Quad Module Assembly and Quality Control for the ITk Pixel Detector Upgrade for the High Luminosity Phase of LHC

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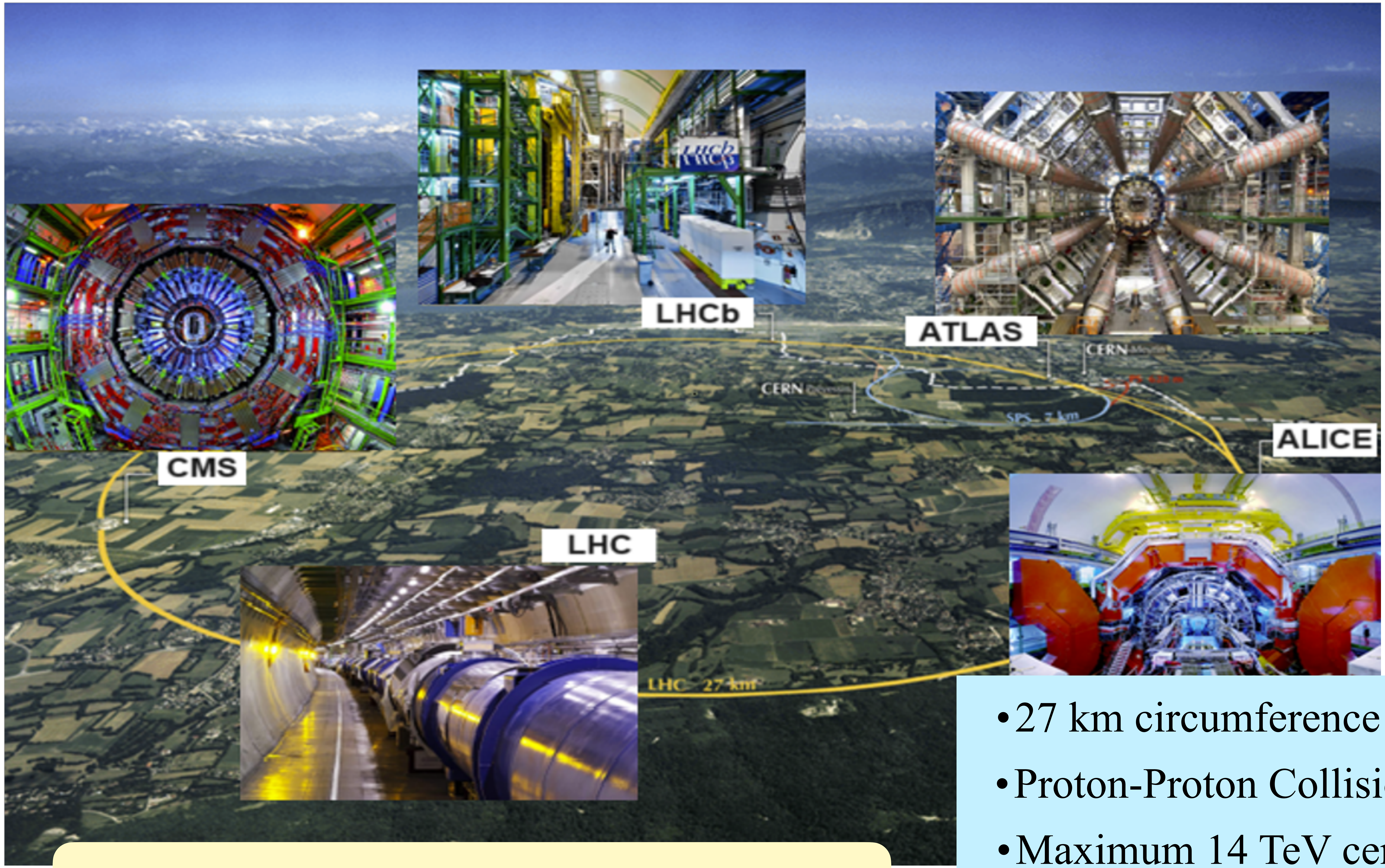
SORBONNE UNIVERSITÉ

LPNHE PARIS

ATLAS ITk

Large Hadron Collider (LHC)



ATLAS & CMS
General purpose detectors
(good for everything…)

LHCb dedicated for
b-physics

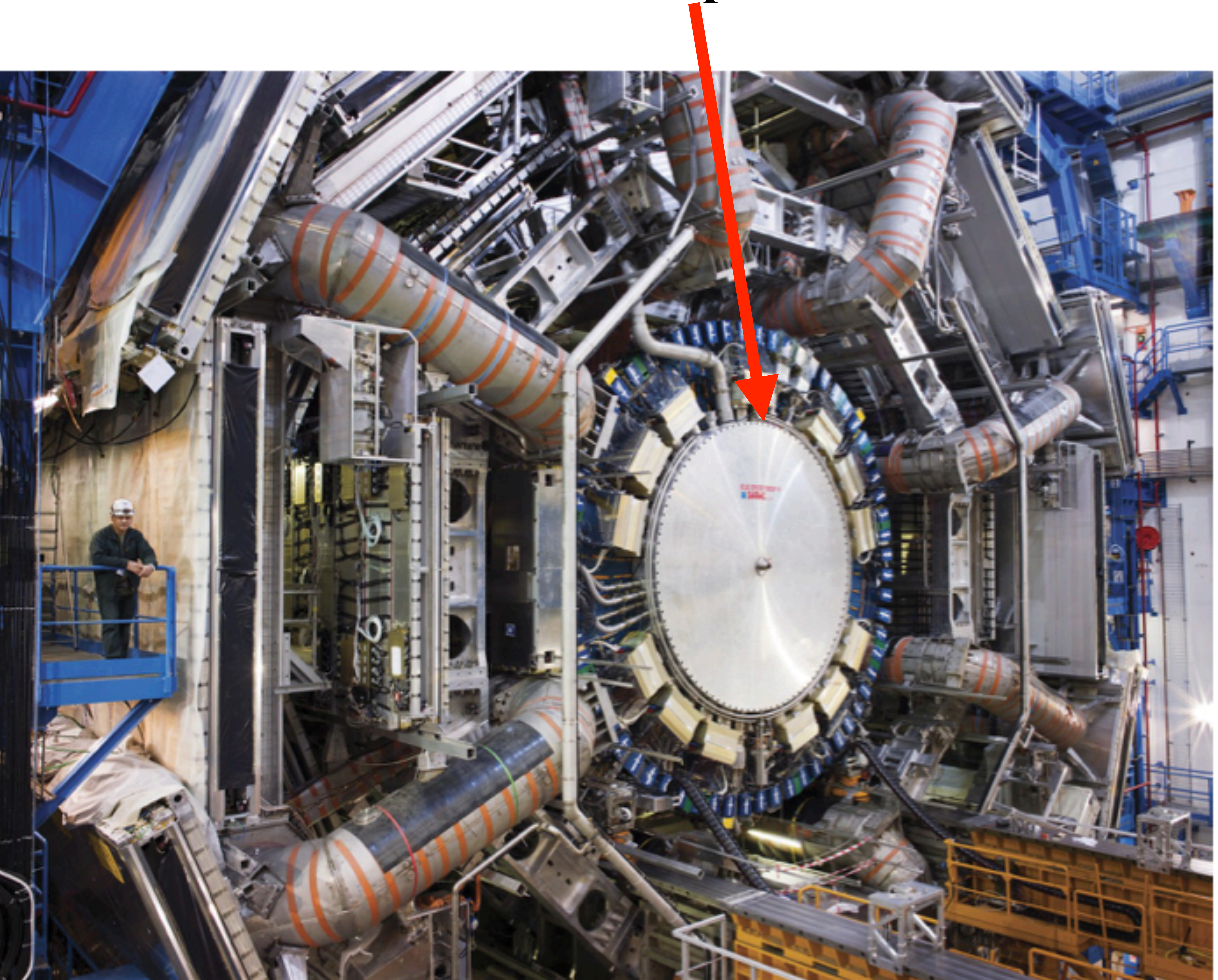
ALICE dedicated for
Heavy Ion collisions

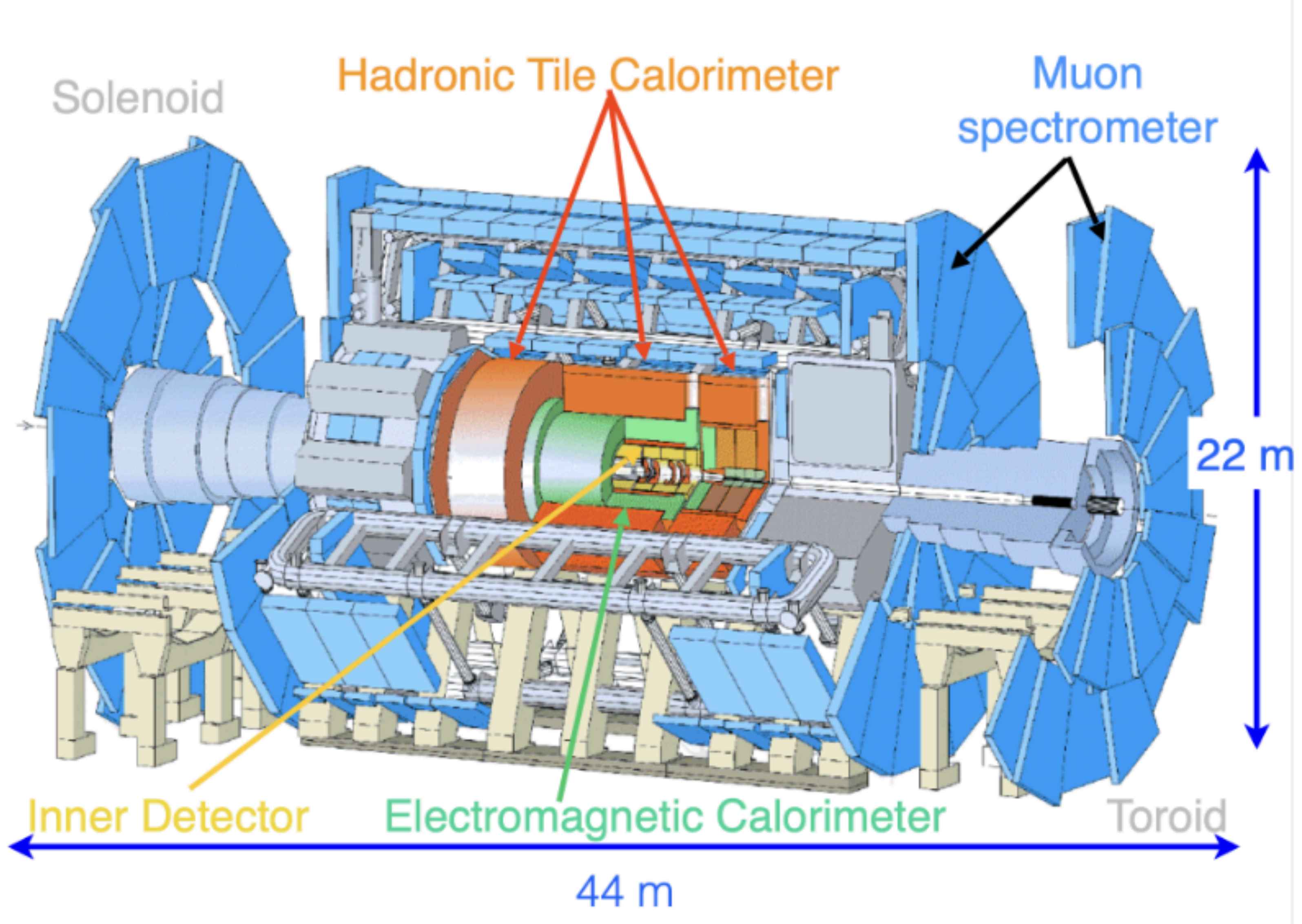
- 27 km circumference - former LEP tunnel at CERN.
- Proton-Proton Collisions (also ion-ion operation).
- Maximum 14 TeV center of mass energy.
- 4 Interaction Regions for Experiments.

Everything is LARGE at the LHC…

A Toroidal LHC ApparatuS - ATLAS Detector

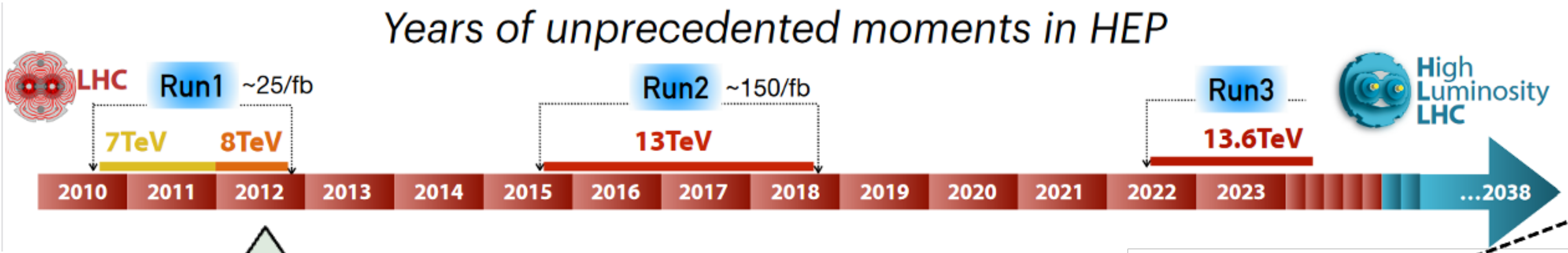
- A view of the ATLAS **Krampouz**





- **Tracking:**
  - $|\eta| < 2.5$, B=2 T
  - Si pixels and strips
- **Calorimetry:**
  - $|\eta| < 5$
  - **EM:** Pb-LAr
  - **HAD (Central):** Fe/scintillator
- **Muon spectrometer:**
  - $|\eta| < 2.7$
  - “air core toroids” with muon chambers

LHC - Collider Figures of Merit

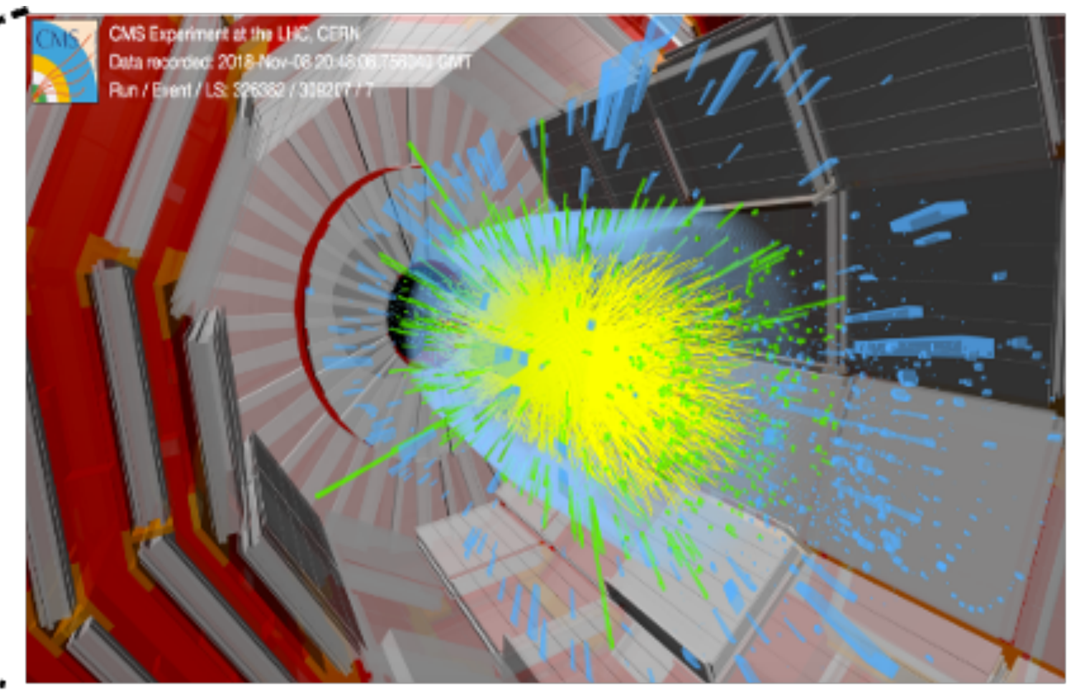


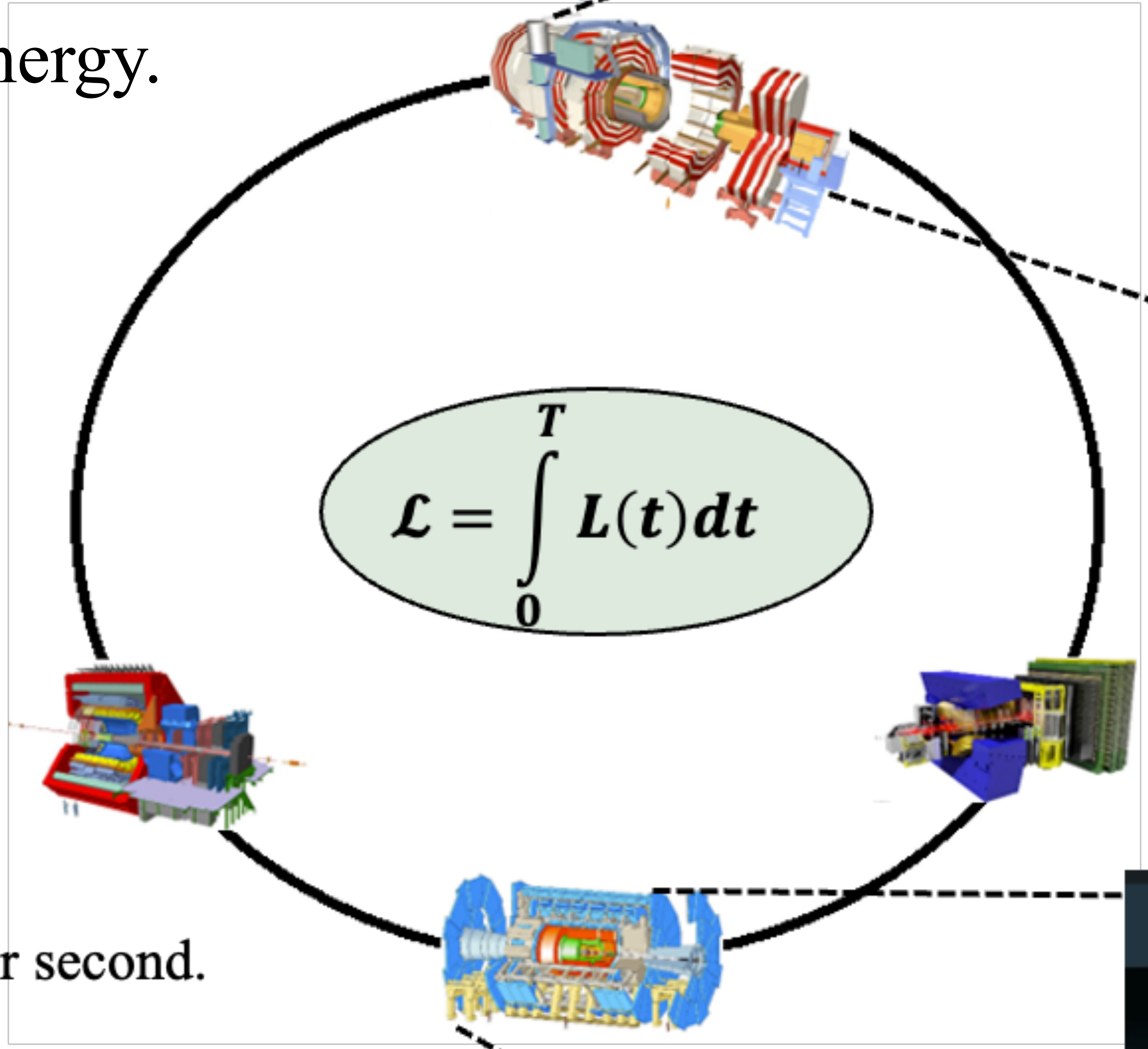
Collision Energy

Key Figures

Luminosity

✦ Maximum 14 TeV center of mass energy.



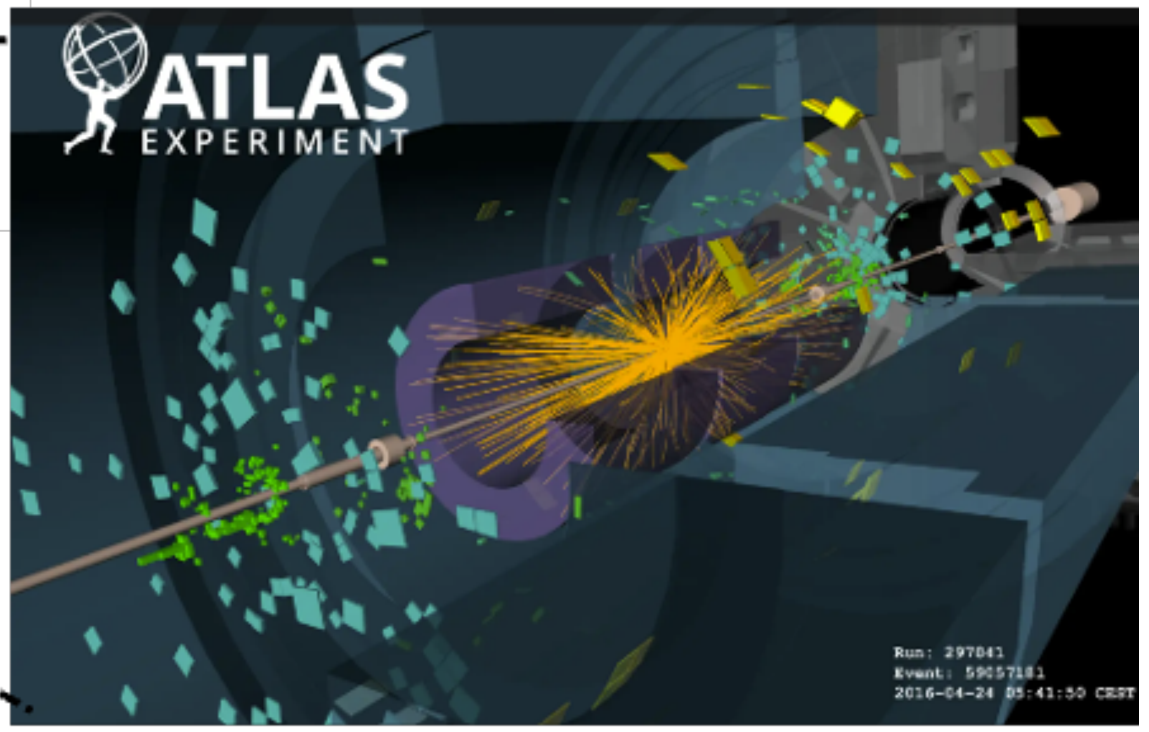


$$\frac{dR}{dt} = L(t) \times \sigma_{int}$$
$$[\, cm^{-2} s^{-1}]$$

$$\mathcal{L} = \int_0^T L(t)dt$$

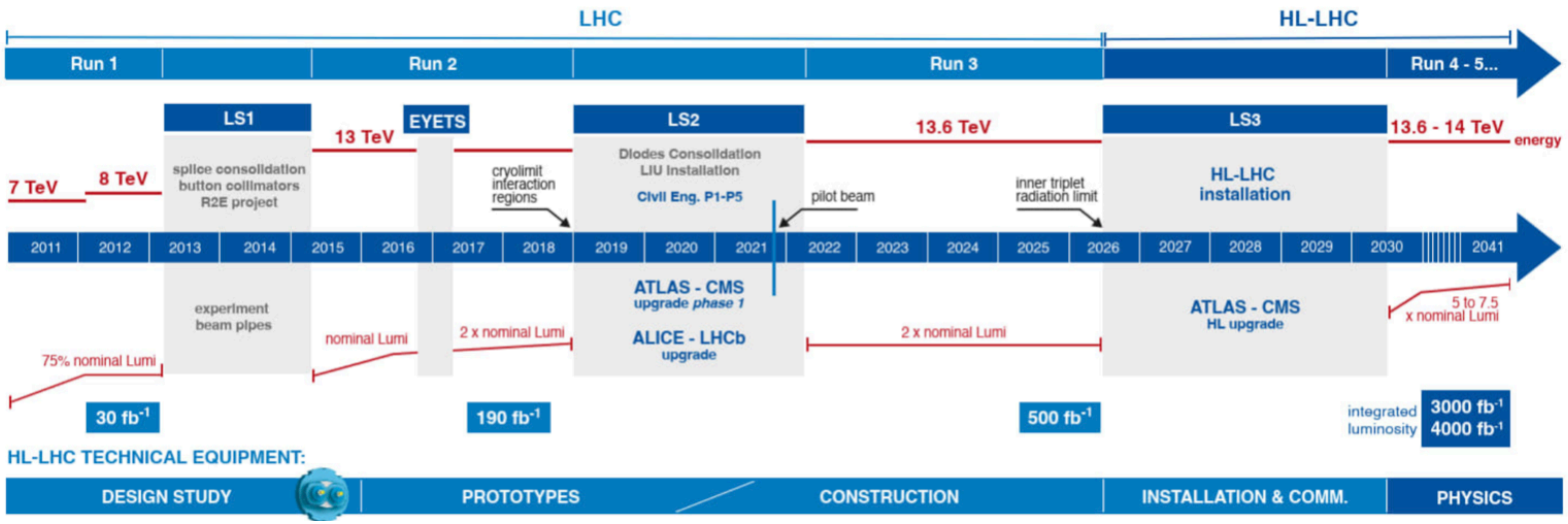
$$R = \sigma_{int}\mathcal{L}$$
$$[\, fb^{-1}]$$
$$(fb^{-1} = 10^{39} cm^{-2})$$

- $\frac{dR}{dt}$: Number of events per second.
- σ_{int}: Cross section.
- $L(t)$: Instantaneous luminosity.
- $\mathcal{L}$: Integrated luminosity.



