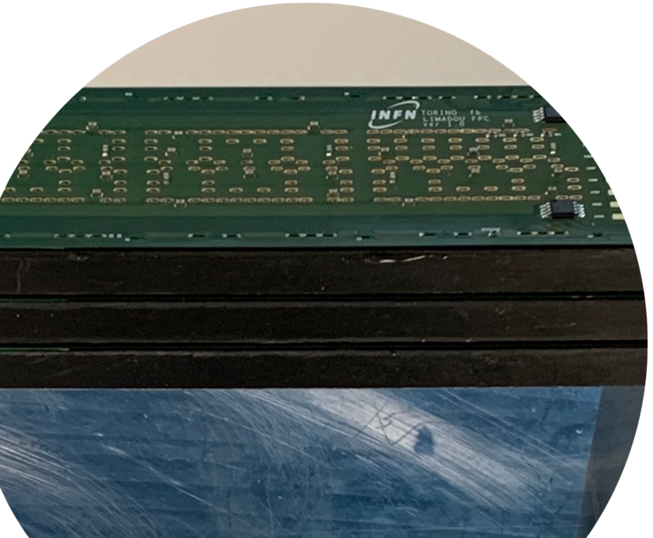
INFN TORINO
Istituto Nazionale di Fisica Nucleare
Sezione di Torino

Agenzia Spaziale Italiana

Seminario gruppo 2 Torino
LIMADOU

29 giugno 2021

Lorenzo de Cilladi

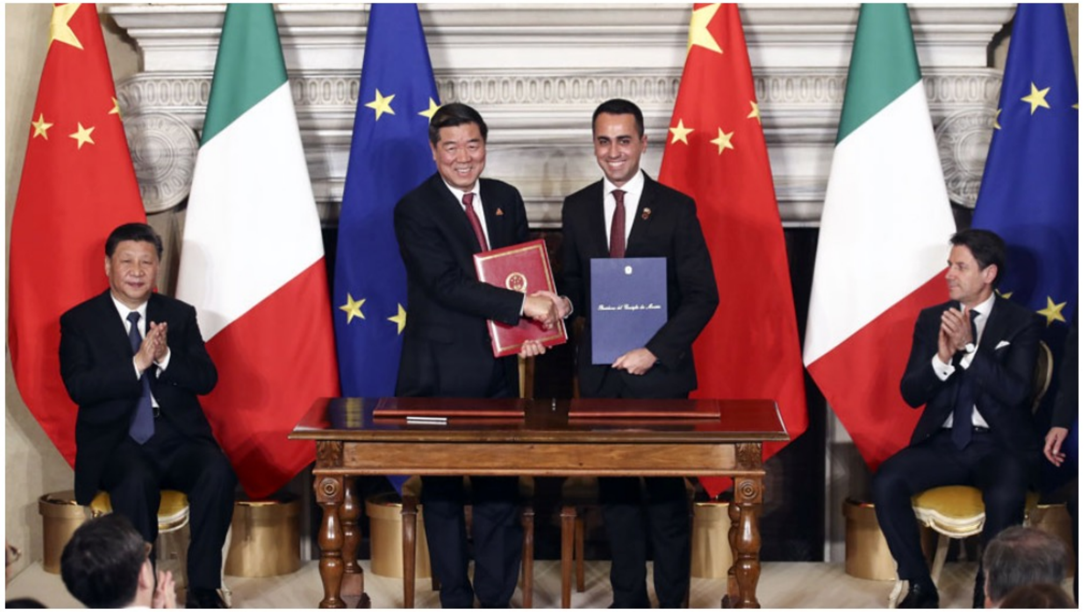


General plan and perspectives

- Development of monolithic sensors for different applications…
  - High energy physics
  - Space applications
  - Medical and applied physics
- …and for different purposes
  - Tracking
  - Time measurements
- LIMADOU
  - First application of monolithic pixels in satellite-based experiment
  - Torino: development, assembly and characterisation of the silicon tracker
    - concluding the engineering model (R&D) phase

China Seismo Electromagnetic Satellites

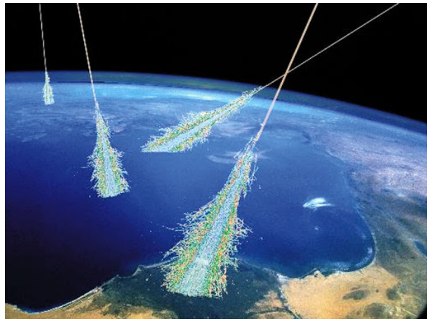
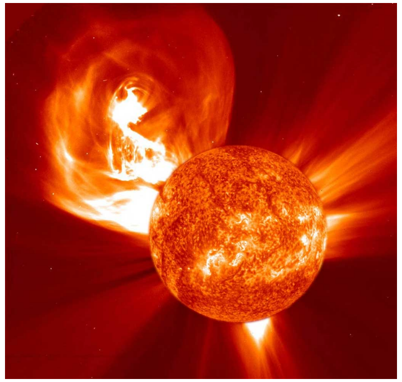
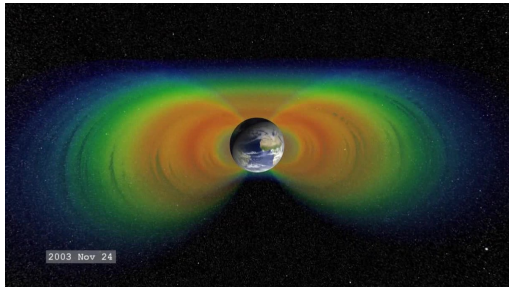
- CNSA-ASI cooperation signed in Rome, March 23, 2019
- LIMADOU: Italian participation in CSES
- Several satellites:
  - CSES-01: in orbit since February 2, 2018
  - CSES-02: launch scheduled for March 2022

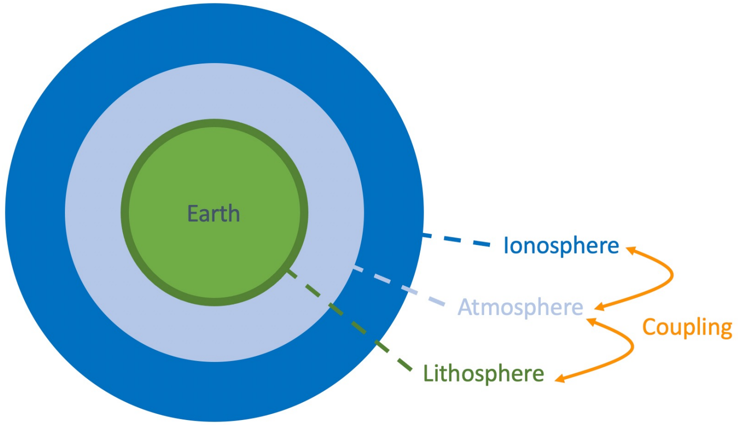


China Seismo Electromagnetic Satellites

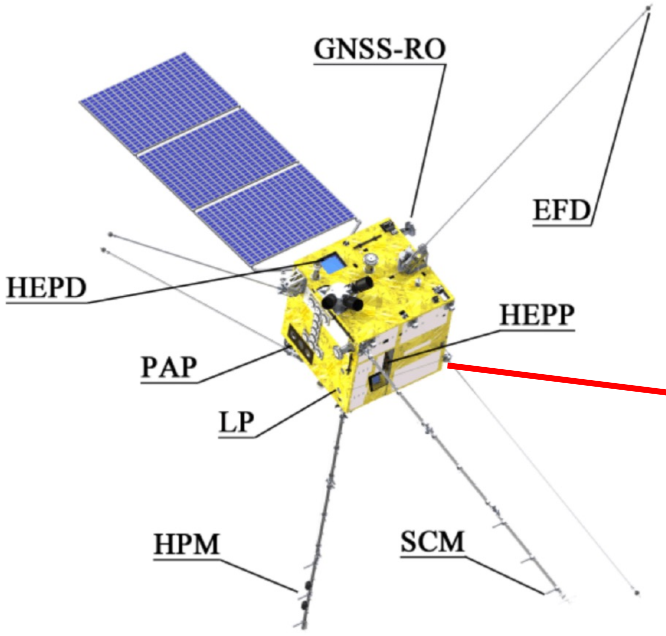
- Scientific space missions: fields of interest
  - Lithosphere-ionosphere coupling
  - Solar Physics (space weather)
  - Cosmic ray fluxes

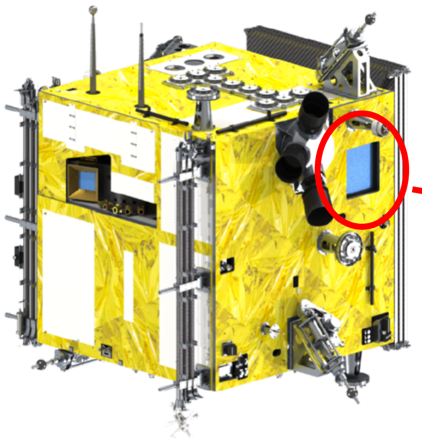
- Precise correlated measurement of EM fields and particle fluxes
  - Electrons: 3-150 MeV
  - Protons: 30-300 MeV

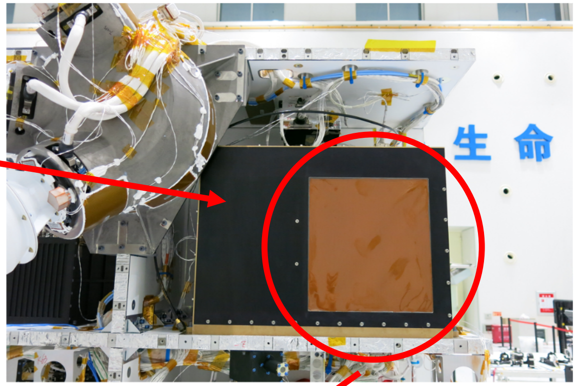






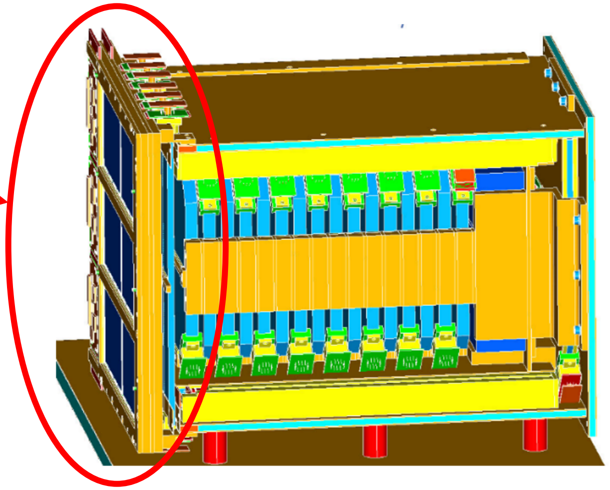
The HEPD onboard the CSES satellite





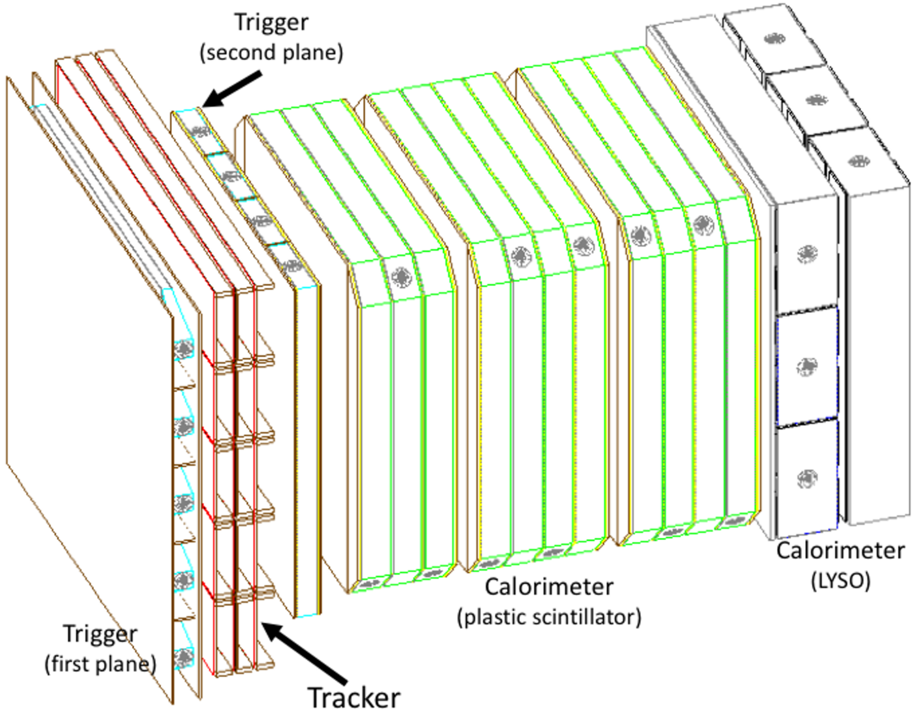


Silicon tracker
and trigger planes



HEPD: High Energy Particle Detector

HEPD-02



Silicon tracker

- Reconstruction of the particle arrival direction
- High spatial resolution and low material budget
- Three planes instead of two in HEPD-02

Trigger

- Two layers of crossed trigger bars

11-tiles of plastic scintillator

Two layers of LYSO scintillators

Surrounded by veto detectors (not shown in the figure)

Double transition from silicon hybrid microstrip to monolithic pixels

From microstrip to pixel

Microstrip detectors:
- Developed for vertexing and momentum measurement
- **Elective technology for tracking particles in space**

Advantages:
- Reliable technology
- Temperature stability
- Wide previous experience of use in space
- Low power consumption

Disadvantages:
- Realised with custom technologies
- Complex readout and track reconstruction if multiple hits are recorded

Possible alternative:
- **Use of pixel detector**

From hybrid to monolithic readout

Hybrid pixel approach:
- Readout and sensor are developed separately and bonded together

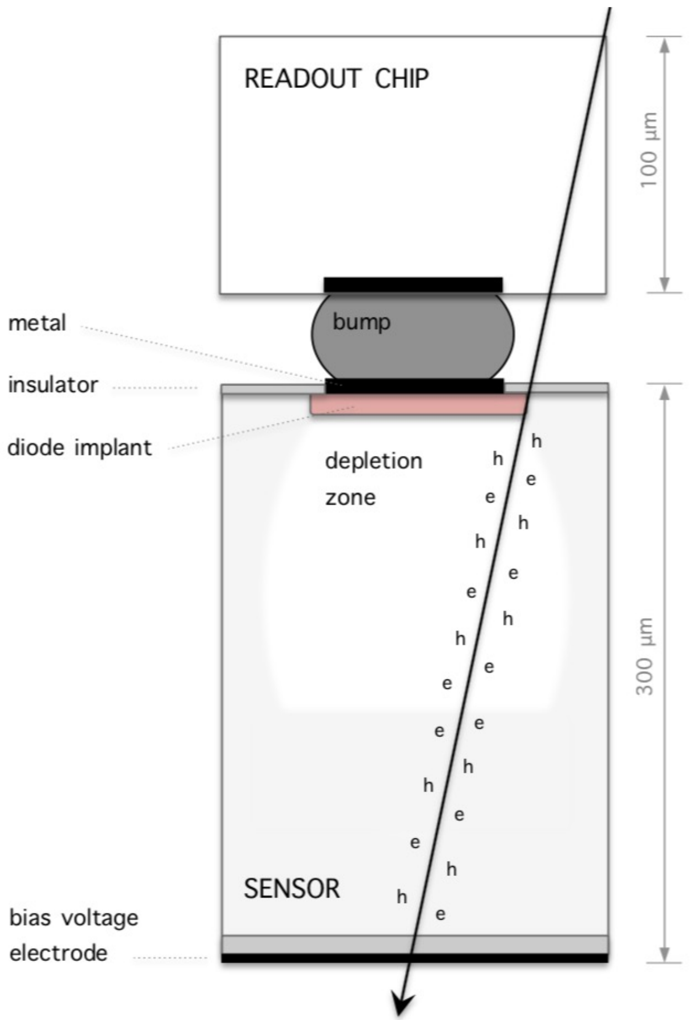
Advantages:
- It is possible to optimise the two parts independently
- The technology is well known and reliable

