Sensor development and test

Ester Ricci
Ester.ricci@unitn.it

Università di Trento
INFN – TIFPA

SPES Kickoff meeting,

The APP group @ UNITN

Astro Particle Physics - Laboratory

Constituted at the beginning of 2017

Group composition:

- 1 Full professor: R. Battiston
- 2 Associate professors: R. Iuppa, P. Zuccon
- 4 Fixted term researchers: F. Dimiccoli, F.M. Follega, A. Perinelli, E. Ricci
- Dottorandi: M. Babu, G. Brianti, L. Cavazzini, A. Dass, A. Lega, D. Mascione, R. Nicolaidis, F. Rossi

INFN-TIFPA members connected to the group:

- 2 researchers: F. Nozzoli, W. Burger
- 1 technologist: C. Neubuser
- 1 junior researcher: V. Vilona

Two core activities:

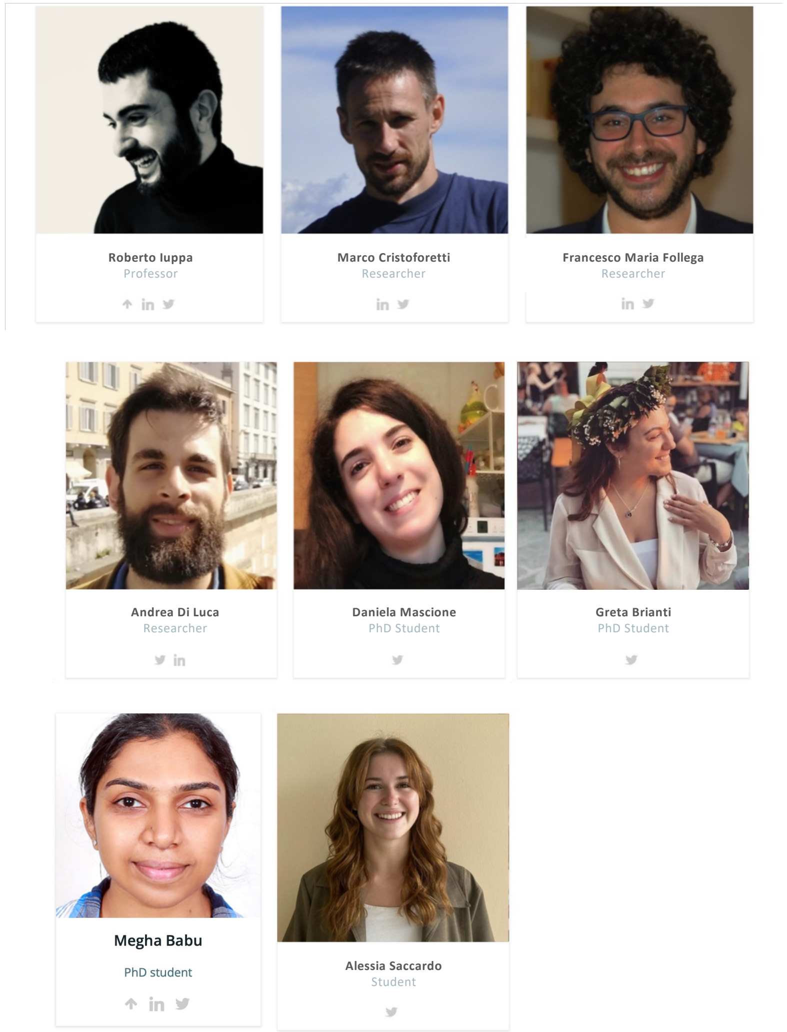
- hardware development for space experiments
- machine learning techniques for data analysis in high energy physics

DEEPPP initiative

The **Deep Learning for Particle Physics** initiative is the software and analysis part of the APP group. They work on ATLAS on:

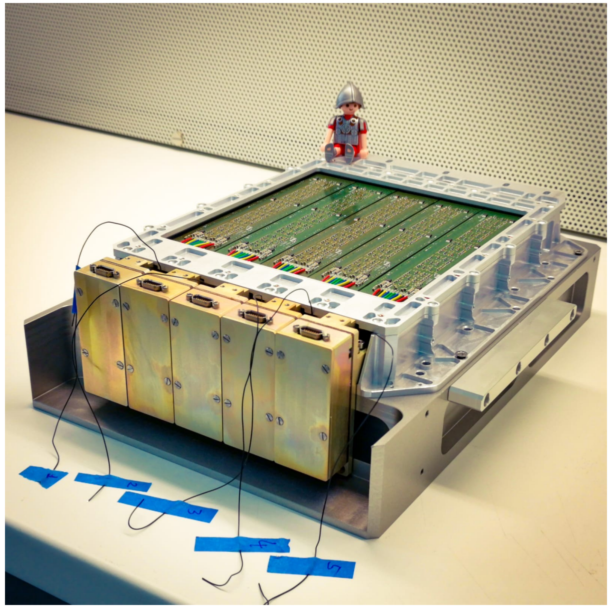
- Data quality monitoring (online and offline)
- Taggers development
- R&D for future online trigger implementation

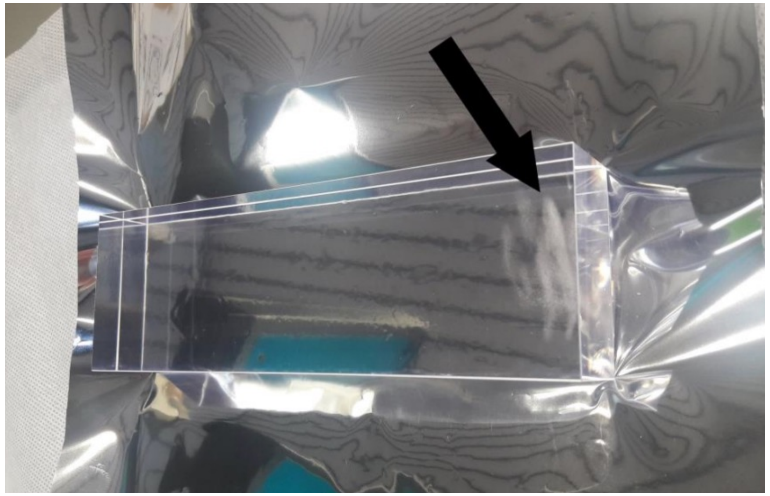
And on Limadou data analysis



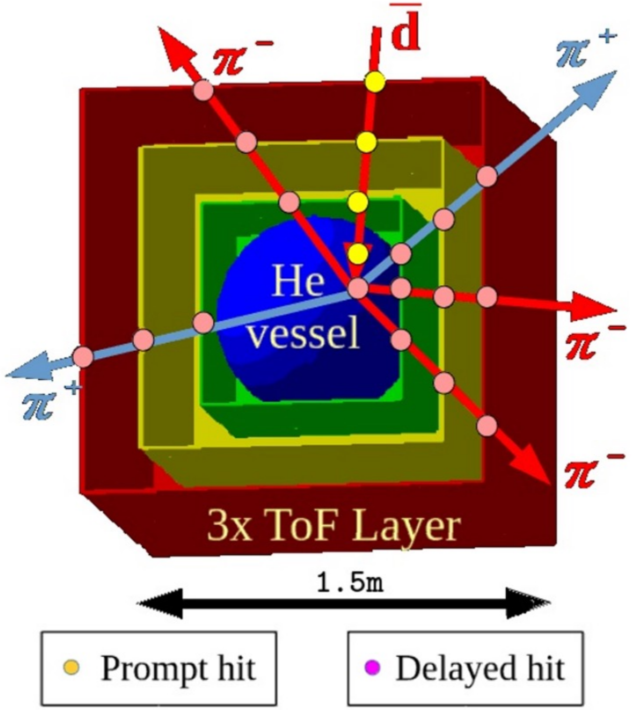
The hardware development team

HEPD-02

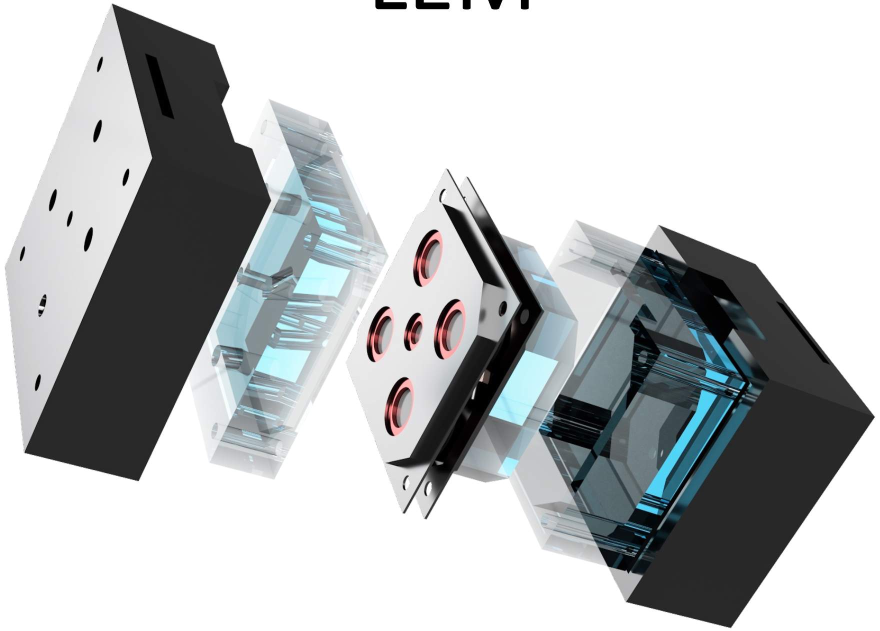




ADHD

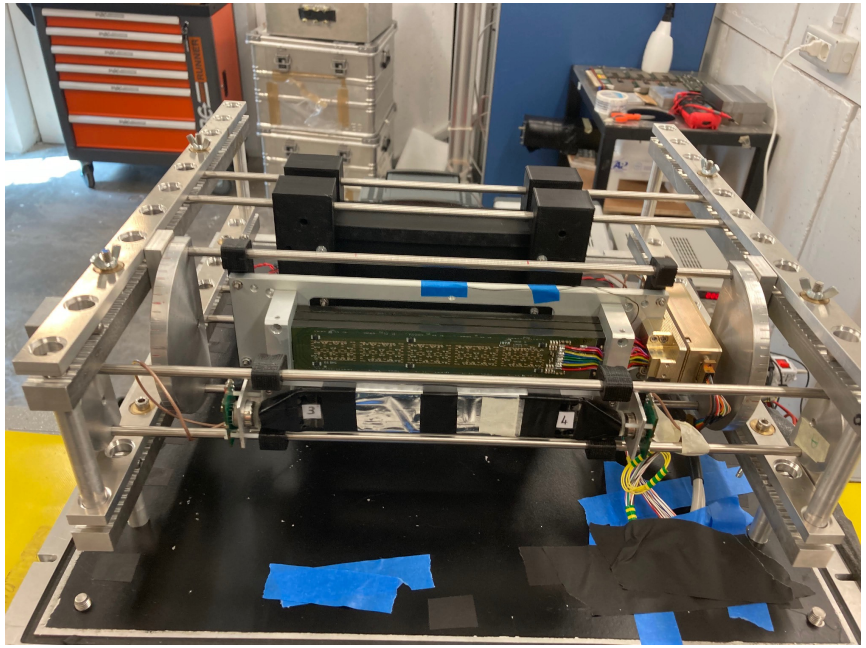


LEM

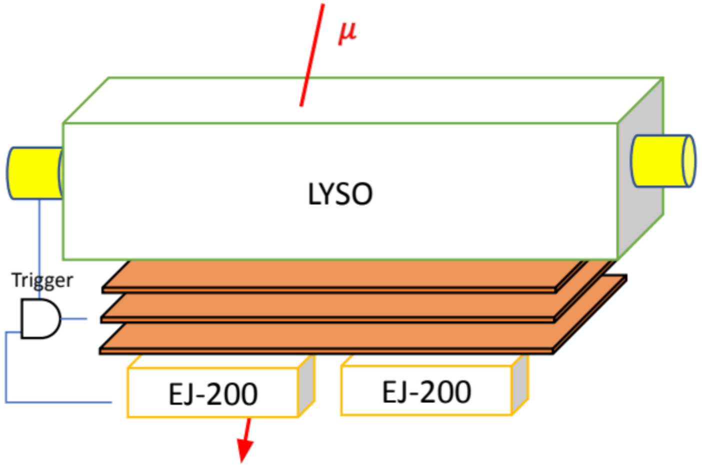


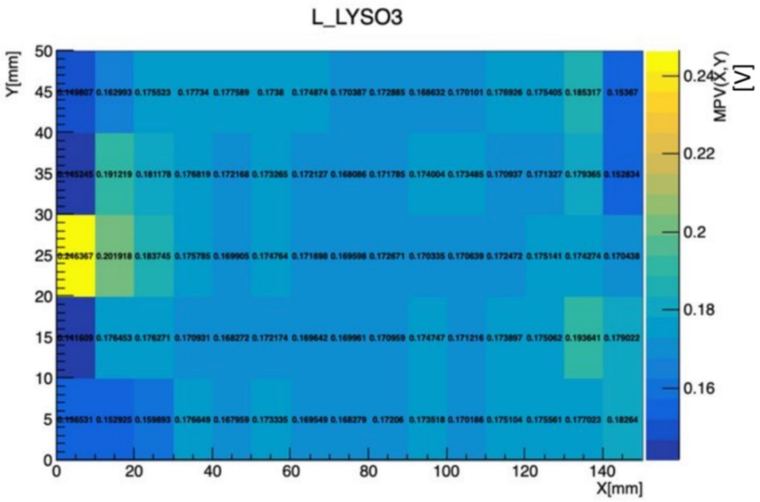
Team: R. Iuppa, A. Lega, R. Nicolaidis, F. Nozzoli, E. Ricci, P. Zuccon

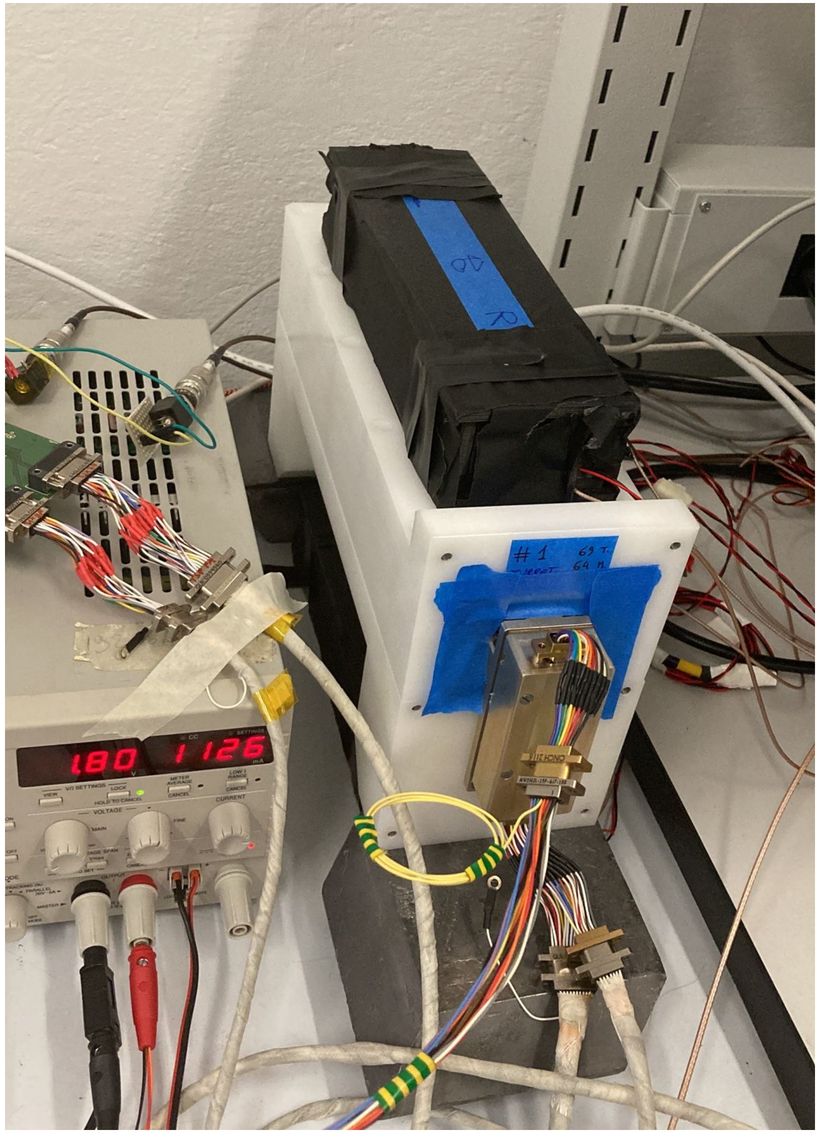
LYSO characterisation



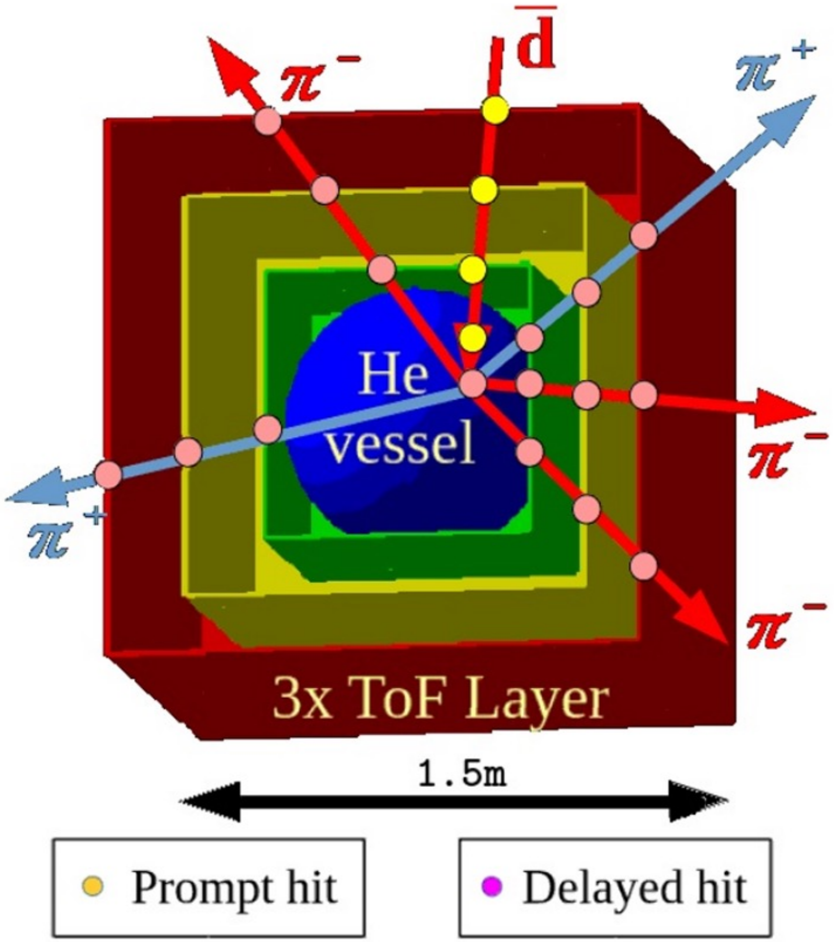
LYSO + HEPD-02 turret
Beam tests



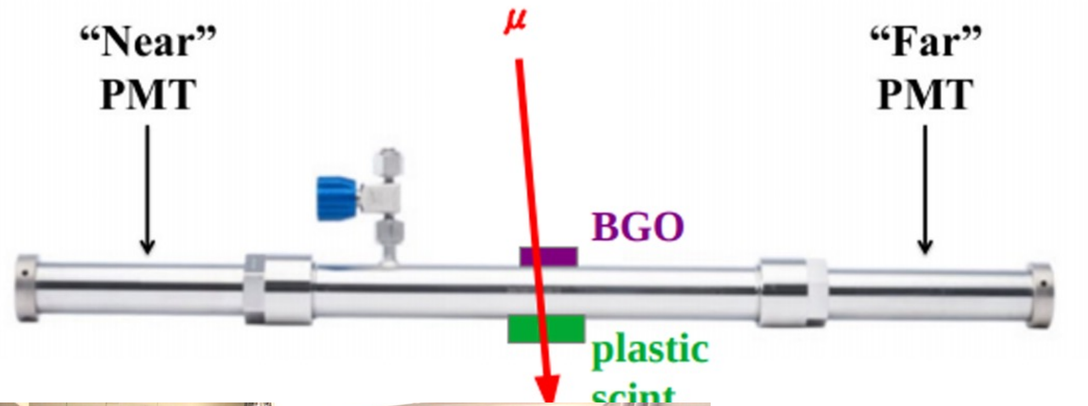


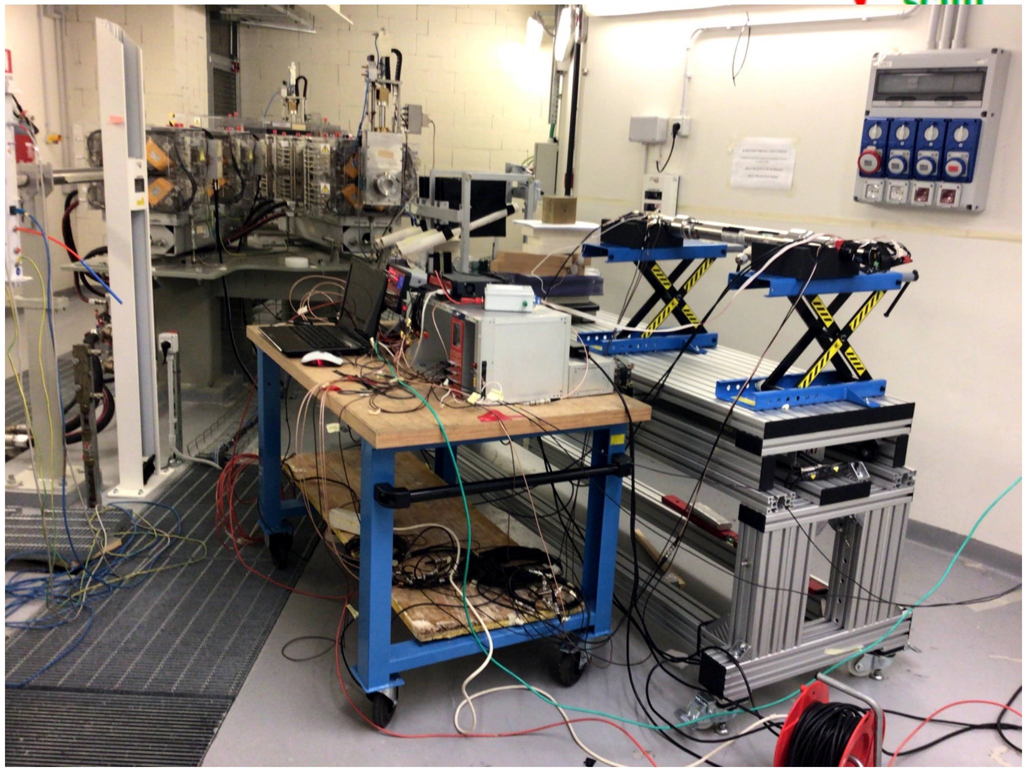


ADHD



PRIN project taking off





LEM detector

- LEM: Compact particle spectrometer (10 x 10 x 10 cm^3)

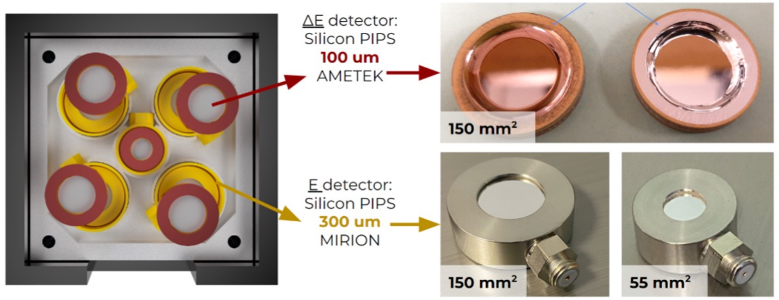
- Active collimation
  standard tracking spoils direction (multiple scattering)

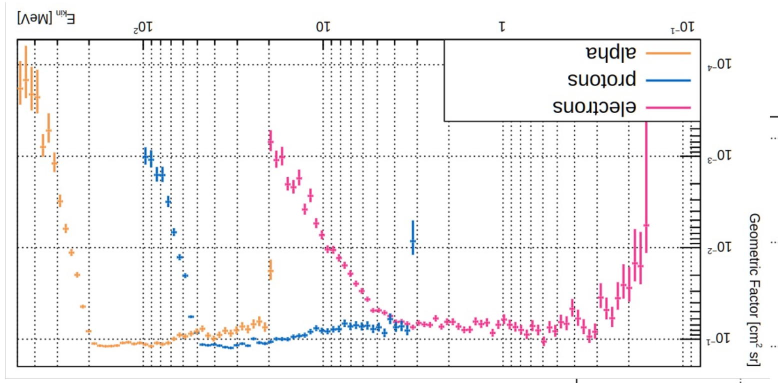
- **ΔE - E** technique: Energy - PID
  - e- [0.1 - 7] MeV
  - proton [3 - 15] MeV
  - alpha [11 - 200] MeV

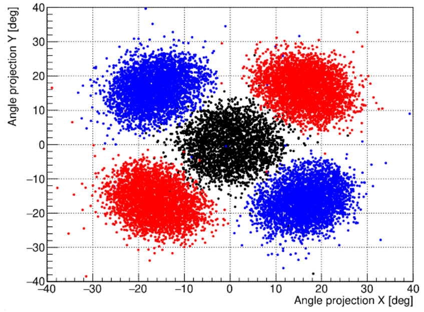
- Angle res:
  - ~12 degs e-
  - ~6 degs protons/alpha

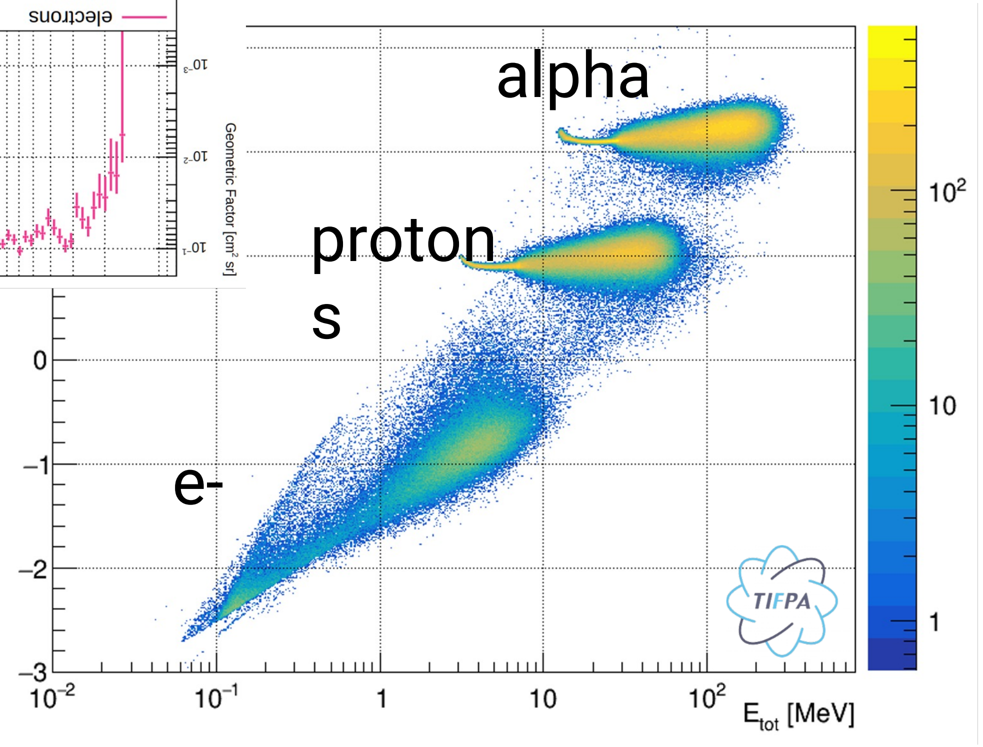
- Geometric factor ~0.1 cm^{2}sr

  - Two operation modes:
    - List mode (below 1 kHz)
    - Histo mode (trig rate > 1 kHz)







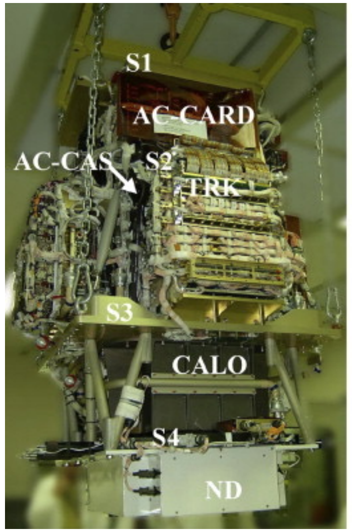


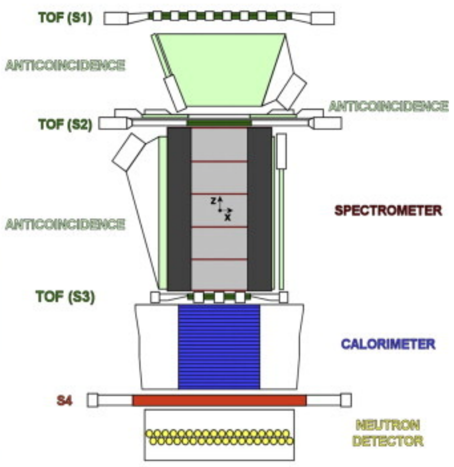
Labs and infrastructures @ Povo

Mechanical Workshop
Electronics Workshop

Magnetic spectrometers

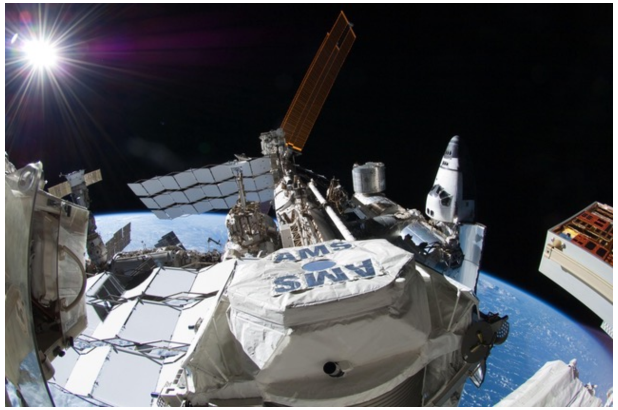
PAMELA

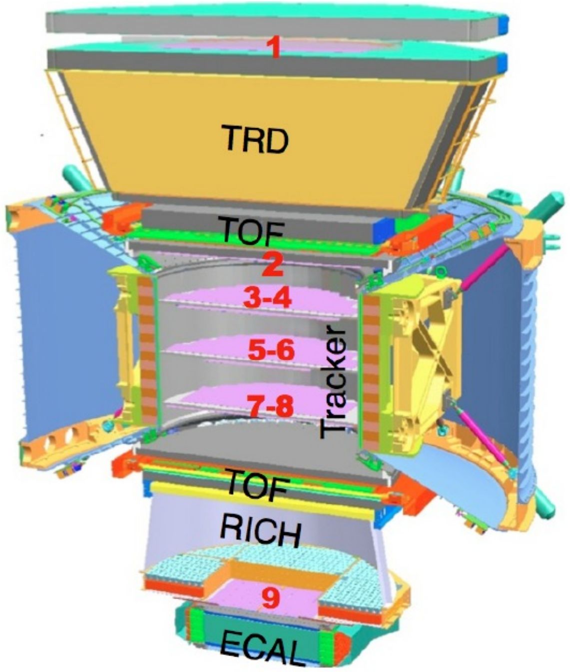




https://doi.org/10.1016/j.asr.2007.07.023

- Measurements of **antimatter fluxes and isotopic composition of cosmic rays**
- Begin of operations: June 2006
- End of operations: February 2016
- Equipped **with 6 planes of silicon microstrip detectors**
- Double sided microstrip detector
- Silicon surface: **0.13 m²**





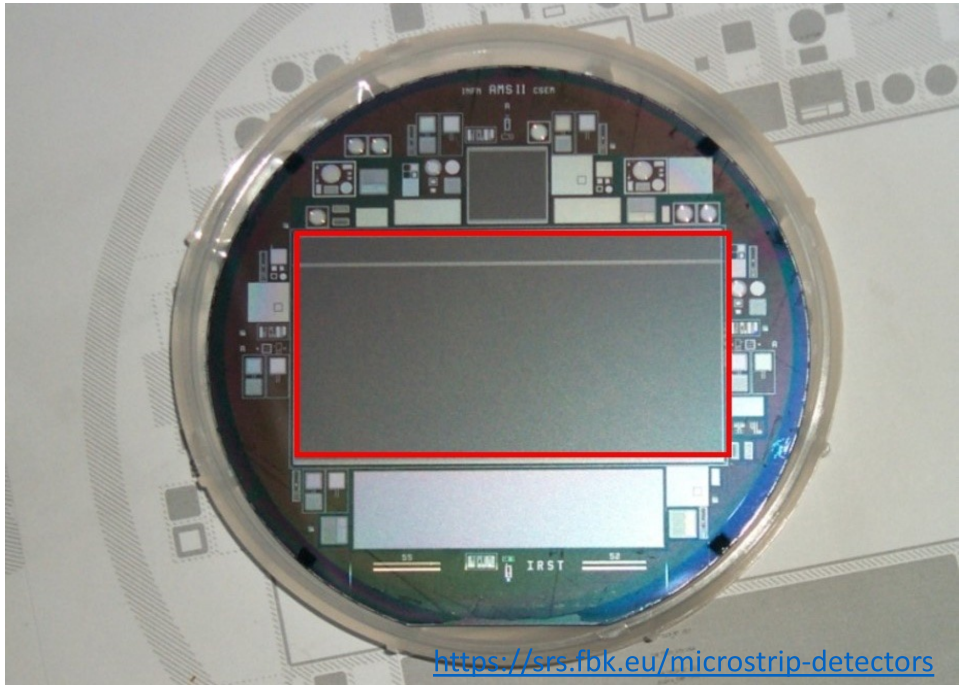
https://doi.org/10.1051/epjconf/20147000026.

AMS-02

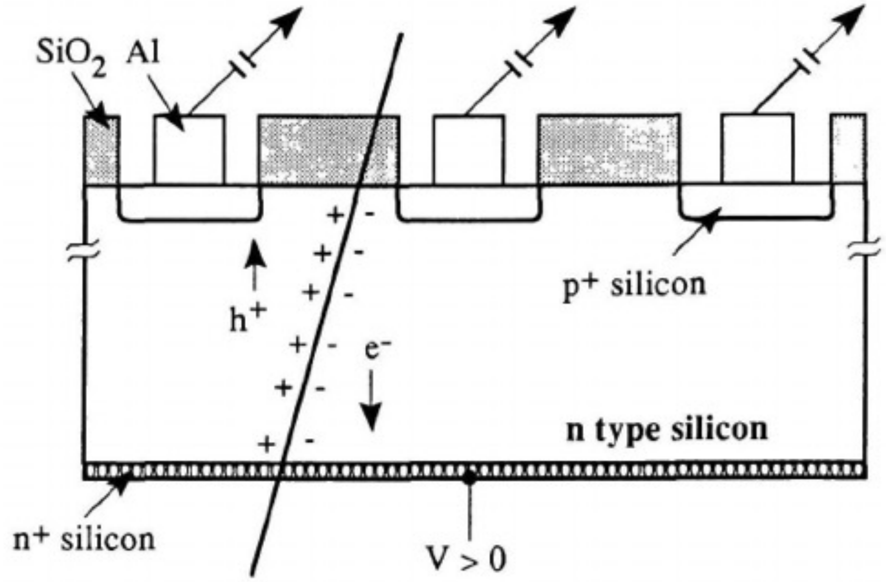
- Search of **dark matter** and study of **antimatter fluxes**
- Begin of operations: May 2011
- Equipped with **nine planes of silicon microstrip detector**
- Double sided microstrip detector
- Silicon surface: **6.4 m²**

Silicon microstrip detectors

- Developed for vertexing and momentum measurement
- Silicon microstrip detectors are the **elective technology for tracking particles in space**
- Charged particle crossing a silicon buffer produces electron-hole pairs.
- Implanting segmented electrodes for the collection, it is possible to measure the position where the particle cross the detector.



https://srs.fbk.eu/microstrip-detectors

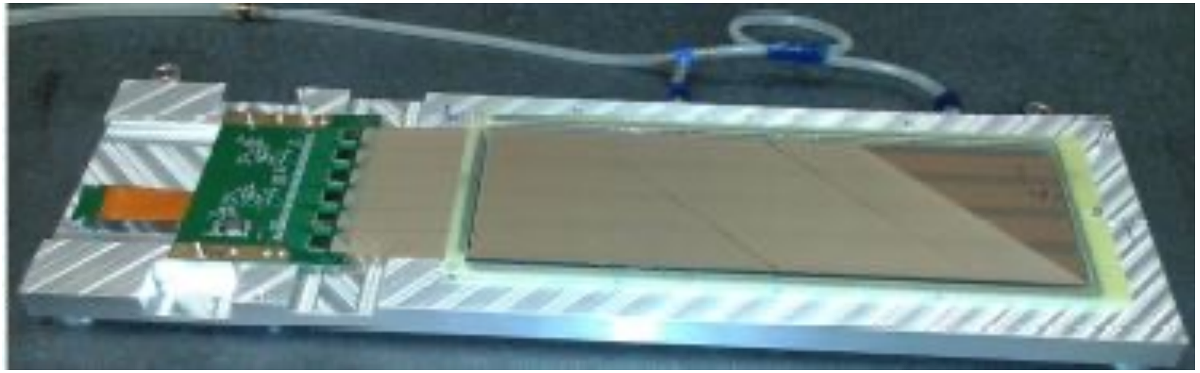


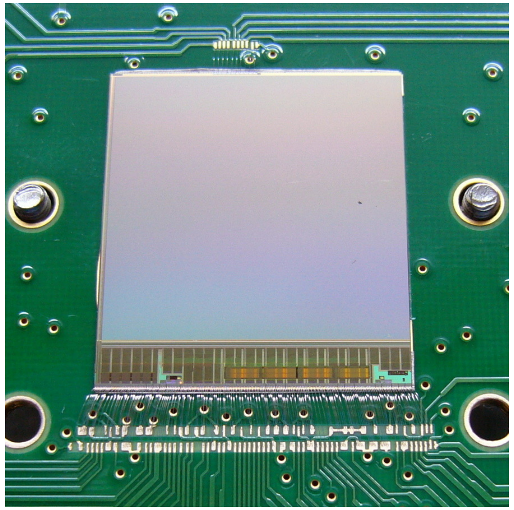
https://doi. org/10.1142/9789814360333_0001

Microstrip vs MAPS detectors

Microstrip advantages:
- Small number of channels
- Low power consumption

Microstrip limits:
- Detector procurement
- High costs (~100 $/cm^2$)
- Custom readout (high costs of procurement and integration)
- Reduced noise control due to external amplification





https://doi.org/10.1088/1748-0221/7/01/C01102

MAPS detector advantages:
- Standard CMOS procedures used allow mass production
- Lower costs (~20 $/cm^2$)
- Readout implanted on detector surface
- Small noise (amplification implanted on pixel)
- Good spatial resolution

MAPS detectors limits:
- High power consumption
- Large number of channels

Hybrid vs Monolithic pixels detectors

Hybrid pixel approach:

- A team realises the sensor structure
- A team realises the readout device

Advantages:

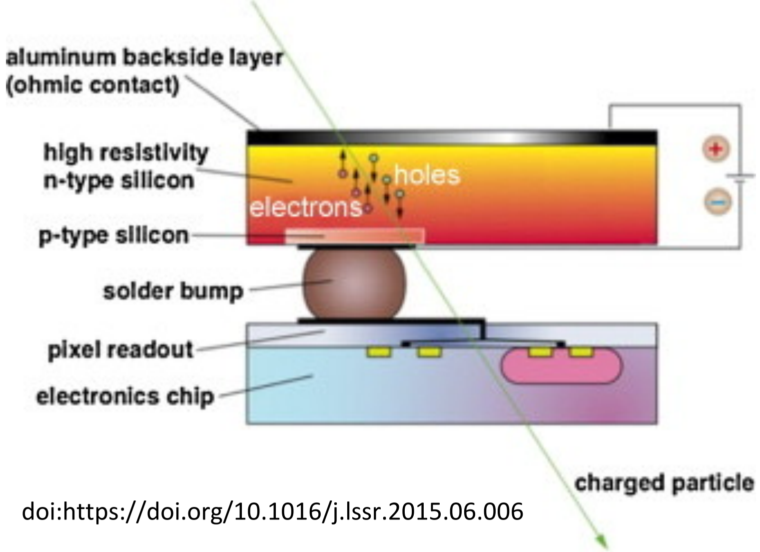
- It is possible to optimise the two parts independently
- The technology is well known and reliable

Disadvantages:

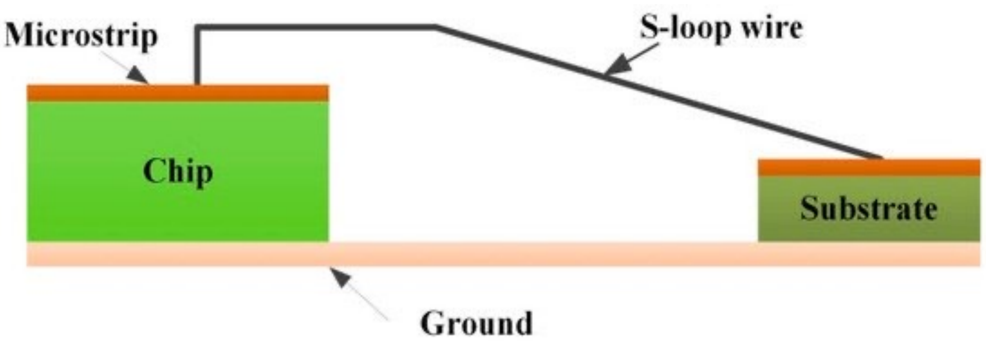
- Sensors are realised with custom technologies (high costs, lower expertise of foundries, only a few foundries accept the work)
- The assembly procedure is complex (high costs and low yield)
- Higher noise
- Technology is several decades years old, and already reached its maximum development

Solution:

- **To implement the readout on the same substrate of the detector (Monolithic approach)**

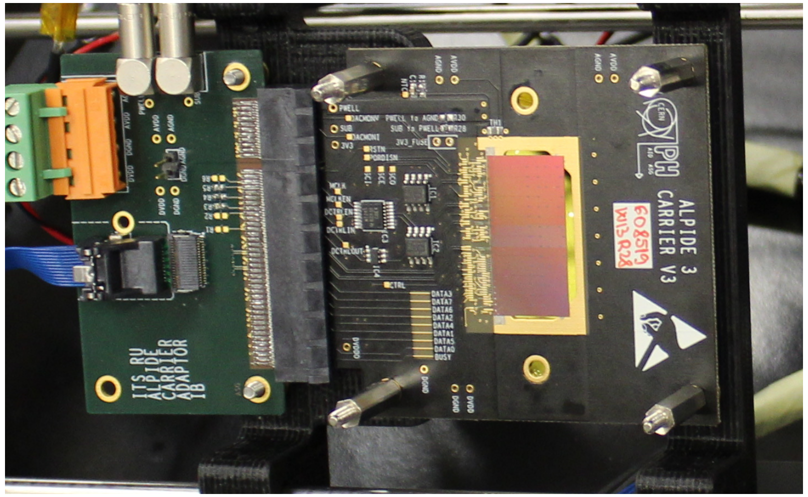


doi:https://doi.org/10.1016/j.lssr.2015.06.006

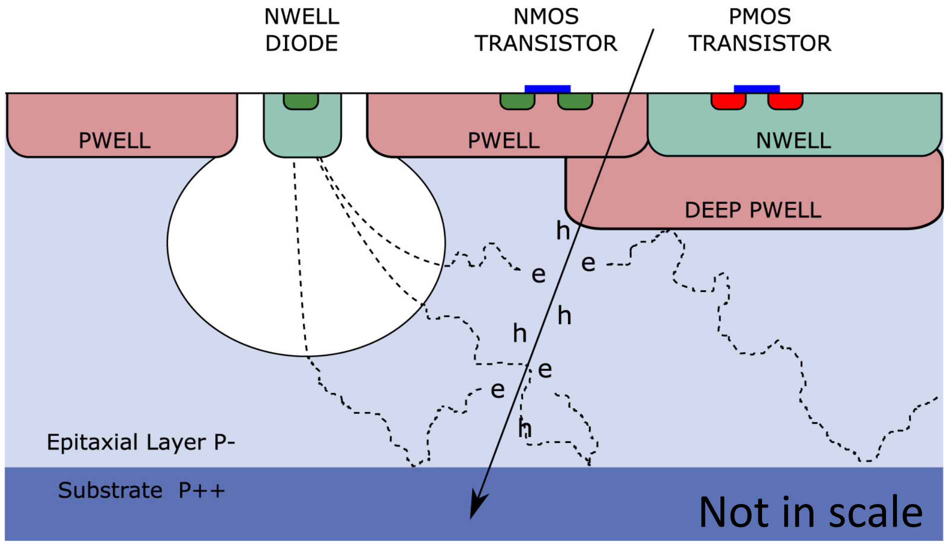


https://doi.org/10.3390/electronics8030365

Each readout channel requires a bond.
If readout is integrated, it is possible to use wire bonding and the number of bonds is widely reduced



ALPIDE/ALTAI



https://doi.org/10.1088/0954-3899/41/8/087002.

