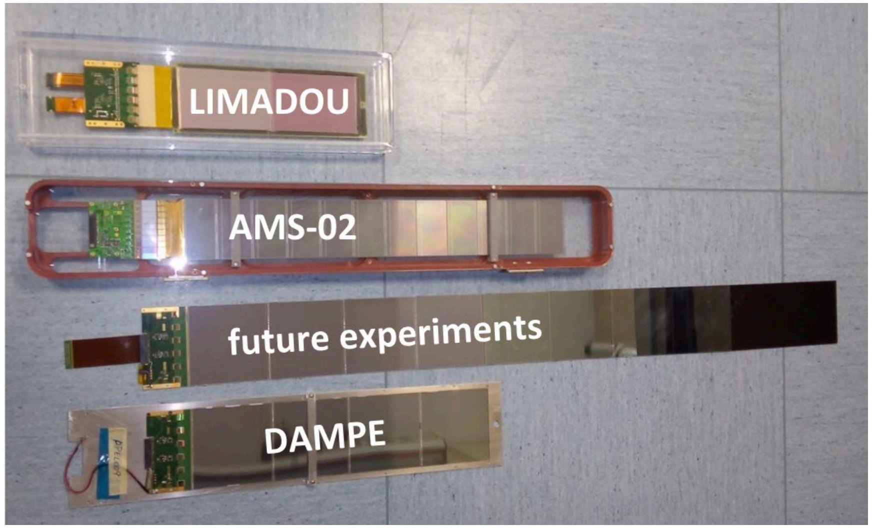


See D. Miao "Design and testbeam study of AMS-02 Layer-0 silicon strip detector ladders " talk

AMS-02 upgrade, Layer-0 (1/4 plane) @ INFN Perugia, Terni labs



INFN Perugia



Capacitance and daisy-chain

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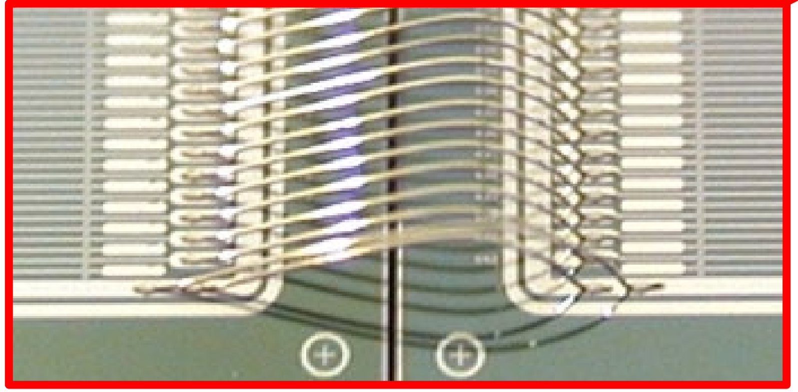
→ 50-100 cm long strips are obtained through daisy-chain



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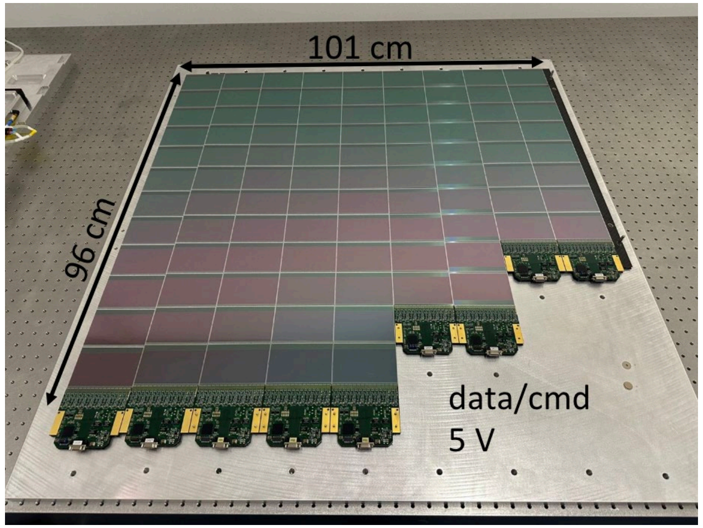
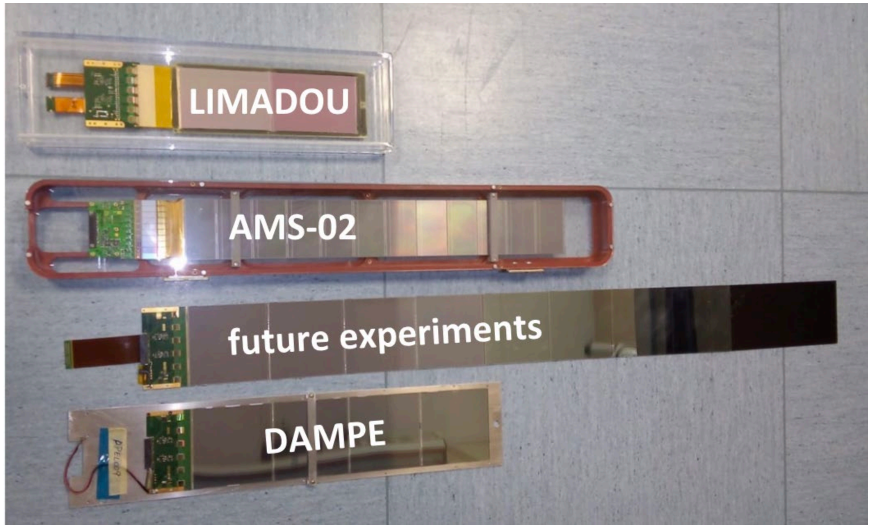


INFN Perugia



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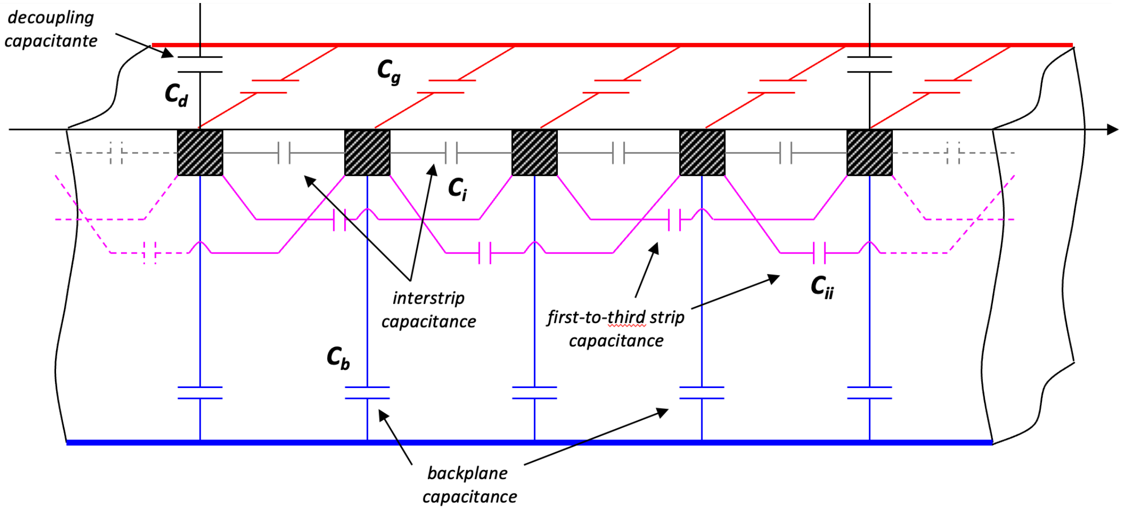
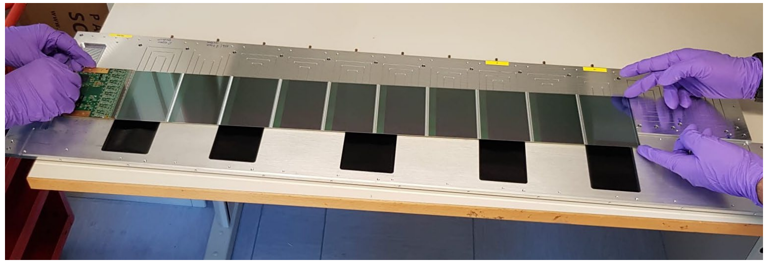


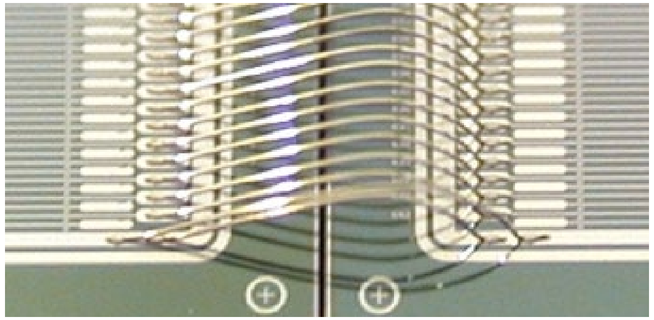
p = pitch (typical 25-50 µm)
l = strip length (typical 50-100 cm)
d = thickness (typical 300 µm)

C_i = interstrip capacitance ~ 1 pF/cm * *l* = 10 – 100 pF
C_d = decoupling capacitance ~ 1000 pF (DC sensors) or 120 pF/mm^2 (AC sensors) > C_i C_b C_g C_{ii}
C_b = backplane capacitance ~ 1 pF/cm * *l* * *p/d* = 1/10 * 10 – 100 pF = 1- 10 pF
C_g = guard-ring capacitance << C_i
C_{ii} = first-to-third strip capacitance << C_i

For thin and long strips, capacitance must be kept under control

AMS-02 upgrade, Layer-0 ladder @ INFN Perugia





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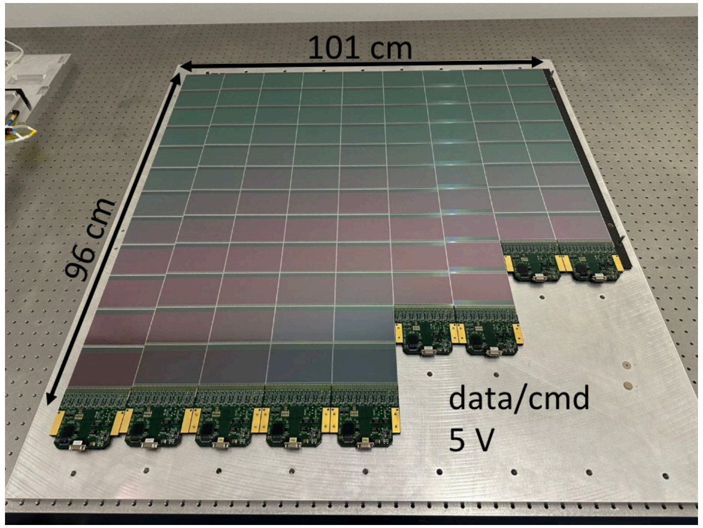

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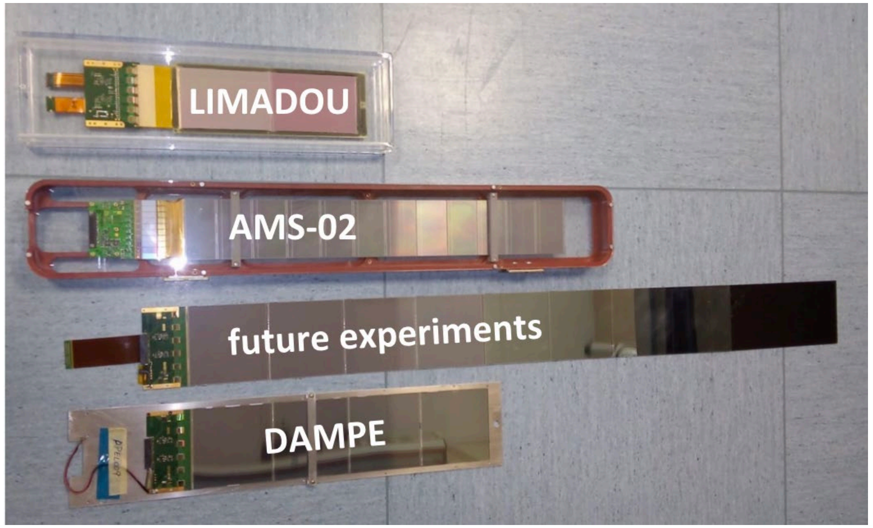

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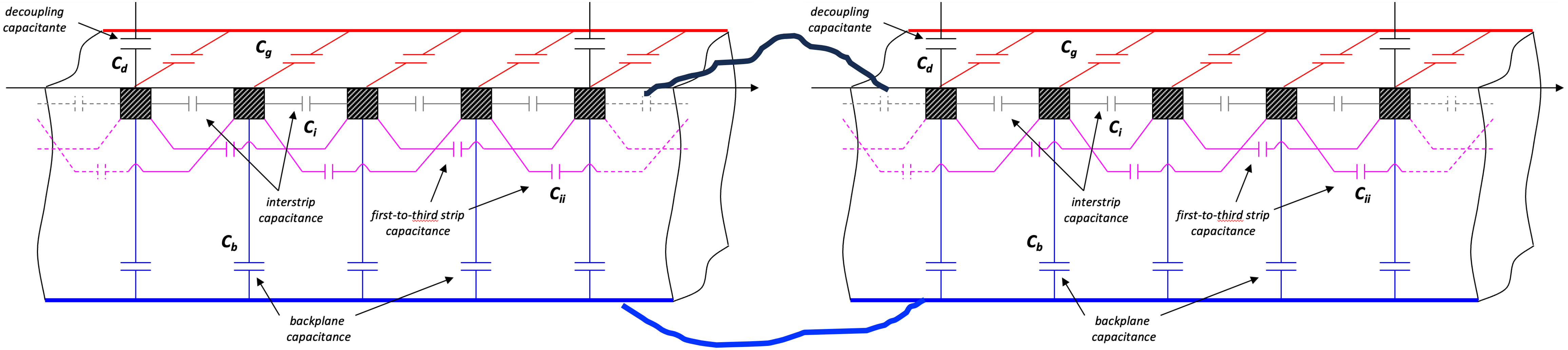

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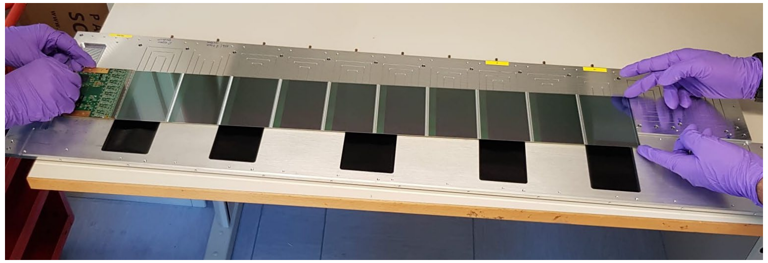

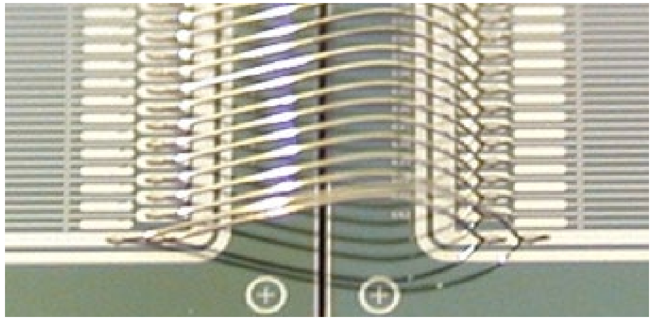

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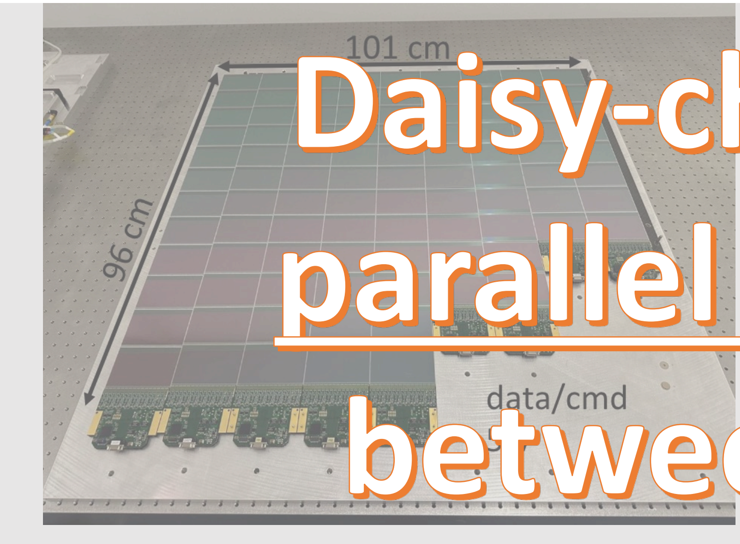
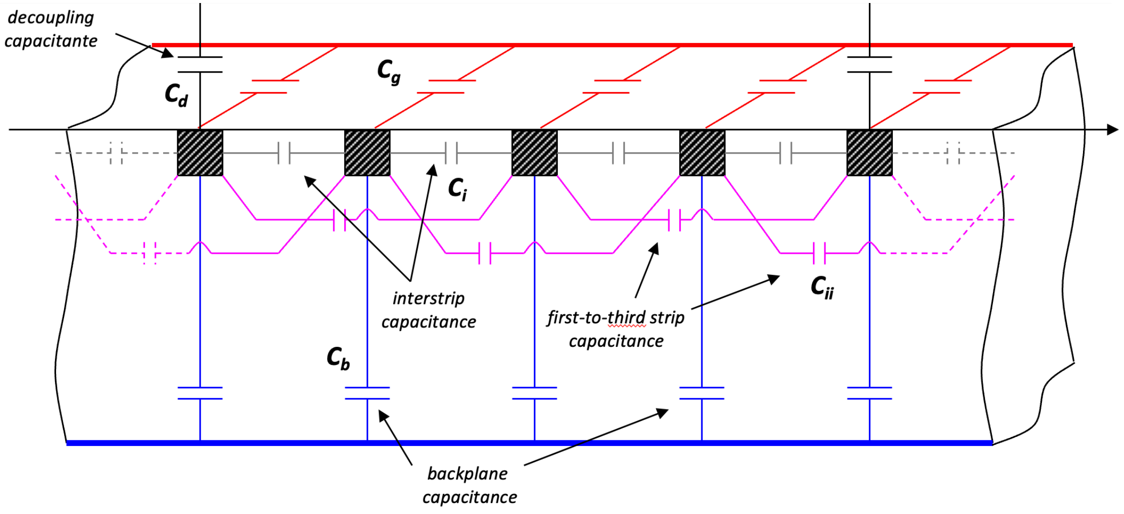


INFN Perugia

Daisy-chain means parallel connection between sensors

Capacitance and daisy-chain



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For thin and long strips, capacitance must be kept under control

$C_{interstrip}$ ~ 1 pF/cm * *l*
→ 50 – 100 pF

C_{back} ~ 1 pF/cm * *l* * *p/d*
→ 100 – 200 pF

Notice that:

- Typically, 300µm (AMS, DAMPE) – 500µm (Fermi-LAT) thick sensors are used
  → C_i is ~ dominant
- when you go thinner (as for LGADs, see later) C_i is negligible with respect to C_b

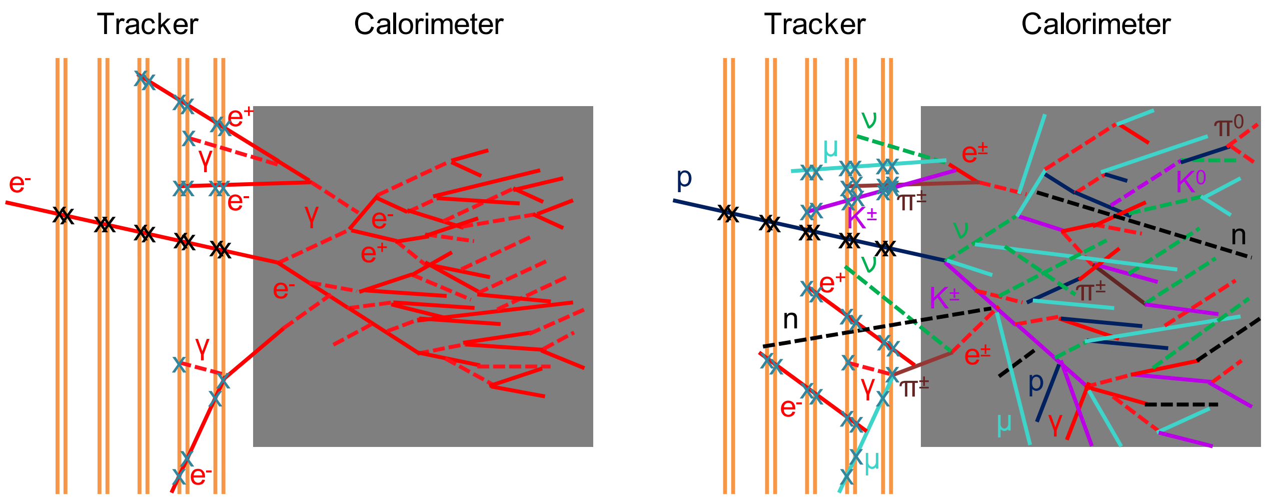
→ a typical "area" of a strip is of *O*(cm^2)
→ a typical "area" for a LHC (LGAD) sensor is < 1 mm^2

Large area 5D-Tracking in space

M. Duranti et al., *Instruments* 2021, 5(2), 20

Backsplash particles from downstream calorimeter affect tracking efficiency by tens % at 1 TeV

Different backsplash timing signatures in upstream tracker from primary $e^{+/-}$ or h



The idea of "exploiting" the backsplash hits in a "timing-tracker"
was firstly and preliminarily discussed in 2019 (TREDI2019)

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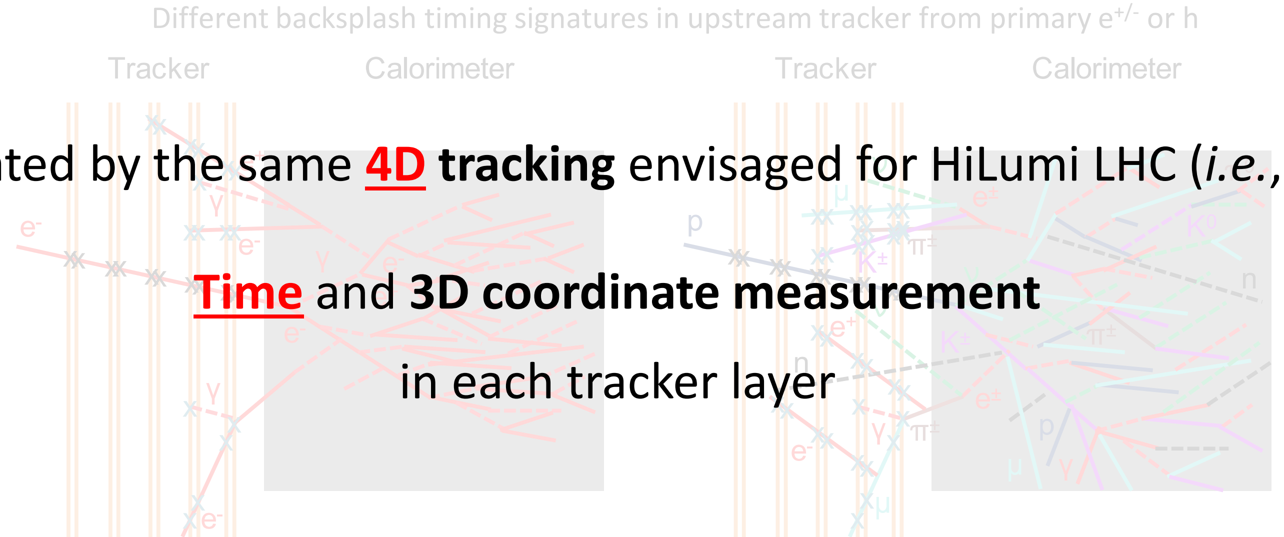

Could be mitigated by the same **4D tracking** envisaged for HiLumi LHC (*i.e.*, high pile-up)

Time and **3D coordinate measurement**

in each tracker layer

In addition to **coordinate** and **charge** |Z| measurements, **concurrent timing information** at hit-level in tracker **(5D-tracking)** may improve reconstruction efficiency and particle ID, such as:

IMPROVED TRACK FINDING
Hit timing information improves track reconstruction on high rate environments and identifies back-scattering hits from downstream calorimeters

REMOVE "GHOST" HITS
Separating tracks in time can mitigate the ambiguity of "ghost" hits in SiMS with strips running in perpendicular directions

