INSTR 2026
Instrumentation for Colliding Beam Physics
October 12–16, 2026, Hefei, China | University of Science and Technology of China

Serial readout of LGAD detectors for cosmic-ray space-borne instruments

M. Duranti[1,2] (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), F. Moscatelli (CNR and INFN), A. Morozzi (INFN), A. Fondacci (UniPg and INFN, now at CERN) and FBK

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

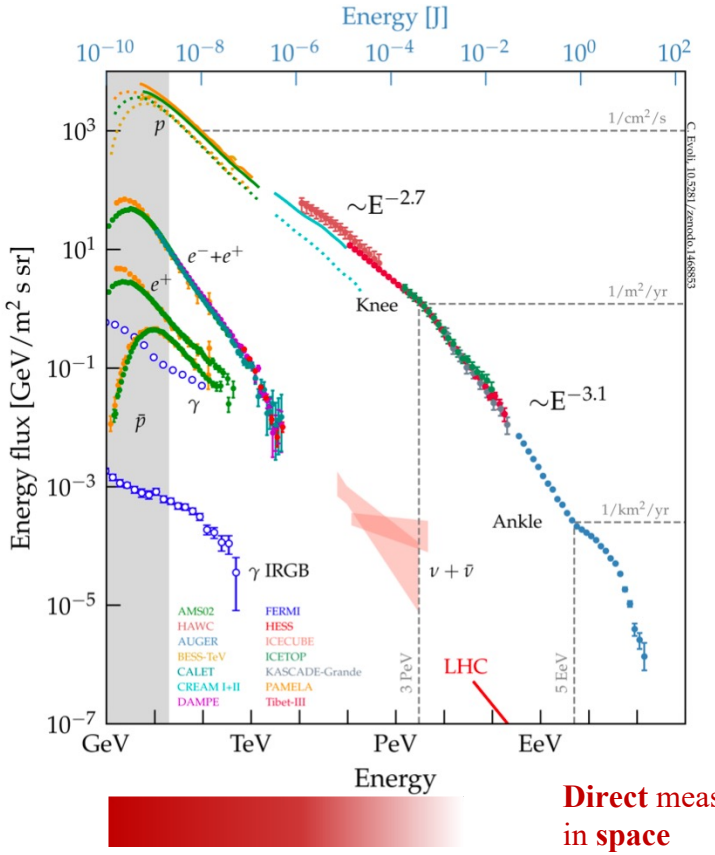
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Serial readout of LGAD detectors for cosmic-ray space-borne instruments

- Scientific context and 5D tracking in space
- Tracking with µstrips
- Charge with µstrips
- The PTSD project: space-driven R&D for LGAD detectors with serial read-out
- Ideas for future…

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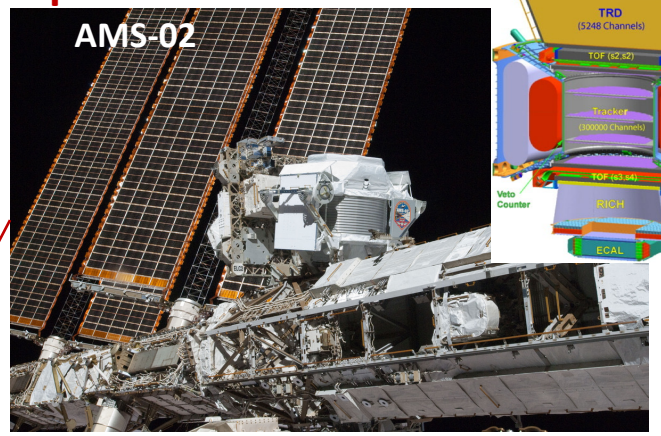
Charged CRs: state of the art



Direct measurements in **space**

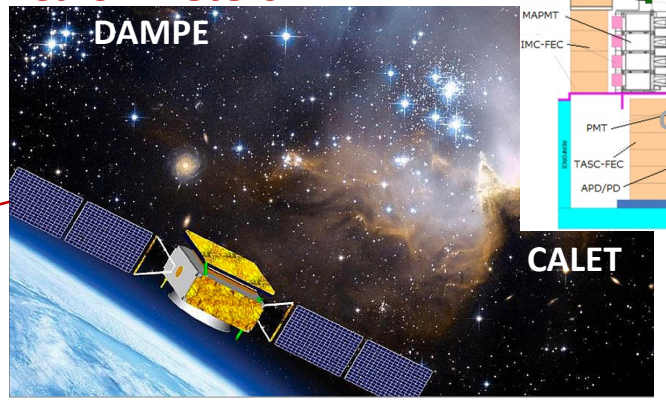
Indirect measurements from **ground**

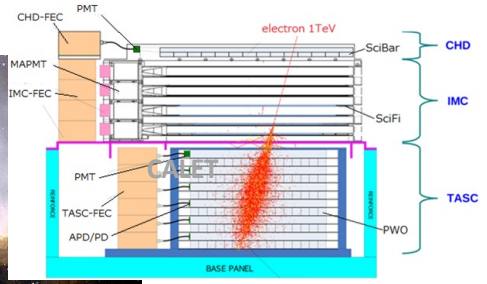
Spectrometers



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 sensitivive to charge sign / mass

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

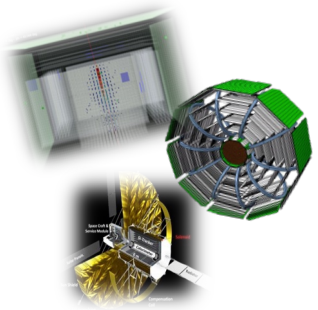
Si-µstrip detectors are the preferred solution to instrument **large area detectors** with larger number of electronics channels coping with the **limitations on power consumption in space (~ 10 W / m²)**

Large area Si-microstrip detectors in space

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

Most of 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	~ 80-$100\,m^2$	19–67 cm	$\sim 2.5 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$
AMS-100	2050	~ 180-$200\,m^2$	~ 100 cm	$\sim 8 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$
AMS-L0	2027	~ 8 m^2	~ 100 cm	~ 70 * 10^3	~ 110 µm	~ 7 µm

[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

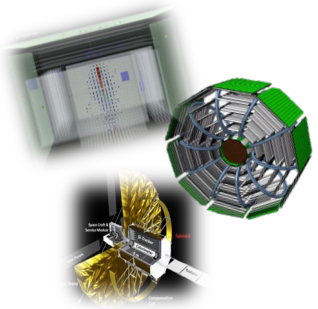
[4] AMS-L0 Collaboration, *Beam Test Characterization of Silicon Microstrip Detector Flight-Model Ladders for the AMS-02 Upgrade, 2026* https://arxiv.org/pdf/2603.25085

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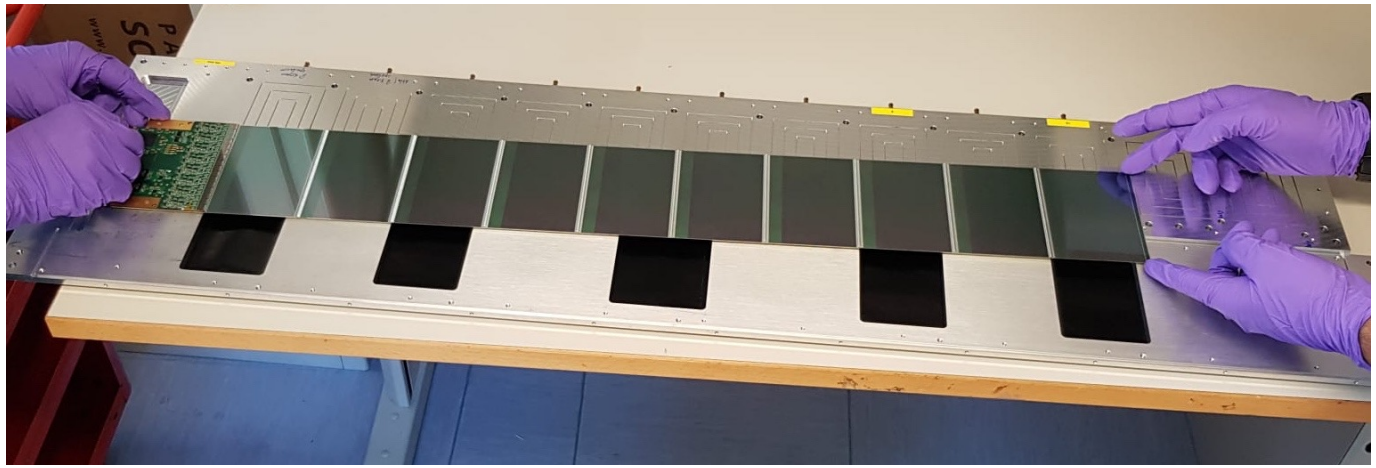
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Capacitance and daisy-chain

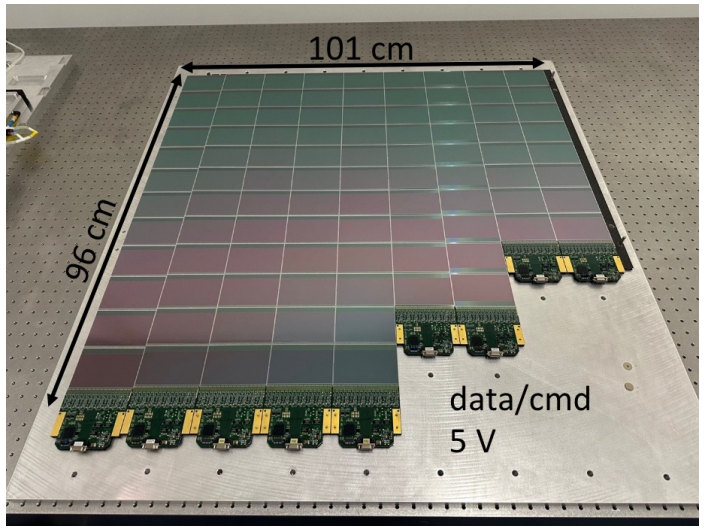
At production level the strips cannot be so long:

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

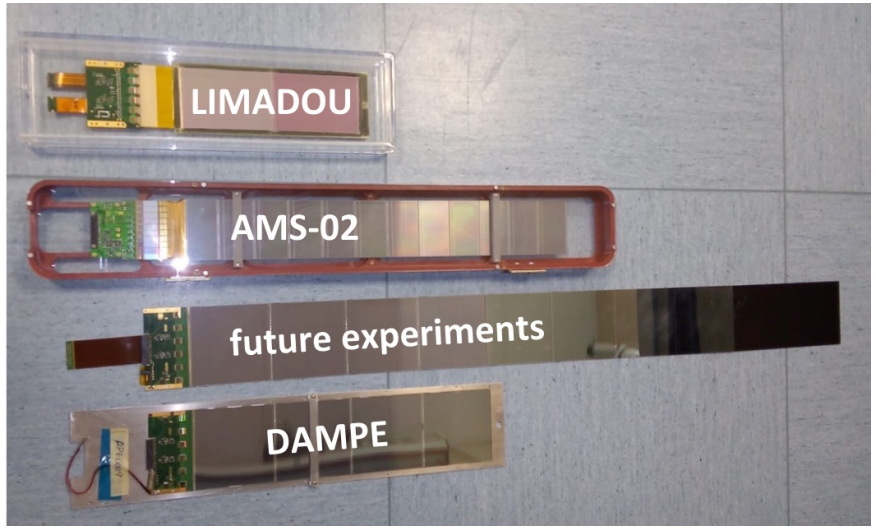
→ 50-100 cm long strips are obtained through daisy-chain



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



INFN Perugia



see Qinze Li (121) talk on 12/10

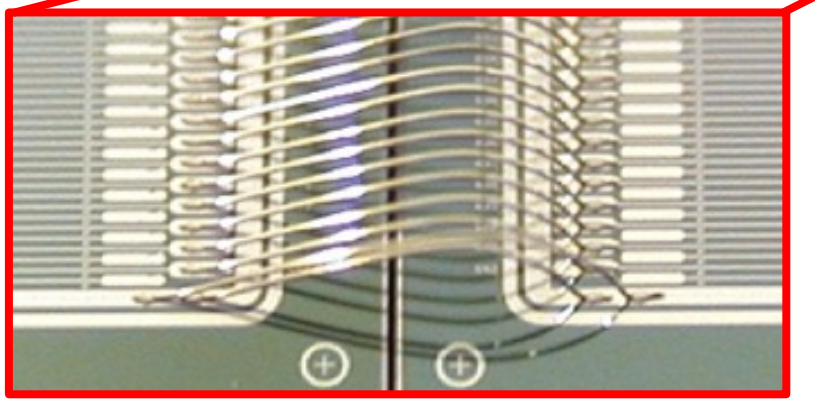
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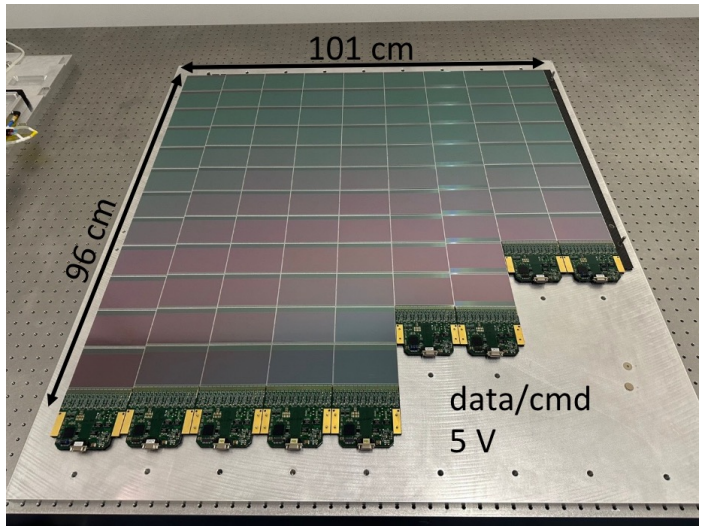
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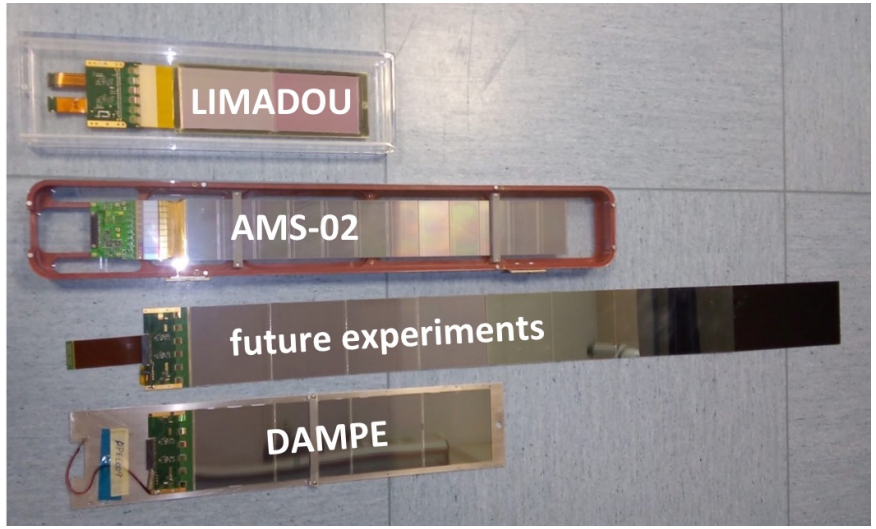




AMS-02 upgrade, Layer-0 (1/4 plane) @ INFN Perugia, Terni labs

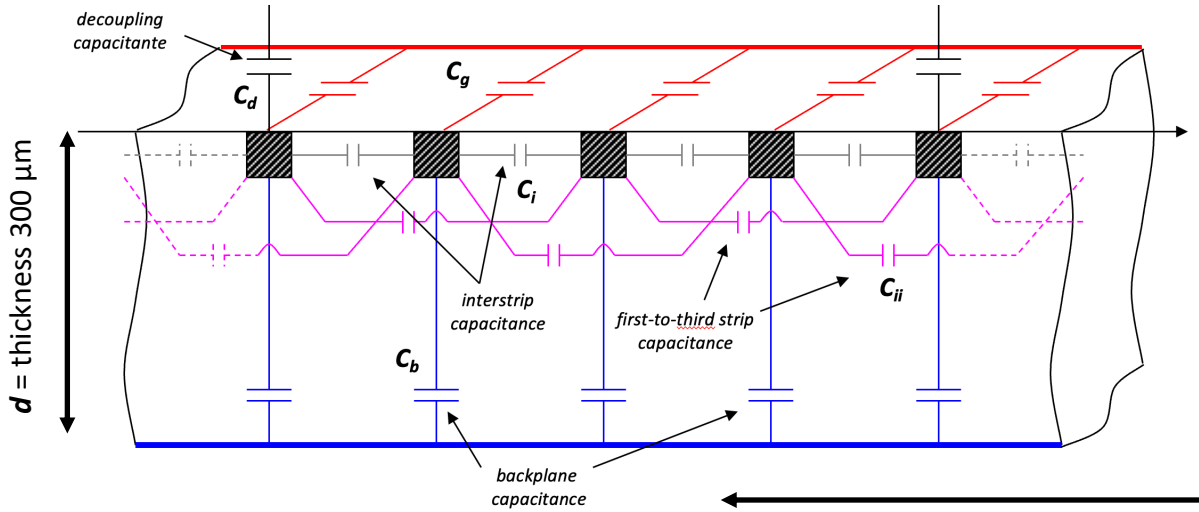


INFN Perugia



see Qinze Li (121) talk on 12/10

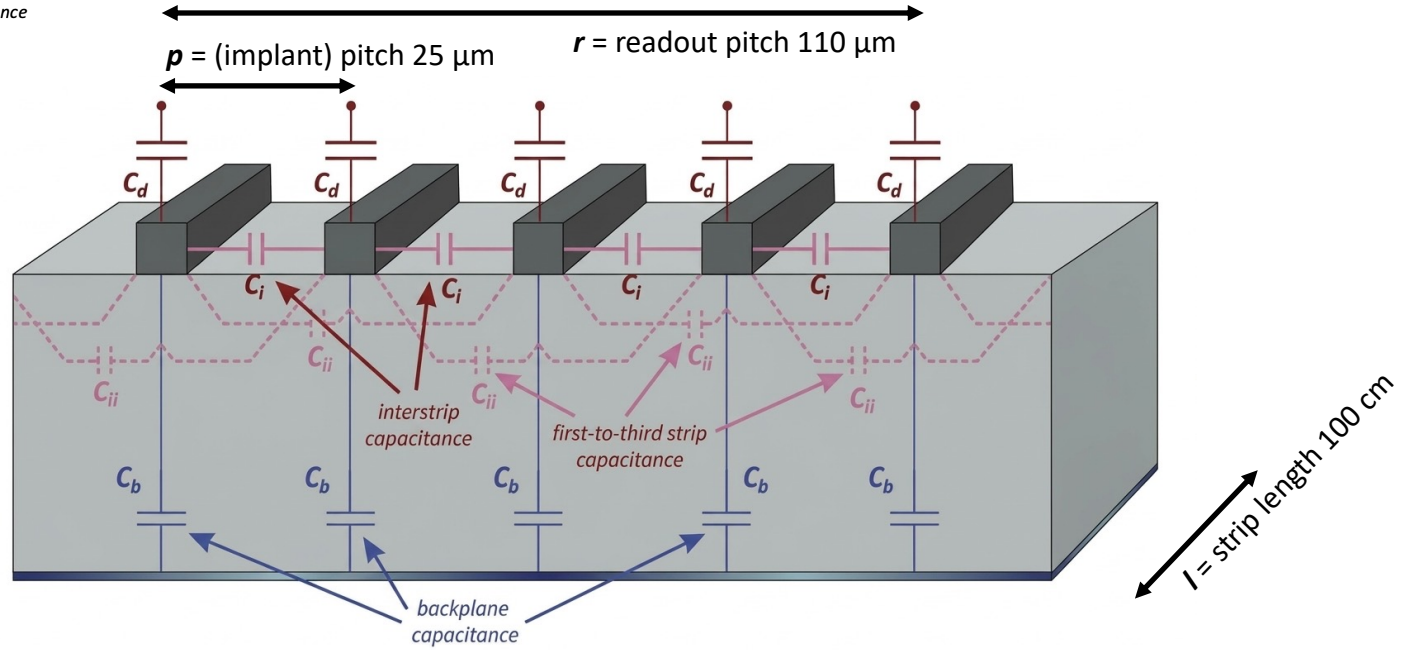
Capacitance



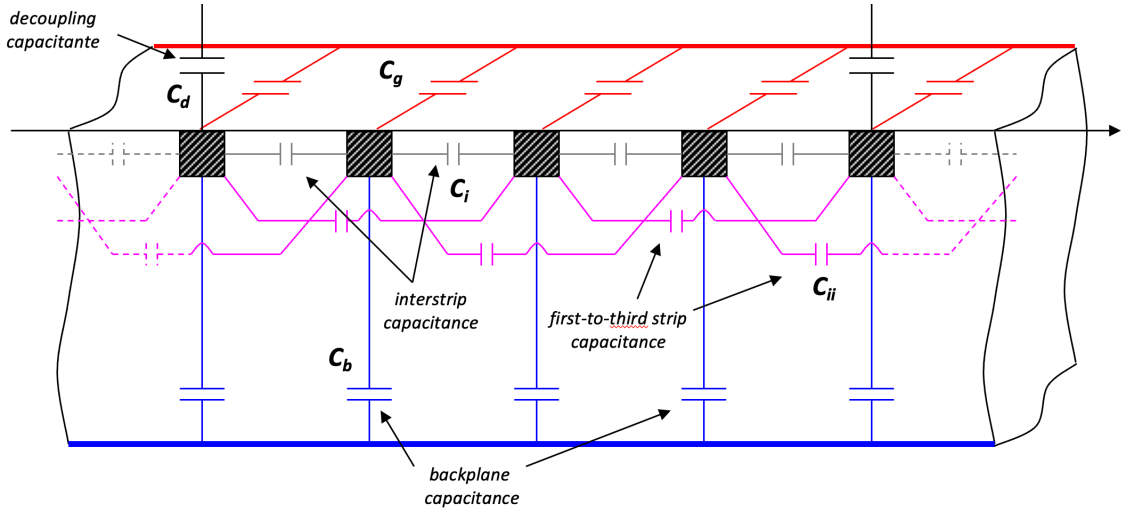
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l = strip lenght (typical 10-100 cm)
d = thickness (typical 300 µm)

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 = guardring capacitance << C_i
C_{ii} = first-to-third strip capacitance << C_i

capacitance must be kept under limit



Capacitance and daisy-chain

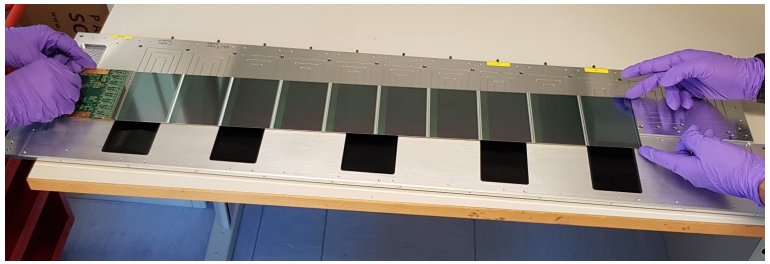


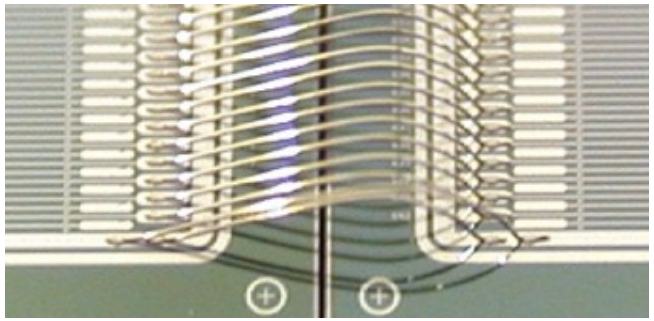
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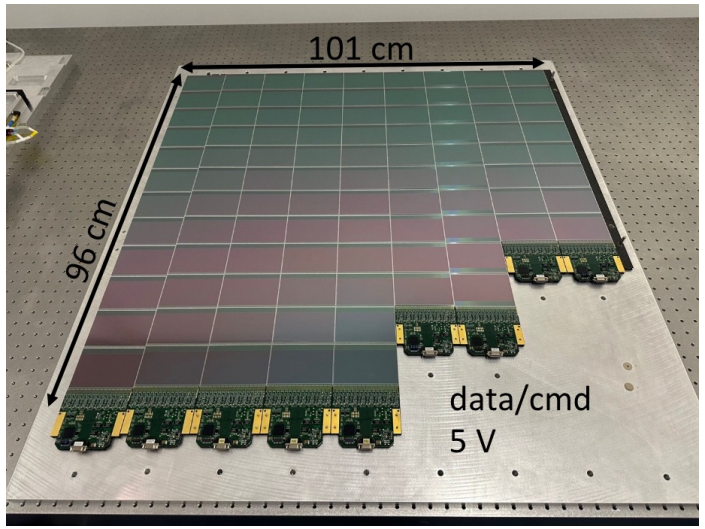
capacitance must be kept under limit

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



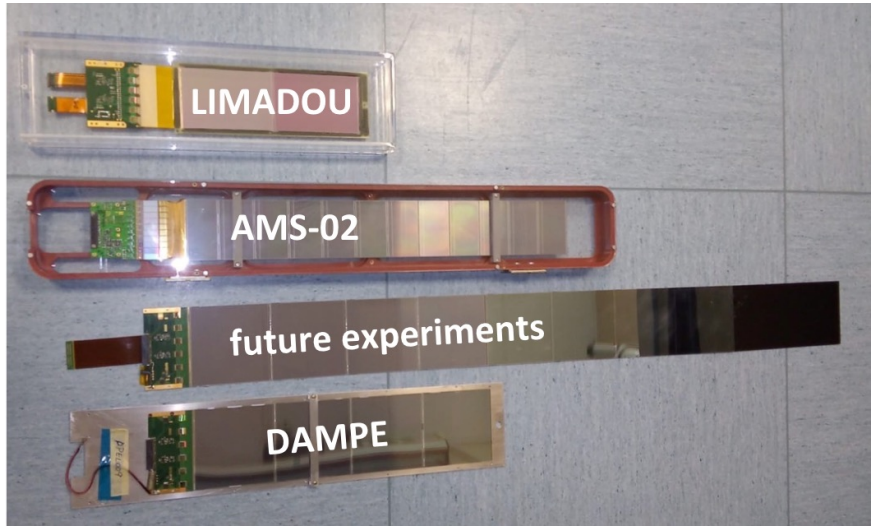


AMS-02 upgrade, Layer-0 (1/4 plane) @ INFN Perugia, Terni labs

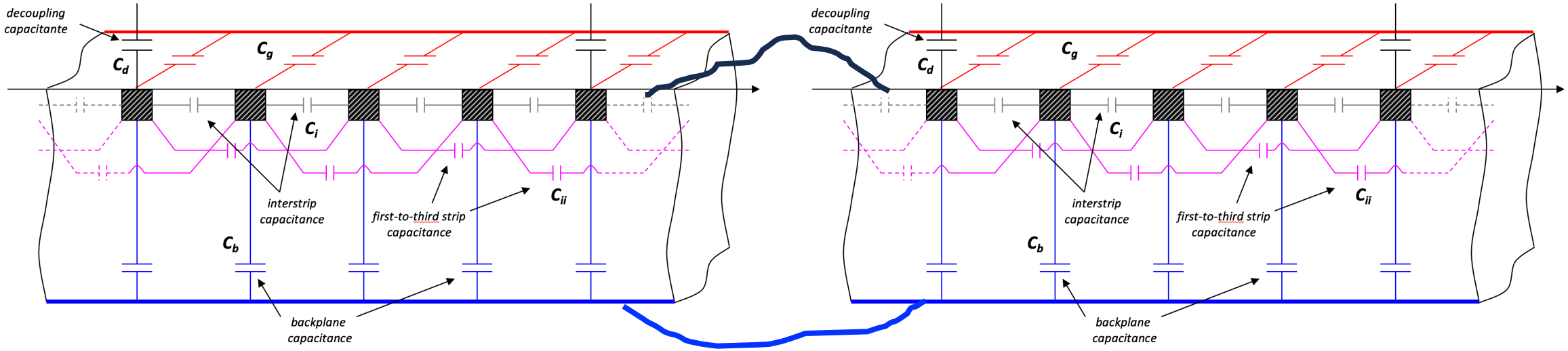


see Qinze Li (121) talk on 12/10

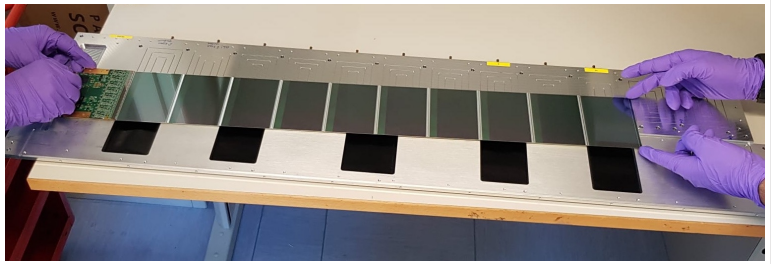
INFN Perugia

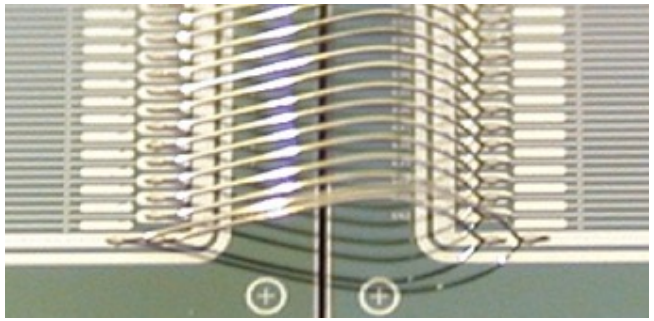


Capacitance and daisy-chain

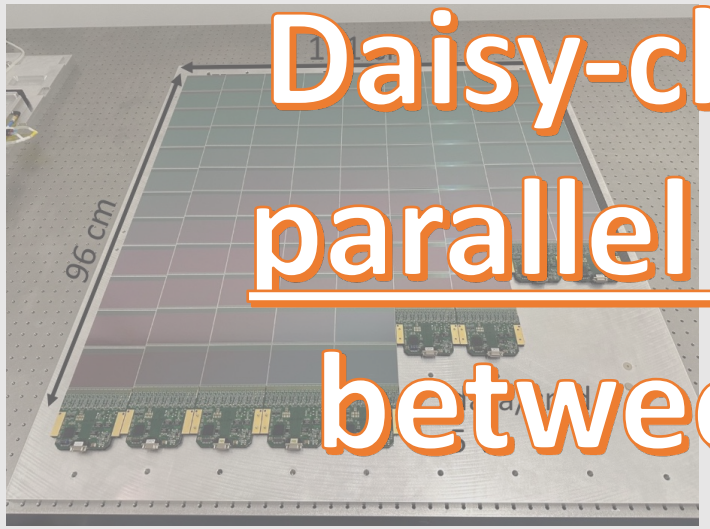


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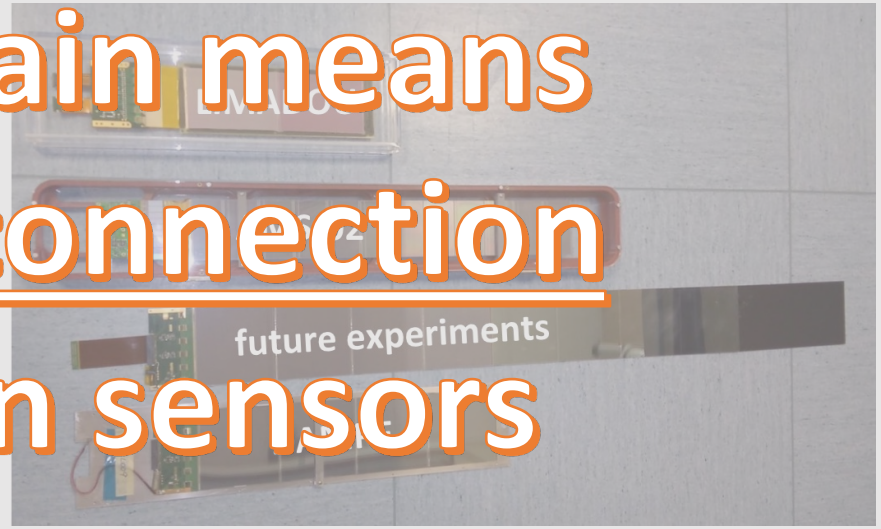




