The ATLAS Muon Detectors Upgrade for High Luminosity LHC

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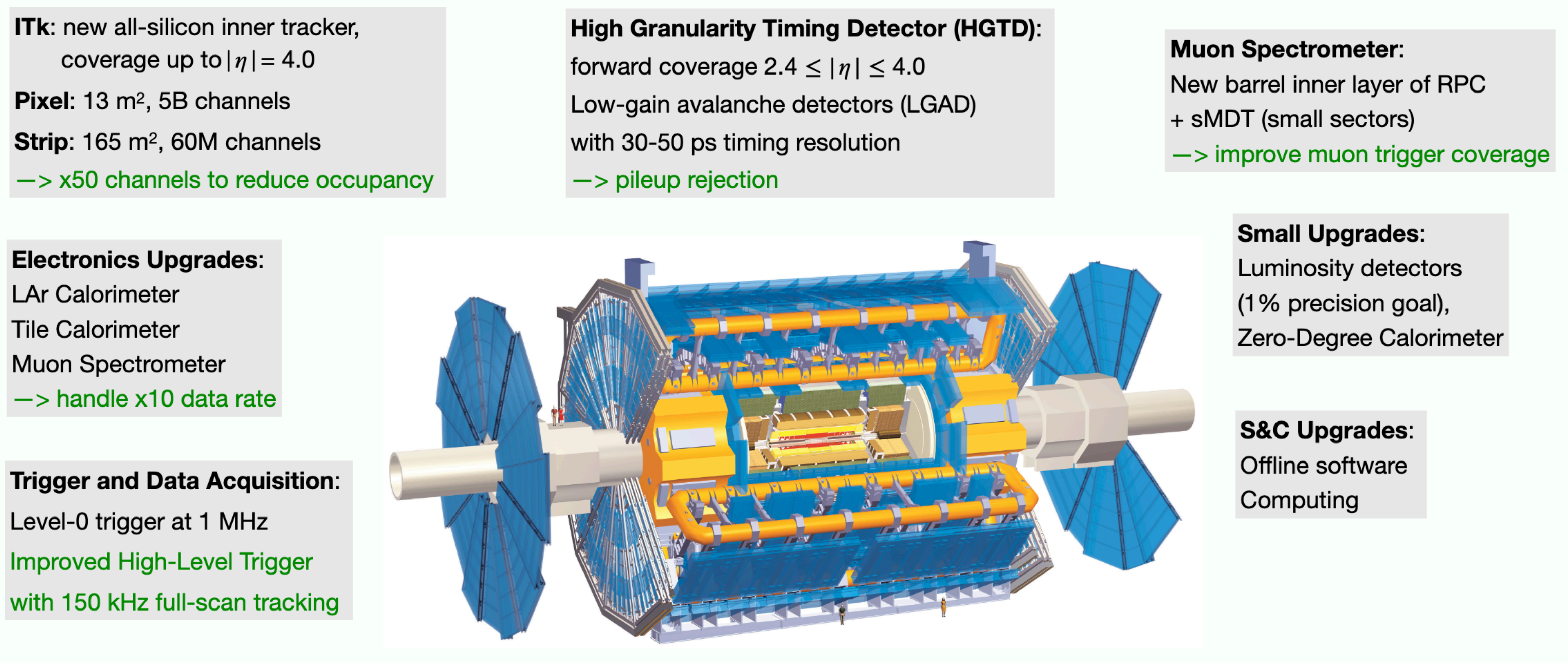
ATLAS Detector and High Luminosity-LHC

- During **High-Luminosity LHC** from 2030, pp collisions will reach the centre-of-mass energy and luminosity:
  - $\sqrt{s} = 13.6 - 14$ TeV
  - $L_0 = 5 - 7.5x10^{34} cm^{-2} s^{-1}$
  - About 140-200 **pile-up collisions** per bunch crossing leading to a significant increase of incident particle rates in ATLAS detector.



The complete plan for ATLAS Phase-II upgrade

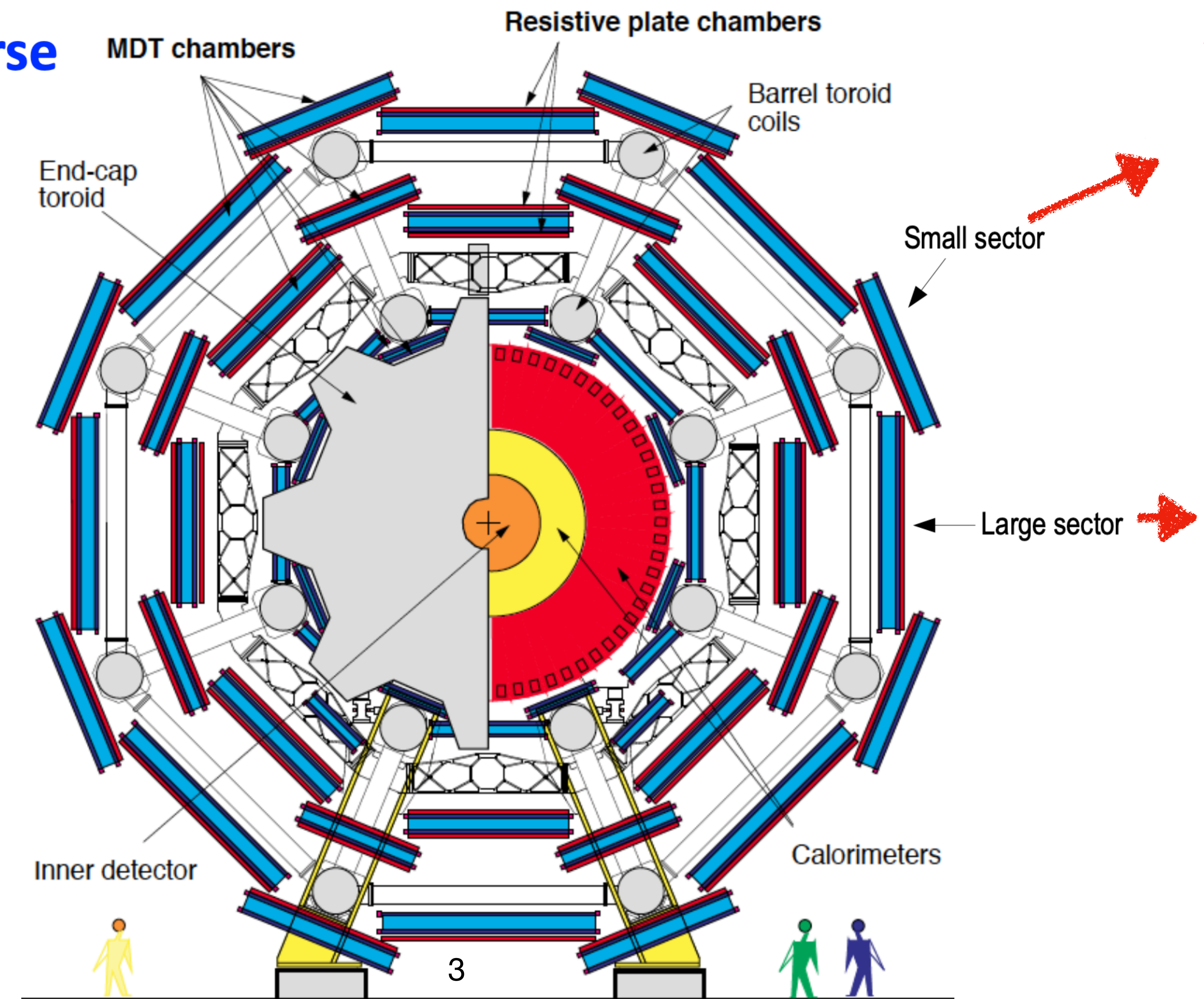
- The **Phase-II upgrade** will help the detector to cope with the extreme conditions of HL-LHC.

ATLAS Muon Spectrometer Phase-II

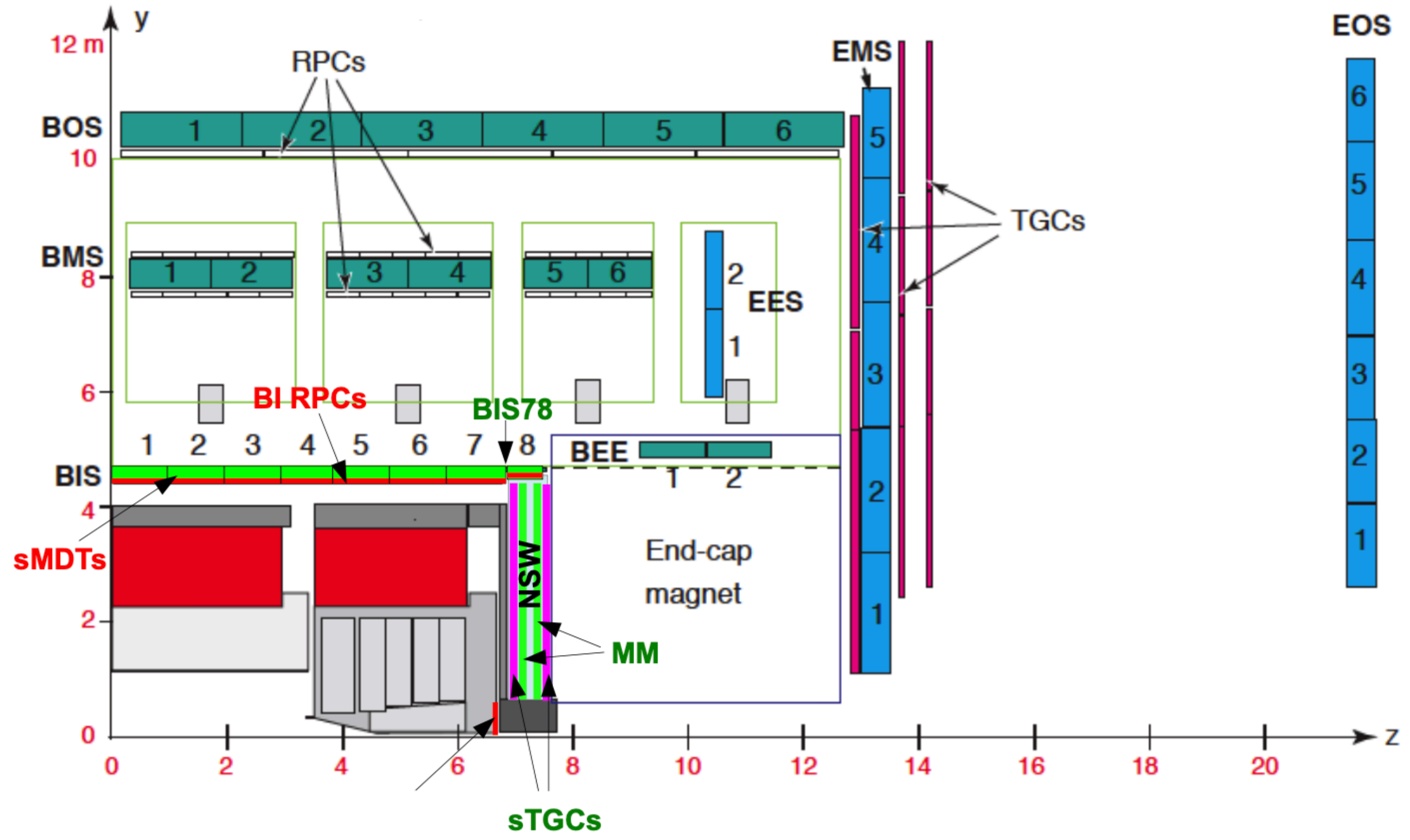
During the Long Shutdown 3 (2026-2030):

- Replacement of **On-detector** electronics of **Monitored Drift Tubes, Resistive Plate Chambers** and **Thin Gap Chambers.**
- New **RPC triplet layer** and replacement of **MDTs** with **small MDT** in small sectors in the inner region of the barrel (BI).
- New **hardware trigger** with 1 MHz (L1 was 100 kHz) rate without changing existing thresholds.
- Complete the upgrade of the endcap inner trigger layer (EIL4) **TGC**, upgraded from doublet to triplets.
- **Power System** upgrade involving the replacement of existing boards affected by aging and radiation damage.

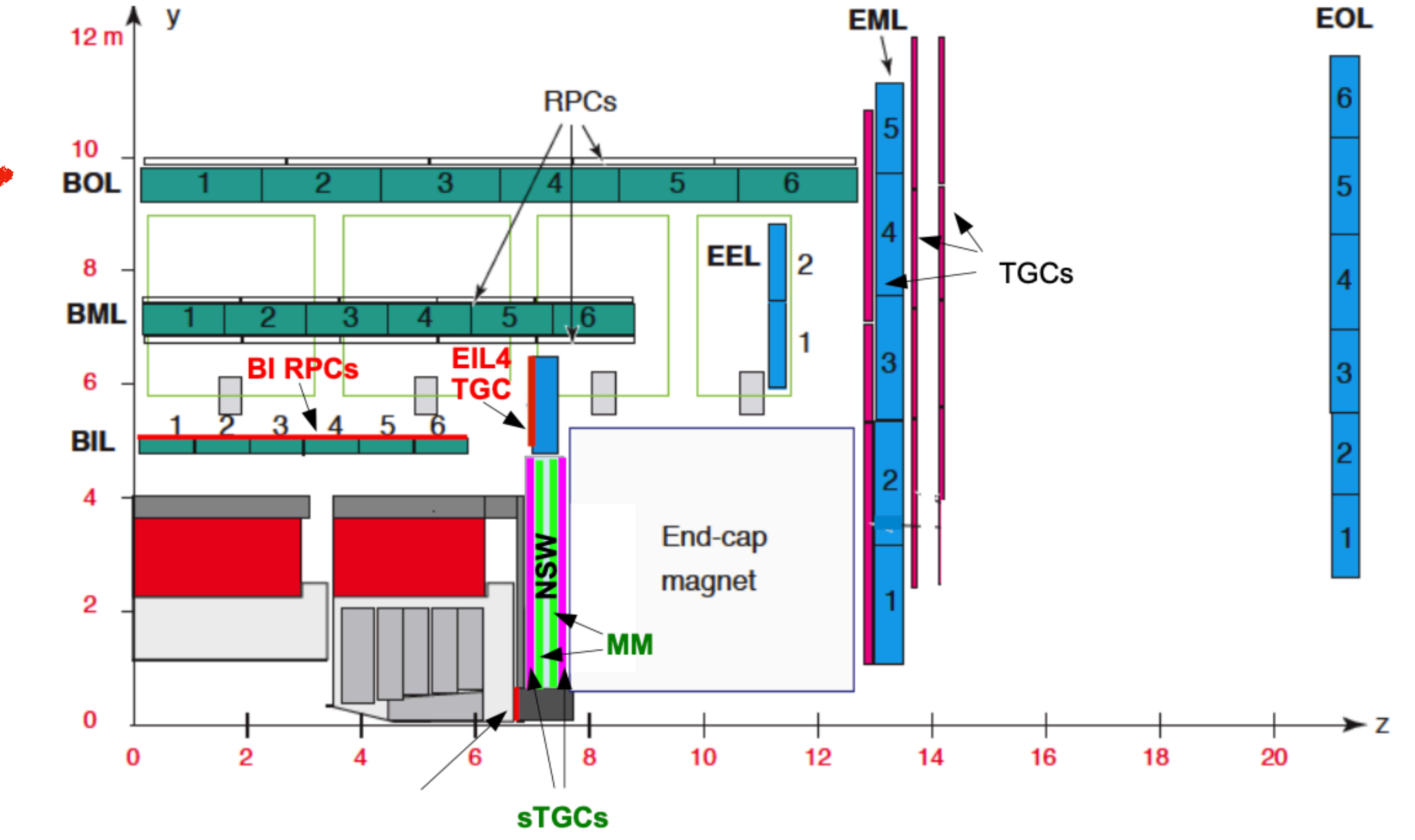
Transverse to beam plane



Beam Line, Small Sectors



Beam Line, Large Sectors

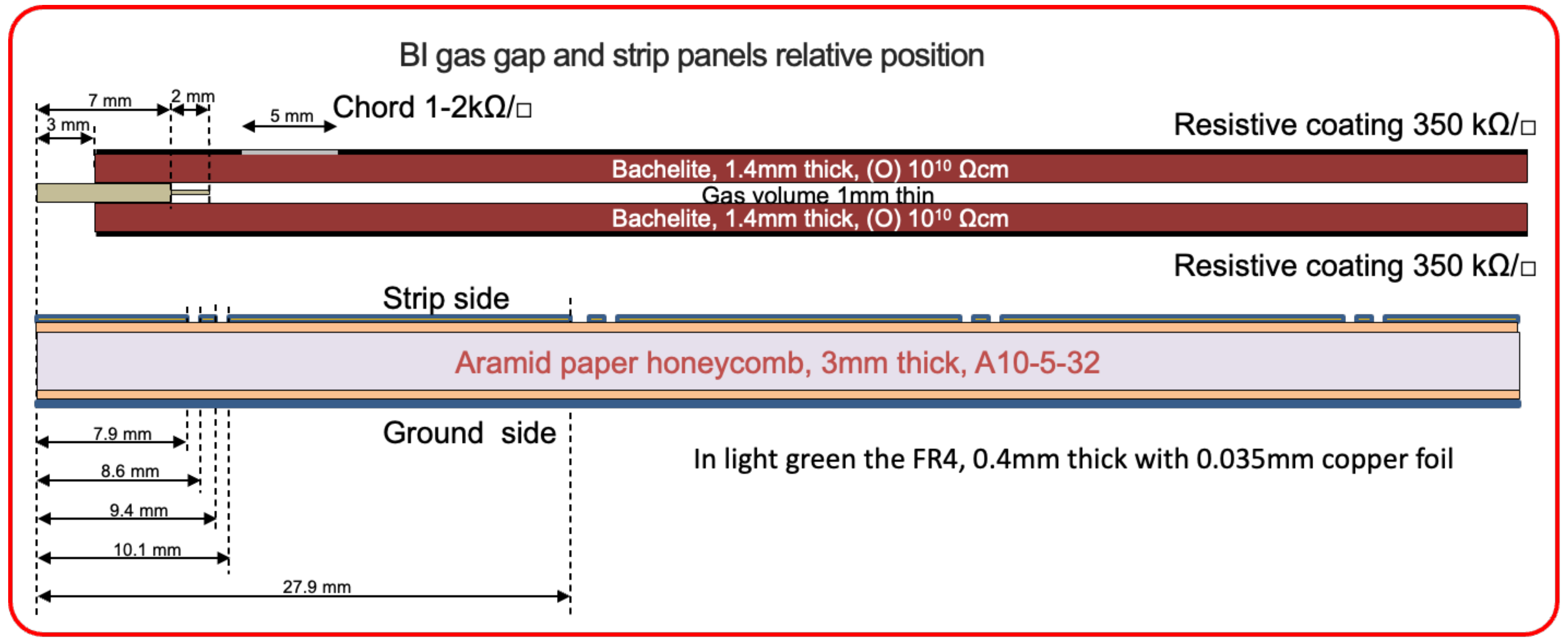


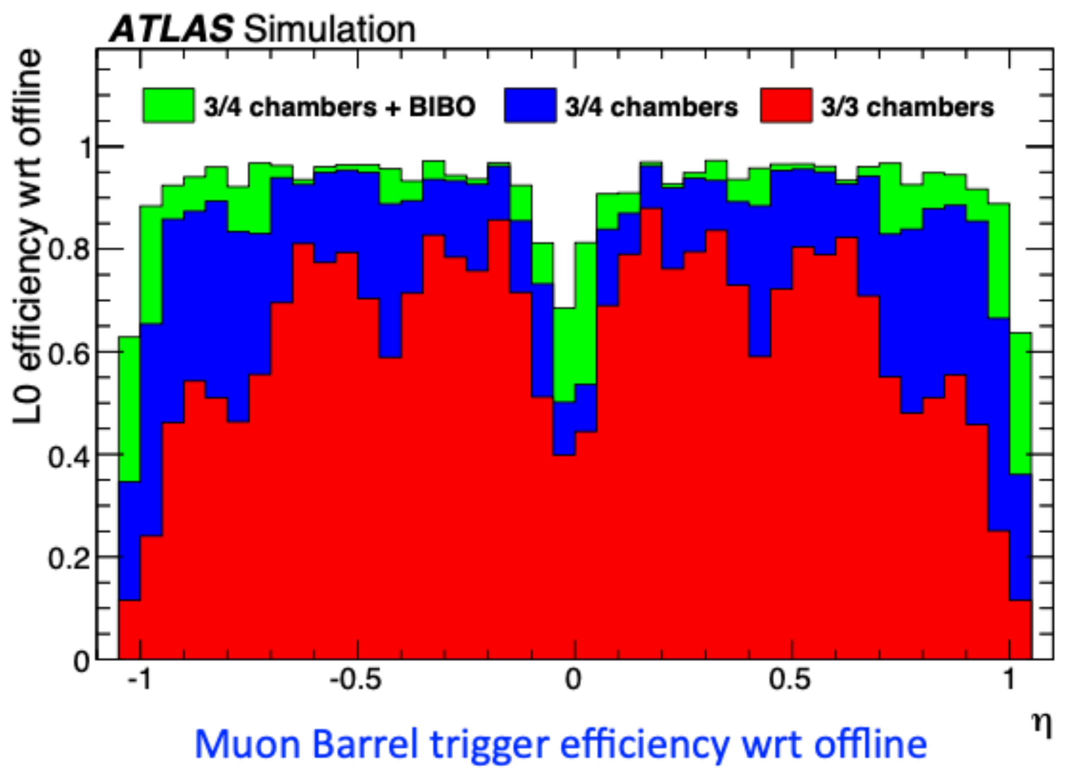
RESISTIVE PLATE CHAMBERS (RPC)

RPC Phase-2 Upgrade

Resistive Plate Chambers (RPCs) provide the trigger in the Muon barrel region and measure the polar (θ) and azimuthal angle (ϕ). Phase-II RPCs main objective:

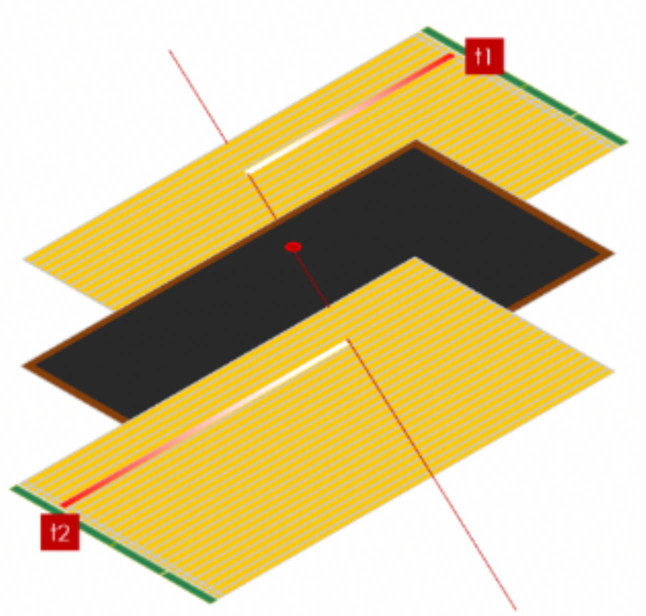
- Improve the **performance** of the stand-alone barrel muon trigger.
- Achieve acceptance levels of up to **96%**, enhancing coverage in regions around the torus support structures.
- Enhance **temporal** and **spatial resolution**, more precise muon momentum cuts.
- Lower the High Voltage of RPCs to **reduce the charge integrated** by the detectors while maintaining efficiency.
- Same gas mixture at atmospheric pressure: **64.5% Tetrafluoroethene** ($C_2H_2F_4$), **30% Carbon dioxide** (CO_2), **5% Isobutane** (C_4H_{10}) and **0.5% Sulfur hexafluoride** (SF_6).
- Add an additional layer of triplets of new generation of RPC with **226** chambers in the Barrel Inner region (BI) and **80** chambers in the outer region, increasing redundancy with **9 layers** instead of **6**.

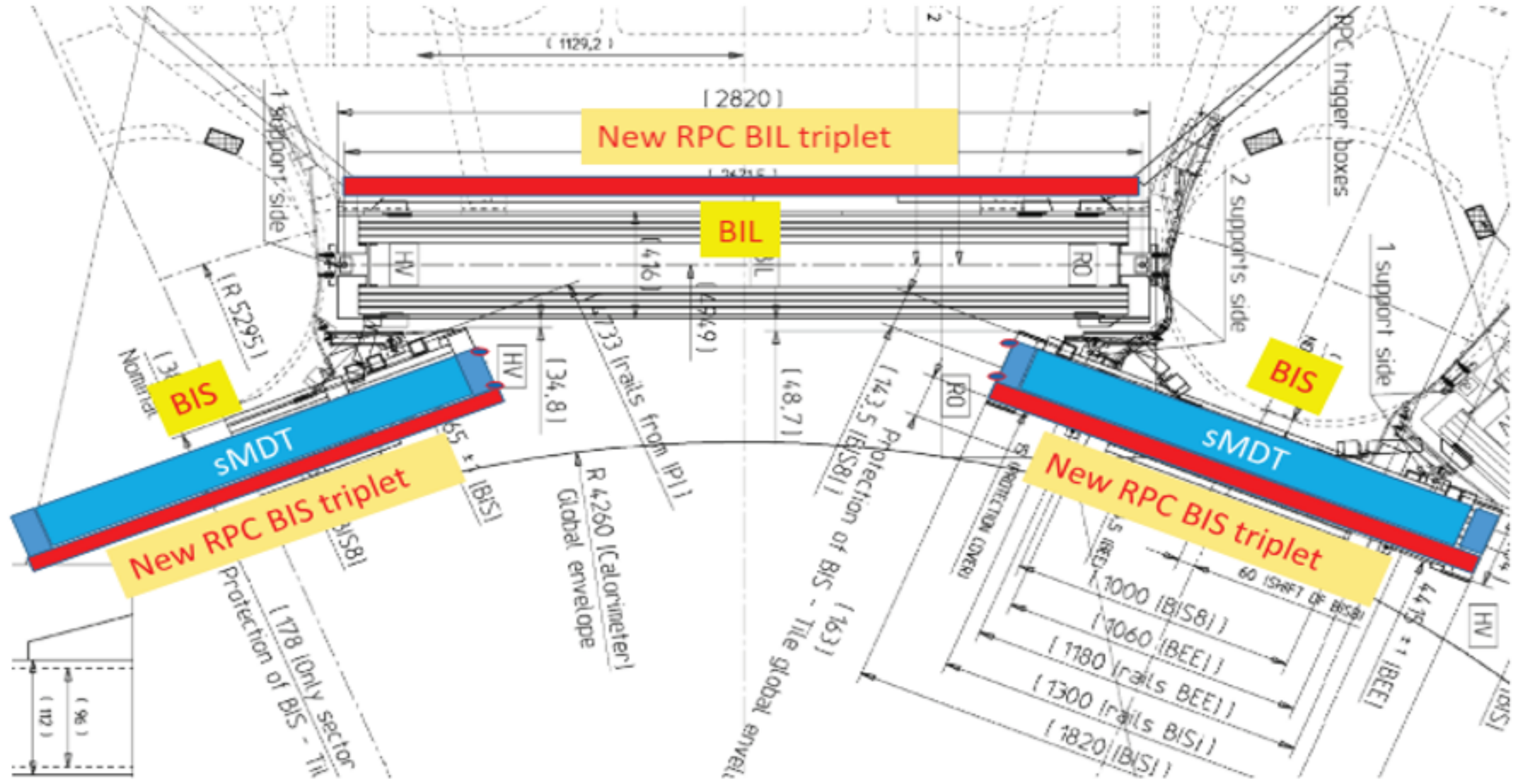




Muon Barrel trigger efficiency wrt offline reconstruction muons with $p_T = 25\ GeV/c$

$\eta - \eta$ reading





Phase-II RPCs compared to ATLAS Legacy RPCs

	Gas gap thickness	Electrodes thickness	Chamber structure	Operative HV	Reading coordinates
Legacy	2 mm	1.8 mm	Doublet	9.1 kV	η-ϕ
BI	1 mm	1.4 mm	Triplet	5.6 kV	η-η

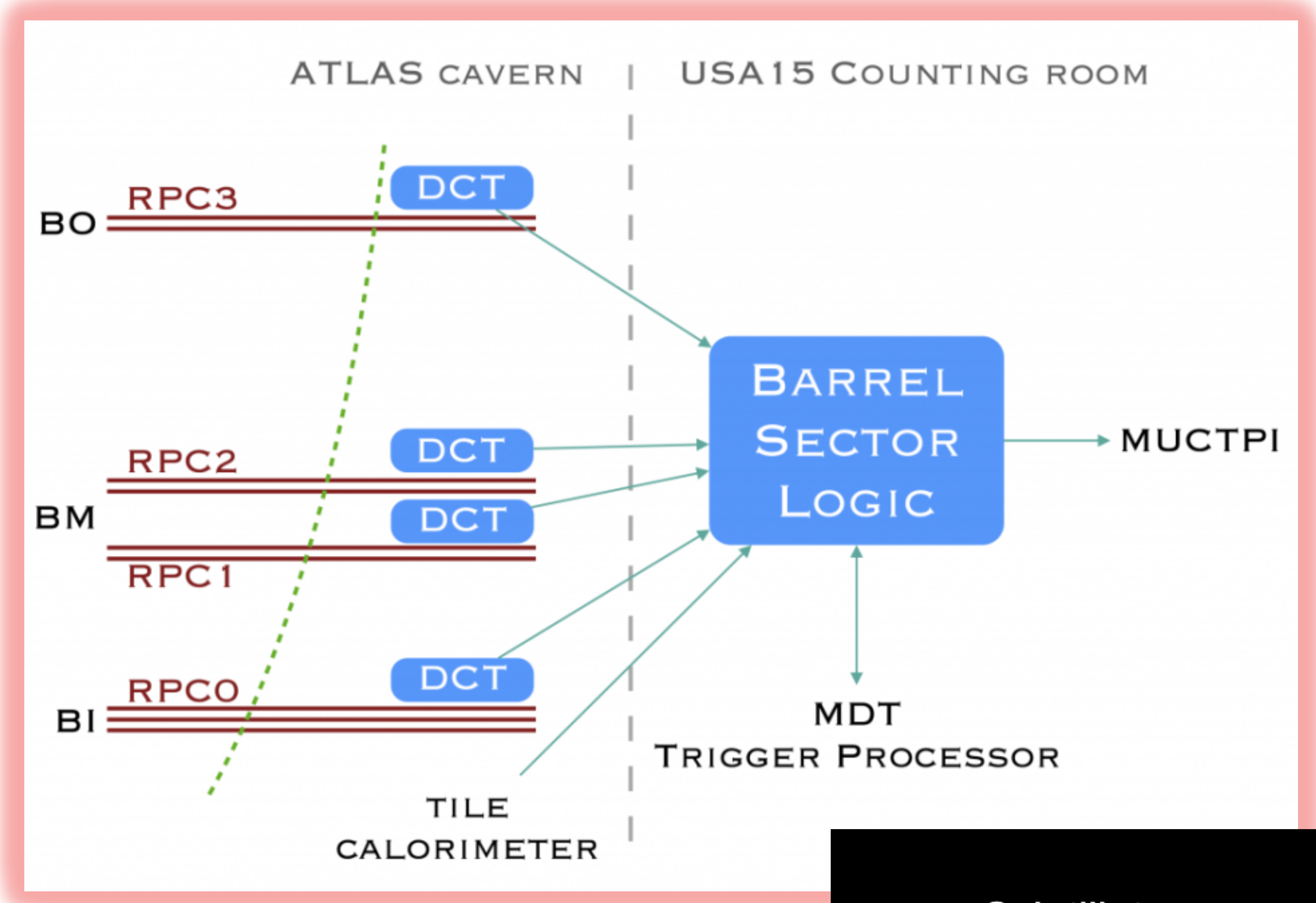
RPC Electronics Phase-2 Upgrade

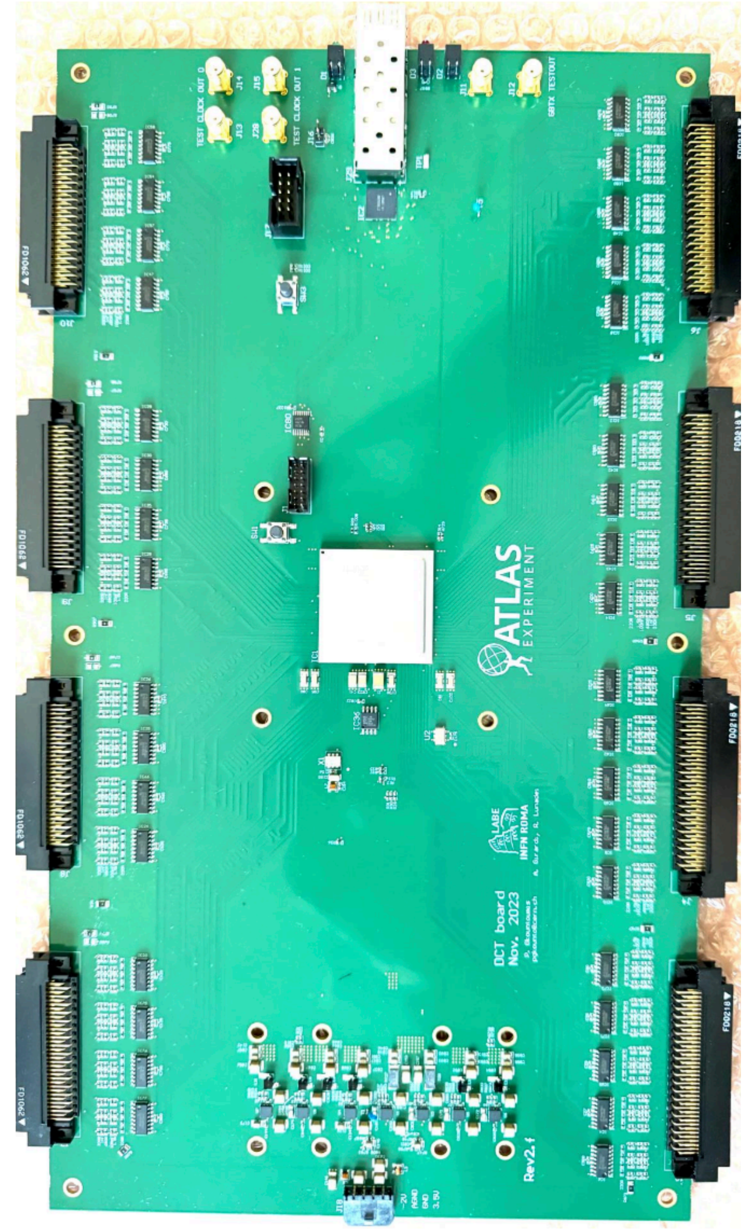
1 mm gaps at a reduced HV and reduced charge multiplication require more sensitive electronics.

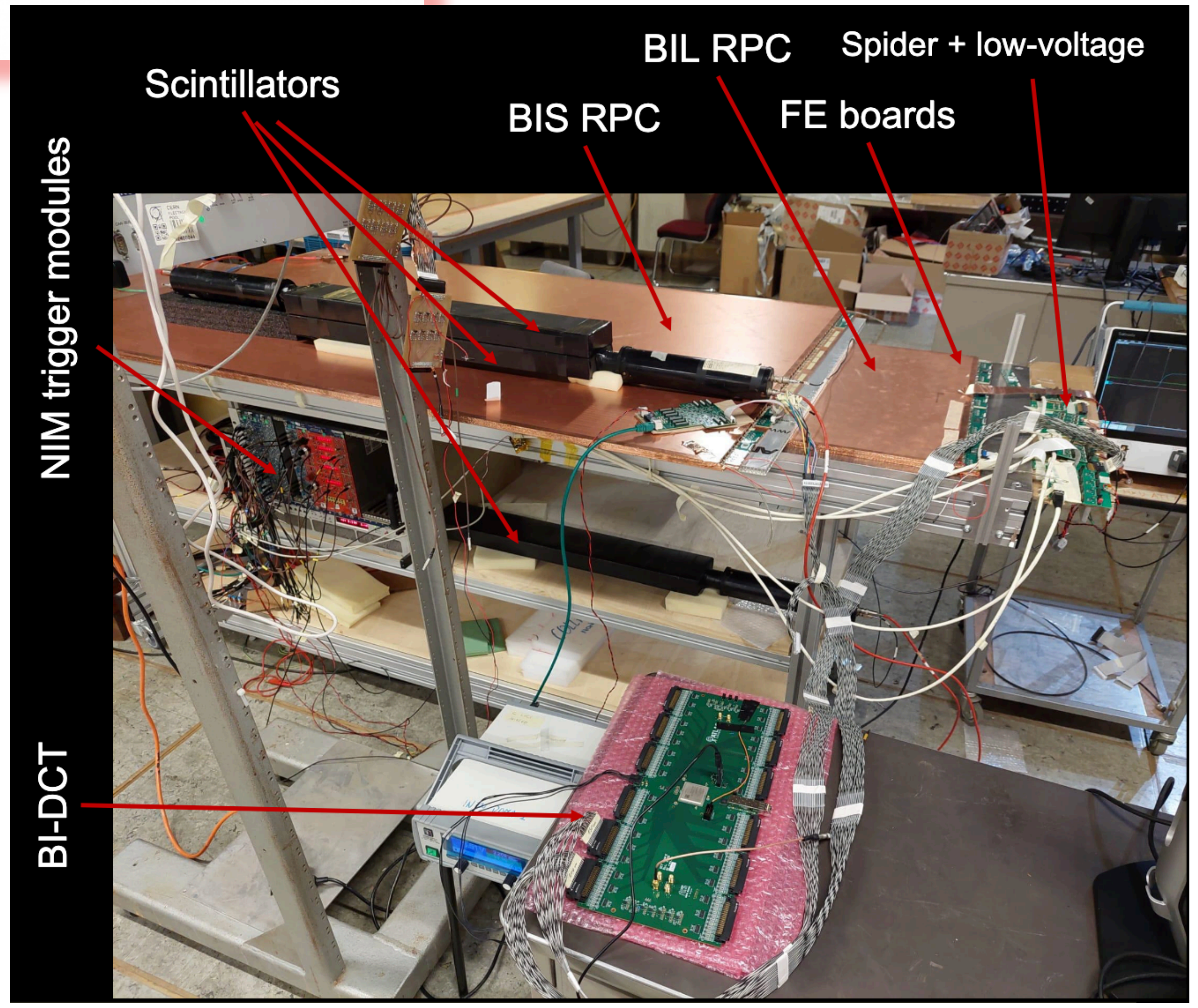
- The Front-End (FE) electronics is implemented using a mixed technology: a **Silicon BJT** is utilised for the discrete component preamplifier and a **custom ASIC** that integrates a discriminator.
- Front-End electronics in the current ATLAS Legacy chambers are **compatible with Phase-II requirements** and do not require replacement.
- However, the **on-detector trigger and readout electronics** (Pad and Splitter boxes) are incompatible with Phase-II and will be replaced by the new DCT boards.

Data Collector and Transmitter (DCT) System

- The Data Collector and Transmission (DCT) board transmits detector hit data to the Barrel Sector Logic that performs complex trigger logics and send back information on the trigger and timing to the DCT.
- A total of **1546 DCT boards** (1208 for the Legacy and 338 for Phase-II) will be deployed in the barrel, connected to **36 off-detector Sector Logic boards.**







RPC-BI Production Status

- **Readout Panel Production Completed** both from China and Italy, with shipment to CERN ongoing.

- Already produced **350 Gas Gap** over a total of **757 volumes**.

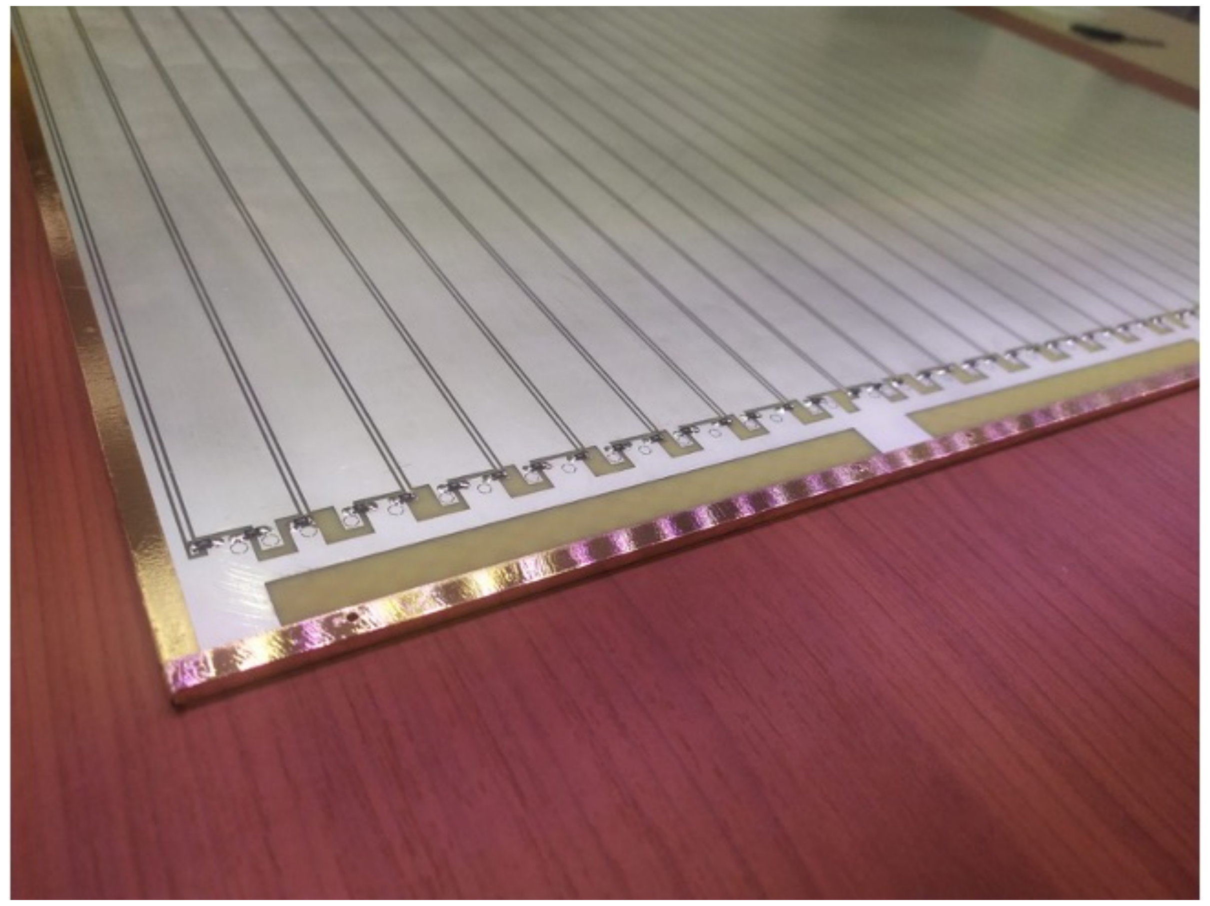
- Singlet production ongoing, full production chain finished and validated. **103 singlets** have been assembled, tested and stored in special containers. FE will be soldered on them and then integrated into the mechanics.

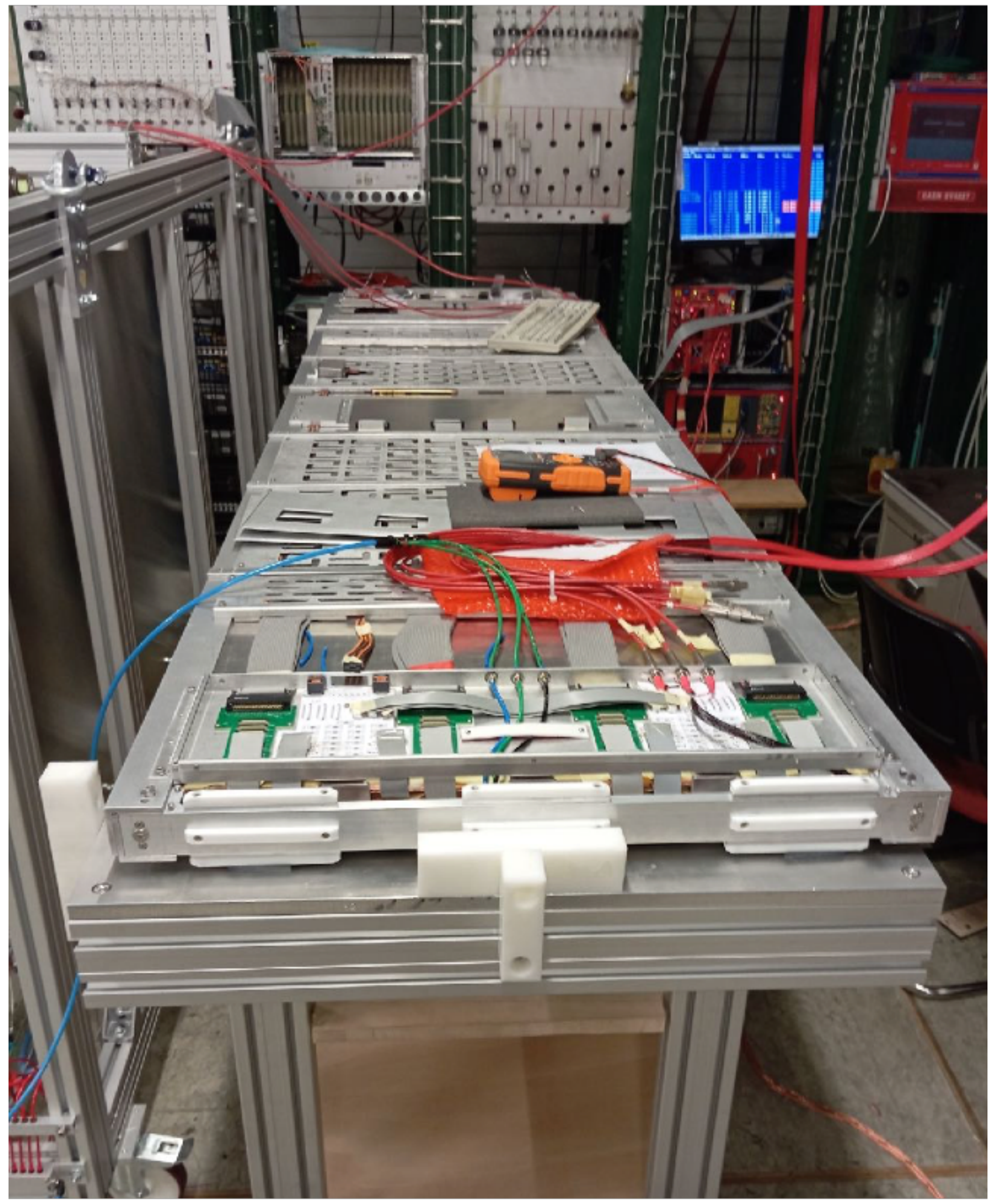
- Front-End electronics ASICs fully produced, the FE electronics production is foreseen within the year.

- Production of the chamber mechanics is starting.

- The chambers in the outer region will be built in Germany. Outer chambers will be installed at the end of the shutdown, prototypes are under construction.

- **DCT** for the Legacy System preproduction starting 2026, **DCT** for Phase-II chambers prototypes under test.



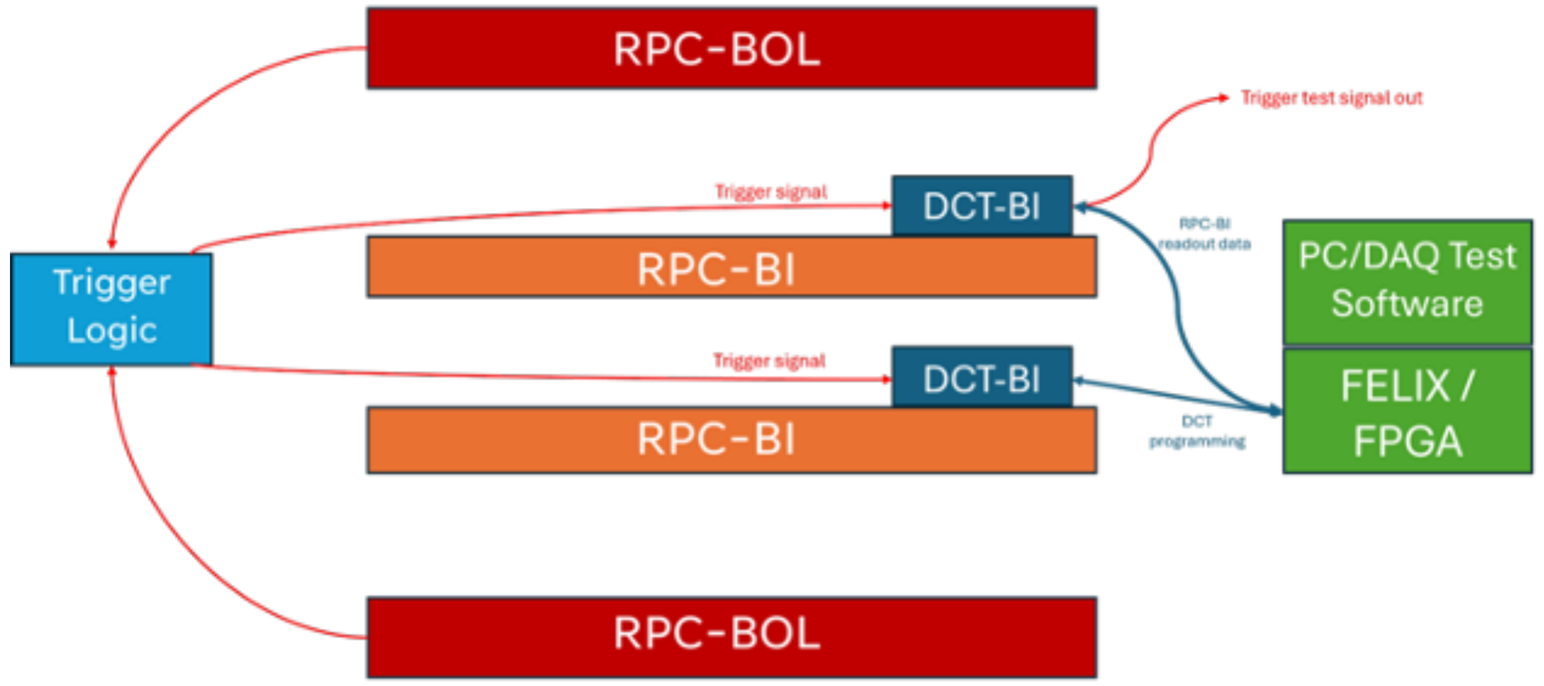


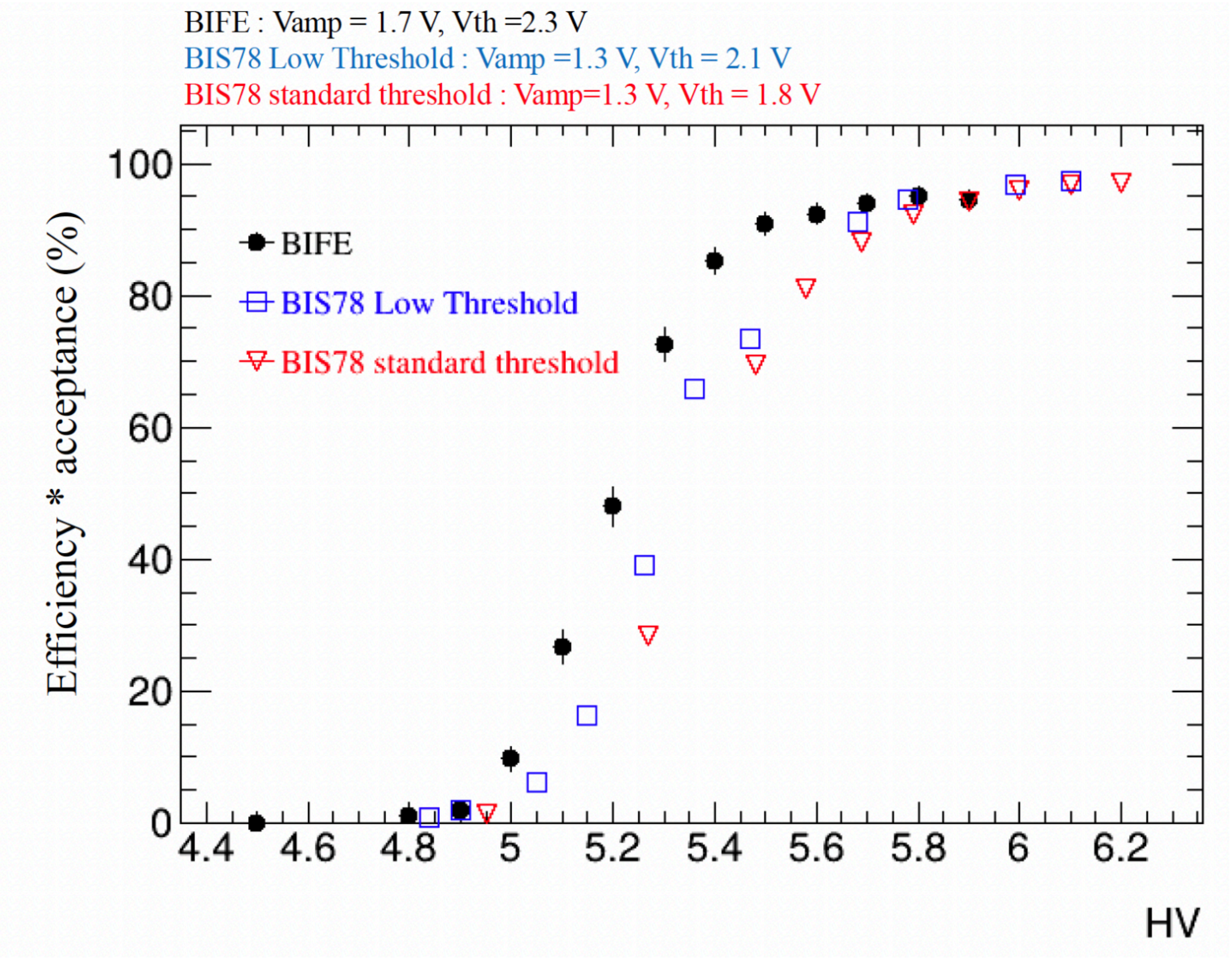
RPC-BI testing

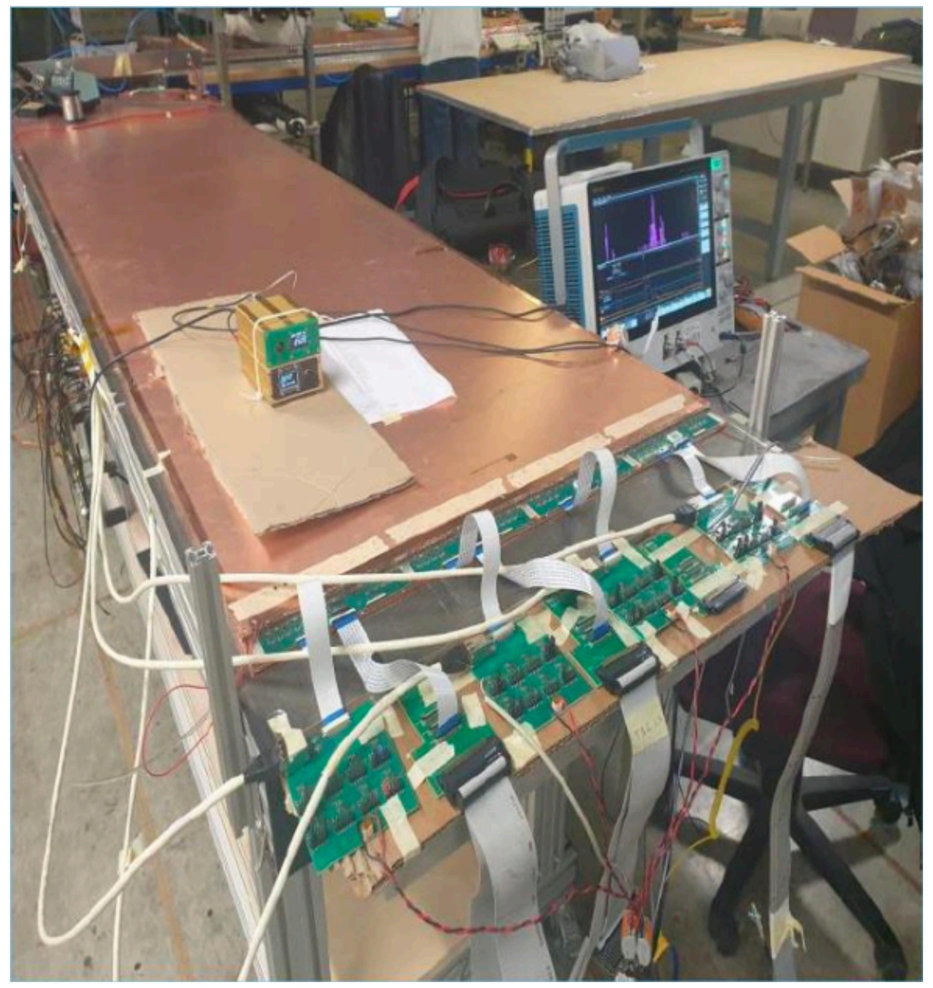
The test conducted on the RPC-BI:

- Gas leak test and current leak test.
- Volt-Amperometric curve both with cosmic rays and with gamma rays source at the Gamma Irradiation Facility.
- Test on Front-End electronics for efficiency and noise estimation.
- Dimensional check on all components before assembling the triplets inside the mechanics.
- Test and commissioning of singlets and triplets inside a **cosmic ray test stand**. The station at CERN has four RPC to provide a trigger and a muon track for the tomography of the RPC-BI under test. The acquisition is done with the new DCT and the trigger is performed by an FPGA.

The Cosmic Ray Test Stand at CERN and its trigger logic







Test of RPC-BI singlets and electronics at CERN

MONITORED DRIFT TUBES (MDT)

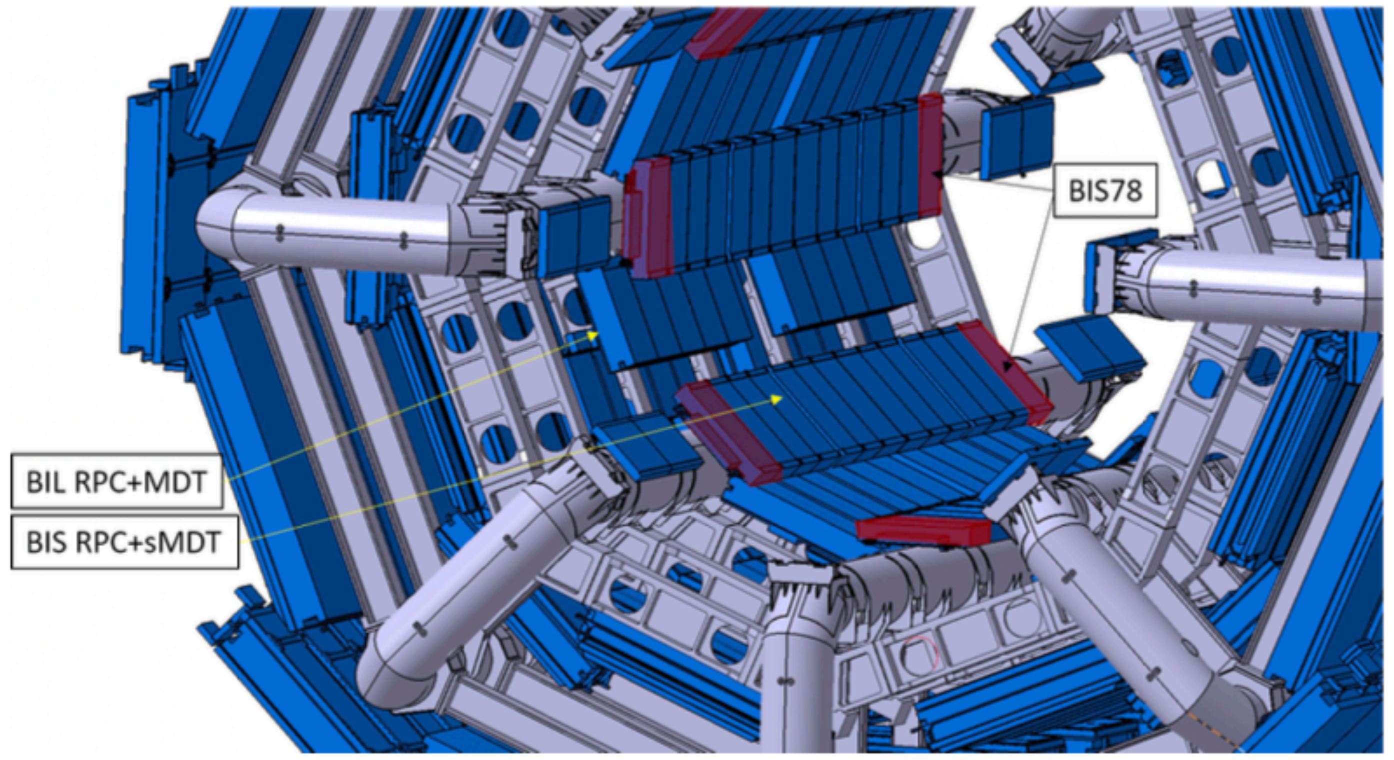
Small-Diameter Monitored Drift Tube

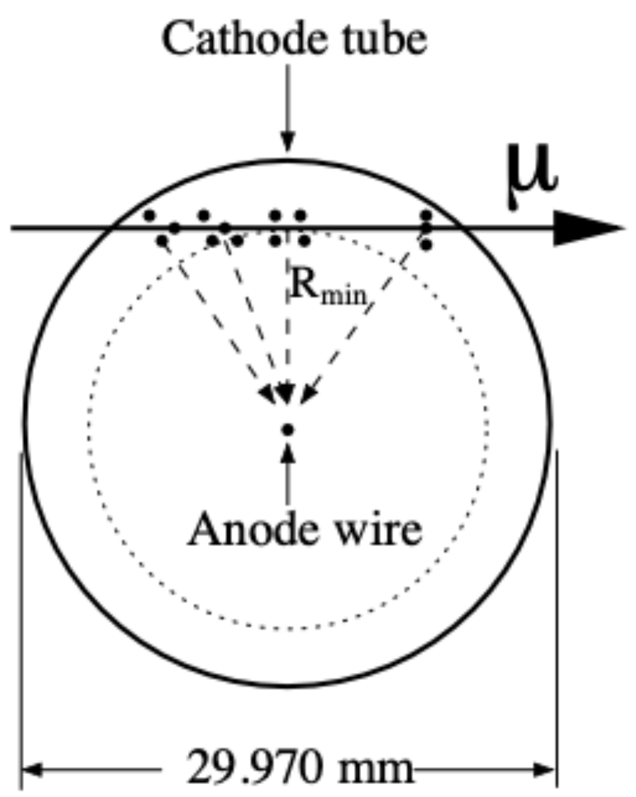
MDT (Monitored Drift Tube) chambers are designed for **precision tracking** in both the Barrel and Endcap regions. MDT tubes can sustain particle rates of up to **500 Hz/cm²** without compromising resolution or efficiency

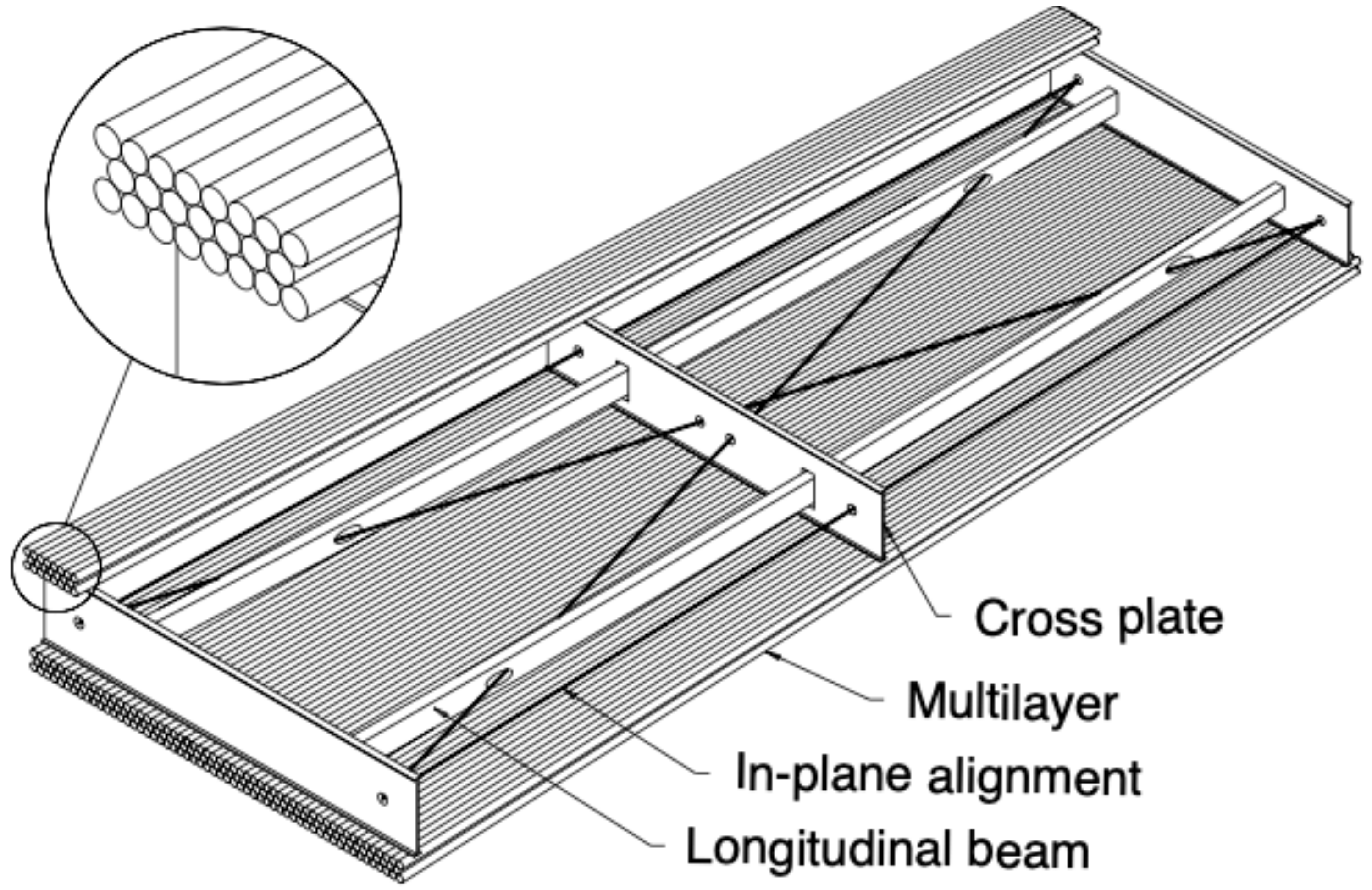
- Operates at **3 bar absolute pressure** with a composition of **93% Argon** (Ar) and **7% Carbon Dioxide** (CO_2).

Compact **sMDT (small Monitored Drift Tube)** chambers will replace the current MDT chambers in small sectors where the space for the new RPC is not sufficient

- The single-tube spatial resolution is approximately **106 µm** w/o background - slightly worse than that of the MDT - but the sMDT is more robust under high background rates.
- The **50 µm-diameter** sense wire is positioned with an accuracy ~**5 µm**, ensuring precise track reconstruction.





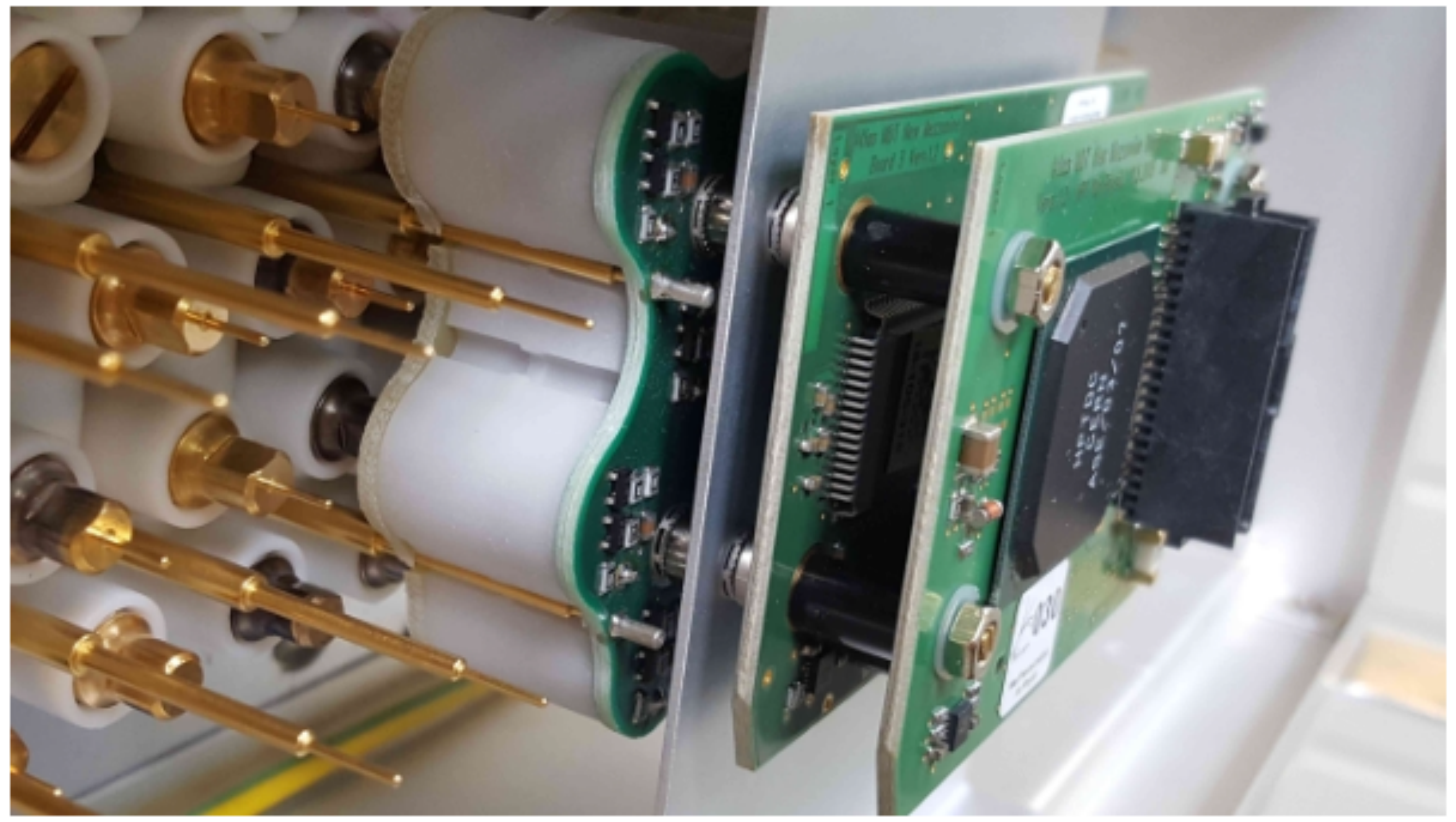


	Tube Diameter	Operative HV	Chamber Structure
MDT	30 mm	3080 V	Two-multilayer of 3–4 tube layers
sMDT	15 mm	2730 V	Two-multilayer of 4 tube layers

sMDT Electronics

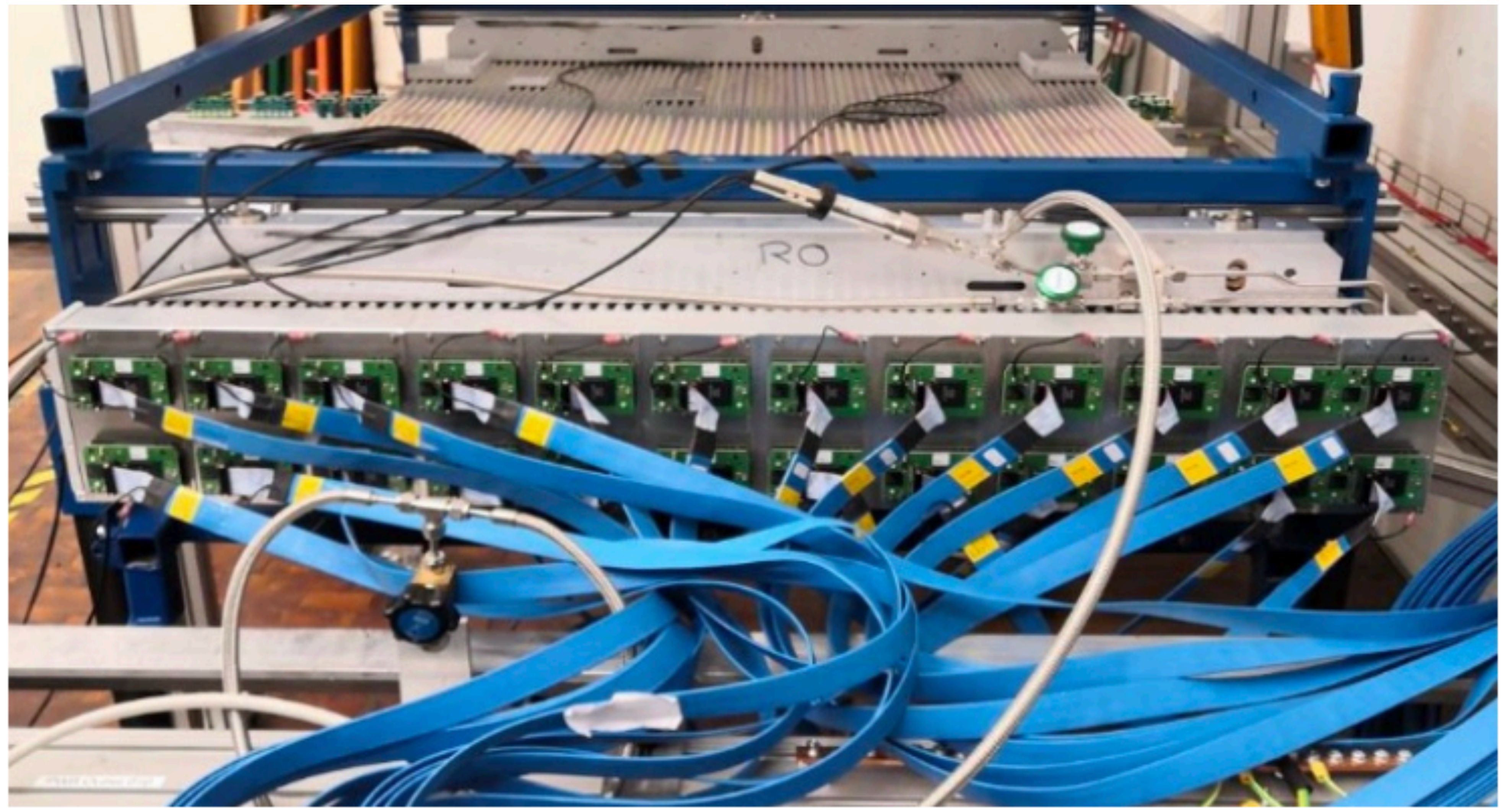
Phase-2 Electronics Update

- **Production and Delivery**:
  - Approximately **3650 Front-End Boards (FEBs)** were delivered from the **University of Würzburg** to CERN.
- **Installation Progress**:
  - FEBs were installed on **all sMDT A-side** chambers and **40 sMDT C-side** chambers by **June 2025**. All tested chambers met acceptance criteria.
  - The testing program began in **November 2024** and it is scheduled for completion by **September/October 2025**.



New signal board and front-end 24-channel stacked mezzanine card mounted on sMDT

A single layer of 4 tubes



A doublet: two 4-layer tube singlets constitute sMDT chamber

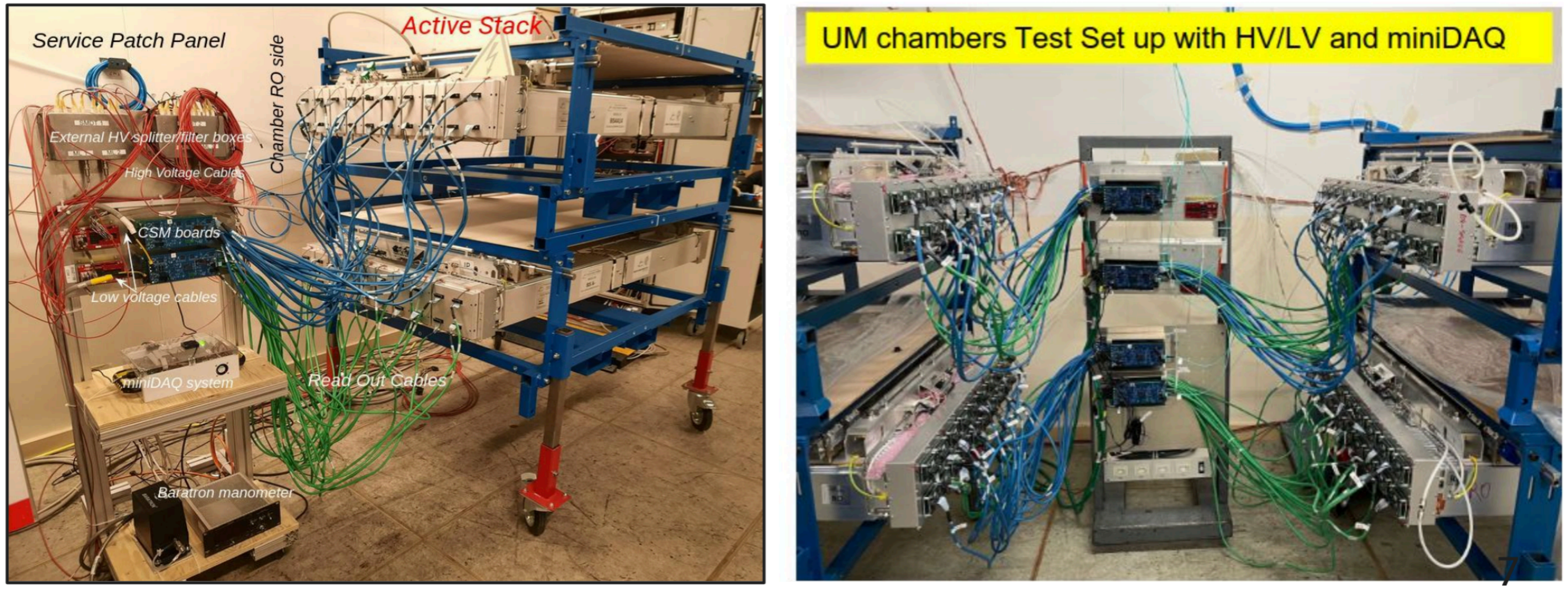
sMDT Production Status

- Chamber production was completed on schedule at both **MPI Munich** and **Michigan** production sites and were delivered to **CERN** by **May 2024.**
- A complete acceptance test of all **A-side chambers** — using prototype front-end electronics after transportation — was conducted at **CERN** in 2023/24 and yielded **excellent results**.
- Performance tests on the **A-side chambers** at **CERN** confirmed that their performance metrics align with those obtained during production at the **MPI site**.

Next Steps

- Test all final mezzanine cables and boars on chambers at **CERN** between **October and December 2025.**
- sMDT–RPC Integration.
- Alignment sensor mounting and final station test at CERN just before installation in the cavern.

All sMDT chambers at CERN



sMDT Test station with the new electronics for final commissioning at CERN

THIN GAP CHAMBERS (TGC)

Thin Gap Chambers TGC

Thin Gap Chambers are multi-wire proportional chambers designed for the low-level trigger in the end-cap region of the Muon Spectrometer and to precisely measure the **azimuthal angle (ϕ)**, using **wires** to measure the polar angle (θ) and **strips** for ϕ.

- