Design and construction of the ATLAS ITk Strip Detector

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17 October 2023

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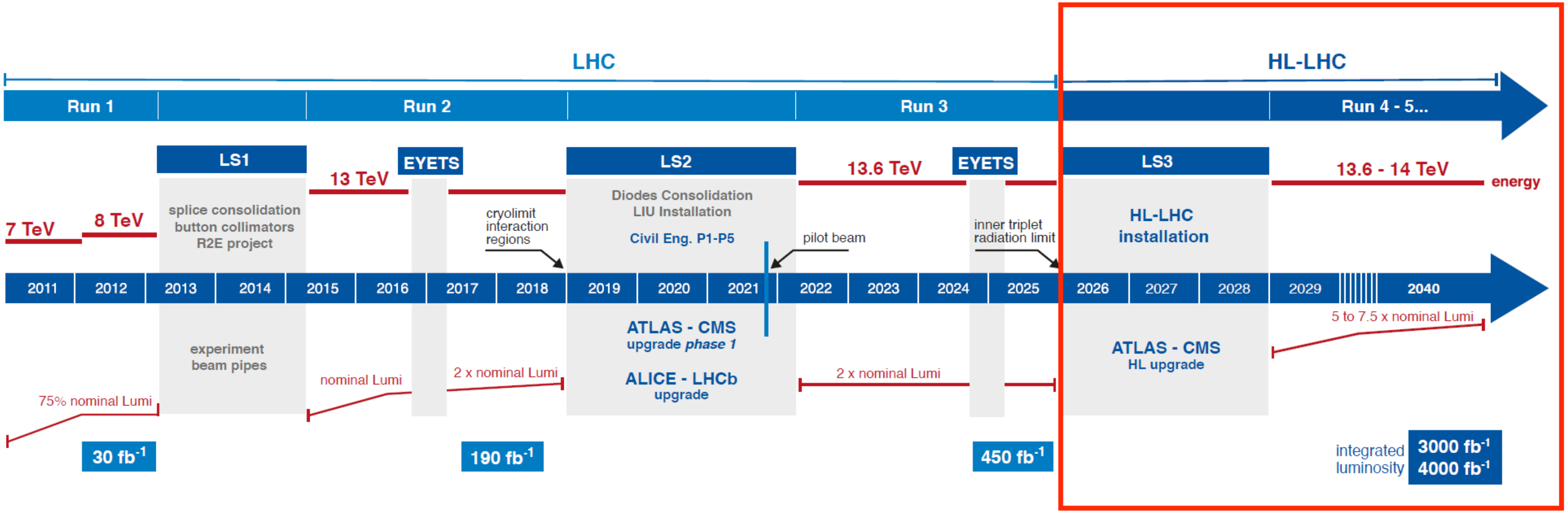
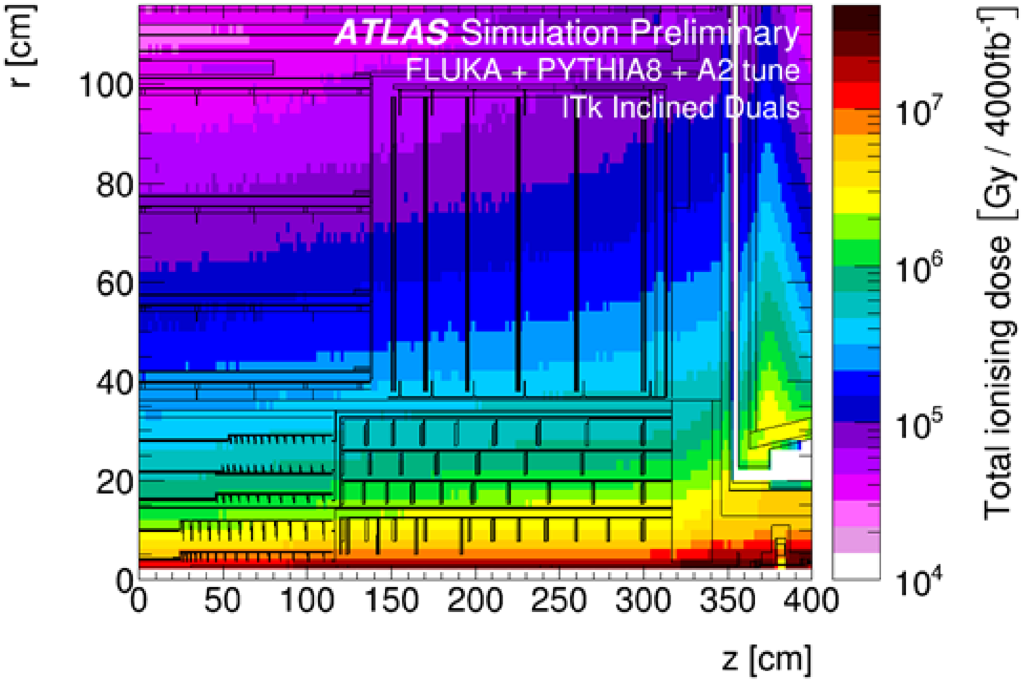
Upgrade to HL-LHC

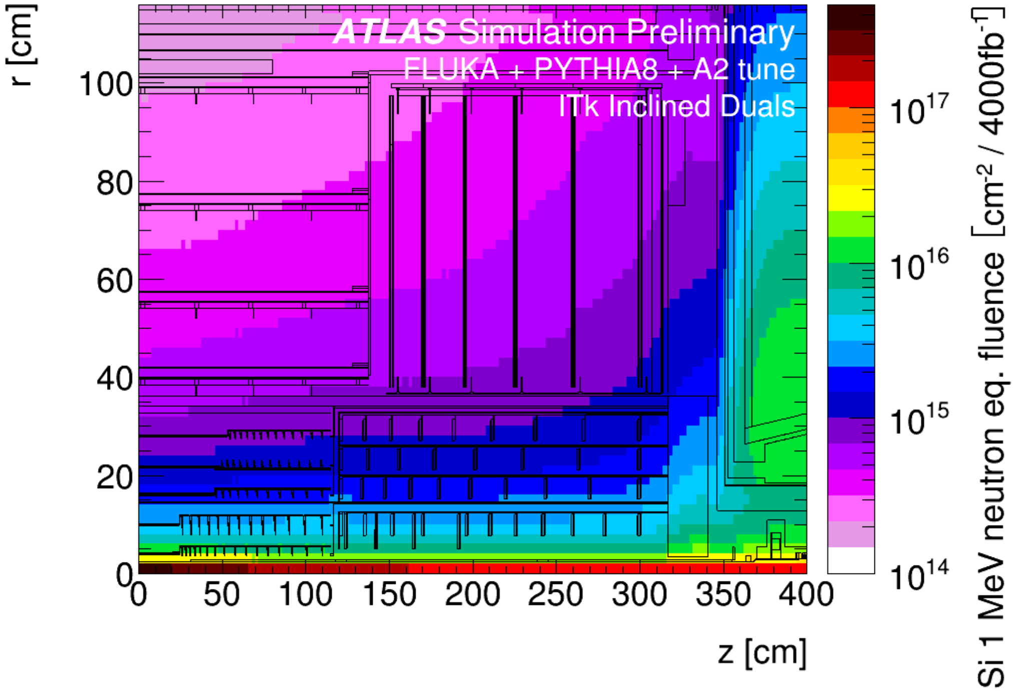
- proton energy similar as LHC: 6.8 TeV - 7 TeV
- increase of luminosity (L_{peak}=7.5x10^{34}cm^{-2}s^{-1})
- aim for integrated luminosity $\boldsymbol{L_{int}}$ **= 3000(4000) fb^{-1}**

➔ 200 p-p collisions per bunch crossing
➔ higher radiation levels



Radiation levels





https://twiki.cern.ch/twiki/bin/view/AtlasPublic/RadiationSimulationPublicResults#Phase_II_Upgrade_Mar_2018_AN1

Radiation levels (including safety factor of 1.5) @ 4000 fb-1 :

➔ Pixels: TID = 10 MGy, Φ_{eq} = $2{\cdot}10^{16}$ n_{eq} /cm^2

➔ **Strips: TID = 660 kGy , Φ_{eq} = $1.6{\cdot}10^{15}$ n_{eq} /cm^2**

ATLAS Phase II upgrade

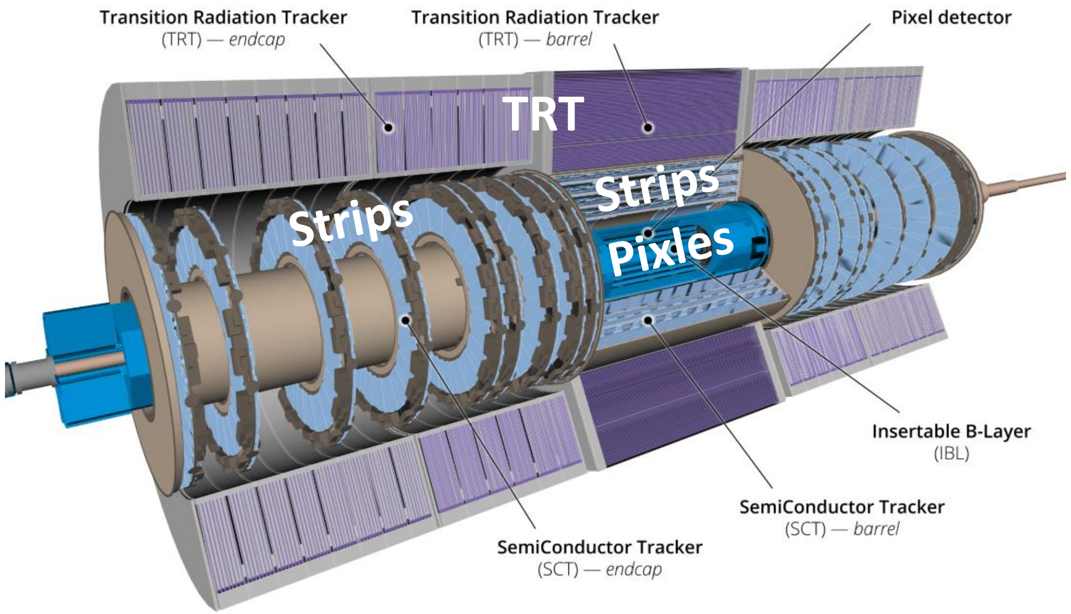
Current ATLAS **Inner Detector** (**ID**) will be replaced with **Inner Tracker** (**ITk**)

➔ not suitable for HL-LHC environment

➔ radiation damage accumulated by many years of successful operation

ATLAS Inner Detector

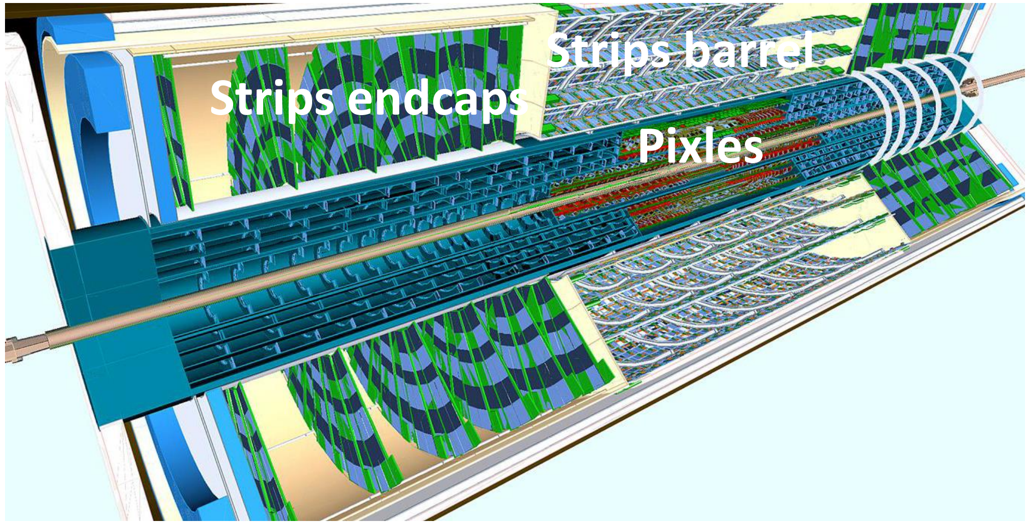
- silicon: **IBL** (pixels), **Pixel Detector, SCT** (strips),
- gas: Transition Radiation Tracker (**TRT**)



GENR-2019-02

New ATLAS Inner Tracker:

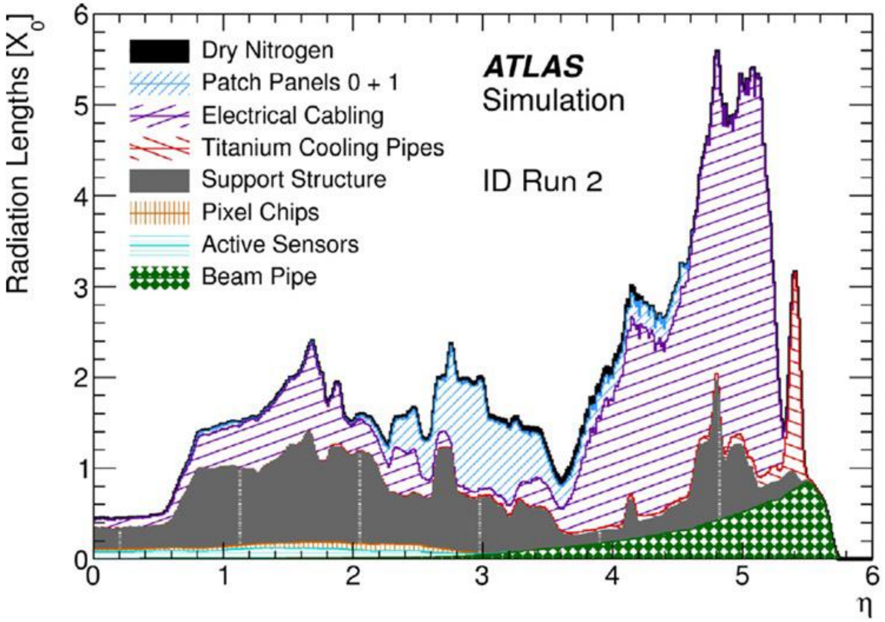
- silicon only: **pixels** and **strips**



ATLAS Phase II upgrade

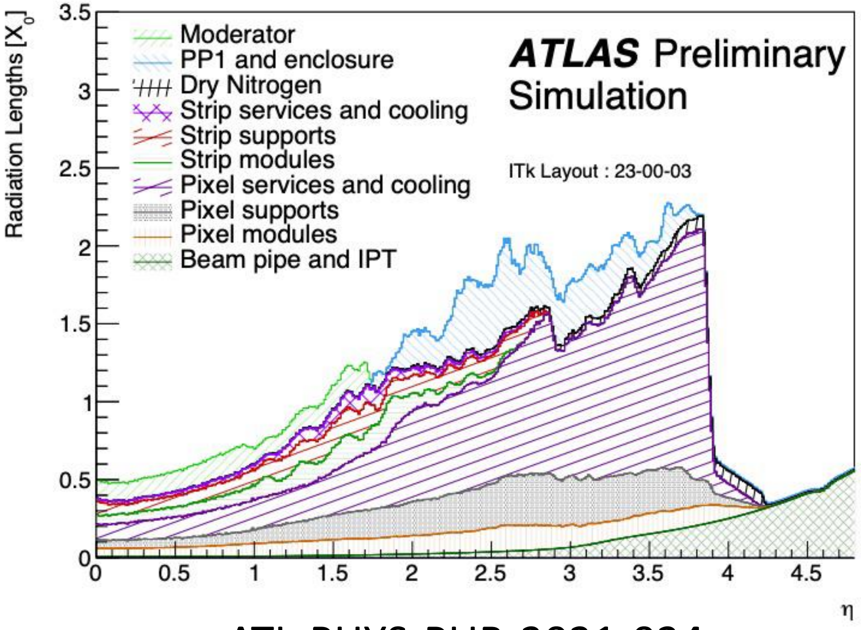
- Improvements of **ITk** compared to **ID**:
  - higher radiation tolerance
  - finer granularity
  - higher trigger rate
  - less material in the tracking volume

ID



ATLAS-TDR-025

ITk

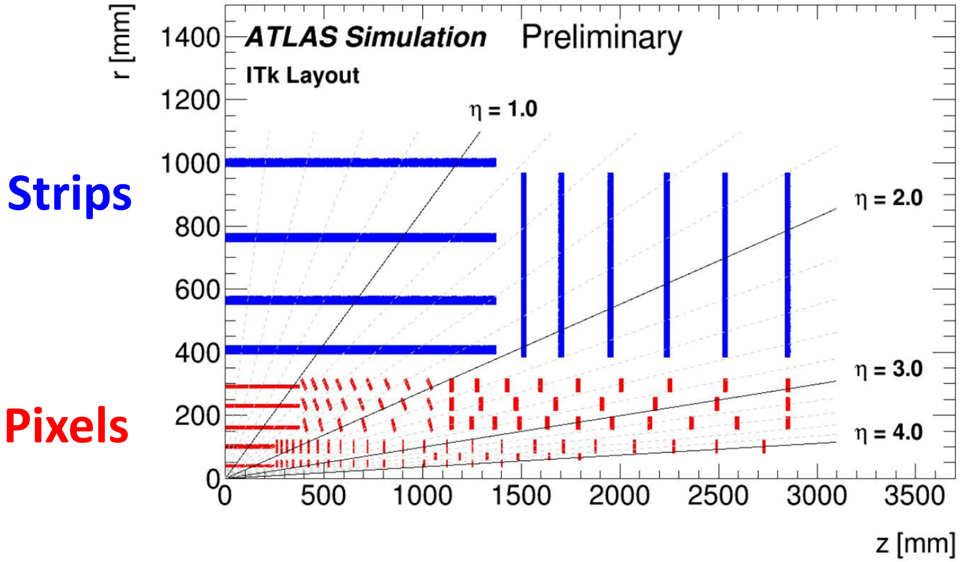


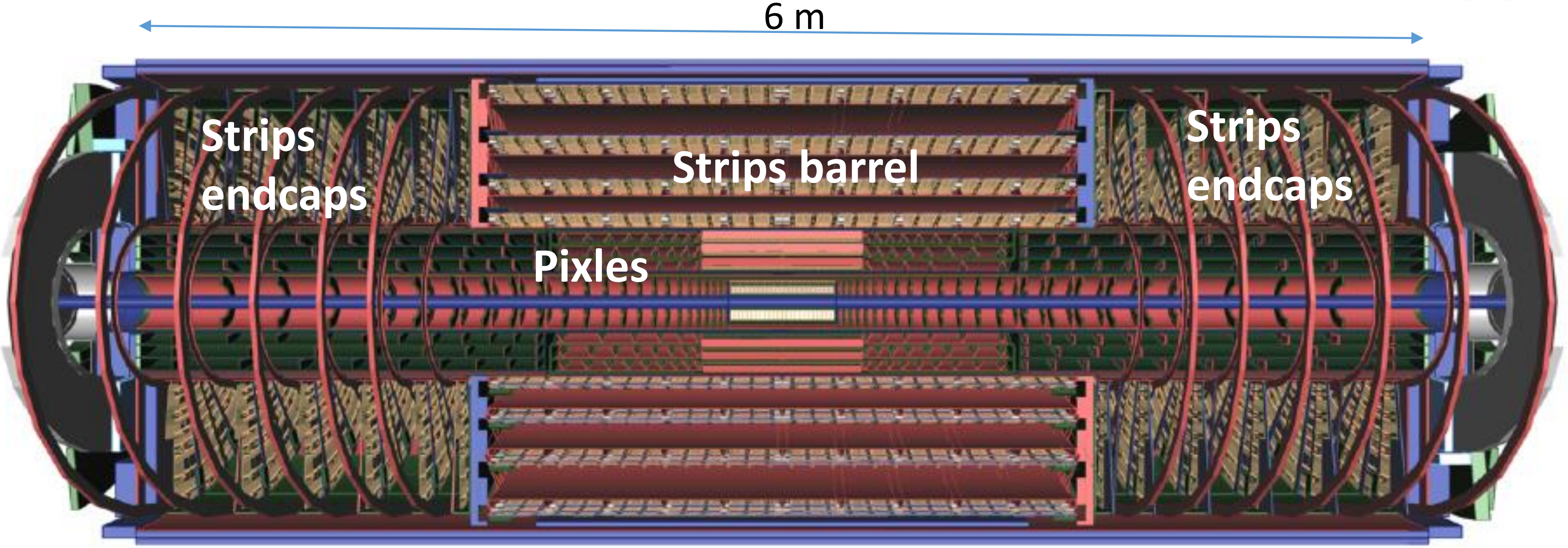
ATL-PHYS-PUB-2021-024

ATLAS Phase II upgrade

ITk strip detector:

- 4 barrel layers
- 6 strip disks in each end-cap
- coverage up to $\eta = 2.7$
  - ➔ ~ 18000 strip sensors
  - ➔ ~165 m^2 of silicon
  - ➔ ~ 60 million channels



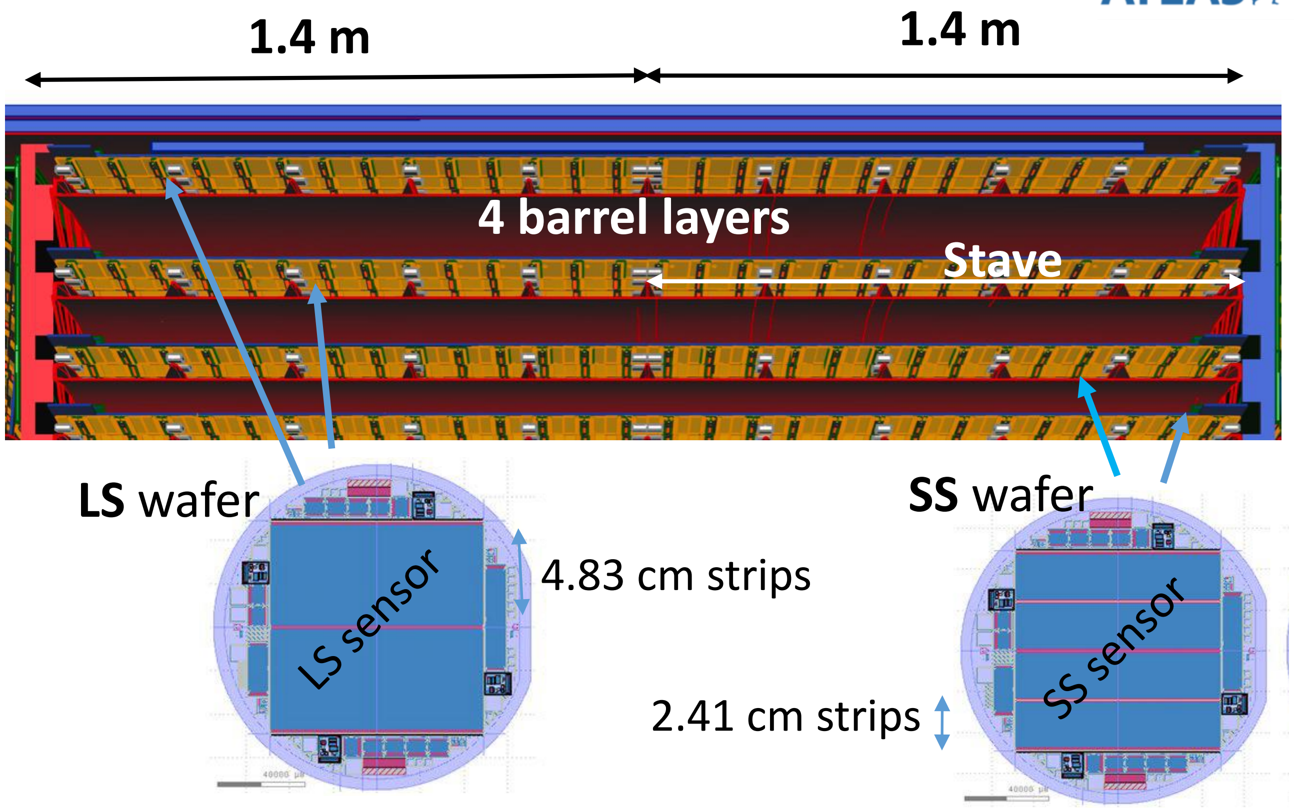


ITk strips - barrel

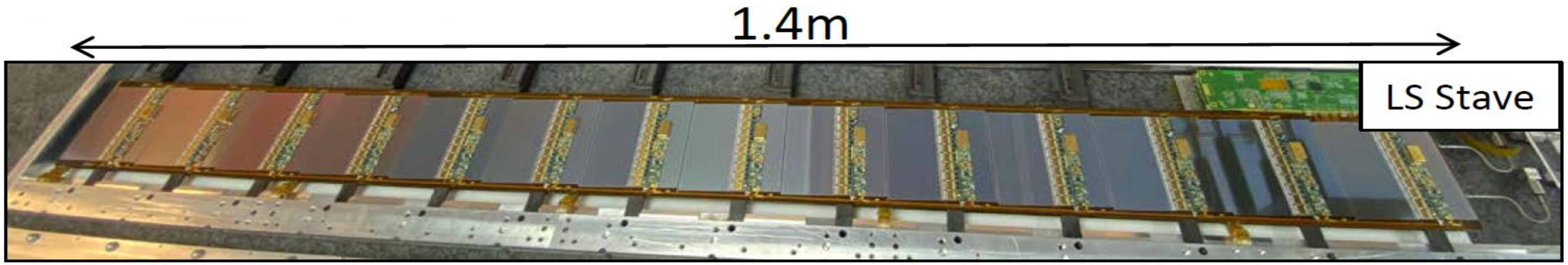
Barrel:

- 4 barrel layers
- barrels are divided in 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**)



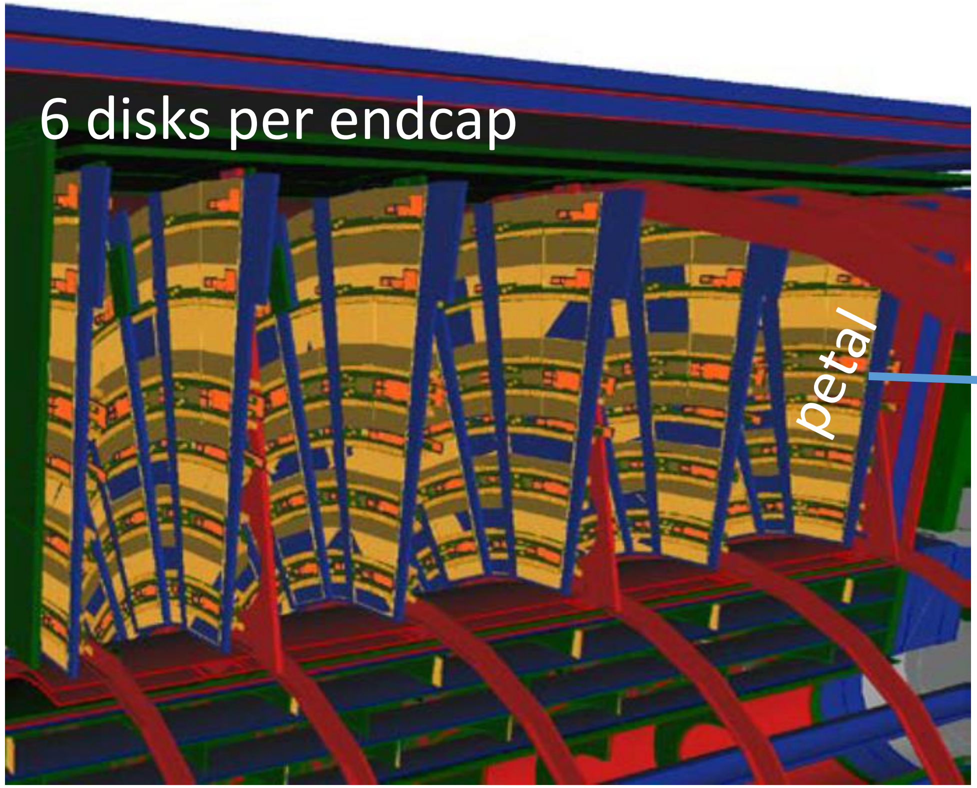
- 14 modules mounted on each side of **stave**



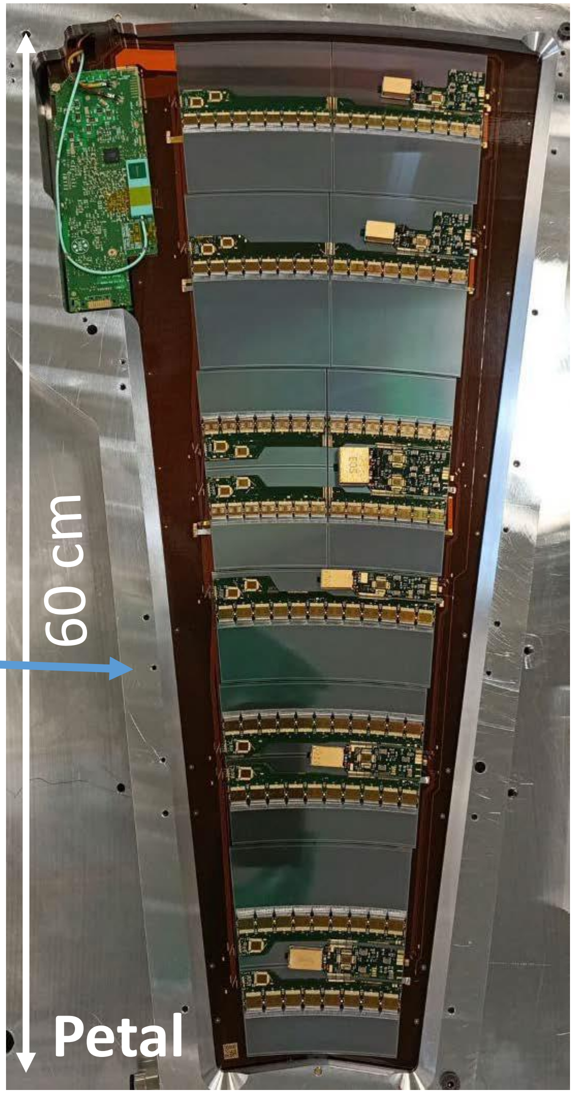
ITk strips - endcaps

Endcaps:
- 2 endcaps
- 6 disks per endcap
- 32 petals per disk
- 6 modules per petal-side
  → **4608** modules

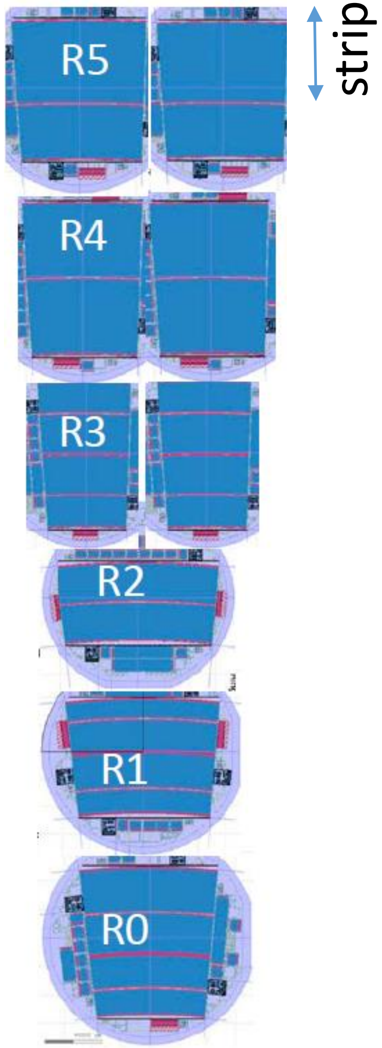
Petal:
- 6 sensor geometries
- R0,R1,R2 one sensor/module
- R3, R4, R5 two sensors
- strip length: 1.4 –6



6 modules on each side



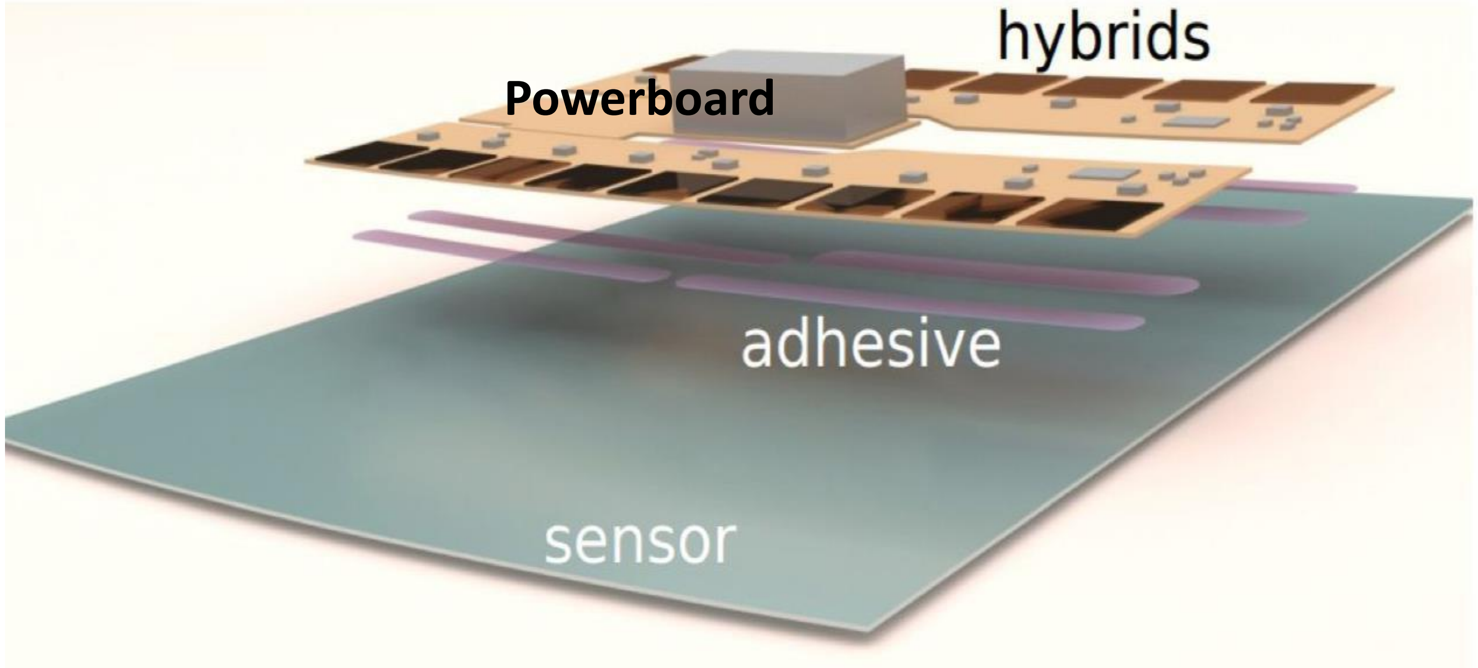
Sensor geometries



Module:
- Silicon sensors + ASICs + Power control

Hybrids, Powerboard:
- flexible printed circuits
  ➔ glued on the sensor

- strips wire-bonded to
  front end ASIC on hybrids



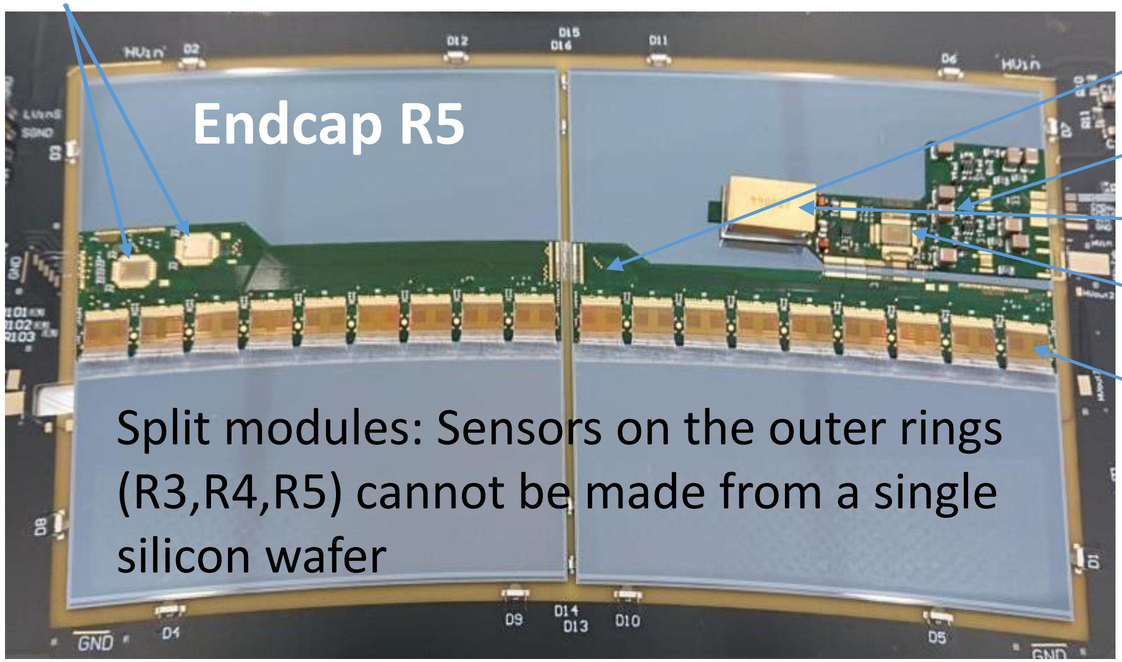
Modules

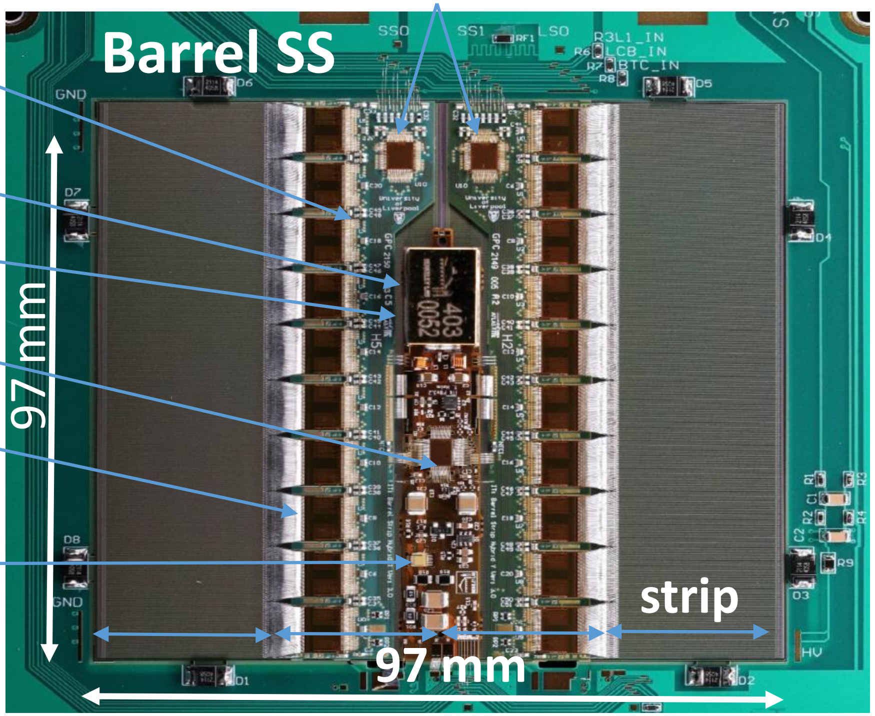
Hybrids:

- ATLAS Binary Chip **ABCstar** (front-end, 256 channels)
- Hybrid Controller Chip (**HCCstar**)

Power-board:

- **DCDC** converters: transform 11 V supply to 1.5 V for ASIC
- Autonomous Monitor And Control chip (**AMACstar**) → monitors currents, temperatures, voltages
- High Voltage filter and switch (**HV-Mux**)

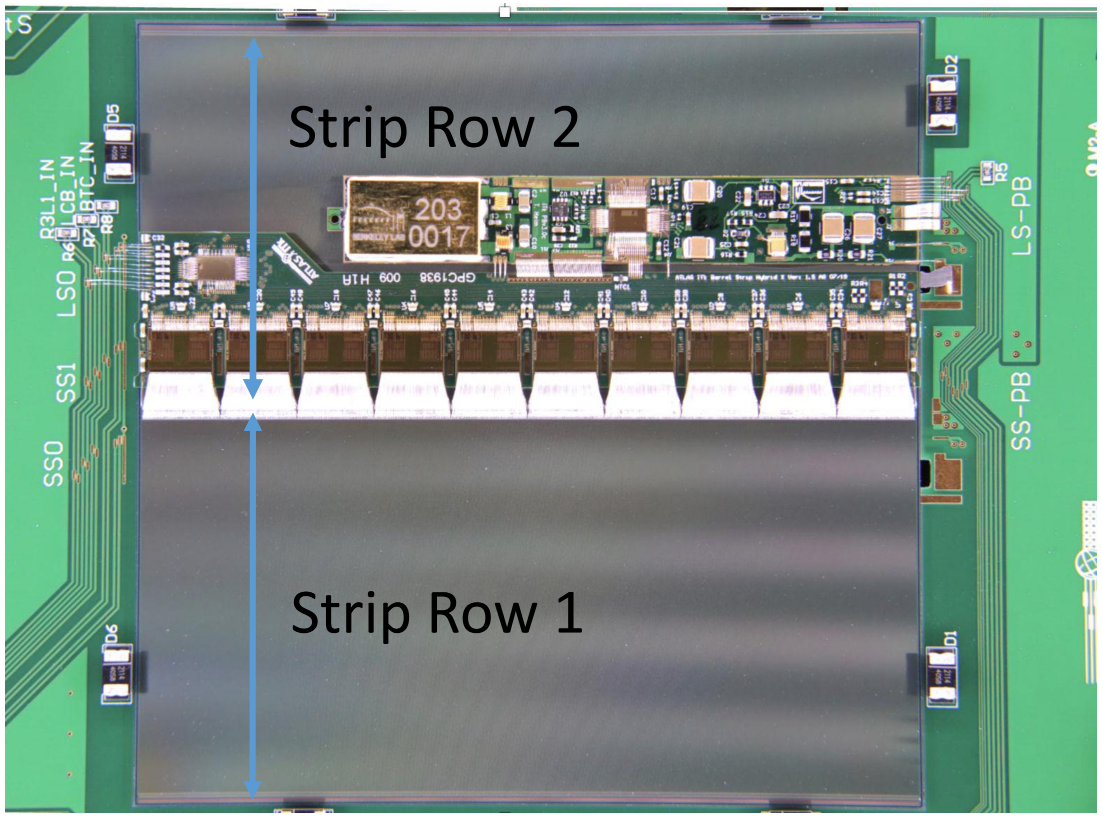




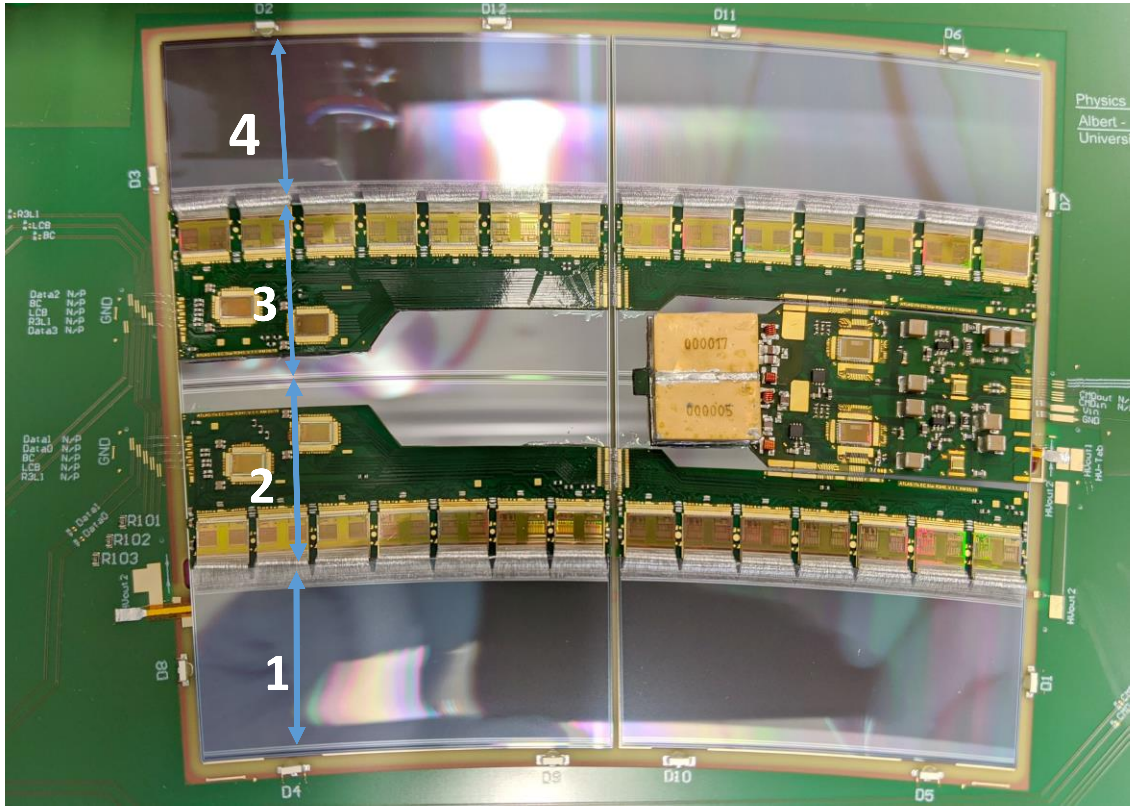
Modules

- Different module flavours:
  - two for barrels: SS and LS
  - six for endcaps: R0 to R5

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

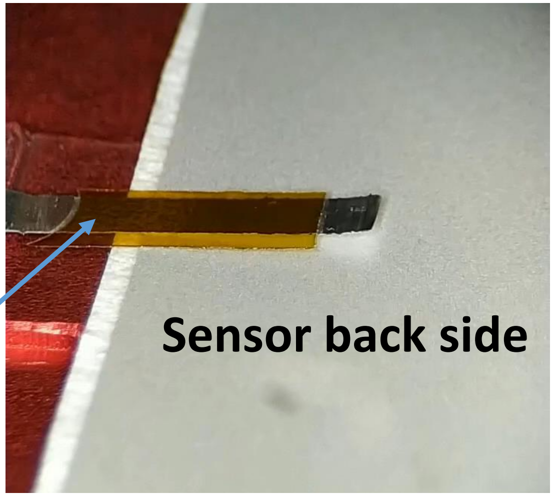


R3 **endcap** module
(4 strip rows, 2 sensors,4 hybrids):

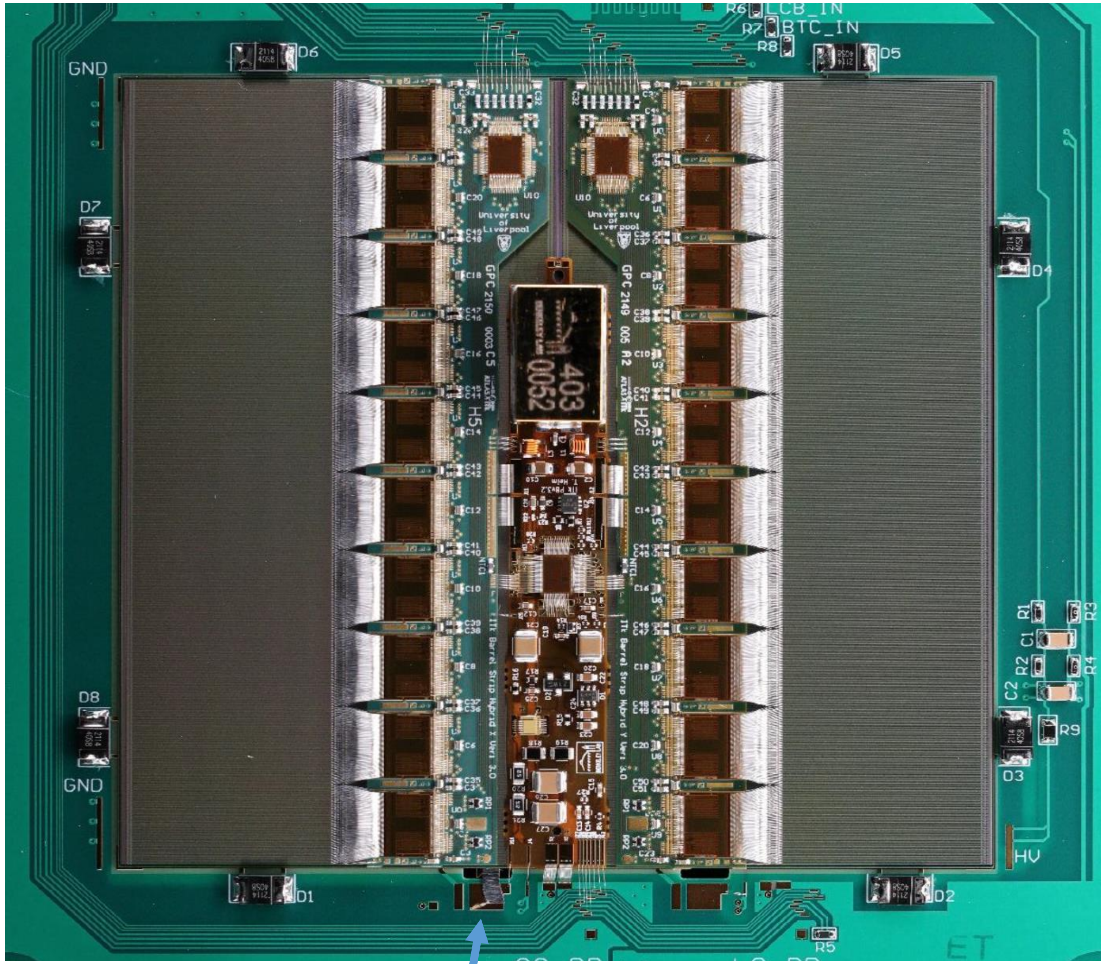


Modules

- High Voltage for sensor bias is connected to sensor back plane by **T**ape **A**utomated **B**onding (**TAB)** bonding
- maximum bias voltage -**500 V**



