The first MAPS based tracker for space applications

Ester Ricci, on behalf of the Limadou collaboration
Ester.ricci@unitn.it

Università di Trento
INFN-TIFPA

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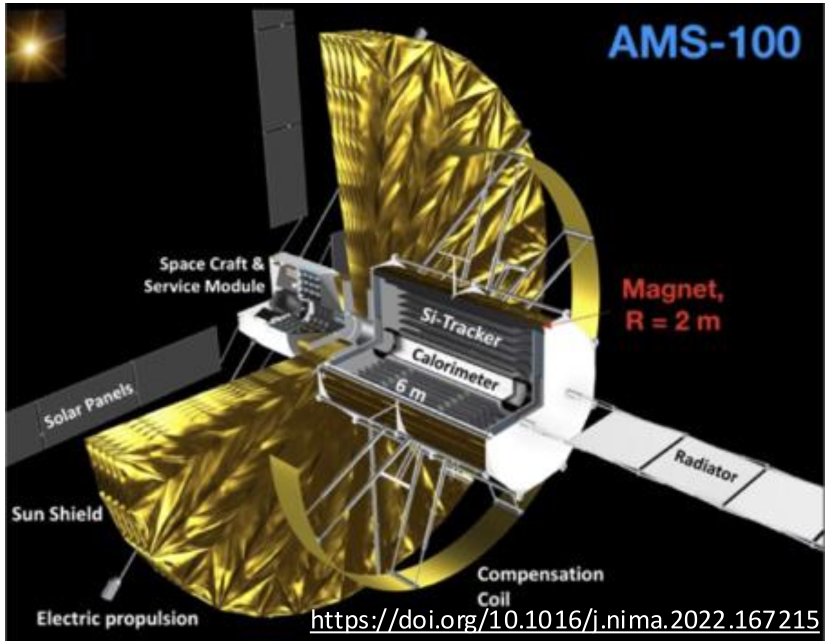
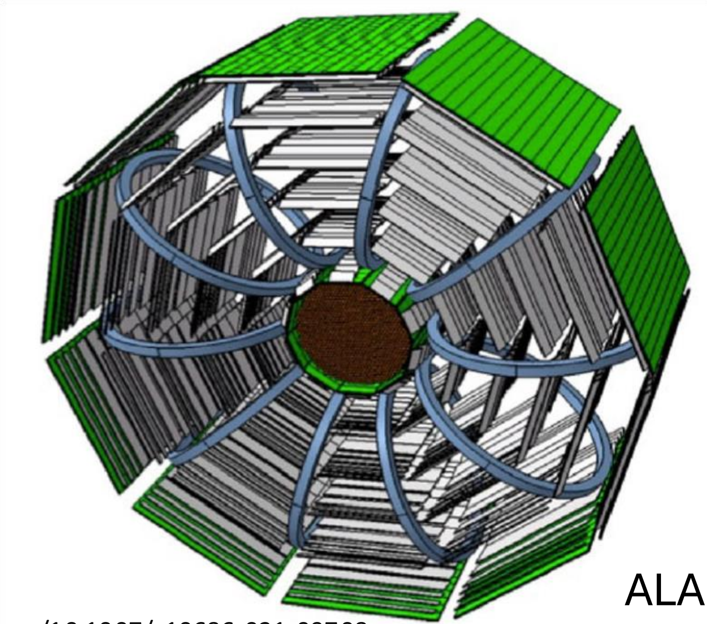
Scientific drivers for the use of MAPS in space



https://doi.org/10.1016/j.nima.2022.167215

- Future **“high-energy” space observatories** require:
  - **tens of squared meters** of tracking layer → diverse purposes
  - **o(µm) point o(100 ps) time resolution**
  - **dm^2/sensor area** to reduce the complexity
  - “**Monolithicity**” seems to be the key for low-noise and high-performance.
- **Gamma-ray astrophysics** would also benefit from HV-CMOS based sensors
- Several dedicated MAPS are under development (AstroPix projects) but it takes time and resources



ALADInO

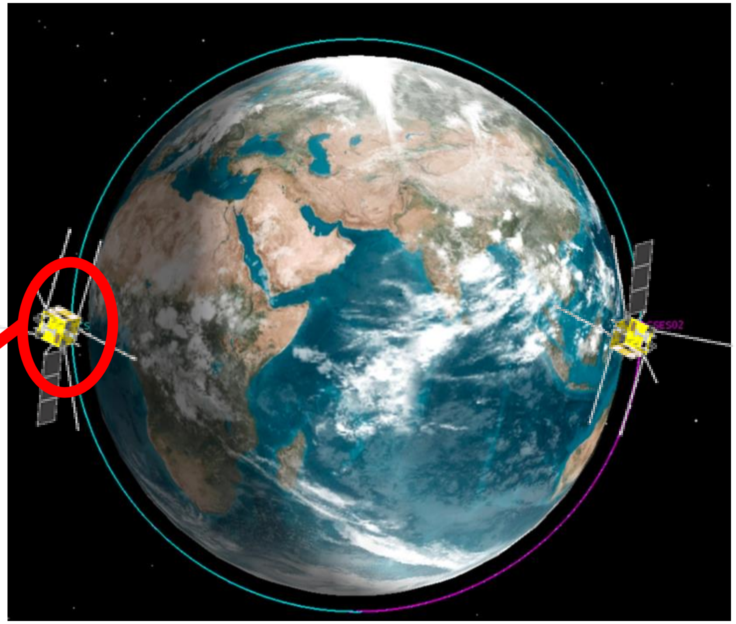
https://doi.org/10.1007/s10686-021-09708-w

AstroPix3

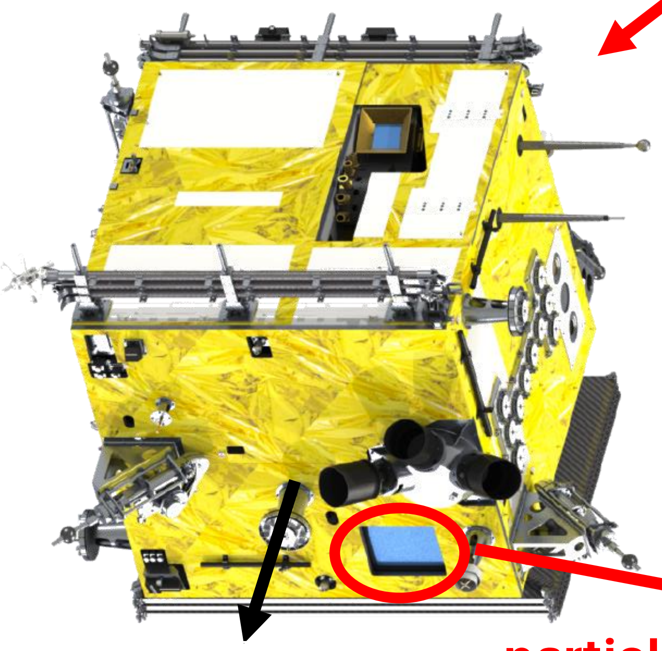
https://doi.org/10.1016/j.nima.2024.169762