TIME OF FLIGHT
Hit timing resolutions of ~ 100 ps enable ToF measurements with SiMS complementary to scintillators with fast light readout

PARTICLE ID
Track timing identifies slow low-energy particles backscattering from downstream calorimeters for primary hadronic particle crossings

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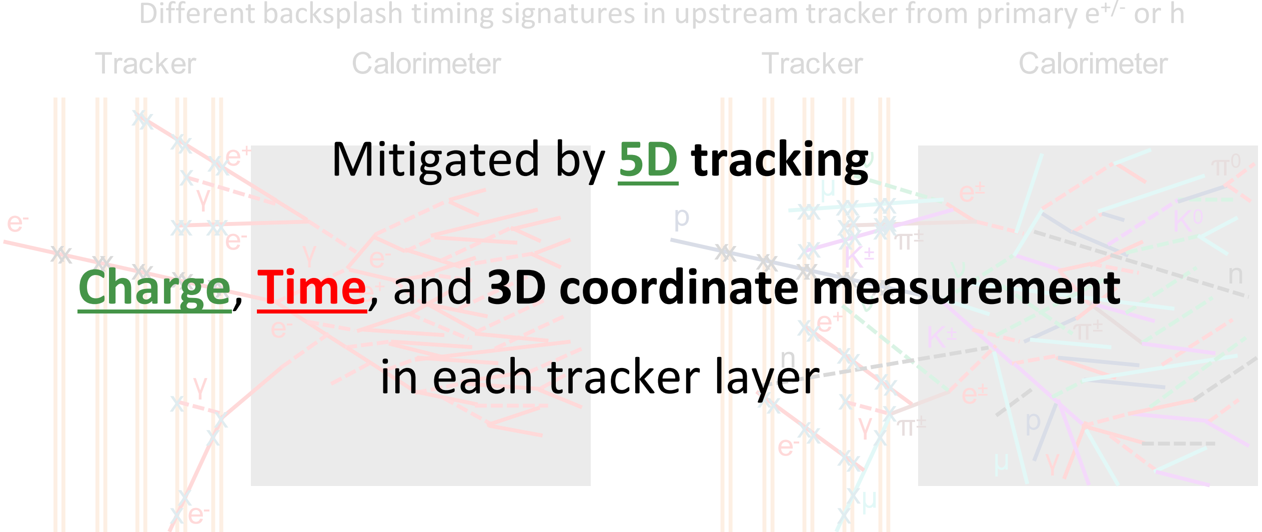

Mitigated by **5D tracking**

Charge, **Time**, and **3D coordinate measurement**

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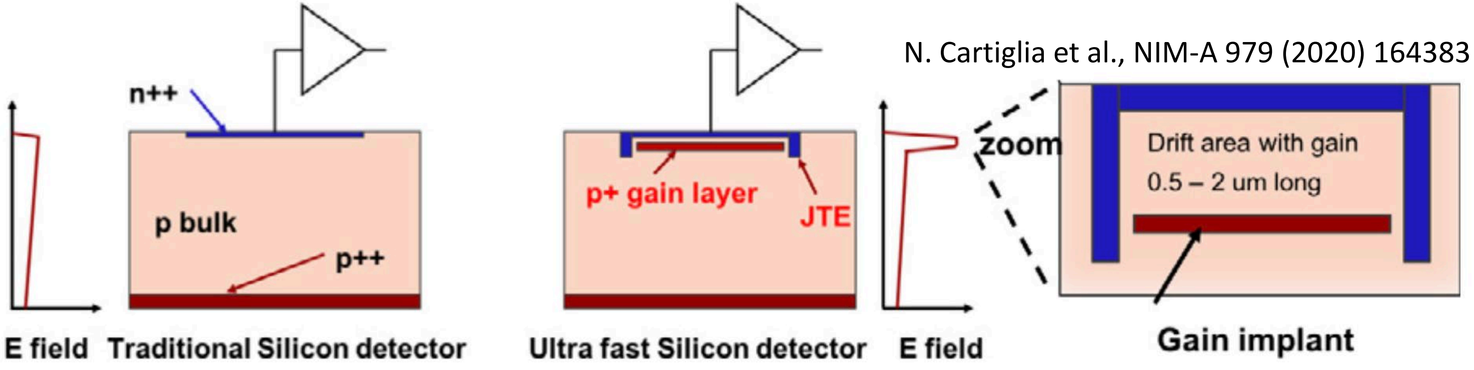
Tracking with Low Gain Avalanche Diodes

R&D mostly driven by next-generation collider detectors / upgrades

Physics requirement: time information on all hit of tracker detectors for high-energy and high-intensity HEP colliders

- < 30ps timing resolution
- O(10)µm spatial resolution
- $O(10^{16}) n_{eq}/cm^2$ radiation tolerance

N. Cartiglia et al., NIM-A 979 (2020) 164383



Basic principle:

- **Thin** Si sensor (<150µm), with intrinsic moderate gain obtained with a gain layer creating high E-field
- **Gain**: 10-50
- Excellent **timing** performances: ~20 ps

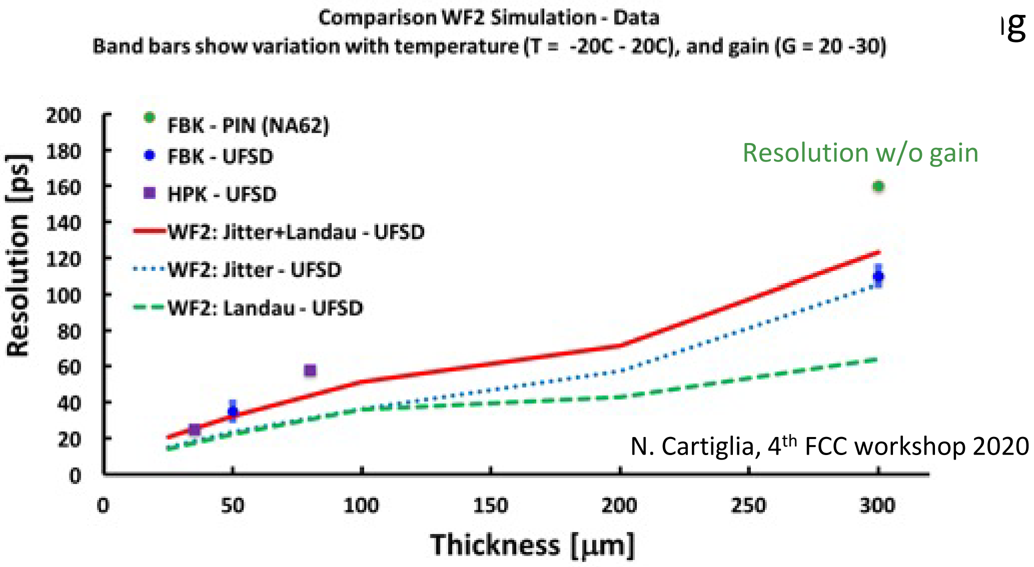
LGAD design optimized for improved timing resolution

(Ultra Fast Silicon Detectors, UFSD)

$$\sigma^2_{TIME} = (\sigma^2_{TIMEWALK} + \sigma^2_{JITTER} + \sigma^2_{TDC})$$

High-V biased thin sensors -→ saturated v_{drift}

increase signal in thin sensors → intrinsic gain



Optimal candidate for large-area 4D Tracking devices

Pentadimensional Tracking Space Detector

R&D activity to increase LGAD Si-μstrip TRL for space from TRL=2 to TRL=5

WP1	WP2	WP3	WP4
Management and dissemination	Sensor design and production	Proto-detector qualification	Scientific applications space mission design
INFN, ASI	**INFN**, ASI	**INFN**, ASI	**ASI**, INFN
	+ FBK as INFN-sub-unit		

INFN
Perugia, Bologna, Roma Tor Vergata
PI: Matteo Duranti

ASI
Headquarters (Roma)
co-PI: Valerio Vagelli

Main objective

Develop a breadboard laboratory model for verification of requirements, functionalities, and space qualification of LGAD μstrip

Funding and activities started in Sep 2023, duration 2 years, c.a. 200k€ fundings

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Pentadimensional Tracking Space Detector - ASI

R&D activity to increase LGAD Si-μstrip TRL for space from TRL=2 to TRL=5

Agenzia Spaziale Italiana

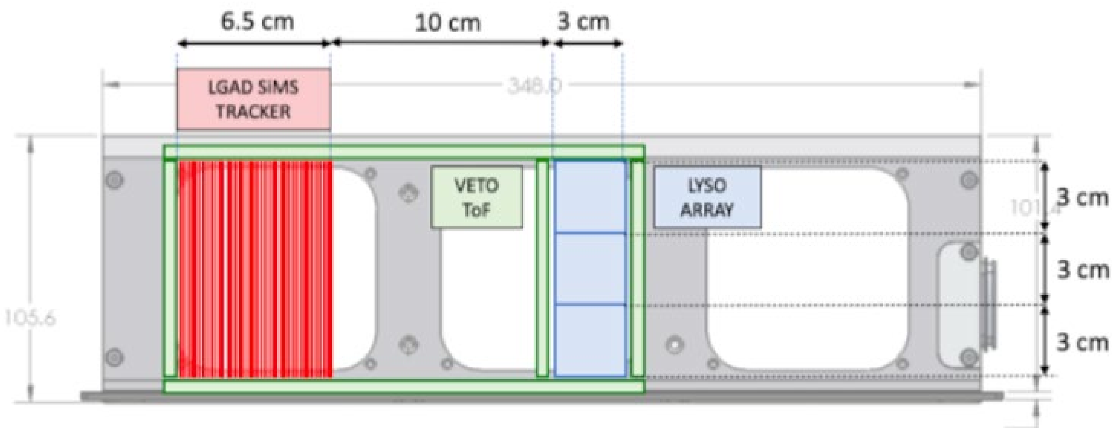
WP1	WP2	WP3	WP4
Management and dissemination	Sensor design and production	Proto-detector qualification	Scientific applications space mission design
INFN, ASI	INFN, ASI	INFN, ASI	ASI, INFN

INFN
Perugia, Bologna, Roma Tor Vergata
PI: Matteo Duranti

ASI
Headquarters (Roma)
co-PI: Valerio Vagelli

A conceptual design of the demonstrator compatible with the constraints in weight, volume, and power budget of a CubeSat platform
Hosted in 2 units of a 3U CubeSat,
with one additional unit dedicated to the FEE and DAQ of the demonstrator.

Weight < 3 kg   Power < 20 W

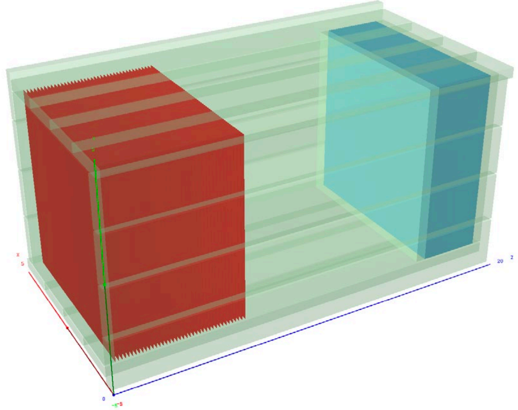


LGAD SiMS Tracker
40 layers of 150 μm thick SiMS LGADs
readout pitch: 150 μm
- expected Δx ~ 15μm

Target timing resolution ~ 100 ps

Veto / Time of Flight system
0.5 cm thick Sci-paddles
SiPM readout using commercial FEE
Δt ~ 30 ps

Electromagnetic Calorimeter
3x3x3 cm^3 array of LYSO crystals
SiPM readout using commercial FEE
Feasibility to add another stack of LYSO array under study



Simulation of the detector performances is ongoing

Perspectives to fly a CubeSat demonstrator to reach TRL=9 in a follow-up activity

Pentadimensional Tracking Space Detector - INFN

R&D activity to increase LGAD Si-μstrip TRL for space from TRL=2 to TRL=5

WP1
Management and dissemination
INFN, ASI

WP2
Sensor design and production
INFN, ASI

+ FBK as INFN-sub-unit

WP3
Proto-detector qualification
INFN, ASI

WP4
Scientific applications space mission design
ASI, INFN

INFN
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ASI
Headquarters (Roma)
co-PI: Valerio Vagelli

Is possible to cover tens of m² of tracking areas with LGADs and:

- <100 (ideally 20-30) ps timing
- <10 μm spatial resolution
- <100 W / m²
- <100 K_{ch} / m²

?

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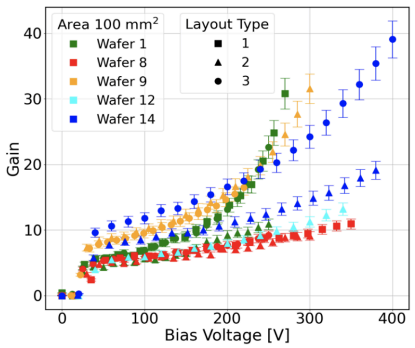
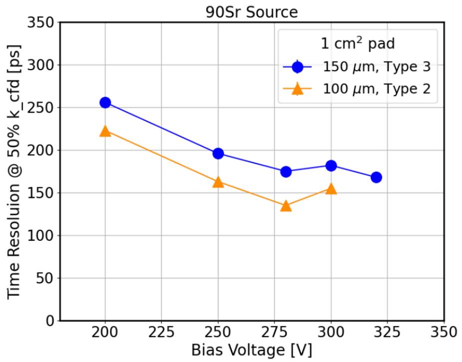
from ASAPP 2025 L. Cavazzini's talk

Space LGADs for AstroParticle Physics: Performances



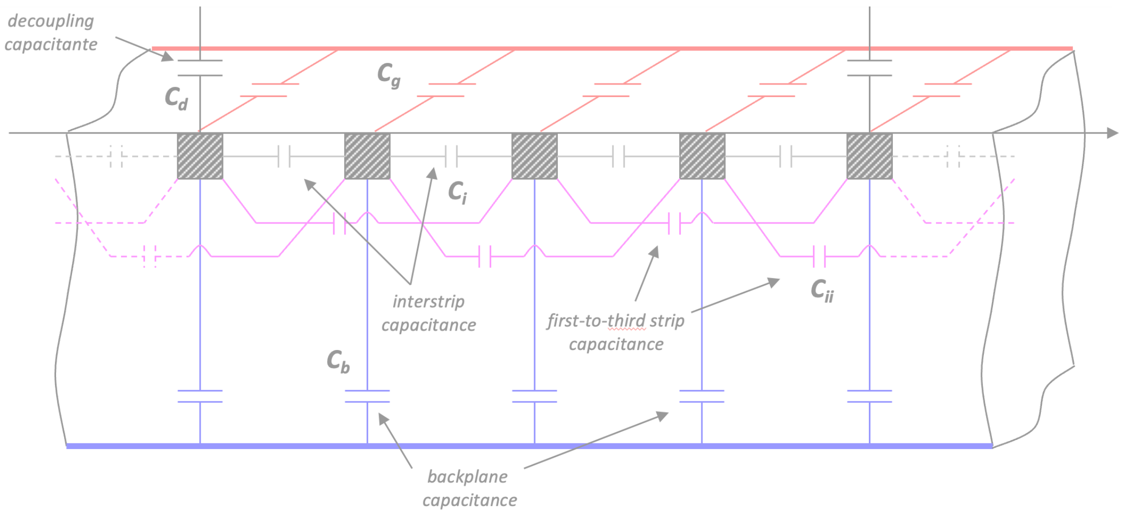


How much is the maximum length of a Si LGAD μstrip?

Is it possible to "daisy chain" LGADs?

Is there a way to mitigate this problems and, for example, reduce the capacitance even with very thin LGAD sensors?

In-series readout of LGADs: the SiPM example

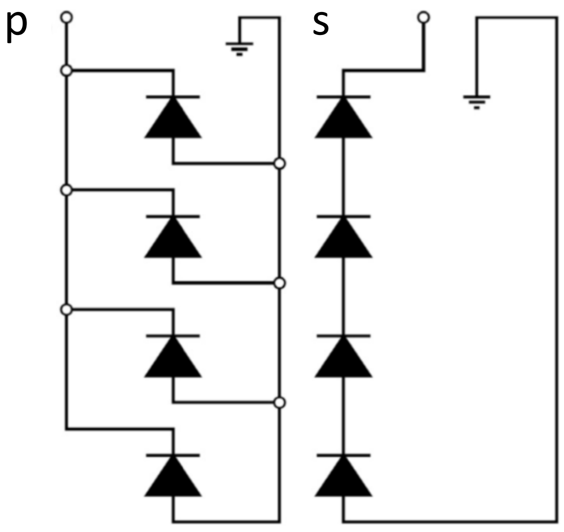


p = pitch (typical 25-50 µm)
l = strip length (typical 50-100 cm)
d = thickness (typical 300 µm)

C_i = interstrip capacitance ~ 1 pF/cm * *l* = 10 – 100 pF
C_d = decoupling capacitance ~ 1000 pF (DC sensors) or 120 pF/mm^2 (AC sensors) > **C_i C_b C_g C_{ii}**
C_b = backplane capacitance ~ 1 pF/cm * *l* * *p/d* = 1/10 * 10 – 100 pF = 1- 10 pF
C_g = guard-ring capacitance << C_i
C_{ii} = first-to-third strip capacitance << C_i

For thin and long strips, capacitance must be kept under limit

p) standard "parallel" readout
√ bias voltage independent on number of sensors
X total capacitance seen by readout FEE scales with number of sensors

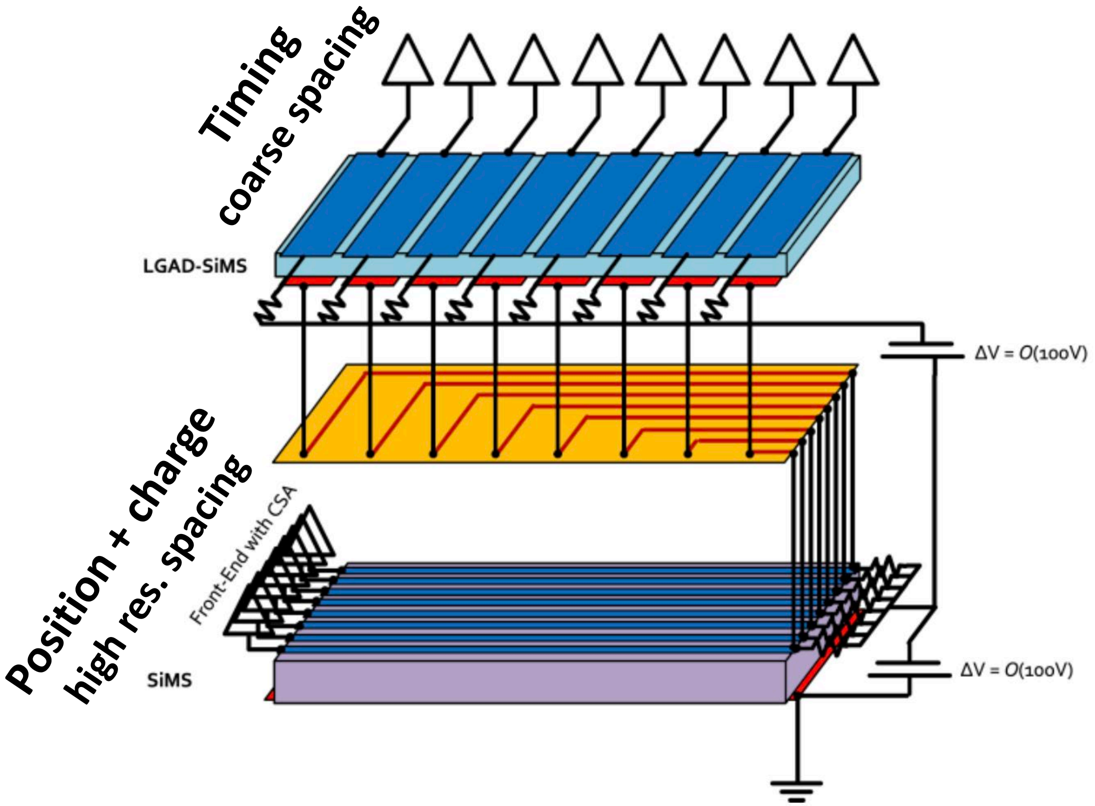


N. Kratochwil et al., **PANDA** experiment

s) "in-series" readout
X bias voltage scales with number of sensors
√ total capacitance seen by readout FEE scales **down** with number of sensors

--> can we "port" this approach to LGADs?

“Stacked” 5D sensor



Starting proposed design
Possible connections for a 5D detector made of a thin LGAD Si-µstrip sensor for timing and moderate resolution coordinate measurement coupled with a thicker standard SiMS sensor for charge and high-resolution coordinate measurement.

Driver design: LGAD + standard Si-µstrip in series readout

- combine a standard µstrip sensor (2D + Z) with an LGAD (2D + timing)
- In-series readout of the "stack" to reduce LGAD capacitance
- use standard µstrip as "structural" material for a very thin LGAD layer

Strips running in opposite directions → measurement of 2D coordinates with different resolutions

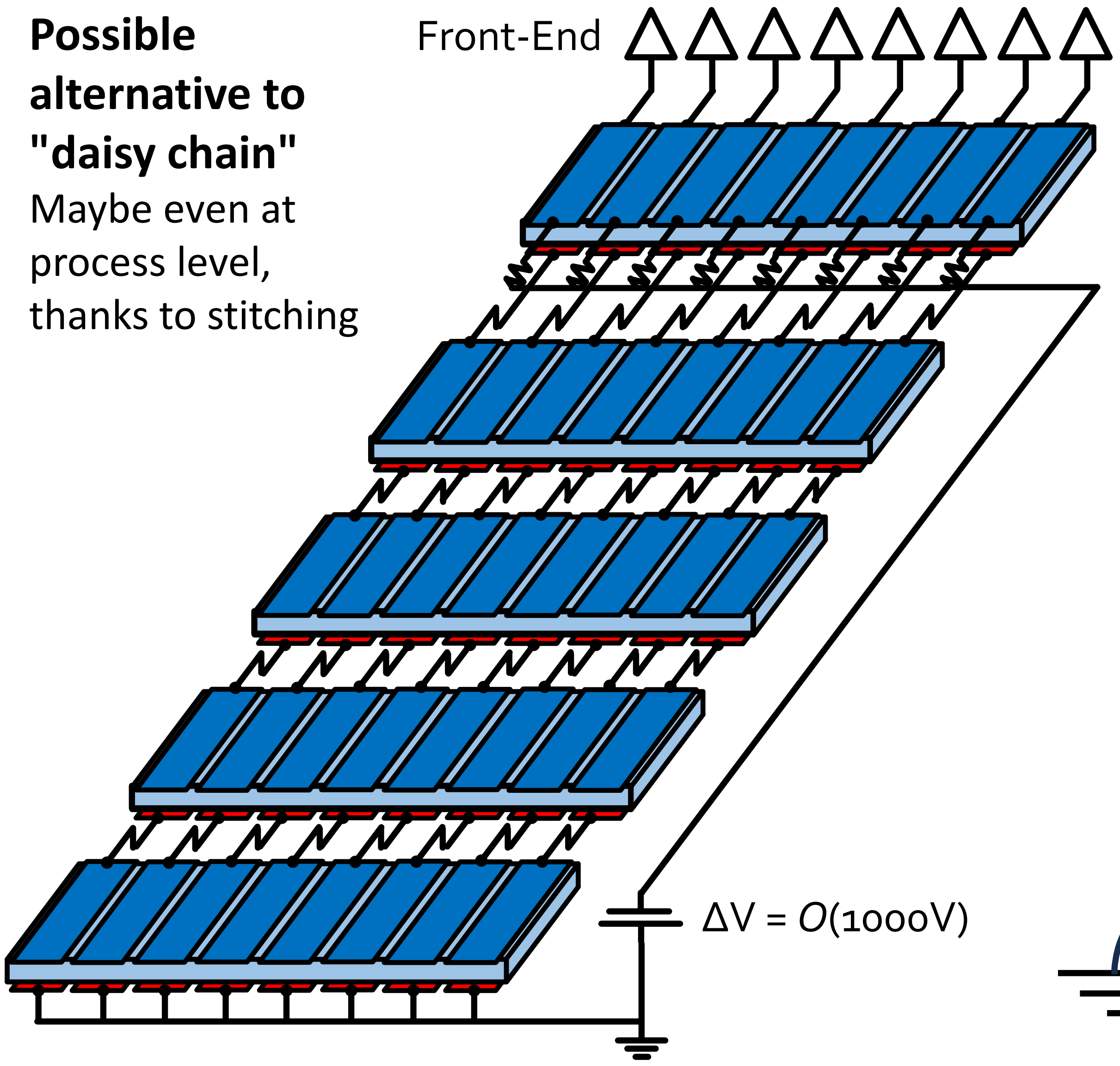
- suits the requirements for a **tracking system in a magnetic spectrometer with oriented magnetic field**