Disadvantages:
- Sensors are realised with custom technologies
- The assembly procedure is complex
- Higher noise

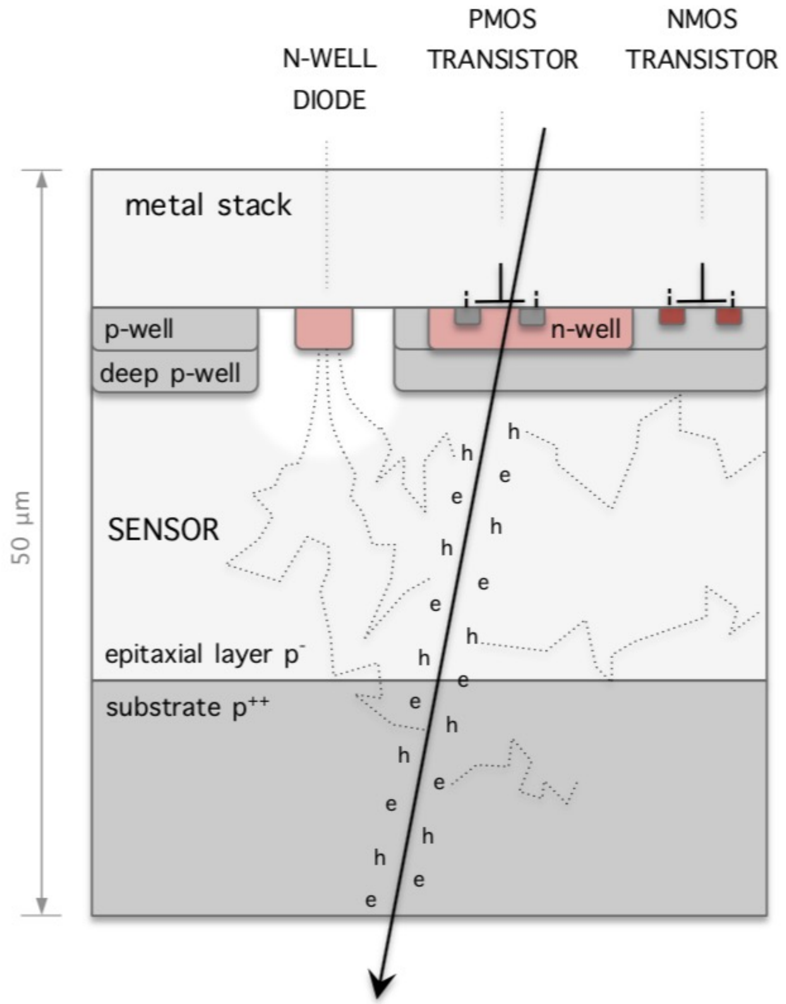
Possible alternative:
- **To implement the readout on the same substrate of the sensor (Monolithic approach)**

Silicon Pixel Technologies

Hybrid Sensors



Monolithic Sensors



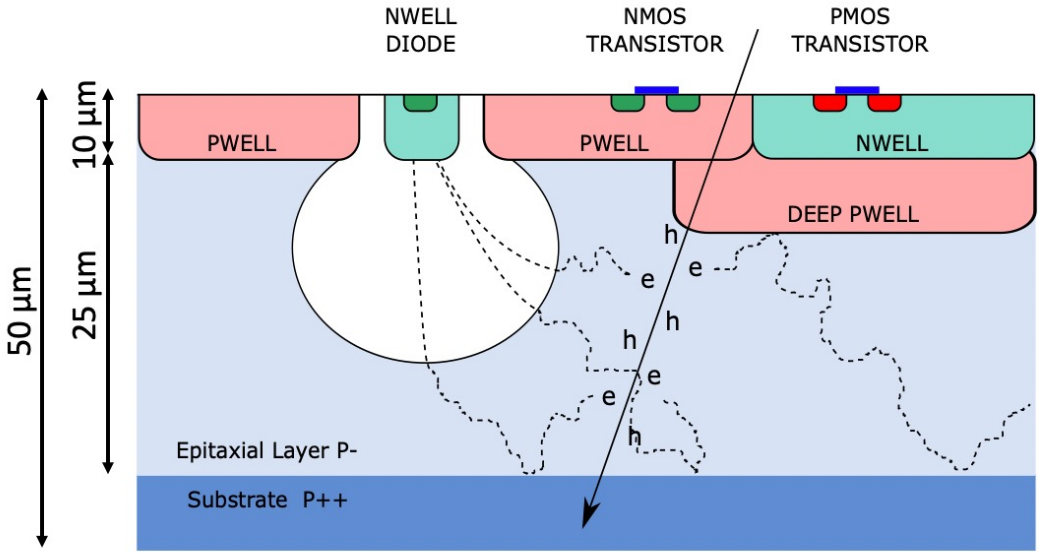
- No interconnections
- Reduced material budget (typical thickness 50-100 µm)
- Commercial CMOS processes
- Lower power consumption

ALPIDE Monolithic Pixel Sensor

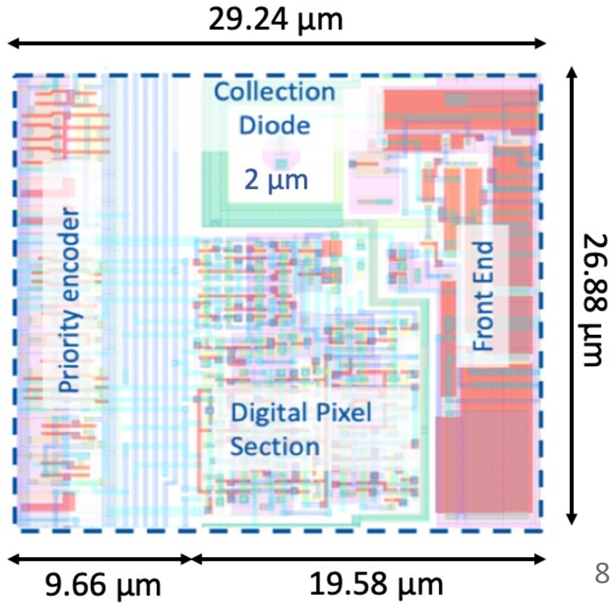
ALPIDE = ALice PIxel DEtector

- ALICE collaboration (Inner Tracker Upgrade 2)
- TowerJazz 180 nm CMOS technology
- 50 μm thick (100 μm also available)
- Deep p-well allows **p-MOSFET implantation** without collection efficiency loss
- Charge collection by **diffusion**
- Low electronic noise **(~ 10 e)**

Pixel Cross Section



Pixel Layout



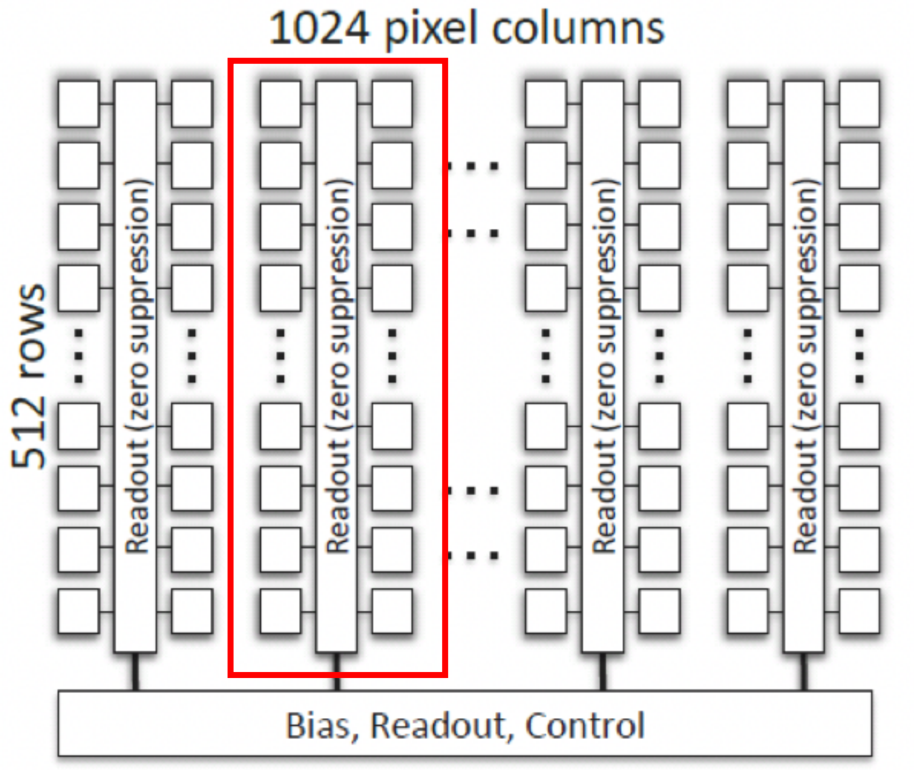
ALPIDE readout

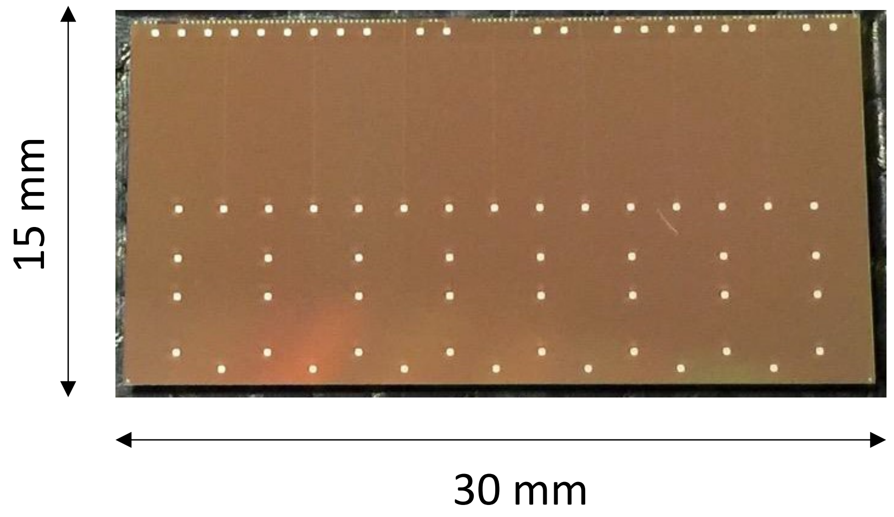
In-pixel signal processing

- Amplification
- Discrimination → digital signal
- Hit storage in pixel memory
- Binary output after trigger

Matrix readout

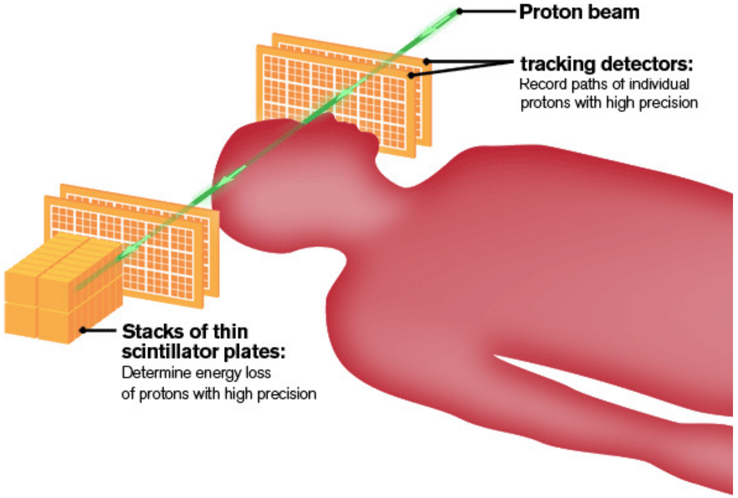
- Chip: 512 x 1024 pixels
- Chip size: 1.5 cm x 3.0 cm
- Double column readout
- Internal zero suppressed (sparsified readout)



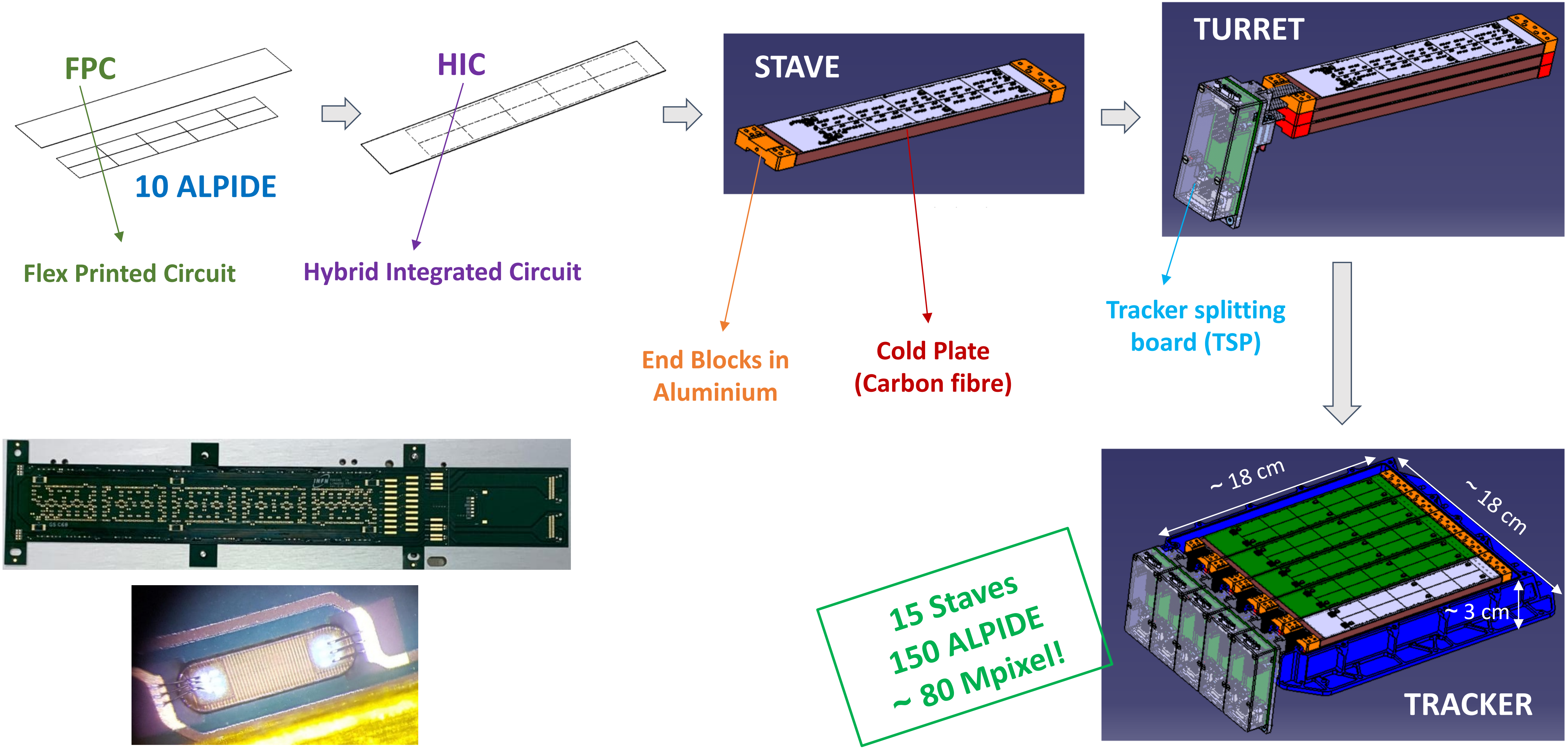


Why pixels?

