Silicon Detector R&D for the CSES missions and beyond

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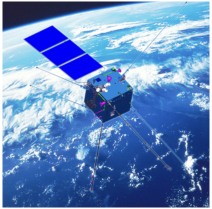
CPPS Seminar @ Uni Siegen, 15/04/2025

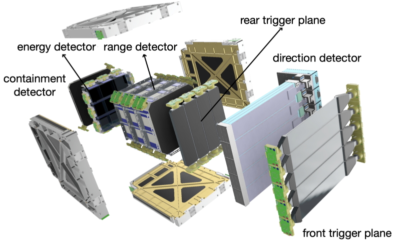
Outline

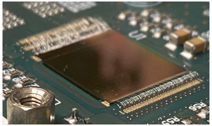
1. CSES-01 mission
   - Main objective: Detection of seismic phenomena from Space
   - Study of terrestrial and astrophysical sources
2. High Energy Particle Detector HEPD-02
   - tracker made of ALTAI chips
   - FM performance in testbeams
3. Next-generation astro-particle silicon detectors
   - Hybrid detector developments
   - ARCADIA project of INFN
     - CMOS LGADs
     - chip design for a gamma-ray telescope
4. Outlook

CSES-01



HEPD-02





ARCADIA MD1

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China Seismo Electromagnetic Satellite (CSES-01)

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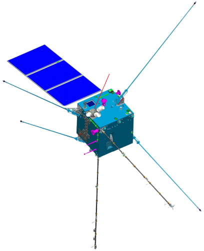
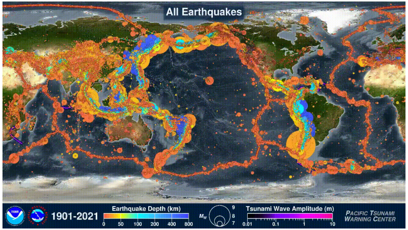
- CSES-01 launched 02/02/2018
- from the Jiuquan Satellite Launch Center in the Gobi Desert (Inner Mongolia)
- sun-synchronous orbit at $\sim$ 500 km altitude
- Inclination 97°
- Period 94 minutes
- Revisit period 5 days
- Mission Life Span ≥5 years



main objective:
Detect Earthquakes from Space



Remote sensing of seismic events

How can signal km below ground travel up to 500km?

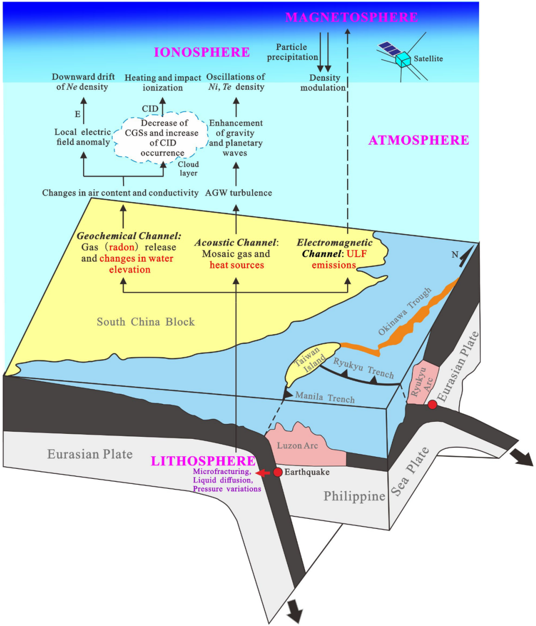
Lithosphere-Atmosphere-Ionosphere Coupling (LAIC)

1. air ionization from the alpha radioactivity of radon
2. EM waves from the cracks in the lithosphere
3. Acoustic Gravity waves (AGW)
4. chemical reactions or others..

single case evidence exists that atmospheric and ionospheric disturbances may precede some earthquakes

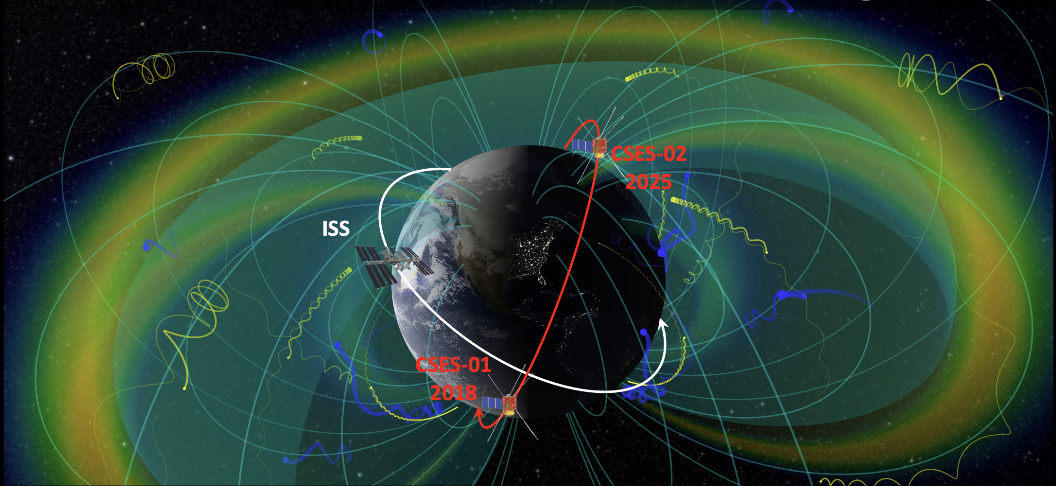
Proof via statistical study very complicated, because

- lithosphere / atmosphere highly irregular
- ionosphere very dynamic
- satellite observations non stationary



[Guo, Y. et al. Atmosphere 2022, 13, 1523.]

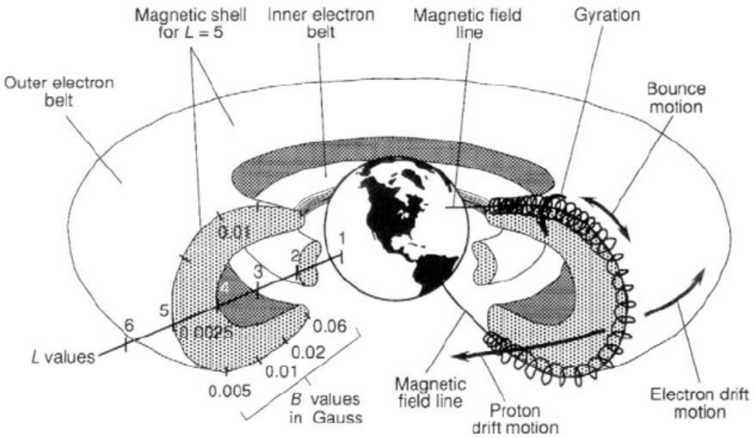
Particles in the Magnetosphere



Particles **trapped** in the Earth magnetic field create regions of **high radiation** called **Van Allen belts**.
The **CSES constellation** allows for **precision measurement of trapped particles composition and stability** in the energy range from **100 KeV to 300 MeV** complementing the current AMS-02 sensitivity **> 500 MeV** and the previous Pamela data **> 50 MeV**

Motion of charged particles in Earth magnetic field

originating from solar winds and cosmic rays



3 types of motion:

1. Gyromotion along magnetic field lines
2. Bouncing between mirror points
3. Longitudinal drift East-wards for negatively charged particles

Inner belt: (1.5-2)R_E in L-shell, electrons $<$ **1MeV** & protons $>$100 MeV
Outer belt: (4-5)R_E in L-shell, electrons **100 keV** - **10 MeV**

- pitch angle (electron velocity vector and B field) at mirror point 90°

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Pitch angle of trapped particles

