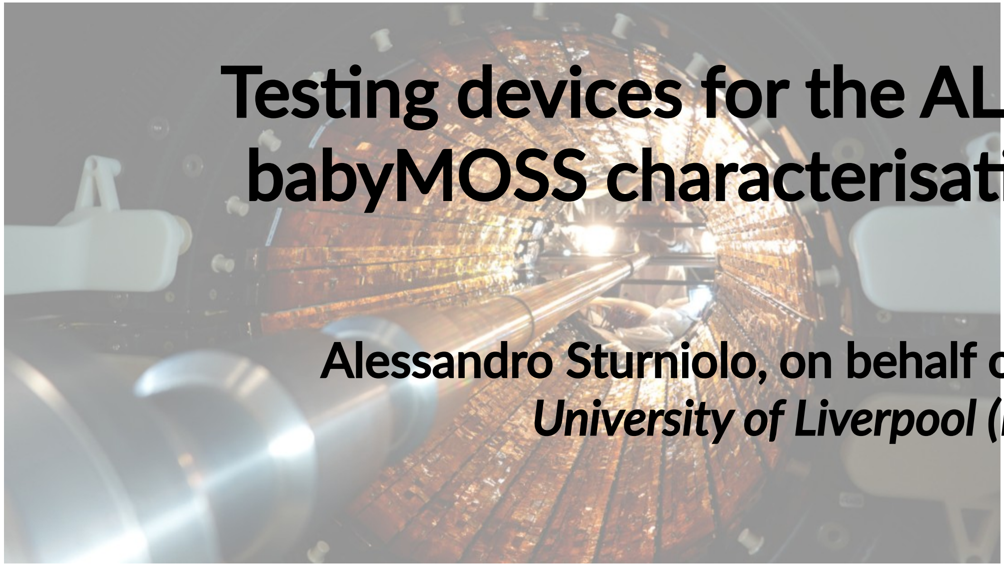
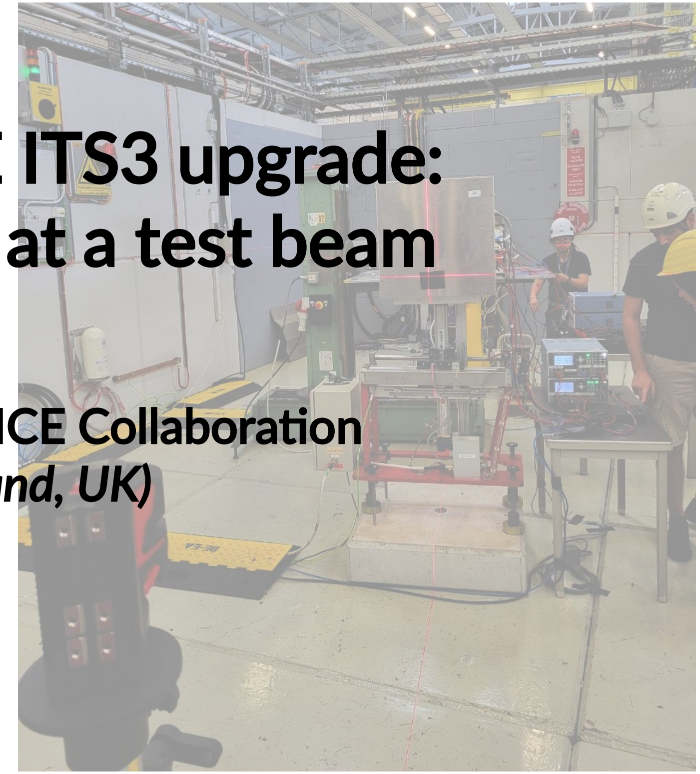


