Norwegian Contributions to the Upgrade of the ATLAS Inner Tracker Pixel System

NorCC workshop 14.-15. September

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Outline

- Introduction
- ITk pixel detector layout
- Norwegian contributions
- System level tests and demonstrators

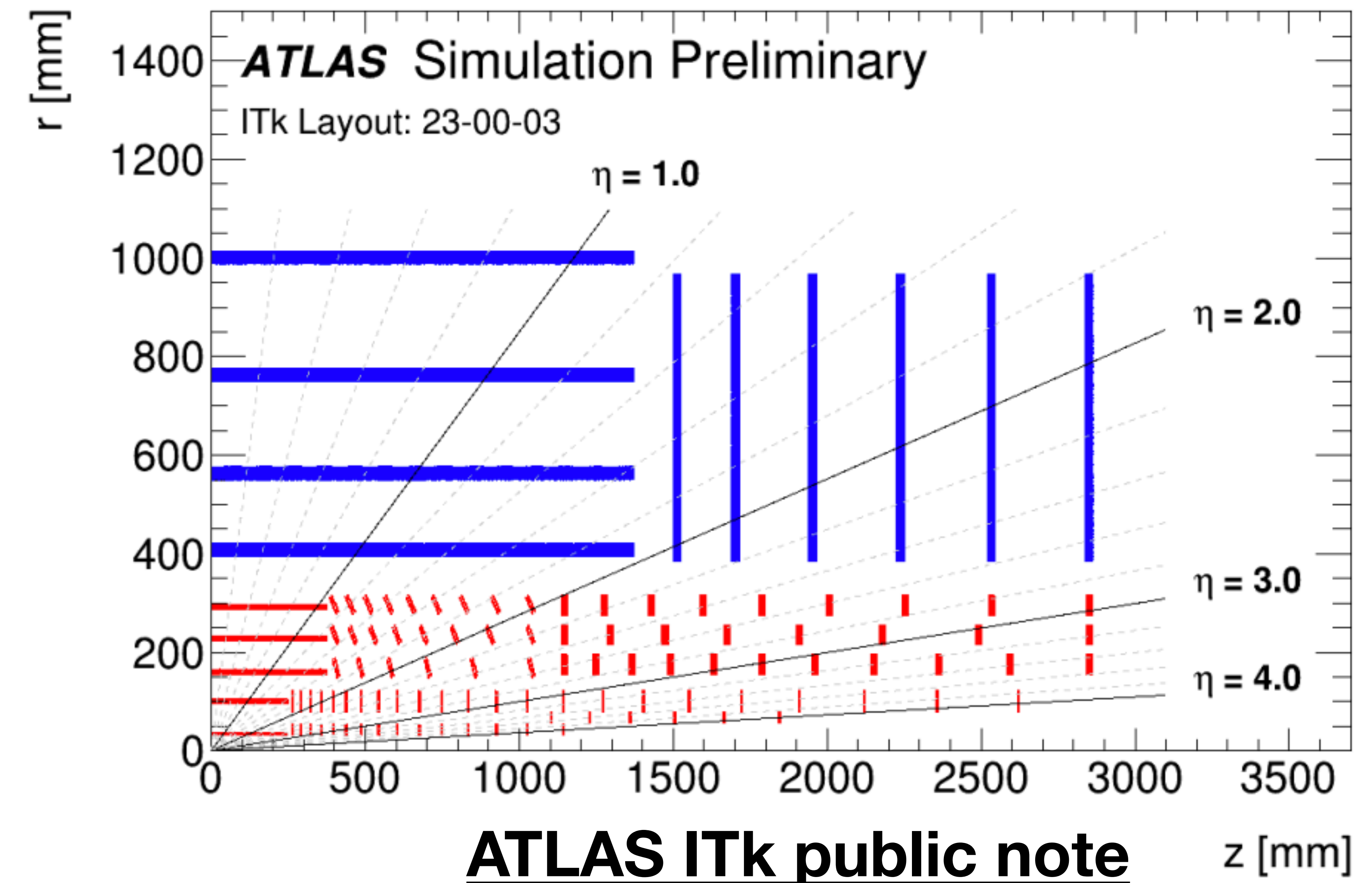
Introduction

- **The LHC will upgrade to HL-LHC in 2027. Which puts strict requirements on the tracking system**
- **The ATLAS inner detector will be replaced by an all silicon tracker called the ATLAS inner tracker (ITk)**
    - Instant. Luminosity (proton-proton collison rate) increases 7-fold $\mathscr{L} = 7.5 \times 10^{34} cm^{-2} s^{-1}$ -> **Higher granularity in sensors**
    - Average multiple pp collisions increases from $<\mu>$ = 50 to $<\mu>$ = 200 -> **Improved data rate handling**
    - Radiation levels will increase by a factor 20, up to $\Phi = 2 \times 10^{16} n_{eq} cm^{-2}$ -> **better radiation tolerance**
    - Integrated luminosity (size of dataset) increases 10-fold (3000 - 4000 fb^{-1})

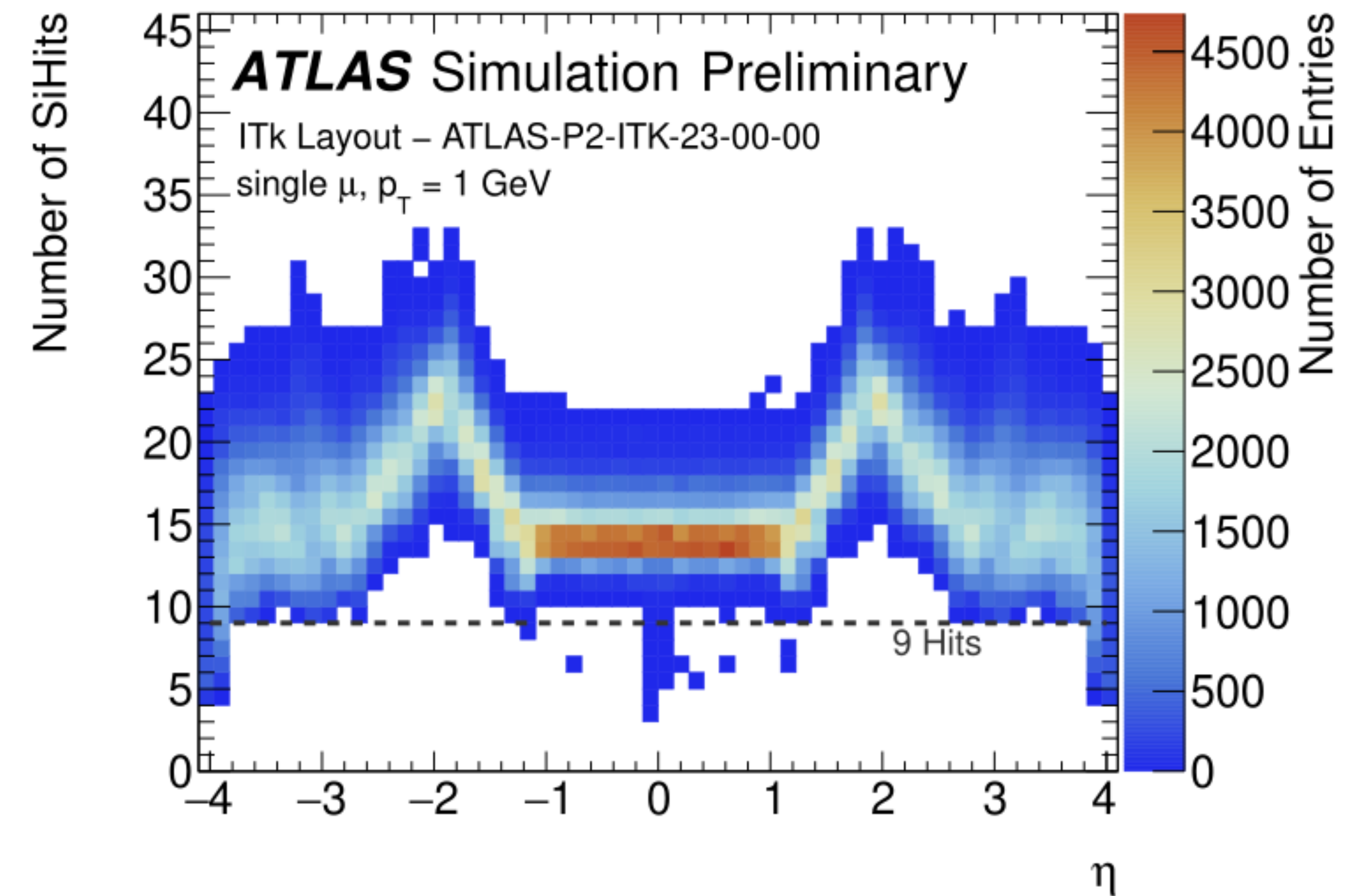
The red region is being replaced

ATLAS Inner Tracker

- Only silicon Pixels and strips
- In total 5 pixel layers
- Combination of planar n-in-p and 3D sensors
- 4 layers of silicon strips
- Coverage up to η = 4 (Nearly 4pi solid angle coverage)
- Will maintain $\geq$ 9 Si hits per charged particle for all pseudorapidities



ATLAS ITk public note



ATLAS ITk pixel detector layout

ATLAS Simulation Preliminary
ITk Layout – ATLAS-P2-ITK-23-00-00
η = 1.0
η = 2.0
η = 3.0
η = 4.0
Outer Barrel
Endcap
Inner System
z [mm]

Inner system:

- **2 barrel layers, staves L0 and L1**
- **3 ring flavours, R0, R0.5 and R1**

Outer Barrel:

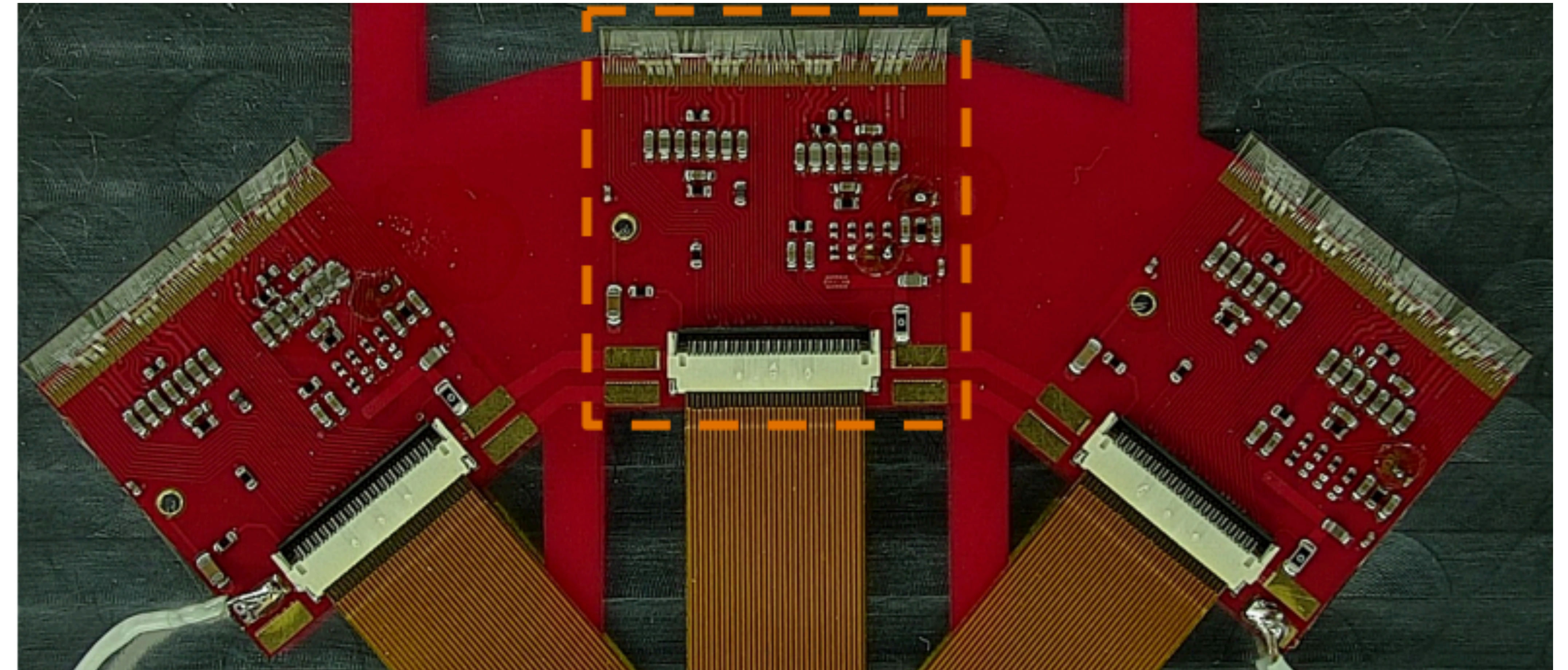
- **3 layers, staves and inclined rings**

Outer Endcaps:

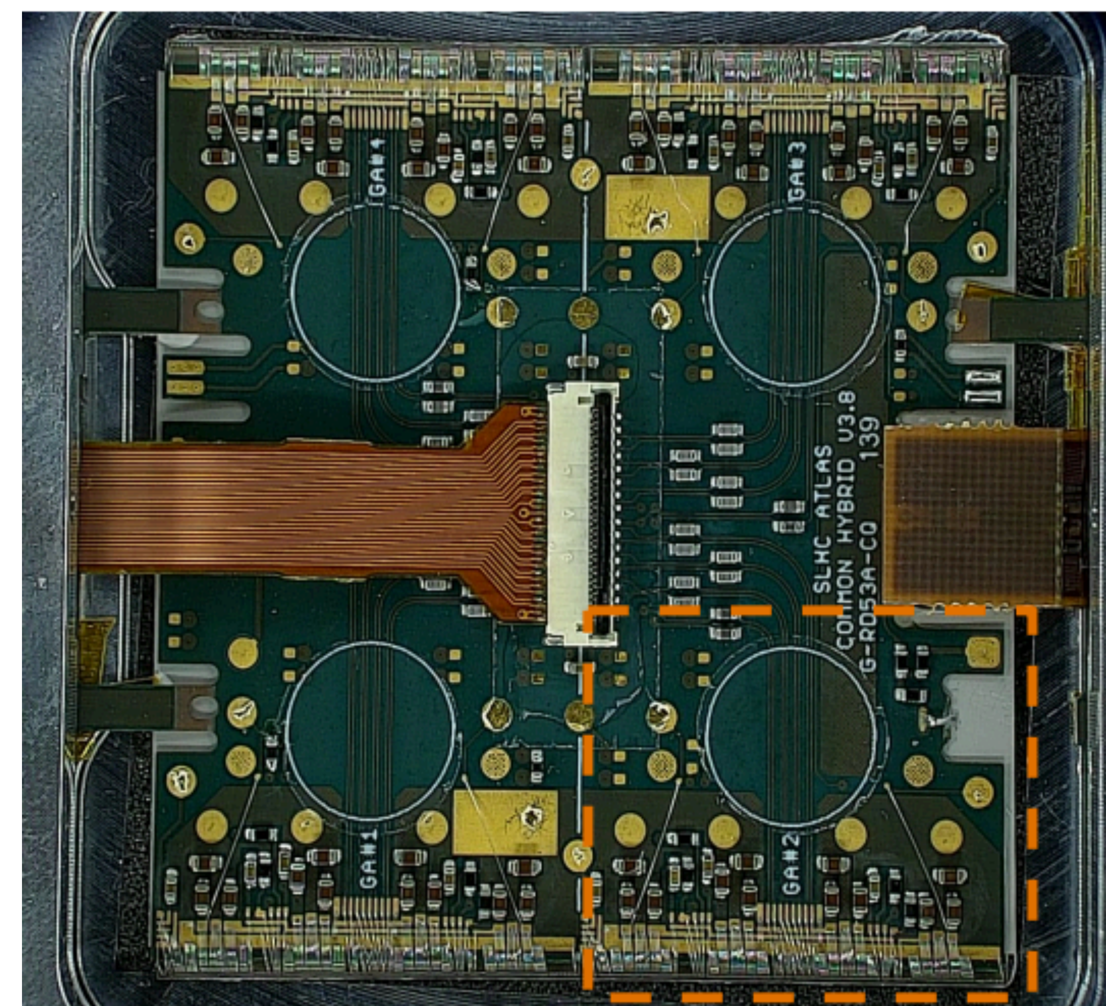
- **3 layers of endcap rings**

ITk pixel module types

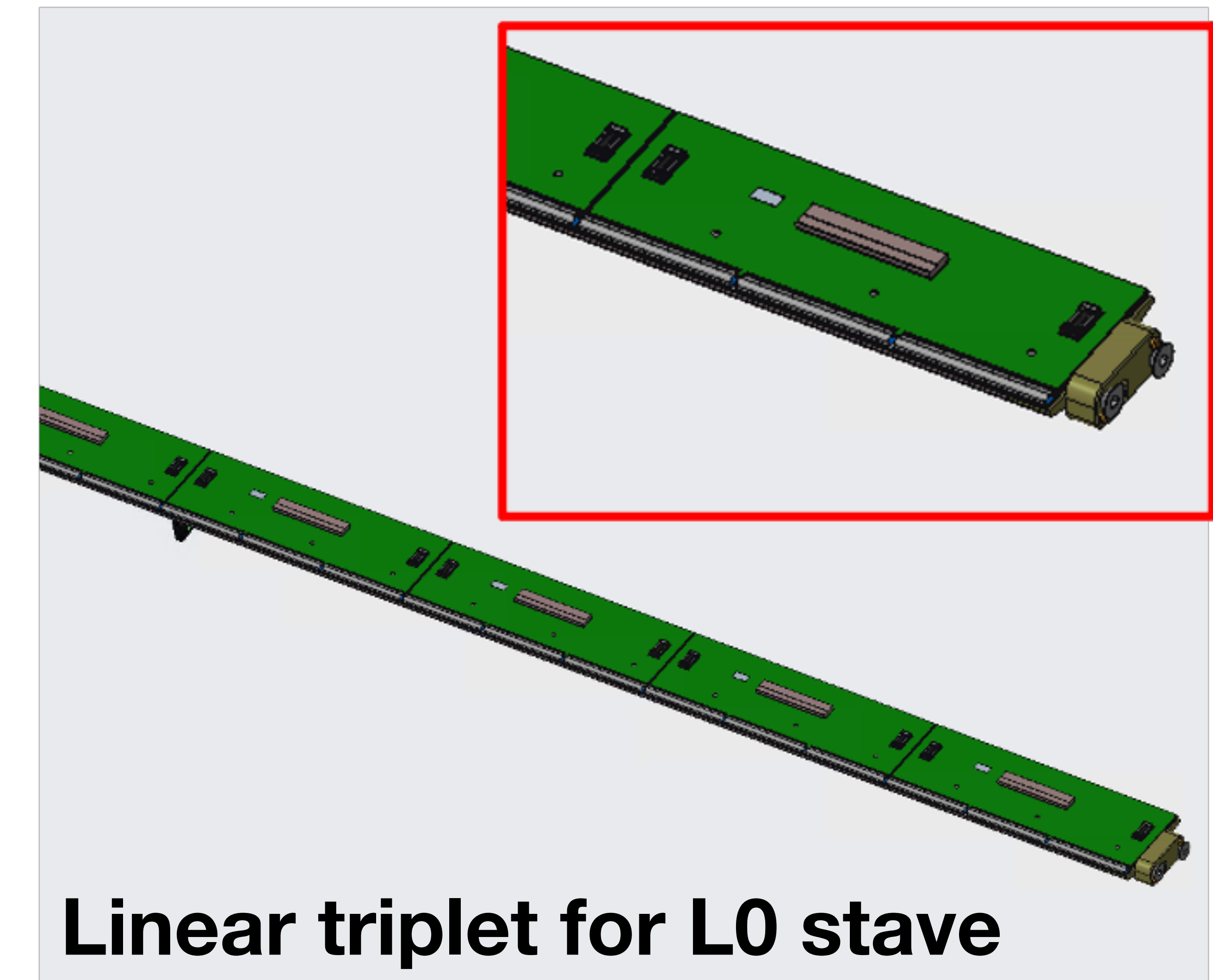
- **Quad modules (four front-end chips, 1 sensor)**:
  - Comes in two sensor thicknesses, 100 μm (for layer 1) and 150 μm (for layer 2-4)
  - 50x50 μm^2 n-in-p planar sensors
- **Triplet modules (three front-end chips, 3 sensors)**:
  - 3D sensors
  - 25x100 μm^2 in the barrel staves (L0)
  - 50x50 μm^2 in the rings (R0-1)