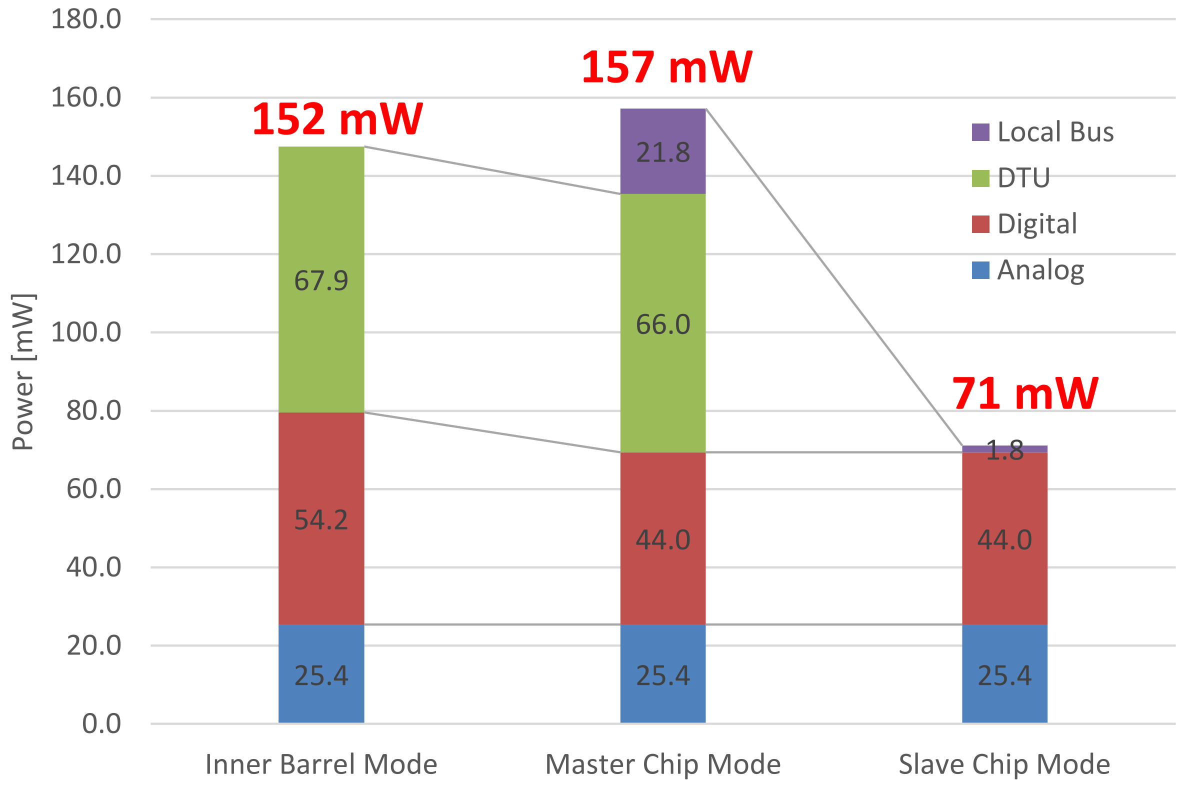
ALPIDE is a MAPS detector designed for ALICE ITS Upgrade. The requirements for the upgrade are reported in the table.

Parameter	IB	OB	Final values
Detector size [mm^2]	15 x 30	15 x 30	15 x 30
Detector thickness [µm]	50	100	50 - 100
Spatial resolution [µm]	5	10	4
Detection efficiency	>99%	>99%	>99%
Fake hit rate [evt^{-1} pixel^{-1}]	$<10^{-5}$	$<10^{-5}$	$<10^{-7}$
Integration time [µs]	<30	<30	~2
Power density [mW/cm^2]	<300	<100	<50 *

* The power consumption depends on the detector configuration

- Sparsified readout
- Pixel pitch: 26.88 x 29.24 µm^2
- Columns x rows: 1024 x 512
- Electrode diameter: 2 µm
- Back bias: 0 V to -6 V
- Producer: TowerJazz

ALPIDE power consumption in ALICE



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

Fermi microstrip power density: 0.2 mW/cm^2
HEPD-01 microstrip power density: 10 mW/cm^2

Inner barrel stave power consumption:

- Nine IB mode detectors: 1.4 W

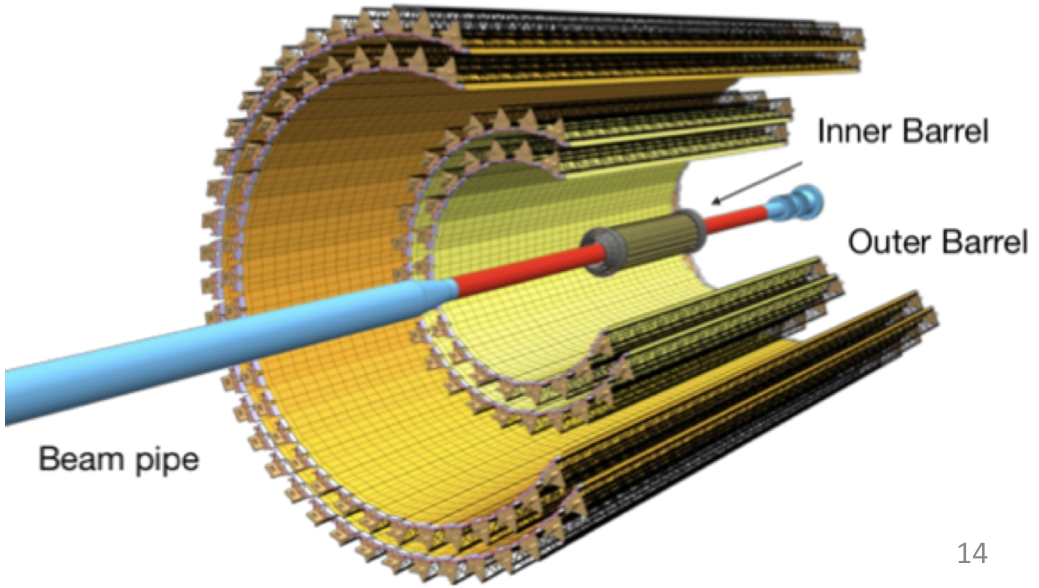
IB power density: 34 mW/cm^2

OB stave power consumption:

- One Master chip mode: 157 mW
- Six Slave chip mode: 426 mW
- Full stave (two columns of seven detectors): 1.2 W

OB power density: 18.5 mW/cm^2

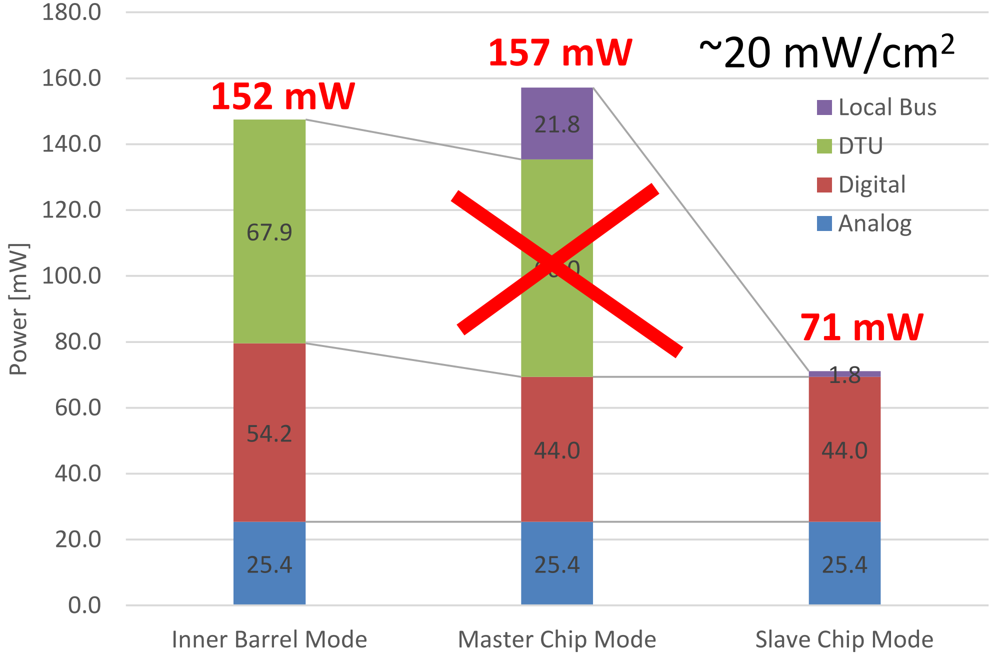
https://doi.org/10.1088/0954-3899/41/8/087002



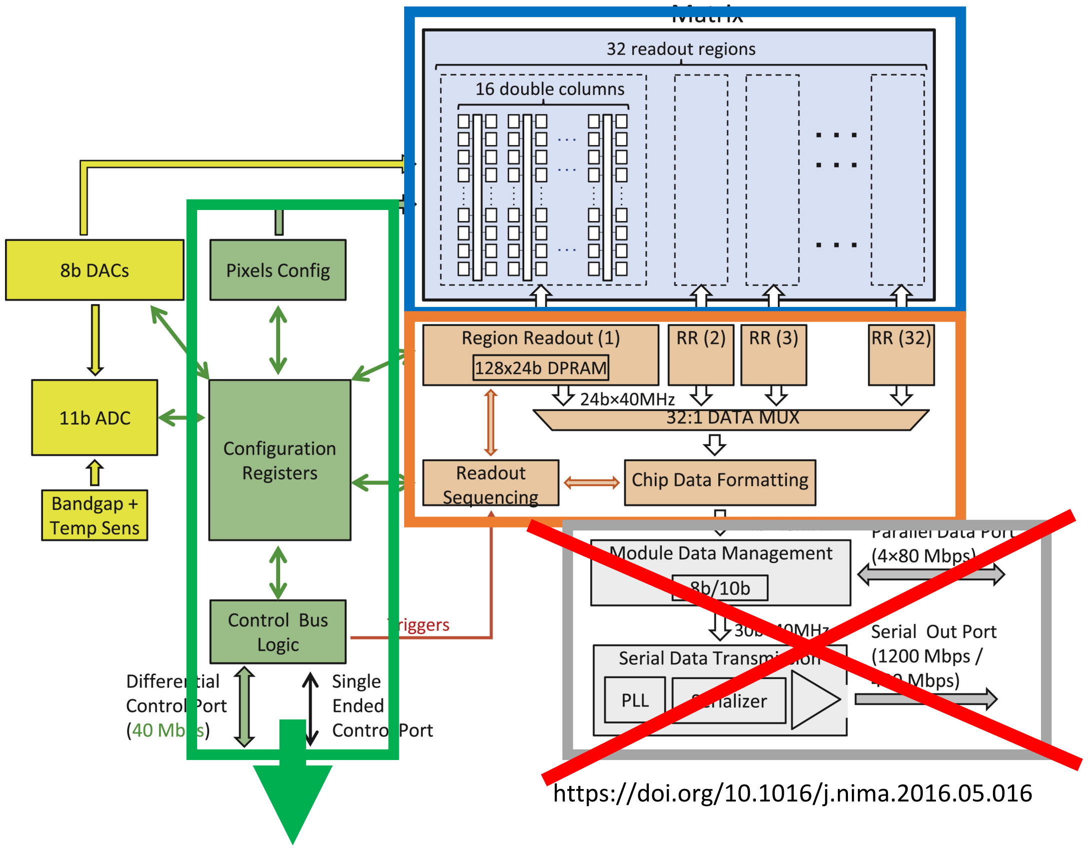
Power consumption reduction strategies

Power consumption have to be reduced to fit requirements of the HEPD-02 payload.
From power consumption characterisation, **the high speed line is the most consuming element of the detector**.

The first solution is to **move the readout to the CTRL line**.
It avoids to activate the PLL.