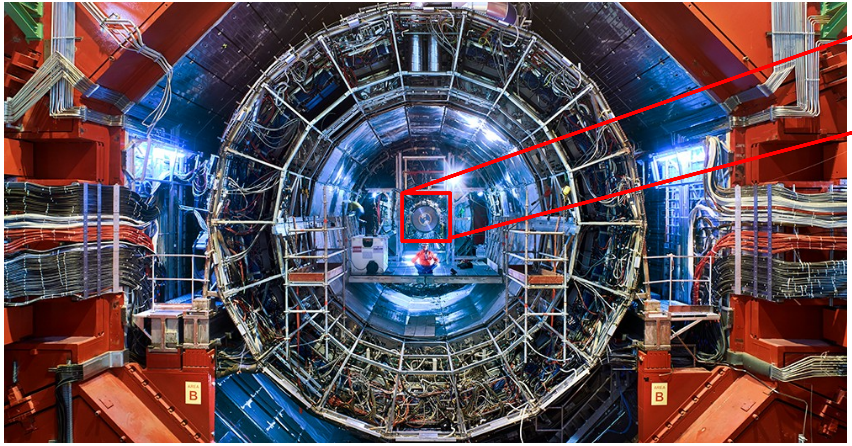


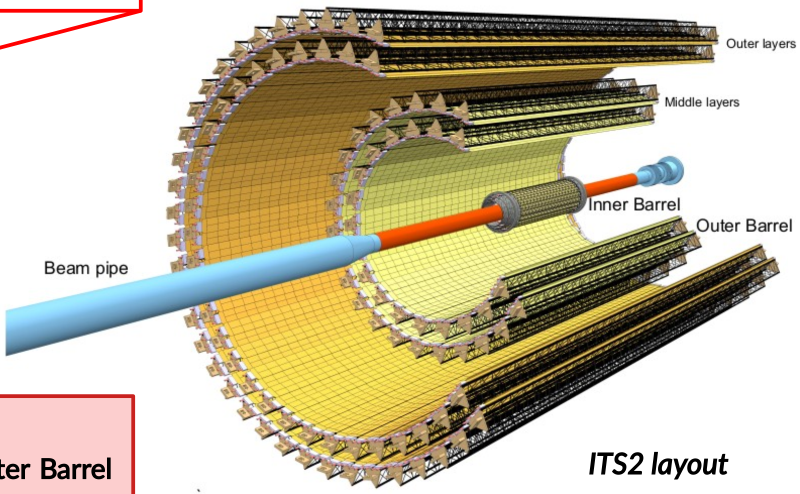
Testing devices for the ALICE ITS3 upgrade: babyMOSS characterisation at a test beam

Alessandro Sturniolo, on behalf of ALICE Collaboration
University of Liverpool (England, UK)

IOP Joint APP and HEP conference 2026 (Edinburgh, UK, 8-10 April 2026)

ALICE Inner Tracking System: the state of the art





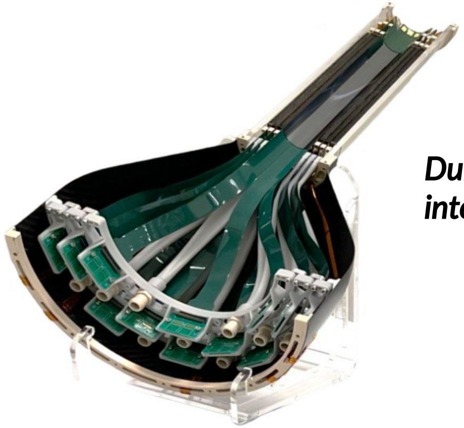
ITS2 layout

ALICE Inner Tracking System (ITS2, current)[1]:
→ **7 layers of 180 nm MAPS*:** divided into **Inner Barrel (IB, L0 to L2),** and **Outer Barrel (OB, L3 to L6)** layers;
→ **Material budget:** average **0.36% X_0 per IB layer, 1.10% X_0 per OB layer**;
→ **Geometry: beam pipe** inner radius of **18.0 mm**, **ITS2 L0** radius of **22.4 mm**;
→ **Maximum pseudo-rapidity coverage**: $|\eta| \leq 1.3$ (L0);
→ **Sensor thinning** could **enhance statistical significance** for **heavy flavour and di-electron** studies!

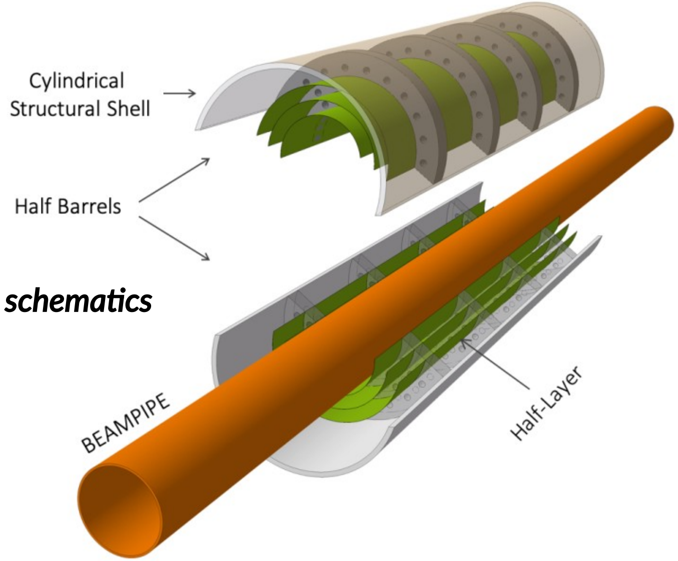
****MAPS = Monolithic Active Pixel Sensors***

[1] **ALICE Collaboration,** *"ALICE upgrades during the LHC Long Shutdown 2"*. JINST **19** (2024) P05062.
DOI: 10.1088/1748-0221/19/05/P05062

The ALICE ITS3 upgrade project: towards truly cylindrical sensors



Dummy model for ITS3 integration studies (EM3)

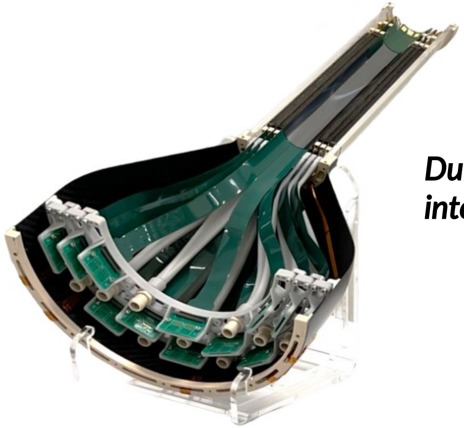


Full ITS3 schematics

Upgraded ITS3 (scheduled after Long Shutdown 3, 2026-2030)[2]:
→ **6 bent, large-scale, stitched 65 nm MAPS** (denser circuits);
→ **Material budget:** average 0.09% X_0 per layer, lightweight carbon foam support;
→ **Geometry: beam pipe** inner **radius** of **16.0 mm**, **ITS3 L0 radius** of **19.0 mm**;
→ **Maximum pseudo-rapidity coverage**: $|\eta| \leq 2.6$ (L0);
→ **Power density:** 40 mW/cm^2, with **air cooling** (T_{air}~20° C);
→ **Enhancing tracking performances, reducing background…**