Ring triplet module on flex

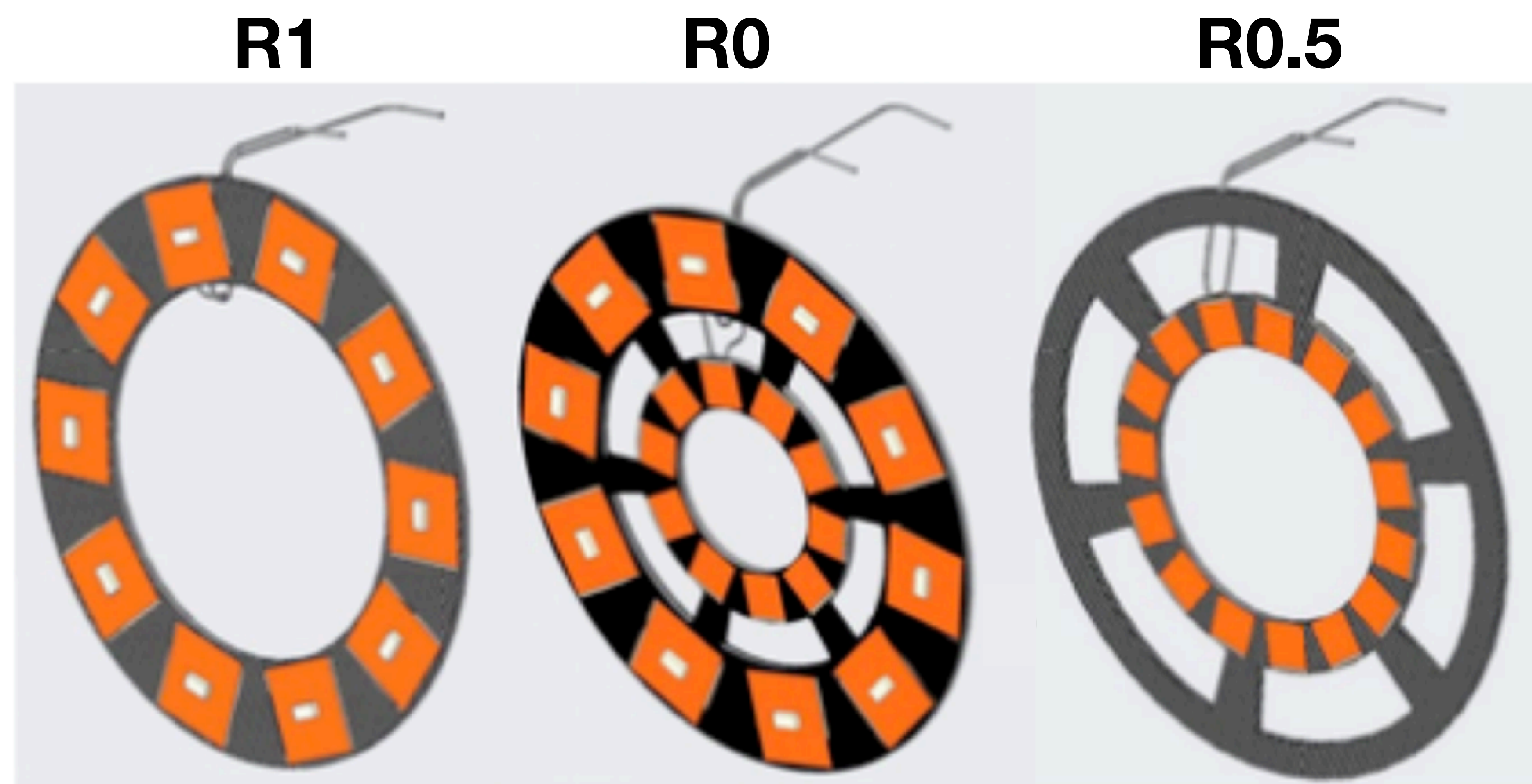


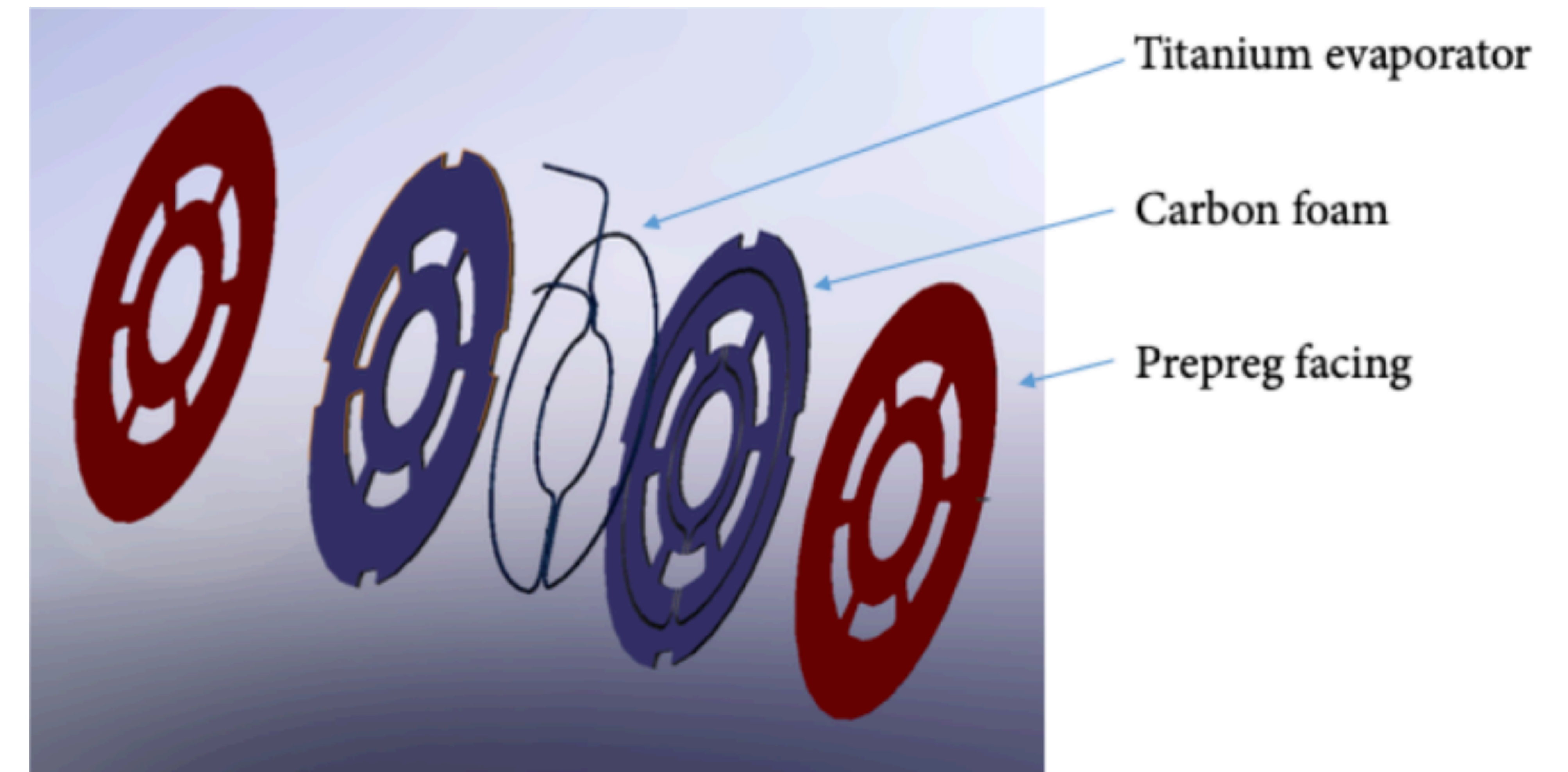
Quad module



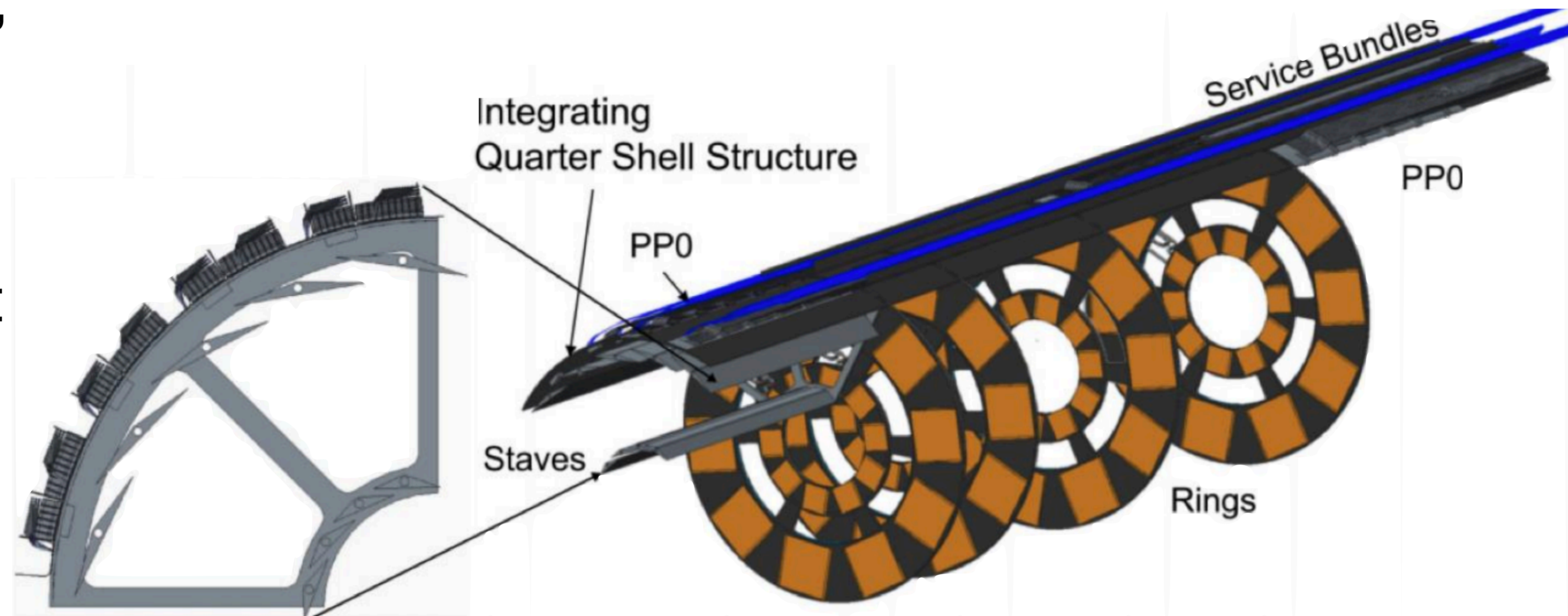
Linear triplet for L0 stave

ATLAS ITk pixel Inner system layout





- Three double sided ring designs (R0, R0.5 & R1)
- Two barrel staves, L0, L1
- Cooling integrated into local support
- Services integrated in shell structure



ATLAS ITk pixel outer barrel layout

- Quad modules (150 μm thickness)
- Modular approach for loading and integration
- Require one extra step “cell loading” for integration w/ cooling

M1 Ti Screws

Module Cell

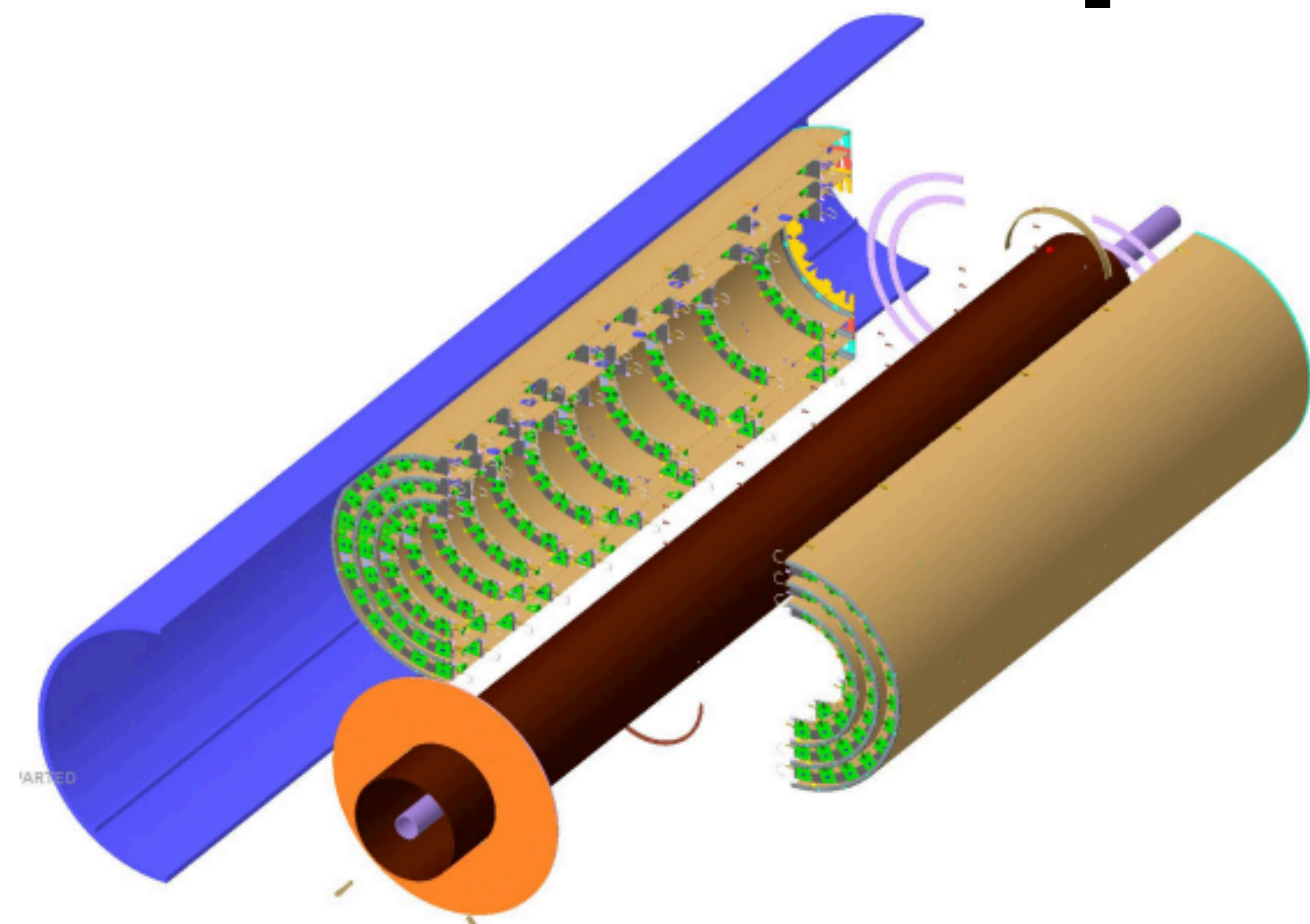
Loaded cell (with module)