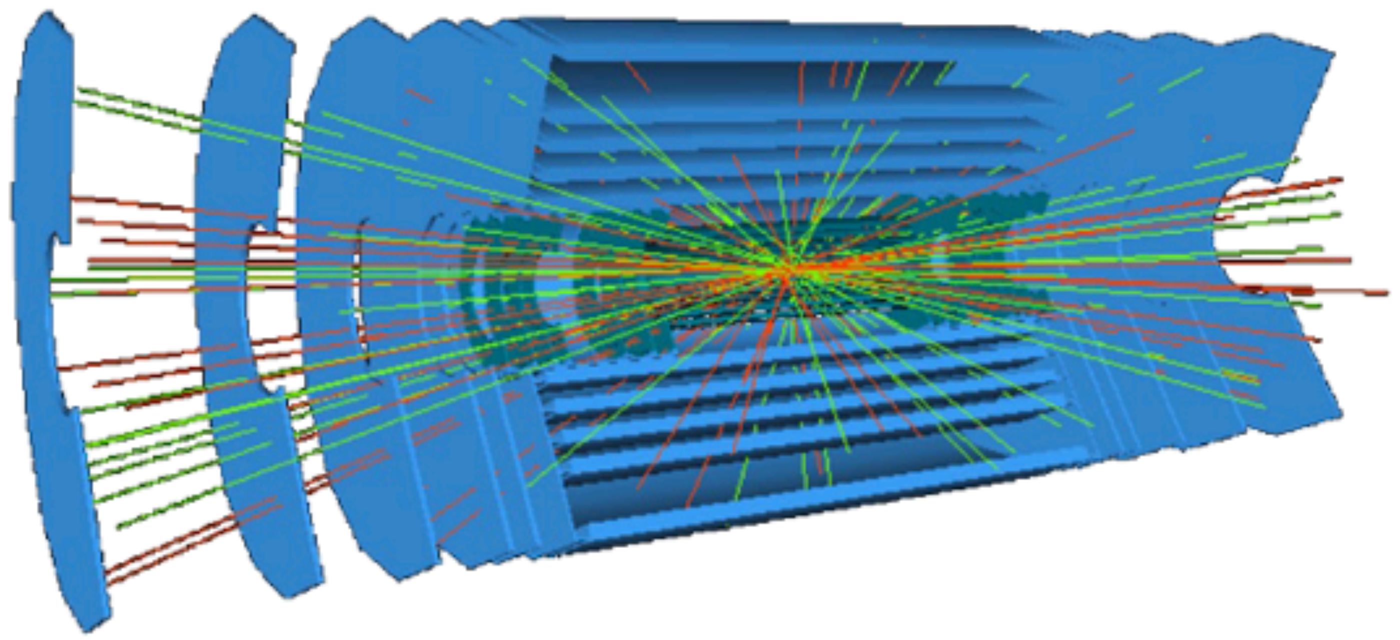
Luminosity is a Machine Parameter ✦ Independent of the physical reaction.

High Luminosity LHC Upgrade (HL-LHC)



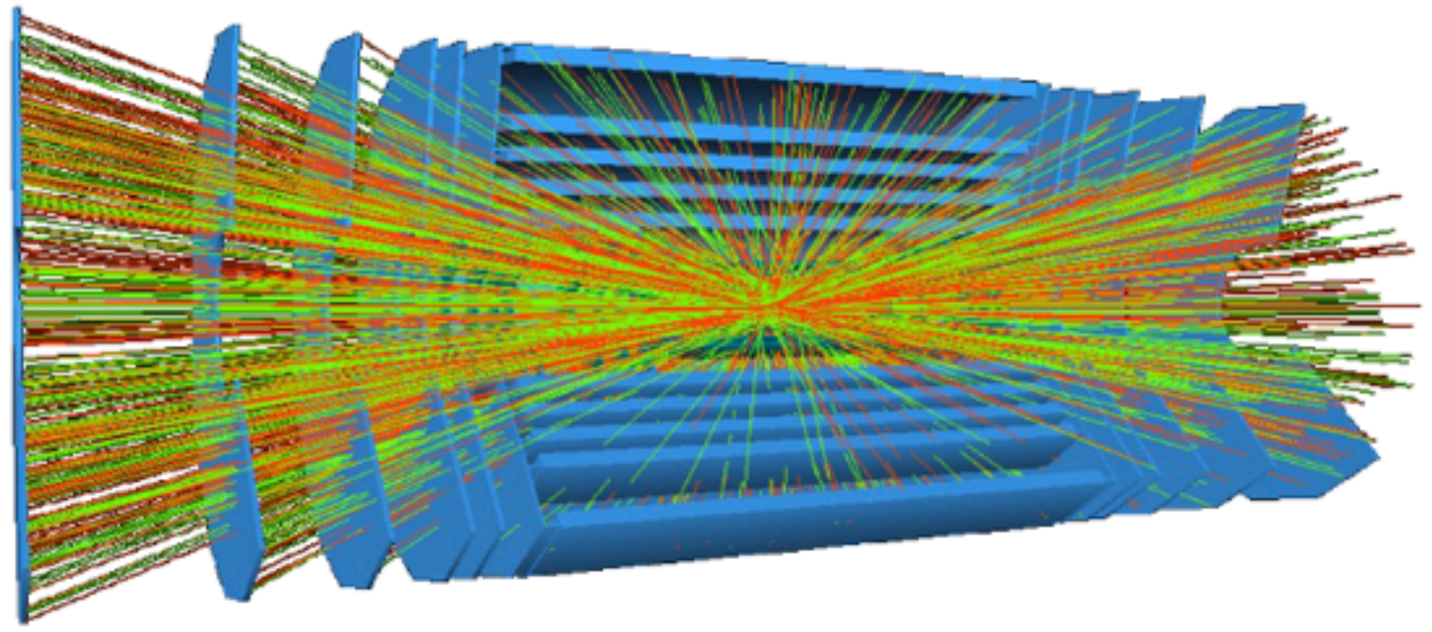
LHC: Inner Detector (ID) system, TRT (gas detector) + Strips + Pixels (with new Insertable B-Layer)

HL-LHC: New all-silicon **Inner Tracker (ITk)**, Strips + Pixels



LHC:
19 – 55
pile up events

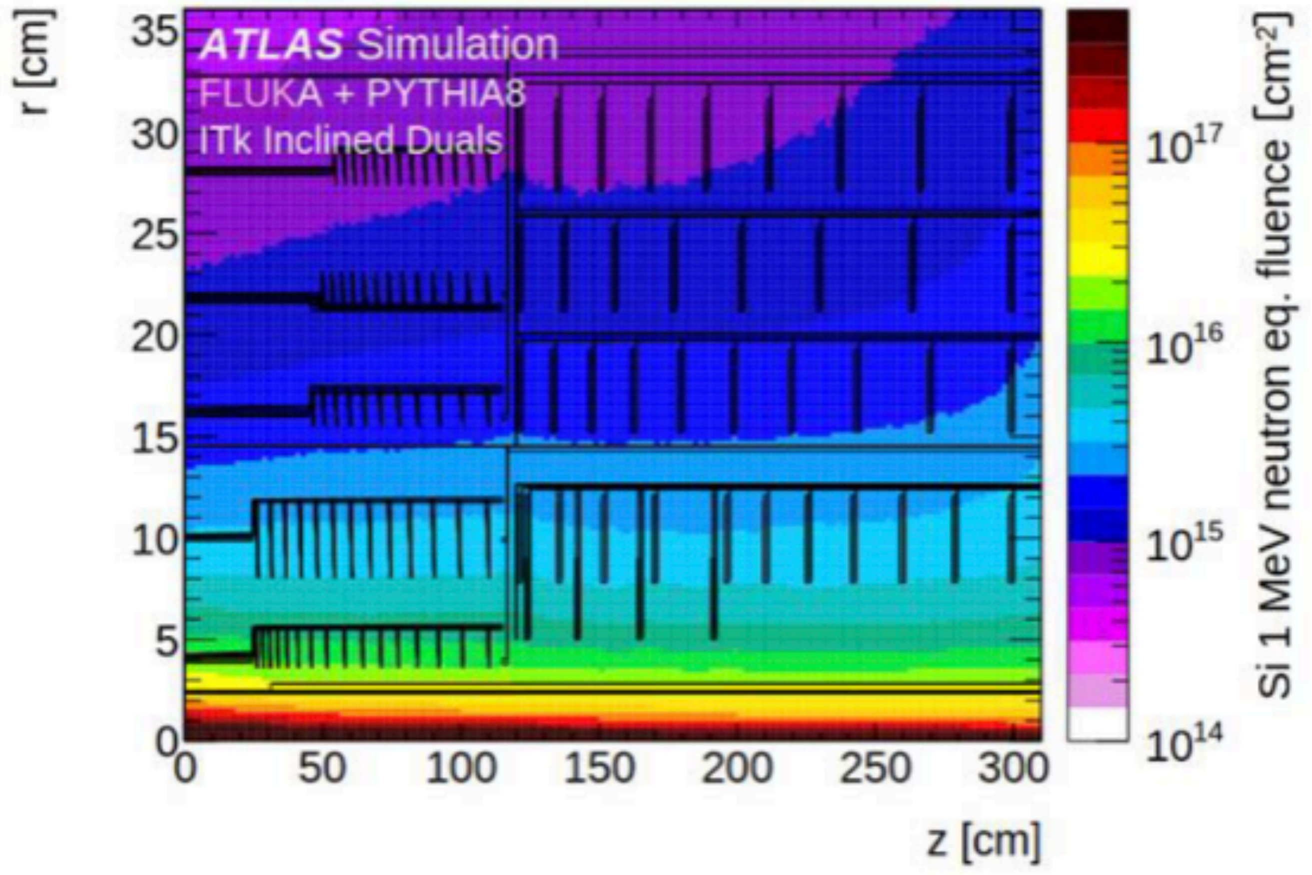
HL-LHC:
140 – 200
pile up events

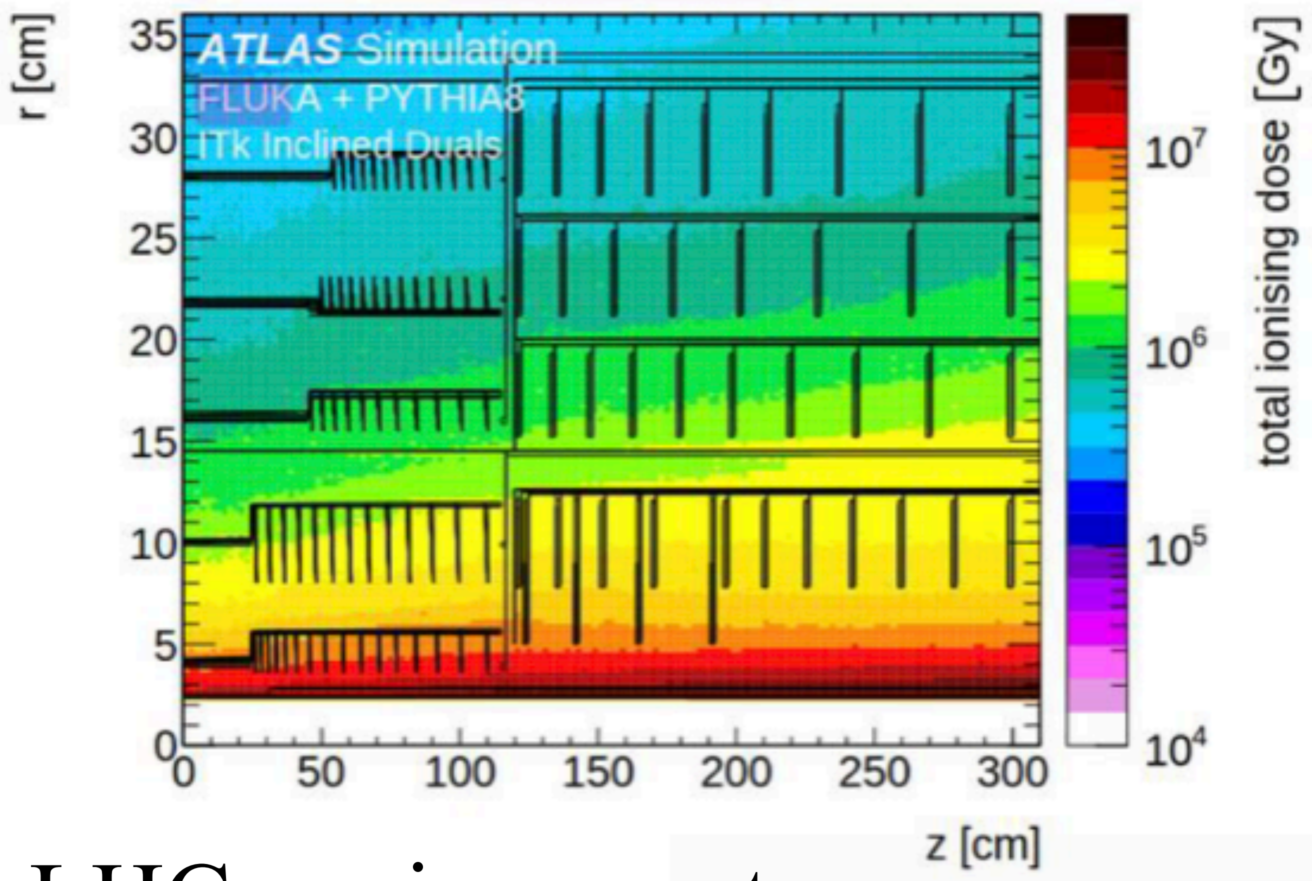


Challenges and Goals at HL-LHC

✦ HL-LHC is a Challenge !

- Instantaneous nominal luminosity **x 5-7** and integrated luminosity **x 10**
  - New radiation hard sensors - complete new tracker
  - Finer sensor granularity
- Increase of overlapping proton-proton events (pile-up) from **<μ> ~ 50** now to **<μ> ~ 200**:
  - Additional energy in calorimeters, accumulation of "pile-up" jets especially in the forward region, High hit rates of up to 3GHz/cm^2 in tracker center, increased occupancy.
- Integrated effects:
  - **Radiation hardness** → Particle fluence up to 2x10^{16} n_{eq}/cm^2 in Pixel Region and 1.6x10^{16} n_{eq}/cm^2 in Strip Region → Total ionizing dose (TID) up to 1MGy.





✦ Physics Goals are Ambitious !

- Require same (or improve) current ID tracking performance, despite the harsher HL-LHC environment.
  - Keep excellent b-jet tagging and lepton tracking
  - Pile-up rejection for jets and missing E_T.
- Processes like **Vector Boson Fusion (VBF) Higgs Production** call for an extended η coverage (< 4)

HL-LHC and ATLAS upgrade

✦ Inner Tracker (ITk) detector upgrade planned for the HL-LHC phase of ATLAS

- The LHC is to be upgraded for higher luminosity ($1x10^{34}cm^{-2}s^{-1}$ to $7.5x10^{34}cm^{-2}s^{-1}$), number of events per bunch encounters (50 to 200) to improve probing SM and BSM. n_{eq}/cm^2 $1.10^{34}cm^{-2}s^{-1}$
- ATLAS must be able to distinguish very close particles, at high frequency
- Must withstand high irradiation fluence in its end of life (up to $2x10^{16}n_{eq}/cm^{-2}s^{-1}$ with a 1.5 safety factor)
- Need for new Particle Tracker for accurate particle identification: ATLAS ITk Pixel Detector.

✦ The current Inner Detector System will be replaced with a Detector New All-Silicon Tracking System - **ITk**

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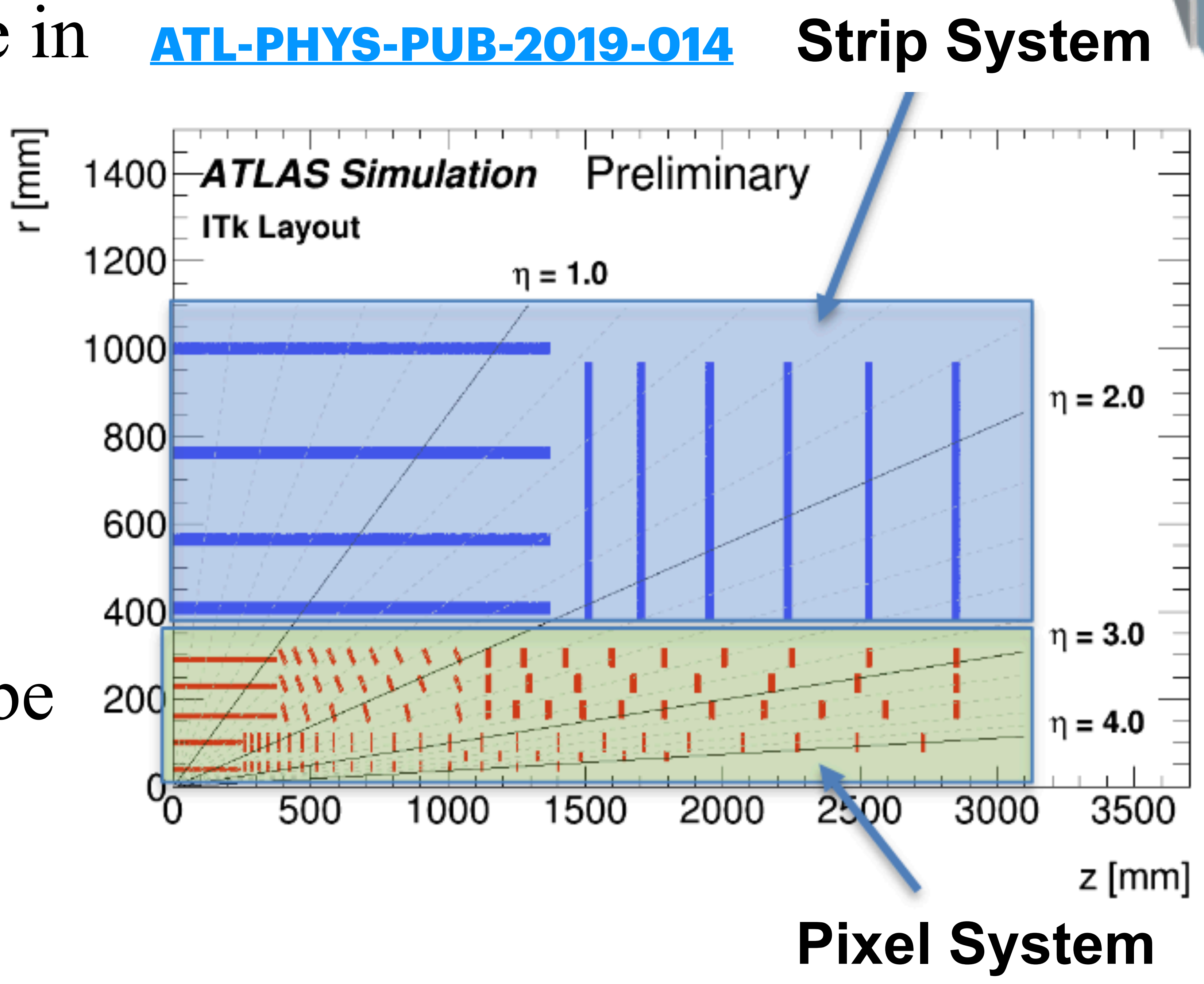
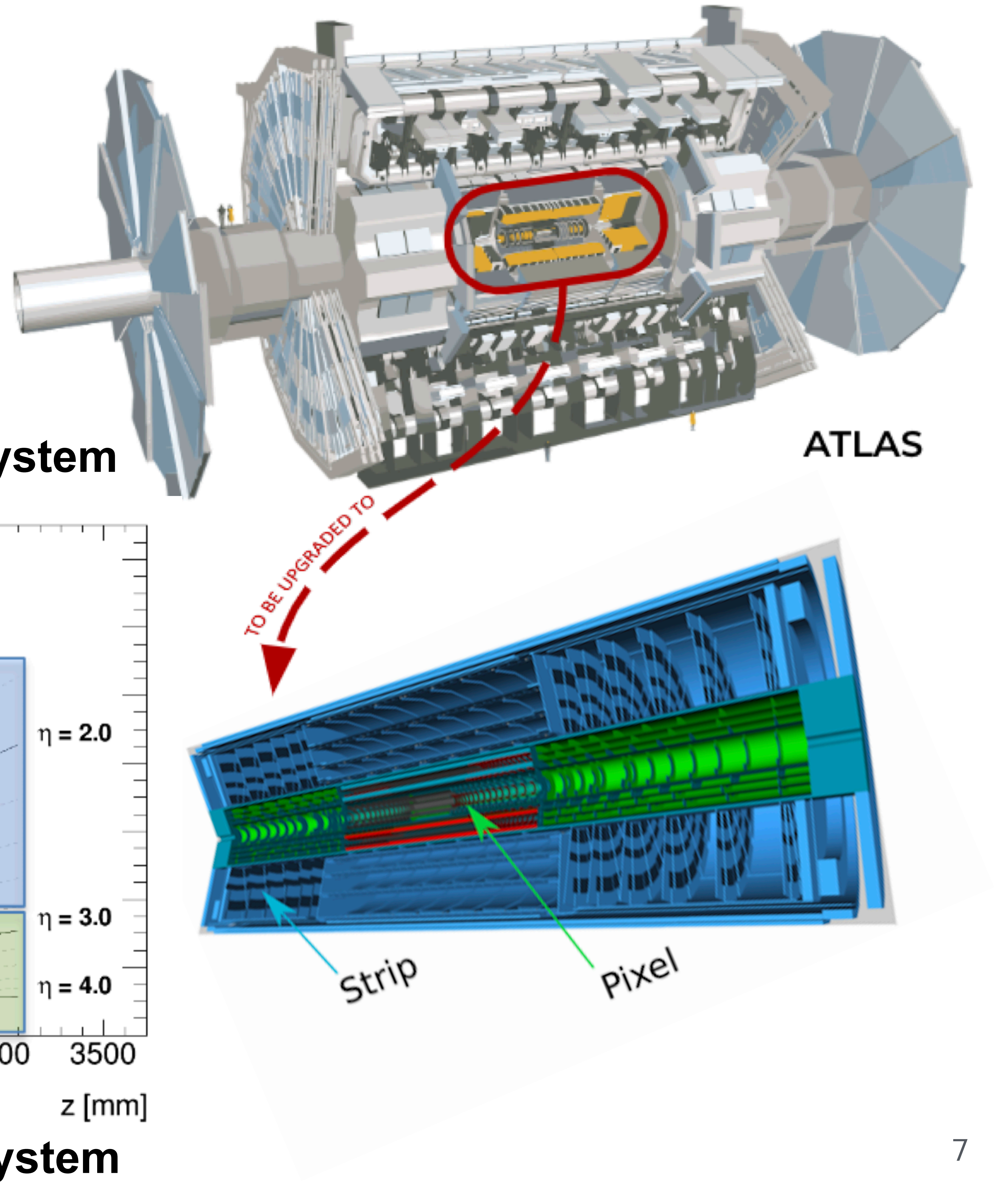
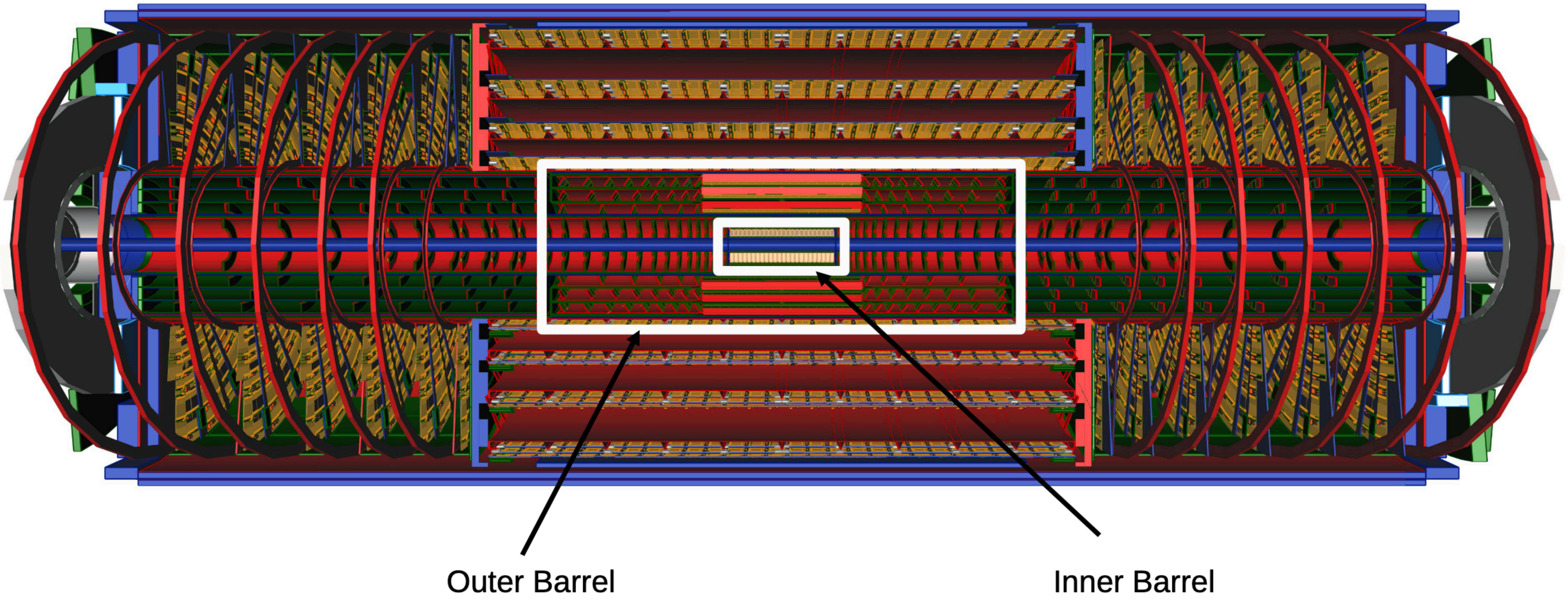
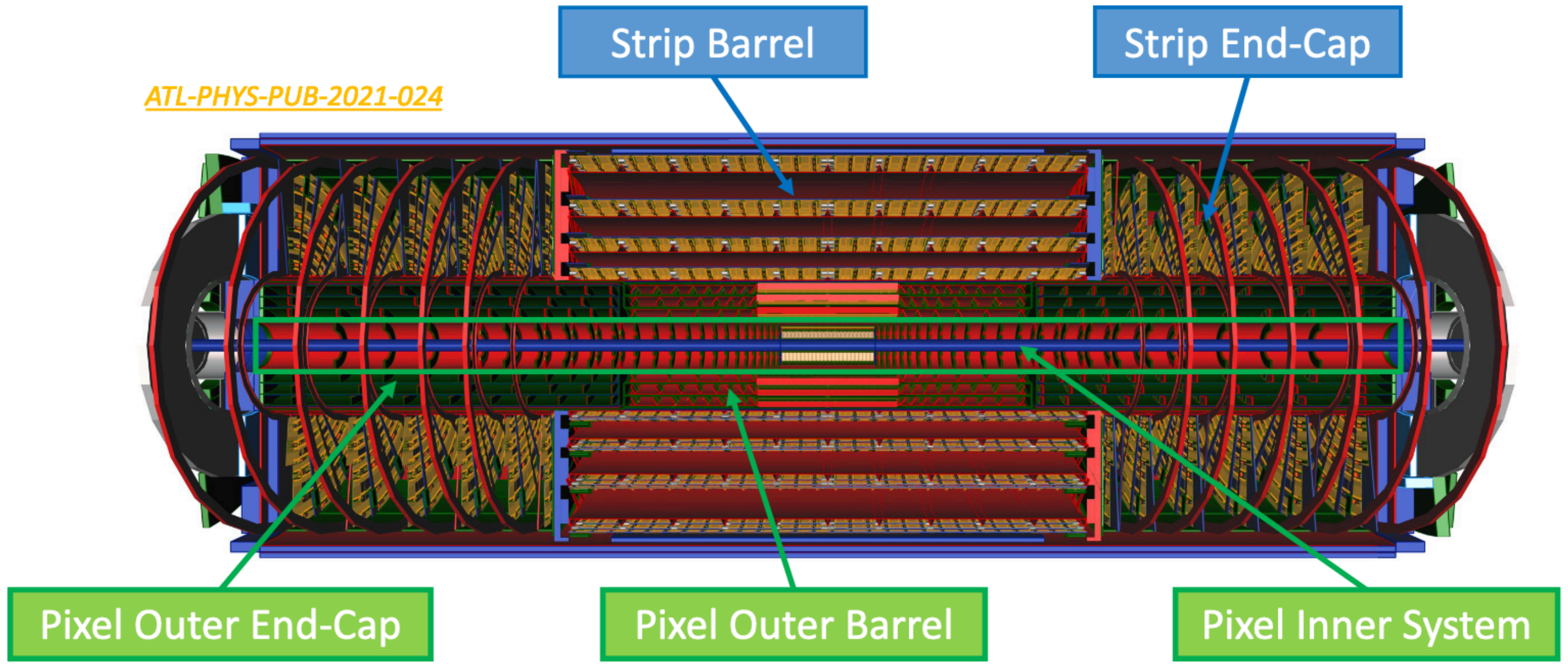


