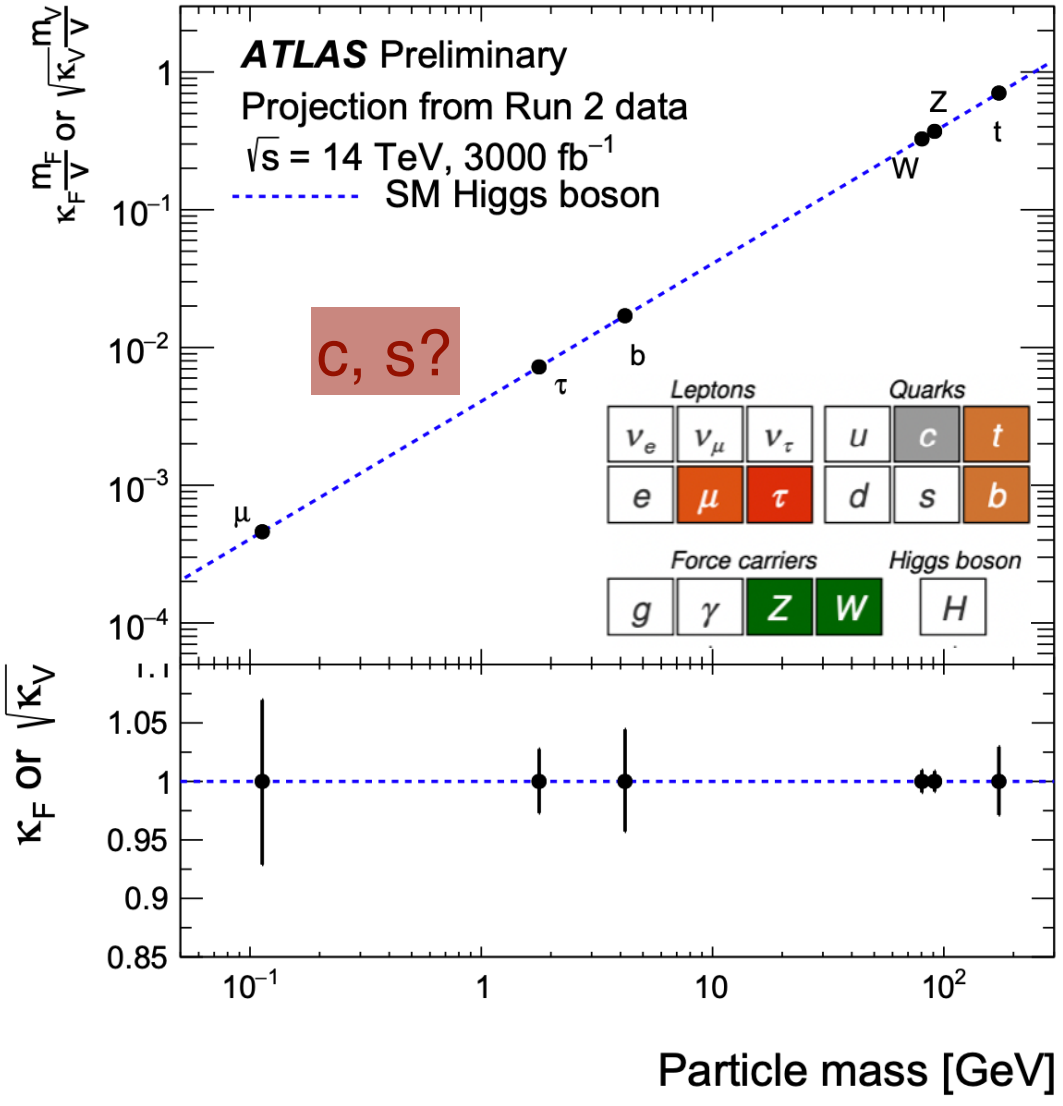
Phase-2 Upgrade of the ATLAS **Inner** Tracker

Caterina Vernieri

On behalf of the ATLAS ITk Collaboration

Higgs at HL-LHC

1902.10229
CERN-LPCC-2018-04
ATL-PHYS-PUB-2025-018



The High Luminosity era of LHC will dramatically expand the physics reach for Higgs physics:

- **2-5% precision for many of the Higgs couplings**
- **BUT much larger uncertainties on Zγ and charm and ~30% on the self-coupling**

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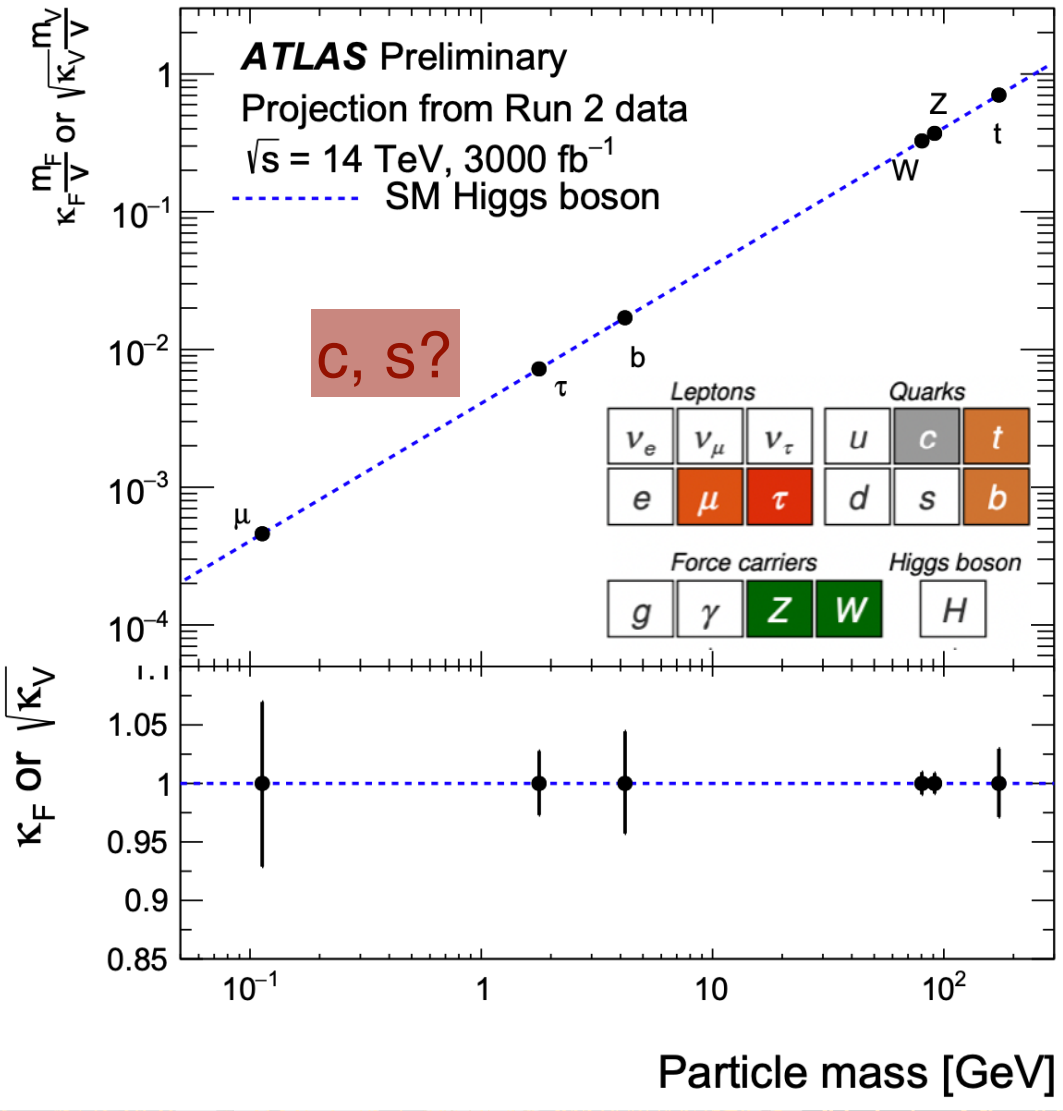

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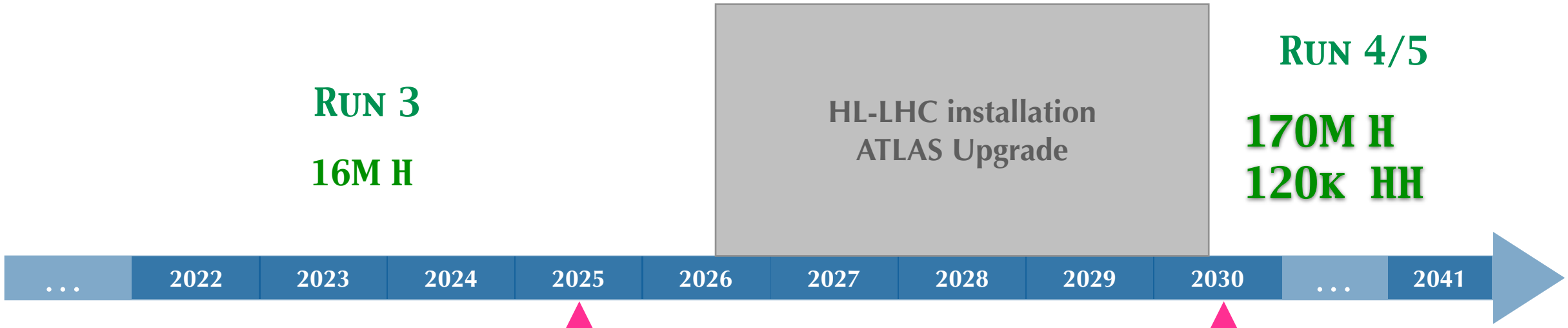
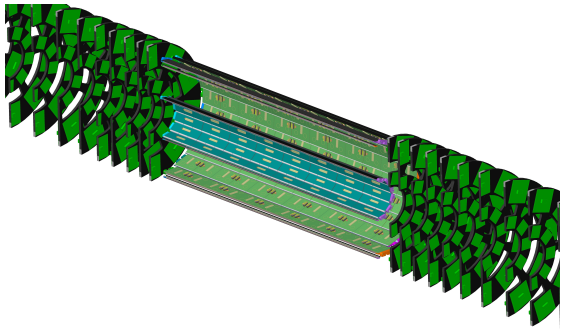
Light Yukawa out of reach in the LHC environment

LHC → High Luminosity LHC

HL-LHC schedule

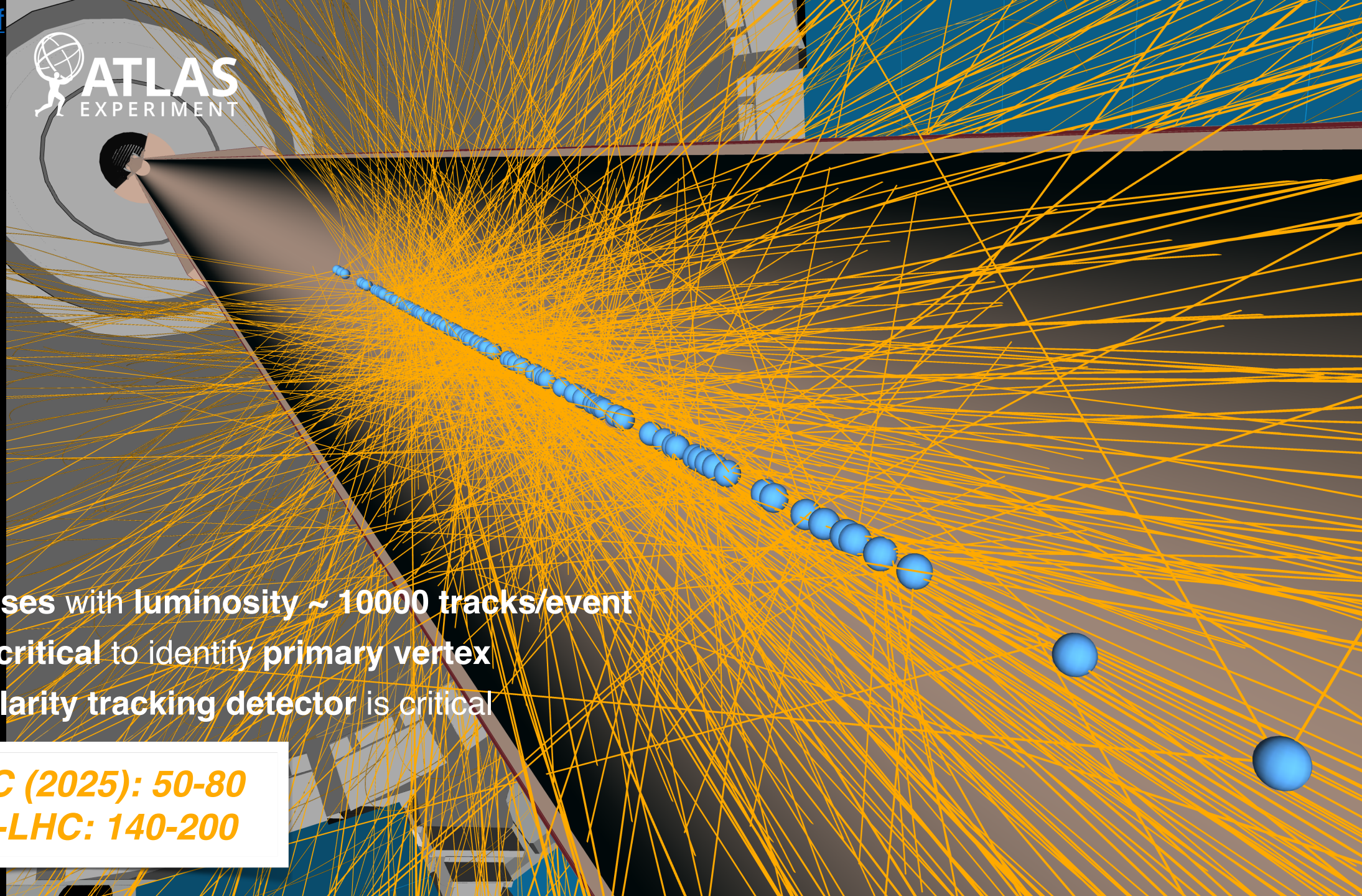




TODAY

Phase-2 HL-LHC detector upgrades are being built

ref



Pileup increases with **luminosity ~ 10000 tracks/event**

z position is critical to identify **primary vertex**

High granularity tracking detector is critical

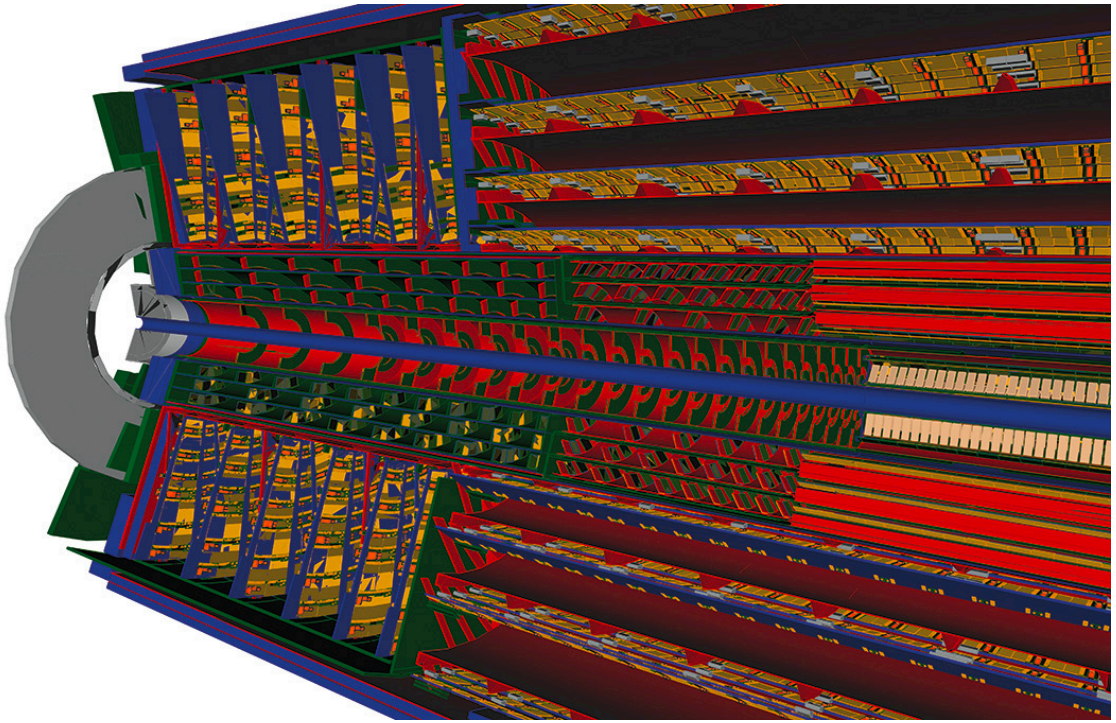
LHC (2025): 50-80
HL-LHC: 140-200

The upgrade of the Tracker Detector for HL-LHC

A new, whole-silicon, tracker (ITk) to maintain physics performance in the harsher HL-LHC environment

- LHC energy and luminosity increase: operate up 7.5 x 10^{34} Hz/cm^2, i.e. 200 PU
- Sustain radiation tolerance up to 10x the dose expected during LHC
- Readout to be compatible with a trigger decision rate ~ 1MHz 10x increase

Extended tracking acceptance, up to η~4
Operated at -35C to mitigate radiation-induced damage and prevent thermal runaway
Improved electronics
Smaller Pixel size, occupancy at per mille level



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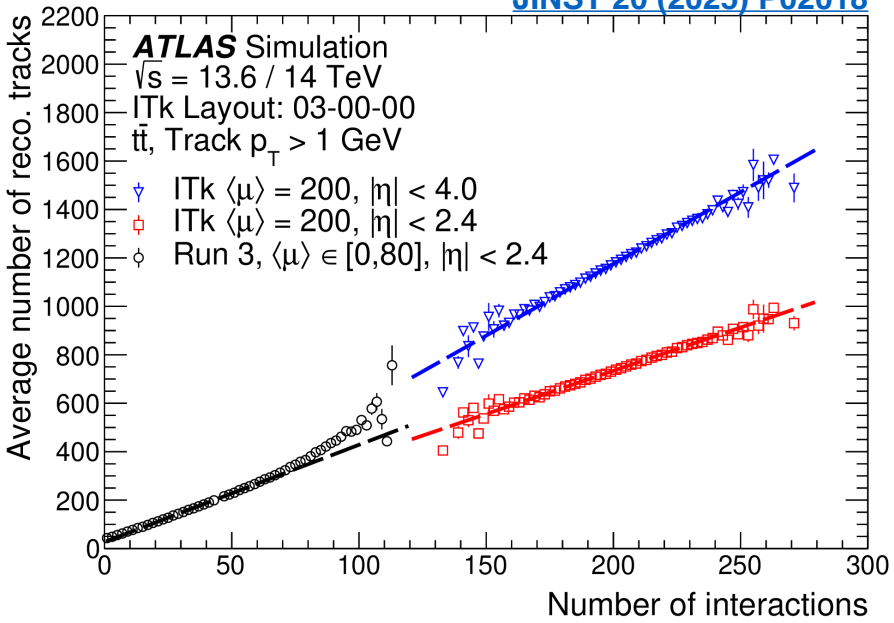
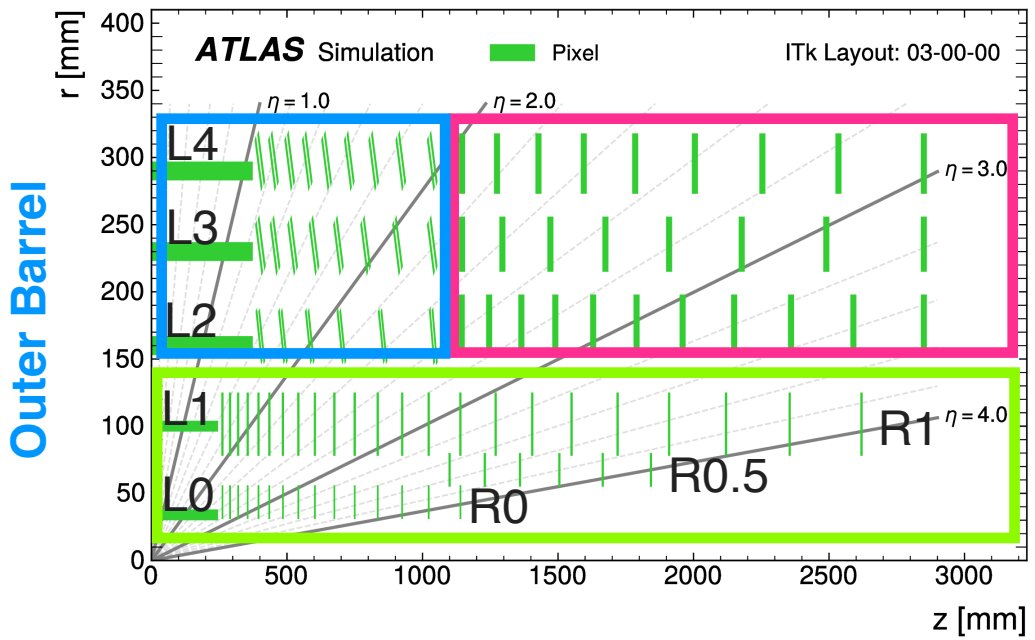
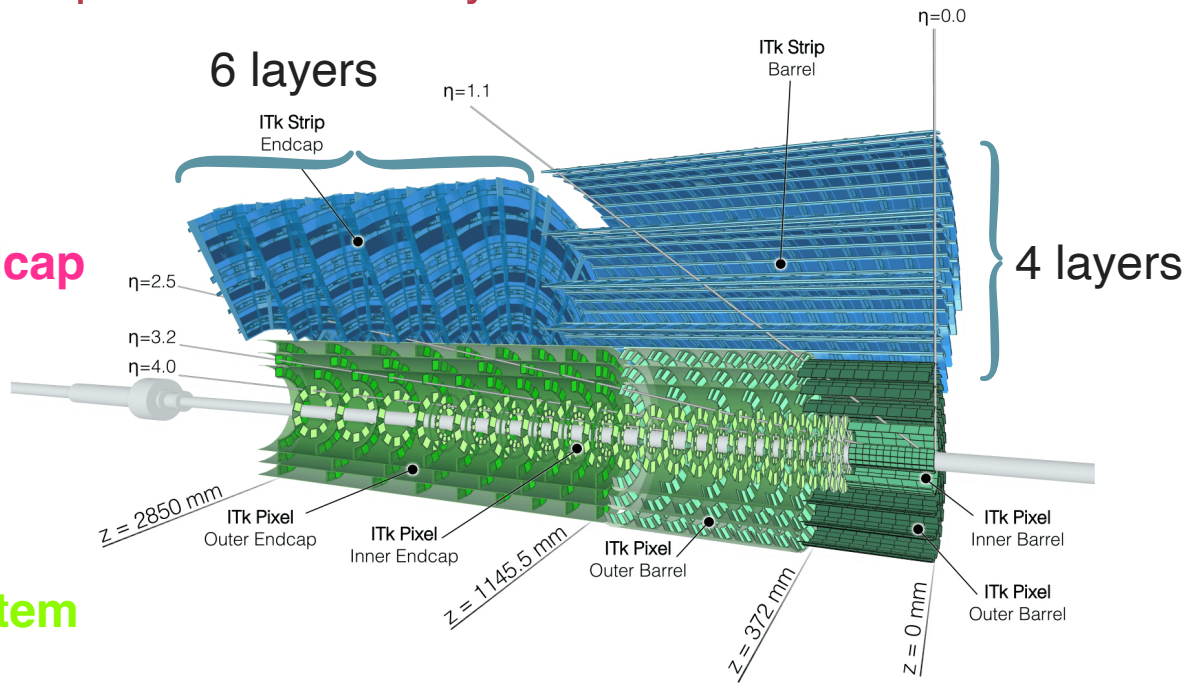


ITK Layout, the largest silicon detector

ITK: 5 pixel + 4 strip layers → at least 9 space points per track. First layer at 33 mm from the IP

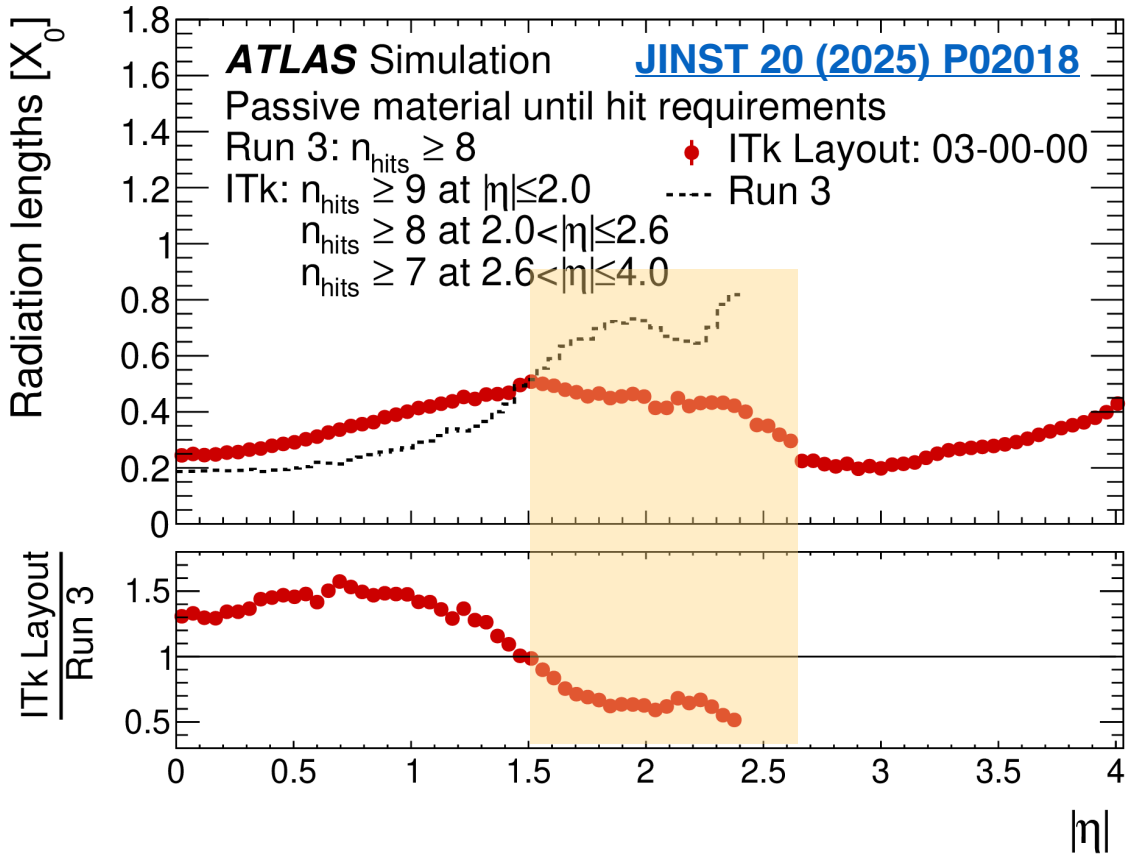




	Eta Coverage	Pixel (m^2)	Pixel Channels	Pixel Modules	Strip (m^2)
Current Tracker	$\|\eta\|<2.5$	2	80×10^6	1.7 K	68
ITk	$\|\eta\|<4.0$	**13**	**5.1×10^9**	8.3 K	165

One more challenge: Material Budget

Additional layers of silicon & more channels compared to the ATLAS current detector (ID+TRT)



- **CO_2** two-phases cooling system
- **Carbon fiber structures** for local supports
- **Link sharing and serial powering** to reduce number of readout and power cables respectively

Pixel services: optical conversion outside the detector volume

Higher granularity

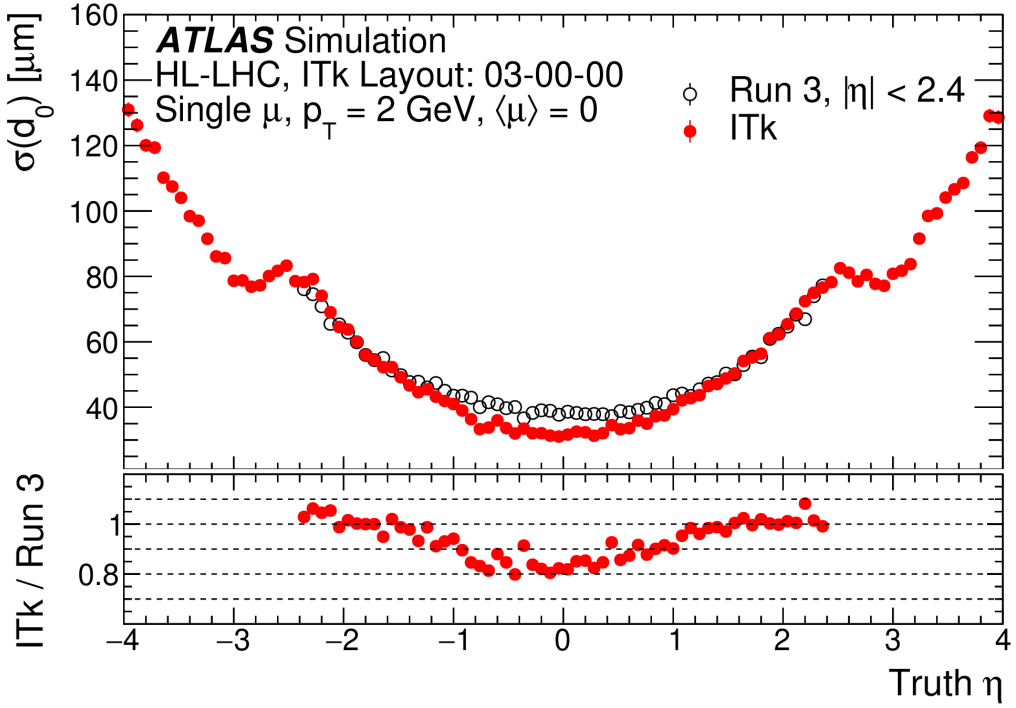
Small pixels → Low occupancy, improved impact parameter resolution.