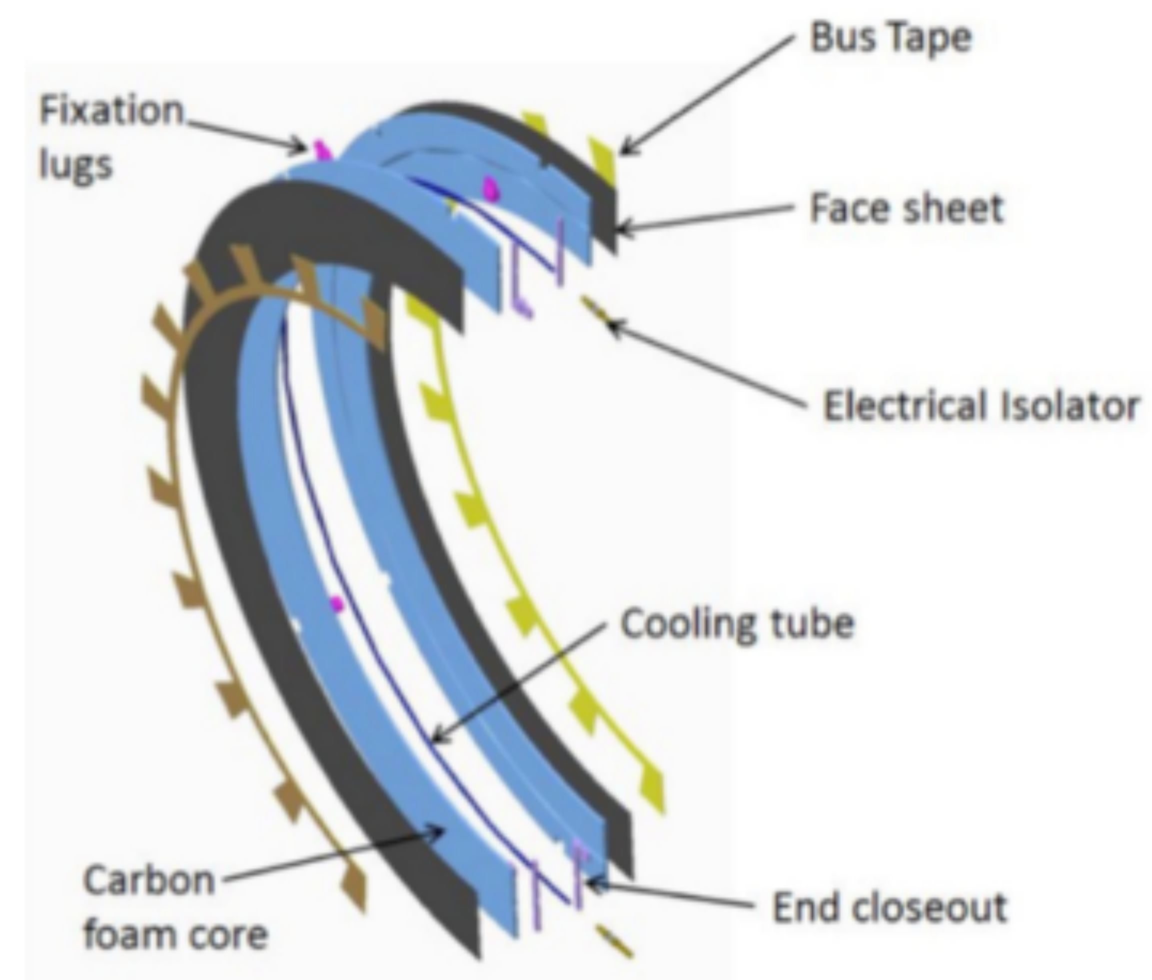
Longeron

Inclined half ring

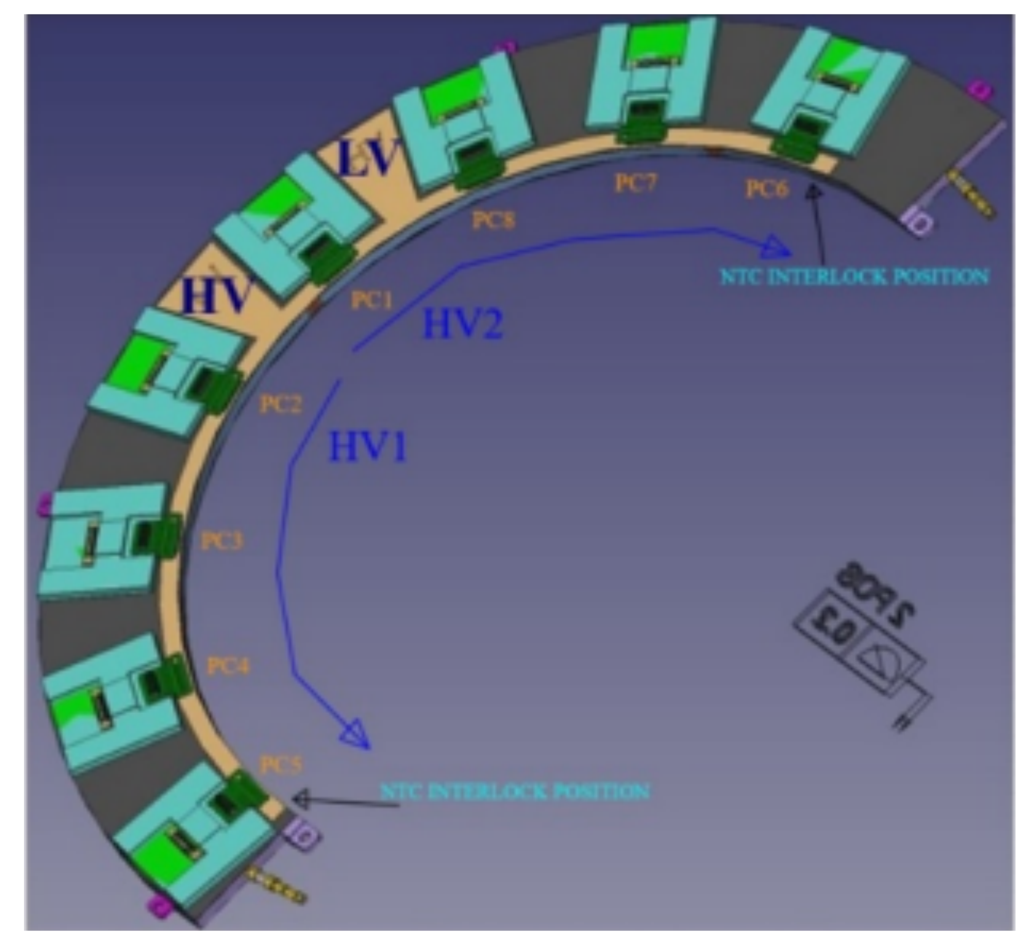
Services

ATLAS ITk pixel outer endcap layout

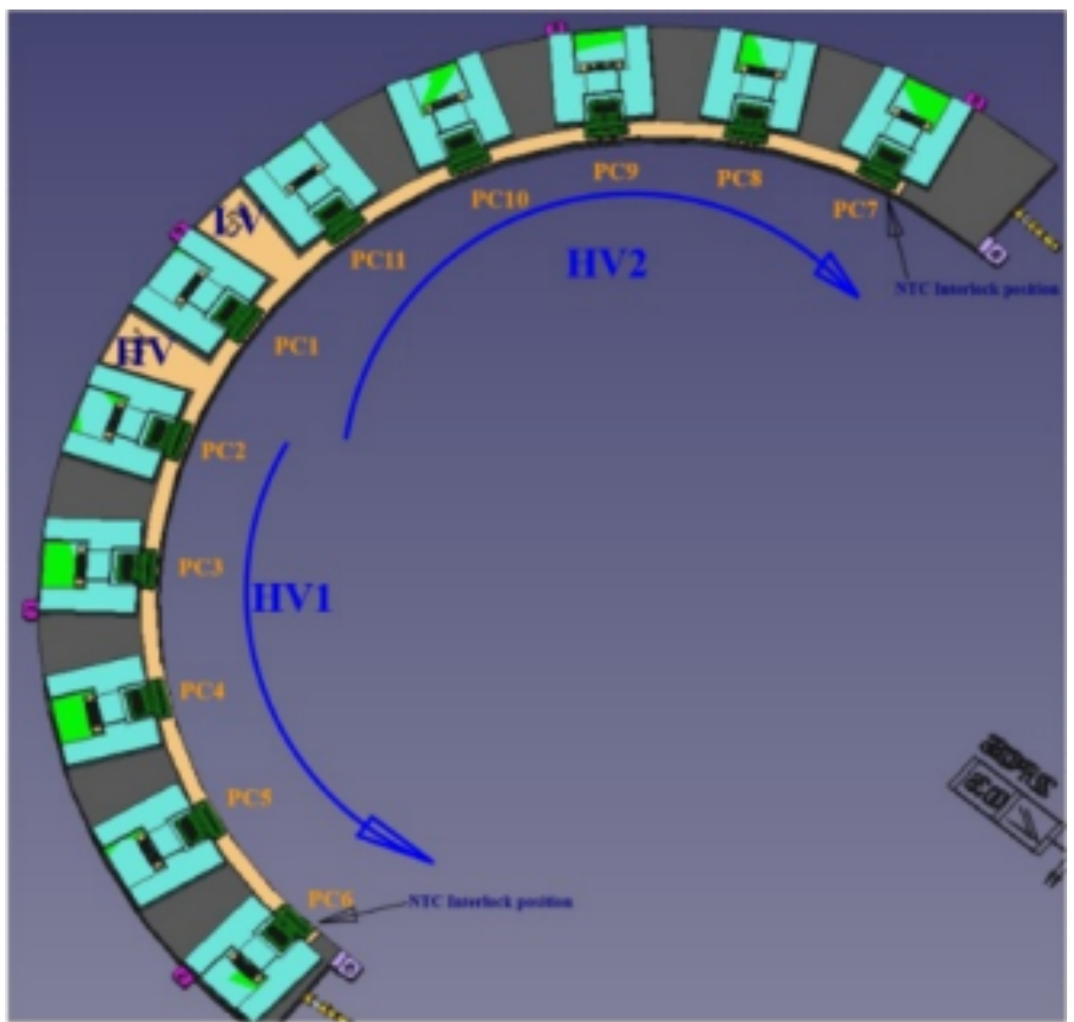




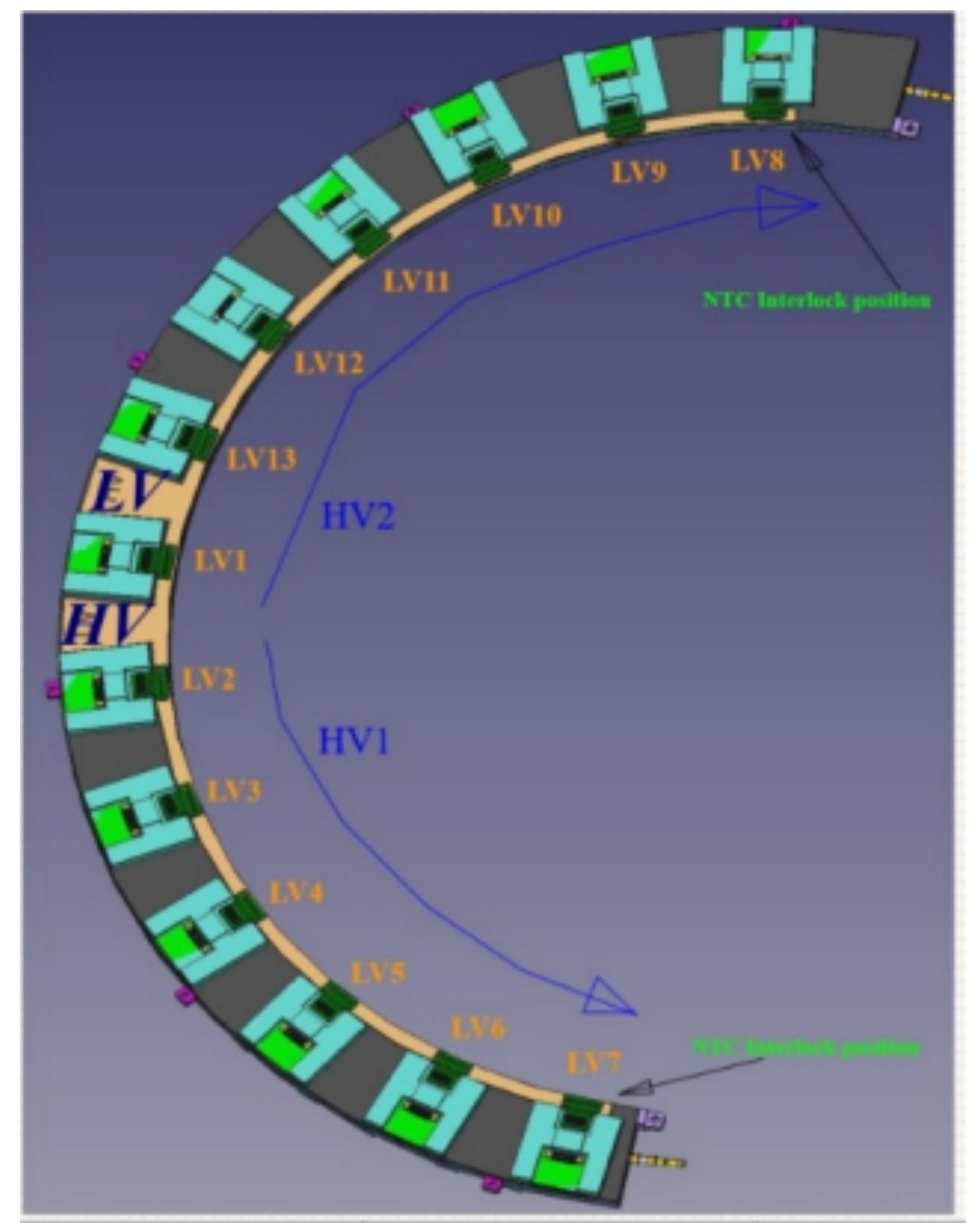
- Three different sizes of local support
- One serial powering chain per side
- Up to 13 modules per SP chain
- As for R0-1, cooling pipes are integrated into local support



L2



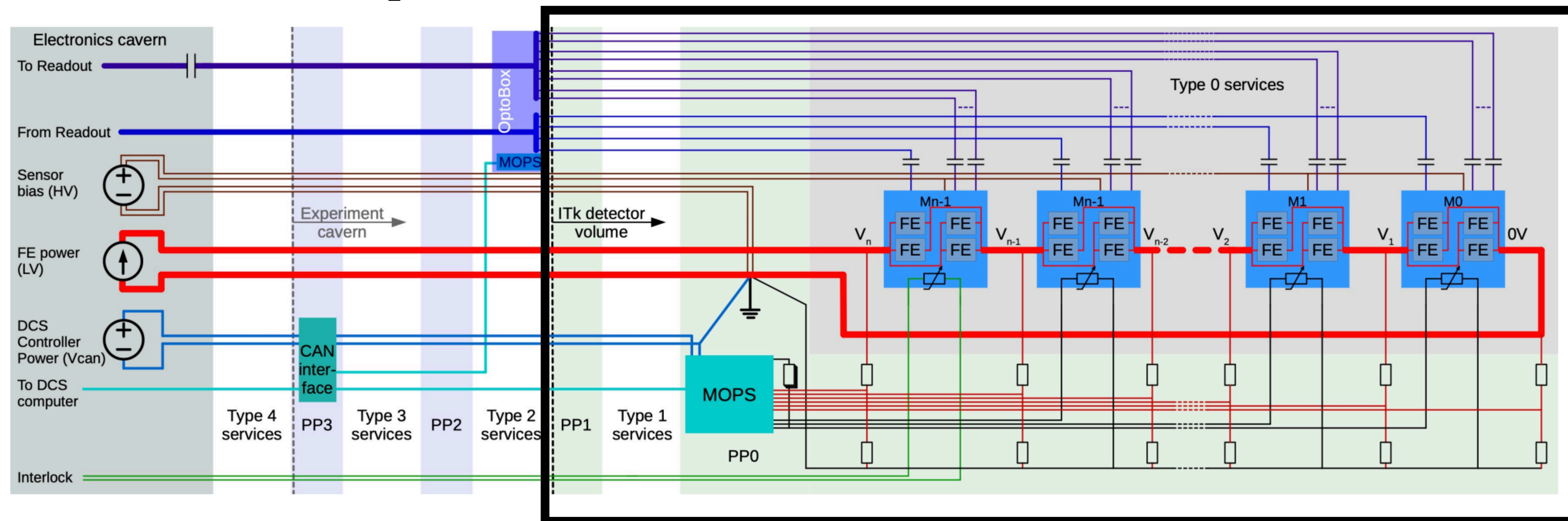
L3



L4

ATLAS ITk pixel services

Inside detector volume



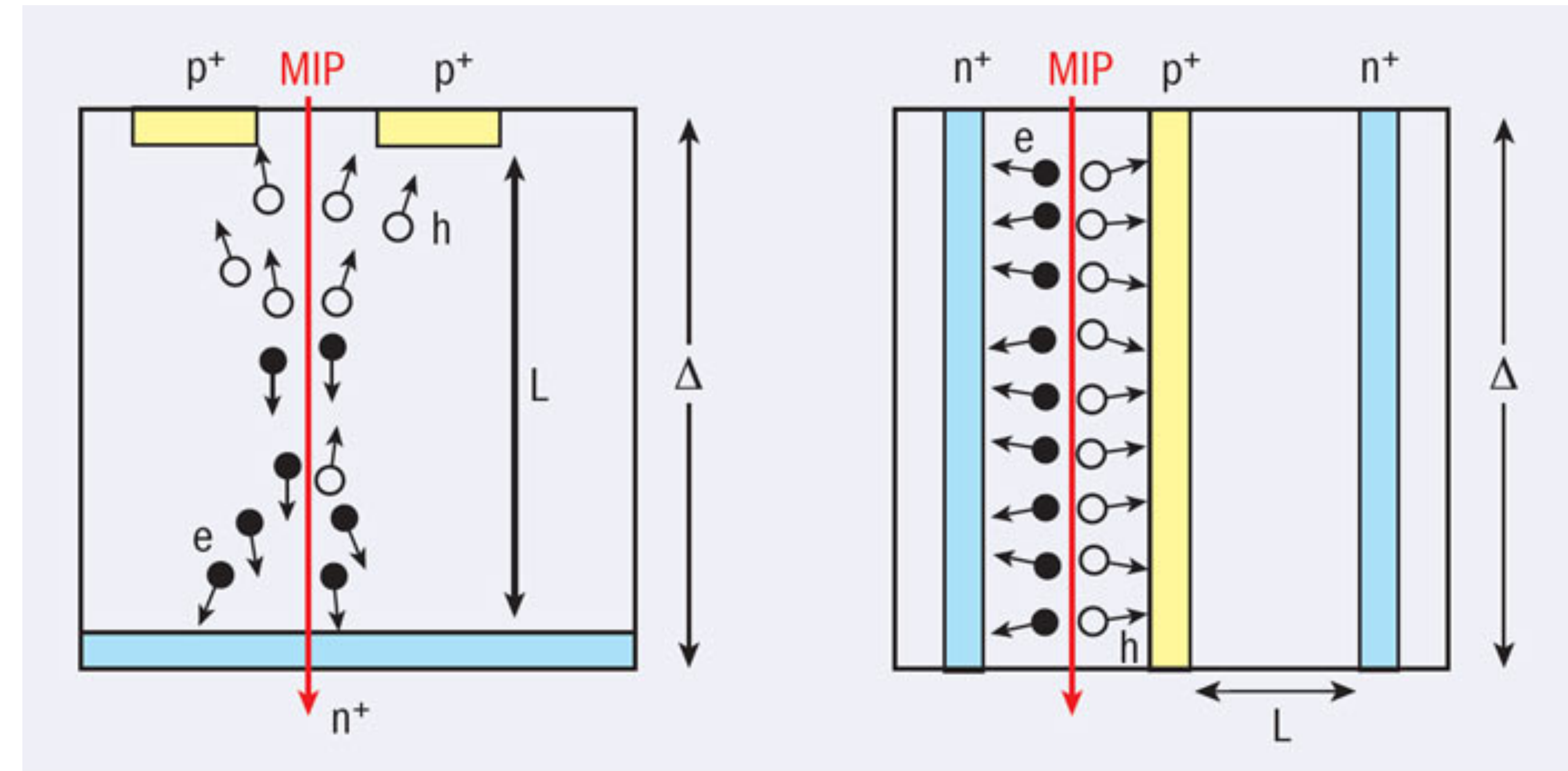
- Serial powering chain of up to 13 modules
- Quad modules connected to patch panel (PP0) via pigtails and type0 services. Voltage and temperature are monitored by one MOPS chip pr. SP chain
- Data is driven to optobox (outside detector volume) by twinax cables at 1.28 Gbps, and by optical fibre from optobox to readout

Overview of the Norwegian contribution

- 3D sensors, in-kind
- Triplet module flex hybrids design and in-kind delivery
- Triplet module assembly, burn-in, testing
- CORE contributions to front end ASICs, thin planar sensors, back-end-of-line (hybridization, flipchip etc.)
- CORE contributions to on/off detector services and integration (cooling, environmental, patchpanels etc.)

