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

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on behalf of the PTSD team
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1) Italian Space Agency
2) INFN
+ many thanks to L. Pacini (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 ASI F53D23001370008

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
Agenzia Spaziale Italiana
Istituto Nazionale di Fisica Nucleare

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

- Scientific context and 5D tracking in space
- Tracking with Low Gain Avalanche Diodes
- The PTSD project: space-driven R&D of LGAD-µstrips detectors

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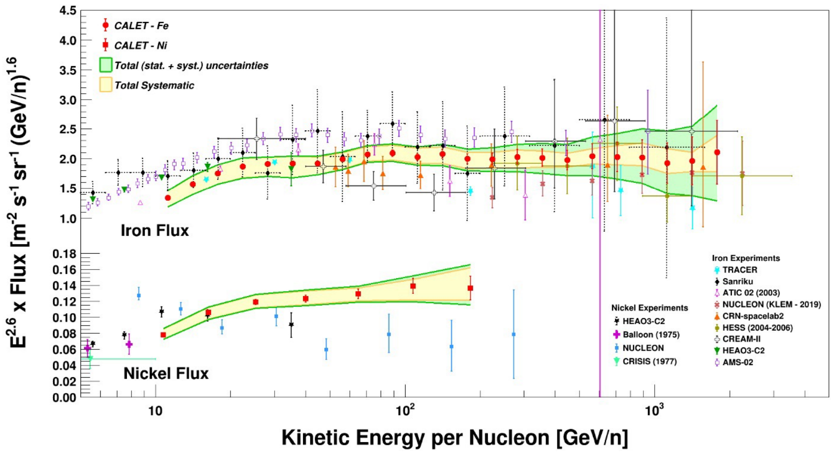
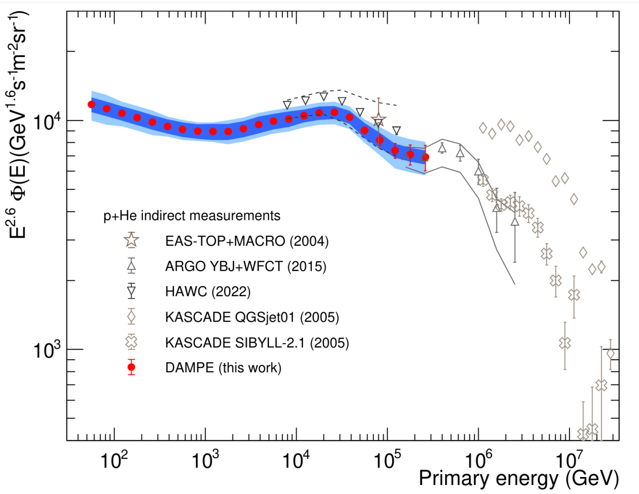
Charged CRs: state of the art

ASI Agenzia Spaziale Italiana — INFN

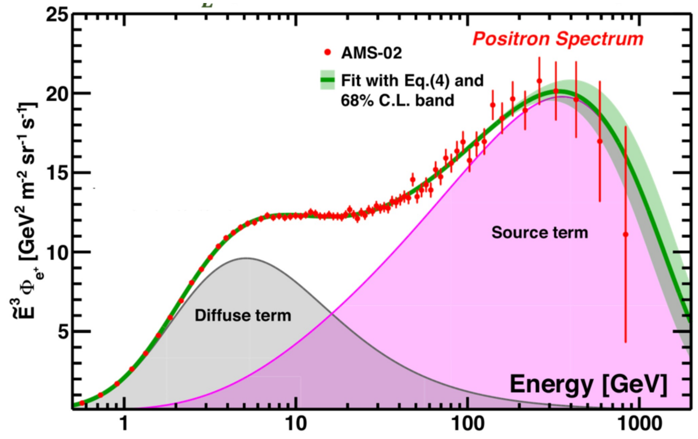
***CALET coll.**, O. Adriani et al., Phys. Rev. Lett. 128, 131103 (2022)*



***DAMPE coll.**, F. Alemanno et al., PoS (ICRC2023) 138*



***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**

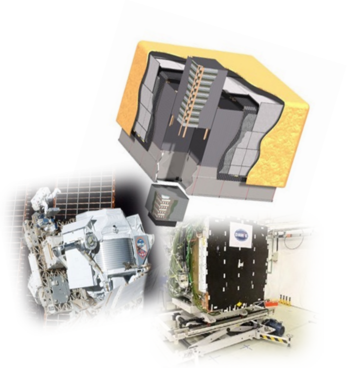
NEW paradigm of CR origin, acceleration and propagation

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**.

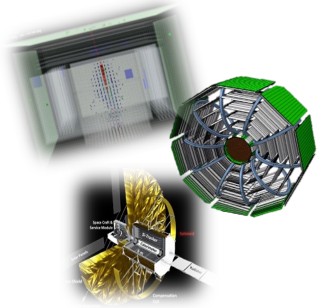
+ synergic activity at ground laboratories and accelerators to tackle **technological challenges** and enable **new observational approaches**

Large area Si-microstrip detectors in space

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	$\sim 74\,\mathrm{m}^2$	38 cm	$\sim 880 \cdot 10^3$	228 μm	$\sim 66\,\mu$m
AMS-02	2011	$\sim 7\,\mathrm{m}^2$	29–62 cm	$\sim 200 \cdot 10^3$	110 μm	$\sim 7\,\mu$m
DAMPE	2015	$\sim 7\,\mathrm{m}^2$	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	$\sim 35\,\mathrm{m}^2$	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

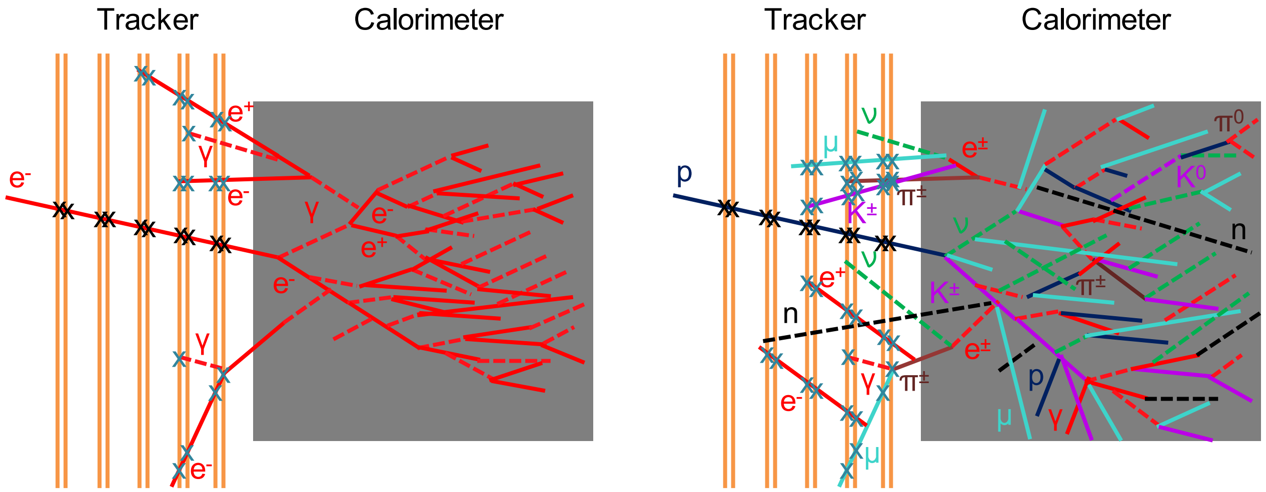
[1] HERD Collaboration. *HERD Proposal, 2018* https://indico.ihep.ac.cn/event/8164/material/1/0.pdf
[2] Battiston, R.; Bertucci, B.; *et al. High precision particle astrophysics as a new window on the universe with an Antimatter Large Acceptance Detector In Orbit (ALADInO)*. Experimental Astronomy 2021. 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