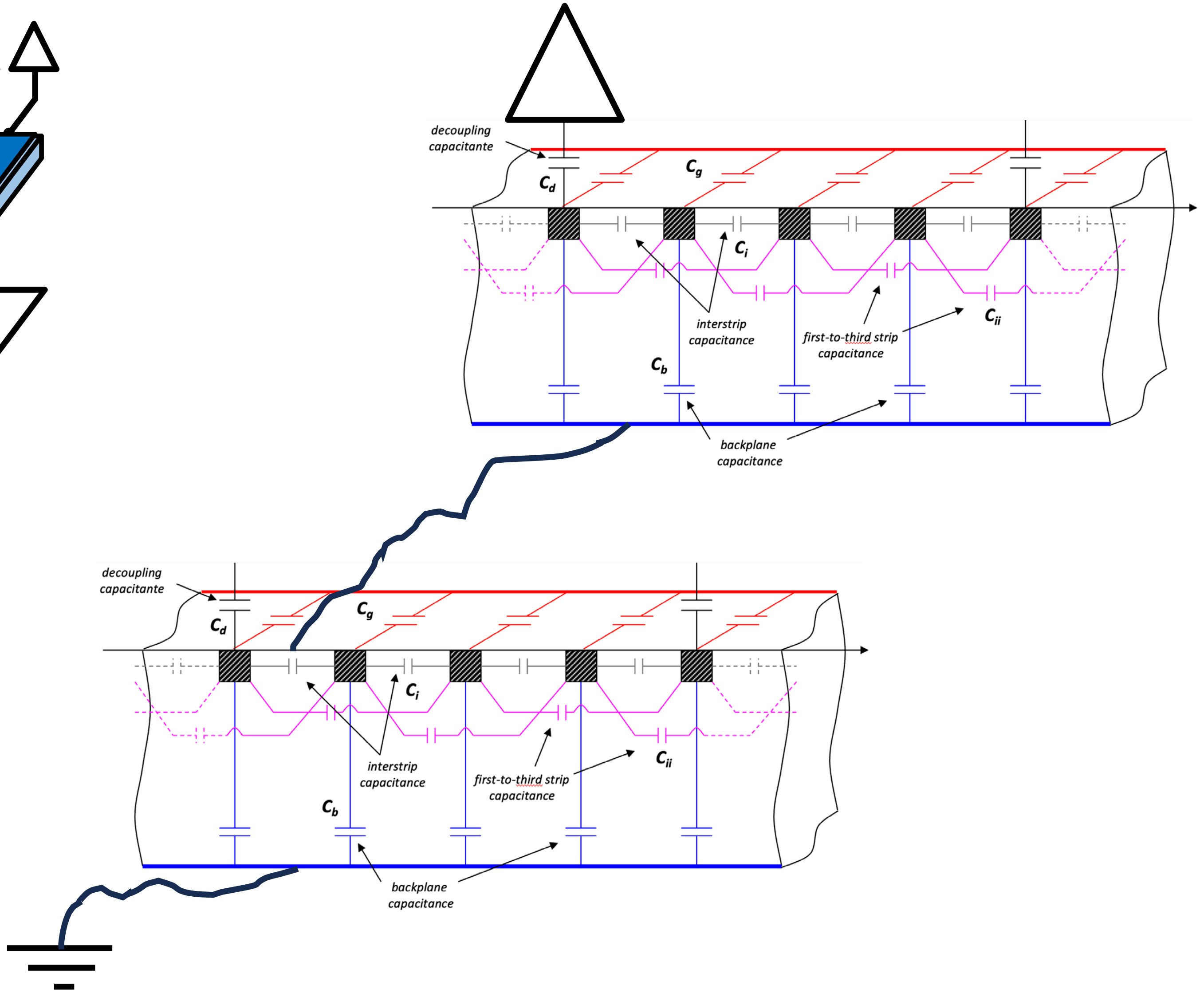
Of course there are not only benefits:

- mechanical structures and interfaces will be an issue
- requires a double-sided LGAD
    - costs and risks of process development, yield, assembly, ... increase

More “advanced” ideas…

Possible alternative to "daisy chain"
Maybe even at process level, thanks to stitching

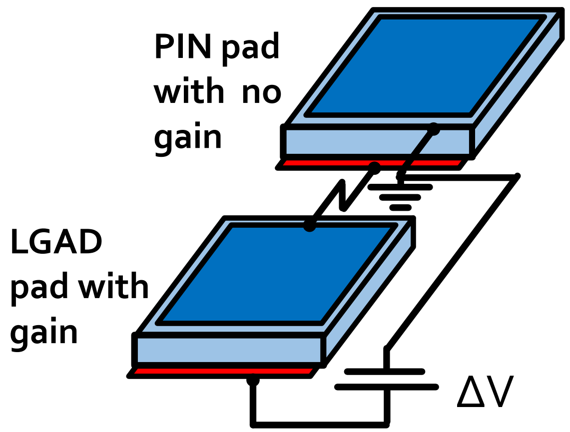


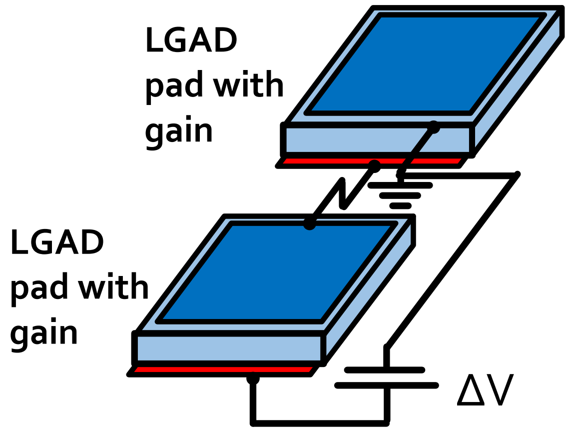


More “advanced” ideas…

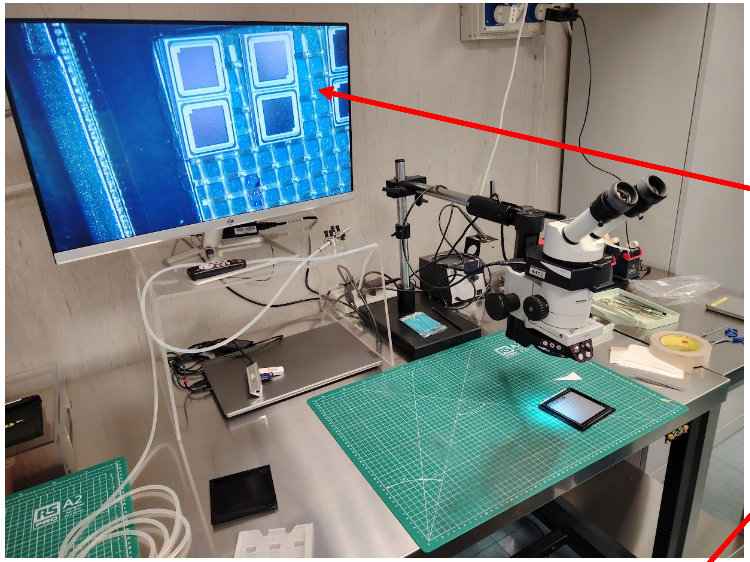
Let's start with a single pad “sandwich”

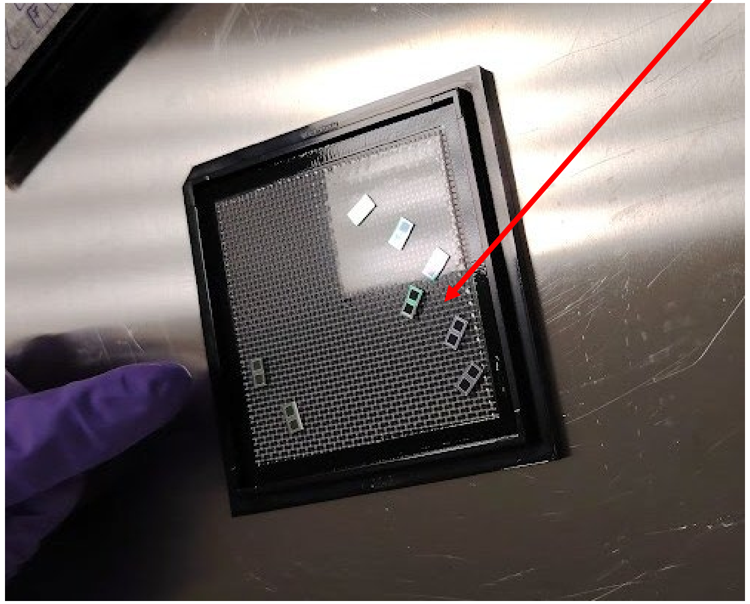
To test the idea



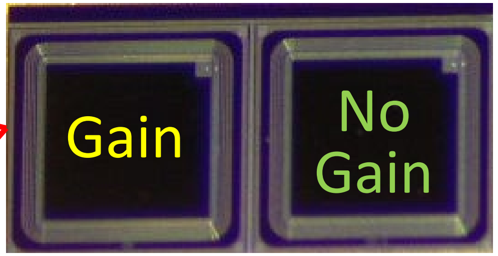


“Stacked” 5D sensor – Proof of concept lab tests

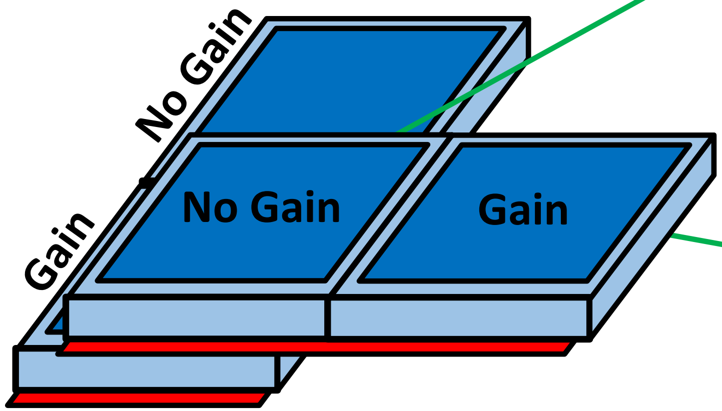




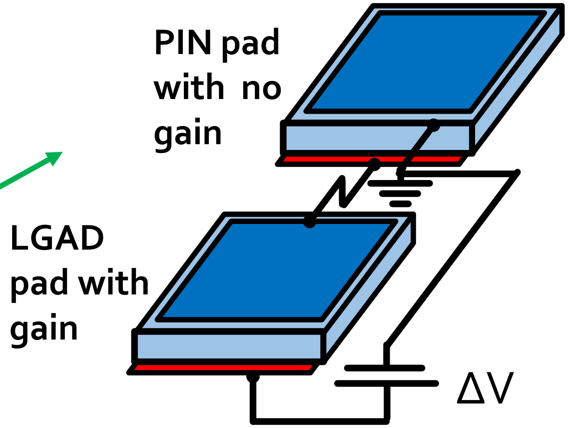
With test structures
(FBK, from the MoveIT project, which we thank)

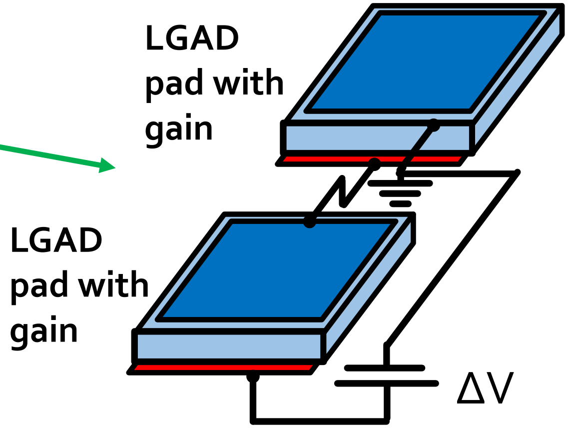


we could test (J. Hu and M. Savinelli) the idea with a prototype like this:

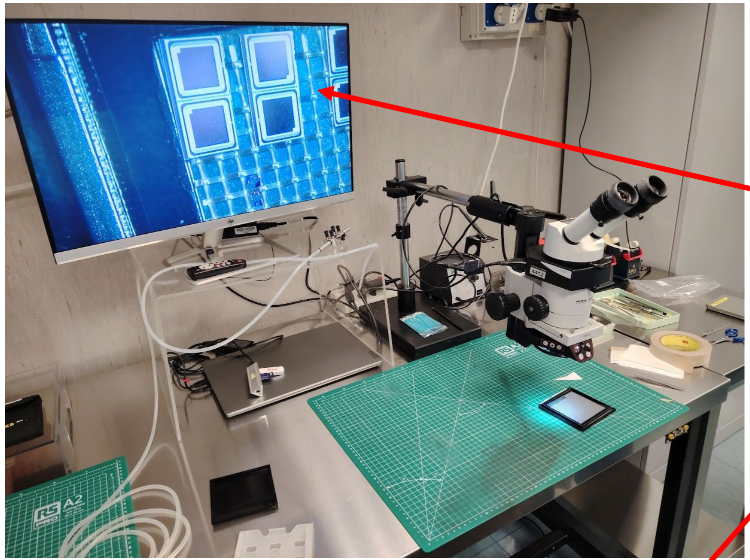


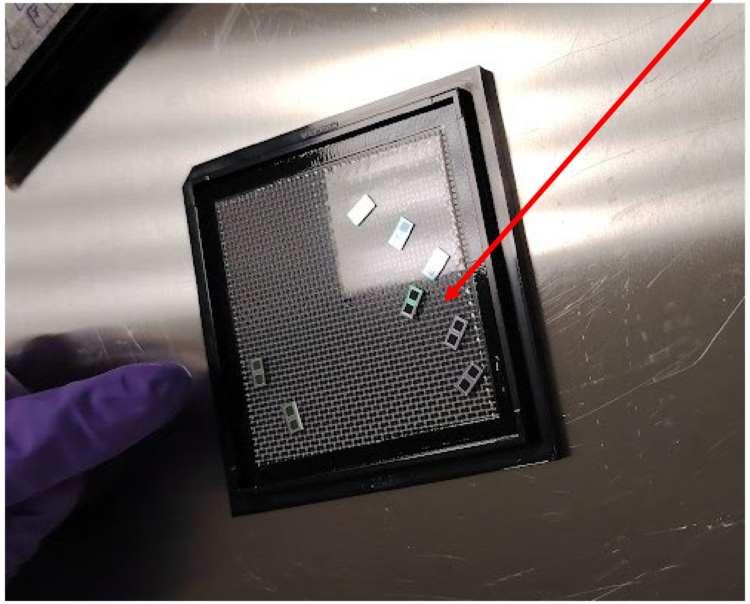
the two devices were glued with small spots of glue: the "No Gain" region on the bottom was "protected" with Kapton so to connect only the "Gain" region with the back of the top device





“Stacked” 5D sensor – Proof of concept lab tests





Thanks to test structures
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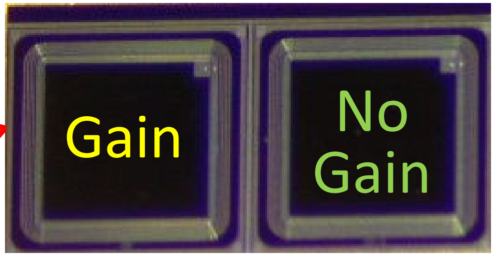

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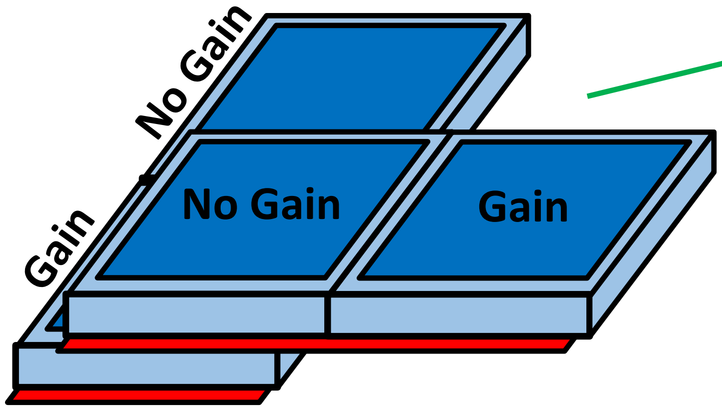

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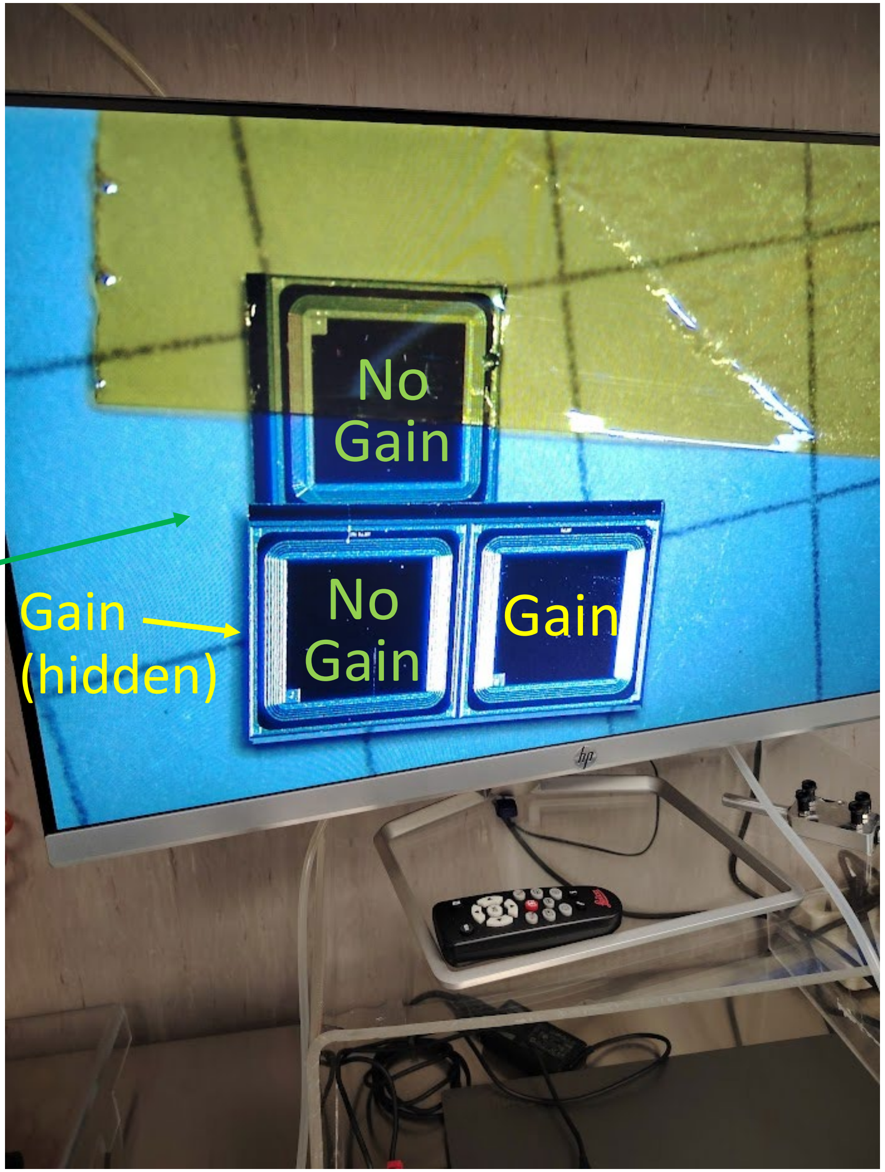
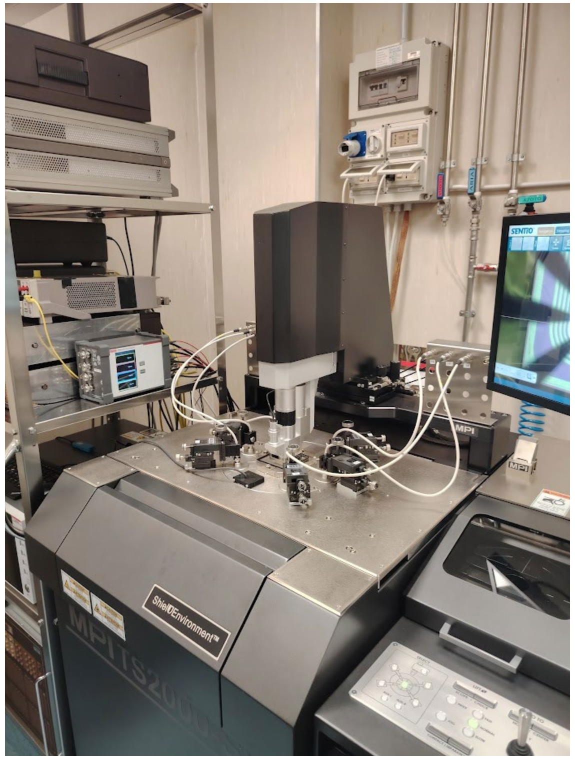


Proof of concept lab tests: single test structure

C-V and I-V measurements with the probe-station in the INFN Perugia Clean Room (thanks to F. Moscatelli)