A brief history of 3D pixel sensors

- Different electrode geometry, which makes pixels ‘3D’
- Decoupled electrode separation and sensor thickness
- Inefficiencies at perpendicular beam incidence
- Very challenging to produce (~60 steps)
- SINTEF MiNaLab have completed 6 runs

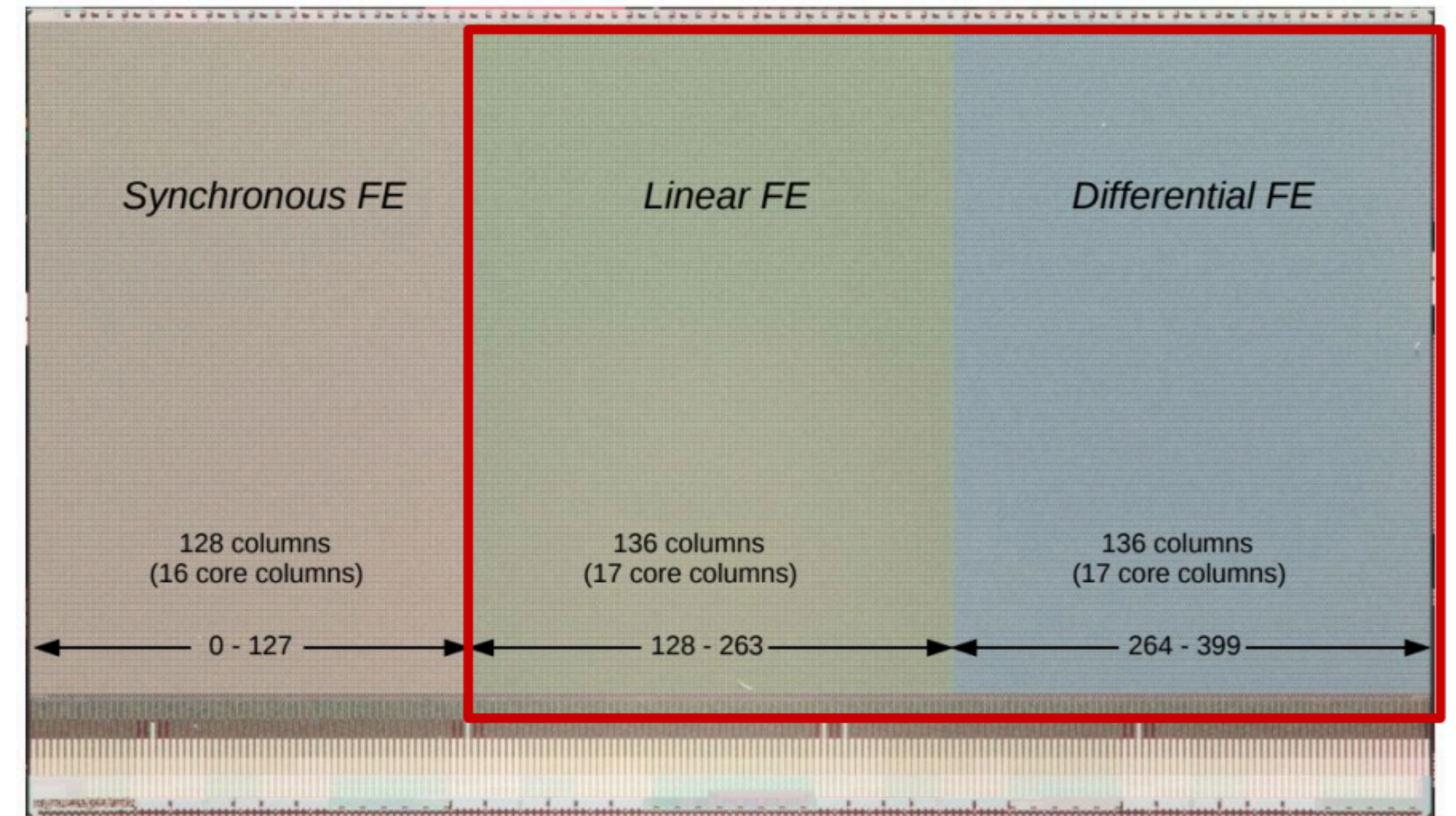


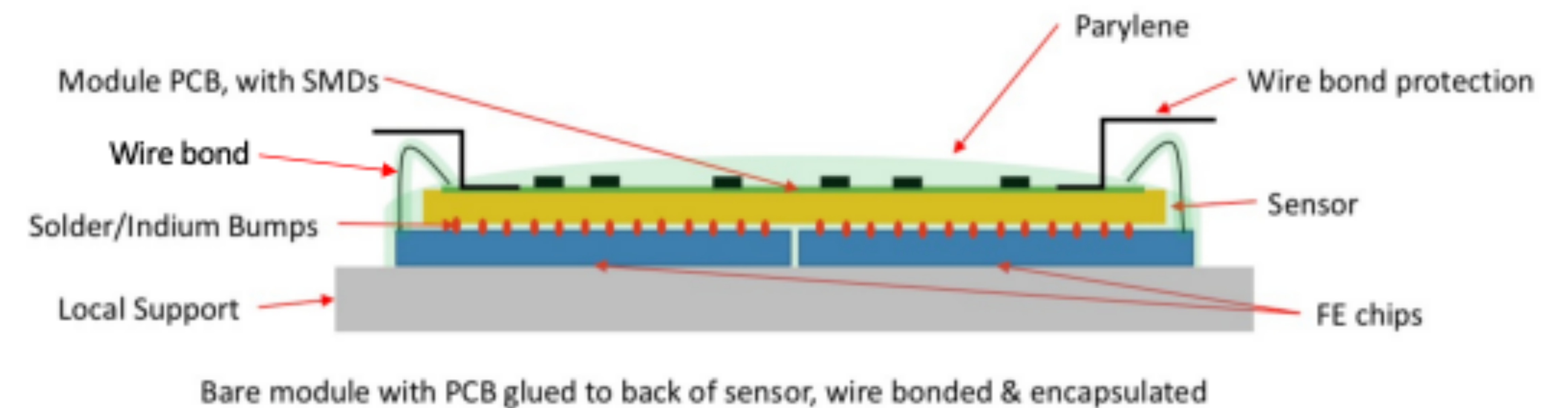
YEAR	Project	Wafer type	Active thickness [µm]	Electrode diameter [µm]	Remarks
2006	Run-1	4" SOI	230	15	N-type, low mechanical yield
2008	Run-2	4" SOI	230	15	50% yield (roughly)
2010	Run-3	4" SOI	230	15	Low yield (2 out of 24 wafer ok)
2018	Run-4*	6" Si-Si	50 & 100	4	Very good yield (FE-I4 layout)
2019	Run-5*	6" Si-Si	150	6	OK yield (RD53 A/B with active edge)
2021	**Run-6***	**6" Si-Si**	**150**	**6**	**Completed Feb. 2021. ATLAS pre-production. (RD53 A/B with common layout with FBK, slim-edge termination)**

RD53A readout chip

- Prototype ASIC that has been used to develop common tooling and sensors
- Contains 3 different front-ends
- RD53A is half the size of the final chip (ITkPix).
- Final chip will consist of one analog FE (differential) and have a size of 2x2 cm^2

Front end flavors in RD53A chip



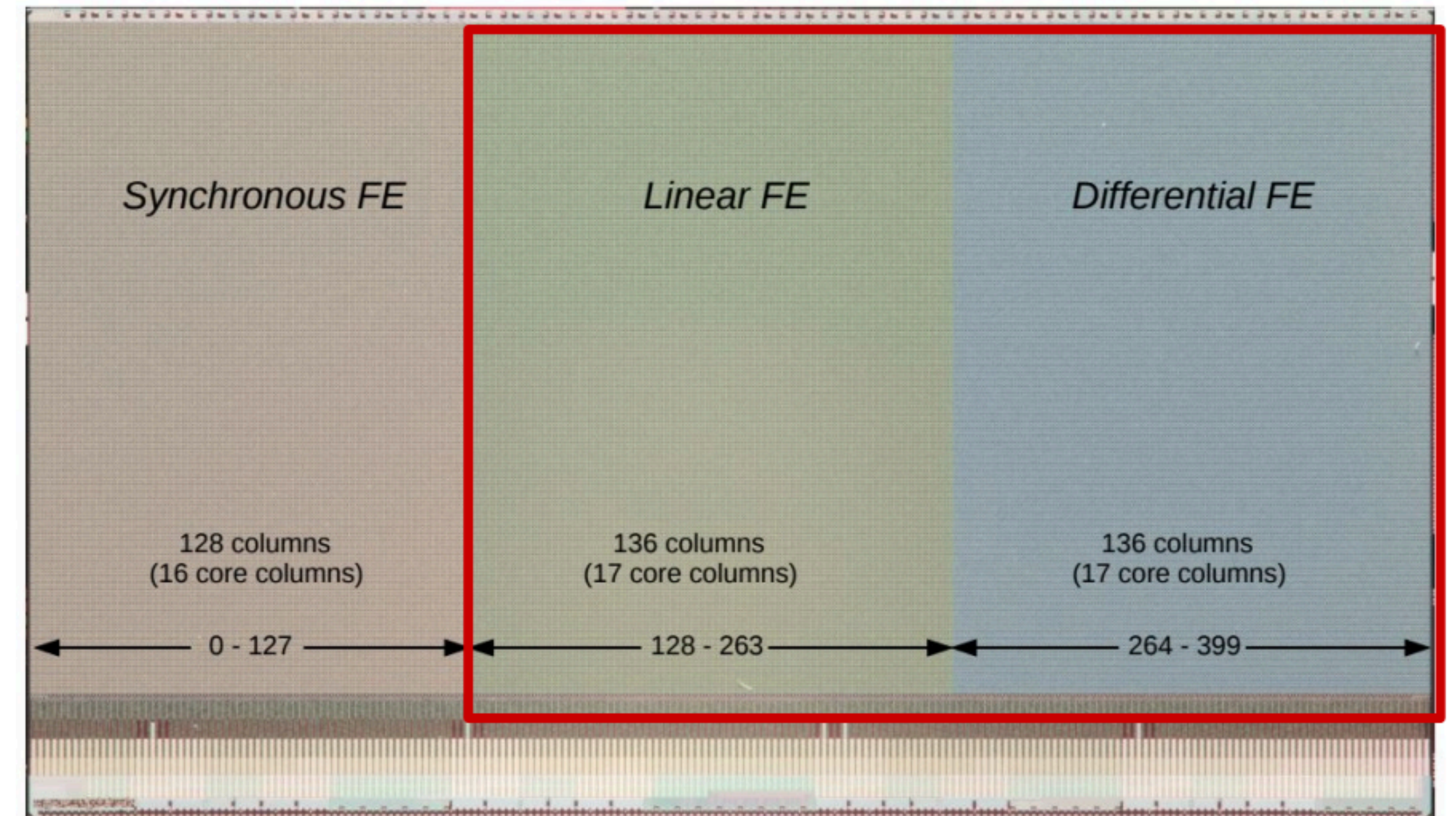


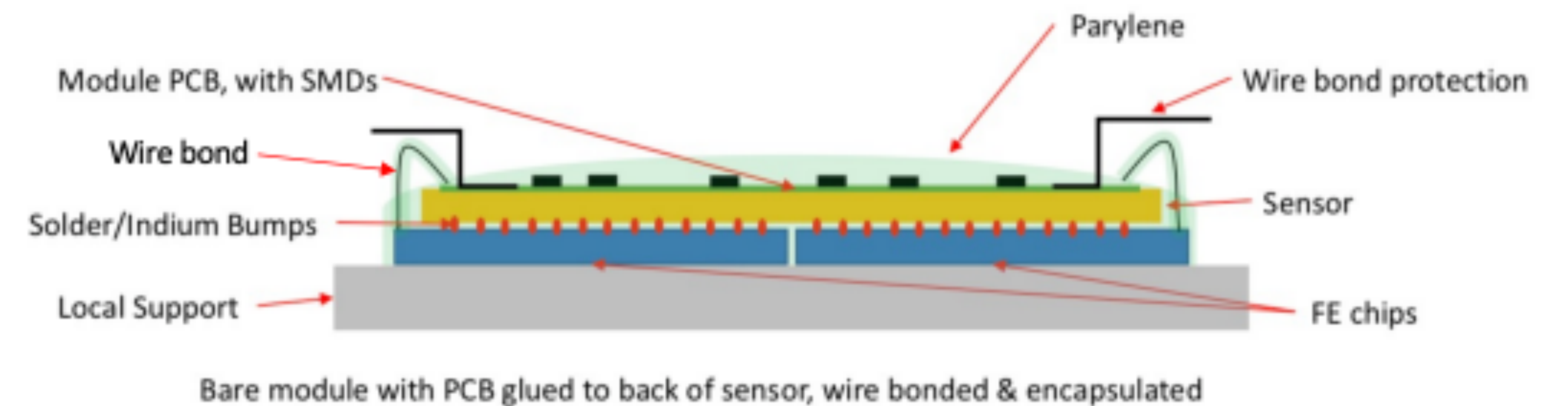
Bare module with PCB glued to back of sensor, wire bonded & encapsulated