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



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

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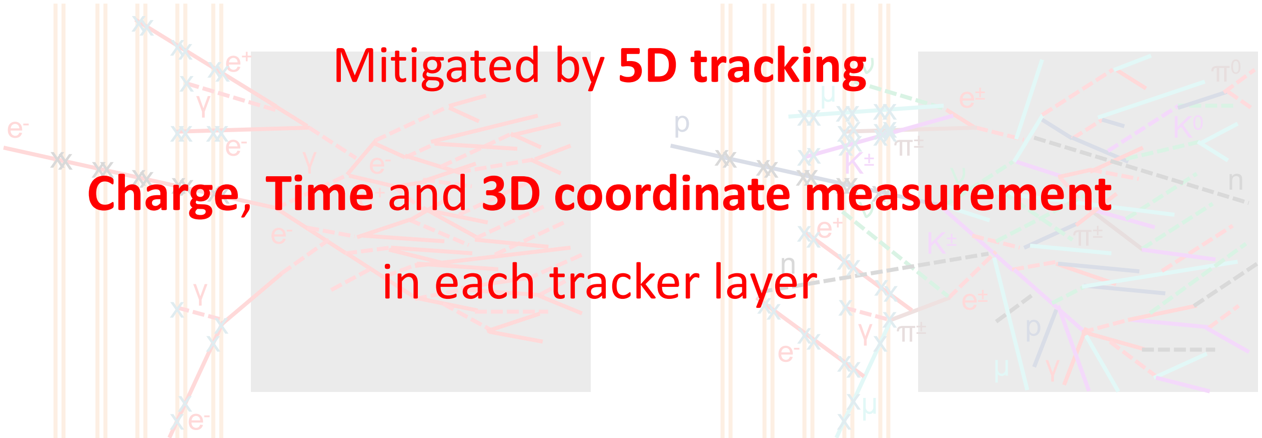


Mitigated by **5D tracking**

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

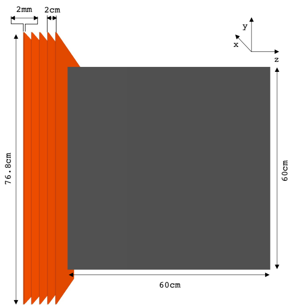
TIME OF FLIGHT
Hit timing resolutions of ~ 100 ps enable ToF measurements with SiMS complementary to scintillators with fast light readout

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

Effects of 5D-Tracking in backscattering events

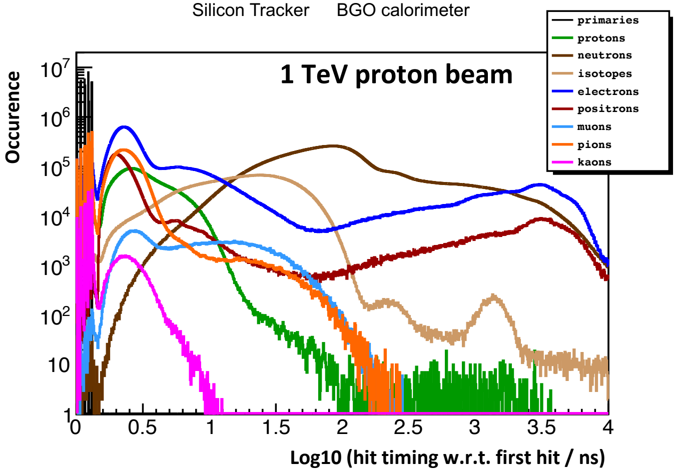
M. Duranti et al., *Instruments* 2021, 5(2), 20

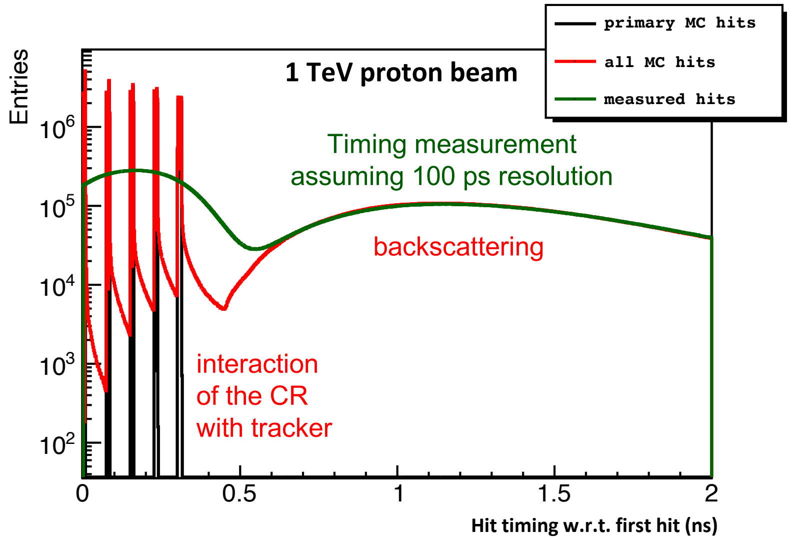
MC simulation of backscatterd particles from downstream calorimeter on tracker layers



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

Silicon Tracker BGO calorimeter



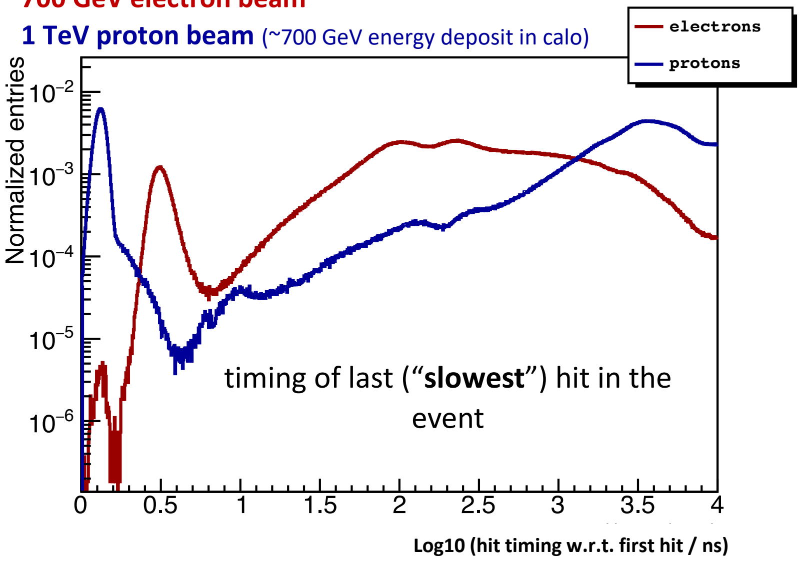


100 ps resolution allows to separate hits from primary particles and from secondary backsplash

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])

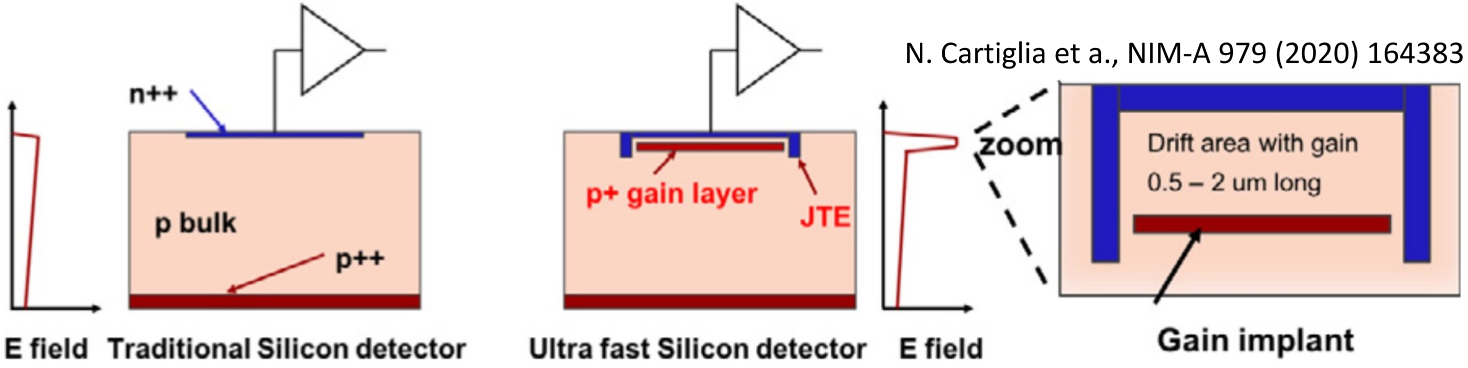
Break-through objectives (e.g.: performant isotope separation**): < 50 ps** (requires readout noise mitigation approaches)