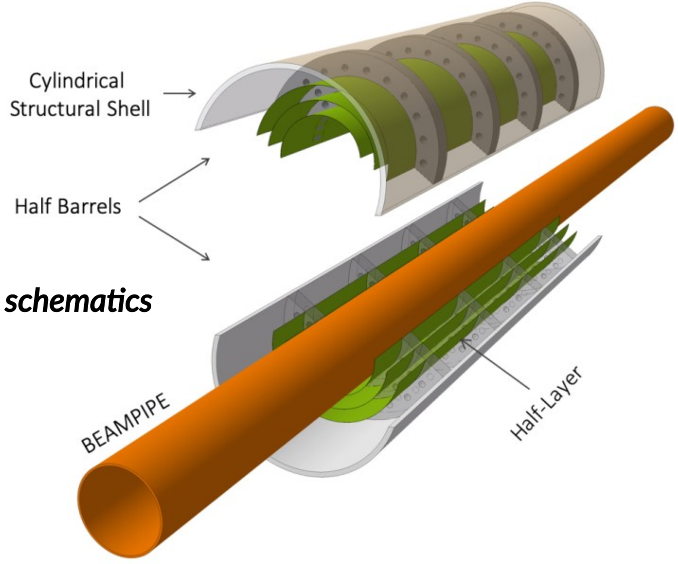
[2] **ALICE Collaboration,** *"Technical Design Report for the ALICE Inner Tracking System 3 – ITS3; a bent wafer-scale monolithic pixel detector".* CERN Document Server (2024). CERN-LHCC-2024-003;

The ALICE ITS3 upgrade project: towards truly cylindrical sensors



Dummy model for ITS3 integration studies (EM3)

Full ITS3 schematics



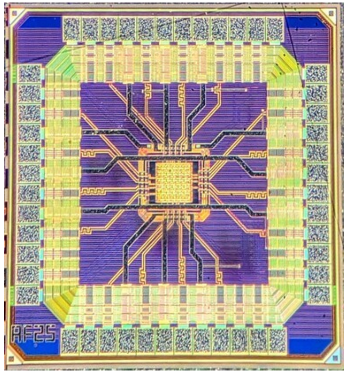
ITS3 sensor requirements (for R&D):

- **Detection efficiency** > 99%;
- **Fake hit rate (FHR)** < 10^{-6} hits per pixel and event;
- **Spatial resolution** < 5 µm;
- **Radiation hardness:** 4 kGy Total Ionising Dose (TID) + $4 \cdot 10^{12}$ 1 MeV n_{eq} cm^{-2} Non-Ionising Energy Loss (NIEL).

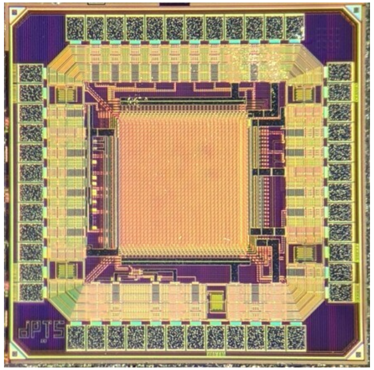
[2] **ALICE Collaboration,** *"Technical Design Report for the ALICE Inner Tracking System 3 – ITS3; a bent wafer-scale monolithic pixel detector".* CERN Document Server (2024). CERN-LHCC-2024-003;

ITS3 R&D: where are we now?

Sensor characterisation (chip submissions)



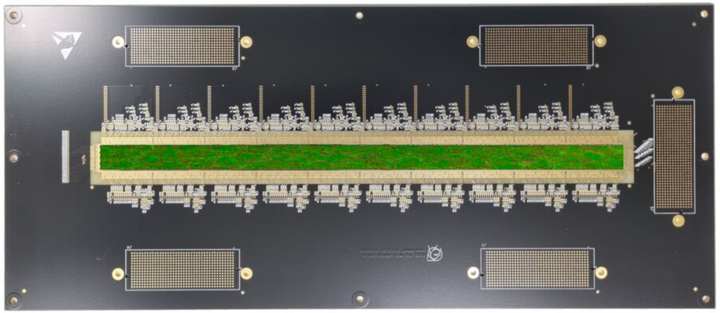
Analogue Pixel Test Structures (APTS)[3]



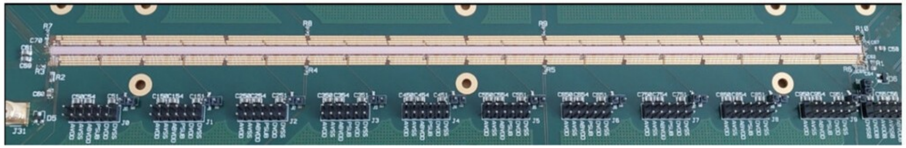
Digital Pixel Test Structures (DPTS)[4]

Multi-Layer Reticle 1:
Small-scale chips for 65 nm technology validation: APTS, DPTS, CE65 (completed)

Engineering Run 1:
Stitched devices for wafer yield and stitching assessment: MOSS, MOST, babyMOSS (completed)