Her kommet attiq sitt bidrag

- placeholder
- placeholder
- placeholder
- placeholder

Front end flavors in RD53A chip

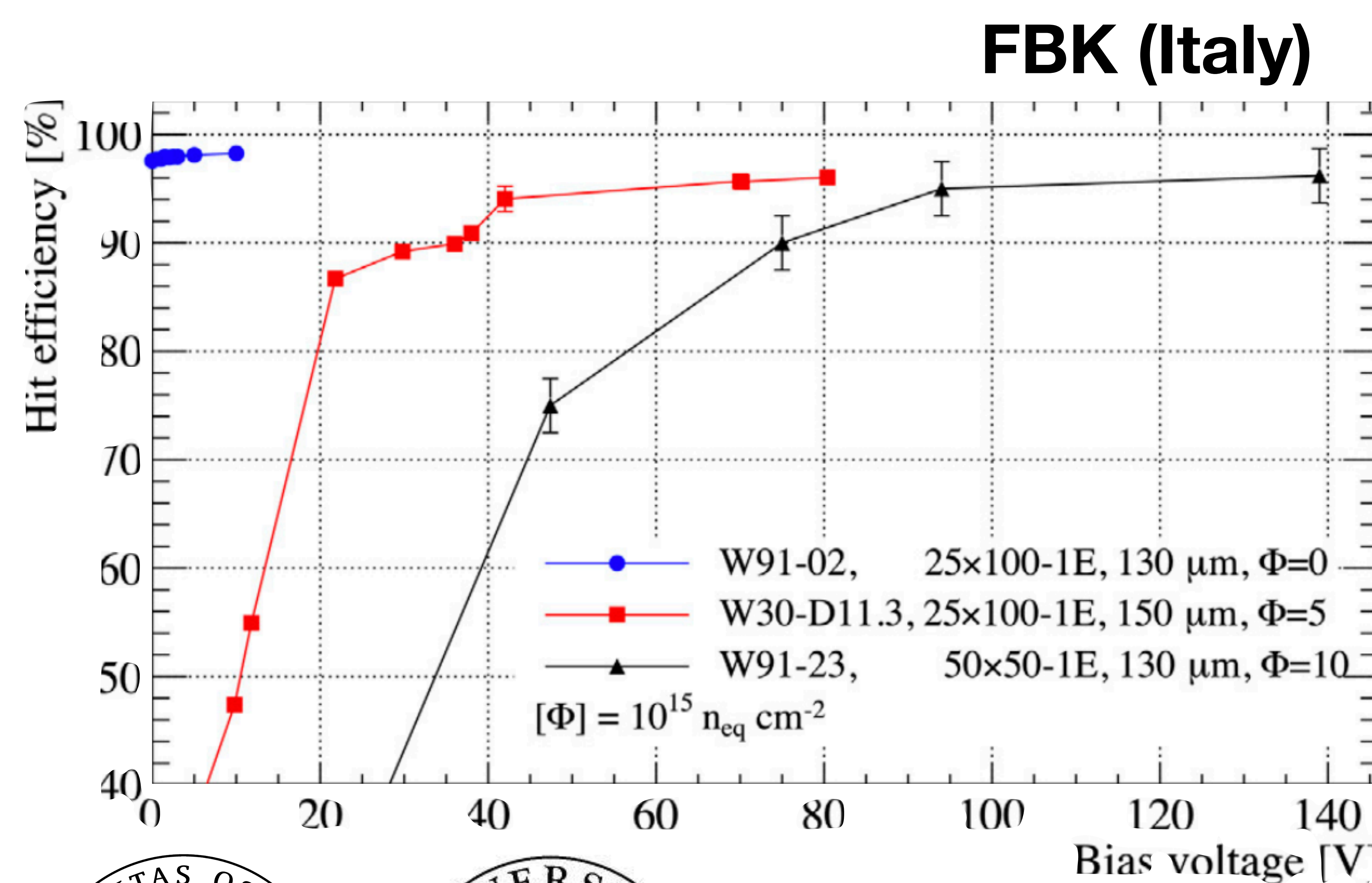


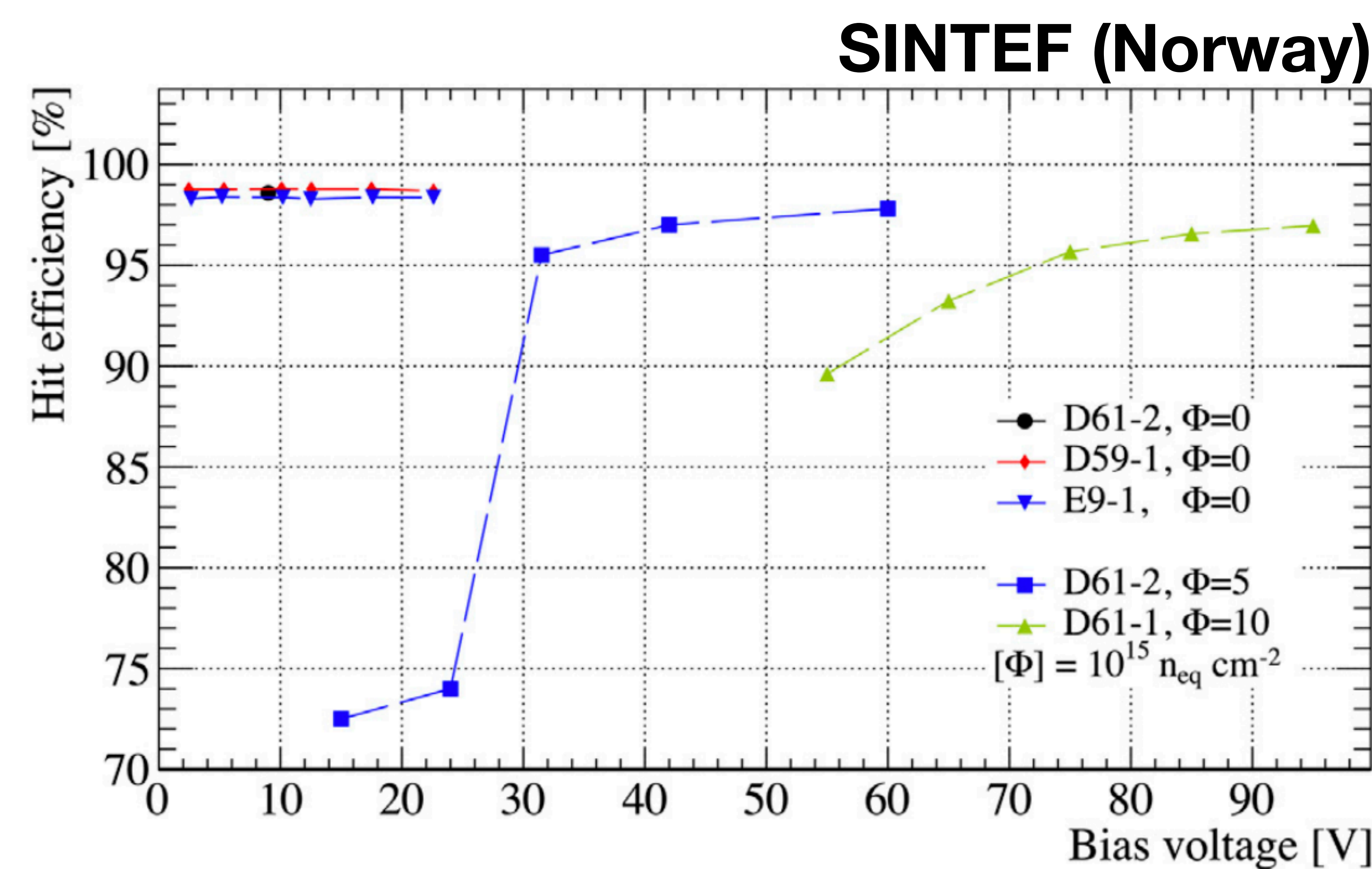


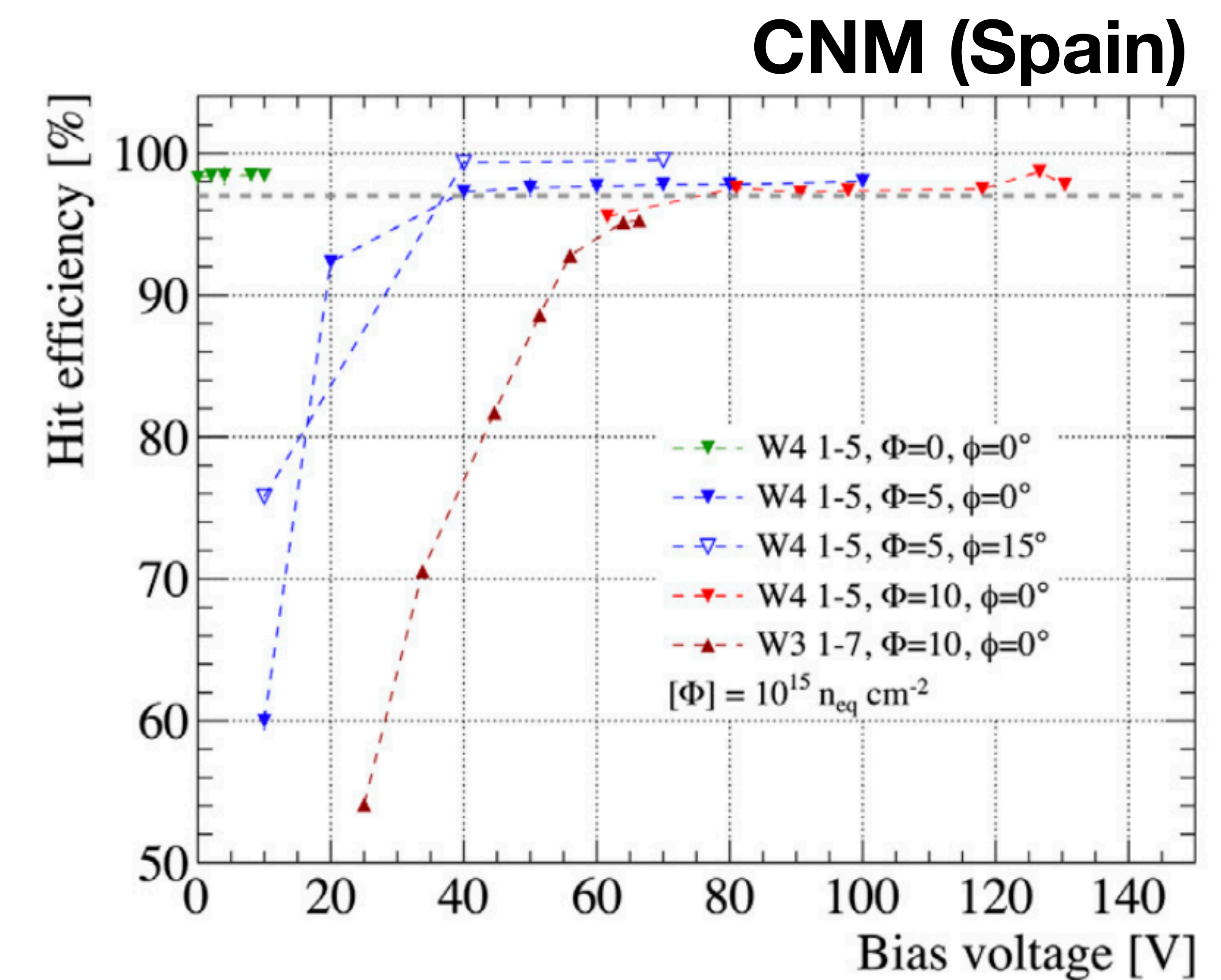
Bare module with PCB glued to back of sensor, wire bonded & encapsulated

RD53A Single chip modules - Irradiation

- 3D modules have been irradiated and tested in testbeams at CERN and DESY
- Sensors from 3 vendors, Italy, Spain and Norway
- Irradiation tests of single chip modules from 3 vendors irradiated to $\Phi \geq 1 \times 10^{16} n_{eq} cm^{-2}$ all show a hit efficiency > 96% at 100 V bias voltage



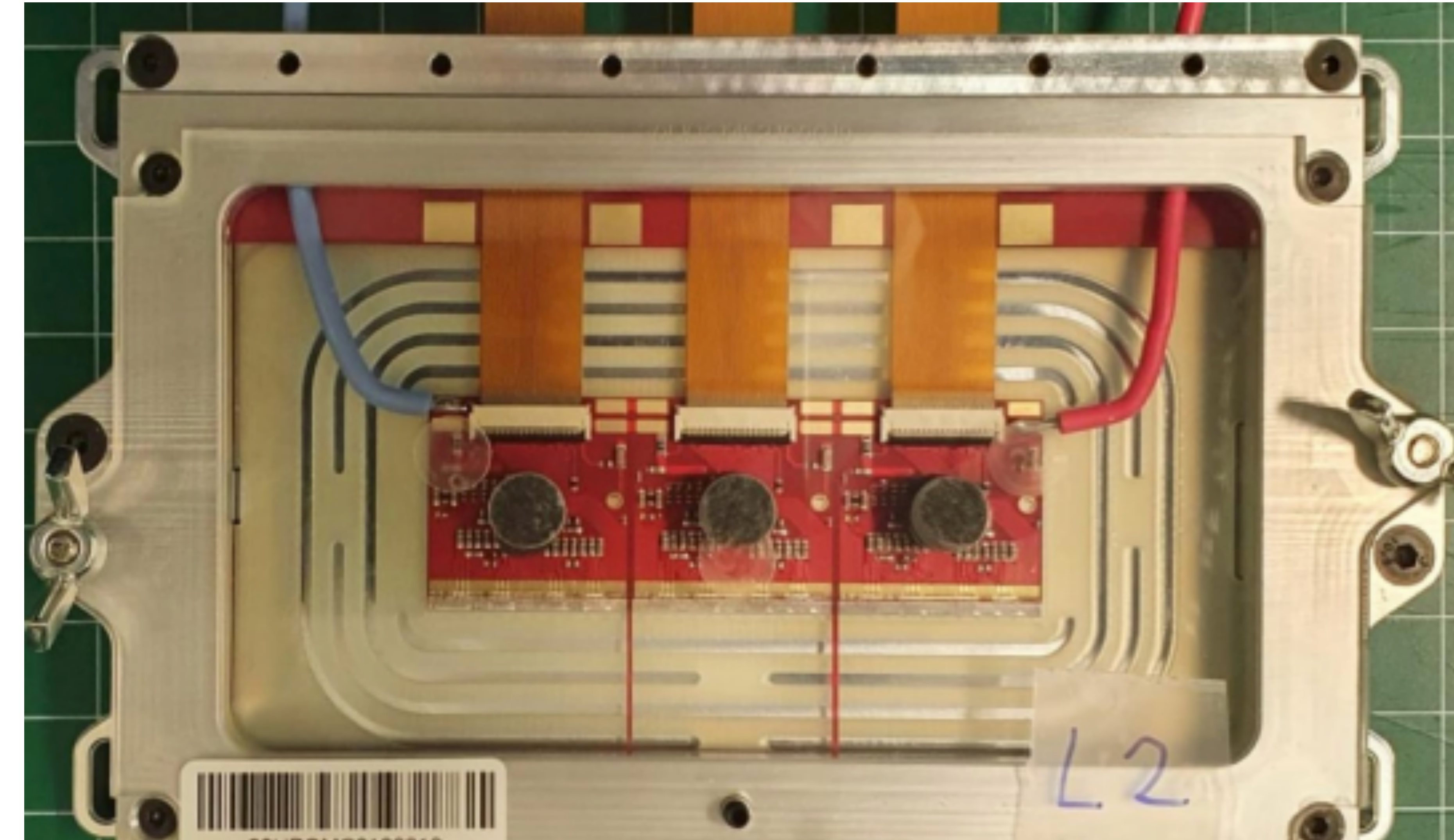


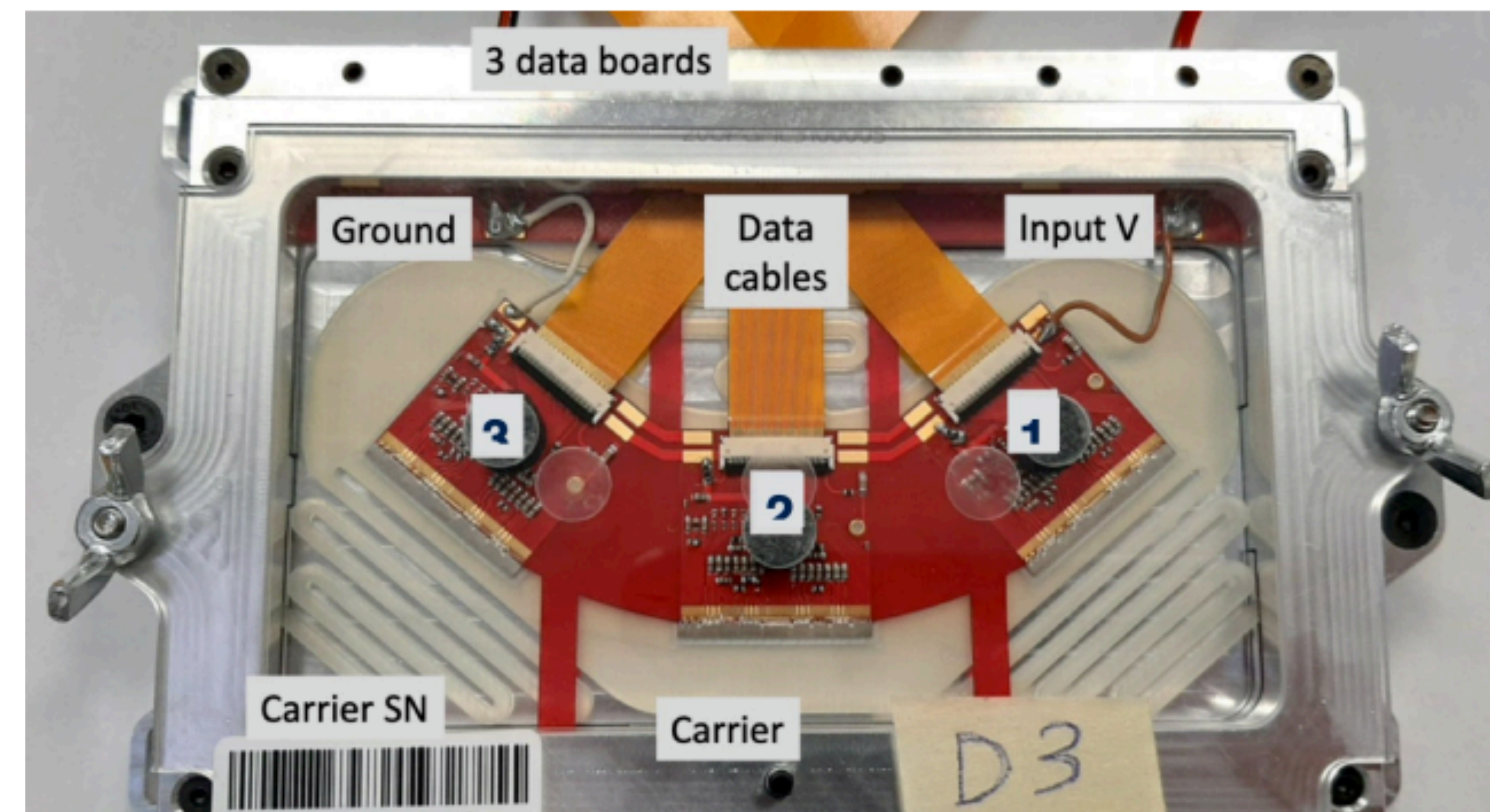


https://doi.org/10.3389/fphy.2021.624668

RD53A triplet modules

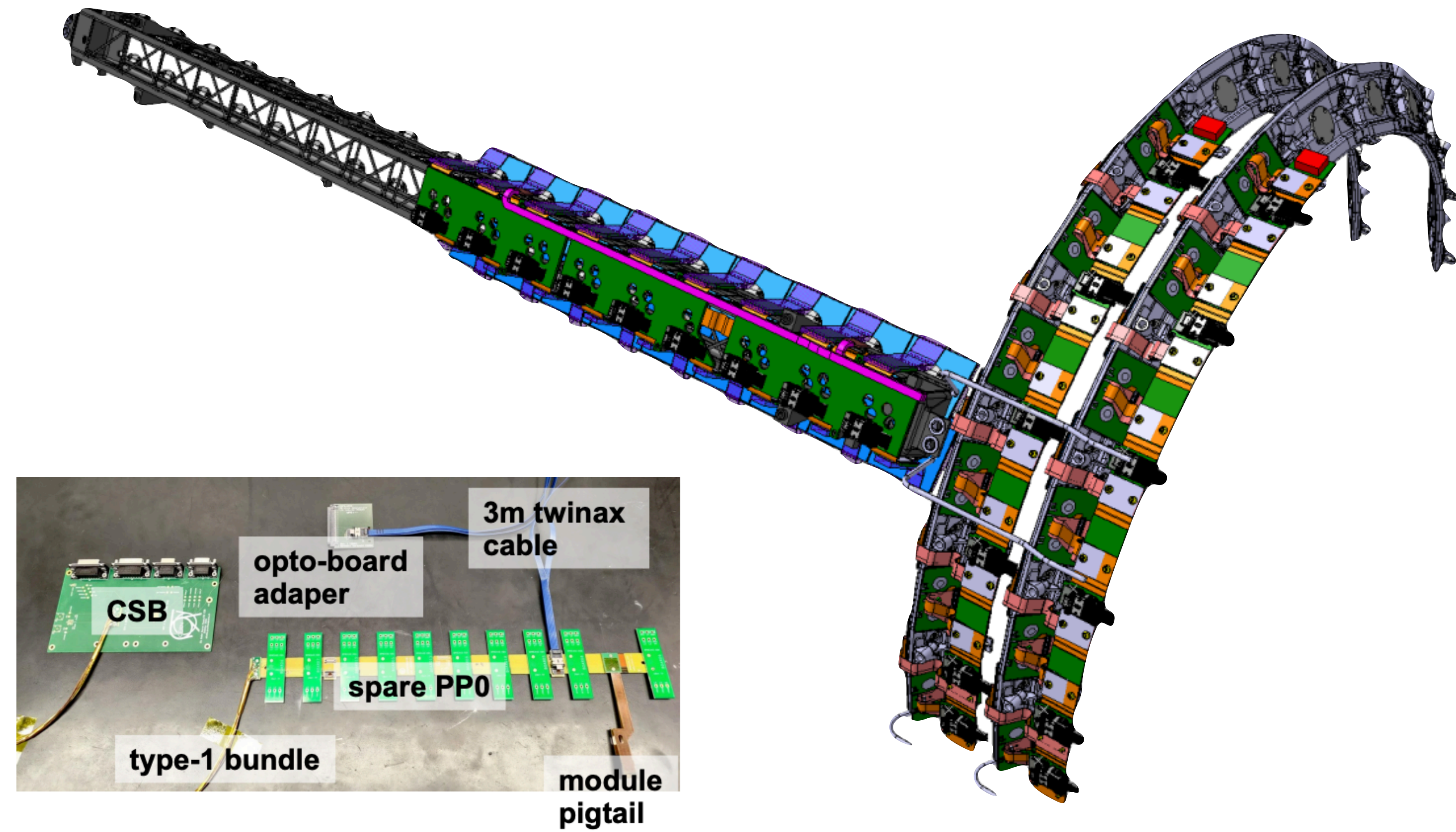
- Two different types: Linear and ring triplets for stave and rings
- Procedures to assemble RD53A linear and ring triplets have been developed
- Norway is building linear triplet modules
- Also designing and delivering triplet module flex hybrids for both ring- and linear triplets