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

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: ~10-20 ps

An 'almost consolidated' technology, yet very challenging

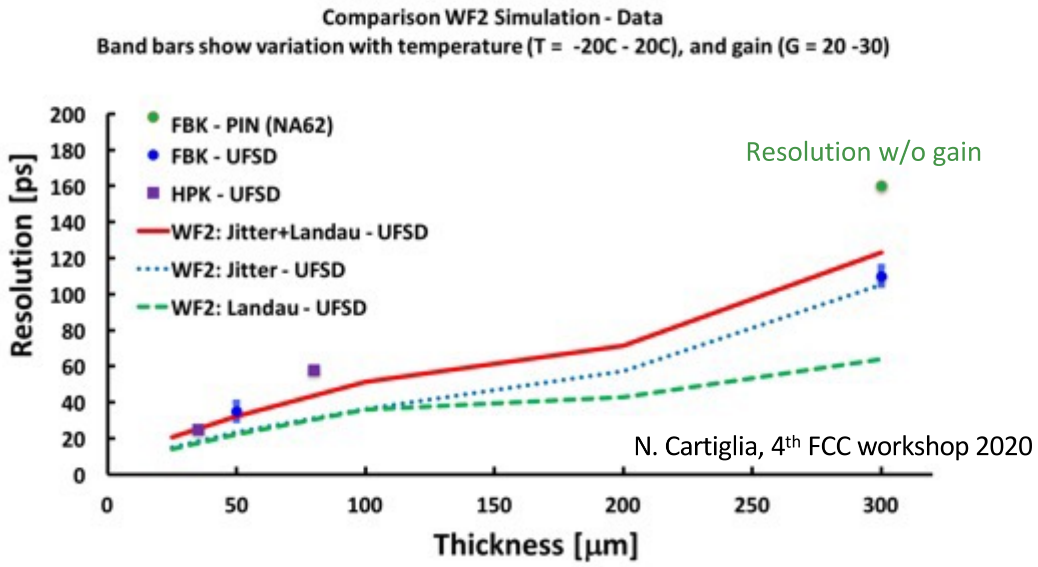
LGAD design optimized for improved timing resolution

(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



N. Cartiglia, 4th FCC workshop 2020

Optimal candidate for large-area 5D Tracking devices

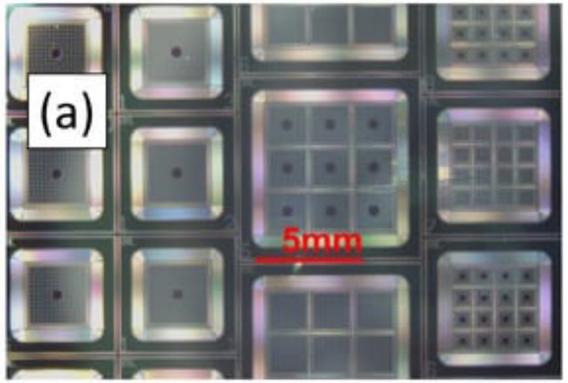
Roadmap to 5D Tracking in Space

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

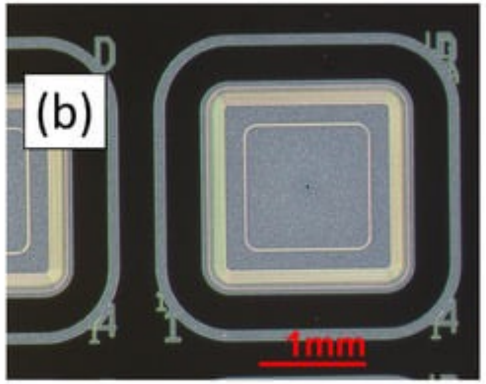
Several facilities involved today in LGAD sensor developments
CNM (ES), FBK (IT), BNL (USA), Hamamatsu (JP), IHEP-NDL (CN), Micron (UK), ...
and readout electronics
Univ. California Santa Cruz (USA), FNAL (USA), INFN (IT)

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



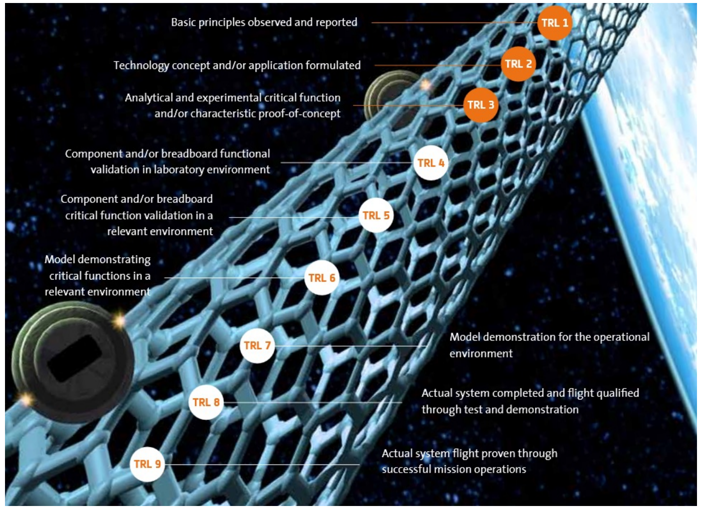
Recent production of 1.3 mm × 1.3 mm devices at BNL (match the pixel size of the CMS and ATLAS timing detectors)

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



Pentadimensional Tracking Space Detector

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

WP1 Management and dissemination	WP2 Sensor production	WP3 Proto-detector qualification	WP4 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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PNRR M4.C2.1.1, PRIN 2022, n. 2022JNF3M4, CUP ASI F53D23001370008

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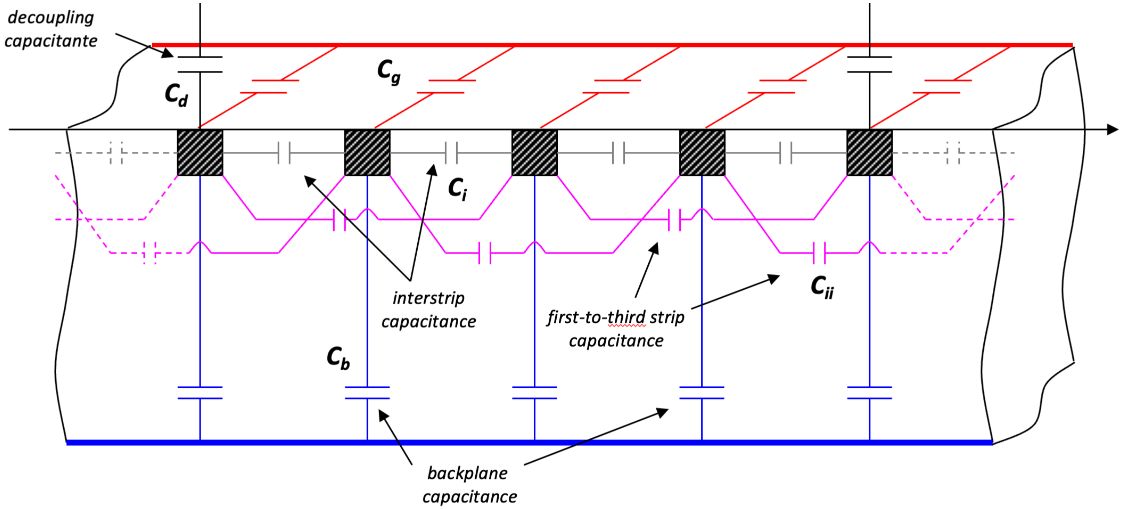
Capacitance in daisy-chained LGADs