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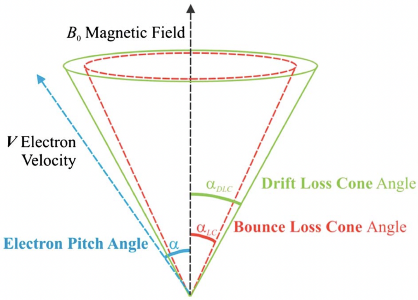
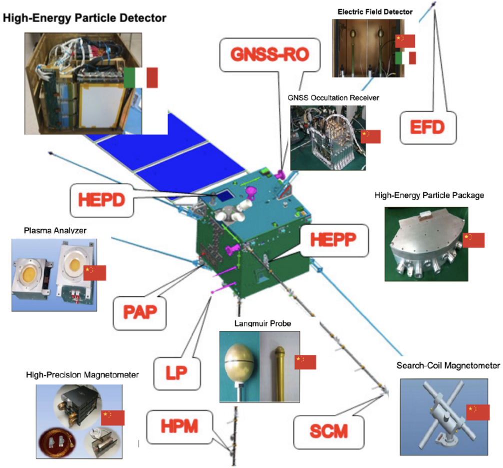


[J.C. Rodger et al., (2013) doi:10.1002/2013JA019439]

- pitch angle changes along the magnetic field line
- locally trapped particle has a pitch angle of 90°
- trapped particles have a range of pitch angle at the geomagnetic equator from 90° down to the bounce loss cone angle, (α_{BLC})
- pitch angles are generally referenced to the geomagnetic equator
- particle whose pitch is smaller than α_{BLC} will mirror at altitudes below ~100 km → lost through precipitation
- angular width of the BLC is dependent on the geomagnetic field strength
- particle with $\alpha_{BLC} < \alpha < \alpha_{DLC}$ drift around world (mirroring above atmosphere)

CSES-01 payloads



9 payloads onboard designed to target all possible propagation chains of LAIC

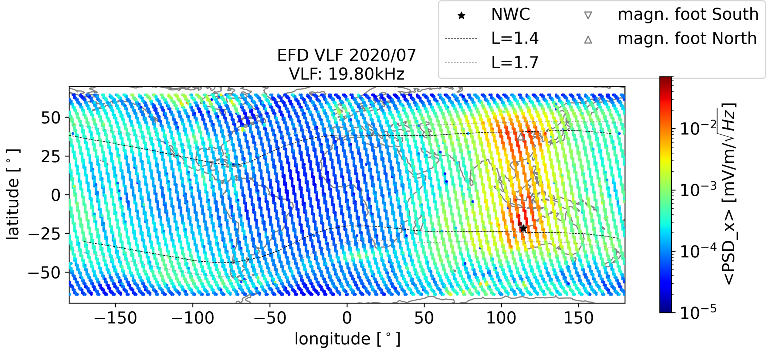
magn. field + EM waves

Ionospheric plasma Particles of magnetosphere

Payloads	Parameters
High Precision Magnetometer (HPM) Two flux gate + one coupled dark state magnetometer (CDSM)	: DC to 16 Hz
Search-Coil Magnetometer (SCM)	10 Hz ~20 kHz
Electric field detector (EFD)	DC~3.5 MHz
Plasma analyzer package（PAP)	Ion density : 10^2~10^7 cm^{-3} Ion temperature: 500~10000 K Ion content: H^+、He^+、O^+ Ion drift velocity: Vxyz
Langmuir probe (LAP)	Electron density：1 0^2~$10^7 cm^{-3}$ Electron temperature： 500~10000K
GNSS Occultation Receiver (GOR) **Tri-Band Beacon (TBB) :** Three bands：50/400/1066MHz	TEC、Ne Profile Air Refraction index, Profile of air temperature and pressure Ionospheric scintillation index
Energetic particle detector (HEPP-H, L, X ray)	Proton flux：1.5MeV ~ 200MeV Electron flux：≥100keV Pitch angle ：5 ° HEPP-X：0.9–35 keV
Italian Energetic particle detector (HEPD)	Proton flux: 30- 200 MeV Electron : 3 – 100 Mev ；

Terrestrial sources – radio transmitters –

EM wave with Electric Field Detector (EFD)



- Very Low Frequency (VLF) transmitter NWC (Australia) at 19.8kHz creates 3rd radiation belt
- Whistler waves in cyclotron resonance cause pitch angle and energy scattering of electrons
  → precipitate to lower L-shell → trapped and drift eastwards

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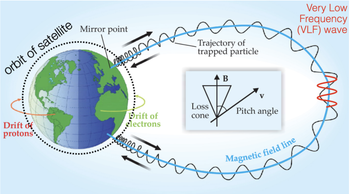
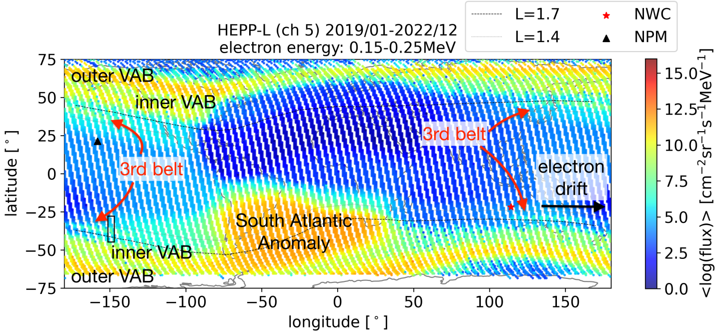


150 - 250keV electron flux



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Terrestrial sources – lighting induced electron precipitation –

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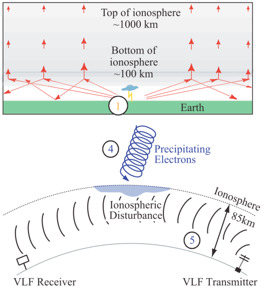
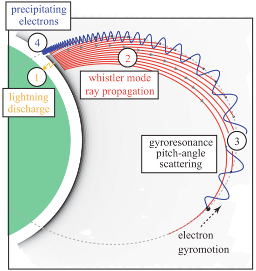
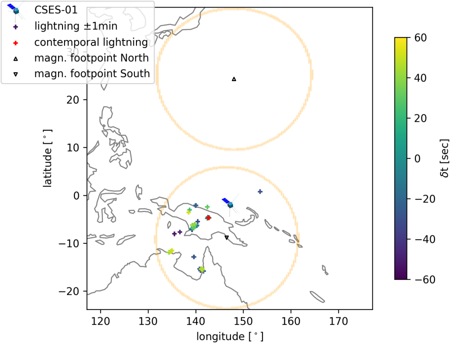






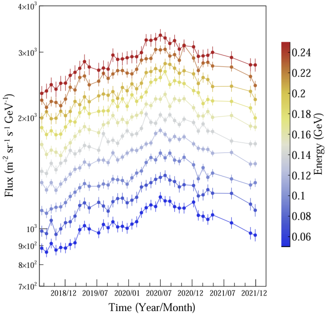
combination of wave and particle observations of CSES-01 + ground-based lightning database:

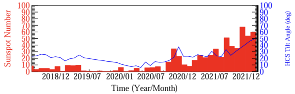
1. lightning strike
2. VLF wave (1-10 kHz) in 10° cone (possibly conjugate footpoint) in 0 to 200 ms
3. short electron burst within 0 to 9 seconds after

→ 2,311 LEP events in 4 years (publication in preparation)

Space Weather – proton flux –

Galactic cosmic ray proton modulation with Sun
- maximum flux at solar minimum

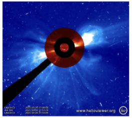


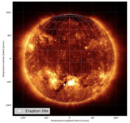


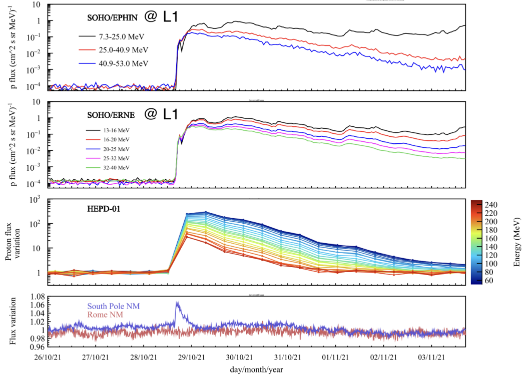
[M. Martucci et al. 2023 ApJL 945 L39]

- selection galactic protons >50 MeV (L > 7)
- excluding high solar activity periods and solar energetic particle (SEP) events

long duration
X1 solar flare





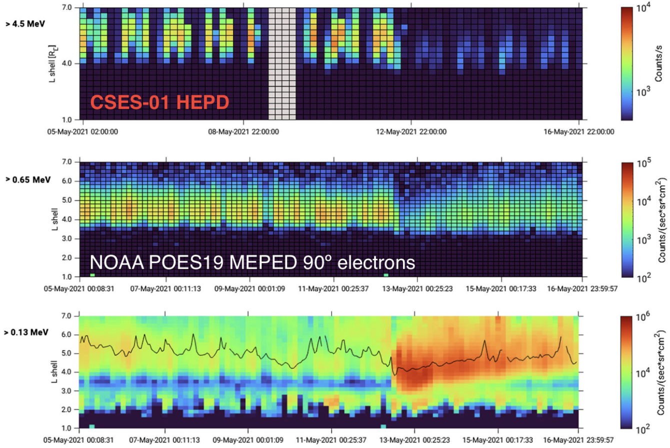


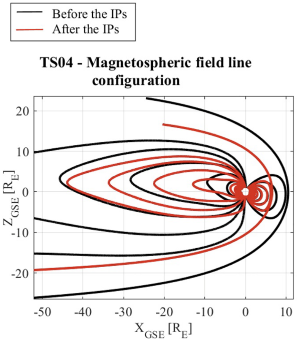
[M. Martucci et al. Space Weather, 21]

- caused Ground Level Enhancement (showers detected by ground-based neutron monitors)
- HEPD-01 provides spectral information

Space Weather – geomagn. storm –

On May 12, 2021, a Coronal Mass Ejection (CME)





[M. Piersanti et al. Space Weather, 20]

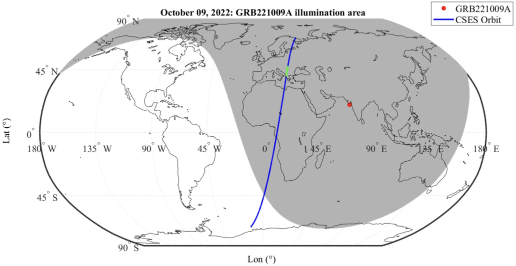
- primary impact of the storm: rapid loss of relativistic electrons from the outer radiation belt

CME emitted on May 9 from a filament on the Sun's surface

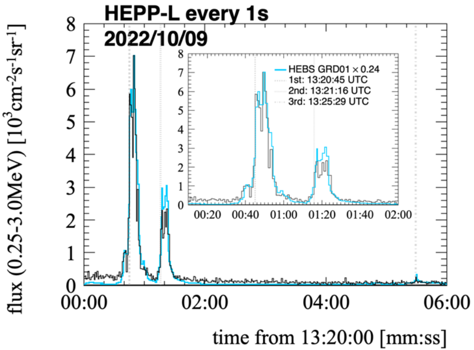
Brightest Of All Times (BOAT) Gamma Ray Burst (GRB)

October 9th 2022: *GRB221009A*

- a massive star undergoing a supernova
- photons with energies above 10 TeV
- HEPP-L measures electrons produced through photon absorption in surrounding passive materials
  $\rightarrow$ impressive agreement in time evolution



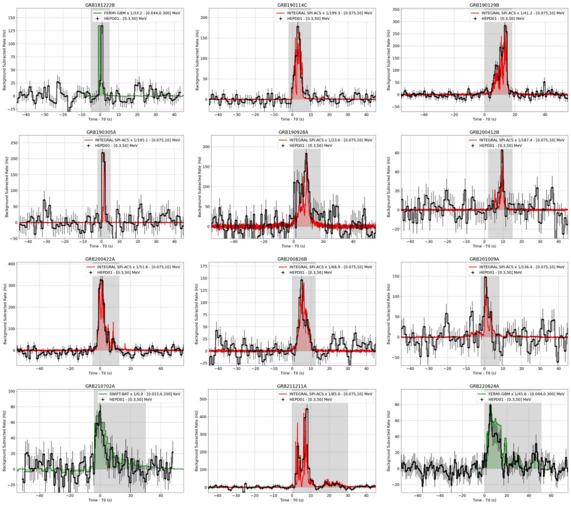
[Piersanti, M., et al. doi:10.1038/s41467-023-42551-5]



[R. Battiston et al, 2023 ApJL 946 L29]

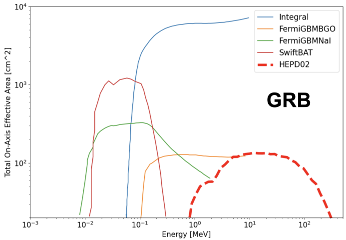
- PBs detected well above 3σ
- here example of lowest/highest energy bins

GRB detection with HEPD-01



- GRBs no target for CSES-01 mission
- found 12 GRBs with HEPD rate meter (1st Scintillator trigger plane)
- automated detection of GRBs above background modelled over ± 16 days in 60s windows
- from 08/2018 to 06/2022

- HEPD-02 includes trigger configurations targeting GRBs

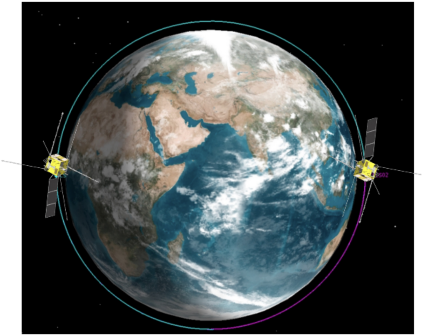


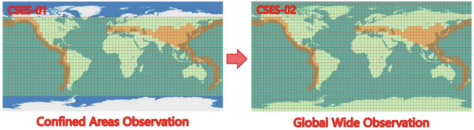
[F. Palma et al 2024 ApJ 960 21]

[S. Bartocci et al 2024 ApJ 976 239]

CSES-02

- Launch scheduled June 11th, 2025
- Same DFH CAST-2000 platform of CSES-01 with some upgrades
- Earth oriented 3-axis stabilization system with orbit manoeuvre capability
- X-Band Data Transmission 120Mbps $\rightarrow$150Mbps
- Storage 160Gb $\rightarrow$ 512Gb
- Total Mass: 730kg $\rightarrow$ 900kg
- Peak Power Consumption: 900W
- Design Life-span: 5 years $\rightarrow$ 6 years
- Complementary Ground Track wrt CSES-01
- Identical Orbit Plane
- **180° Phase Difference**
- Track interval: $5^\circ \rightarrow 2.5^\circ$
- Return cycle: 5 days $\rightarrow$ 2.5 days
- **Operation mode: Full time operational**



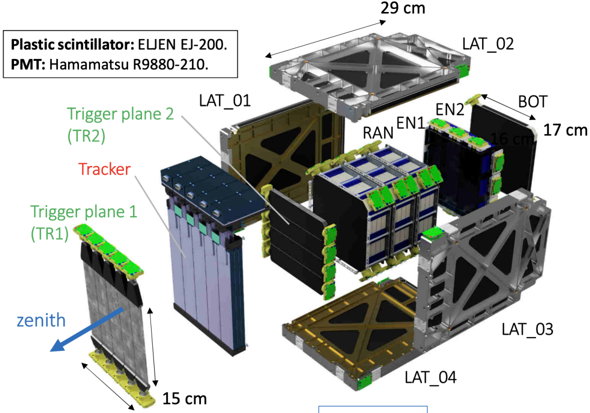


R. Iuppa @ CRIS-MAC13

The HEPD-02 instrument

- **1/5. Trigger detectors (TR1, TR2).**
  - **Plastic scintillators / PMTs:** 2 planes, 5+4 mutually orthogonal bars.
  - *HEPD-01 had a single plane.*
- **2/5. Particle tracker.**
  - **Si Monolithic Active Pixel Sensors (MAPS):** 3 planes in 5 adjacent "turrets".
  - *HEPD-01 had double-sided Si microstrips, 2 planes.*
- TR1 and tracker **tightly packed together,** matching active area and segmentation.
  - **Asymmetric wave-guide read-out** on opposite ends of TR1 bar.
- **TR1 thickness minimized to** 2 mm (mechanically challenging).
  - This **reduces multiple scattering** before tracker **and energy threshold** for coincidence with TR2.

Plastic scintillator: ELJEN EJ-200.
PMT: Hamamatsu R9880-210.

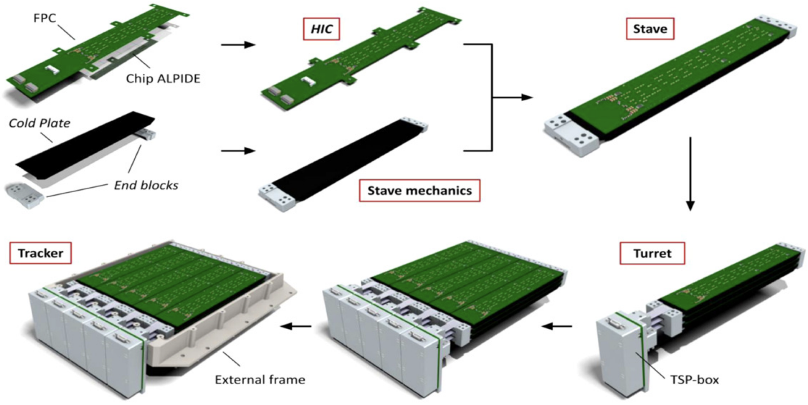


SB Ricciarini - PM2024 7

S. Bruno Ricciarini @ PISA2024

HEPD-02 tracker

a 80 megapixel CMOS camera for charged radiation



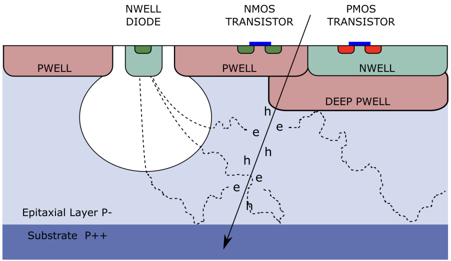
10 chips per stave → 3 staves per turret → total 5 turrets: 150 chips

everything × 2 for QM & FM

E. Ricci, R. Iuppa @ TREDI18
B. Di Ruzza, R. Iuppa @ IFAE 2018
E. Ricci, R. Iuppa @ COSPAR2022
[R. Iuppa et al. PoS(ICRC2021)070]

ALTAI – updated ALICE ALPIDE chip

Monolithic Active Pixel Sensor (MAPS) [NIM A 824 (2016) 434–438]



- integrated readout electronics
- CMOS 180nm technology from Tower Jazz
- non-depleted → charge collection by diffusion

Advantages

- reduces systematic uncertainties
- cheaper than standard microstrips
- extremely low material budget

Parameter	Values
Detector size [mm^2]	15 x 30
Columns x rows	1024 x 512
Pixel size [µm x µm]	26.9 x 29.2
Detector thickness [µm]	50
Spatial resolution [µm]	5
Detection efficiency	>99%
Fake hit rate [evt^{-1} $pixel^{-1}$]	$<10^{-7}$
Integration time [µs]	~2
Power density [mW/cm^2]	<50

70k chips produced and tested for $10m^2$ active silicon area, 12.5 x 10^9 pixels at ALICE ITS

Space qualification MAPS

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Challenges

1. limited power budget
2. heat dissipation
3. rigidity to withstand launch acceleration and vibrations
4. digital readout: limited info on charge

Space qualification MAPS

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Solutions

1. mitigating power consumption to target of ∼13 W

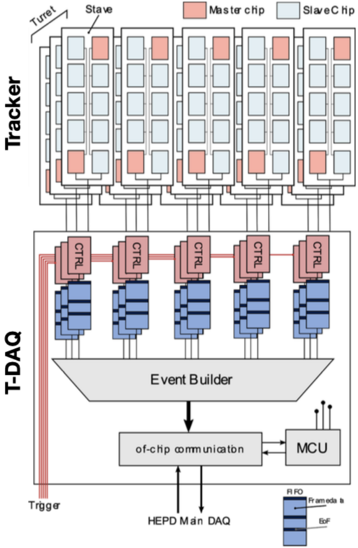
ALICE ITS OB Master-slave architecture (1 master out of 5 chips) with sequential slave

Permanent switch-off of fast data transmission unit (DTU) and read-out through serial slow-control line.

- Acceptable increase of dead time, given the relatively low trigger rate (up to few kHz).

Clock gating: clock normally off, set on with trigger:

- trigger: clock on (17 mW/cm2);
- wait for signal digitization;
- transmit data to control/read-out electronics;
- clock off (7 mW/cm2): wait for new trigger



G. Gebbia, PhD Thesis

Space qualification MAPS

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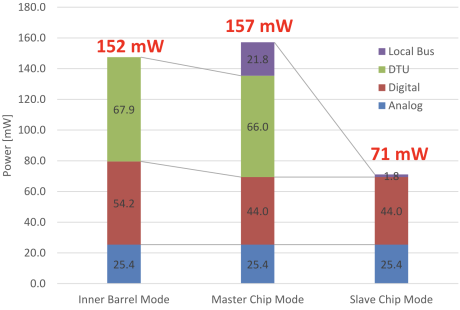

G. Gebbia, PhD Thesis

Space qualification MAPS

Solutions

2. heat dissipation and mechanical support

Conditions:

- vacuum of 6.65 10^{-3} Pa
- repeated thermal cycles from -30° to +50°
- needs to resist 10G

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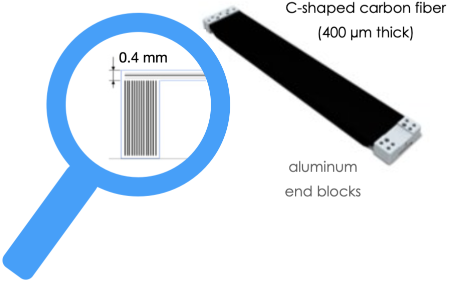
Mechanical support



TARGET: stiffness and thermal drain

Cooling is granted by material thermal conductivity
support has to be **stiff** enough to resist to 10G
the **material budget** has to be minimized

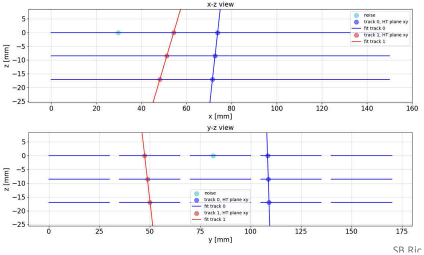
Material budget of STAVEs

STAVE element	material	thick [µm]	rad.length X_0 [%]
FPC board	capton	135	0.048
FPC tracks	Cu	36	0.251
glue	ARALDITE 2011	130	0.029
ALTAI	Si	50	0.053
cold plate	Carbon fiber + epoxy resin	350	0.134
Total:			0.515

[E. Serra et al. 2022 Conf. Ser. 2374 012049]

Performance of HEPD-02 tracker – testbeams

- noisy pixels of ∼1 k over 80 M
- "non-noisy" hit pixels are clustered (DBSCAN) and track seeds are identified (Hough transform)
- residual noise clusters are easily identified by requiring 3-planes tracks