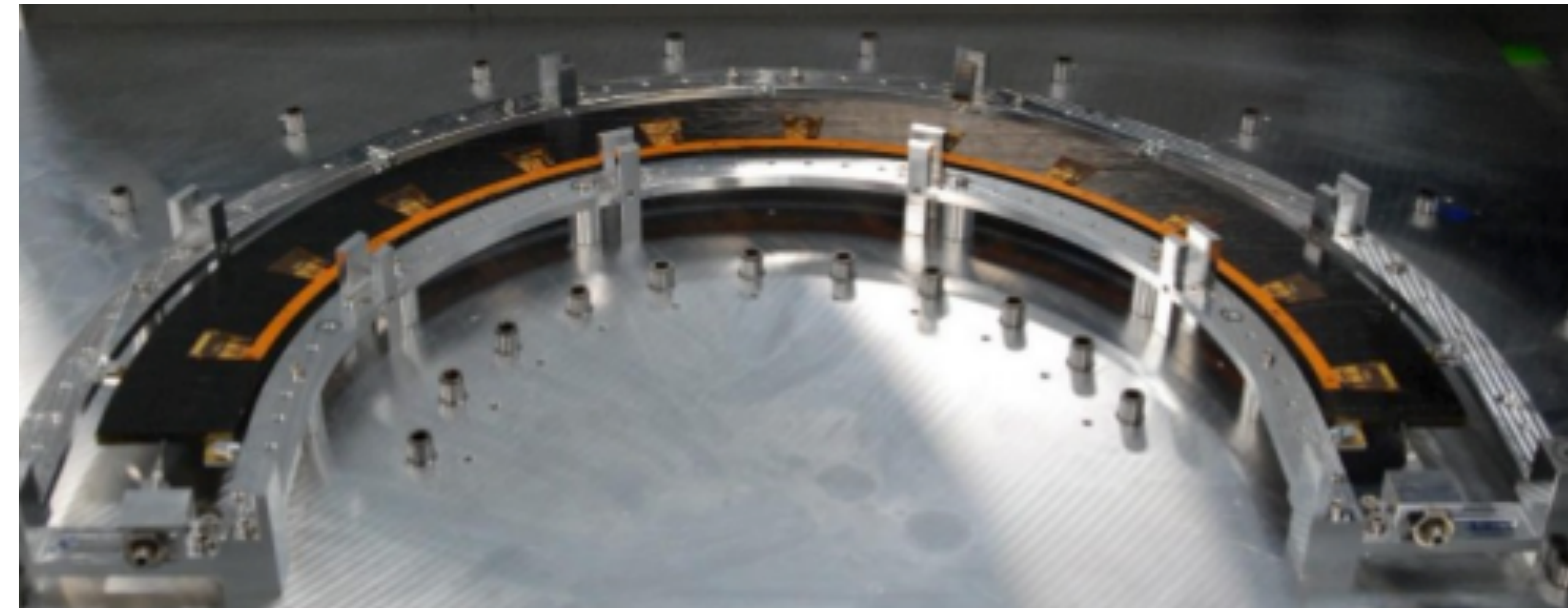


Prototypes for system tests

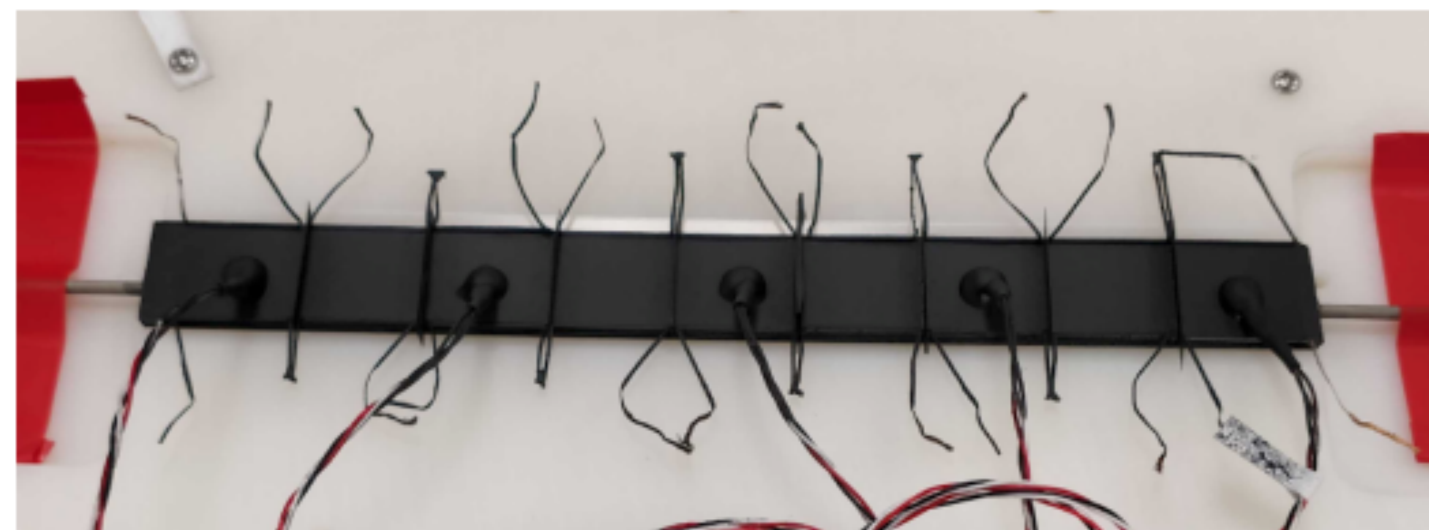
Outer Barrel

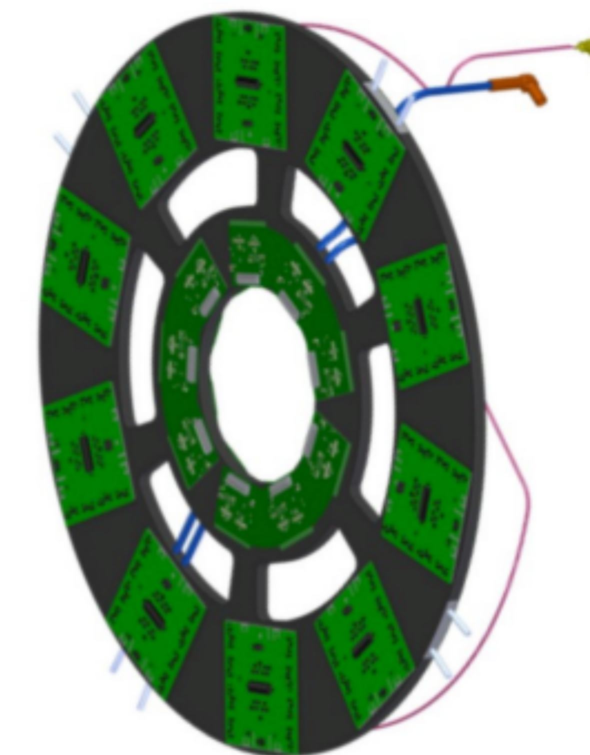


Outer endcaps



Inner system





Inner system tests

Electric / DAQ prototypes:

- First loaded R0 ring with RD53A prototypes
- Tested with modules powered at room temperature
- No significant difference in digital scans / disconnected bump bond scans before and after loading -> no significant damage during loading
- One RD53A module read out with Type-0 ring + Ring flex + PP0

Electrical R0 ring prototype

Type0 ring test setup

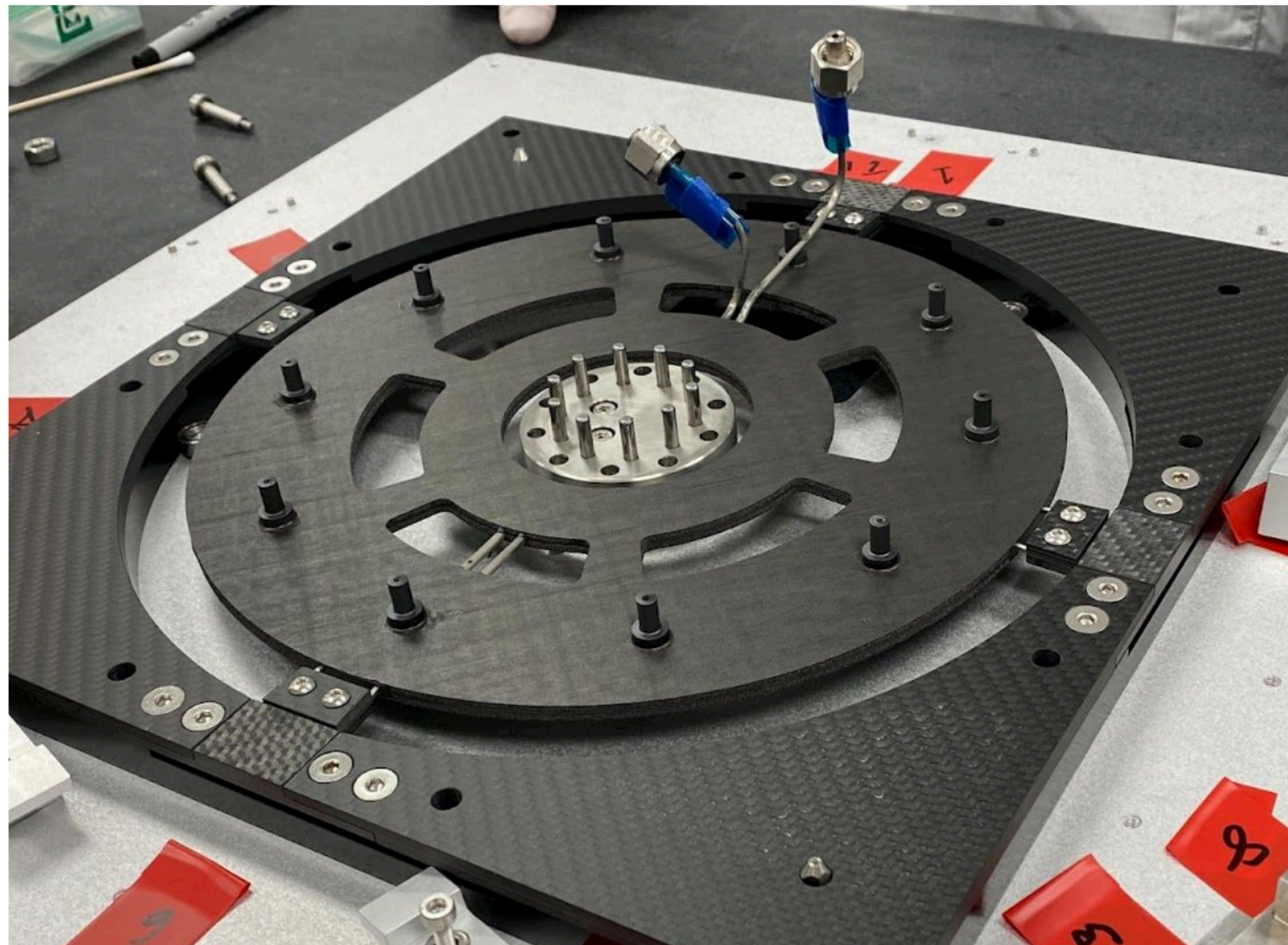
Summary

- The new ITk will be comissioned by 2028 and will consist of only silicon based tracking detectors
- Norway is heavily involved in this work, and are contributing with designs, modules, sensors as well as CORE contributions.
- Irradiation campaigns and testbeams show that modules can be operated efficiently after heavy irradiation (up to ITk fluence)
- Activities in subsystem demonstrators and system level tests are progressing, and preliminary results are within specifications

Thank you!

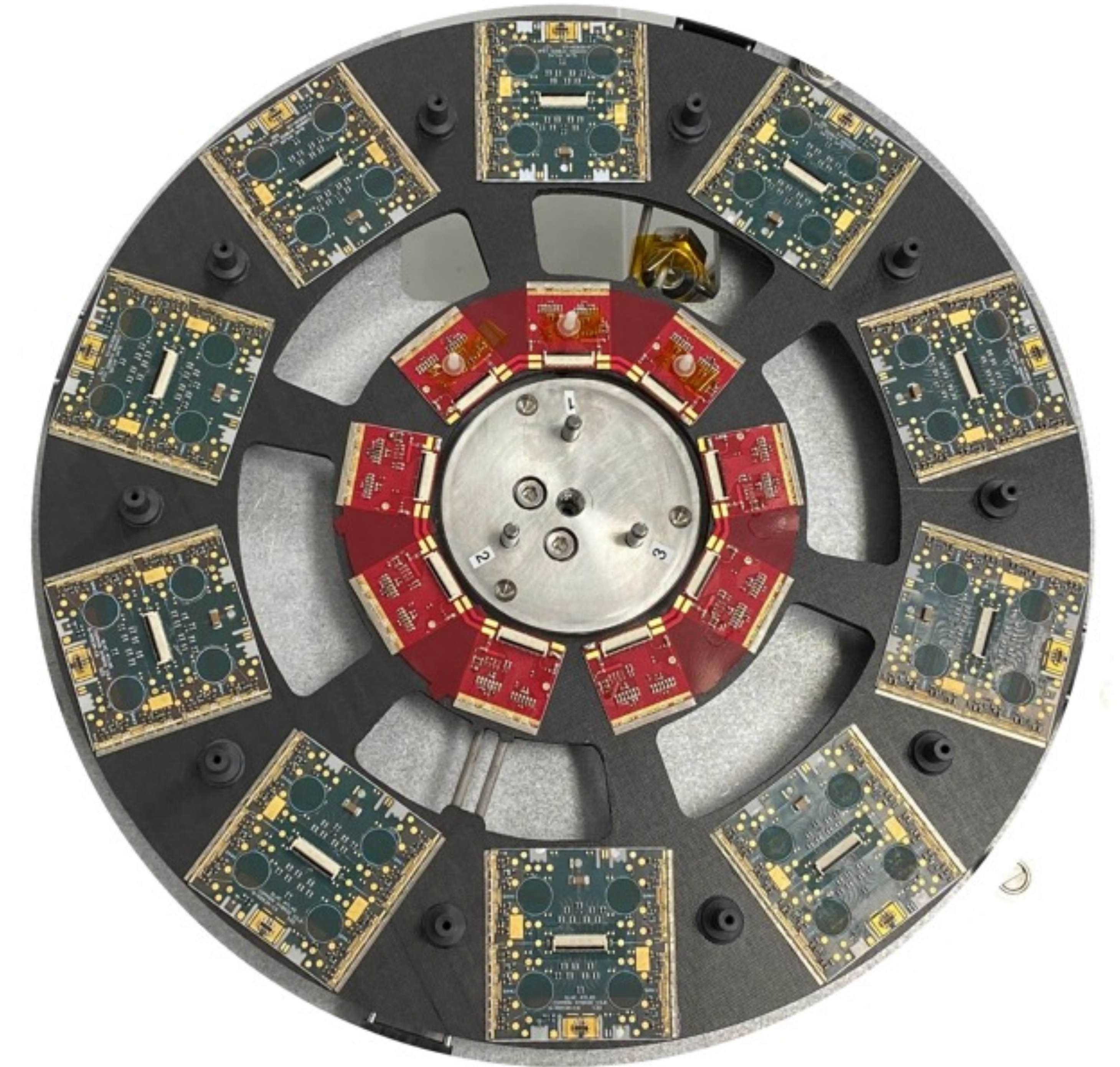
Backup slides

ATLAS ITk pixel loading: Inner system



Carbon R0 local support prototype

Glue deposition on local support

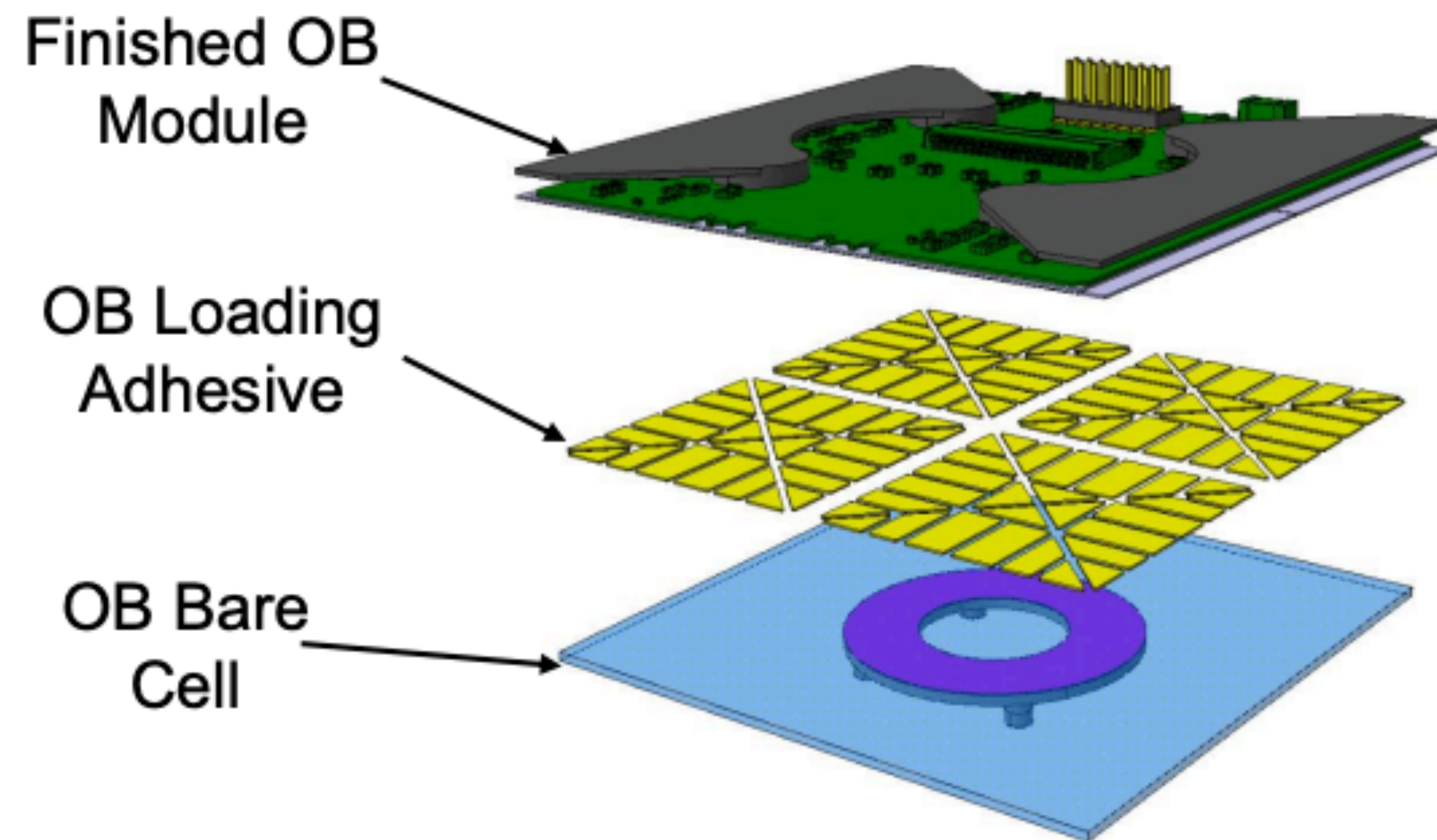


Loaded local support

ATLAS ITk pixel loading: Outer Barrel

1. Cell Loading [1]

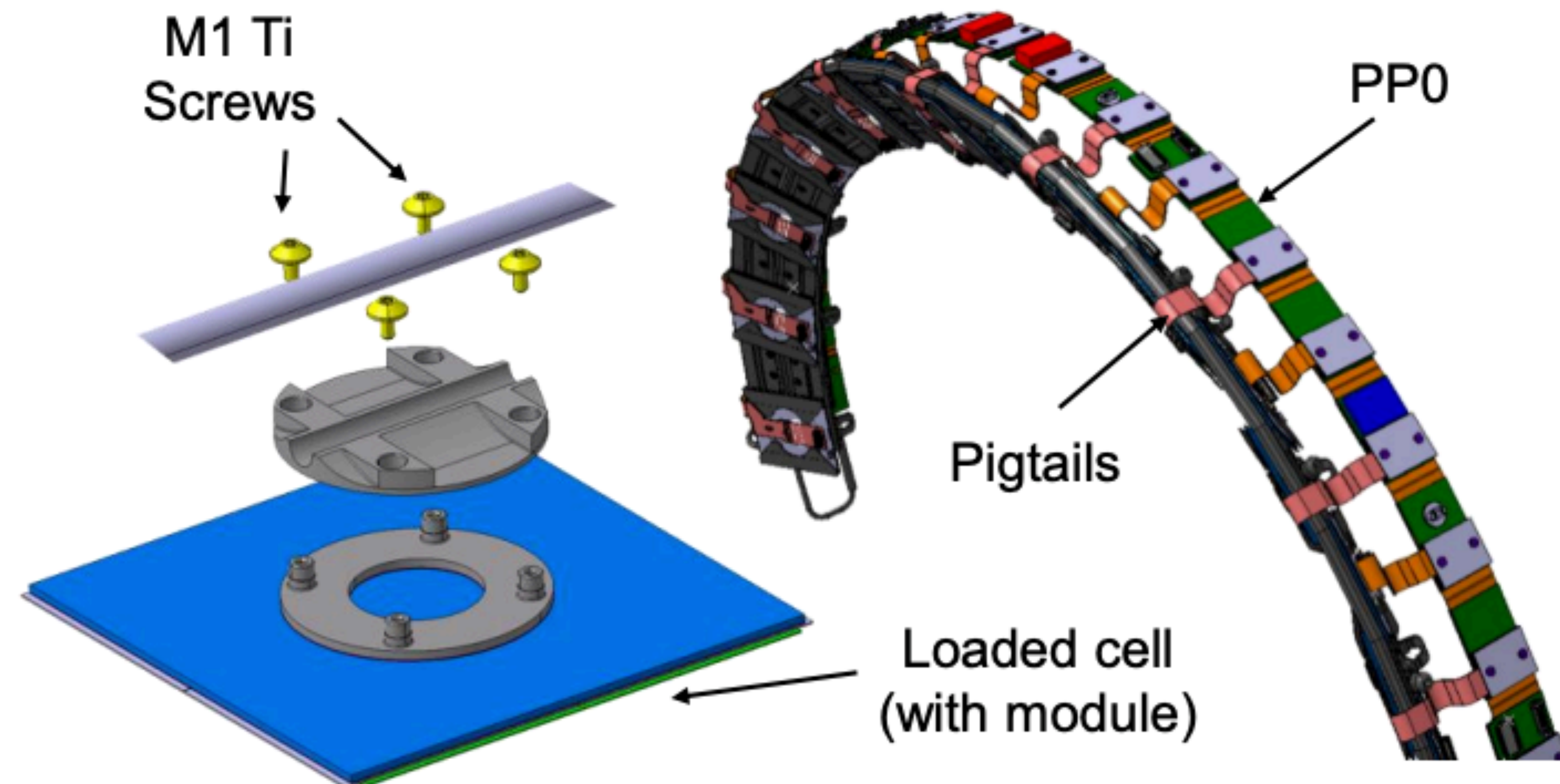
1.1 Installation of Bare Cell on loading tooling
1.2 Glue deposition
1.3 Module pick-up & placement on cell
1.4 QC testing of Loaded Cells