AMS-02 upgrade, Layer-0 (1/4 plane) @ INFN Perugia, Terni labs



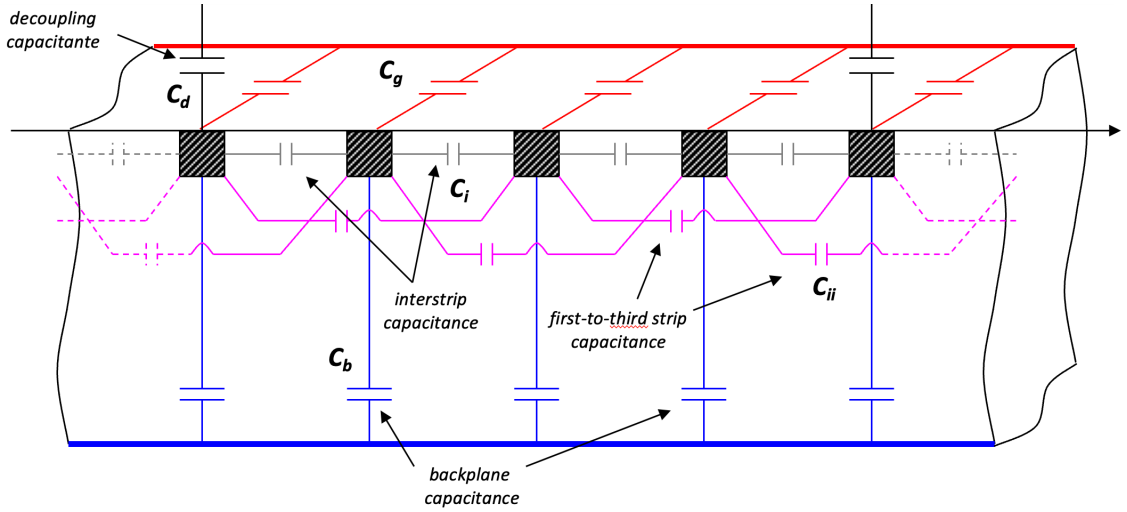
INFN Perugia



Daisy-chain means parallel connection between sensors

see Qinze Li (121) talk on 12/10

Capacitance and daisy-chain



p = pitch (typical 25-50 µm)
l = strip lenght (typical 50-100 cm)
d = thickness (typical 300 µm) (thin LGAD 30 µm)

$\mathbf{C_i}$ = interstrip capacitance ~ 1 pF/cm * *l* = 50 – 100 pF
$\mathbf{C_d}$ = decoupling capacitance ~ 1000 pF (DC sensors) or 120 pF/mm^2 (AC sensors) > $\mathbf{C_i}$ $\mathbf{C_b}$ $\mathbf{C_g}$ $\mathbf{C_{ii}}$
$\mathbf{C_b}$ = backplane capacitance ~ 1 pF/cm * *l* * *p/d* = 1/10 (~1) * 50 – 100 pF = 1- 10 pF (10-100 pF)
$\mathbf{C_g}$ = guardring capacitance << C_i
$\mathbf{C_{ii}}$ = first-to-third strip capacitance << C_i

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

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

$\mathbf{C_{back}}$ ~ 1 pF/cm * *l* * *p/d*
→ 5 – 10 pF (thick)
→ 50 – 100 pF (thin)

Notice that:

- typically 300µm (AMS, DAMPE) – 500µm (Fermi-LAT) thick sensors are used
  → C_i is ~ dominant
- when you go thinner (as for LGADs) C_b is not anymore negligible with respect to C_i

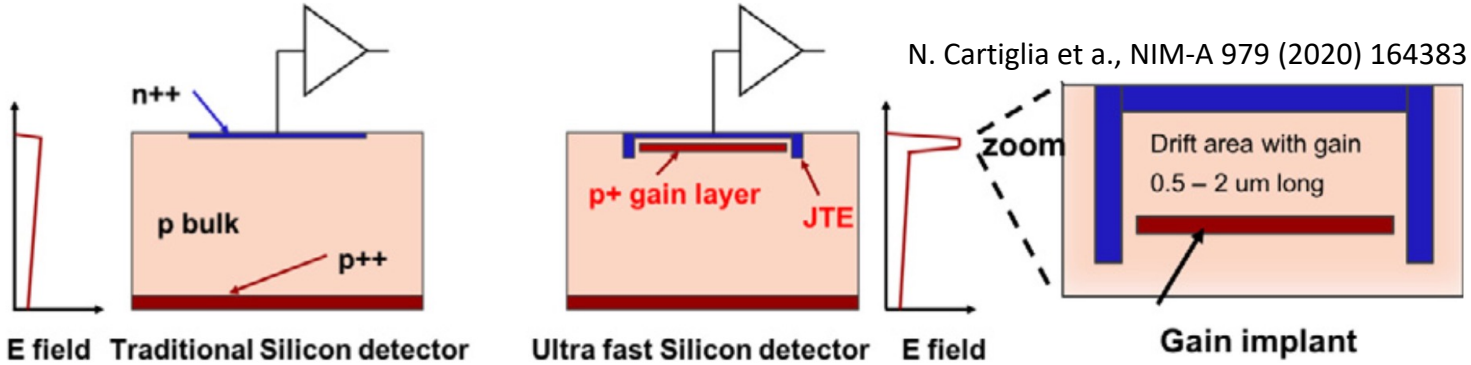
→ a typical "area" of a strip is of *O*(cm^2) (i.e. 0.01 mm * 100 mm)
→ a typical "area" for a LHC (LGAD) sensor is < 1 mm^2

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 a., NIM-A 979 (2020) 164383

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}

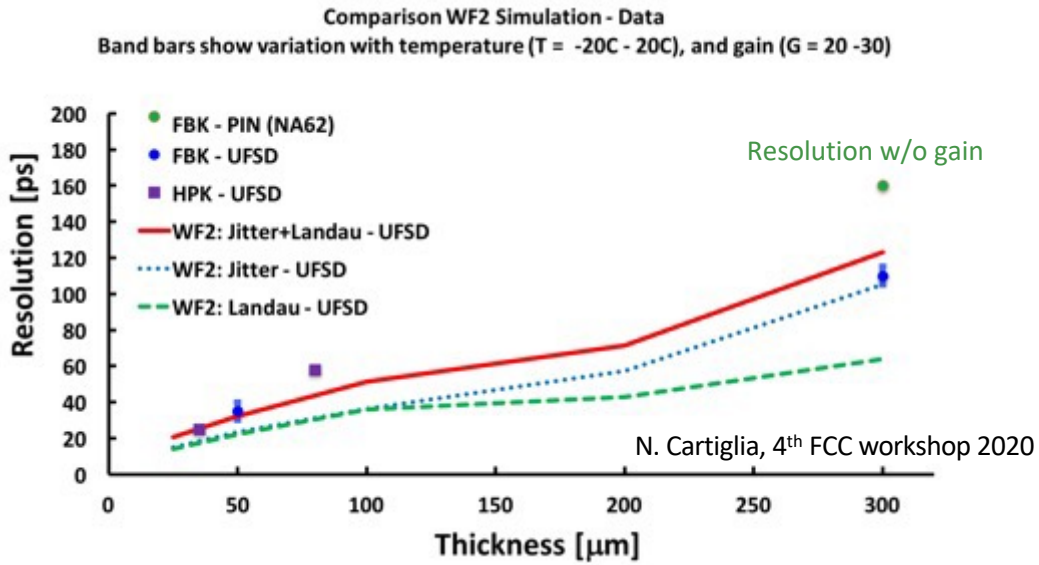
increase signal in thin sensors → intrinsic gain

Optimal candidate for large-area 4D Tracking devices

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

An 'almost consolidated' technology, yet very challenging



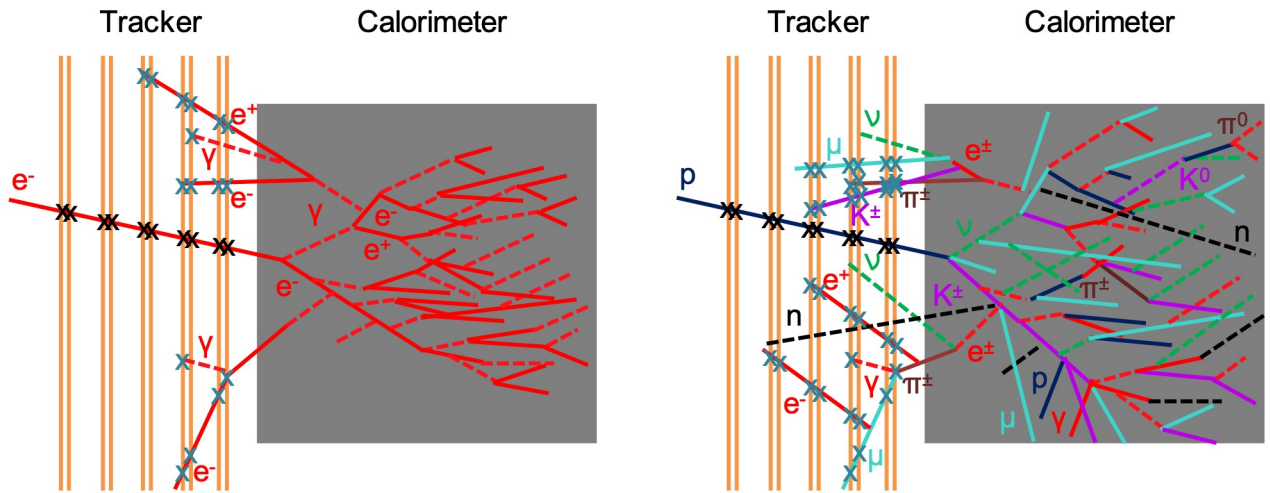
N. Cartiglia, 4th FCC workshop 2020

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

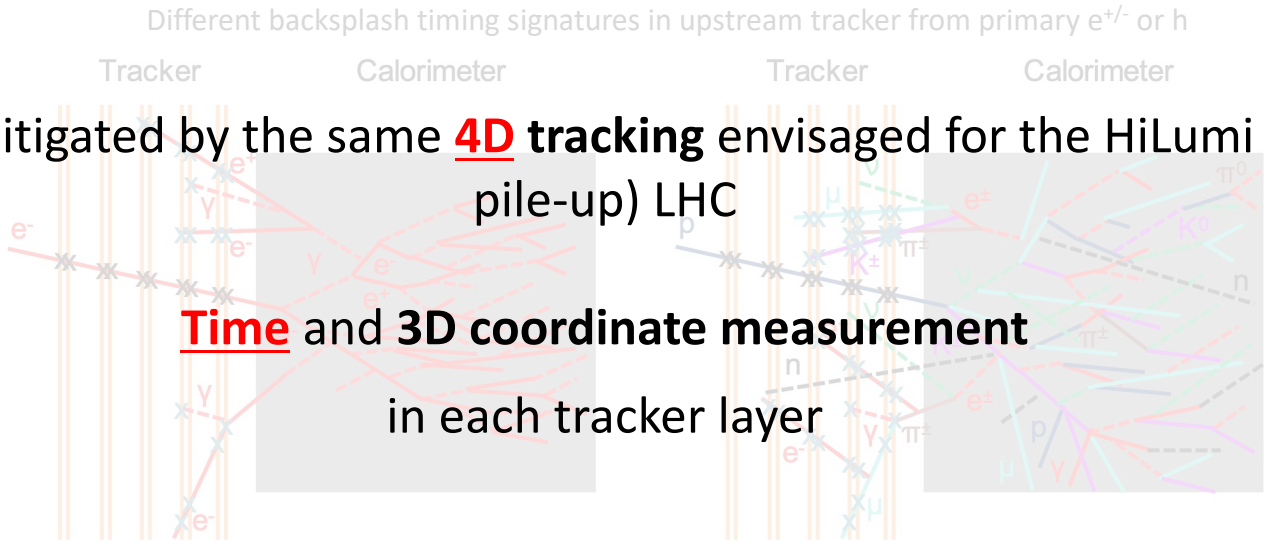


The backsplash is a problem but can be also "exploited" to do Particle ID.
This has been firstly proposed in 2021 (M. Duranti et al., *Instruments* 2021, 5(2), 20)

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



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

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:

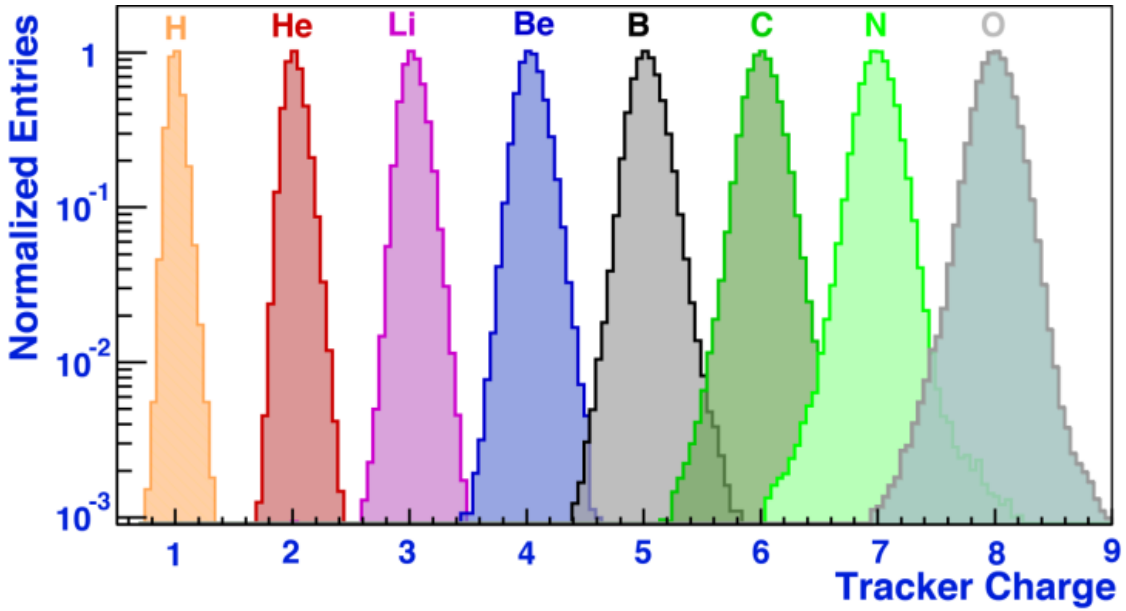
IMPROVED TRACK FINDING
Hit timing information improves track reconstruction on high rate environments and identifies back-scattering hits from downstream calorimeters

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

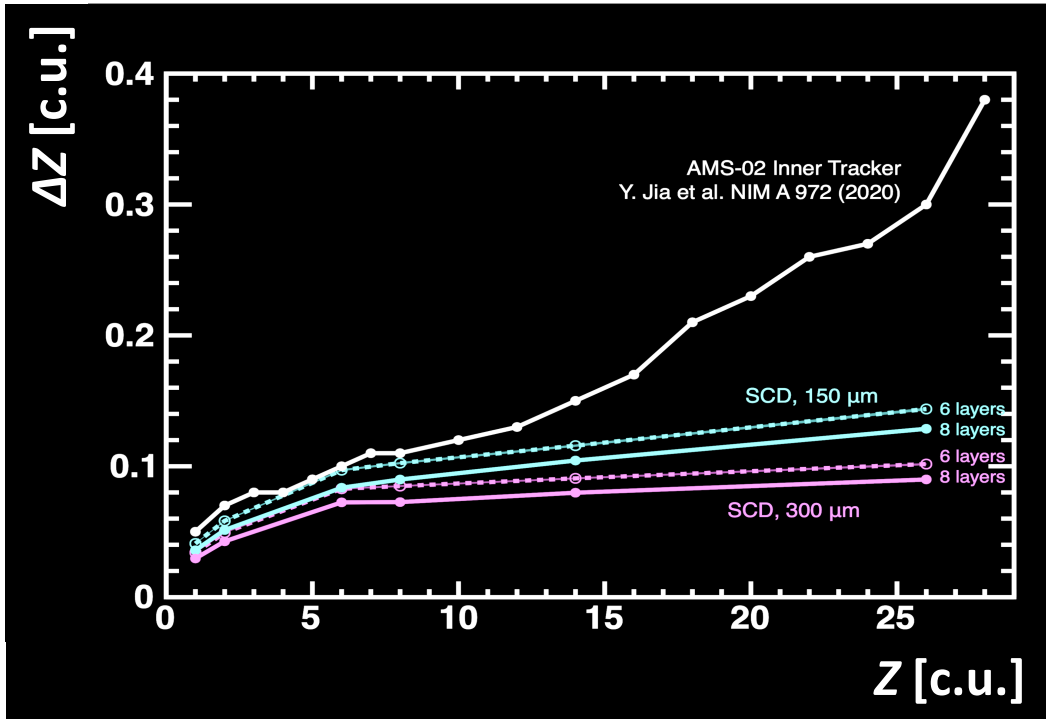
PARTICLE ID
Track timing identifies slow low-energy particles backscattering from downstream calorimeters for primary hadronic particle crossings

Charge measurement



The charge resolution:

- improves with the number of layers
- essentially doesn't improves with the increase of the S/N (for high Z this is "for free"…)
- strongly improves with the thickness (i.e. the number of generated carriers)



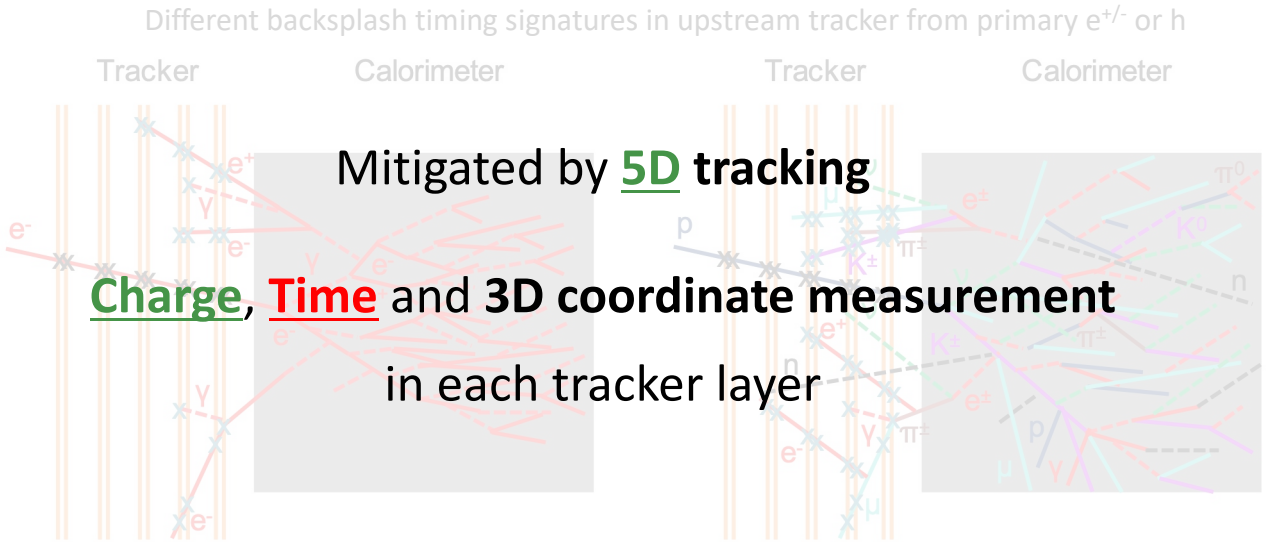
Typical Charged Cosmic Rays space-experiment:

- incoming flux are all the nuclei in the Periodic Table (at least up to Fe)
- many (>=2) detectors to measure the same quantity
- Silicon sensors are the key instrument (also) to measure Z

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



Mitigated by **5D tracking**

Charge, **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:

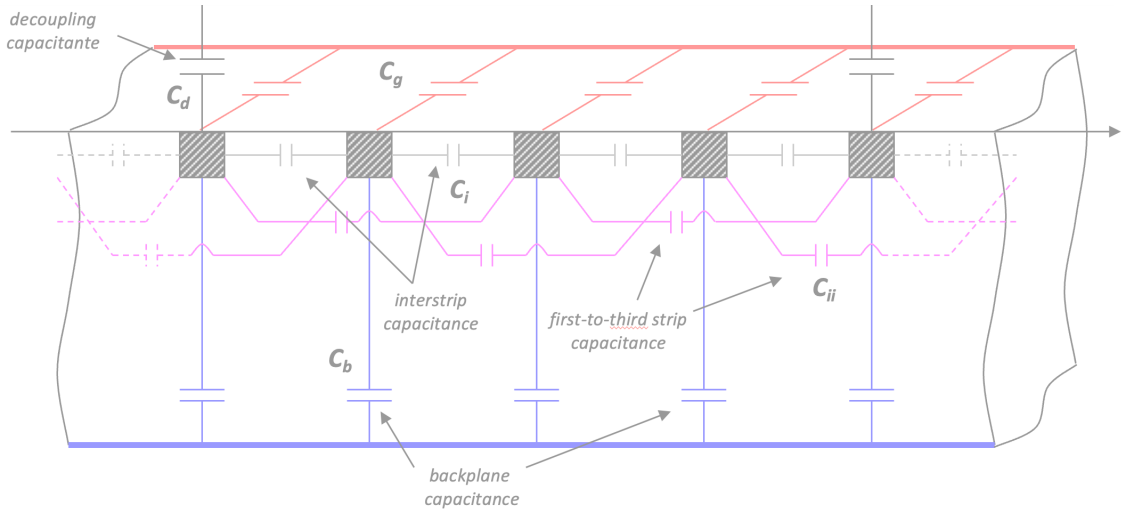
IMPROVED TRACK FINDING
Hit timing information improves track reconstruction on high rate environments and identifies back-scattering hits from downstream calorimeters

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

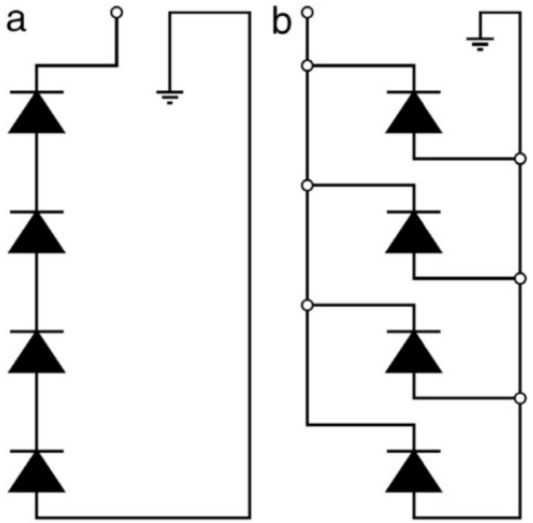
Serial readout of LGADs



p = pitch (typical 25-50 µm)
l = strip lenght (typical 50-100 cm)
d = thickness (thin LGAD 30 µm)

C_i = interstrip capacitance ~ 1 pF/cm * *l* = 50 – 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 * 50 – 100 pF = 10-100 pF
C_g = guardring capacitance << C_i
C_{ii} = first-to-third strip capacitance << C_i

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



N. Kratochwil et al., PANDA experiment

b) standard "parallel" readout

√ bias voltage independent on number of sensors

X total capacitance seen by readout FEE scales with number of sensors

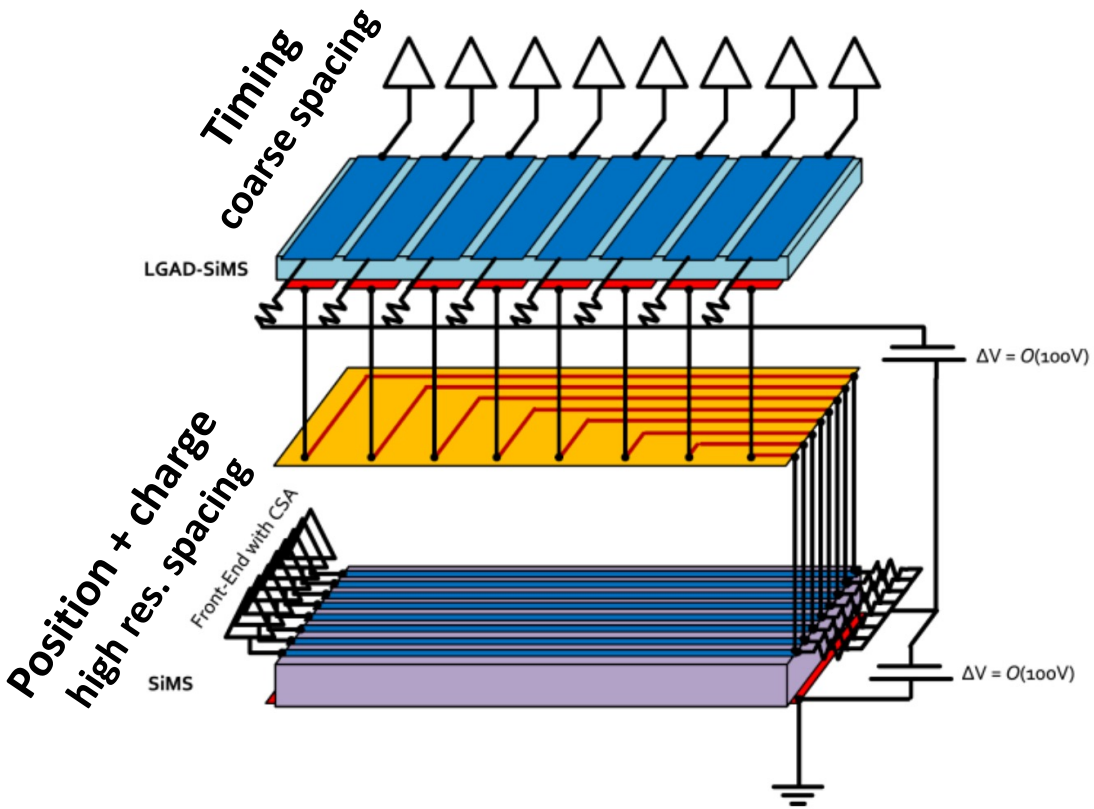
a) "serial" readout

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 – initial (too naïve) idea



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 serial readout

- combine a standard µstrip sensor (2D + Z) with an LGAD (2D + timing)
- serial 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

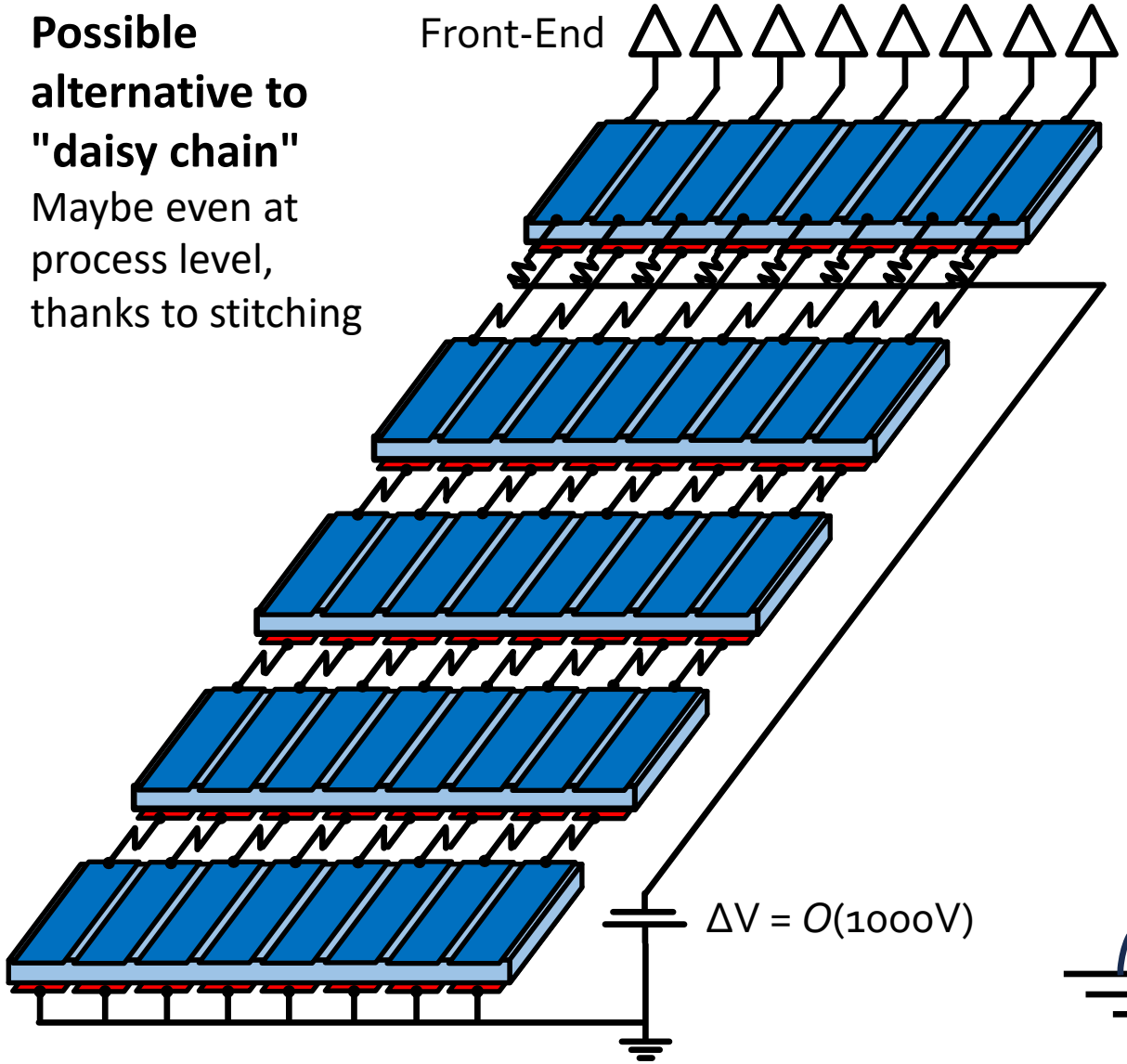
- suits the requirements for a **tracking system in a magnetic spectrometer with oriented magnetic field**

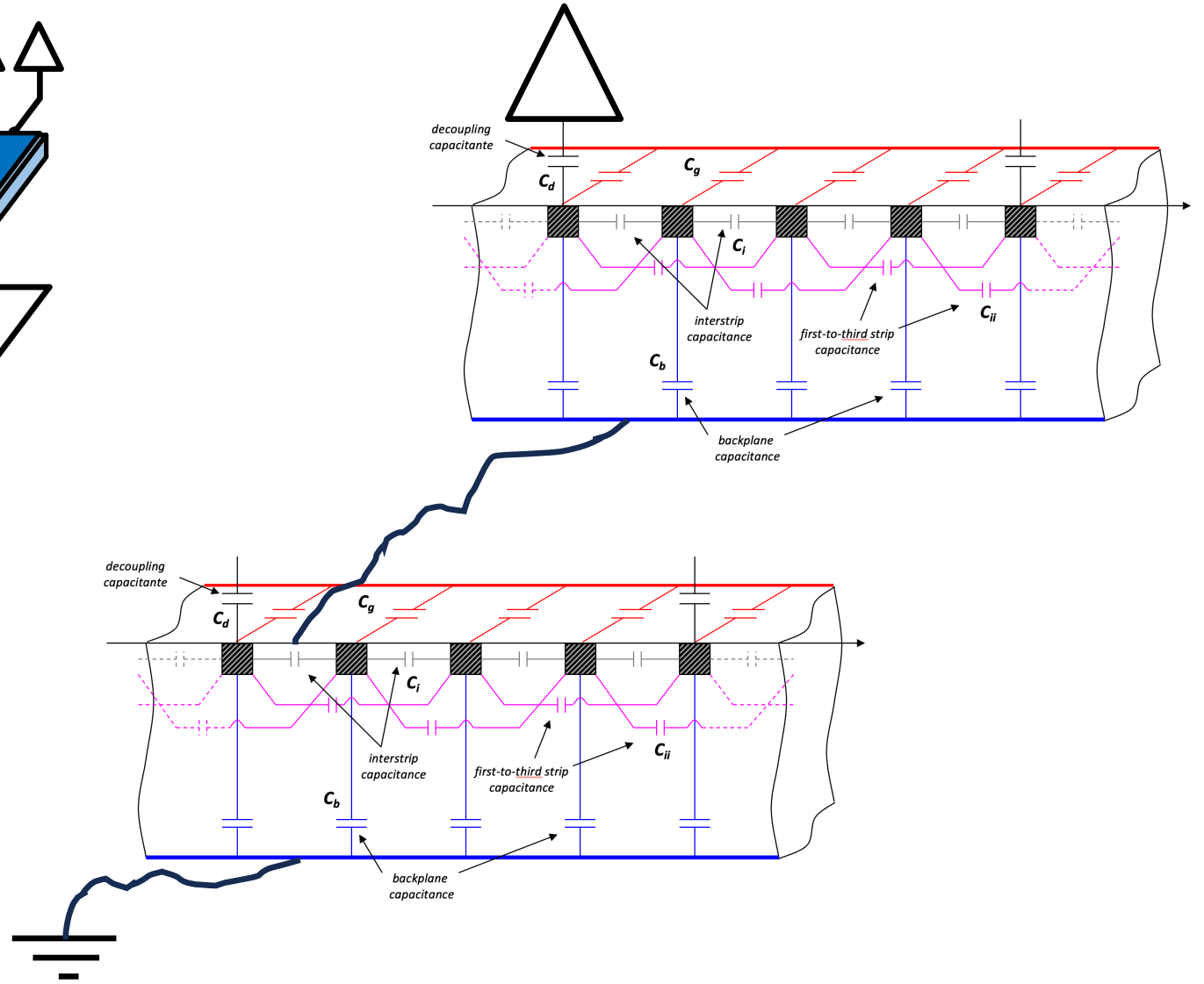
Of course there are not only benefits:

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

More "evolved" ideas…

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



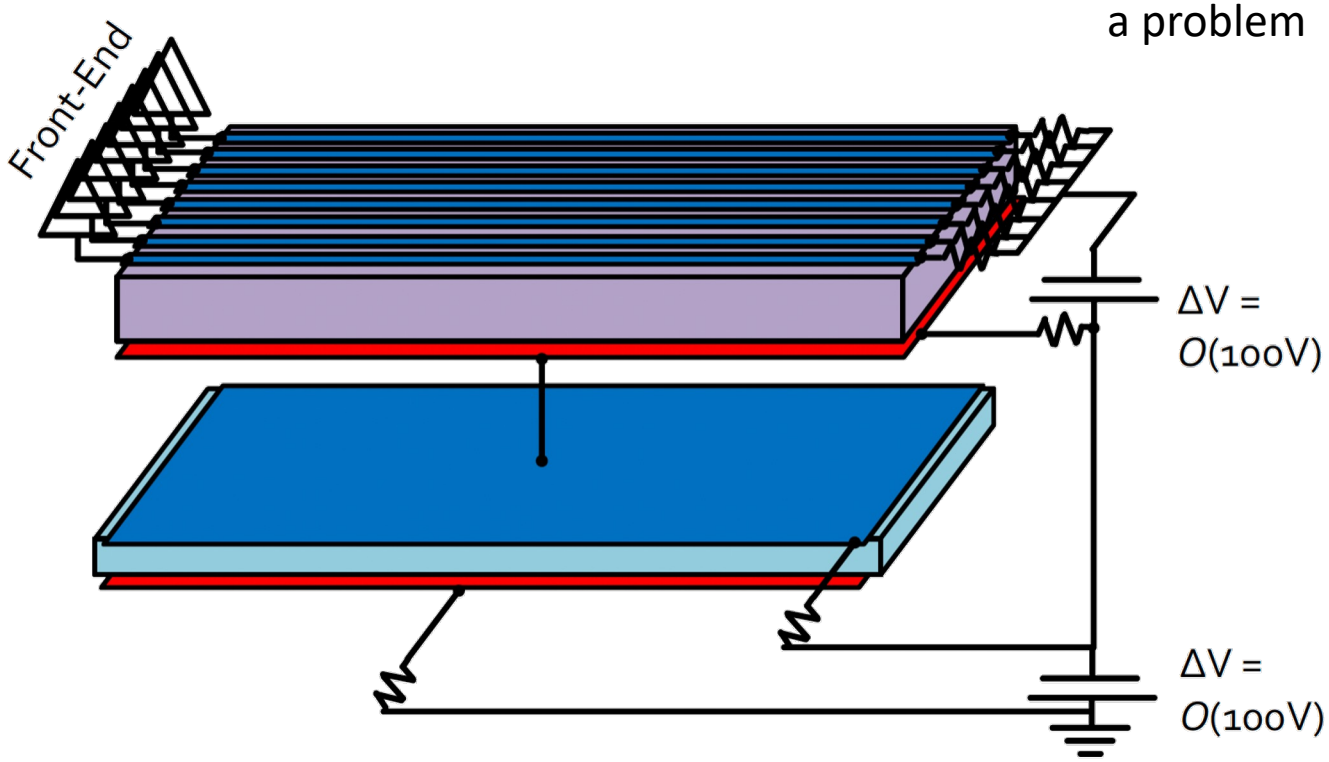


More "evolved" ideas…

Single timing microstrip sensor
Fill factor naturally not a problem

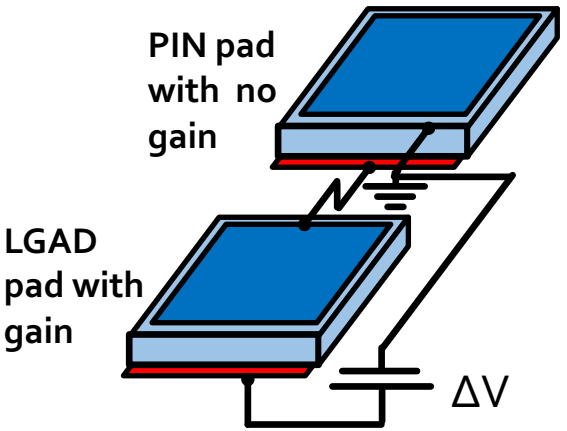
multi-strip SiMS

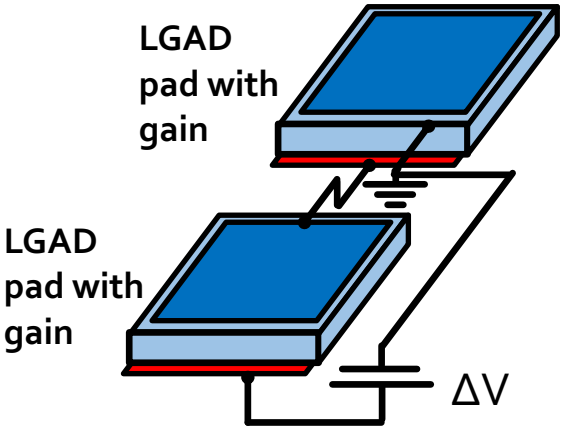
single channel LGAD



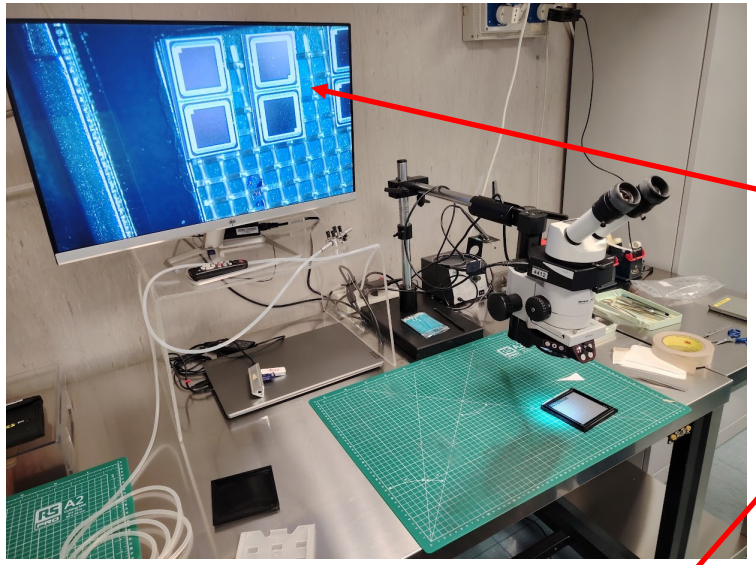
Starting prototypes…

Let's start with a single pad "sandwich"
To test the idea

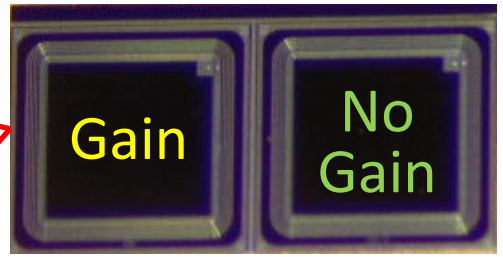


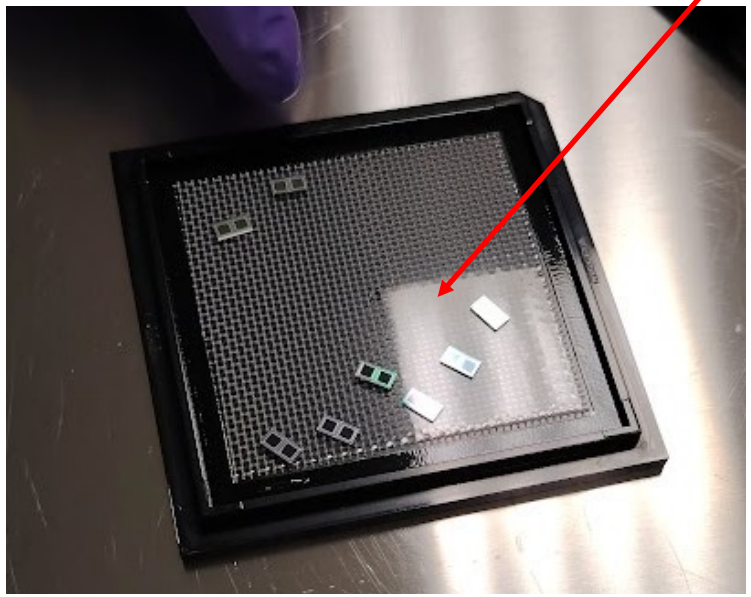


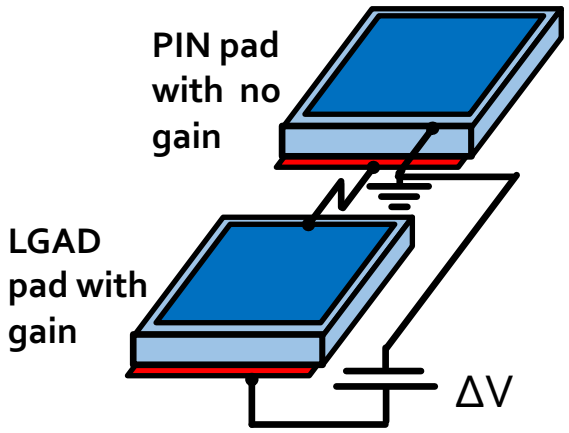
“Stacked” 5D sensor – Proof of concept lab tests

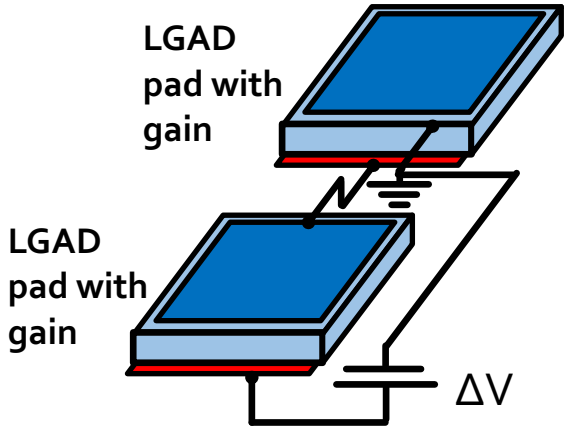


Thanks to test structures
(FBK, from the MoveIT project, that we thanks)

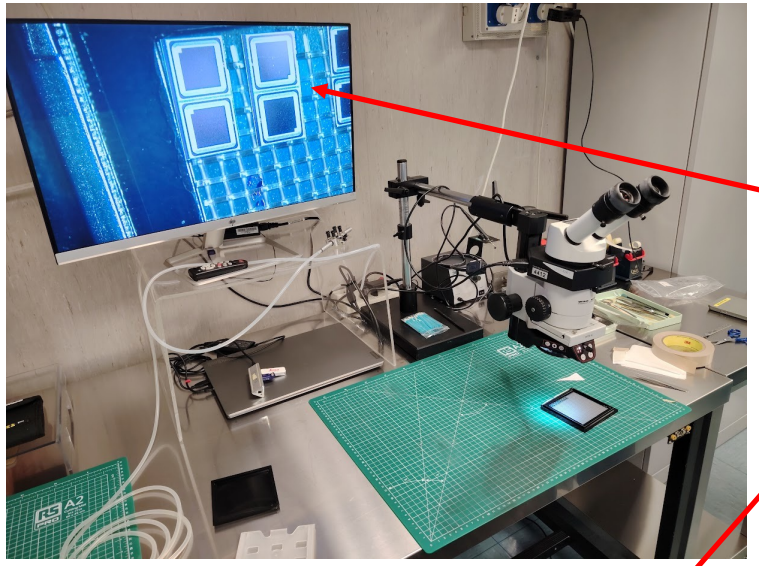




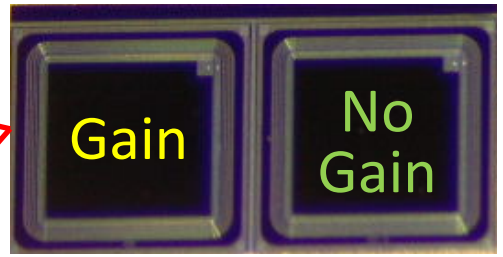


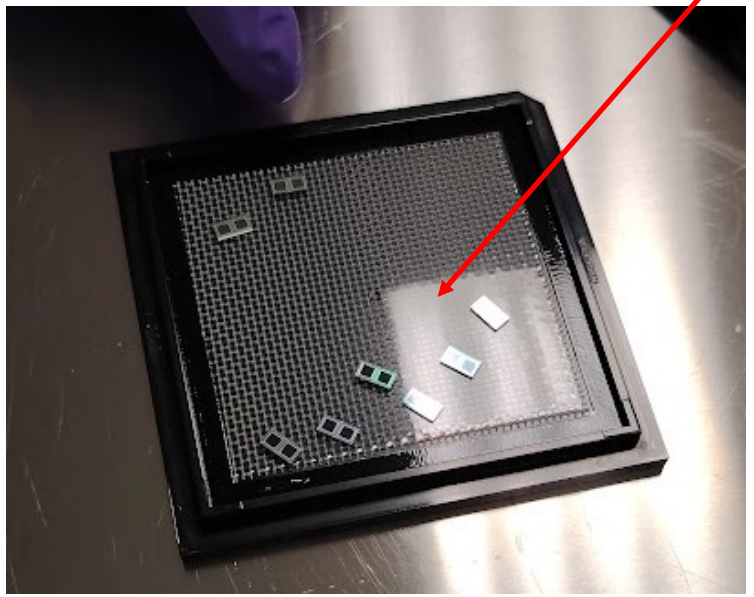


“Stacked” 5D sensor – Proof of concept lab tests

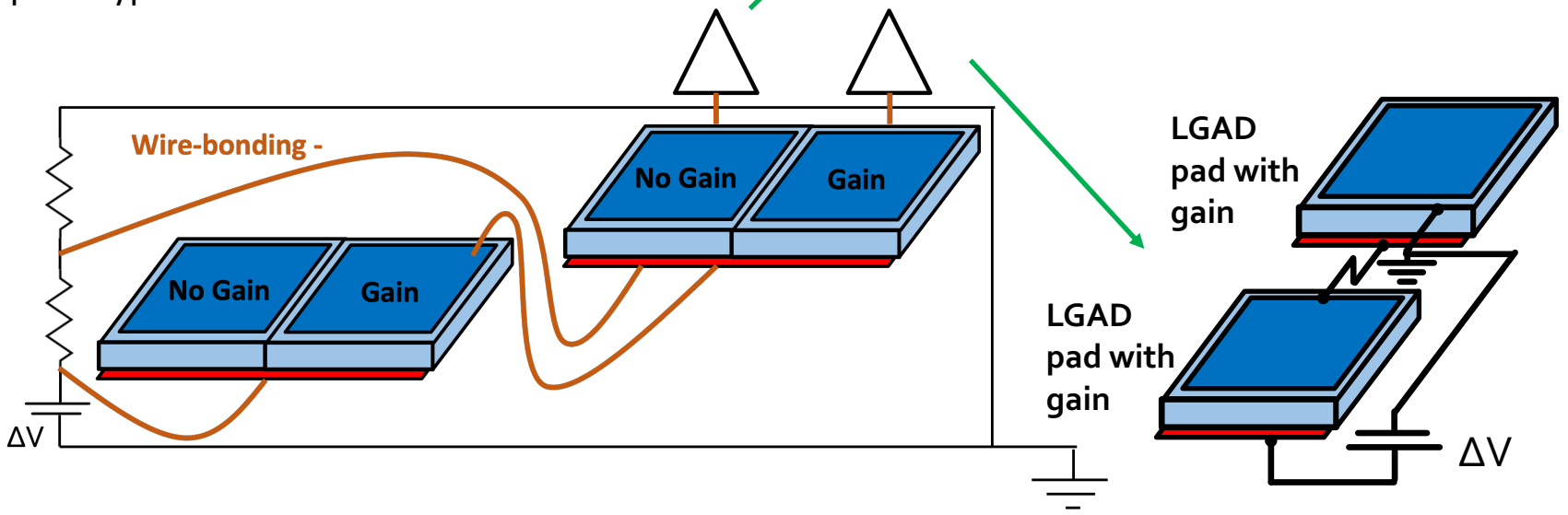


Thanks to test structures
(FBK, from the MoveIT project, that we thanks)

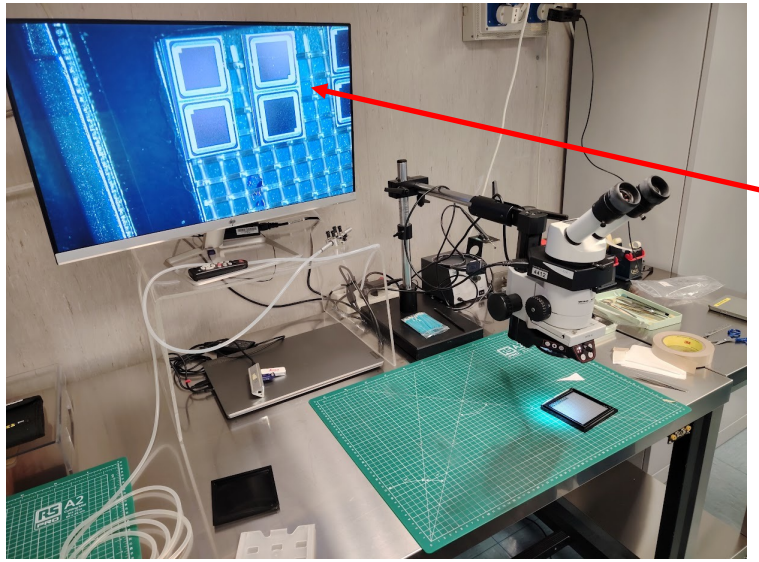




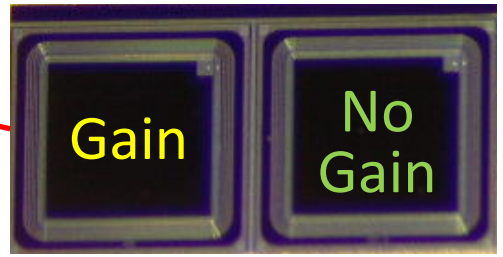
we could test the idea with a
prototype like this:

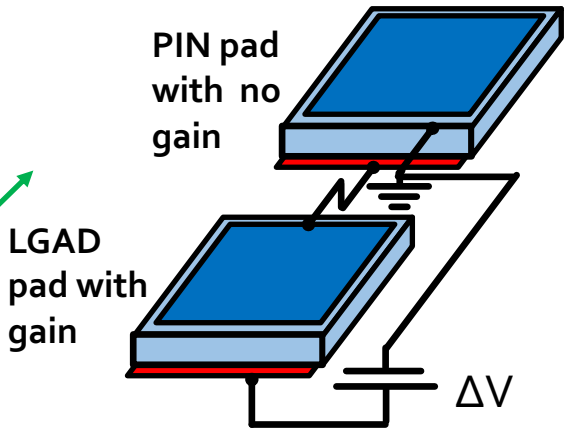


“Stacked” 5D sensor – Proof of concept lab tests

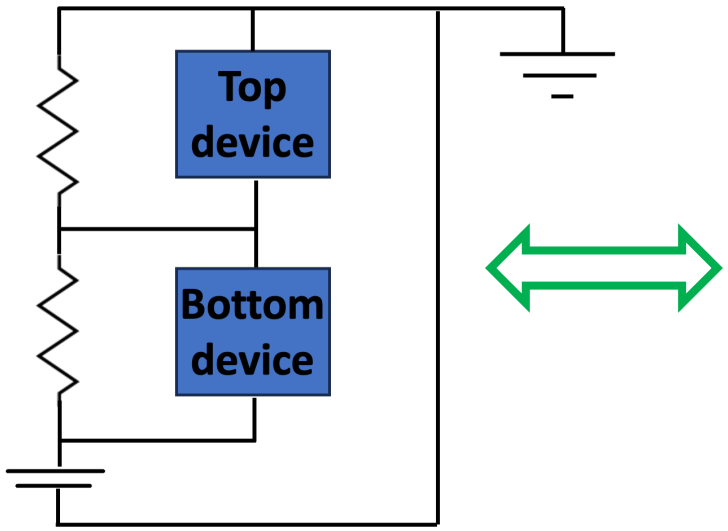


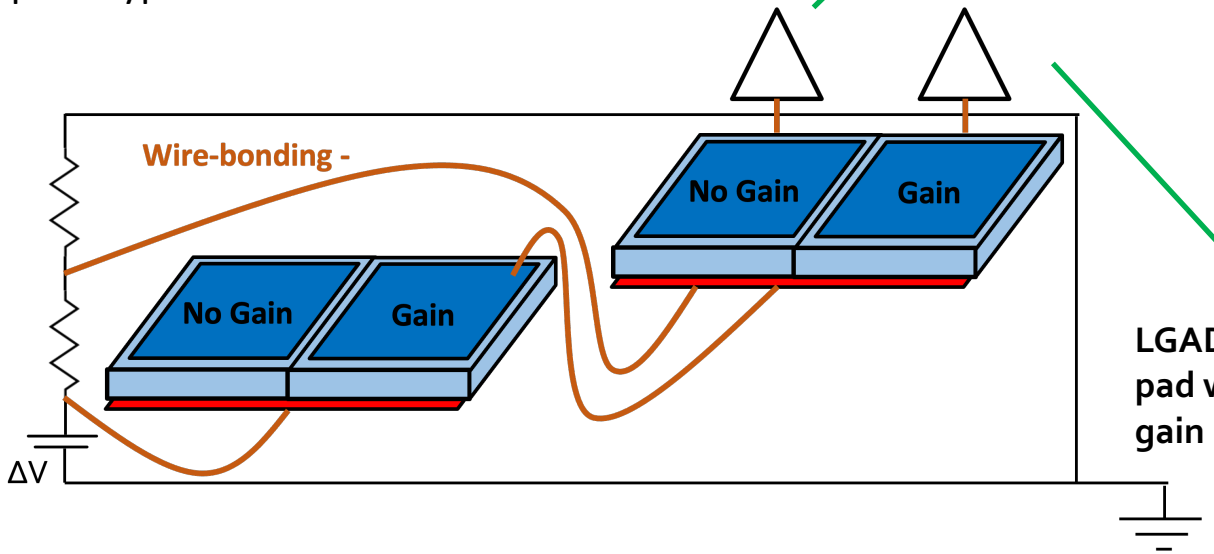
Thanks to test structures
(FBK, from the MoveIT project, that we thanks)

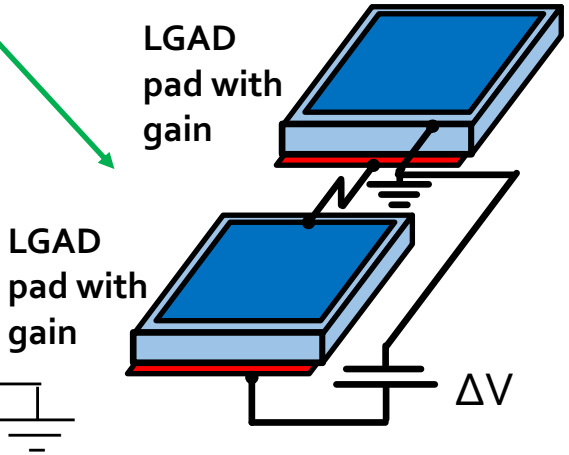




we could test the idea with a prototype like this:

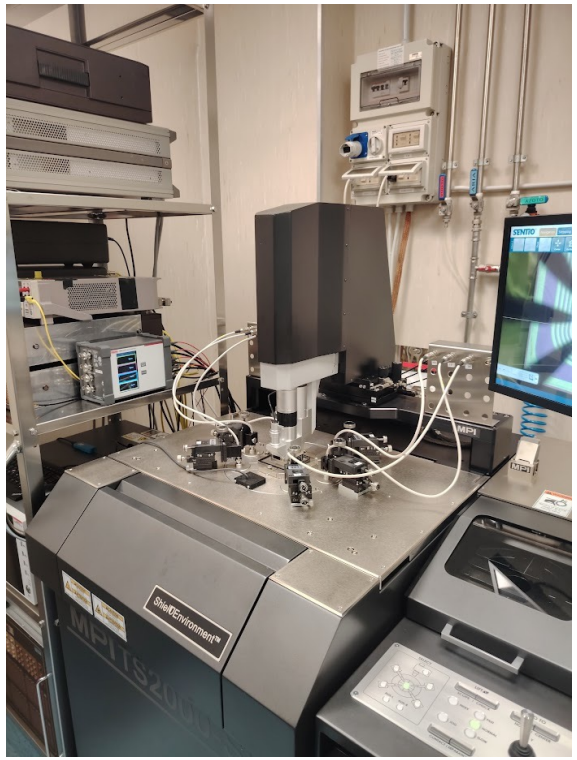






Proof of concept lab tests

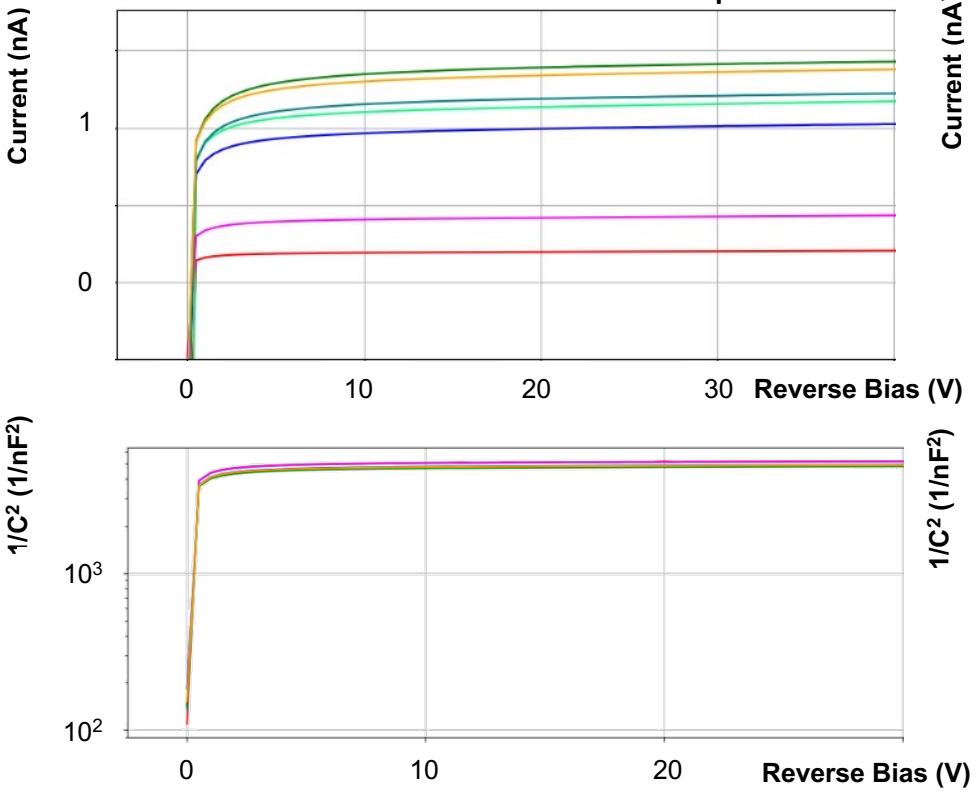
C-V and I-V measurements with the probe-station in the INFN Perugia Clean Room (thanks to F. Moscatelli)



"No gain" / PIN

I_{LEAK}: 0.5 – 1.5 nA

C: 13.9 – 14.7 ± 0.2 pF

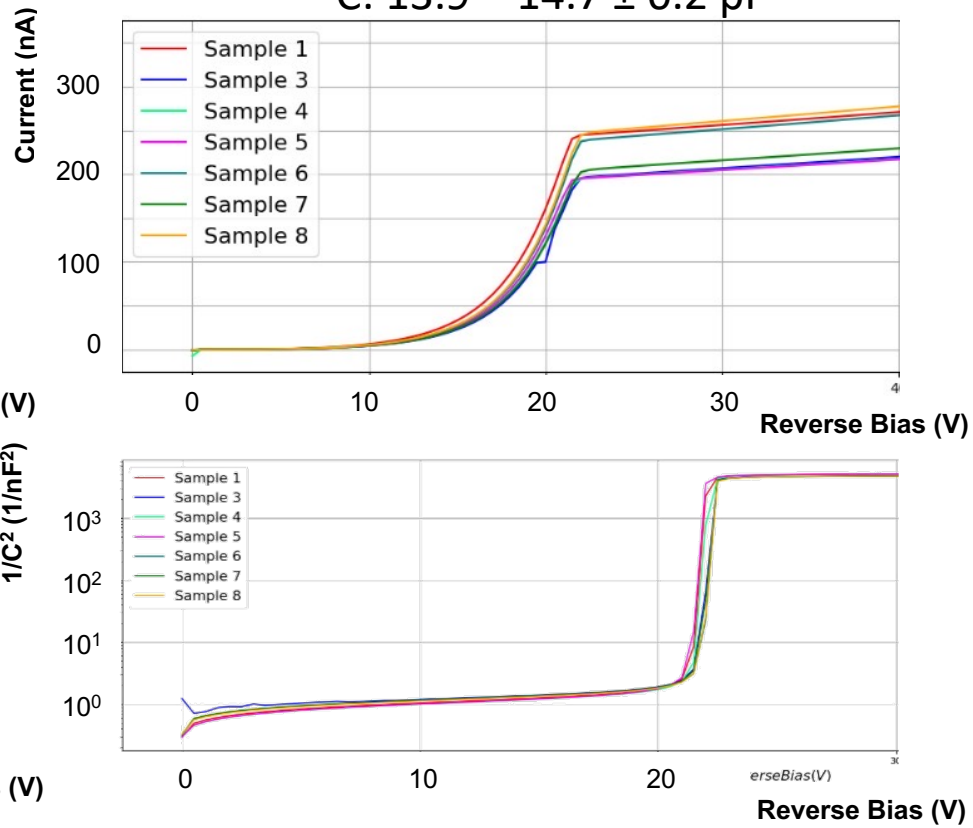


full depletion at ~ 1 V

"Gain" / LGAD

I_{LEAK}: 250 – 350 nA

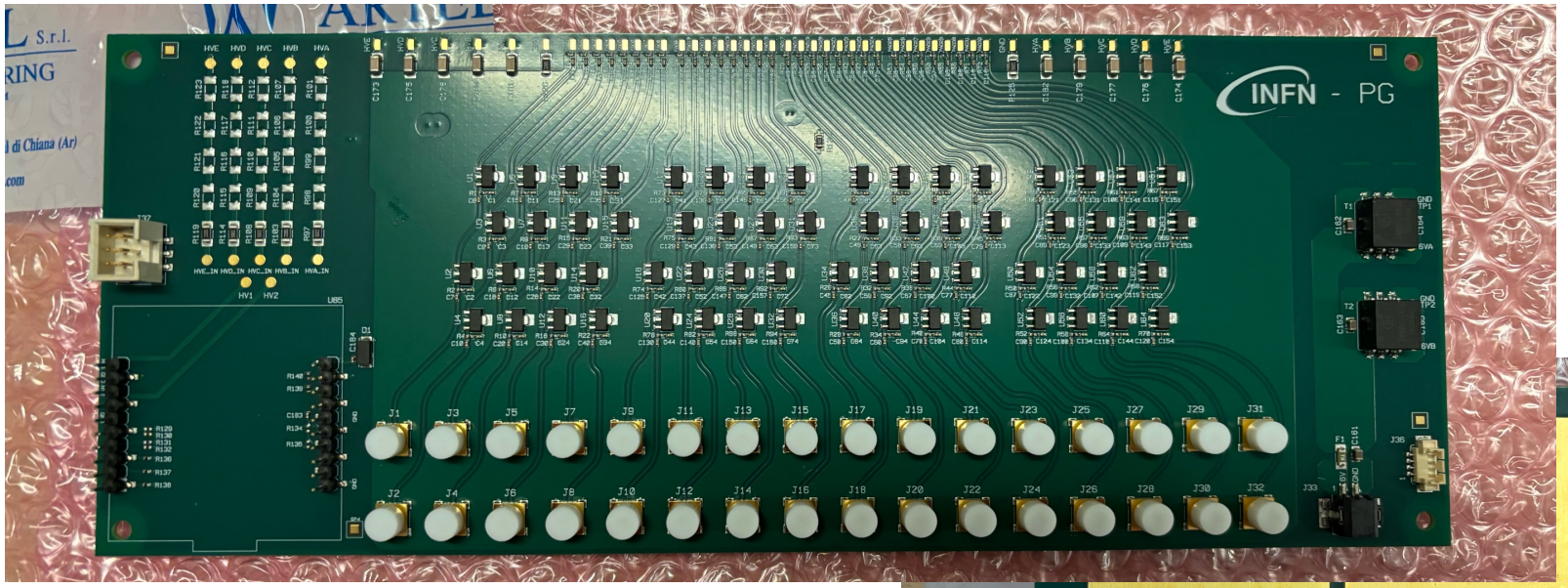
C: 13.9 – 14.7 ± 0.2 pF



full depletion at ~ 22 V

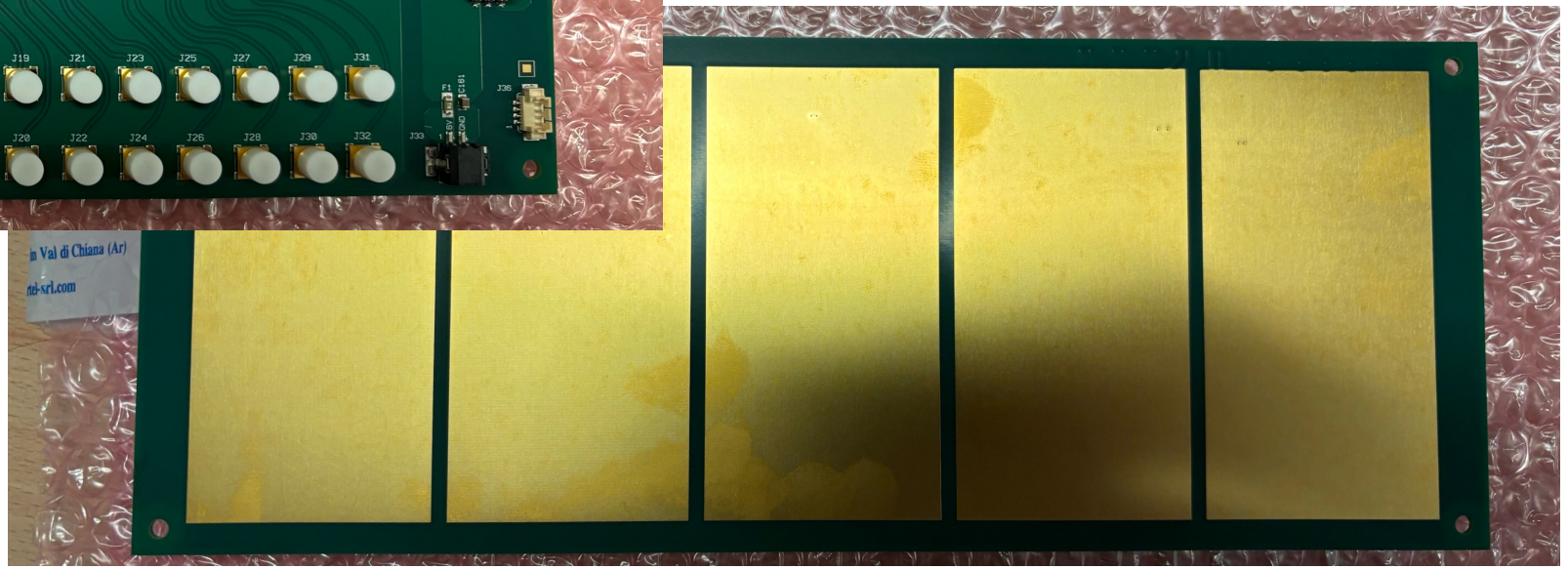
FEE board

Based on the design of the Fermilab board, we developed our own read-out board:
- 2 stage amps (Gain: 17 Ω * 10 * 10)
- 32 channels
- "plate" (with back bias) to stick (conductive tape) the samples to be tested



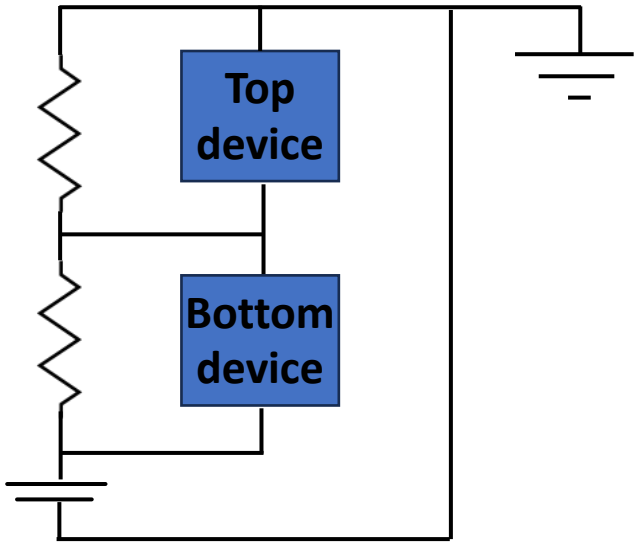
The 32 channels can be read directly to an oscilloscope or to a digitizer





The board enables us to measure the timing performances without the need of a dedicate ASIC

Prototype (v2)

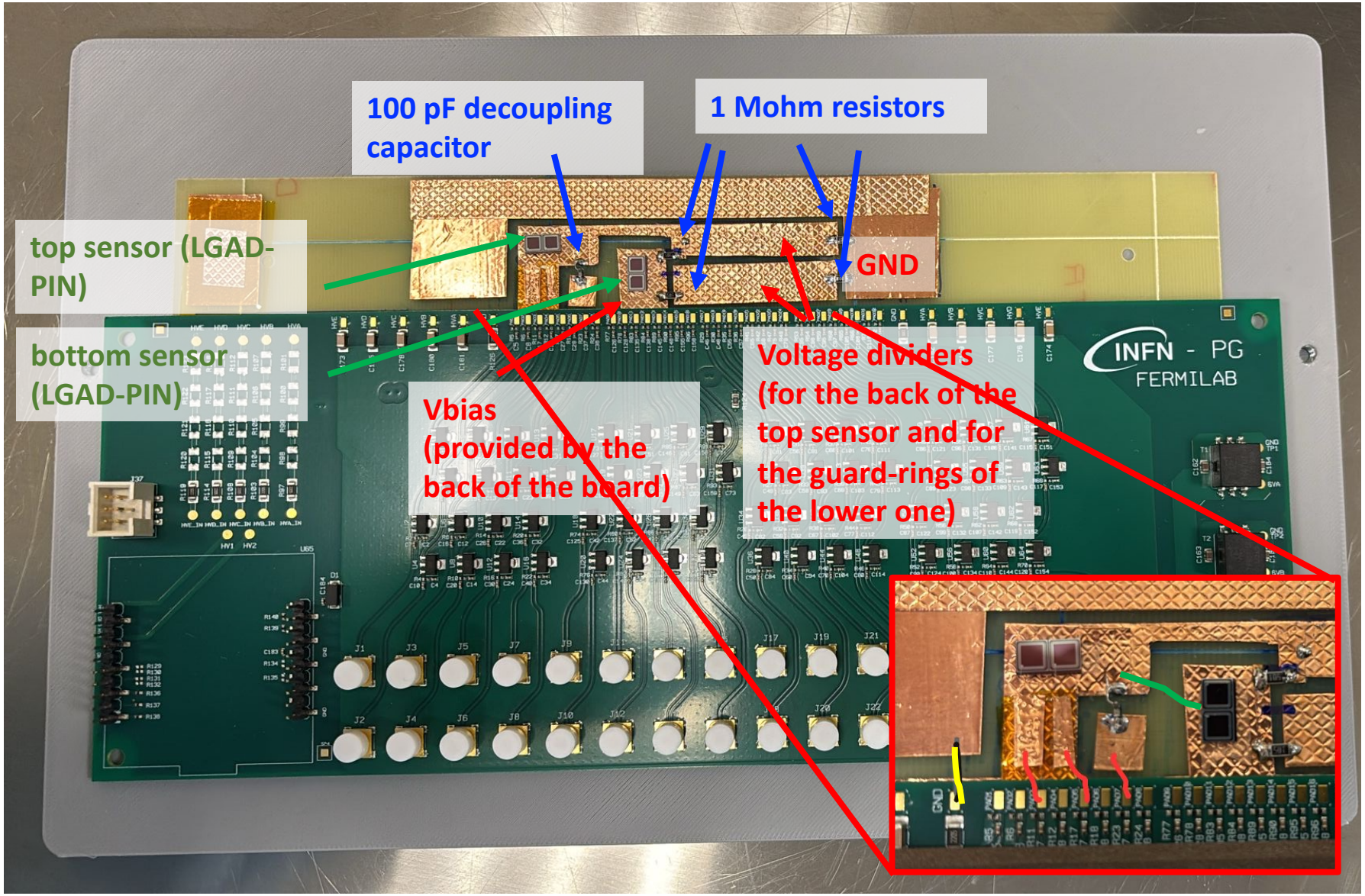


we expect:

√ leakage current dominated by the lowest in the sensor stack

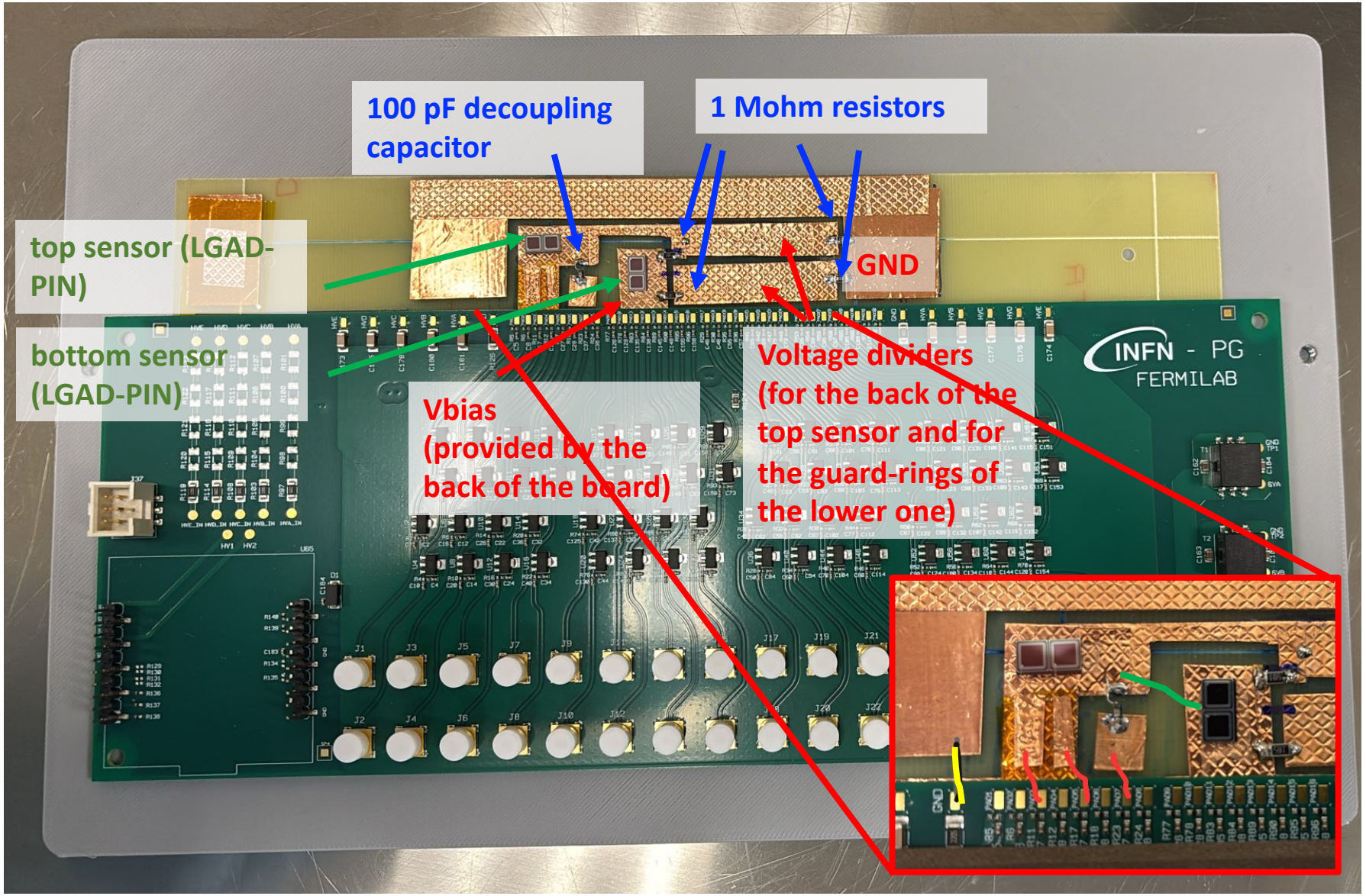
√ capacitance of the stack being half of the single sensors

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



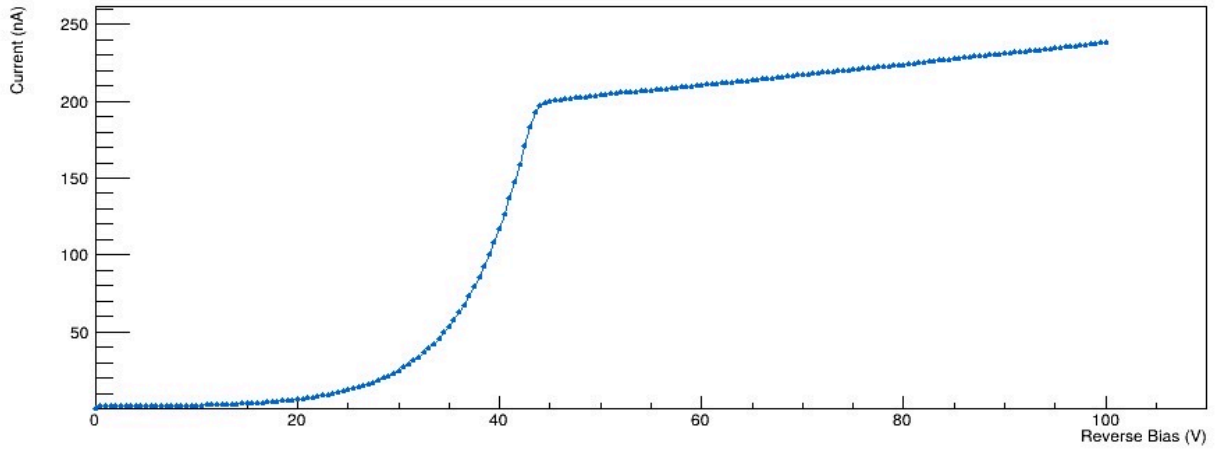
Prototype (v2)

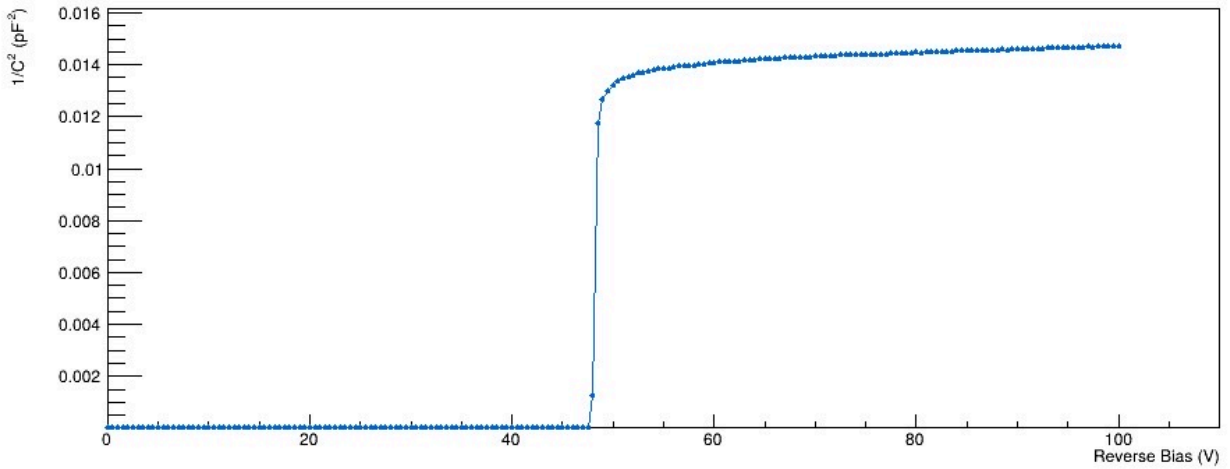
- using test structures (LGAD-PIN)
- V_{bias} provided by the board
- GND provided by the board
- voltage dividers (1 MΩ resistors) to force the potential in the middle
- wire bonding from the LGAD read-out pad of the bottom sensors to the back of the top one
- wire bondings to readout the two stacks (LGAD-LGAD and PIN-LGAD)
- wire bondings to readout the lower LGAD (through a 100 pF decoupling capacitor to read at GND a device kept between V_{bias} and $V_{bias}/2$)
- wire bonding for the GND



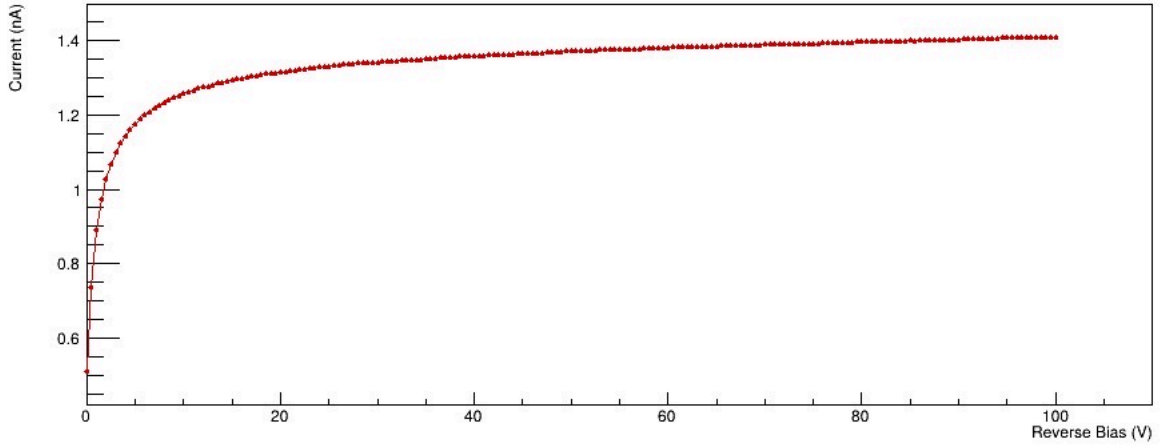
CV and IV results

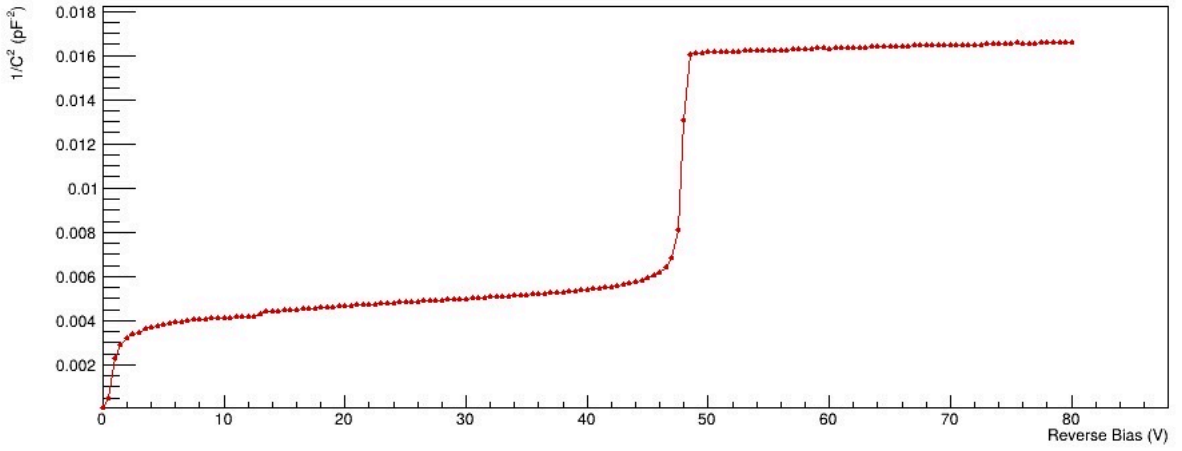
LGAD - LGAD
I_{LEAK}: ~ 200 nA @depletion (22+22V)
C: ~ 8 ± 02 pF @depletion





PIN - LGAD
I_{LEAK}: ~ 1.5 nA
C: ~ 8 ± 0.2 pF @depletion





TCT and timing performances



TCT system acquired (by Particulars) and in place. This allows:

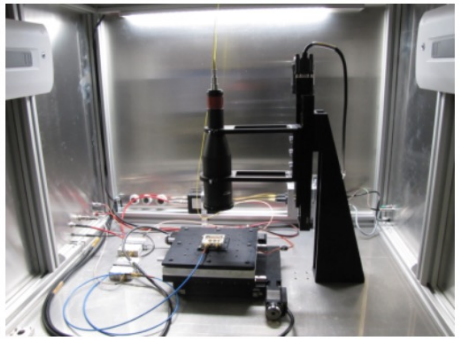
- spatial resolution estimation
- timing resolution estimation

Still the system is not "calibrated" so we're not sure of "how many MIPs" we fire…

Specifications:

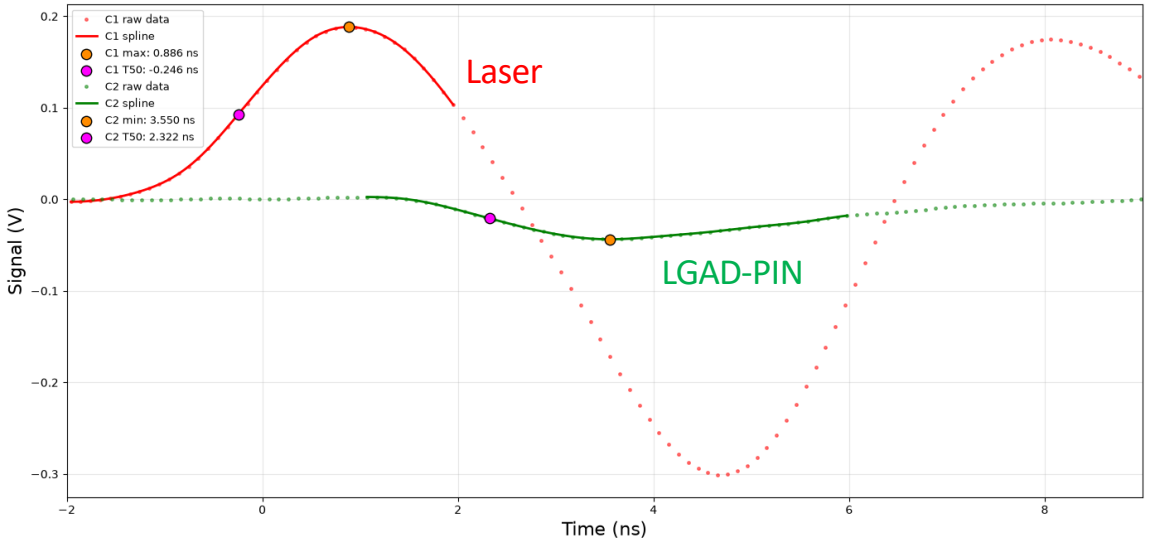
Component	Parameter	Properties
Laser		
particulars, *advanced measurement systems*	**Laser diode**	
	wavelength:	660 nm or 1064 nm (optional others on demand)
	pulse power:	few m.i.p. - 100 m.i.p. (equivalent in 300 micron Si)
	pulse width:	<350 ps - 4000 ps (tunable)
	coupling:	single core fibre
	Driver	
	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

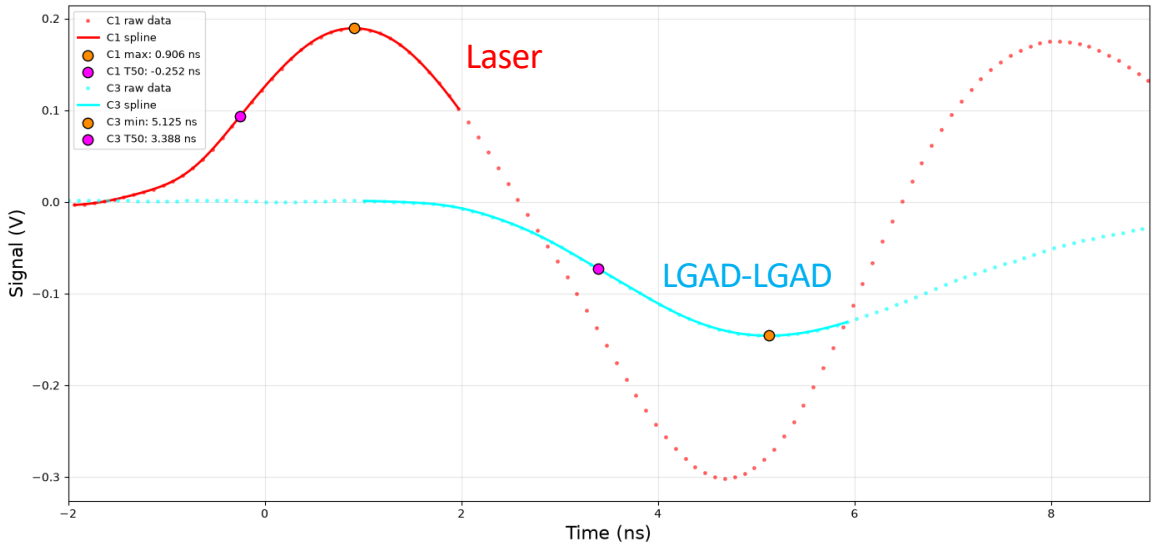
large scanning tct



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.

TCT and timing performances





- Laser driver as trigger
- Laser sampled
- Output from LGAD-PIN sampled
- Output from LGAD-LGAD sampled

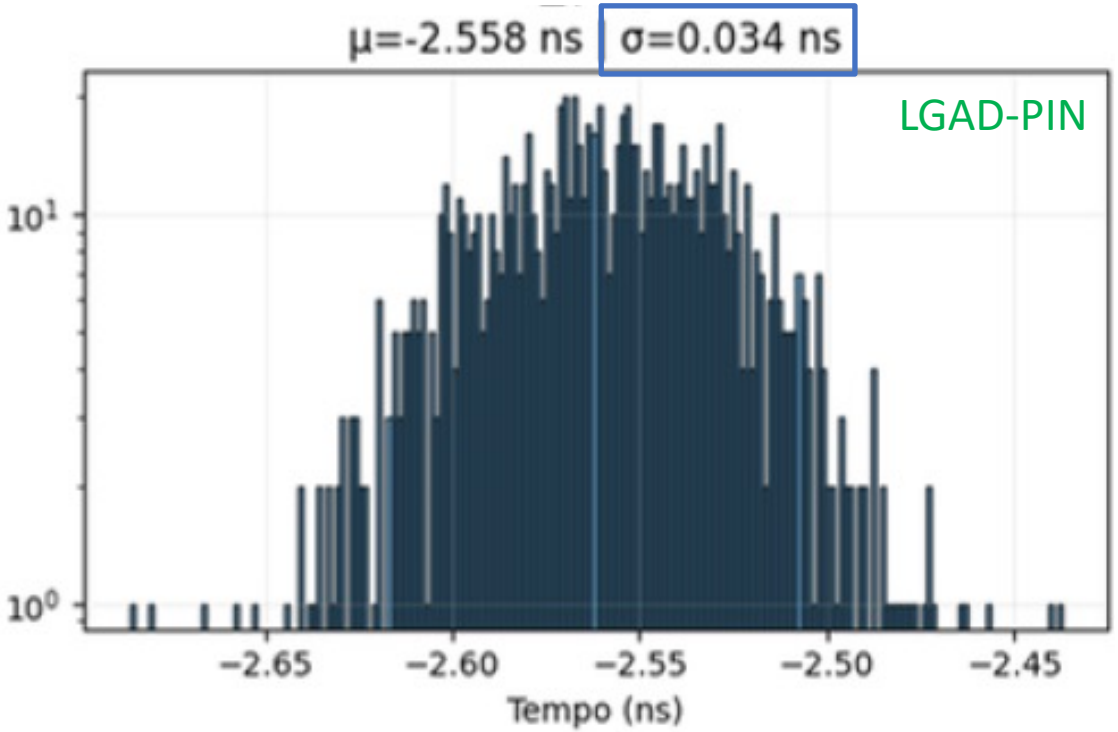
→ spline fit to the data points

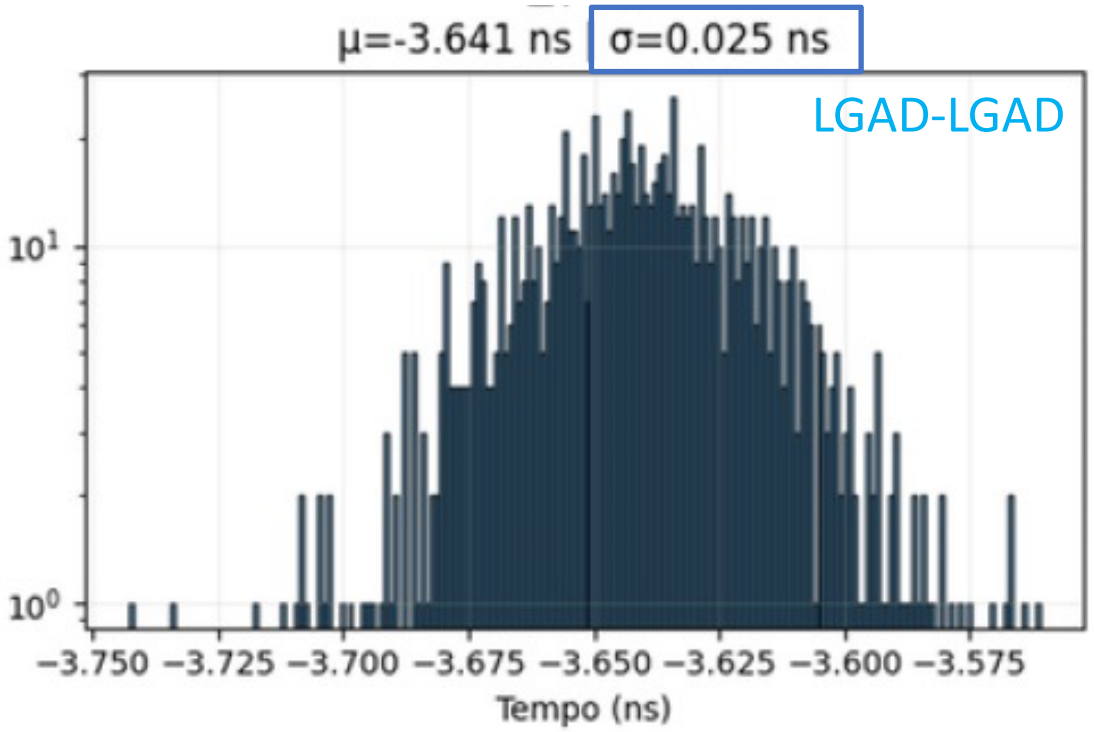
(i.e. ideal case with respect to an ASIC)

→→ constant fraction

→→→ evaluation of the Δt (mean, sigma)

TCT and timing performances





25-35 ps resolution. Is this resolution reasonable?

→ yes, since the TCT laser was, most likely comparable to several MIPs

Even if this is often forgot, in space we have, and we want to measure, all the Z's…

→ ~ 30 ps resolution, starting from Li or B, almost proved… This would be game changer for isotopical composition measurements

Did we prove that we're able to get 25-35 ps resolution?

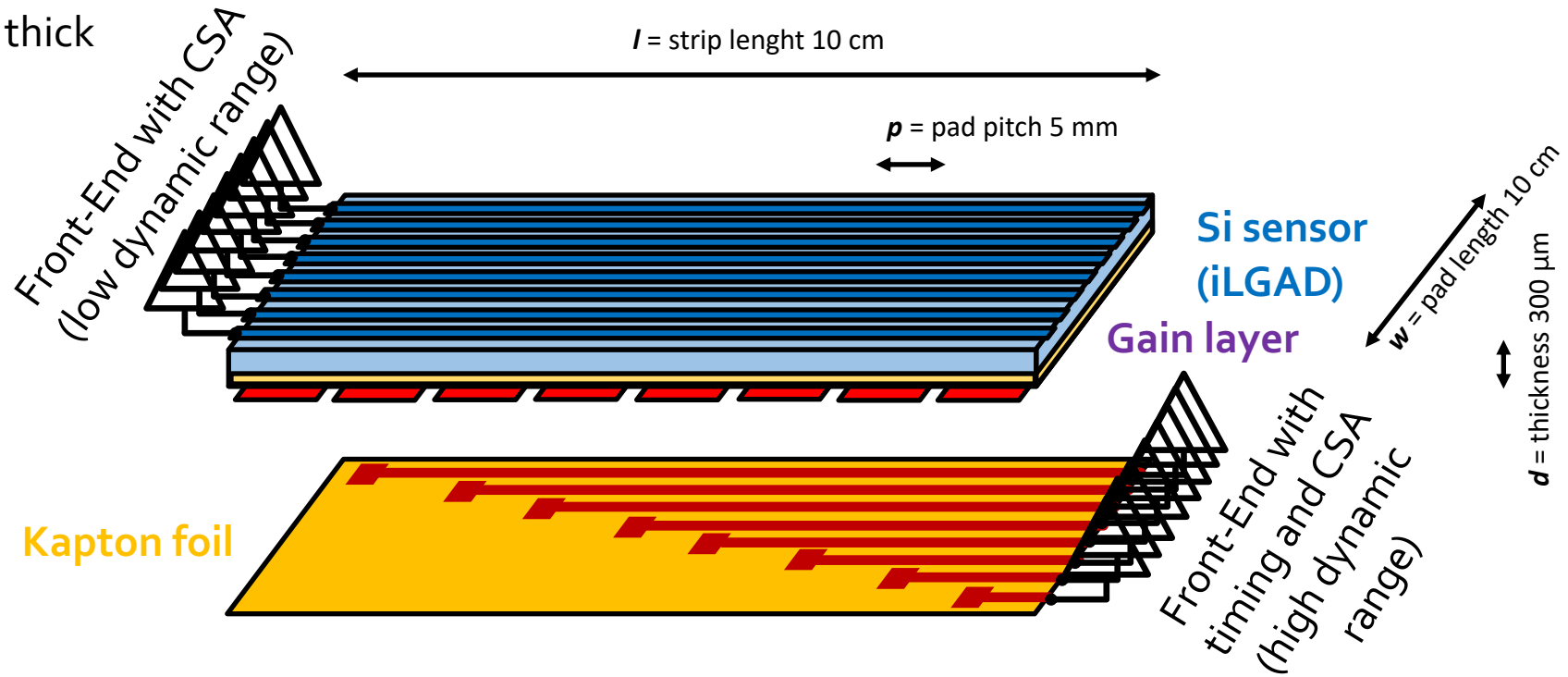
Not at all, unfortunately… Or at least not for Z=1 particles…

But we proved that the serial read-out doesn't destroy the timing…

Ideas for future…

In parallel let's focus on the 5D design:

- inverted LGAD (iLGAD) to have ~ 100% fill factor
- back (ohmic side) with standard long (10 cm) µstrips (25-50 µm implant pitch, 100-200 µm readout pitch)
- front (juncton side) with large pads Trench-Isolated (~ 5 mm width)
- thick



- ***l*** = strip lenght = 10 cm
- ***p*** = pad pitch 5 mm
- ***w*** = pad lenthgt 10 cm
- ***d*** = thickness 300 µm
- ***A*** = pad area ***w*p*** = 5000 µm * 10 cm

$C_b = \varepsilon_o * \varepsilon_{Si} * A/d$

$\varepsilon_o * \varepsilon_{Si} = 12 * 8.85 * 10^{-12}$ F/m
= 106 pF/m = 1.06 pF/cm

C_b = 1.06 pF/cm * 10 cm * 5000 µm / 300 µm =
1.06 pF * 10 * 17 ~ 180 pF

design in finalization for starting production, by FBK (IT)

Conclusion

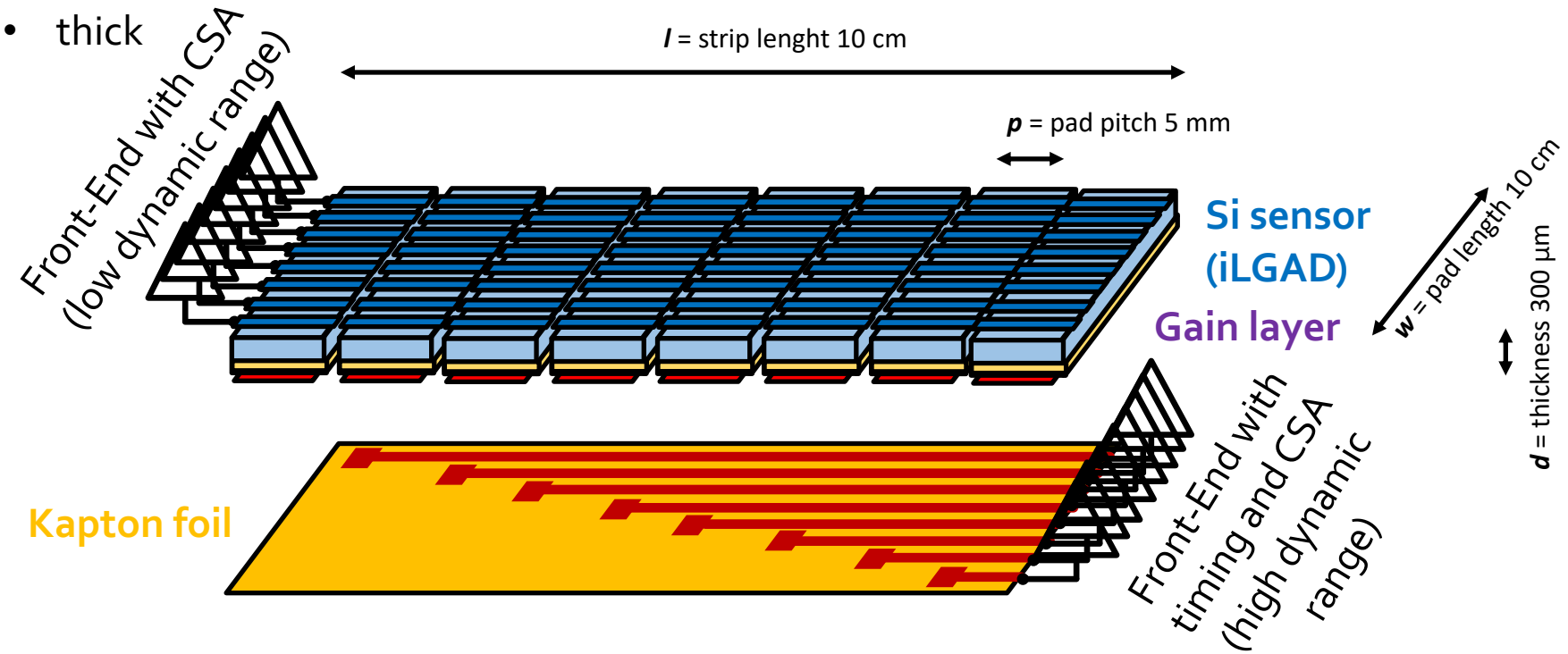
- capacitance reduction working almost as expected
- measured timing performances prove the serial readout does not "destroy" the timing capability
- TCT laser still to be calibrated but already the performance is game-changer for isotopic composition Cosmic Ray measurement
- go for a Beam Test with ions…

Backup

Ideas for future (alternative)…

In parallel let's focus on the 5D design:

- inverted LGAD (iLGAD) to have ~ 100% fill factor
- back (ohmic side) with standard (0.5 cm long → 10 cm in daisy chain) µstrips (25-50 µm implant pitch, 100-200 µm readout pitch)
- front (juncton side) with large**, separate devices**, pads (~ 5 mm width)
- thick



- ***l*** = strip lenght = 10 cm
- ***p*** = pad pitch 5 mm
- ***w*** = pad lenthgt 10 cm
- ***d*** = thickness 300 µm
- ***A*** = pad area ***w*p*** = 5000 µm * 10 cm

$C_b = \varepsilon_o * \varepsilon_{Si} * A/d$

$\varepsilon_o * \varepsilon_{Si} = 12 * 8.85 * 10^{-12}$ F/m
= 106 pF/m = 1.06 pF/cm

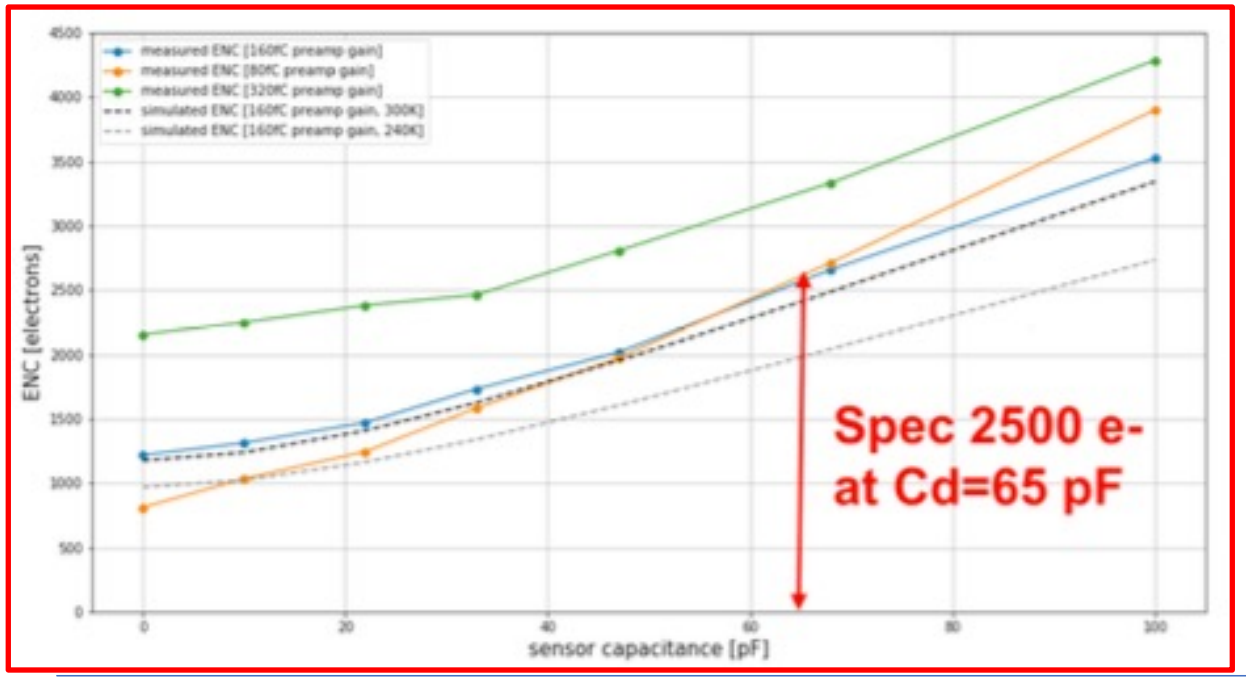
C_b = 1.06 pF/cm * 10 cm * 5000 µm / 300 µm =
1.06 pF * 10 * 17 ~ 180 pF

design in finalization for starting production, by FBK (IT)

FEE?

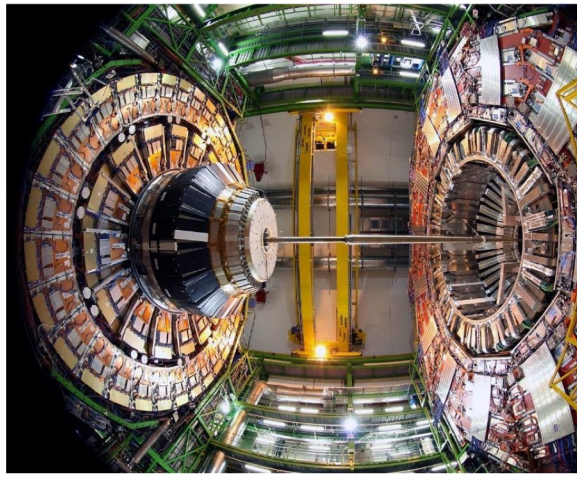
HGCAL FEE already close to our needs:

- reasonably low power
- factor 50000 for HDR: our target is $Z^2_{Fe}/(Z_p/10)^2 = 100*26^2 \sim 70000$
- design capacitance load close to our target (~ 200 pF)

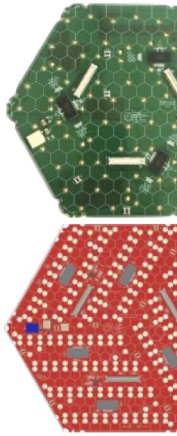


HGCAL: CMS EndCap Calorimeters for the LHC Phase-II

- **HGCAL covers 1.5 < eta < 3.0**
- Full system maintained at -30°C
  - ~ 640 m² of silicon sensors, 6.1M Si channels, 0.5 or 1.1 cm² cell size
  - ~ 370 m² of scintillators, 240k scint-tile channels
- Data readout from all layers
- Trigger readout from alternate layers in CE-E and all in CE-H
- Active Elements
  - Electromagnetic calorimeter (CE-E): Si, Cu/CuW/Pb absorbers
  - Hadronic calorimeter (CE-H): Si & scintillator, steel absorber
- New Front-end electronics
  - Two versions: Silicon and SiPM
  - Rad.tolerant (200 Mrad, 1.1016 neq / cm²)
  - Power consumption: 15 mW per channel
  - Noise: 0.4 fC
  - Charge: 0.2 fC to 10 pC
  - Pileup mitigation: Fast shaping (peak < 25 ns), precise timing capability (25 ps)

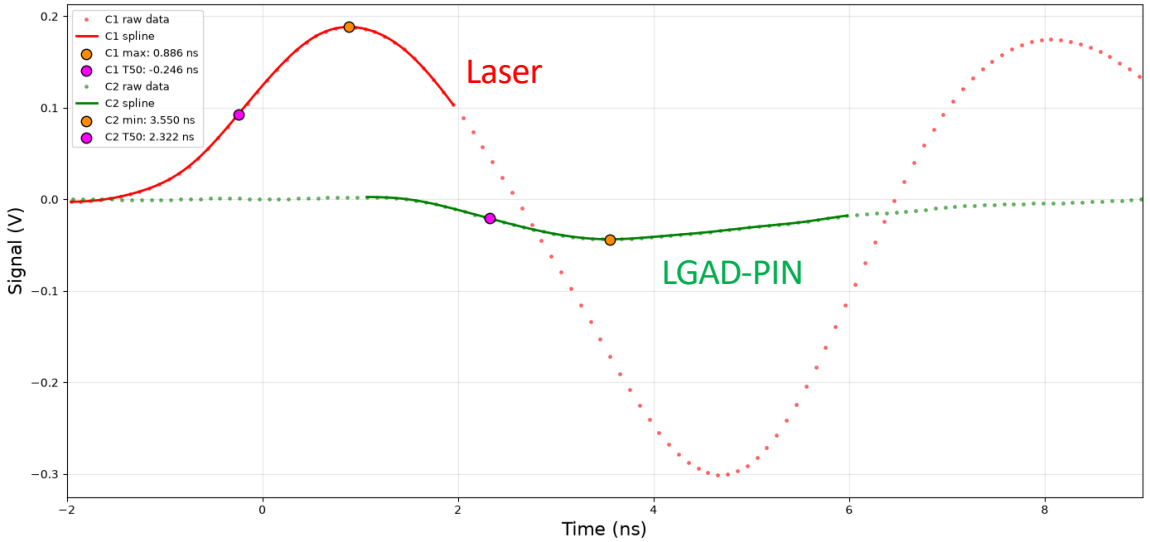


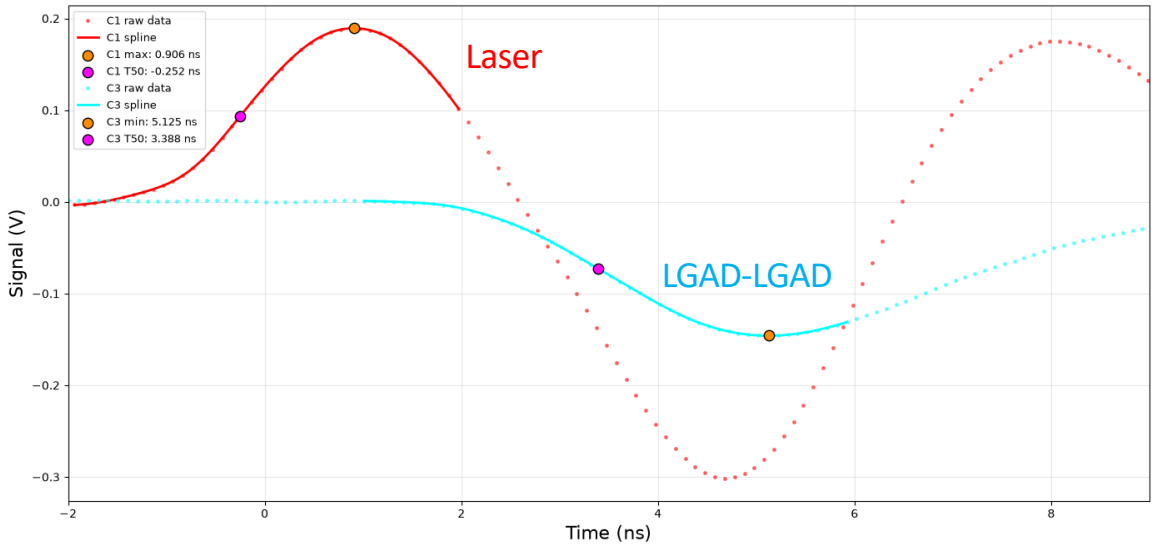




HGCROC - FEE 2023 - Torino

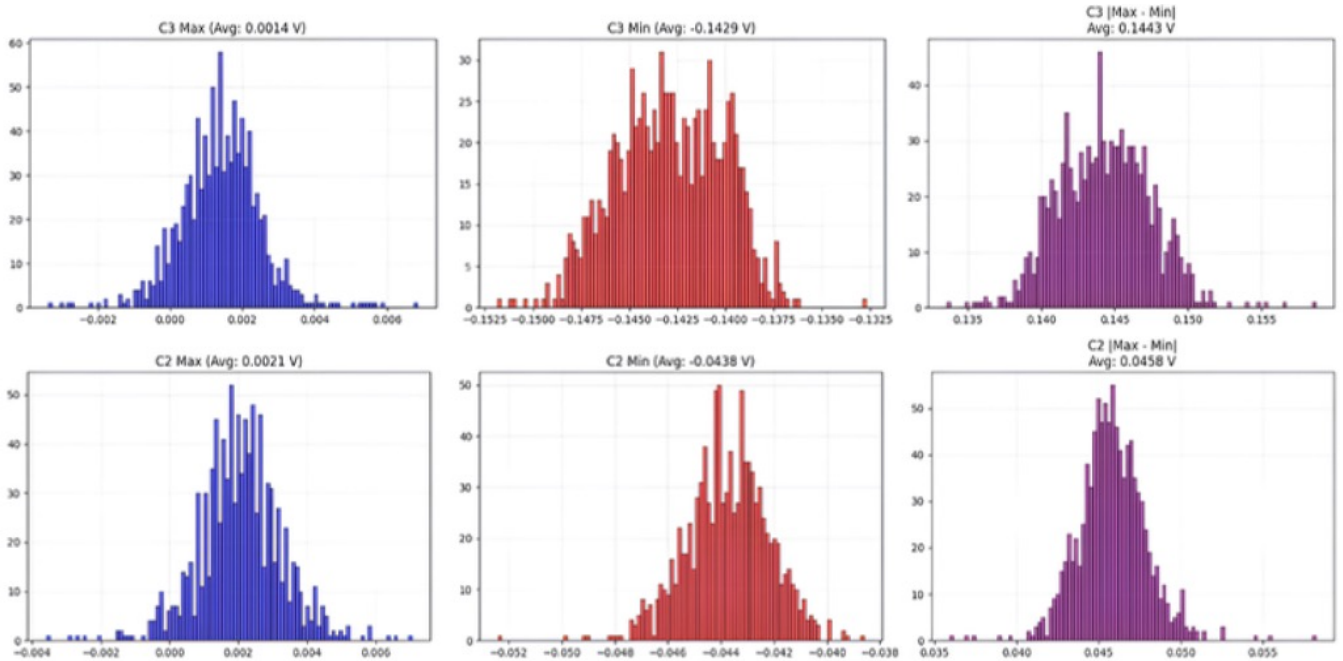
TCT and timing performances





- V_{pp} (LGAD)/V_{pp} (PIN) ~ 3.2
- while expected was ~ 10

→ still something to be fully understood

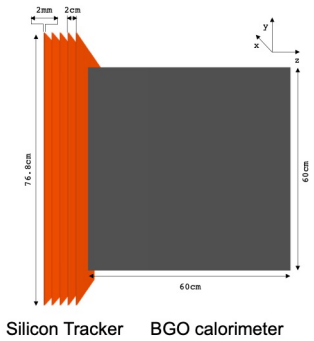


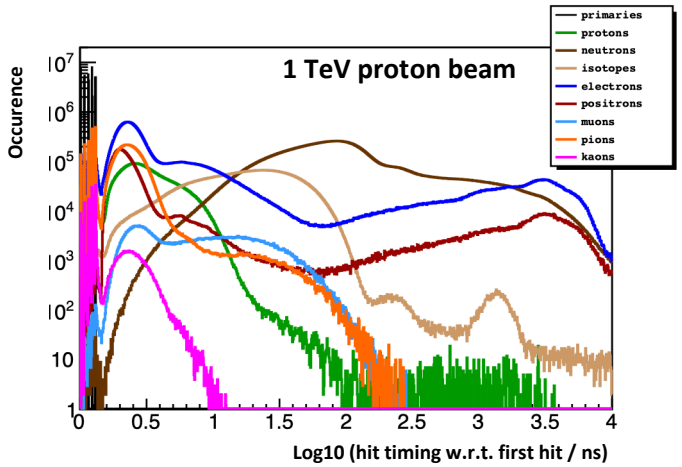
Effects of 5D-Tracking in backscattering events

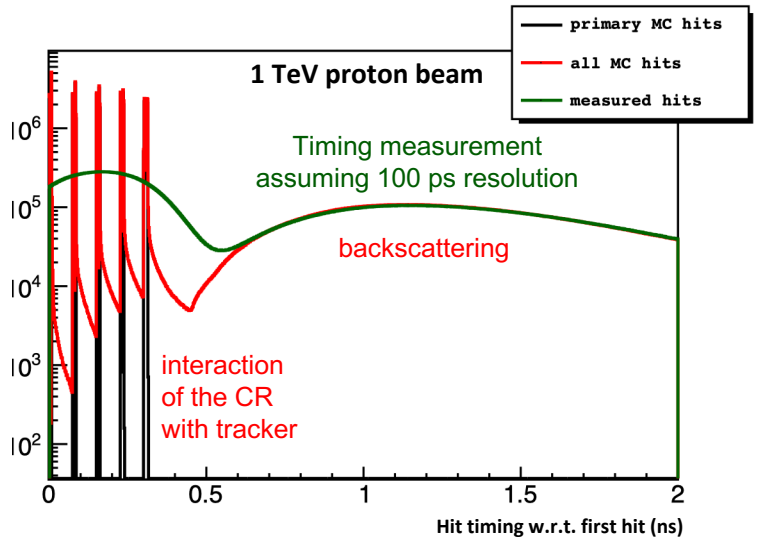
M. Duranti et al., *Instruments* 2021, 5(2), 20

MC simulation of backscatterd particles from downstream calorimeter on tracker layers

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





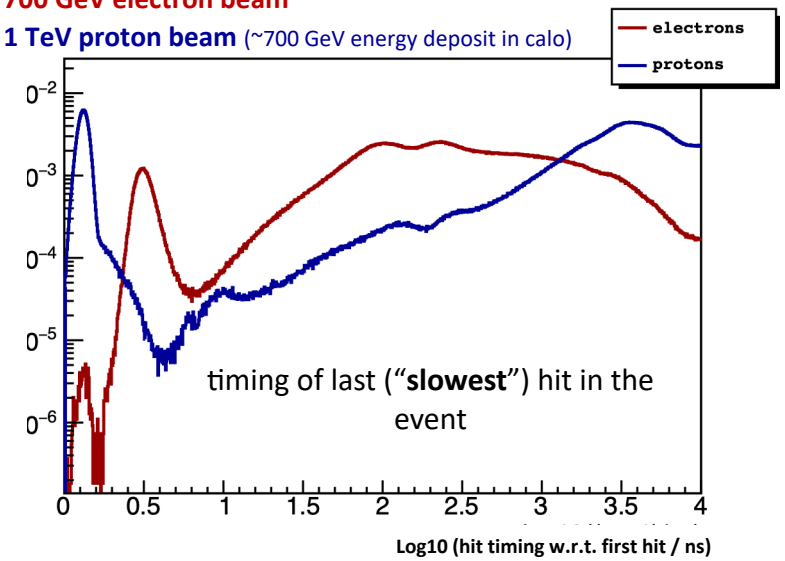


100 ps resolution allows to separate hits from primary particles and from secondary backsplash (tracker and calorimeter are 2cm far from each other)

Prospects for improved tracking efficiency

700 GeV electron beam

1 TeV proton beam (~700 GeV energy deposit in calo)



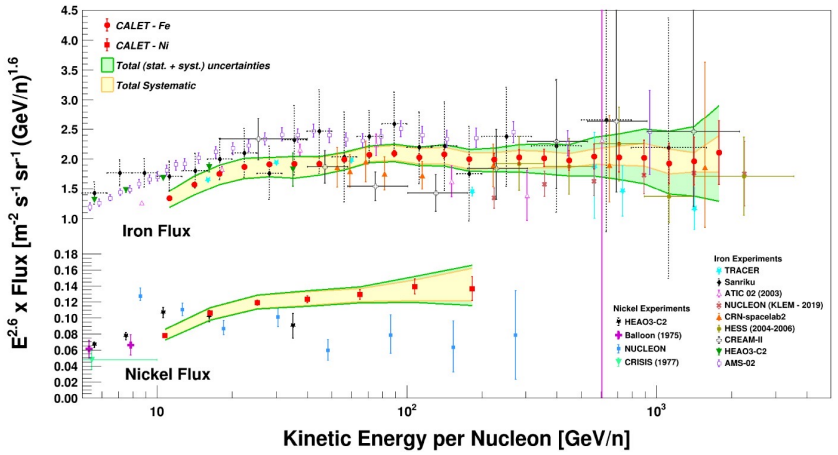
Different timing signatures from p and $e^{+/-}$ showers