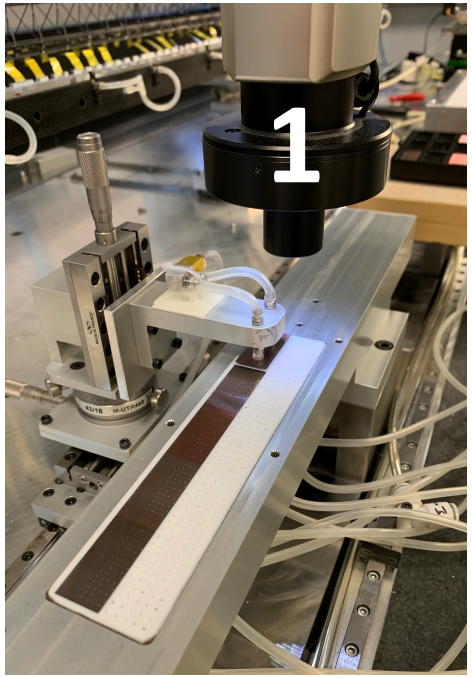
- Microstrips have very good resolution in one direction and low power consumption
- But MAPS technology starts being mature enough
  - ALICE ITS2
- And is being studied for other experiments / applications
  - Heavy ions physics (sPHENIX, RHIC – NICA MPD, Dubna)
  - Medical Proton CT (ImPaCT (Padova), pCT (Bergen))
  - Space (HEPD-02)

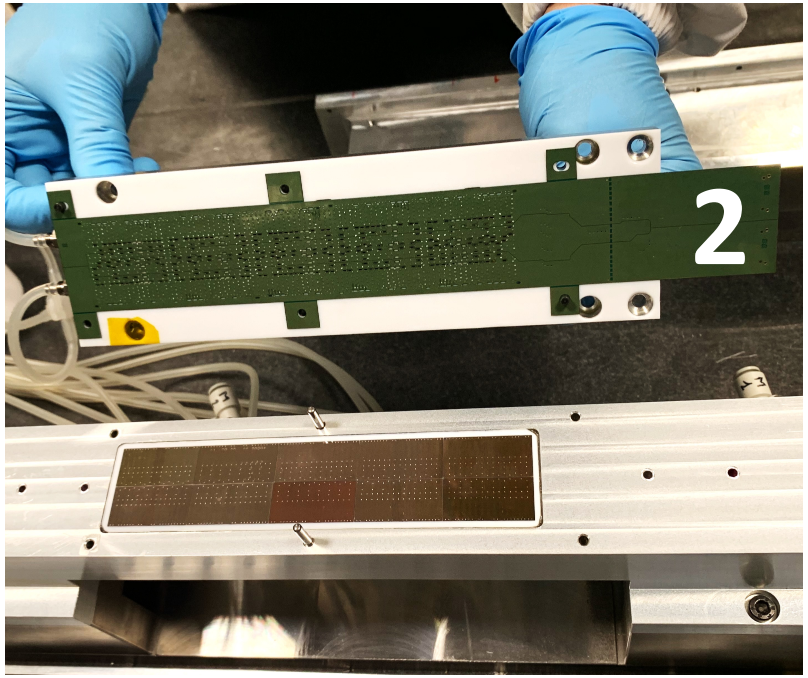


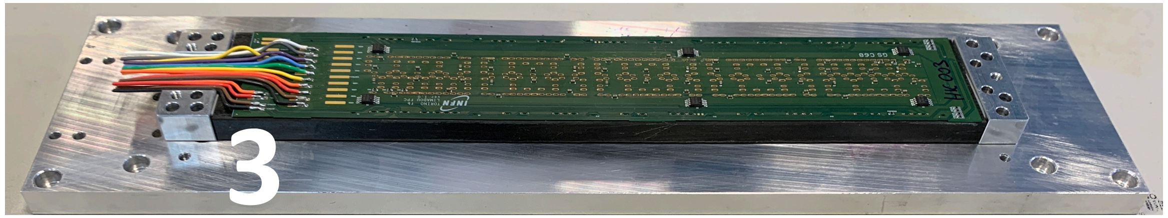
HEPD-02 tracker design

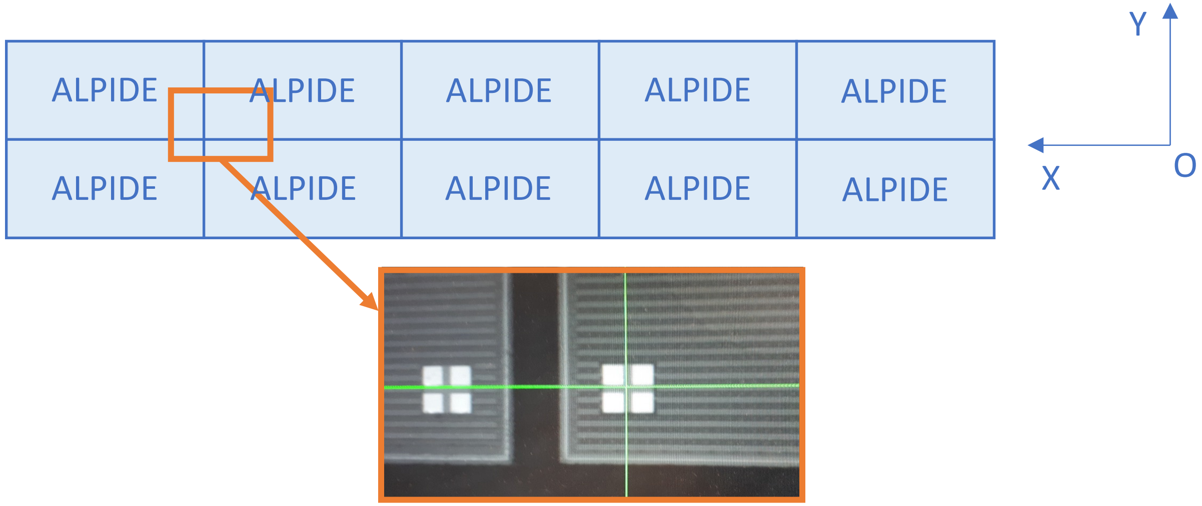


Tracker assembly

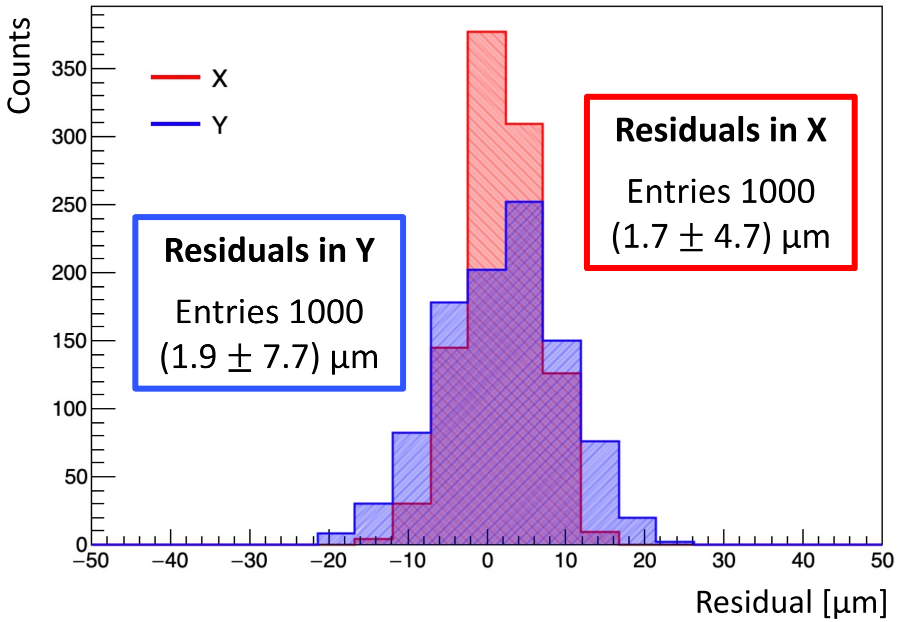




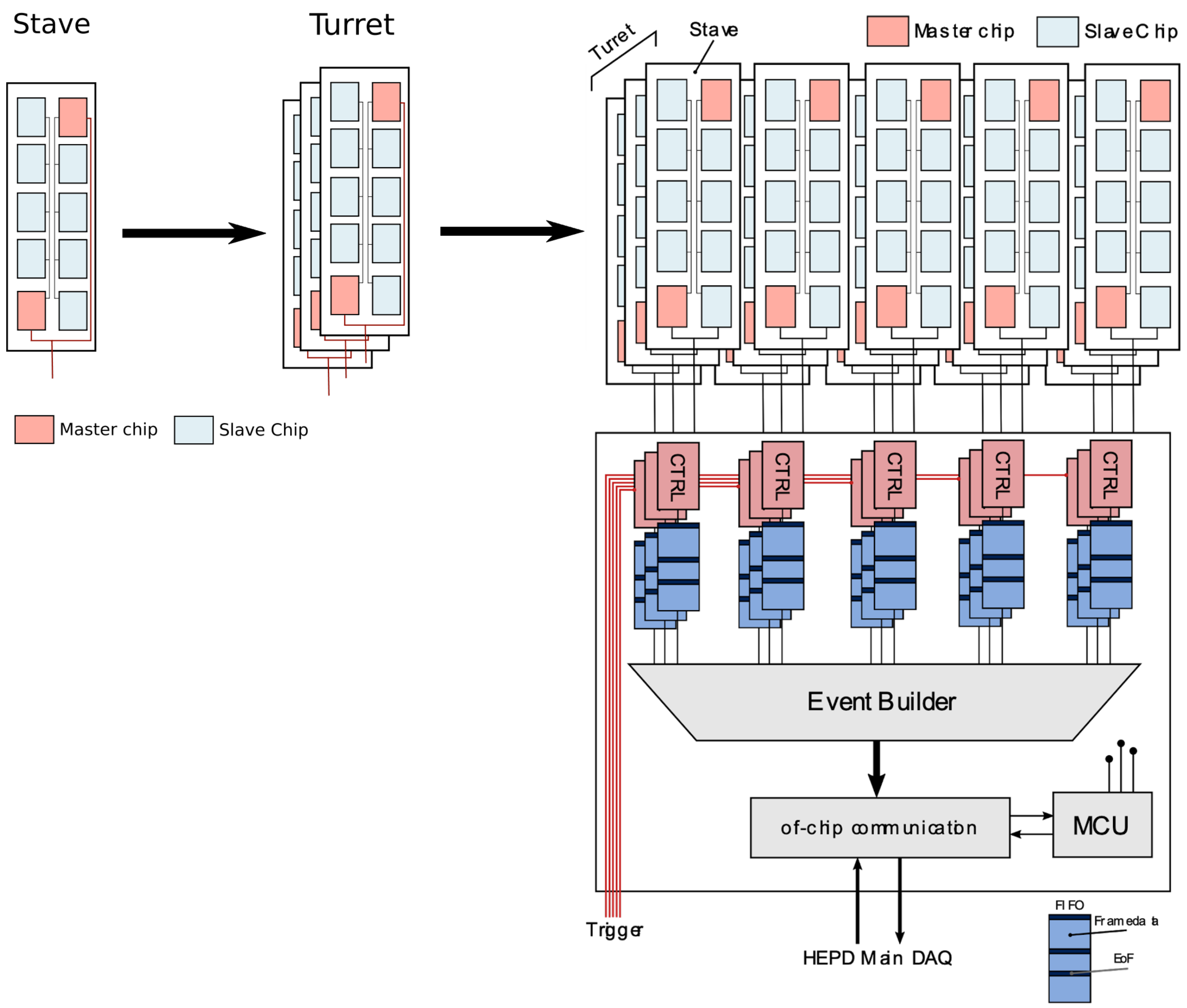




Distributions of the marker shifts in X and in Y



Tracker readout



Readout

- Stave: 10 chips = 2 master + 4 slaves each
- High speed (1.2 Gbps) serial line (not connected)
- Control line (3-5 Mbps)

The two masters share the same CTRL line, used for the readout of the entire stave

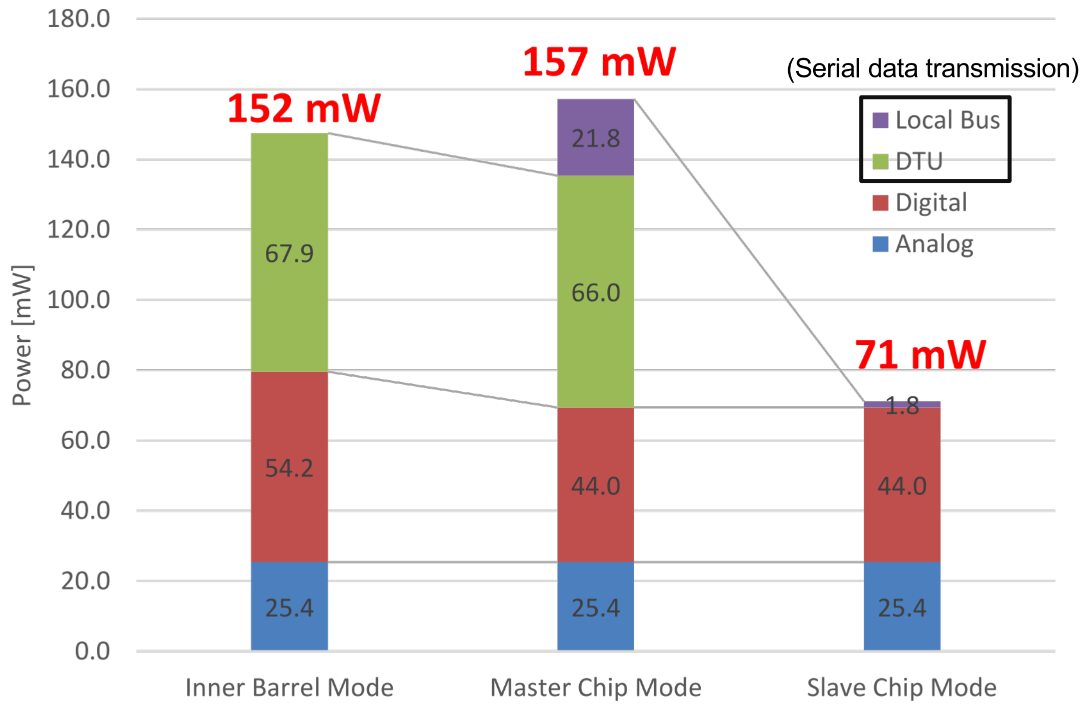
- acceptable considering the expected event rate: max ~100-200 bytes @ 100Hz typical

Tracker readout managed by a single board (TDAQ) with a low power FPGA (schematic and firmware developed in-house)

Readout in parallel on each stave

Power consumption mitigation

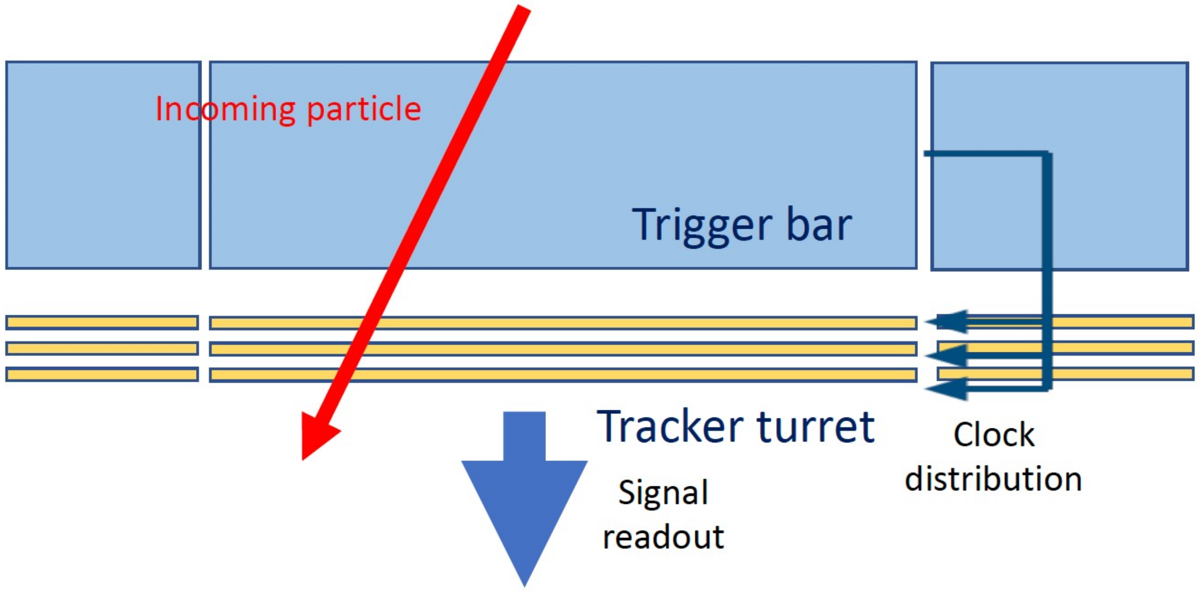
- **Power budget** of satellite payload (**49 W**)
  - defined at the beginning of the mission design, **cannot be exceeded.**
- Chip nominal power consumption overshoots HEPD-02 power budget for the tracker
  - Digital power consumption is critical
- Switch off the data transmission unit (high speed serial data output port)
- Readout through the slower (3-5 Mbps) control line
  - Ok due to small event rate/size expected

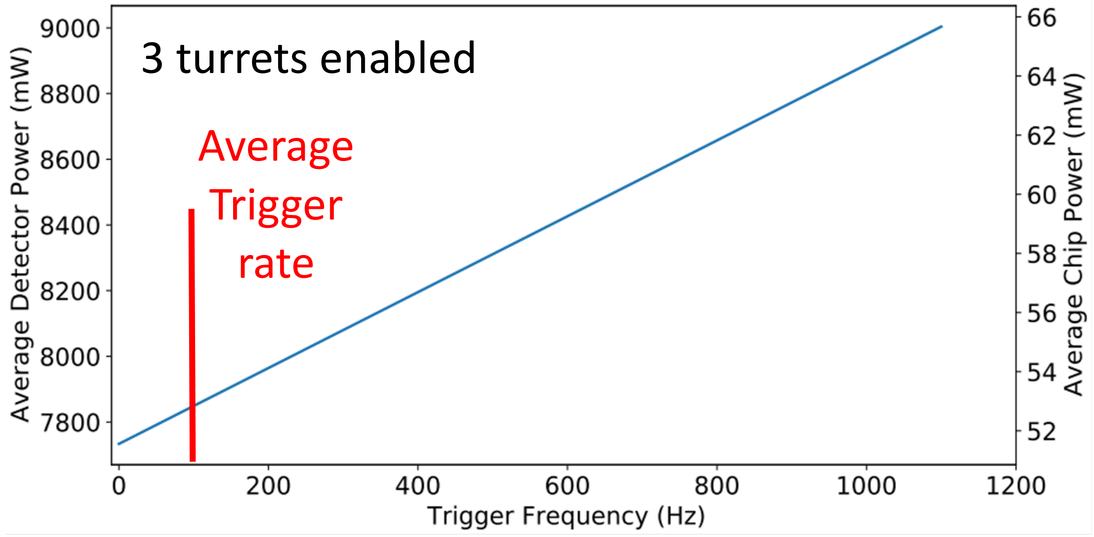


Mean tracker power consumption ~ 14 mW/cm^2
Power limit for the tracker 10 W

Clock ON: 17 mW/cm^2
Clock OFF: 7 mW/cm^2

Clock gating





- Analog front-end kept always powered on
- Digital part needed only for data readout

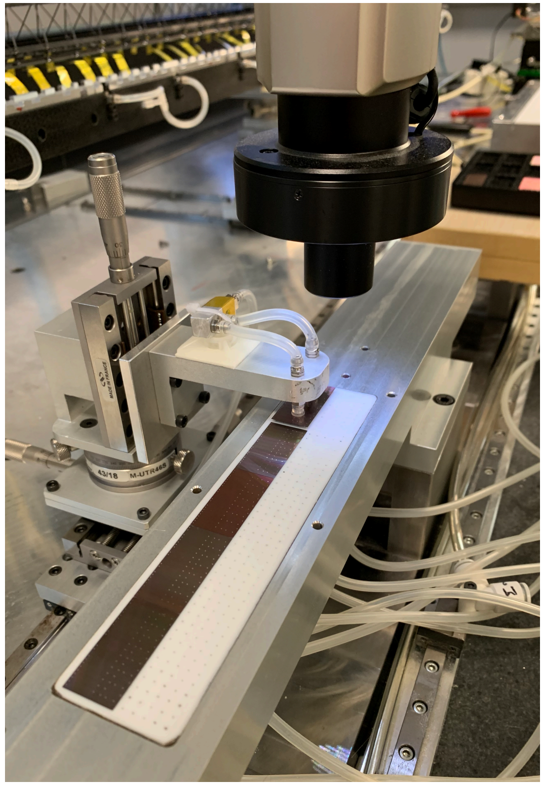
To save power, clock is distributed ONLY

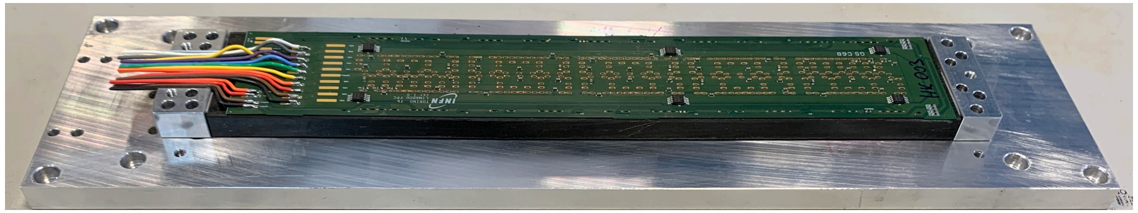
- to the triggered turret and to the two adjacent ones
  - smart segmentation of trigger plane
- for the time necessary for event readout

Clock is OFF when not needed

With a typical trigger rate of ~100 Hz (and maximum of 1 KHz) the detector is functionally “off” for most of the time.

Functional tests and QA procedures

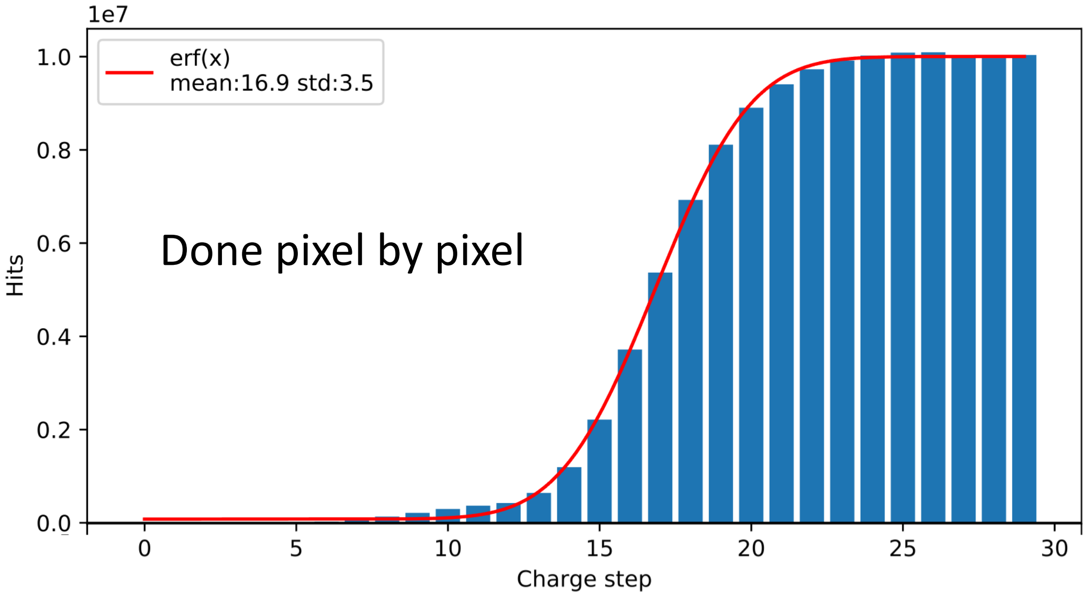


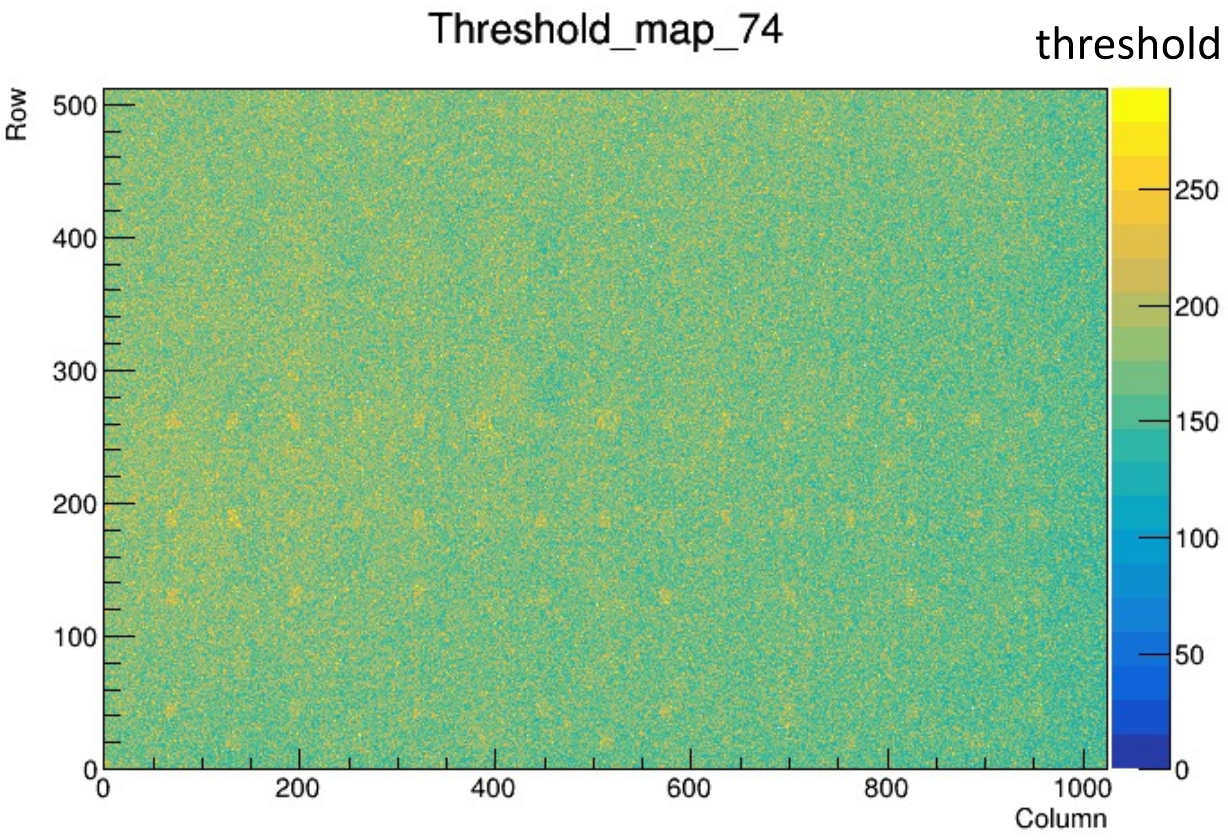


After the assembly, tests to
- characterize the detector performance
- define QA parameters and procedures

- Threshold scan
- Masking of noisy pixels: degrade dead time and data rate
- Detector diagnostics such as stave temperature
- Visual inspection to ensure that no chip are broken before or immediately after the assembly and gluing

Threshold scan and tuning

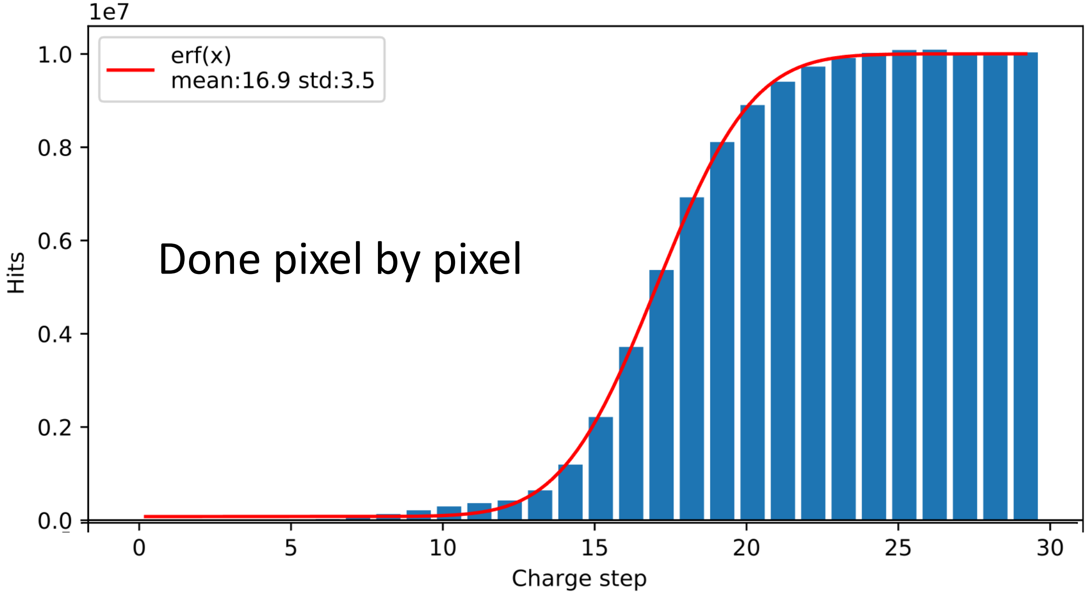


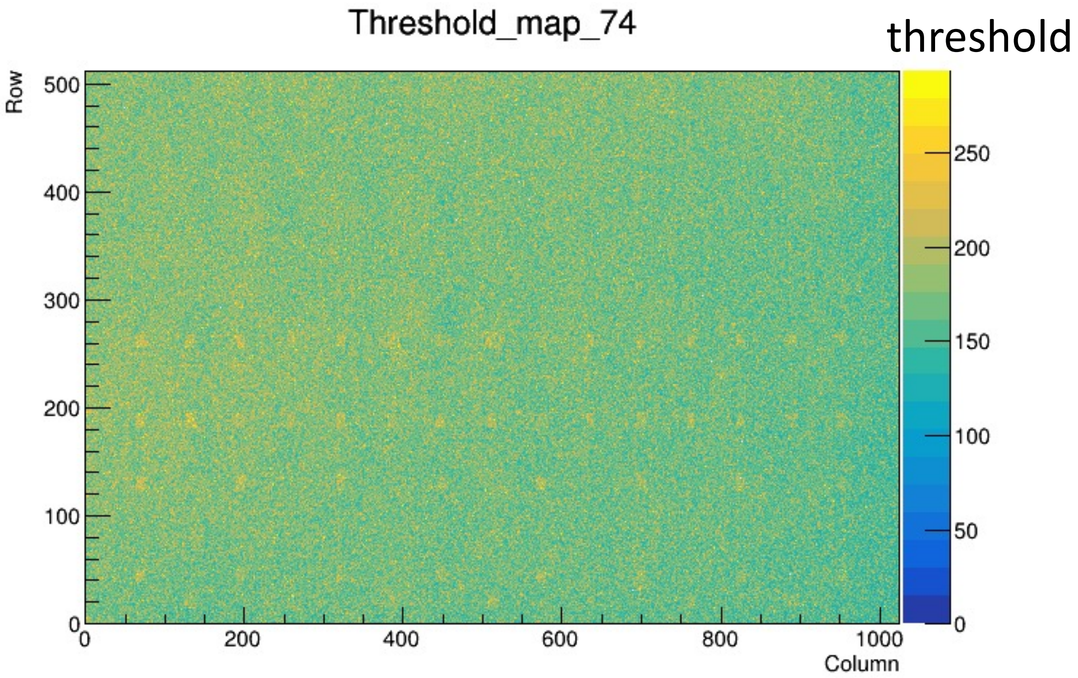


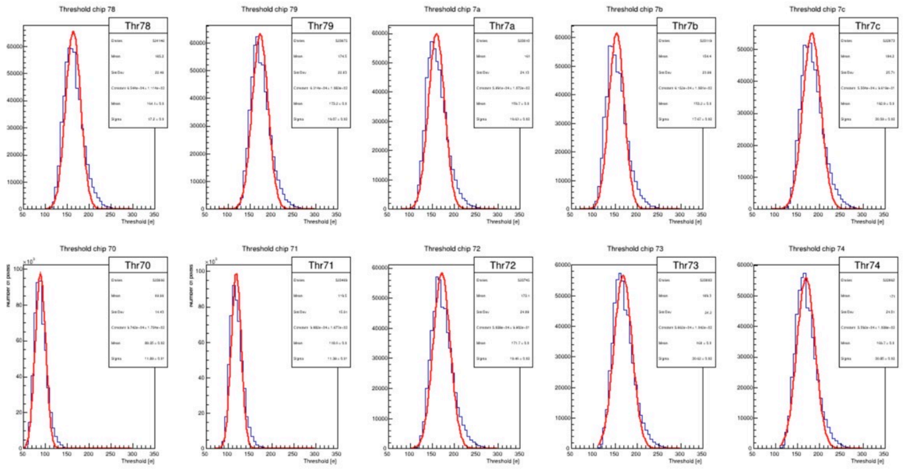
In-pixel charge injection to measure the comparator threshold