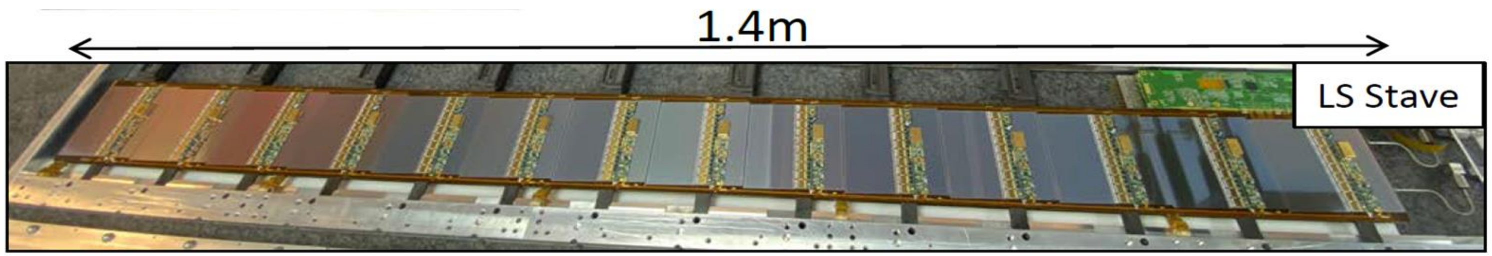
HV tab



HV tab

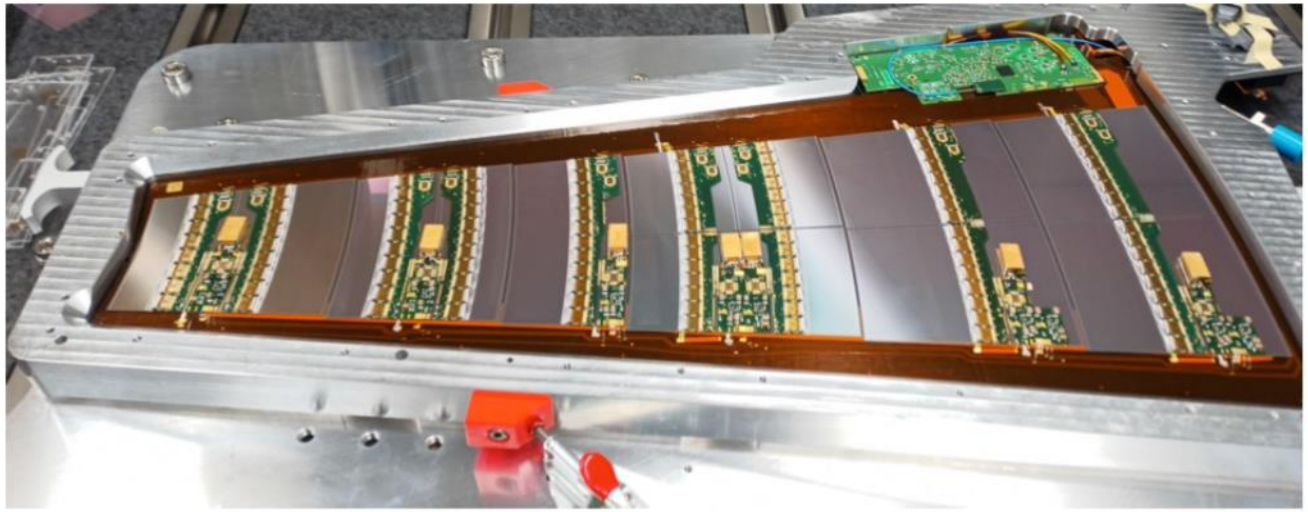
Support structures

- modules are mounted on light weight support structure: **cores**
  - barrel modules on “stave cores”
  - endcap modules on “petal cores”



Stave

Petal



Low mass support structures

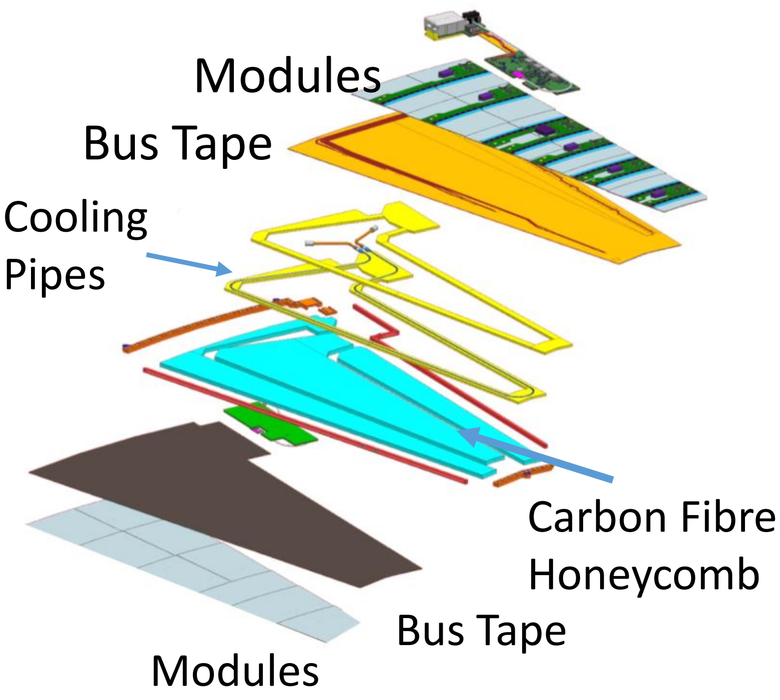
Cores:

- copper on Polyimide (kapton) bus tapes is routing electrical connections for power and signals
- pipes for evaporative CO_2 cooling in highly thermal-conductive carbon-fibre structure

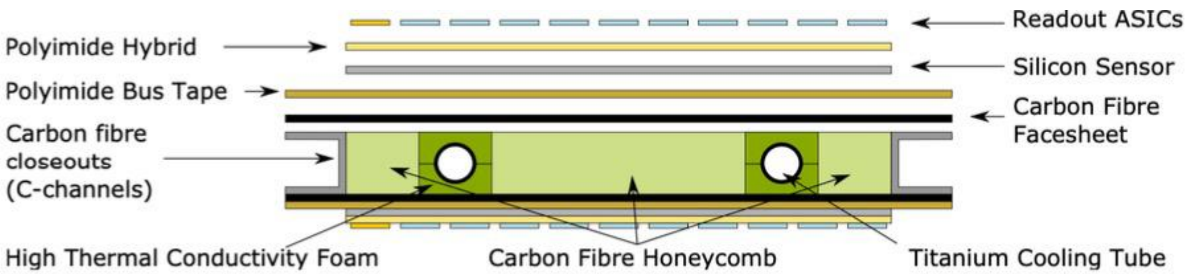
co-cured

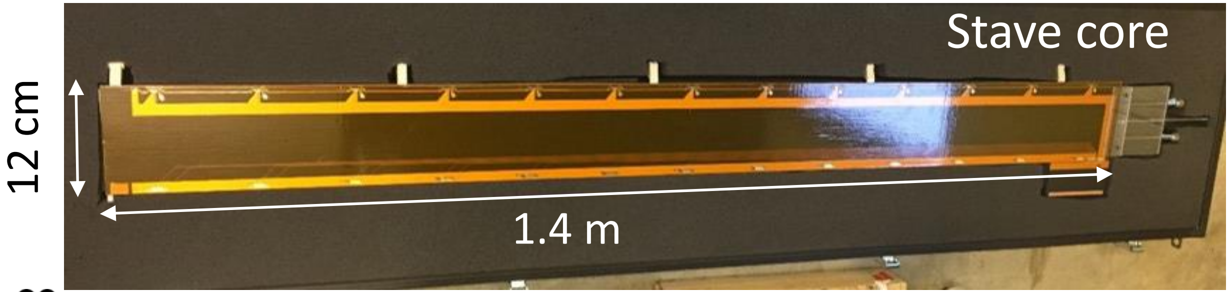
➔ **modules are glued to both sides of cores**
➔ **wire-bonds from modules to bus-tapes (tab bonds for HV)**

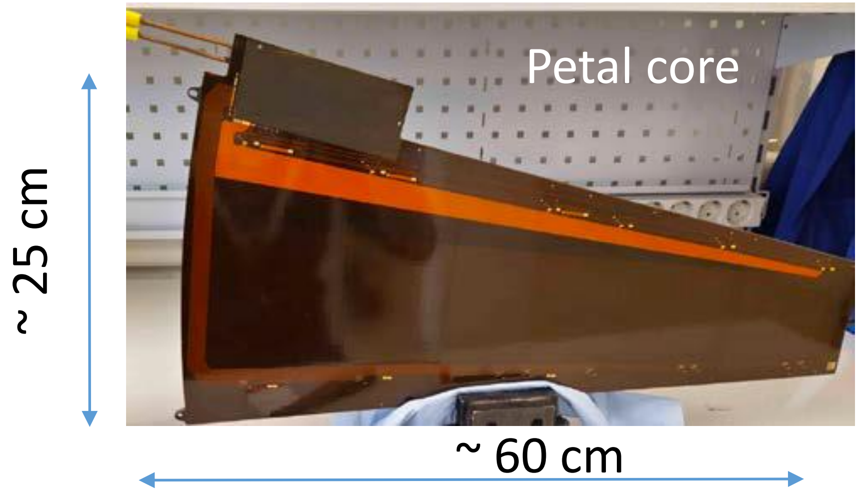
Petal core exploded view



Stave Cross section





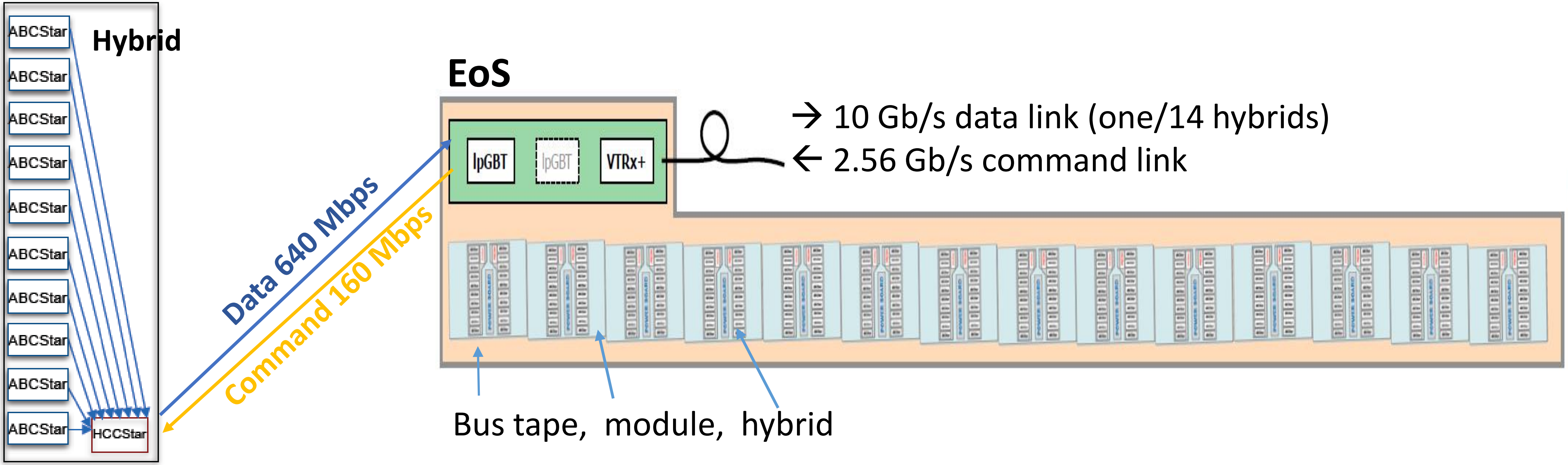


Readout and control electronics

- **ABCDstar:** front-end chips communicate with **H**ybrid **C**ontroller **C**hip **HCCstar** on each hybrid
- **HCCStar:** sends data at 640 Mbps to and receives clock and commands at 160 Mbps from **E**nd **o**f **S**ubstructure board over bus tapes (e-links)

End **o**f **S**ubstructure board (**EoS**):

- **lpGBT** (**L**ow **P**ower **G**iga**B**it **T**ransceiver, 65nm CMOS ASIC) and **VTRx+:** fibre optic driver/receiver
  → communicates with off detector electronics: 10 Gb/s data link (uplink), 2.56 Gb/s command link (downlink)



Powering

- one Low Voltage power supply channel per stave/petal side
- to reduce voltage drop in cables: start with 48V → transform to 11V on PP2 → to 1.5 V(2.5 V) on modules/EoS
- High Voltage: 4 channels per SS stave side, 2 channels (multiplexed to 4 at PP2) per LS/EC stave/petal side

Powersupply&PP4
LV: 48 V
HV: 550 V

Type IV
~ 90 m
(reused)

PP3
(passive)

Type III
~ 30 m

PP2
48 V → 11 V
DCDC

Type II
~ 15 m

PP1
(passive)