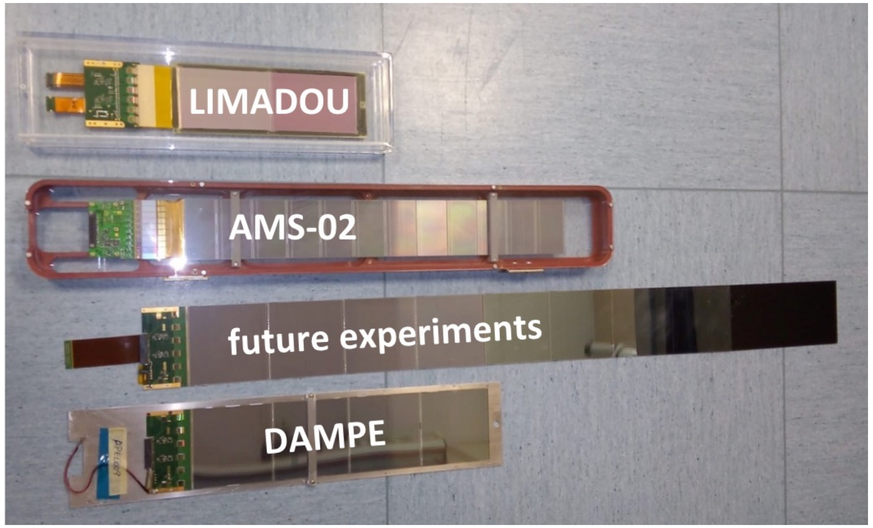


p = pitch
l = strip lenght
d = thickness

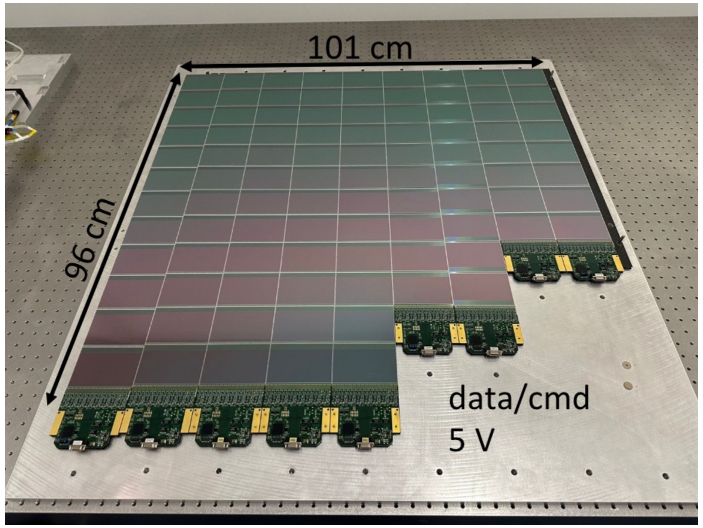
C_i = interstrip capacitance ~ 1 pF/cm * *l* = 10 – 100 pF
C_d = decoupling capacitance ~ 1000 pF (DC sensors) or 120 pF/mm^2 (AC sensors) > C_i C_b C_g C_{ii}
C_b = backplane capacitance ~ 1 pF/cm * *l* * *p/d* = 0.5 – 2 * 10 – 100 pF
C_g = guardring capacitance << C_i
C_{ii} = first-to-third strip capacitance << C_i

For thin and long strips capacitance must be kept under limit

INFN Perugia



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



M. Duranti, TREDI 2024

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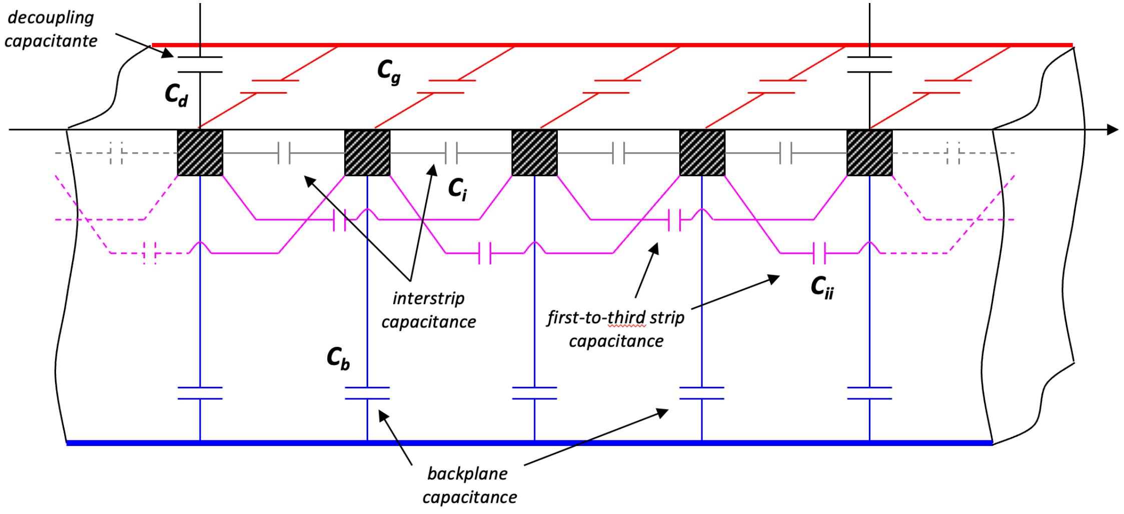

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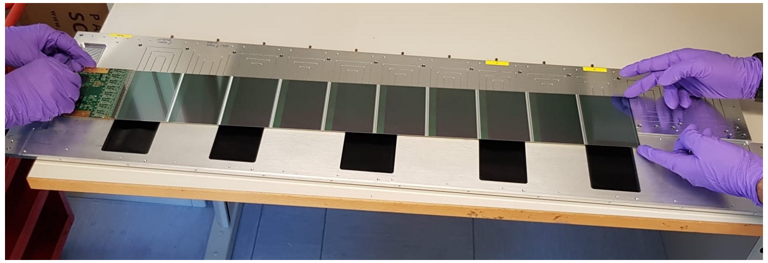
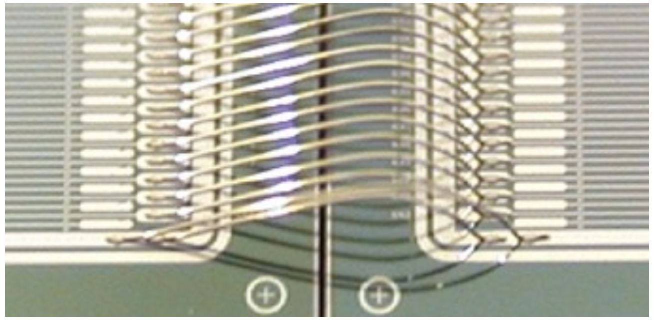
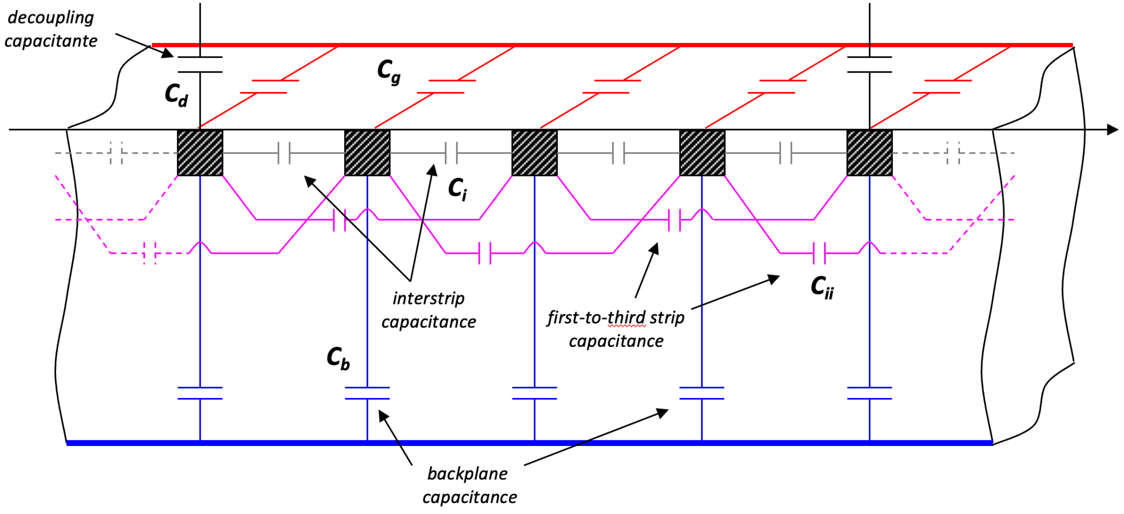
AMS-02 upgrade, Layer-0 ladder @ INFN Perugia





Capacitance in daisy-chained LGADs



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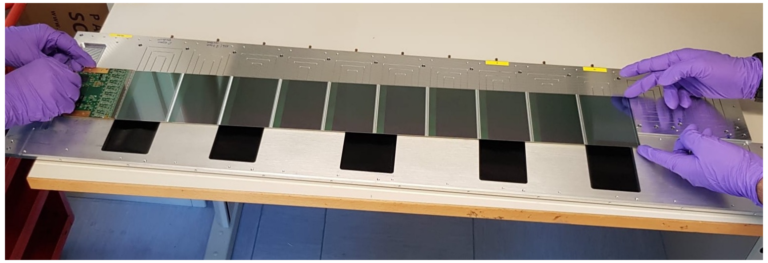
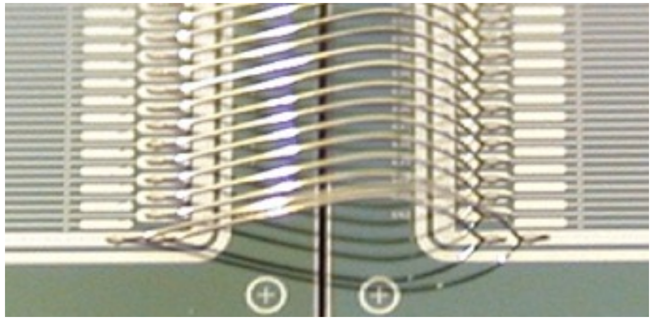
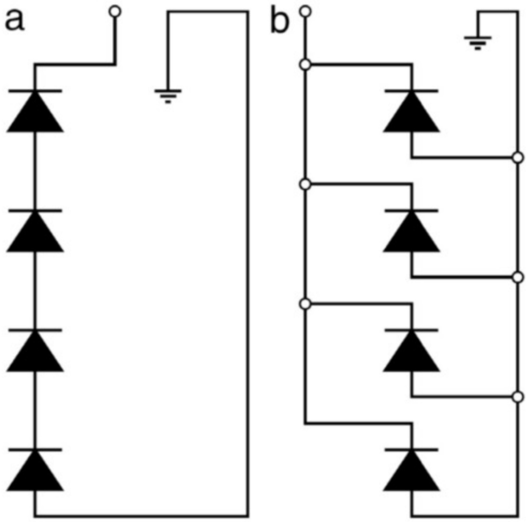