“No gain” / PIN

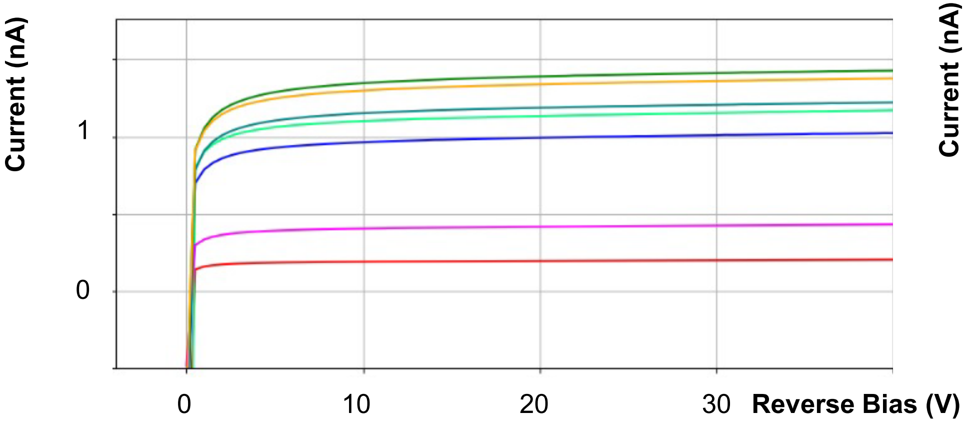
I_{LEAK}: 0.5 – 1.5 nA

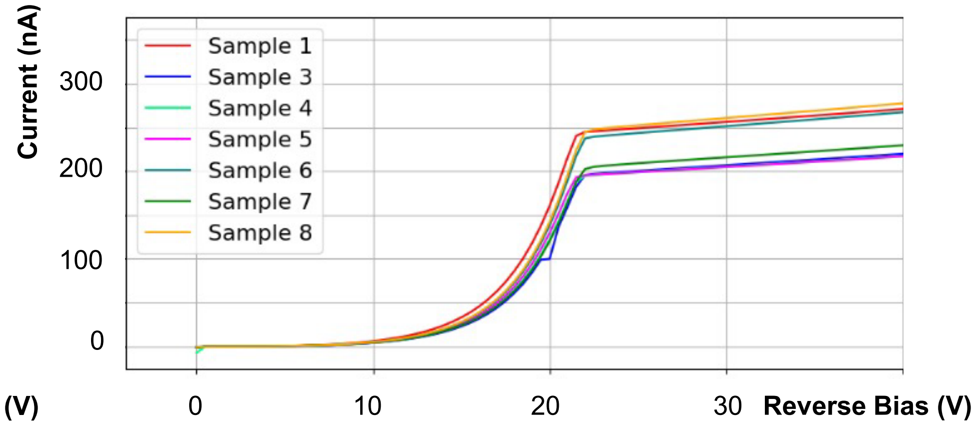
C: 13.9 – 14.7 +/-0.2 pF

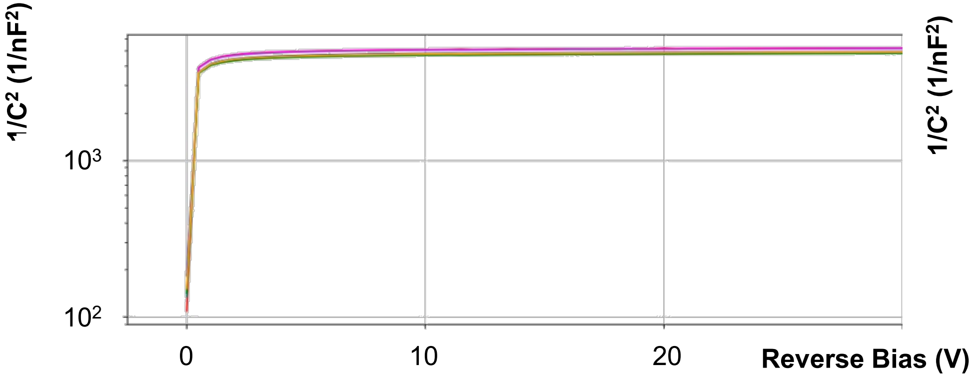
”Gain” / LGAD

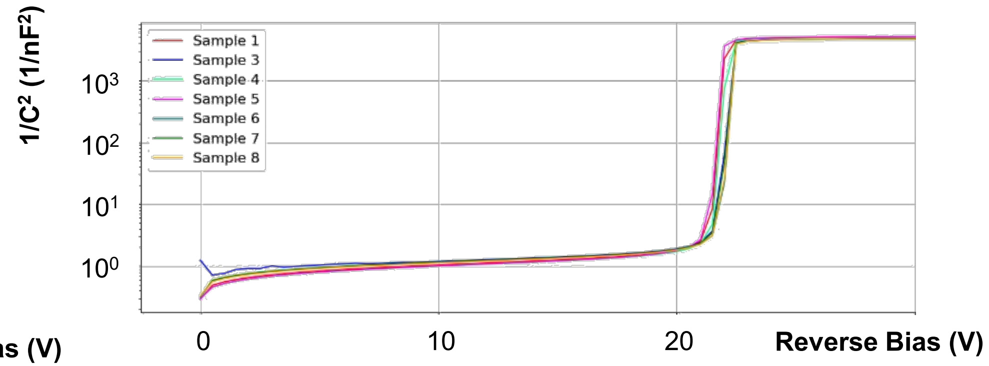
I_{LEAK}: 250 – 350 nA

C: 13.9 – 14.7 +/-0.2 pF

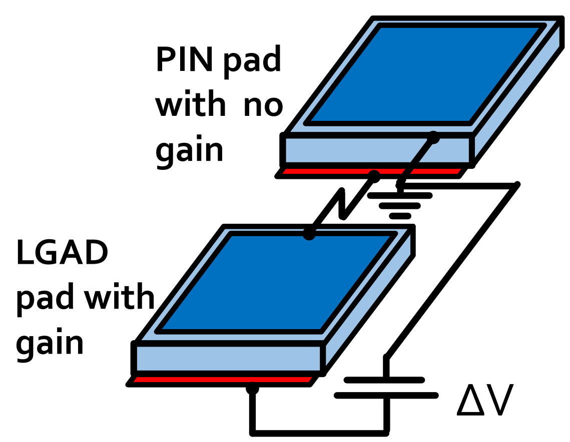


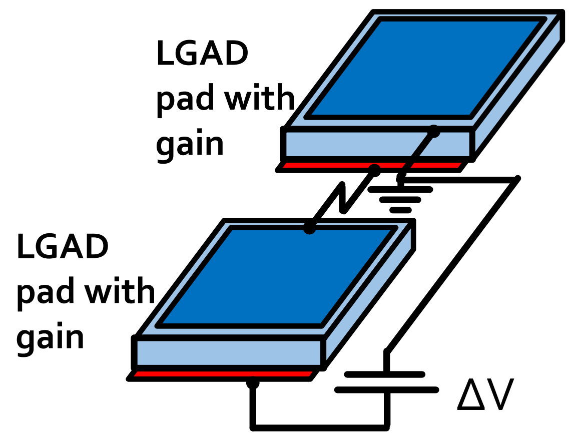


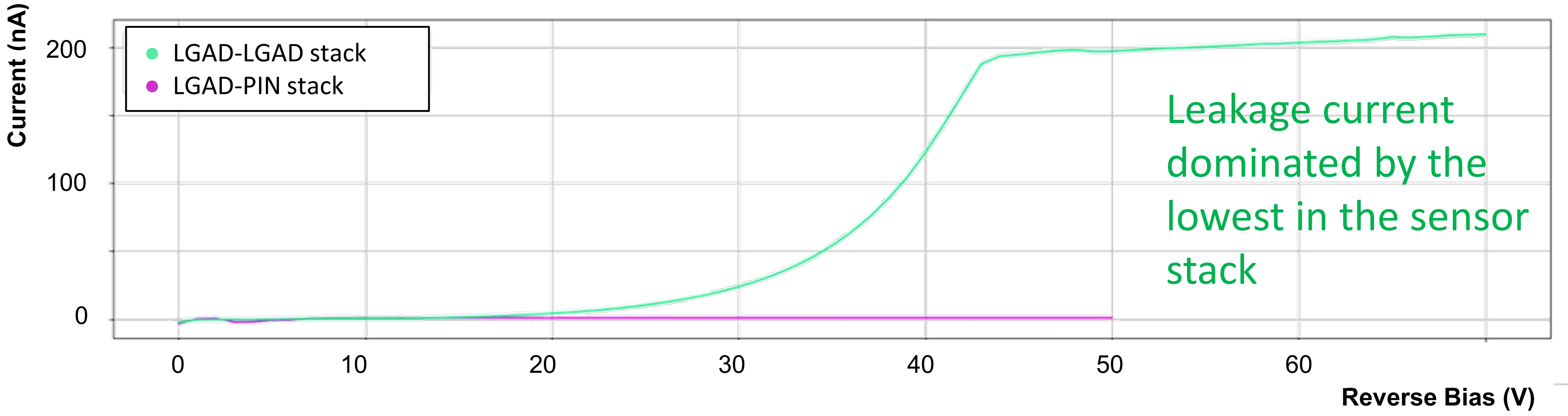




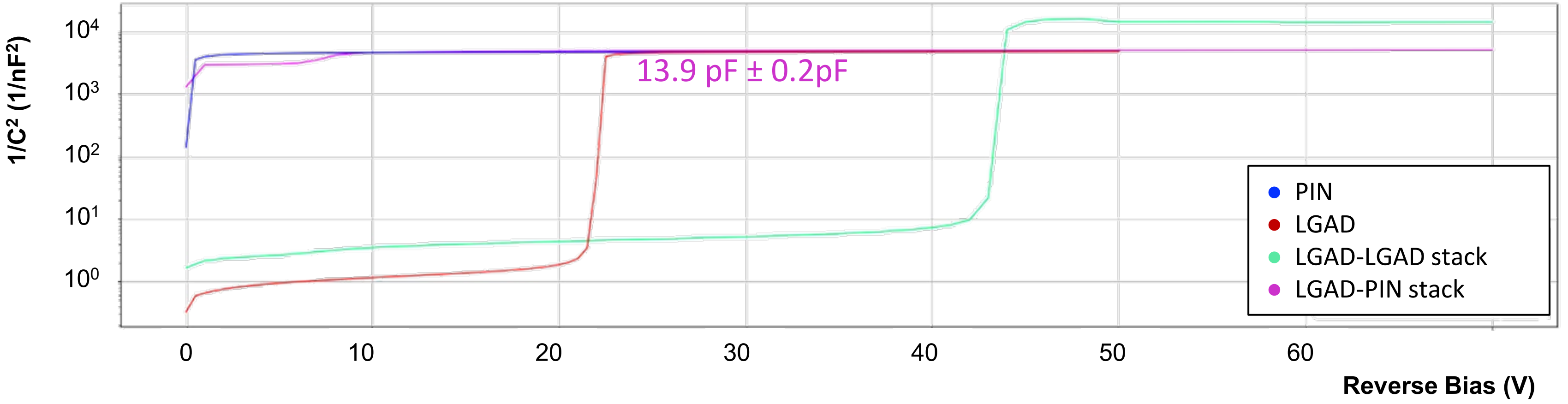
Proof of concept lab tests: “stacked” test structures







Leakage current dominated by the lowest in the sensor stack



$$C_{tot} = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}$$

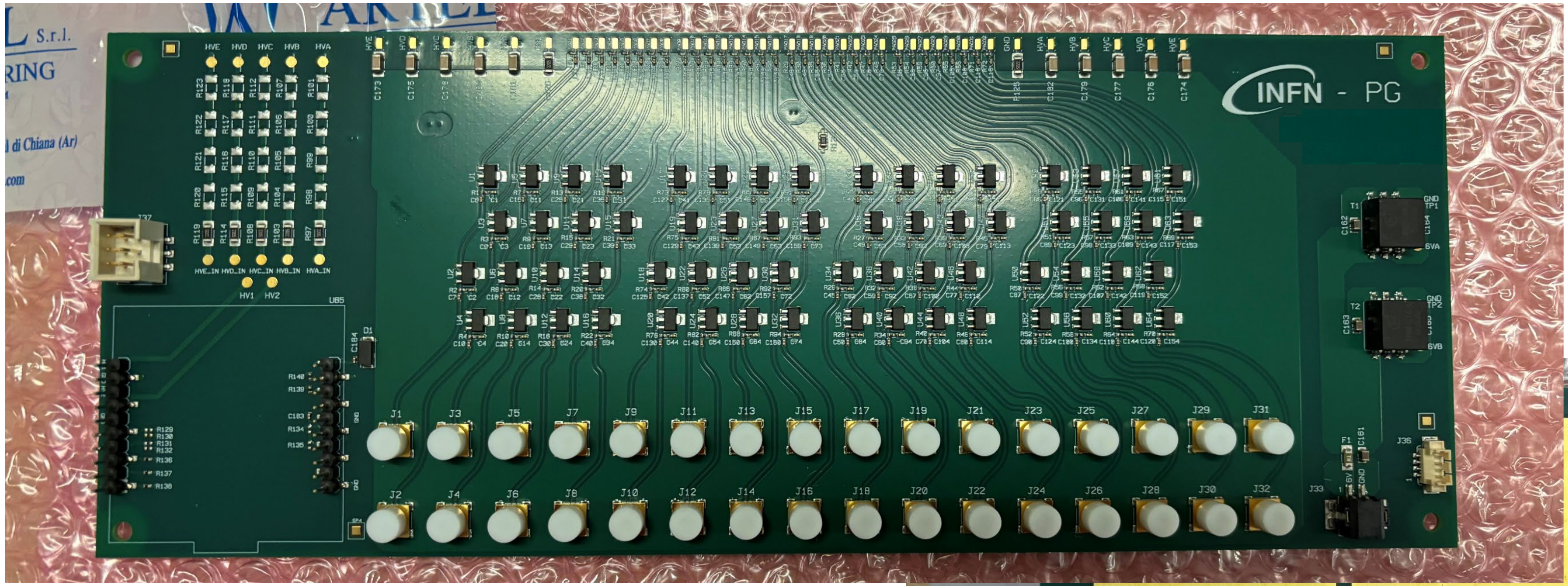
LGAD-LGAD stack C ~ half C_{PIN}
LGAD-PIN stack C ~ C_{PIN}

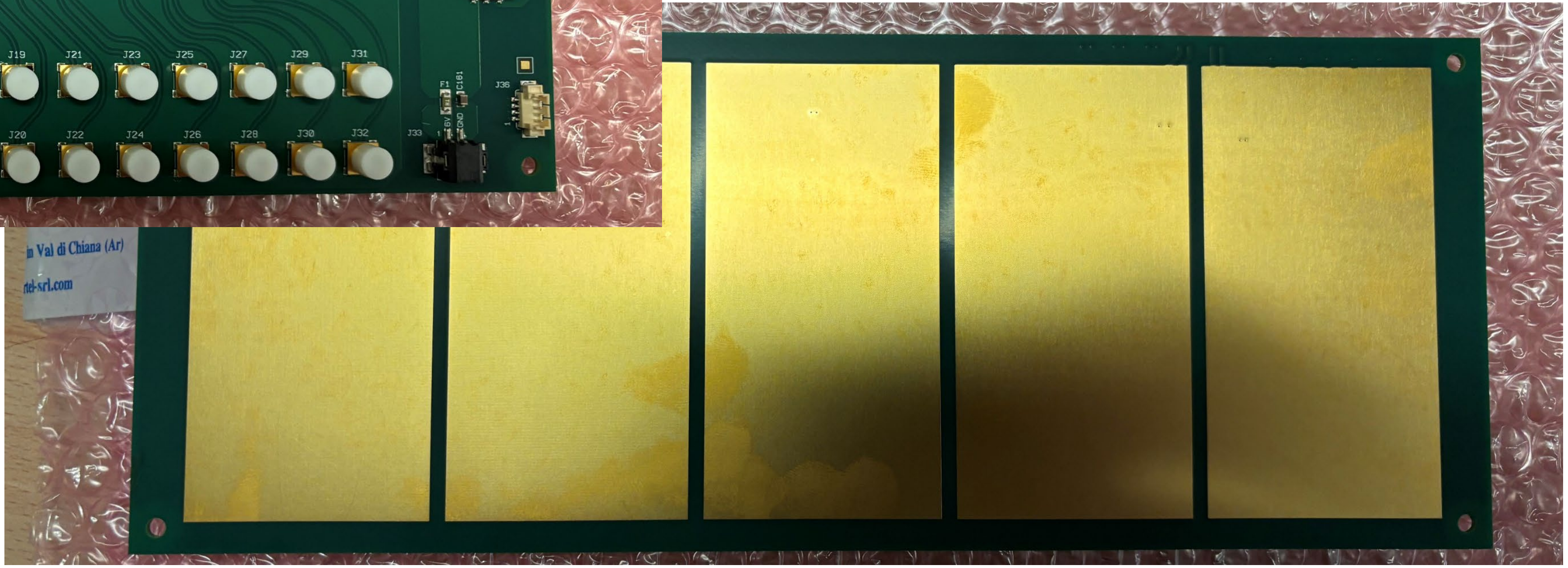
interesting results, more measurements to address discrepancies

FEE board

Based on the Fermilab board (thanks V. Sola, INFN Torino) we're developing our own read-out board:
- 2 stage amps
- 32 channels
- "plate" (with back bias) to stick (conductive tape) the samples to be tested

The 32 channels can be read directly to an oscilloscope or to a digitizer





The board lets us measure the timing performances without dedicate ASICs

TCT

TCT system to measure:
- spatial resolution estimation
- timing resolution estimation

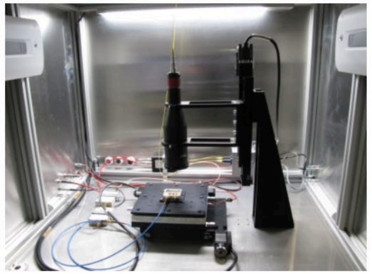
on
- “stacked” test structures
- larger detector (test structures on silicon spares)
- custom sensors (production by end of 2026)

Specifications:

particulars, advanced measurement systems

Component	Parameter	Properties
Laser		
	Laser diode	
	wavelength:	660 nm or 1064 nm (optional others on demand)
	pulse power:	few m.i.p. - 100 m.i.p. (equivalent in 300 micron Si)
	pulse width:	<350 ps - 4000 ps (tunable)
	coupling:	single core fibre
	Driver	
	control:	with PC over USB
	running mode:	single pulse: 50 Hz - 1MHz
		pattern mode: mHz to 100 kHZ
		1024 bits deep sequence of pulses
		minimum distance between two pulses 440 ns
	external control:	external NIM logical signal
	I/O:	ext. trigger in/trigger out MC/trigger out laser

large scanning tct



Large Scanning-TCT aims for the same applications as Scanning TCT. The main difference with respect to the latter is the vertical placement of the optical system and larger and more robust stages that can carry heavy load. The mounting surface is cooled by a combination of several Peltier elements with the combined power of 200W. The mounting plane is much larger and allows also for wider range of movements. Performance wise the properties of both systems are similar.

Conclusions

Pentadimensional Tracking Space Detector (PTSD)
is a project funded by NextGenerationEU and Italian Ministry of University and Research
PNRR M4.C2.1.1, PRIN 2022, n. 2022JNF3M4, CUP ASI F53D23001370008
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani | ASI | INFN

The Pentadimensional Tracking Space Detector project, R&D for space-borne LGAD Si-microstrip tracking detectors

- **5D tracking in space** may open new diagnostics and approaches in cosmic-ray and gamma-ray next-generation instruments
- LGAD best candidate technology to achieve **<100 ps resolution in large area space trackers**
- **R&D** and **spin-in / spin-off** from ground accelerator detectors is needed to increase the TRL

The **PTSD program** aims at:

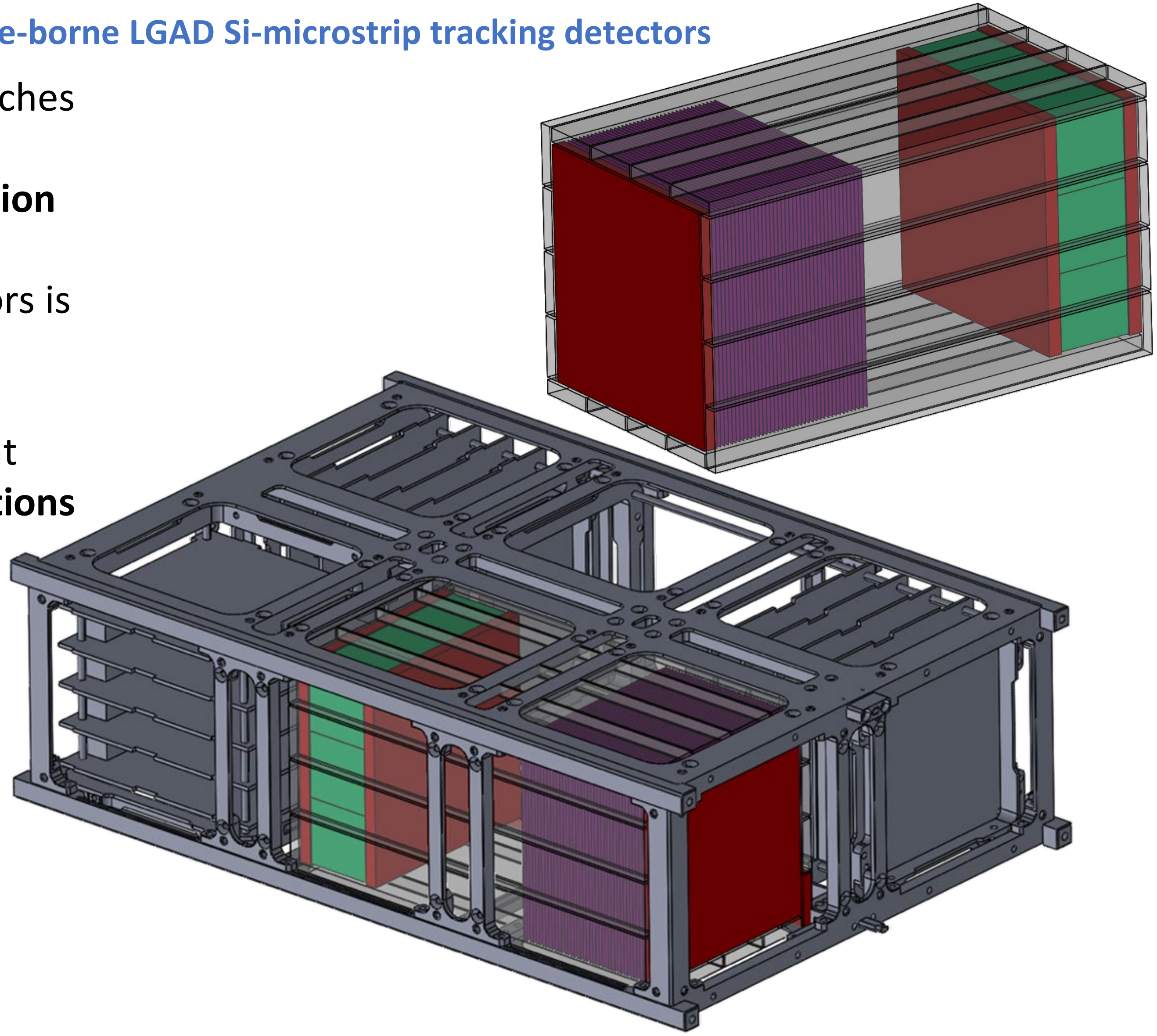
→ verifying proof-of concept and test a breadboard instrument

→ reach **TRL=5 for a timing Si-LGAD system for space applications**

- Design optimization through simulations and laboratory measurements
- Stacked LGAD device laboratory tests as proof of concept
- Details on readout board design and production in progress
    - **Results are encouraging**

→ Consolidating **mission requirements** for a **CubeSat demonstrator to reach TRL=9**

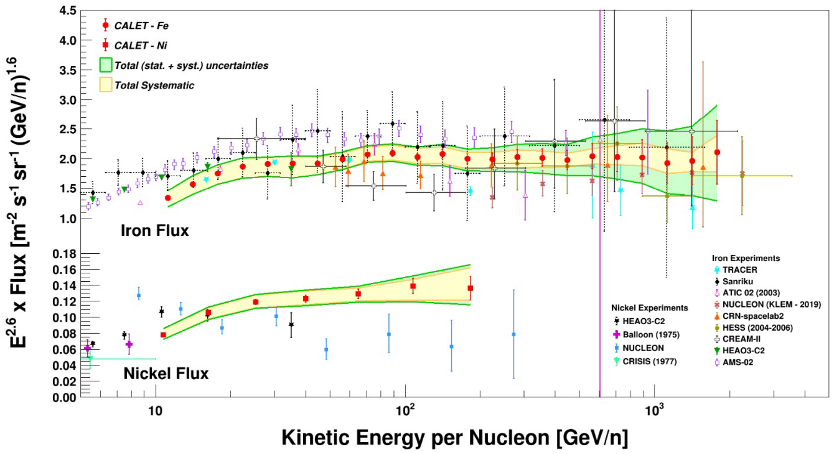
- Ongoing in the Italian Space Agency (ASI) Concurrent Engineering Facility (CEF) (6 out of 8 sessions already done)



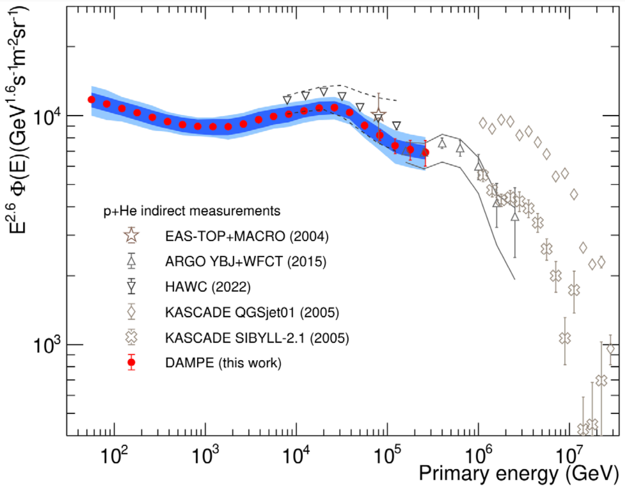
Backup

Charged CRs: state of the art

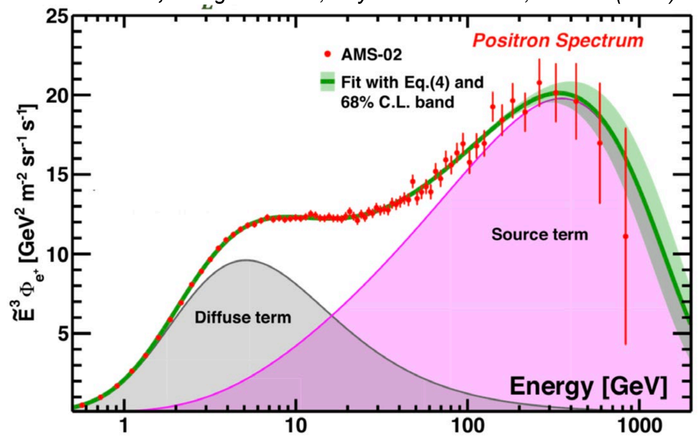
***CALET coll.**, O. Adriani et al., Phys. Rev. Lett. 128, 131103 (2022)*



***DAMPE coll.**, F. Alemanno et al., Phys. Rev. D. 109, L121101 (2024)*



***AMS coll.**, M. Aguilar et al., Phys. Rev. Lett. 122, 041102 (2019)*



I. What is the origin of the **hardening observed in the spectra of CR nuclei** at rigidity of 300 GV and ~10 TV?

II. Why is the slope of the spectrum of CR **proton and helium different**?

III. What is the origin of the prominent **break** observed at a particle energy of **1 TeV in the electron spectrum**?

IV. Why do the **proton, positron, and antiproton** spectra have roughly same slopes at particle energies larger than 10 GeV?