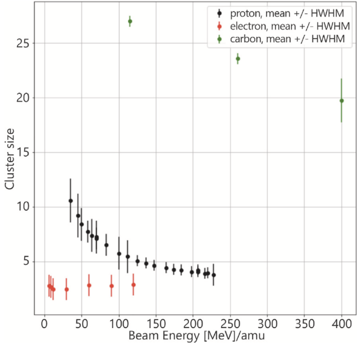
S. Bruno Ricciarini @ Pisa Meeting 2024

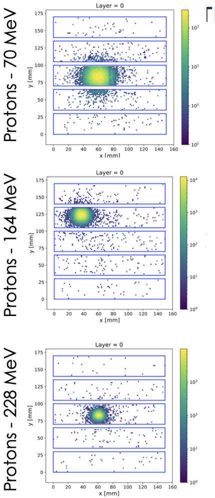
Electrons: 30-450MeV @ BTF, Frascati

Electrons: 6-12MeV/γ @ Medical LINAC

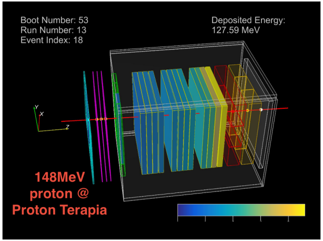
Protons: 20-230MeV @ Proton Terapia

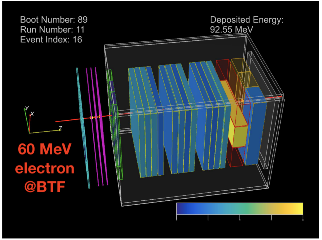
Carbon: 115-400MeV/amu @ CNAO, Pavia



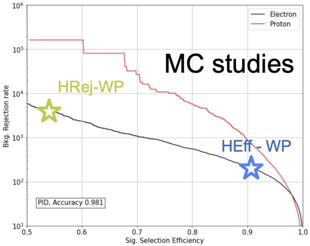


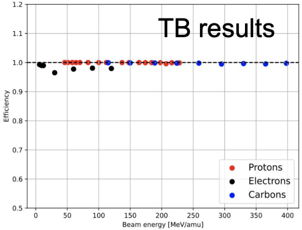
Performance of HEPD-02 – particle identification





Courtesy of F. M. Follega





- PID results obtained using a DNN, combined inputs of cross-correlation between release in front (TR2) and inner (RAN) scintillator layers
- PID efficiency in TB tested to be $> 95\%$ for low energy electrons

Performance of HEPD-02 tracker – cosmic muons

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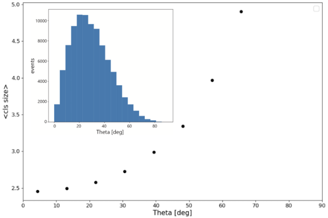
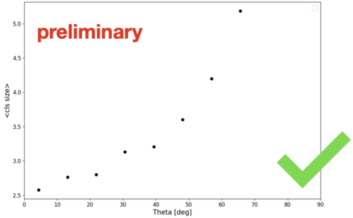
Cosmic rays data acquisition
before integration in CSES-02
statistics: about 117,000 events



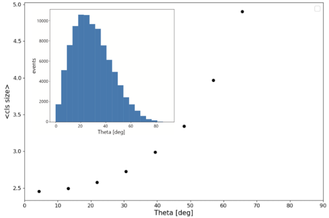
Cosmic rays data acquisition
after integration in CSES-02
after vibrational tests
statistics: about 7,000 events



U. Savino @ CRIS-MAC13

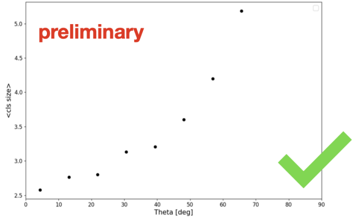
Performance of HEPD-02 tracker – cosmic muons

Cosmic rays data acquisition
before integration in CSES-02
statistics: about 117,000 events



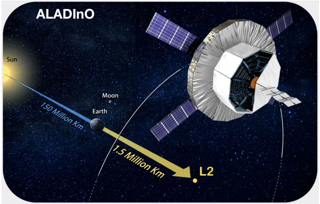
→ **ready for launch in June!**

Cosmic rays data acquisition
after integration in CSES-02
after vibrational tests
statistics: about 7,000 events

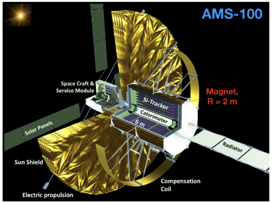


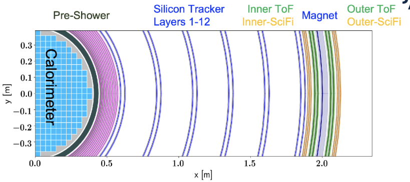
U. Savino @ CRIS-MAC13

Next generation Astro-particle experiments

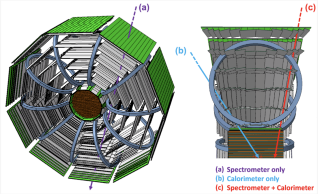


[O. Adriani, et al. Instruments 2022, 6(2),19]

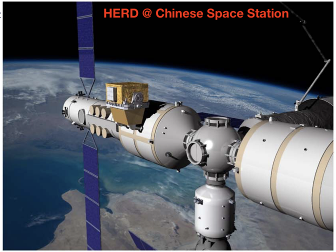


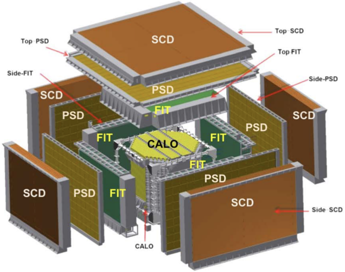


[C. Chung et al. Instruments 2022]



[R. Battiston, et al. Exp Astron 51 (2021)]





[D. Kyratzis et al. Phys. Scr. 97]

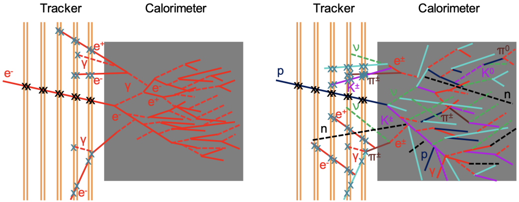
Requirements on tracking detectors

TIFPA

Operating Missions						
	Mission Start	**Si-Sensor Area**	**Strip-Length**	**Readout Channels**	**Readout Pitch**	**Spatial Resolution**
Fermi-LAT	2008	$\sim 74\,m^2$	38 cm	$\sim 880 \times 10^3$	228 µm	∼66 µm
AMS-02	2011	$\sim 7\,m^2$	29–62 cm	$\sim 200 \times 10^3$	110 µm	∼7 µm
DAMPE	2015	$\sim 7\,m^2$	38 cm	$\sim 70 \times 10^3$	242 µm	∼40 µm
Future Missions						
	Planned Operations	**Si-Sensor Area**	**Strip-Length**	**Readout Channels**	**Readout Pitch**	**Spatial Resolution**
HERD	2030	$\sim 35\,m^2$	48–67 cm	$\sim 350 \times 10^3$	∼242 µm	∼40 µm
ALADInO	2050	$\sim 80\text{–}100\,m^2$	19–67 cm	$\sim 2.5 \times 10^6$	∼100 µm	∼5 µm
AMS-100	2050	$\sim 180\text{–}200\,m^2$	∼100 cm	$\sim 8 \times 10^6$	∼100 µm	∼5 µm

- large area
- high number of readout channels
  → clever readout architectures for low power
- 5D tracking = position + charge + **timing**

hit time resolution of ∼100 ps:
→ improves track reconstruction (mitigate ghost hits & backscattered particle contamination)
→ provide Time of Flight (ToF) measurement
→ improves e/p separation



- affect tracking efficiency by tens % at 1 TeV

[M. Duranti et al. Instruments 2021, 5, 20]

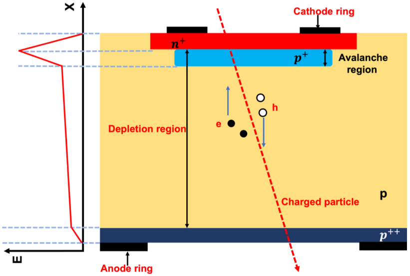
Possible realisations of 5D tracking detectors

timing layers within Si micro-strip detector: Low Gain Avalanche Diodes (LGADs)

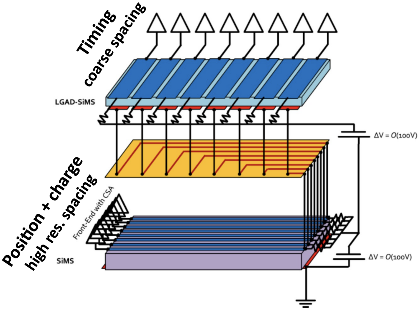
- **development of large area Low Gain Avalanch Diodes (LGADs)**

challenges:

- long strips/large channel size → large capacitance: decreases S/N ratio
- signal propagation: delay (30ps ∼ 1cm@c) & signal distortion
- gain uniformity



[A. Bisht et al. Instruments 2024,8,27.]