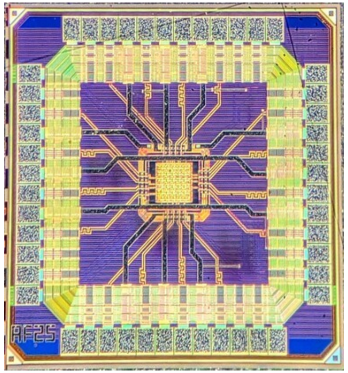
Monolithic Stitched Sensor (MOSS)[5]



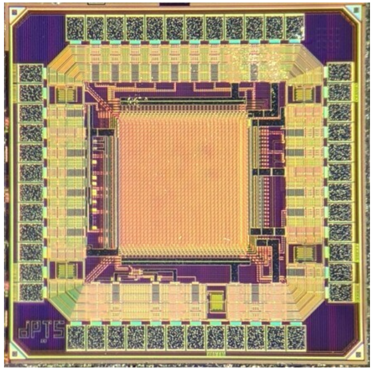
Monolithic Stitched Sensor with Timing (MOST)[6]

ITS3 R&D: where are we now?

Sensor characterisation (chip submissions)



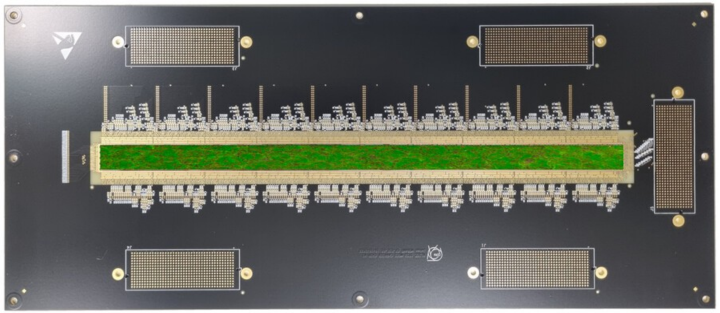
Analogue Pixel Test Structures (APTS)[3]



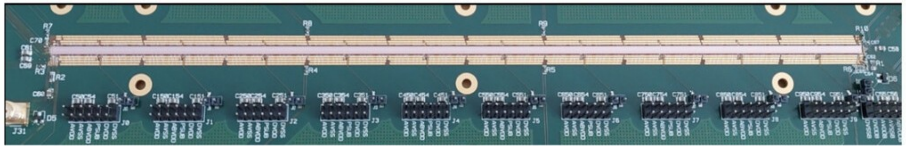
Digital Pixel Test Structures (DPTS)[4]

Multi-Layer Reticle 1:
Small-scale chips for 65 nm technology validation: APTS, DPTS, CE65 (completed)

Engineering Run 1:
Stitched devices for wafer yield and stitching assessment: MOSS, MOST, babyMOSS (completed)

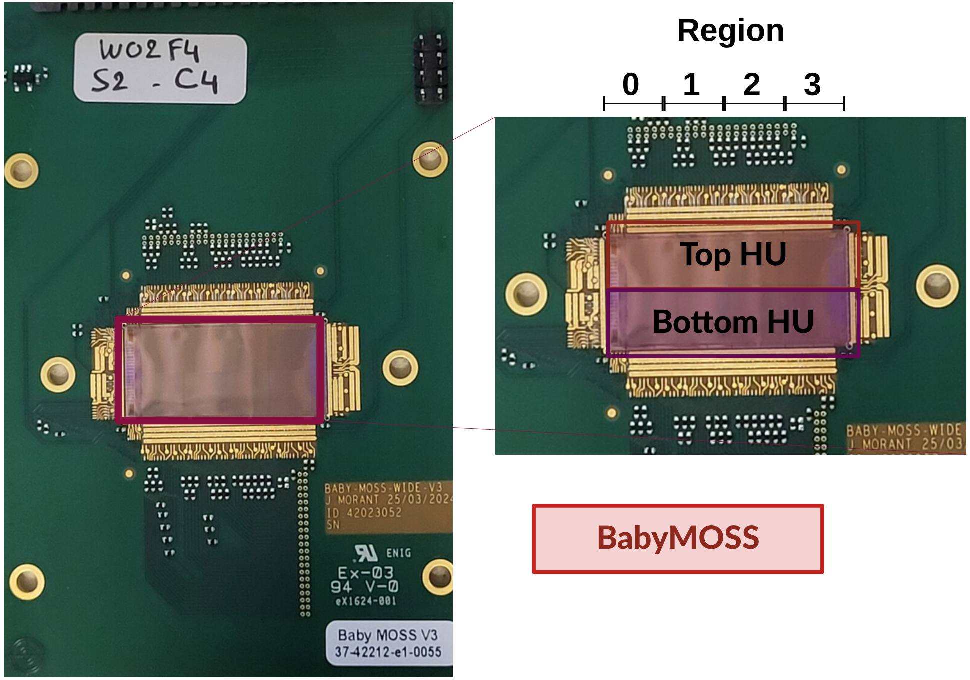


Monolithic Stitched Sensor (MOSS)[5]



Monolithic Stitched Sensor with Timing (MOST)[6]

BabyMOSS test devices (ER1): an overview

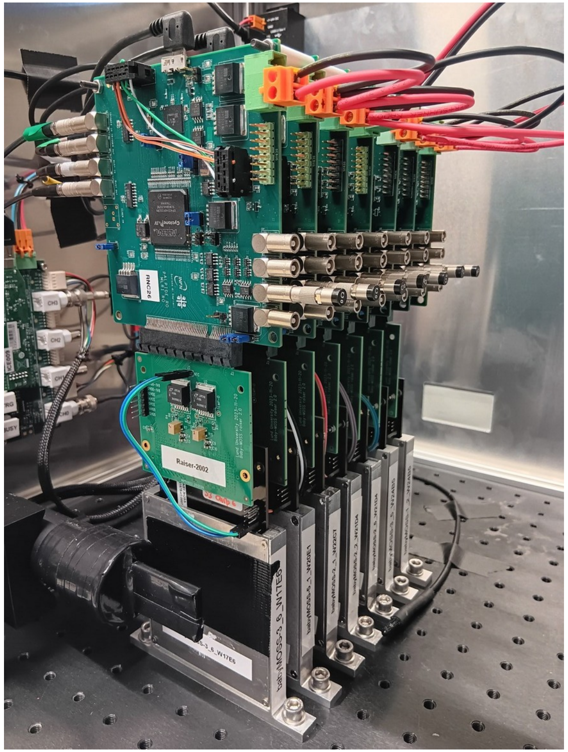


BabyMOSS

BabyMOSS chips:

- **Small-scale** (~30×14 mm^2), **stitched** test sensor from the **ER1** submission. Includes **8 pixel matrices** (***regions***), arranged in **2 rows** (***half-units*, or *HUs***):
  → **Top HU:** 256×256 matrices (22.5 µm pixel pitch);
  → **Bottom HU:** 320×320 matrices (18 µm pixel pitch);
  → **Regions differing** by transistor geometries in the analogue circuitry and by front-end gain;
- **Tested** both **in laboratories and under beam tests** to assess stitched **sensor performances (w/o irradiation)**;
- Smaller replica of the large-scale (~26 cm long), Monolithic Stitched Sensor (MOSS).

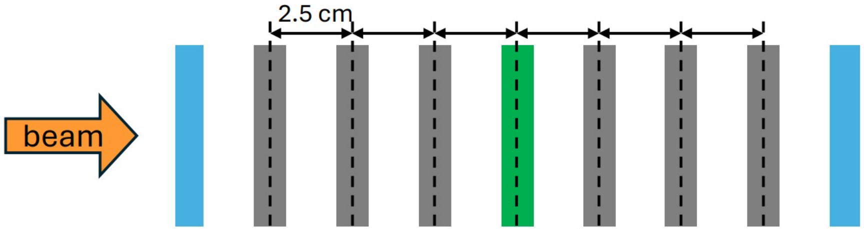
September 2024 test beam setup



- **BabyMOSS** chips have been studied in **test beam campaigns** since March 2024:
  → Performances under **varying front-end settings** and **radiation scenarios (NIEL and TID)** have been investigated;

- **September 2024 test beam campaign:**
  → **Devices Under Test (DUTs):** 1 non-irradiated babyMOSS chip and 2 neutron-irradiated (10^{13} 1 MeV n_{eq}/cm^2 NIEL) babyMOSS chips;
  → **Beam and facility:** 7 and 10 GeV/c $\pi^{\pm}$ beams at CERN Proton Synchrotron (PS);
  → **Telescope setup:** 6 babyMOSS tracking planes, 1 babyMOSS DUT, 2 scintillators for trigger.

  This campaign has been a collective effort by University & INFN Bari, Catania, Padova (Italy), Lund University (Sweden) and CERN (Switzerland).



Telescope setup schematics

September 2024 test beam setup

DUT (chip ID)	Irradiation
babyMOSS-2_1_W22C7	None
babyMOSS-2_2_W02F4	10^{13} 1 MeV n_{eq}/cm^2 NIEL
babyMOSS-3_3_W02F4	10^{13} 1 MeV n_{eq}/cm^2 NIEL

List of DUTs investigated in September 2024

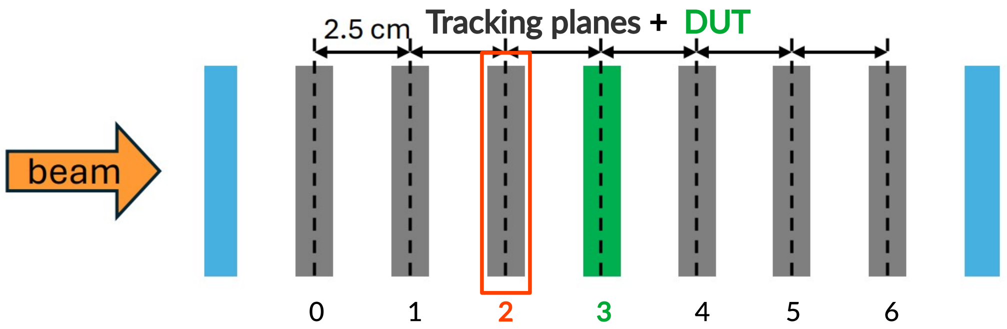
- **BabyMOSS** chips have been studied in **test beam campaigns** since March 2024:
  → Performances under **varying front-end settings** and **radiation scenarios (NIEL and TID)** have been investigated;

- **September 2024 test beam campaign:**
  → **Devices Under Test (DUTs):** 1 non-irradiated babyMOSS chip and 2 neutron-irradiated (10^{13} 1 MeV n_{eq}/cm^2 NIEL) babyMOSS chips;
  → **Beam and facility:** 7 and 10 GeV/c $\pi^{\pm}$ beams at CERN Proton Synchrotron (PS);
  → **Telescope setup:** 6 babyMOSS tracking planes, 1 babyMOSS DUT, 2 scintillators for trigger.

  This campaign has been a collective effort by University & INFN Bari, Catania, Padova (Italy), Lund University (Sweden) and CERN (Switzerland).

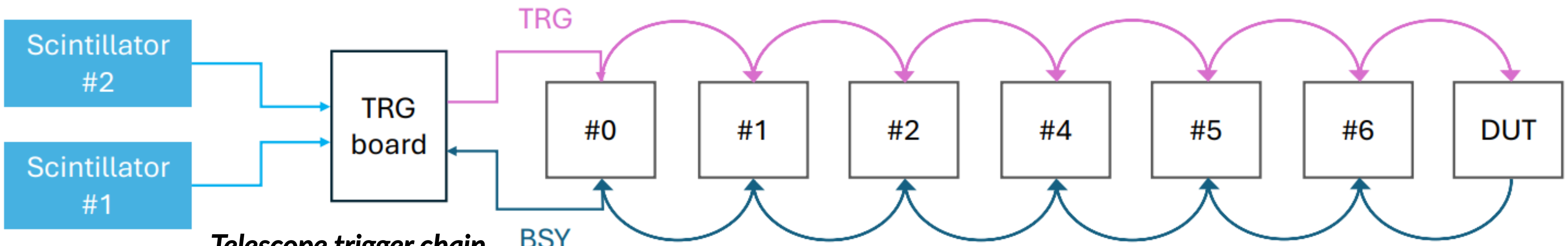
September 2024 test beam setup

Tracking plane #2: reference plane for analysis (see following slides)



Schematics of the Sep 2024 test beam telescope. Scintillators highlighted in blue. Planes numbered 0 to 6, DUT in green.

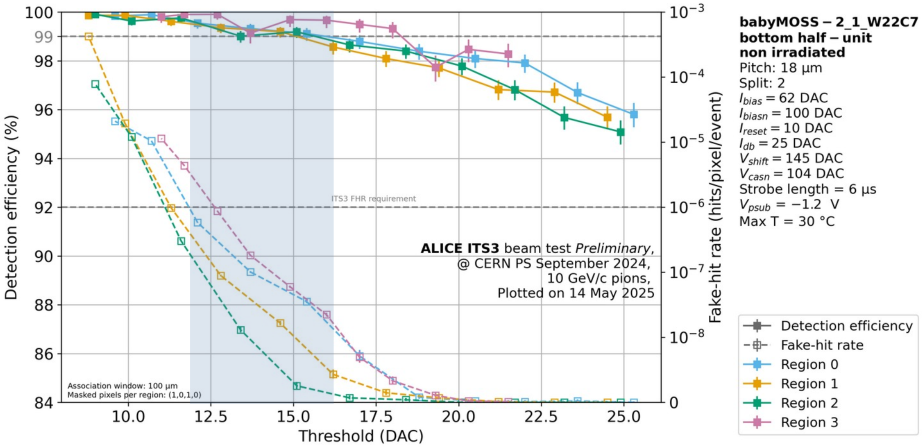
- **Trigger:** coincidence of **2 scintillator signals** from both ends of the telescope;
- **Trigger signal** travelling through tracking planes 0 to 6 and to the DUT;
- **Busy signal** sent by the DUT when recording a hit, backwards through tracking planes 6 to 0 and to the trigger board.

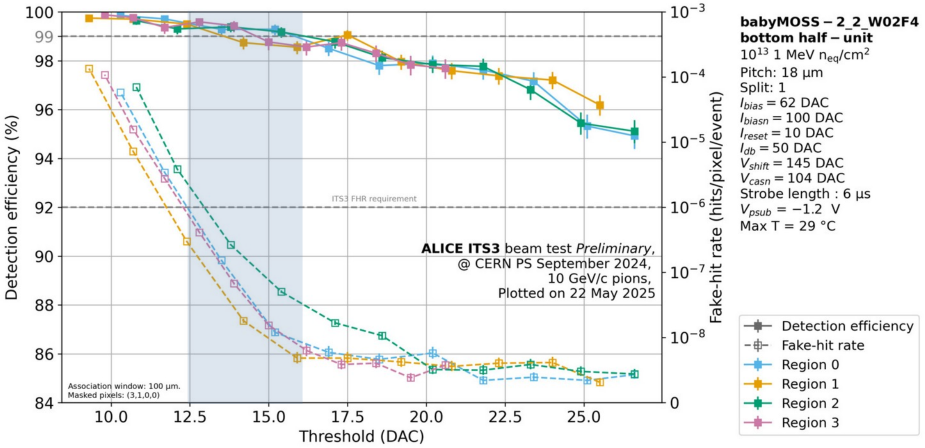


Telescope trigger chain

Test beam results: detection efficiency and fake-hit rate

Analyses performed with Corryvreckan framework [7]





babyMOSS-2_1_W22C7, non-irradiated
Bottom regions, V_{bb} = -1.2 V:

- Found a threshold window with detection efficiency > 99% and FHR < 10^{-6} hits/pixel/event:
  → **Region 0 between ~12 and ~16 DAC** units.