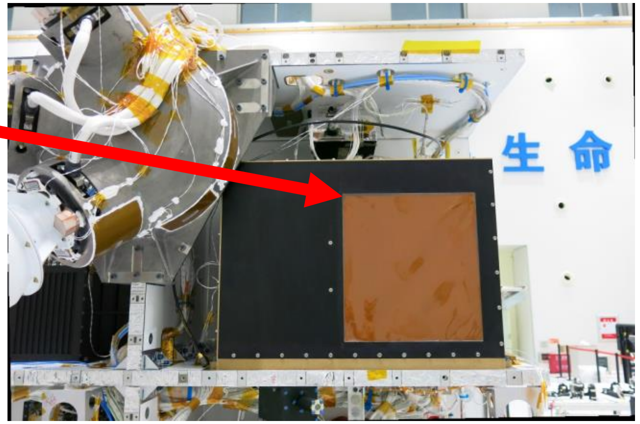
The CSES mission

电磁监测卫星计划
China Seismo-Electromagnetic Satellite Program



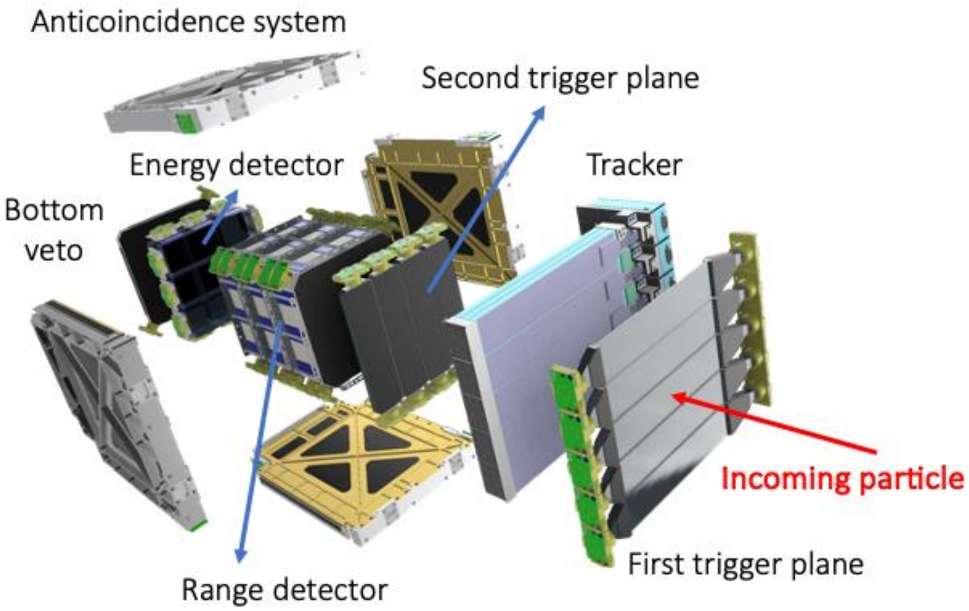
- **CSES: China Seismo-Electromagnetic Satellites.**
  - Program developed by Chinese and Italian Space Agencies.
  - CSES-01: launched on Feb 2018 and operating.
  - **CSES-02: launch scheduled on 30 Dec 2024.**

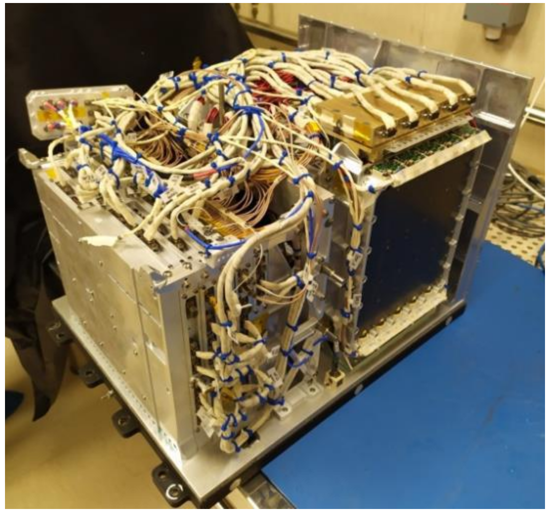


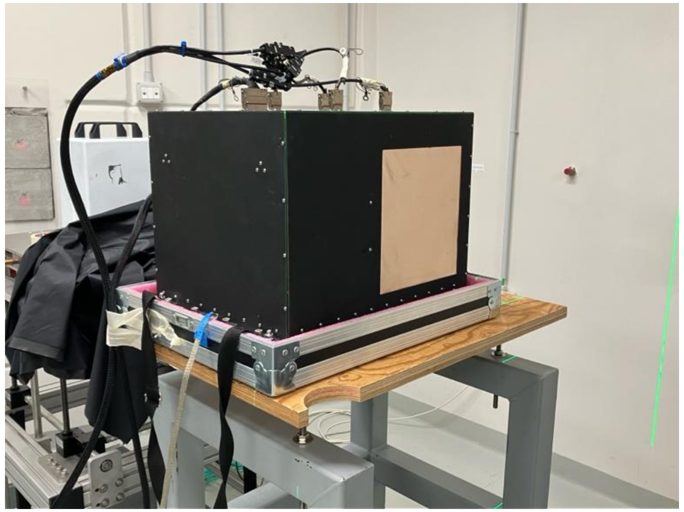


- **Main scientific objectives.**
  - Monitoring of **electromagnetic and plasma environment in near-Earth space.**
  - Measurements of **ionospheric and magnetospheric perturbations** of different origins: seismic phenomena, tropospheric and anthropic transients, solar activity...
  - Study of fluxes of **charged particles precipitating from the Van Allen radiation belts.**