V. What is the origin of the **rise in the positron fraction** at particle energies above 10 GeV?

VI. ....

S. Gabici @ ICRC 2023
CR direct rapporteur

COMPOSITION frontier | **ENERGY frontier** | **ANTIMATTER frontier**

NEW paradigm of CR origin, acceleration and propagation

Novel experimental approaches that target all opportunities of space platforms must be addressed, from **cubesats and nanosatellite constellations** up to **large-size space missions** and **Moon**, including **stratospheric balloon flight missions**.

+ synergic activity at ground laboratories and accelerators to tackle **technological challenges** and enable **new observational approaches**

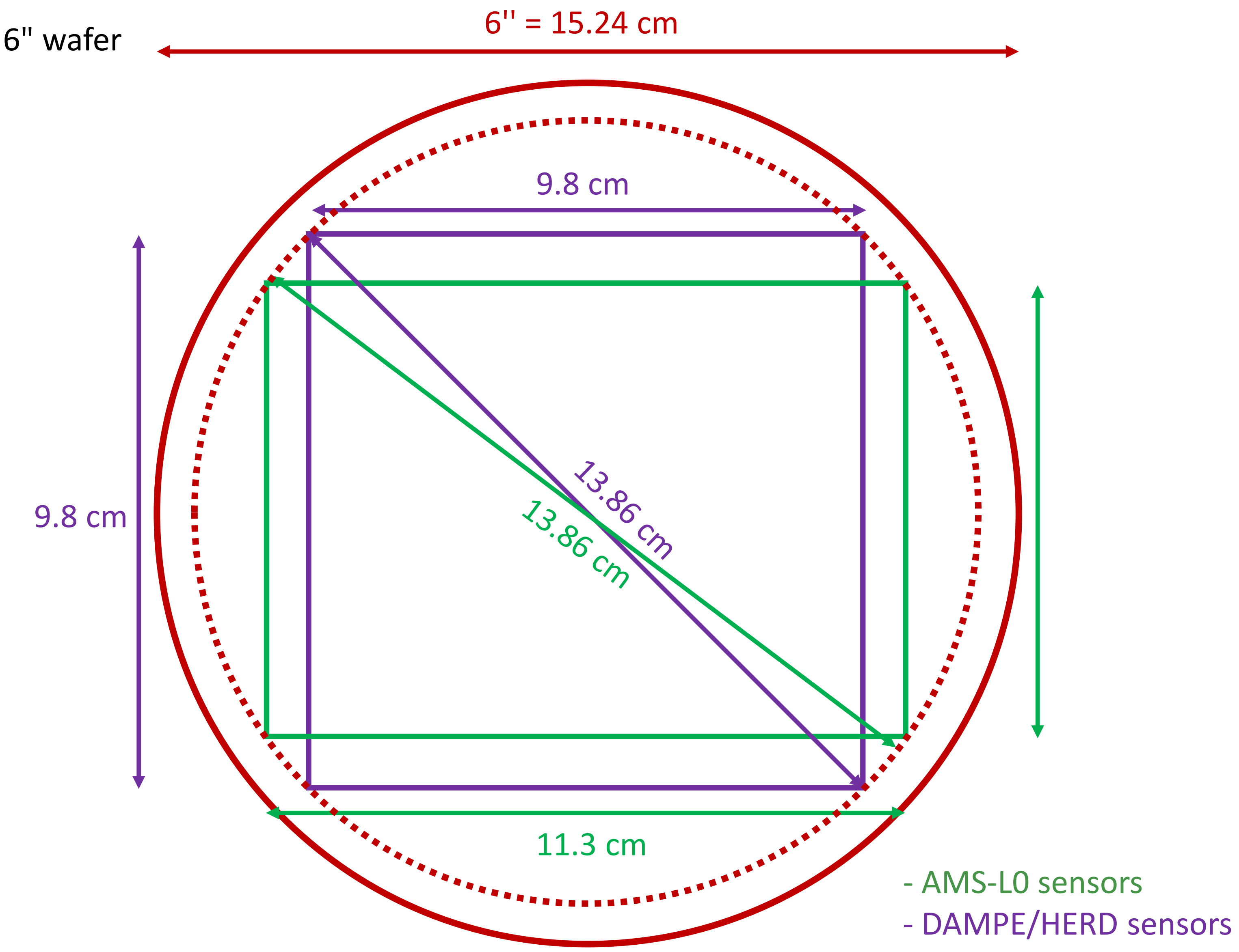
Large acceptance missions remain the most promising approach to new discoveries and high-accuracy space measurements

Capacitance and daisy-chain

At production level the strips cannot be so long:

- they must be at least shorter than the wafer diagonal (i.e. 6'' – some margin)
- typically is at most ~ 10 cm long

→ 50-100 cm long strips are obtained through <u>daisy-chain</u>

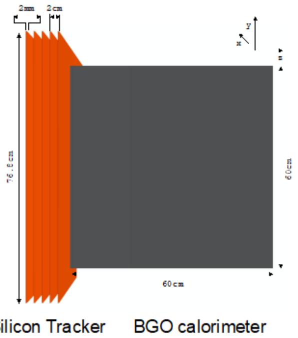


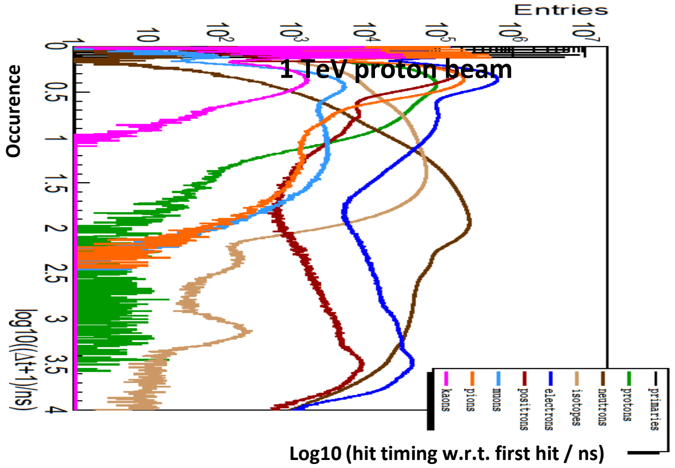
Effects of 5D-Tracking in backscattering events

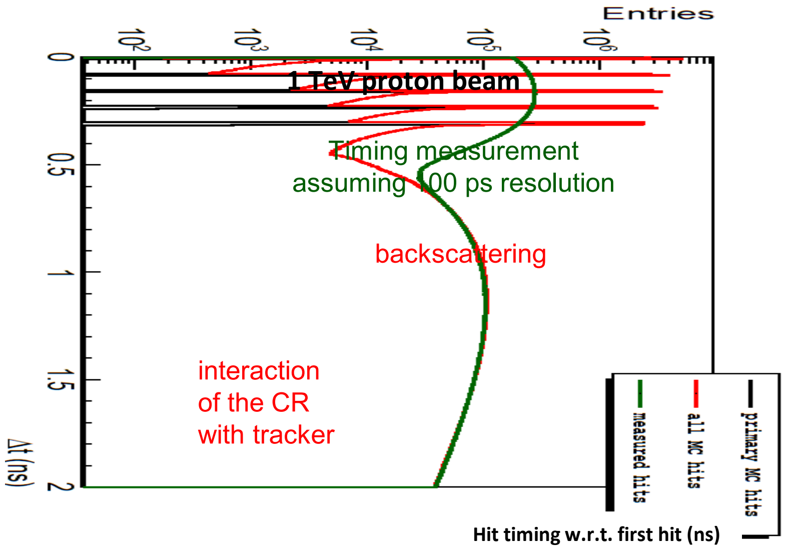
M. Duranti et al., *Instruments* 2021, 5(2), 20

MC simulation of backscatterd particles from downstream calorimeter on tracker layers

Simulation based on GGS Generic Geant Simulationn *Mori N, NIM-A 1002, 2021*

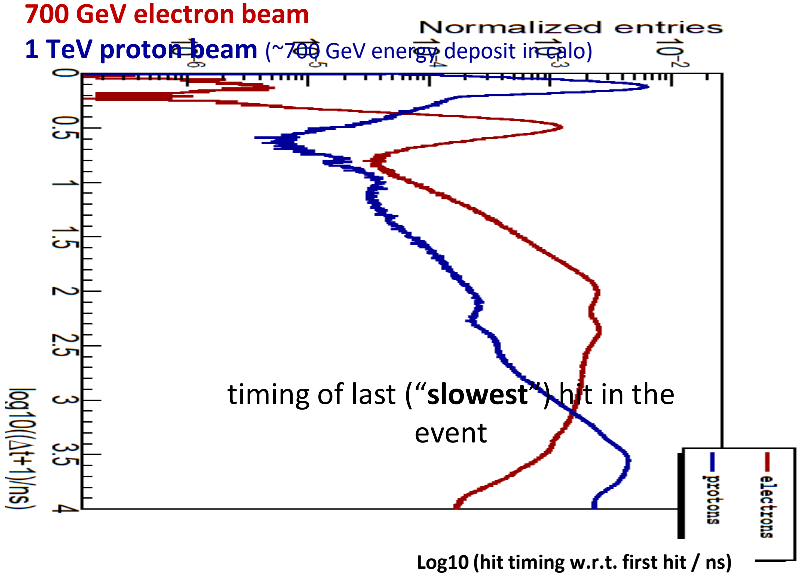






100 ps resolution allows to separate hits from primary particles and from secondary backsplash (tracker and calorimeter are 2cm far from each other)

Prospects for improved tracking efficiency



Different timing signatures from p and $e^{+/-}$ showers

Prospects to use in MVA classifiers for e/p separation

Timing resolution benchmark: < 100 ps (enabled with Si-µstrip LGAD [+ mitigation of FE consumption])

Break-through objectives (e.g.: performant isotope separation**): < 50 ps** (requires readout noise mitigation approaches)

Tracking with Low Gain Avalanche Diodes

Gains from material budget reduction in low-energy CR and g-ray measurements

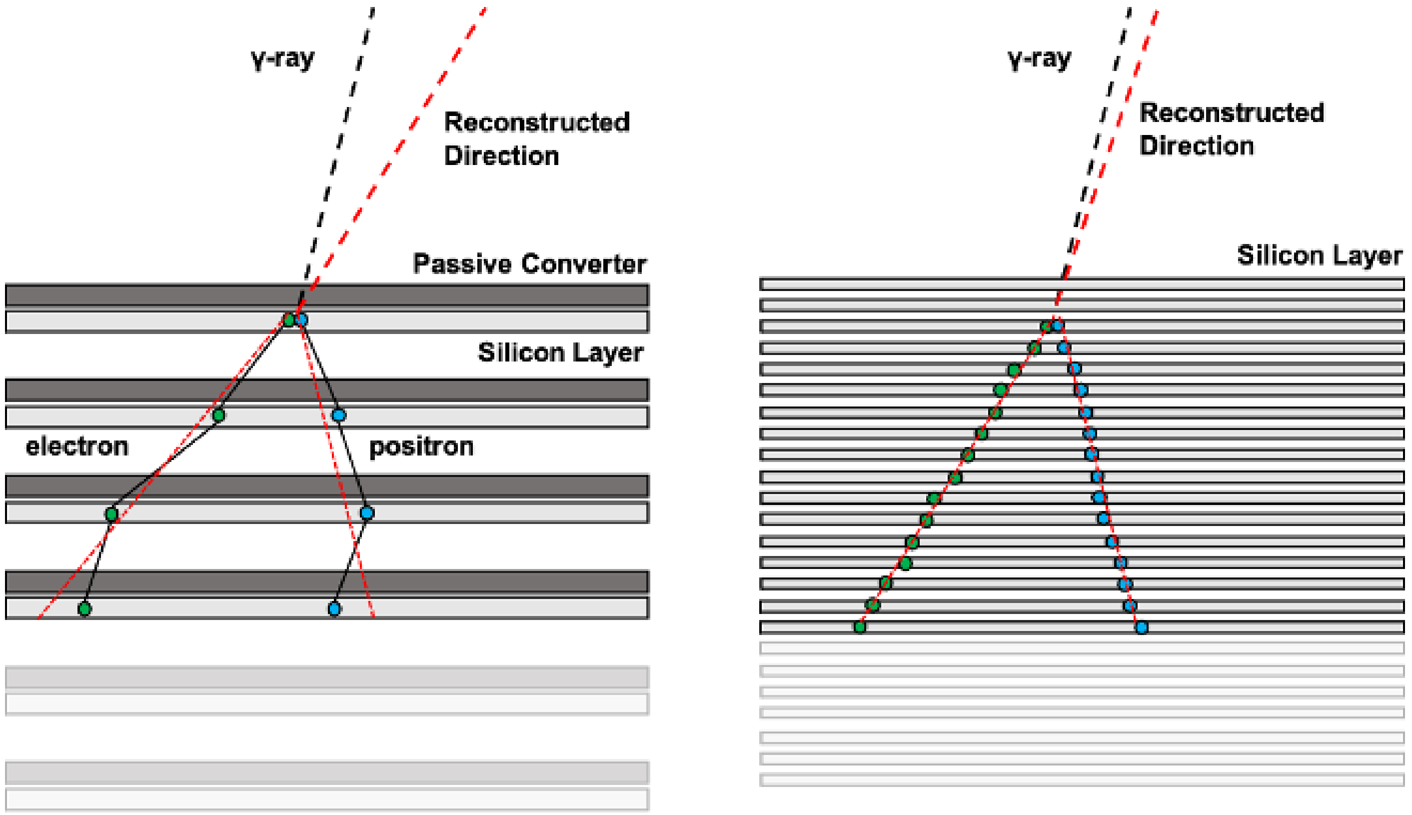
Thin high signal Si sensors: the LGAD intrinsic gain improves the SNR for thin sensors and allows for reduced active material budget tracking planes

The PSF of γ-ray experiments (Fermi-LAT, DAMPE, ...) is degraded at low energies by Coulomb MS in materials (passive converter and Si-sensors)

- **Remove passive materials**
- **Use thin active detectors**
- **Increase number of active layers to boost the GR conversion probability** (approach first proposed in X. Wu et al., "PANGU: A high resolution gamma-ray space telescope", Proc. SPIE 9144 (2014))

Sub-GeV γ-ray detectors
Opportunity for improved PSF below 1 GeV

PANGU ref.: 1 deg PSF @ 100 MeV (1/5 Fermi-LAT)
0.2 deg PSF @ 1 GeV (1/5 Fermi-LAT)



Standard approach
converter tracker

Novel approach
fully active multi-layer tracker

Pentadimensional Tracking Space Detector - INFN

R&D activity to increase LGAD Si-μstrip TRL for space from TRL=2 to TRL=5

WP1
Management and dissemination
INFN, ASI

WP2
Sensor design and production
INFN, ASI

WP3
Proto-detector qualification
INFN, ASI

WP4
Scientific applications space mission design
ASI, INFN

+ FBK as INFN-sub-unit

INFN
Perugia, Bologna, Roma Tor Vergata
PI.: Matteo Duranti

ASI
Headquarters (Roma)
co-PI: Valerio Vagelli

Is possible to cover tens of m² of tracking areas with LGADs and:

- <100 (ideally 20-30) ps timing
- <10 μm spatial resolution
- <100 W / m²
- <100 K_{ch} / m²

?

Future Missions						
	Planned operations	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
HERD	2030	$\sim 35\,m^2$	48–67 cm	$\sim 350 \cdot 10^3$	$\sim 242\,\mu m$	$\sim 40\,\mu m$
ALADInO	2050	$\sim$ 80-100 m^2	19–67 cm	$\sim 2.5 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$
AMS-100	2050	$\sim$ 180-200 m^2	~ 100 cm	$\sim 8 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$

from ASAPP 2025 L. Cavazzini's talk

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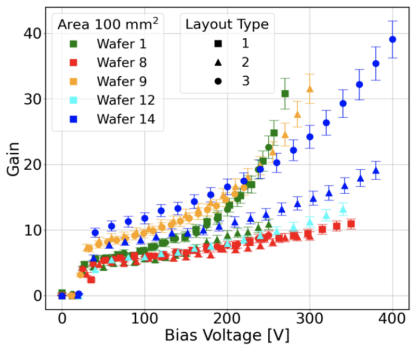
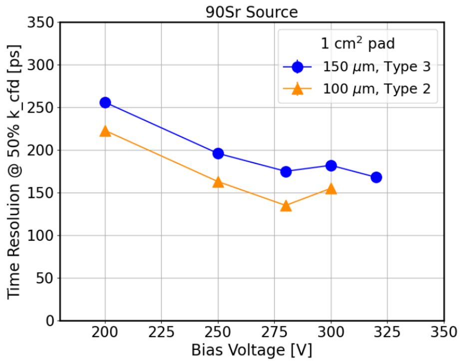




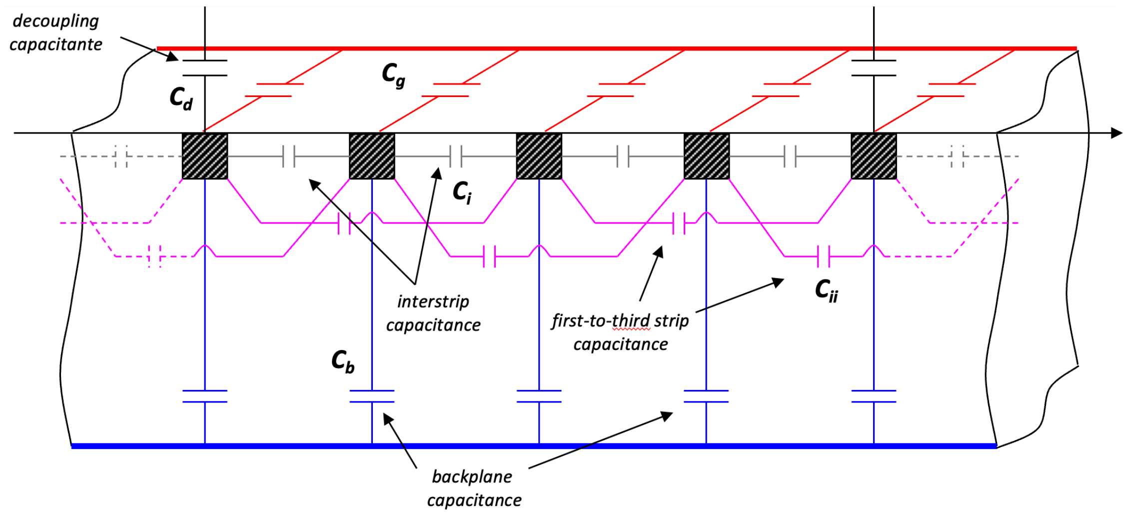
BUT WE ARE NOT HAPPY JUST YET!

How much is the maximum length of a Si LGAD μstrip?

Is possible to "daisy chain" LGADs?

Is there a way to mitigate this problems and, for example, reduce the capacitance even with very thin LGAD sensors?

Capacitance and daisy-chain



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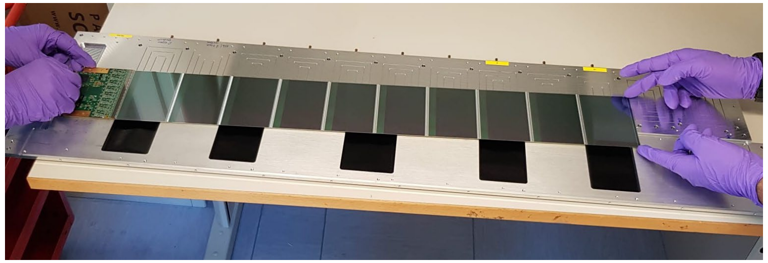
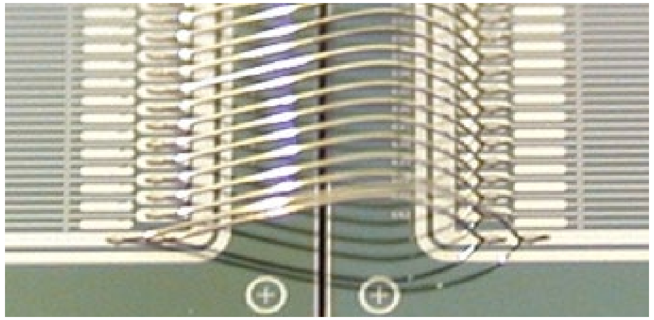
l = strip length (typical 50-100 cm)
d = thickness (typical 300 μm)

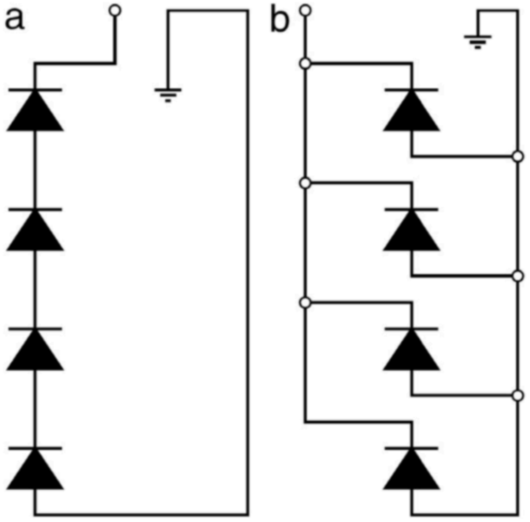
C_i = interstrip capacitance ~ 1 pF/cm * l = 10 – 100 pF
C_d = decoupling capacitance ~ 1000 pF (DC sensors) or 120 pF/mm^2 (AC sensors) > C_i C_b C_g C_{ii}
C_b = backplane capacitance ~ 1 pF/cm * l * p/d = 1/10 * 10 – 100 pF = 1- 10 pF
C_g = guard-ring capacitance << C_i
C_{ii} = first-to-third strip capacitance << C_i

For thin and long strips, capacitance must be kept under limit

AMS-02 upgrade, Layer-0 ladder @ INFN Perugia







N. Kratochwil et al., PANDA experiment

For SiPMs:

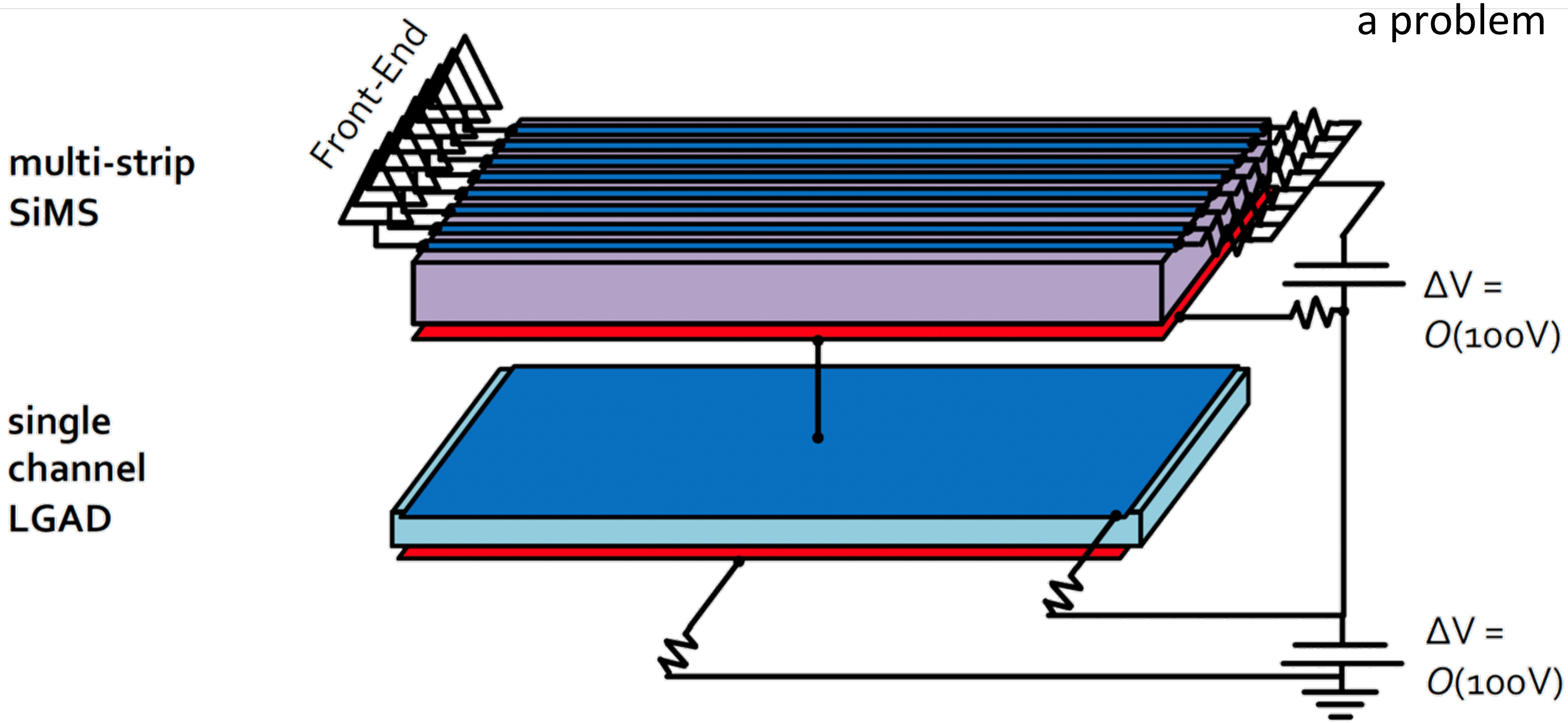
b) standard "parallel" readout
✓ bias voltage independent on number of sensors
✗ total capacitance seen by readout FEE scales with number of sensors

a) "in-series" readout
✗ bias voltage scales with number of sensors
✓ total capacitance seen by readout FEE scales **down** with number of sensors