Prospects to use in MVA classifiers for e/p separation

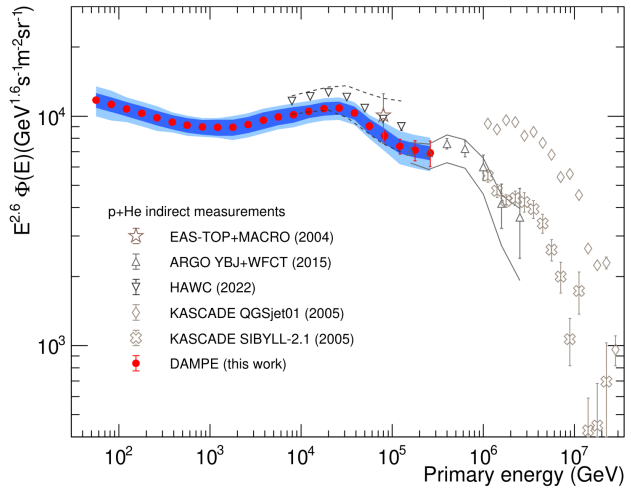
Timing resolution benchmark: < 100 ps (enabled with Si-µstrip LGAD [+ mitigation of FE consumption])
Break-through objectives (e.g.: performant isotope separation**): < 50 ps** (requires readout noise mitigation approaches)

Charged CRs: state of the art

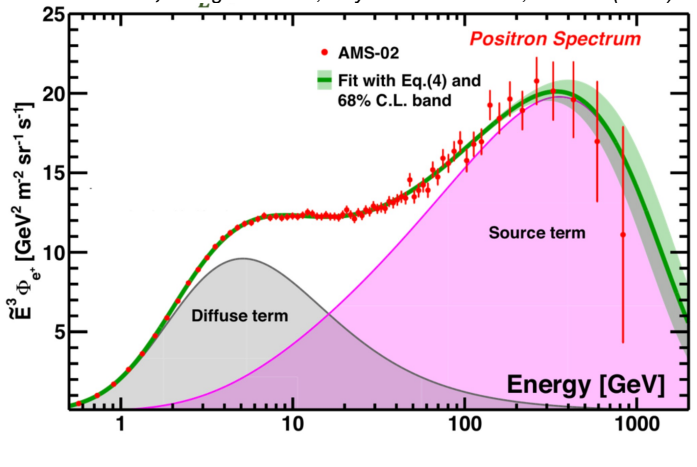
***CALET coll.**, O. Adriani et al., Phys. Rev. Lett. 128, 131103 (2022)*



***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

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 objectives:

- design and try to implement an LGAD (µstrip) sensor optimized for large areas, with capacitance mitigation strategies and combining LGAD time performances with standard Si sensor charge and spatial resolution ones
- enhance the TRL level of LGAD sensors for space, investigate the possibility of a CubeSat mission to prove the usage in space, design and perform the engineer phase of the mission

Funding and activities started in Sep 2023, duration ~ 2.5 years, c.a. 200k€ fundings

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

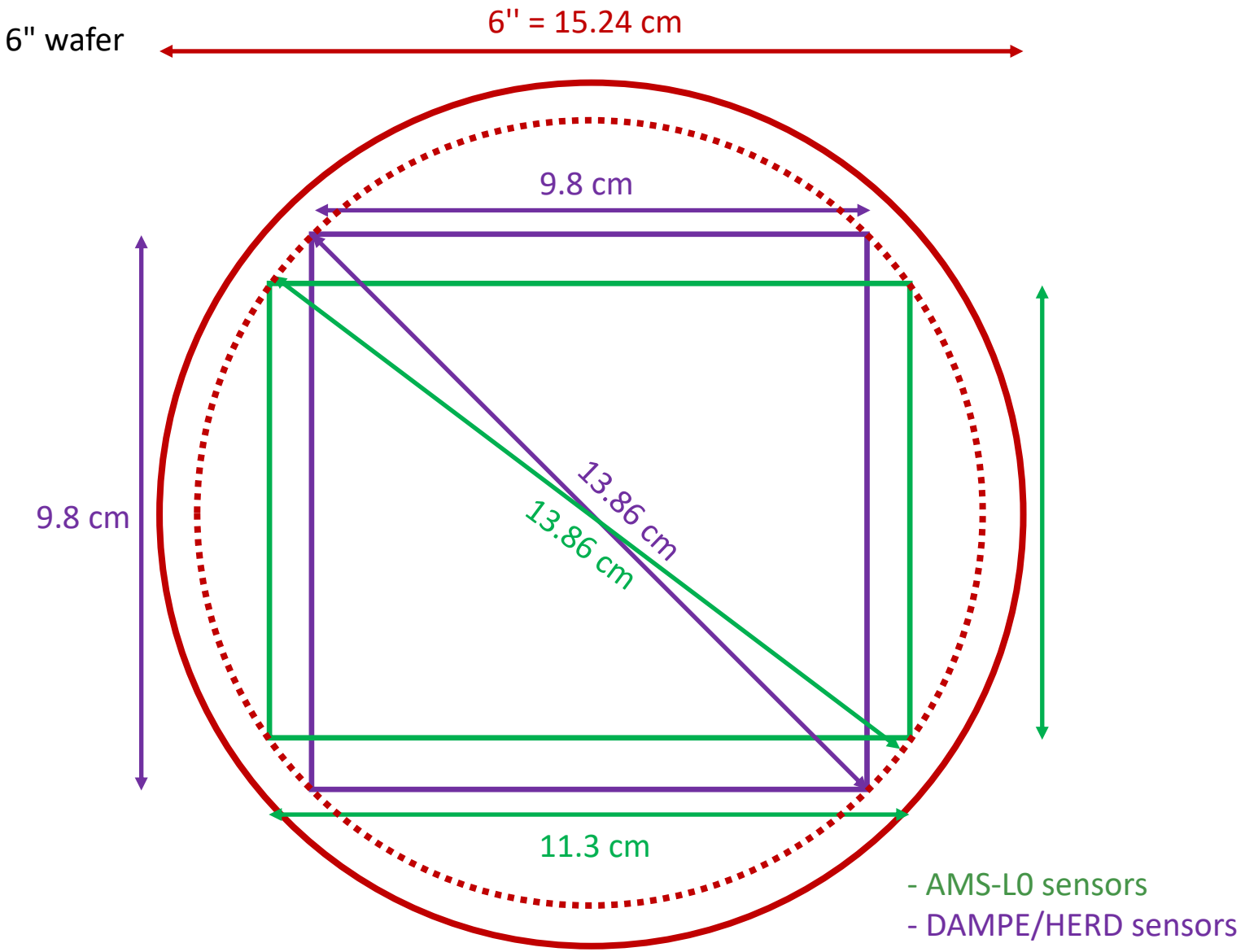
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Capacitance and daisy-chain

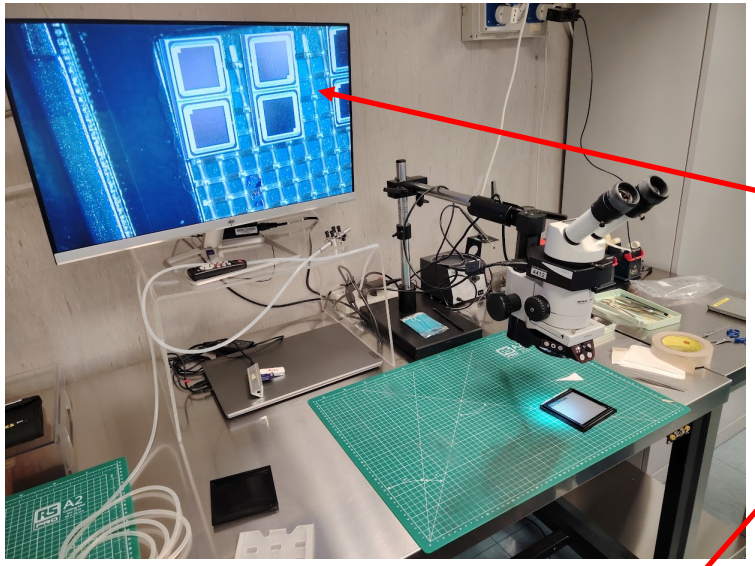
At production level the strips cannot be so long:

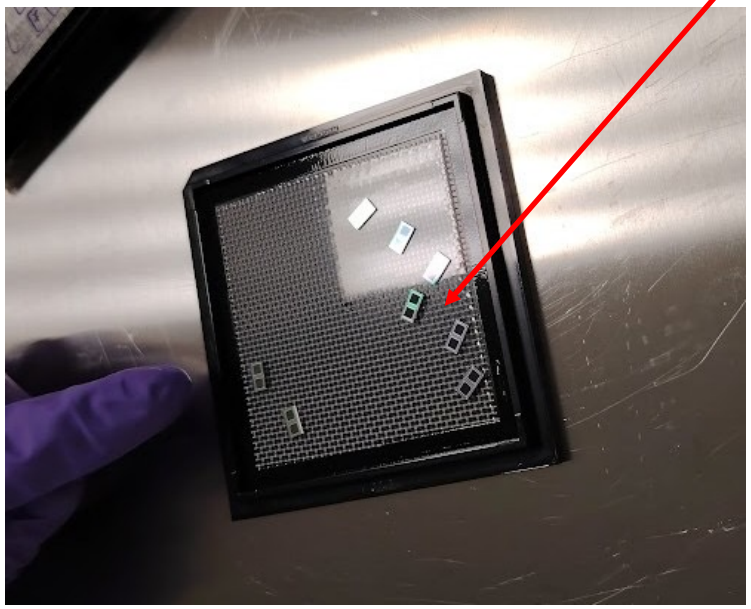
- they must be at least shorter than the wafer diagonal (i.e. 6'' – some margin)
- typically is at most ~ 10 cm long

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

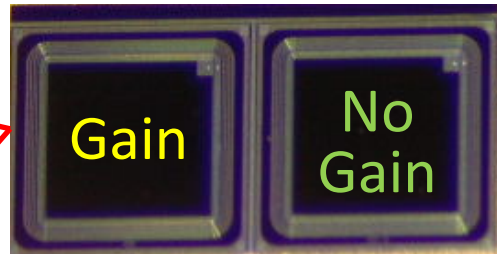


“Stacked” 5D sensor – Proof of concept lab tests

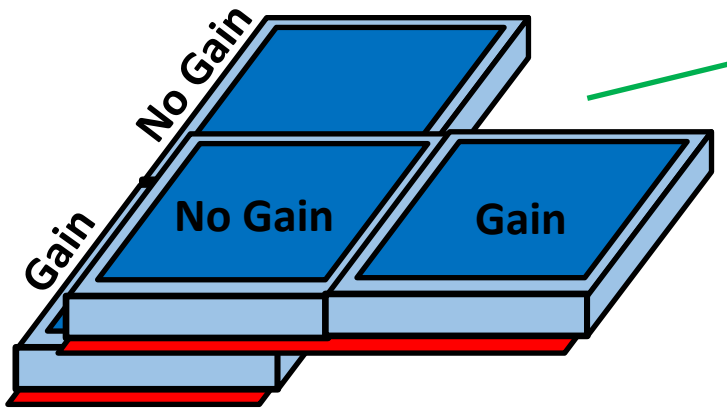




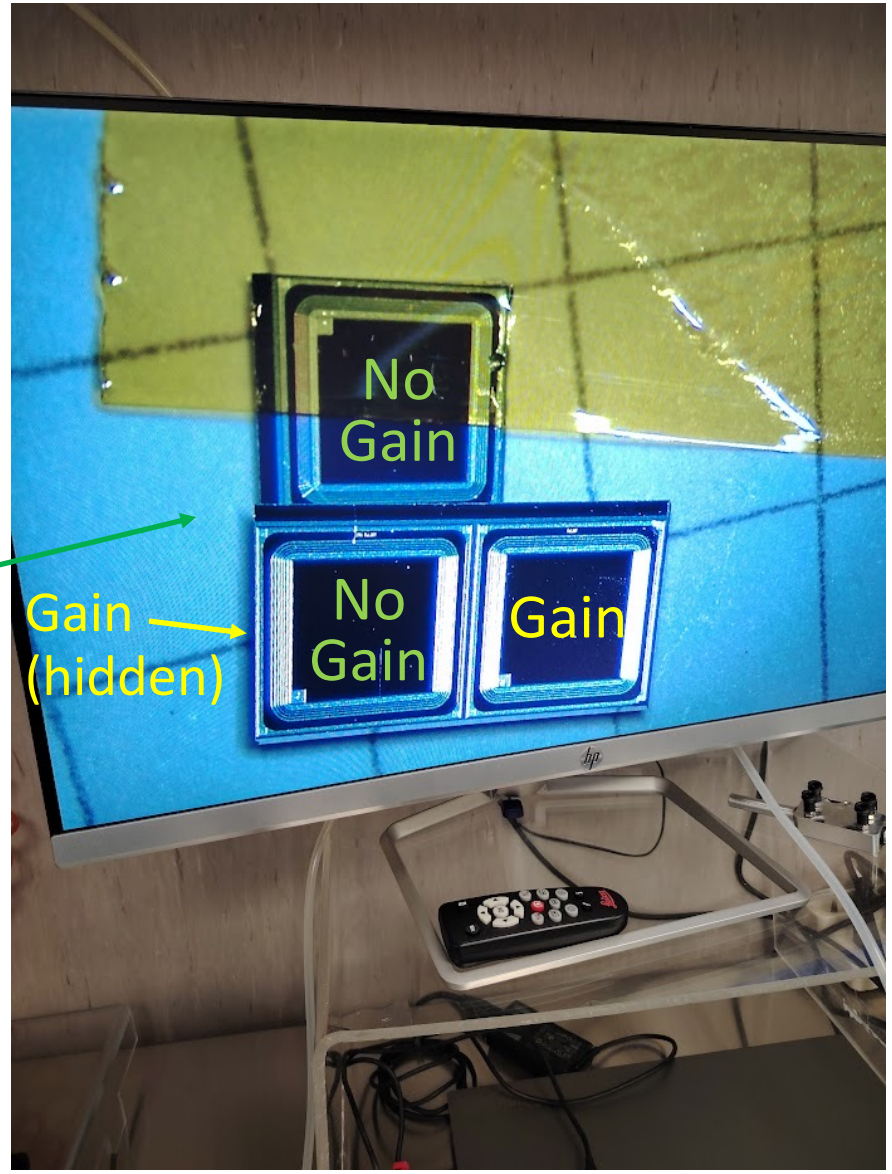
Thanks to test structures
(FBK, from the MoveIT project, that we thanks)



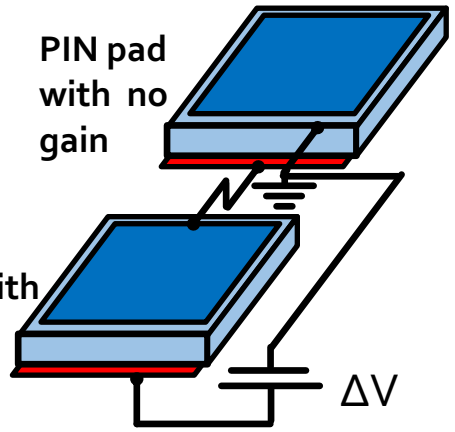
we could test the idea with a prototype like this:

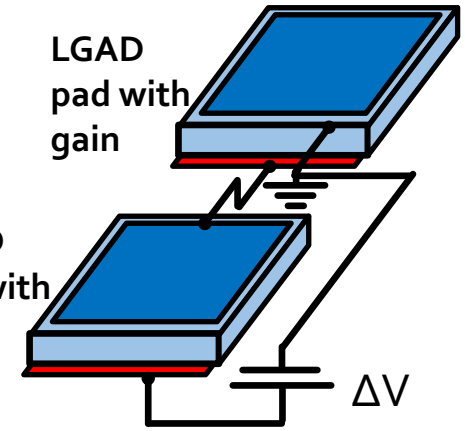


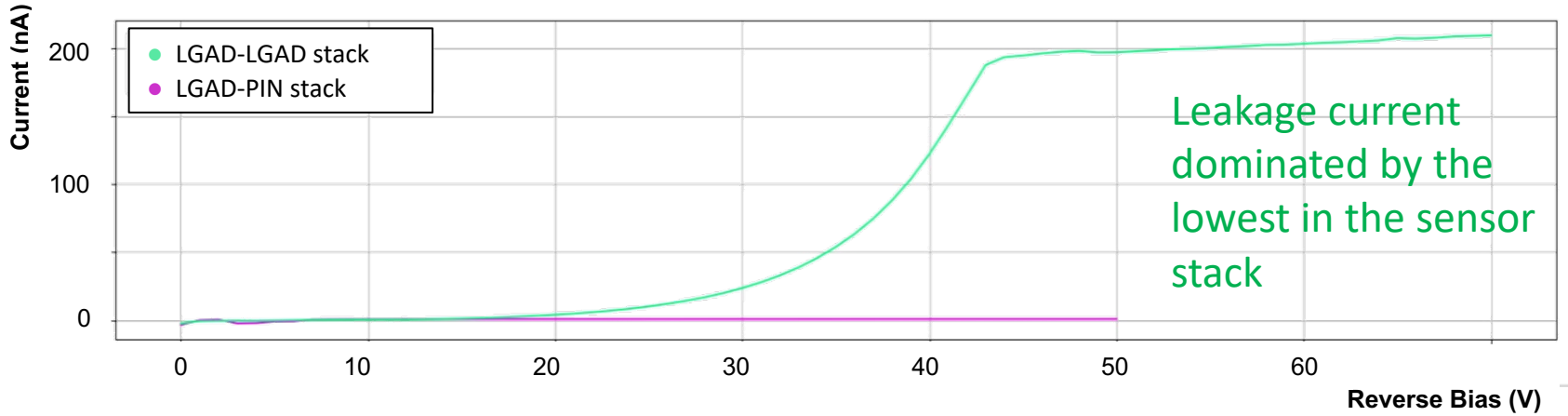
the two devices were glued with small spots of glue: the "No Gain" region on the bottom was "protected" with kapton so to connect only the "Gain" region with the back of the top device

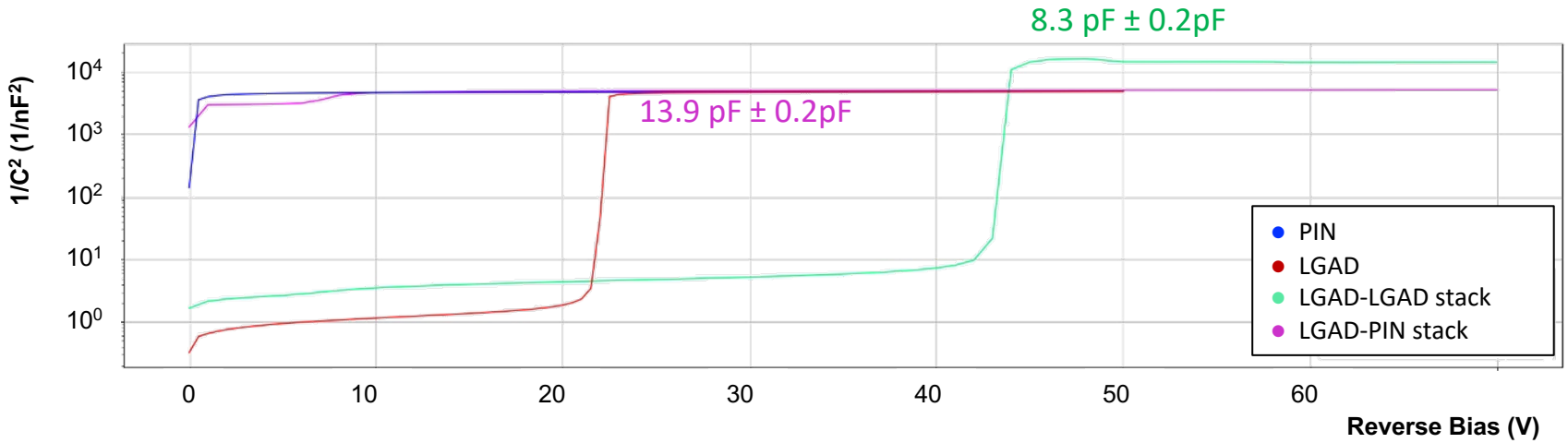


Proof of concept lab tests







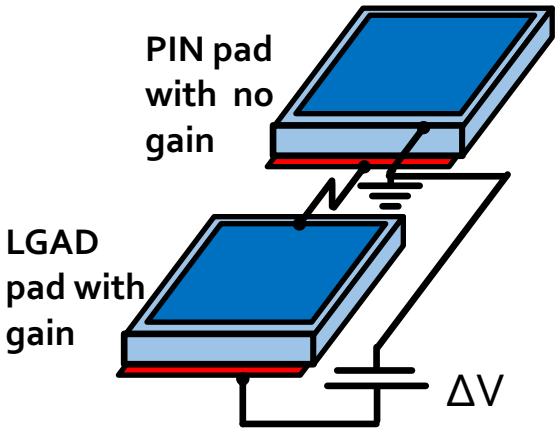


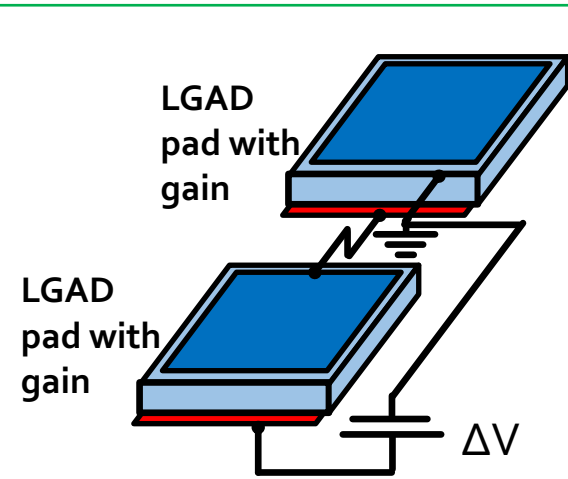
$$C_{tot} = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}$$

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

interesting results, more measurements to address discrepancies

Proof of concept lab tests

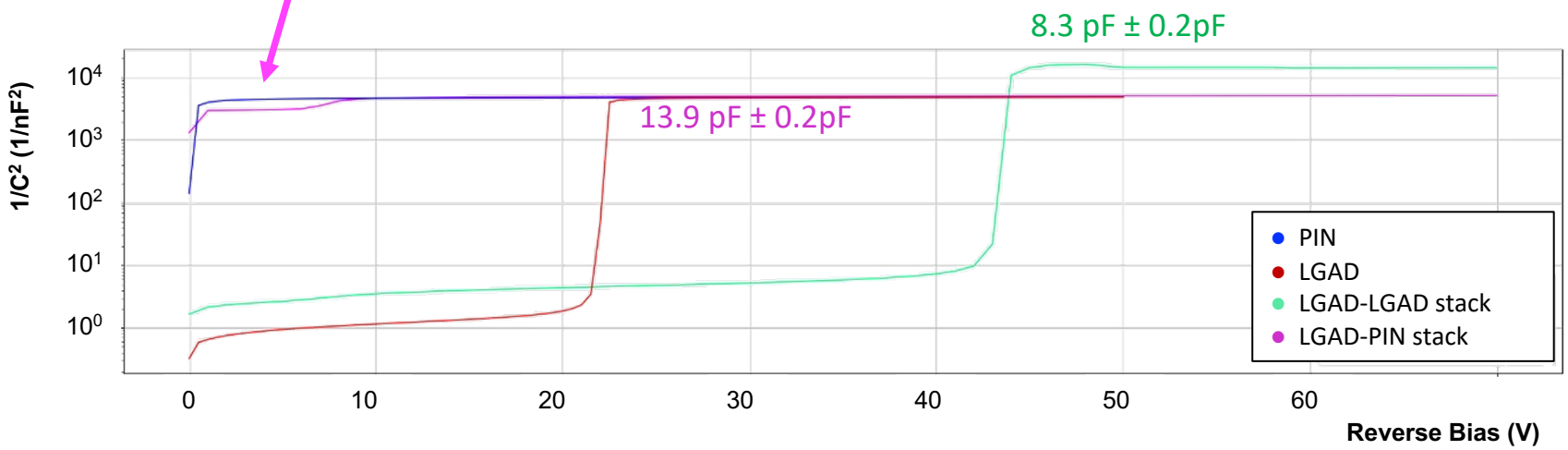




Please note that the LGAD-PIN stack was completely "wrong":

- I-V curve as expected
- C-V almost flat like the PIN alone

→ the assembled device doesn't force the bias on the LGAD so the almost all the voltage drop is on the PIN and the LGAD is not depleted

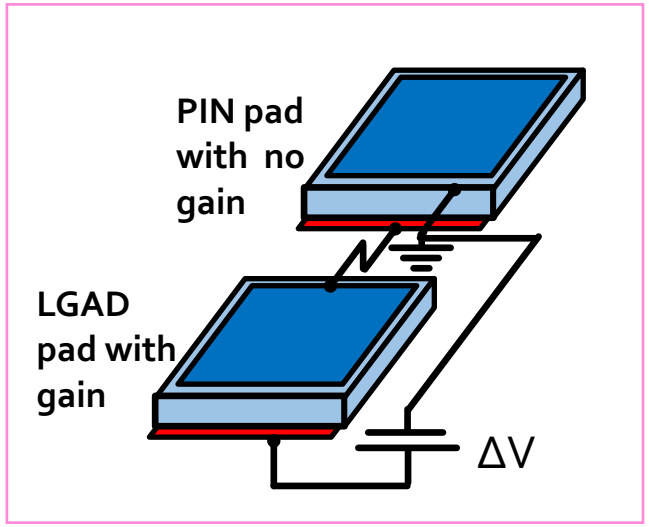


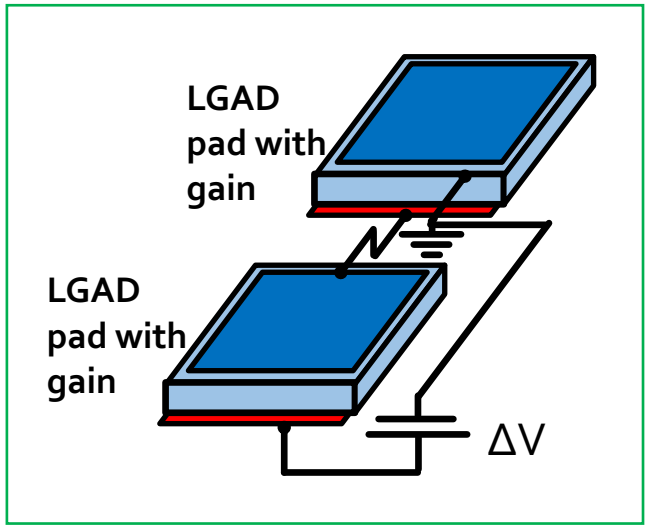
$$C_{tot} = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}$$

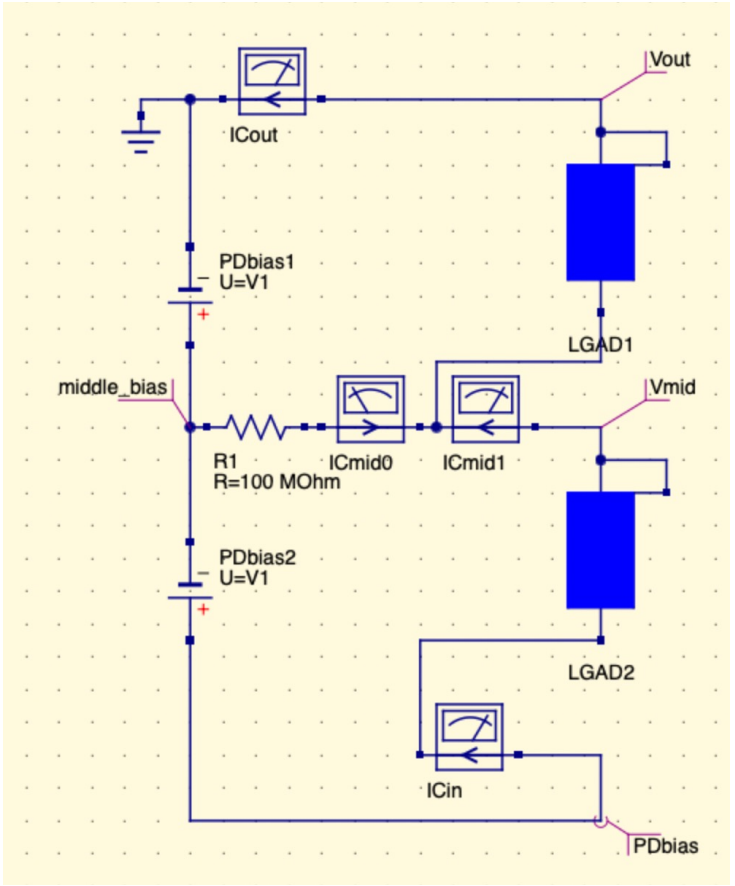
LGAD-LGAD stack C ~ half C_{PIN}
LGAD-PIN stack C ~ C_{PIN}

interesting results, more measurements to address discrepancies

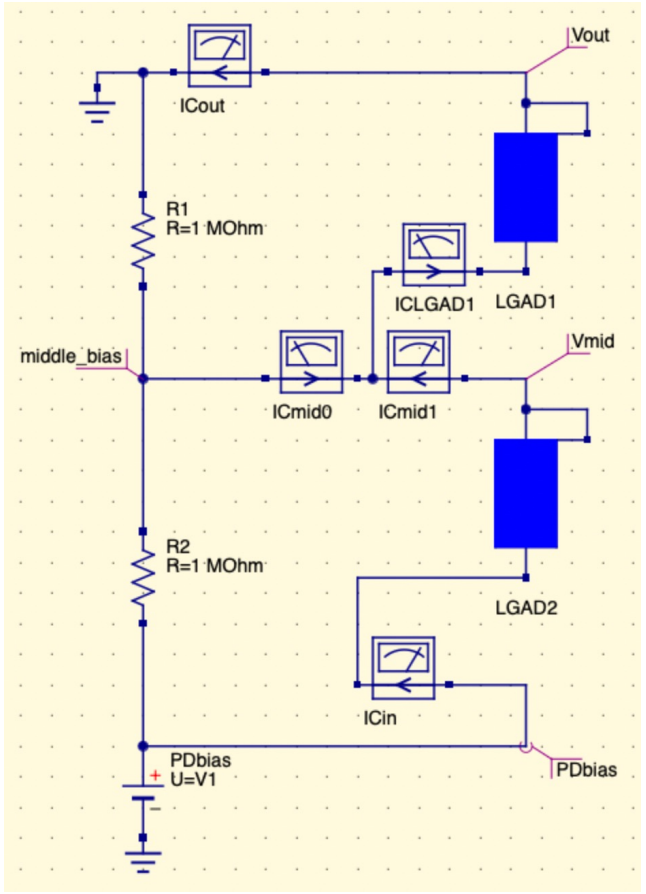
New version of the prototype







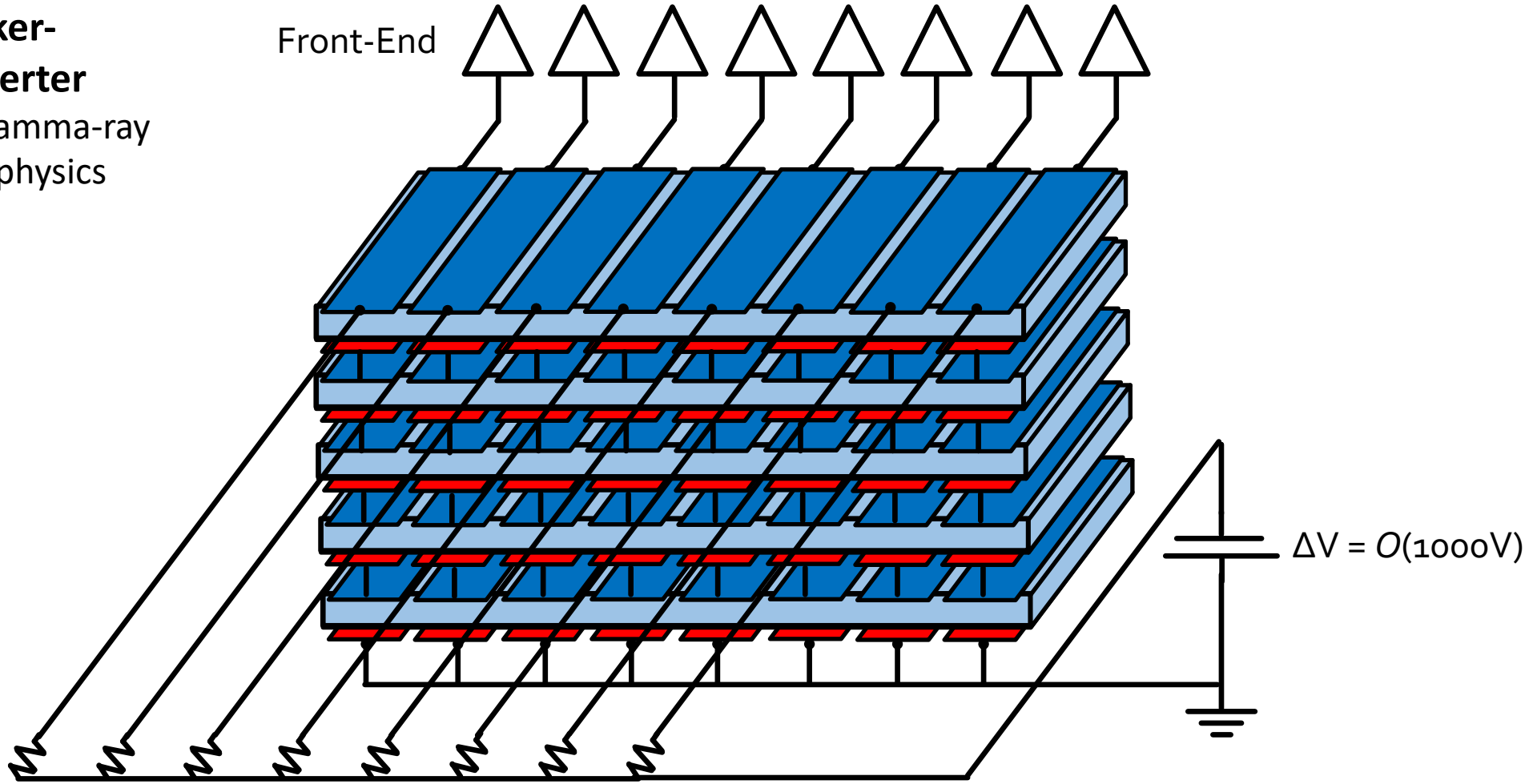
Instead of using two power supplies to force the potential in the middle



