The ATLAS upgrade and the contribution of the Laboratory for Testing of Semiconductor Particle Detectors

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ATLAS EXPERIMENT

FZU
Institute of Physics of the Czech Academy of Sciences

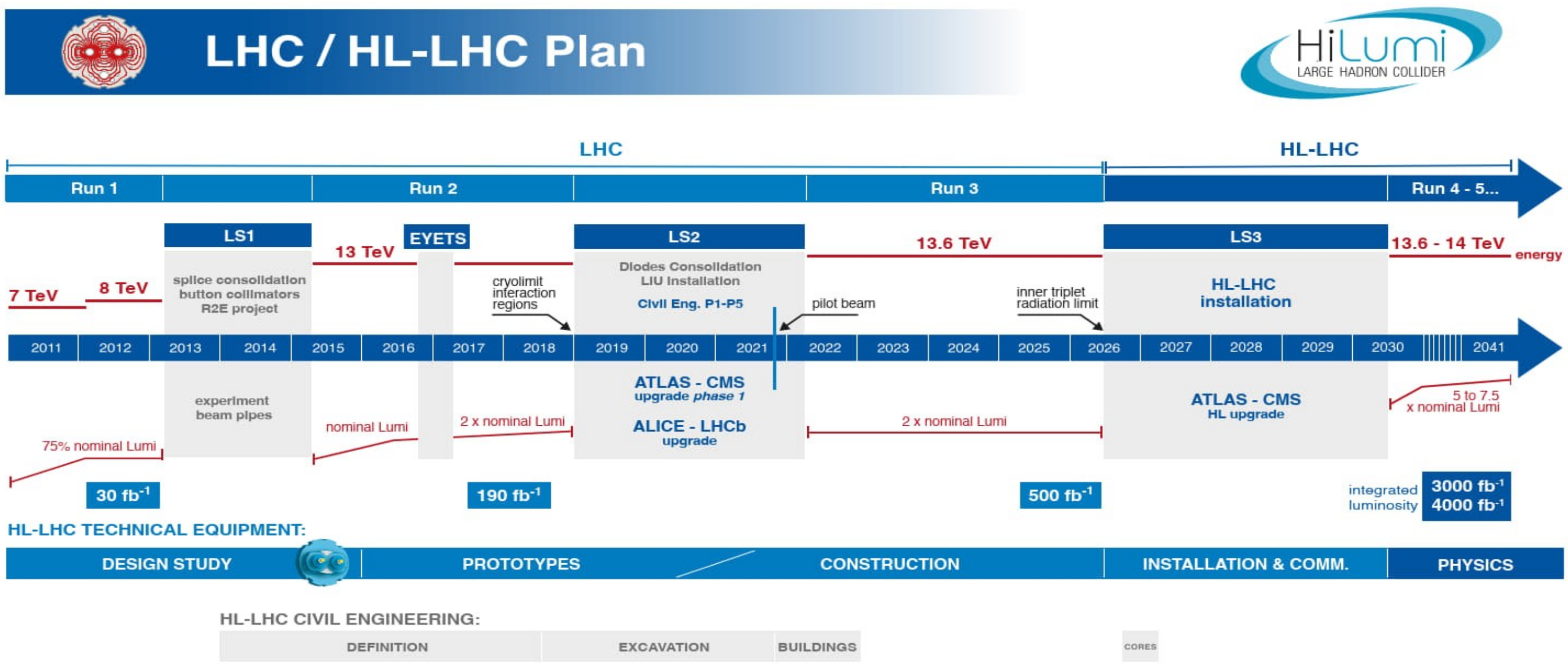
ATLAS ITk

Outline

1) The High-Luminosity LHC project
2) The ATLAS upgrade
3) The ATLAS Inner Tracker (ITk)
4) The ATLAS ITk Strips
    a) Barrel
    b) Endcap
5) The QC and QA testing in the FZU lab
6) Module production
7) Irradiation and testbeams
8) The ATLAS ITk strip integration
9) Summary

High-Luminosity LHC project

High-Luminosity LHC project



Updated October 2024

- HL-LHC will deliver **200** proton-proton interactions per bunch crossing at the maximal peak luminosity of $\mathbf{7.5 \times 10^{34}}$ $cm^{-2}\ s^{-1}$.
    - Total integrated luminosity will reach the value of **4000** fb^{-1}.
    - Significantly increased radiation damage of detector components (radiation hardness of ID PIX ~ 400 fb−1 , ID SCT ~ 700 fb−1 , IBL ~ 850 fb−1).

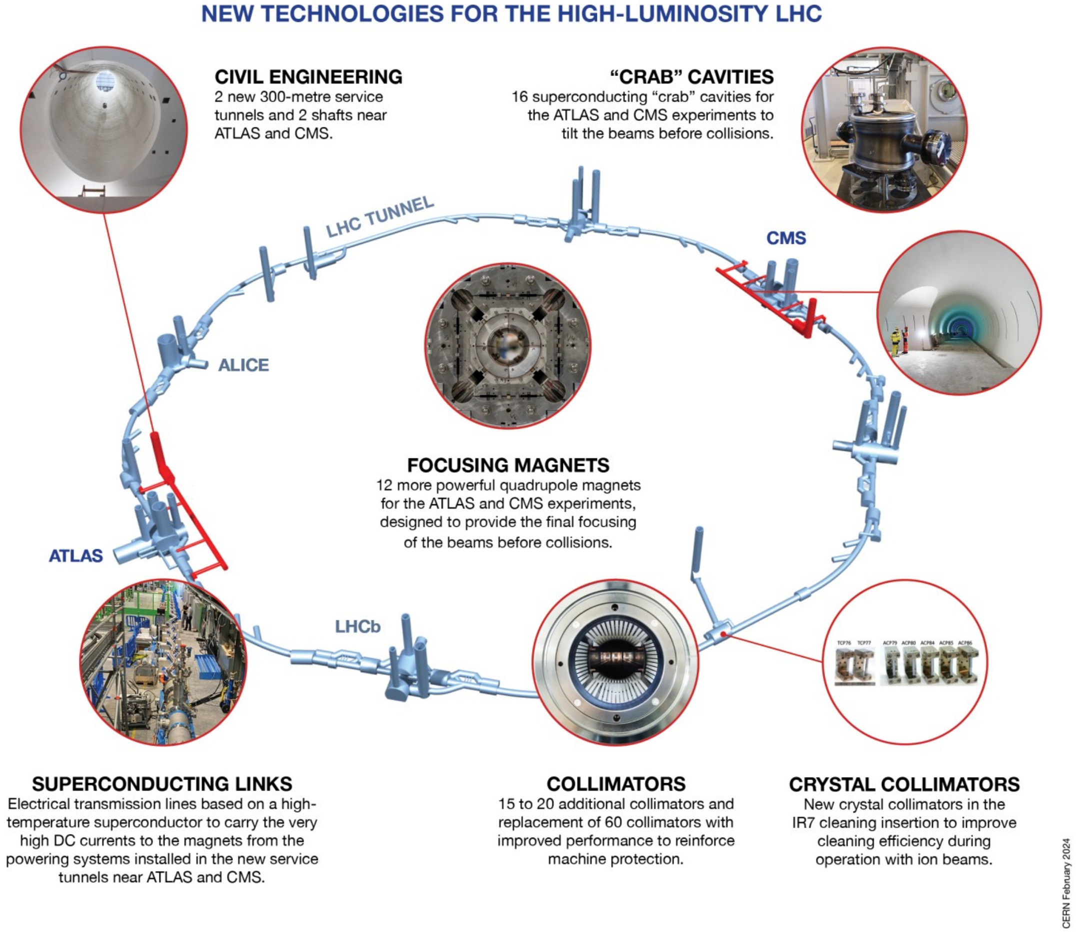
- ATLAS upgrade projects for HL-LHC will be installed during LS3, between years **2026** and **2030.**

High-Luminosity LHC project

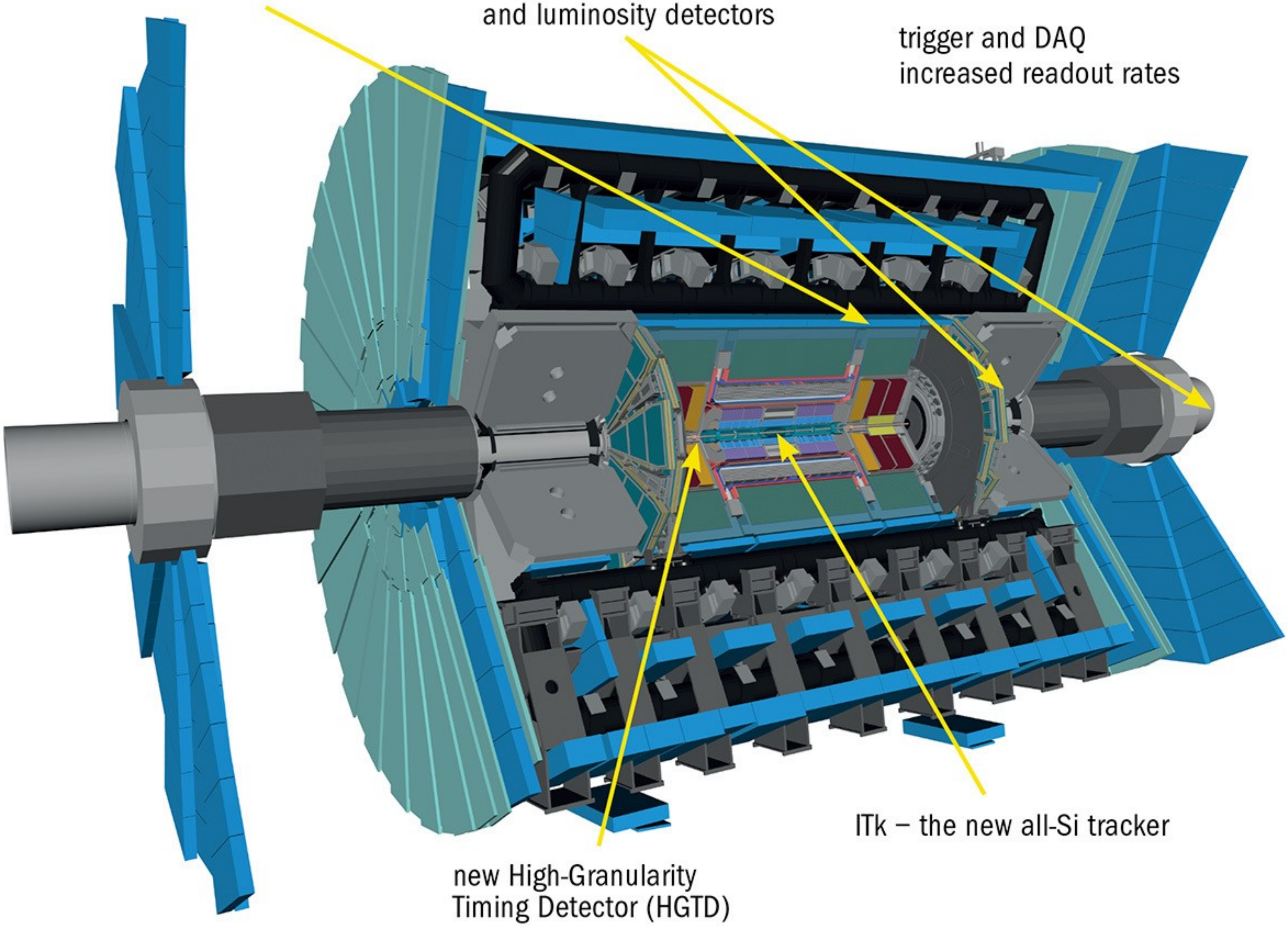
Upgrade of:

1) Experiments:
- Cooling systems,
- Four major experiments **ATLAS**, ALICE, CMS, and LHCb,
- Electronics and DAQ (read-out),
- Tracking and reconstruction systems.

2) Accelerator:
- Superconducting cavities,
- Magnets in the interaction regions (Nb-Ti → Nb_3Sn),
- Cooling systems,
- Collimators,
- Trigger systems,
- Electronics and DAQ (read-out),...



ATLAS upgrade



ATLAS upgrade

1) **Inner Tracker** (ITk) - Pixels and **Strips**
   - complete replacement of inner detector by all-silicon ITk

2) **High-Granularity Timing Detector**
   - covering $2.4 < |\eta| < 4$, time resolution of of 30 to 50 ps, Si LGADs

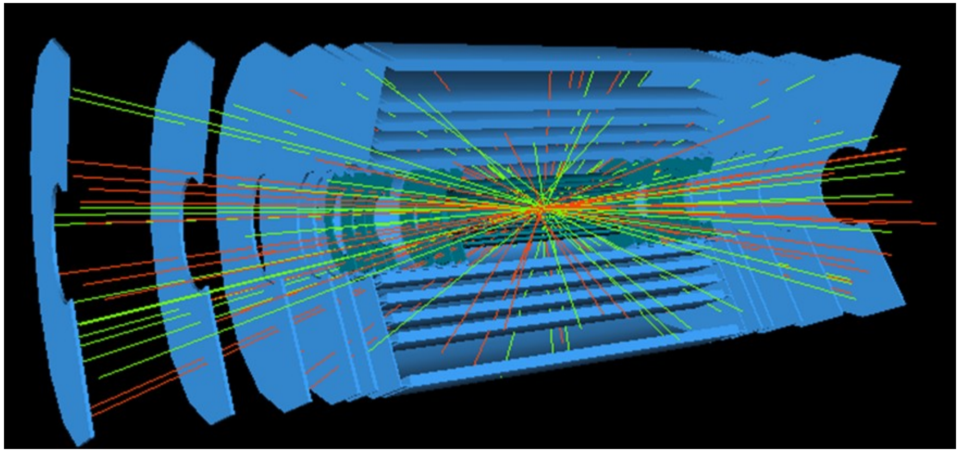
3) **Liquid Argon Calorimeter and Tile Calorimeter**
   - complete replacement of readout and powering el., individual readout of $\sim$ 200 k cells for every bunch crossing, providing info to trigger

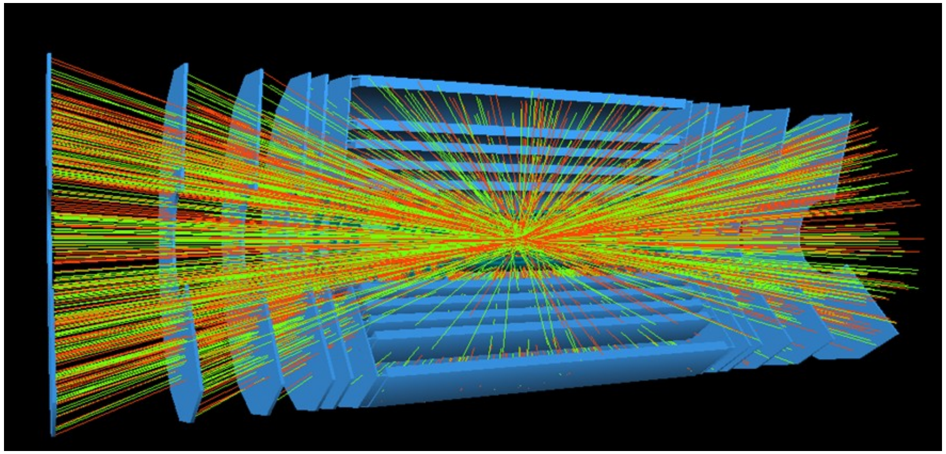
4) **Muon Spectrometer**
   - new on-detector el. for resistive plate chamber (RPC), thin-gap chambers (TGC), and muon drift tubes (MDT), new layer of RPCs and MDTs

5) **Luminosity detectors**
   - upgrade of Luminosity Cherenkov Integrating Detector (LUCID), new luminosity info from HGTD, other new detectors

6) **TDAQ System and HL-LHC Computing**
   - readout rate of 1 MHz (x 10 current) requires a new architecture with L0 trigger based on calorimeter and muon system, 50 Tb/s as input

ATLAS Inner Tracker (ITk)

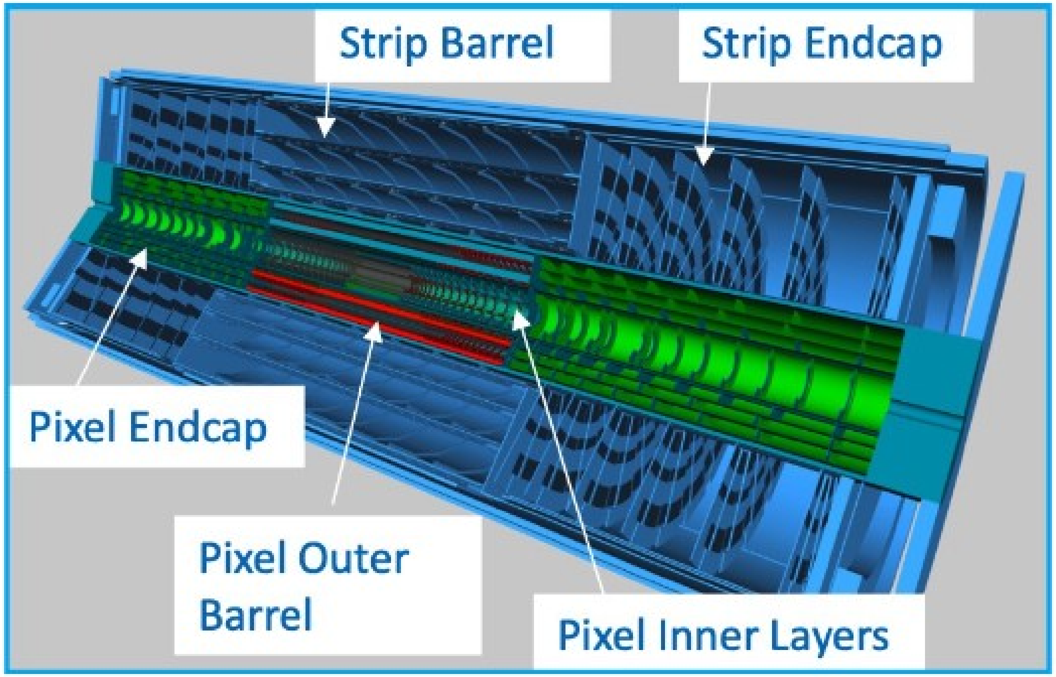


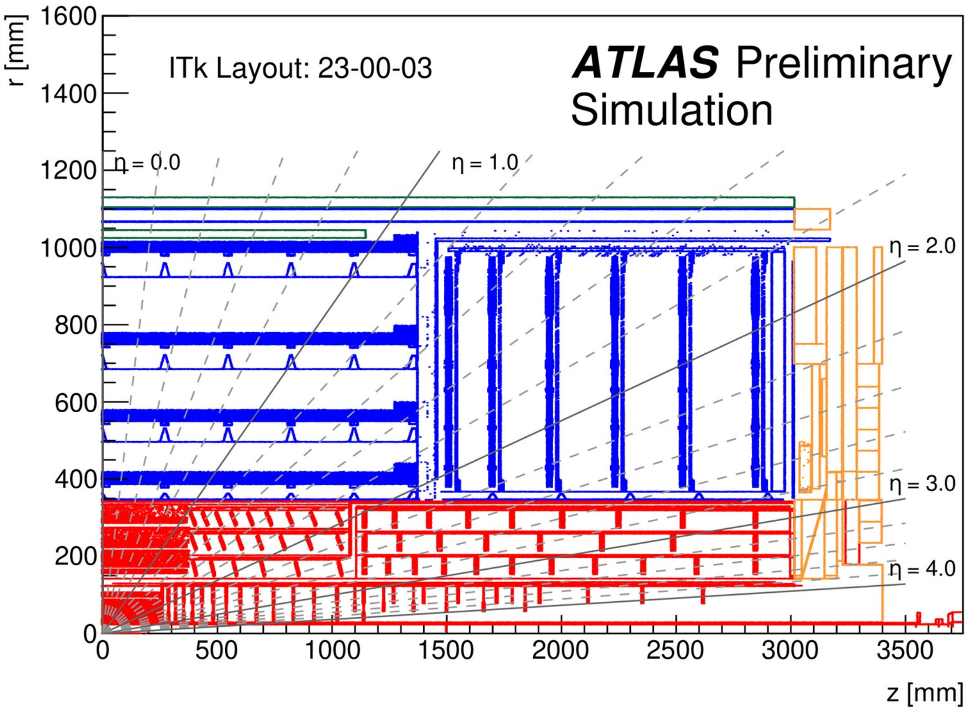


ATLAS Inner Detector will be completely replaced by the new all-silicon
ATLAS Inner Tracker

- higher (~ 10 times) radiation hardness sufficient to withstand HL-LHC conditions,
- extended η coverage ($|\eta| < 2{,}5 \rightarrow |\eta| < 4$),
- pixel detector with 13 m^2 and 5B channels,
- **strip detector** → the active area will be increased from 60 m^2 to 160 m^2 with 60M channels.

ATLAS Inner Tracker (ITk) - layout

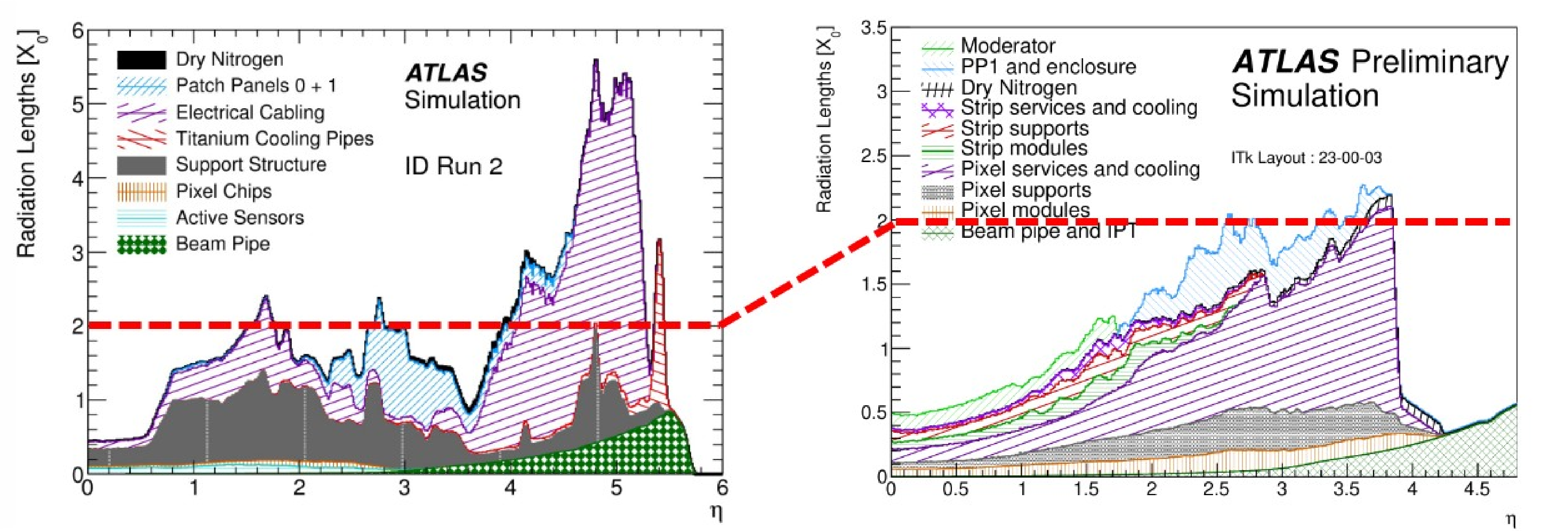




- All-silicon system
- Increased granularity to keep <1% occupancy
    - Pixel: 50x400 (μm^2) → 50x50 (μm^2) : 1/8
    - Strip (length) : 128 mm → 24 mm : 1/5
- Wide coverage in η : 2.5 → 4.0

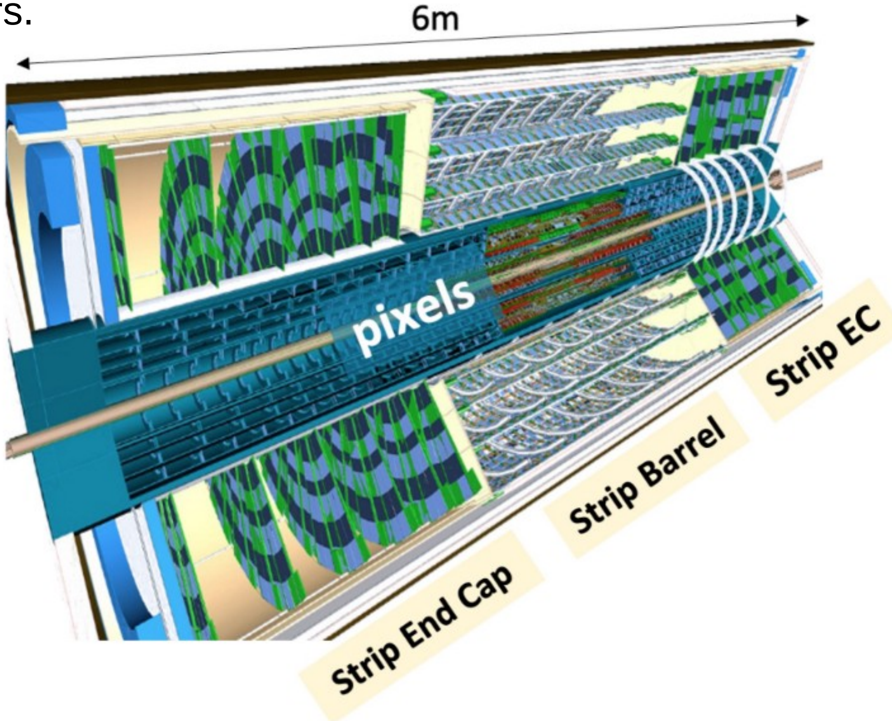
ATLAS ITk – material budget

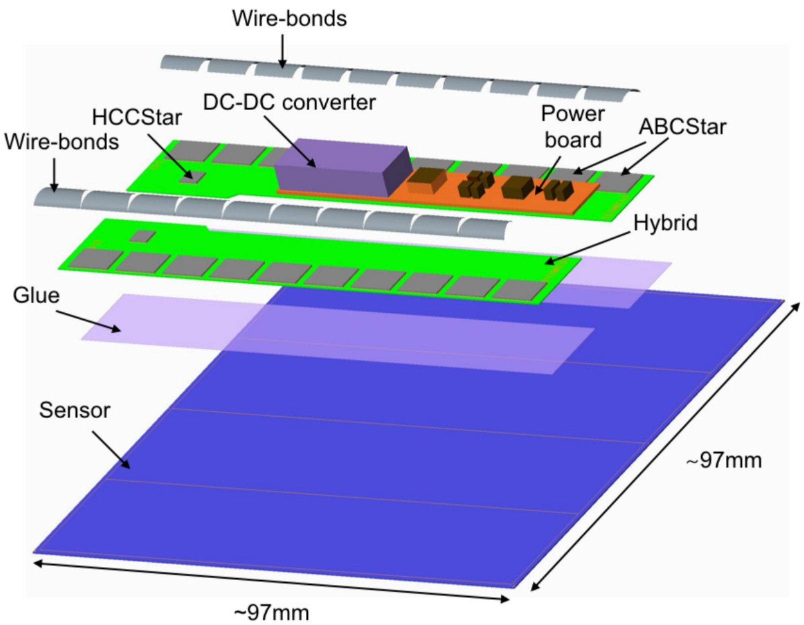
- **Sufficient reduction of material:**
    - CO_2 cooling with thin titanium pipes.
    - Low mass carbon structures.
    - Minimizing material in modules using thin Si layers.
    - Reducing cabling by serial powering and data sharing for pixels.



ATLAS ITk Strip

- **General features:**
  - Four layers of barrel and two six-disk endcaps.
  - Six types of endcap sensors and two types of barrel sensors.
  - 18k modules
- **Sensors:**
  - Strip pitch ~75 μm
  - Total Fluence: 1,1E15 neq/cm^2
  - Total Ionizing Dose: up to 53.2 Mrad
- **Production:**
  - Sensors: in production
  - Hybris and modules: in pre-production
  - Mechanics: in production





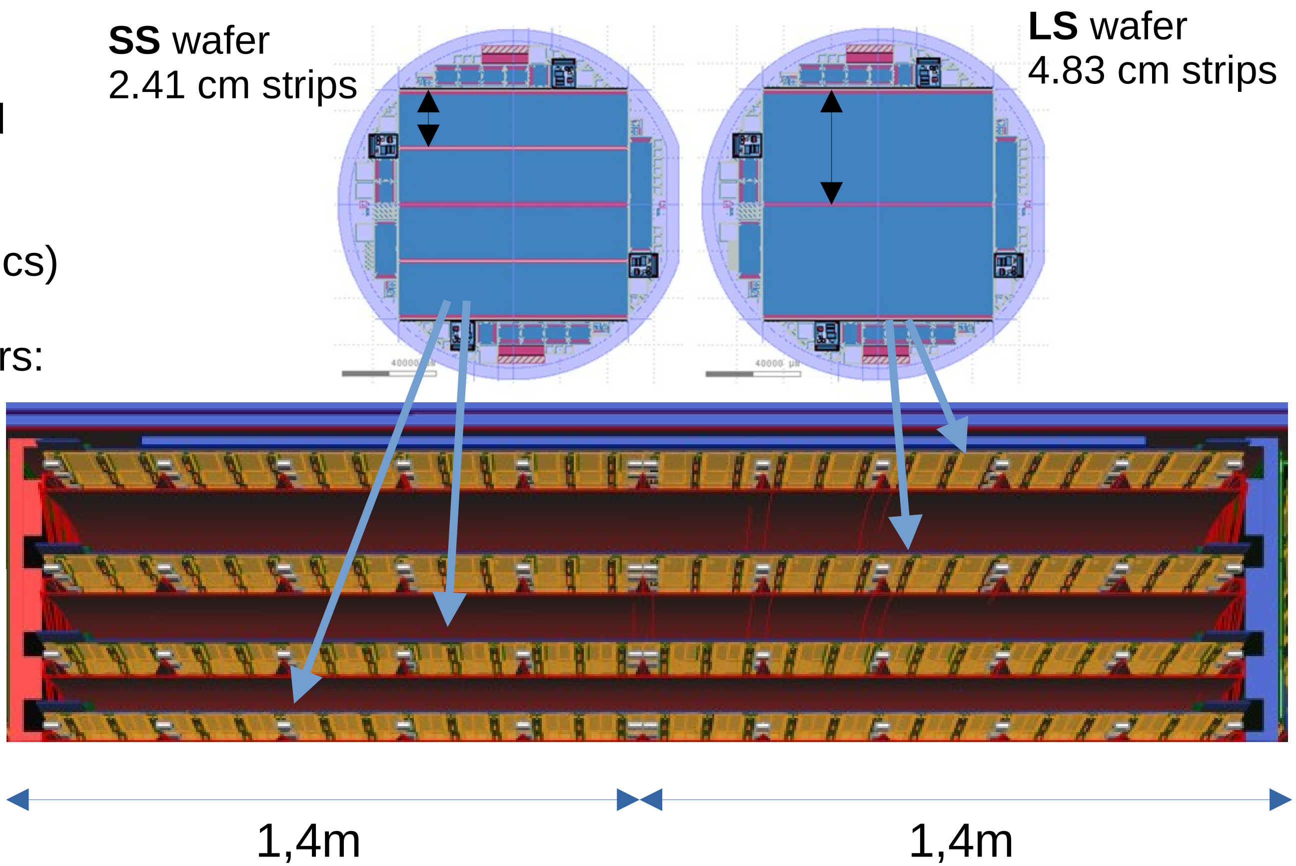
Module: strip silicon sensor + hybrid with chips + power board (everything is glued and wire-bonded together)

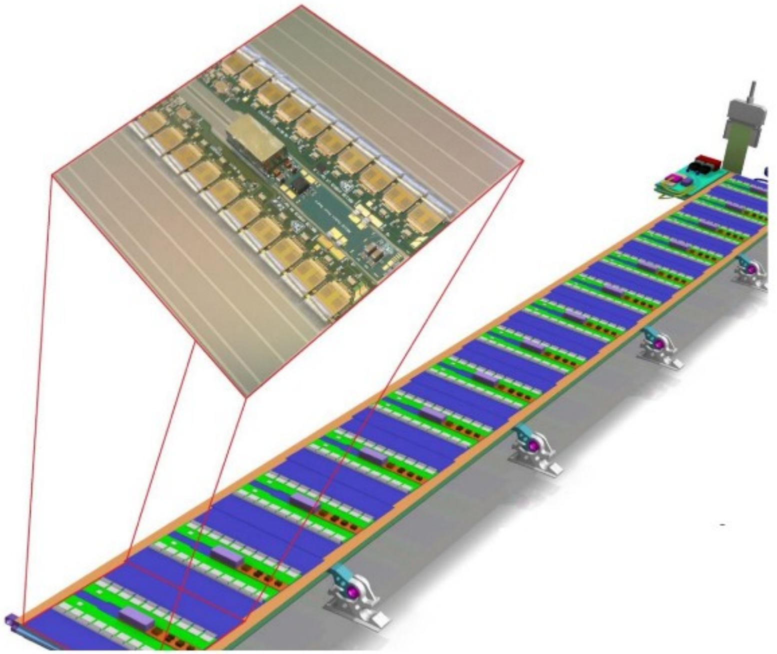
ATLAS ITk Strips barrels

4 barrel layers

- barrels consist of 392 double sided staves
- 14 modules/stave/side
- 10976 modules (sensor + electronics)

- Two types of ~ 9.7 cm x 9.7 cm sensors:
  - outer 2 layers: Long Strips (LS)
  - inner 2 layers: Short Strips (SS)



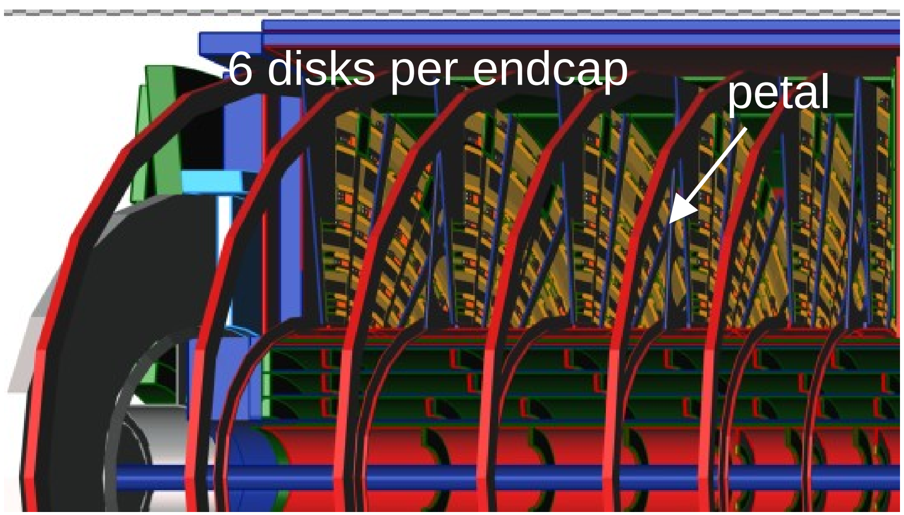


ATLAS ITk Strip endcaps

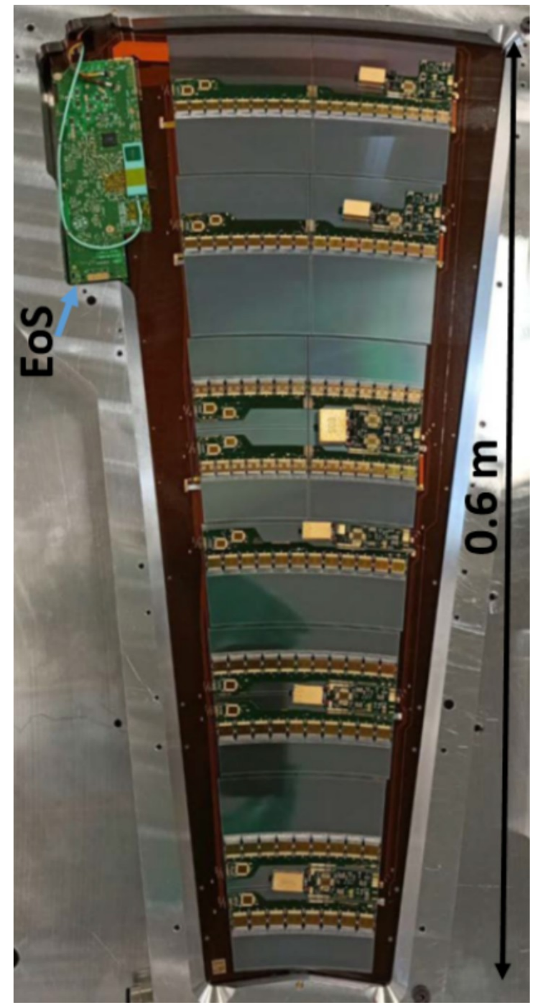
Endcaps:
- 2 endcaps
- 6 disks per endcap
- 32 double-sided petals per disk
- 6 modules per petal-side

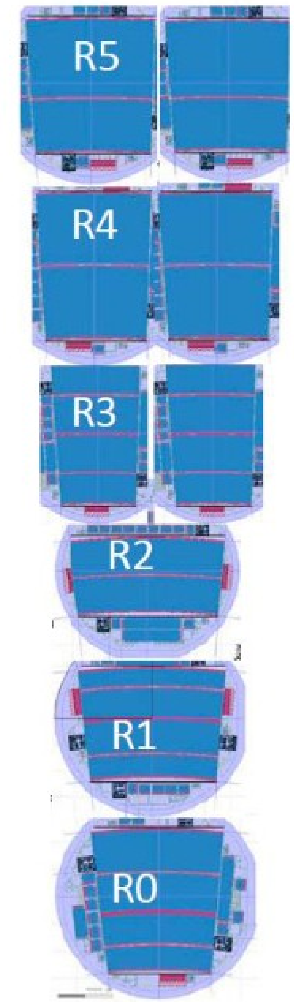
=> **4608** modules

Petal:
- 6 sensor geometries
- R0,R1,R2 one sensor / module
- R3, R4, R5 two sensors / module
- strip length: 1.4 – 6 cm



Petal





ATLAS ITk Strip - sensors

Strips implanted on p-type silicon bulk (n+-in-p)

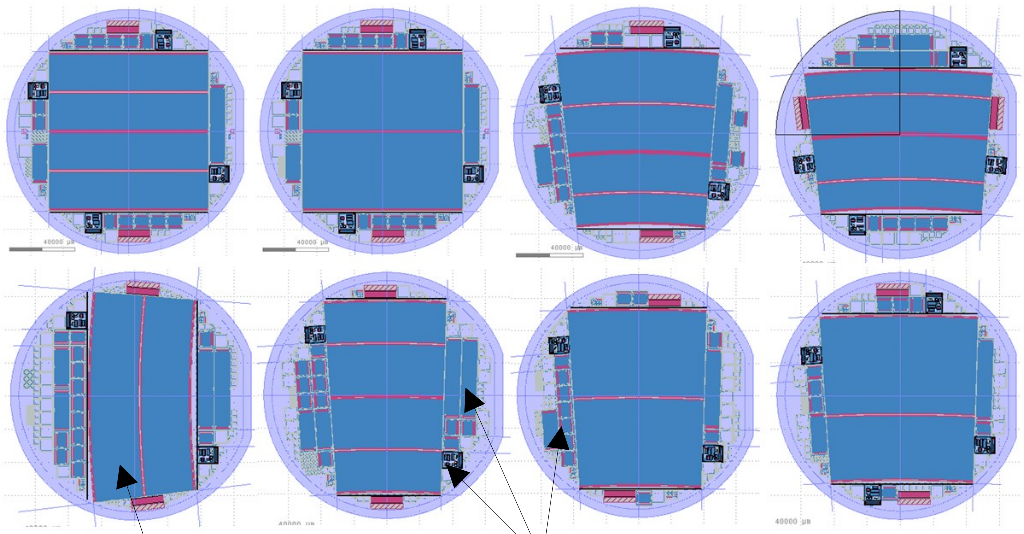
- single sided, AC coupled, produced by Hamanatsu Photonics (Japan)

- 320 µm thick (active thickness 300 µm)
- full depletion voltage VFD ~280 V (specifications VFD < 350 V)

- 8 sensor geometries:
    - 2 for the barrel, 75.5 µm strip pitch
    - 6 for the end-caps, trapezoidal + arc, 70 to 80 µm pitch
- one sensor per 6 inch wafer + test structures

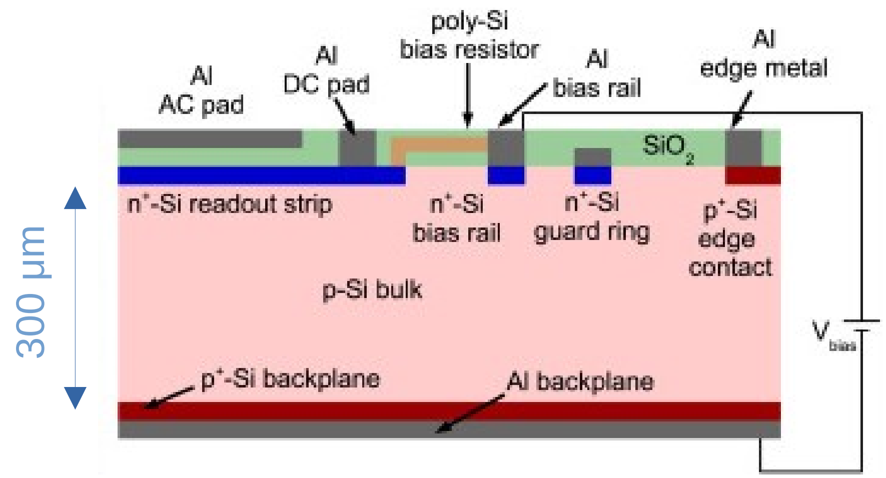
- spatial resolution ~ 20 µm
- time resolution ~ 3 ns

- Barrel strip length: 2.41 and 4.83 cm
- Endcap strip length: 1.5 – 6 cm
- Barrel strip pitch: 75.5 µm
- Endcap strip pitch: 70 – 80 µm



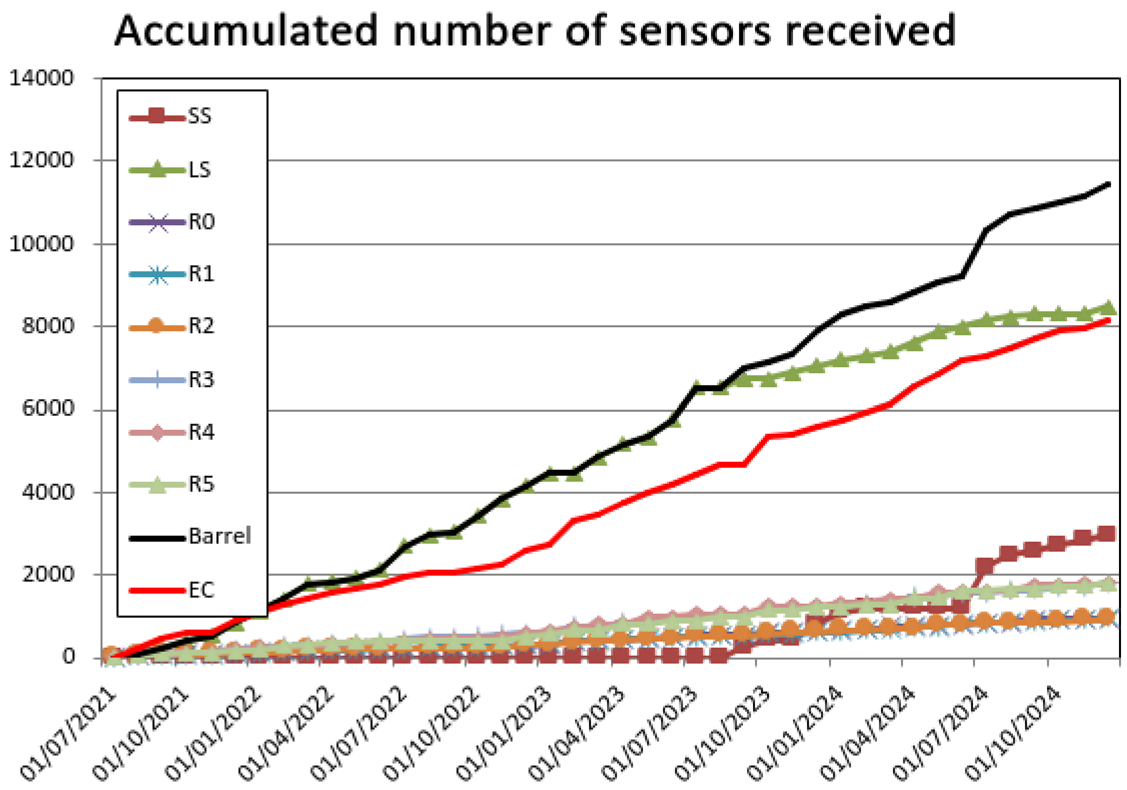
Main sensor

Test structures



ATLAS ITk Strip - sensors

- production at HPK started in 2021 and will be finished in 2025
- totally ~ **24 000** sensors will be delivered
- ~ **82%** already delivered (following the original plan, almost 20 000 sensors already delivered)



QC main sensor testing

- Upon delivery, ATLAS performs detailed measurements of sensors to monitor quality of all fabricated devices to ensure that their characteristics are within specifications defined by the ATLAS collaboration

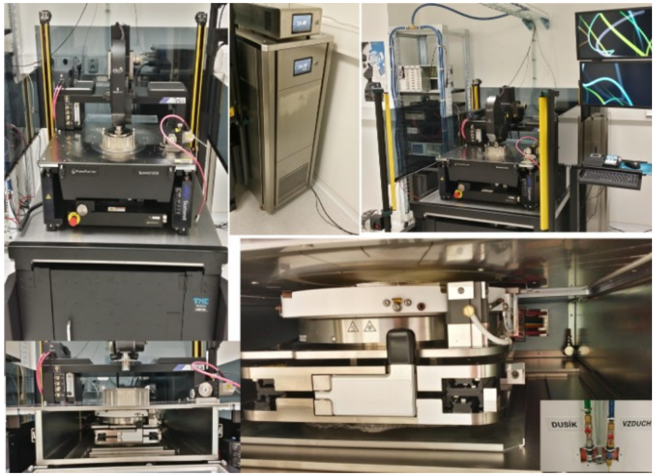
• QC tests

1) Visual Inspection and Visual Capture tests,
2) Mechanical tests (bow and thickness),
3) Current-voltage (IV),
4) Capacitance-voltage (CV),
5) Leakage Current Stability: 10%-20% samples,
6) Full Strip Tests: 2%-5% samples.

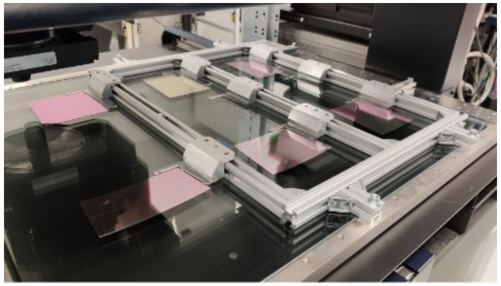
• QC sensor testing sites

1. KEK/Tsukuba, Japan,
2. SCIPP, California, USA,
3. Univeristy of Cambridge, UK,
4. Queen Mary University in London, UK,
5. FZU Prague, CZ,
6. SFU/TRIUMF Vancouver, Canada,
7. Carleton University, Canada.

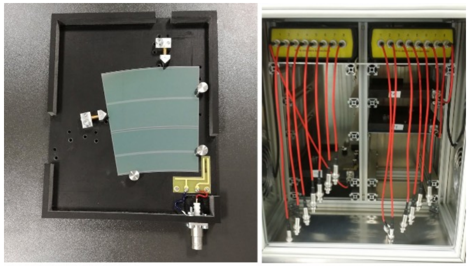
Probe station



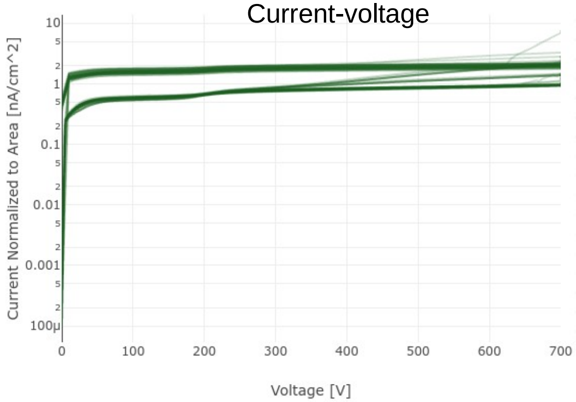
Metrology



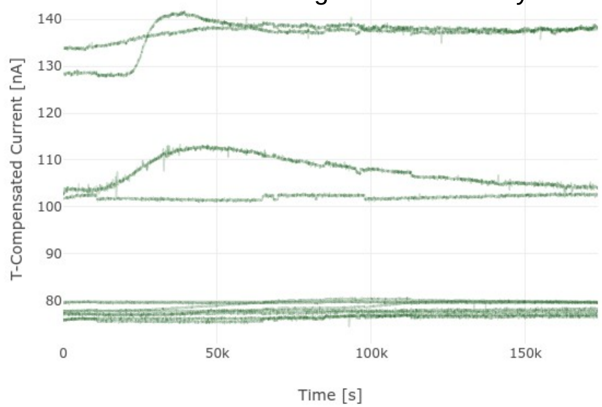
Leakage cuurent stability setup



Current-voltage

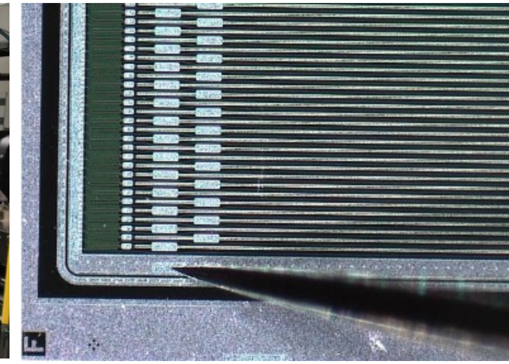


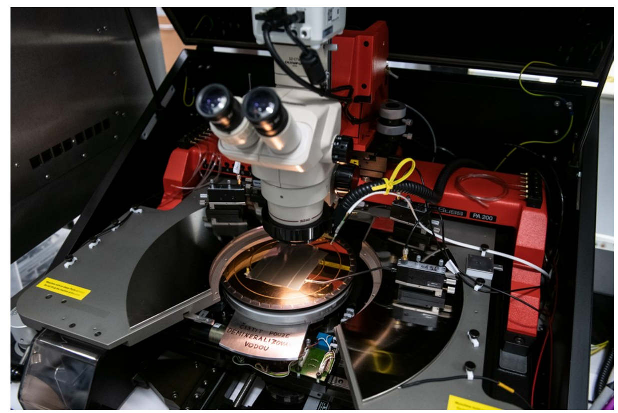
Leakage current stability

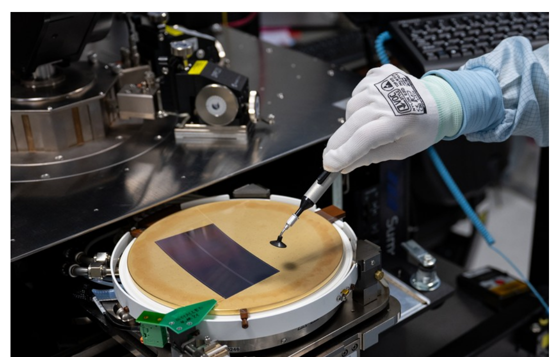


QC main sensor testing - FZU

FZU is responsible for QC testing of one half of all EC sensors (~ **4500** sensors). Currently, testing of almost **4000** sensors successfully finished.



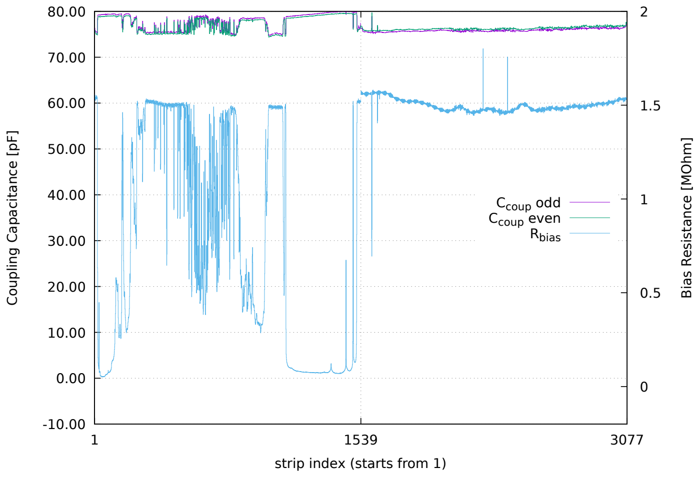



ATLAS ITk Strip – rejection and recovery

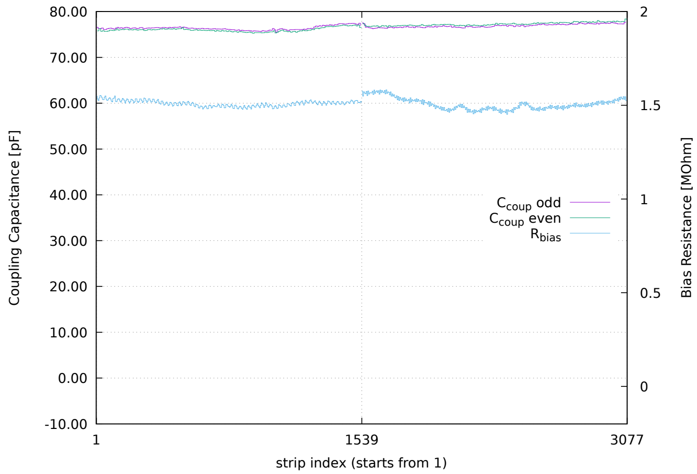
- very low rejection rate ~ **3 %**

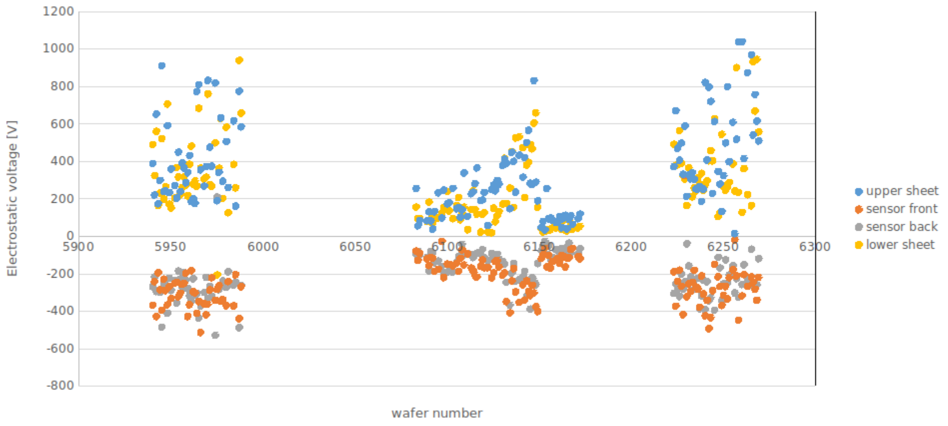
- strong correlation with high static charge measured on sensors and electric tests failures
- big part of failed sensors can be recovered with different treatments:
  1) UV-A (315-400 nm) light setups with typical exposure between 2 and 8 hours,
  2) UV-C (100-280 nm) light setups with typical exposure of 60 seconds,
  3) ionizing air blowers with typical exposure of a few minutes up to 30 minutes,
  4) High-temperature (160 ˚C) exposure ("**baking**") of sensors in an oven for more than 16 hours

Strip test



UV treatment





QA chips testing

- structures sampled from batches of wafers

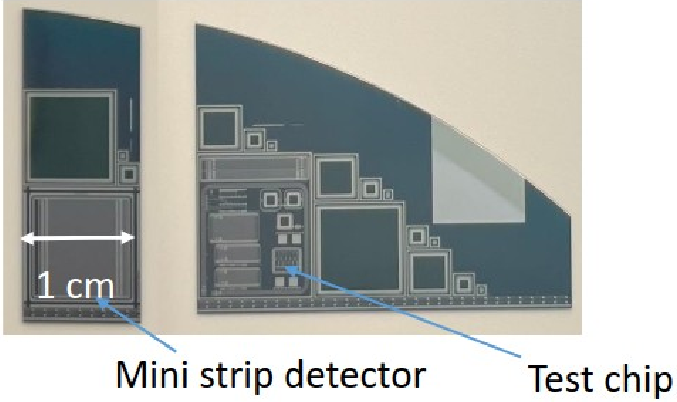
- irradiated with:
  - up to 1.6e15 neq/cm^2 neutrons at TRIGA reactor in Ljubljana + TID to 660 kGy with ɣ from ^{60}Co source in **UJP Prague**
  - protons at CYRIC(KEK) (70 MeV) or Birmingham (27 MeV)
  - CSNS (70 MeV protons) Dongguan, China, is being qualified

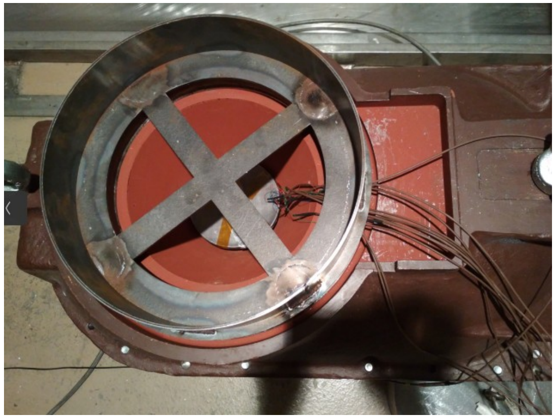
- various parameters and tests are measured:
  - Charge Collection efficiency,
  - Vbd (Breakdown voltage),
  - Rint (Internal resistance),
  - PTP (Punch through protection),
  - Cint (Internal capacitance)
  - …

- A few imperfect batches were identified and had to be rejected.

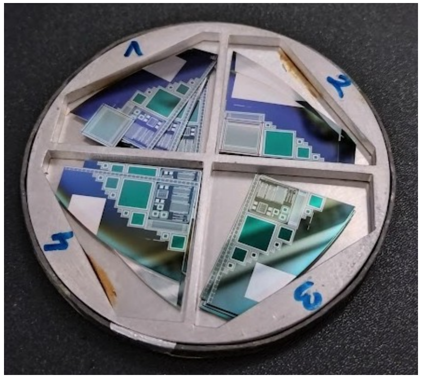
- **QA testing sites:**

1) FZU Prague,
2) JSI Ljubljana Slovenia,
3) Birmigham UK,
4) Toronto Canada,
5) Valencia Spain,
6) Barcelona Spain.