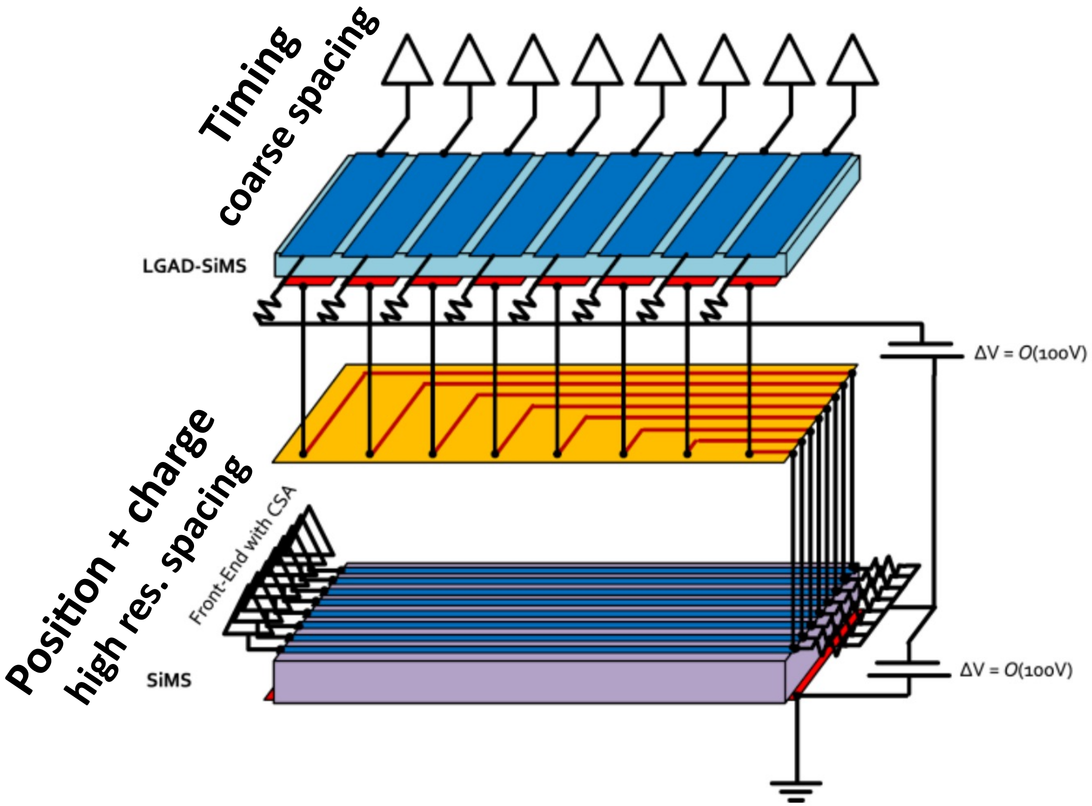


N. Kratochwil et al., PANDA experiment

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

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

“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 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

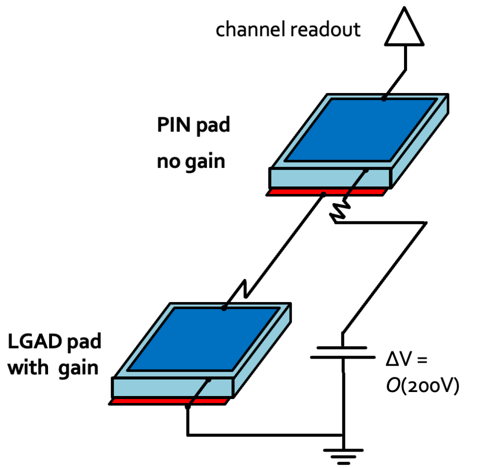
- suits the requirements for a **tracking system in a magnetic spectrometer with oriented magnetic field**

Mechanical structures and interfaces will be an issue

Requires a double-sided LGAD

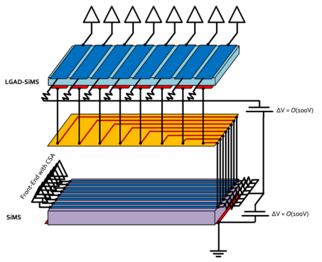
- costs and risks of process development, yield, assembly... increase

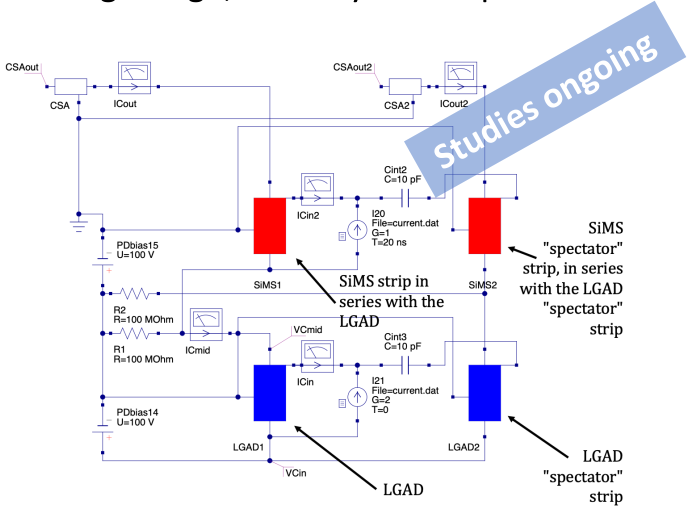
“Stacked” 5D sensor – Proof of concept design