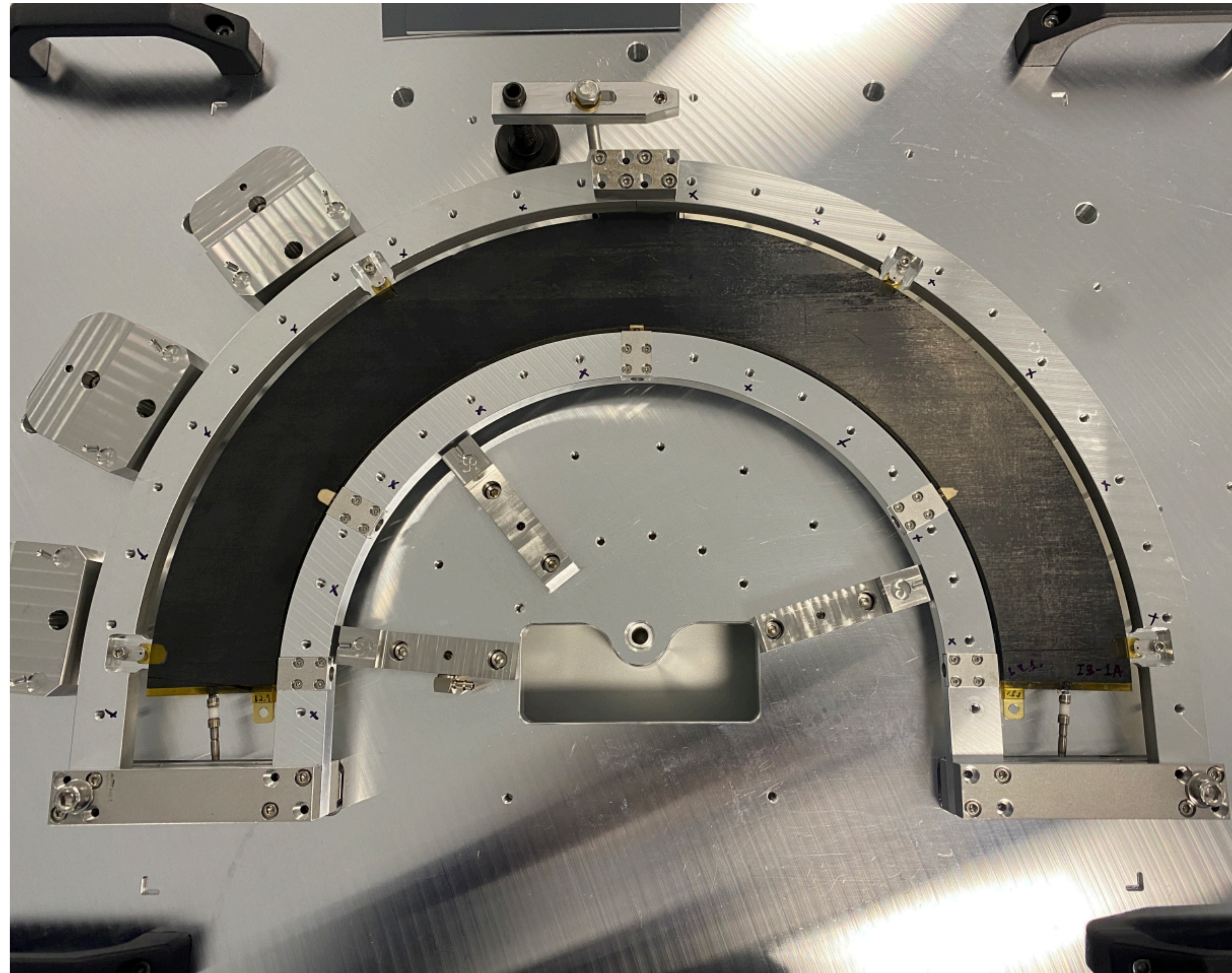
[1] A modified version developed in Japan combines 'Module Assembly' and 'Cell Loading' in a single step

2. Cell Integration

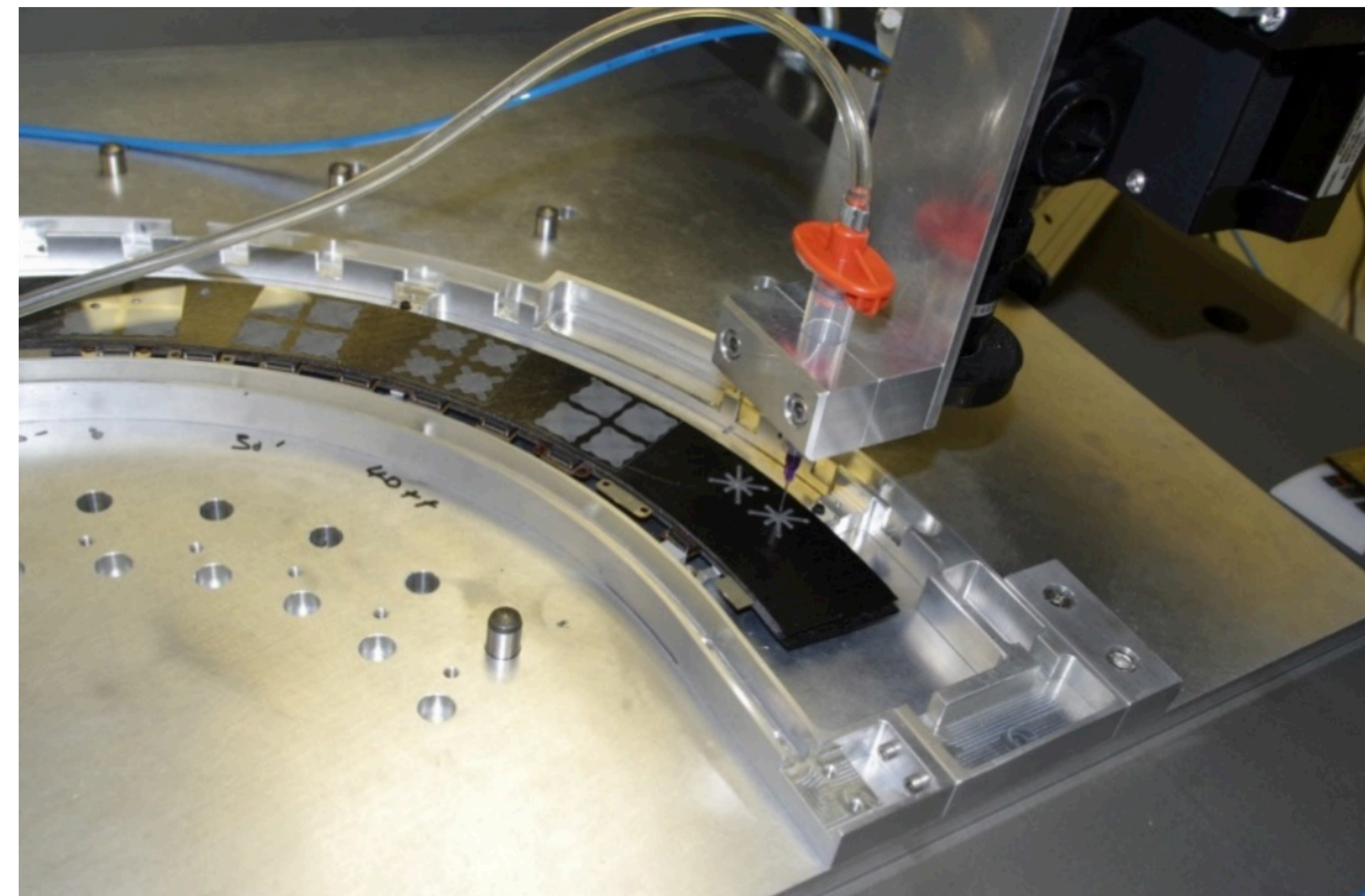
2.1 Installation of pre-bent module pigtails on Loaded Cells
2.2 Mounting loaded cells on the functional local support
2.3 Installation of PP0s
2.4 Module-Type-0 Connections
2.5 QC Testing of Loaded Longeron/IHR



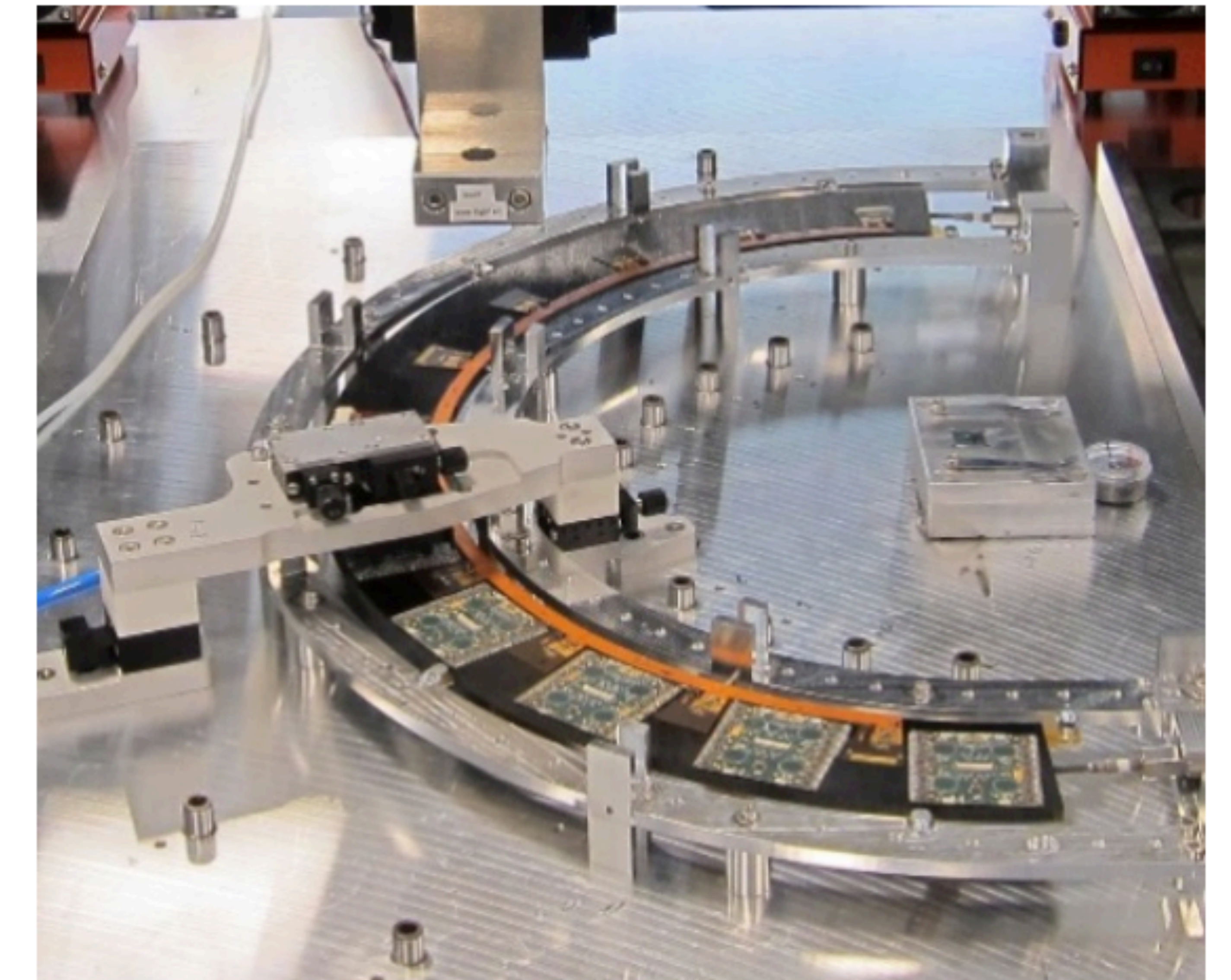
ATLAS ITk pixel loading: Outer endcaps



Local support prototype



Glue deposition



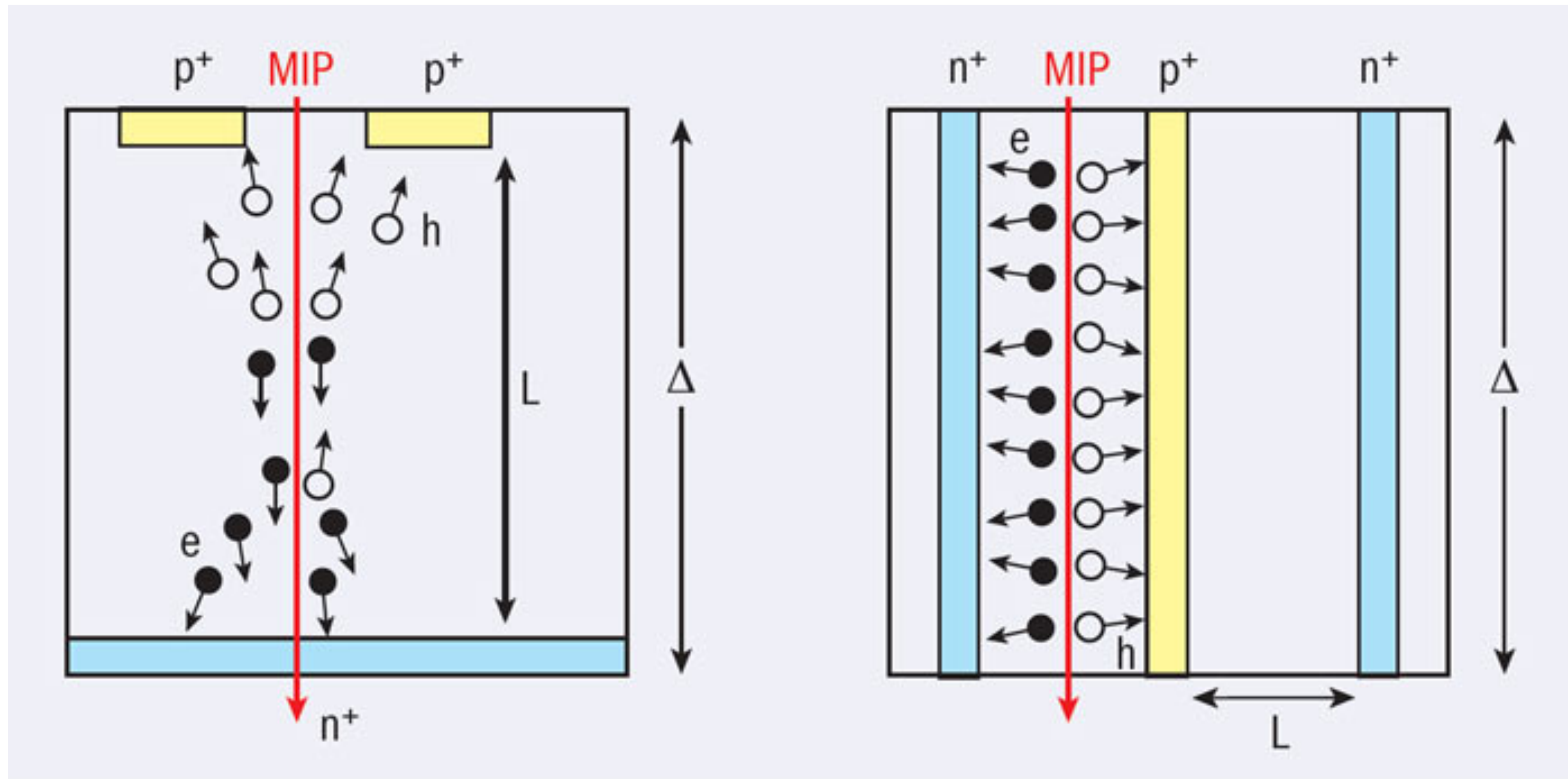
Placing modules and bus tape on local support

- 4 different institutes working on loading (Genova, Lecce, Oxford and RAL)
- Demonstrate different techniques of glue deposition and loading

UNIVERSITAS OSLOENSIS MDCCCXI

UNIVERSITAS BERGENSIS

3D vs planar sensors



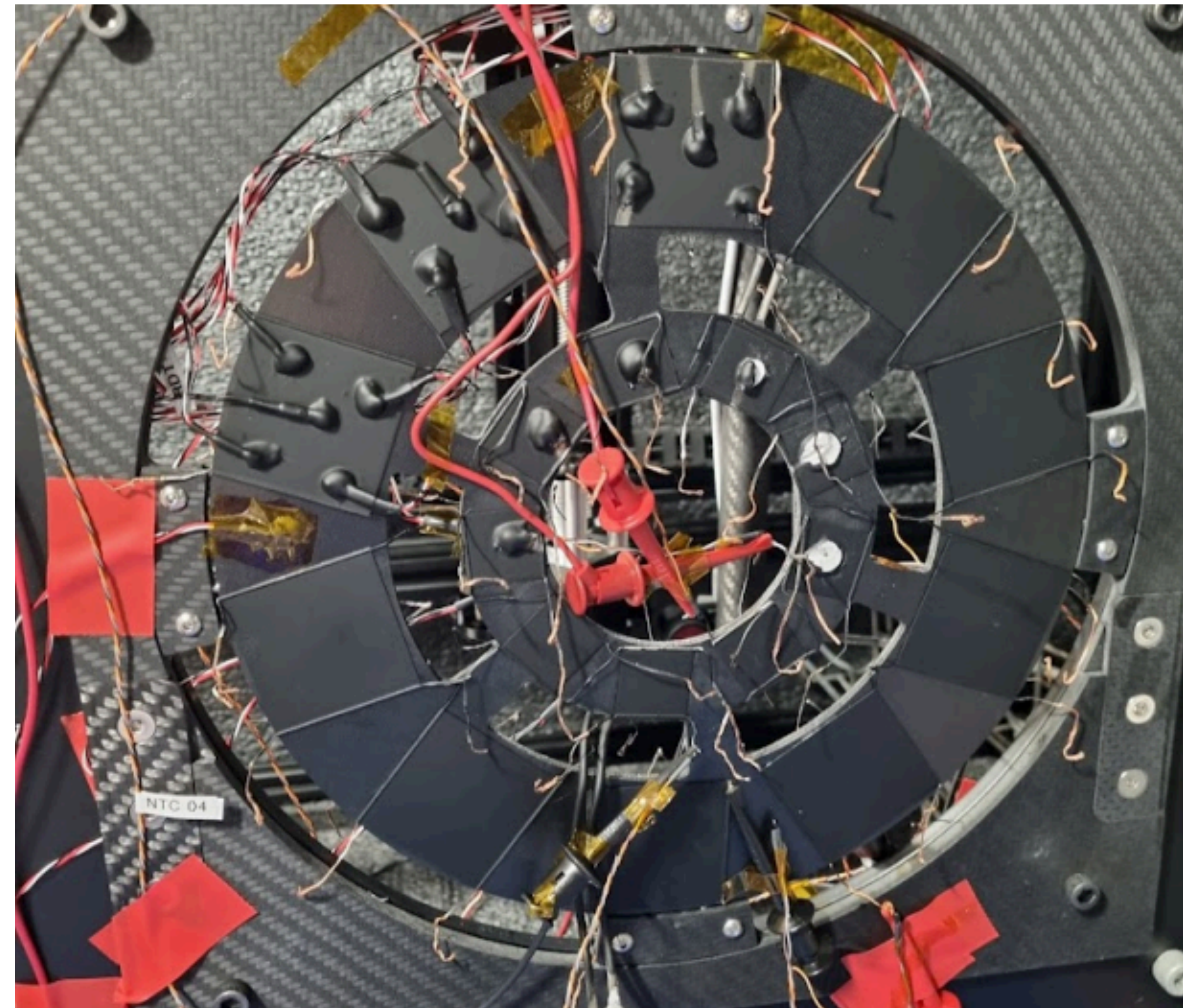
RD53A readout chip

- Prototyping chip
- 3 analog front ends
- Different preamps. ->different tuning procedures
- Chosen differential FE as the ITkPix front end
- Half the size of the final chip