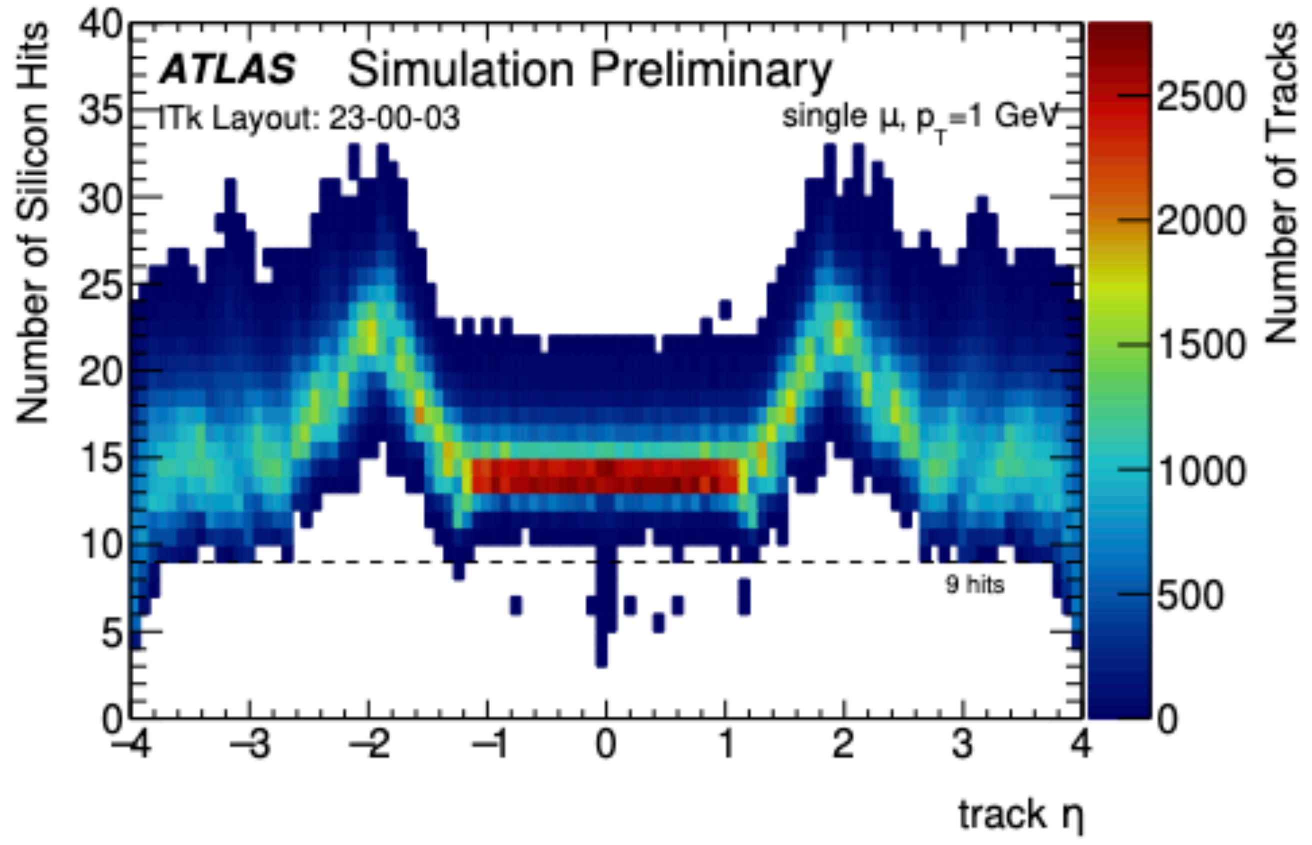


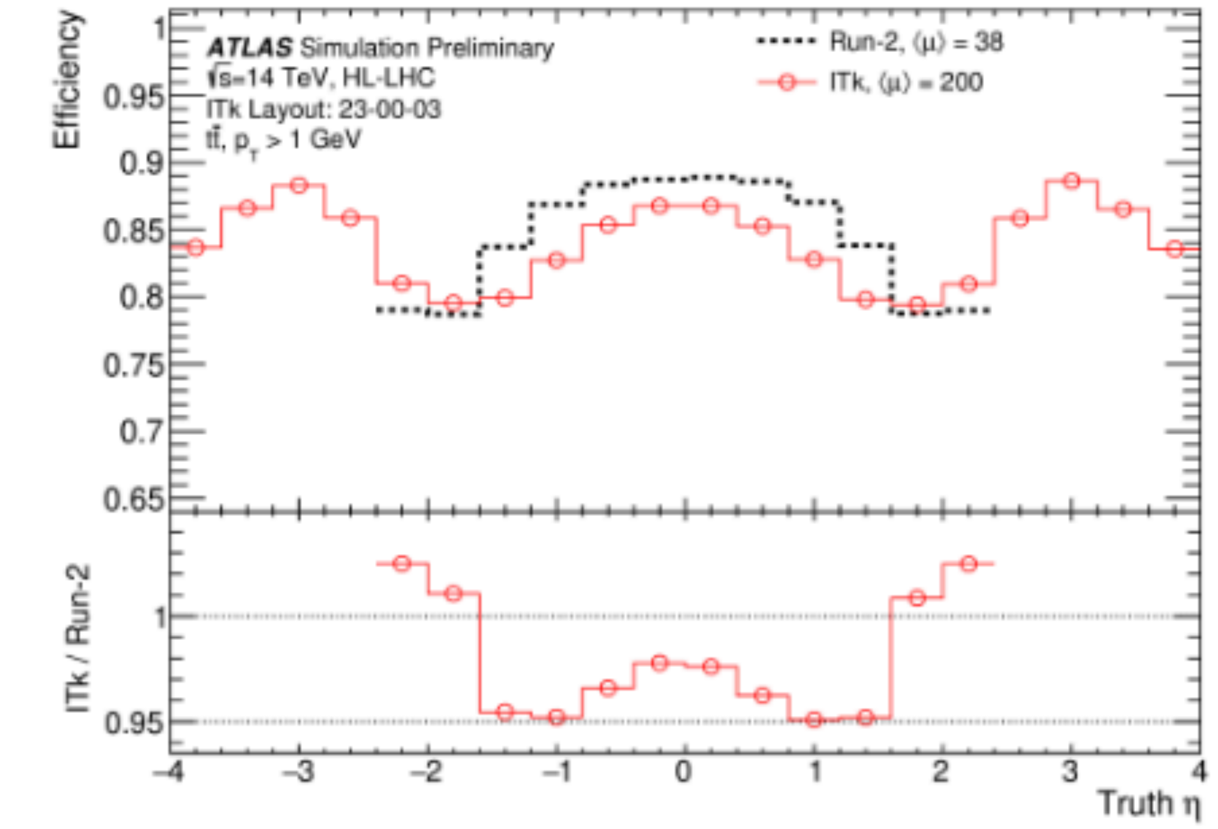
The ATLAS Inner Tracker - ITk



The ATLAS Inner Tracker - ITk







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✦ ITk tracker consists of outer strip tracker and inner pixel tracker to replace current ATLAS "Inner Detector"

- 165 m^2 of silicon strip and 13 m^2 of silicon pixel
- designed to withstand up to 10^{16} n_{eq}/cm^2 on inner most pixel

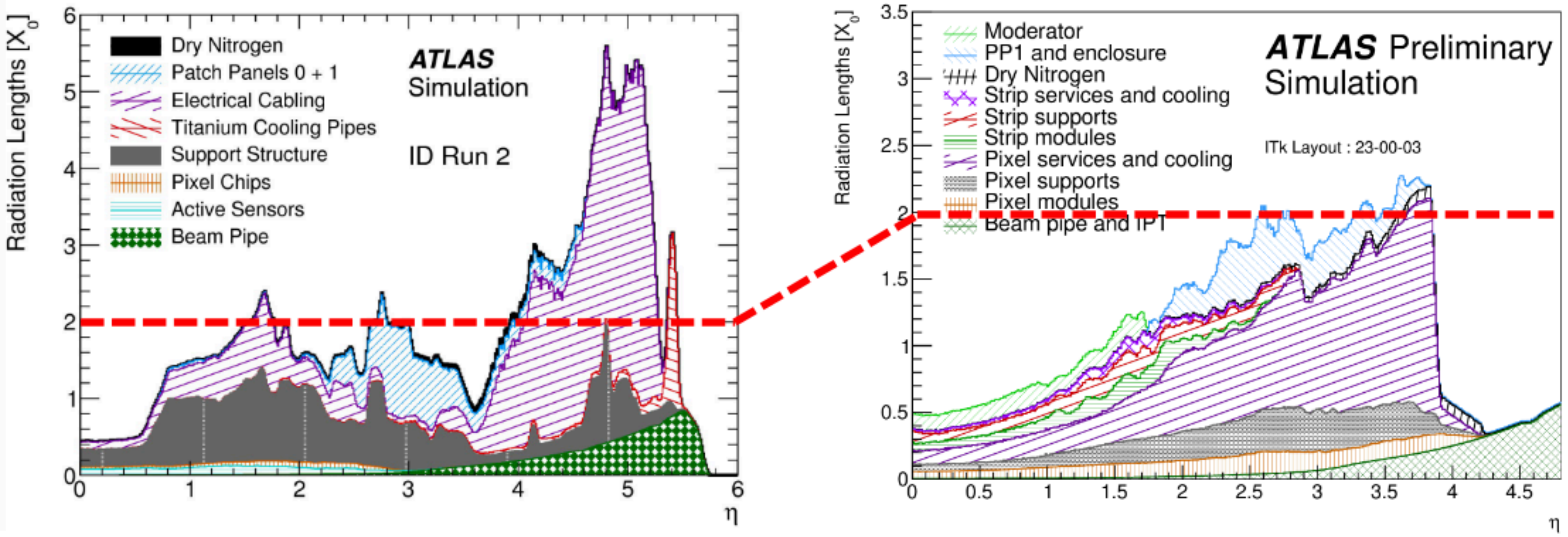
ITk (ID)	Area (m²)	# Modules	# Channels (M)
Pixels	13 (1.6)	9164 (2000)	5100 (92)
Strips	165 (61)	17888 (4088)	60 (6.3)

✦ Current status & activities

- Global ITk support mechanics in production
- CO2 Cooling studies and optimisation
- Preparation for ITk integration in ATLAS Point 1
- The Production of ITk module will start early 2025

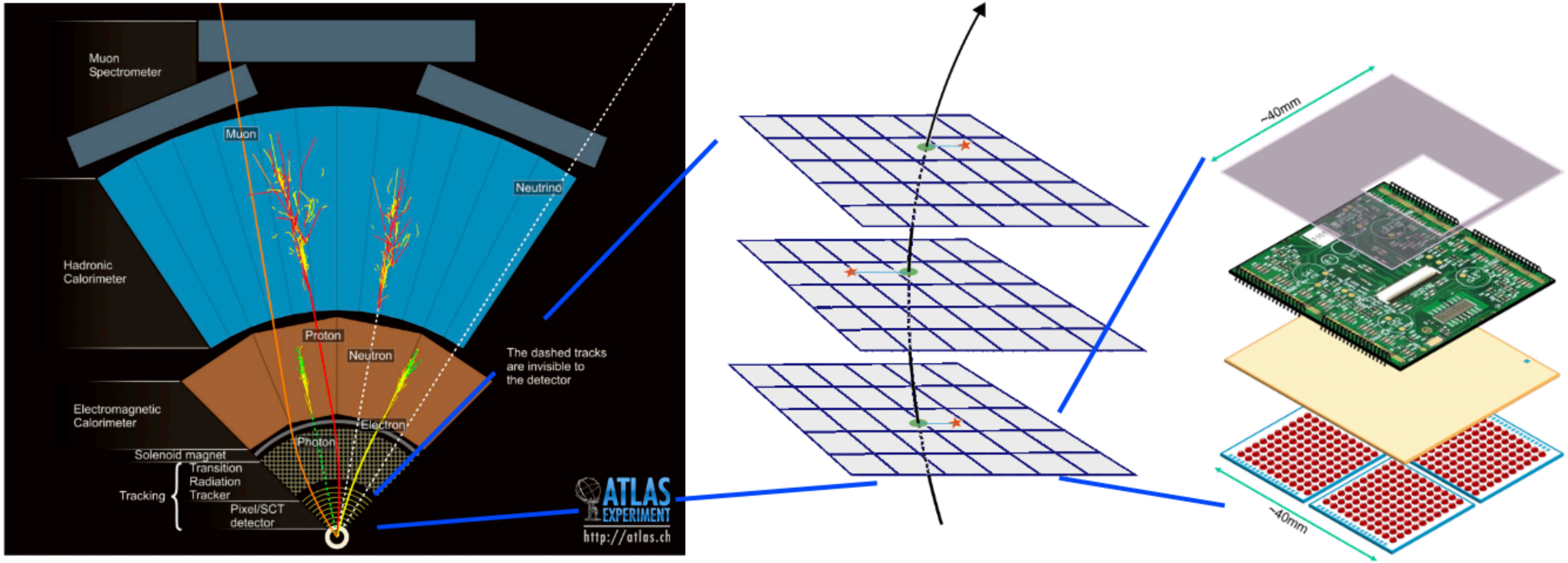
✦ Improve impact parameter resolution and robust tracking

- Coverage increases from |η|<2.5 (ID) to |η|<4 (ITk)
- Provides >9 silicon hits per track
- Reduced material and finer segmentation



ITK Principle

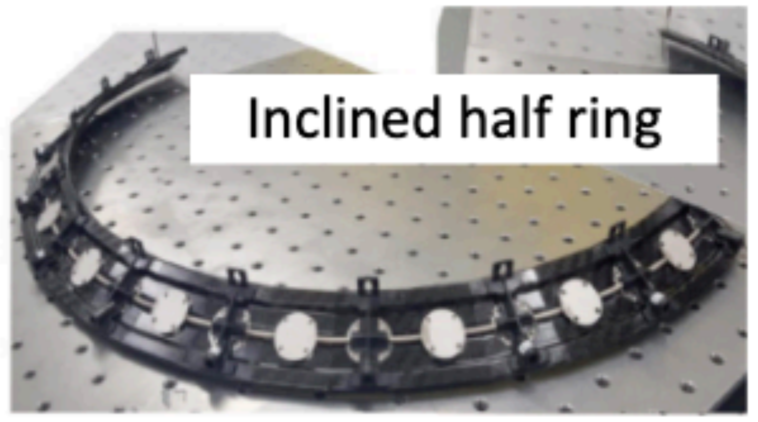
✦ ITK is a particle tracker → Find particle path to identify them.

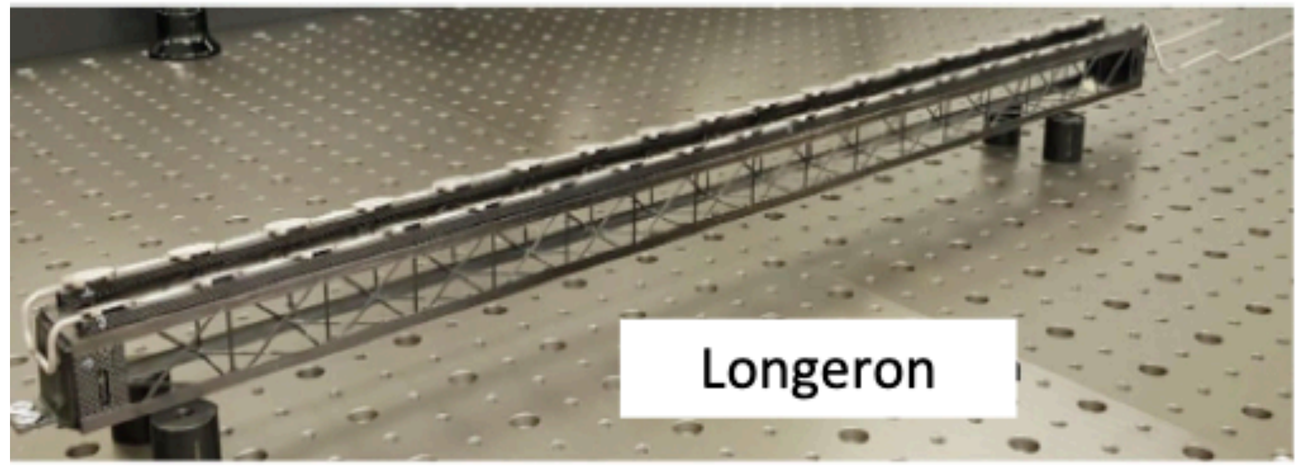


- Particles created at the interaction point → strong magnetic field → bending charged particles trajectory.
- Crossing pixels → deposit energy → detection.
- Layers of pixels: coordinate on each layer → bended track radius, association with other observed particles, origin of the vertex.
- Radius, orientation of curve, magnetic field intensity → particle mass, energy...

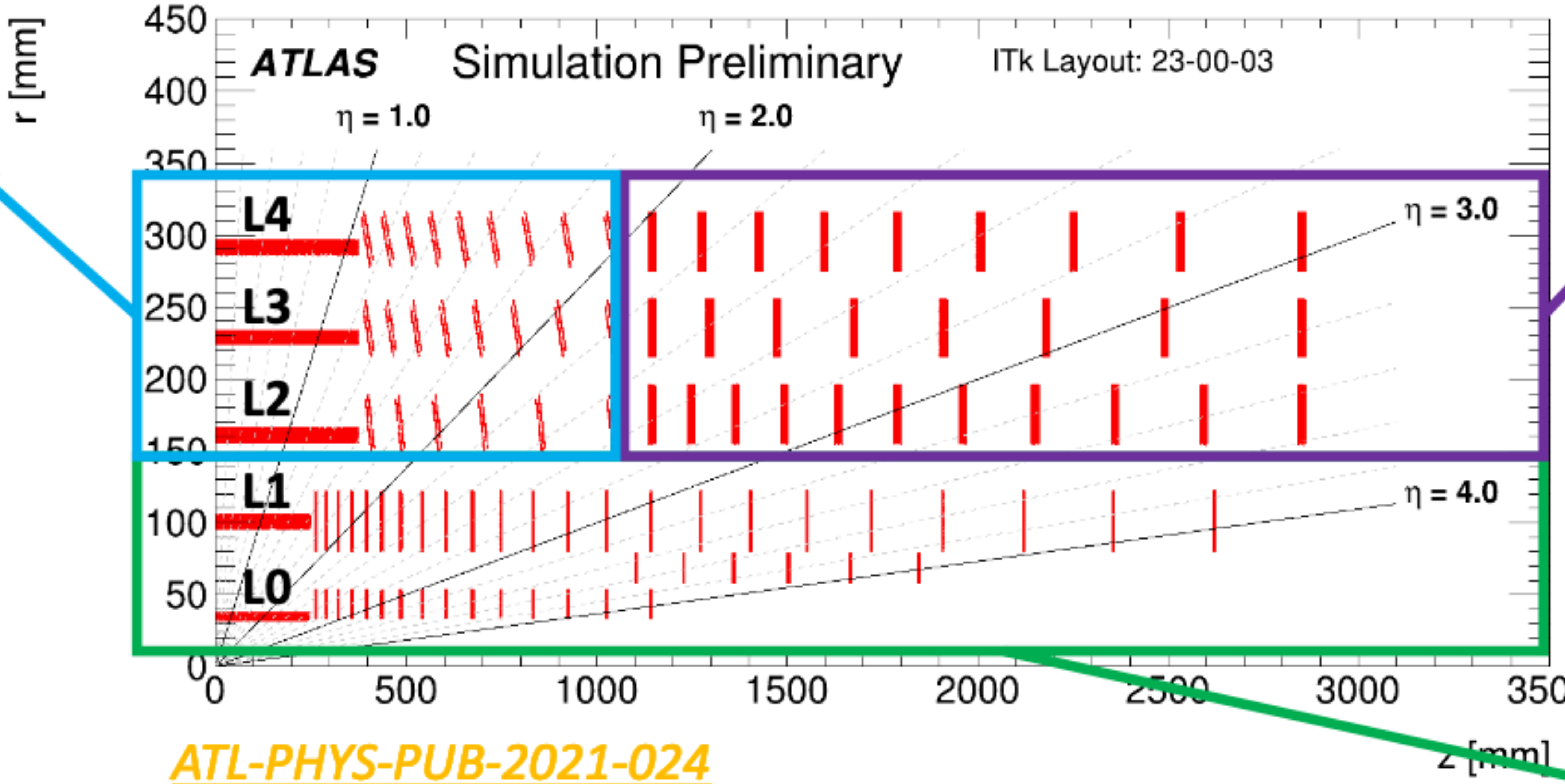
ITK Pixel Modules

- **Modules**: two main module types, quad & triplet. (Variations of pixel size and sensor thickness within each type)





Outer Barrel (OB)



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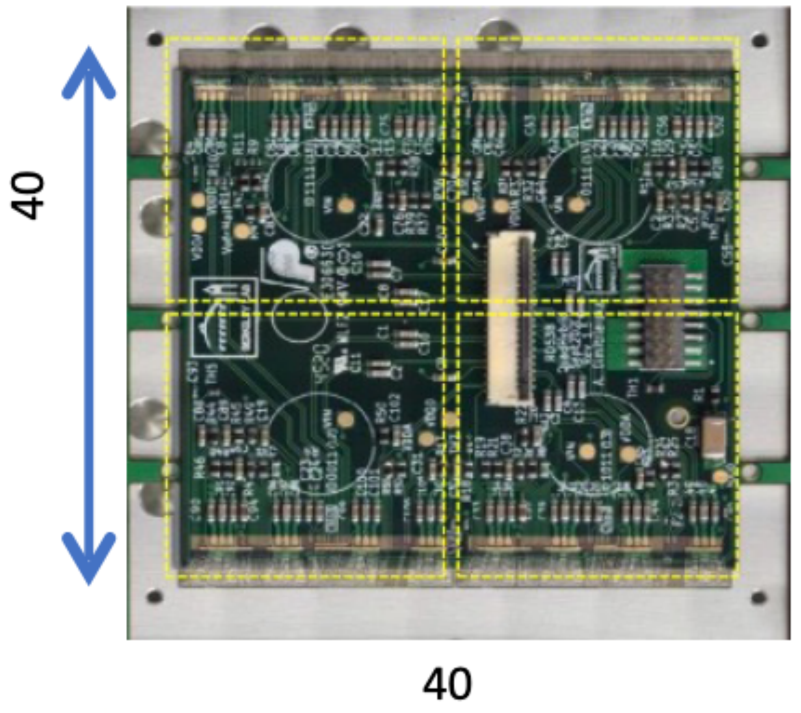
Outer End-Cap (EC)

- Outer Pixel system (OB & EC): 3 layer of planar quad modules

- Inner System (IS): 1 layer 3D sensors (L0) + 1 layer planar Quad modules (L1) → to be replaced after 2000 fb^{-1} to reduce radiation damage.