Simple simulations confirm the approach

Feedback on starting design, circuitry to be optimized

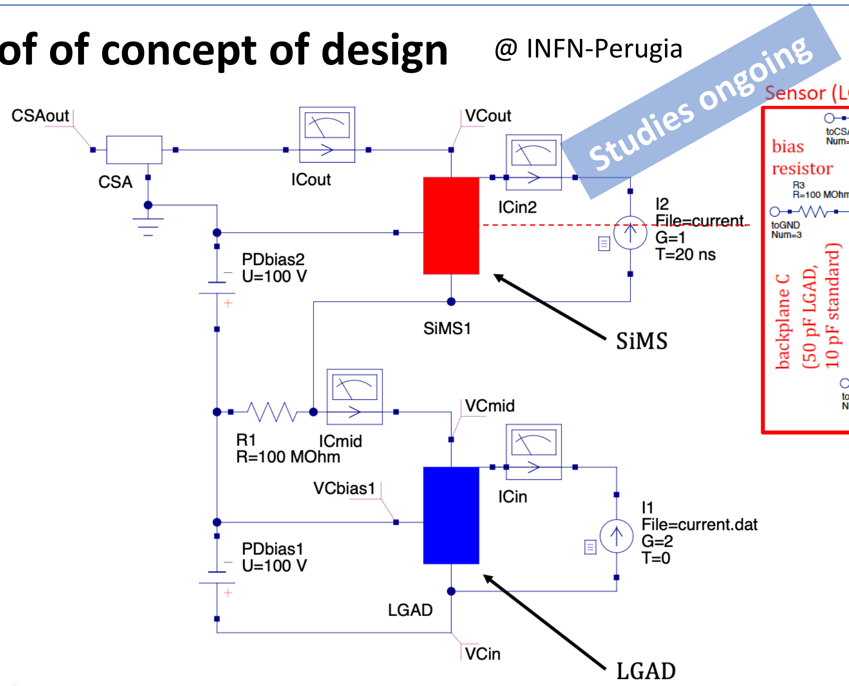


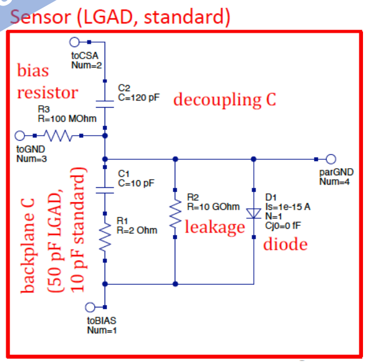


Design confirmed also adding adjacent strips

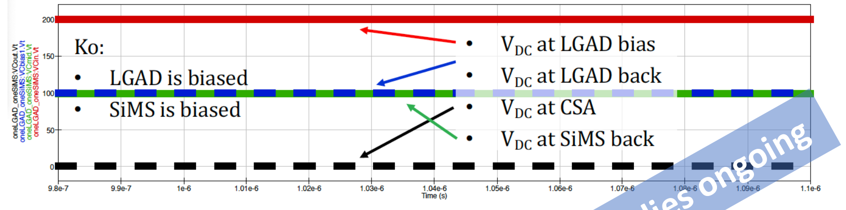
Proof of concept of design

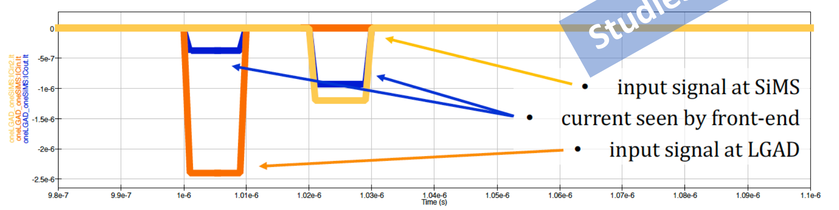
@ INFN-Perugia



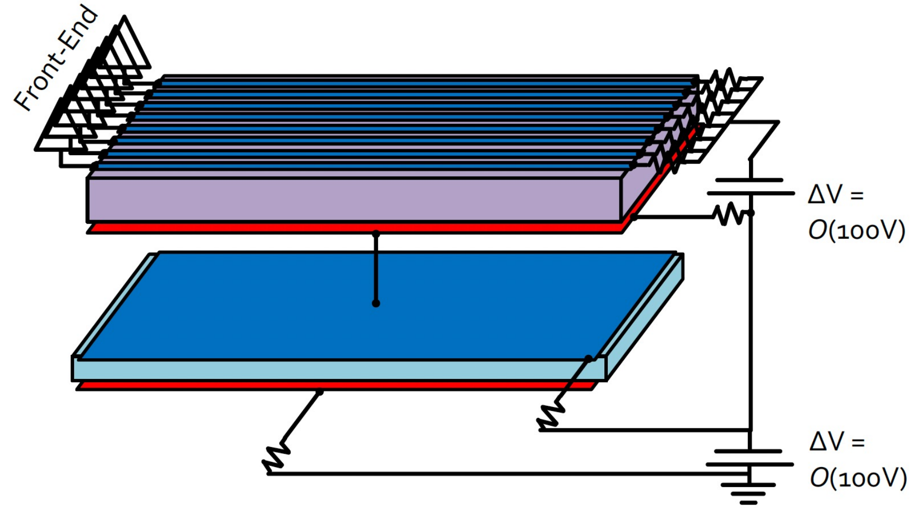


Qucs *Quite universal circuit simulator*





"Stacked" 5D sensor – Proof of concept design

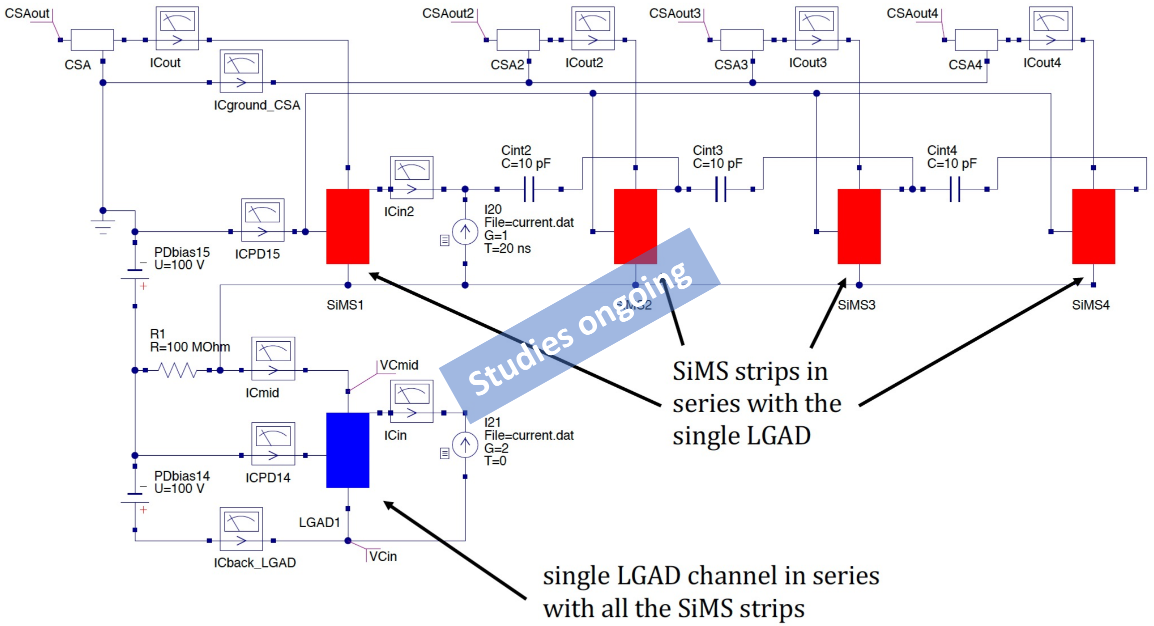


Variant approach

This config could reduce the assembly complexity:

- No bonding/kapton between LGAD and SiMS: only glue
- Time information common to all channels

Preliminary studies are encouraging



Pentadimensional Tracking Space Detector

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

Agenzia Spaziale Italiana

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

ASI
Headquarters (Roma)
co-PI: Valerio Vagelli

WP1
Management and dissemination
INFN, ASI

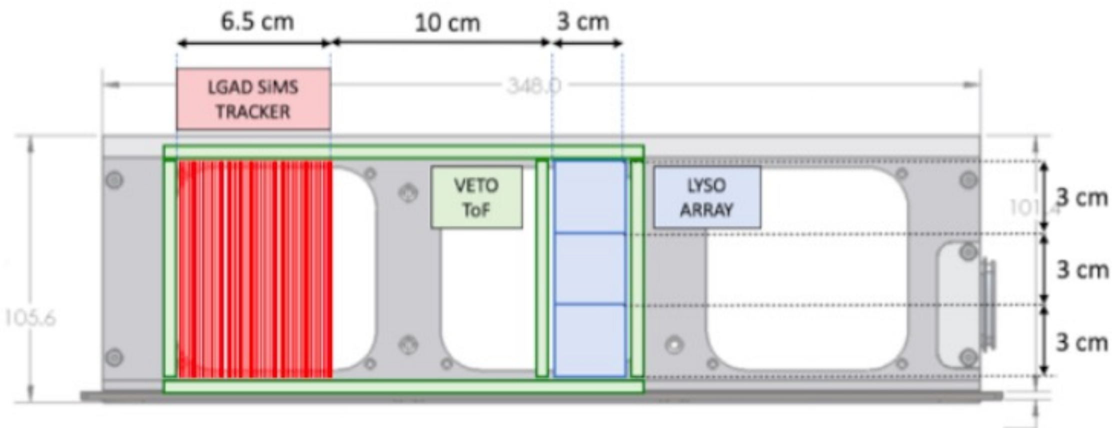
WP2
Sensor production
INFN, ASI

WP3
Proto-detector qualification
INFN, ASI

WP4
Scientific applications space mission design
ASI, INFN

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

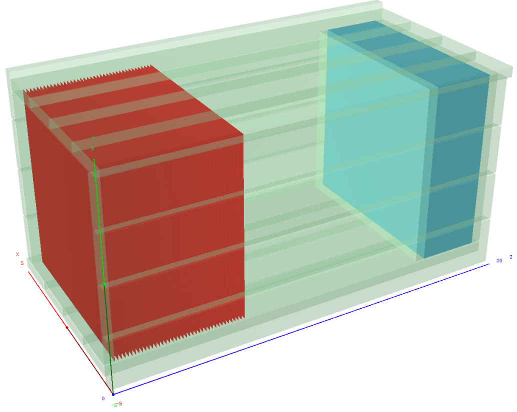


LGAD SiMS Tracker
40 layers of 150 μm thick SiMS LGADs
readout pitch: 150 μm
- expected Δx ~ 15μm