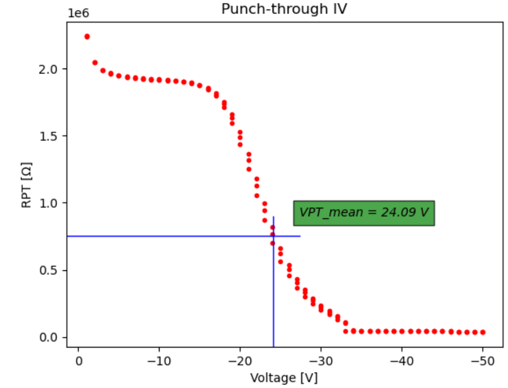
UJP ɣ source

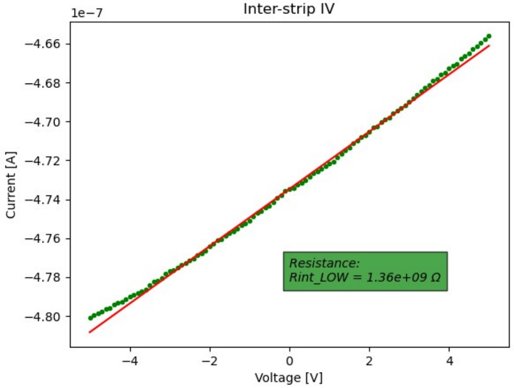


Irradiated testchips in the housing

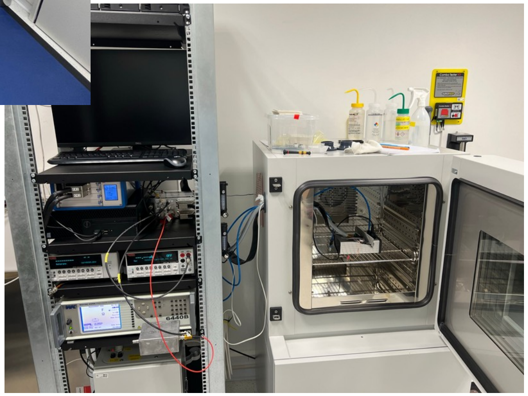
QA chips testing - FZU

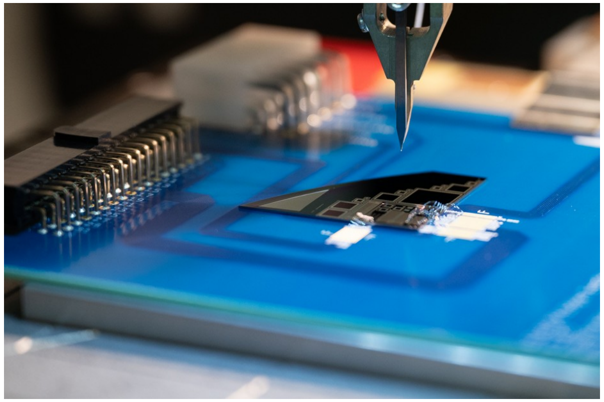
In FZU, around **700** testchips were **γ** irradiated and around **150** were measured up to now.
FZU is the only testing site that performs both QC and QA measurements.





QA measurement setup





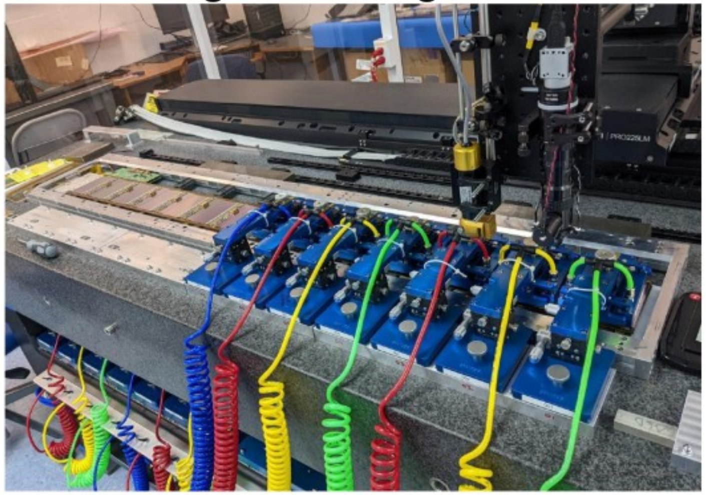
Module production

- starting production for barrel LS and endcap modules
  - silicon sensor + readout electronics + power control
  - precision work:
    - parts need to be positioned within 10 μm,
    - the glue thickness controlled with 50 μm accuracy,
    - wire-bonding

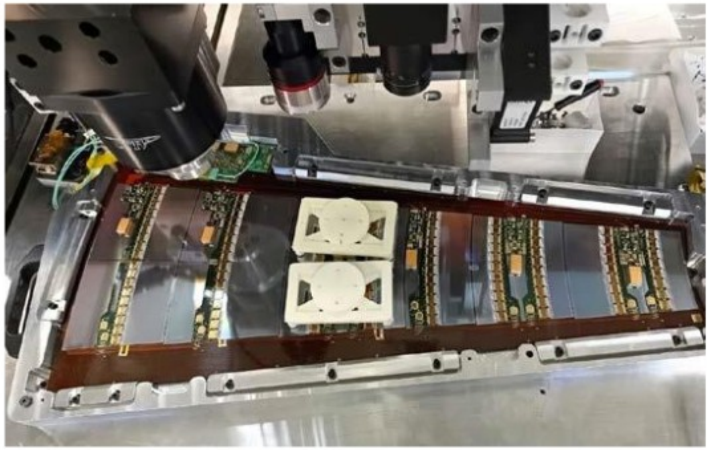
- modules are mounted (“loaded”) to stave and petal cores at loading sites
  - again a high precision module positioning
  - wire-bonding

- staves and petals will be then assembled into barrels and endcaps at CERN, Nikhef, and DESY

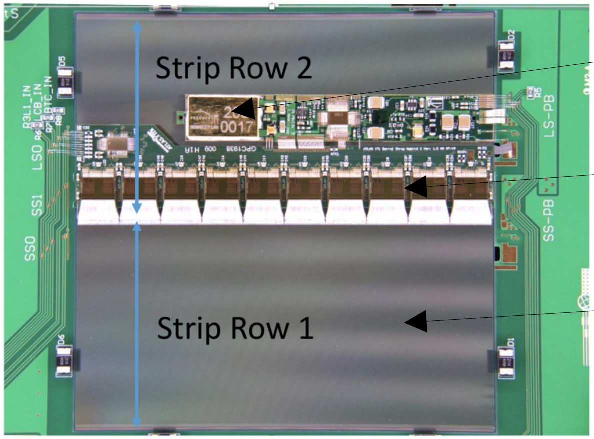
Stave loading – mounting modules on cores



Petal loading system

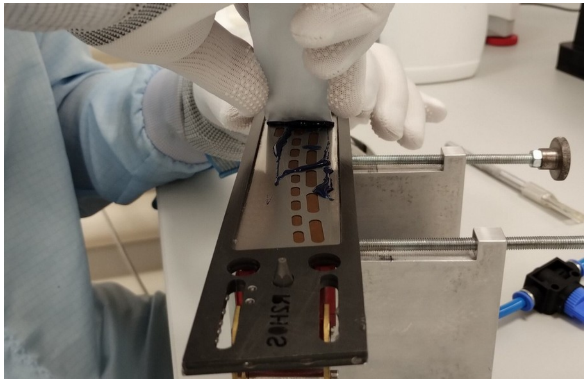


Long **S**trips **barrel** module (2 rows of strips):

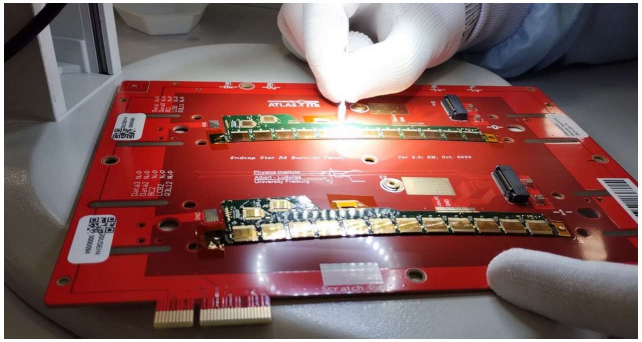


Module production in MFF UK

- Prague is responsible for module assembly and testing of ~ **500 ITk strip modules** (R2 and R4 EC types)
- reception of module components (MFF/FZU), assembly and wire bonding (Argotech), final QC testing and shippment to IFIC Valencia
- thermal cycling of modules - electrical tests + study of module bow after thermal cycling
- preparation of technical drawings for new module metrology procedures
- building of **a new clean room**



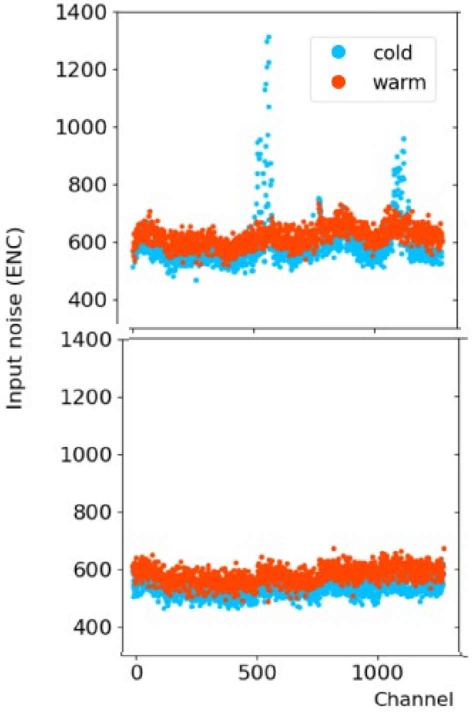
Module assembly



Module production – cold noise

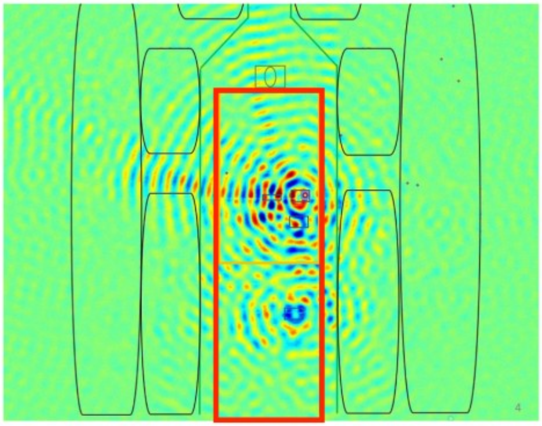
- First observed on SS modules when thermal cycling to detector operating temperatures (-35 °C) ~ June 2022.
- Vibrations of capacitors on module powerboard were transfered to sensor via the frozen glue found as a source of cold noise.
  - Using an alternative glue for module assembly removes fully the cold noise for LS modules.
  - For SS modules works also an alternative glue + interposers integration.
- End-cap modules **do not see** this problem.

➡ After a hard work of the whole community this problem is fixed and cold noise is not a barrier for module production anymore.



Under power board

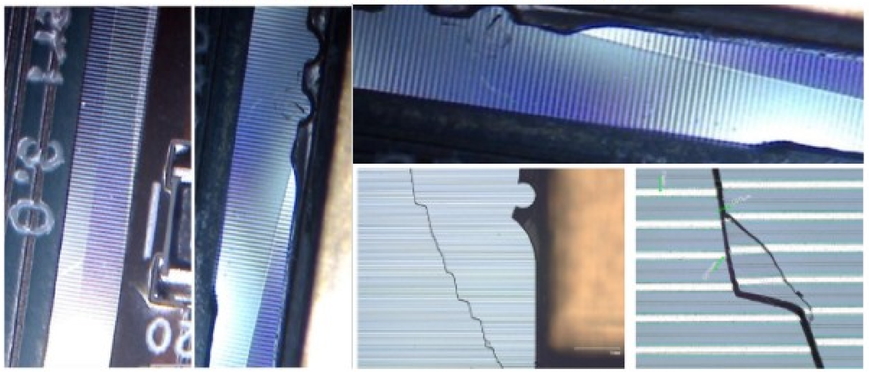
Away from power board

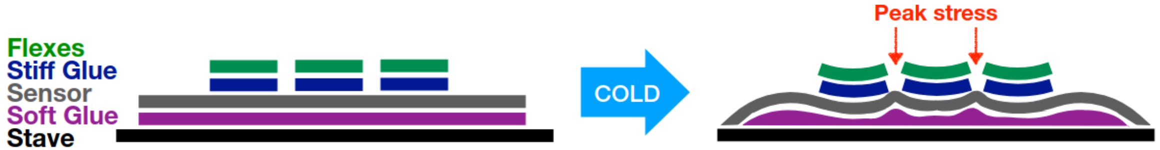


Power board

Module production – cracking

- Discovered ~ May 2023 in sensors while thermal cycling modules loaded to staves/petals.
- Different thermal expansion of flexes, sensors, and glue causes stress.



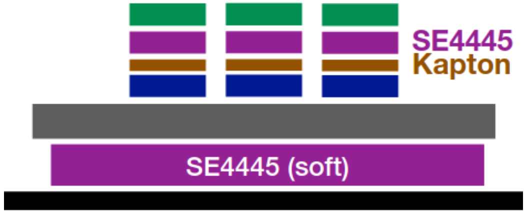


Mitigation:

Option#1: **Hysol**

- Rigid Hysol glue
- Simulation predicts ~ 50 % stress reduction.
- After building testing staves and petals, some improvement observed, but issue not solved completely
- **It is not the solution**

Option#2: **Interposers**



- Add soft glue + kapton under flexes
- Simulation predicts ~ 95% stress reduction.
- After building testing staves and petals **no cracks** seen down to -70°C.

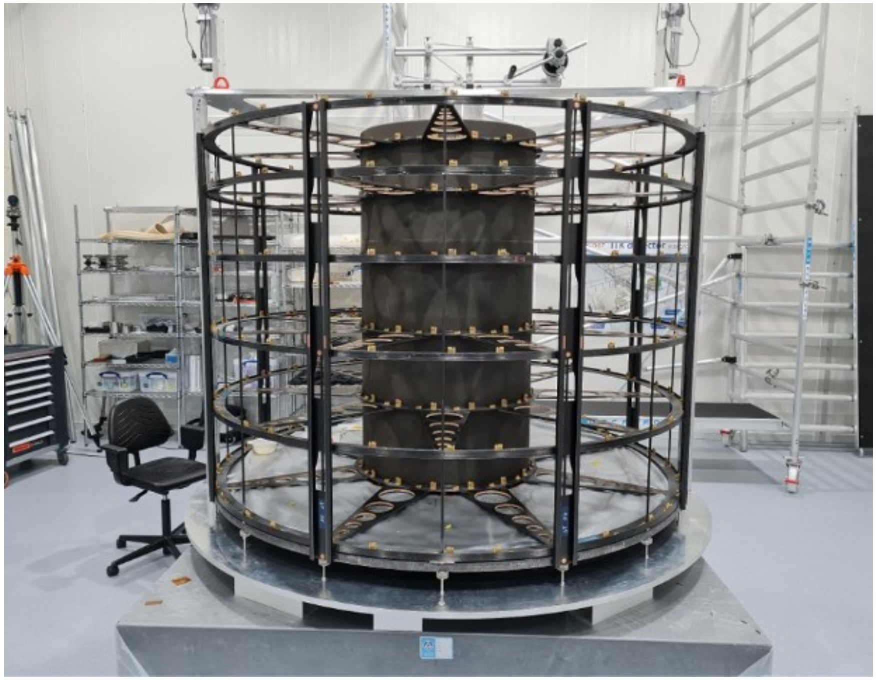
Irradiation and testbeam campaigns

- FZU group part of many irradiation and testbeam campaigns related to ATLAS ITk upgrade
  → *a huge amount of work*
- Irradiation of ITk strip modules at CERN IRRAD and FNAL(USA) - protons
- DESY testbeams - electrons
- CERN SPS testbeam - protons
- Irradiations of ITk strip components by ^{60}Co source - gammas

Global structures

Global structures are mostly Carbon Fibre
• the first endcap structure finished, the second in production
• 4 barrel cylinders in production

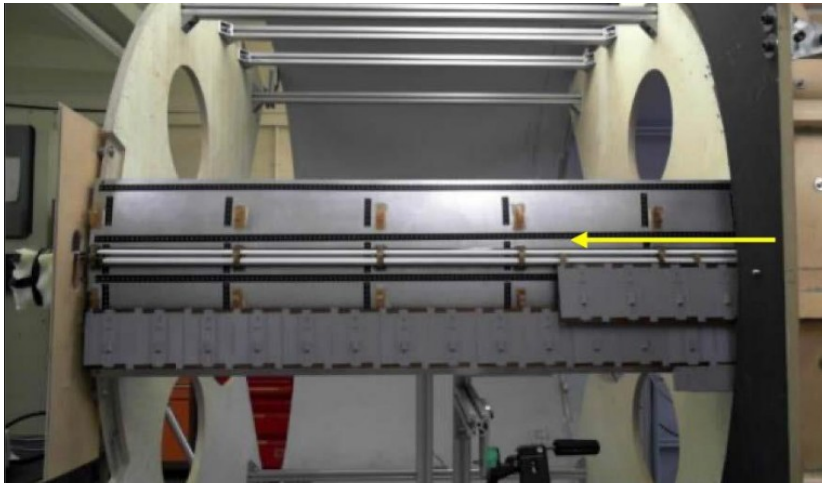
Barrel cylinder with mounting brackets



Endcap support structure

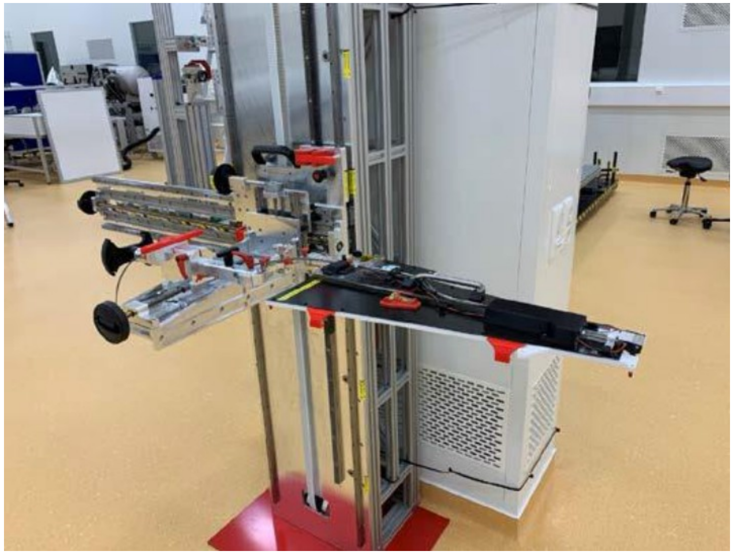
ITk Strip - integration

Preparing for integration:
- staves inserted to barrel at CERN
- petals inserted to endcap at DESY and Nikhef
- barrel and endcaps will be integrated into ITk at CERN



Stave insertion tool

ITk integration area at CERN



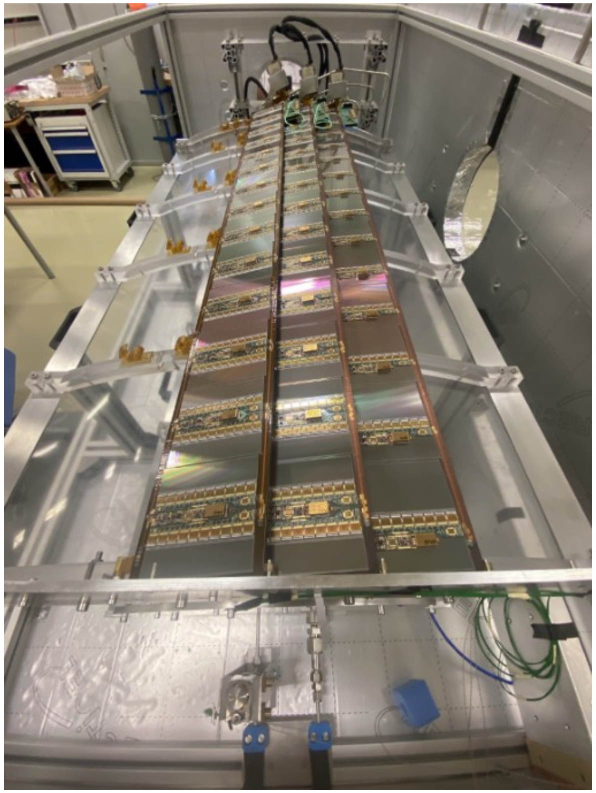
Petal insertion tool

ITk Strip – system testing

System tests to validate the full ITk Strip systems (cooling, powering, readout,….)

Barrel testing infrastructure (at CERN):
- can host up to 8 staves
- tests made with 4 preproduction staves
- demonstrated parallel readout of multiple staves at 1 MHz
- first tests with CO_2 cooling system

End-cap testing infrastructure (at DESY):
- can host up to 12 petals
- electrical services and cooling infrastructure ready
- full powering chain installed and tested
- installation of the first petal in progress



Barrel system test at CERN

Endcap system test at DESY

Conclusion & Summary

- Building a „new“ detector for operation at the HL-LHC is a challenge
  → Radiation hardness, increased granularity, low mass
- The new tracking system for the ATLAS experiment for the HL-LHC will cope with increased particle multiplicity and radiation levels
- ITk provides large acceptance, large number of points per track, high granularity, and radiation hardness with minimised material budget.
- The ITk Strip detector is progressing through production and integration
  → sensors, ASICs, modules, structures, global mechanics
- Complete ITk (Strips and Pixels) installation in the ATLAS experiment planned for 2029.

BACK UP