The HEPD-02 detector

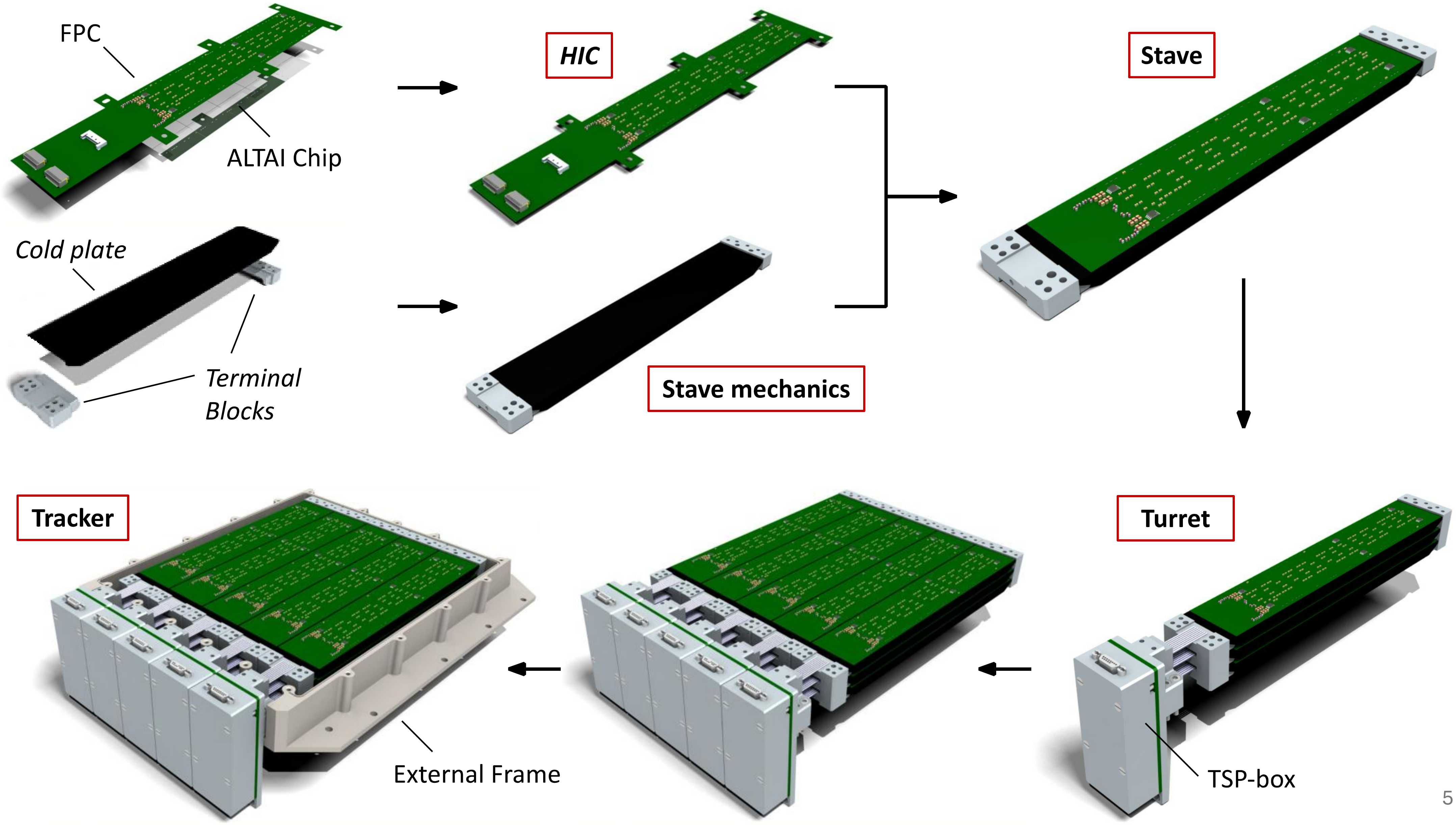






Kin. energy range (electron)	3 MeV to 100 MeV
Kin. energy range (proton)	30 MeV to 200 MeV
Angular resolution	**≤10° for E_{kin} > 3 MeV electrons**
Energy resolution	≤10% for E_{kin} > 5 MeV electrons
Particle selection efficiency	> 90%
Detectable flux	up to 10^7 $m^{-2}s^{-1}sr^{-1}$
Operating temperature	-10 °C to +35 °C
Operating pressure	≤ 6.65 · 10^{-3} Pa ("vacuum")
Mass budget	50 kg
Power Budget	**45 W**
Data budget	≤ 100 Gb/day