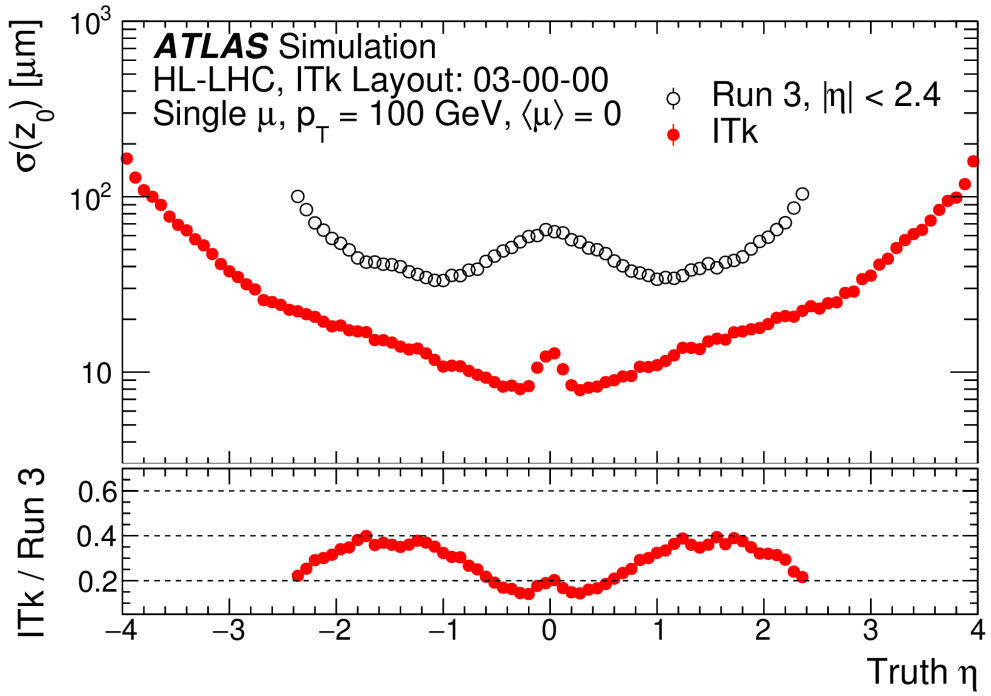
ITk will feature :

- **25 x 100 *μ*m** for the innermost layer of the barrel (L0)
- **50 x 50 *μ*m** pitch everywhere else

Run-3

- **50 x 250 *μ*m** for the two innermost layers
- **50 x 400 *μ*m** pitch everywhere else





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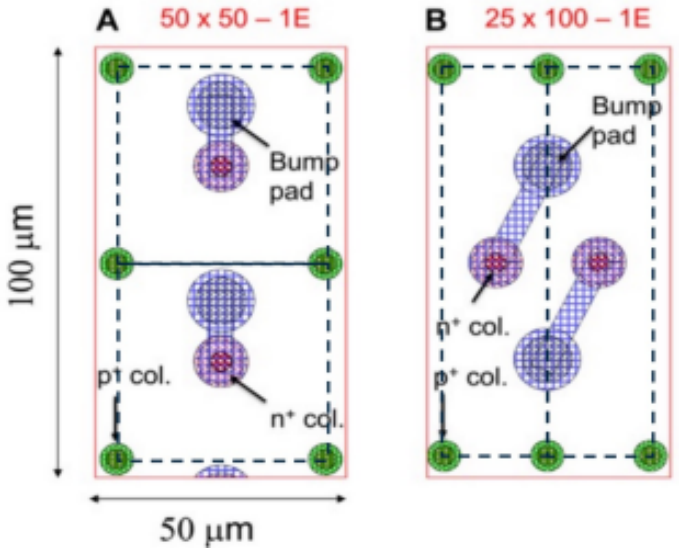
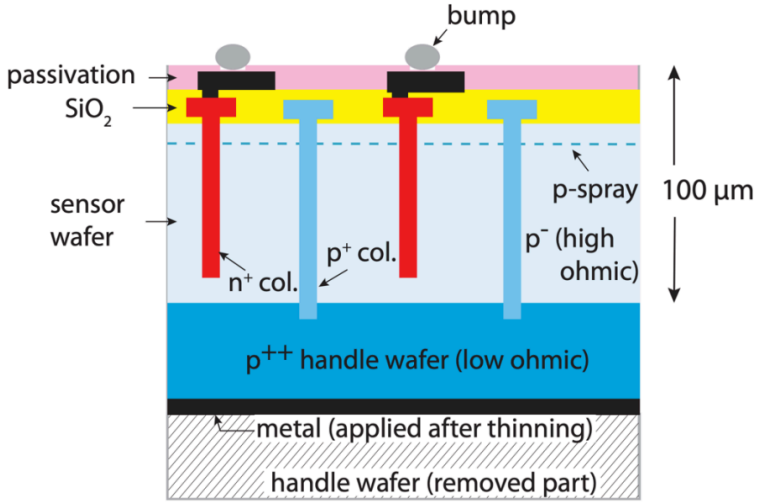
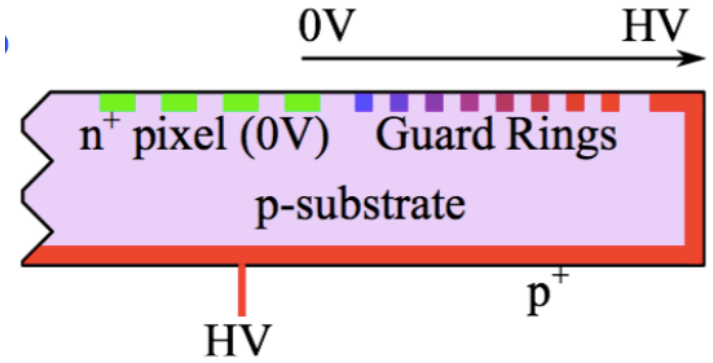
The tracking efficiency in the central region of the ITk detector is within 5% to the one of the Run 2

Pixel Sensors

Thin active substrates (100-150 μm) → Reduced cluster size and data rates







- For L/R0 **3D sensors (25μm x100μm or 50μm x50μm)** with new single-side technology
  - Bias <150V
  - Radiation hard up to ~ 1.6 x 10^{16} n_{eq} cm^{-2}
  - Vendors: SINTEF, FBK
- For R/L1+ layers feature **n-in-p planar sensors (50μm x50μm)**
  - 100μm for the innermost layer, then 150μm
  - Radiation hard to ≈ 4 x 10^{15} n_{eq} cm^{-2}
  - Bias voltages up to 600 V
  - Vendors: HPK, Micron, FBK

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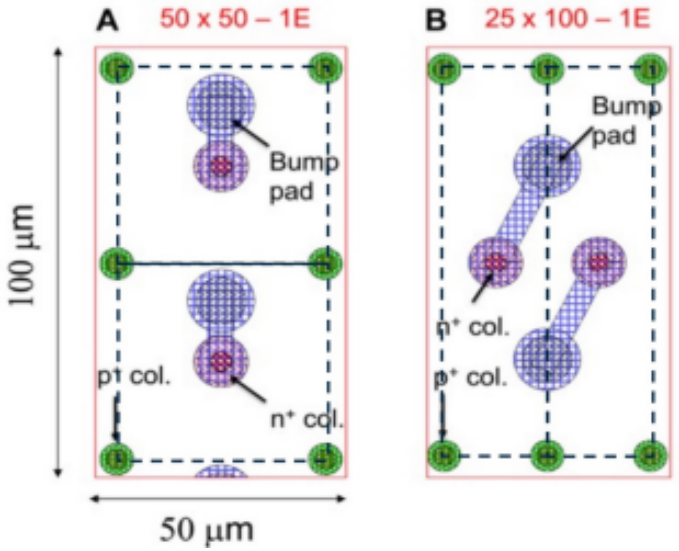

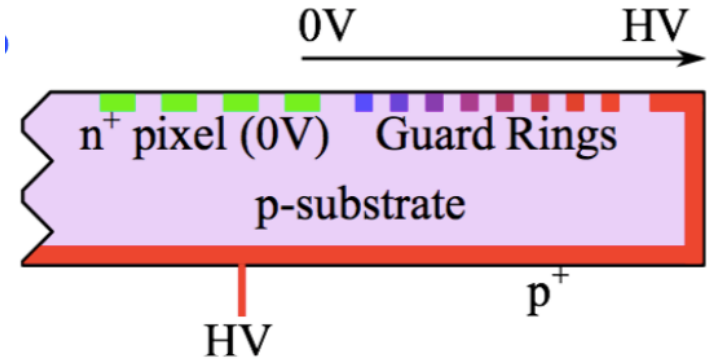

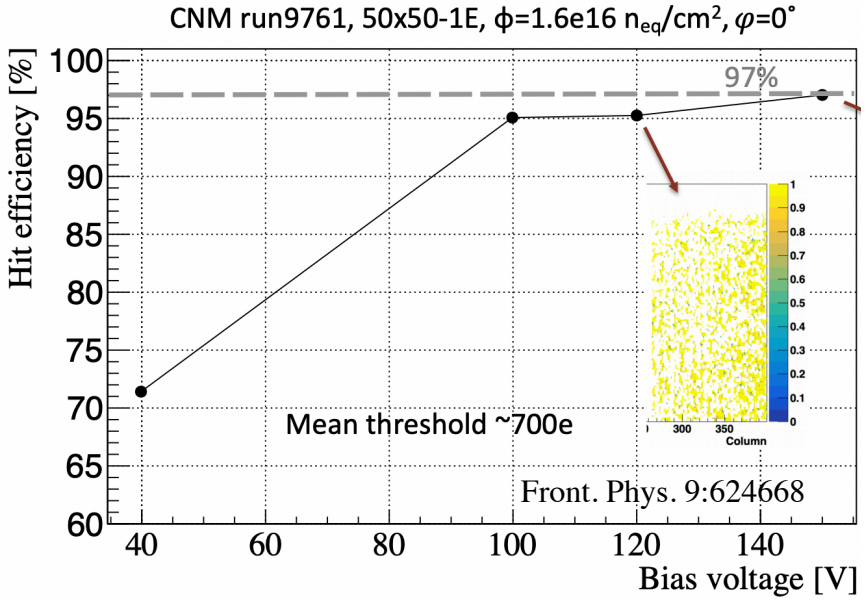

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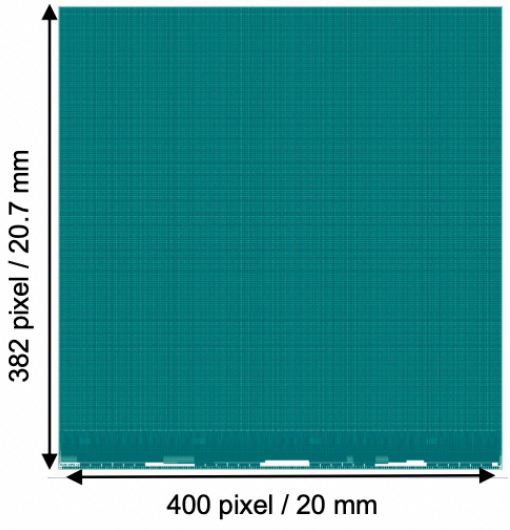
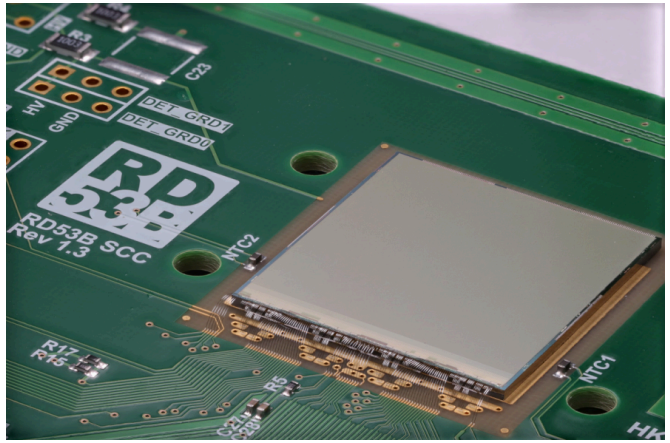
Pixel Front End

RD53 Collaboration shared between ATLAS and CMS R&D - a decade long development



New Front-end ASIC in 65 nm CMOS technology

- Final chip consists of one analog differential FE of 2x2 cm^2
- Low threshold ~600 e-
- Digital Readout with Time over Threshold (ToT)
- Design power 0.8 W/cm^2
- Radiation hard up to 1 GRad and single-event-upset hardened
- 4 data lines at 1.28 Gbps with data compression in output



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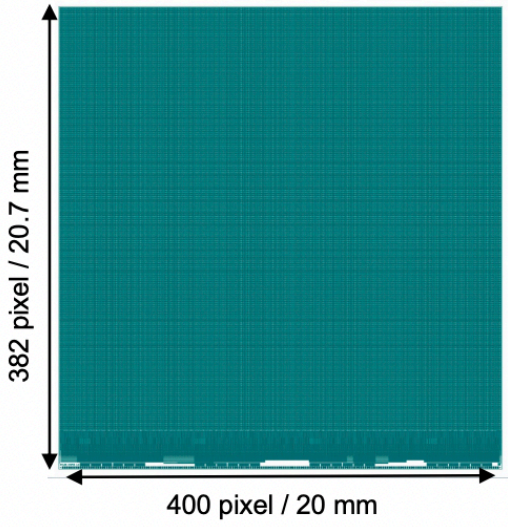

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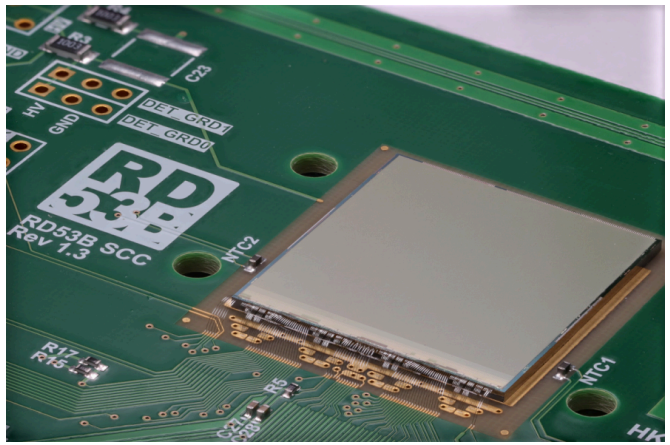

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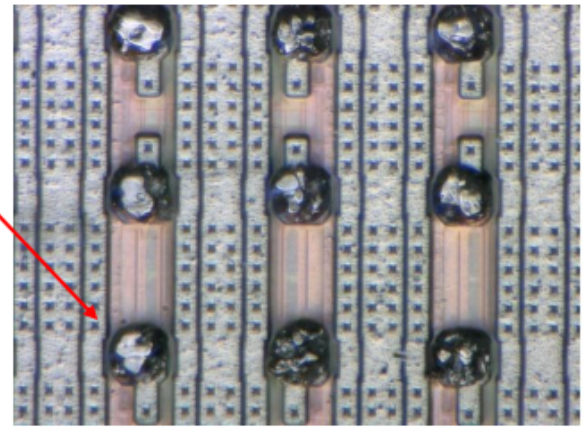


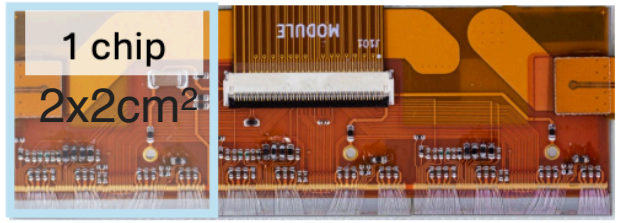
Bump deposition SnAg or In
Under Bump Metallization
Flip-chip
(IZM, HPK)

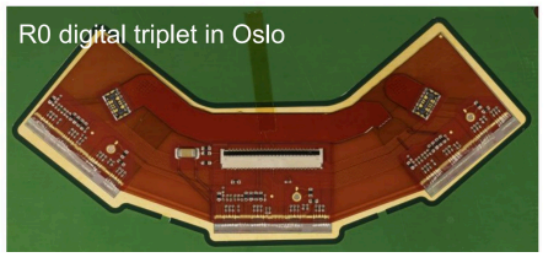
More in Charles's talk

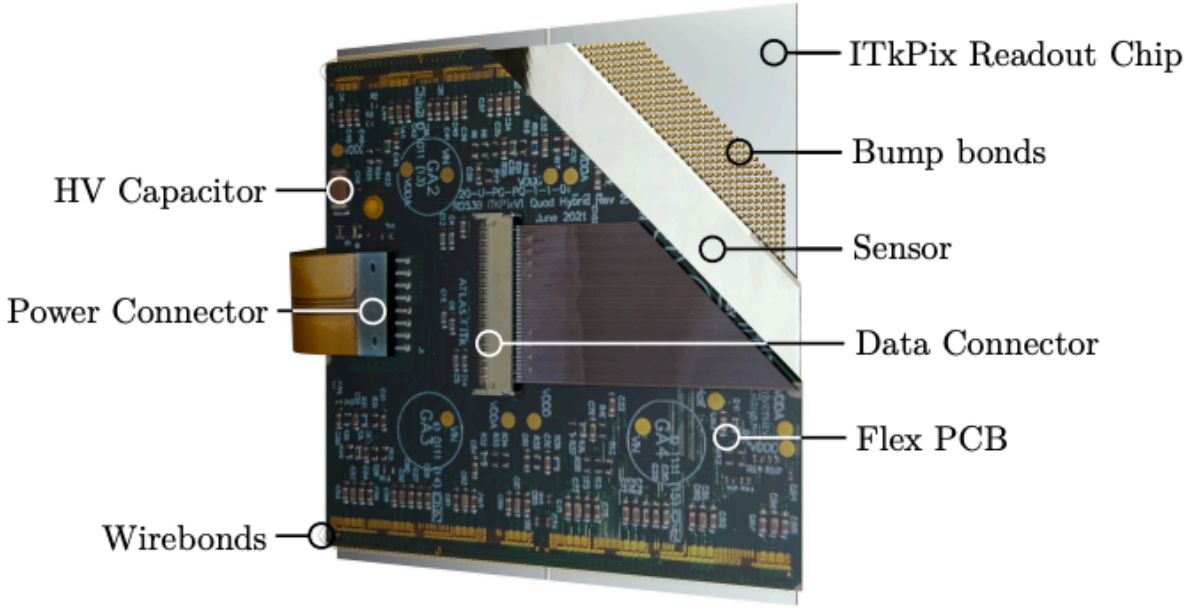
Pixel Modules

2412.04686

Module = Sensor + ASIC + flex circuit.





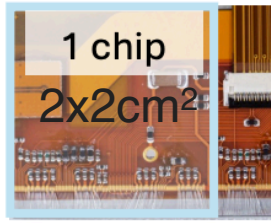


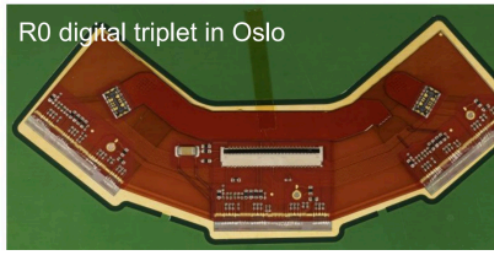
- Parylene protection deposition: reinforce bonds, avoid corrosion, prevent discharge between sensor and front-end.
- **Preproduction O(800) ITKPix-v.1 modules built**
  - Performance after radiation & thermal tests within specs for both 3D single and planar quad modules
- Production is starting NOW in 2025, ~9000 modules in 2 years in 20 assembly sites

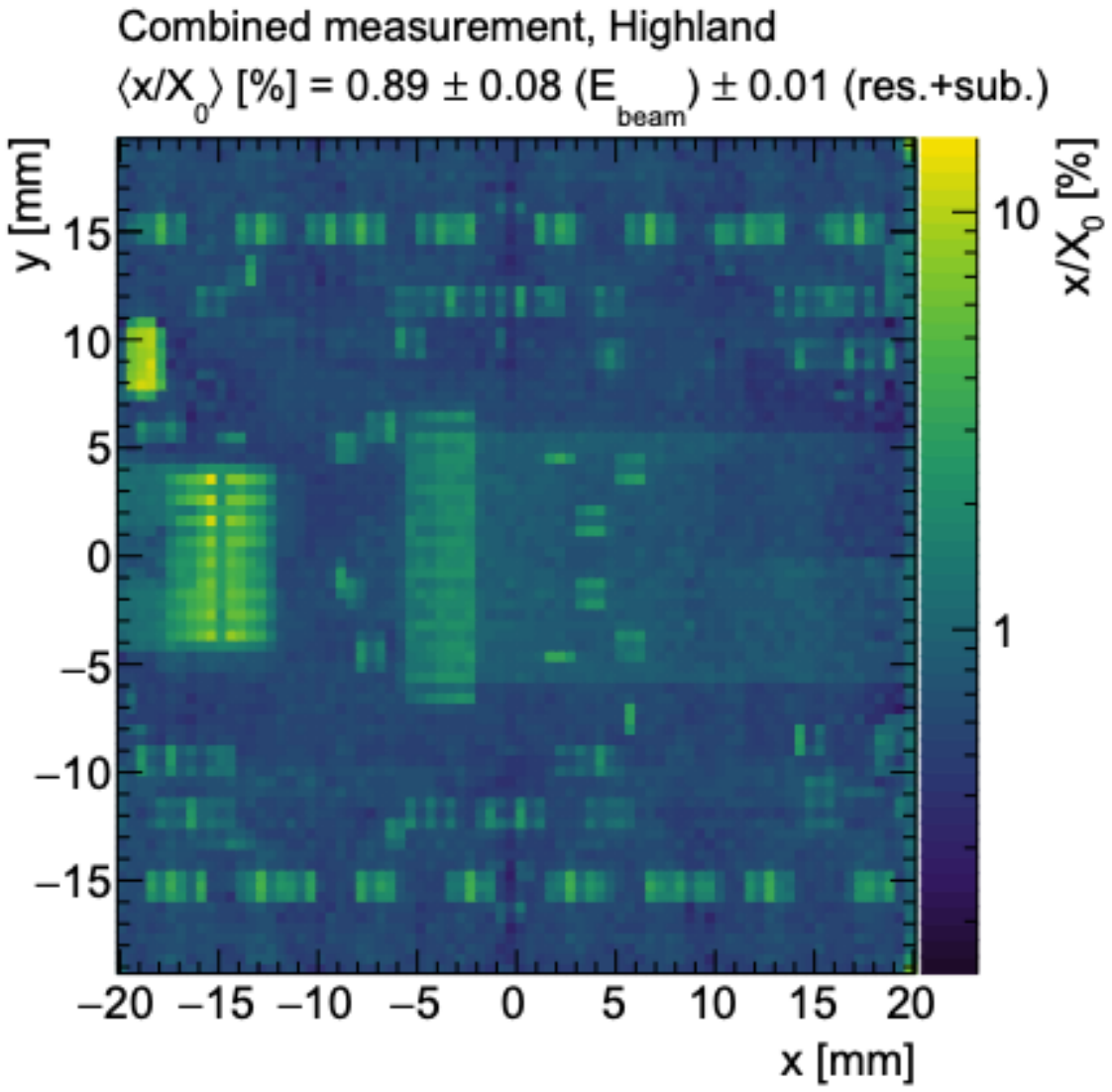
Pixel Modules

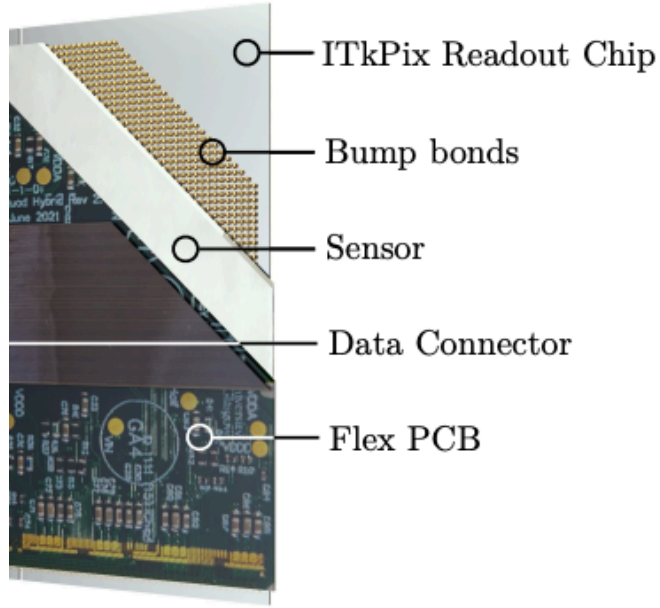
2412.04686

Module = Sensor +









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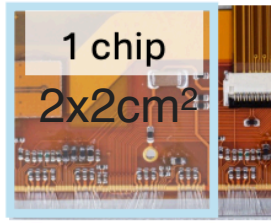

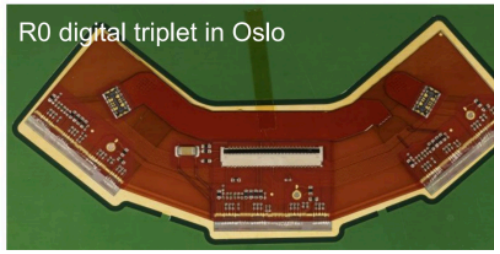

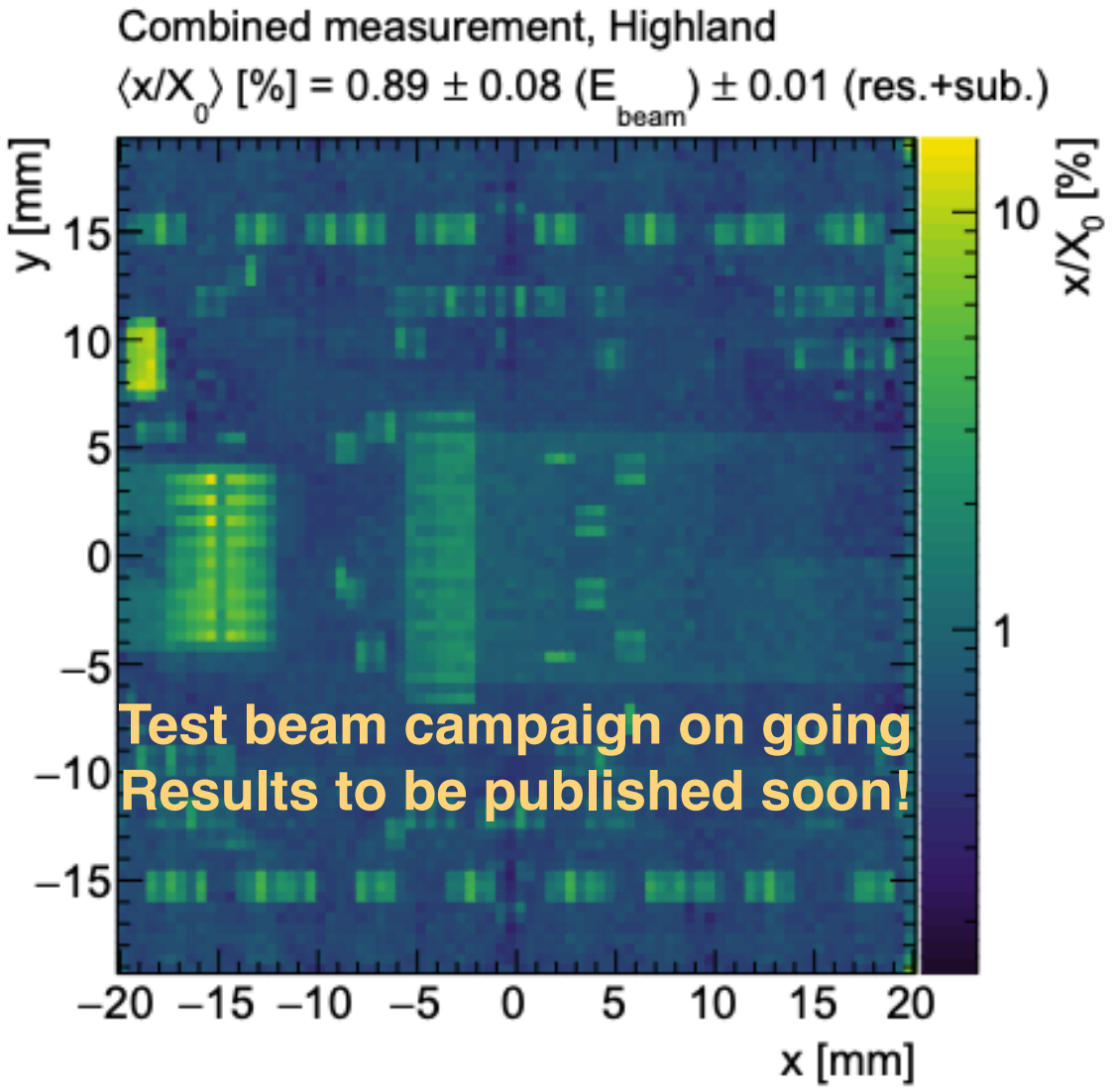

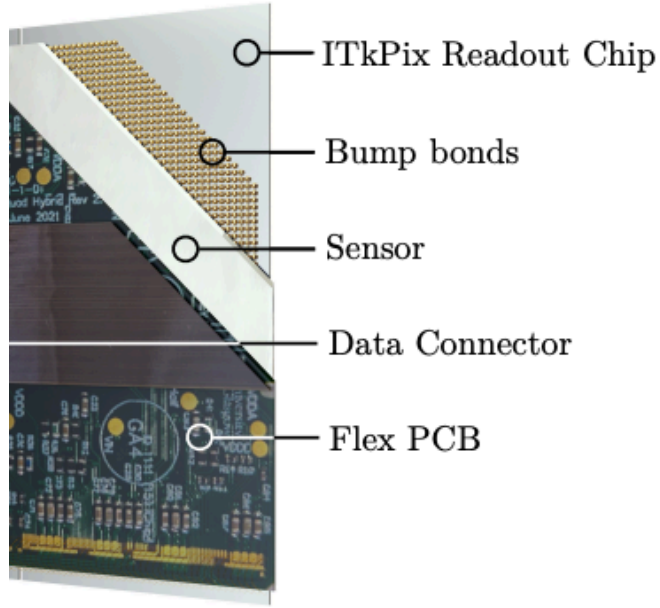

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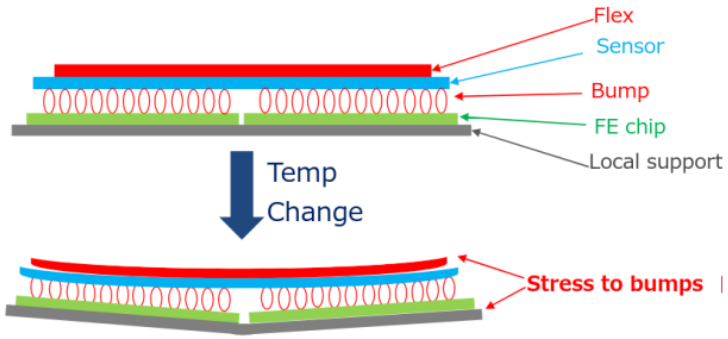
From design to construction

Design validated through extensive prototyping and mockups



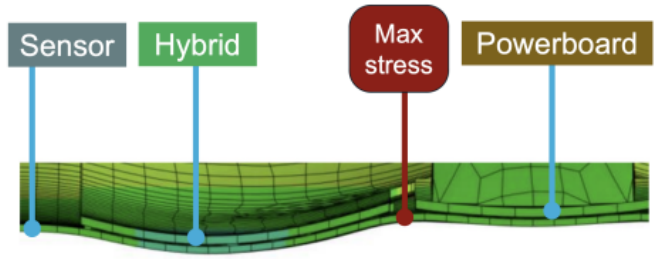
ATL-ITK-PROC-2024-018

Operating conditions:

- Temperature: –45 °C to +40 °C (–55 °C to +60 °C failure margins)
- 10 years lifetime are ~equivalent to 100 thermal cycles
- Radiation: **up to** 1 GRad (varies with the detector radius)

Mechanical & Interface Considerations

- Test parts of the assembly for CTE mismatch to prevent stress-induced failures
- Critical interfaces: **module bump bonds**, adhesives, electrical services
- Electrical services routed on local supports and half shells

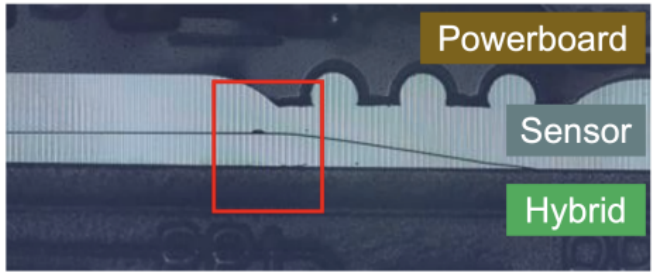


Readiness Approach

Design Validation (QA) to detects weaknesses in design

- Prototypes qualified to limits; some stressed to failure to define margins

- Production Readiness (QC) to identify defects in production



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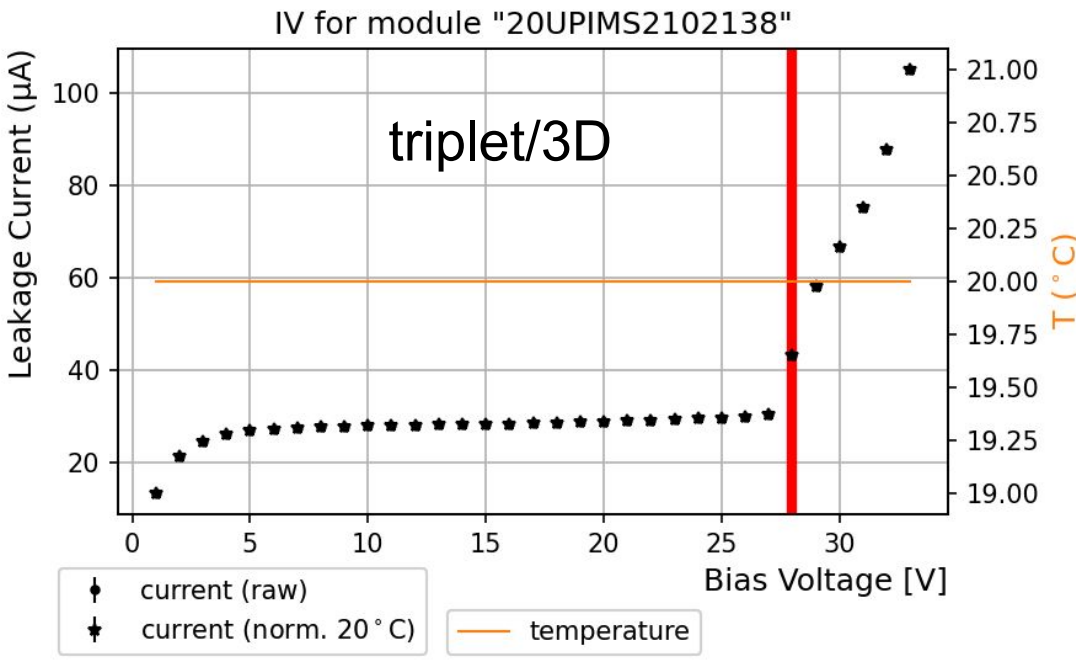
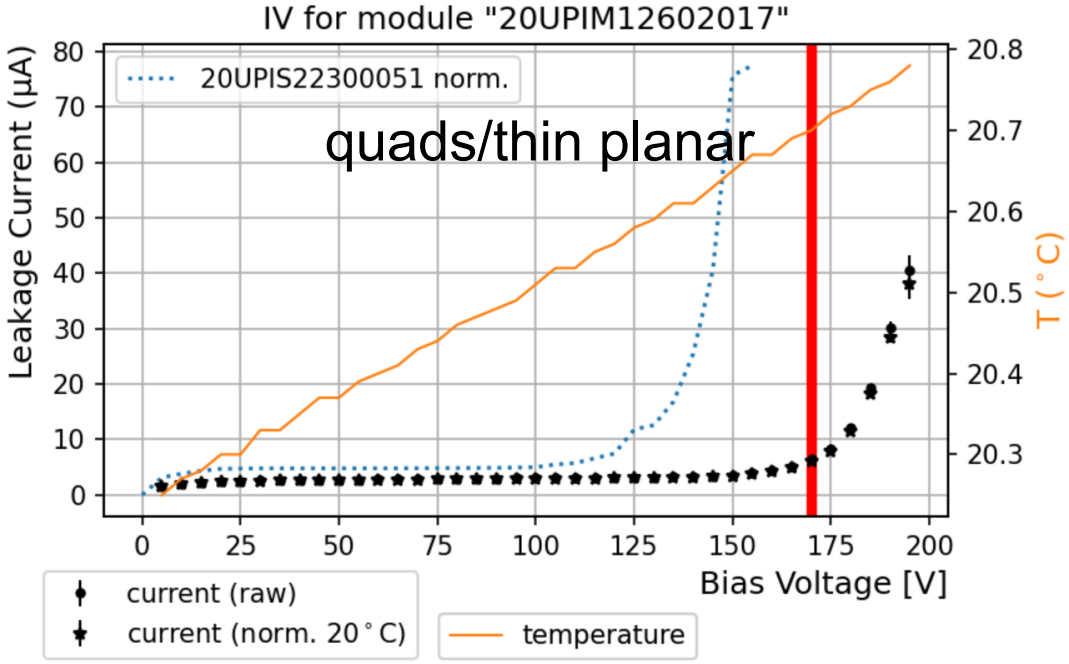
Module testing

Several QC steps at 20C and -10C to probe modules viability for loading





Module QC include: Visual inspection, sensor I–V scan, digital/analog/threshold/ToT/disconnected bump bond tests

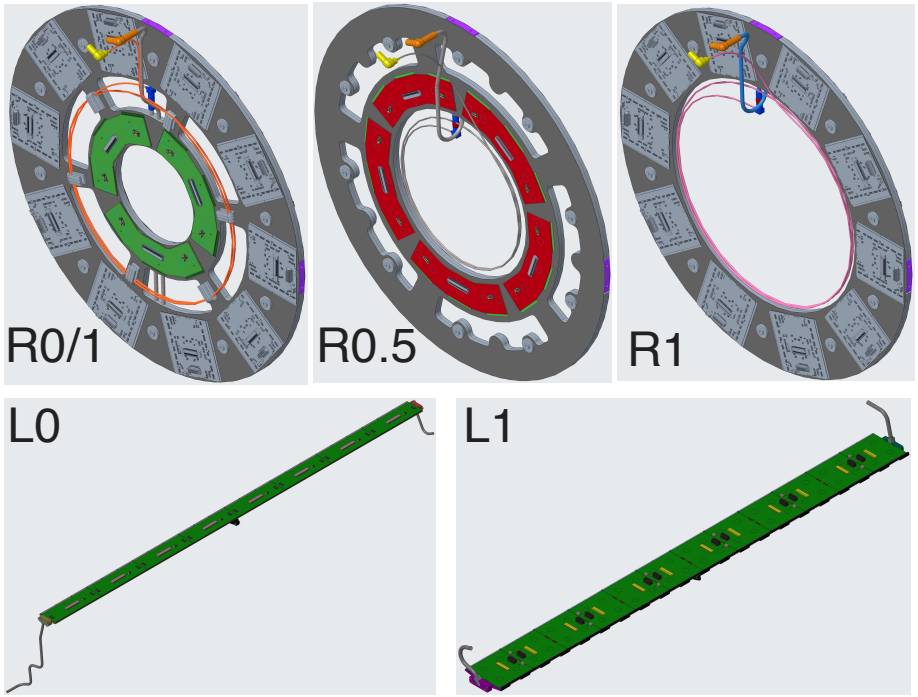
More in Lingxin's and Matias's talks

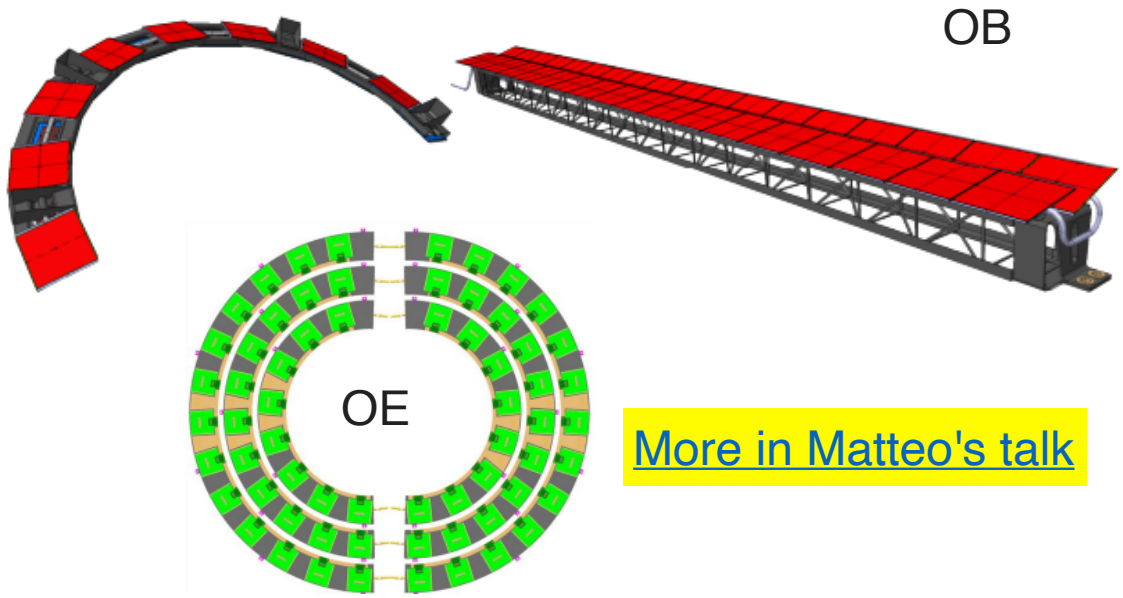
Pixel Local Supports

Local support prototypes using carbon fibre and carbon foam to minimize mass and maximize thermal performance

Different geometries optimized for the various layers and region of the pixel detectors:

- **Inner system** : two layers of staves and double-sided rings in the endcaps
- **Outer Barrel** : three layers of longeron and inclined rings
- **Outer Endcap** : three layers of endcap rings





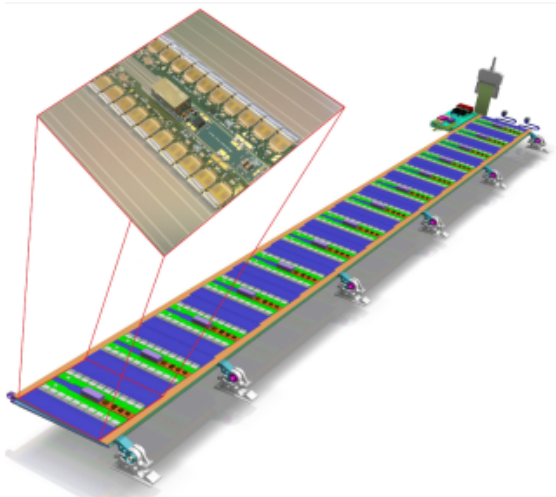
[More in Matteo's talk]

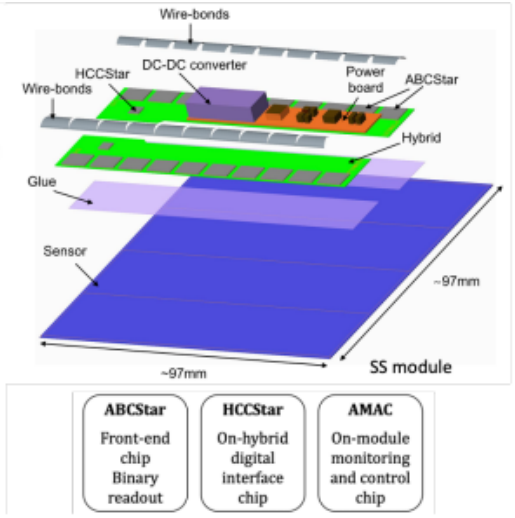
Titanium Cooling Tubes embedded into the CF foam

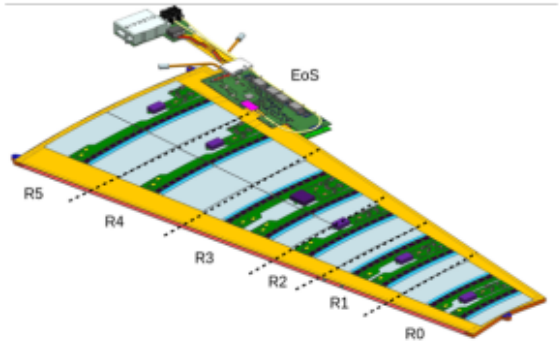
Strip Assembly

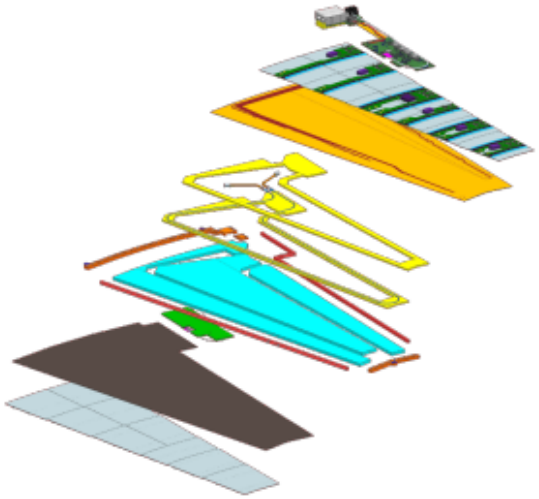
Module = sensor + ASIC + power board

- AC-coupled, **n-in-p** silicon sensors, more radiation resistant than p-in-n up to 10^{15} n_{eq}/cm^2
- 75.5μm pitch, 320 µm thick and >300V depletion voltage
- Barrel modules:
  - Two ~ 9.7 cm x 9.7 cm sensor geometries: short strip (SS) for the inner and long strip (SS) for the outer layers
  - 14 modules per side per stave
- Endcap modules:
  - 6 sensor geometries depending on radial distance from center.







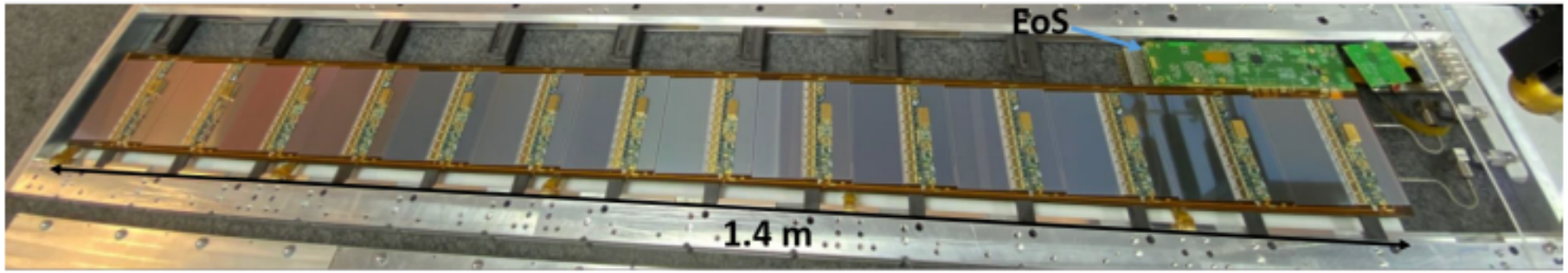


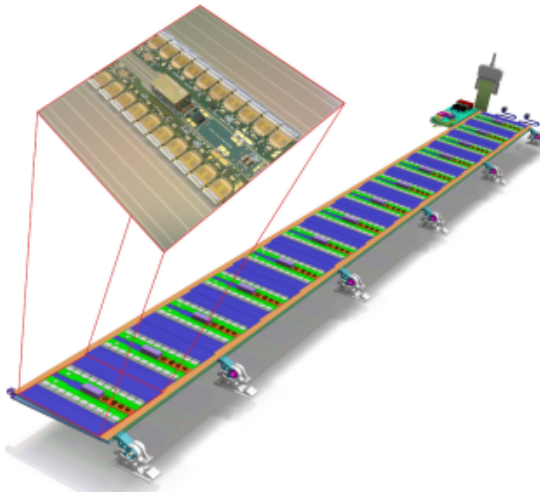
[ATL-ITK-PROC-2024-016]

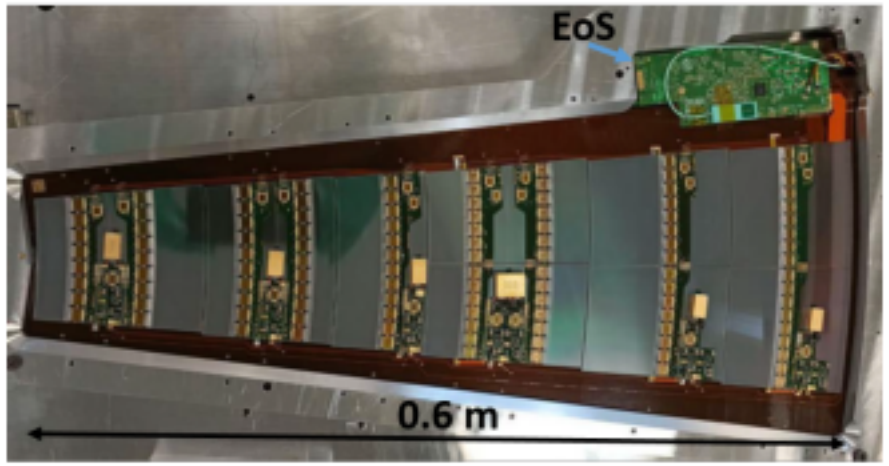
Strip Assembly

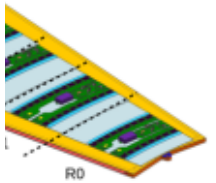
Module =

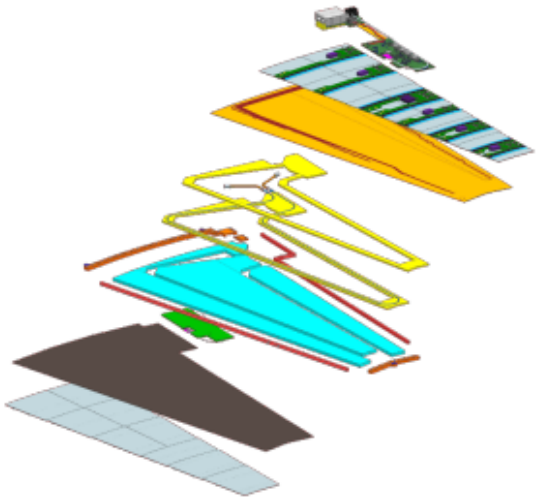
- AC-coup
- 75.5μm p
- Barrel m
  - Two
  - 14 n
- Endcap modules:
  - 6 sensor geometries depe





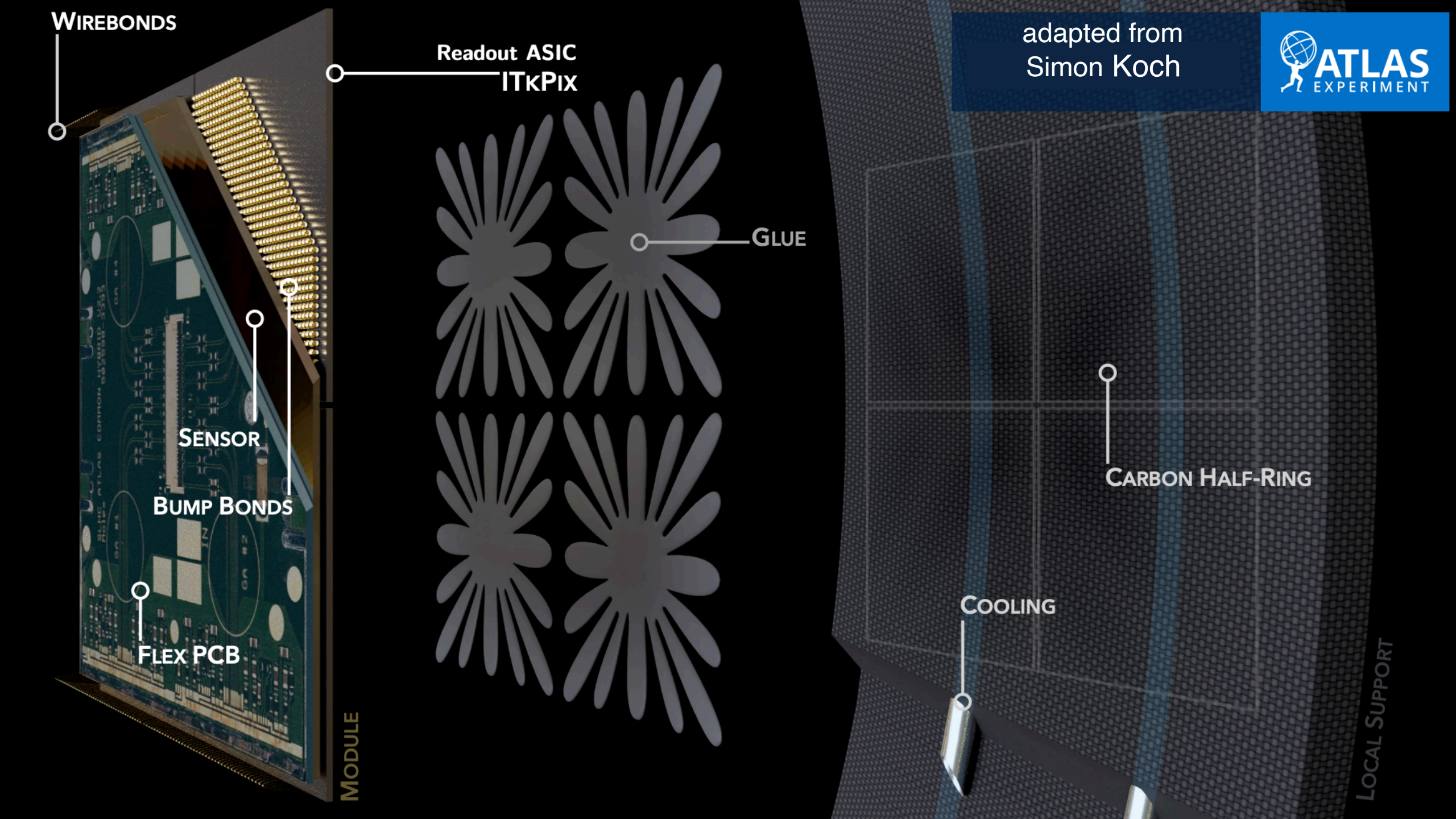


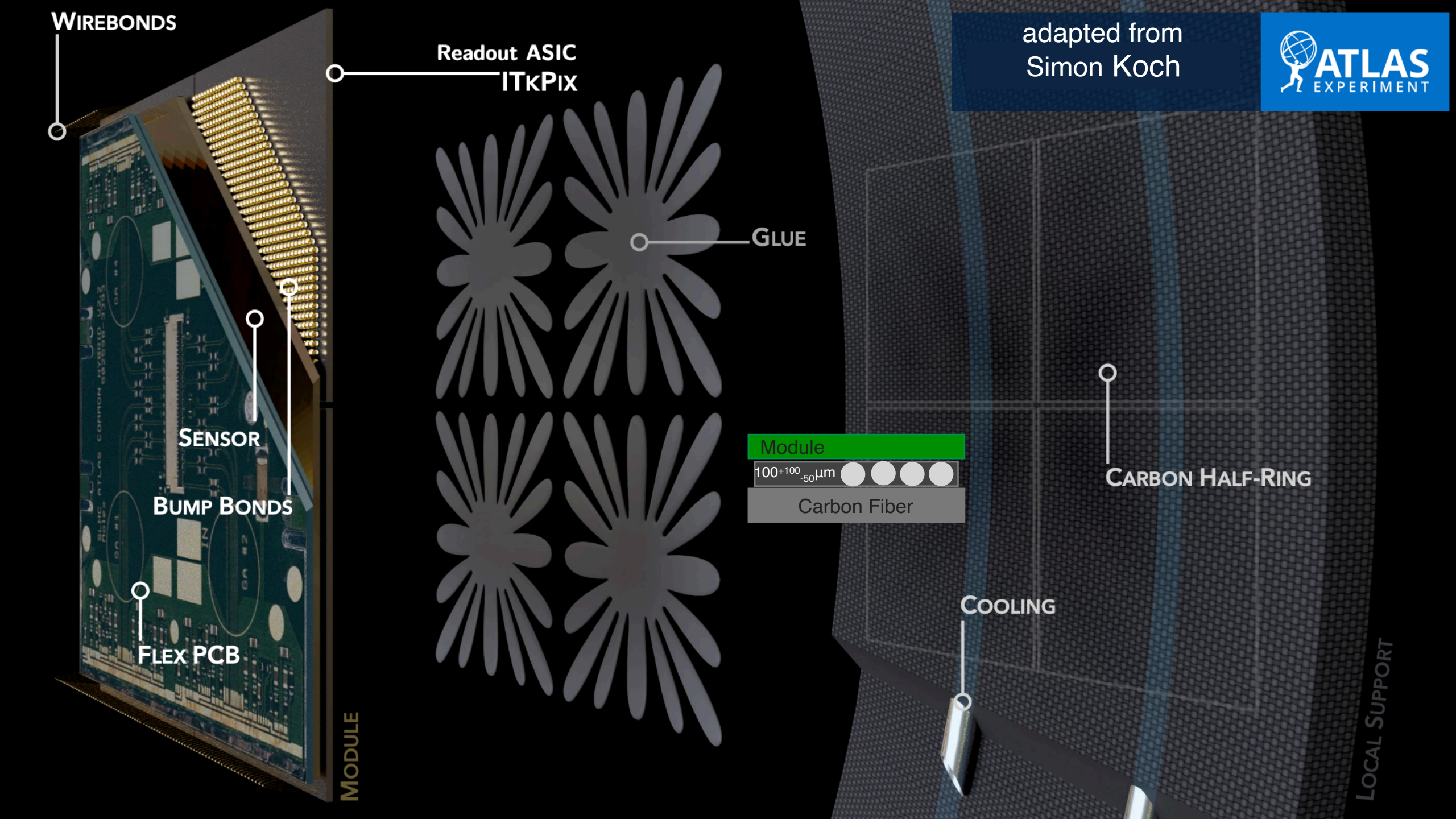




ATL-ITK-PROC-2024-016

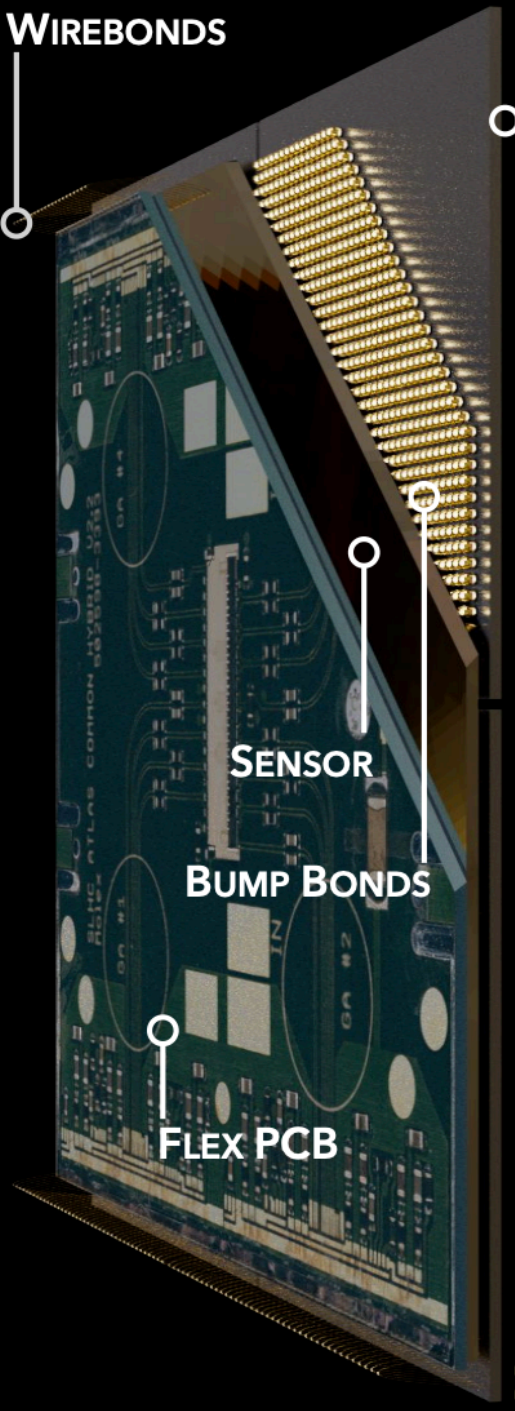
About 90% sensors received, 85% tested are viable for loading