M. Duranti @ TREDI25

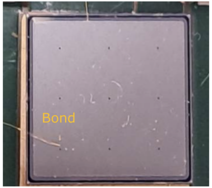
LGADs for Space @ FBK

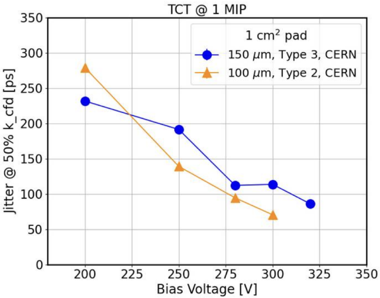
strategy: increase signal with thicker substrate and higher gain

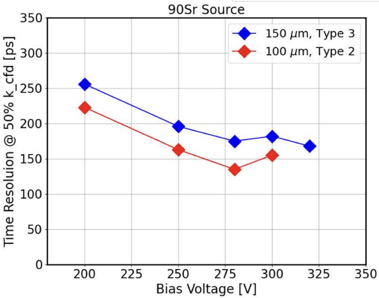
TIFPA

[L. Cavazzini TREDI2025]

1 cm^2





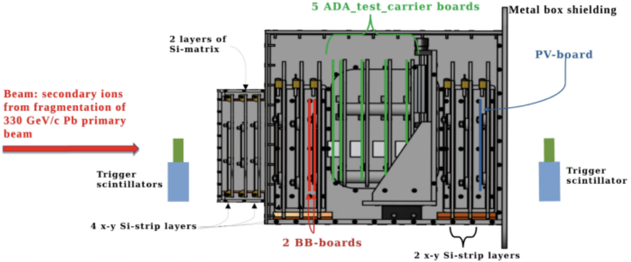


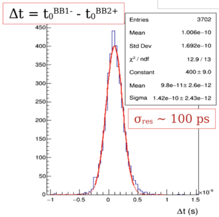
- Signal propagation and gain variation expected to account for 32 ps
- **Time resolution of 135 ps on 1 cm^2, 100 μm thick sensor**
- Expected improvement with different electronics
- Next batch for: gain tuning, signal propagation studies

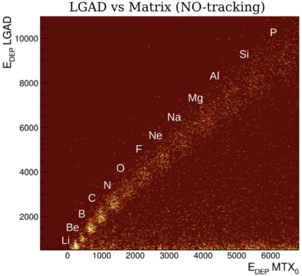
M. Centis Vignali @ VCI25

Avalanche Diodes Array (ADA_5D)

[P. Brogi TREDI2025]



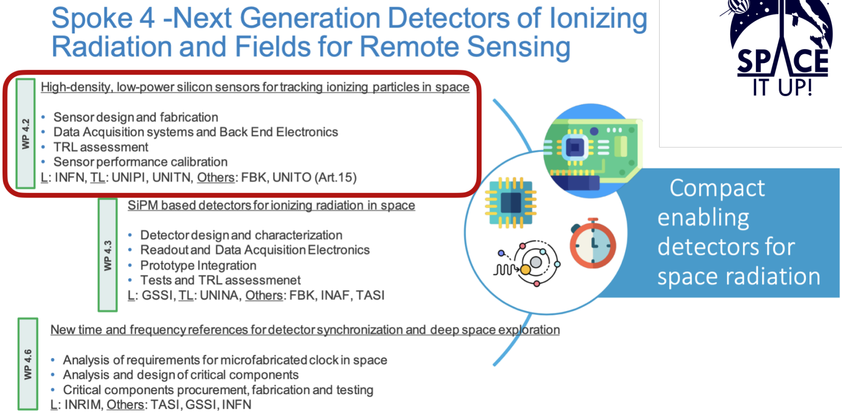




- 5^{th} dimension is charge
- Atomic number ID from charge deposit $\Rightarrow$ thicker sensors
- Mixed ions beam
- Data analysis ongoing
- **Time res. 100 ps on $3\times3\,mm^2$ channel, 150 μm thick**
- Charge correlation between LGAD and other sensors

M. Centis Vignali @ VCI25

Developments of MAPS for space



M. Rolo @ SpaceItUp - Spoke4 1st Plenary Meeting

SPACE IT UP!

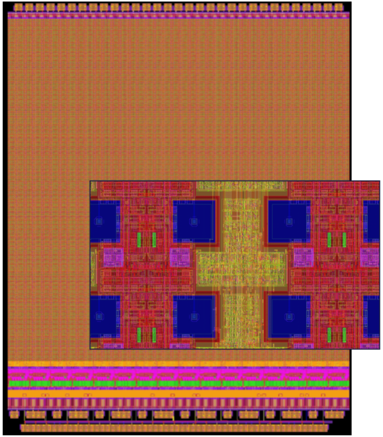
TIFPA

Embedded electronics, less components and connectors:

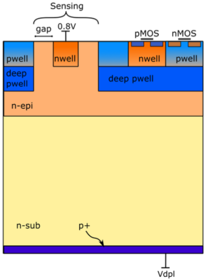
- no need for costly fine-pitched flip-chip assembly
- less (failing) connectors and lower material budget
- cost reduction for large productions

ARCADIA DMAPS R&D at INFN

Main Demonstrator (MD1)

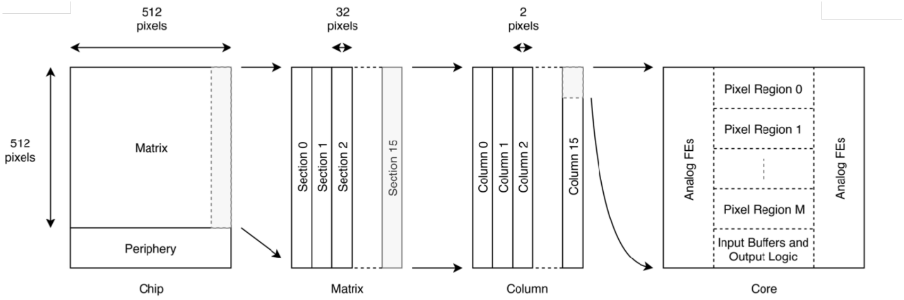


M. Rolo, INFN Torino



- 110 nm CMOS process with 1.2 V transistors, developed between INFN and LFoundry
- fully depleted, charge collection by drift
- backside processing (diode+GR)
- low resistivity epi-layer for delayed on-set of punch-through currents
- matrix core 512 × 512 pixels of 25 μm pitch
- trigger-less and binary readout
- matrix and EoC architecture, data links and payload ID: scalable to 2048 × 2048 pixels
- pixels are ∼(50/50)% analog/digital
- sensor diode about 20% of total area
- 'side-abuttable' to accommodate a 1024 × 512 silicon active area (2.56×1.28 cm^2)

MD3 chip architechture

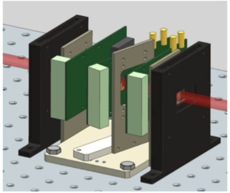


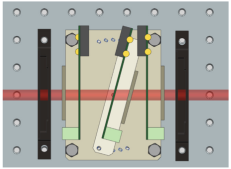
- Pixel size 25 μm x 25 μm, Matrix core 512 x 512, 1.28 x 1.28 cm^2 silicon active area, side-abuttable
- Trigger-less data-driven readout and low-power asynchronous architecture with clock-less pixel matrix
- Event rate up to 100 MHz/cm^2 (design post-layout simulations)
  - High-rate operation (16 Tx): 17-30 mW/cm^2 depending on transceiver driving strength (measured)
  - Low-power operation (1 Tx): 10 mW/cm^2 (all data conveyed in 1 transceiver, others turned-off)