→ **can we "port" it to LGADS?**

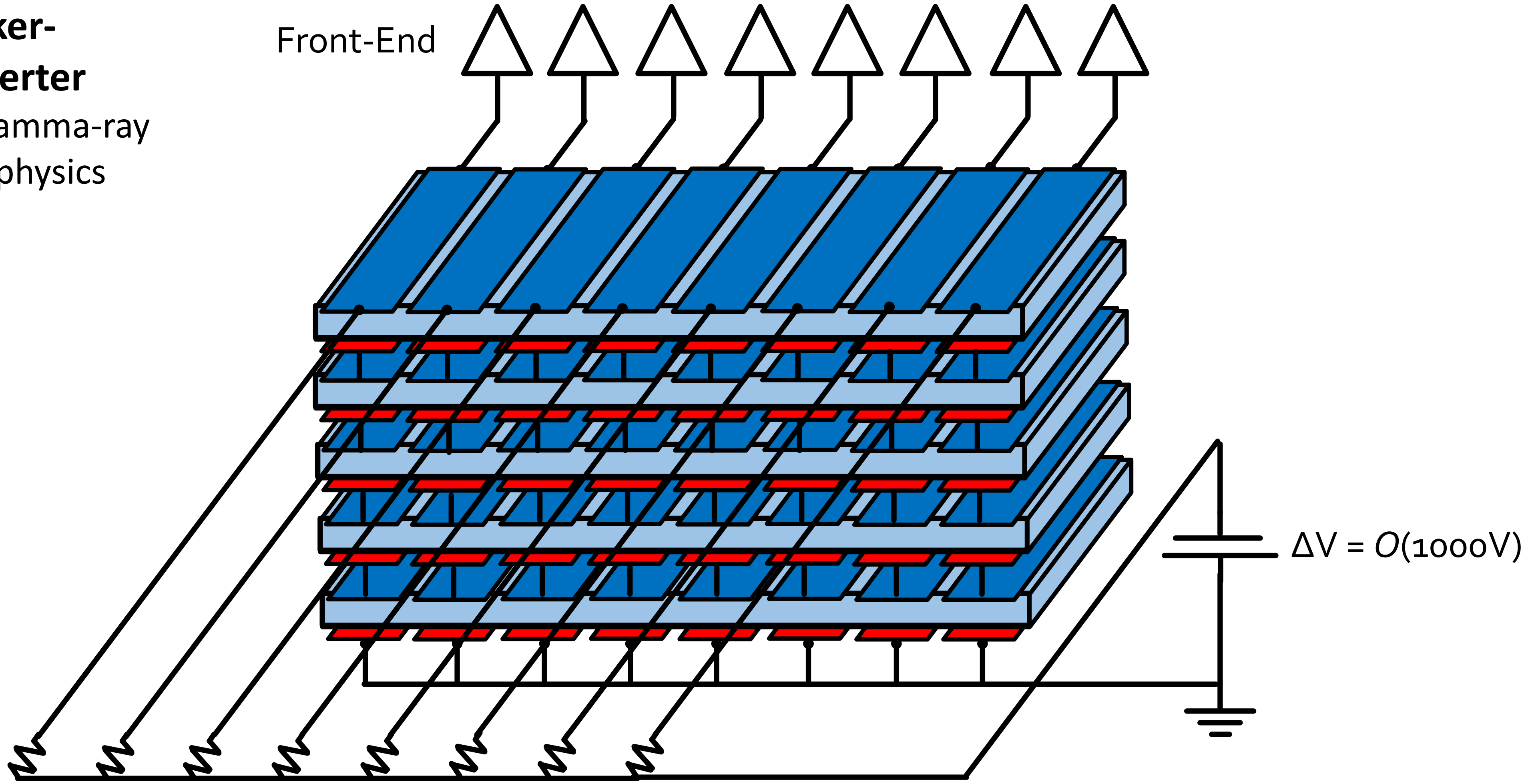
More "evolved" ideas…

Single timing microstrip sensor
Fill factor naturally not a problem



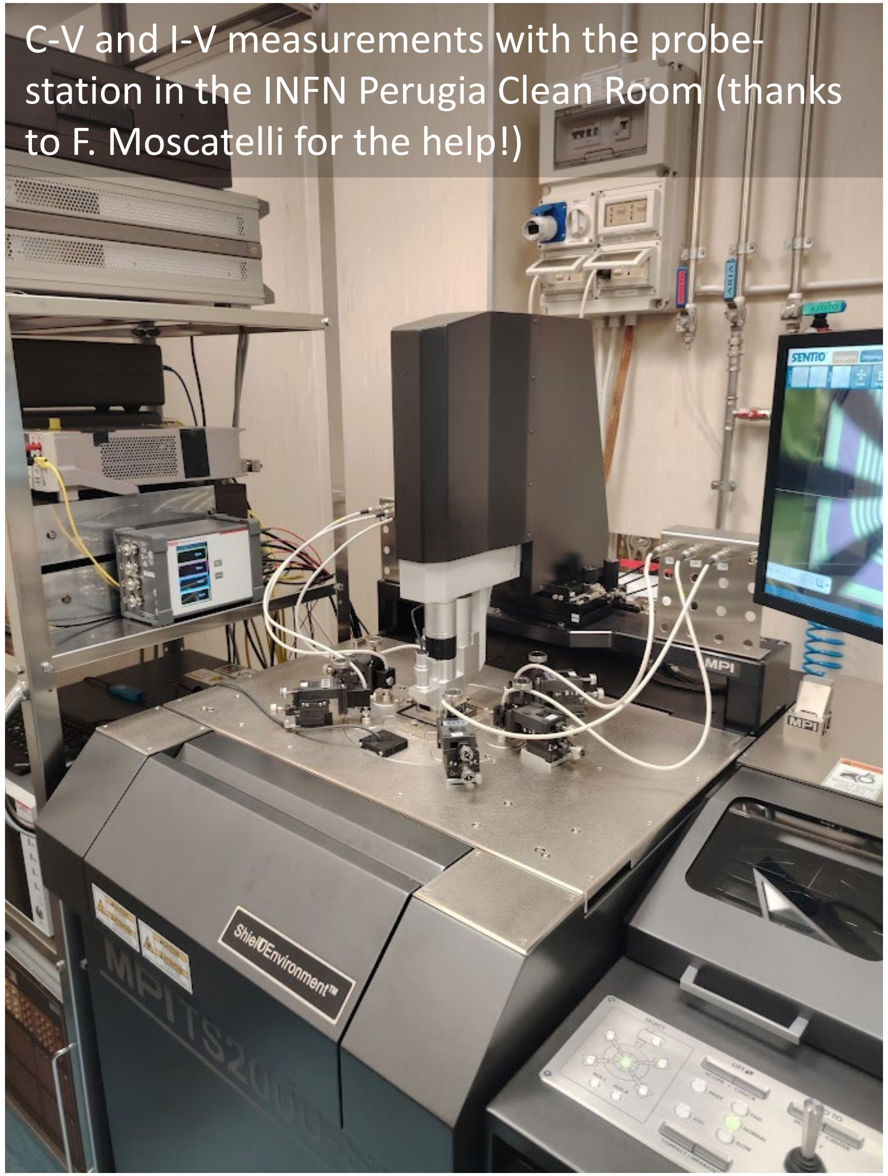
More "evolved" ideas...

Tracker-converter
For gamma-ray astrophysics



"Stacked" 5D sensor – Proof of concept lab tests

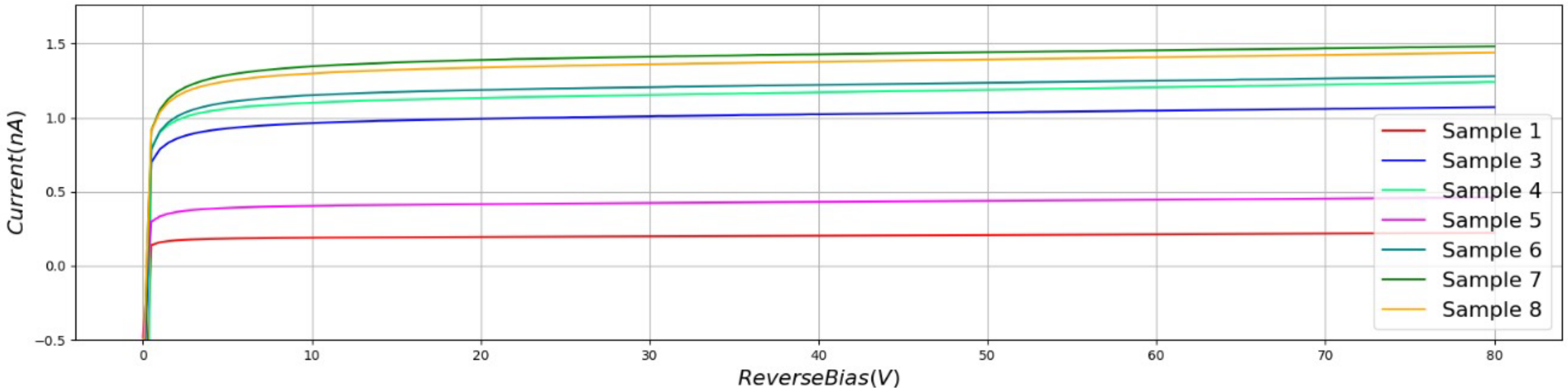
C-V and I-V measurements with the probe-station in the INFN Perugia Clean Room (thanks to F. Moscatelli for the help!)



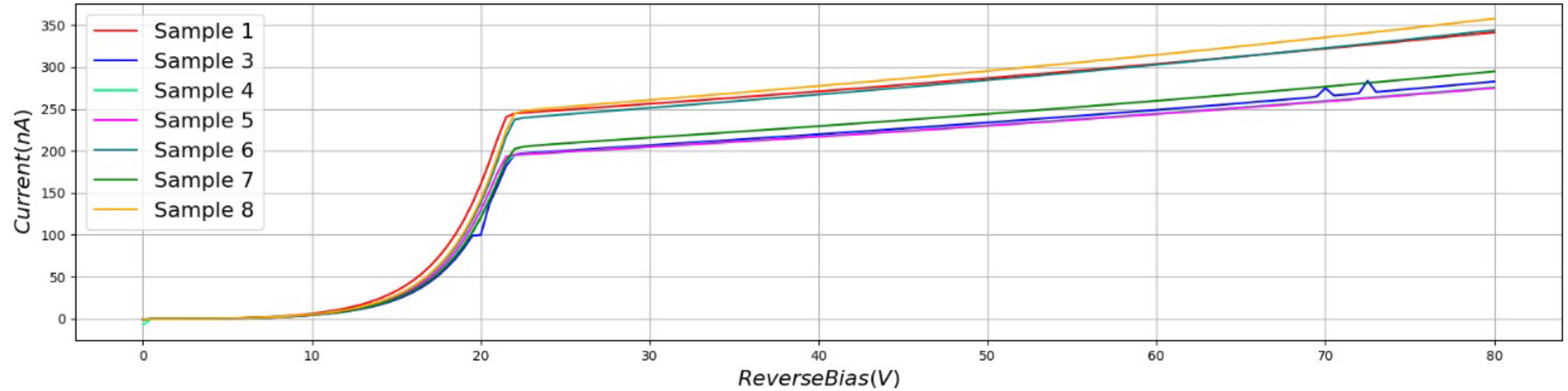
We tested:

- 7 samples (sample 2 was damaged)
- IV: 0.5 – 1.5 nA (PIN), 250 – 350 nA (LGAD)

" No Gain"/PIN



"Gain"/LGAD



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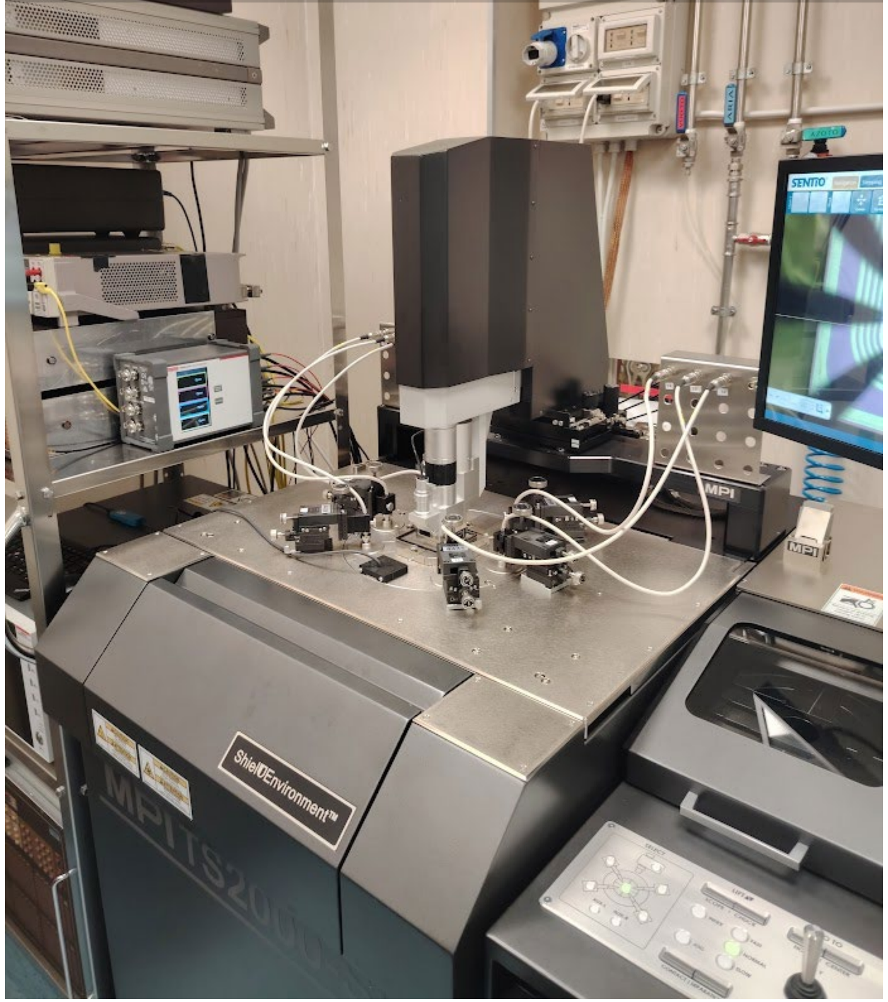
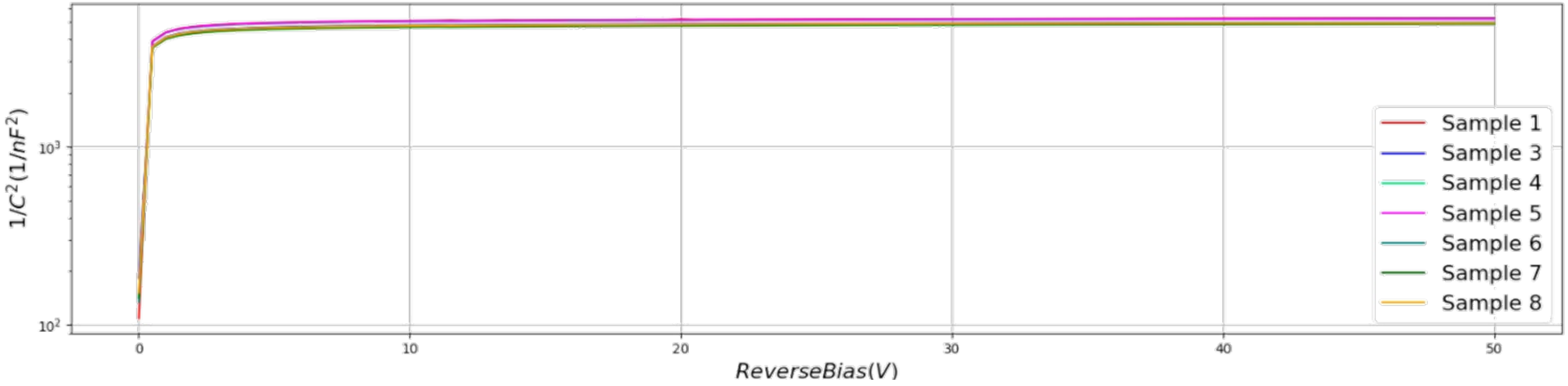


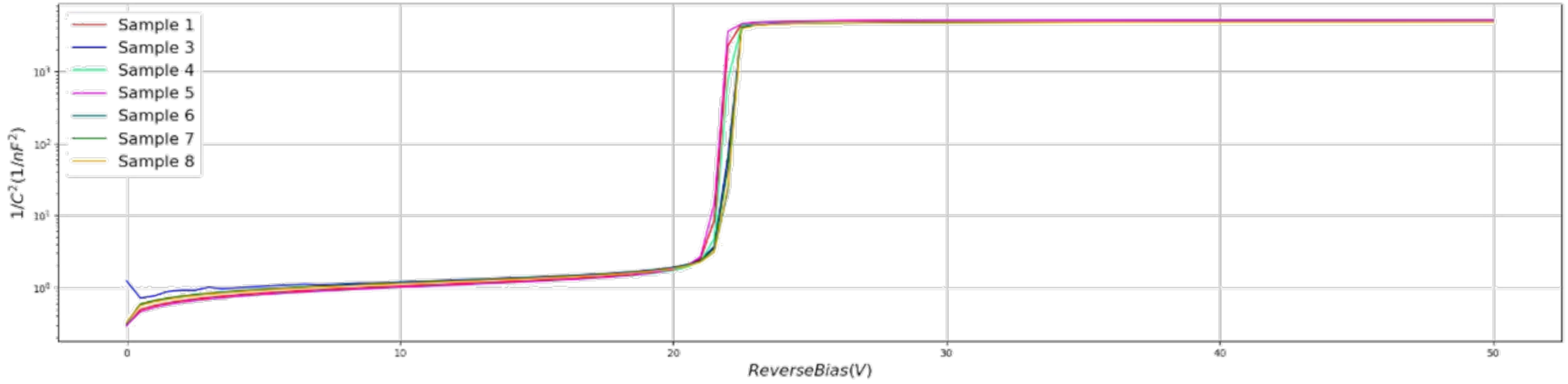
We tested:

- 7 samples (sample 2 was damaged)
- IV: 0.5 – 1.5 nA (PIN), 250 – 350 nA (LGAD)
- CV: 13.9 – 14.7 pF ± 0.2pF (PIN e LGAD)

" No Gain"/PIN



"Gain"/LGAD



“Stacked” 5D sensor – Proof of concept lab tests

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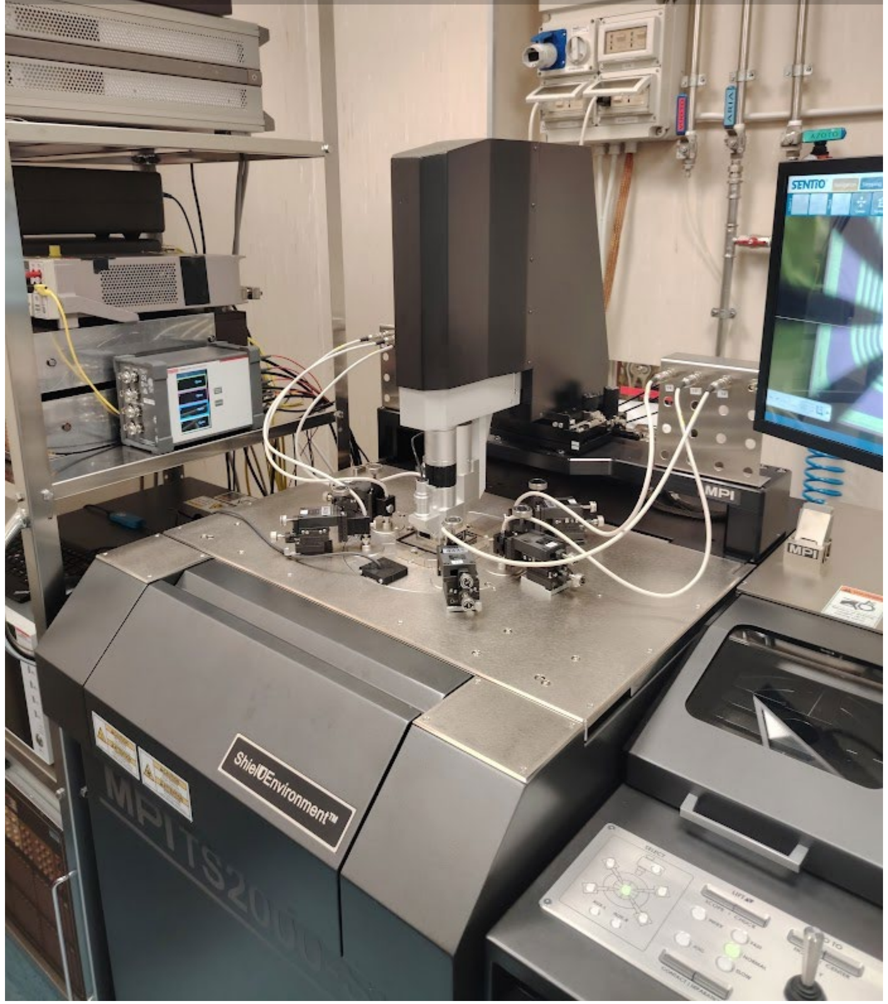
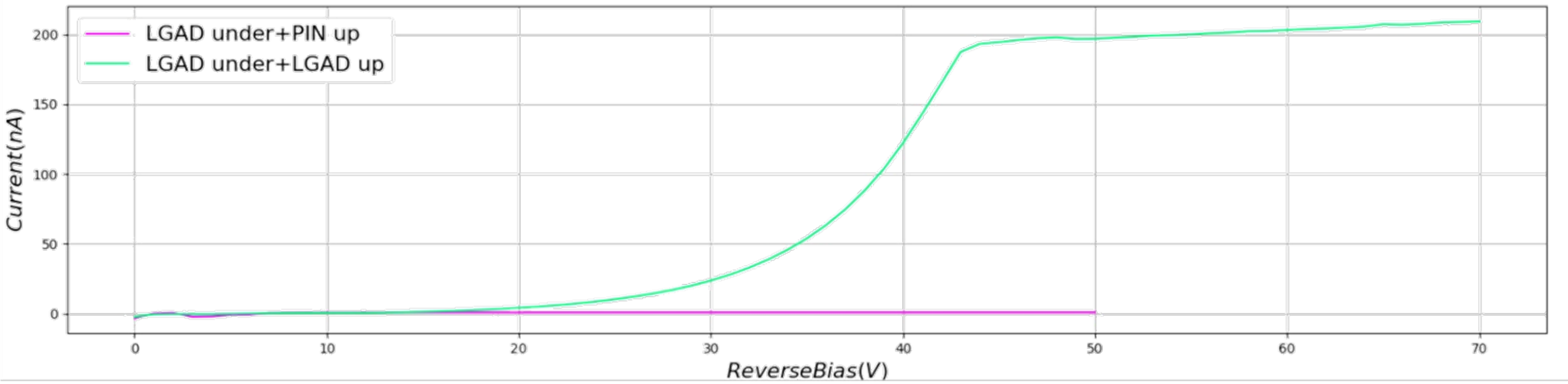


We tested:

- stacked device
- IV: 1.5 nA (LGAD-PIN), ~ 200 nA (LGAD-LGAD)

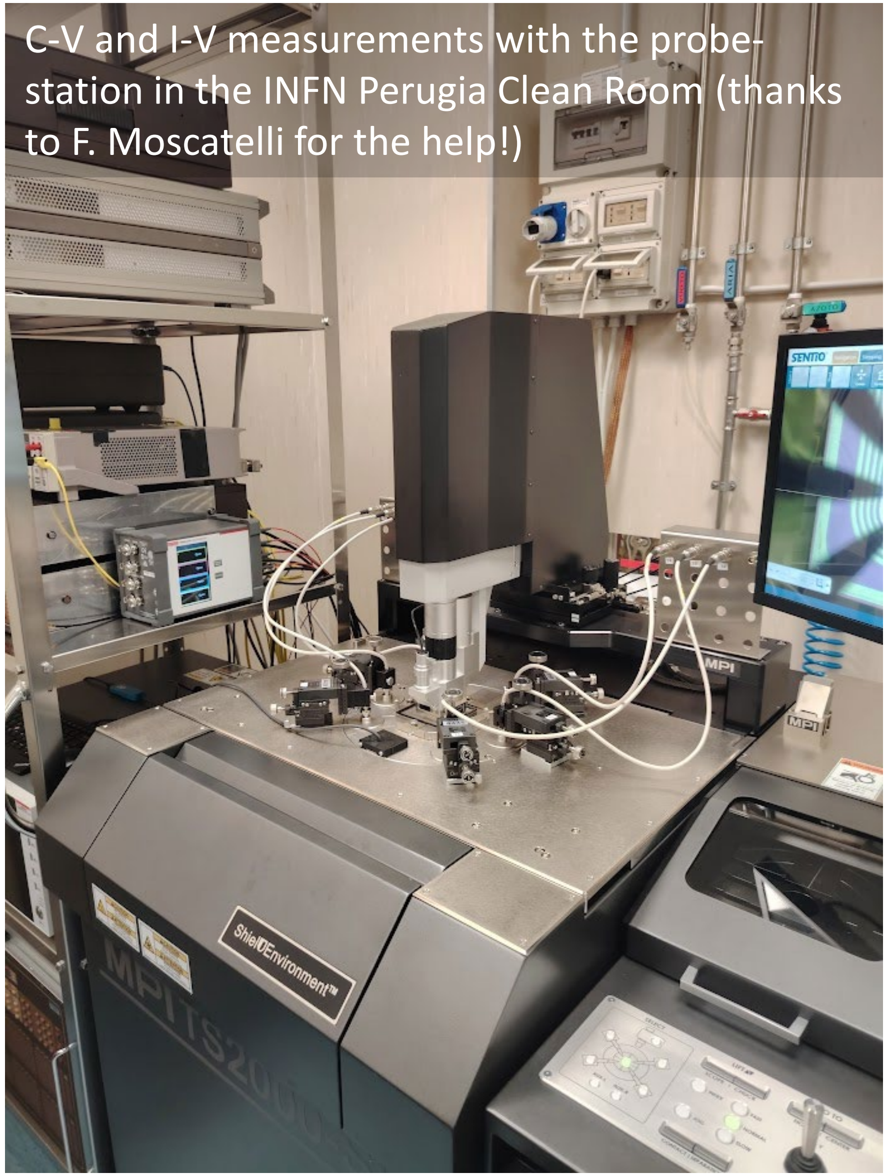
I-V



The current is dominate by the one with less leakage!

