HGTD Mainz · Johannes Gutenberg-Universität Mainz

HGTD Modules production and test

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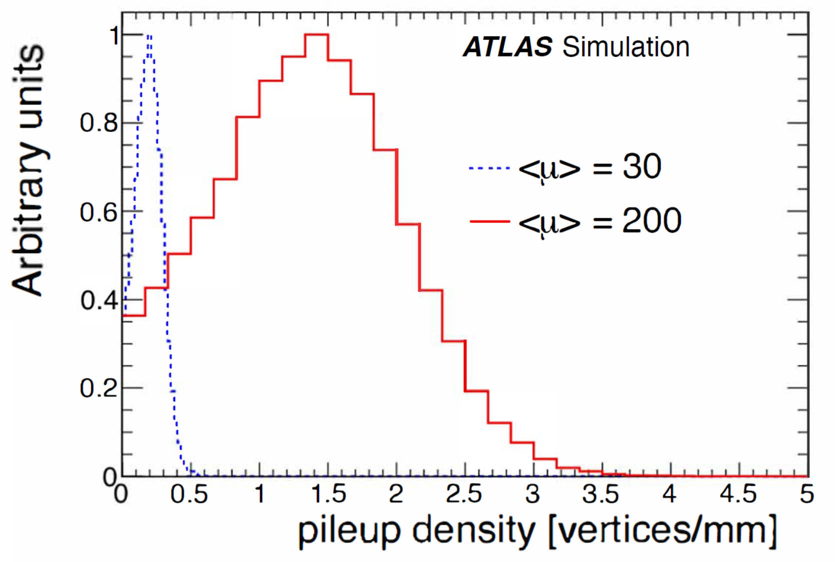
Why a timing detector at the HL-LHC

THE PROBLEM: pile-up

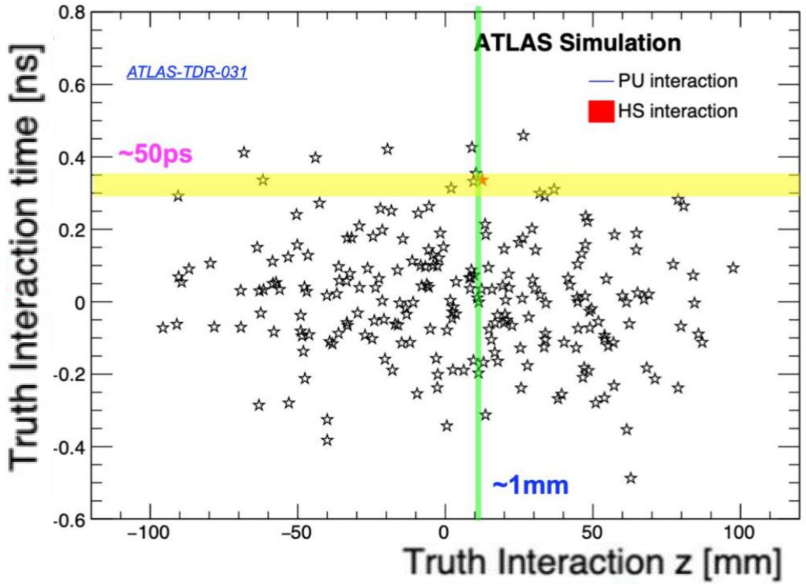
- <μ> = 200 pp interactions in every bunch crossing
- 1.6 vertices per mm along the beam (Run 2: 0.24)
- in the forward region σ(z0) exceeds the ~0.6 mm vertex spacing → tracks get assigned to the wrong vertex

THE ANSWER: HGTD

- one time stamp per track: 30 ps at start, 50 ps at end of life
- interaction time spread is ~175 ps, far larger than σt → overlapping vertices separate in time
- covers 2.4 ≤ |η| < 4.0, where tracking alone is not enough



Local pile-up density: <μ> = 30 vs <μ> = 200
ATLAS HGTD TDR, CERN-LHCC-2020-007



Interactions in (z, t): ~1 mm in z holds many vertices, ~50 ps in t resolves them
ATLAS HGTD TDR, CERN-LHCC-2020-007

HGTD inside the ATLAS detector

Where it sits

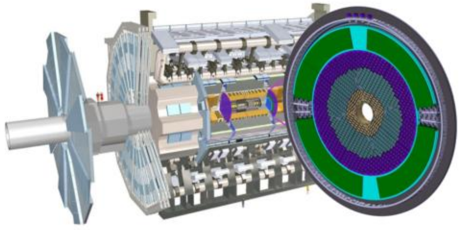
- between the inner tracker and the end-cap calorimeters

Layout

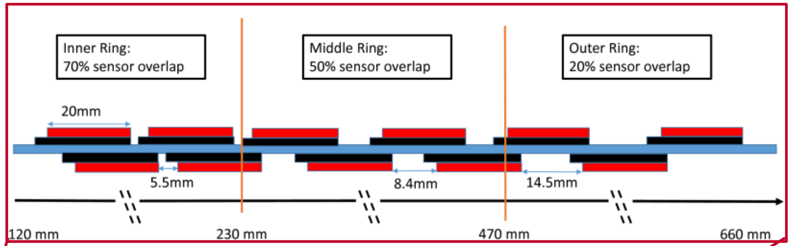
- two instrumented double-sided layers per end-cap
- active region $2.4 \le |\eta| < 4.0$
- modules arranged in 3 rings, overlap increasing towards small radius

Operation

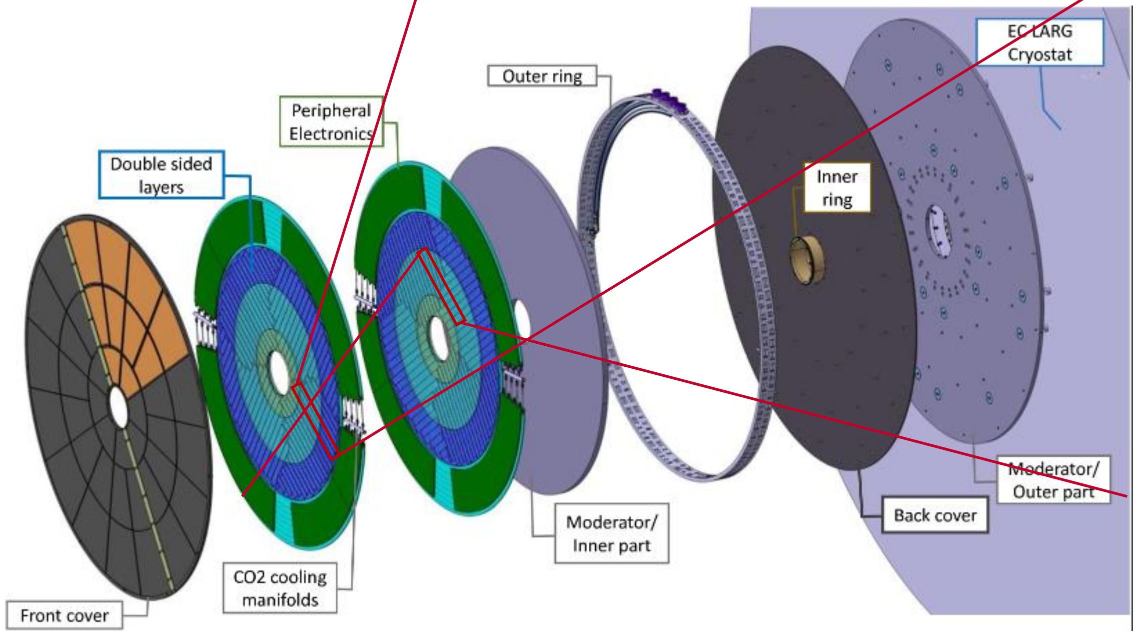
- Working temperature -30 ºC (CO_2 cooling system) to mitigate the impact of irradiation on sensors
- Replacement of the modules of the inner ring after Run 4



HGTD position in ATLAS



Sensor overlap: 70 % inner, 50 % middle, 20 % outer ring



Exploded view of one HGTD end-cap vessel

HGTD Active Detection Region
Detector Modules

Module:

2 Sensors

2x2 cm² each, 1.3 x 1.3 mm² pads

- Sensor choice: Si-based Low Gain Avalanche Detector (LGAD)
- Excellent time resolution of σt = 30-50 ps per MIP track

2 ASICs

2x2 cm² each, bump bonded to sensor (ALTIROC A3.1)

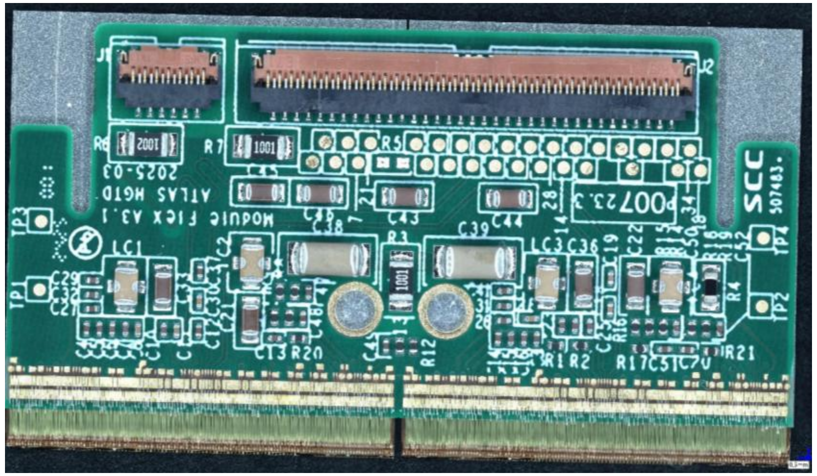
- ASIC = custom chip designed for one specific job → Ours: turn the analogue pulse into a digital signal, 225 times in parallel

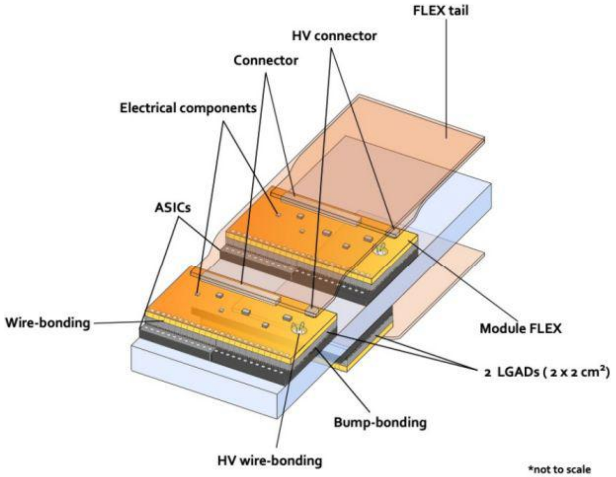
Module flex

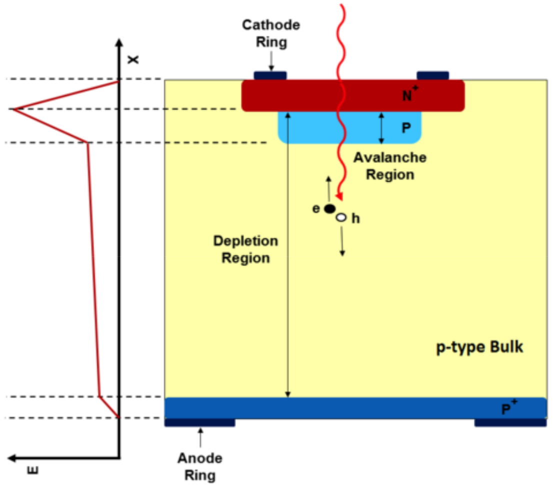
Glued to sensors and wire bonded to sensors (bias voltage) and ASICs (signals and power)

Flex tail

connects the module to the peripheral electronics boards (PEB)

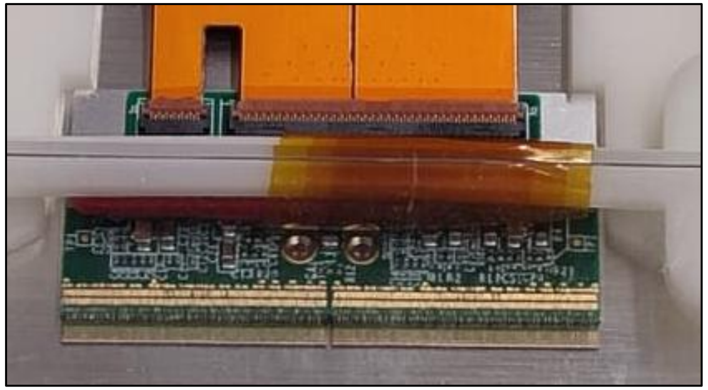






Status and Mainz role

- **Currently in preproduction**
  - 36 preproduction modules assembled so far
  - Exercising the full assembly chain
- **After the transition to the production phase**
  - In total: ≈ 1000 modules (and ≈ 50 – 60 detector units) will be produced in Mainz (out of 8032 modules)
  - Corresponds to a production rate of approximately 15 modules and 1 DU per week for roughly 1.5 years



Preproduction module

Module hybrids
2 ASICs bump-bonded to 2 LGADs

›

Module gluing
Module flex glued to 2 hybrids

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Module metrology
Alignment and height profile

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Wire bonding
Connect ASICs and sensors with the module flex

›

Module testing
Testing the modules for functionality

›

DU loading
Modules glued onto support unit

›

DU testing
Survival check after loading

›

Shipment to CERN
Installation into ATLAS

Established on preproduction
Under optimisation
Validated with dummies
Not started

Module assembly: gluing

Hybridization | **Gluing** | Metrology | Wire bonding | Testing | DU loading | DU testing | Shipment

Before Mainz

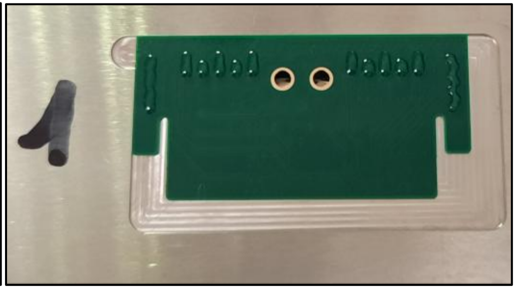
- Hybridization: each LGAD is bump-bonded to an ALTIROC at an external site
- Mainz receives 2 hybrids and 1 module flex per module

Gluing at Mainz

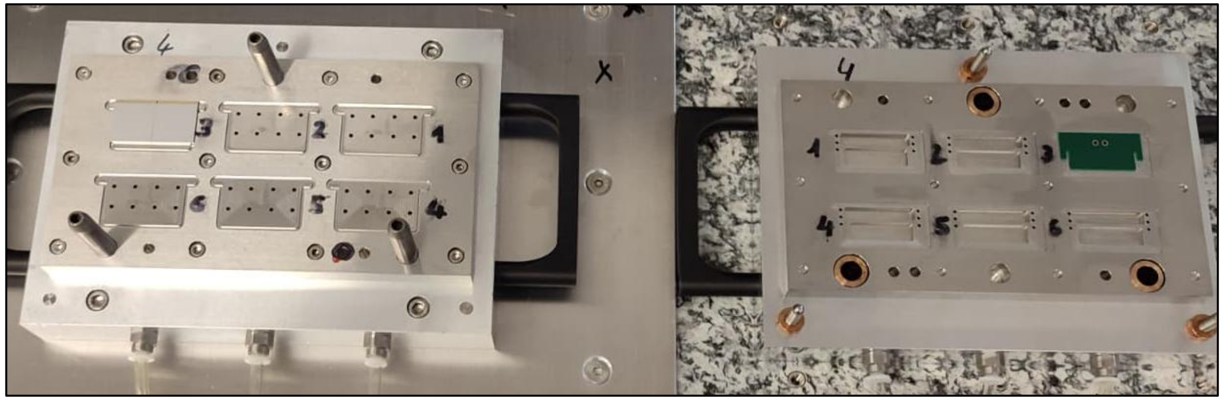
- glue deposited by a gantry system following a fixed pattern (backup)
- custom jig aligns and holds up to 6 modules at the same time
- partial fixation by vacuum while the glue cures

6 modules glued in one cycle

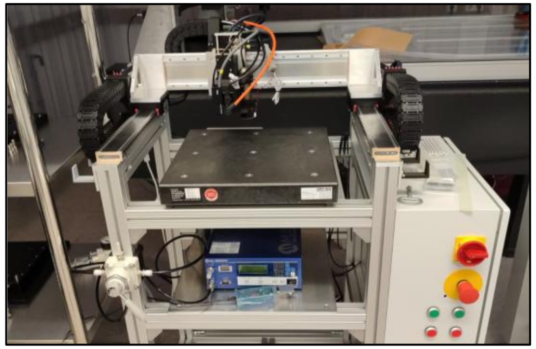
Hybrids



Module flex with glue pattern



Multi-module assembly jig



Gantry system

Module assembly: metrology

Hybridization | Gluing | **Metrology** | Wire bonding | Testing | DU loading | DU testing | Shipment

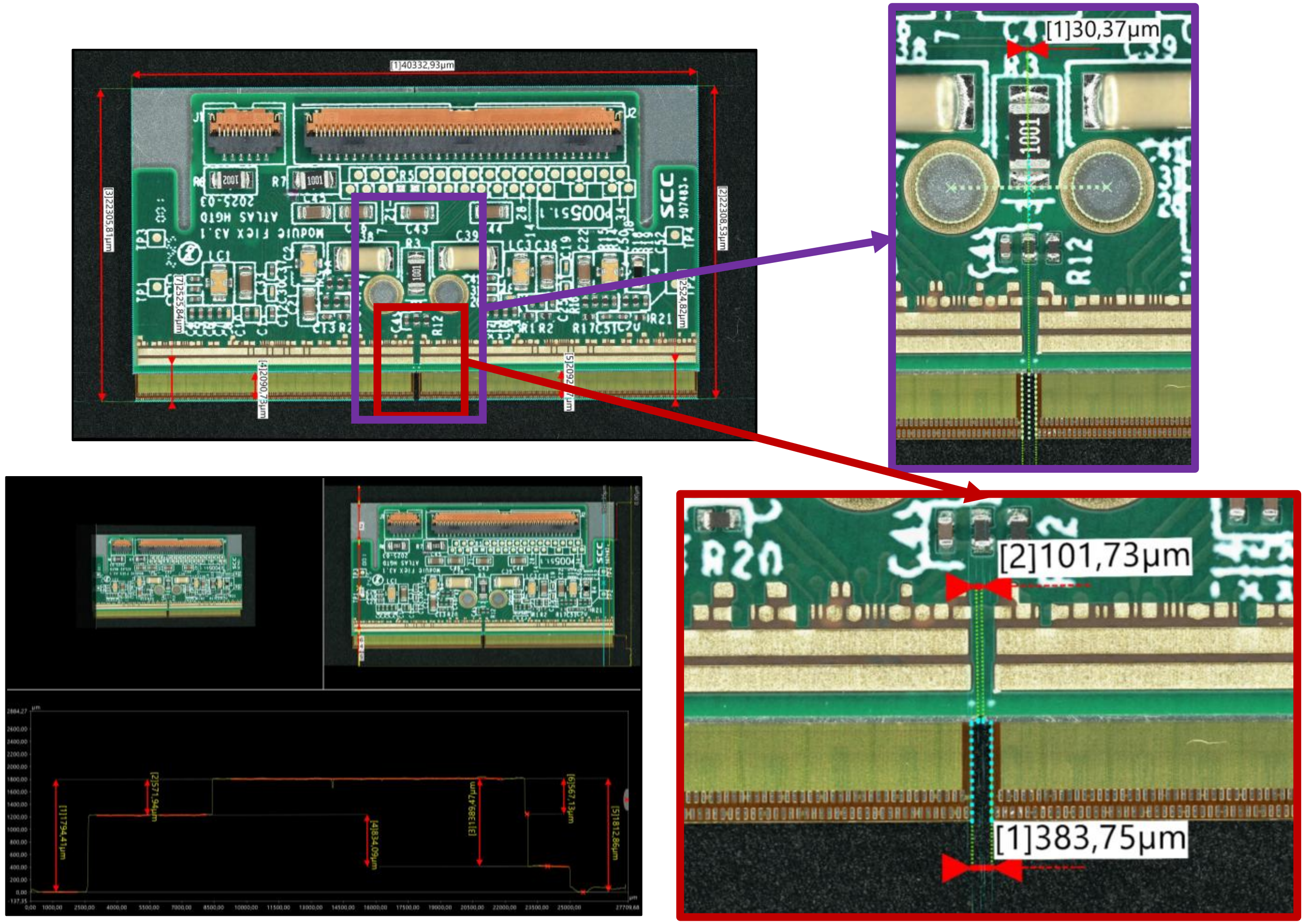
Why it matters

- out-of-spec distances may prevent the module from working, or from fitting into the detector

Keyence VH-Z20U, automated x–y stage

- alignment and overall dimensions of every module
- image stitching over the full module surface
- height profile across flex, ASICs and sensors
- all results uploaded to the production database

every module measured and archived



Module assembly: wire bonding

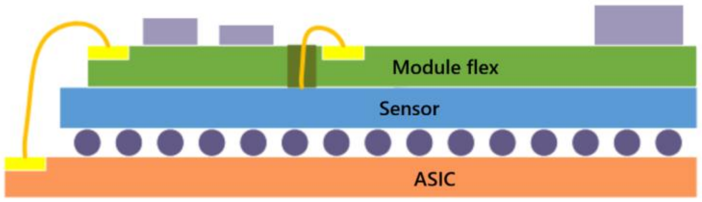
Hybridization | Gluing | Metrology | **Wire bonding** | Testing | DU loading | DU testing | Shipment

HESSE Bondjet BJ855

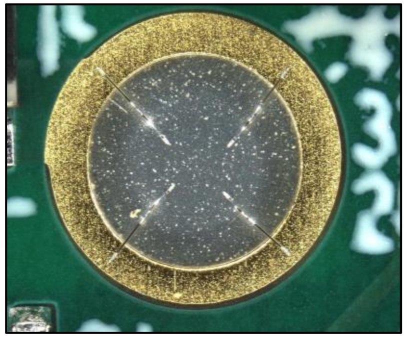
- 25 µm thick aluminium wire
- 8 different wire lengths in one pattern

What gets connected

- sensors to module flex: 4 wires per sensor, for the bias
- ASICs to module flex: 235 wires per ASIC

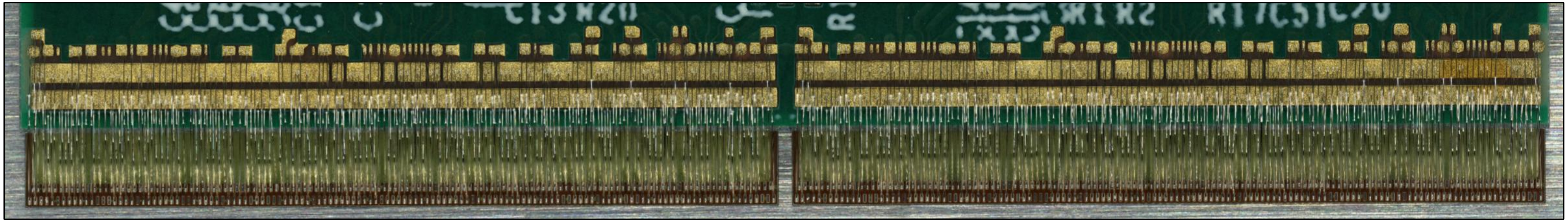


Wire bonds in the module stack



Bond on a sensor pad

478 wire bonds per module → ~480 000 for the Mainz production

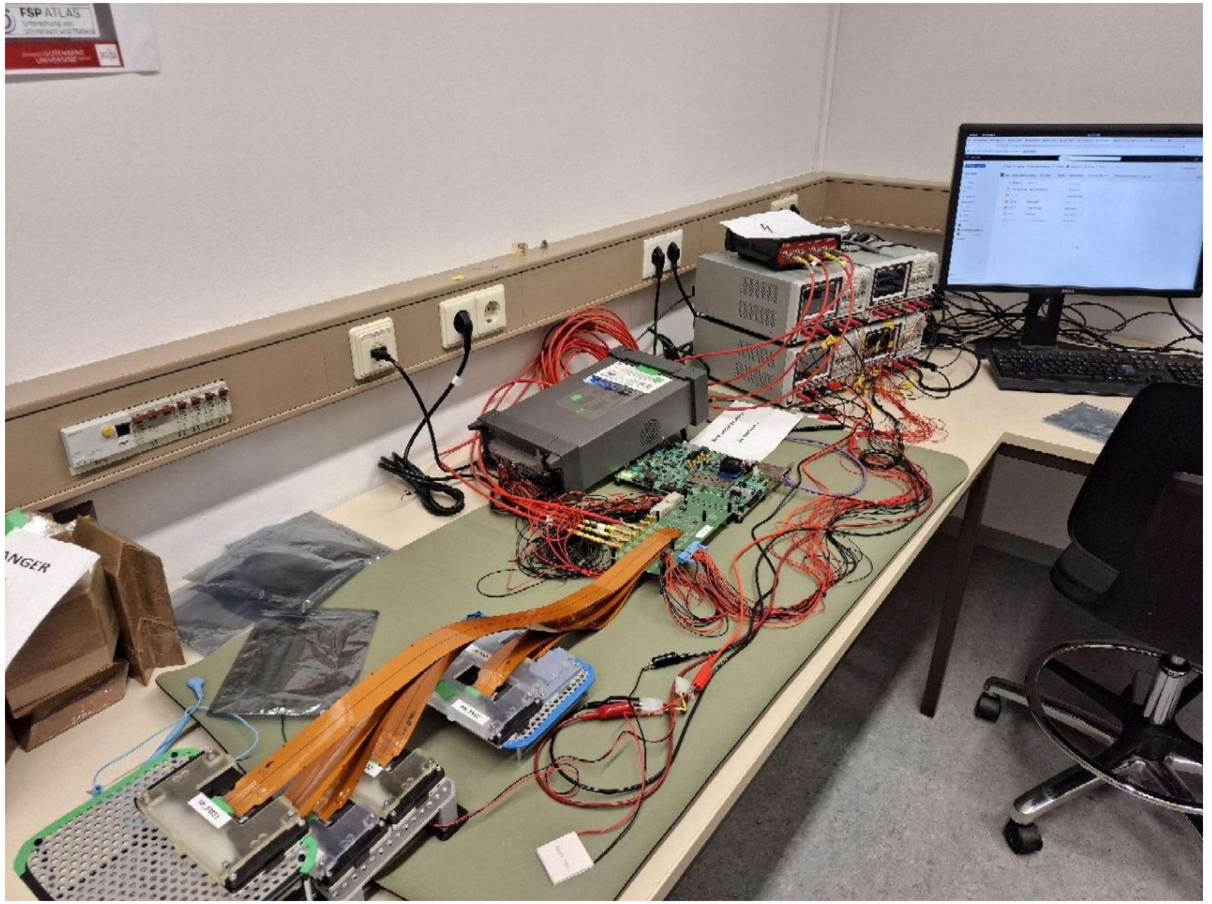


ALTIROC A3.1 wire bonding: 2 × 235 wires

Module Testing - setup

Hybridization | Gluing | Metrology | Wire bonding | **Testing** | DU loading | DU testing | Shipment

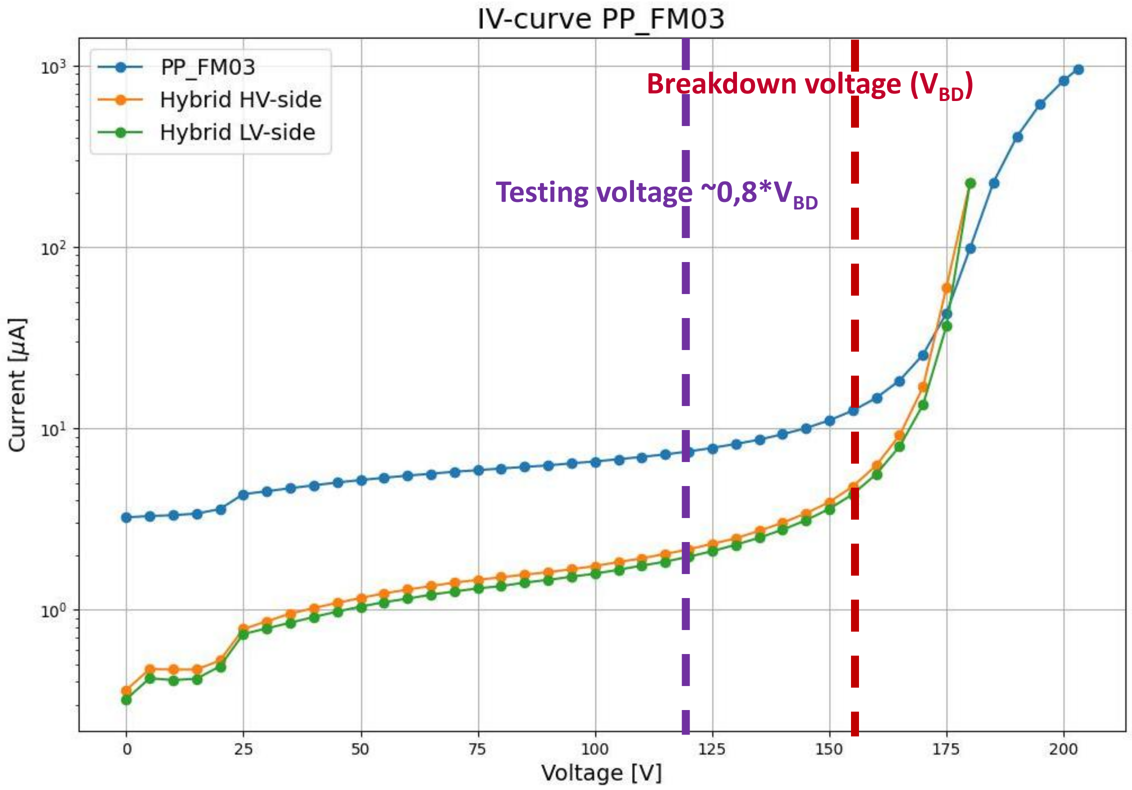
- **FPGA setup for module testing**
  - FPGA for readout
  - Modules connected via an adapter board and flex tails
  - Single and multi module test stand
- **IV characterization of the module sensors**
- **Threshold scans, and module tuning by injecting test charge**
- **Measurements with ^{90}Sr-source**
- **Thermal cycling**



Module Testing - IV

Hybridization | Gluing | Metrology | Wire bonding | **Testing** | DU loading | DU testing | Shipment

- **FPGA setup for module testing**
- **IV characterization of the module sensors**
  - V_{BD} where leakage current start increasing exponentially
  - Ideal operation point: 120 V → in the linear region
  - Comparison of module IV with the IV values of its individual hybrids, which are taken from the database
- **Threshold scans, and module tuning by injecting test charge**
- **Measurements with ^{90}Sr-source**
- **Thermal cycling**

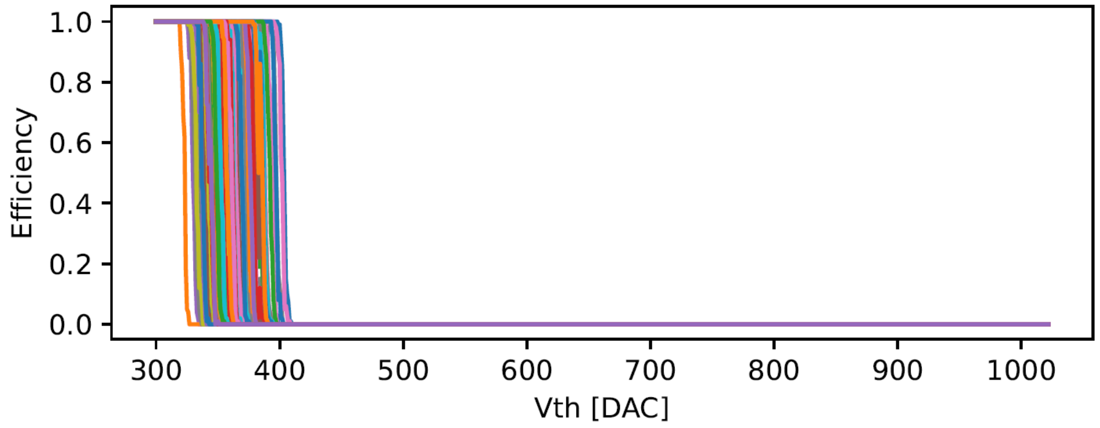


IV-curve of a preproduction module and its hybrids (PP_FM03)

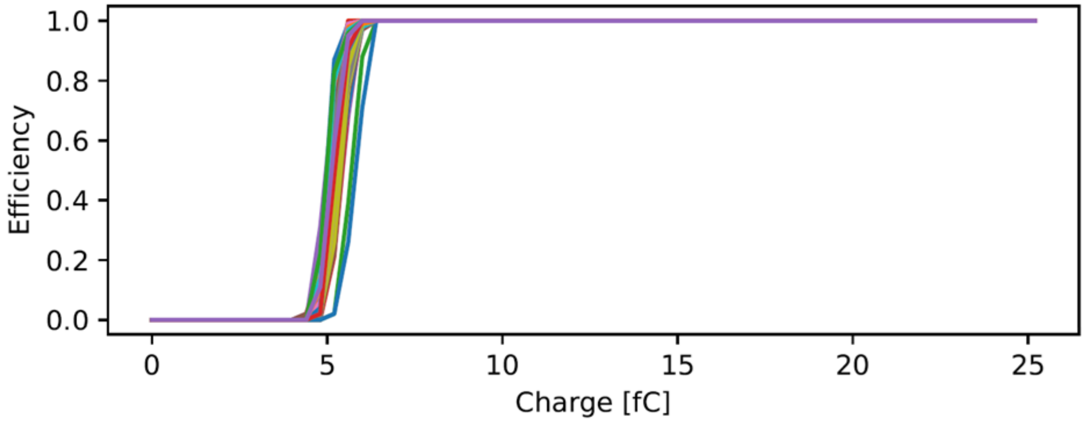
Module Testing – Electrical Test

Hybridization | Gluing | Metrology | Wire bonding | **Testing** | DU loading | DU testing | Shipment

- **FPGA setup for module testing**
- **IV characterization of the module sensors**
- **Threshold scans, and module tuning by injecting test charge (one of multiple electrical tests)**
  - ASICs can inject a test charge
  - Find the threshold voltages at which the efficiency drops to 50 %
  - Tune the module so that every pixel has the same efficiency for a given charge
- **Measurements with ^{90}Sr-source**
- **Thermal cycling**



Threshold scan results of one chip of a preproduction module (PP_FM05)

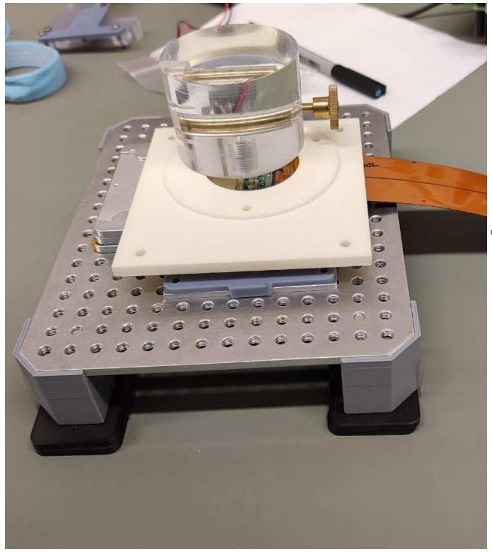


Charge scan results of one chip of a preproduction module (PP_FM05)

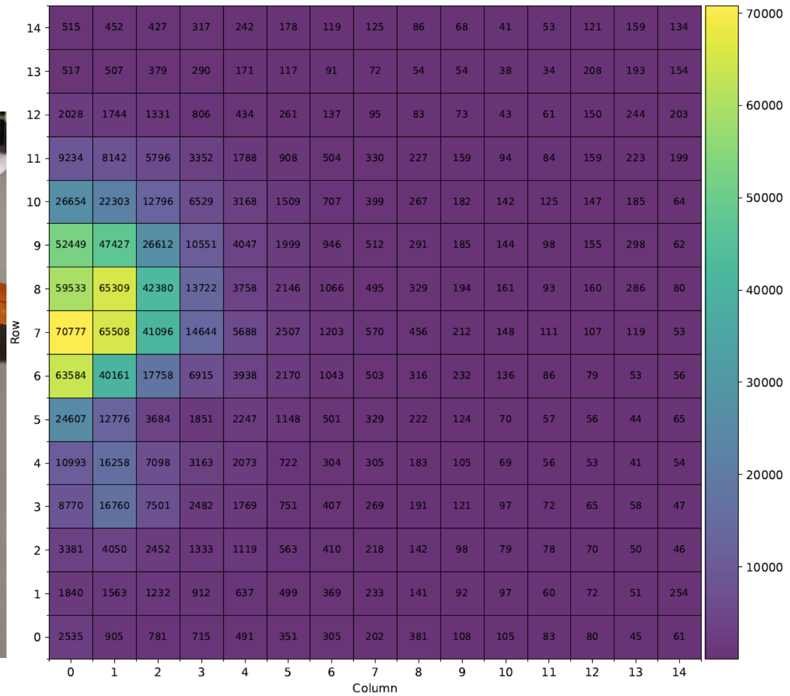
Module Testing – source and TC

Hybridization | Gluing | Metrology | Wire bonding | **Testing** | DU loading | DU testing | Shipment

- **FPGA setup for module testing**
- **IV characterization of the module sensors**
- **Threshold scans, and module tuning by injecting test charge**
- **Measurements with ^{90}Sr-source**
  - Beta source placed over the module and hits are recorded
  - Test if all 15 x 15 pixels are properly connected
  - TOA distribution
- **Thermal cycling**
  - Cycling between -40 °C and +40 °C and then test if all the pixels are still connected



Source scan setup



Source scan results of one chip of a preproduction module (PP_FM08)

Summary and take home

Why we build it: At HL-LHC 200 pp collisions overlap in every bunch crossing, 1.6 vertices per mm along the beam. In the forward region tracking alone cannot tell them apart → **HGTD adds a second, independent coordinate: time.**

Module assembled
Gluing, wirebonding and testing

›

Glued onto the DU
Glue dots and screws: no longer recoverable

›

Installed in ATLAS
Behind the ITk. No access during a run

›

~10 years of running
The outer ring must survive 4000 fb^{-1}

Every defect not caught on the test bench may become a dead channel for a decade.

Where we are:

- 36 preproduction modules assembled and tested
- Full chain exercised, from gluing to thermal cycling
- Keep optimising the process and the modules

What comes next:

- Production: ≈ 1000 modules at Mainz, 15 per week
- Six-module test station; QC statistics over the full sample
- Tight schedule

This is why we test every module, and why we test the procedure before we test at scale.

APPENDIX

Backup slides

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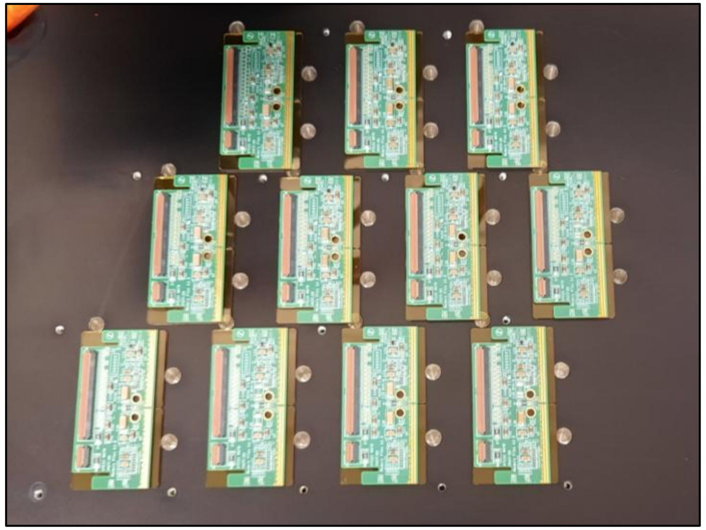
Detector Unit loading

Hybridization | Gluing | Metrology | Wire bonding | Testing | **DU loading** | DU testing | Shipment

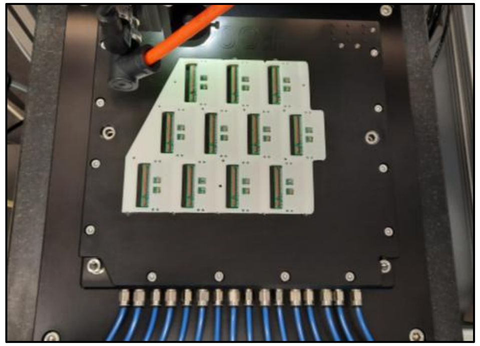
Glue assembled modules onto support units

- Functioning modules will be arranged on a loading plate using alignment pins
- Correctly positioned modules are fixated with vacuum
- 4 glue dots on each module are distributed using the gantry system
- SU is placed manually using a custom handle and fixated with screws

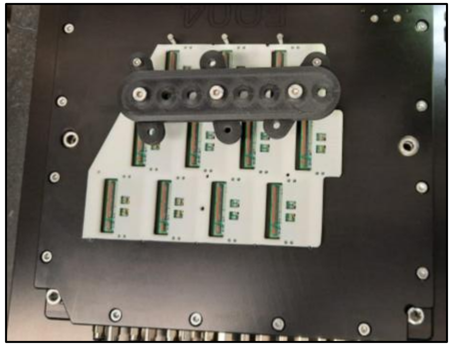
- So far only tests with 3D-printed dummies due to lack of material
- 4 different types of DU to be loaded in Mainz
- SU are made from PEEK



Dummy modules on loading plate



Loaded dummy detector unit

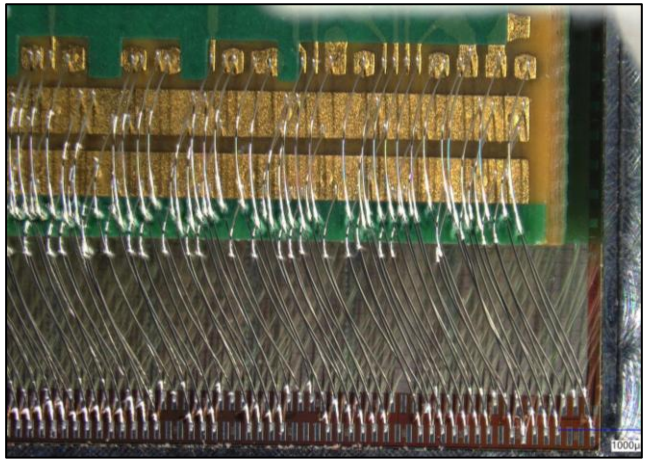


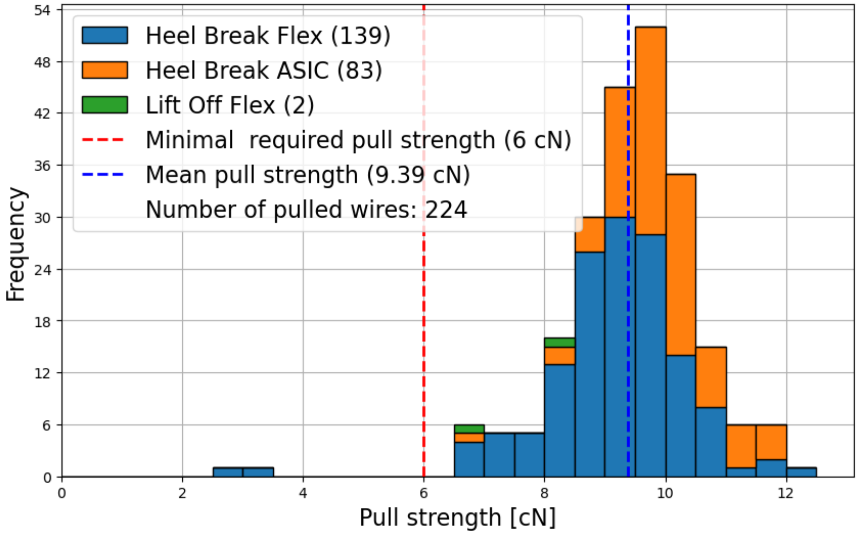
3D-printed dummy SU with handle

Module Assembly: Wire bond quality control

Optical inspection
- Form and height of the wire loops
- Form and width of the bond contacts

Pull tests
- Determine the strength of the wire bonds by pulling them off
- Pull strength requirements for HGTD:
  - Ø > 8 cN
  - MIN > 6 cN
- Wire bonding of new pattern still under optimisation
  - A few wires failed the minimum pull strength
  - Complicated wire pattern makes it difficult

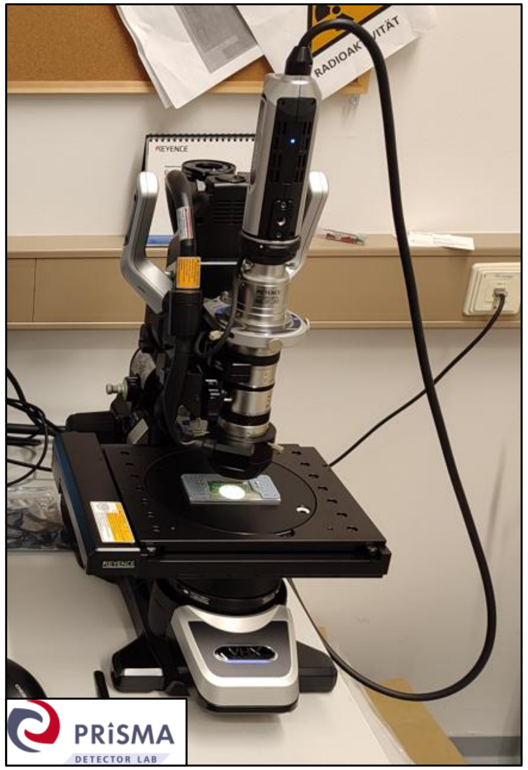




Pull tests results for ALTIROC A3.0 wire bonding (previous chip version)

Machines

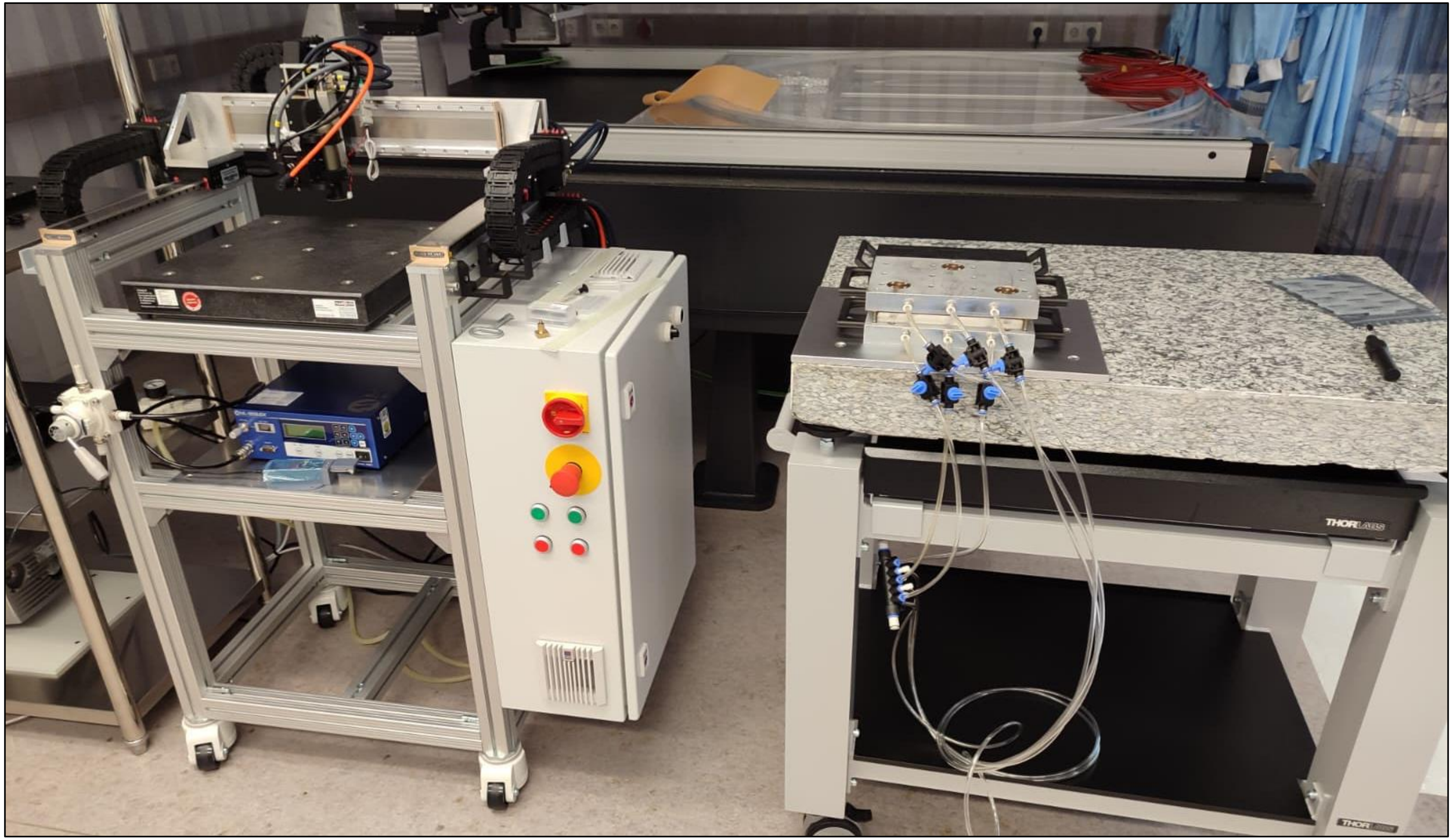
xyztec Sigma pull tester



Keyence Microscope
With automated x-y stage

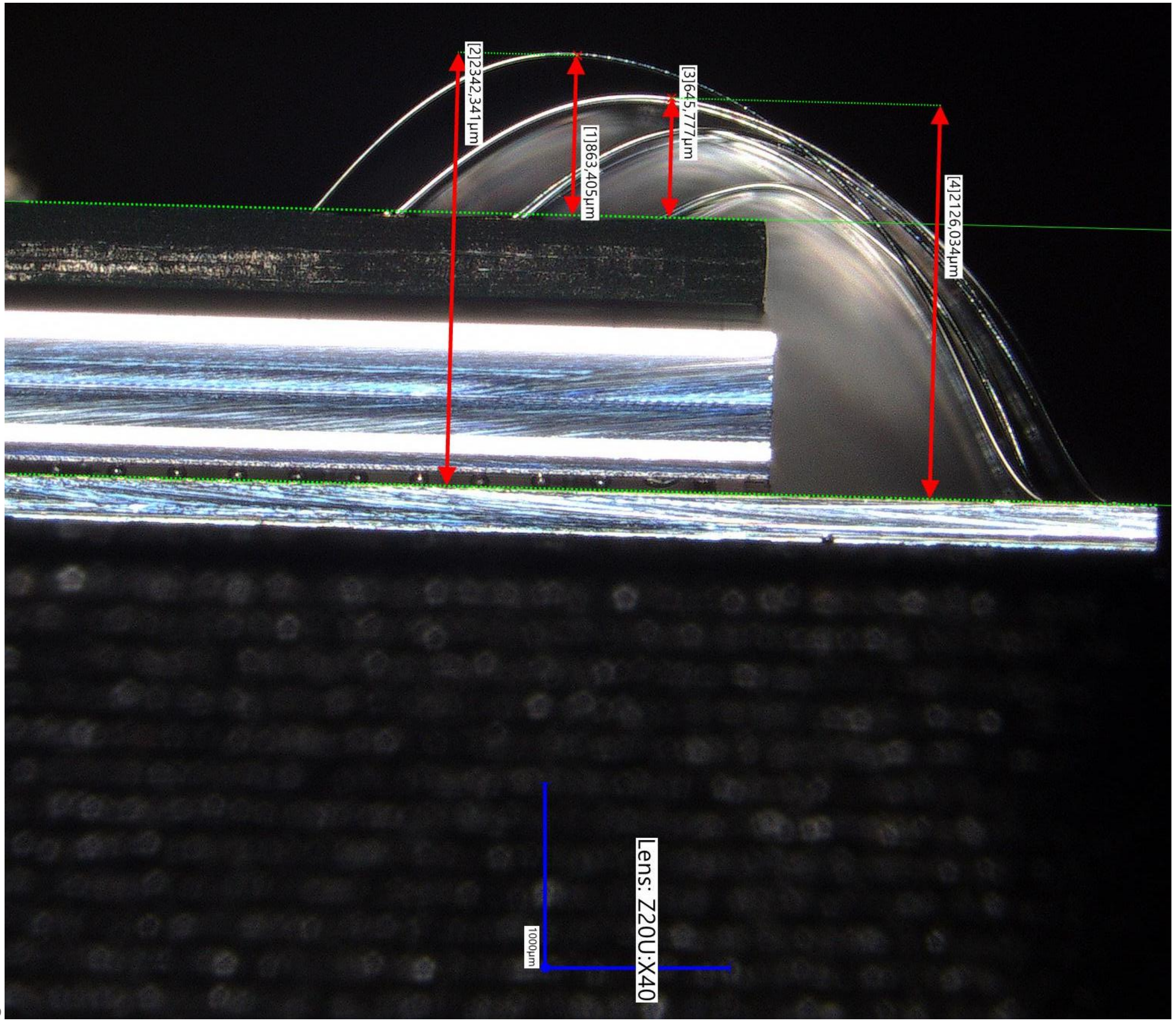
HESSE Mechatronics Bondjet BJ855

Glue bot setup



Glue pattern module assembly

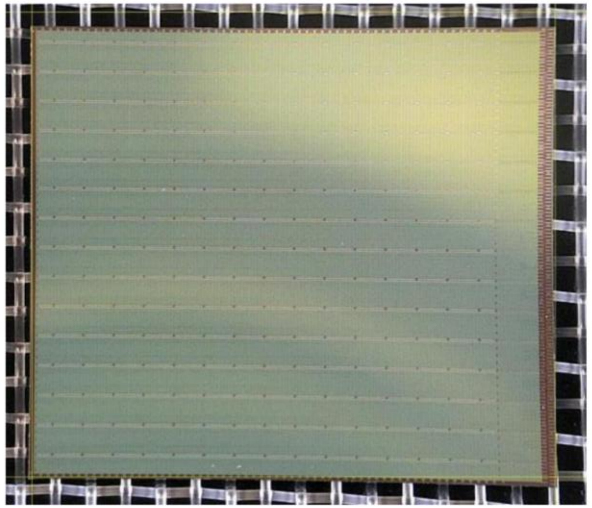
Wirebonds heights (still under optimization)

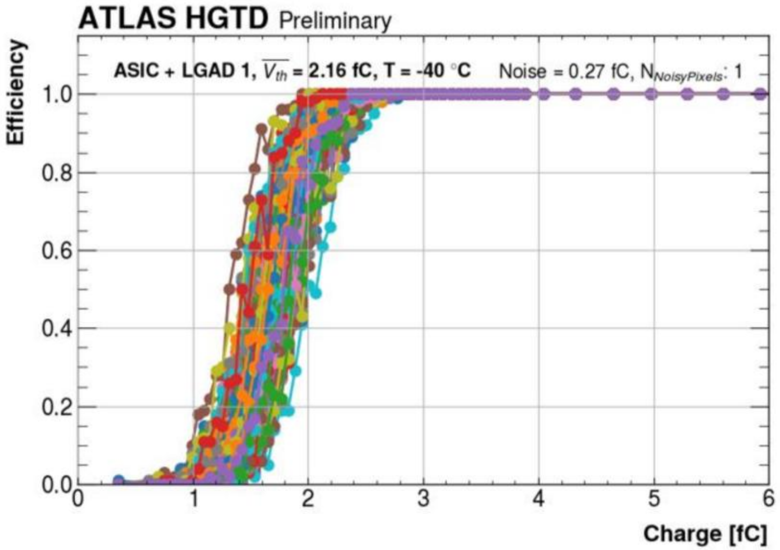


Front-End Readout: ASIC

ATLAS LGAD Timing Integrated Read-Out Chip (ALTIROC)

- 130 nm CMOS from TSMC
- Jitter: < 25 ps at 10 fC (< 65 ps at 4 fC)
- Radiation hard up to 2 MGy
- Discriminator threshold minimum: 2 fC
- Provides Time-Of-Arrival (TOA) and Time-Over-Threshold (TOT) information
- TDC for timing information
- Final version: ALTIROC-A3.1 (under test)





S-Curves of ALTIROC-3 + LGAD sensor tuned at 2fC

HGTD Sensor

- Low Gain Avalanche Detector (LGAD) technology
- 15×15 pads
- Pad size: 1.3 mm×1.3 mm
- Active thickness: 50 μm
- Carbon-enriched gain-layer for radiation hardness
- Time resolution per-hit: 35 ps (start) - 70 ps (end)

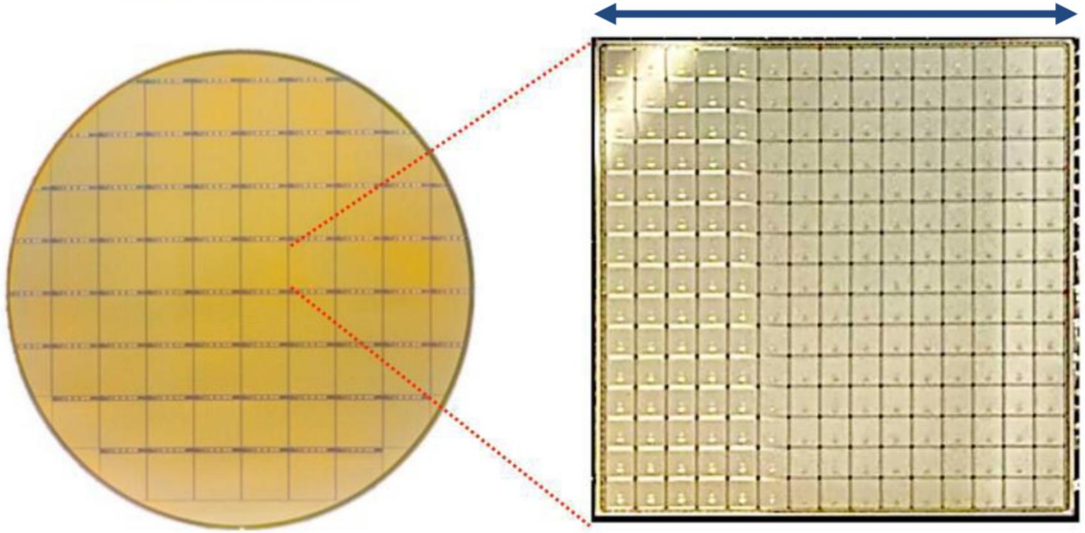
LGAD Technology:

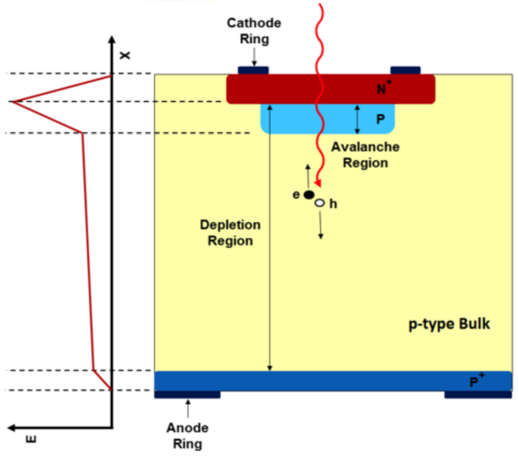
- N-in-P diode structure with extra p-type gain-layer
- Moderate gain: 10 – 20
- Extra gain layer: Fast rise time and larger signal-to-noise ratio

→ Excellent time resolution

8'' wafer
52 sensors

15×15 LGAD pads
2×2 cm^2 sensor



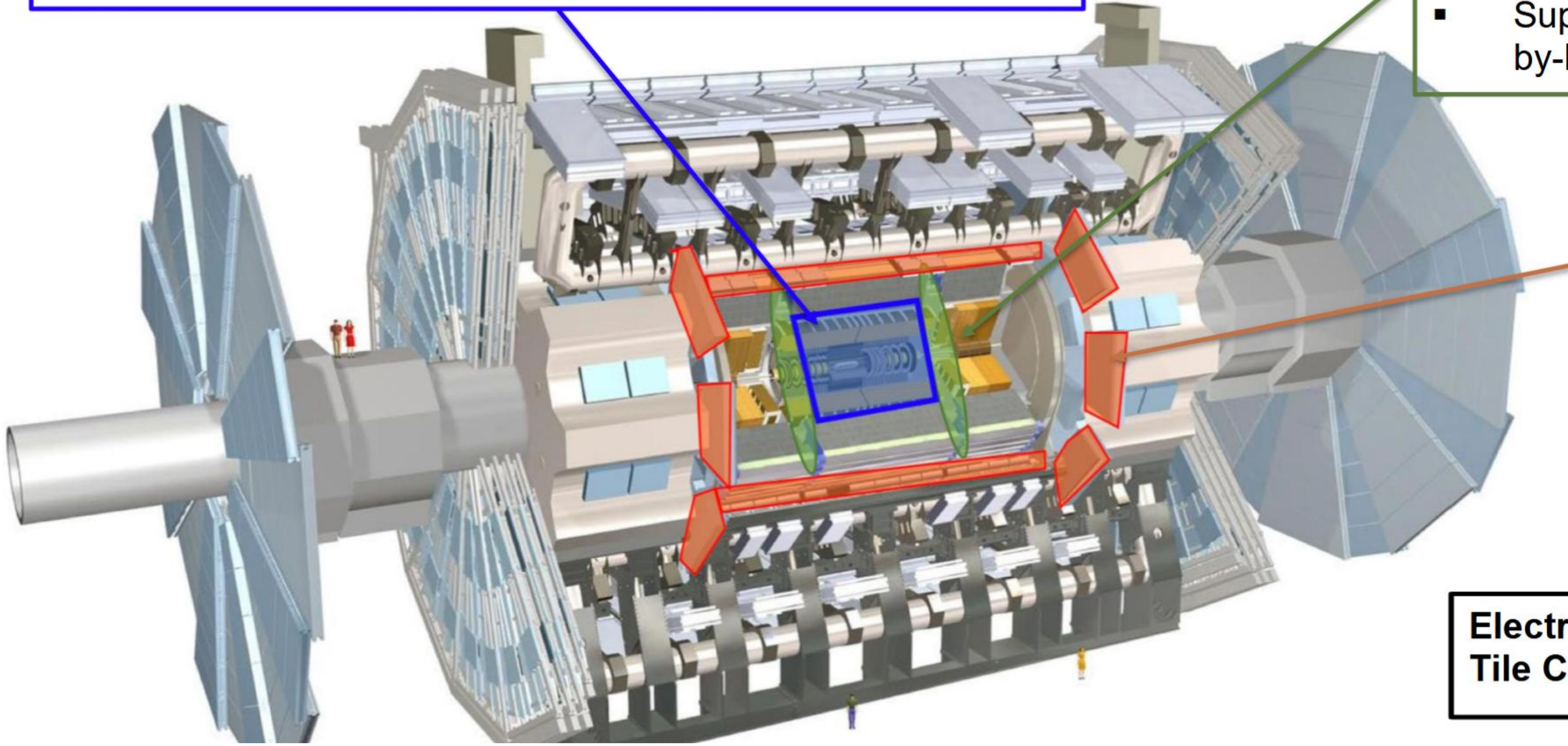


ATLAS Upgrades for HL-LHC

- Major upgrades to achieve physics goals of HL-LHC

Fully silicon inner tracker (ITK)
- Coverage up to $|\eta|$ = 4.0, less material, finer segmentation

High-Granularity Timing Detector (HGTD)
- 30 ps timing resolution with LGAD
- Coverage: $2.4 < |\eta| < 4.0$
- Suppress pile-up and measure bunch-by-bunch luminosity



Additional muon coverage

Trigger/Data Acquisition
- Upgrade for higher rates

Electronics upgrades for LAr Calo, Tile Calo and Muon detectors