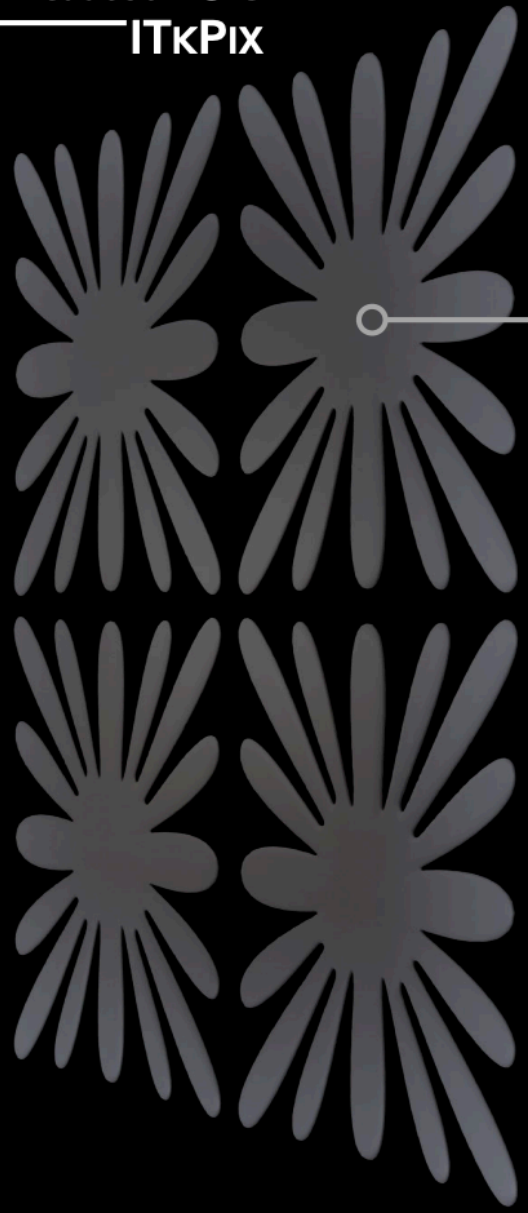

WIREBONDS
Readout ASIC
ITKPIX
GLUE
SENSOR
BUMP BONDS
FLEX PCB
MODULE
CARBON HALF-RING
COOLING
LOCAL SUPPORT
adapted from
Simon Koch
ATLAS
EXPERIMENT

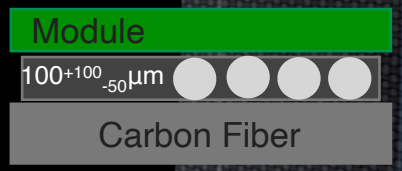

Wirebonds
Readout ASIC
ITkPix
Glue
Sensor
Bump Bonds
Flex PCB
Module
Module
100+100-50µm
Carbon Fiber
Carbon Half-Ring
Cooling
Local Support
adapted from
Simon Koch
ATLAS
EXPERIMENT

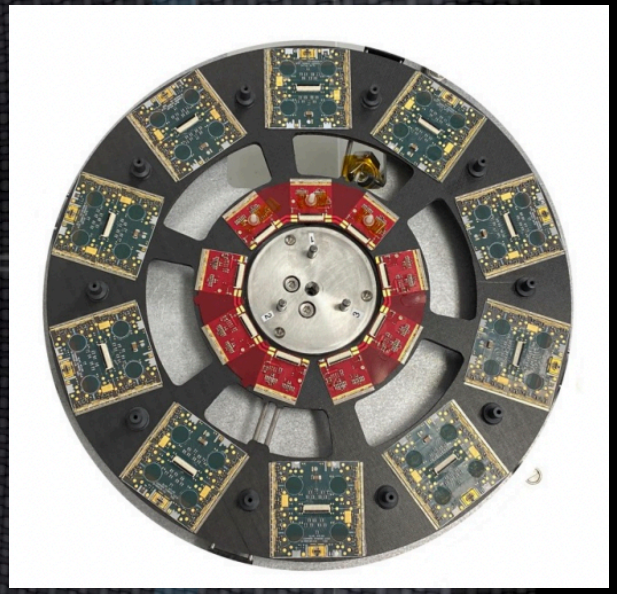
adapted from
Simon Koch

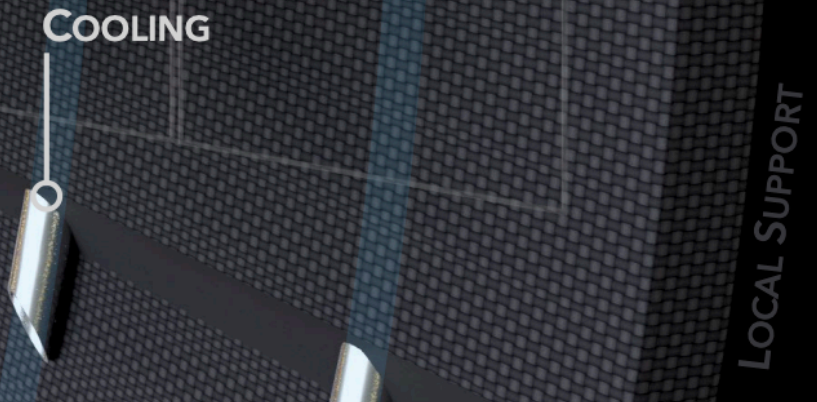
ATLAS EXPERIMENT





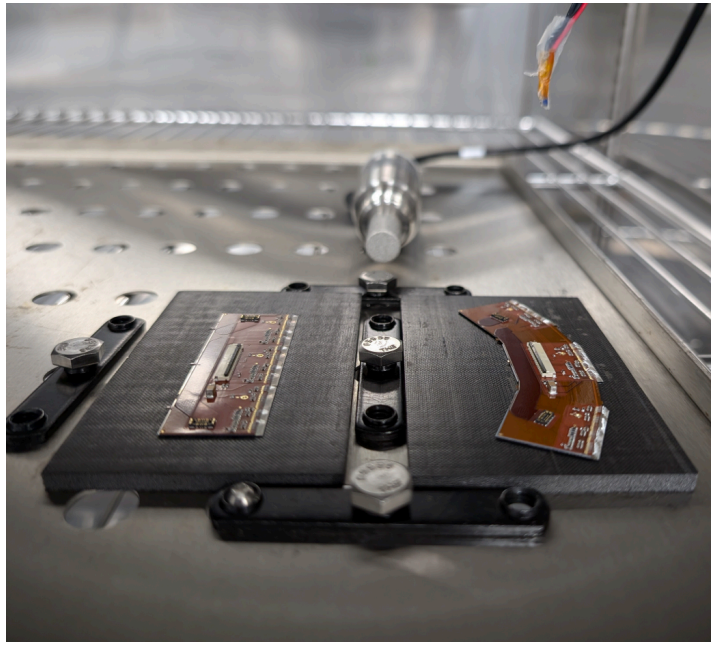


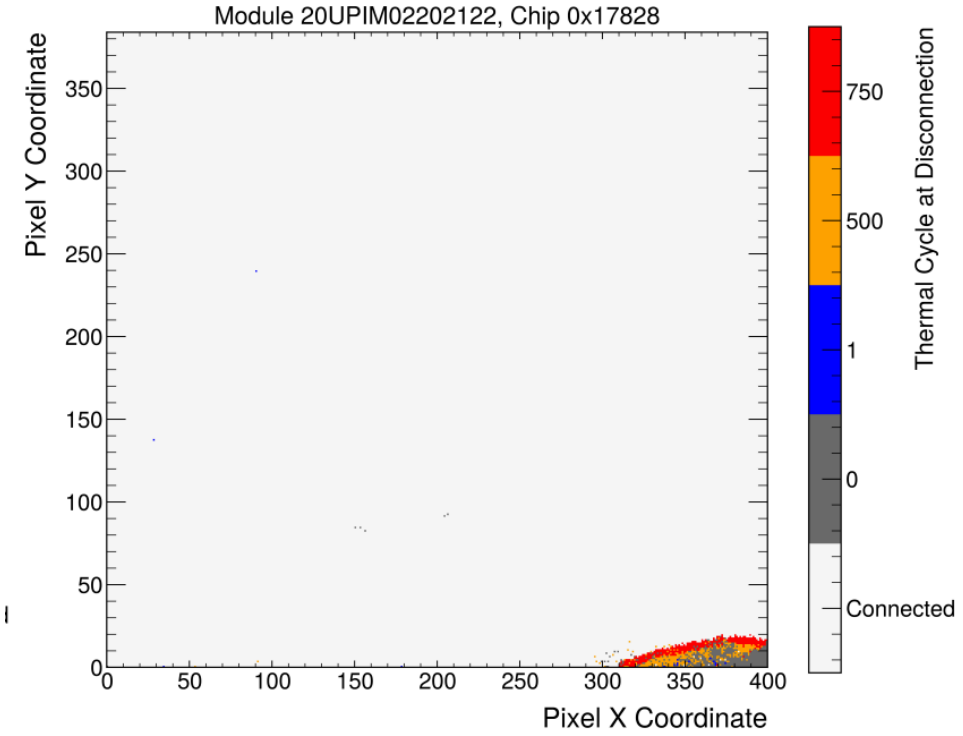




Pixel - The Glue(s)

- Both IS and Outer Endcap will use SE4445
  - a two part silicone based encapsulant gel
  - qualified up to 15 MGy with dedicated radiation testing campaigns (***pre-print in preparation***)
- The Outer Barrel uses Stycast (more rigid)
- Delamination studies have been performed to validate the glue doesn't add stress on the bump bonds
  - Modules glued onto a CF sample and thermal cycled between -55+60C for ~750 cycles





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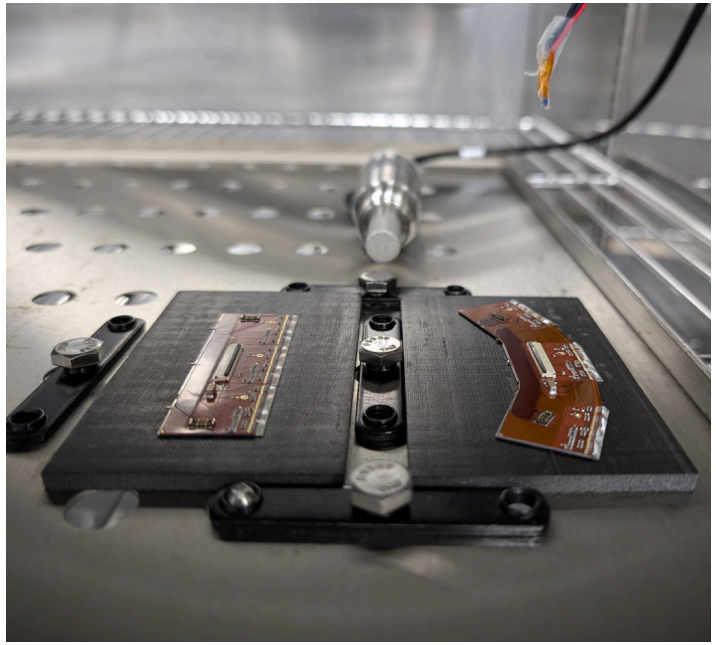
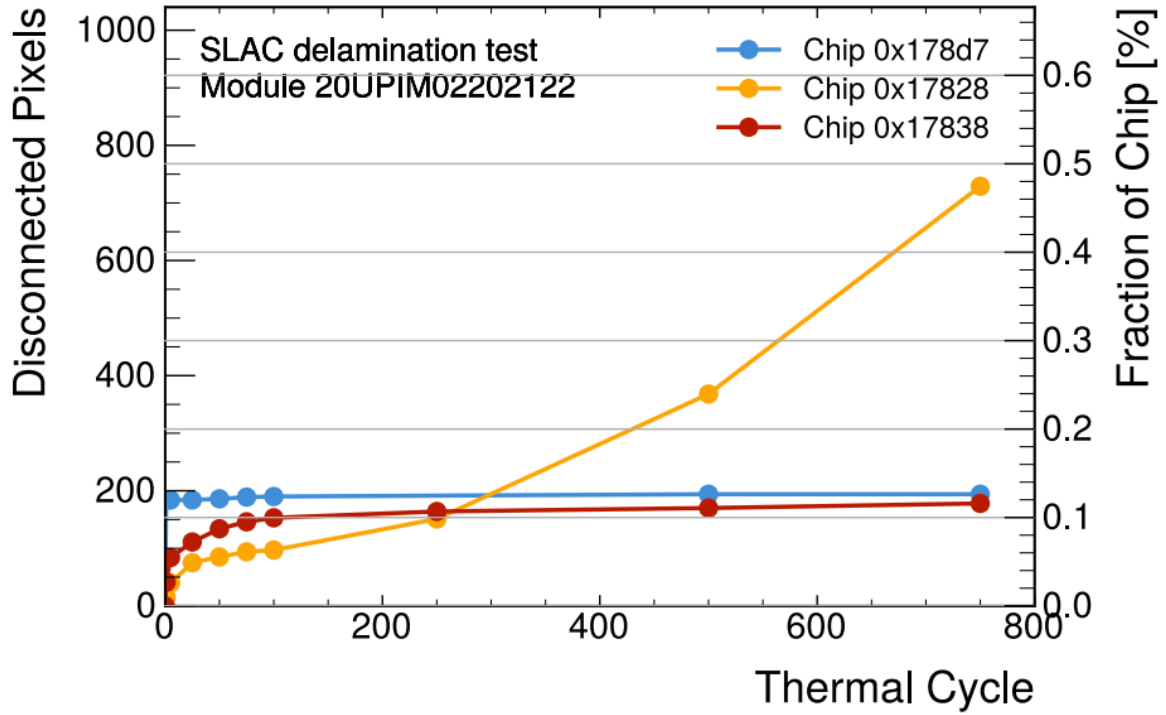
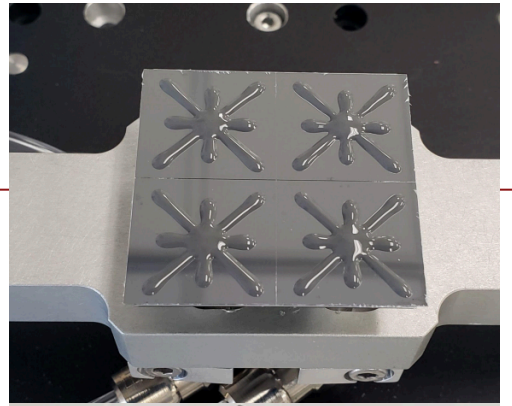


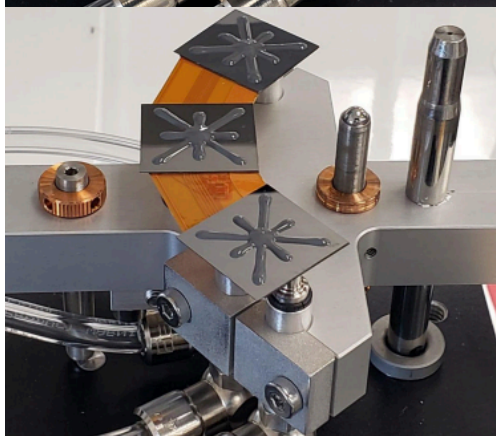


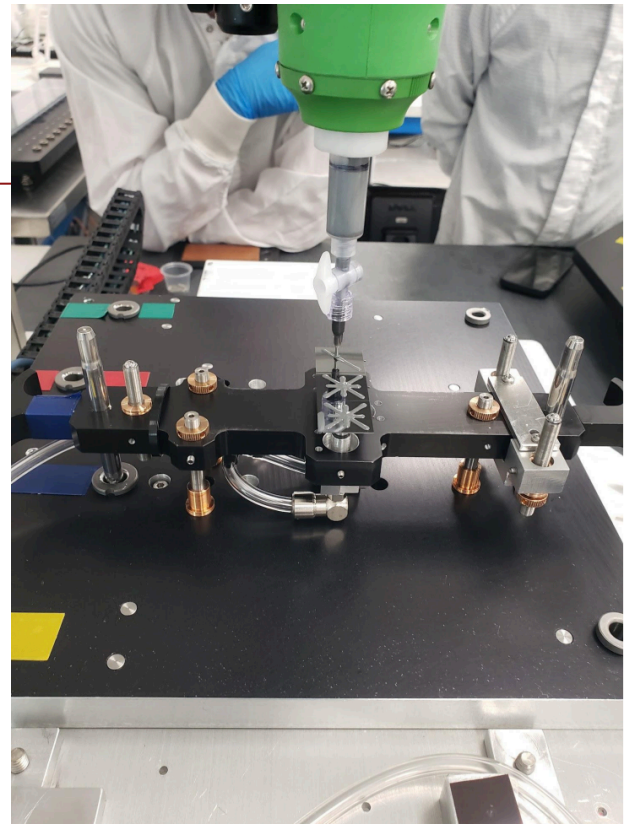
Pixel - Loading process

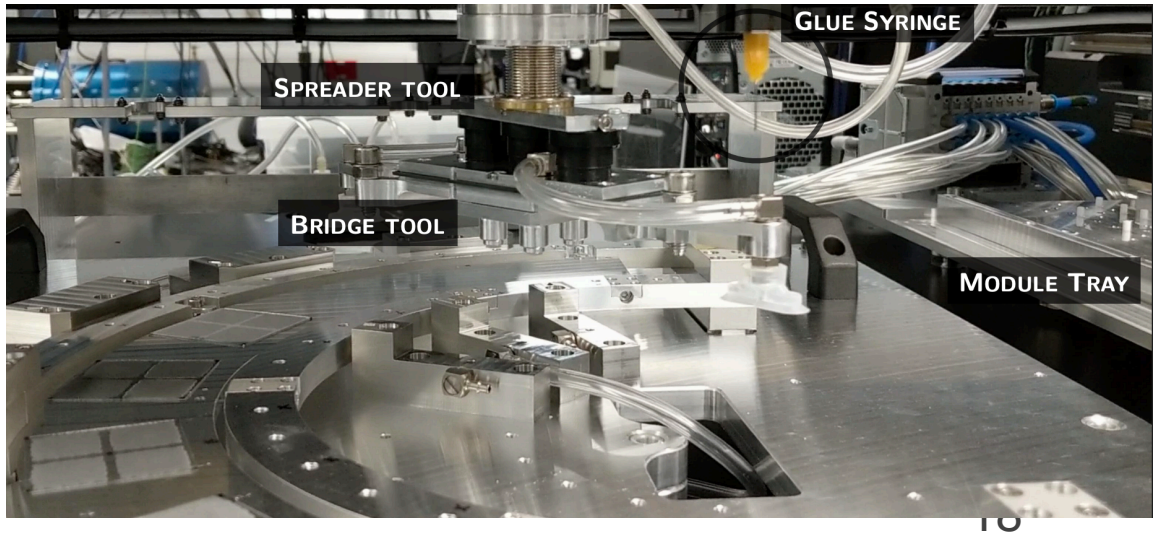
Gluing modules into the local supports

- Star pattern chosen to achieve good coverage without leaving trapped air
- Thickness & coverage of the adhesive optimized to ensure good thermal conductivity
  - 100^{+100}_{-50}µm thickness
  - 70-90% coverage
- Using 105 mg per deposition with a volumetric dispenser
- Primary bond line controlled by 106 μm beads (1% by mass in glue)









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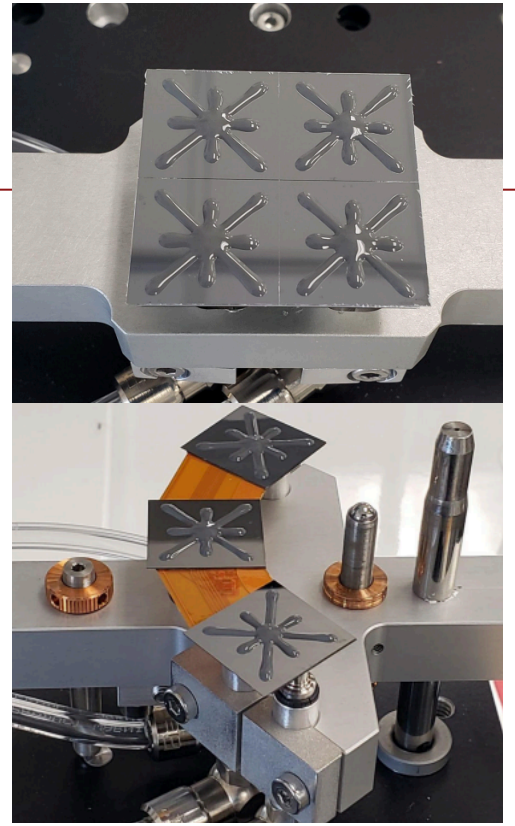
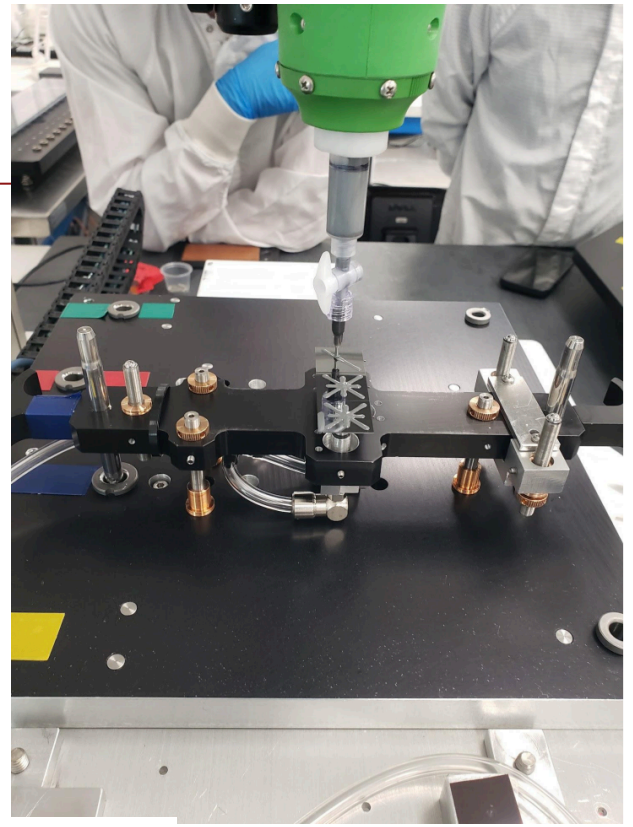
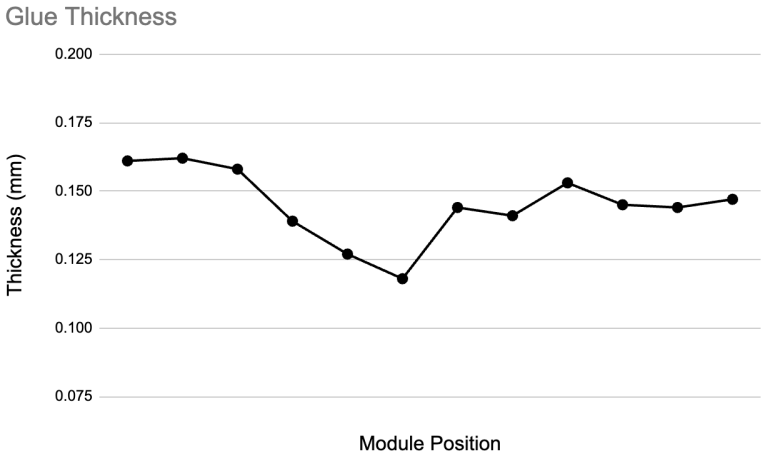
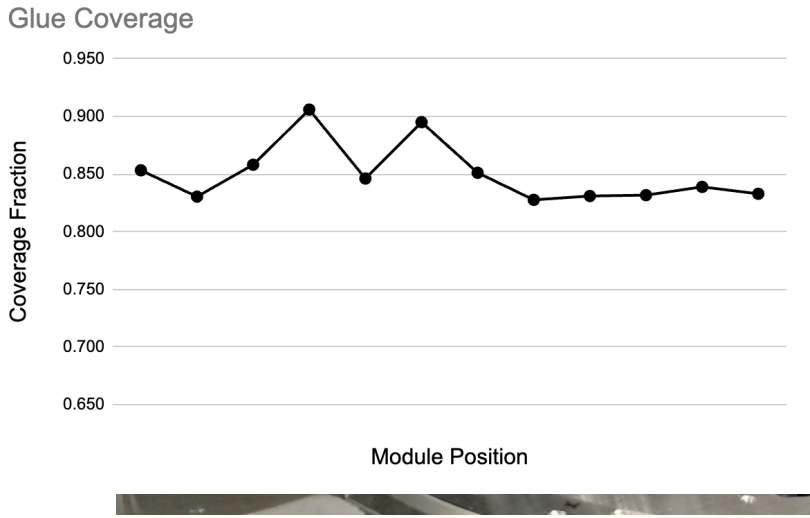
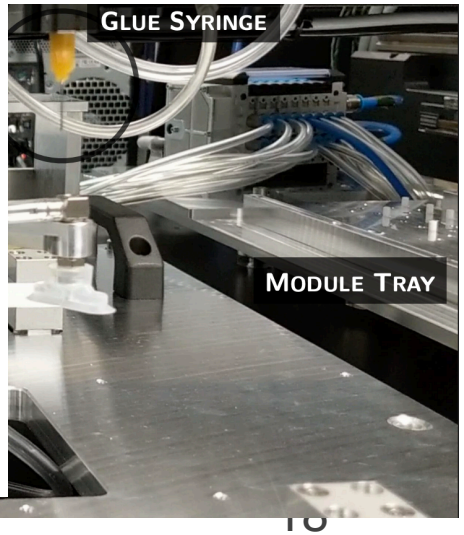