- Analogue signal ramp up
- At a given charge level (threshold), pixels will give hits
- Threshold and electronic noise (uncertainty on threshold) from the S-curve
- Tuning of the threshold between chips (~ 150 e)

Threshold scan and tuning





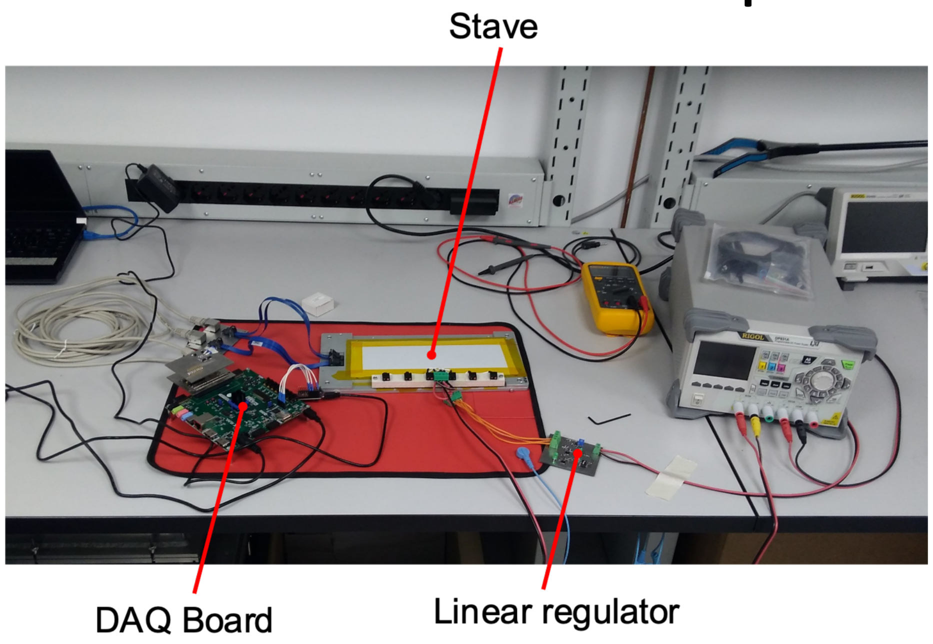


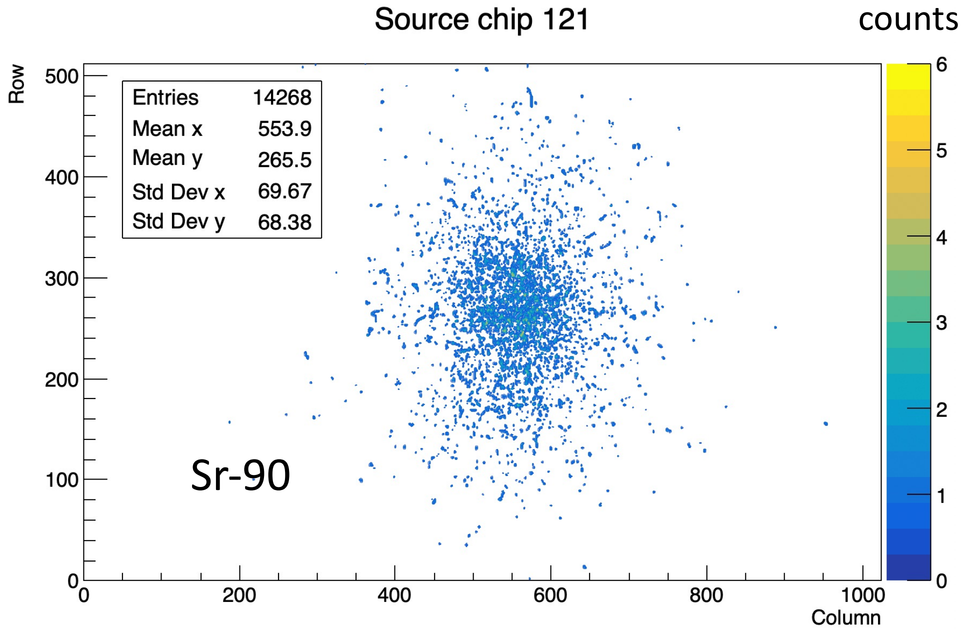
threshold distributions for each chip before tuning

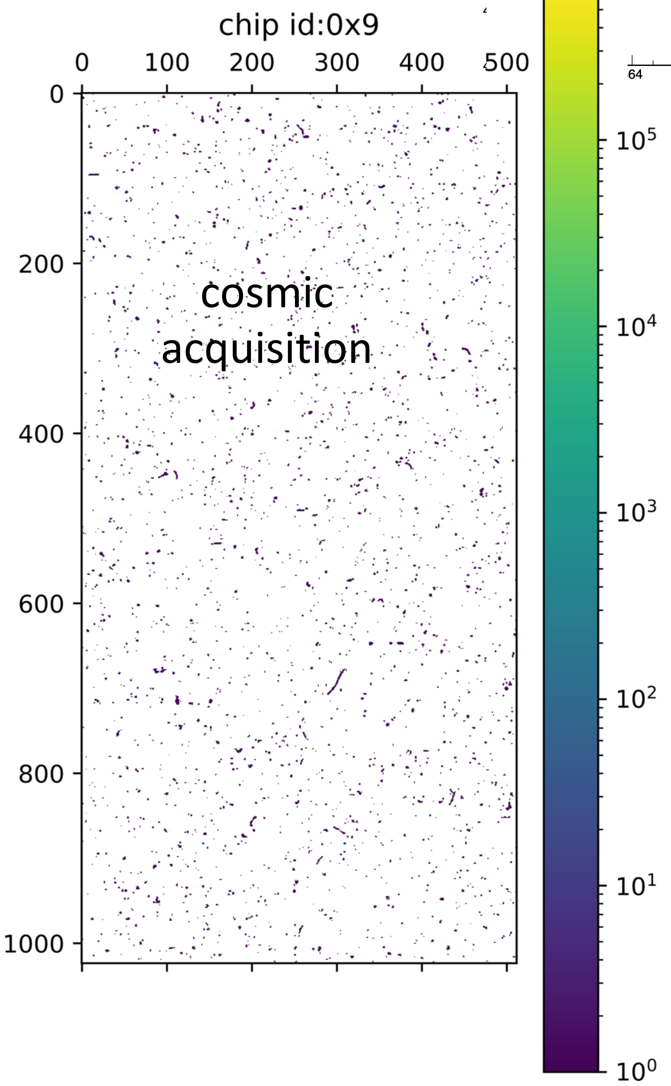
In-pixel charge injection to measure the comparator threshold

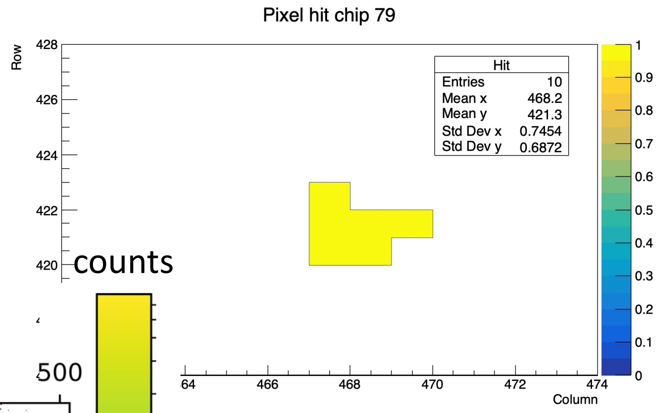
- Analogue signal ramp up
- At a given charge level (threshold), pixels will give hits
- Threshold and electronic noise (uncertainty on threshold) from the S-curve
- Tuning of the threshold between chips (~ 150 e)

Test data acquisition



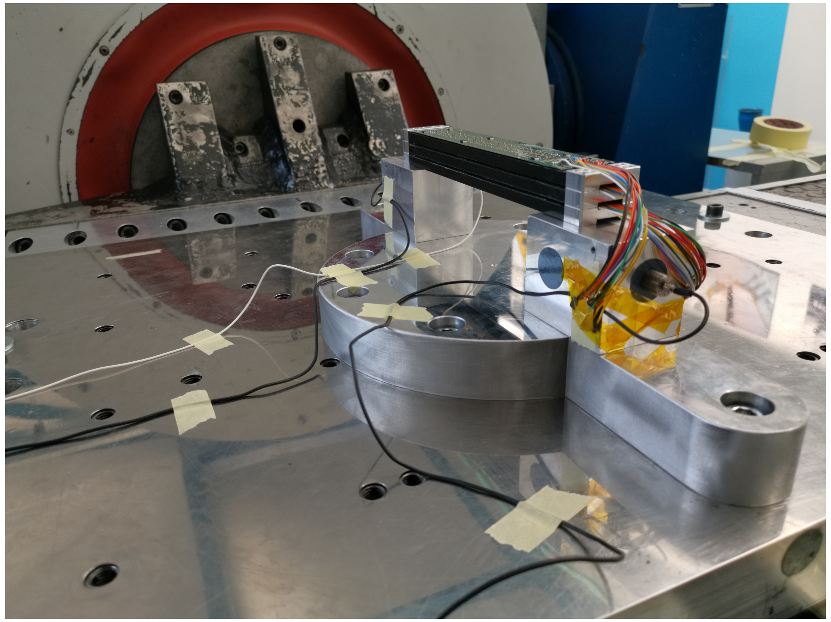


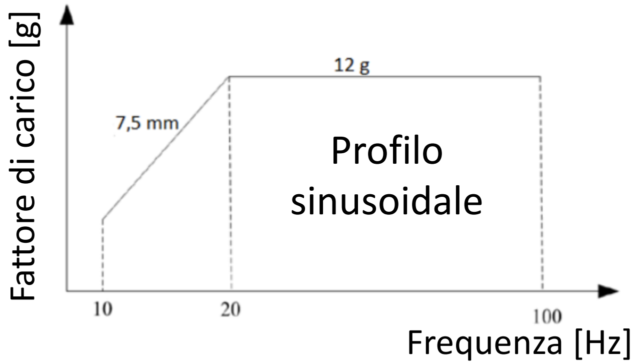


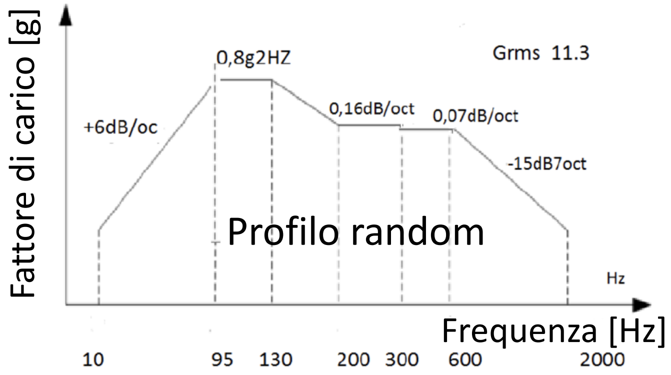


Vibration tests

- Carried out at SERMS s.r.l. in Terni, Italy
- Sinusoidal and random vibration profiles given by Chinese Space Agency for space qualification
- Simulate the vibration profile and the stresses of the launch
- Stress applied on the three axes of the DUT
- Accelerometers on the DUT and on the fixture
- Search for resonances
- HIC, Stave, Turret: **passed**
    - 1st mode ~ 800 Hz >> requirements
    - Functional electrical tests compatible before and after vibration

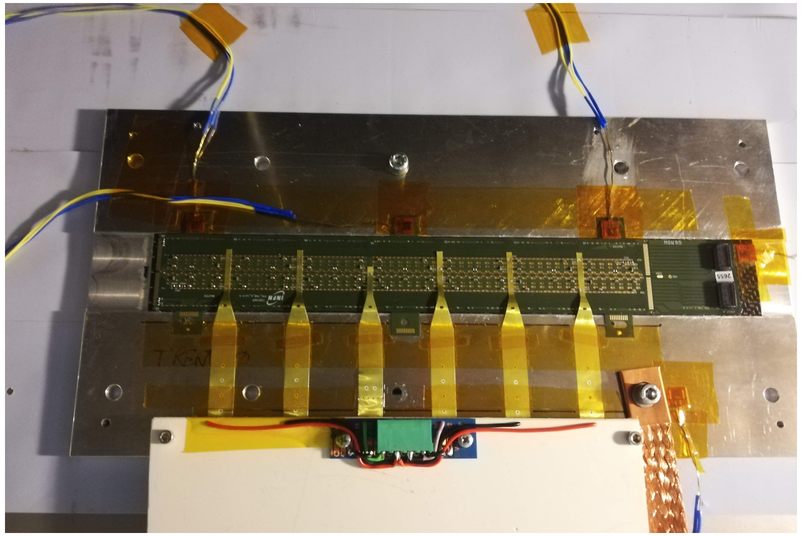




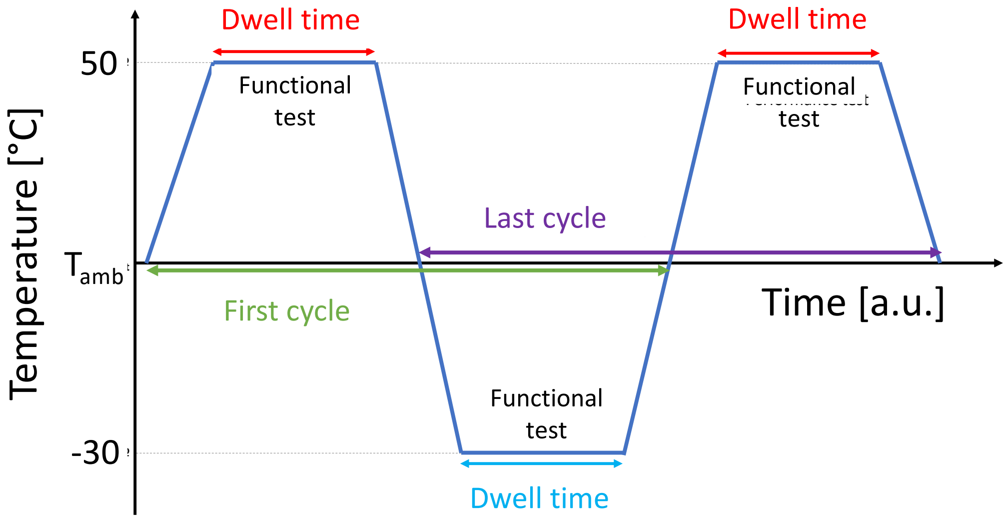


Thermal-vacuum tests

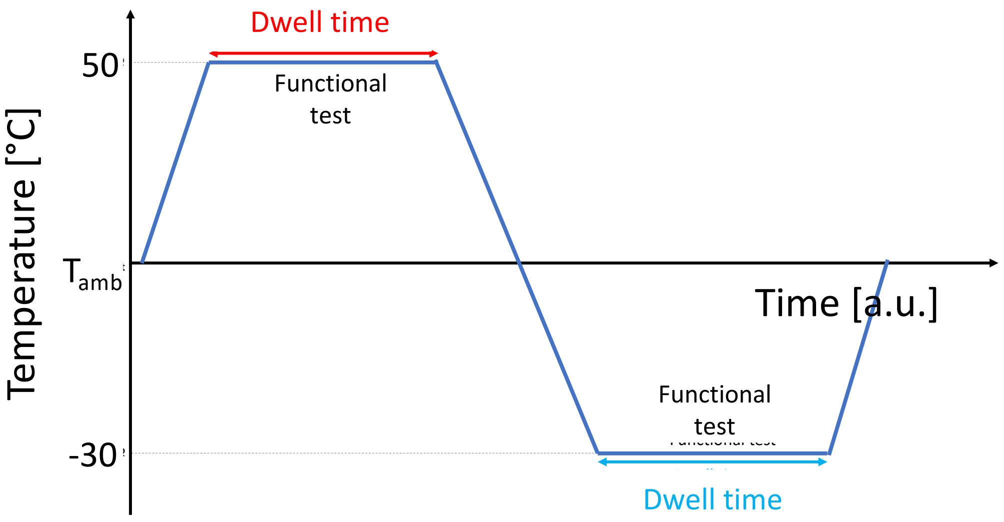
- Thermal qualification
- CSES operative temperatures up to 35°C
- Functional tests during thermal cycles
- HIC: stable performance during and after thermal cycles