Inner Krampouz (IS)

Layer 1 – Layer 4



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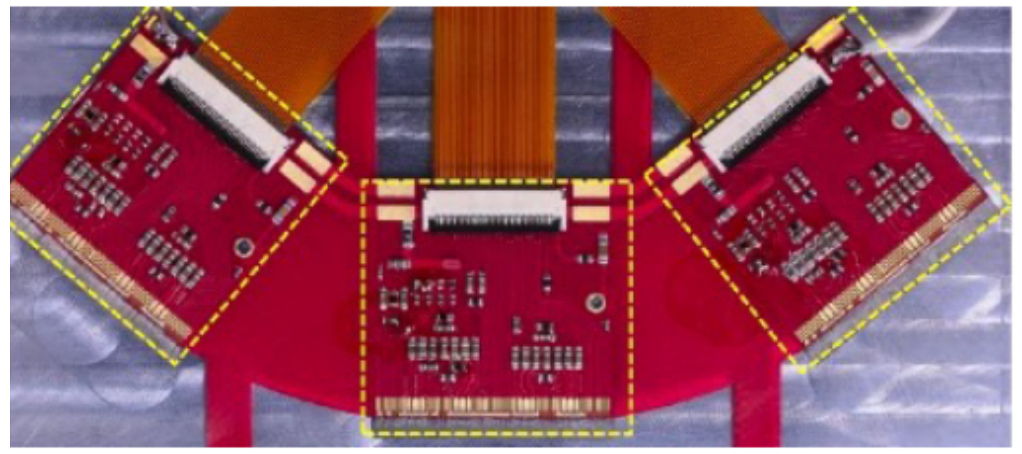


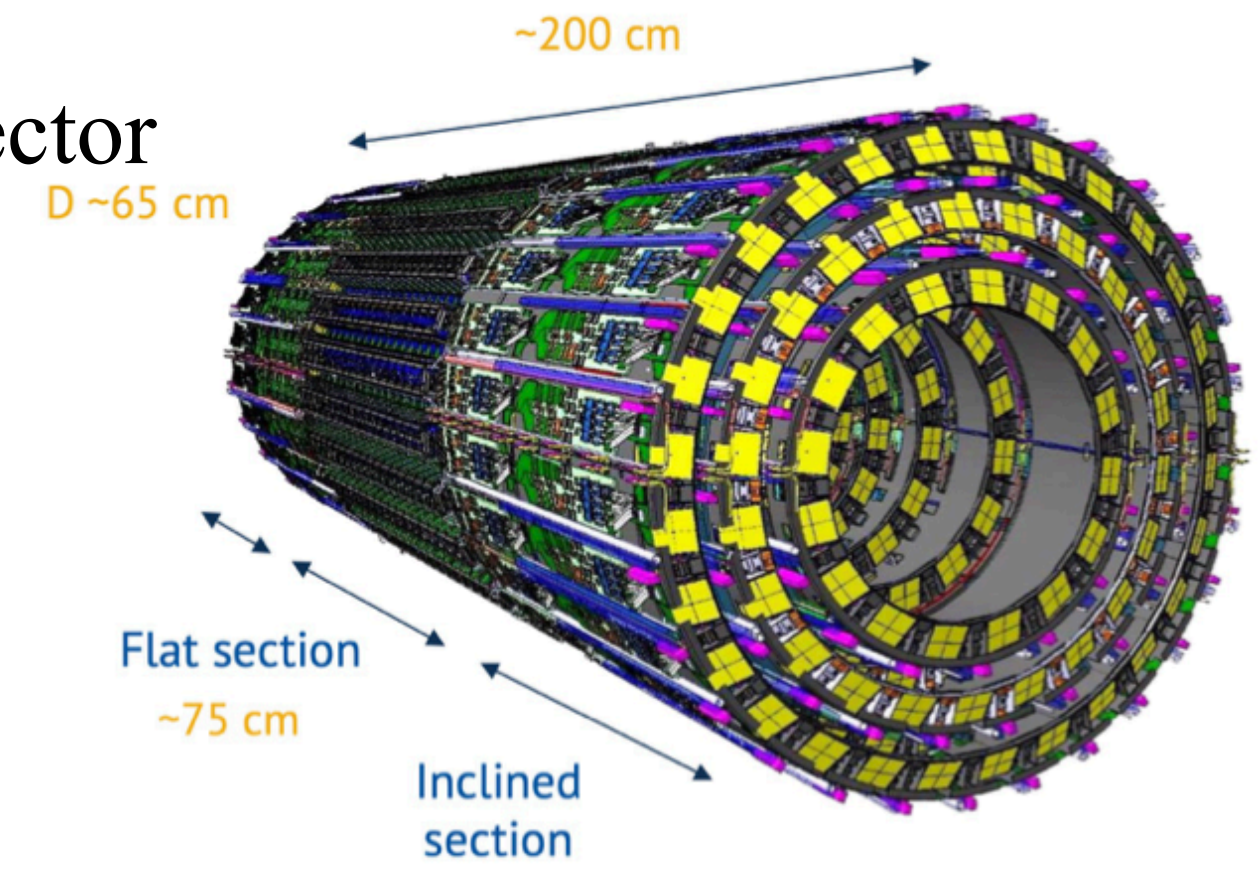
Layer 0

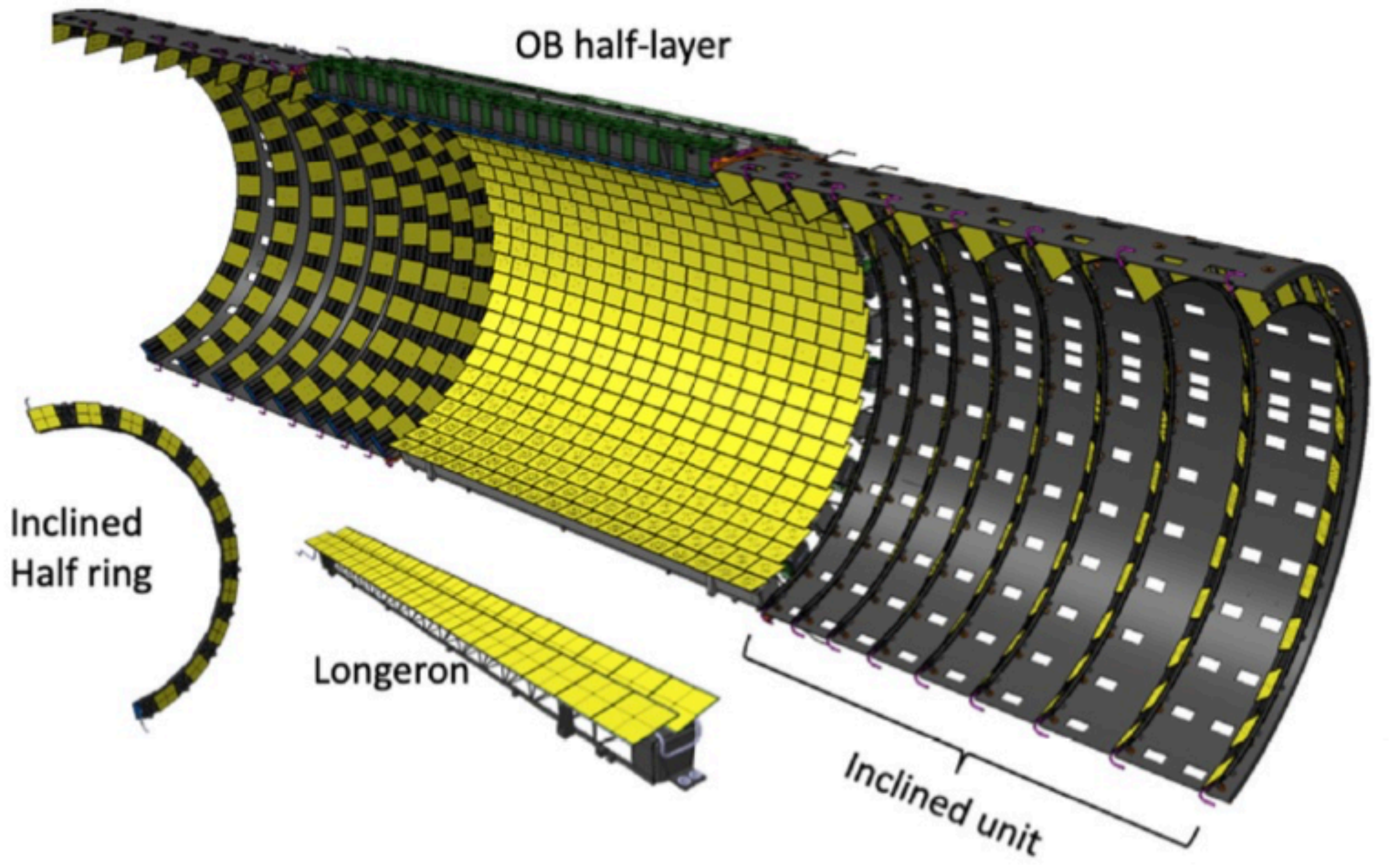
Layer	Module type	Sensor type	Sensor thickness [um]	Pixel size [um^2]
L0 barrel	Triplet	3D n-in-p	150	25x100
L0 rings	Triplet	3D n-in-p	150	50x50
L1	Quad	Planar n-in-p	100	50x50
L2-4	Quad	Planar n-in-p	150	50x50

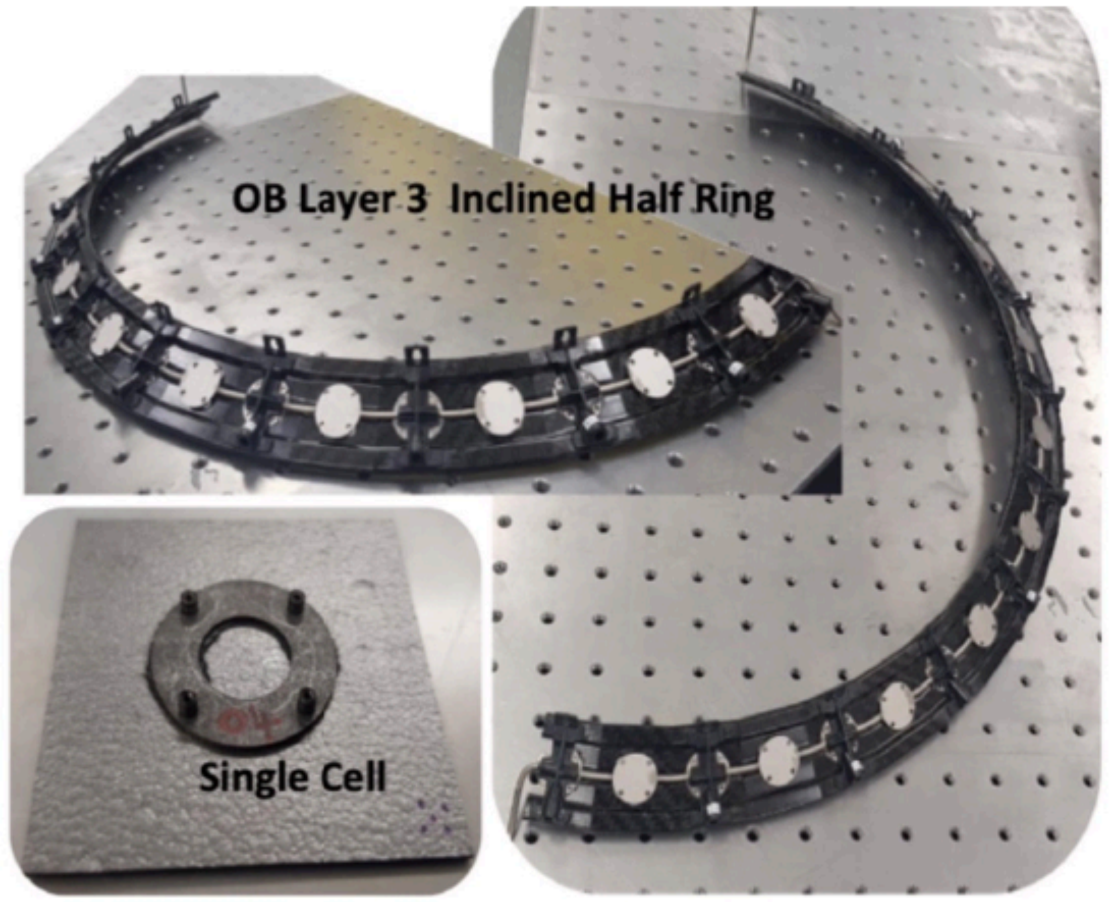
The Pixel Outer Barrel (French Groups Involvement)

✦ **Pixel Outer Barrel (OB), 3 coaxiales cylinders**

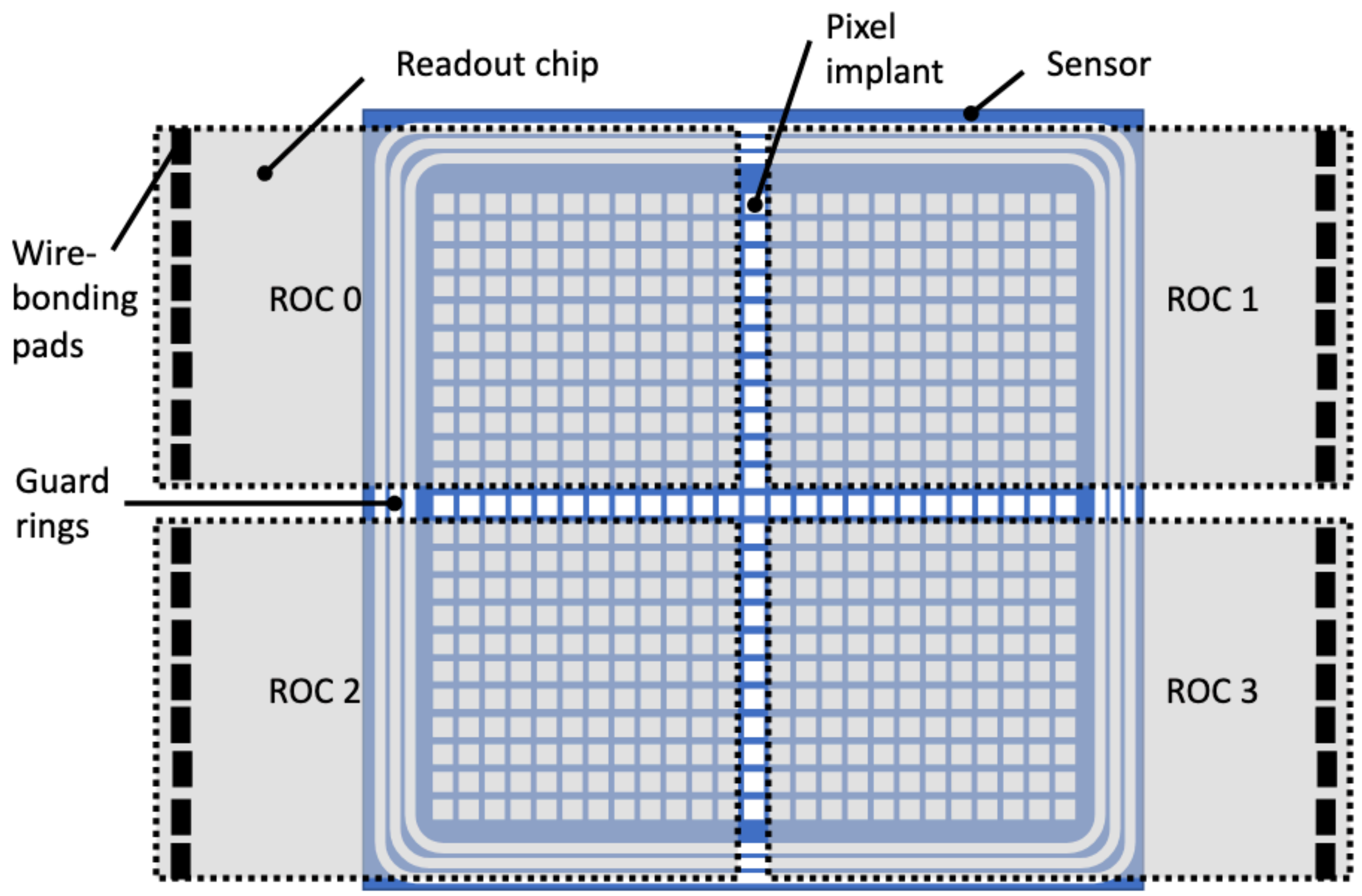
- Outer barrel is the largest system of ITkPixel detector
  - ~4.5k Modules, ~50% of ITk-Pixel Modules.
- International Collaboration:
  - CERN, Japon, **France**, Germany, Switzerland
- French activities are organised in two clusters:
  - **Paris Cluster: IJCLab/IRFU/LPNHE**
    → For module assembly and testing.
  - **ALPACA Cluster: CPPM/LAPP/LPSC**
    → For loading and integration.







ITK Quad Module Concept



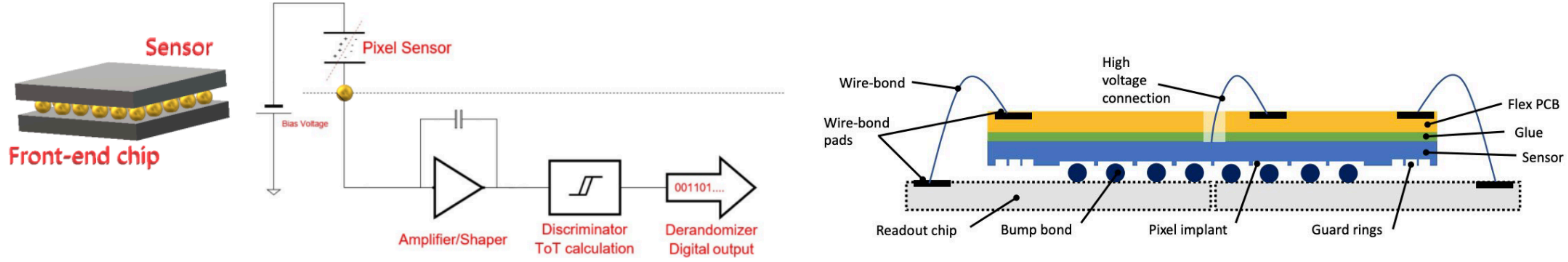
(a) Top view

The baseline ITk module concept for the quad chip configuration employing thin planar n-in-p sensors. Basic building block is the pixel module → Top view in (a) and side view in (b) Schematics of a hybrid quad module

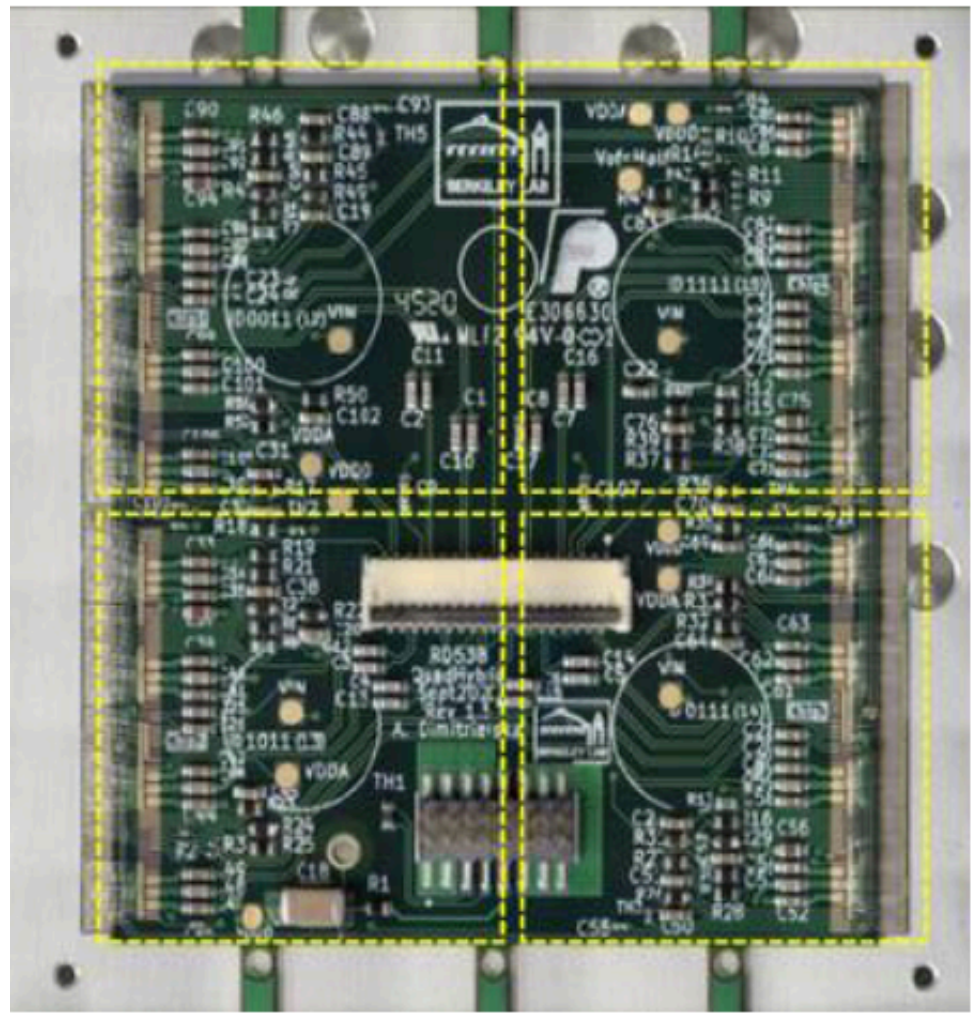
Pixels → $50 \times 50\ \mu m^2$ Si n-in-p planar sensors with a 150µm thick substrate.

Sensor → are bump-bonded to read-out front-end chips → bare-module.

Bare-module → then glued and wire-bonded to a flexible PCB (Printed Circuit Board) → Module.