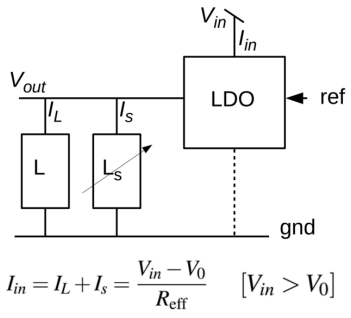




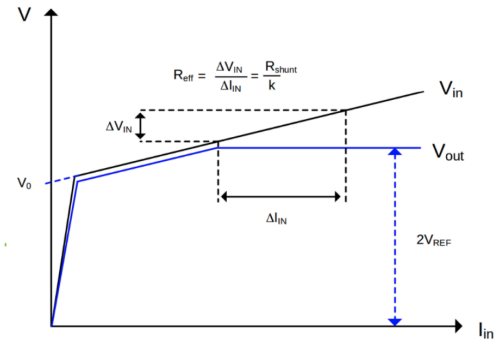


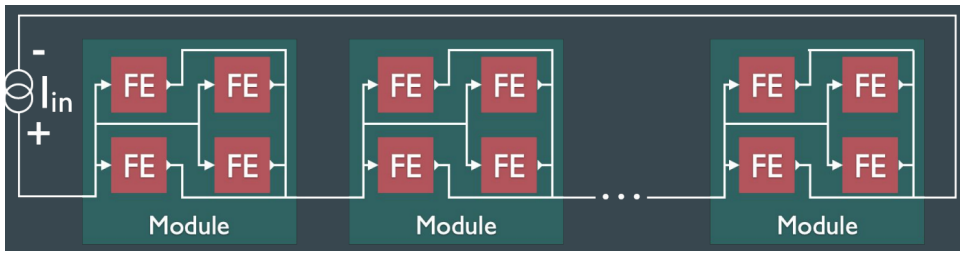


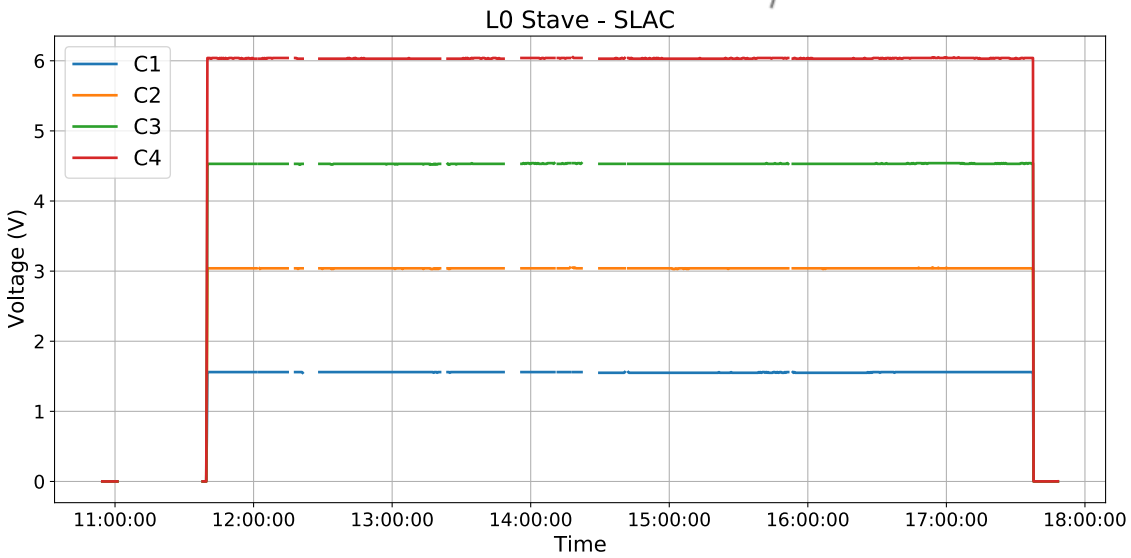
Pixel - Serial powering



$$I_{in} = I_L + I_s = \frac{V_{in} - V_0}{R_{eff}} \quad [V_{in} > V_0]$$



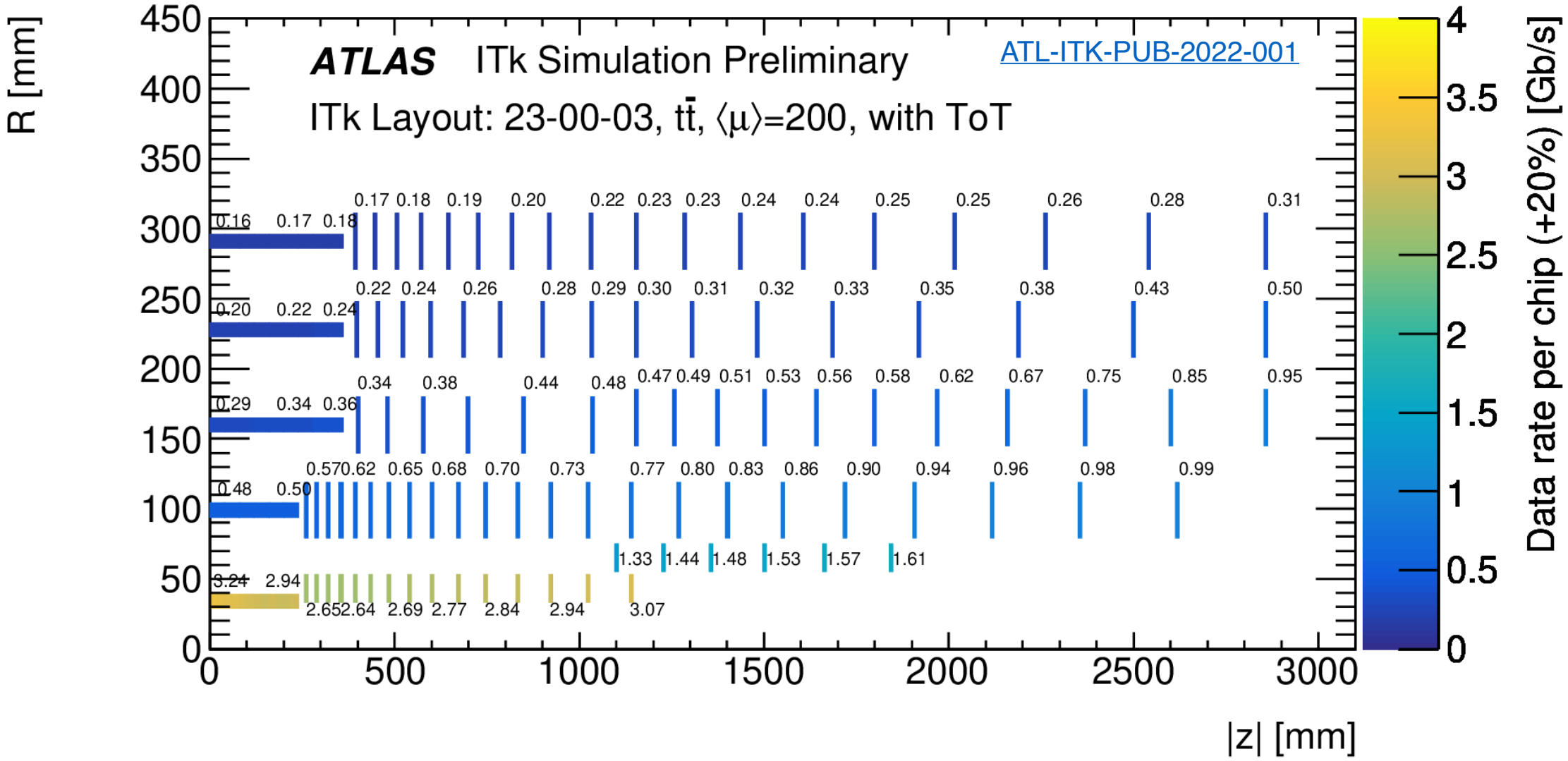




- Modules are powered in series to reduce material budget: the number of supply lines is greatly reduced
- Each ITkPix chip has a radiation-hard Shunt Low Drop Output (SLDO) power regulator
  - It takes a constant input current and dynamically adjust their shunt current to maintain stable on-chip voltages.
  - Within a module, chips are powered in parallel to ensure local voltage regulation on each chip and improves chain robustness
- The ITk will use O(1000 serial) powering chains, each driving up to 14 quad and 5 triplet modules.

Pixel - Data transmission scheme

Link sharing on all layers to reduce material



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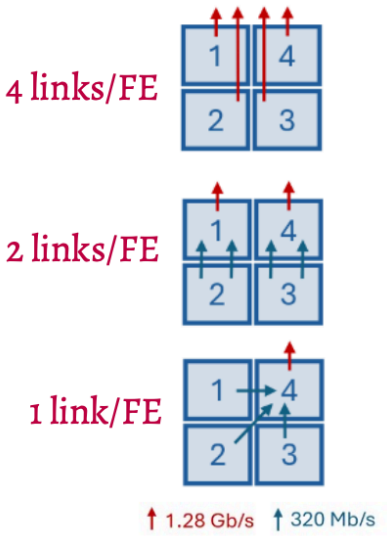
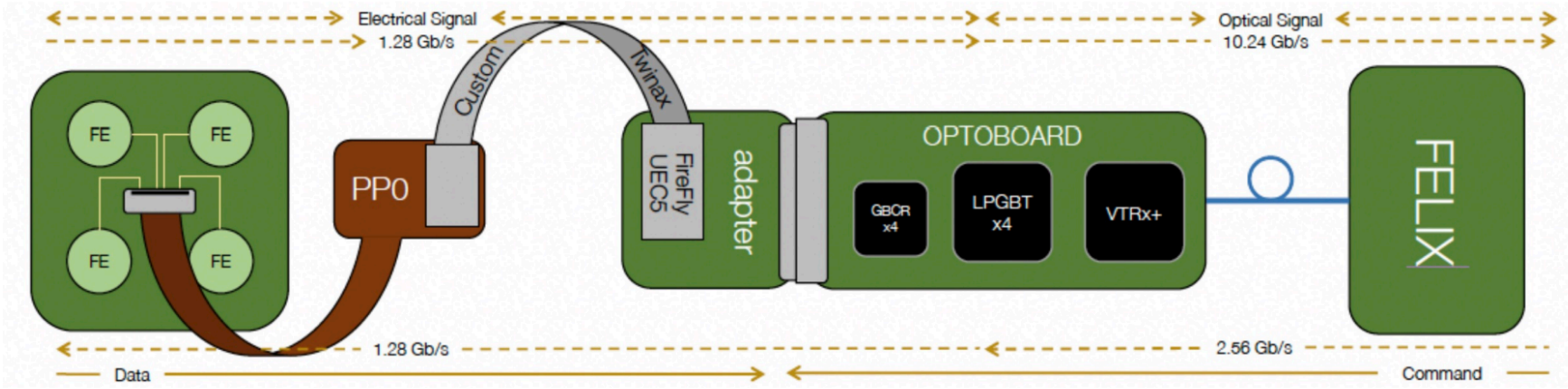
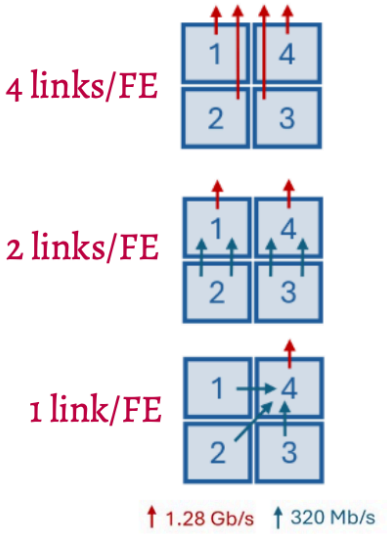


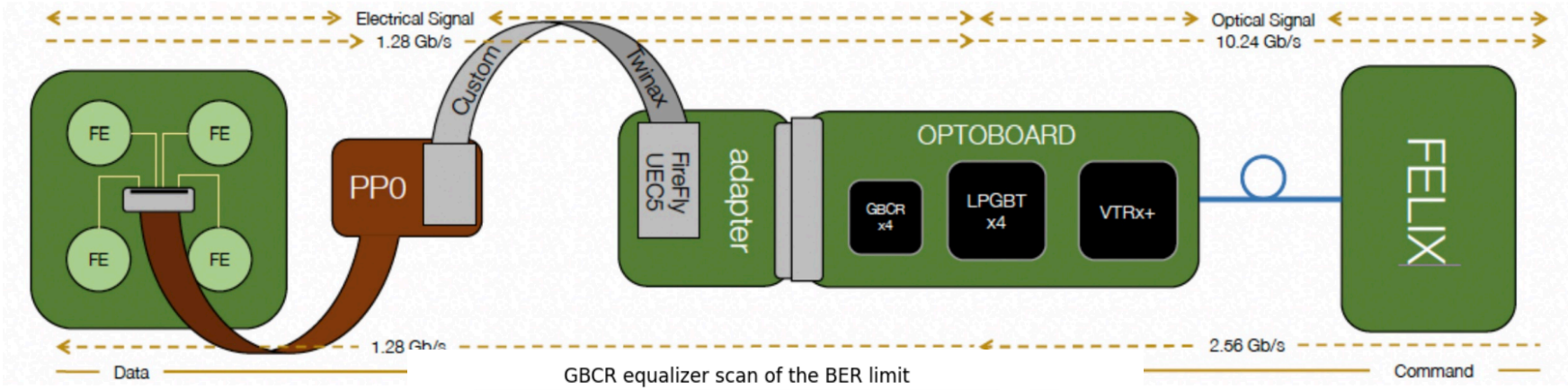


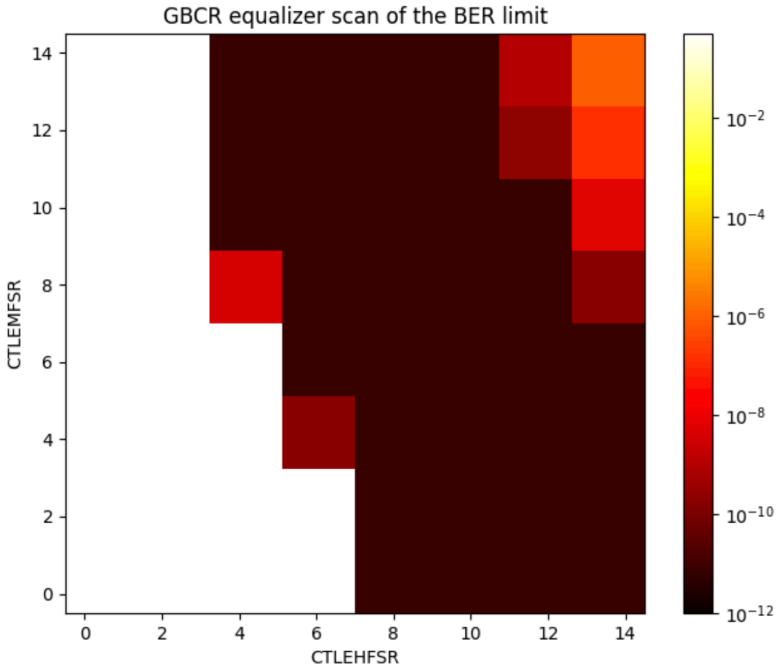
- Module: 1–4 FE links → consolidated into 1–3 × 1.28 Gb/s outputs.
- lpGBT/GBCR: up to 6 module inputs → multiplexed onto 1 × 10.24 Gb/s fiber.
- CMD: 1 × 2.56 Gb/s link per lpGBT/GBCR → fanout to 1–6 modules.
- **Transmission**: custom 34 AWG twinax (≤6 m) with polyethylene dielectric for rad-hard + signal quality
  <20 dB loss @ 640 MHz (FE → GBCR).
- Aggregation + electro-optical conversion: lpGBTx + VTRx+, with recovery at GBCR for equalization

Pixel - Data transmission scheme

Link sharing on all layers to reduce material







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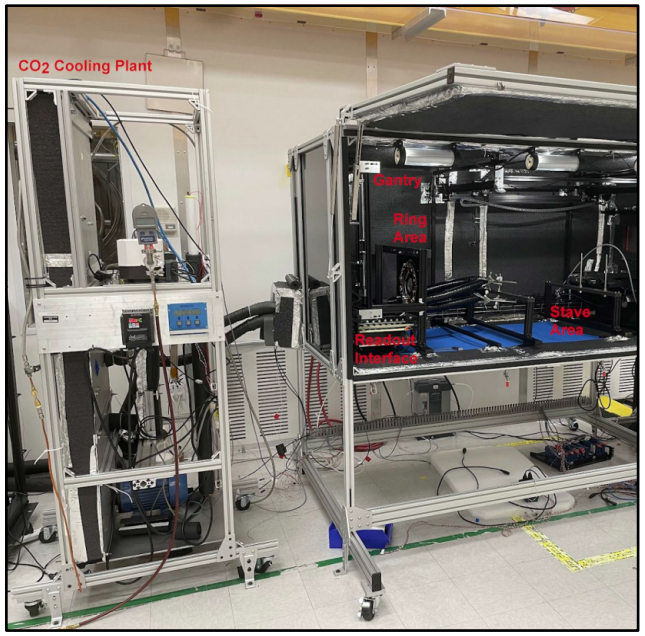
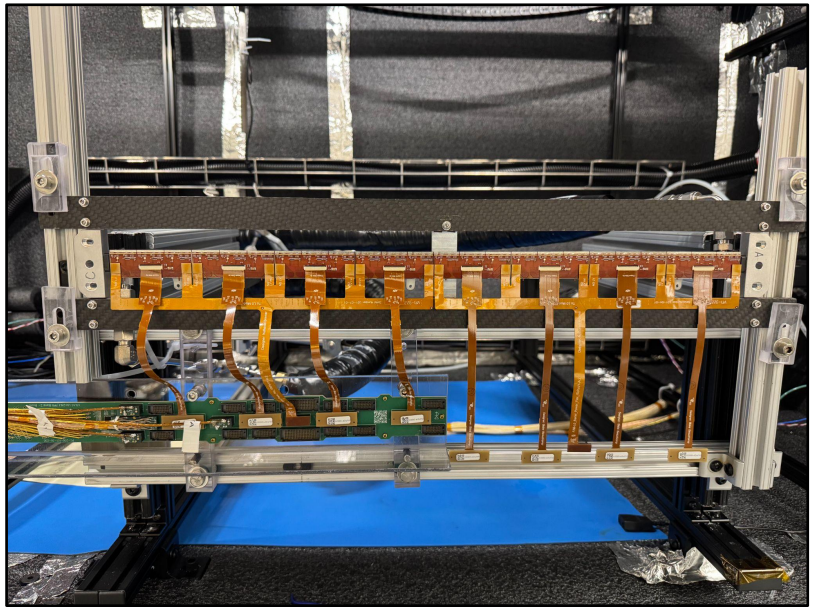
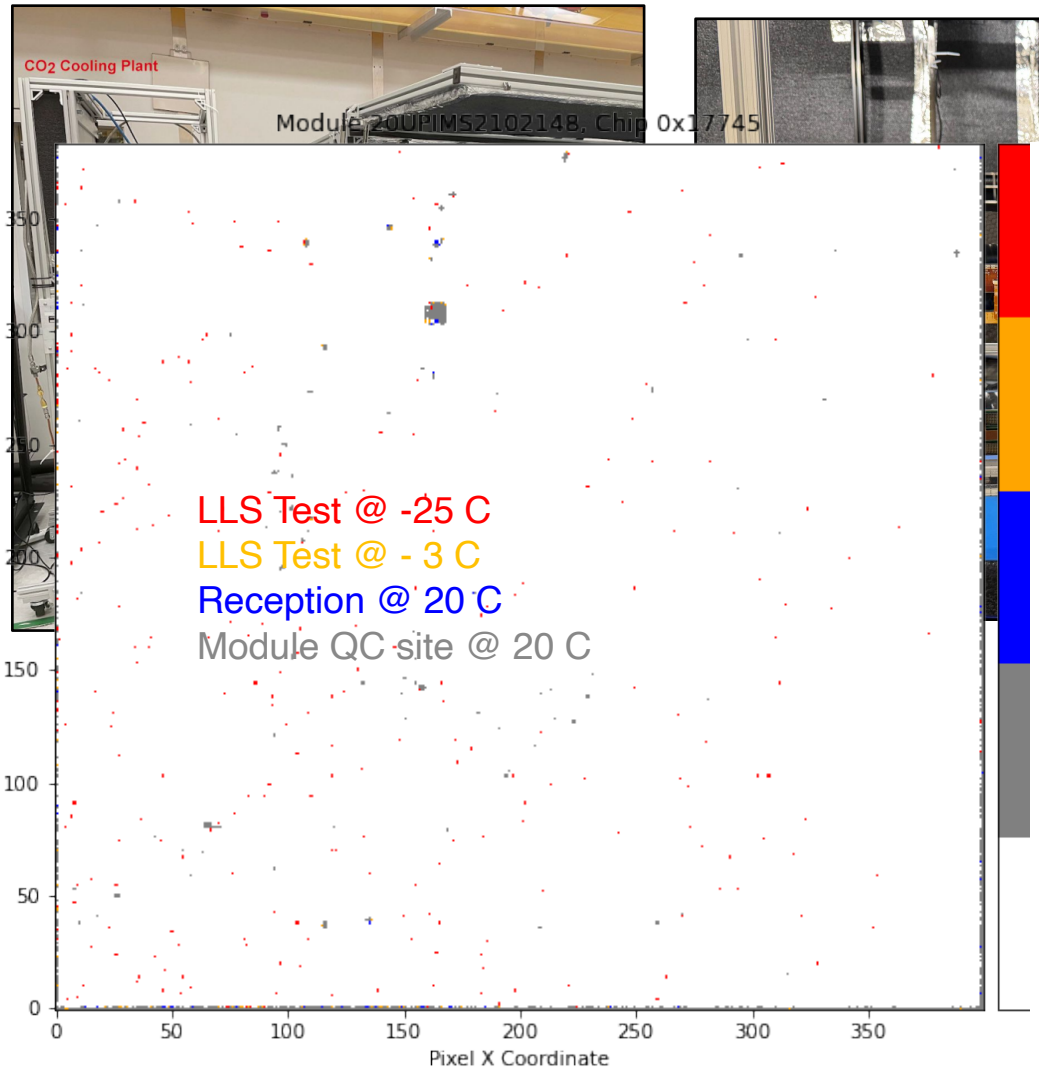
System Tests - full chain services demonstration

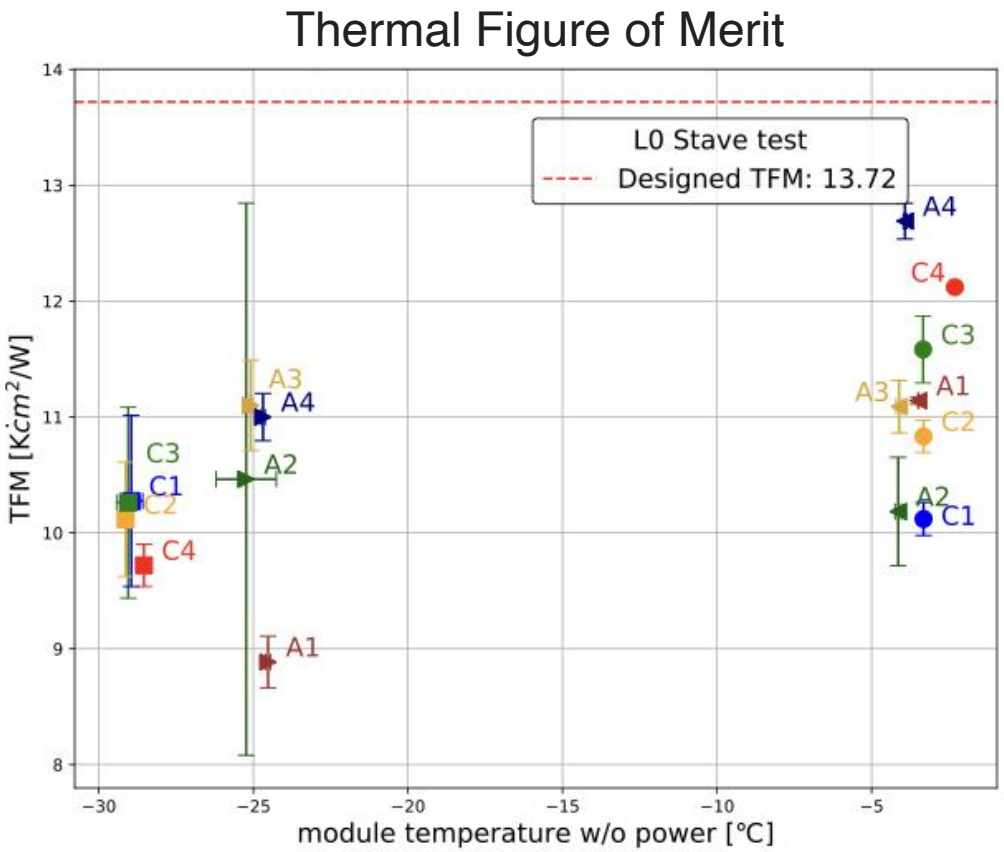




IS full validation of services chain with pre-production parts

System Tests - full chain services demonstration





chain

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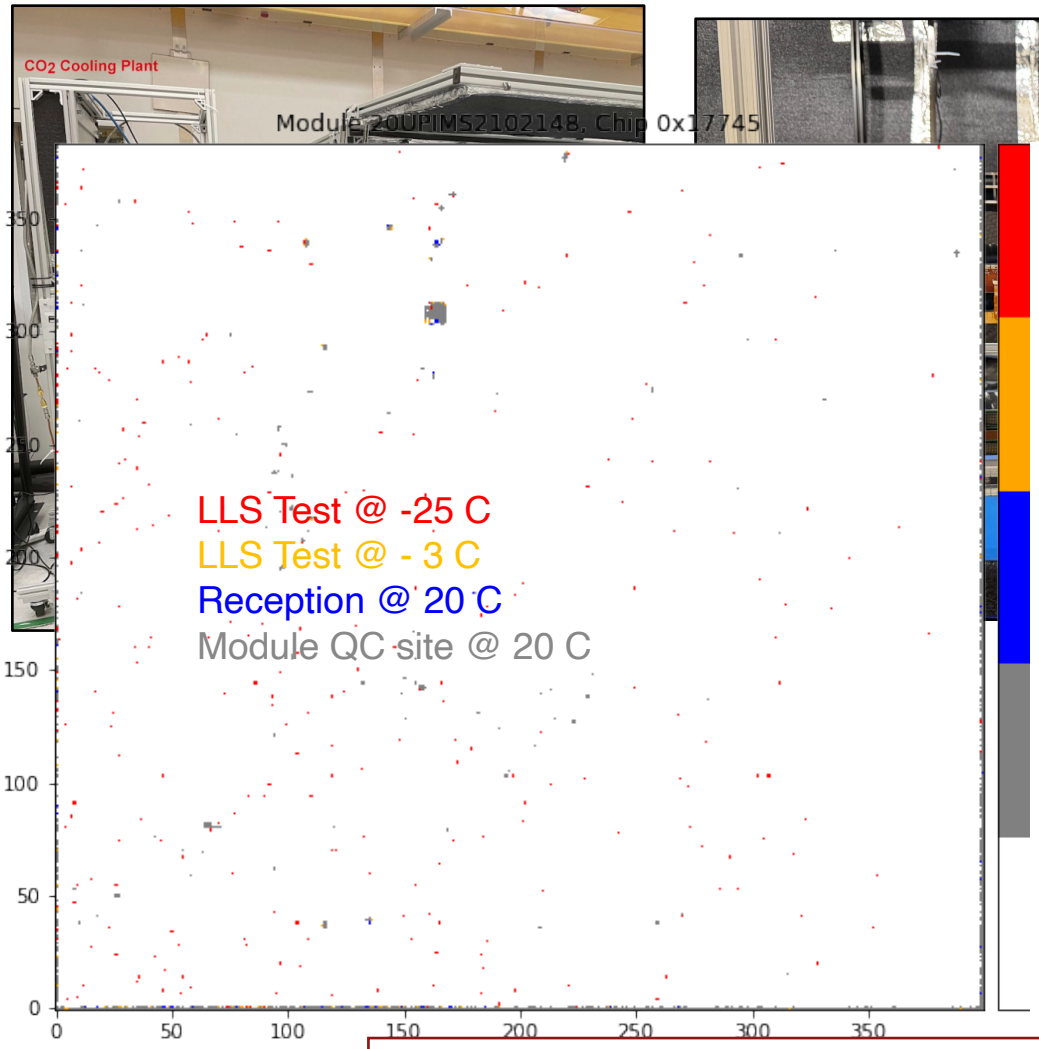
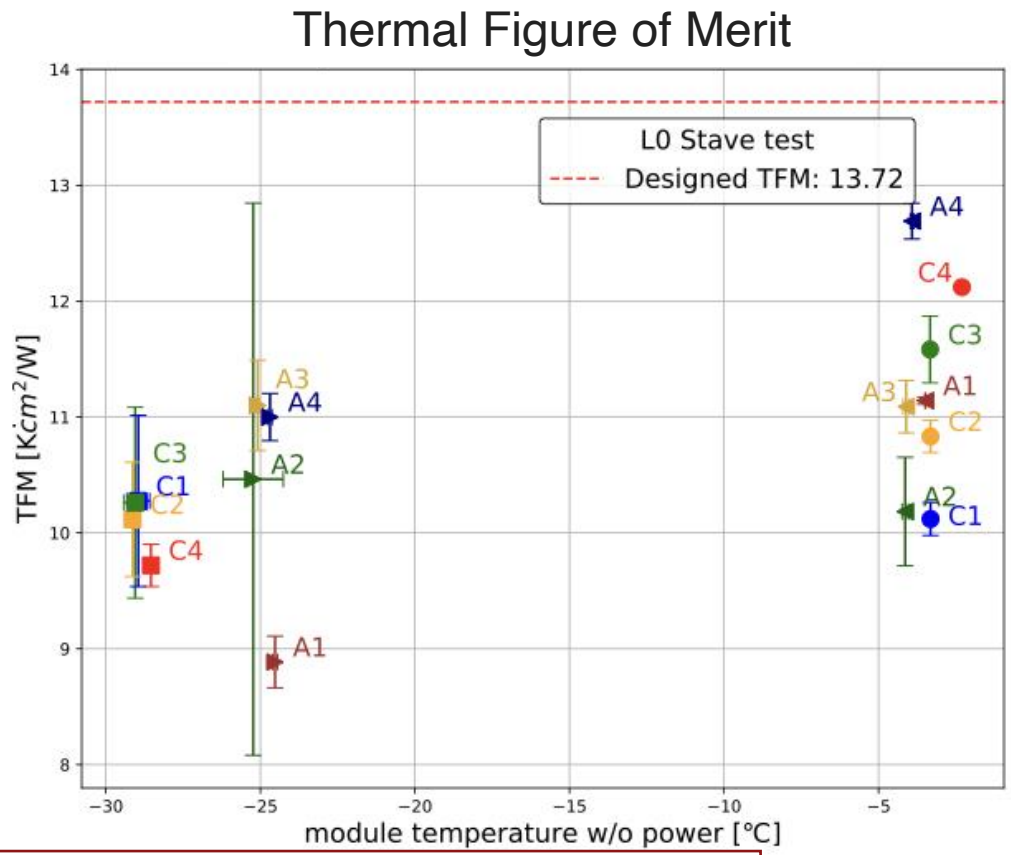