babyMOSS-2_2_W02F4, 10^{13} 1 MeV n_{eq}/cm^2 NIEL-irradiated
Bottom regions, V_{bb} = -1.2 V:

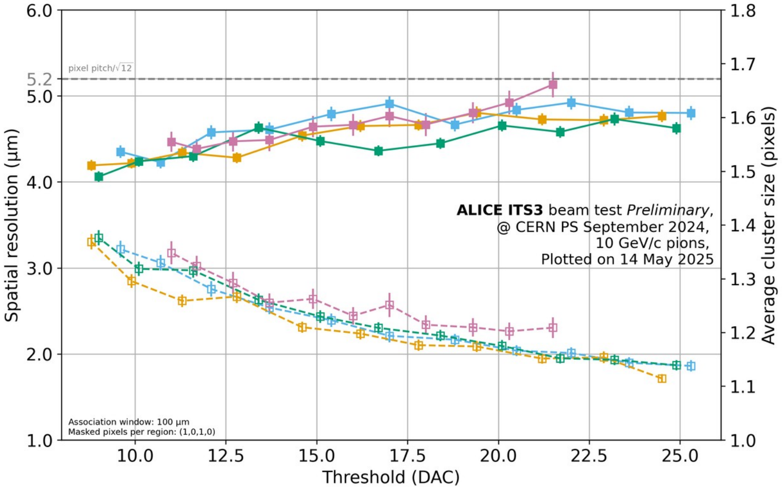
- **Operational margin** narrower, but still found:
  → **Region 0 between ~12.5 and ~16 DAC** units;
- **FHR plateau at high thresholds,** due to residual radiation levels and leakage current.

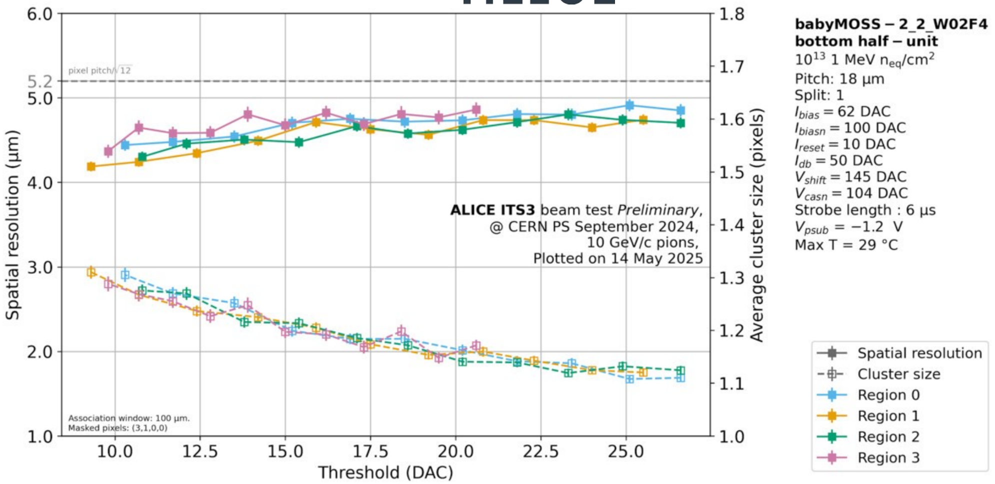
1 DAC ~ 8 e^-

[7] **D. Dannheim *et al.***, *"Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data".* JINST **16** (2021) P03008. DOI: 10.1088/1748-0221/16/03/P03008.

Test beam results: spatial resolution and average cluster size

Analyses performed with Corryvreckan framework [7]





babyMOSS-2_1_W22C7, non-irradiated
Bottom regions, V_{bb} = -1.2 V:

- **Slight degradation** of the **spatial resolution** and **reduced cluster size after NIEL irradiation:**
  → Linked to the creation of trapping centres.

babyMOSS-2_2_W02F4, 10^{13} 1 MeV n_{eq}/cm^2 NIEL-irradiated
Bottom regions, V_{bb} = -1.2 V:

- **Spatial resolution** < 5 µm for all bottom regions, meeting ITS3 sensor goals.

1 DAC ~ 8 e^-

[7] **D. Dannheim *et al.***, *"Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data"*. JINST **16** (2021) P03008. DOI: 10.1088/1748-0221/16/03/P03008.

Conclusions

- **After Long Shutdown 3** (2026-2030), the ALICE ITS will be upgraded to the new **ITS3** version, featuring **lightweight**, **stitched**, and – for the first time in a HEP experiment – **truly cylindrical sensors**;
- **ITS3 sensor goals: det. efficiency > 99%, fake hit rate < 10^{-6} hits per pixel and event** and **spatial resolution ≲ 5 µm;**
- **BabyMOSS chips** are **small-scale and compact**, with **8 sensing regions** arranged in **2 half-units**, **varying matrix dimensions**, **pixel pitches**, and **front-end circuitry**;
- **Test beams campaigns**, such as the **September 2024** one, have aimed to assess detection efficiency, fake hit rate, spatial resolution of both non-irradiated and neutron-irradiated chips;
- **BabyMOSS devices** have been shown to **meet ITS3 sensor performance goals**, even with **irradiation** levels **2.5 times the expected NIEL load**. This is also consistent with findings on similar, but large-scale MOSS devices[5].

New paper on babyMOSS test beam results is currently in preparation!

Say "Cheese"!

Thanks to all the fellow test beam crew members: Angelo, Caterina, Rajendra, Michele, Joey, and our crew leader Iaroslav!