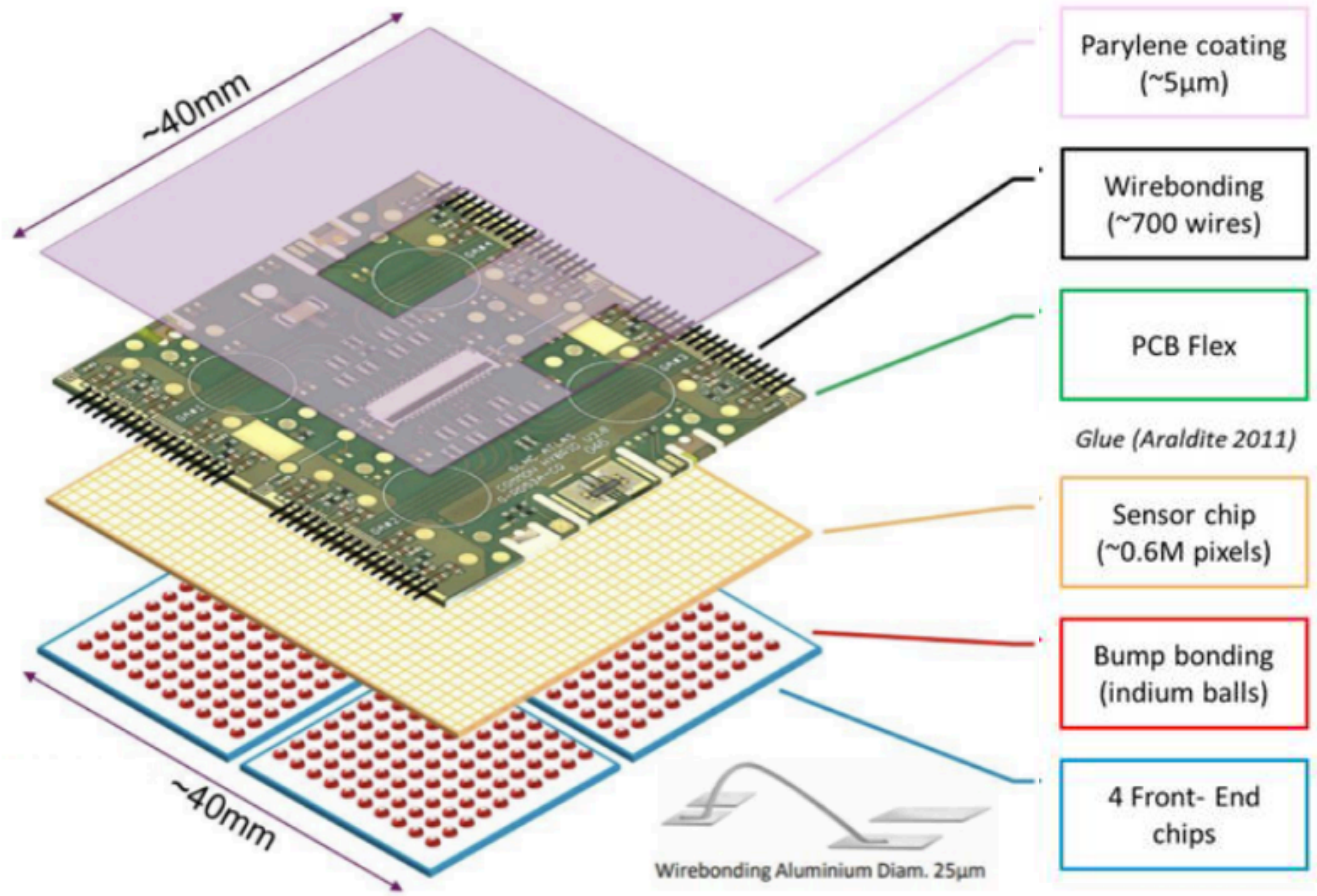


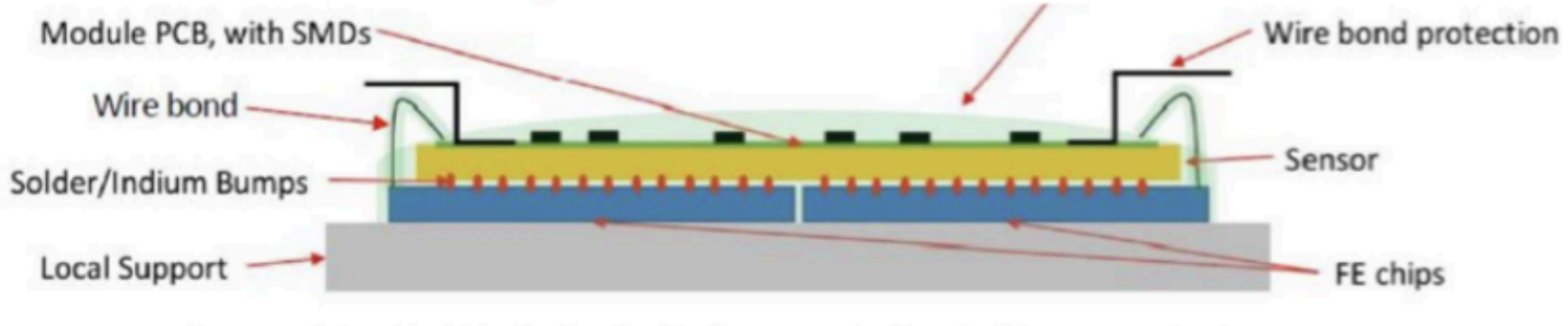
(b) Side view



- Particles passing in Si sensor → electron-hole pairs are created by ionization.
- Bare-module → then glued and wire-bonded to a flexible PCB → Module.

ITK Flex & Module Assembly



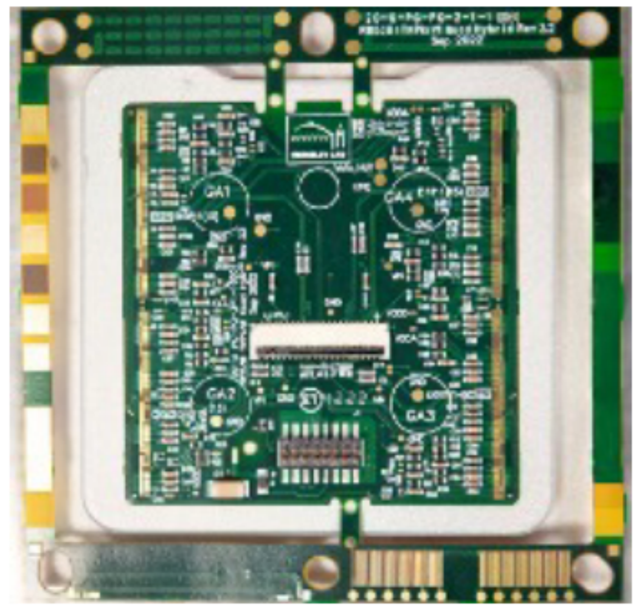


Bare module with PCB glued to back of sensor, wire bonded & encapsulated

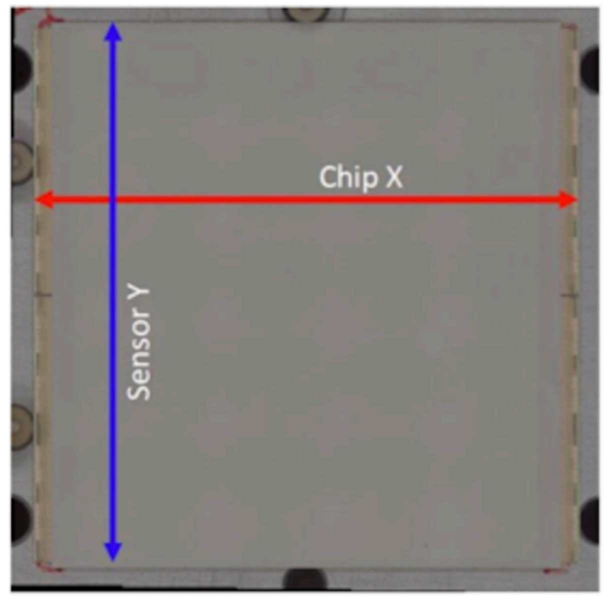
4.5k modules in Outer Barrel

→ **Paris Cluster** to produce ~ **2100 modules**.

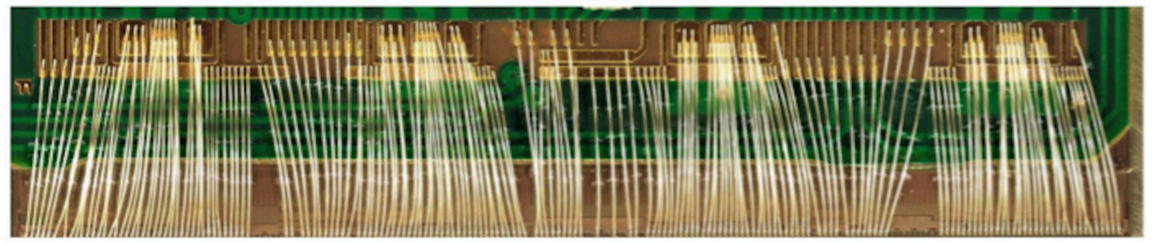
- **Currently in Pre-Production Phase**
  - It ensures that the designs, tools, and procedures can produce high-quality components at scale.
  - Qualify assembly process, Quality Control (QC) test procedures and assembly sites
  - Provide modules to system test and loading of support structures
  - Test of bump-bonding quality and strength after Assembly and QC process.



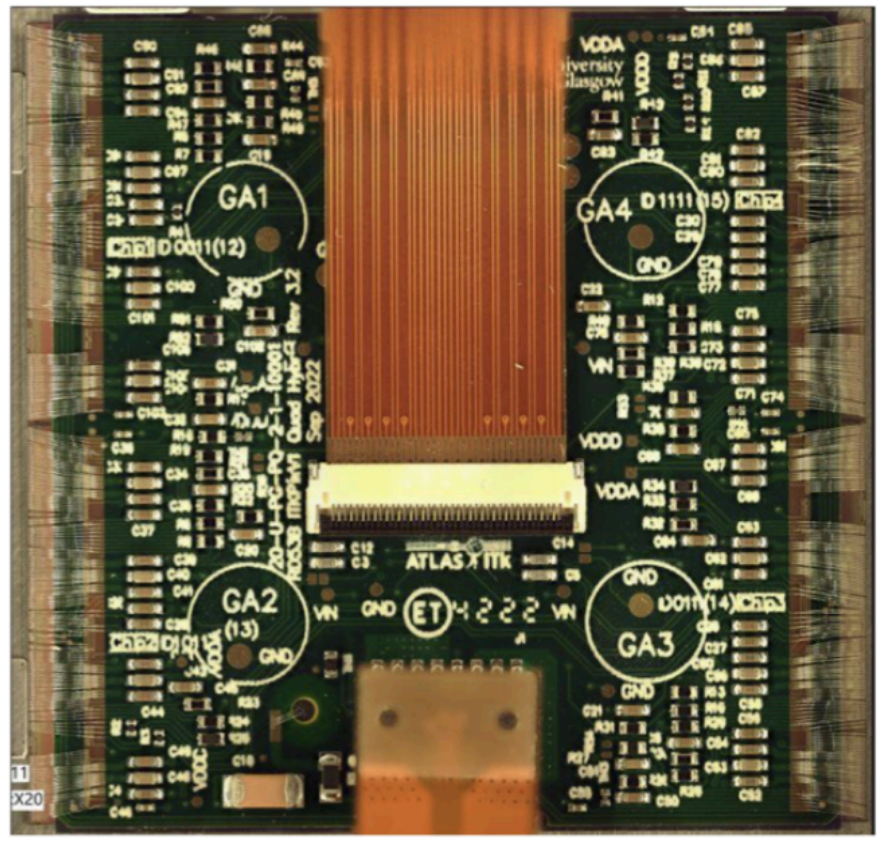
Flex PCB



Bare Module



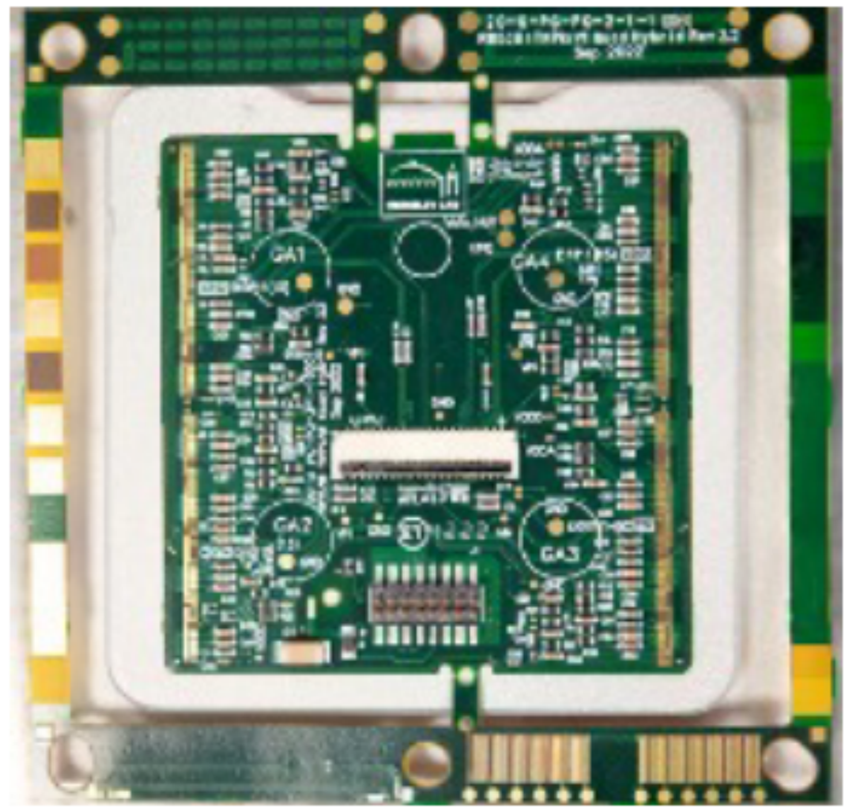
Wire bonds ~ 700 wires



Flex & Module Assembly

ITK Quad Module Assembly

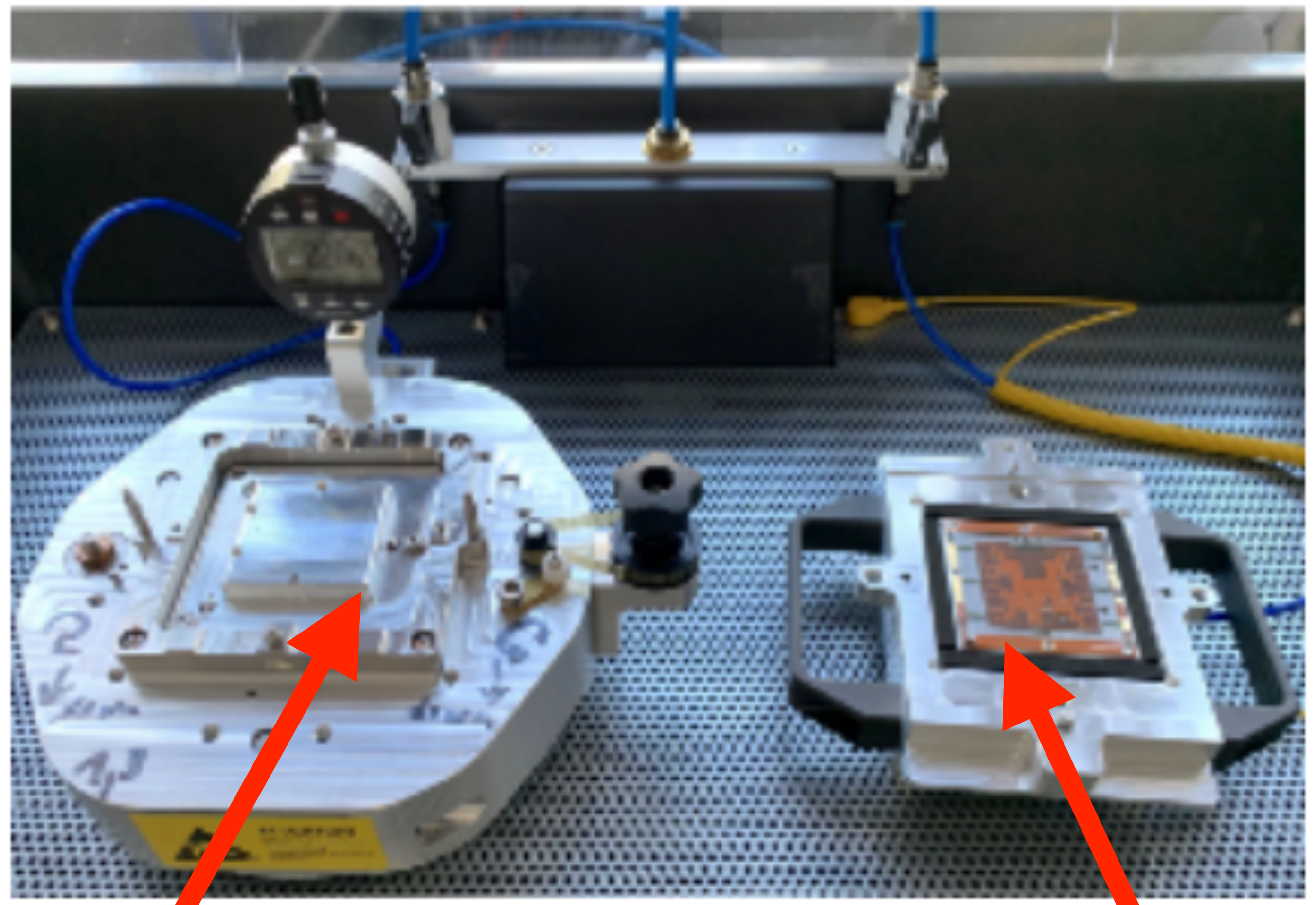
Flex PCB



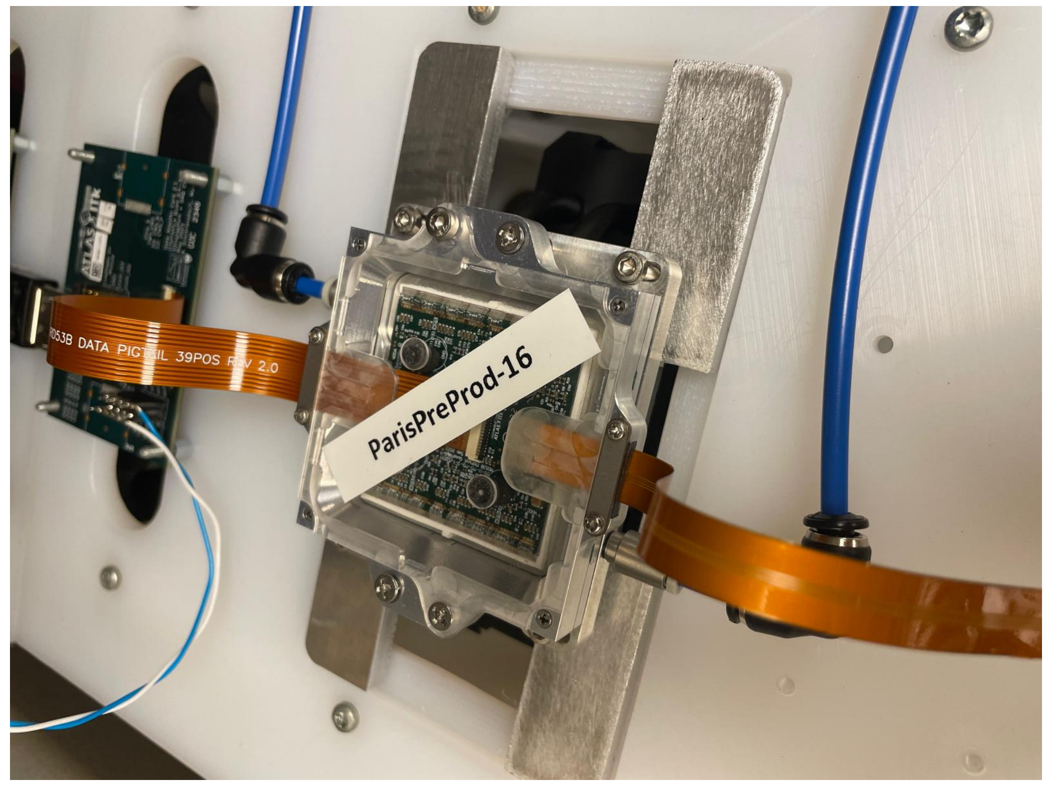
Bare Module

Canopy "WBMP"