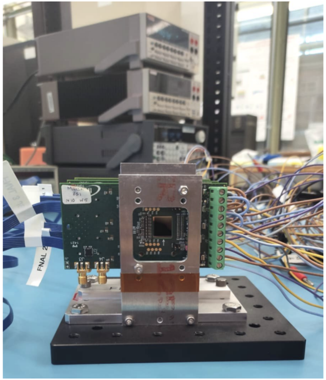
Courtesy of M. Rolo

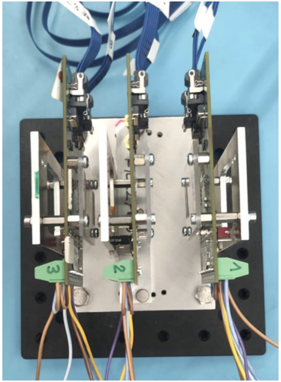
MD3 at test beam

- Test beam at FNAL (120 GeV protons): very good results from <u>data analysis ongoing</u>
- mini-telescope with 3 ARCADIA-MD3 200 μm thick sensors
- Threshold, sensor HV and incidence angle parametrisation: study of cluster size, collection efficiency, spatial resolution



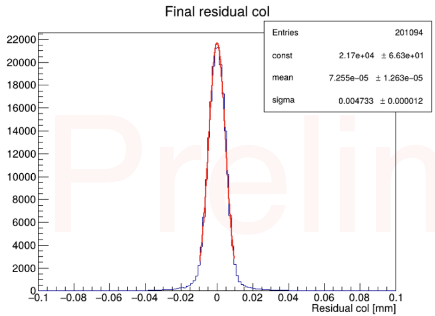


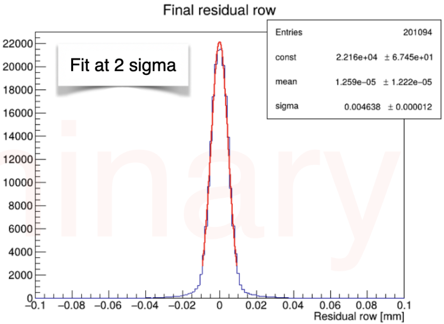




Courtesy of M. Rolo

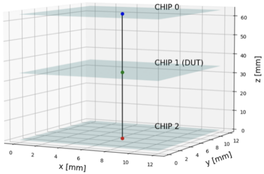
Spatial resolution





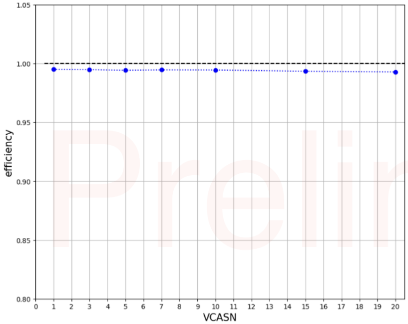
- Residuals plots @VCASN = 5 (~ 600 e-), still includes contributions from tracking planes
- angle of tilt = 0°
- Data with 1 cluster per plane, excluding clusters with multiplicity above 20

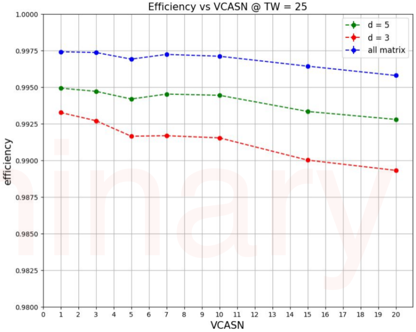
Single-point resolution ~ 4.7 μm



Courtesy of M. Rolo

Efficiency





- Efficiency plot *vs*. Threshold, scanned from 800 down 300 e^-
- Time Window = 5 μs, Spatial cut = 5 [pixels]

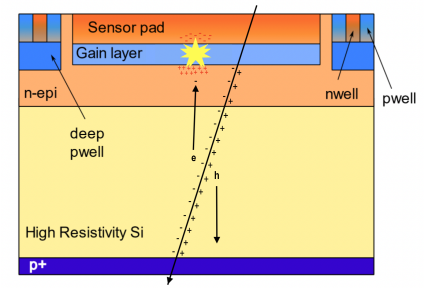
average efficiency 0.9941 +/- 0.0003

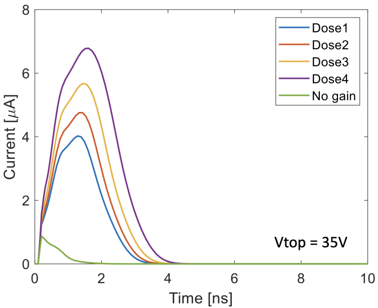
- d = spatial cut on DUT hits (pixel)
- d = 5 → 11x11 matrix
- d = 3 → 7x7 matrix

Courtesy of M. Rolo

Current R&D: ARCADIA CMOS LGADs

passive and active pixel matrices included in 3rd ARCADIA run





Courtesy of L. Pancheri

- $250 \times 100\,\mu\text{m}^2$ pixels in active (8×8) and passive (2×4) matrices
- gain layer biased from top, depleted from bottom
- expected gain 10-30

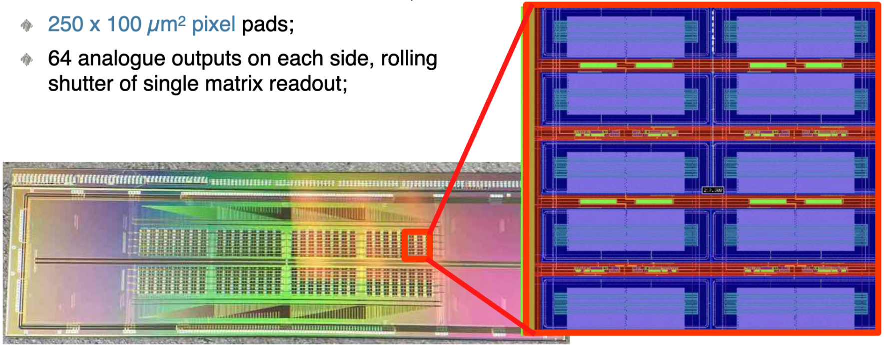
- highly doped p+ layer below the collection n-well results in high electric field that accelerates arriving electrons which creates a cascade of charge carriers
- 4 dose splittings with 3 wafers per dose

MadPix chip

Monolithic CMOS Avalanche Detector PIXelated Prototype

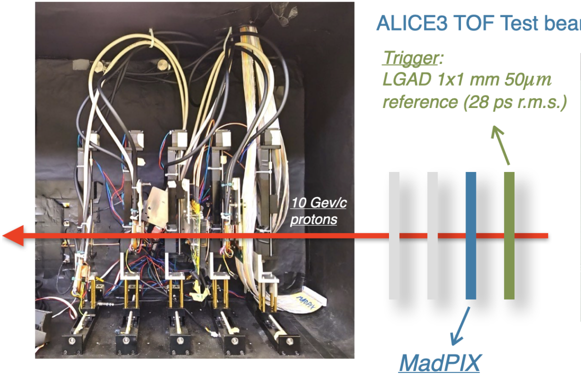
- MadPix prototype with gain layer and integrated electronics
- first small-scale demonstrator 4 x 16 mm²;
- 8 matrices (64 pixel pads each) implementing different sensor and front-end flavours;
- 250 x 100 μm^2 pixel pads;
- 64 analogue outputs on each side, rolling shutter of single matrix readout;

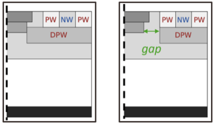
U. Follo, S. Durando, G. Gioachin, C. Ferrero