References

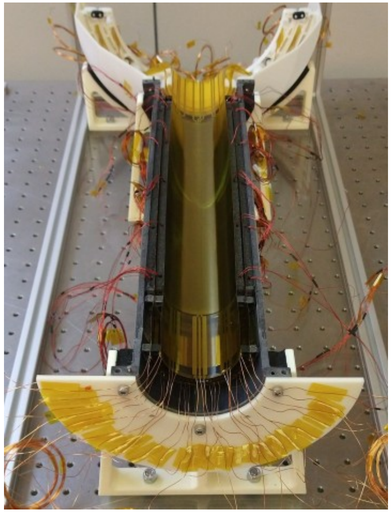
[1] **ALICE Collaboration,** *"ALICE upgrades during the LHC Long Shutdown 2".* JINST **19** (2024) P05062. DOI: 10.1088/1748-0221/19/05/P05062;
[2] **ALICE Collaboration,** *"Technical Design Report for the ALICE Inner Tracking System 3 – ITS3; a bent wafer-scale monolithic pixel detector"*. CERN Document Server (2024). CERN-LHCC-2024-003;
[3] **G. Aglieri Rinella *et al.*,** *"Characterization of analogue Monolithic Active Pixel Sensor test structures implemented in a 65 nm CMOS imaging process"*. Nuclear Instruments and Methods in Phys. Res. A **1069** (2024) 169896. DOI: 10.1016/j.nima.2024.169896;
[4] **G. Aglieri Rinella *et al.*,** "Digital pixel test structures implemented in a 65 nm CMOS process". Nuclear Instruments and Methods in Phys. Res. A **1056** (2023) 168589. DOI: 10.1016/j.nima.2023.168589;
[5] **O. Abdelrahman *et al.*,** *"Characterisation of the first wafer-scale prototype for the ALICE ITS3 upgrade: the monolithic stitched sensor (MOSS)"*. Submitted: 13 Oct 2025. DOI: 10.48550/arXiv.2510.11463;
[6] **J. Sonneveld *et al.* on behalf of the ALICE collaboration,** *"Yield, noise and timing studies of ALICE ITS3 stitched sensor test structures: The MOST"*. Nuclear Instruments and Methods in Phys. Res. A **1080** (2025) 170764. DOI: 10.1016/j.nima.2025.170764;
[7] **D. Dannheim *et al.*,** *"Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data"*. JINST **16** (2021) P03008. DOI: 10.1088/1748-0221/16/03/P03008.

Thank you for your attention!

Backup slides

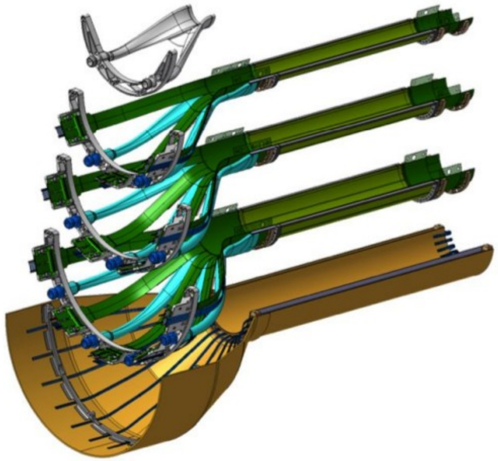
ITS3 R&D: where are we now?

Cooling and integration studies



BreadBoard Models:
partially representative of the future ITS3, used for cooling studies

Engineering Models:
mixing final-grade and commercial components



Qualification Models:
Final-grade models for full qualification tests to come later this year!

Test beam data analysis with Corryvreckan

Corryvreckan[7]: analysis framework for test beam data, integrating different modules to perform individual tasks such as:
→ Noisy pixel masking;
→ Telescope alignment;
→ Particle track reconstruction, etc…

- **Reference plane is needed:** plane 2, in our analysis;
- **Correlations:** defined in Corryvreckan as the differences between *x*(*y*) coordinates of all cluster centres on any given plane and *x*(*y*) coordinates of all clusters on the reference plane;
- **Residuals:** differences between interpolated track intercepts and associated clusters, on any given plane;
- **Tracking algorithm:** all pairs of hits from plane 0 and 6 linked by straight line tracks, hits and clusters are associated if falling within a defined window.

Test beam data analysis with Corryvreckan

1. Mask creation:
Noisy pixel masking based on measured Fake Hit Rate

2. Pre-alignment:
Shifting planes by *x*(*y*) mean correlation, for afirst alignment with the reference plane

- **Det. Efficiency** = N_{assoc}/N_{tot}:
  → N_{assoc} = number of tracks with associated clusters;
  → N_{tot} = total number of tracks.
- **Spatial resolution $\sigma_{x(y)}$:** estimated from std. dev. of *x*(*y*) DUT residual distributions.

This analysis cuts:
- Pixels masked if hits > 1000 times the average hit counts (tracking planes);
- DUT pixel masks based on off-beam FHR scans;
- Min. 7 hits per track, 50 μm spatial cut for track hits;
- 100 μm cluster association window.

3. Alignment (DUT excluded):
Shifting and rotating planes to minimise track χ^2 (excluding DUT)

4. Alignment (DUT included):
Shifting and rotating planes until convergence (including DUT)

5. Analysis:
Extracting information about DUT detection efficiency and spatial resolution