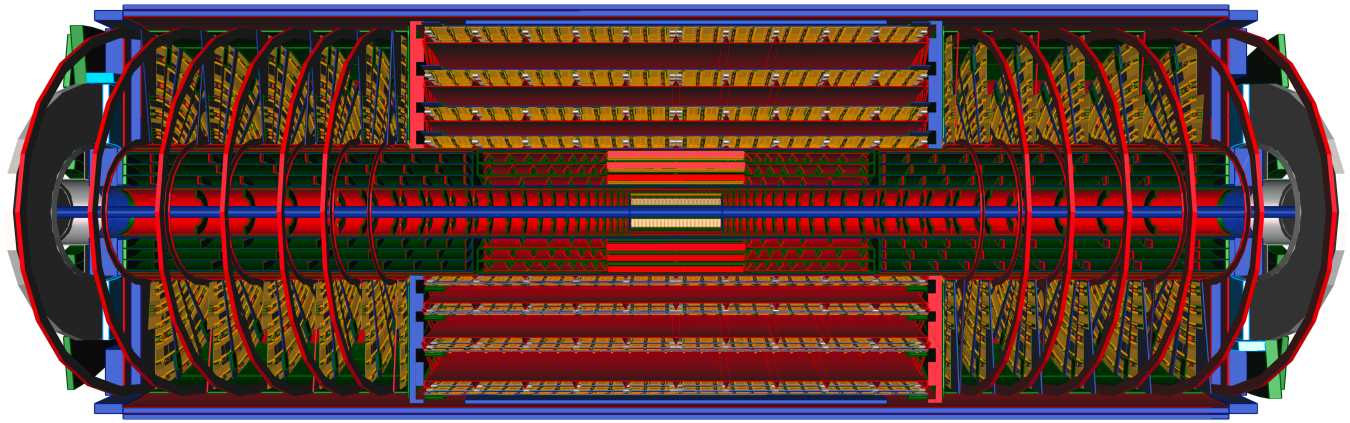
chain

Each sub-system has developed a large-scale system test setup to validate design of detector and services

Integration

Complex large assemblies for both barrel and endcaps

Mock-ups and prototypes to validate the integration sequence and data transmission



ATL-PHYS-PUB-2021-024

Integration

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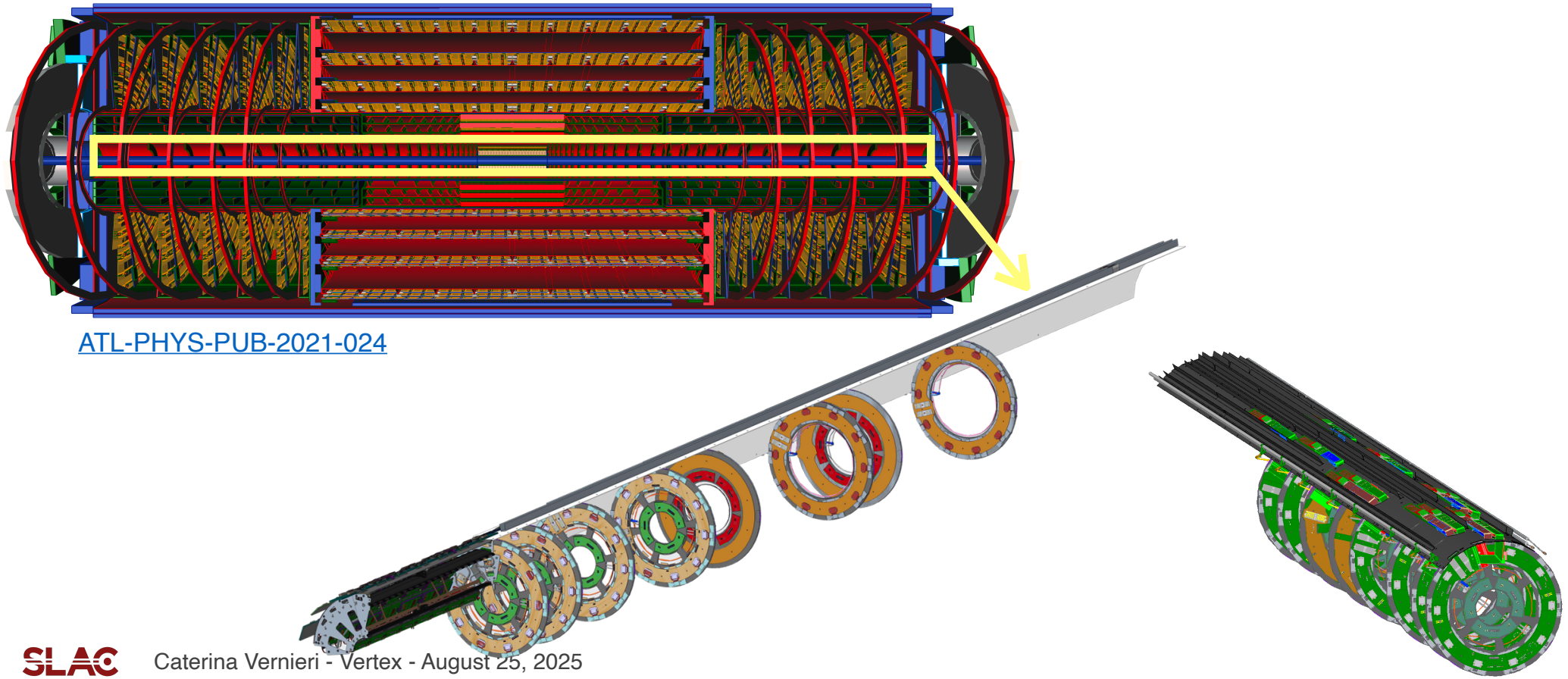

ATL-PHYS-PUB-2021-024

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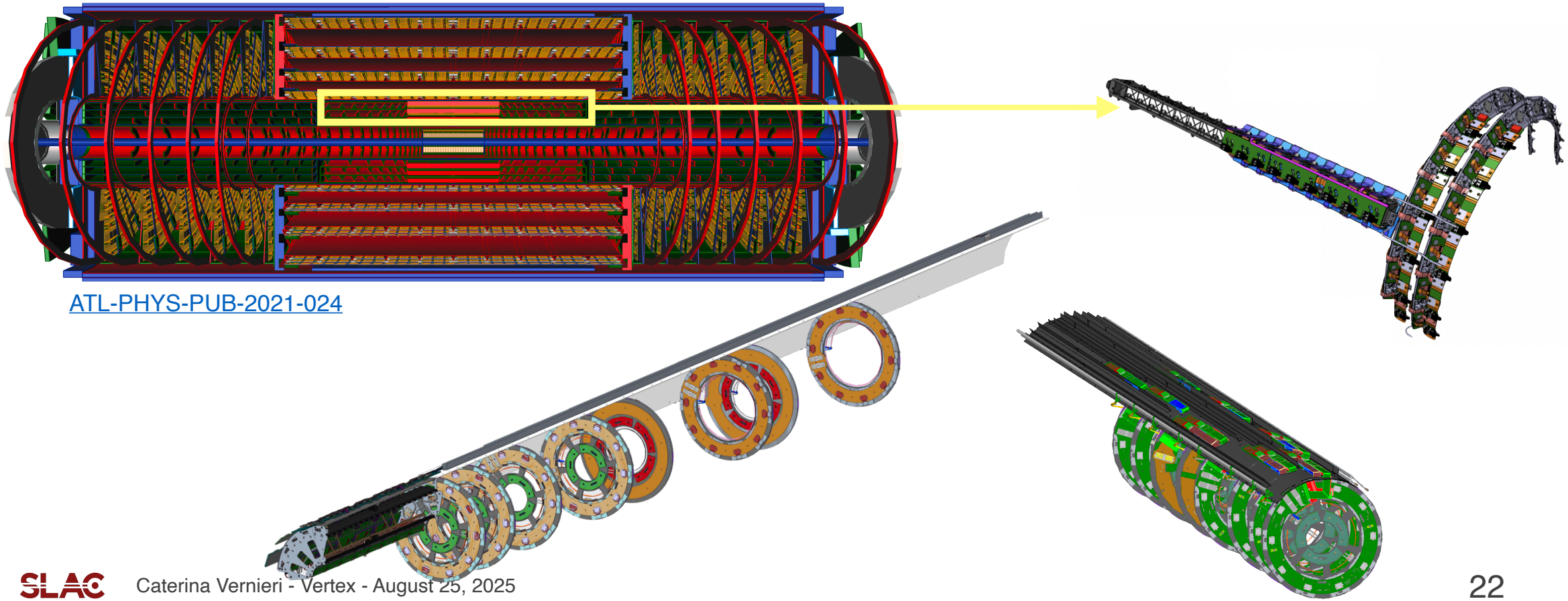

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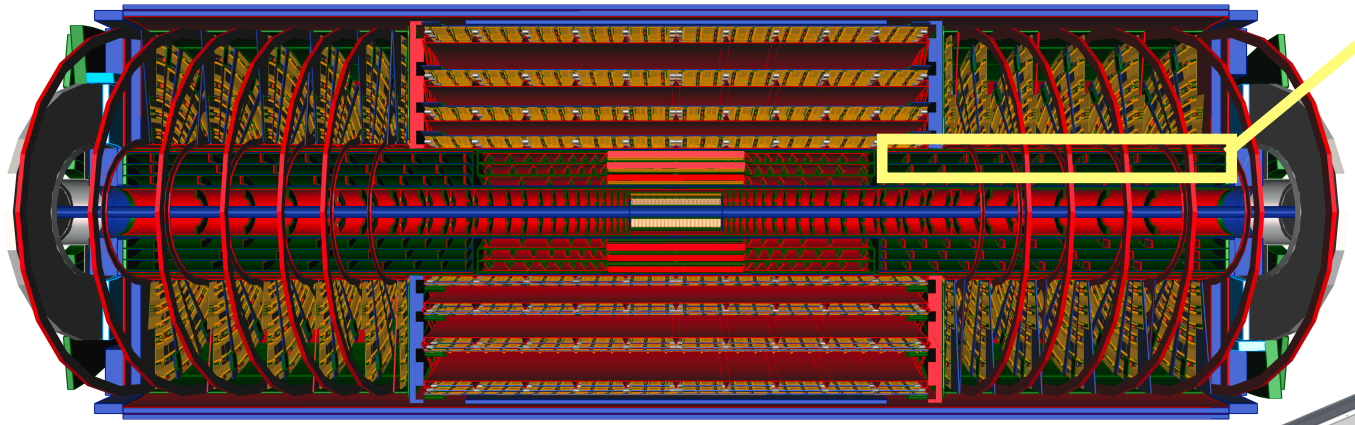
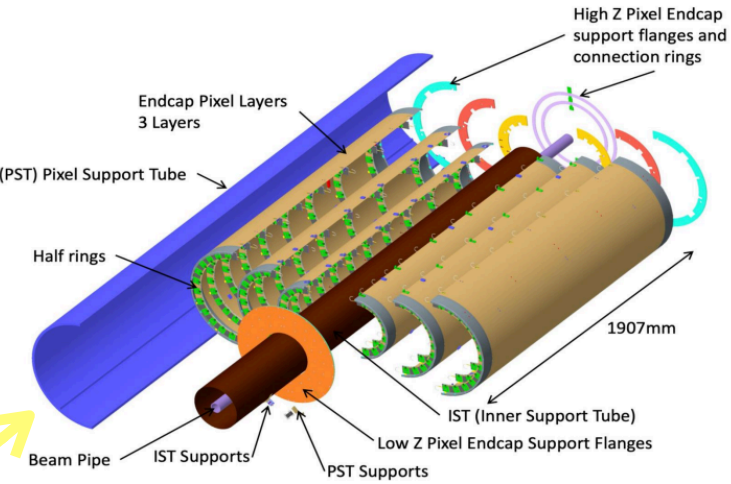
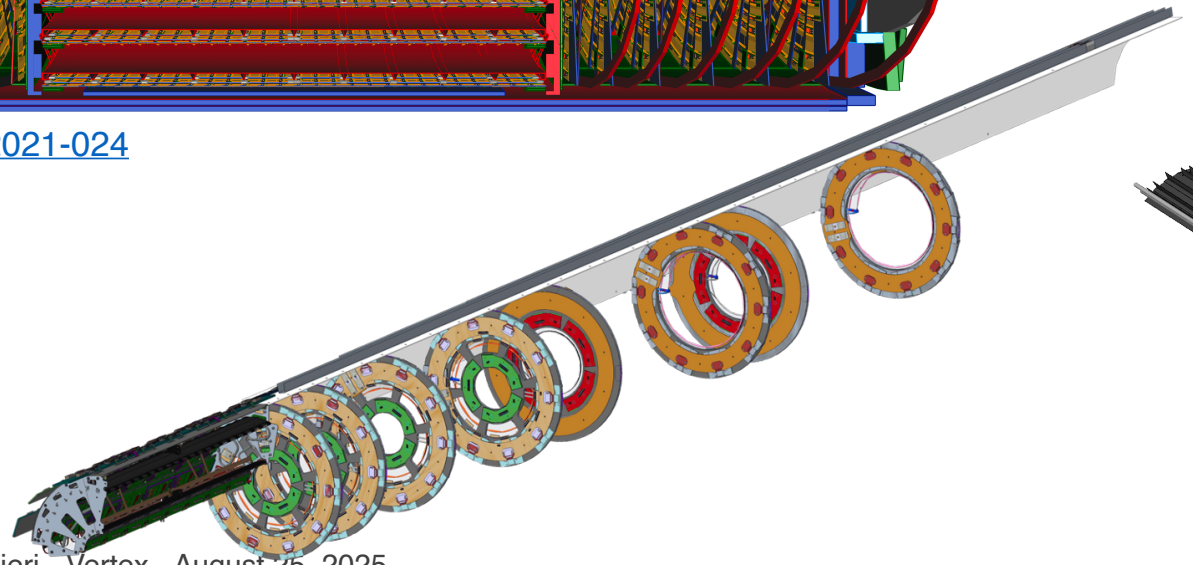
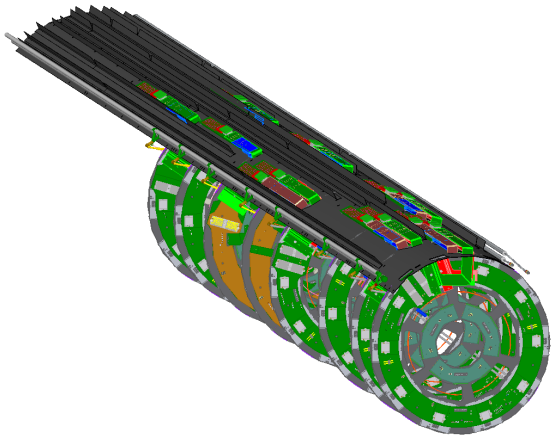


ATL-PHYS-PUB-2021-024



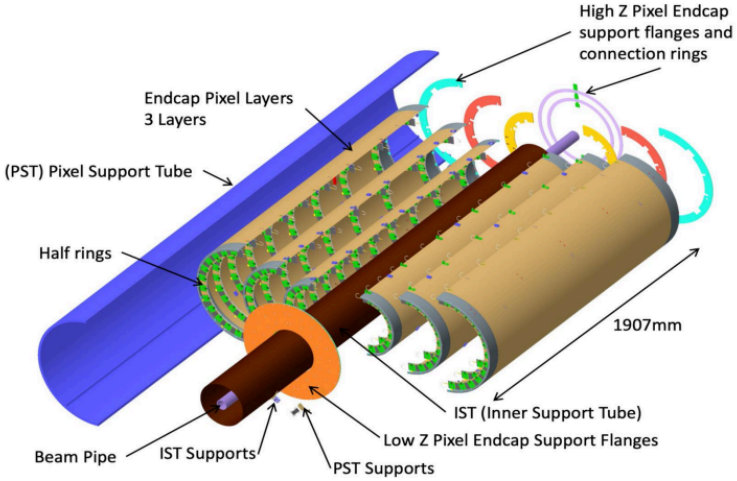


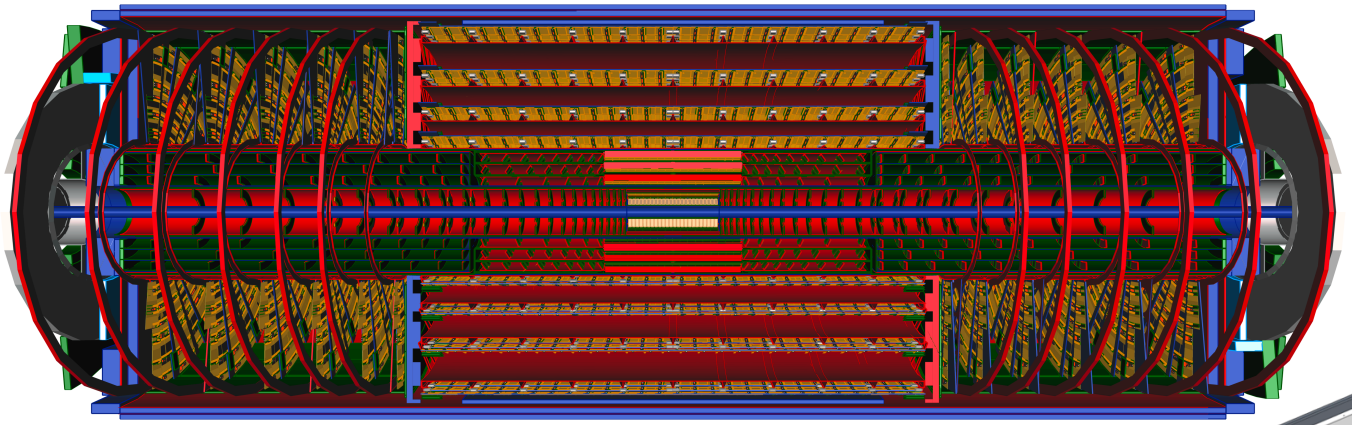


Integration

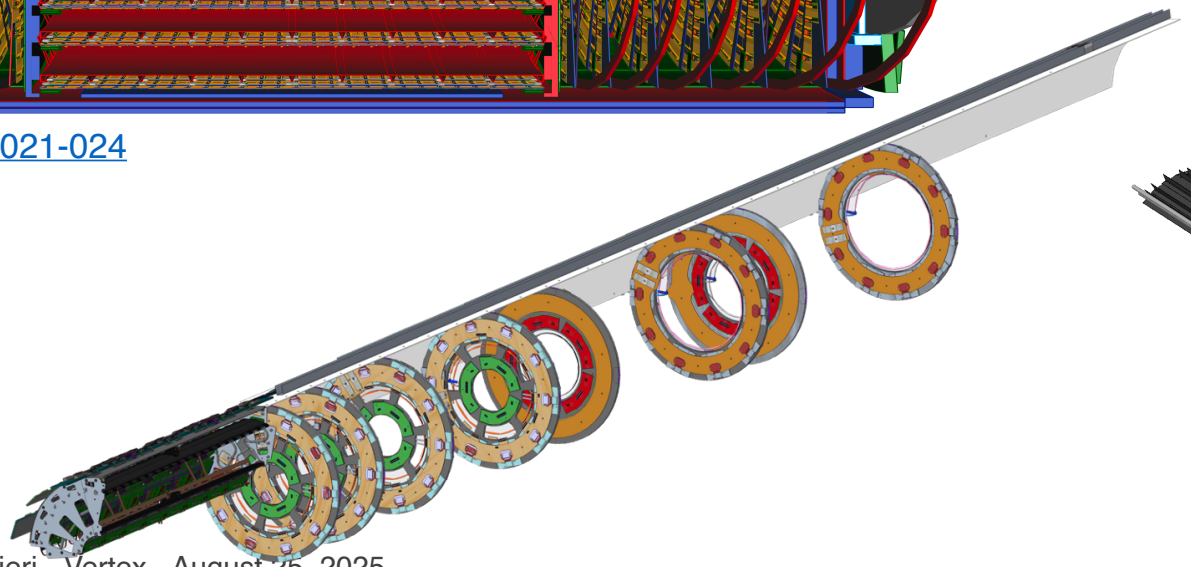
Complex large assemblies for both barrel and endcaps

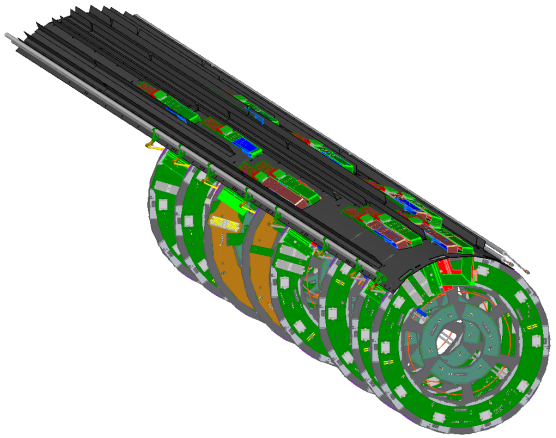
Mock-ups and prototypes to validate the integration sequence and data transmission





ATL-PHYS-PUB-2021-024



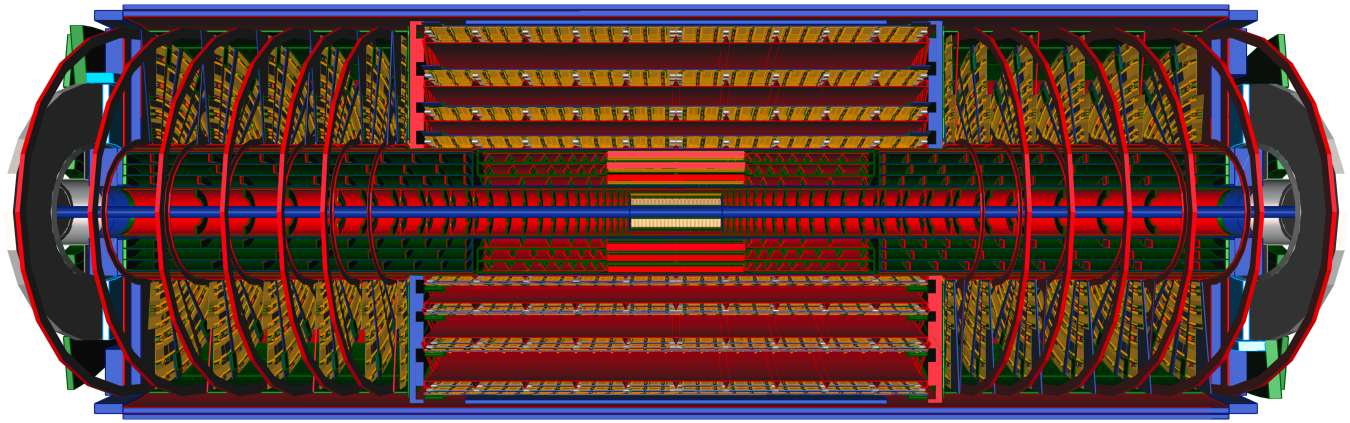


Integration cont'd

Complex large assemblies for both barrel and endcaps

ATL-ITK-PROC-2024-016

Mock-ups and prototypes to validate the integration sequence and data transmission



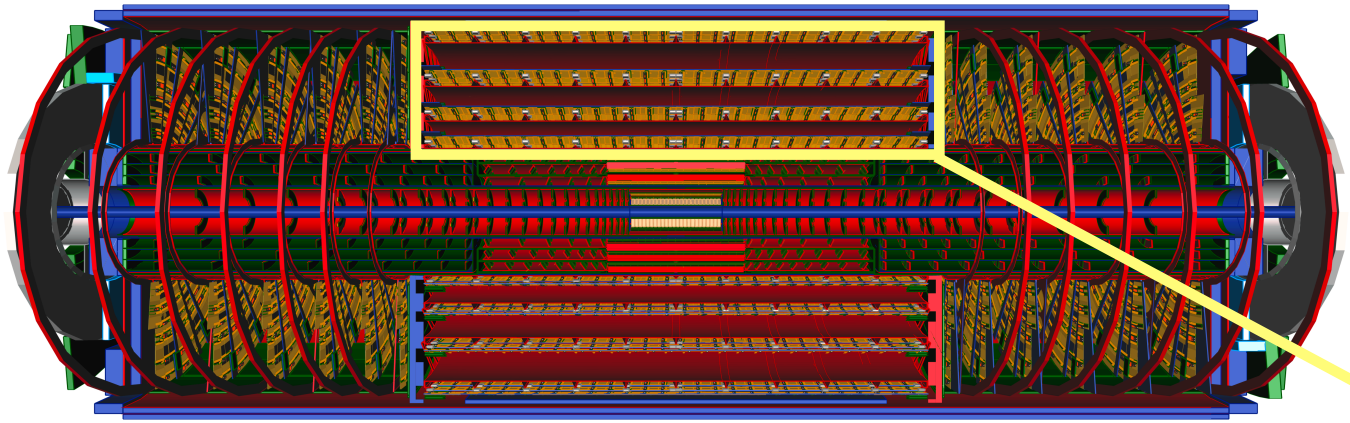
ATL-PHYS-PUB-2021-024

Integration cont'd

ATL-ITK-PROC-2024-016

Complex large assemblies for both barrel and endcaps

Mock-ups and prototypes to validate the integration sequence and data transmission



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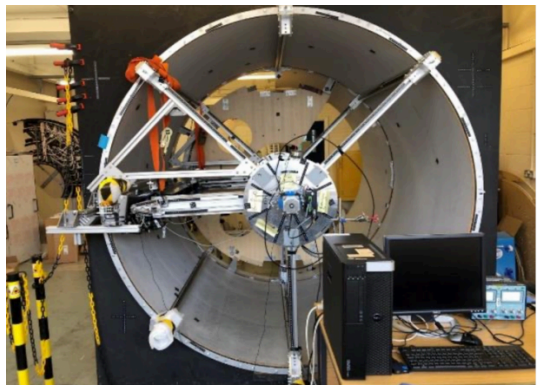
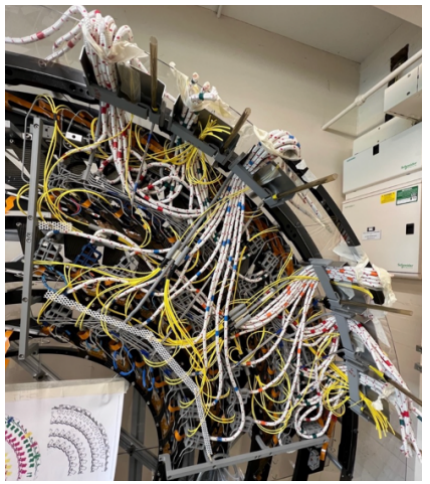
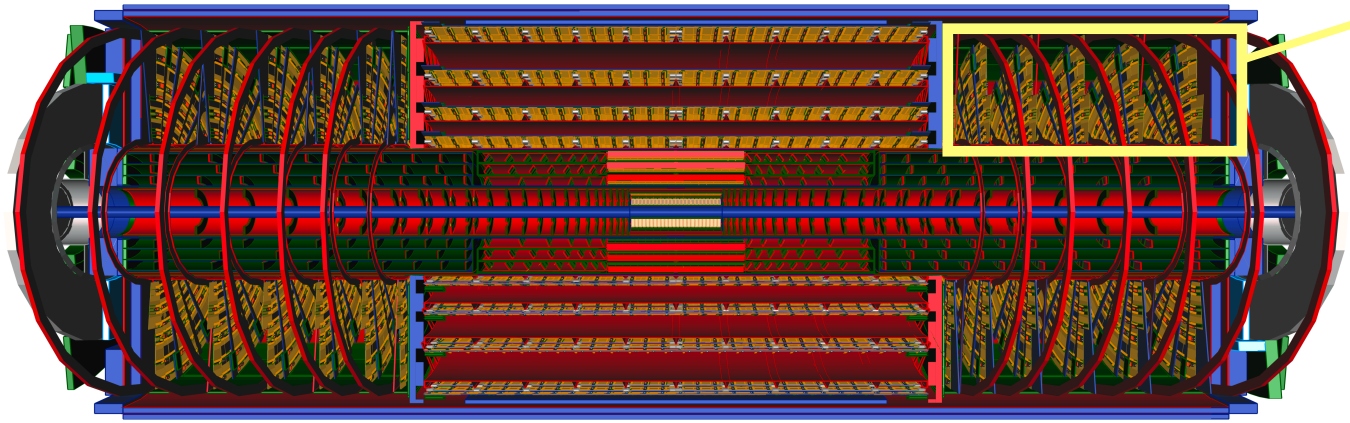




Integration cont'd

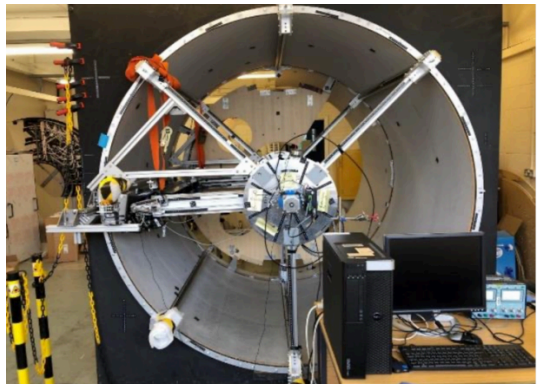
Complex large assemblies for both barrel and endcaps

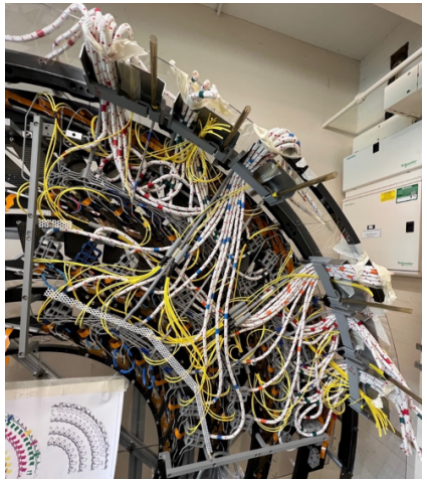
Mock-ups and prototypes to validate the integration sequence and data transmission