Common Flex Attach Tooling

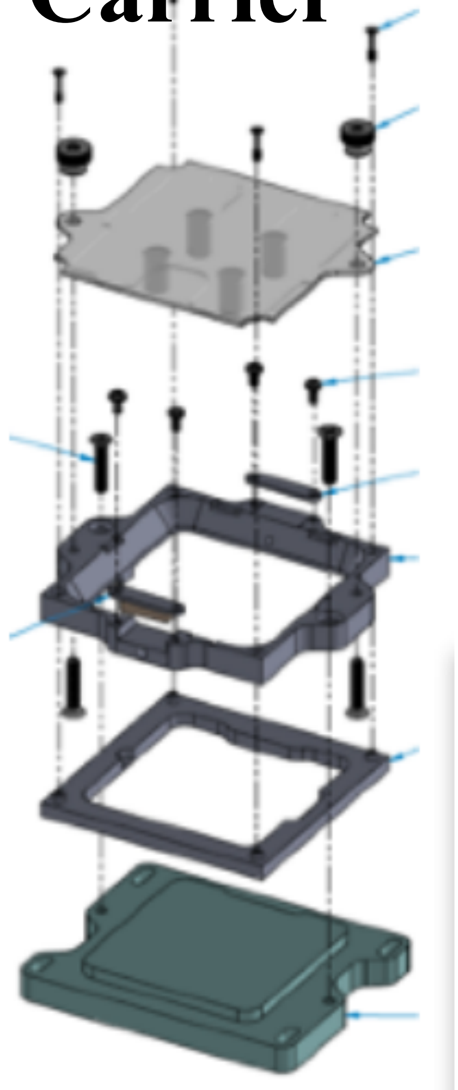


Module Jig **Flex Jig**

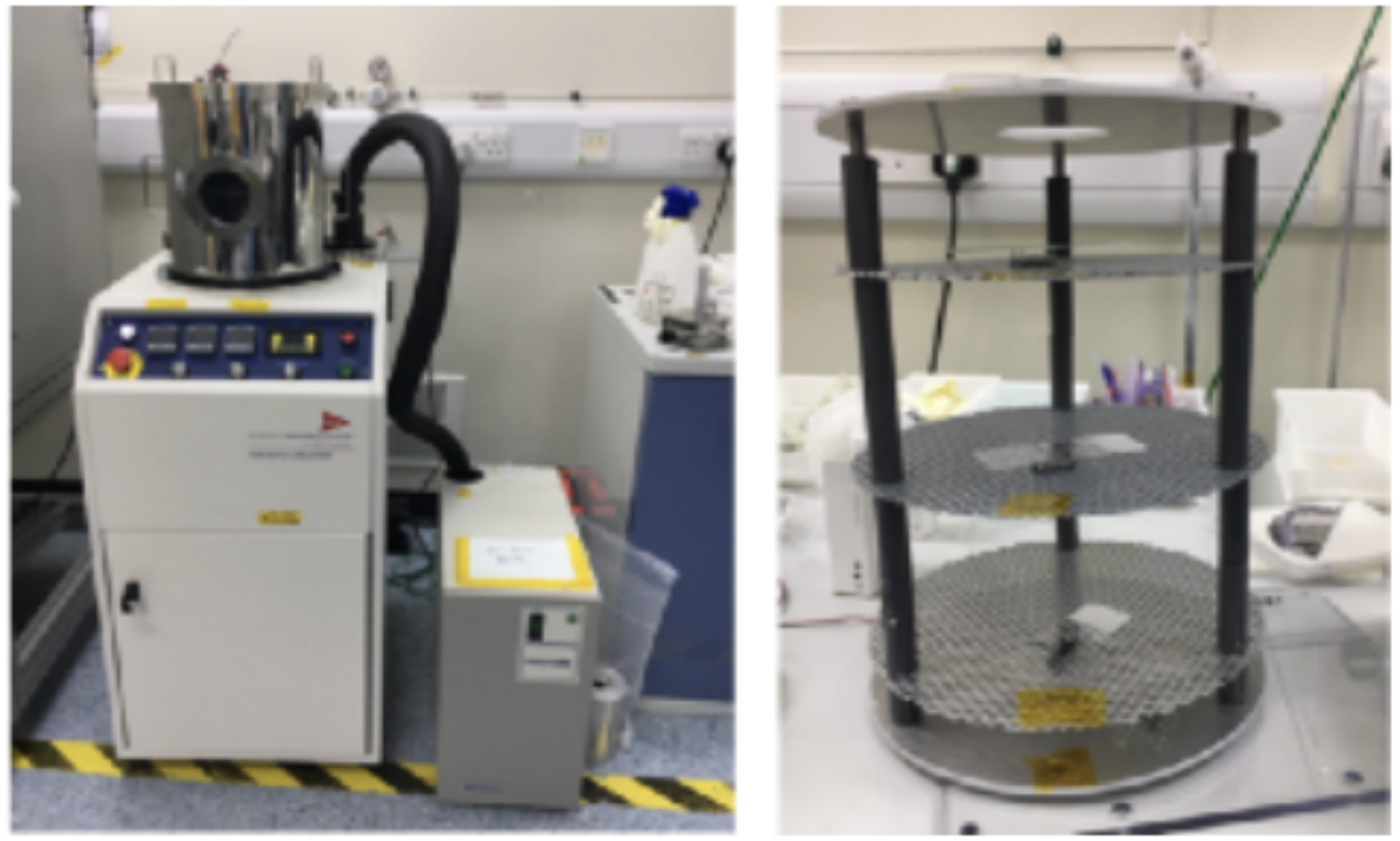


Electrical Test

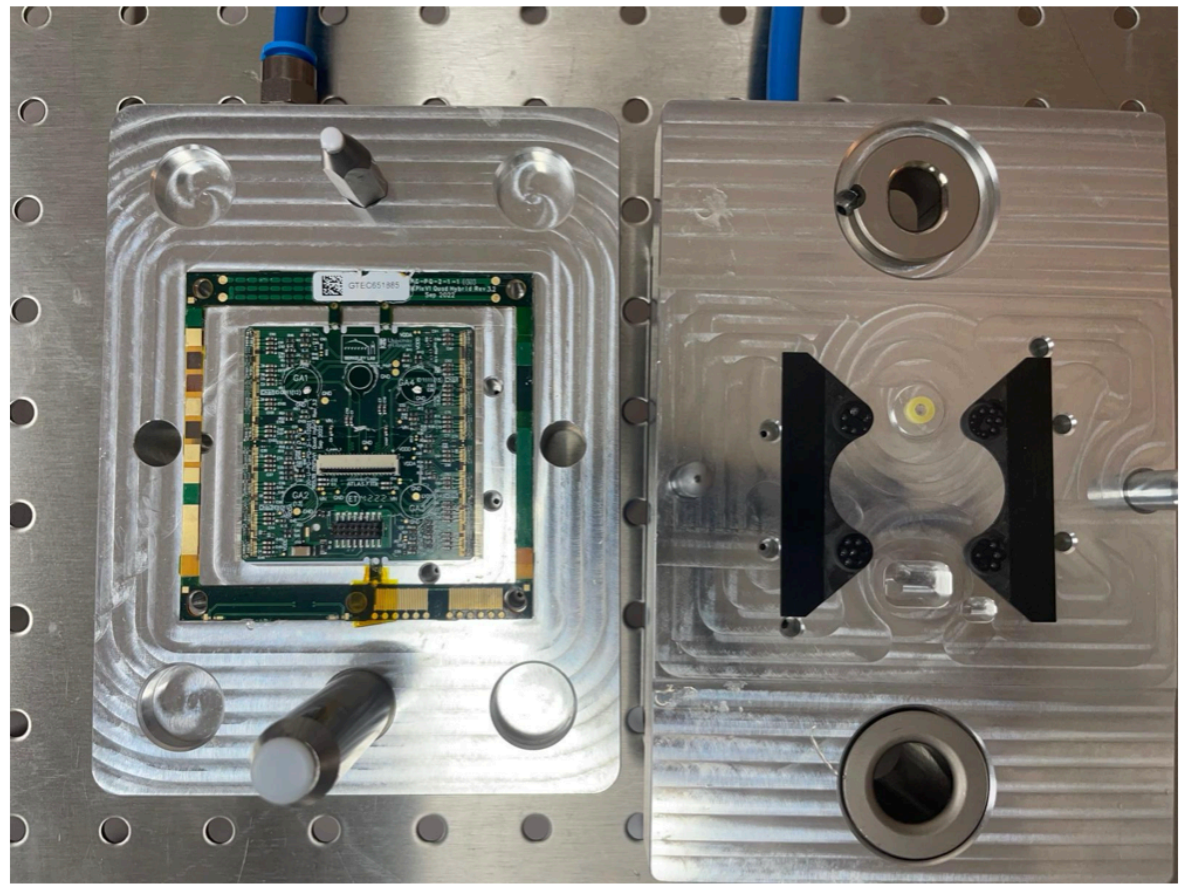
Carrier



Parylene Coating



OB WBMP Quad Module Assembly

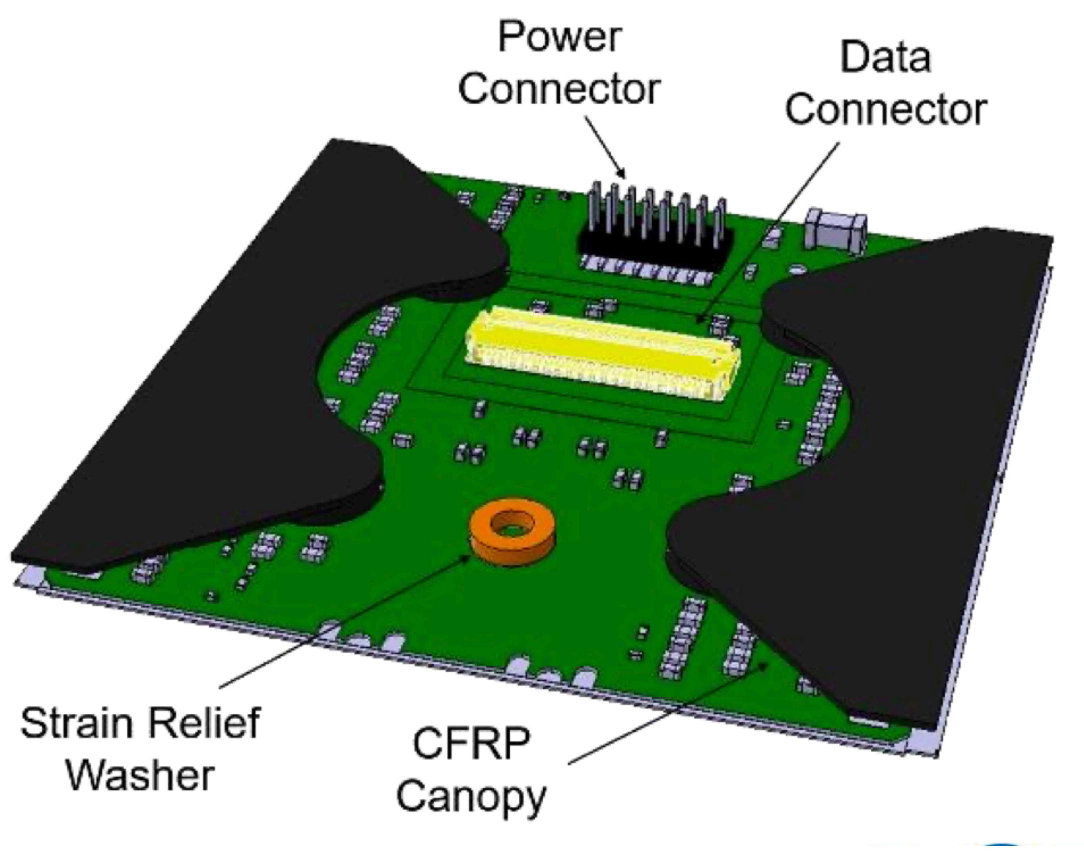


WBMP Tooling

Outer Barrel Wire-Bond Mechanical Protection

Wire Bond Mechanical Protection (WBMP)

→ is a **C**arbon **F**iber-**R**einforced **P**lastic cover "**CFRP Canopy**" extending over the wire bonds region



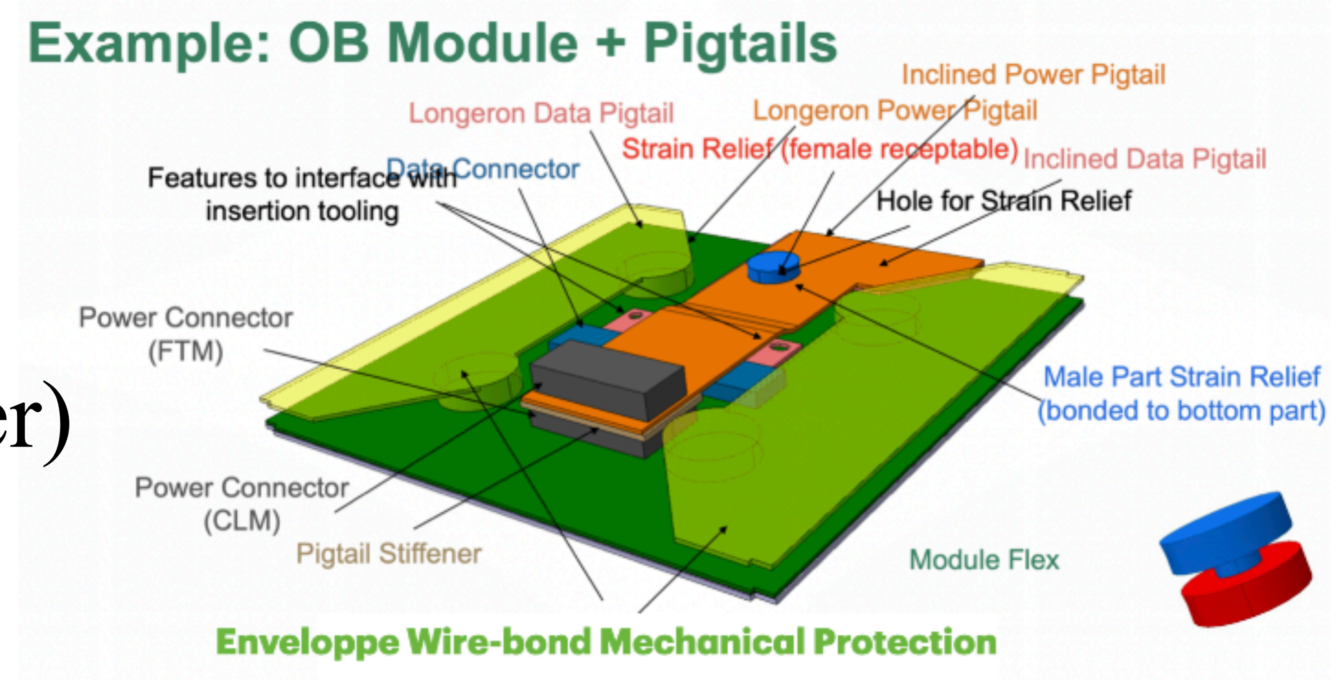
✦ **WBMP** in the Outer Barrel (OB) Modules covers the wire-bond areas as a mechanical barrier between the pigtails and the wire-bonds.

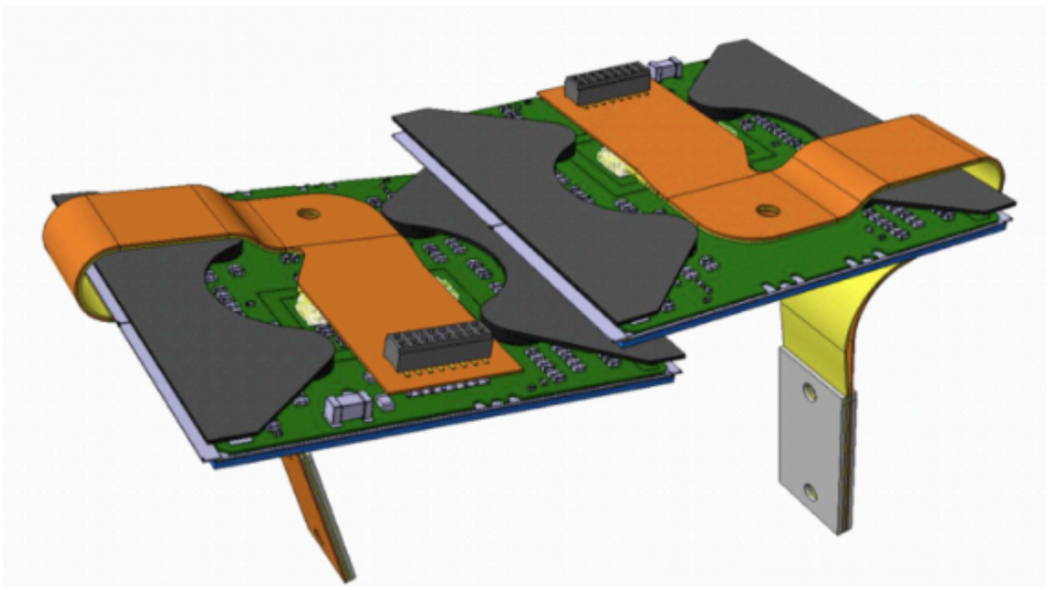
- To prevent damage caused by pigtails routed atop wire-bonds along the longerons.
- Safeguarding wire-bonds from damages of cabling and external forces during the cell loading and integration stages.

- All OB modules wire-bond regions are equipped with WBMP.

✦ My Contribution:

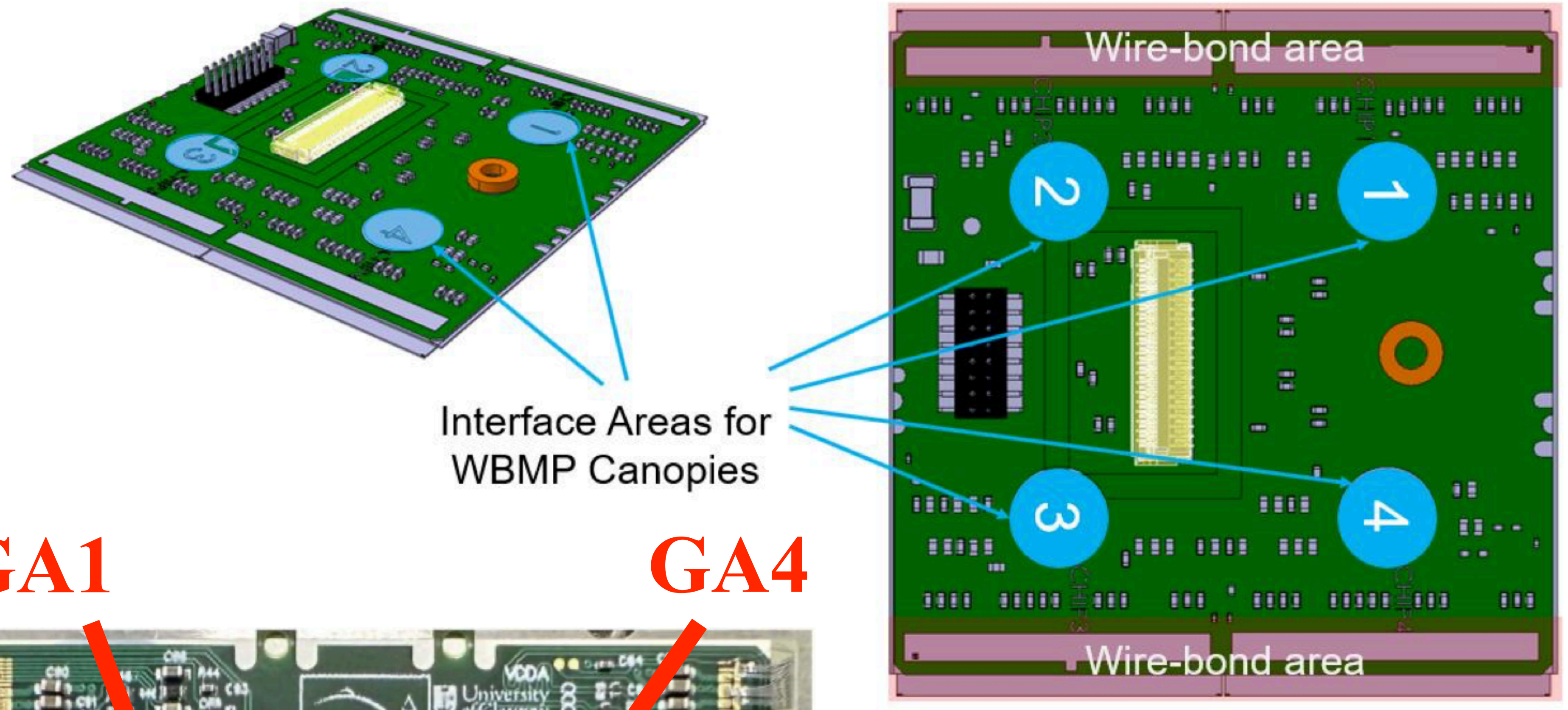
- Participating in the ITK Quad Module Assembly (Paris Cluster)
- Test and provide feedback regarding the design of the Wire bond area protection.
- Characterize the Outer Barrel Wire-Bond Mechanical Protection assembly process → LPNHE OB WBMP Module Assembly Site Qualification

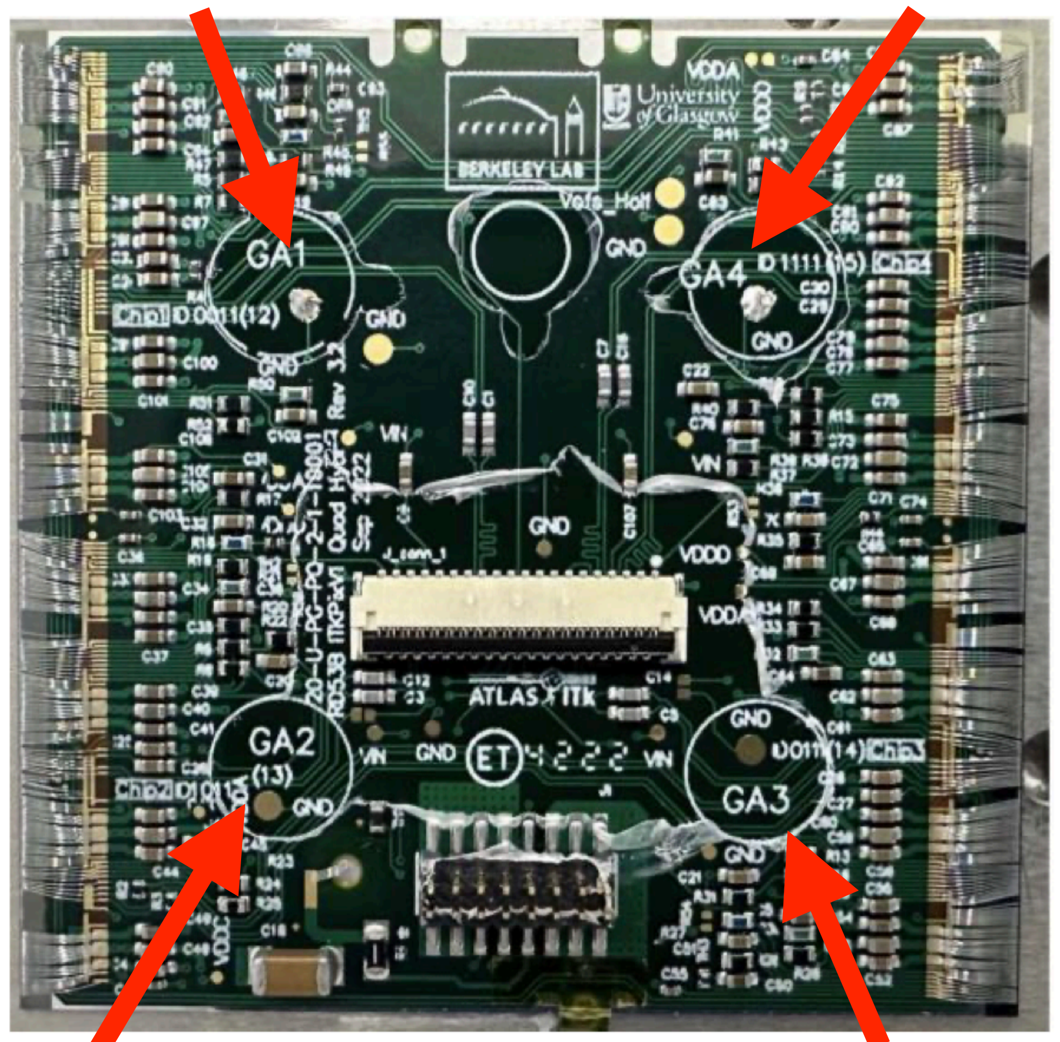




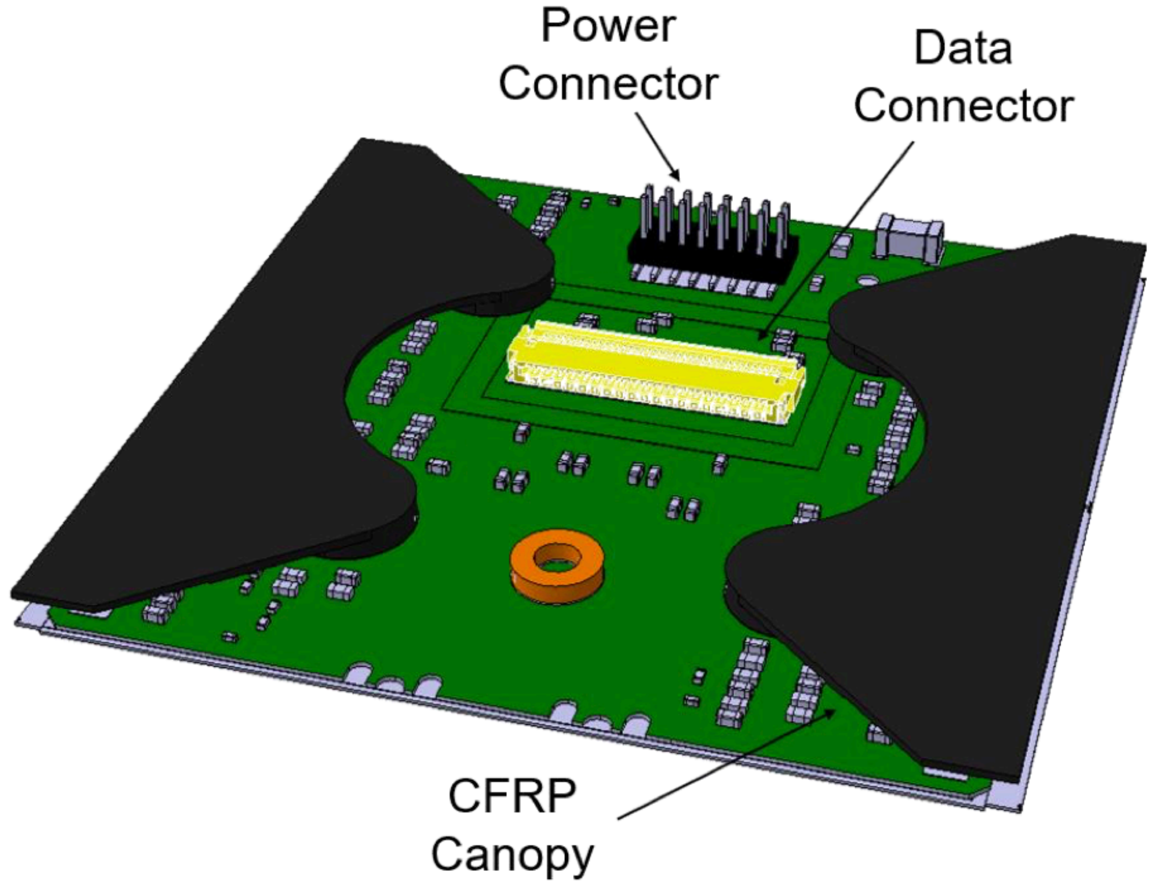
OB WBMP Module Assembly

✦ To simplify production, all OB modules are identical so that they can be used in both longerons and inclined half rings (IHRs) regardless of the layer.