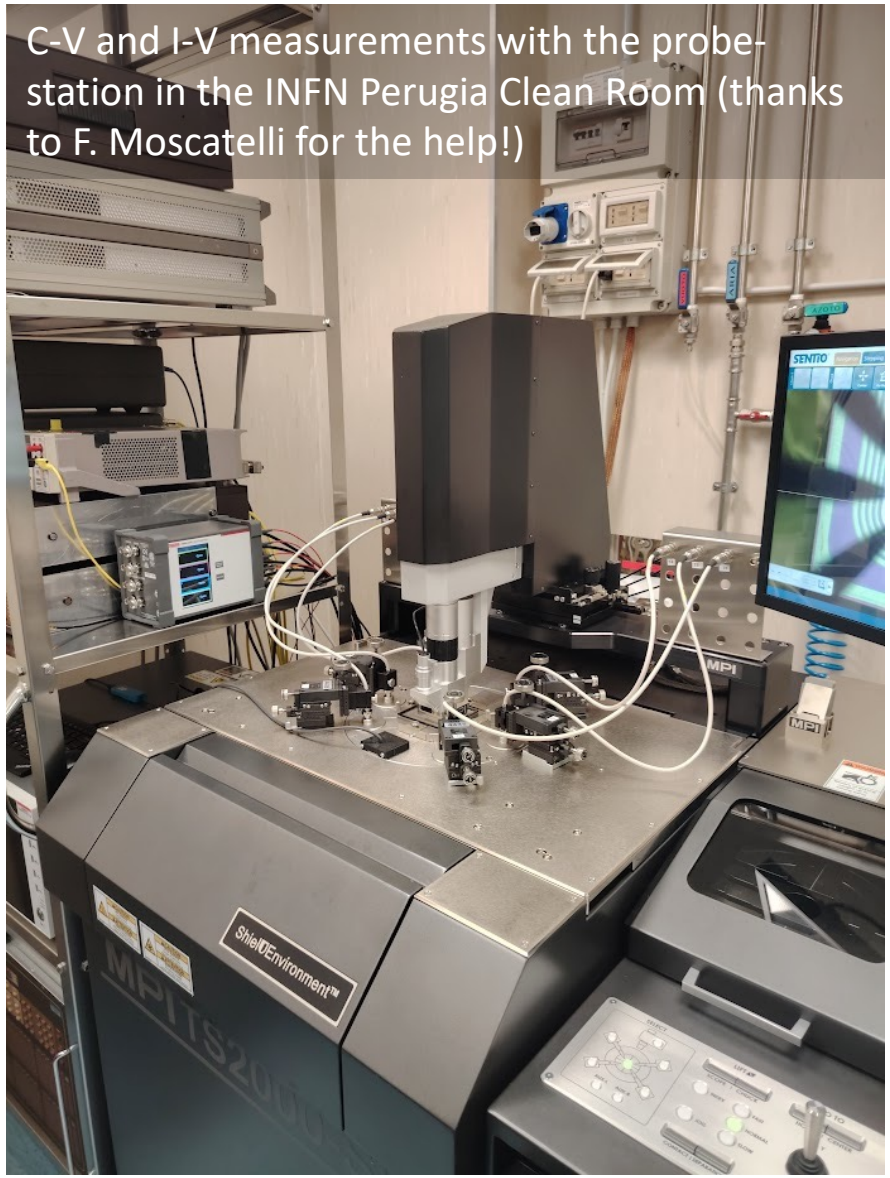
let's use a voltage divider

More "evolved" ideas…

Tracker-converter
For gamma-ray astrophysics



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

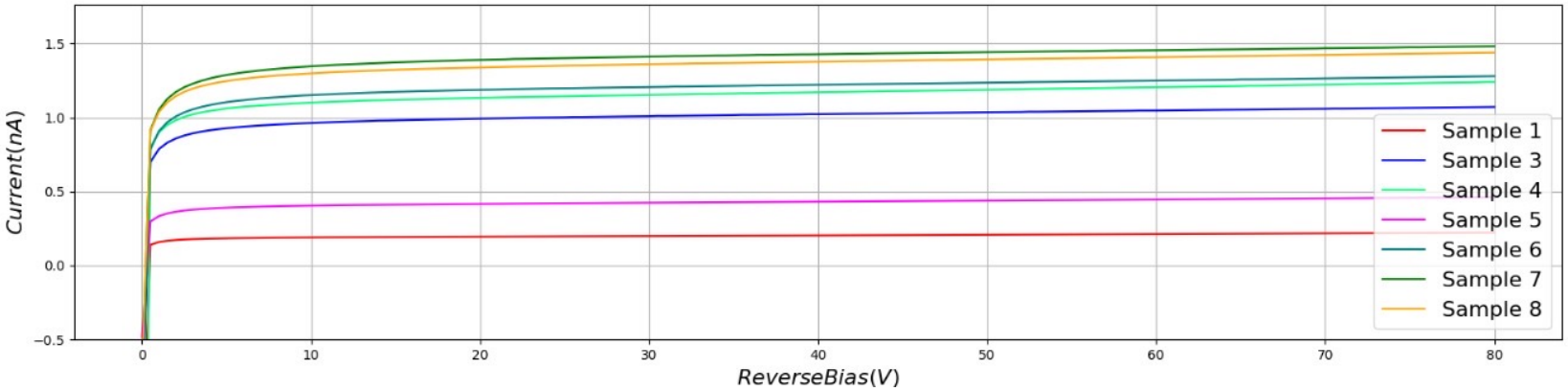


C-V and I-V measurements with the probe-station in the INFN Perugia Clean Room (thanks to F. Moscatelli for the help!)

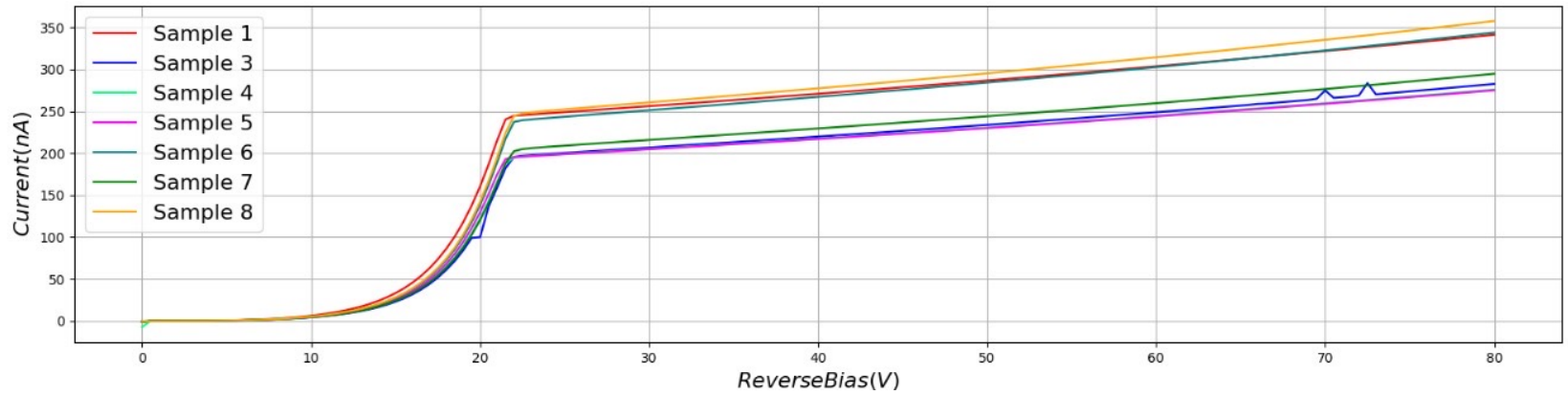
We tested:

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

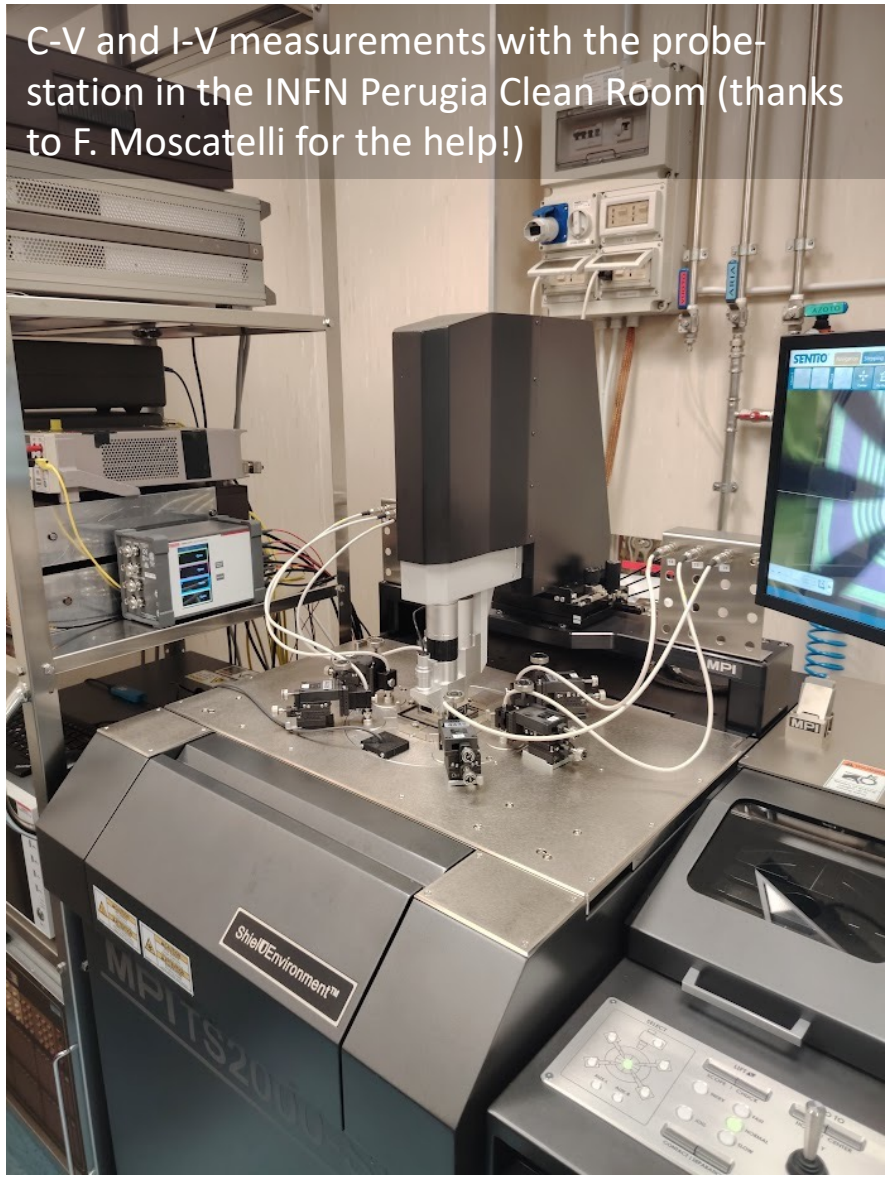
" No Gain"/PIN



"Gain"/LGAD



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

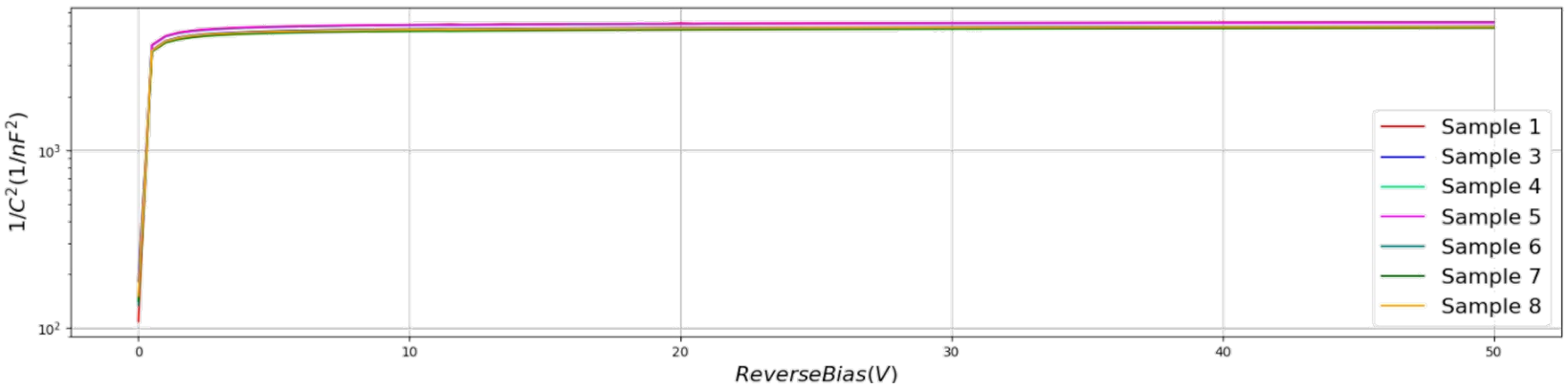


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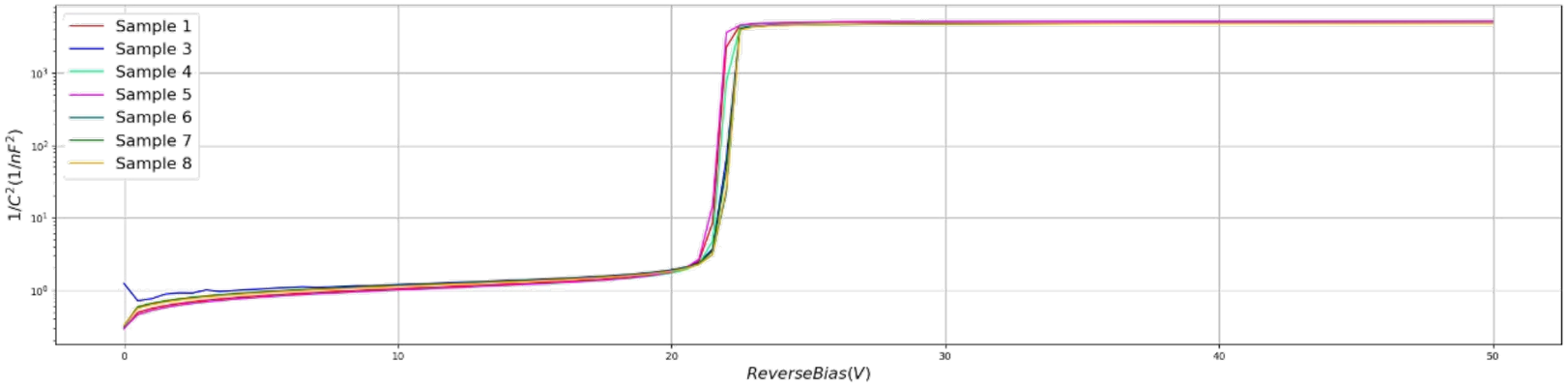
We tested:

- 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)

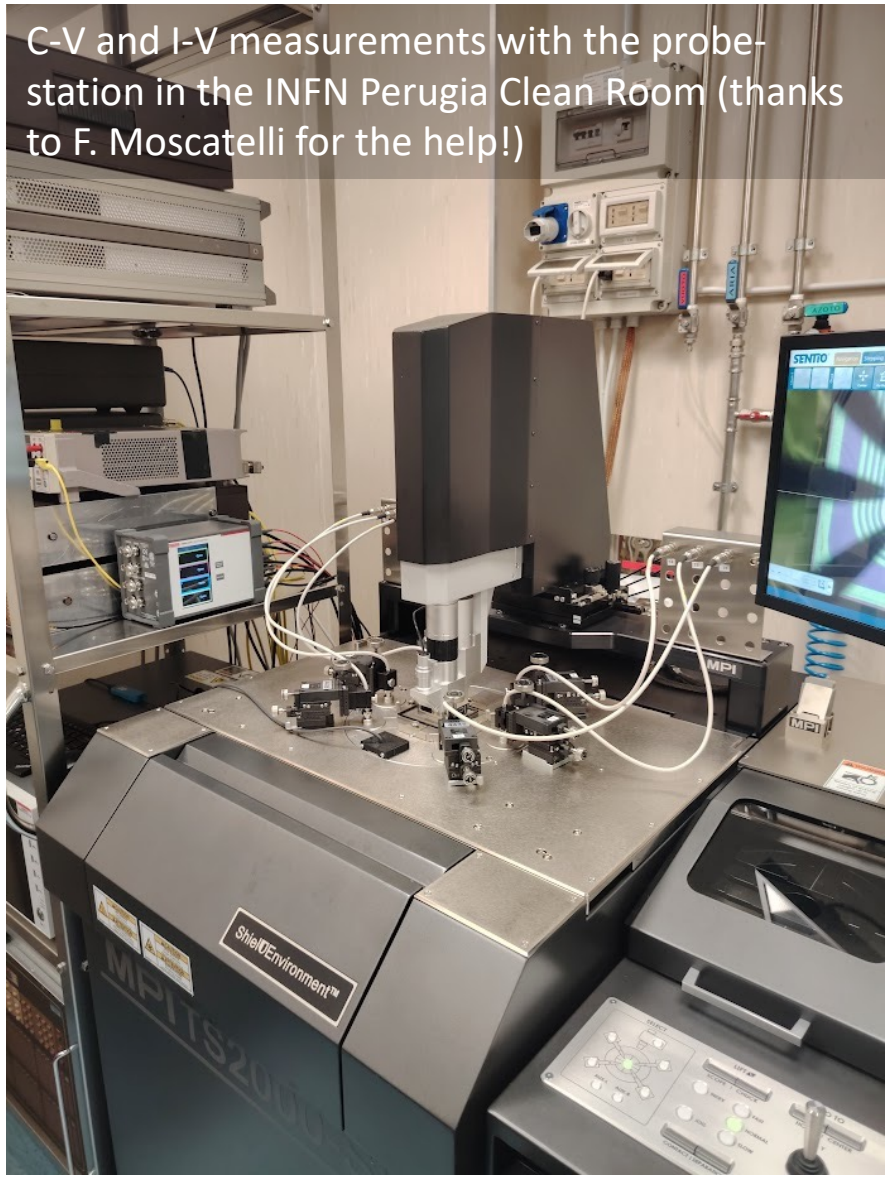
" No Gain"/PIN



"Gain"/LGAD



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

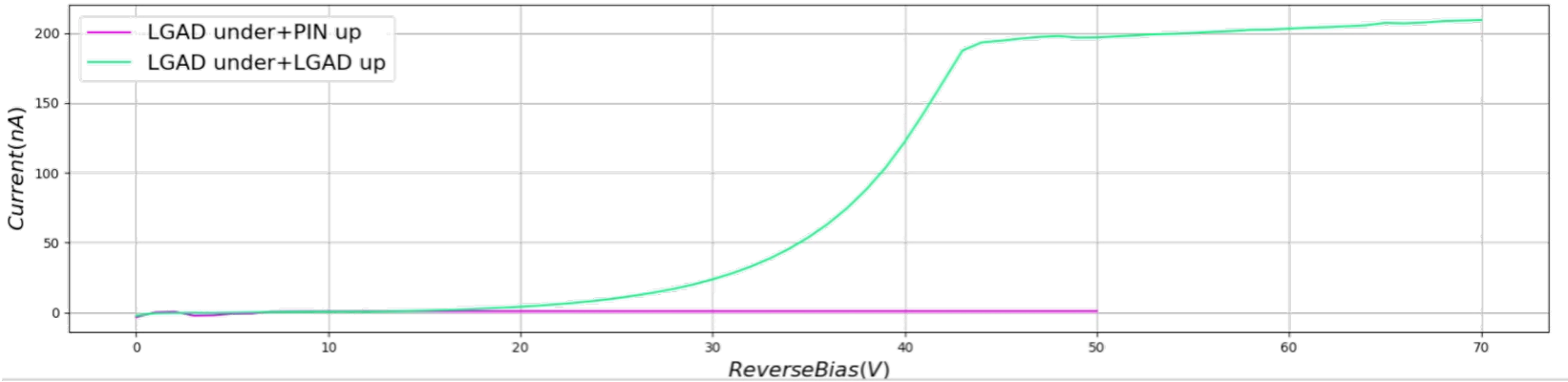


C-V and I-V measurements with the probe-station in the INFN Perugia Clean Room (thanks to F. Moscatelli for the help!)

We tested:

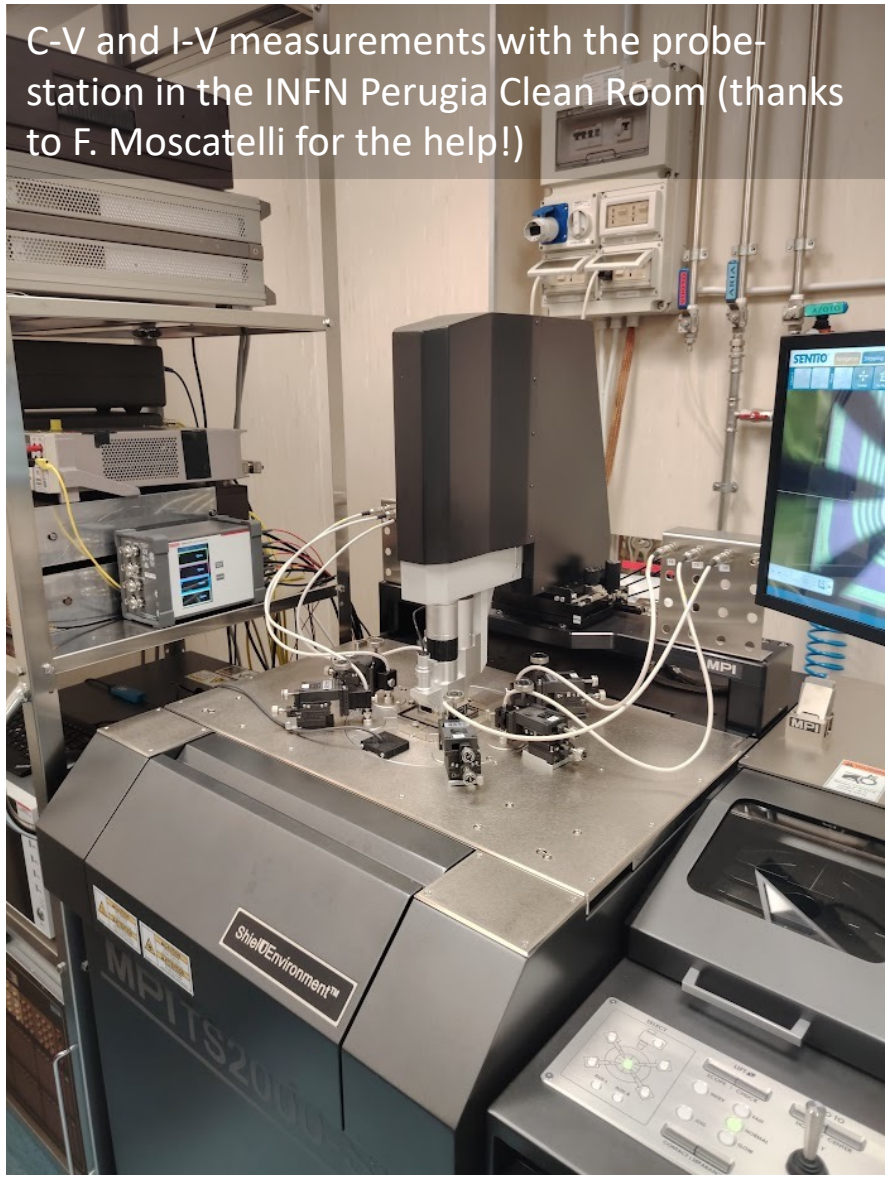
- stacked device
- IV: 1.5 nA (LGAD-PIN), ~ 200 nA (LGAD-LGAD)

I-V



The current is dominate by the one with less leakage!