ATL-PHYS-PUB-2021-024

ATL-ITK-PROC-2024-016

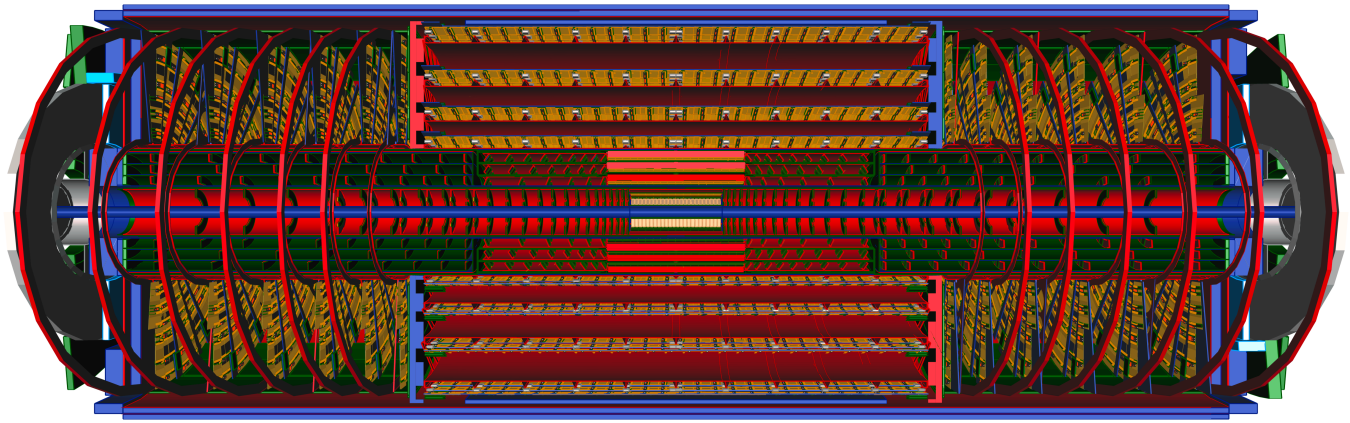




Integration cont'd

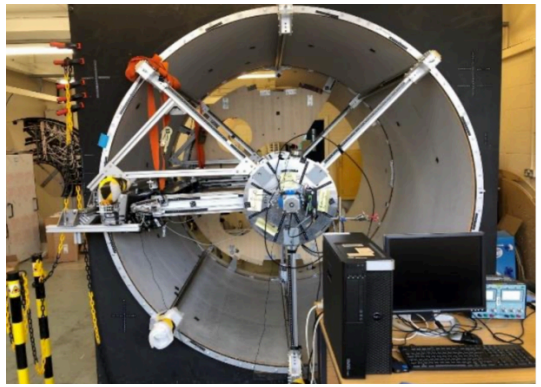
Complex large assemblies for both barrel and endcaps

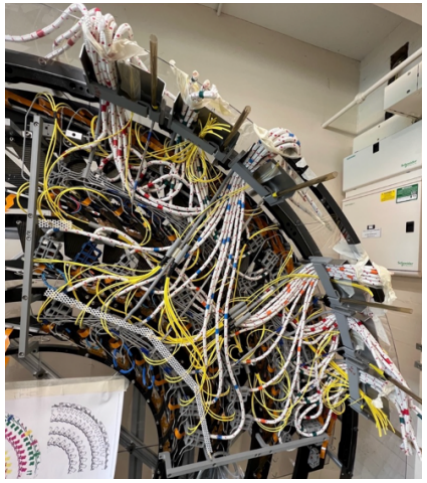
Mock-ups and prototypes to validate the integration sequence and data transmission



ATL-PHYS-PUB-2021-024

ATL-ITK-PROC-2024-016





Mockups …

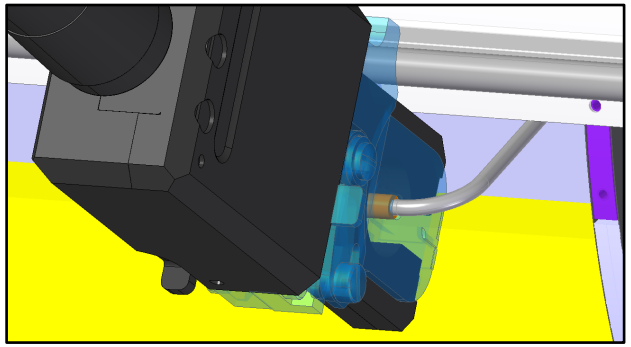
Learning how to manage all the cables

Mockups …

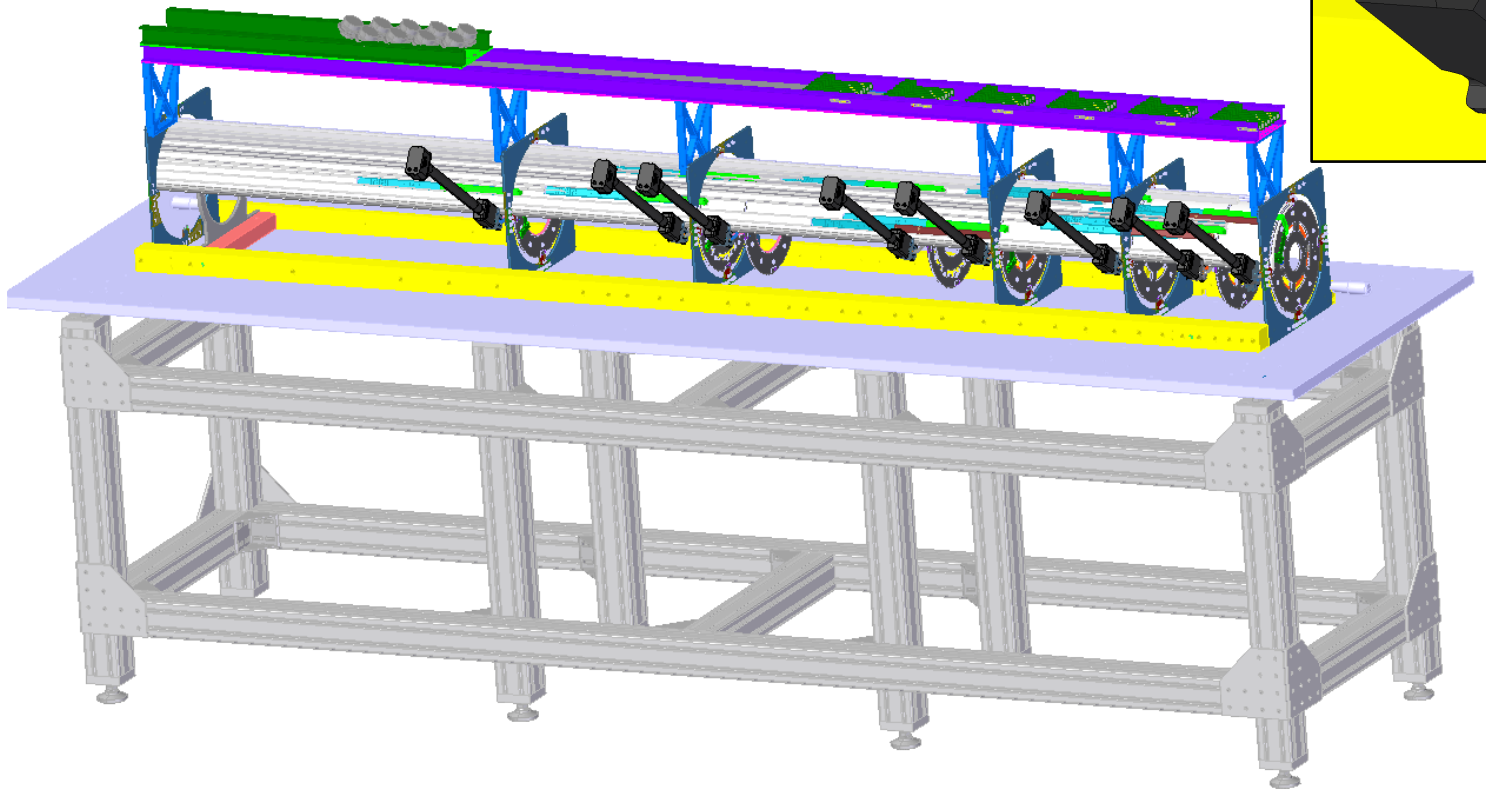
Learning how to manage all the cables

IS Endcap integration

One quarter shell at the time



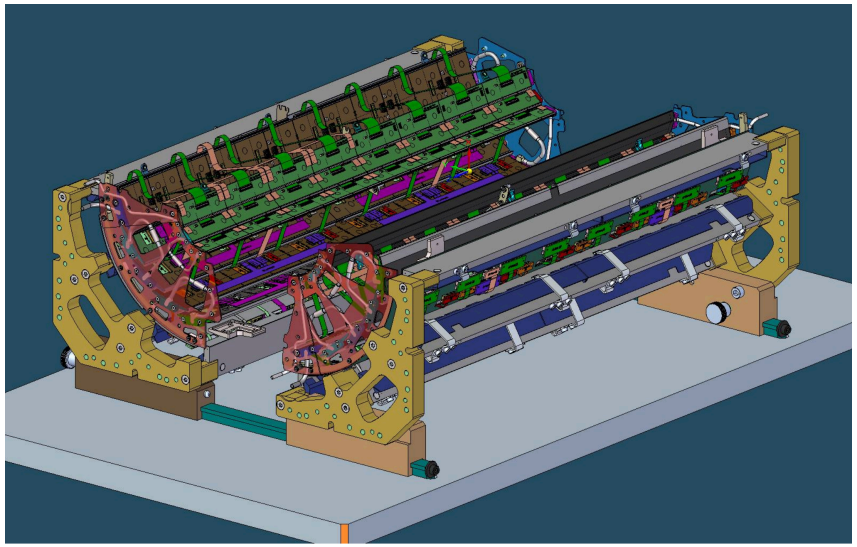
Weld Approach Angle is 35 Degrees

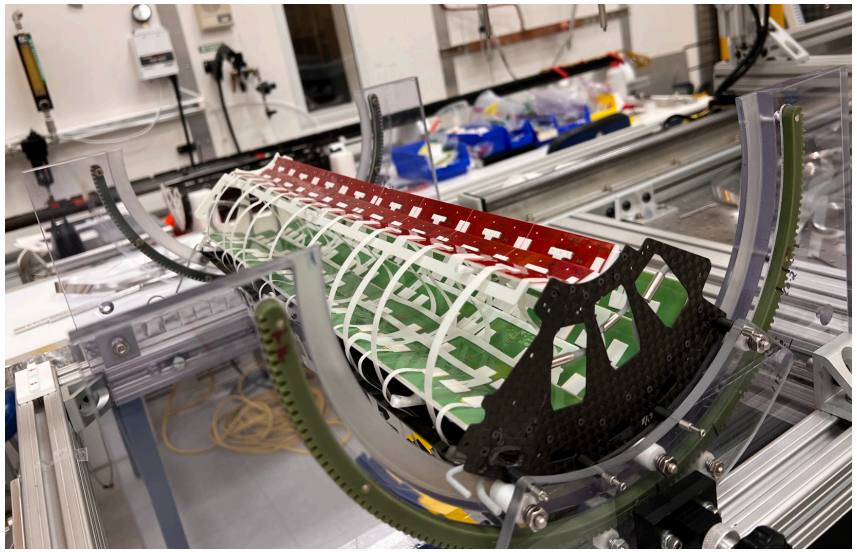


CAD representation of the Quarter Shell assembly for the IS

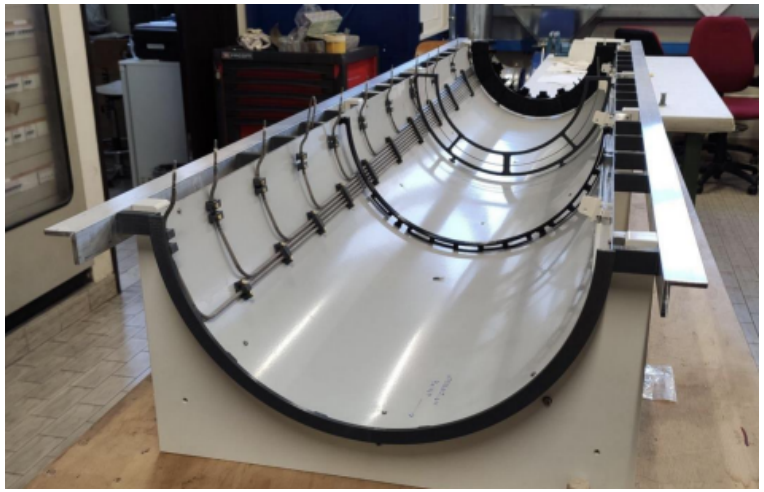
Mockup test

More Stages of integration





Integration test of L0+L1 barrel with 3D printed parts



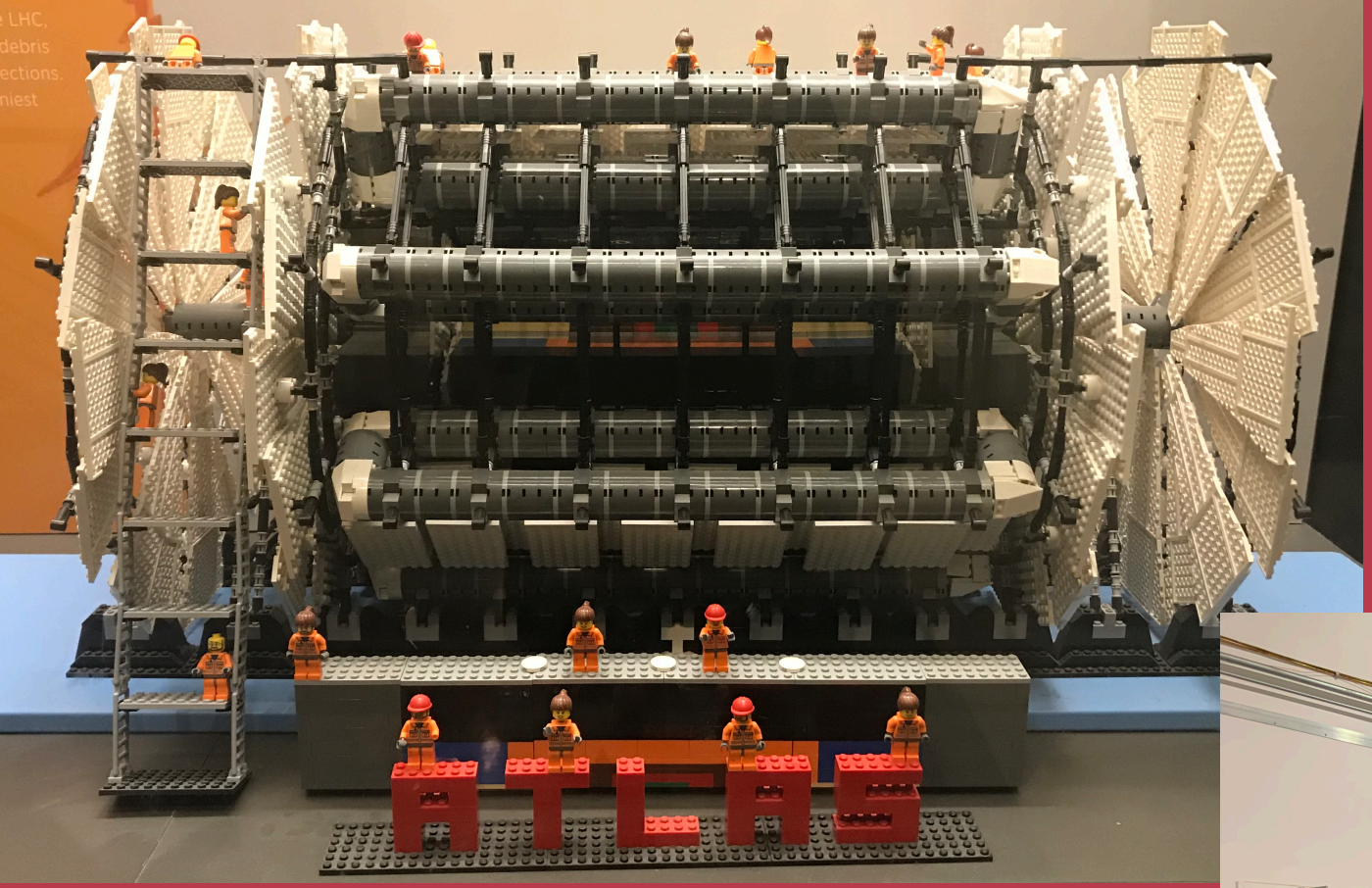
Integration test of L2 cooling system on mockup half shelf

PP1 Glenair connector like mockups

Conclusions and perspectives

A new ATLAS detector for HL-LHC with the largest silicon detector ever built

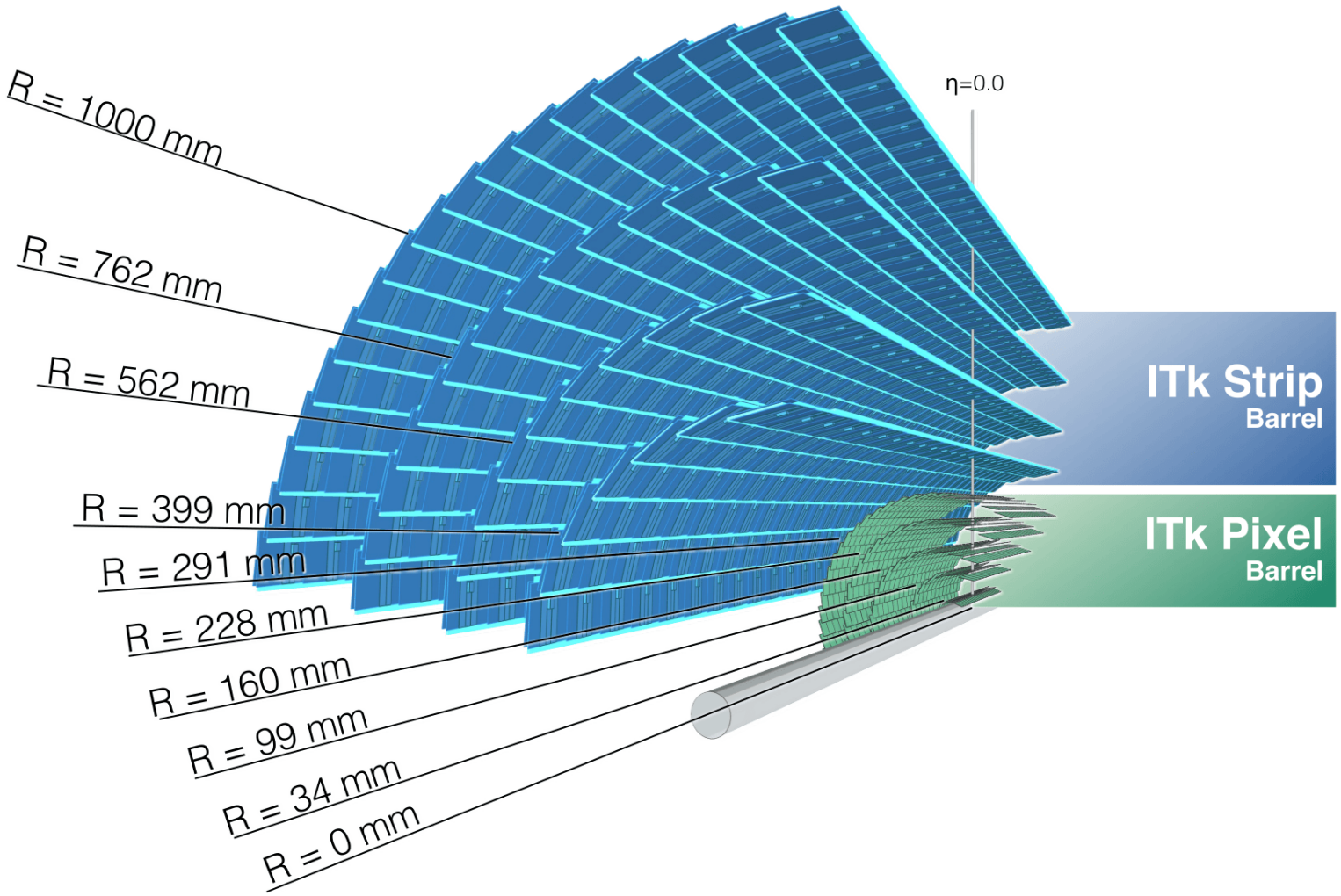
- An all silicon tracking system is being developed for the ATLAS experiment upgrade at the HL-LHC to cope with increased particle multiplicity and radiation levels.
  - **ITK will provide increased acceptance up to η~4 , a large number of points per track, high granularity and radiation hardness with minimized material budget.**
- The ITK systems have finalized an extensive prototyping & pre-production phase and have recently started production of some components.
  - System tests and demonstrators for all subsystems
  - Finalize production version of readout chip, services, loading and integration procedures.
  - Production will start by the end of 2025 and end by 2027 (pixel) / 2028 (strips)
    - Integration in 2028
    - **Commissioning *starts* in 2029**



thank you!