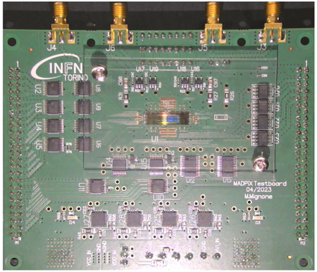


MadPix test beam

ALICE3 TOF Test beam @ CERN PS - October 2024



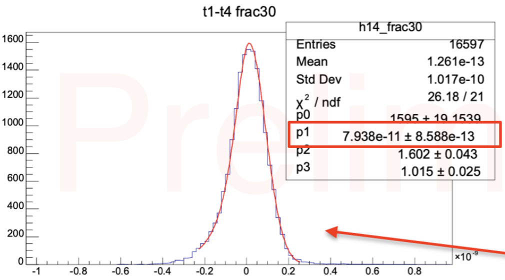


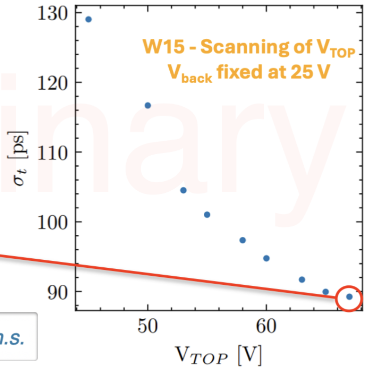


- 3 Test boards
- 2 Flavours
  - A1 and A2
- 4 Pixels
  - J3, J4, J5, J6

Courtesy of M. Rolo

MadPix performance





Measured timing resolution (sensor) ~ 72 ps r.m.s.

Courtesy of M. Rolo

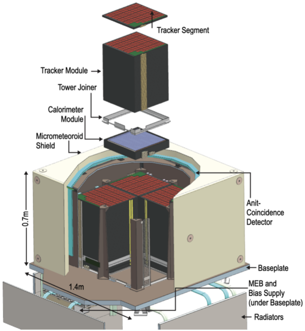
- Gain layer implemented (5-15) with very good matching with TCAD simulation framework
- MadPix test beam just concluded, timing resolution measured < 75 ps (very preliminary results)
- 48 μm thick active layer on a p+ substrate, timing resolution is sensor limited (FEE jitter ~ 20 ps r.m.s.)
- Up next: new short-loop with ARCADIA mask set and thinner n-epi active layer, *start full-chip IP design for ALICE3 TOF*

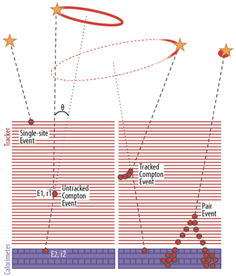
Coming up...

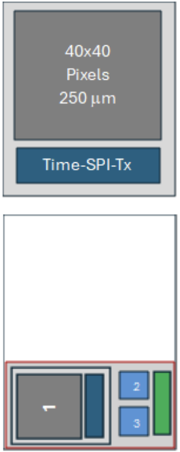
CMOS and Sensor design for next generation Gamma-ray telescope:
2 ARCADIA runs with specialised chips

- Pilot run with thick (600 μm) wafers scheduled for Q2, FZ substrates procured and delivered
- demonstrator chip: 250 μm pixels + $\sim$1mW/cm^2 power + analog readout (peak) + ADC on pixel + asynchronous readout to periphery

[R. Caputo et al. astro-ph.IM 4 Nov 2022]







L. Latronico @ TREDI25

~~Conclusions~~ Take home messages

TIFPA

- Space experiments at LEO like CSES need versatile set of detectors for identification of signal sources (terrestrial/solar/galactic)
- HEPD-01 has demonstrated capabilities of GRB detection $\rightarrow$ exploited further with CSES-02
- HEPD-02 detector will be the first space experiment with MAPS tracker

Future space experiments...

- need large area, low power, 5D tracking detectors
- technologies to be ready in order to pass all qualification tests in time!
- profit from technology platforms like ARCADIA allow for parallel development for diverse applications

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TIFPA

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Thank you for your attention!

Acknowledgments & References

Thanks to all collaborators from the CSES-Limadou and the ARCADIA collaboration!

Especially: Roberto Battiston, Roberto Iuppa, Matteo Martucci, Umberto Savino, Francesco Follega, Manuel Rolo, Matteo Duranti, Matteo Centis Vignali, Alessio Perinelli, Ester Ricci e Lucio Pancheri

Links to presentations:

[R. Iuppa @ CRIS-MAC13]

[E. Ricci @ TREDI18]

[B. Di Ruzza, R. Iuppa @ IFAE 2018]

[E. Ricci, R. Iuppa @ COSPAR2022]

[S. Bruno Ricciarini @ Pisa Meeting 2024]

[U. Savino @ CRIS-MAC13]

[M. Duranti @ TREDI25]

[L. Cavazzini @ TREDI25]

[L. Latronico @ TREDI25]

[G. Gioachin @ IFD 2025 – INFN Workshop on Future Detectors]

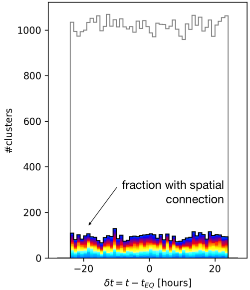
[M. Centis Vignali @ VCI25]

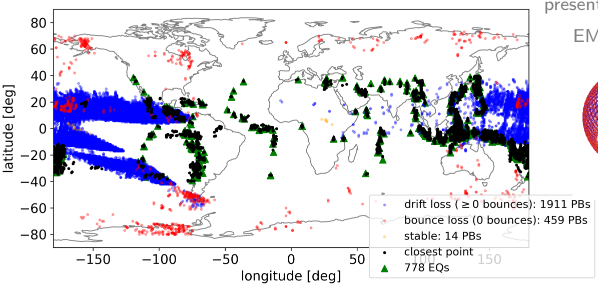
BACKUP

Correlation search for co-seismic signal

NOAA POES-19 PBs: electrons > 110keV, telescope 0°

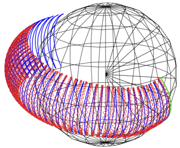
TIFPA





presented at

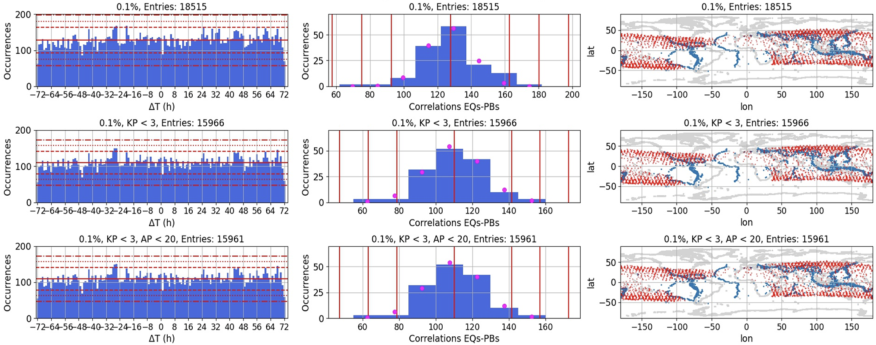
EMSEV2022



- tested: 913 EQ in three years (Magn. > 5.5, $\pm 40^\circ \lambda$, max. depth 100 km, isolated)
- followed approach of [R. Battiston, V. Vitale, doi:10.1016/j.nuclphysbps.2013.09.002.] with much less statistics
- classified PBs by possible EQ origin, evaluated with back-tracing algorithm
- no significant excess in δt distribution found

Correlation search for precursor signal

HEPD-01 PBs: 3 MeV < electron energies < 15 MeV



- tested: 8293EQ in four years (Magn. >4.5, max. depth 100 km, $L_{eq} \leq 2$)
- following approach of [V. Sgrigna, et. al., doi:10.1016/j.jastp.2005.07.008]
- no significant excess in δt distribution found