HEPD-02 tracker design

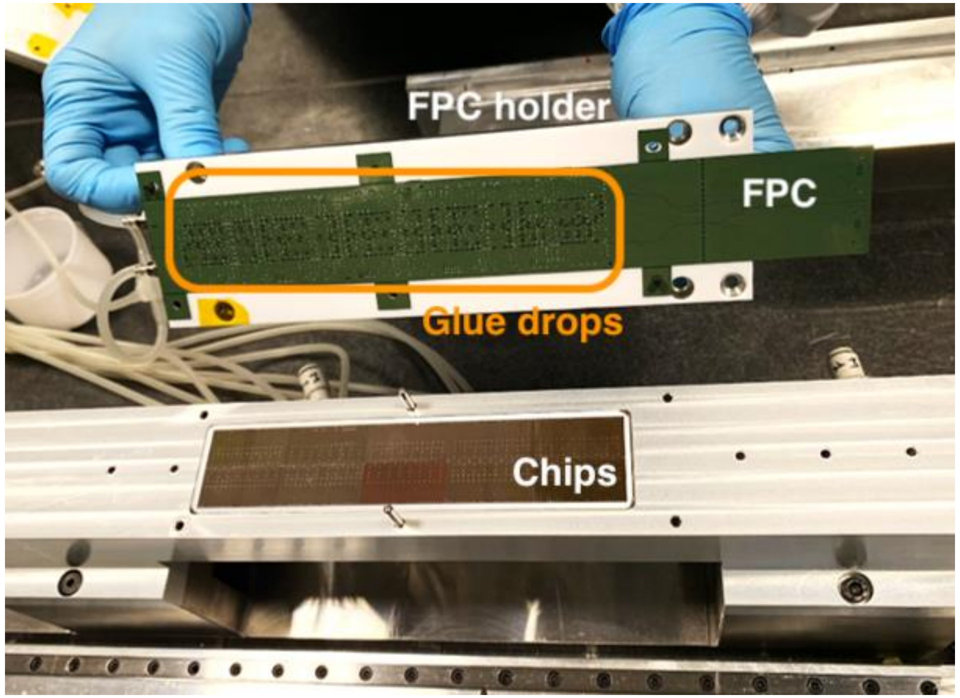


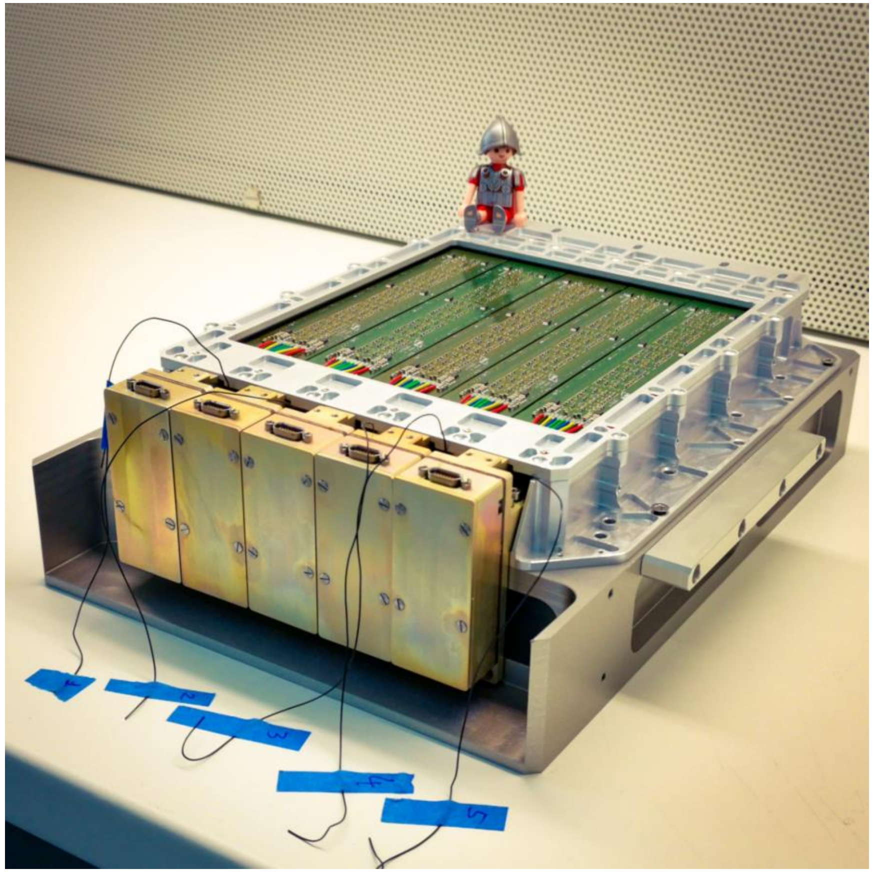
Tracker construction and integration

A team effort:

- HIC assembly in **Torino**
- Wire bonding in **Bari**
- Stave assembly in **Torino**
- Turret assembly in **Trento**
- Turret characterisation in **Trento**
- Tracker assembly in **Roma Tor Vergata**
- Integration on HEPD-02 in **Roma Tor Vergata**

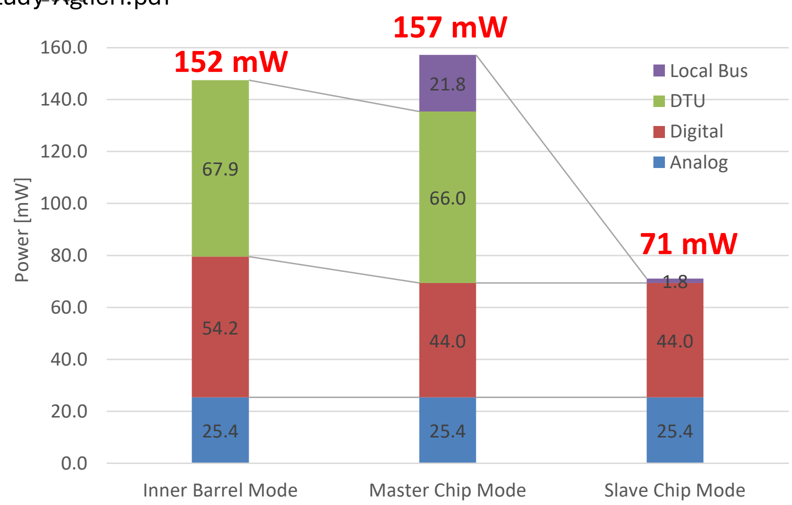
Quality TAG	HIC assembly + bonding	HIC post Tab/Wings cut	Stave Assembly
Total:	68	42	35
GOLD	25 = 36.8%	19 = 45.2%	19 = 54.3%
SILVER	15 = 22.1%	14 = 33.3%	11 = 31.4%
BRONZE	3 = 4.4%	3 = 7.1%	3 = 8.6%
NOT OK	25 = 36.8%	6 = 14.3%	2 = 5.7%

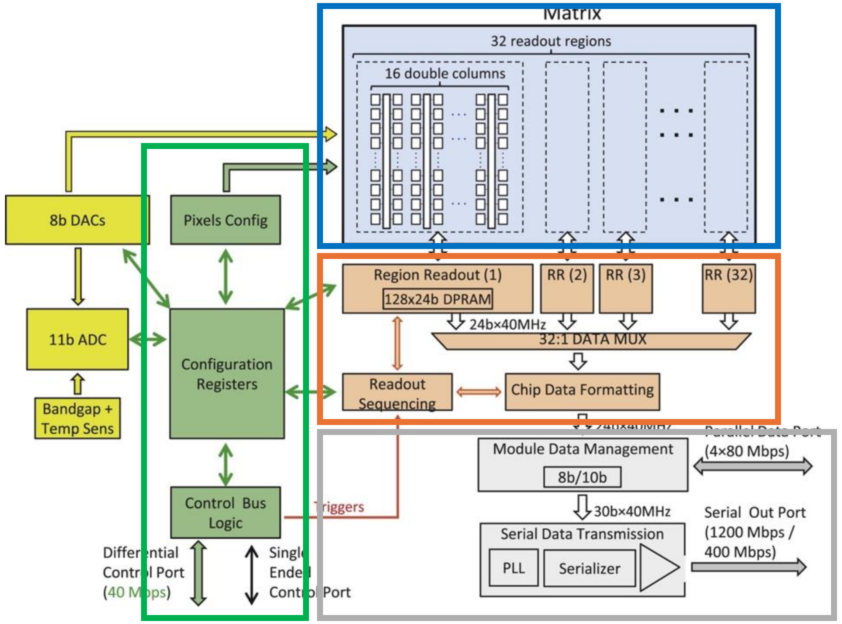




Power management of ALTAI

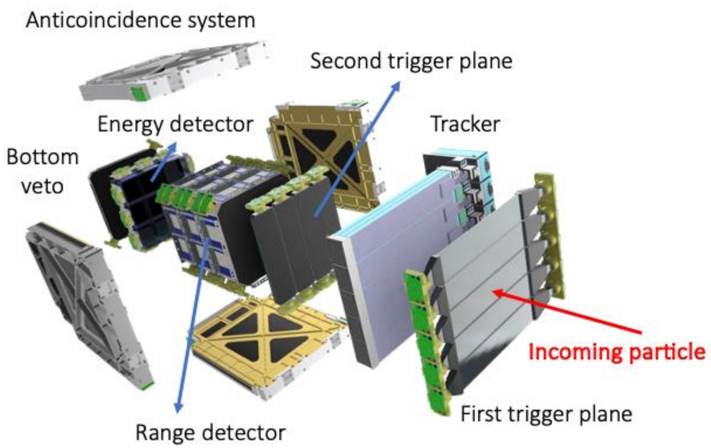
https://indico.cern.ch/event/666016/contributions/2722251/attachments/1523408/2380925/ 20170914-ALPIDE-FoCal-Study-Aglieri.pdf