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

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

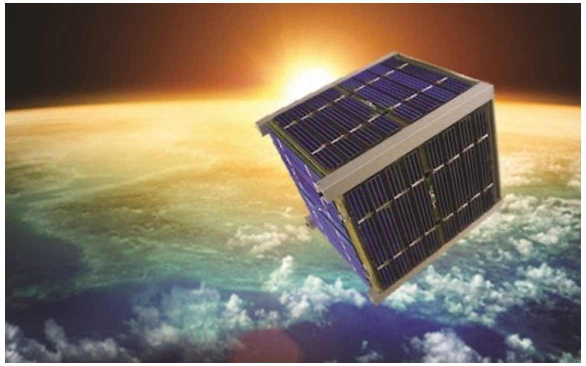
Study of charged CRs using the 5D tracking (position, energy deposit and timing) enabled by the LGAD SiMS tracker
Data-driven characterization of Tof capabilities for LGAD SiMS detectors
Data-driven characterization of e/p separation capabilities for LGAD SiMS detectors
Monitor the time variation of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

Concurrent Engineering Facility study @ ASI CEF

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



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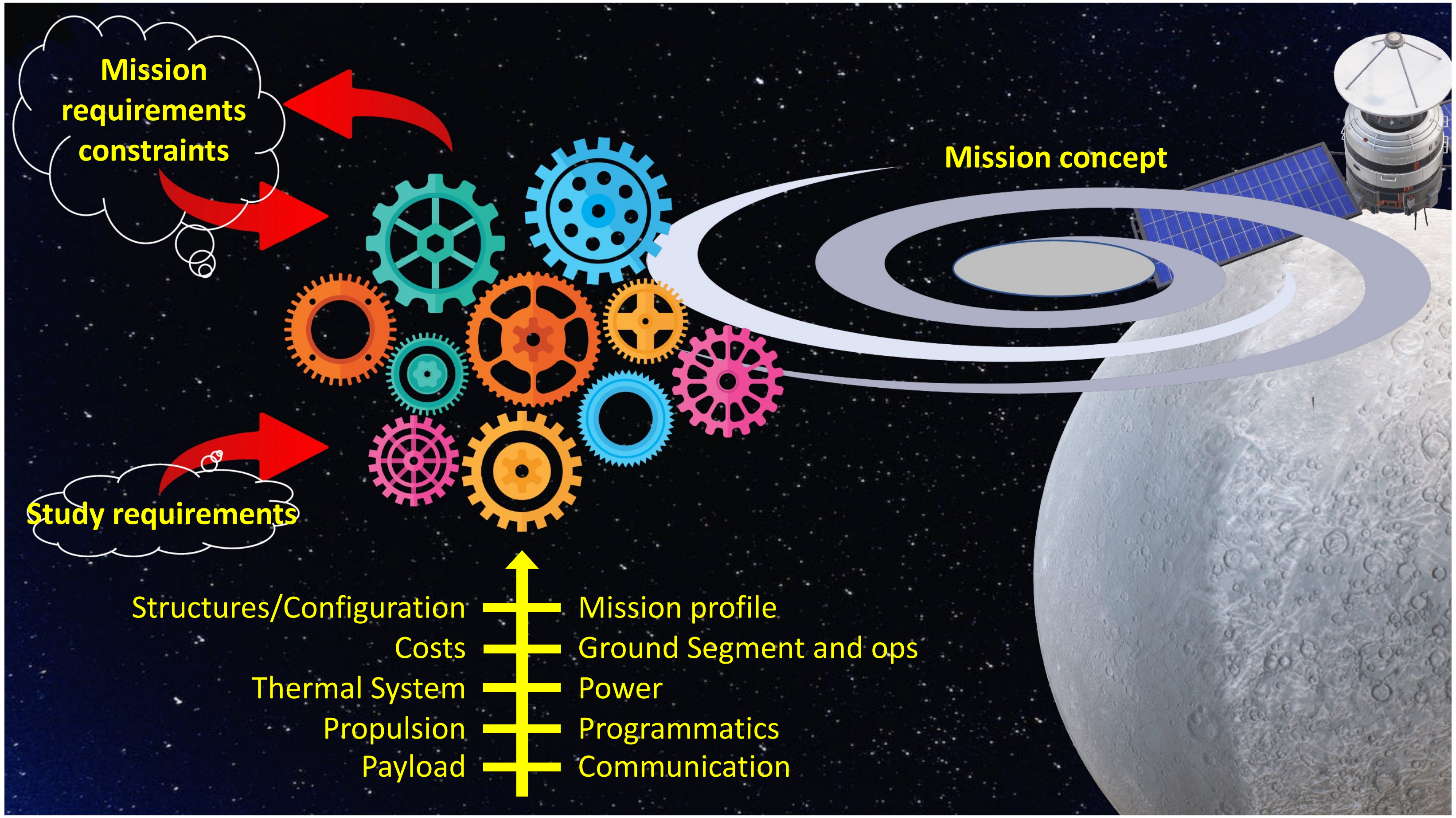


https://www.asi.it/tecnologia-ingegneria-micro-e-nanosatelliti/lingegneria/concurrent-engineering-facility/

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

Tracking with Low Gain Avalanche Diodes

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

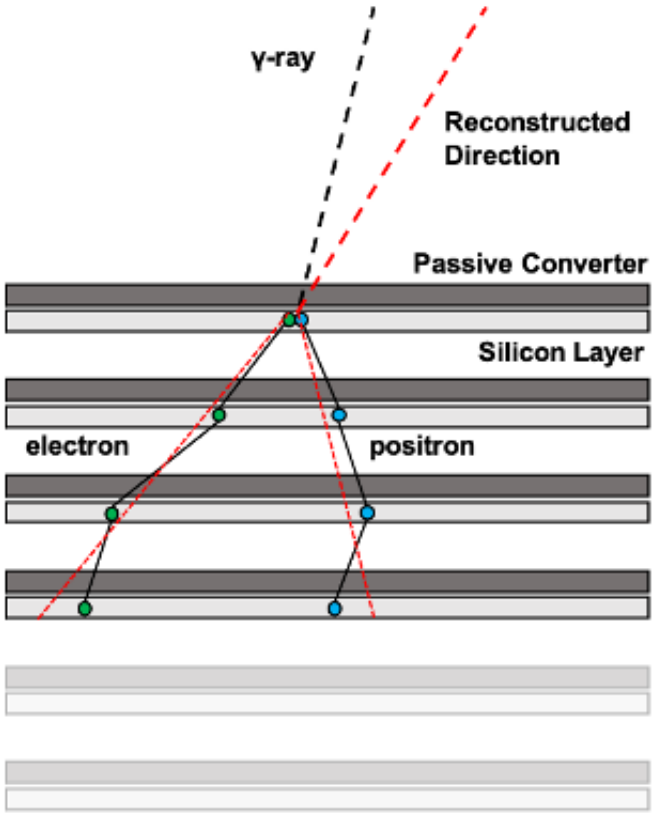
Thin high signal Si sensors: the LGAD intrinsic gain improves the SNR for thin sensors and allows for reduced active material budget tracking planes

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

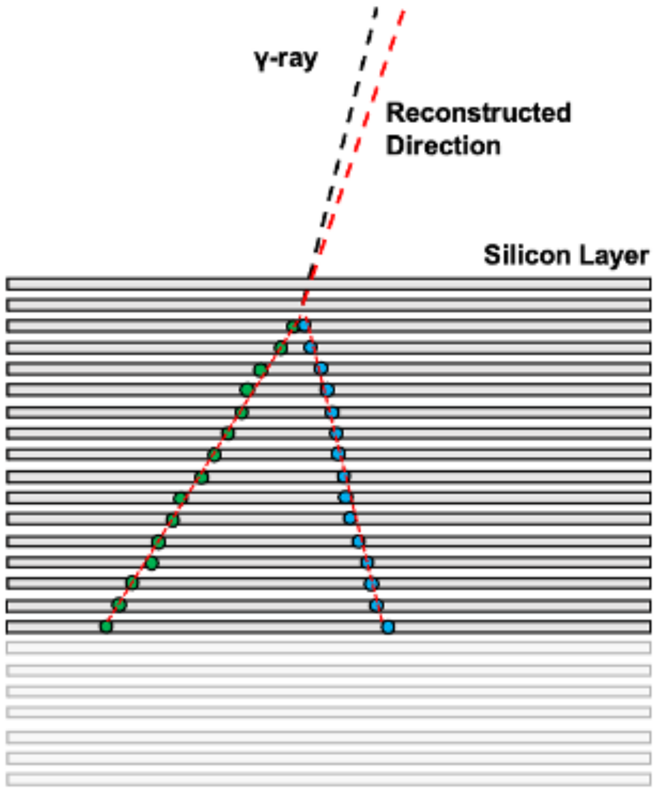
- **Remove passive materials**
- **Use thin active detectors**
- **Increase number of active layers to boost the GR conversion probability** (approach first proposed in X. Wu et al., "PANGU: A high resolution gamma-ray space telescope", Proc. SPIE 9144 (2014))

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 (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
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!