First/last ciclo



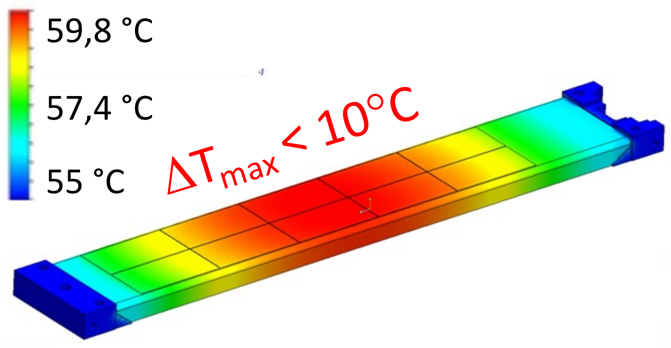
Intermediate cycles



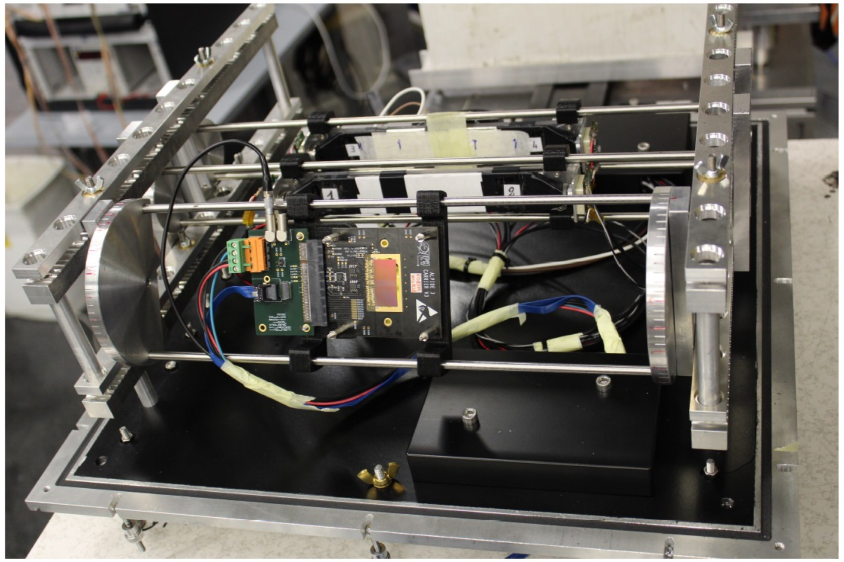
Heat dissipation

- Heat dissipation in vacuum
- Radiative dissipation negligible at these temperatures
- Structure optimised to **remove heat by conduction**
- Heat passes to the carbon fibre cold plate with oriented fibres to facilitate heat conduction
- Aluminium support and heat collection structure connected to the radiative plate
- Double thermal interface

- Operating temperature -10°C to +35 °C

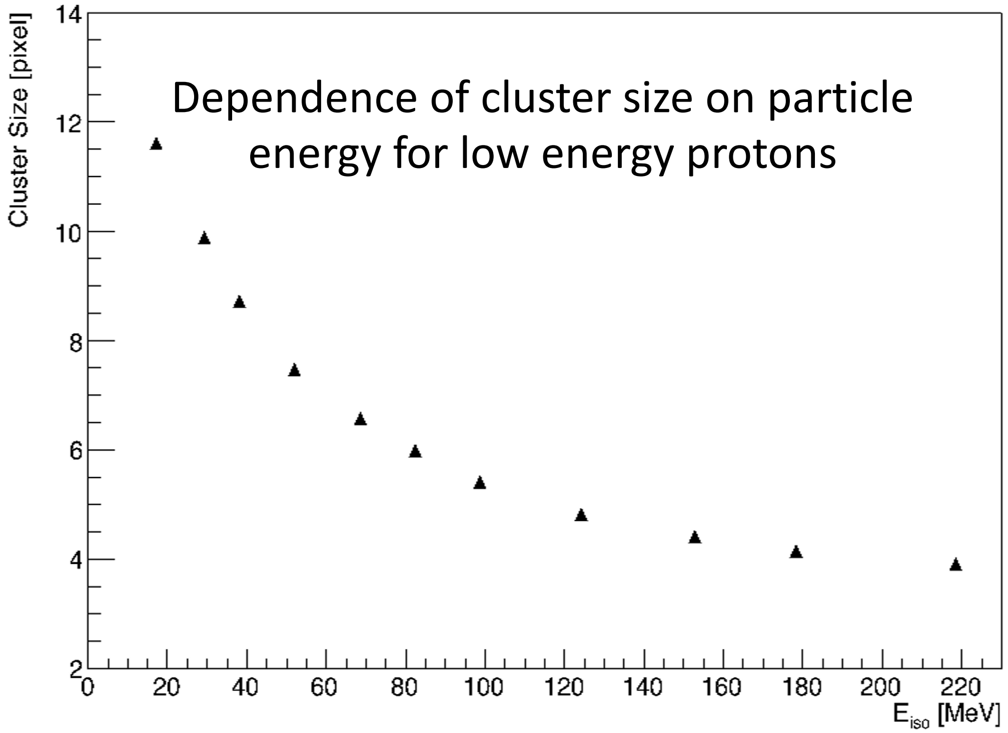


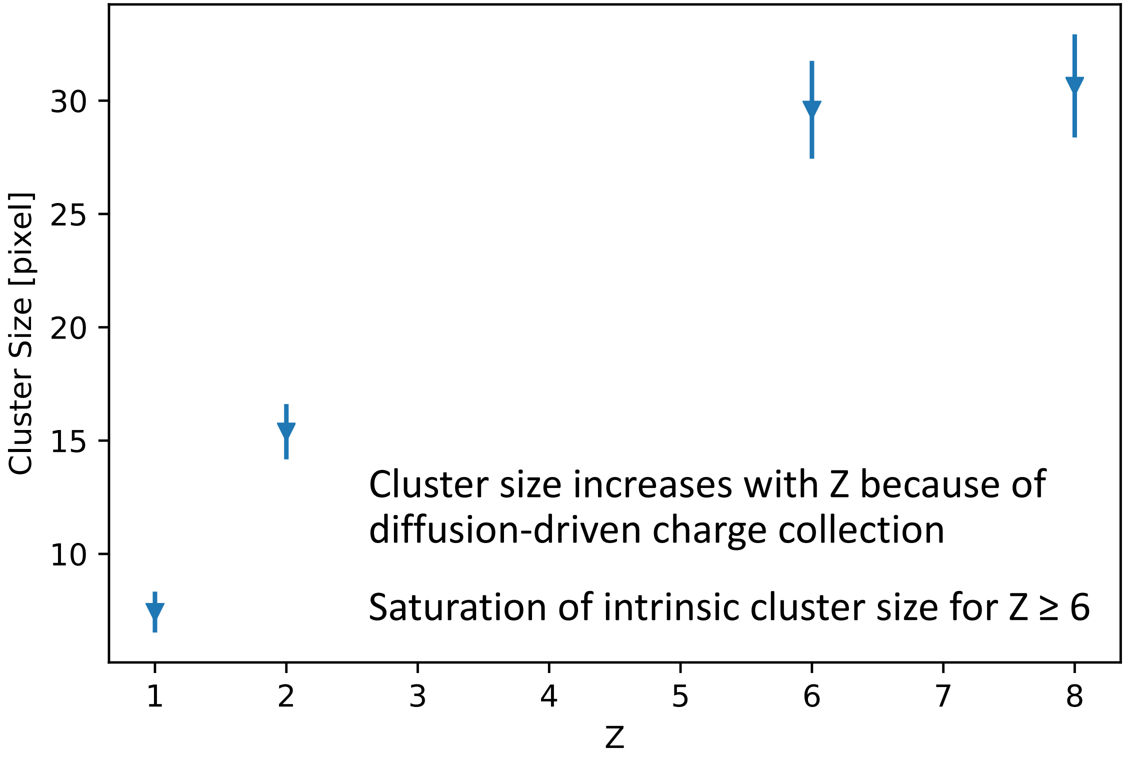
ALPIDE response to low energy ions



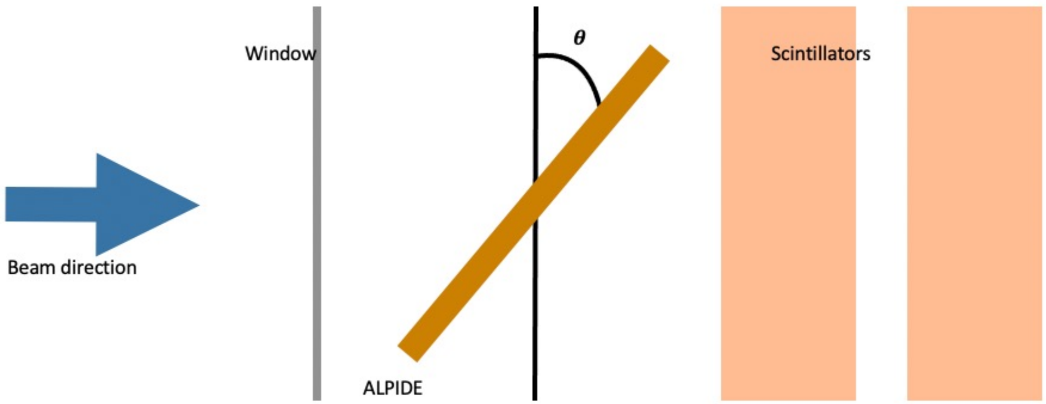
- ALPIDE characterised for MIPs detection
- Response to HEPD energy range had to be characterised
- Tests with 20 MeV protons @ Trento Proton Therapy Centre
- Tests with nuclei @ LNS, Catania (62 MeV/a.m.u.)

- Fully digital readout (no dE/dx measurements)
- Observable: cluster size

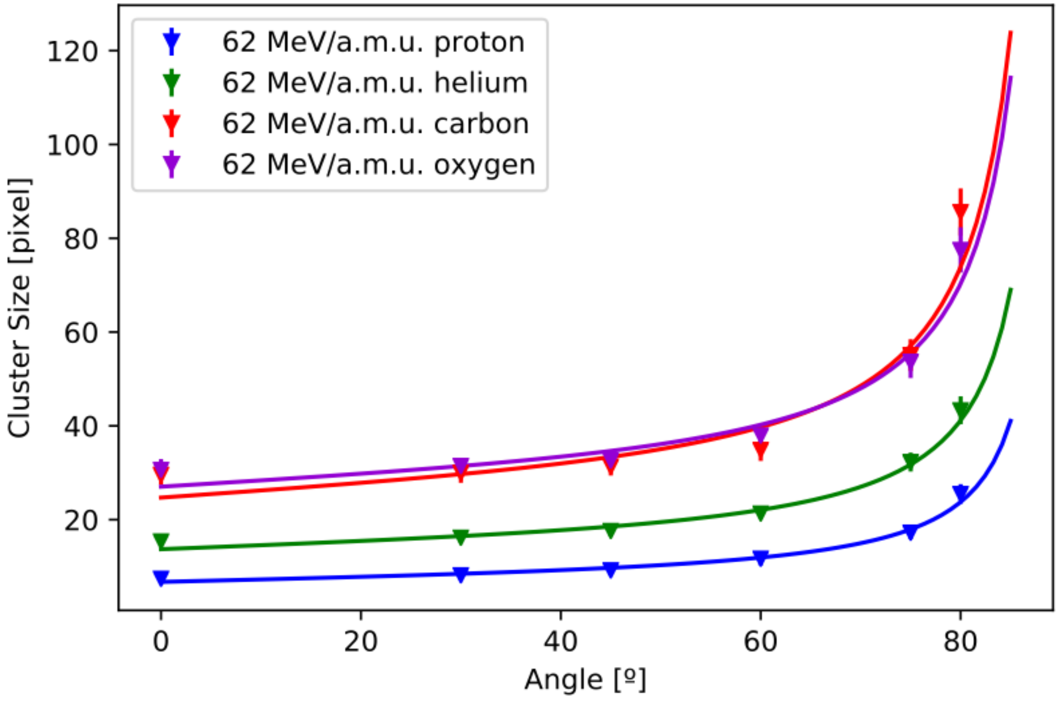


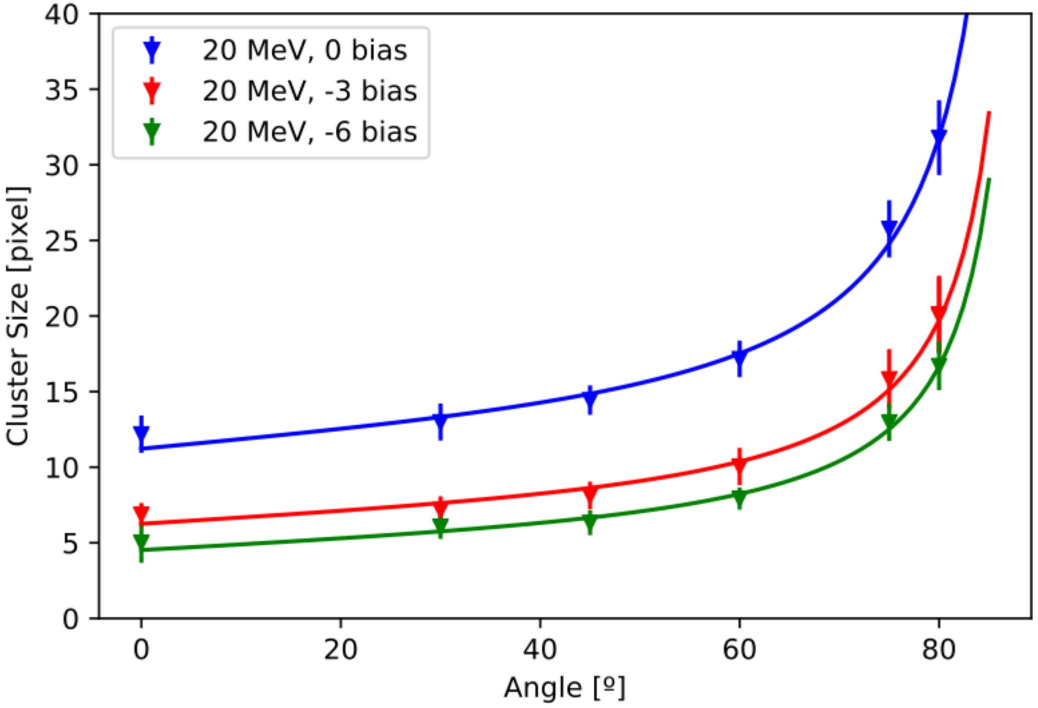


Measurements at different angles



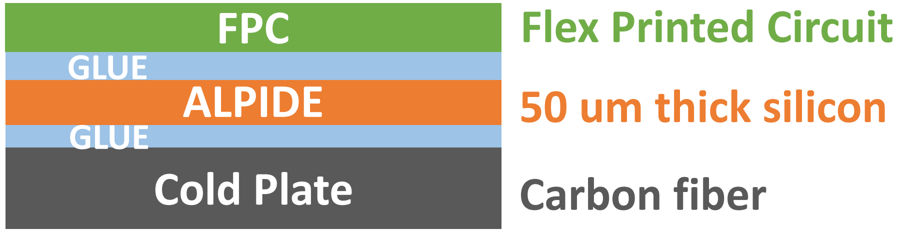
When the back bias is applied, the charge collection is more efficient and the cluster size decreases.