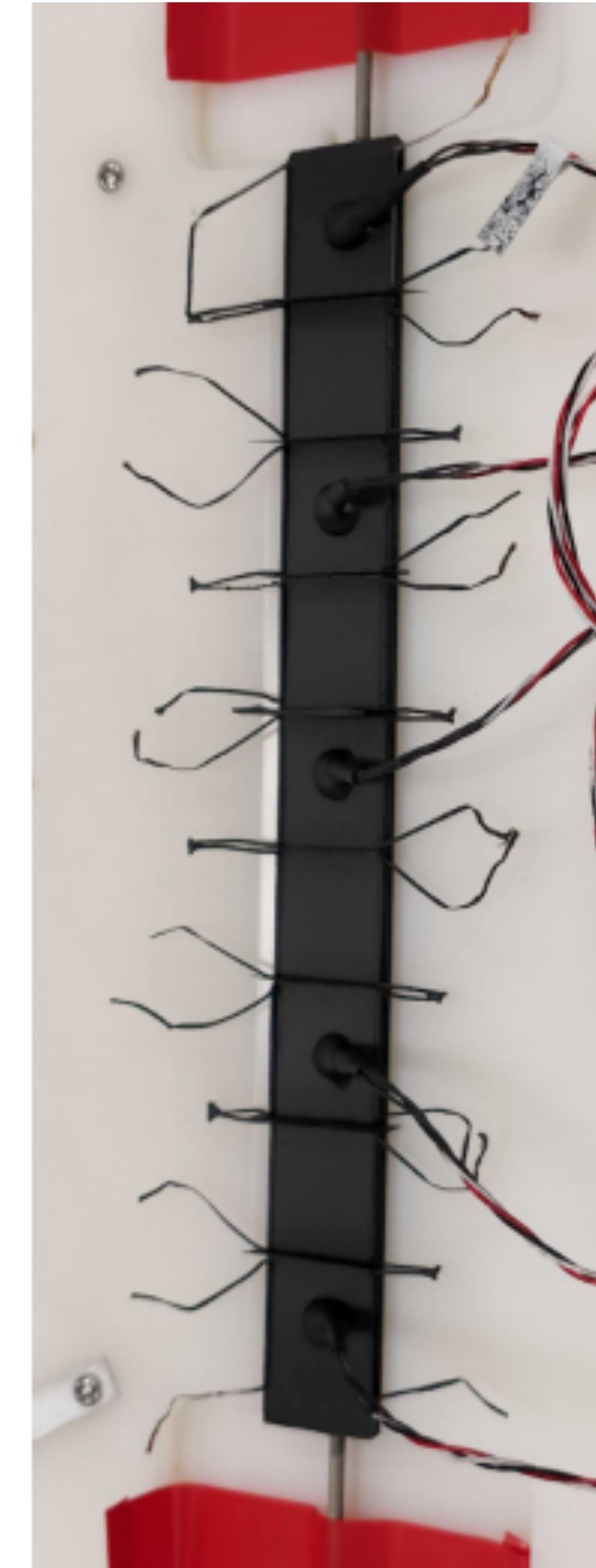
Synchronous | Differential | Linear

Inner System prototypes and tests

- L0 Thermal prototype assembled
- R0 ring thermal prototype assembled
- Tested with CO_2 cooling to -35 $^{\circ}C$ at SLAC
- Thermal performance is within local support design specifications



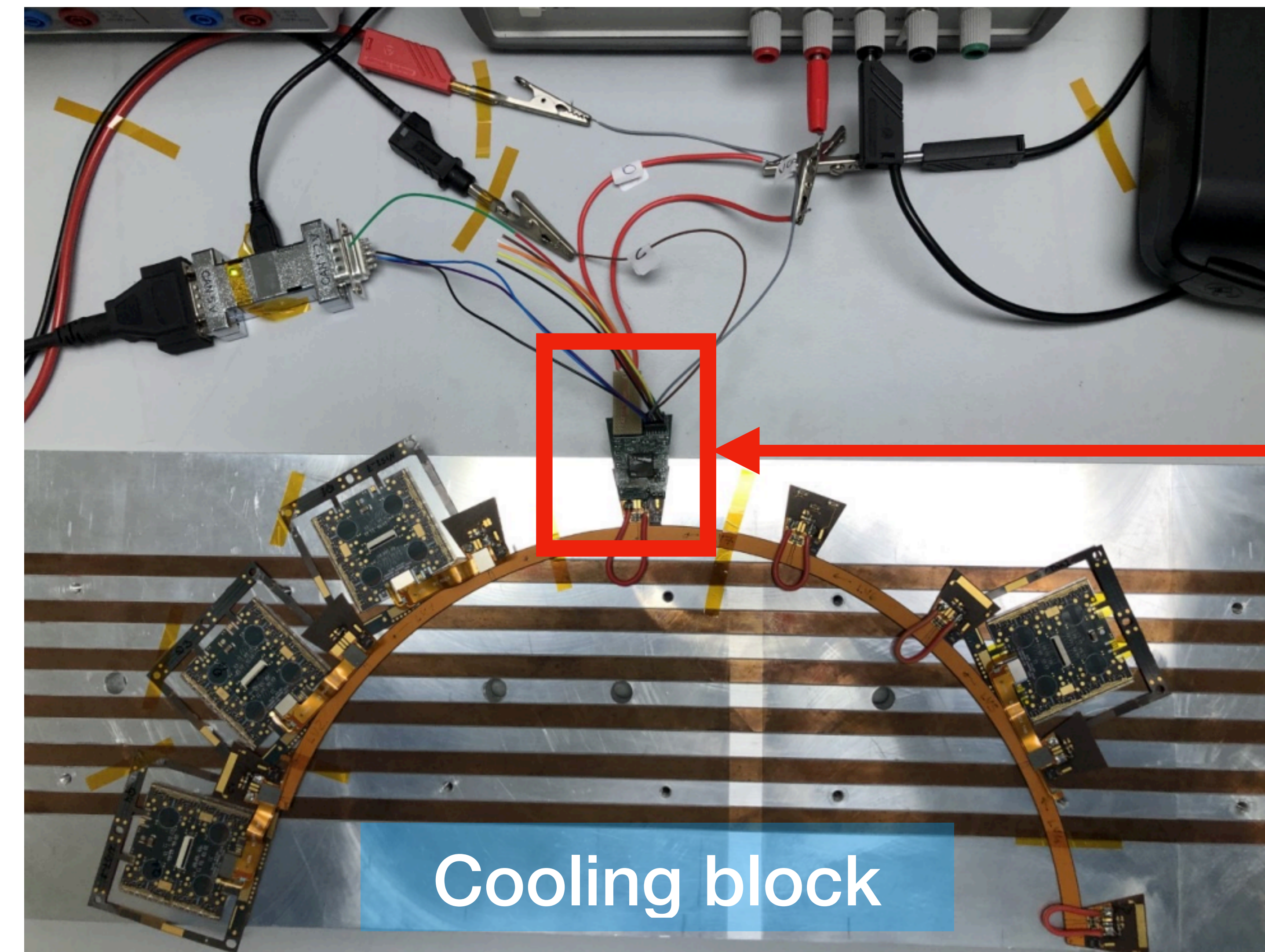
R0 ring thermal prototype



L0 thermal prototype

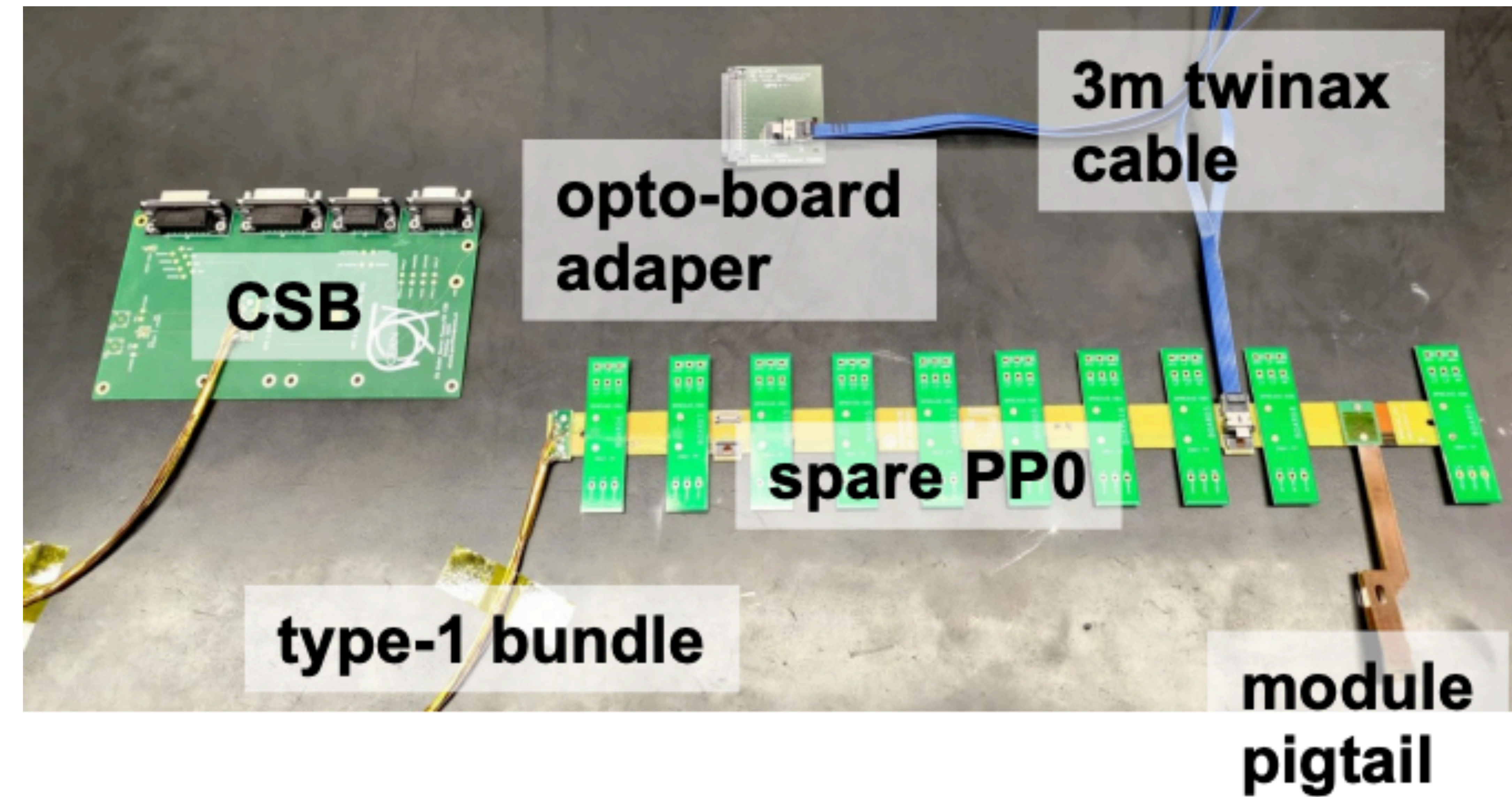
Outer Endcaps tests

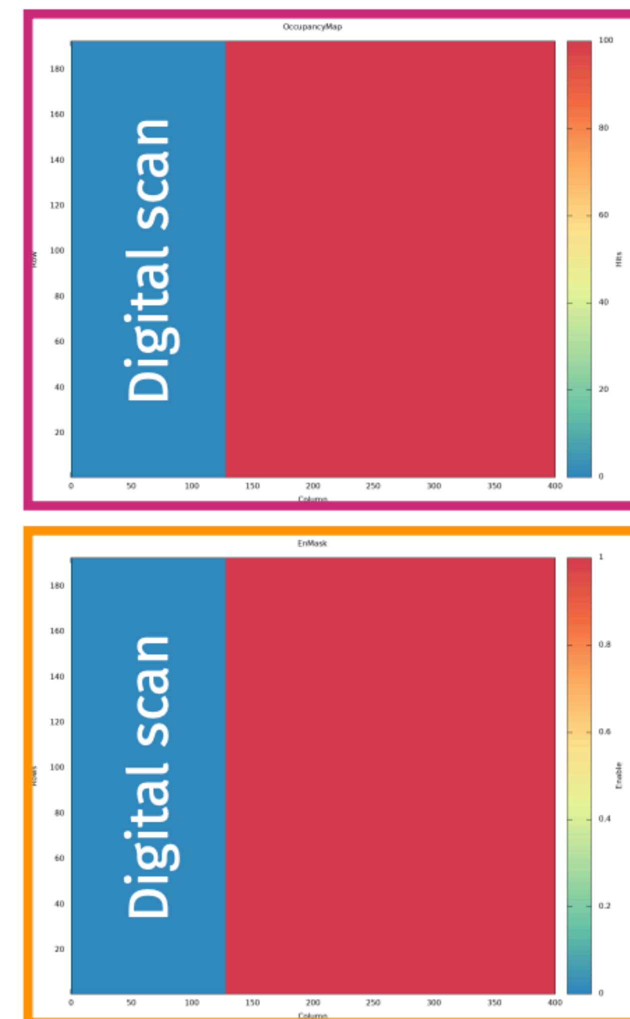
- Loaded one half-ring with RD53A modules and bus tape
- Performed tests on tape and with cooling
- Testing of MOPS chip monitoring

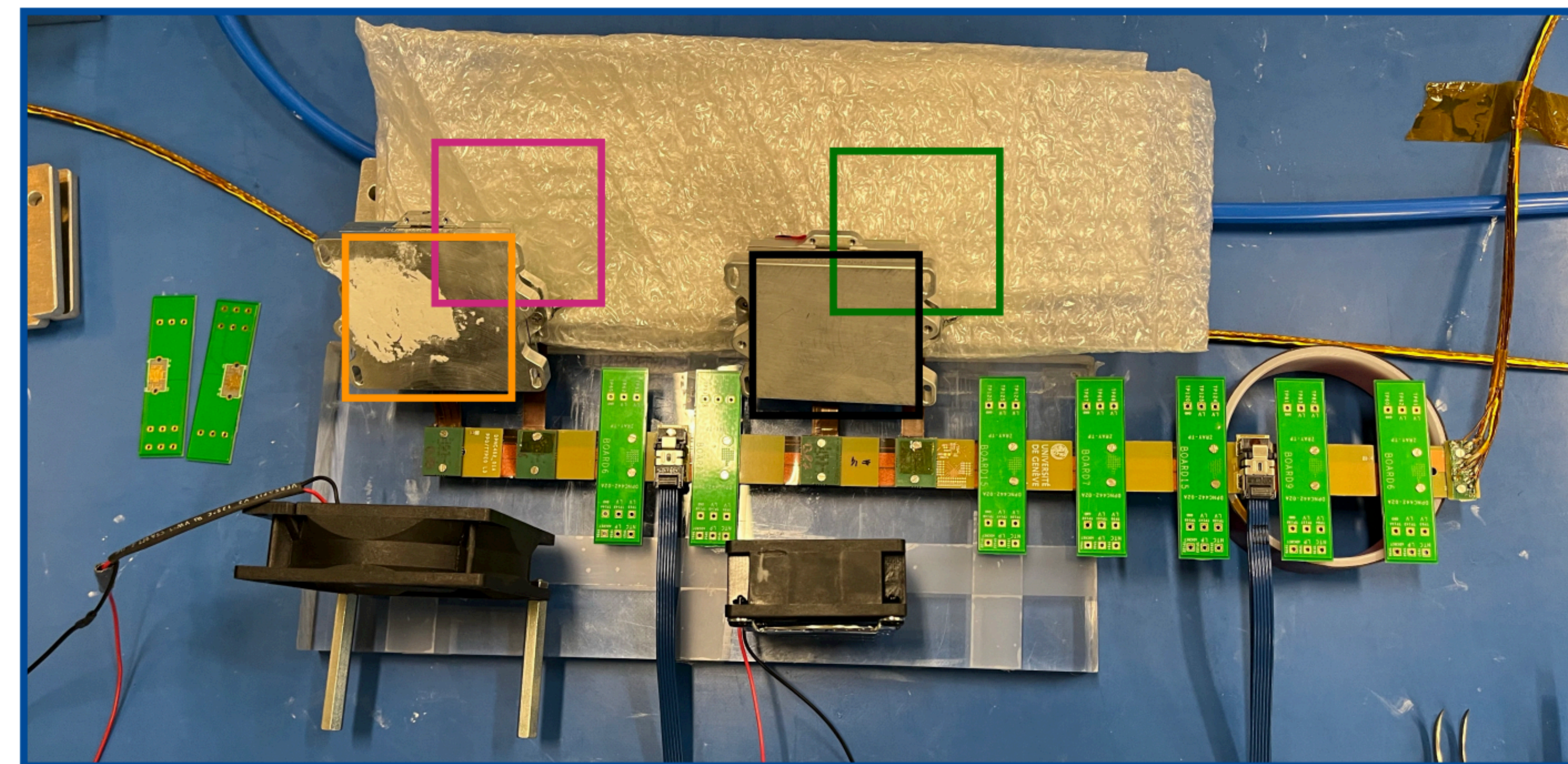


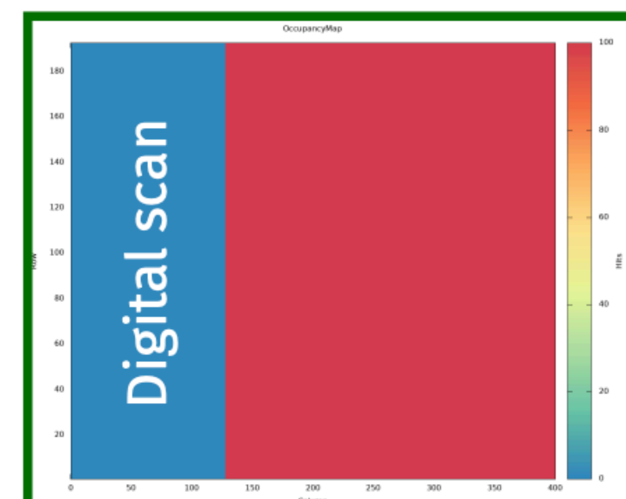
Outer Barrel tests

- No loaded local support yet
- Demonstrator to simulate real working conditions, module + pigtail + pp0 + optoboard
- Tested DAQ with 4 quad modules
- Managed to read 3 modules simultaneously and perform a digital scan of front ends









does not work

RD53A quad modules - Irradiation

- 1 RD53a planar quad module (50x50 μm^2) irradiated to $5 \times 10^{15} n_{eq} cm^{-2}$, tested in testbeam
- Due to RD53A's smaller size only half the sensor is connected. Sync. FE disabled
- Observed > 99% hit efficiency at 600 V