PM2024 - 16th Pisa Meeting on Advanced Detectors

Contribution ID: 343 Type: Poster

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

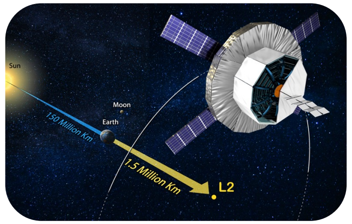
Collaboration **ADA-5D**

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

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

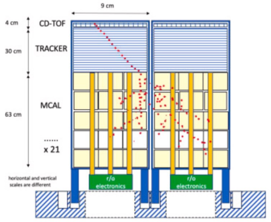
LGAD sensors in future CR space observatories

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



ALADInO
magnetic spectrometer Si-Tracker

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



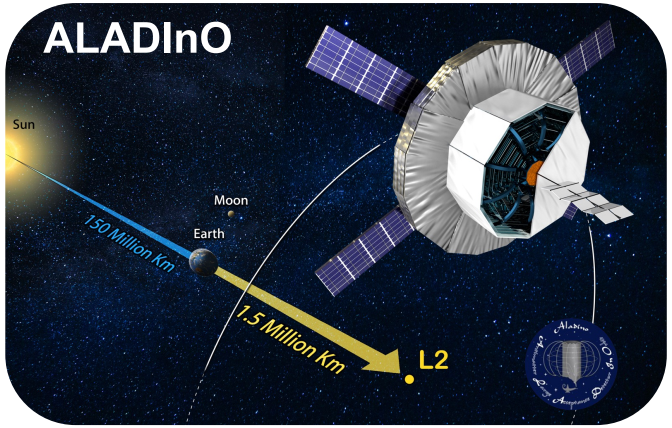
MOONRAY
Charge Detector ToF

Next-generation space magnetic spectrometers
(based on High Temperature Superconducting Magnets)

Following up on PAMELA, AMS-02, DAMPE and CALET: calorimeters and spectrometers

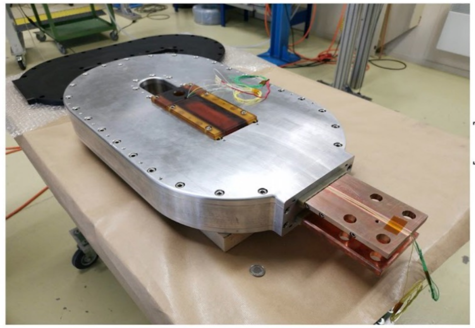
Enlarge acceptance and maximum detectable energy to extend statistical limits and explore highest energies

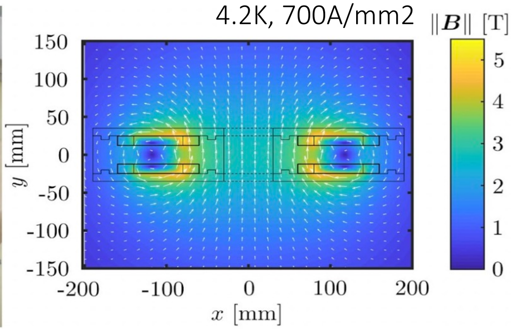
O.Adriani et al., *Instruments* 2022, 6(2), 19



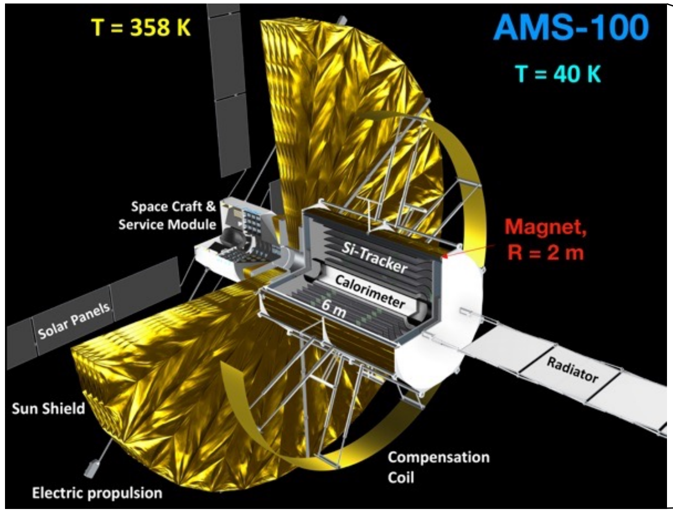
Large acceptance HTSM spectrometer planned for operations in L2

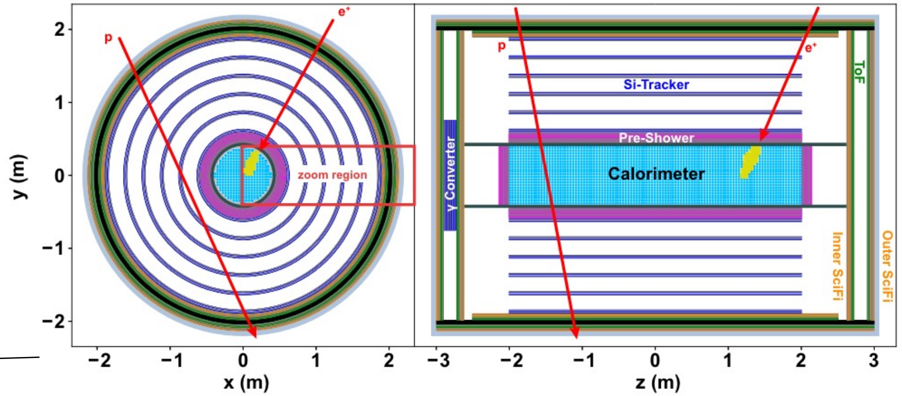
- Extend at least 10x AMS-02 acceptance
- PeV nuclei CRs + TeV e^+ and p-bar + GeV D-bar and He-bar
- Mission concept EU-driven





HTSM Demonstrator coil
HDMS ASI-CERN (2022)



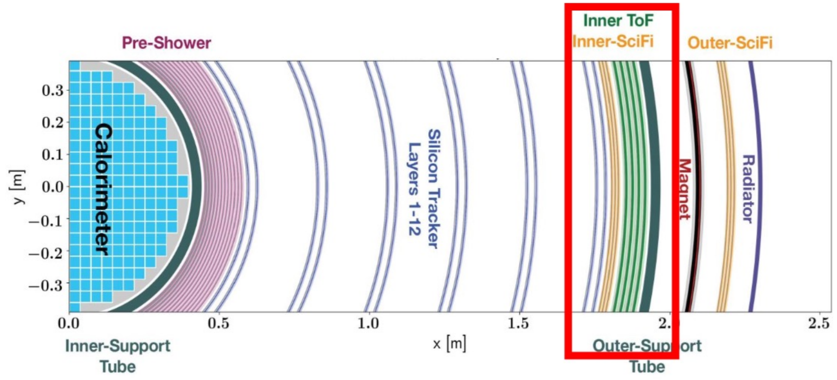


S. Schael et al., *NIM-A* 944 (2019) 162561

AMS-100 Time of flight

T. Kirn, VCI 2022

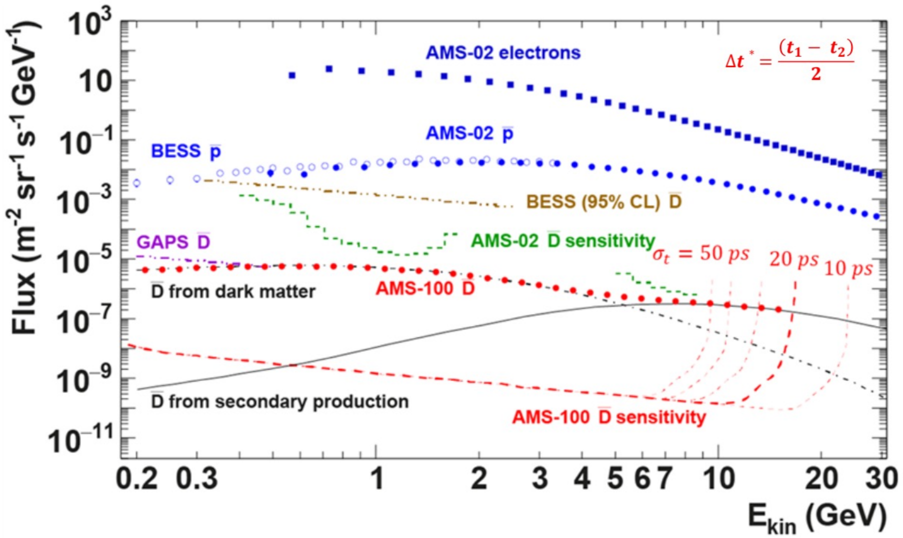
AMS-100: Time of Flight System



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



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