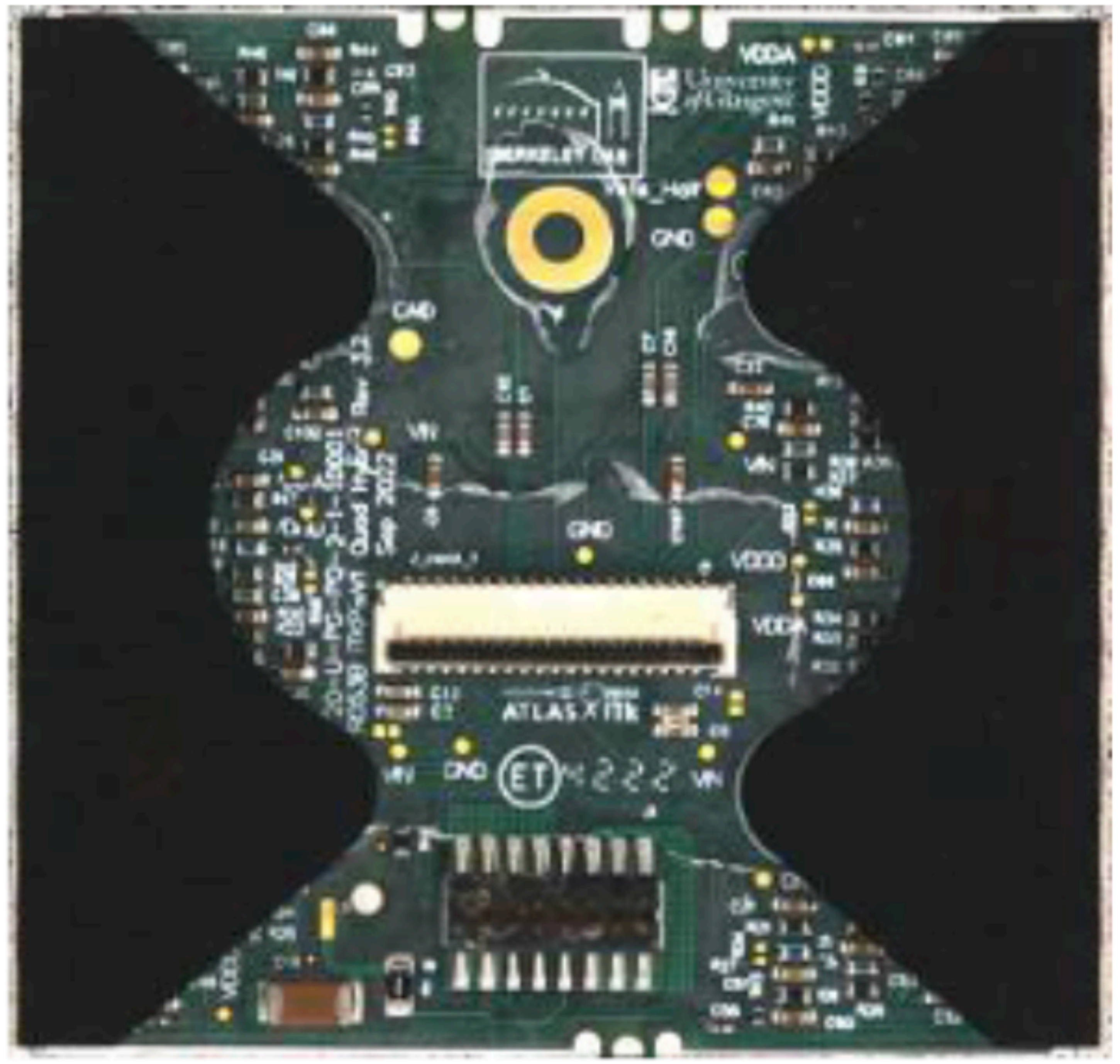
OB module on Post-Parylene stage



- Symmetric design (of modules and tools)

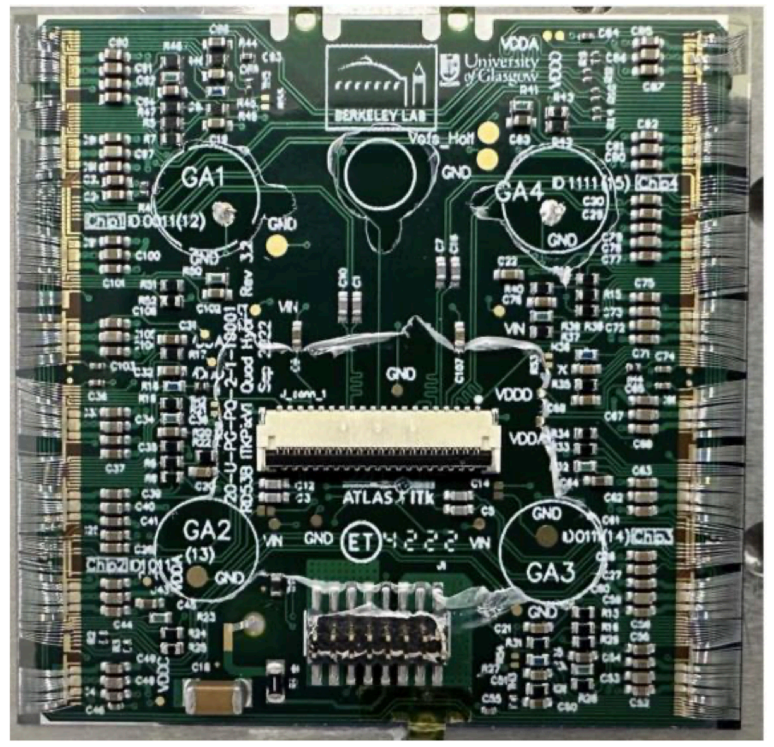
→ The OB modules are equipped with 2 canopies, which are glued to the OB module at the 4 pick-up point areas (GA1, GA2, GA3 & GA4)

→ The four Pick-up points serve as the interface areas on the Flex for the WBMP canopies.



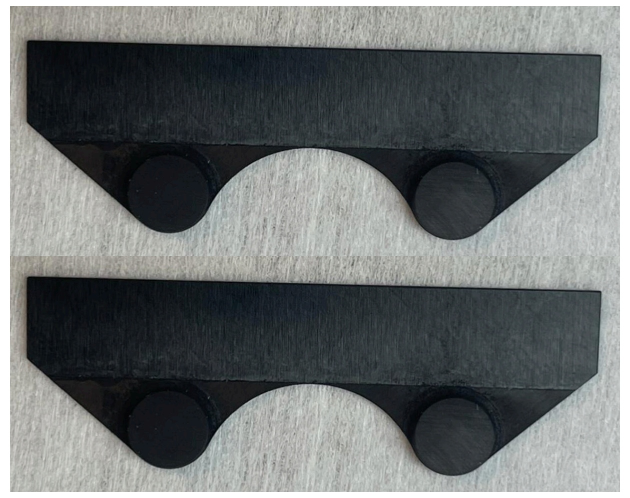
OB Pre-Production Module attached with WBMP

OB WBMP Components & Assembly

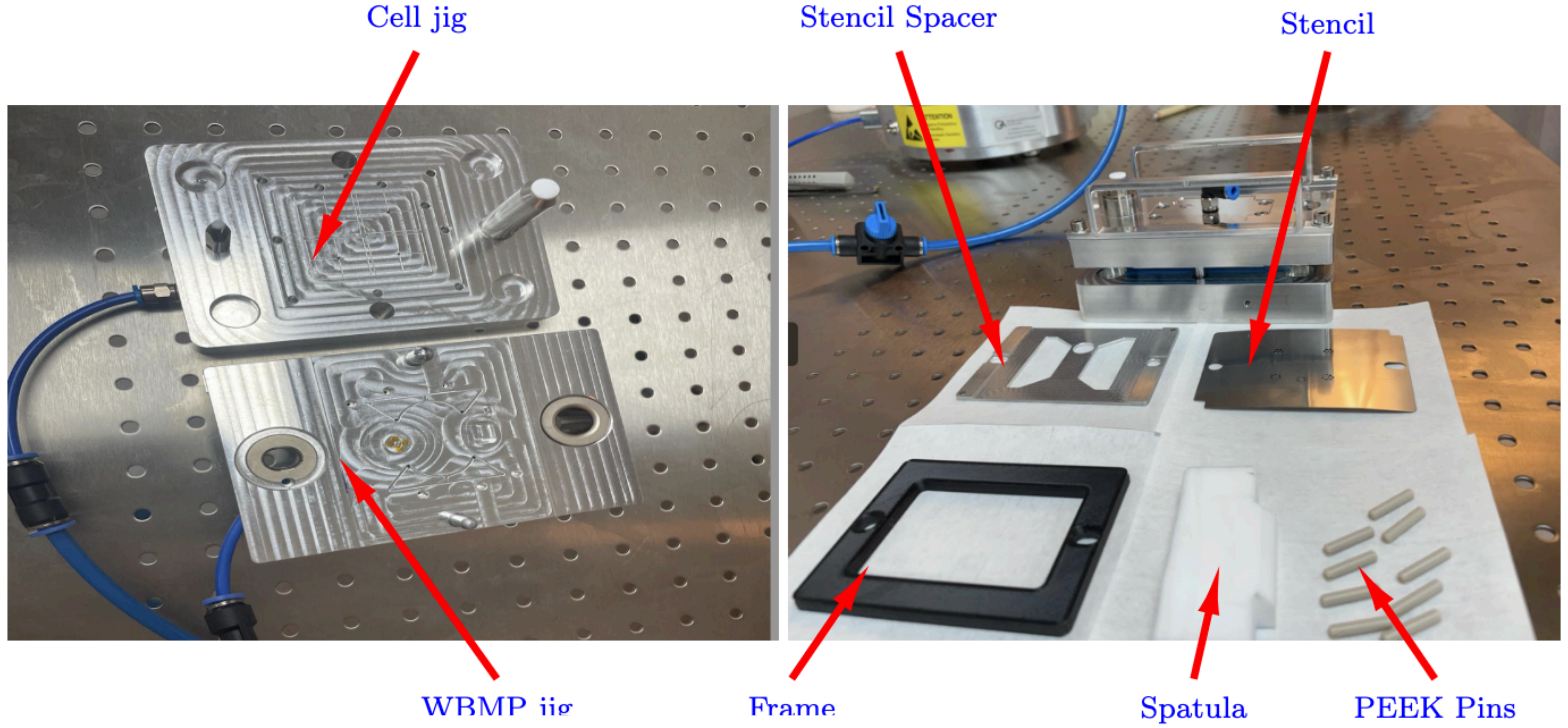


OB module on Post-Parylene stage

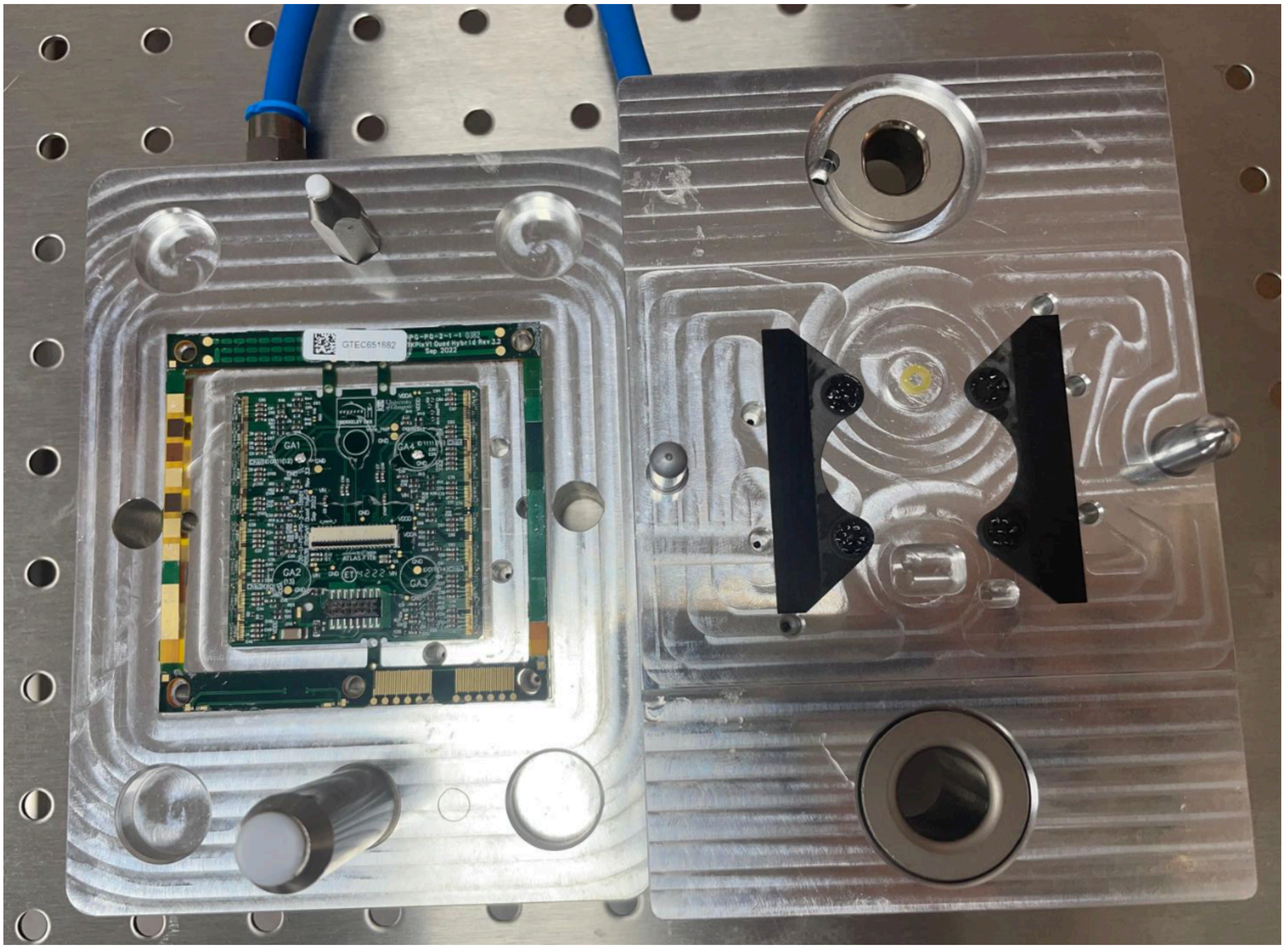
Strain Relief (SR)

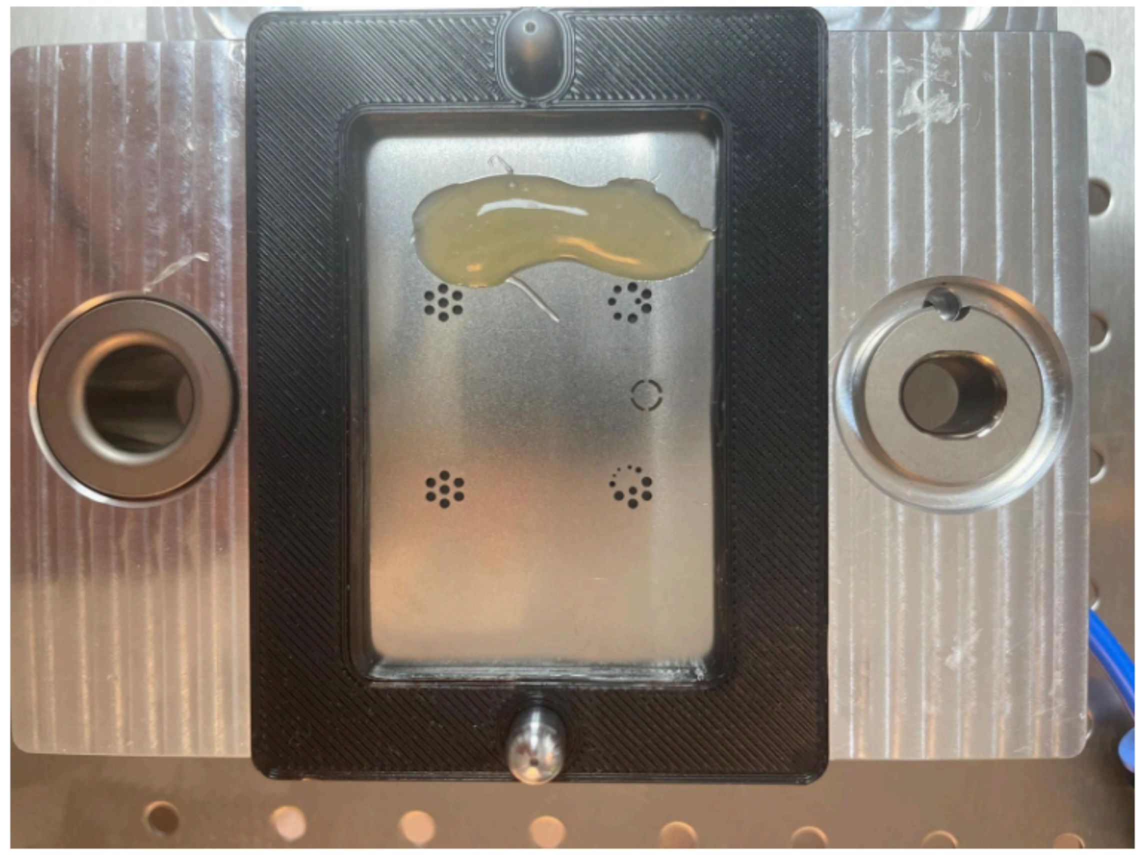


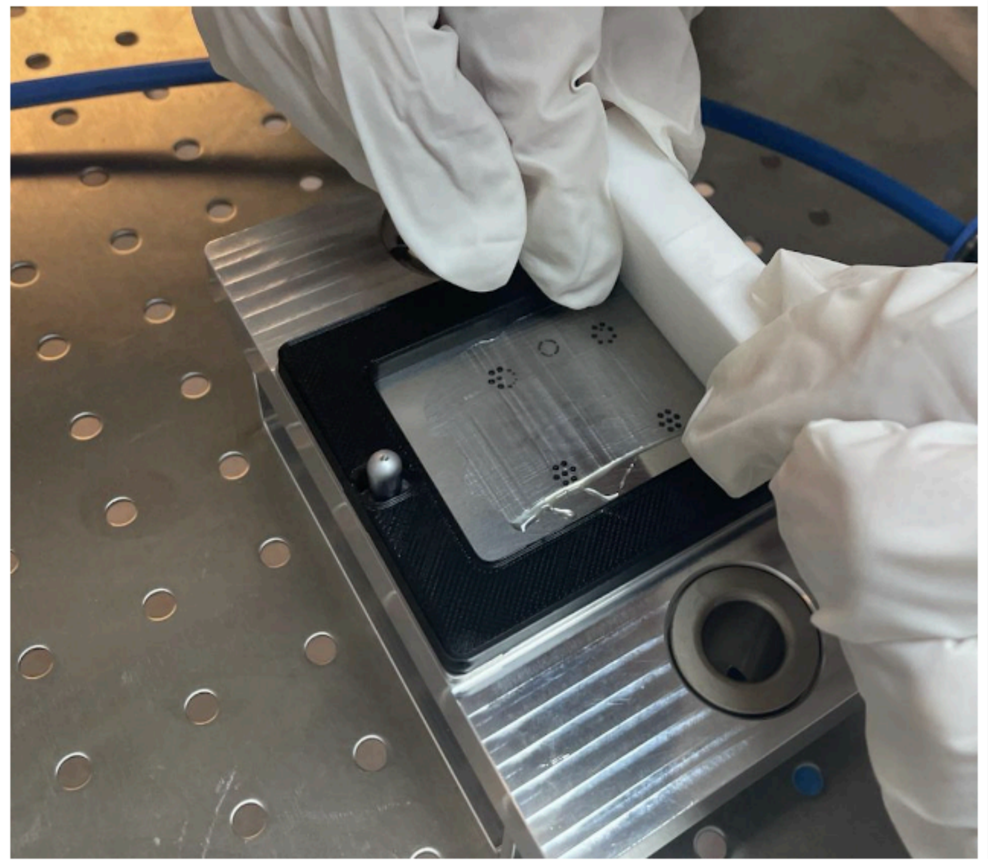
Canopy Pair

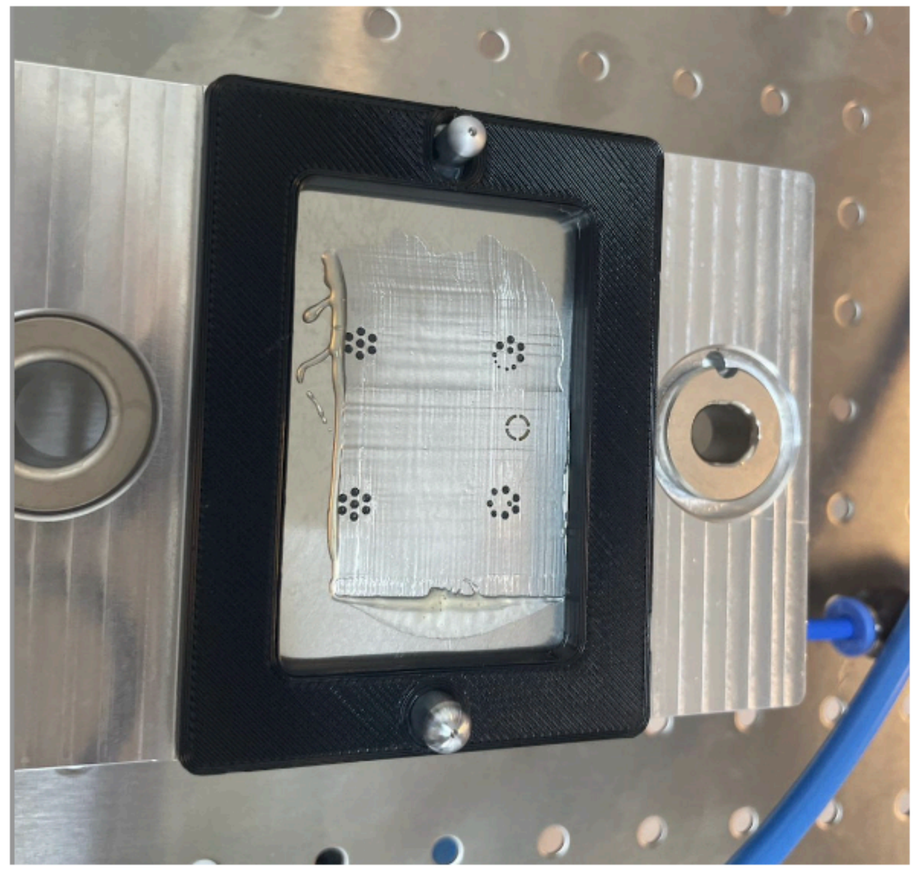


Common **WBMP Glue Tooling** at Assembly Sites



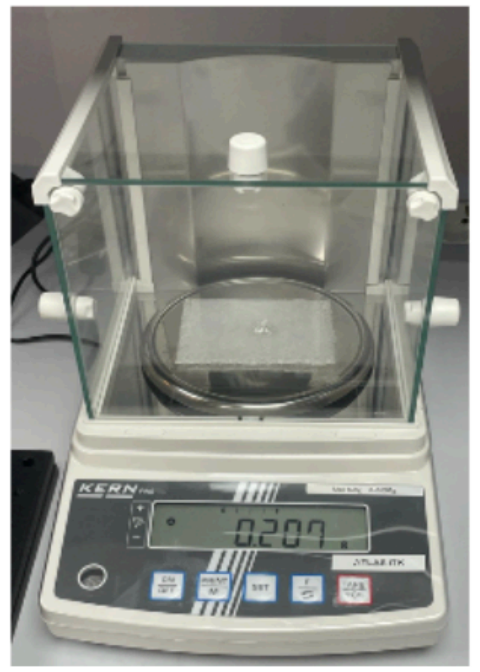


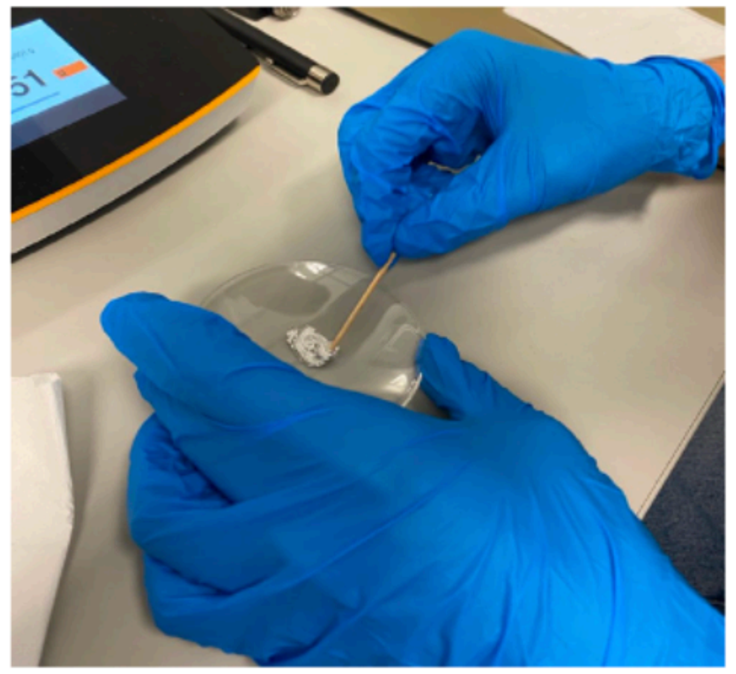




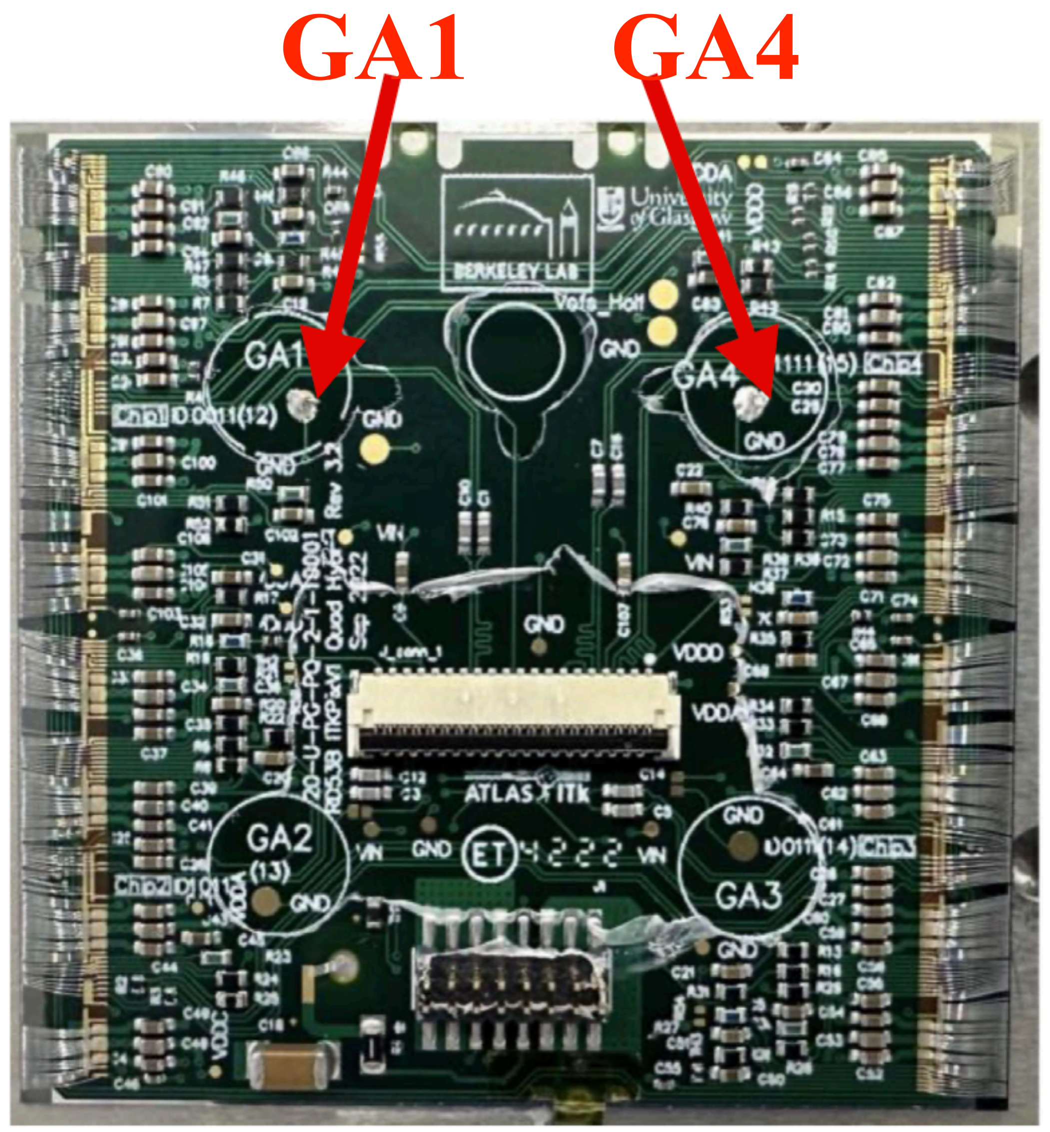
- Place OB Module on Post-Parylene stage is placed in the Cell Jig & Canopy pairs and Strain Relief are placed on WBMP Jig.
- Use spatula to place the Araldite 2011 Glue above the pick-up points holes of the Stencil.