“Stacked” 5D sensor – Proof of concept lab tests

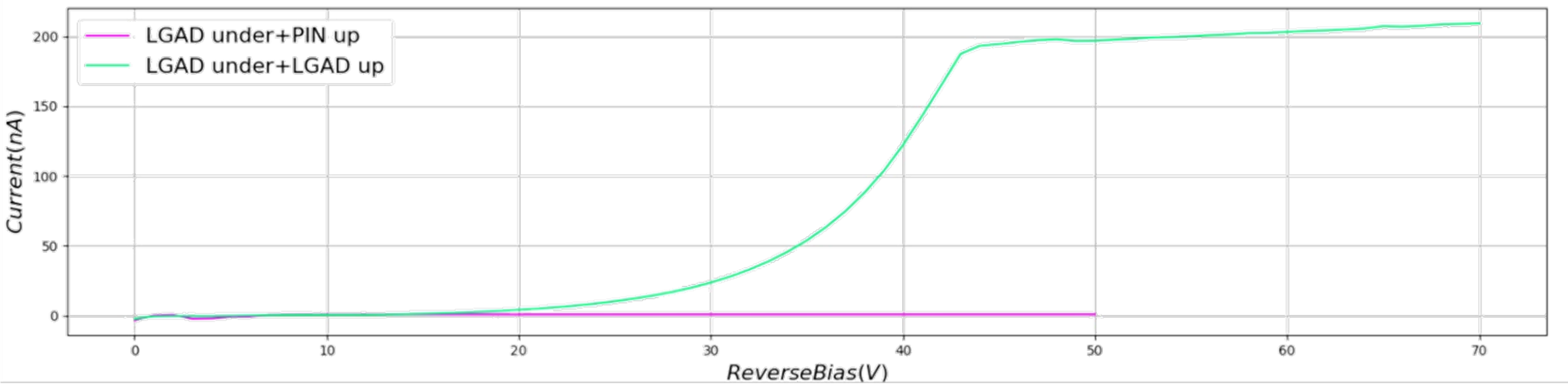
C-V and I-V measurements with the probe-station in the INFN Perugia Clean Room (thanks to F. Moscatelli for the help!)



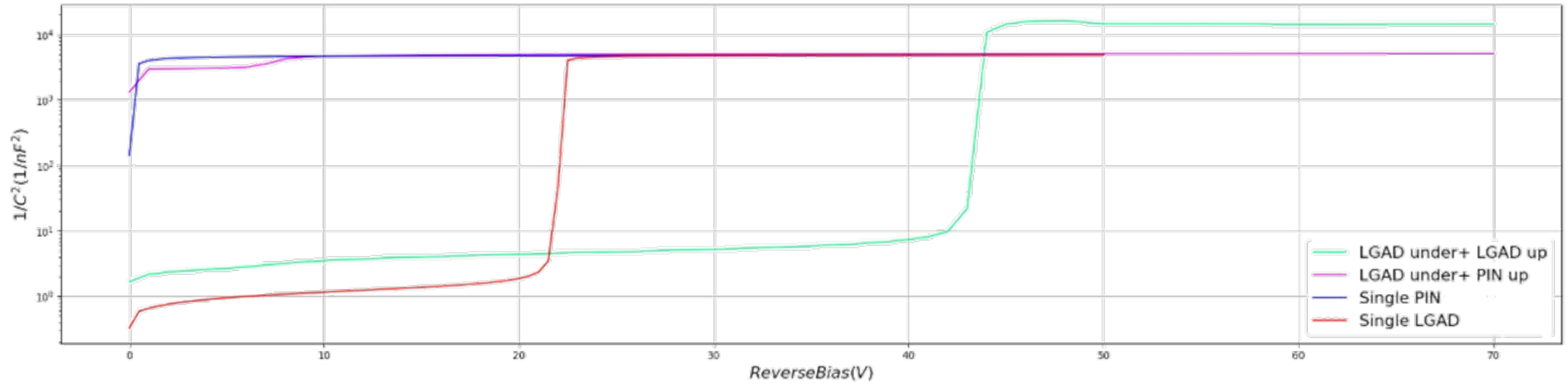
We tested:

- stacked device
- IV: 1.5 nA (LGAD-PIN), ~ 200 nA (LGAD-LGAD)
- CV: 13.9 pF ± 0.2pF (LGAD-PIN) ?? 8.3 pF ± 0.2pF (LGAD-LGAD)

I-V



C-V



“Stacked” 5D sensor – Proof of concept lab tests

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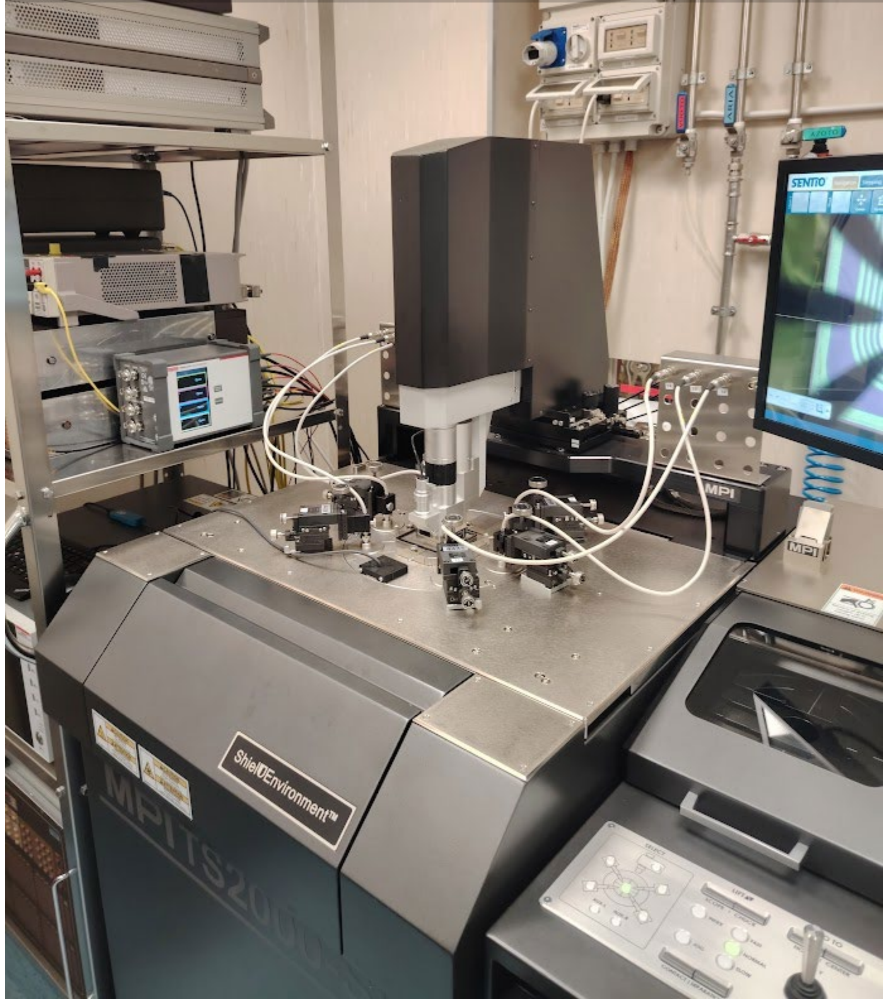


We tested:

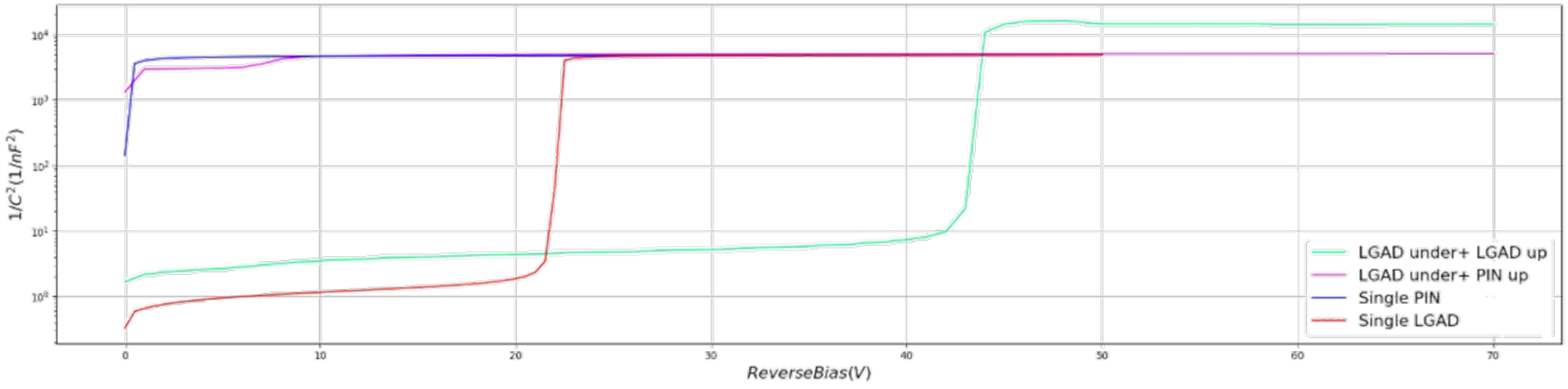
- stacked device
- IV: 1.5 nA (LGAD-PIN), 250 – 350 nA (LGAD-LGAD)
- CV: 13.9 pF ± 0.2pF (LGAD-PIN) ?? 8.3 pF ± 0.2pF (LGAD-LGAD)

- the capacitance of the LGAD-LGAD stack is (almost…) half of the two single capacitances (14.3 pF and 13.9 pF → 7.1 pF). Why there's around 1 pF more?

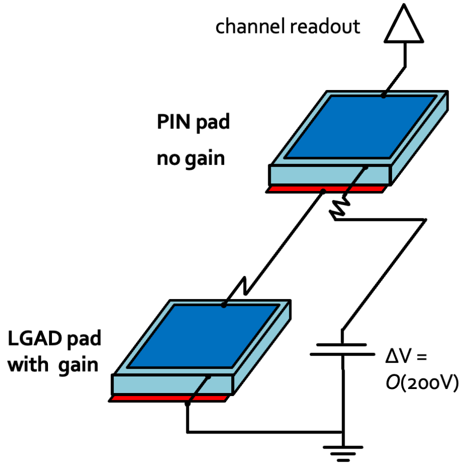
$$C_{tot} = \left(\frac{1}{C_1} + \frac{1}{C_2} \right)^{-1}$$

- the capacitance of the PIN-LGAD stack is almost the same of the PIN alone. We know why…

C-V

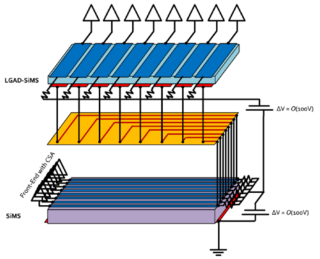


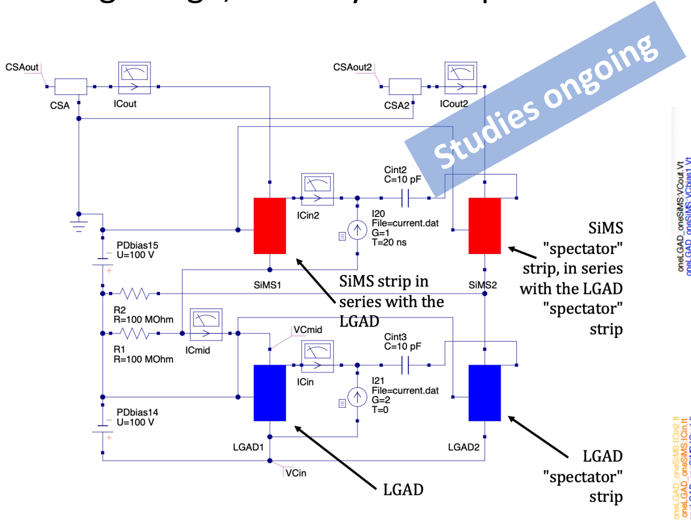
"Stacked" 5D sensor – Proof of concept design



Simple simulations confirm the approach

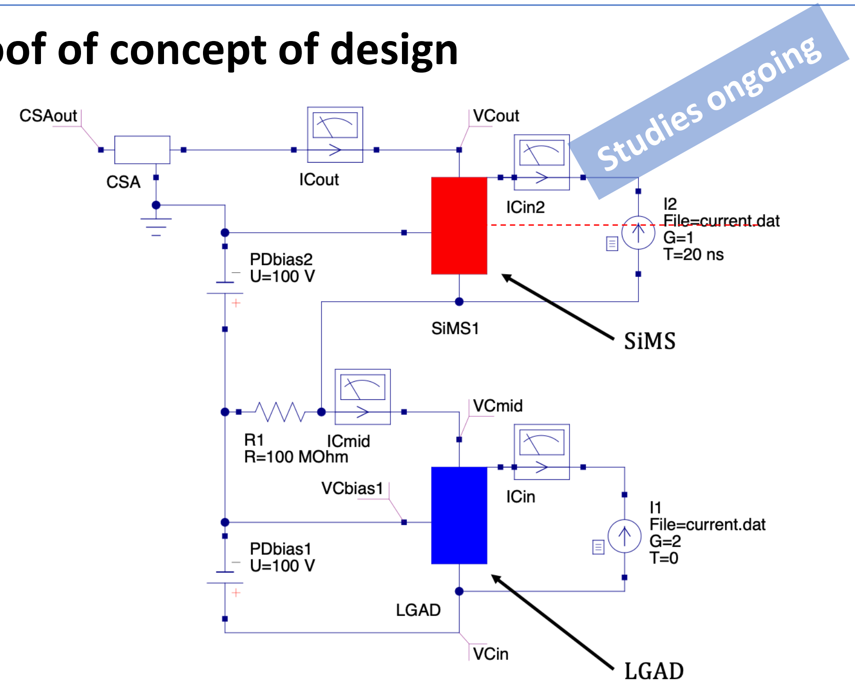
Feedback on starting design, circuitry to be optimized

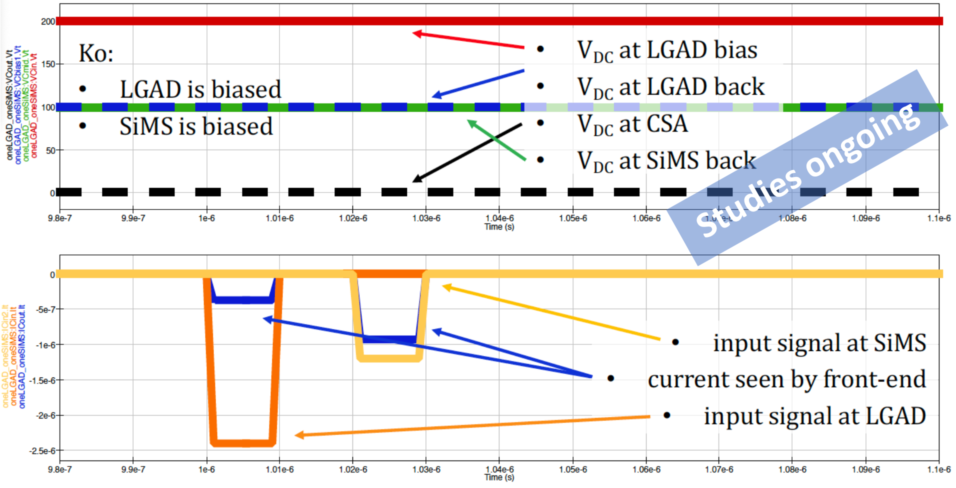




Design confirmed also adding adjacent strips

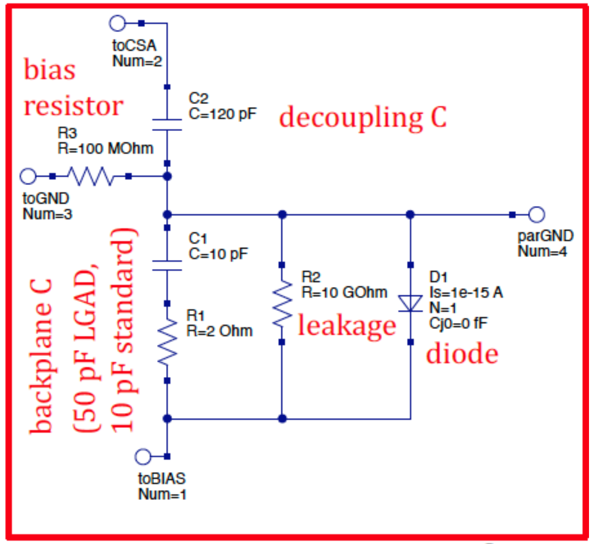
Proof of concept of design





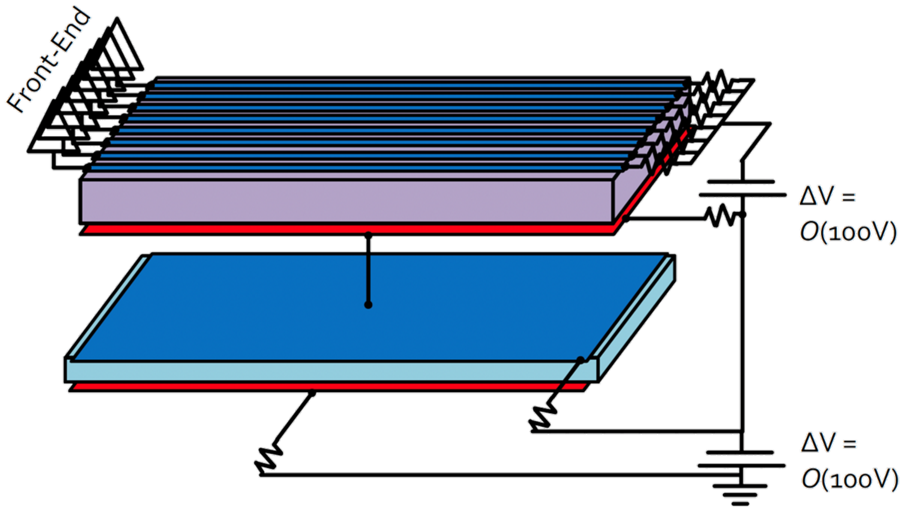
Qucs
Quite universal circuit simulator

Sensor (LGAD, standard)



- some modifications needed (additional bias resistor in the middle of the stack)
- LGAD signal seen reduced by the ratio of the SiMS/LGAD capacitances

"Stacked" 5D sensor – Proof of concept design



✓ ALL the readout channels see the LGAD signal (reduced by capacitance ratios

✗ signal seen by the LGAD is reduced by the ratio of the SiMS/LGAD capacitances

✗ signal seen by left strip is PROVIDED by the neighbour strips (i.e. no charge couple but the other strips are current sources)

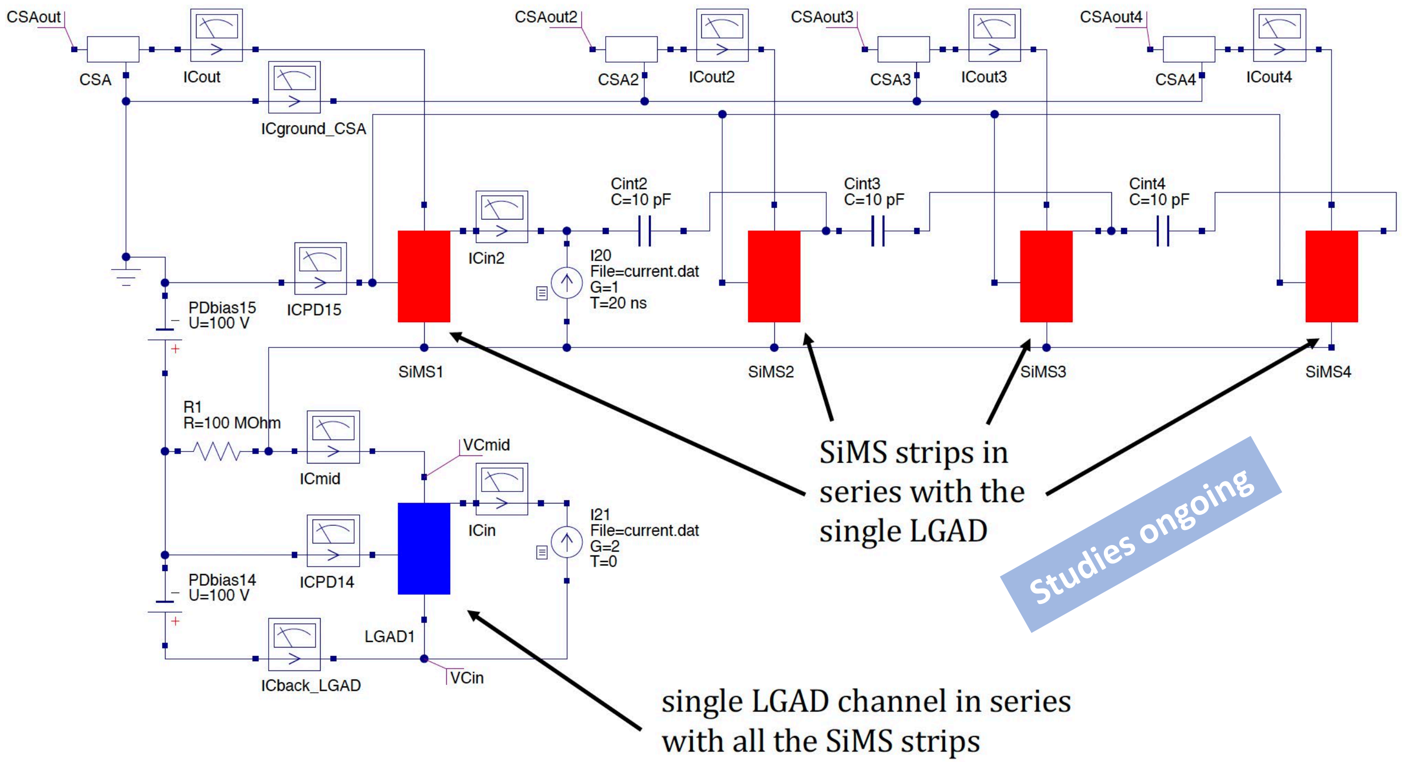
Variant approach

This config could reduce the assembly complexity:

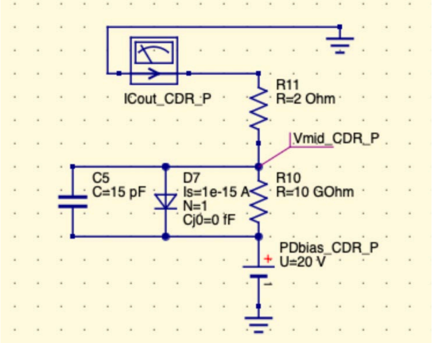
✓ no bonding/kapton between LGAD and SiMS: only glue

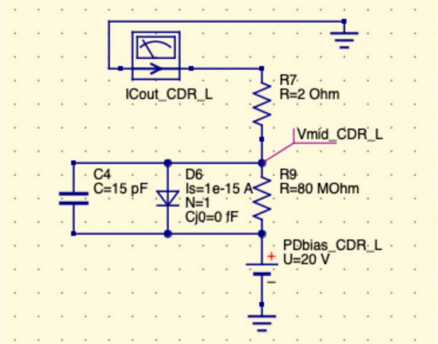
✗ time information common to all channels (✓ that could mitigate the power need)

→ preliminary studies are encouraging



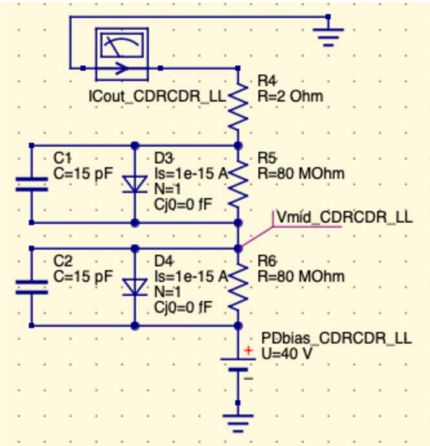
"Stacked" 5D sensor – Proof of concept lab tests

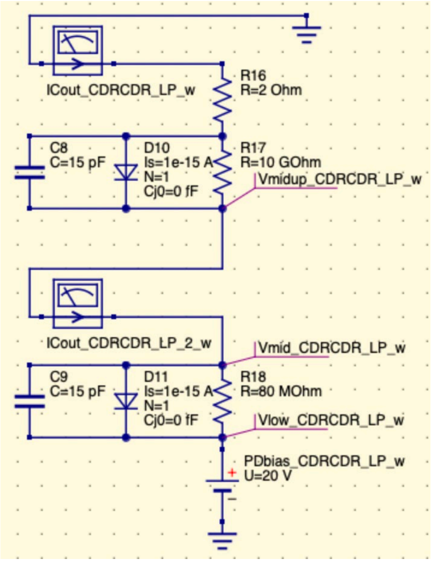




PIN: 10 GΩ
to simulate 2nA

LGAD: 80 MΩ
to simulate 250nA





LGAD-LGAD stack: same "resistance" → $V_{bias}/2$ in the center

PIN-LGAD stack: $R_{LGAD} << R_{PIN}$ → LGAD essentially not biased

We tested:

- stacked device
- IV: 1.5 nA (LGAD-PIN), 250 – 350 nA (LGAD-LGAD)
- CV: 13.9 pF ± 0.2pF (LGAD-PIN) ?? 8.3 pF ± 0.2pF (LGAD-LGAD)

- the capacitance of the LGAD-LGAD stack is (almost…) half of the two single capacitances (14.3 pF and 13.9 pF → 7.1 pF). Why there's almost 1 pF more?

$$C_{tot} = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}$$

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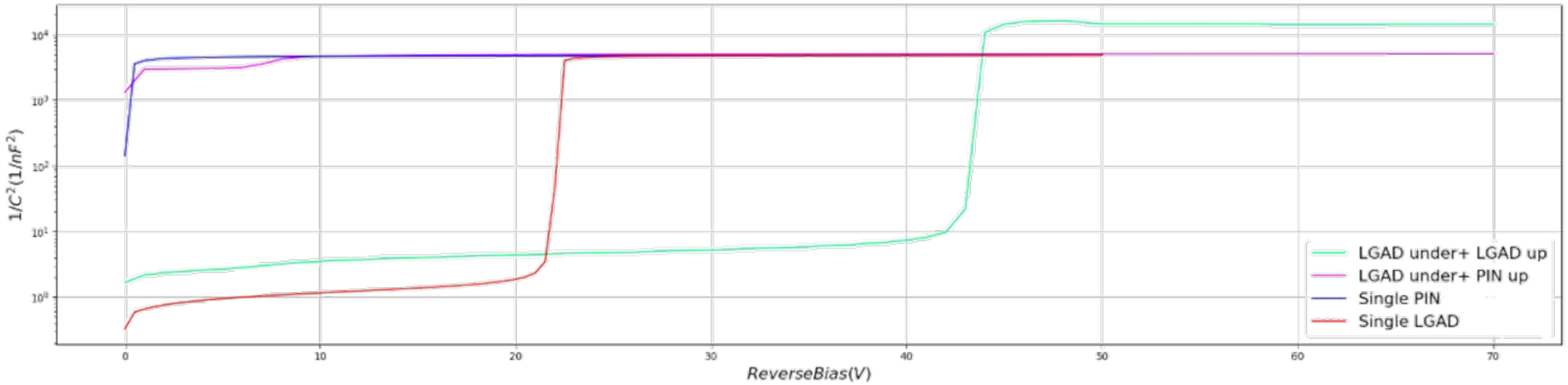
C-V



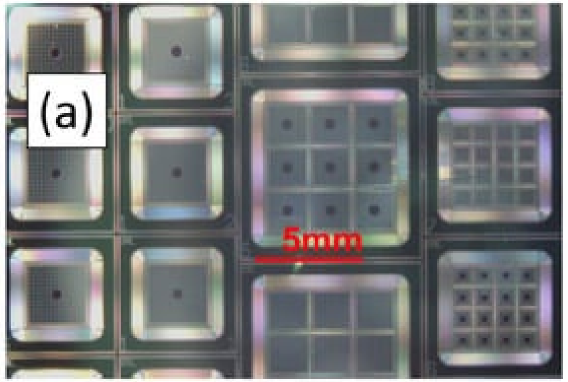
Roadmap to 5D Tracking in Space

Technology first assessed by CNM (G. Pellegrini et al., NIM-A 765, 2014) and CERN-RD50

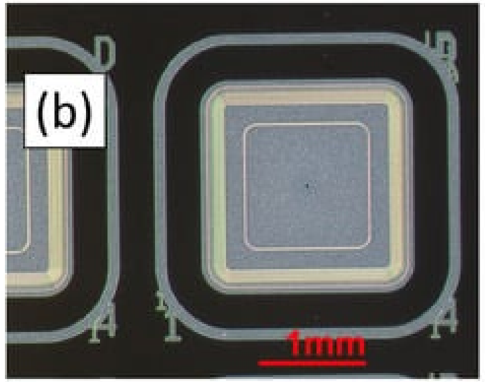
Several facilities involved today in LGAD sensor developments
CNM (ES), FBK (IT), BNL (USA), Hamamatsu (JP), IHEP-NDL (CN), Micron (UK), ...
and readout electronics
Univ. California Santa Cruz (USA), FNAL (USA), INFN (IT)

Typical sensor layouts: 20µm-100µm substrates, single sided, O(mm^2) area

G. Giacomini, *Sensors* **2023**, *23*(4), 2132



Early production of single channel devices and arrays at BNL



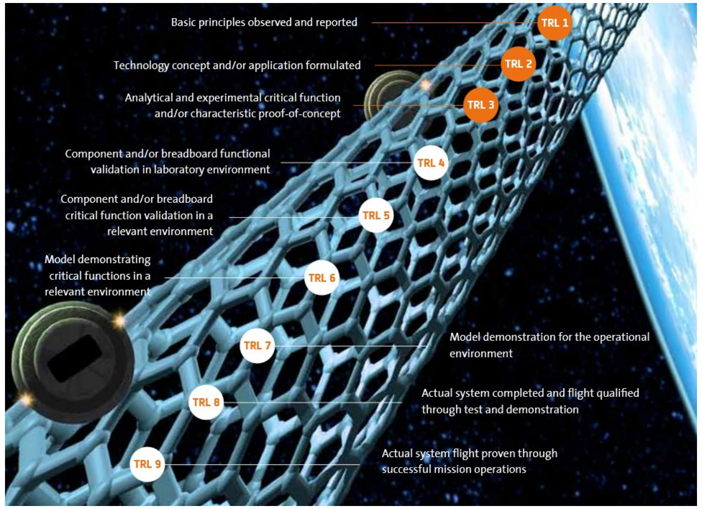
Recent production of 1.3 mm × 1.3 mm devices at BNL (match the pixel size of the CMS and ATLAS timing detectors)

Some considerations on large area 5D tracking in space:

- LGAD R&D driven by acceleration applications on pixel layout
- Si-µstrip are consolidated technology largely employed for particle detection in space
- µstrip LGAD detectors not optimized for space applications
- Low Gain Avalanche Diode to be space qualified

- Sensor dimensions will not probably go larger than few cm^2 (see K. Nakamura, TREDI 2024)

R&D to mitigate capacitance noise and power consumptions in daisy-chained sensors



Cubesat payload: mission objectives

GOAL 1. (Technological)
Demonstrate the feasibility of constructing and operating thin LGAD Si-µstrip sensors in harsh space environment – TRL 9

GOAL 2. (Scientific)
Show that LGAD performances are adequate for next generation astroparticle experiments in space

Measurement of converting photons with E > 20 MeV in the LGAD Si-µstrip tracker with reconstruction of the e^+/e^- pair angle in the tracker
with improved vertex reconstruction by identification of backsplash hits

Observation of photons with E > 20 MeV from the Crab Nebula
Verification of detector PSF and confirmation of conversion technique
Observation of photons from Crab in the 20 MeV – 50 MeV range
Comparison with previous experiments (e.g., CGRO/EGRET) above 50 MeV

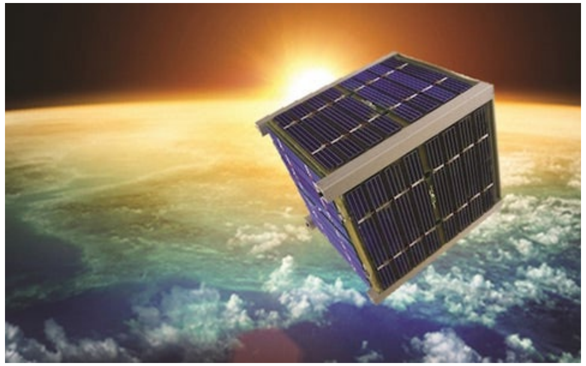
Study of charged CRs using the 5D tracking (position, energy deposit and timing) enabled by the LGAD SiMS tracker
Data-driven characterization of ToF capabilities for LGAD SiMS detectors
Data-driven characterization of e/p separation capabilities for LGAD SiMS detectors
Monitor the time variation of charged CRs and SEP events

Concurrent Engineering Facility study @ ASI

Through a **cooperative** and **parallel study activity** of the domain experts, ASI-CEF is able to define the feasibility of a space mission and its preliminary technical requirements

Phase 0 or pre-Phase-A mission concept studies, including, e.g.:

- new mission concept assessment
- new technology validation at system/mission level
- space system trade-offs and evaluation of opportunities
- payload instrument conceptual design
- mission/system scientific requirements definition and consolidation
- mass / power / data budget



Concurrent Engineering Facility study @ SI

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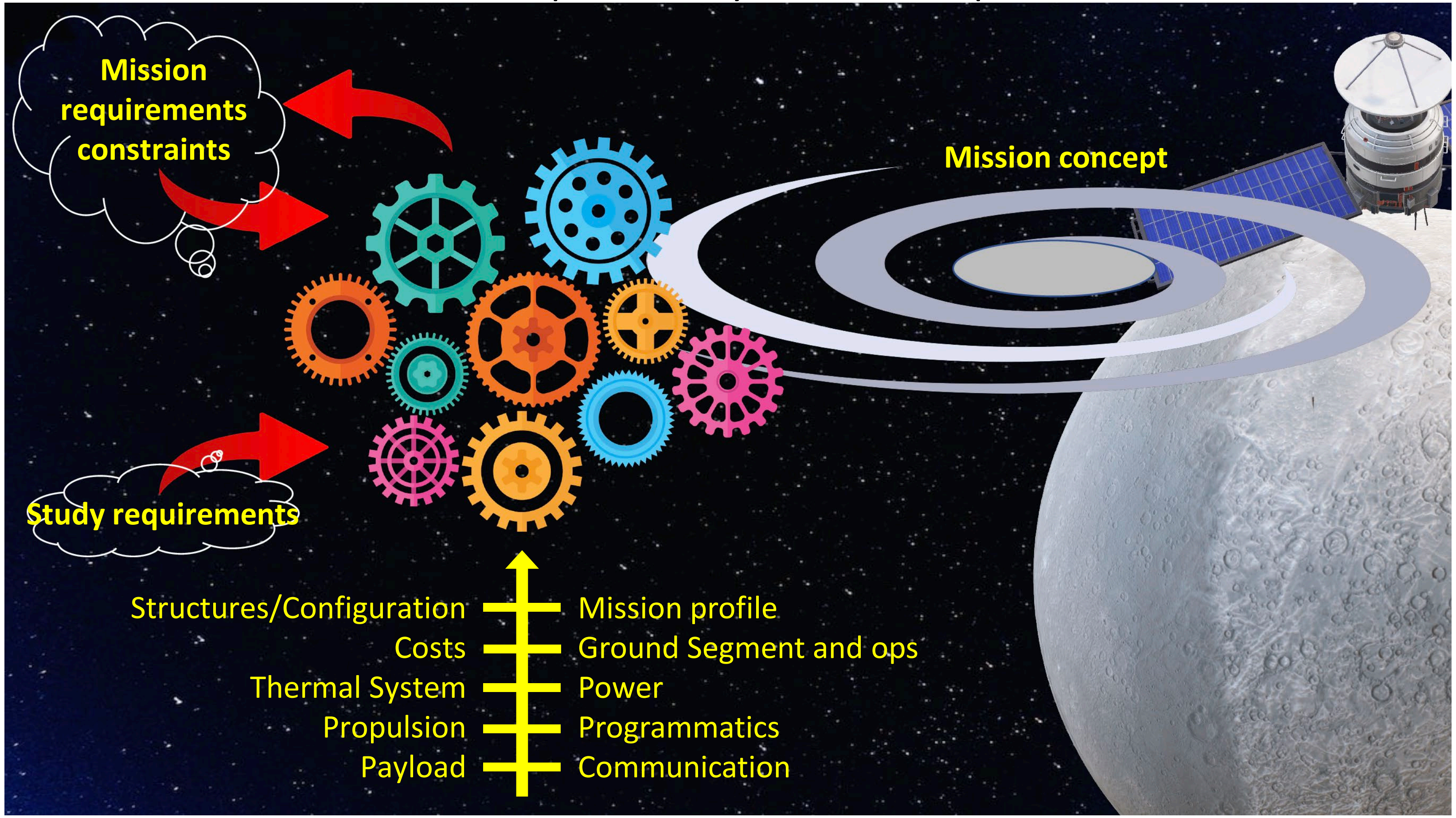

https://www.asi.it/tecnologia-ingegneria-micro-e-nanosatelliti/lingegneria/concurrent-engineering-facility/

including an open call for opportunity (3 deadlines/year) to italian research centers to perform space mission studies @ ASI-CEF

Concurrent Engineering Facility study @ ASI

ASI-CEF: **Cooperative** and **parallel study** of satellite domains to:

- Define the feasibility of a space mission
- Define preliminary technical requirements

Phase 0 or pre-Phase-A mission concept studies, including, e.g.:

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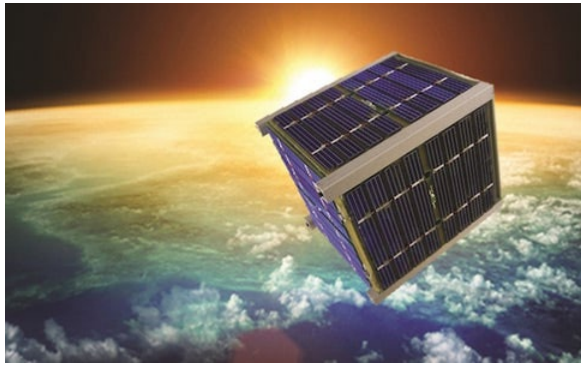

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Pentadimensional Tracking Space Detector (PTSD)
is a project funded by NextGenerationEU and Italian Ministry of University and Research
PNRR M4.C2.1.1, PRIN 2022, n. 2022JNF3M4, CUP ASI F53D23001370008
Finanziato dall'Unione europea NextGenerationEU · Ministero dell'Università e della Ricerca · Italiadomani · ASI · INFN

Agenzia Spaziale Italiana · INFN

Si-microstrip LGAD detectors for cosmic-ray space-borne instruments

- **5D tracking in space** may open new diagnostics and approaches in cosmic-ray and gamma-ray next-generation instruments
- LGADs are the candidate technology to achieve **<100 ps resolution in large area space trackers**
- **R&D** and **spin-in / spin-off** from ground accelerator detectors is needed to increase the TRL

The **PTSD program** aims in verifying the proof-of concept and test a breadboard instrument to validate **TRL=5 for a timing Si-LGAD system for space applications**

- Activities just started with focus on design optimization through simulations – results are encouraging
- details on readout board design and production in progress.
- µstrip-LGAD sensor production to be planned

Wide interest in the community to operate LGAD-based detectors in space

(what follows is just a subset of italian programs to the best of my knowledge)

Spoke 4 -Next Generation Detectors of Ionizing Radiation and Fields for Remote Sensing

SPACE IT UP!

ASI Agenzia Spaziale Italiana · MUR

PM2024 - 16th Pisa Meeting on Advanced Detectors

Contribution ID: 343 Type: Poster

Analog Front-End for the Readout of LGAD Based Particle Detectors

Collaboration **ADA-5D**

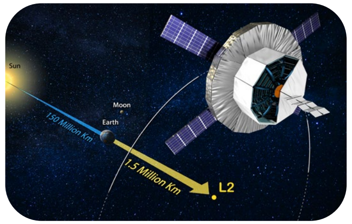
Poster by **Simone GIROLETTI**
Thu afternoon / Fri morning

INFN

Large area (3x3mm^2) pixels with timing and high dyn. range for Z=40

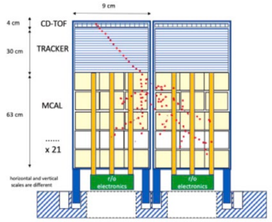
LGAD sensors in future CR space observatories

O.Adriani et al., *Instruments* 2022, 6(2), 19



ALADInO
magnetic spectrometer Si-Tracker

P.S.. Marrocchesi, *Astrop. Phys.* 152 (2023) 102879

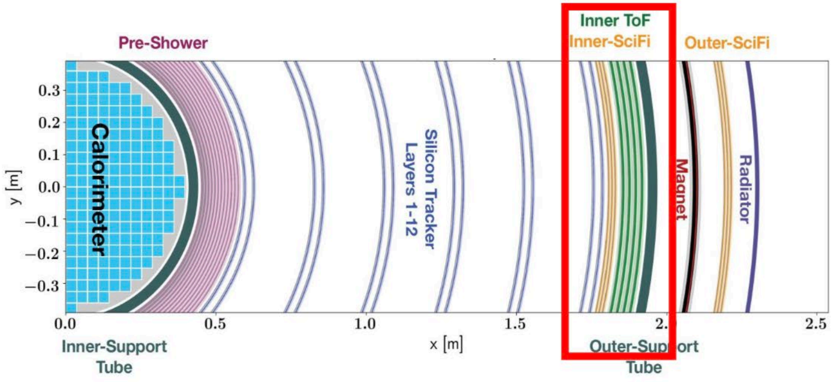


MOONRAY
Charge Detector ToF

AMS-100 Time of flight

T. Kirn, VCI 2022

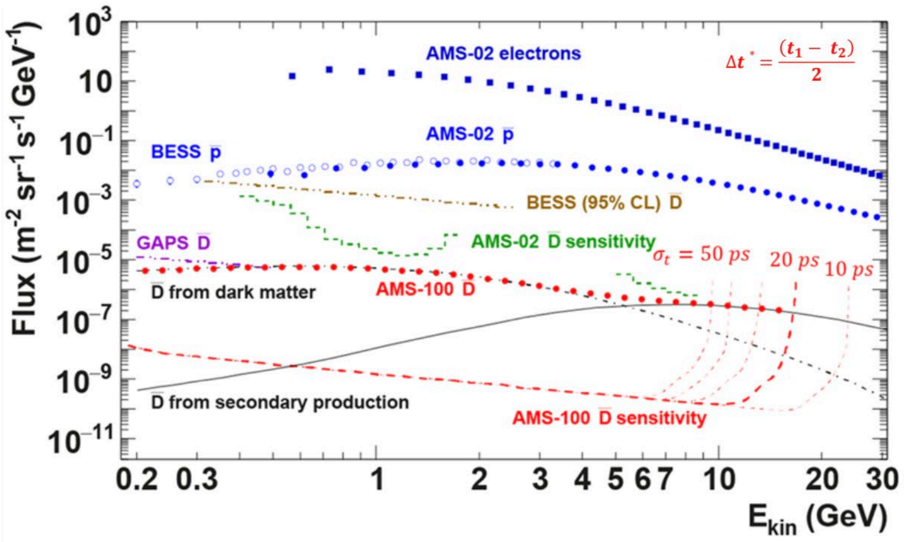
AMS-100: Time of Flight System



Anti-Deuterons are the most sensitive probe for New Physics in Cosmic Rays

AMS-100 would observe thousands of Anti-Deuterons in Cosmic Rays

- Required ToF-Single Counter time resolution : 20 ps
- Z measurements from the signal height
- Provides the trigger and measures **β** = v/c



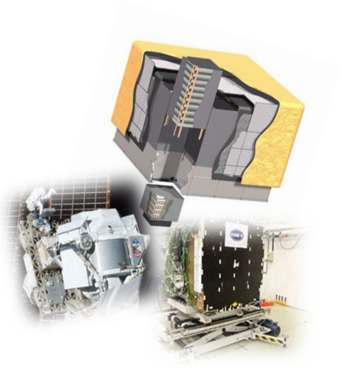
16

I.PI I. Physikalisches Institut | RWTH AACHEN UNIVERSITY

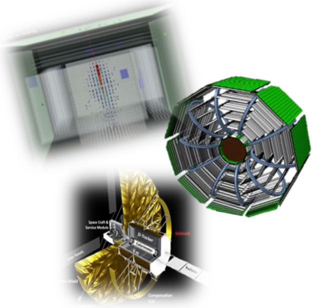
Large area Si-microstrip detectors in space

M. Duranti et al., *Instruments* 2021, 5(2), 20

Most space detectors for charged cosmic ray and γ-ray measurements require **solid state tracking systems based on Si-µstrip sensors.**
Si-µstrip detectors are the preferred solution to instrument **large area detectors** with larger number of electronics channels coping with the **limitations on power consumption in space**



Operating Missions						
	Mission Start	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
Fermi-LAT	2008	$\sim 74\,m^2$	38 cm	$\sim 880 \cdot 10^3$	228 μm	$\sim 66\,\mu m$
AMS-02	2011	$\sim 7\,m^2$	29–62 cm	$\sim 200 \cdot 10^3$	110 μm	$\sim 7\,\mu m$
DAMPE	2015	$\sim 7\,m^2$	38 cm	$\sim 70 \cdot 10^3$	242 μm	$\sim 40\,\mu m$



Future Missions						
	Planned operations	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
HERD	2030	$\sim 35\,m^2$	48–67 cm	$\sim 350 \cdot 10^3$	$\sim 242\,\mu m$	$\sim 40\,\mu m$
ALADInO	2050	$\sim$ 80-100 m^2	19–67 cm	$\sim 2.5 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$
AMS-100	2050	$\sim$ 180-200 m^2	$\sim$ 100 cm	$\sim 8 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$

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