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

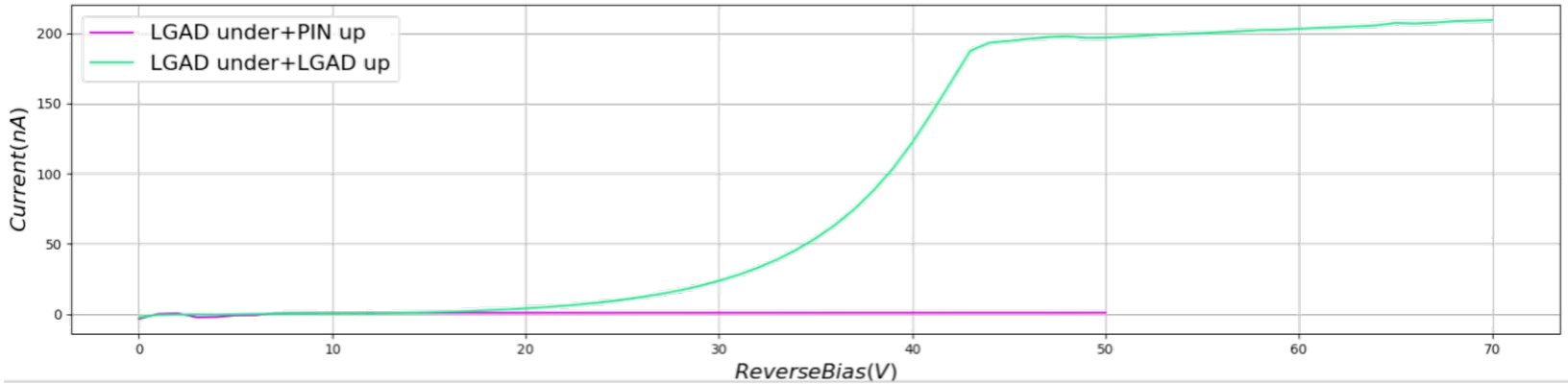


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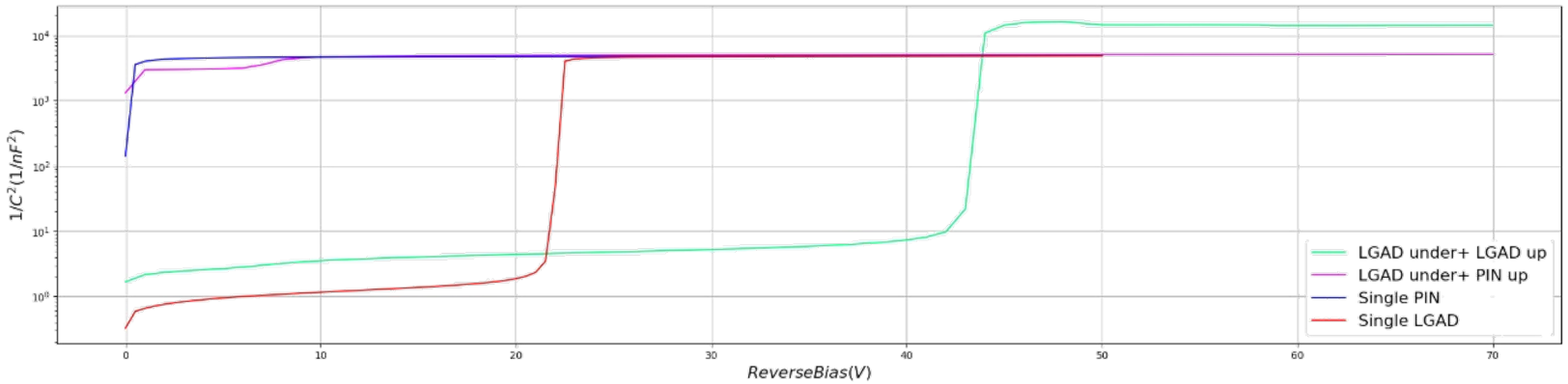
We tested:

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

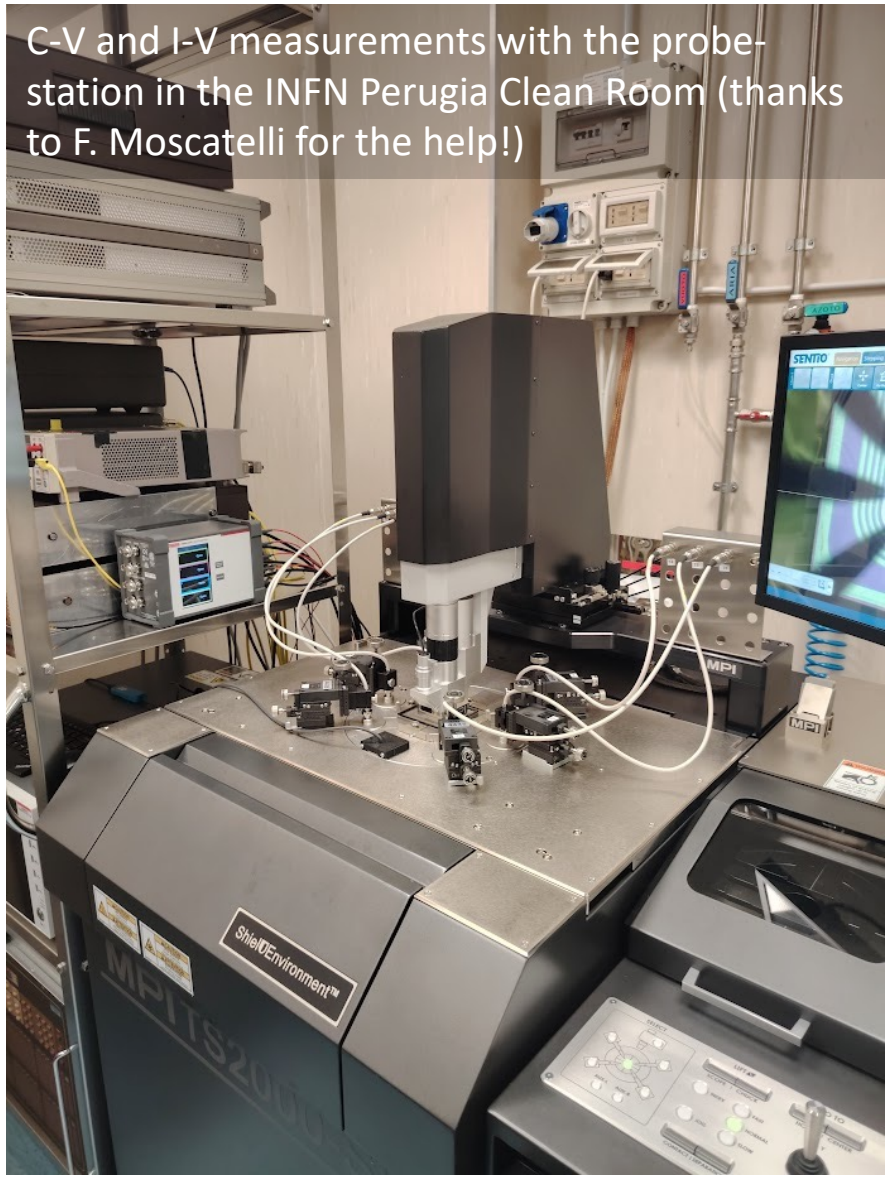
I-V



C-V



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



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:

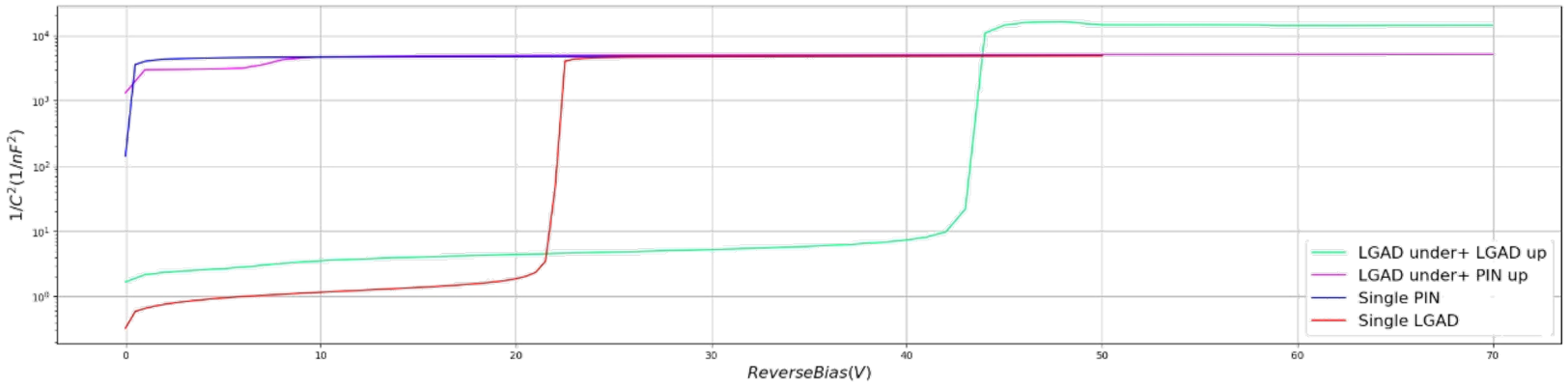
- stacked device
- IV: 1.5 nA (LGAD-PIN), 250 – 350 nA (LGAD-LGAD)
- CV: 13.9 pF ± 0.2pF (LGAD-PIN) ?? 8.3 pF ± 0.2pF (LGAD-LGAD)

- 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?

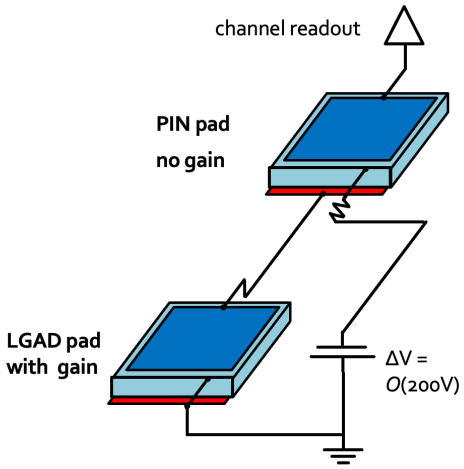
$$C_{tot} = \left(\frac{1}{C_1} + \frac{1}{C_2} \right)^{-1}$$

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

C-V

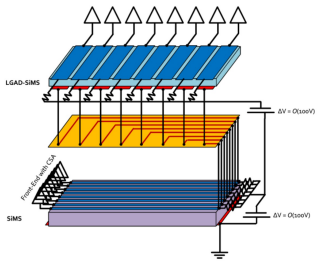


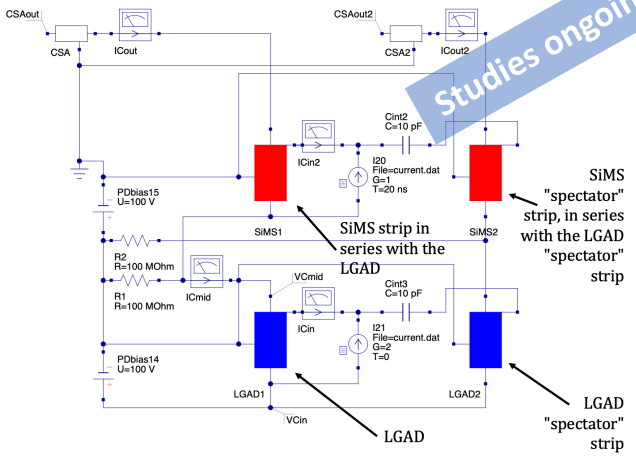
“Stacked” 5D sensor – Proof of concept design



Simple simulations confirm the approach

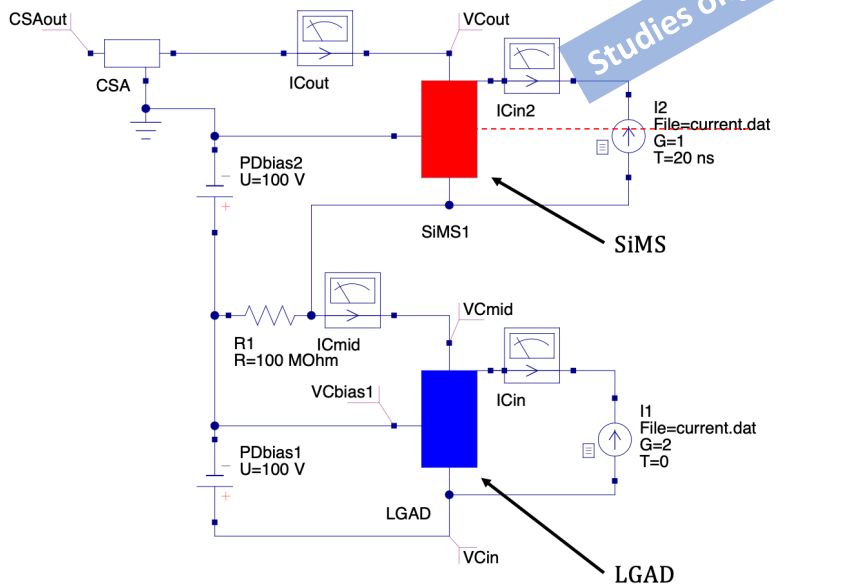
Feedback on starting design, circuitry to be optimized

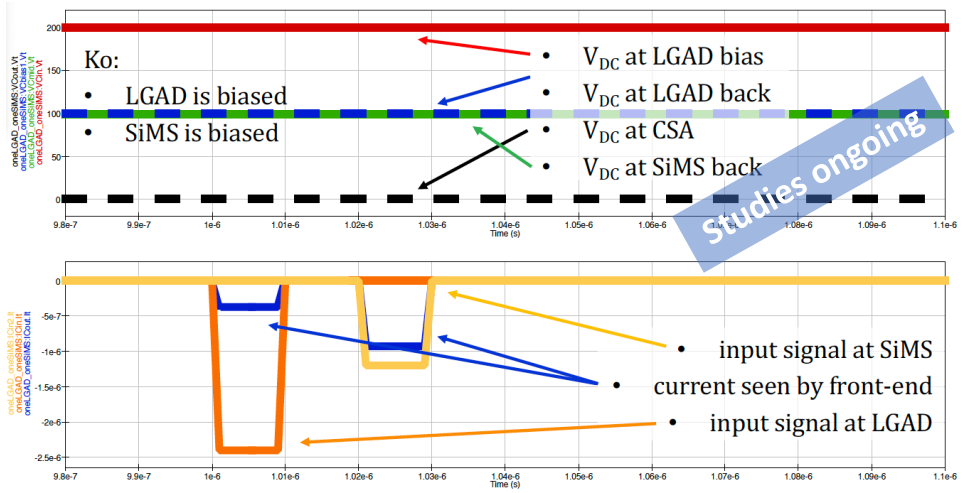




Design confirmed also adding adjacent strips

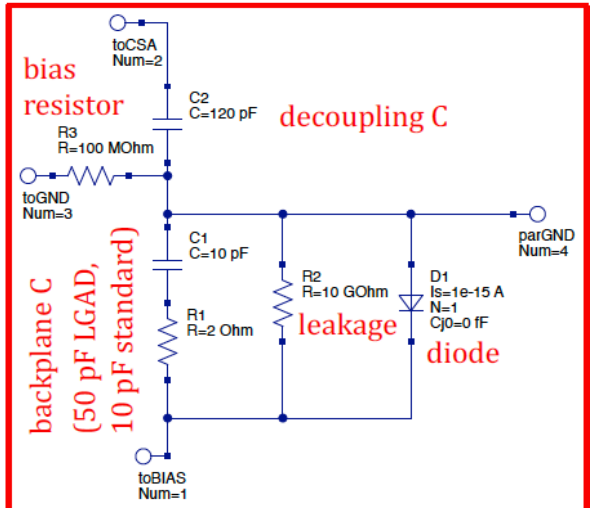
Proof of concept of design





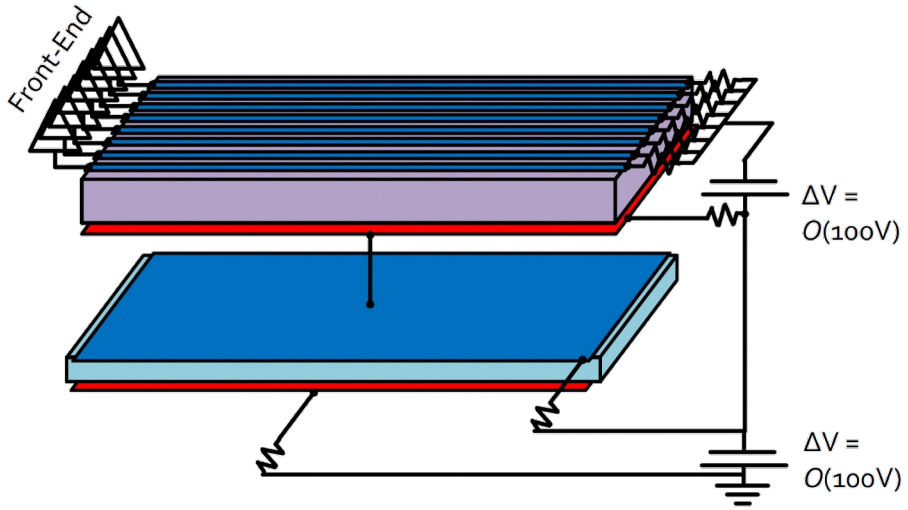
Qucs
Quite universal circuit simulator

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)

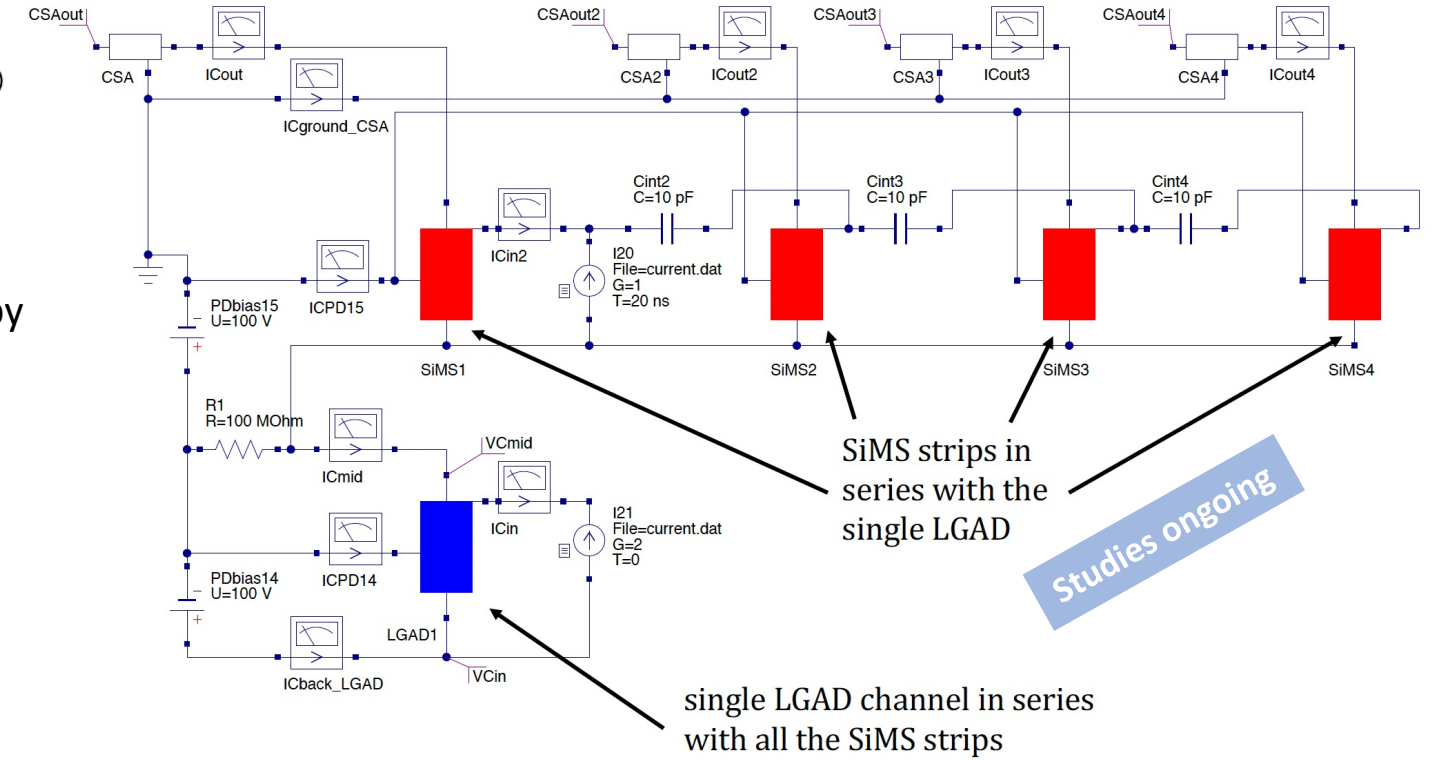
Variant approach

This config could reduce the assembly complexity:

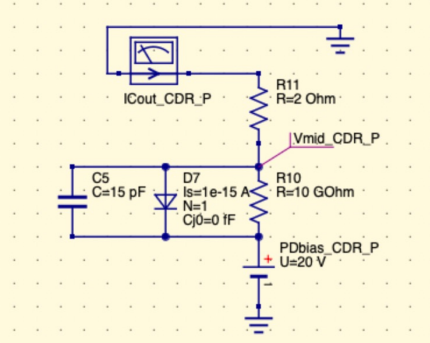
✓ no bonding/kapton between LGAD and SiMS: only glue

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

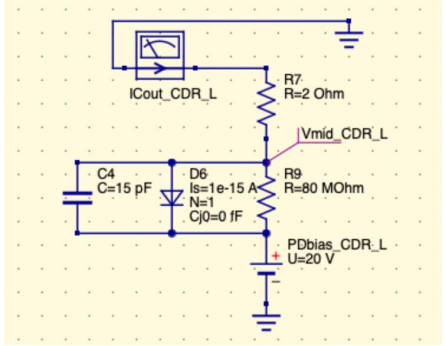
→ preliminary studies are encouraging



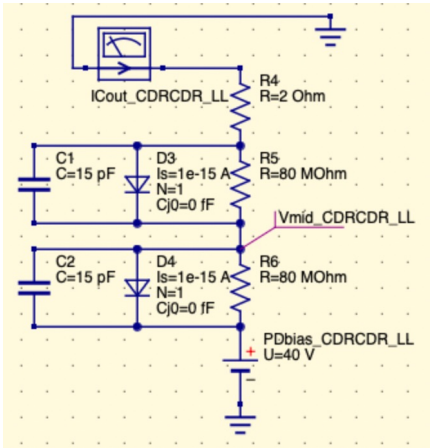
“Stacked” 5D sensor – Proof of concept lab tests



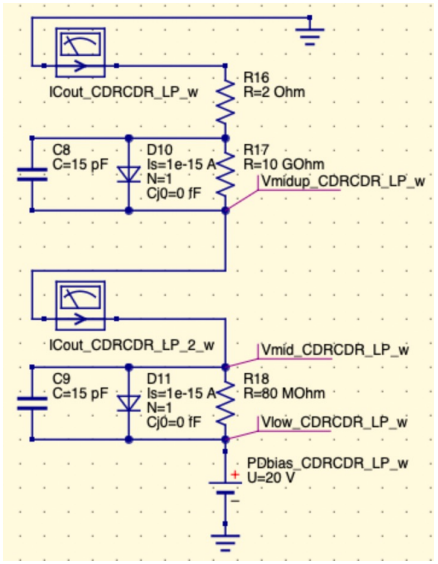
PIN: 10 GΩ
to simulate 2nA



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:

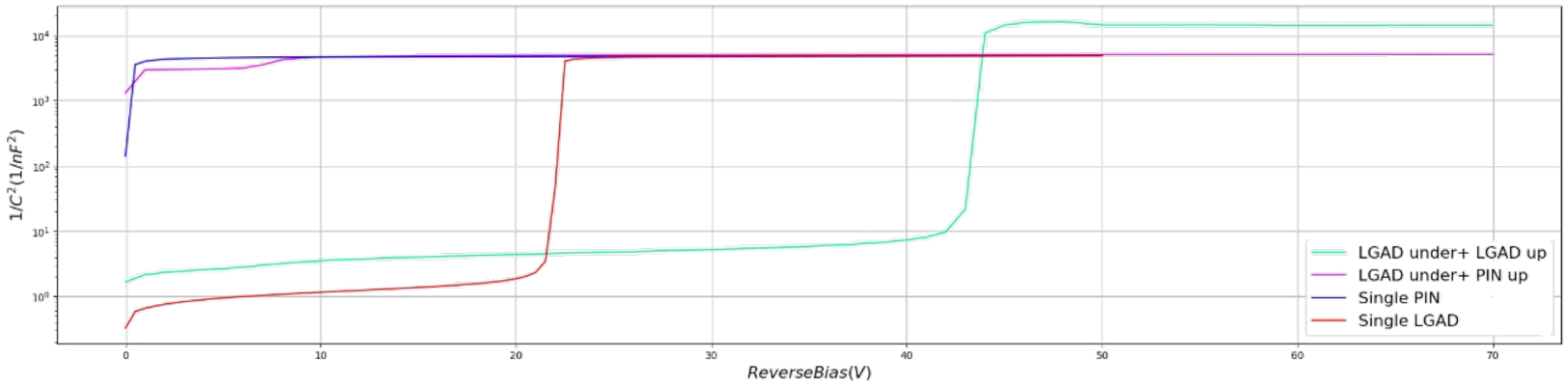
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  - the capacitance of the LGAD-LGAD stack is (almost…) half of the two single capacitances (14.3 pF and 13.9 pF → 7.1 pF). Why there's almost 1 pF more?

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

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

C-V



Pentadimensional Tracking Space Detector - ASI

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

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 units dedicated to the FEE and DAQ of the demonstrator.

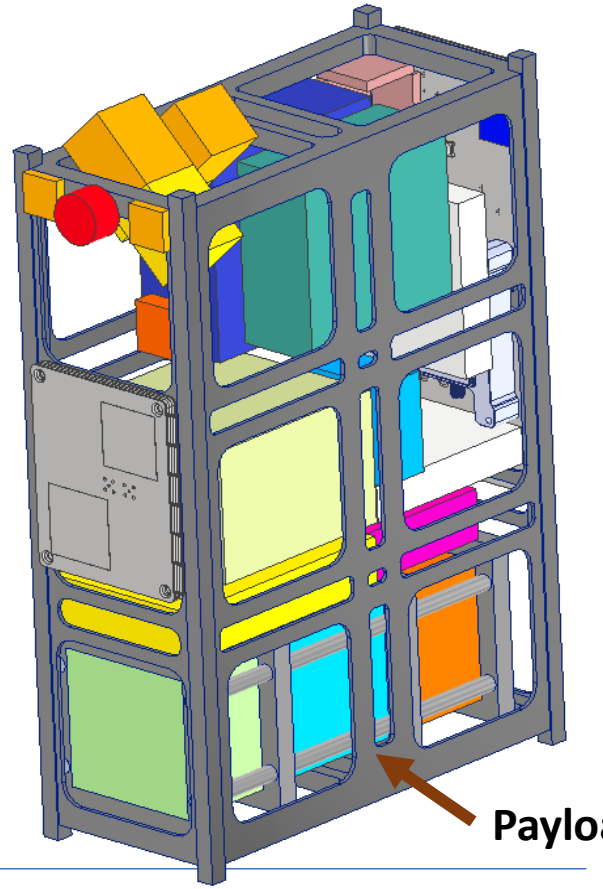
Weigth < 3 kg Power < 20 W

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

Concurrent Engineering Facility study @ ASI

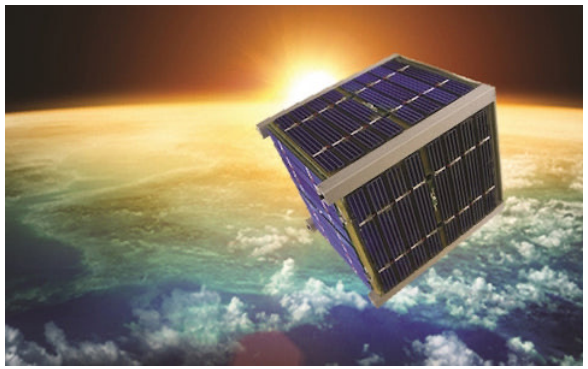
Through a **cooperative** and **parallel study activity** of the domain experts, ASI-CEF is able to define the feasibility of a space mission and its preliminary technical requirements





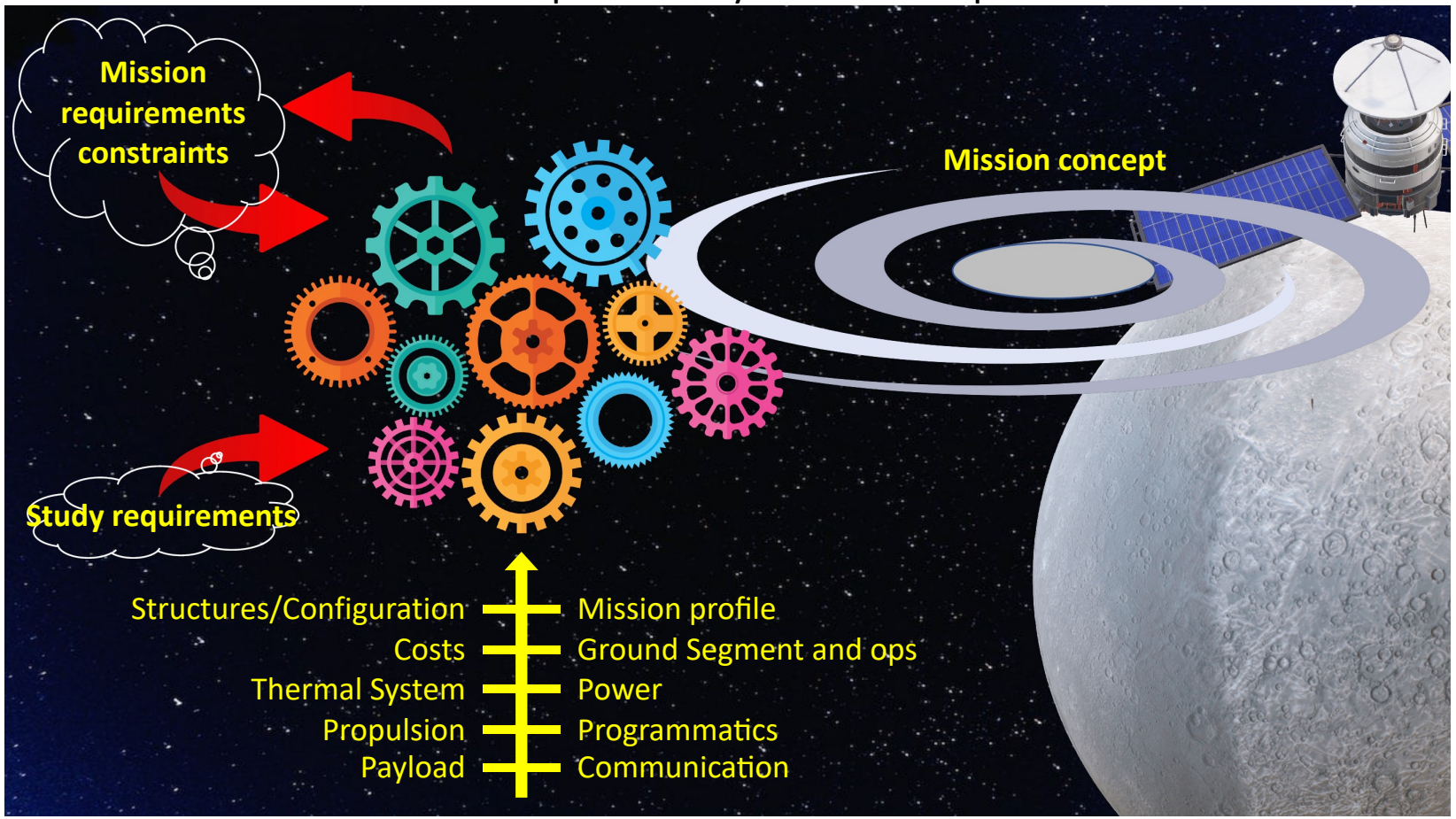
Phase 0 or pre-Phase-A mission concept studies, including, e.g.:

- 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 @ 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



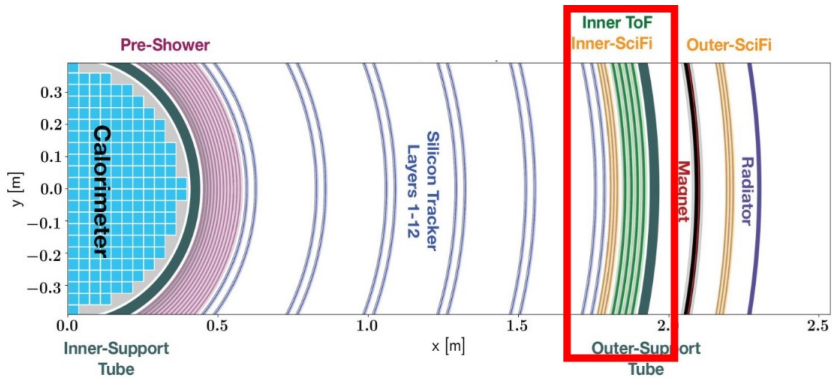
https://www.asi.it/tecnologia-ingegneria-micro-e-nanosatelliti/lingegneria/concurrent-engineering-facility/

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

AMS-100 Time of flight

T. Kirn, VCI 2022

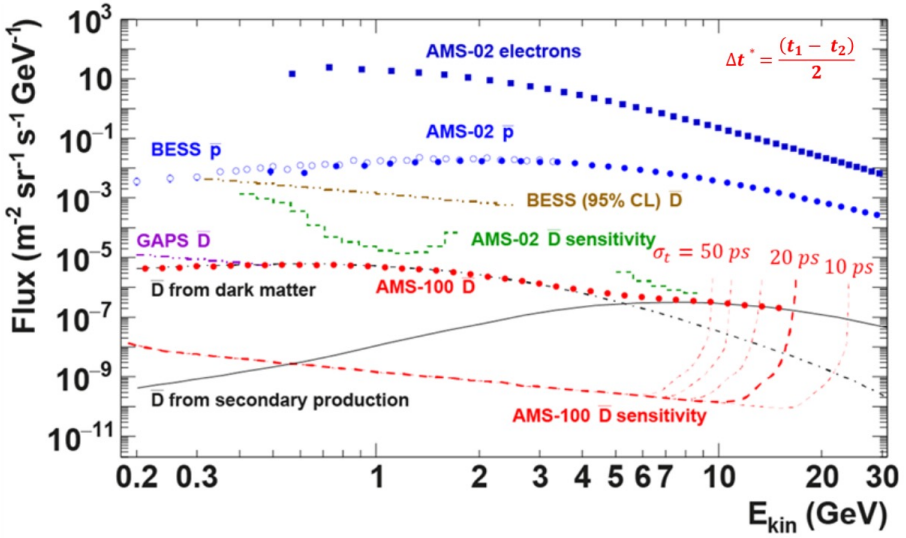
AMS-100: Time of Flight System



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

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

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



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