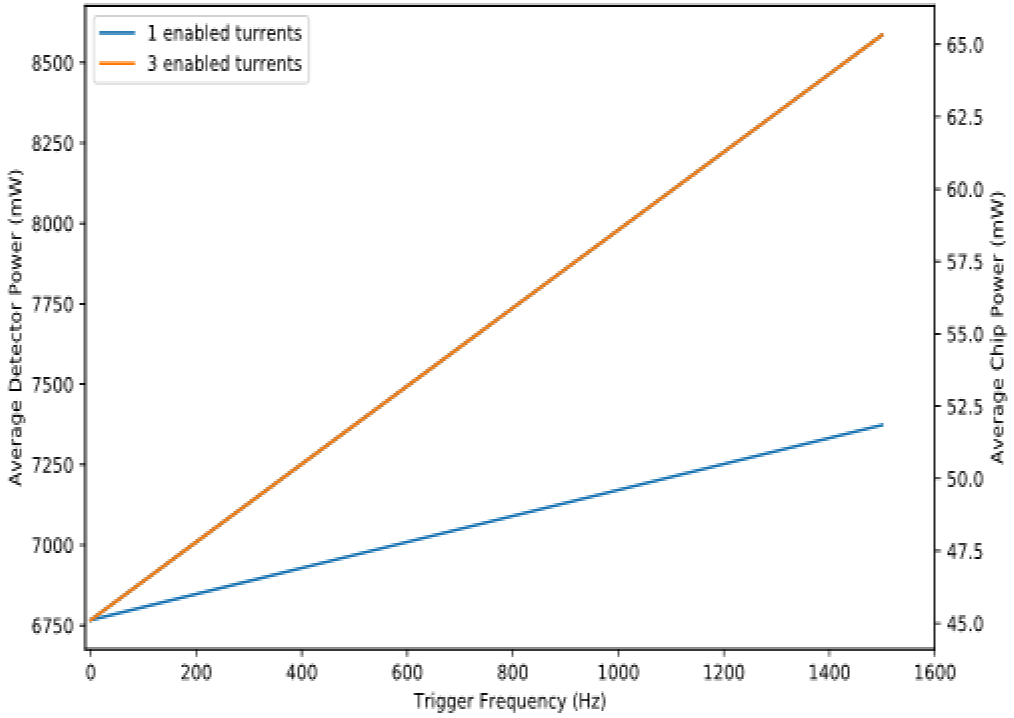




- The building block of HEPD-02 detector is the **ALTAI detector**
- ALTAI power consumption **~ 35 mW/cm²**
- HEPD-02 power budget allowed only **~10 mW cm²**
- The first solution was to work on **ALICE Outer barrel mode**, 1 master chip every 5
- We also decided to move the data readout to the **slow control line**
- Another solution implemented was **to hold the clock between triggers**

Power management of ALTAI





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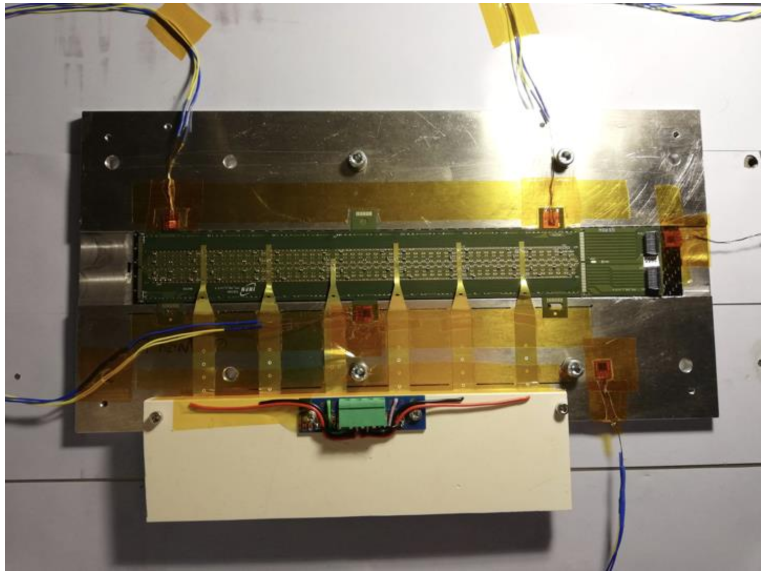
- To further reduce the control, we designed the trigger plane of the experiment with the same segmentation of the tracker
- **Only the turrets that are most probably involved in the event are read out**

Space qualification

June 2019

Technology qualification:

- On a ALICE Outer barrel stave
- Vibration test
- Thermal vacuum test



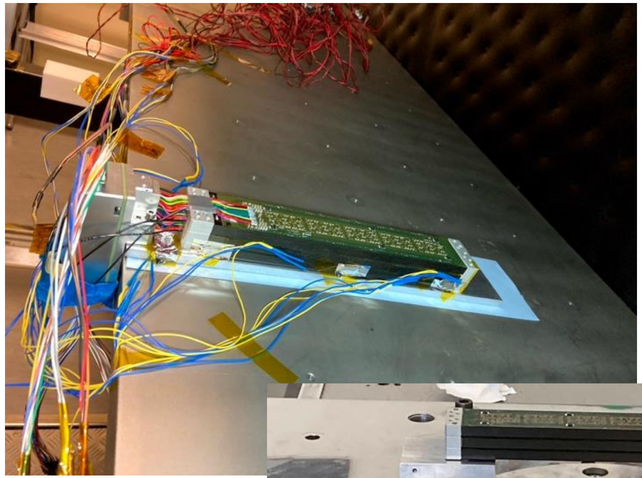
Thermal vacuum and vibration tests @ SERMS (Terni, Italy)

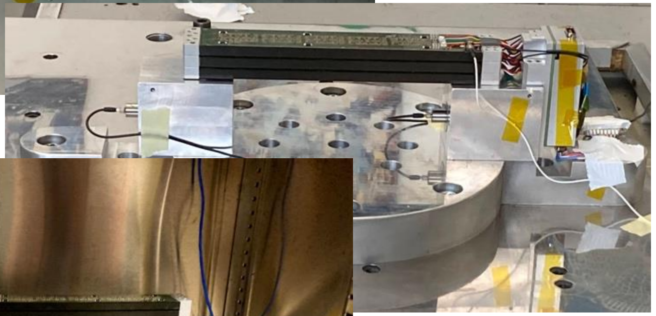
Thermal cycles @ FBK (Trento, Italy),
DII department of Trento University and SERMS

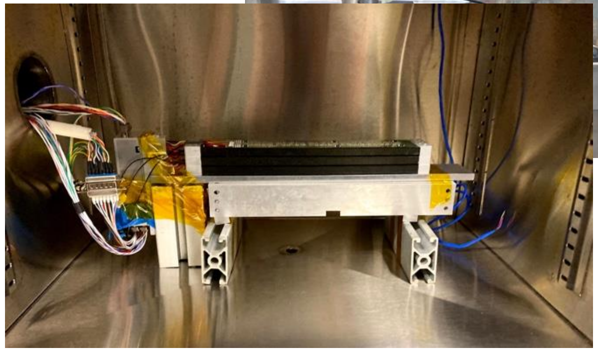
January 2021

Design qualification:

- On HEPD-02 turret
- Vibration test
- Thermal vacuum test
- Thermal cycles



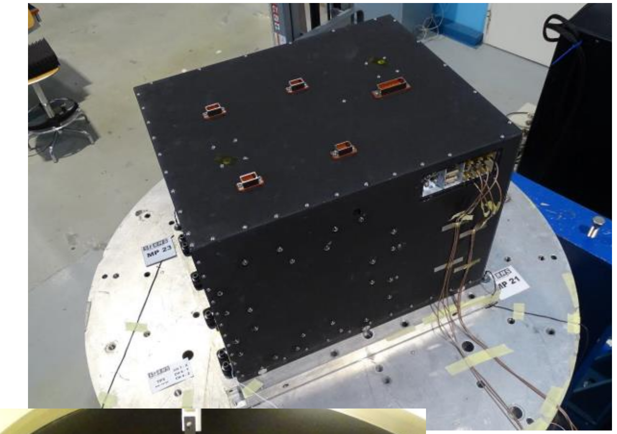


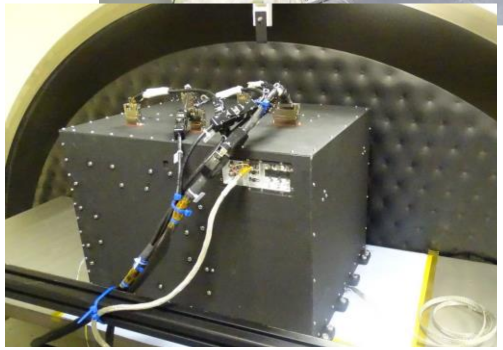


March – May 2023

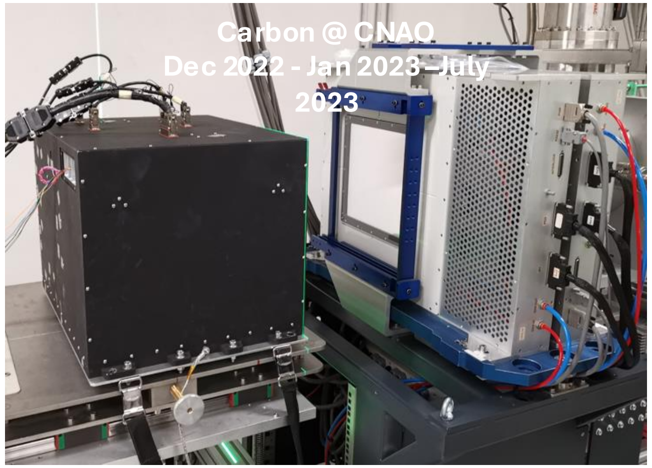
HEPD-02 qualification:

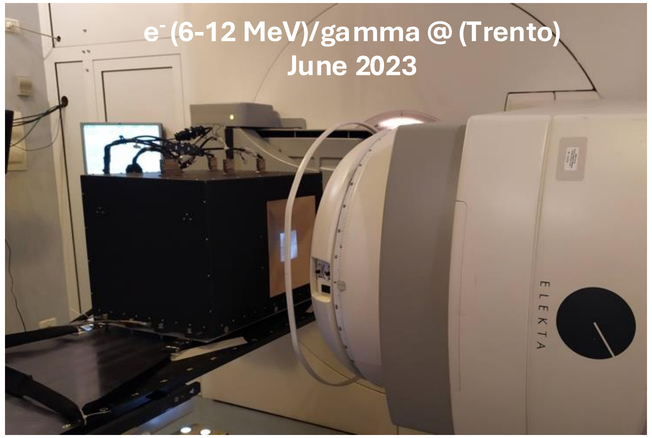
- On HEPD-02 QM and FM
- Vibration test
- Thermal vacuum test
- Thermal cycles
- Pyroshock (only on QM)





HEPD-02 characterisation campaign





Calibration tests:

- **Carbon** @ **CNAO** (Pavia, Italy) in December 2022 and January 2023
- **Electrons** (30-450 MeV) @ **BTF** (Frascati, Italy) April 2023

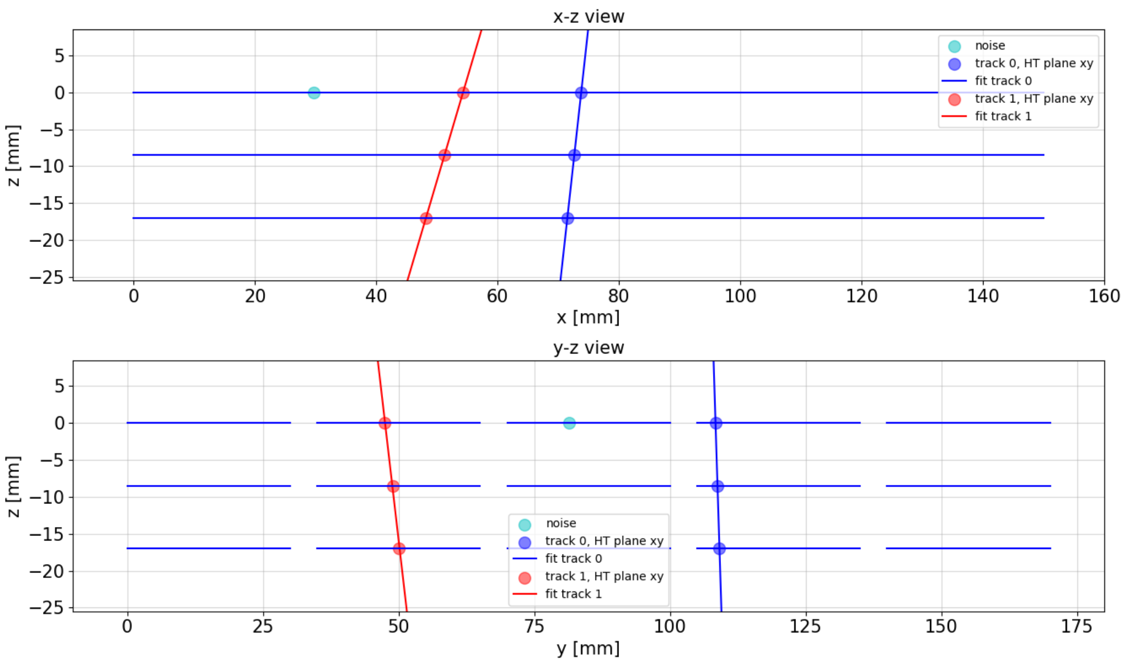
Full characterisation:

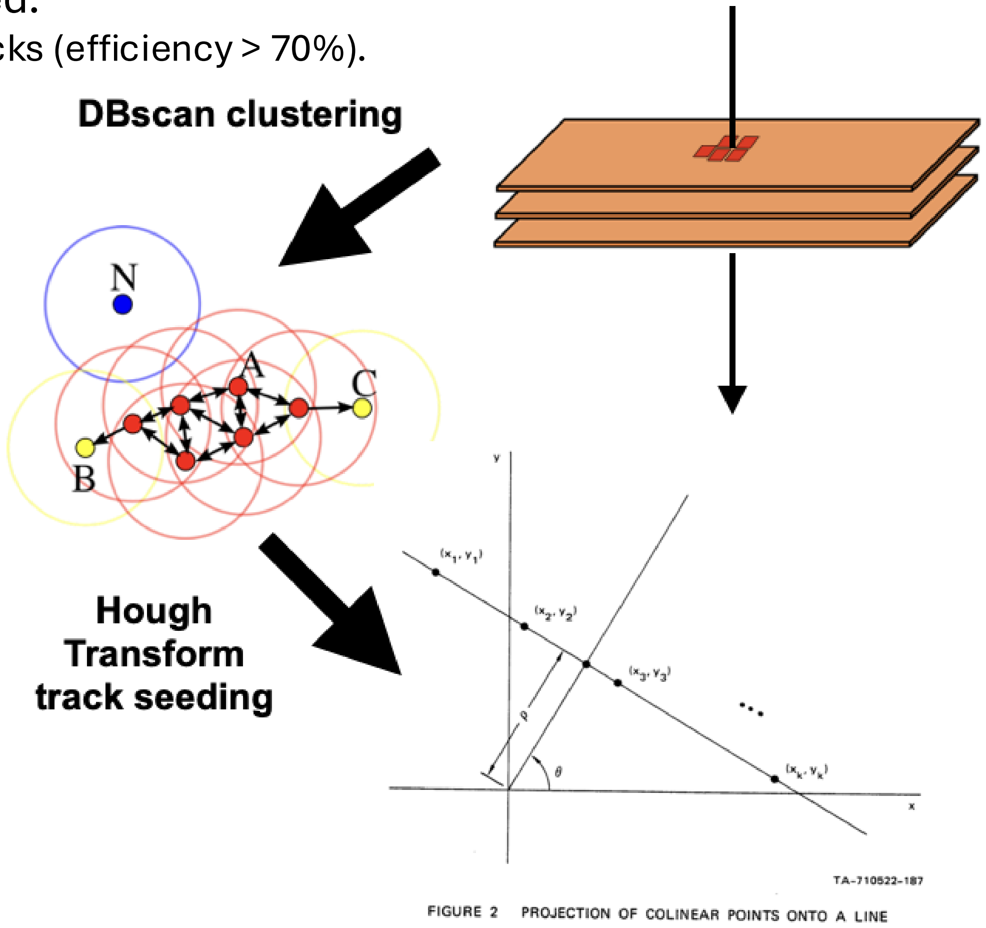
- **Protons** @ **Proton Therapy Center** (Trento, Italy) June 2023
- **Electrons** (6-12 MeV) **and photons** (4-10 MV) @ **S. Chiara Hospital** (Trento, Italy) June 2023
- **Electrons** (30-450 MeV) @ **BTF** (Frascati, Italy) June 2023
- **Carbon** @ **CNAO** (Pavia, Italy) July 2023

HEPD-02 performance: arrival direction reconstruction

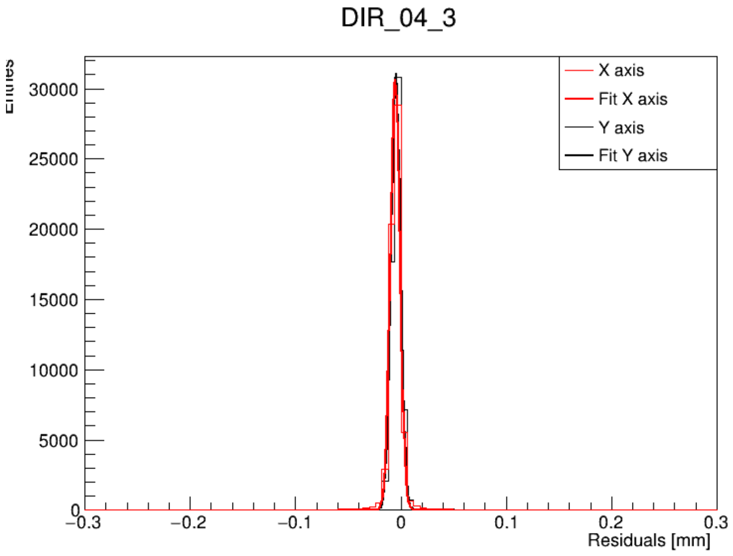
- **Map of tracker noisy pixels** (~ 1 k over 80 M) obtained with periodic on-line calibration.
- For each event, **"non-noisy" hit pixels are clustered** (DBSCAN) and **track seeds are identified** (Hough transform).
- **3D best-fit track** (or tracks, for multi-particle events) is determined.
  - Residual noise clusters are easily identified by requiring 3-planes tracks (efficiency > 70%).

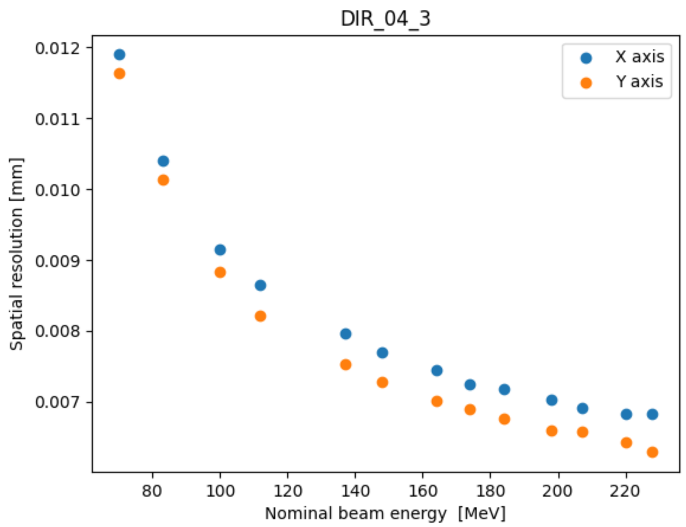
Example: side views of a **real event with two cosmic-muon tracks and a noise cluster.**



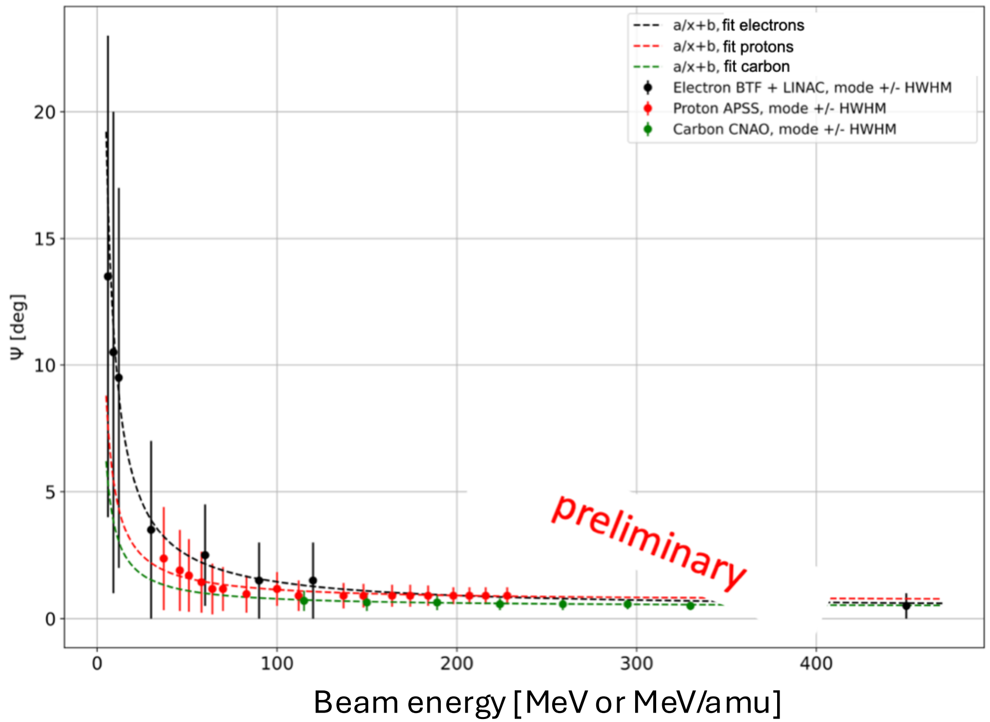


Tracking performance



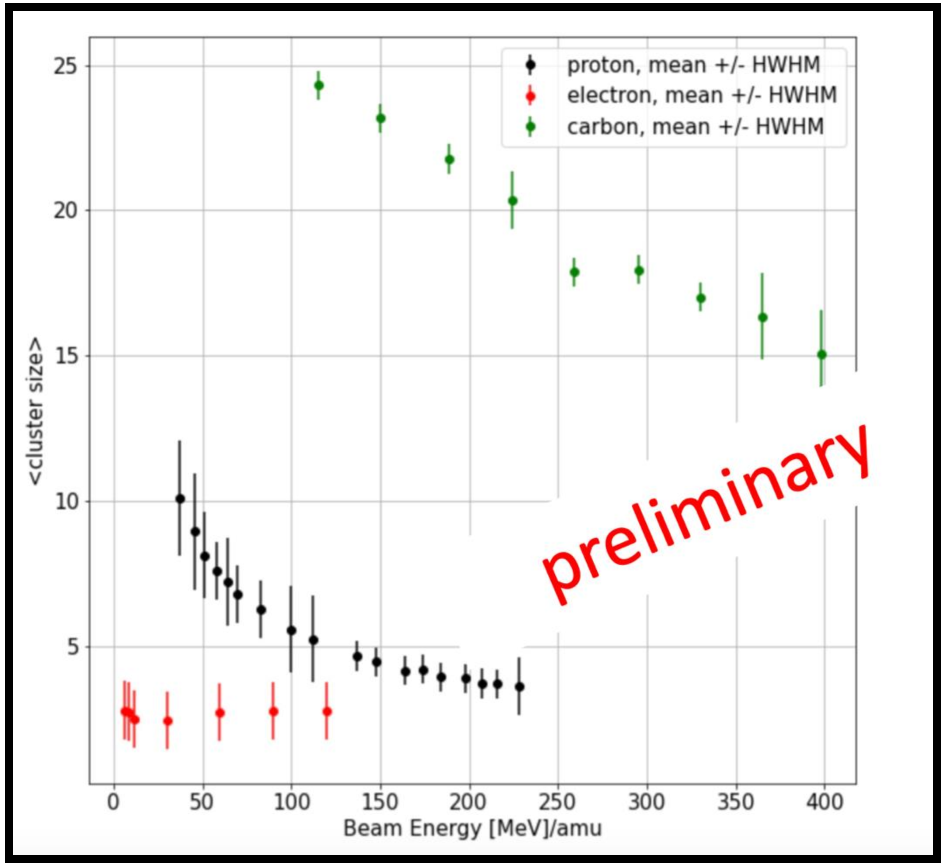


- **Spatial resolution** obtained from the squared sum of mean and sigma obtained from the fit of residuals
- Discrepancies are to be attributed to the mean value of distributon (it can be corrected!)
- Spatial resolution for the pixel detectors is **4 µm** for MIPs
- Without any kind of software correction we have **7 µm**
- **Software corrections** under development



Uncertainty ψ of reconstructed direction for quasi-vertical incidence (beam test data).

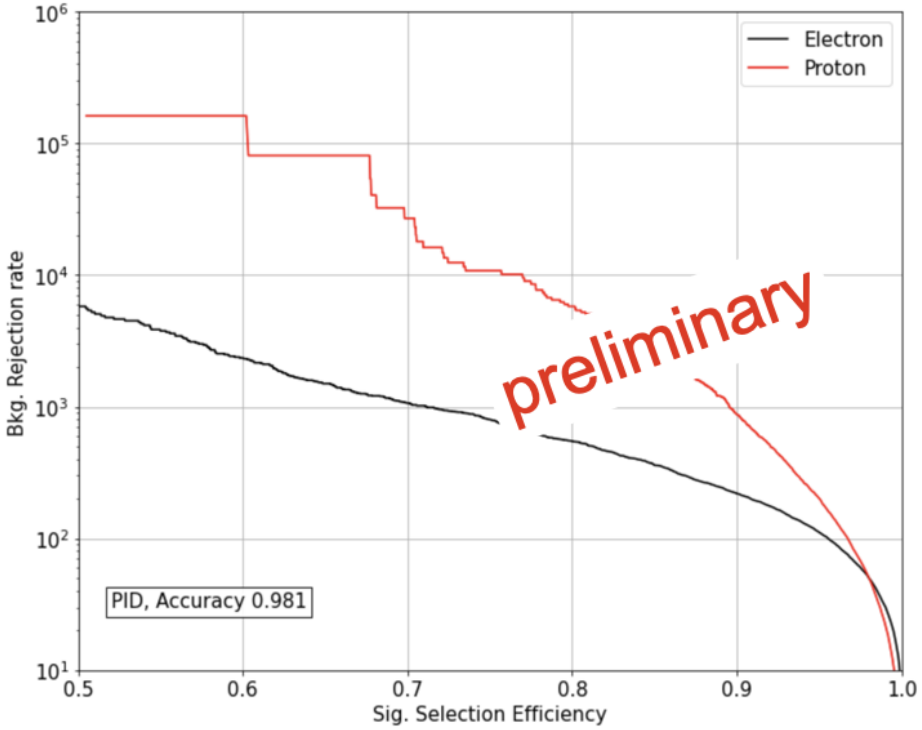
Particle identification: tracker contribution



- **Clear beam particle (e⁻/p/carbon) separation** by the energy dependence of tracker cluster size (pixel number).
- The cluster size can give hints for particle identification but has to work in synergy with the information from the calorimeter

- The relevant information is combined via **Deep Neural Network (DNN)**, to optimize background rejection rate vs. selection efficiency.

Simulated **e⁻/p separation performance**, with expected particle flux along the orbit.



Conclusions

- There is a **wide interest** on using **MAPS for space based observation** of neutral and charged radiation
- The HEPD-02 detector will be the **first experiment in space** with a **particle tracker realised with MAPS**
- The technology and the design have been **qualified to TRL 8**, the launch is scheduled for December 30, 2024
- With the successful use of ALTAI in space a **new benchmark on tracking technologies for space** will be set
- The approach used by the Limadou collaboration **significantly shortened** the typical delay between establishment on ground and use in space of a technology
- We are already working for the **space qualification of the newest technologies** (stitched detector)

Thank you!