Material budget for different flex printed circuit choices

- Low energy threshold
- Reduced multiple scattering



Stave element	Material	Thickness [µm]	X_0 [%]
Glue	Araldite	130	0.029
ALPIDE	Si	50	0.053
FPC lines	**Cu**	**36**	**0.251**
FPC	Kapton	135	0.048
Cold plate	Carbon fibre	350	0.134
TOTAL			0.515

Stave element	Material	Thickness [µm]	X_0 [%]
Glue	Araldite	130	0.029
ALPIDE	Si	50	0.053
FPC lines	**Al**	**50**	**0.056**
FPC	Kapton	115	0.040
Cold plate	Carbon fibre	350	0.134
TOTAL			0.312

First table: ALICE OB FPC → copper FPC lines
Second table: ALICE IB FPC → Aluminium FPC lines

Evaluation of their effect on the energy threshold for protons and electrons

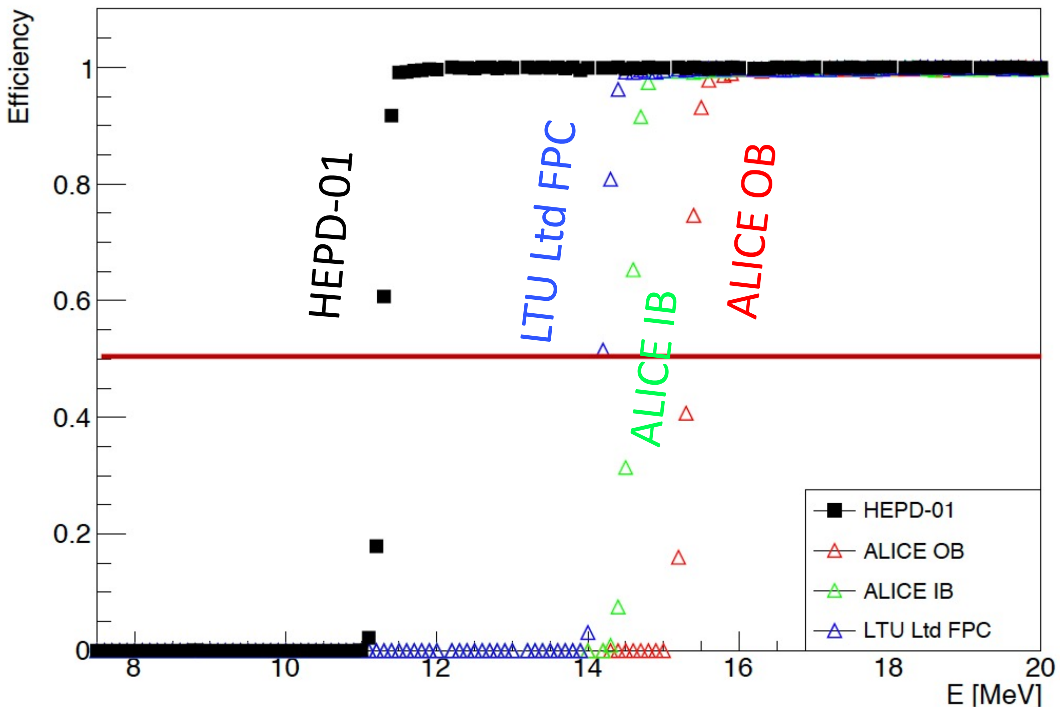
Tracker energy threshold studies

HEPD-02:

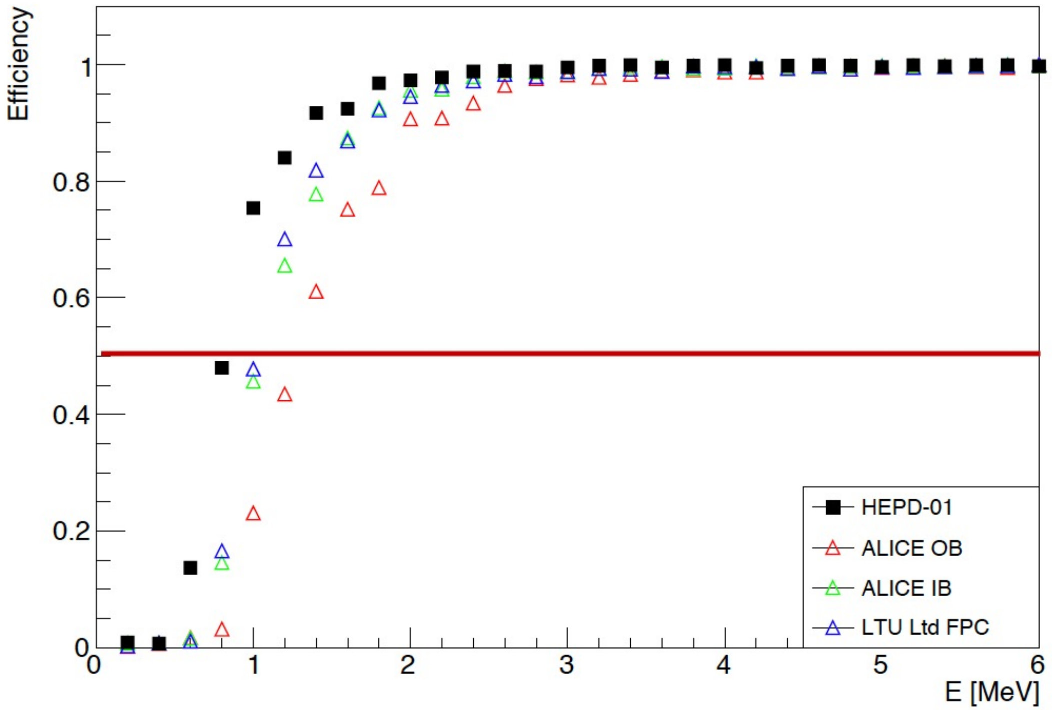
- More detector planes (but factor 6 reduction in silicon!)
- ALPIDE requires auxiliary electronics in the FPC
    - Copper lines for power supply, control and readout

Just received aluminium FPC (used for ALICE ITS2 inner barrel)

- Never tested for space
- Planned thermal-vacuum compliance tests

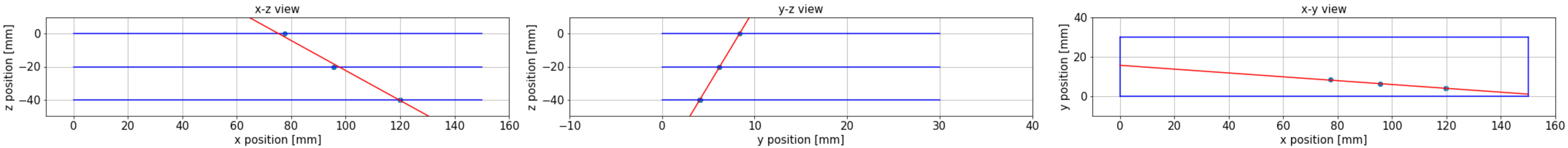


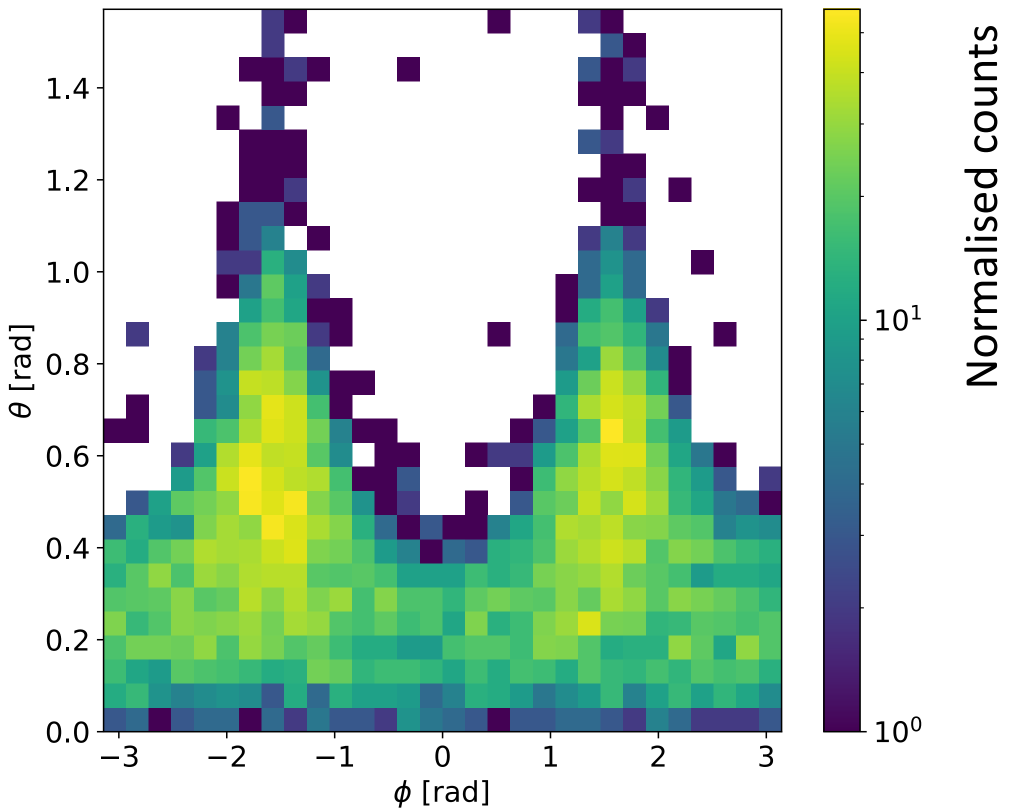
Protons



Electrons

Tracking of cosmic muons with a turret





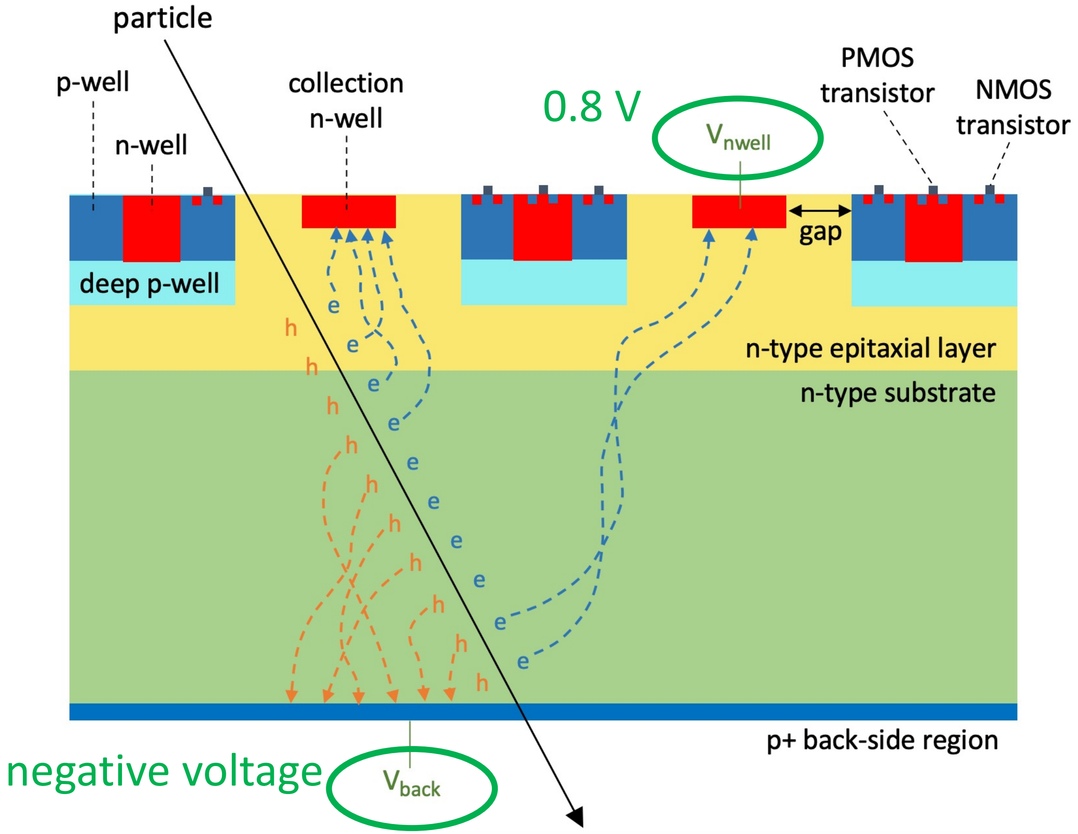
Ongoing developments

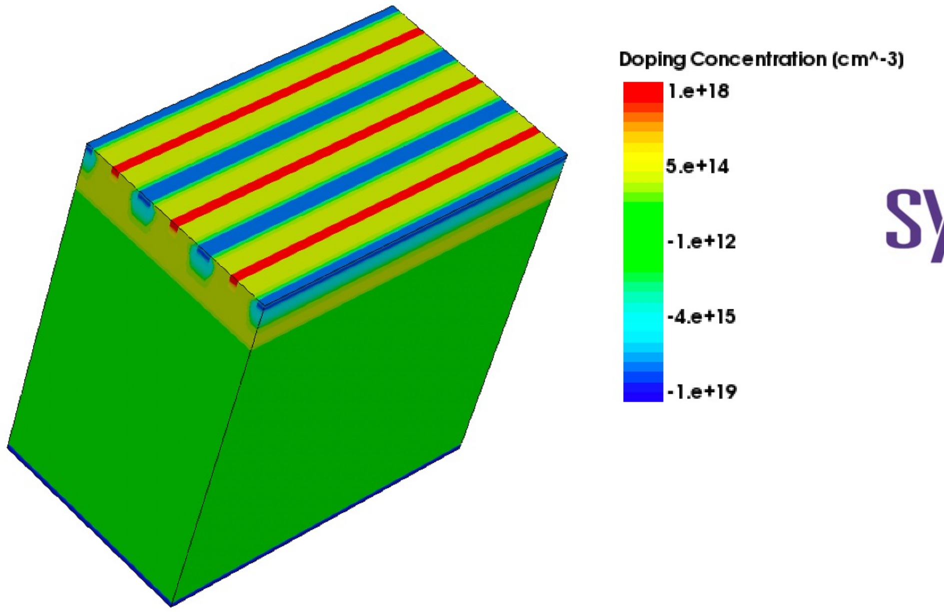
- ARCADIA
  - Fully Depleted Monolithic Microstrip Sensors
  - Strixel
- ALICE3
  - Evaluation of MAPS for time measurements, not only tracking

ARCADIA microstrip sensor

- Synopsys Sentaurus TCAD 3D simulations
- Inter-strip region wide enough to host monolithic integrated CMOS electronics
- High spatial resolution, simpler readout, lower power density
- Reduce complexity of detector assembly (no 1-by-1 strip bonding)

Microstrips: up to now hybrid
Our proposal: strip-shaped CMOS monolithic sensor
(1.2 cm length, 25μm and 10μm pitch)

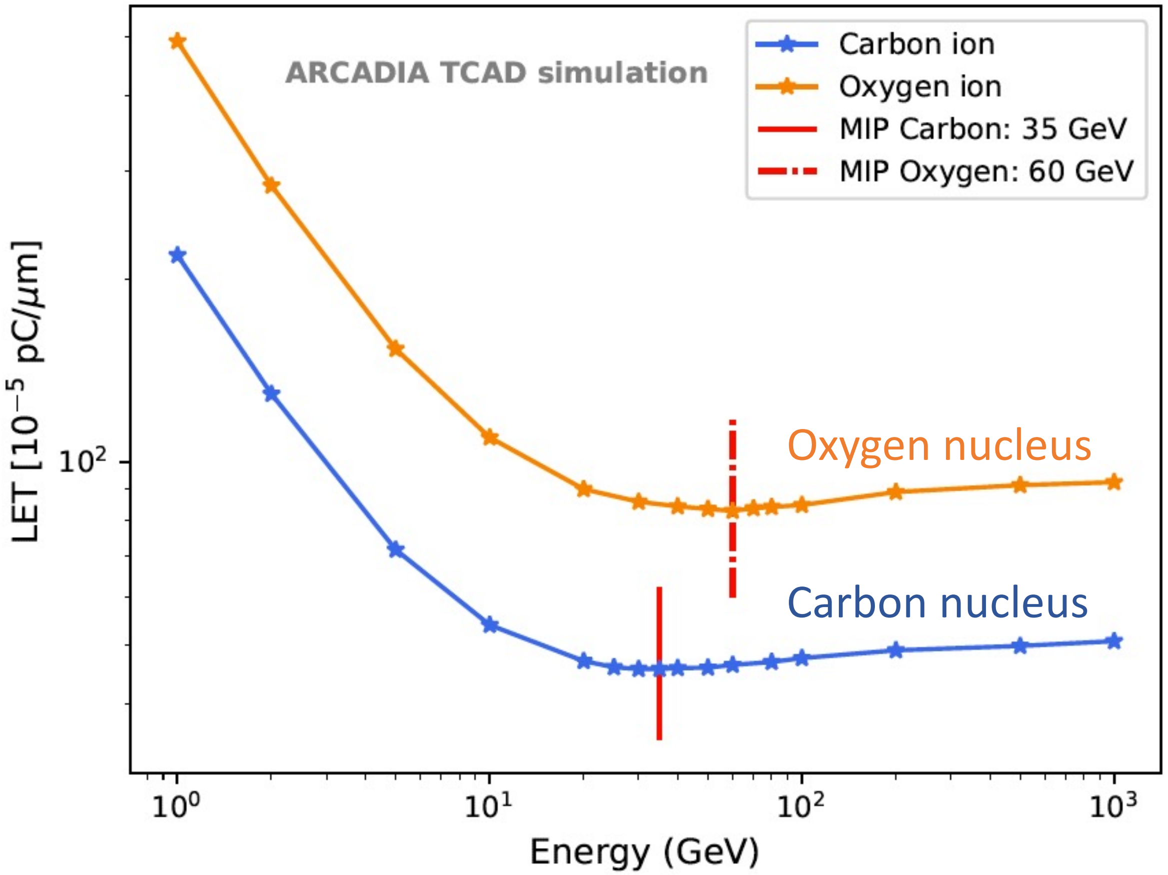


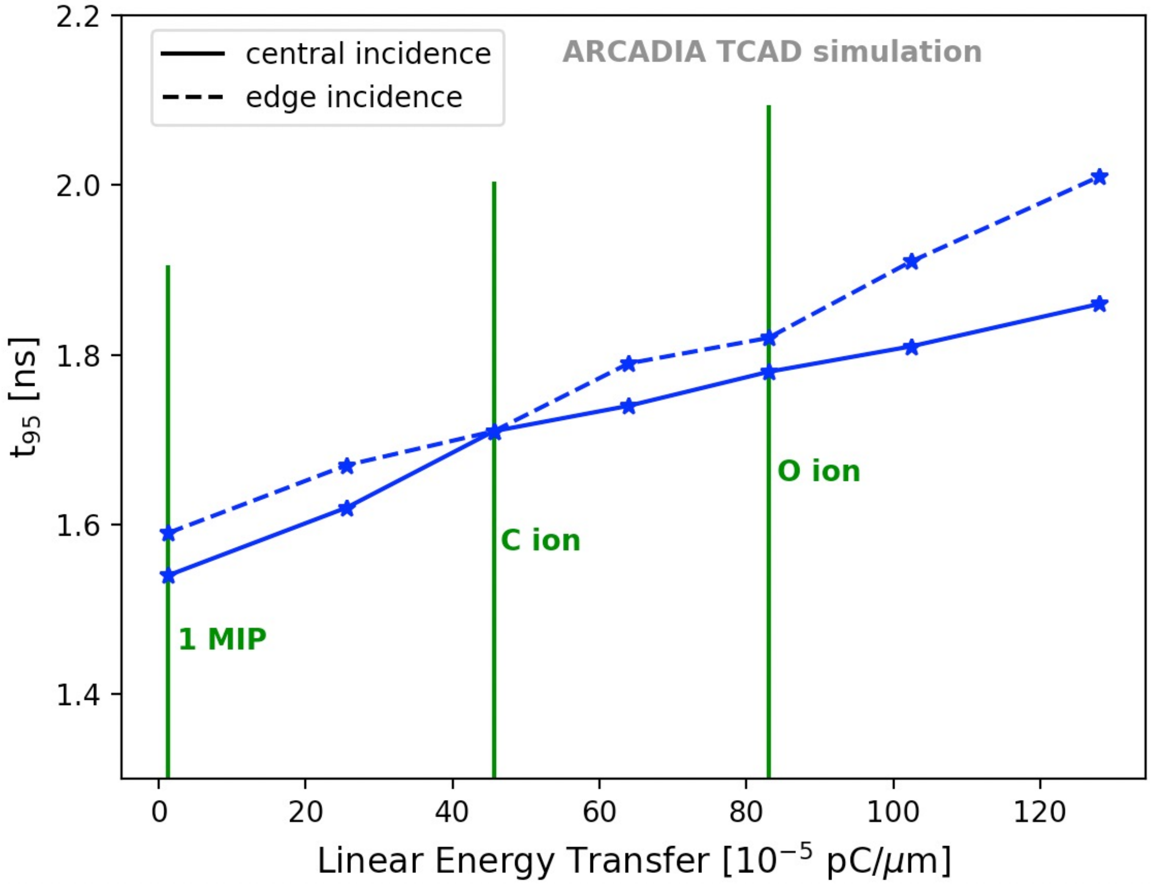


- Optimised geometry → 95% charge collection in
  - ~ 1.6 ns (with deep p-well)
  - ~ 1.2 ns (without deep p-well)

Heavy ion nuclei

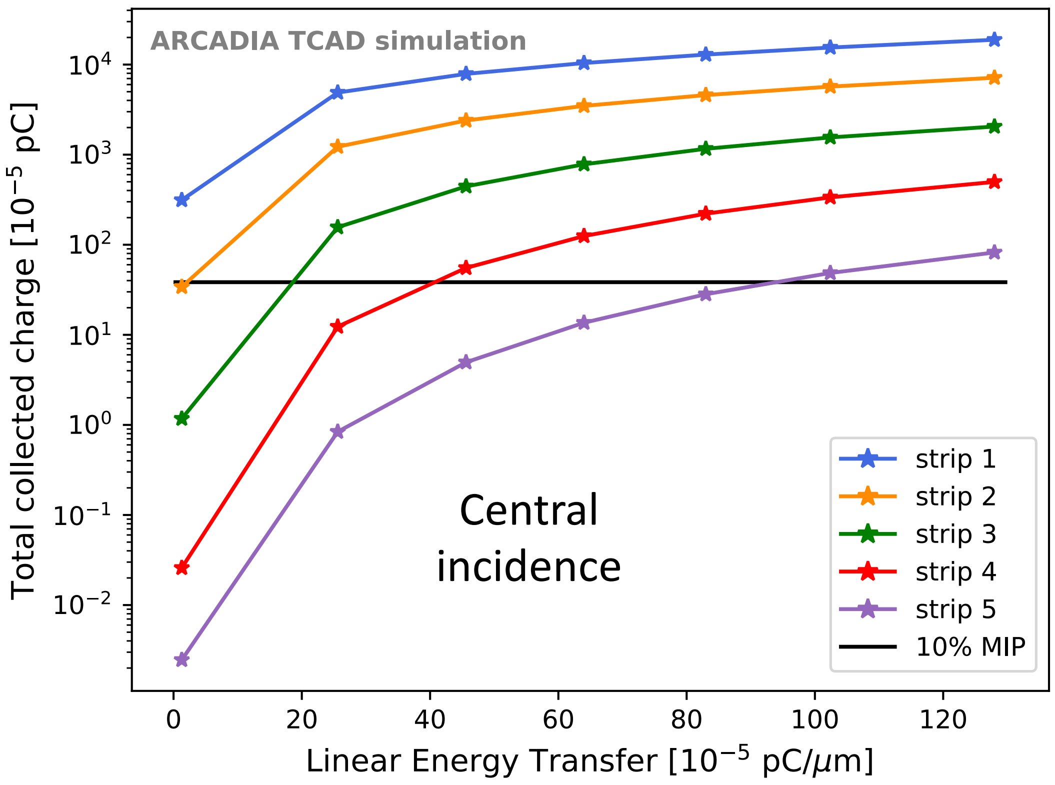
- 95% collection time raises by 300-400ps over a factor 100 increase in LET
- Never > 2 ns with 50μm thick sensors



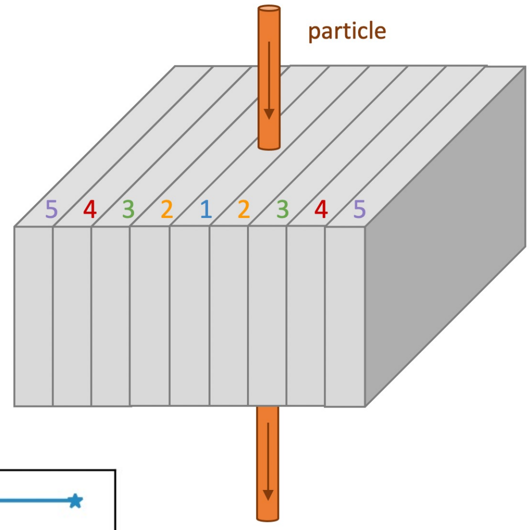


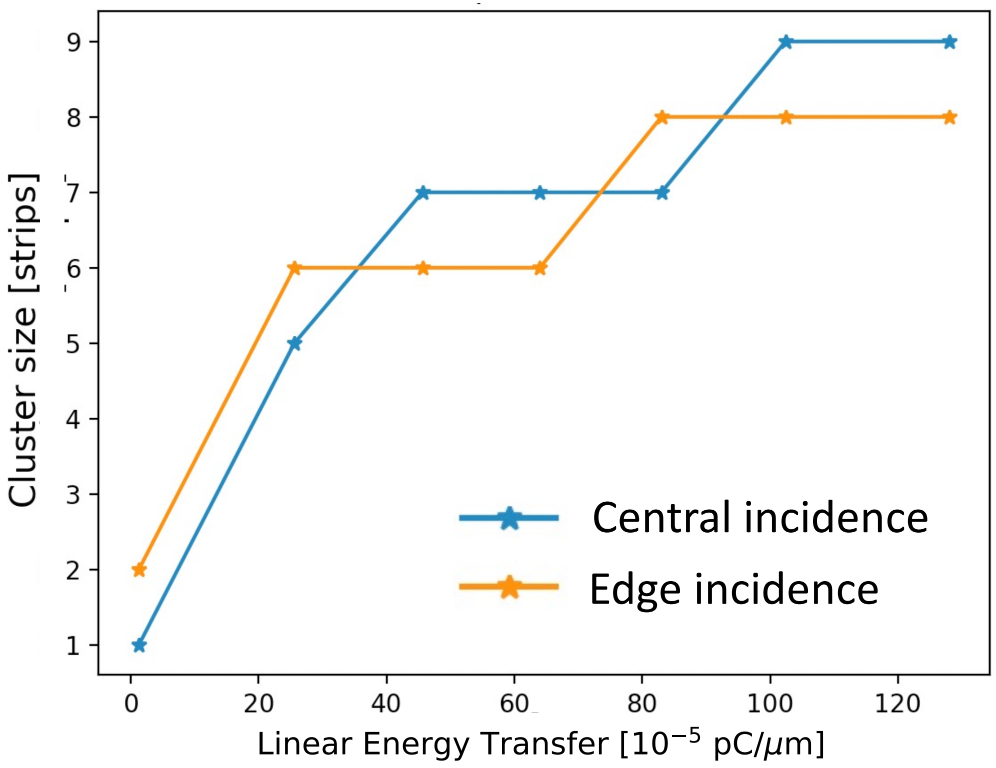
Geant4: https://github.com/mcentis/muonOnSilicon

Charge sharing

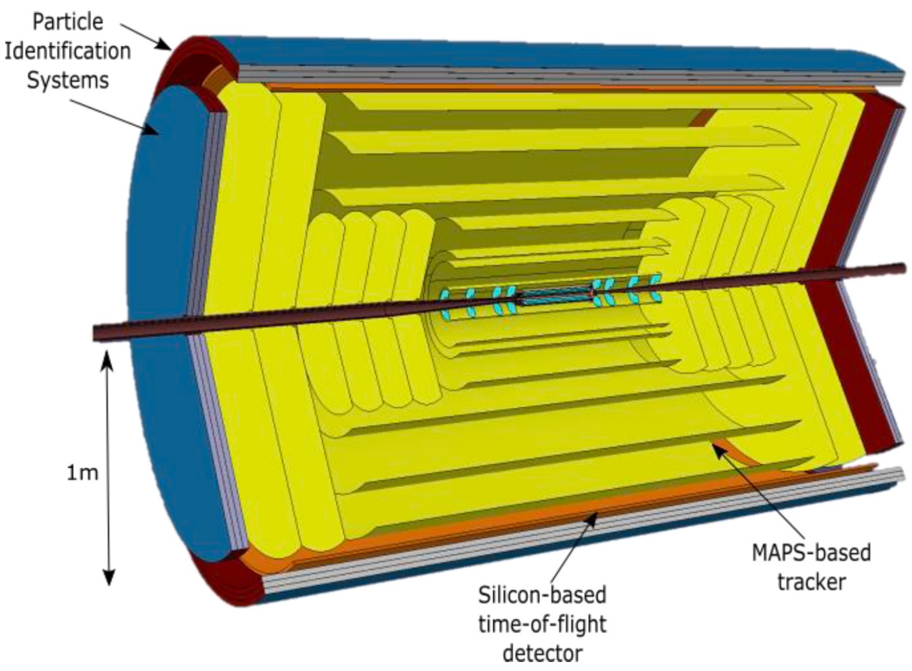


300μm thick sensors





Developments for fast timing



Time-Of-Flight detector for ALICE3

Under investigation: modification of ARCADIA pixel layout
Goal: timing resolution ~ 20 ps

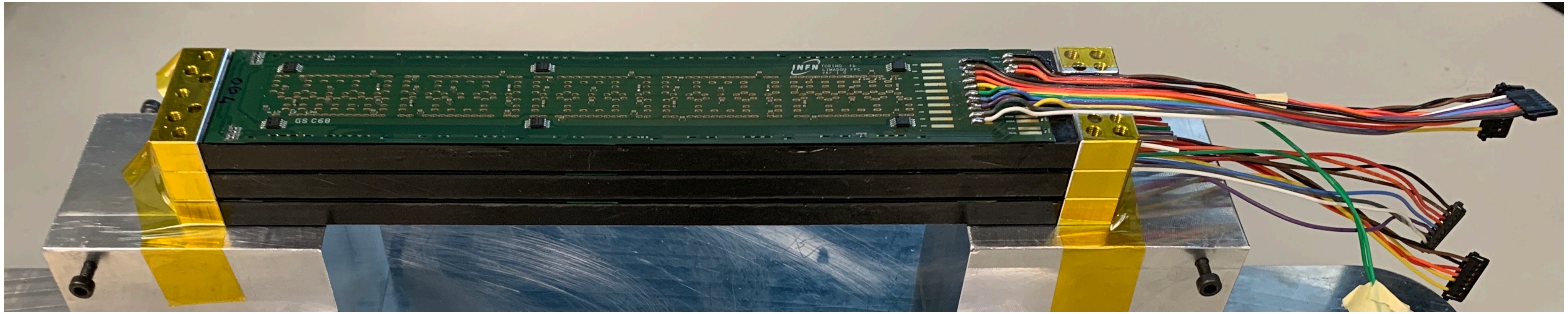
Advantages of MAPS:
- Excellent radiation hardness demonstrated for several processes
- Cost-effectiveness, on chip digitization, time-tagging and data pre-processing

Challenges of MAPS:
- Fast collection (100s of ps) and low capacitance at the same time
- Low threshold: uniformity and excellent shielding from interference
- 20ps resolution still not demonstrated experimentally

ALICE

Conclusions

- First application of MAPS for space satellite-based experiment
- Design has been finalized
- Addressed space requirements (power consumption, vibration, heat dissipation, energy threshold, data rate…)
- Engineering model phase almost completed
- Focus on characterisation and QA control of production
- First acquisition tests with cosmic rays and sources
- Mass production for qualification model is starting
- Further developments on monolithic sensor for space, tracking and timing applications




Thank You