Type I
~ 1.5 m

Stave/petal/EoS
11 V → 1.5 V(2.5V)
DCDC

Cold Noise

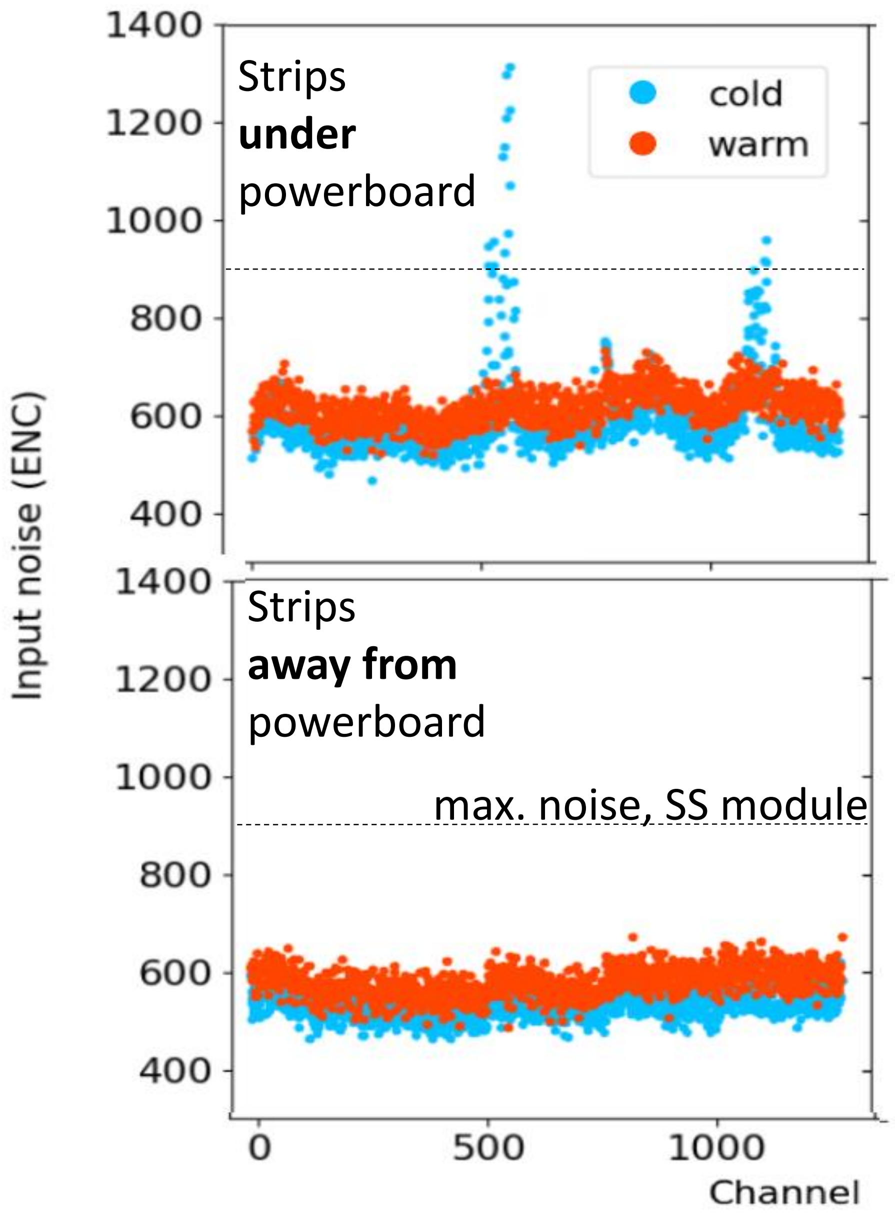
High noise channels observed when testing modules at low temperatures (-40°C) ➔ Cold Noise

- **CN** seen only in **barrel** modules, for strips under power-board
  ➔ **source of noise:** mechanical vibrations of capacitors on power-boards
- **CN not** observed in **endcap** modules
  ➔ different power-board circuit material and layout, curved geometry…

Solution for barrel **LS** modules:

➔ use right glue (Eccobond F112) for module assembly
➔ production of LS modules **started**

- changing the glue doesn't fully cure the problem for **SS** modules
  ➔ investigating: thicker glue, filling glue gaps, endcap-style power-board
  - time to find solution by summer 2024

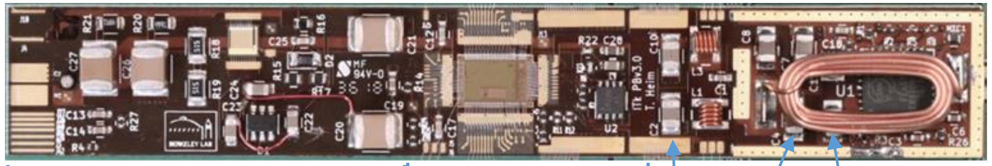


Cold Noise

- buck converter switching at 2 MHz with air core coil used for DC-DC conversion form 11 V to 1.5 V
  - ➔ vibrations in capacitors because of switching
  - ➔ vibrations are transferred to sensor
    - → mechanism of coupling between mechanical vibrations and electronic noise not yet understood

DC-DC converter (no shield)

Powerboard



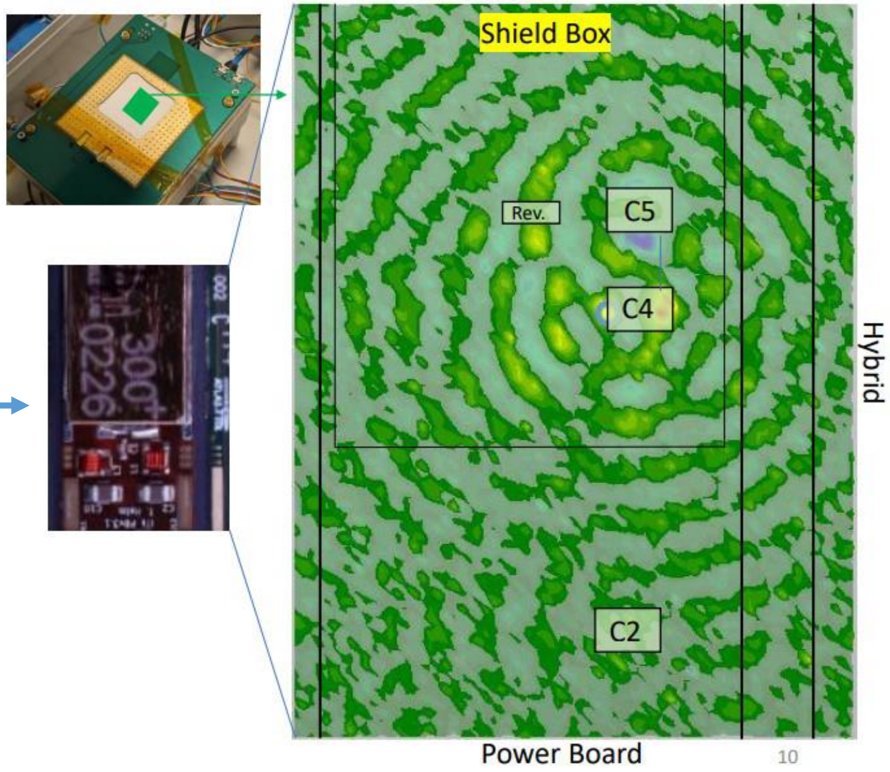
11 mm

High Voltage part

AMAC

C2 C4 C5

Vibration pattern measured on the back side of sensor



[More information about CN presented at TWEPP 2023](https://indico.cern.ch/event/1255624/contributions/5445245/)

https://indico.cern.ch/event/1255624/contributions/5445245/

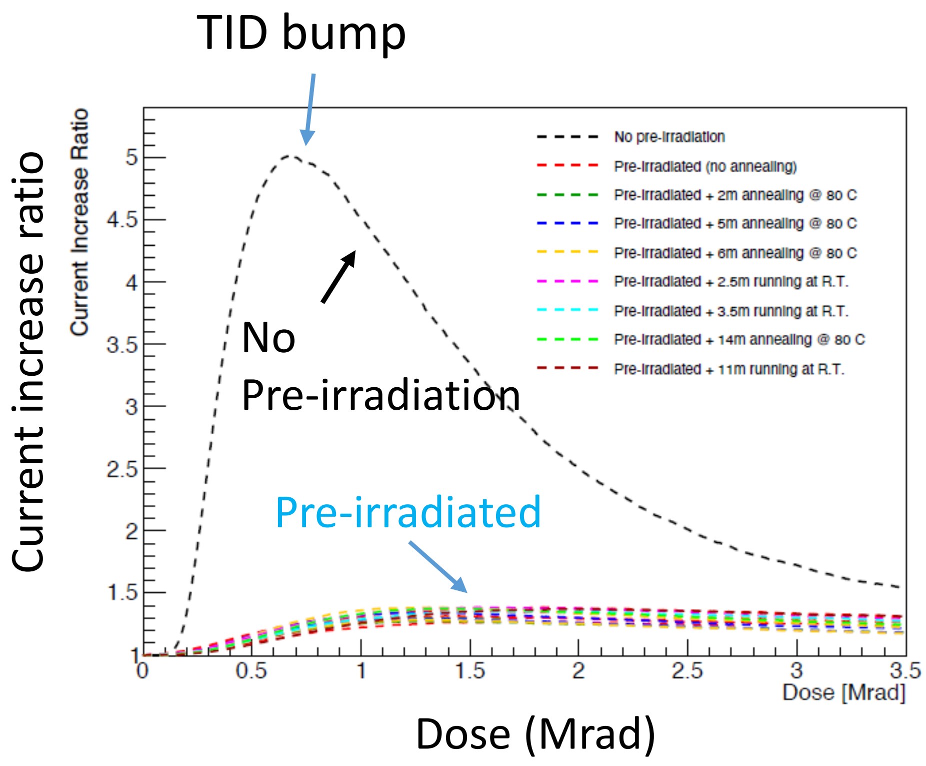
ASICs

- all three ASICs (**ABCstar, HCCstar, AMACstar**) produced by Global Foundry (GF) in **130 nm** technology

- chips are pre-irradiated to 5 Mrad with ^{60}Co to avoid TID bump
  ➔ pre irradiation of production chips at RBI, Zagreb, Croatia

Production of ASICs going on

ASIC	Manufactured	Probed	Probing Yield	Diced	Pre irradiated
ABCStar	330000 (95%)	49%	88%	30%	3%
HCCStar	32000 (93%)	93%	97%	71%	21%
AMACStar	28000 (117%)	100%	93%	88%	27%



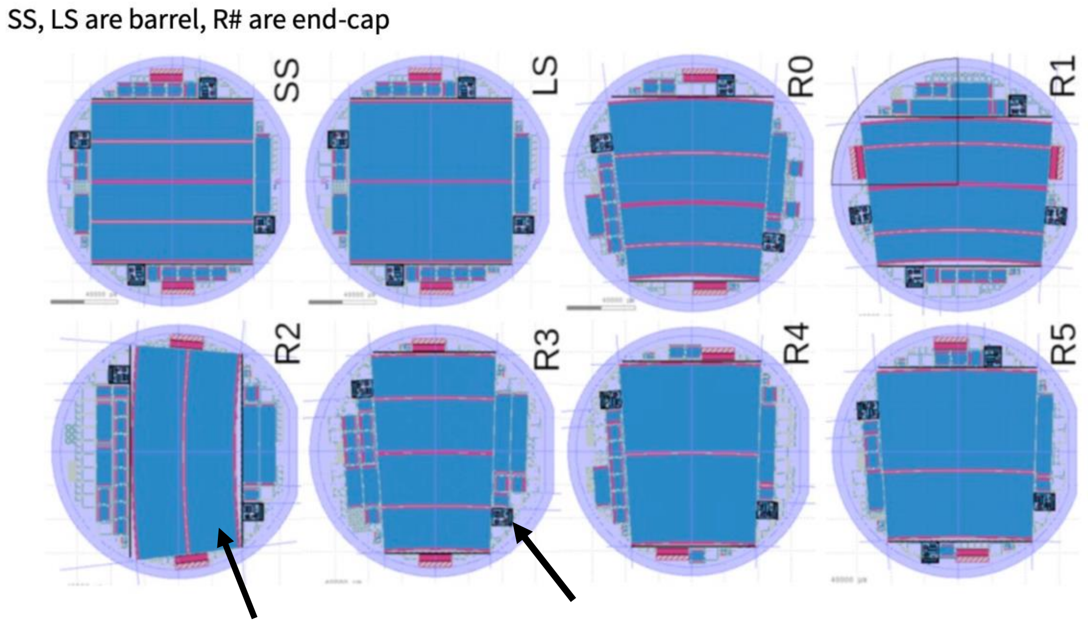
Sensors

- n-in-p type, float zone, AC coupled, single sided
- active thickness 300 µm

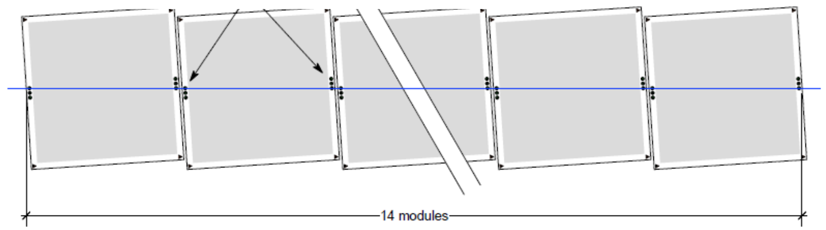
- full depletion voltage V_{fd} ~280 V
  (specifications V_{fd} < 350 V)