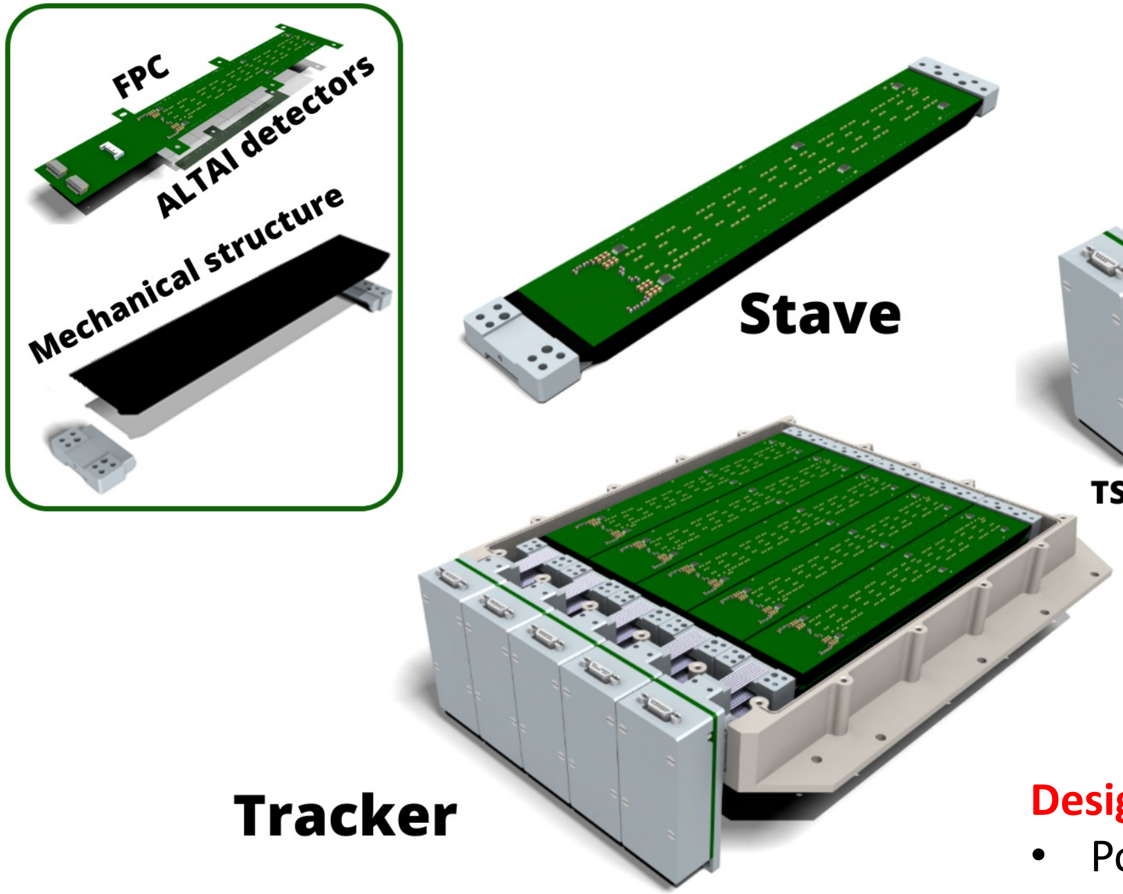
https://indico.cern.ch/event/ 666016/contributions/2722251/attachments/1523408/2380925/ 20170914-ALPIDE-FoCal-Study-Aglieri.pdf

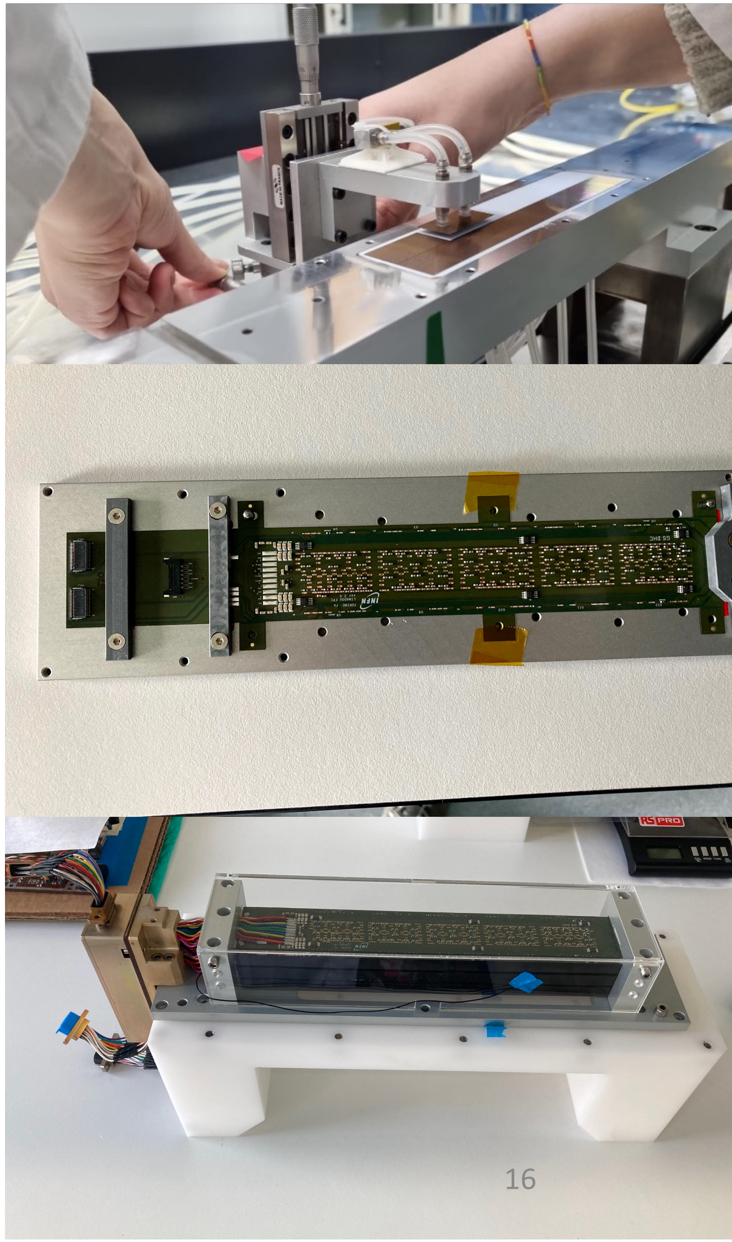


https://doi.org/10.1016/j.nima.2016.05.016

ALPIDE control and data readout

HEPD-02 tracker design





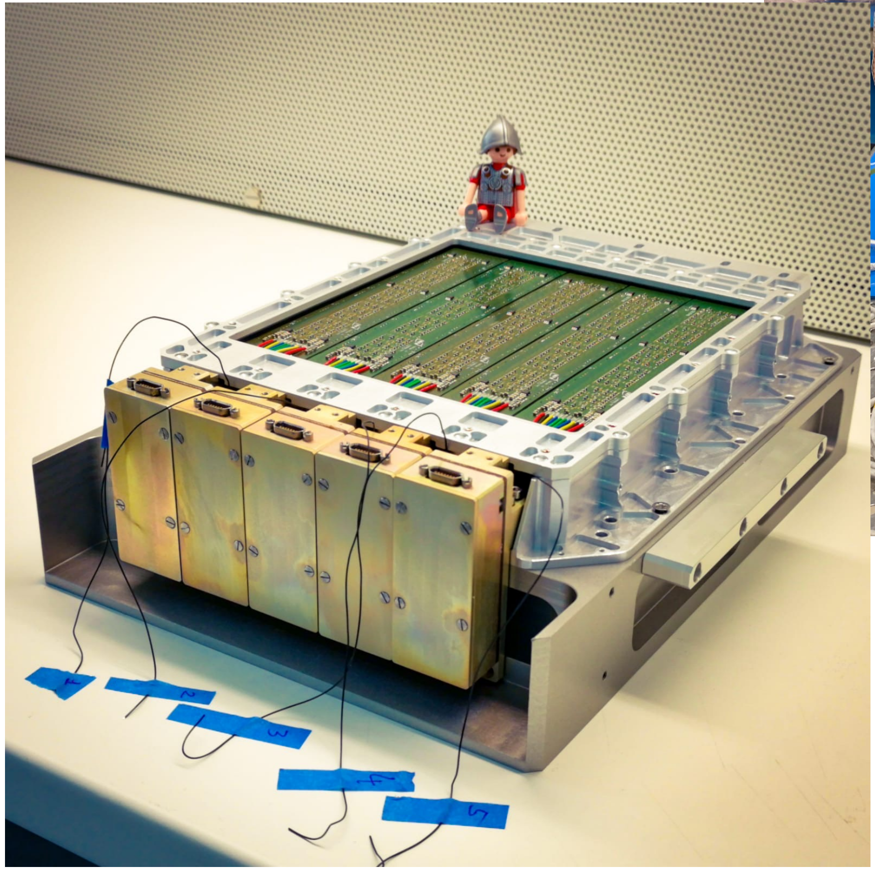
Design requirements:

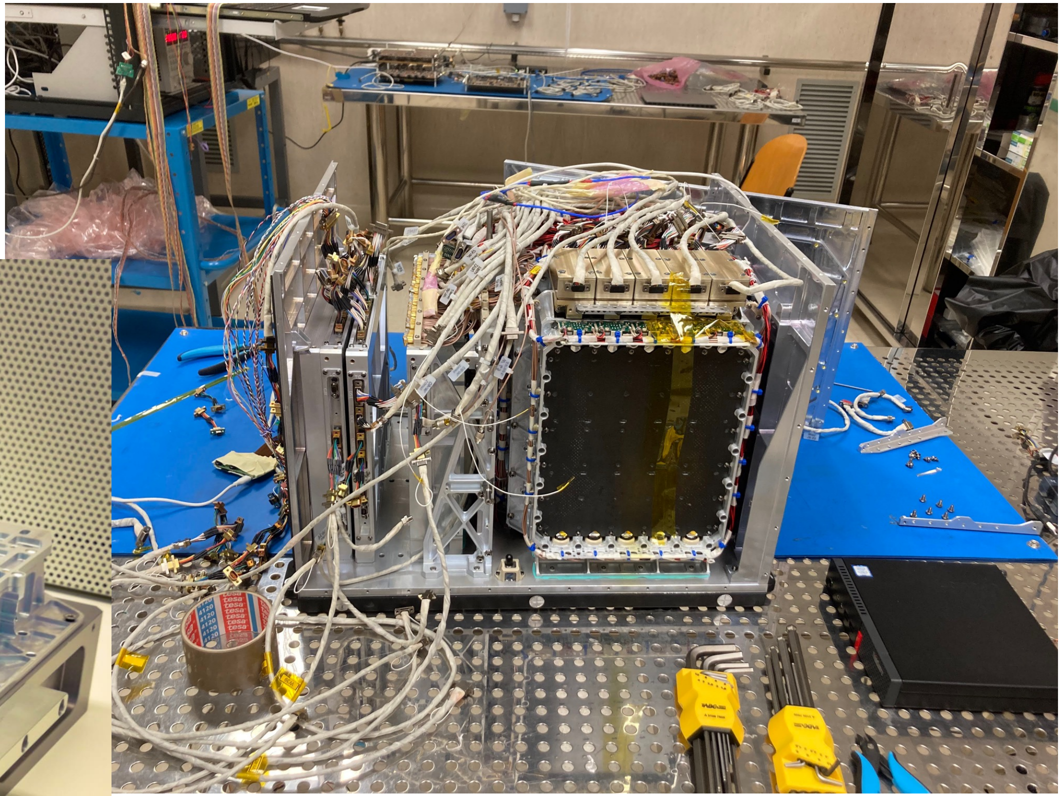
- Power consumption reduction
- Temperature control
- Mechanical stability
- Material budget minimisation

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**

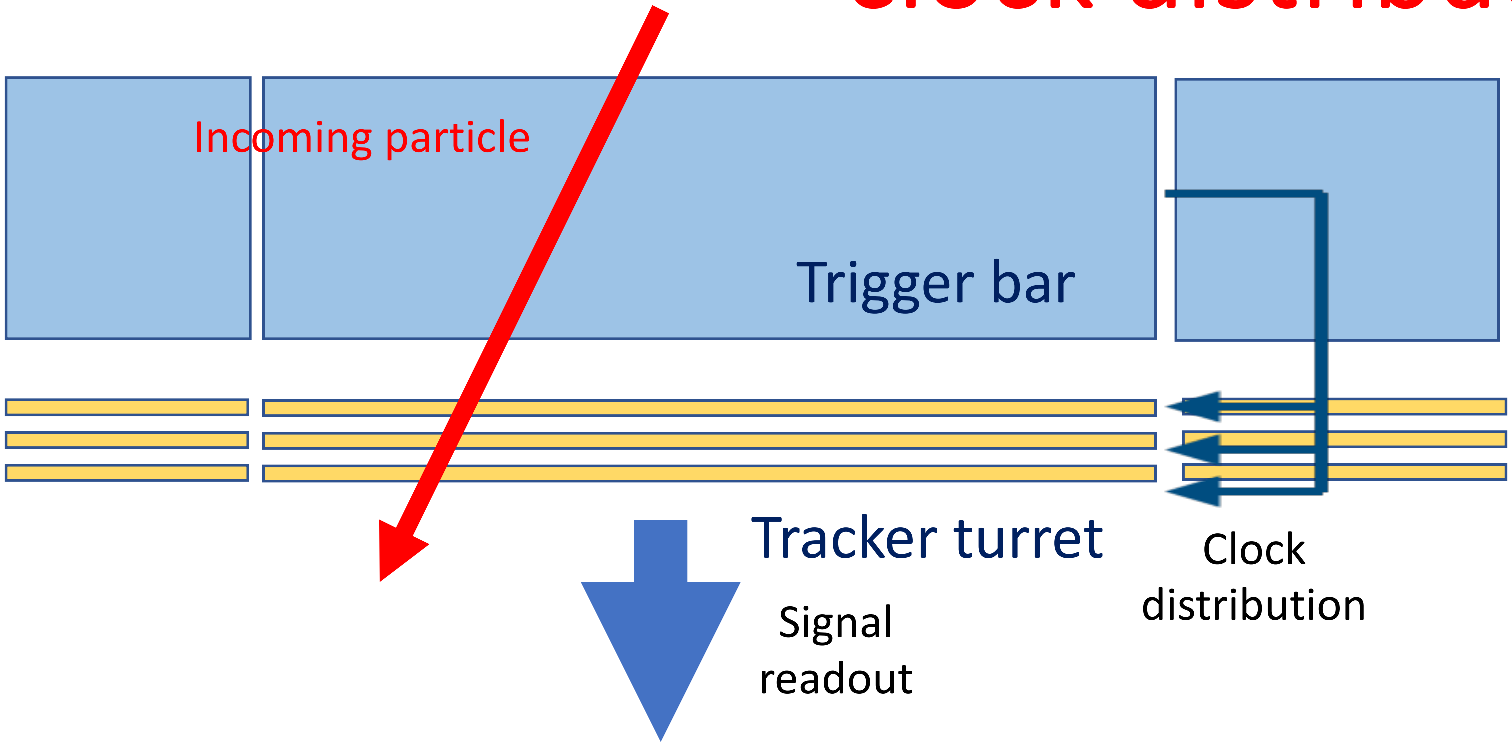


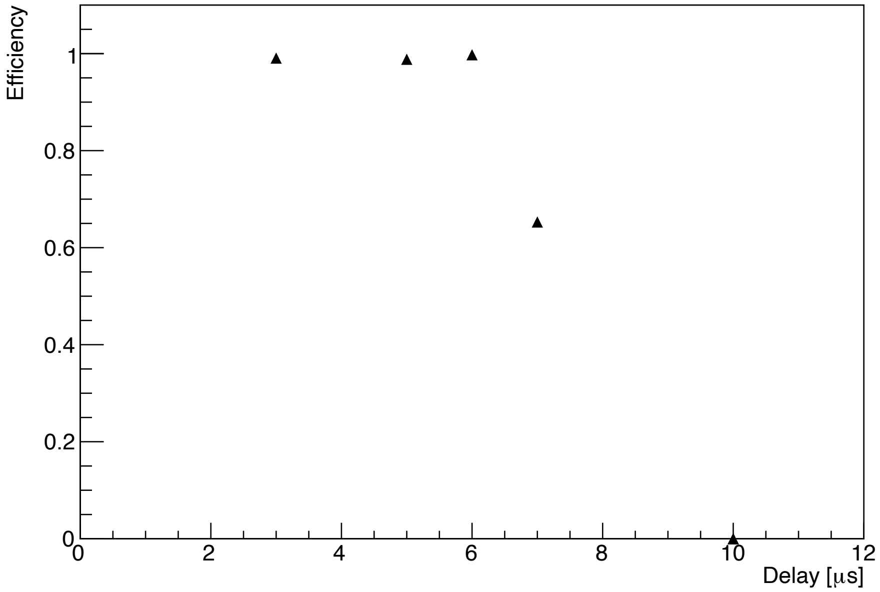


Production summary:

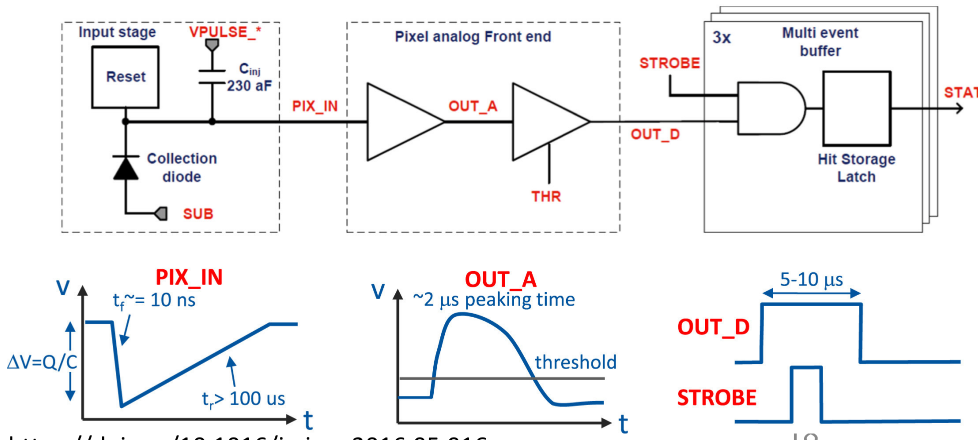
- 84 HIC assembled
- 48 STAVE assembled
- 11 turrets assembled (1 EM level, 10 QM/FM level)
- 2 trackers

Power consumption reduction: clock distribution



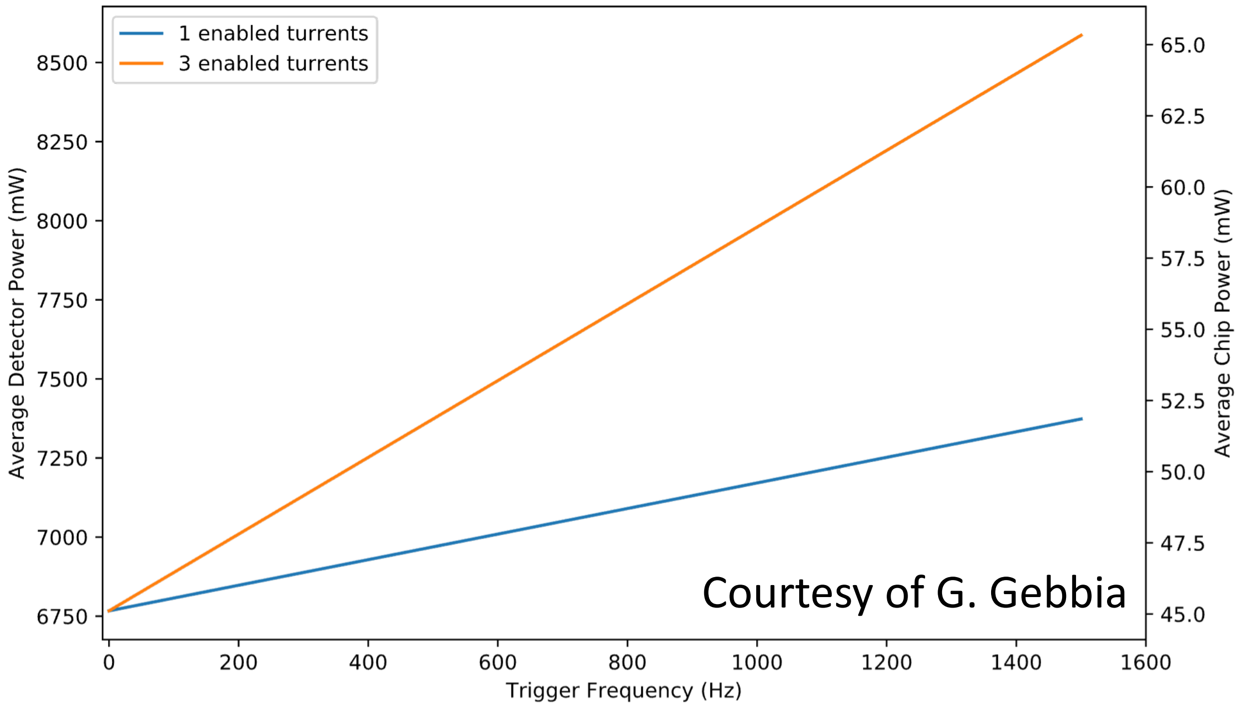


- Analog front-end is kept constantly powered on
- The digital part is needed only for the readout of the data
- The clock is distributed only after the trigger signal is produced
- The smart segmentation of trigger allows to distribute the clock only to the section of tracker involved on the event



https://doi.org/10.1016/j.nima.2016.05.016

Full tracker power consumption

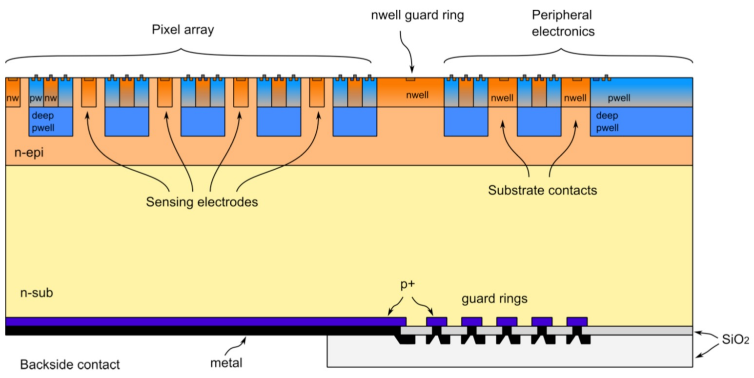


- Power consumption is plot as a function of trigger rate
- To increase the probability to intercept the section of the tracker hit by the particle, three turrets are read out
- Power consumption of the full tracker in this configuration is well below the 10 W of HEPD-01 tracker
- The maximum trigger rate will be defined by the dead time required for the readout.

MAPS evolution: DMAPS

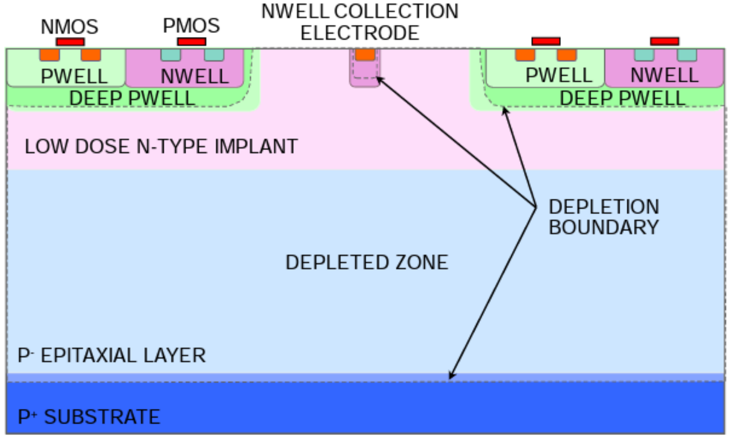
- One of the most impacting limits of MAPS is the low radiation hardness
- The design of detectors that can be operated in a fully depleted state
- The use of a detector in a full depleted state also increase the timing performance of the detector

ARCADIA



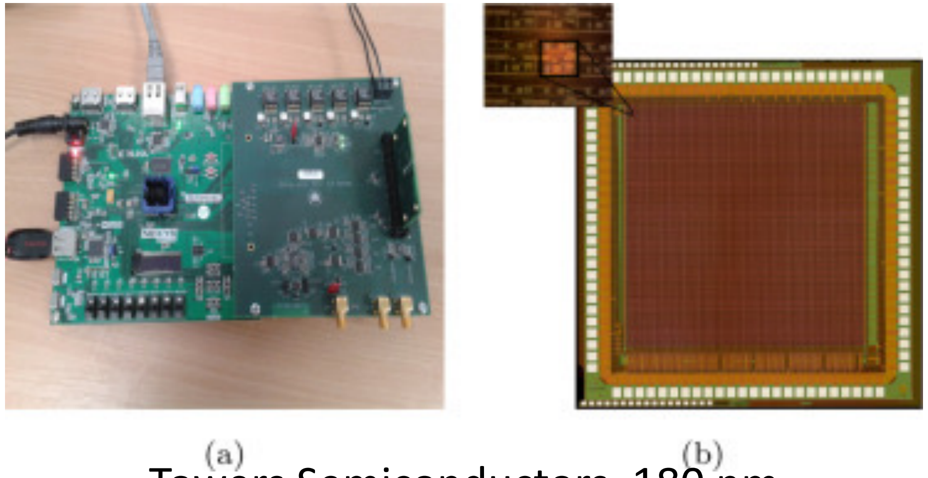
L-Foundry, 110 nm
Multi-purpose INFN R&D

MALTA



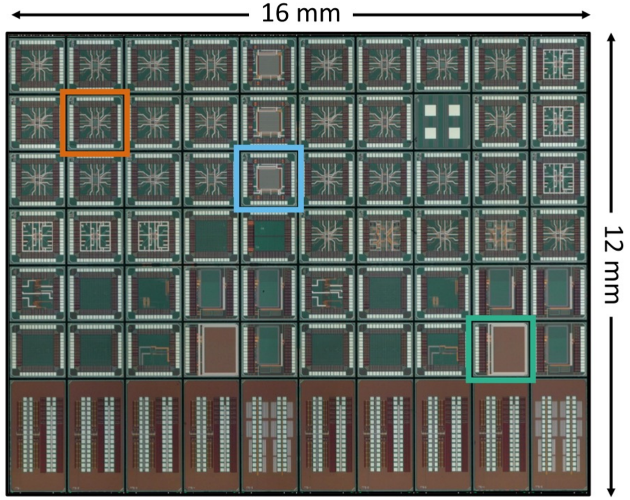
Towers Semiconductors, 180 nm
R&D for ATLAS experiment

DECAL



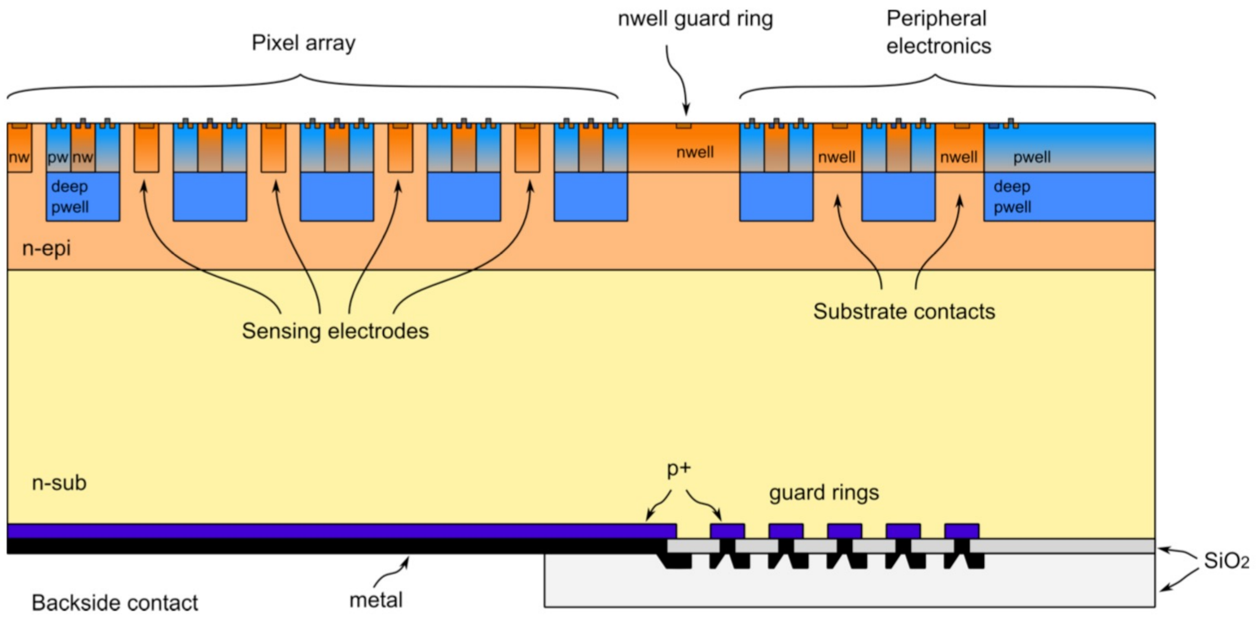
Towers Semiconductors, 180 nm
Larger pixels for calorimetry applications

MLR1



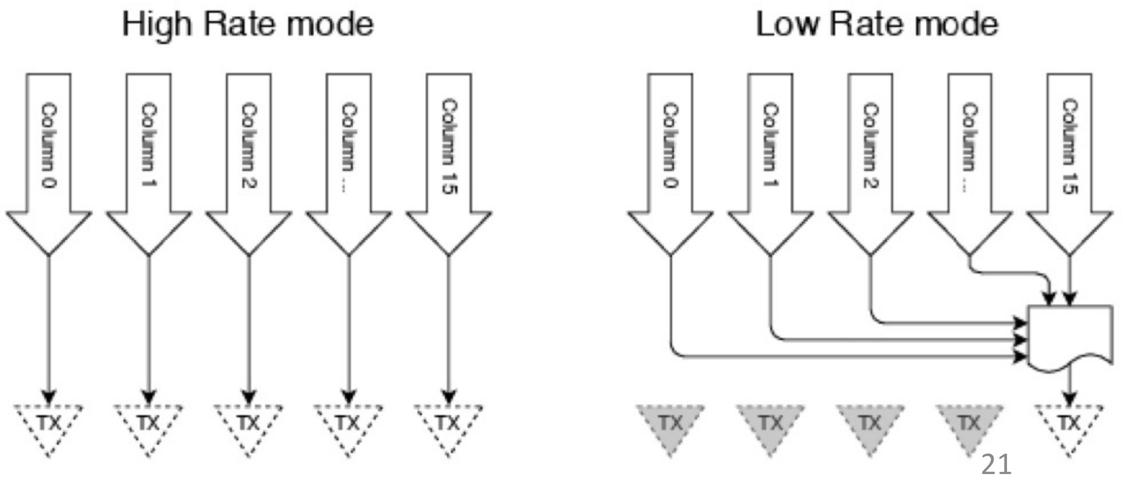
Towers Semiconductors, 65 nm
R&D for ALICE experiment

Designed (also) for space: ARCADIA



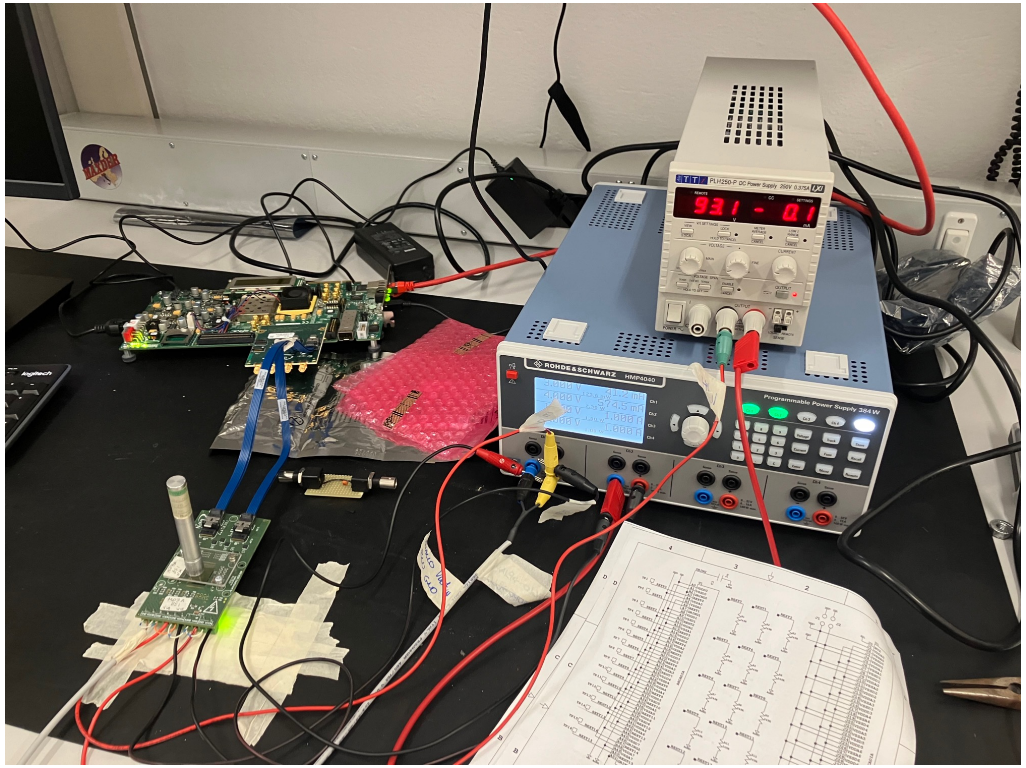
Requirements	
Pixel pitch [µm]	20 - 25
Thickness [µm]	50 - 500
Scalability [cm]	Up to ~ 4x4
Hit rate	10 - 100
Timing resolution [ns]	10
Power consumption [mW/cm^2]	<20
Radiation hardness [Mrad]	1

- Developed on the framework of a INFN group V call as multi-purpose platform
- The production of the last version, MD3 was completed at the beginning of 2023
- Tests are ongoing
- The target of 10 mW/cm2 has been achieved in a dedicated Low Rate mode



ARCADIA ongoing activities @TN

- Noise and threshold characterisation
- Software development
    - External trigger
    - Characterisation tool developing

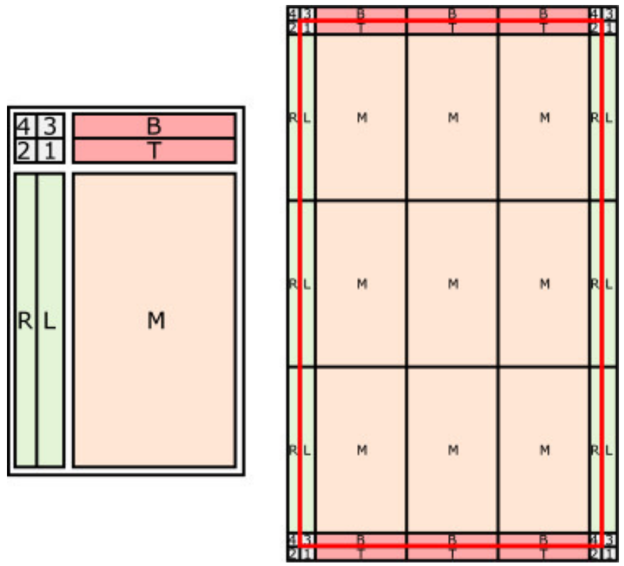


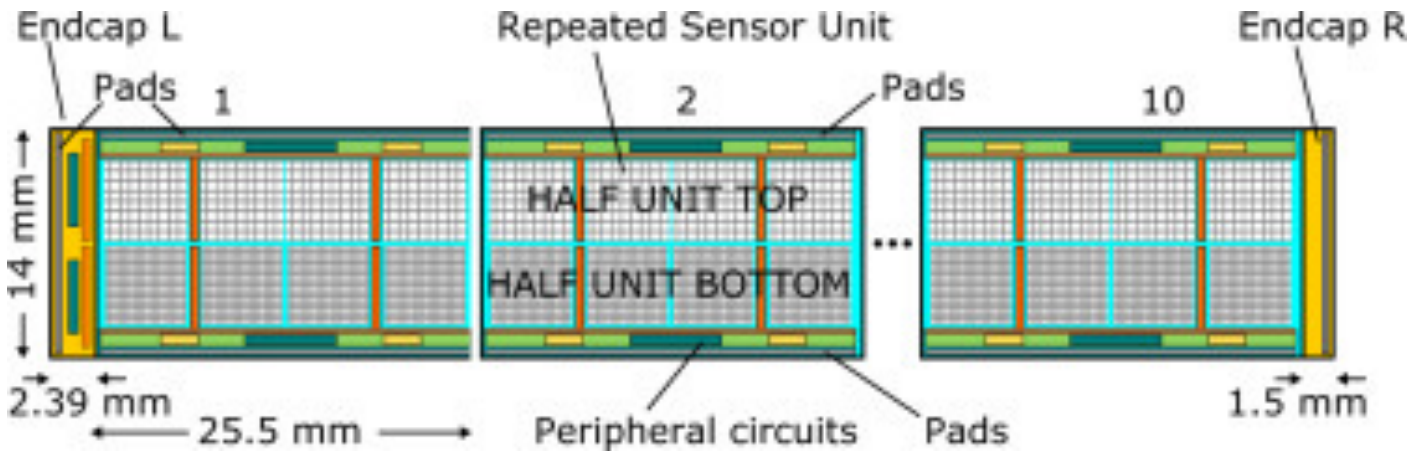
Space mode tests:
- Power consumption characterisation:
    - Static measurements
    - Dynamic measurement
- Response as a function og the temperature
- Test of data acquisition limits

Test at hig rate @Protontherapy centre:
- Procurement of fast scintillators and SiPMs
- Procurement of a fast electronic readout chain
- Test of the trigger chain
- Protontherapy test plan
- Beam test
- Data analysis

MAPS evolution: Stitching

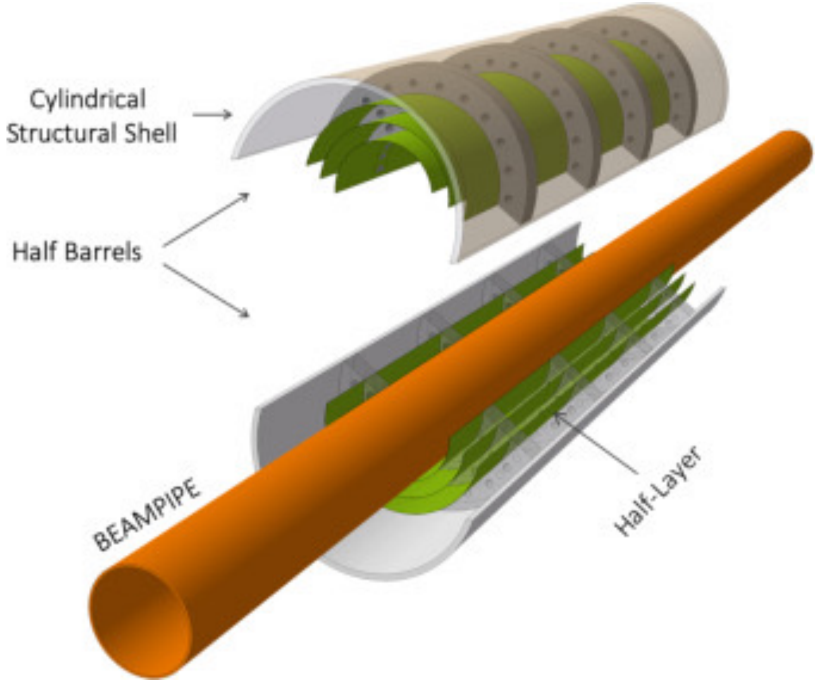
- The small dimension of the currently available MAPS requires complex assembly procedures, power distribution and mechanical support
- The realisation of wafer-scale detector would widely increase the design possibilities
- The solution pursued by most R&D projects is stitching
- Stitching technique allows to connect single reticles to obtain a larger structures (usual reticles are limited to ~2x3cm^2
- ALICE collaboration R&D team has recently got the first batch of stitched detctors and the first tests are ongoing

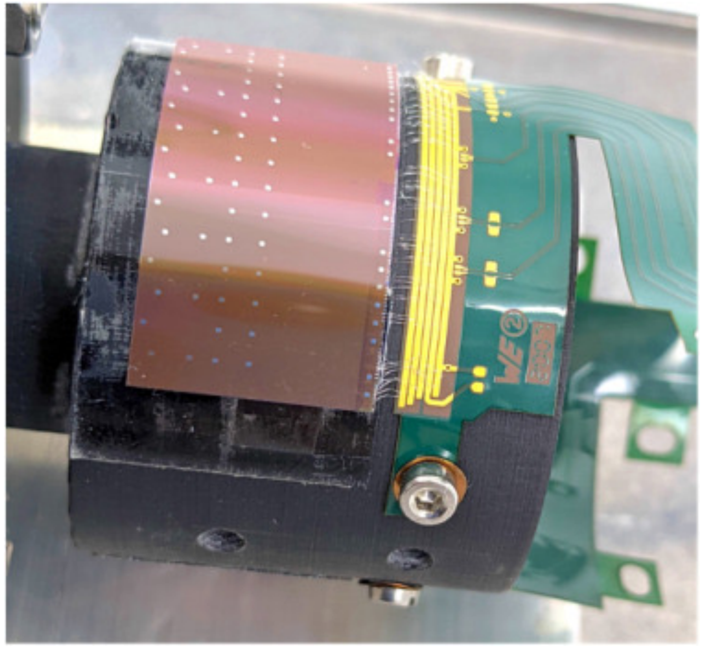


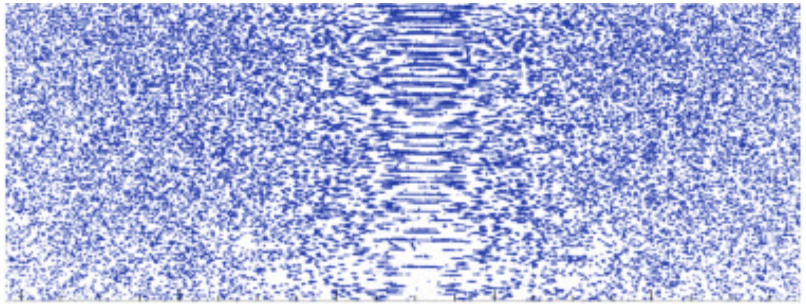


MAPS evolution: curvature

- Thinning procedures are well established in MAPS production
- With a further reduction from the 50 µm of ALPIDE produced for ALICE Inner Barrel, it is possible to bend the detector
- ALICE ITS3 design will require a full cylindrical shape, with the innermost layer designed with a 18 mm curvature radius.
- Tests have been carried out with ALPIDE, with good results





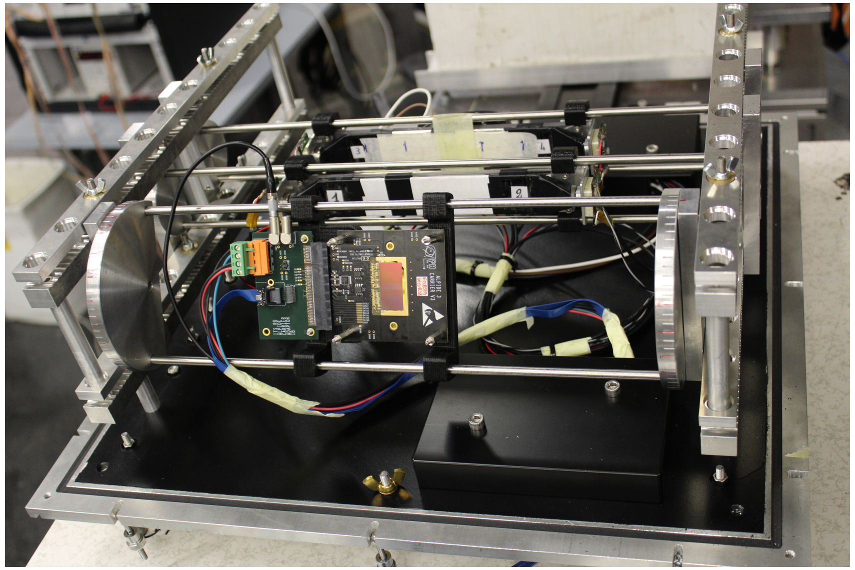


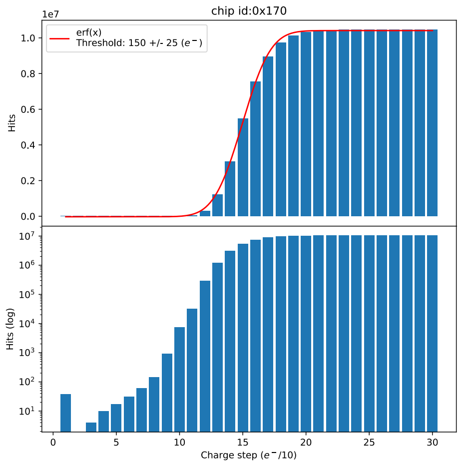
Beam trough a bent ALPIDE

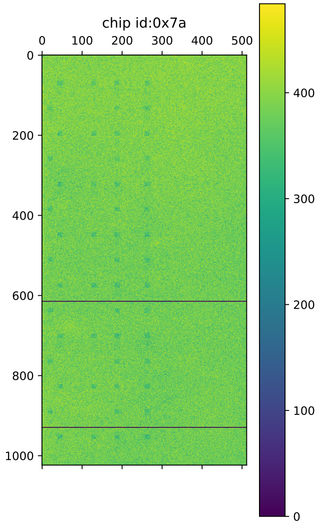
Development activities: lab characterisation

Power consumption charcaterisation

Setup design and realisation

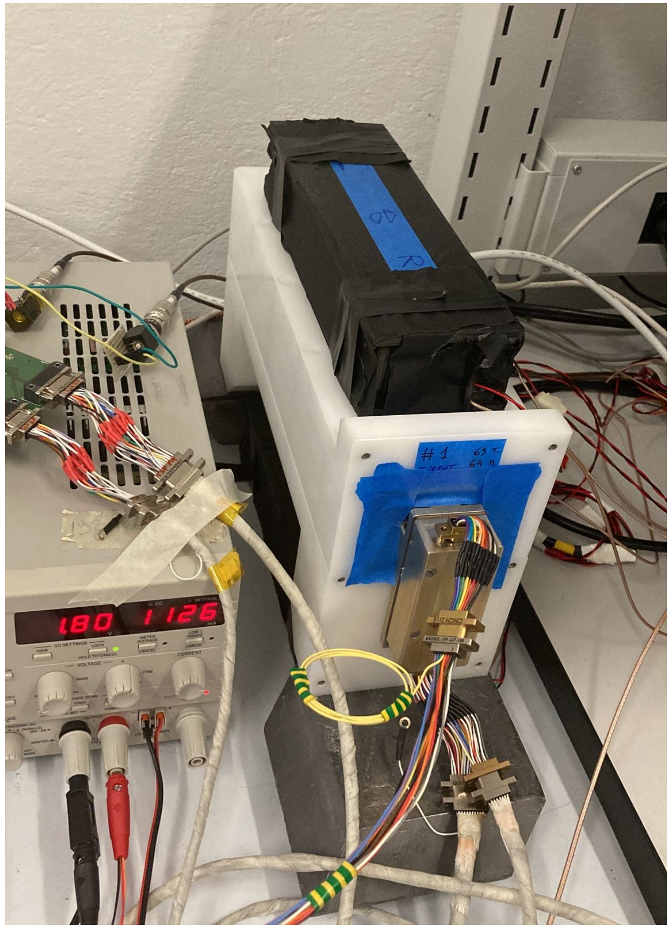




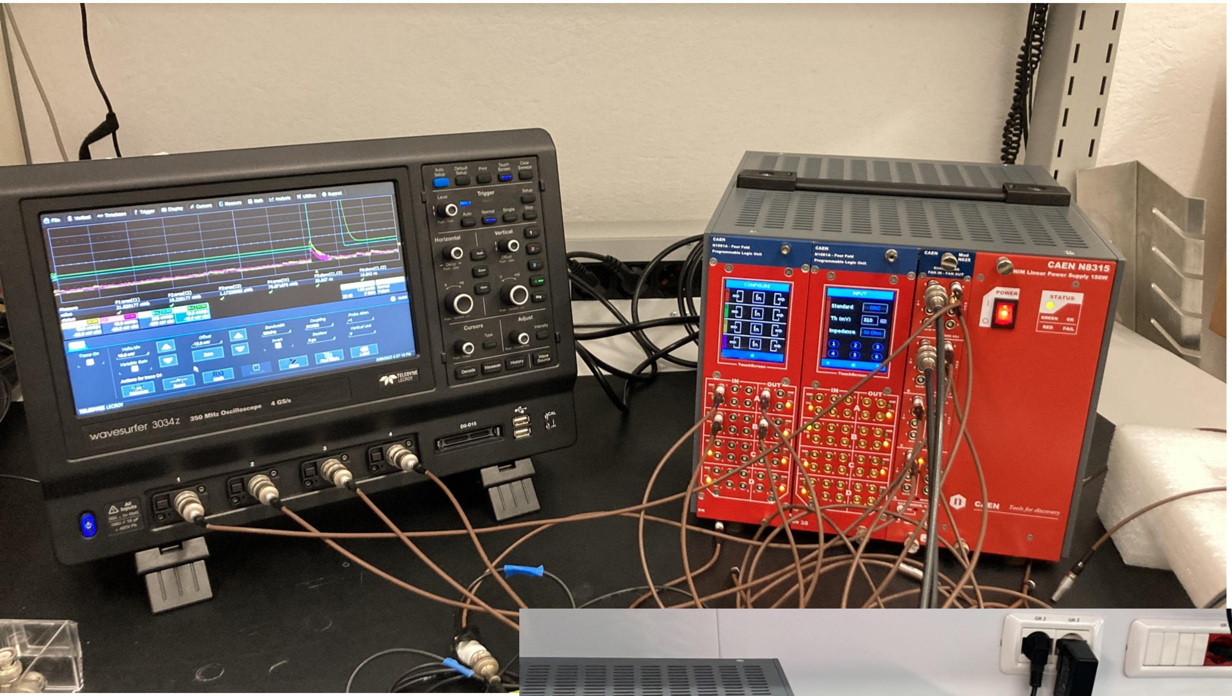


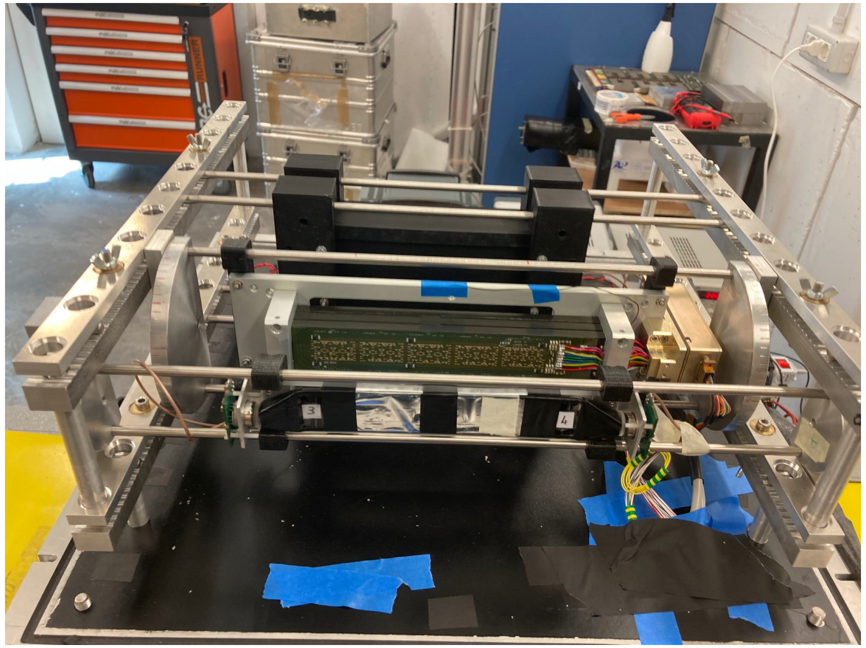
Parameter scans

Acquisitions with cosmic rays



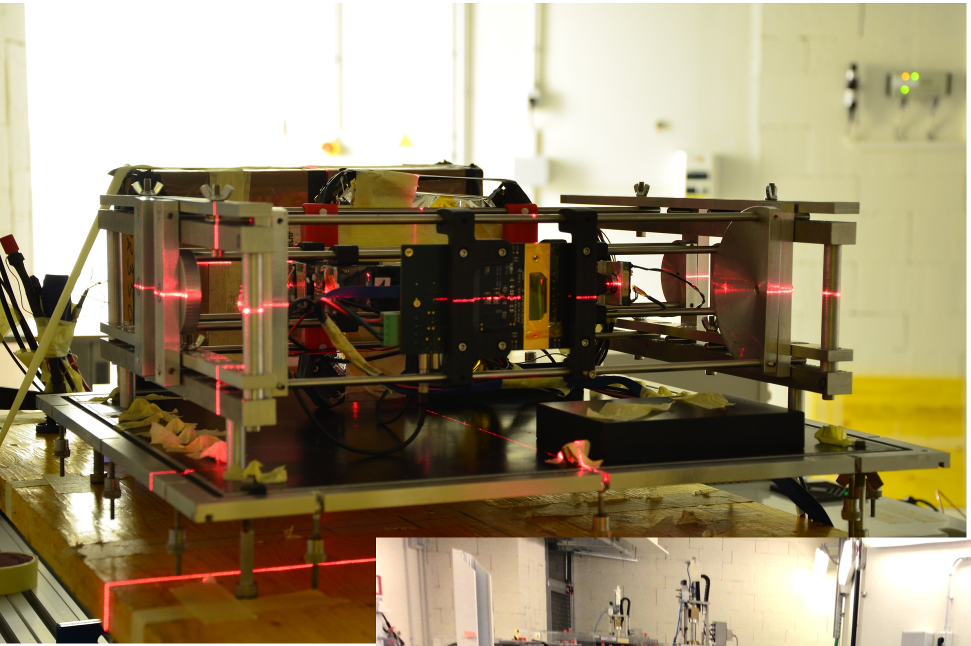
Development activities: trigger systems

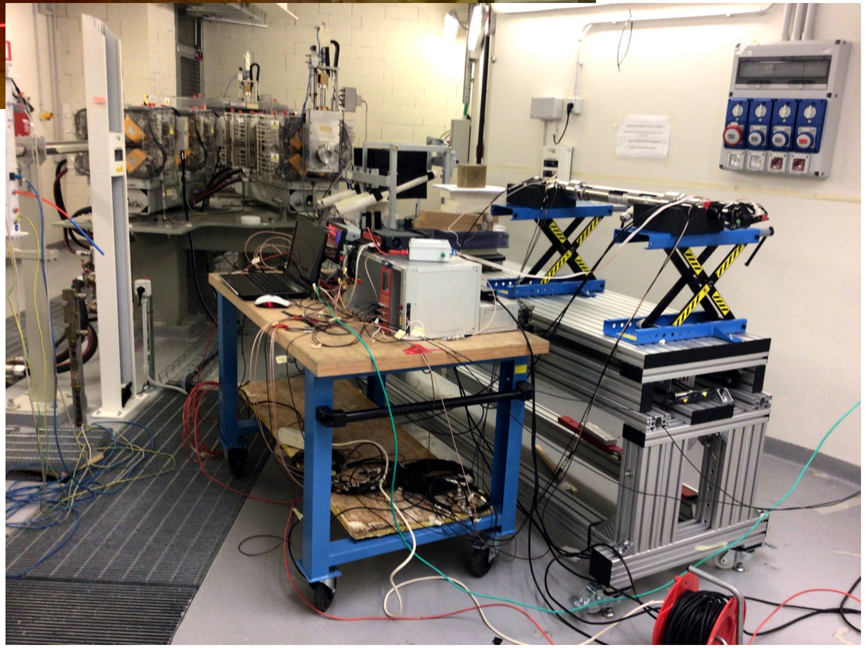


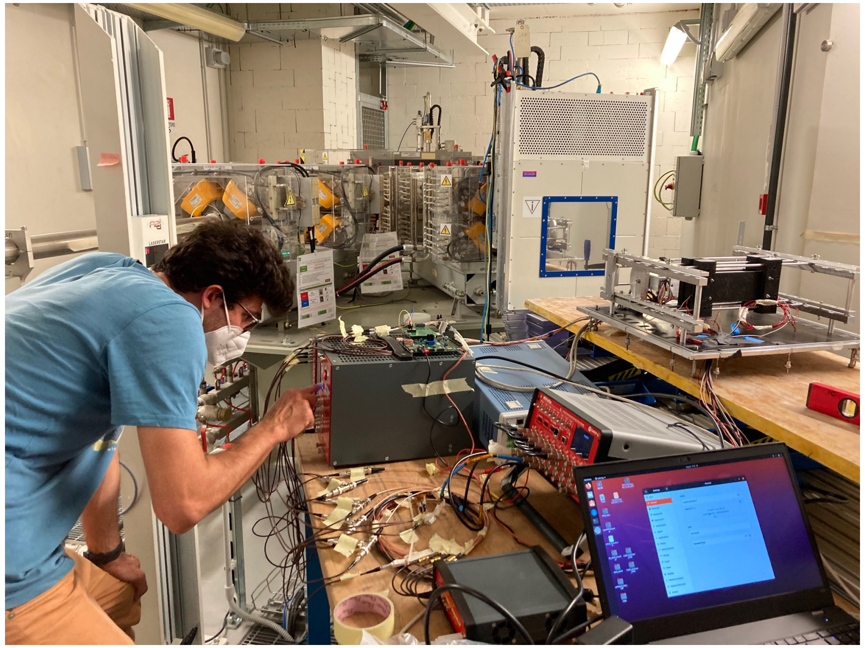


Fast scintillators
Thin slabs
Dense crystals for calorimetry

Development activities: beam tests







- Two beam lines
- Energies between 70 and 228 MeV (lower energies reachable with degrader
- Available on week days from 7pm to 10 or 10:30pm and on Saturday mornings
- 1 “preposto” is from the group, available for groups with similar beam requirements (physics line, low rates)

Conclusions

- The APP group in Trento was constituted in 2017
- In 6 years we were able to design, realise, qualify and characterise a tracker for space applications realised with an innovative technology
- MAPS technology was promoted from TRL 4 to TRL 8
- In the process, we gained experience in all the process, we equipped our labs and we built our network of facilities and labs that can supply us the infrastructures we lack
- Other new space-based initiatives (LEM and ADHD) are under development
- With the HEPD-02 ready for shipment to China, we are ready for a new adventure