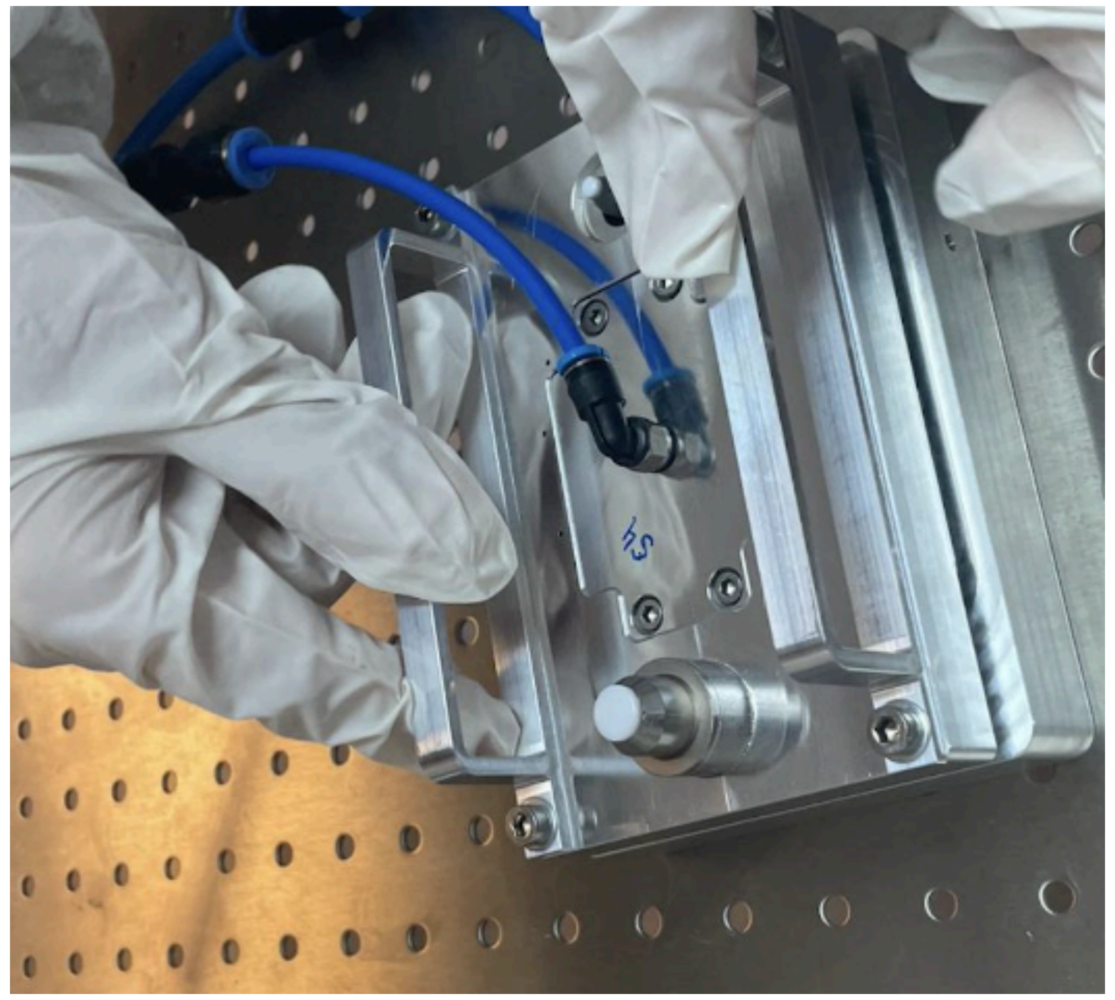
OB WBMP Components & Assembly



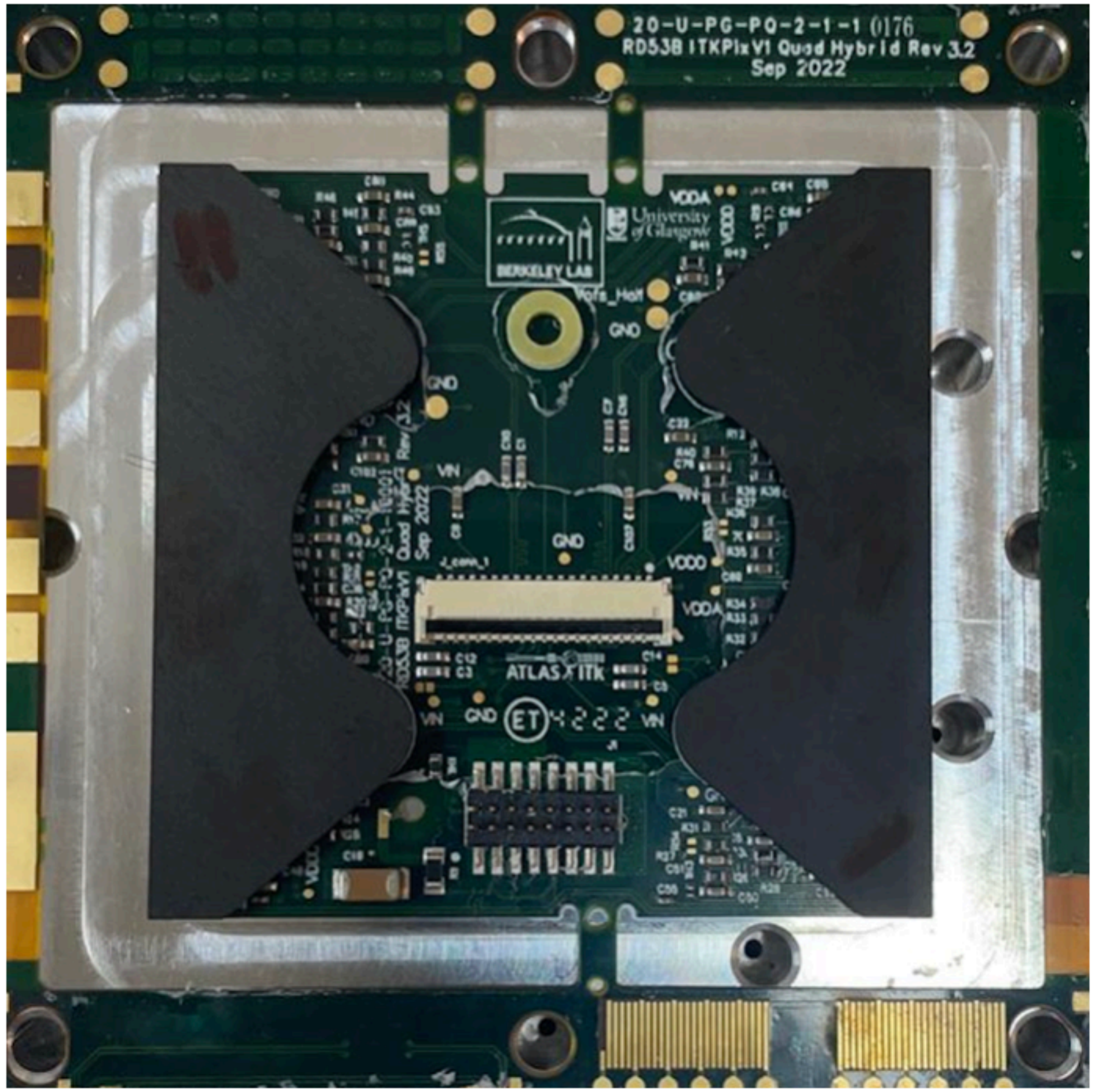


- Mixing Silver and Hardener Glue
  → Mixing ratio is 100:5
  → Silver Epoxy deposition on **GA1** & **GA4**





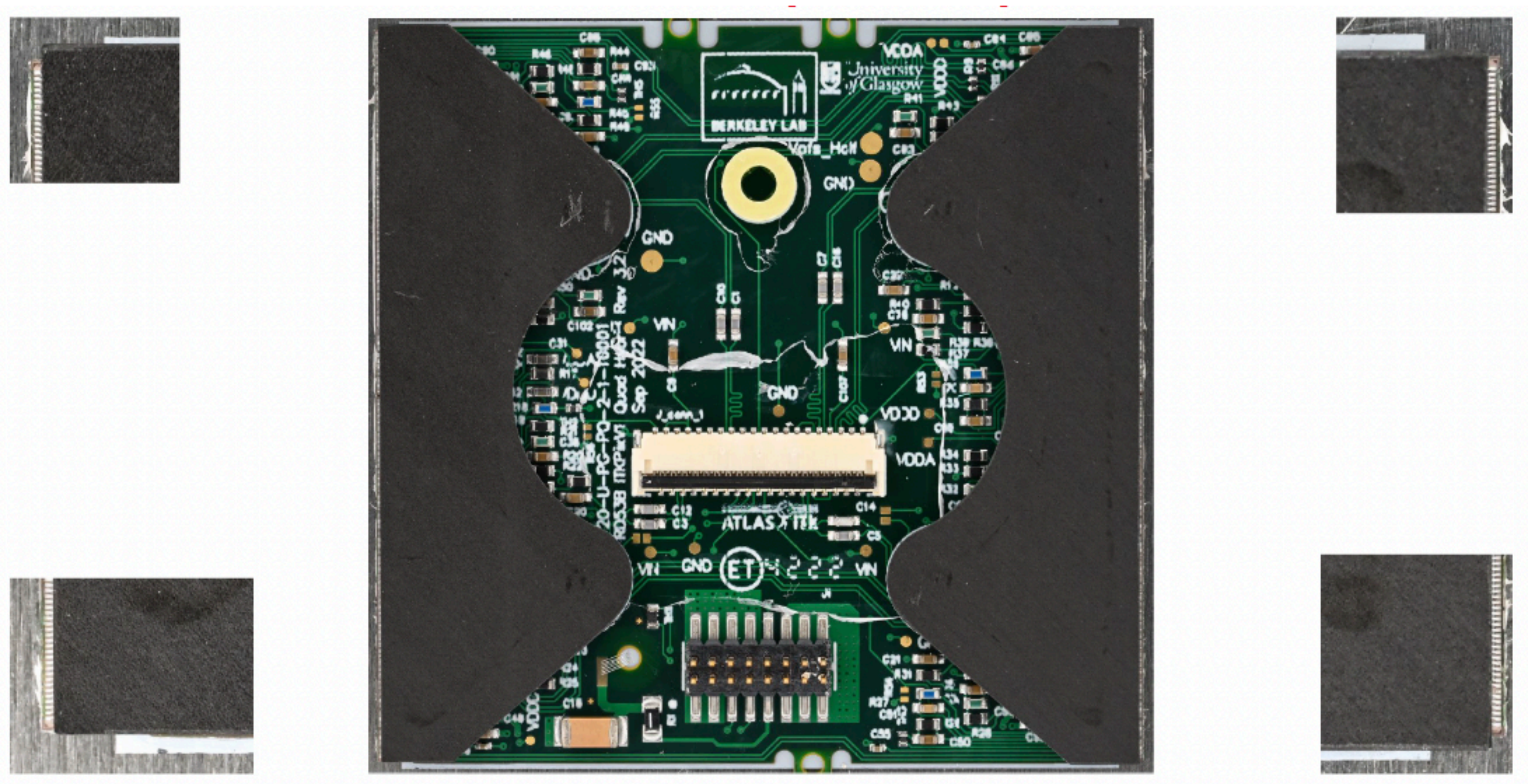
- **Place WBMP jig on top of Module jig.**
  → leave to cure at least 8 hour



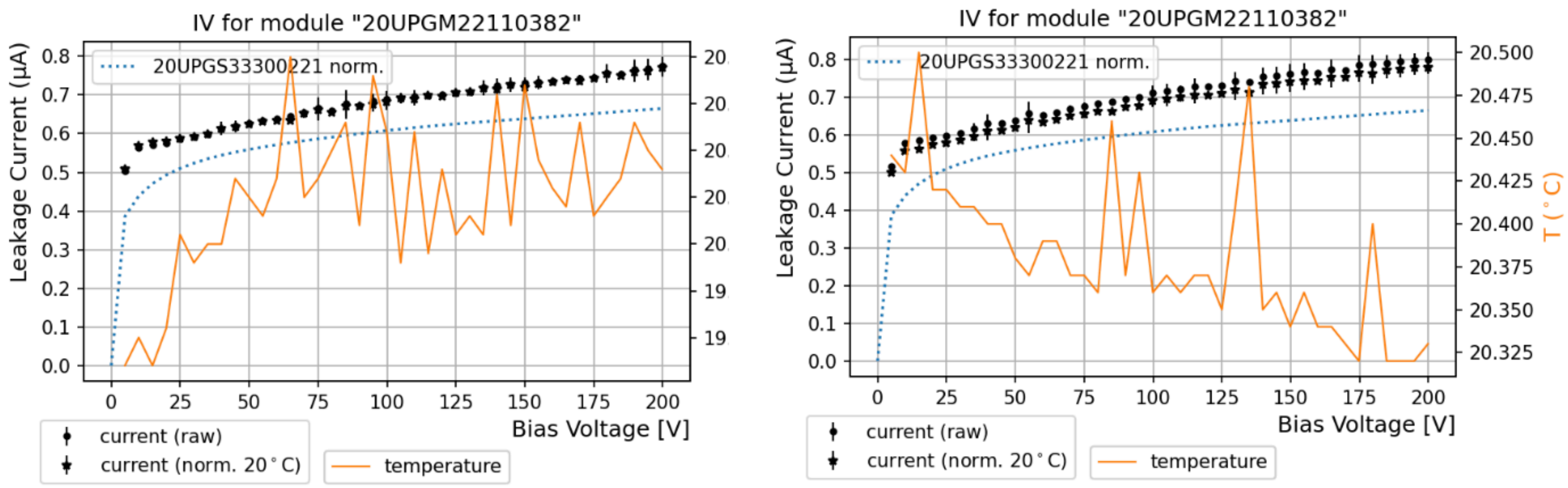
OB Pre-Production Module attached with WBMP

Measurements After OB Module Attachement to WBMP

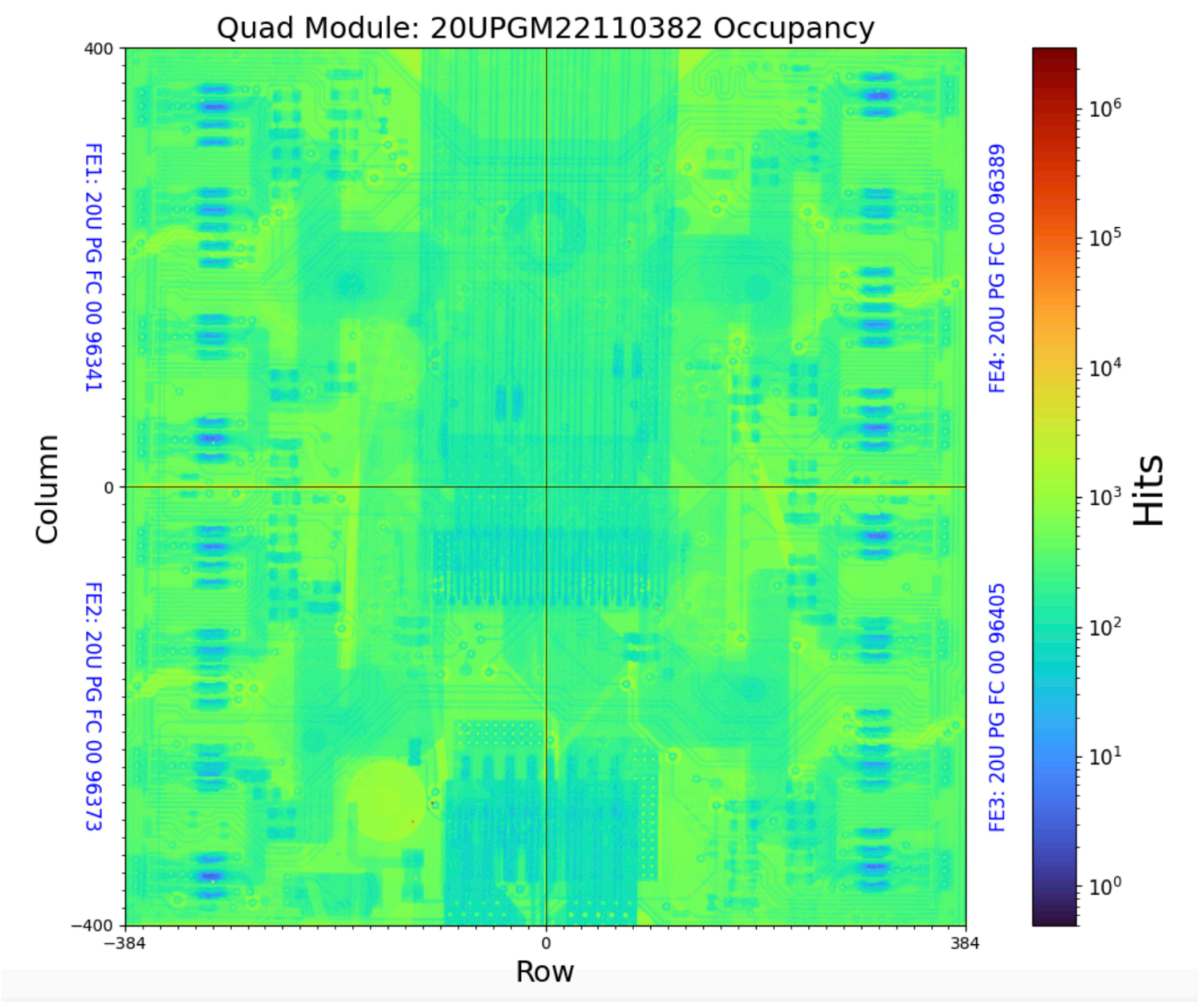
- **Metrology:** Measure the total height of the module attached with WBMP to get the glue thickness at each pick-up point (**GA1**, **GA2**, **GA3** & **GA4**).
- **Visual Inspection (VI):** Photo from front side to check the visibility of module corners → Verification of the envelope to see four corners of the module.
- **Connectivity check by probing:** Get Get the resistivity at **GA1** and **GA4** pickup points.
- **Electrical Tests:** Showing IV curves, Front End (FE) THRESHOLD & Pixel Failure Analysis (PFA) tests before OB WBMP (i.e. After Parylene Coating) & after OB WBMP, X-ray scans after OB WBMP.



VI: Photo from front side to check the visibility of all four FE corners



IV Curves Before (Post-Parylene Stage) and After OB WBMP Assembly



X-rays scan after OB WBMP Assembly

Summary

- The ATLAS ITk Pixel Detector will be installed during the LS3 at the center of the new ATLAS tracker for HL-LHC Run 4.

  → Challenging conditions in terms of pile-up, data rates, radiation, ...

- ITk pixel system has been designed to meet these challenges

- France institutes have a primary role in the design and construction of several key components of the ITk-Pixels Outer Barrel.

- The detector is currently progressing in Pre-Production for modules as well as support structures, services and readout.

- Individual components have been verified in prototype runs during last two years and passed final design reviews.

- The production of modules will start early 2025, production of sensors, FE-ASIC and local supports is already in progress.

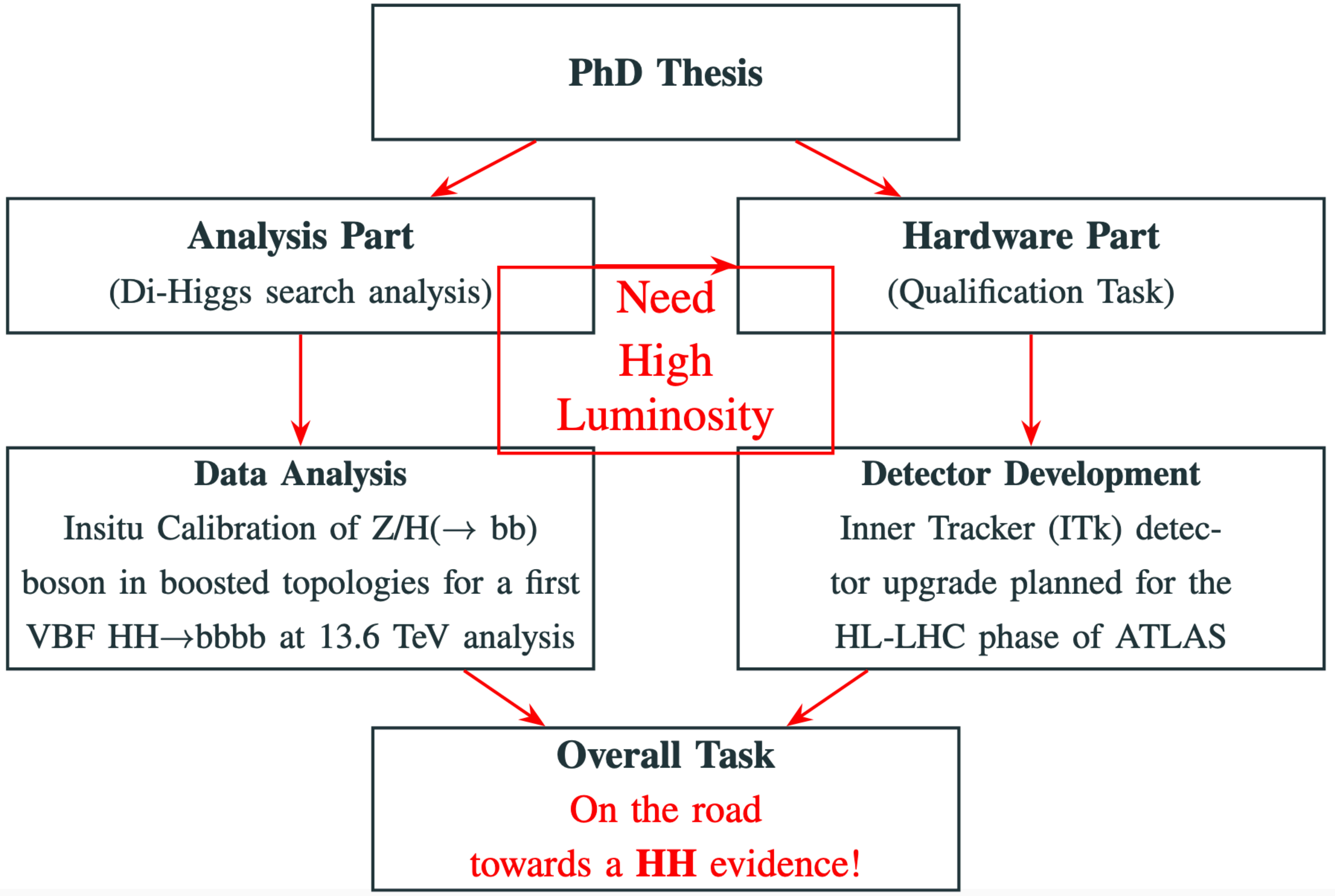
Upgrade Physics Goals

- Improve Higgs boson precision measurements.
  → More precise measurements of Higgs boson couplings.
  → Di-Higgs boson production.
  →Study of Higgs boson self coupling.
- Vector Boson Scattering and other precision SM measurements
  → VBS cross section.
- Search for New Physic
  → Mass reach for new particle searches extends significantly, e.g. for stops to 1.2 TeV.

- Many challenges for reconstruction
  → High multiplicity events and highly boosted jets require improved granularity and resolution
  → VBS/VBF forward jets: forward tracker for pile-uprejection by jet-vertex association
  → Rare events: improve in coverage and reconstruction efficiency

RoadMap

- This PhD combines data analysis, detector performance and detector development.
- Contributing to the ITK Quad Module Assembly (Paris Cluster) and Outer Barrel Wire-bond Mechanical Protection for **LPNHE Site Qualification**. → This is my Qualification Task



After finding the **Higgs Krampouz** in 2012,

The challenge is to find **two Krampouz Higgs's**

- The second part of my study focuses in di-Higgs search analysis for a first **VBF HH→bbbb** at 13.6 TeV