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

Wafers with 8 sensor geometries

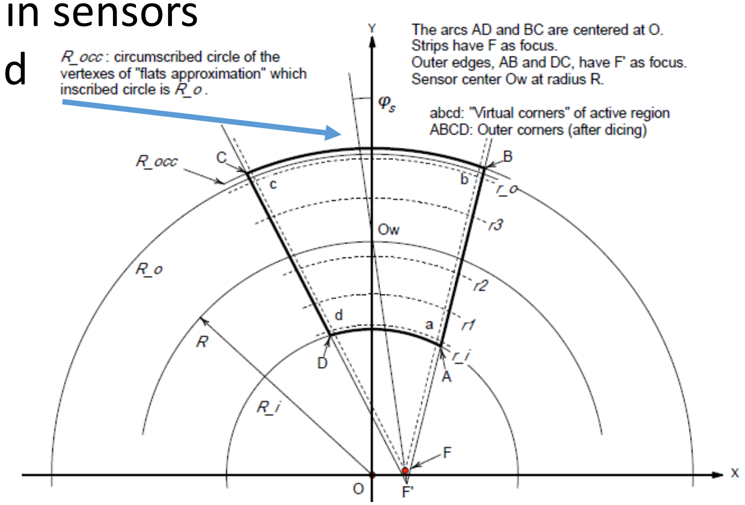


Barrel: sensors are rotated by 26 mrad to stave axis for stereo hit reconstruction



Endcap: stereo angle is "built" in sensors

- strips rotated by φ_s = 20 mrad around centre of sensor



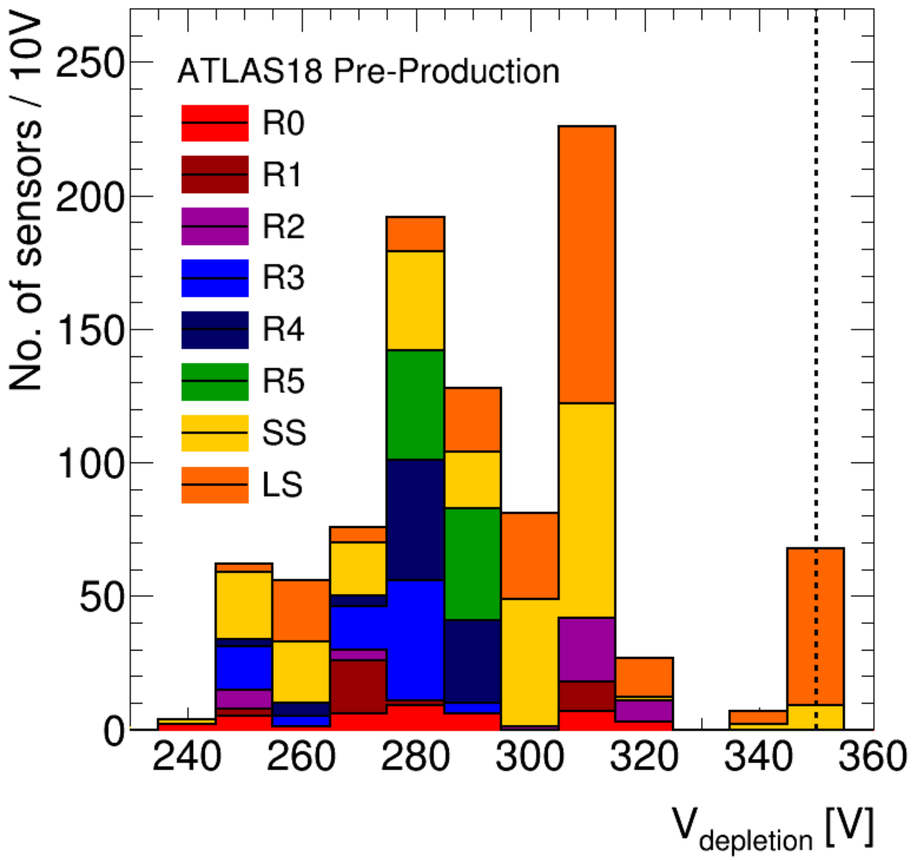
Y. Unno et al., 2023 JINST 18 T03008

Sensors

- production at HPK started in 2021 and will finish in 2025
- ~ 22000 sensors will be produced
  ➔ **57%** sensors delivered according to the plan
- extensive **Q**uality **C**ontrol and **Q**uality **A**ssurance procedures
- low rejection rate **2 to 3 %**
  - sensors mostly fail breakdown criteria (**V_{bd} > 500 V**)
    - some correlation with high static charge on sensors
    - part of failed sensors can be recovered with different treatments (UV, ion blowing, baking …)

    ➔ more detail in talk by M. Mikestikova on Thursday 15:50

Full depletion voltage V_{fd} distribution



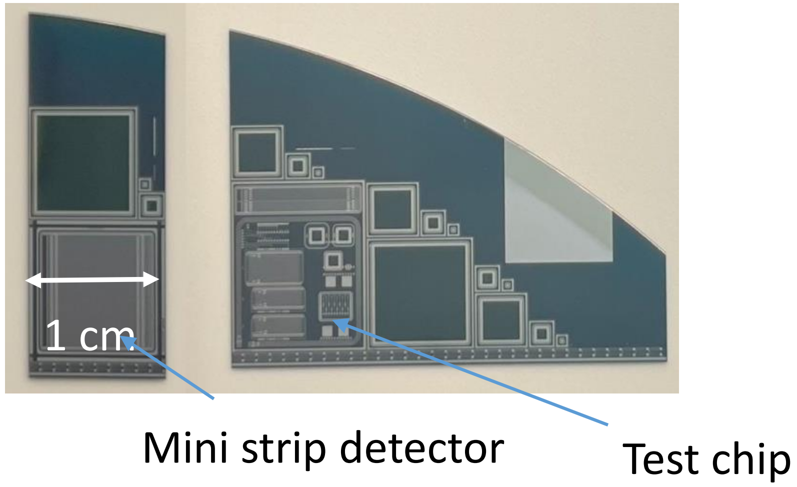
C. Klein et al., ATL-ITK-PROC-2023-002

Sensors QA

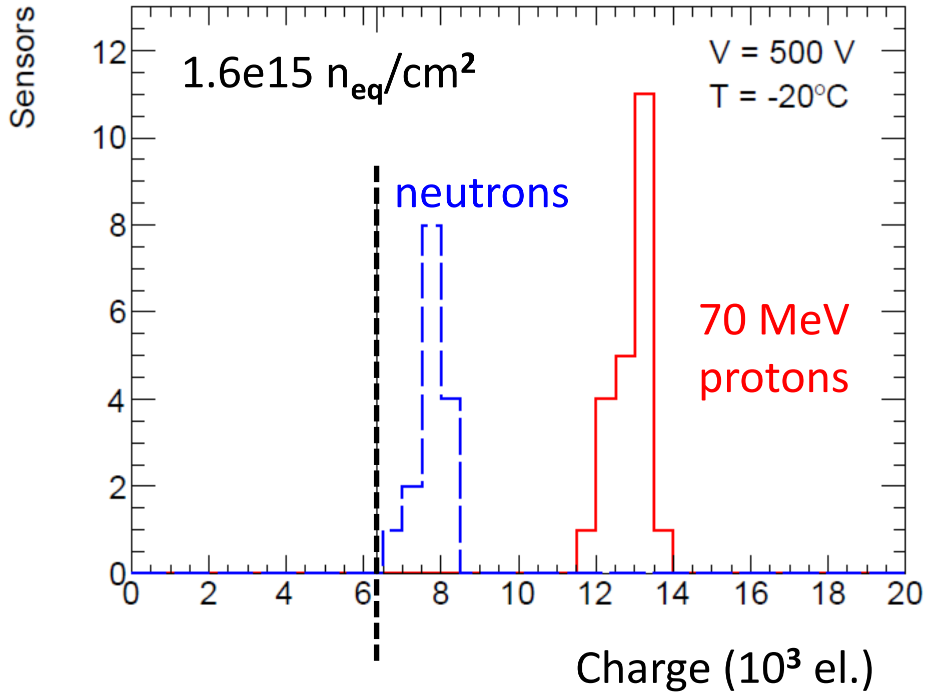
- structures sampled from batches of wafers
- **irradiated up to 1.6e15 n_{eq}/cm^2** with:
  - neutrons at TRIGA reactor in Ljubljana
  - protons at CYRIC(KEK) (70 MeV) or Birmingham (27 MeV)
  - ➔ CSNS (70 MeV protons) Dongguan, China, is being qualified
- **TID** to **660 kGy** with γ from ^{60}Co source in Prague

- various parameters followed (Charge Collection, V_{bd}, R_{int}, *PTP*…)
- few imperfect batches identified

Tests structures cut from wafer



Mini strip detectors, Φ_{eq} = 1.6e15 n_{eq}/cm^2
- collected charge measured with ^{90}Sr on AliBaVa system
- **acceptance: Charge > 6350 electrons** at sensor bias = 500 V



S. Hirose et al., ATL-ITK-PROC-2023-001

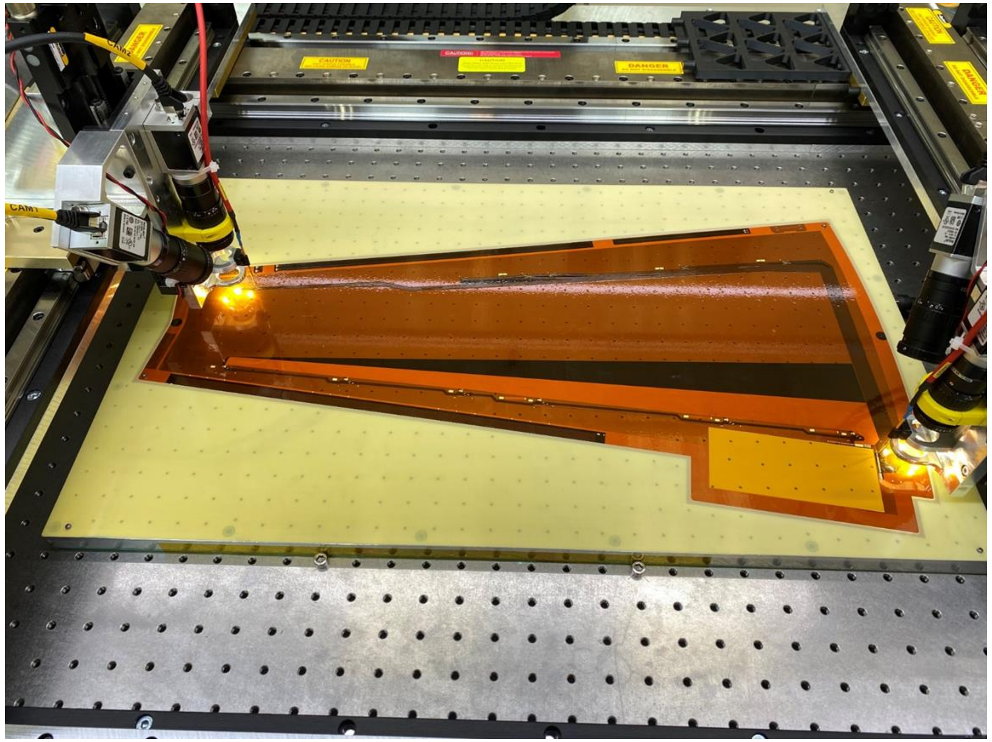
Core production

- stave and petal cores in pre-production stage

- **Barrel:**
  - some delays with start of bus tape production because of problems with nickel gold plating, ..
  - solutions searched, recent results encouraging
  - expect to start production soon

- **Endcap:**
  - production of bus tapes ongoing
  - 16 pre-production cores finished, good results
  - production of cores will start soon

Robot testing of petal bus tape

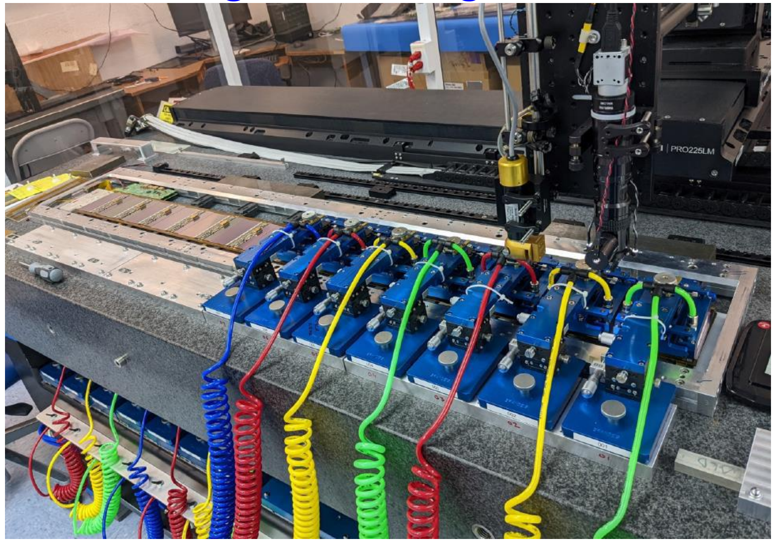


Module production

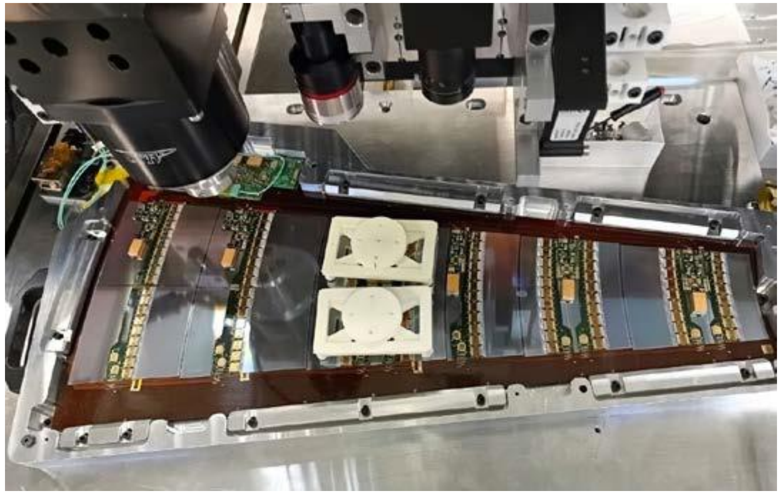
- starting production for **barrel LS** and **endcap** modules at **module production sites**:
  - precision work:
    - parts need to be positioned within 10 μm
    - glue thickness controlled with 10 μm accuracy to ensure good thermal contact etc..
    - wire-bonding
- modules are mounted ("loaded") to stave and petal cores at **loading sites:**
  - dispensing the glue
  - high precision module positioning
  - wire-bonding to bus tapes
- staves and petals will be inserted into barrels and endcaps at CERN, Nikhef and DESY

See poster by L. Franconi
https://agenda.infn.it/event/35597/contributions/211792/

Stave loading – mounting modules on cores



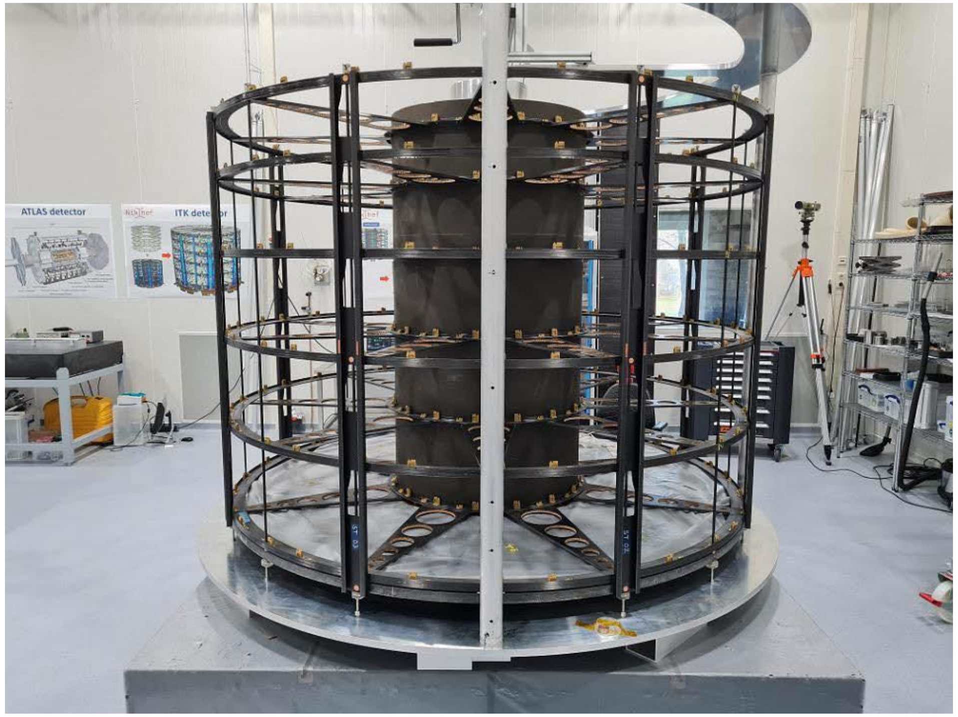
Petal loading system



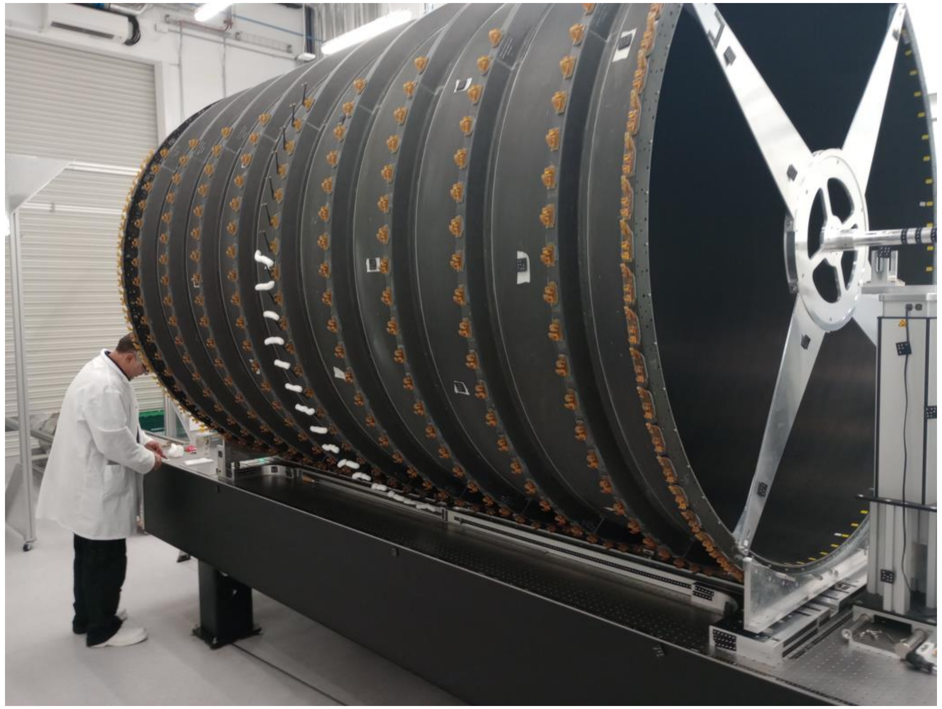
Global structures

- carbon fibre structures holding staves and petals
- first endcap structure finished, second in production
- 4 barrel cylinder in production
  - outer barrel cylinder (L3) finished, being equipped with mounting brackets in Oxford

Endcap structure



Barrel cylinder with mounting brackets



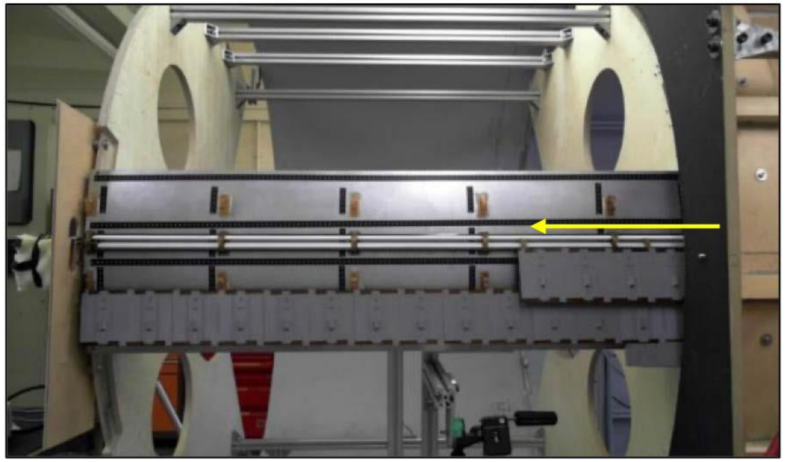
Integration

Preparing for integration:

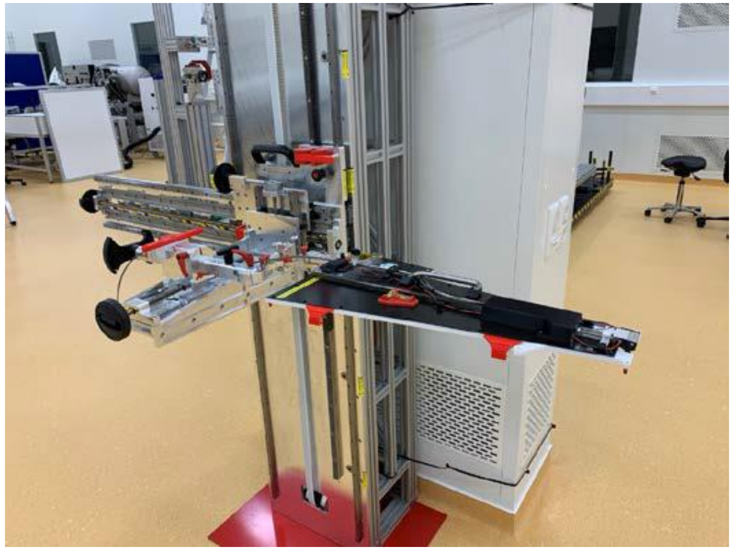
- staves inserted to barrel at CERN
- petals inserted to endcap at DESY and Nikhef
- barrel and endcaps will be integrated into ITk at CERN

Barrel (and later ITk) integration room at CERN

Stave insertion tool



Petal insertion tool

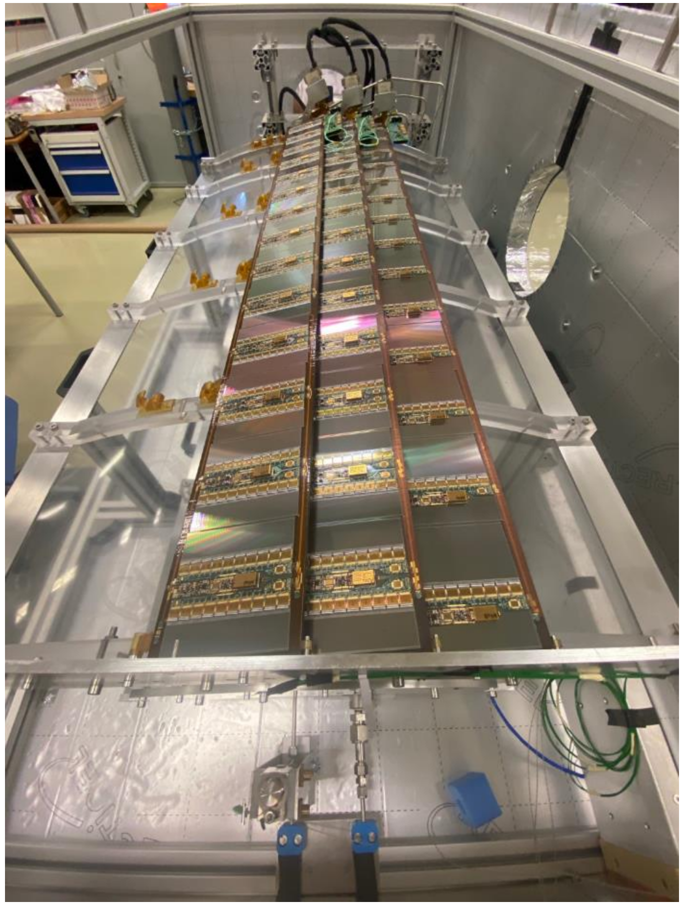


System Tests

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

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

Barrel System Test at CERN



End-cap System Test at DESY

Summary

ITk Strip Detector will provide excellent particle tracking in the extremely demanding HL-LHC environment!

- components in pre-production (final confirmation of the design before production):
  - ➔ staves, petals, services, power supplies
- components in production:
  - ➔ sensors, ASICs, modules, global structures

- building of staves and petals should start soon
- installation of first staves and petals in the global structures is starting in 2024 and should finish by the end of 2026

- barrel and both endcaps should be ready to integrate with pixel detector in 2027

- complete ITk (Strips and Pixels) installation in ATLAS planned for 2028
  - ➔ many challenges to overcome
  - ➔ on track for installation of the integrated ITk system in 2028