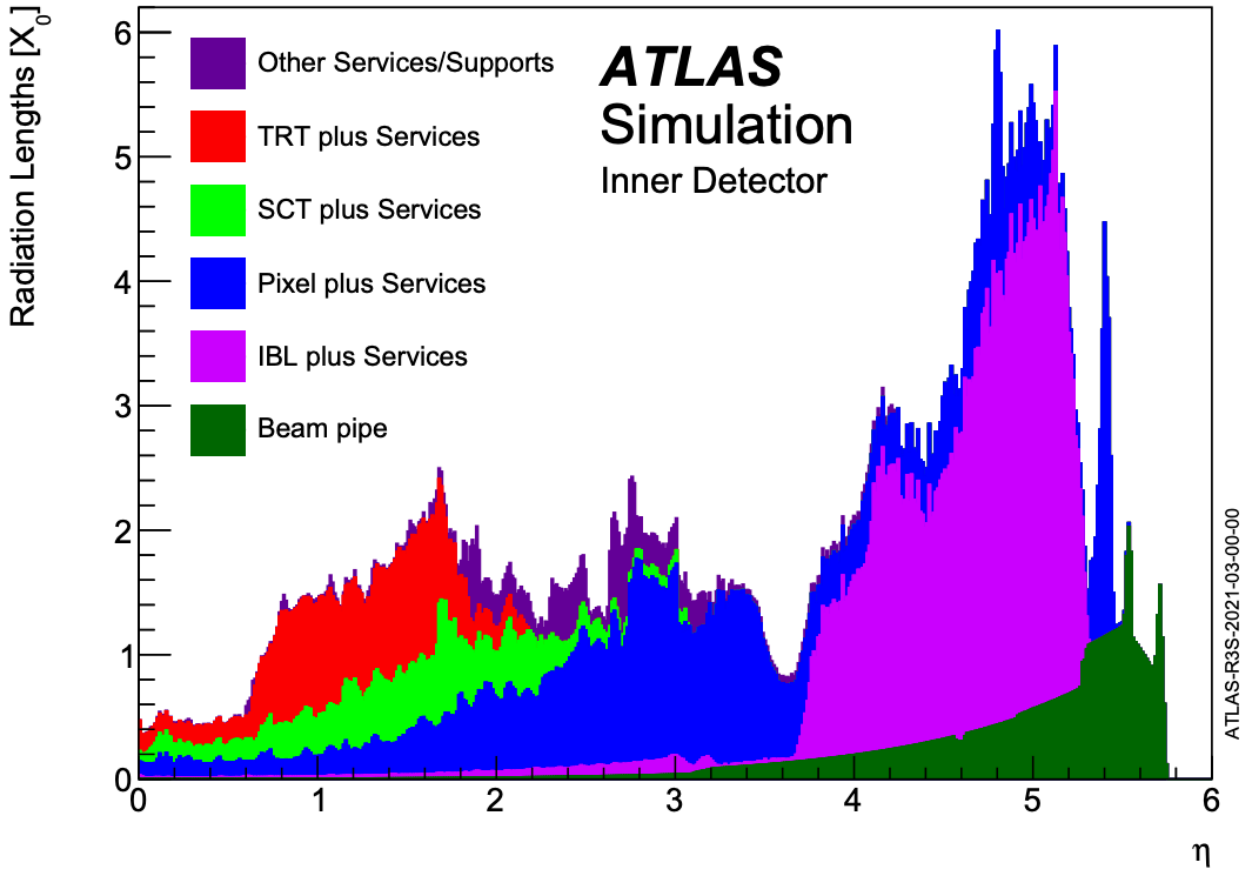
ITk layout - R view

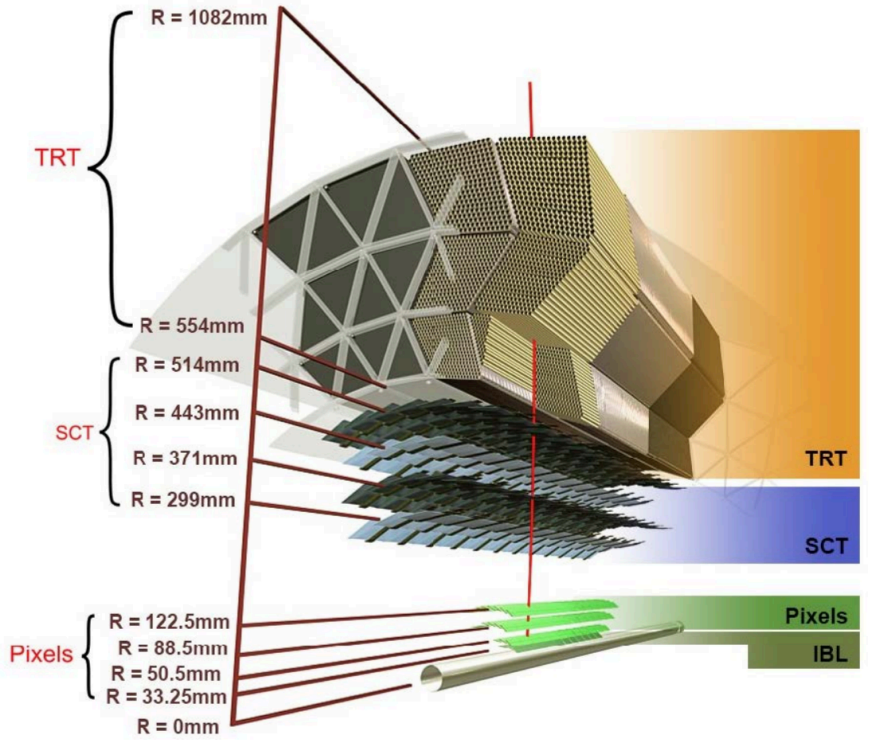
JINST 20 (2025) P02018



Current ATLAS detector

JINST 19 (2024) P05063

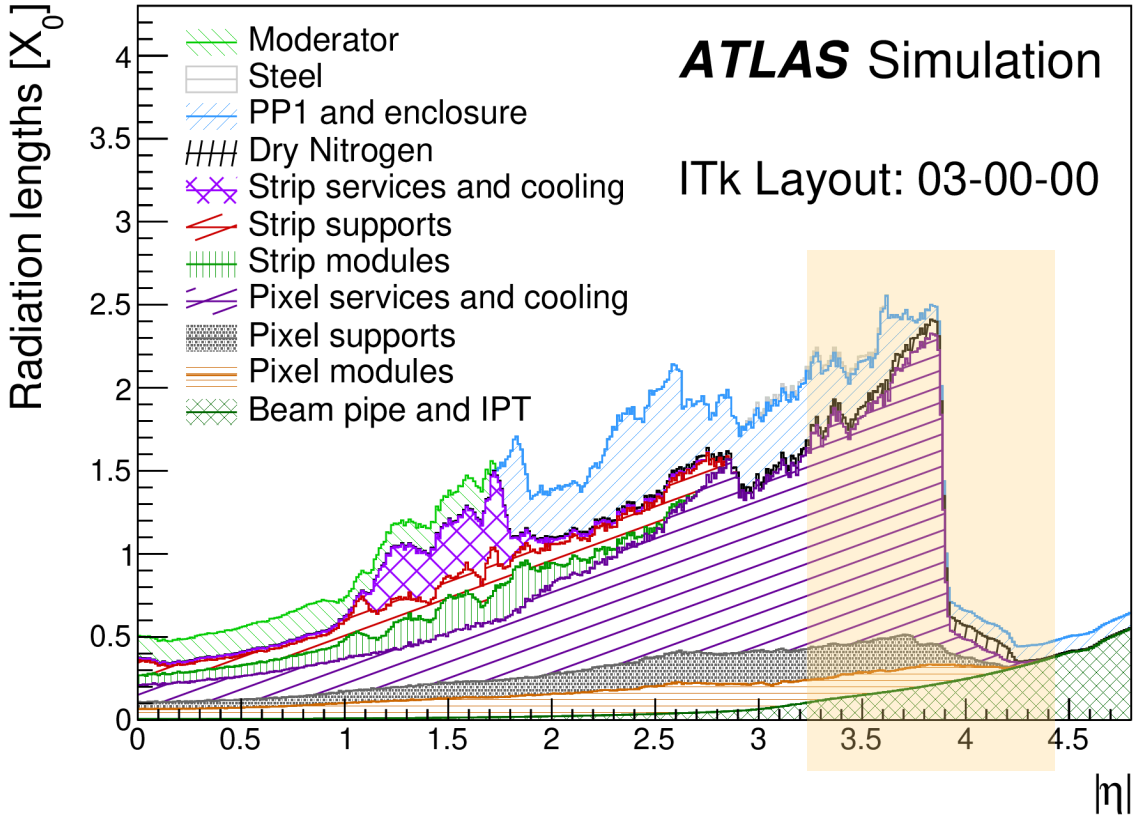




One more challenge: Material Budget

JINST 20 (2025) P02018

Lower material budget than ATLAS ID, from 1.6 → 0.6 X_0 at η ~1

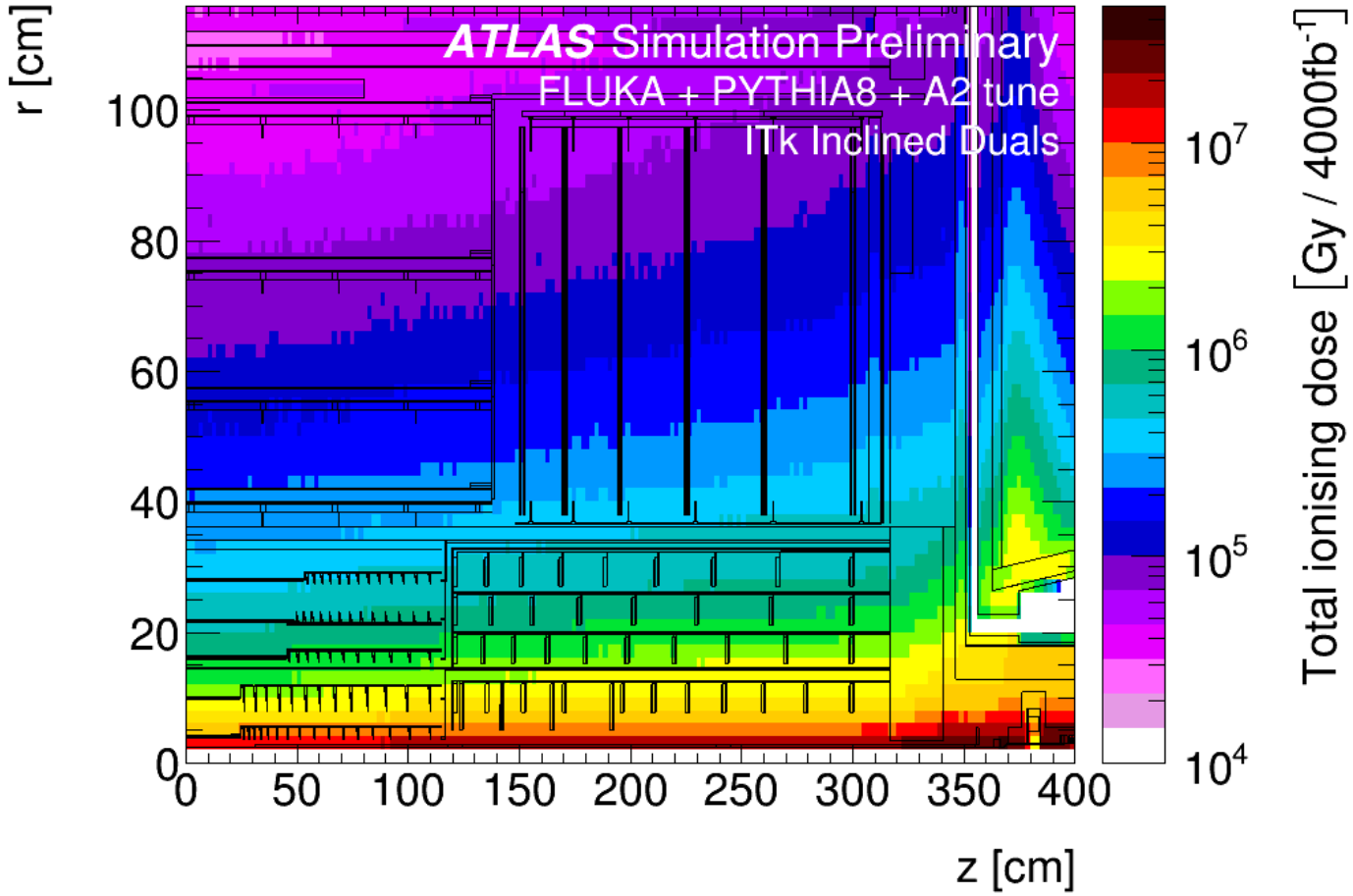


- **CO_2** two-phases cooling system
- **Carbon fiber structures** for local supports
- **Link sharing and serial powering** to reduce number of readout and power cables respectively

Pixel services: optical conversion outside the detector volume

Challenge

Radiation levels are unprecedented x 10 increased with respect to LHC



- For 4000/fb 2×10^{16} n_{eq} /cm^{-2} and 15 MGy
- **Fluence** decreases as we move to large radius
  - The Inner system - first two layers - designed for up to **2000/fb**
  - ITk will be operated at -35C to mitigate radiation-induced damage and prevent thermal runaway

Wish list for the glue

The adhesive used for module loading should satisfy certain properties

Chemical cure (not solvent evaporation)

Minimum pot life 30 min

Cures at or close to room temperature

Good thermal conductivity (> 1W/mK)

Electrically insulating

Viscosity suitable for deposition with a standard commercial dispenser

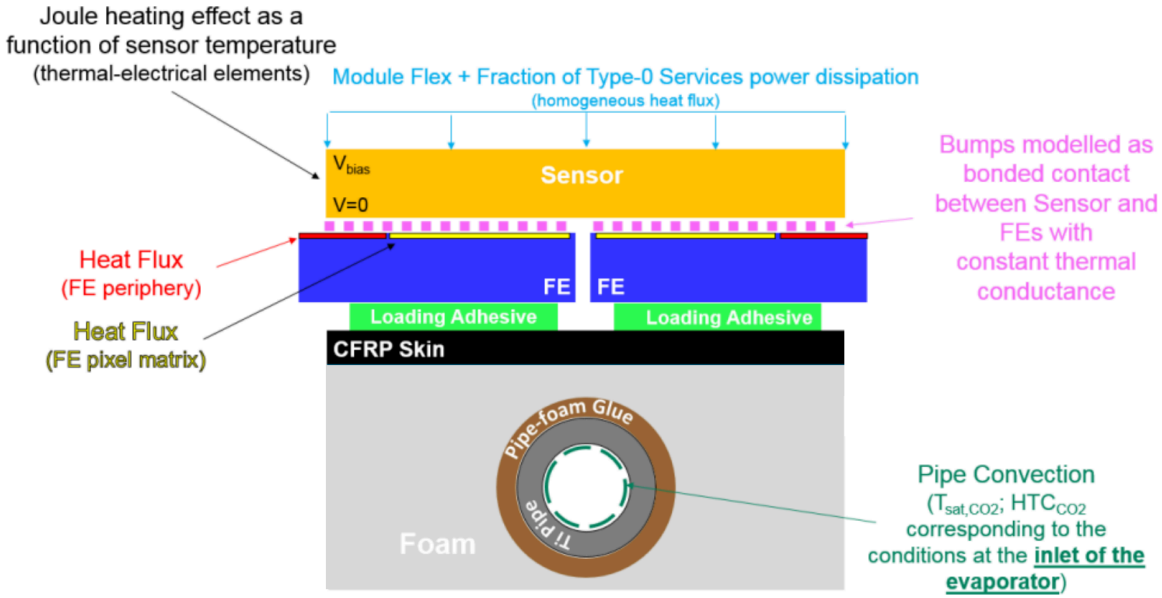
Viscosity low enough that excessive pressure is not needed to push the module onto the adhesive.

Reworkable – this in general implies softness/flexibility, a result of a low TG. Moderate heating may be used to soften such adhesives during rework.

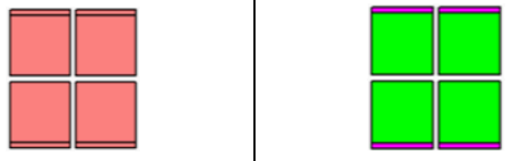
Radiation hard – Lap joints, DCB and thermal conductivity to be tested.

Cooling ITk - CO_2

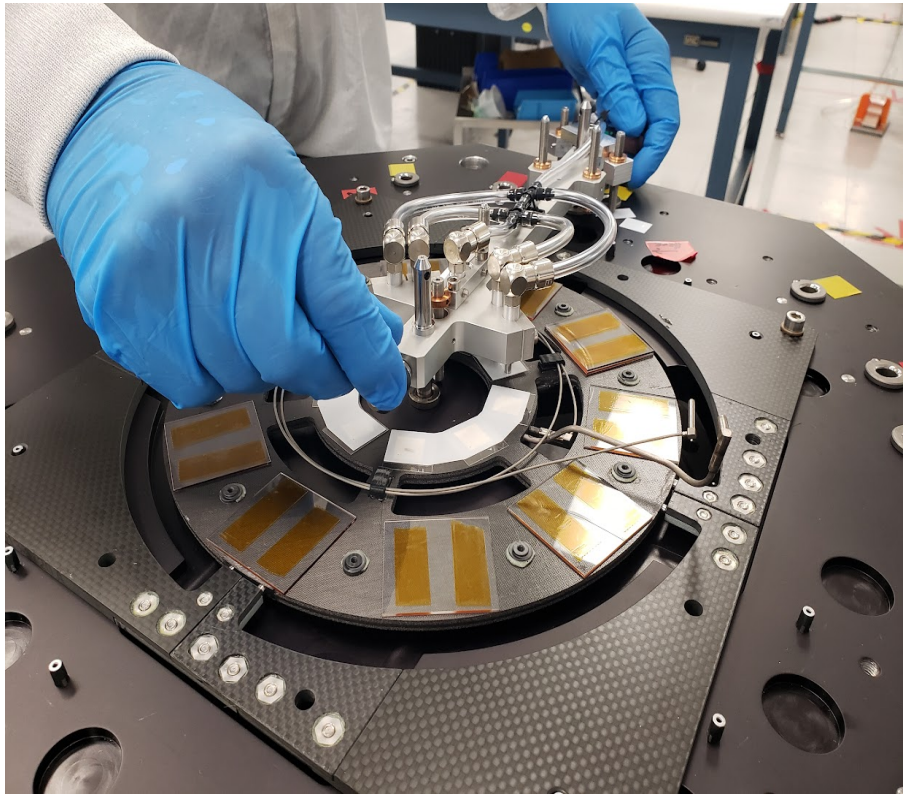
- Two-phase properties allow efficient, stable heat removal with small tube diameters, low material budget, high radiation hardness, and minimal environmental impact.
  - Min cooling temperature during operation: -45C (100 cycles by end of life)
  - Min cooling temperature during a failure: -55C
- Simulations were used to derive the tube inner/outer diameters, the bending radius, and to validate the manifold structure through thermo-electric and thermo-fluidic modeling.
- The non-homogeneous power dissipation of the FE chip requires further optimization of the bending radius of the local supports.

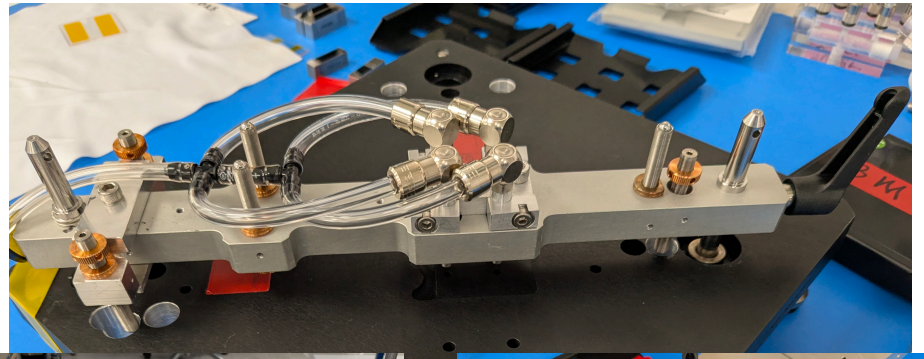


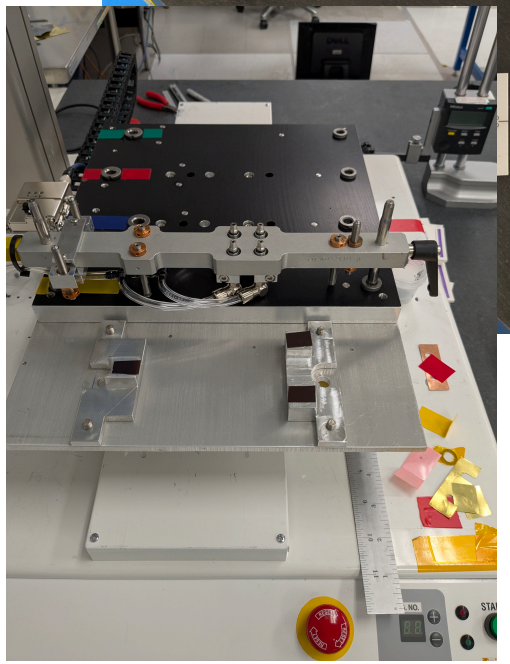
	Case 1		Case 2	
Sensor	**Matrix**	**Periphery**	**Matrix**	**Periphery**
3D	0.8	0.8	0.33	4.16
Planar	0.8	0.8	0.30	3.75

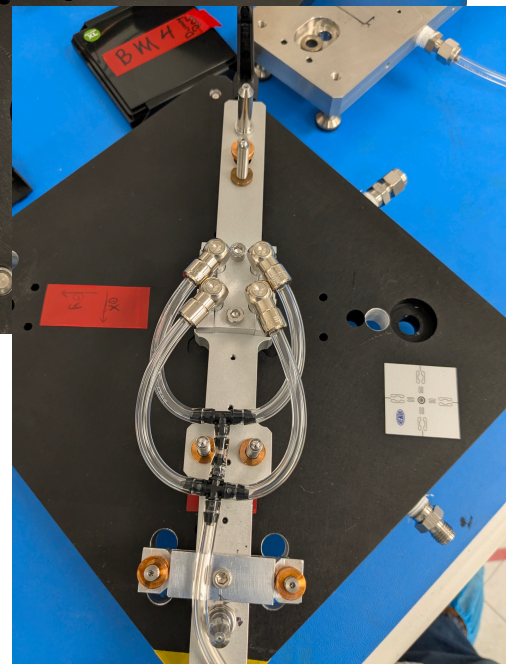


Ring & L1 tooling



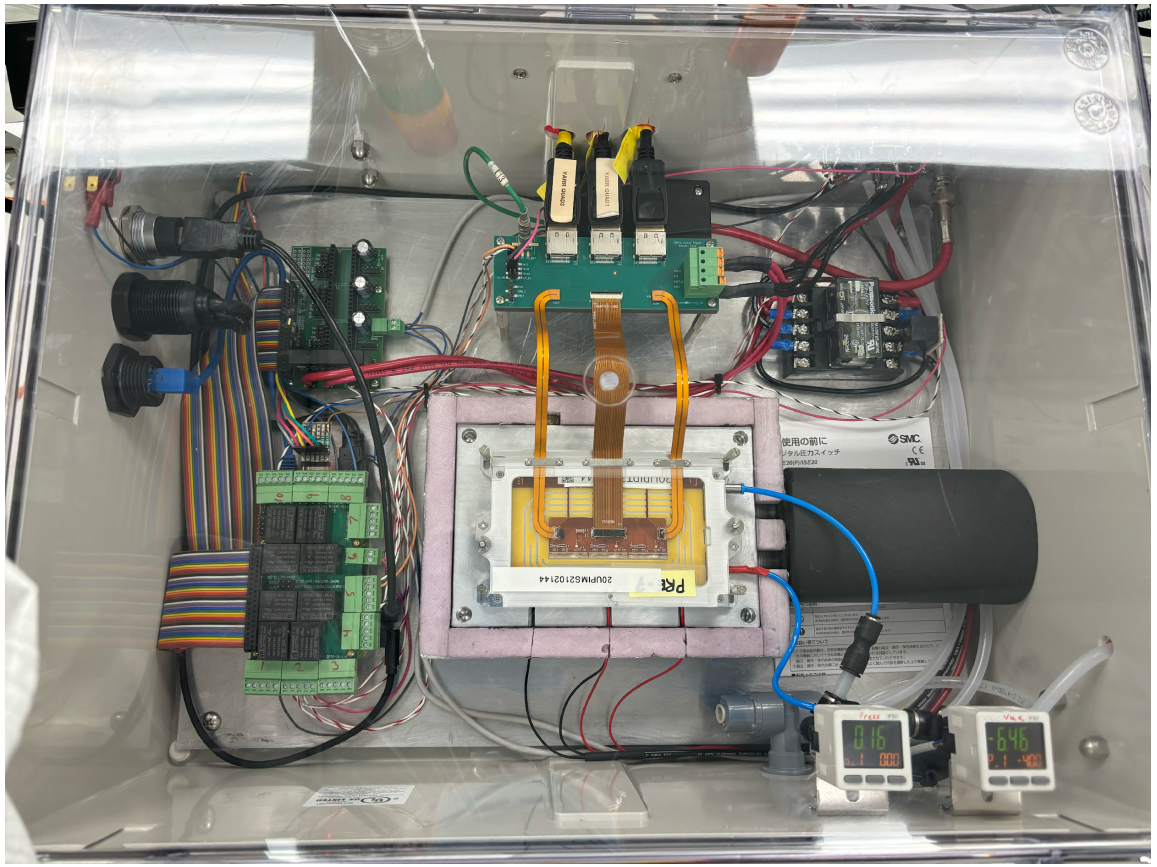






Reception area

- We have 3 boxes from Argonne for module testing
  - One for each module flavor (L0, R0/R05, Q)
  - They can be operated in parallel
  - YARR readout
- Following module QC recommendations
  - Readout at 1.28 Gbps
  - Powering triplet at 5.5A (2V)
  - Module temperature ~20C w/ water cooling
  - YARR software v1.5.2, firmware v1.4.0



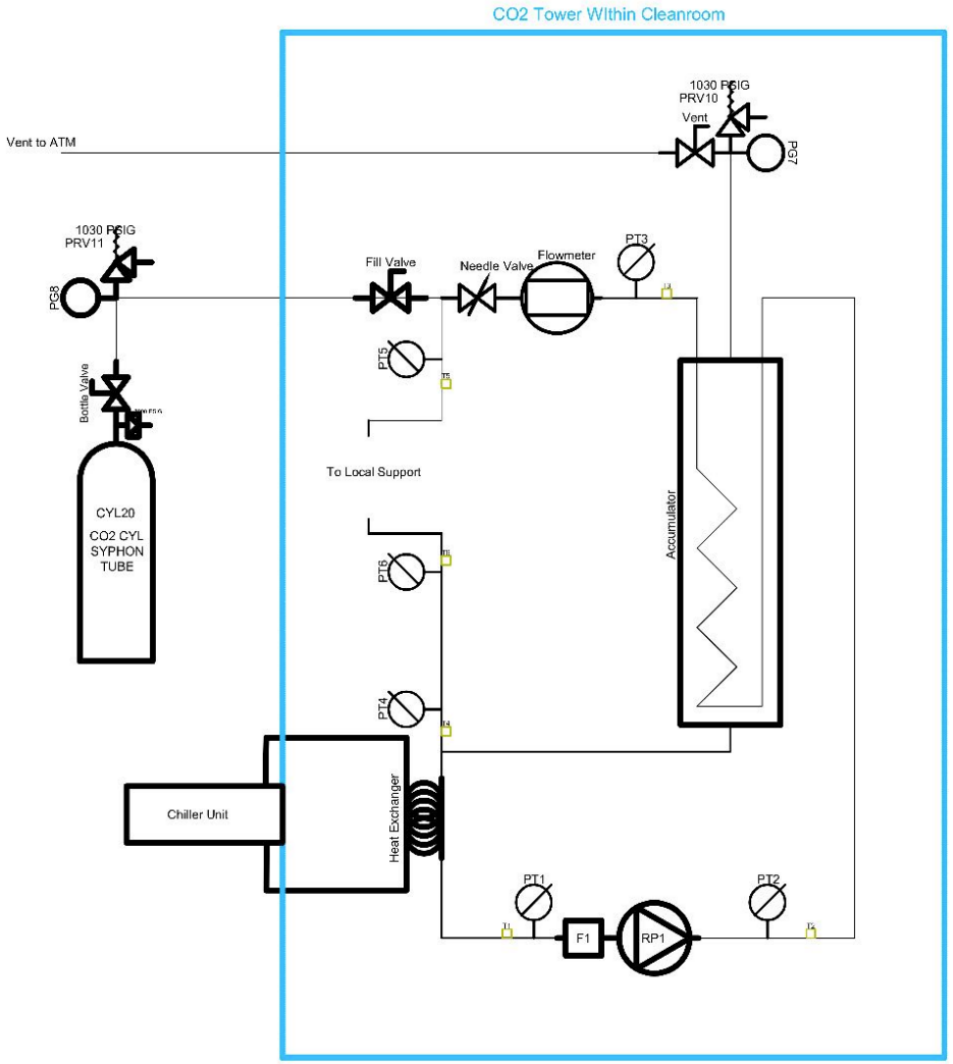
Module Reception tests at SLAC

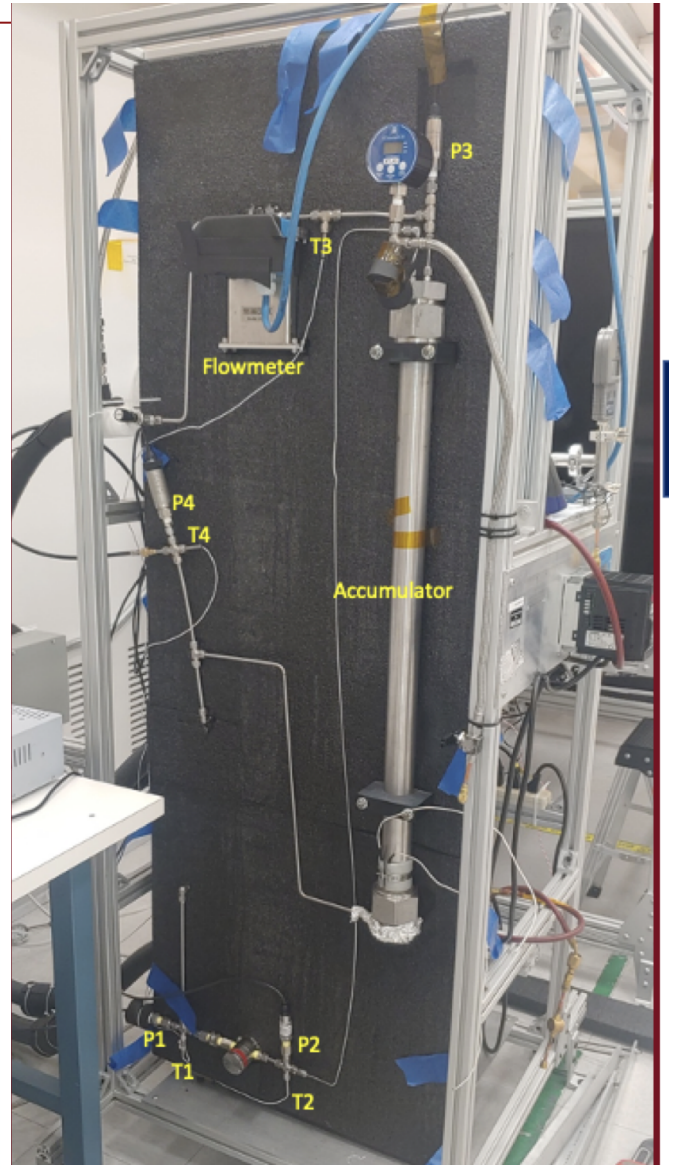
List of tests we perform at SLAC as part of module reception

- Visual inspection :
  - One photo for full module, zoomed photo for each chip, and additional photos of notable features (checking for damage to wirebonds)
- At room temperature ~20C
  - Sensor I-V Scan
  - Digital, analog and threshold scans, Time-over-Threshold (ToT), and disconnected bump bond scan (i.e. both *Minimal Health Test* and *Pixel Failure Analysis*)
    - Using module's last configuration and thresholds - as derived during the module QC and uploaded to the ProdDB by the testing sites.
    - These results are then uploaded onto the production database and compared against the module QC results from the module QC sites.
      - Any significant deviations is investigated and reported
  - SLDO verification

CO2 Cooling Plant at SLAC

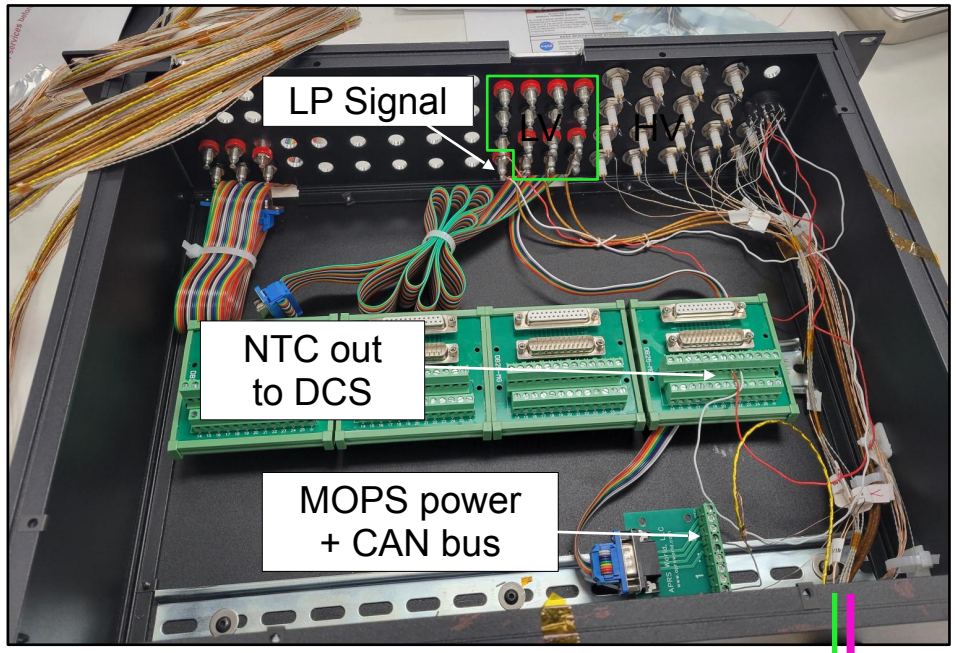
- **Upgraded CO2 Plant**
  - New max ΔP 14 bar
  - Sufficient for ring capillarie
- Test Box dew point ~-60 °C using dry-air
- Nominal CO2 pressure at room temp ~800 psi
- CO2 plant pump VFD ~12 Hz
- L0 Testing flow rate 1-2 g/cm^3



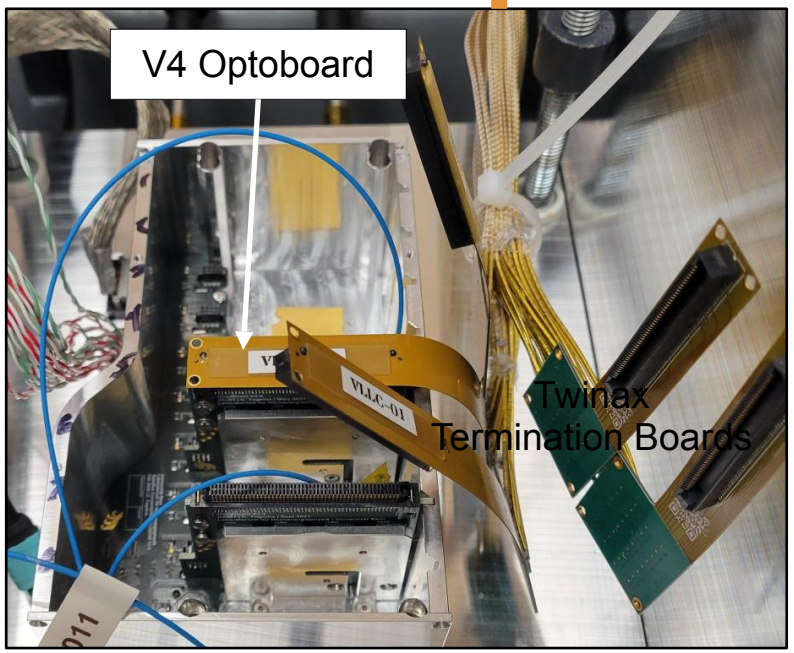


LLS Test Infrastructure - Type-1 Services + Data

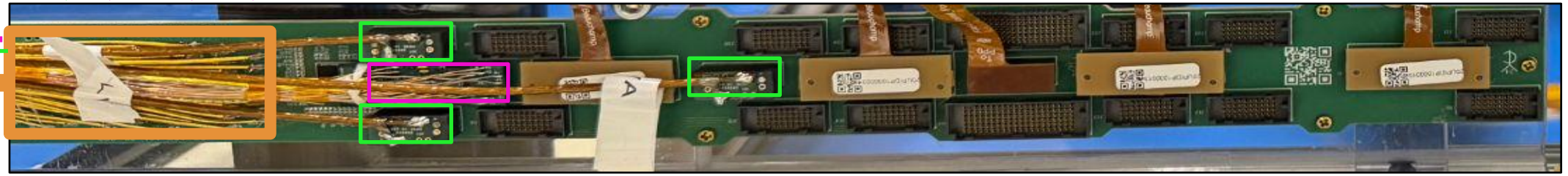
Type-1 Services Breakout Box



Optobox



Type-1 Services Bundle →
LV Power, HV, MOPS, NTC, LP Mode



Data Twinax Bundle →

L0 - disconnected bumps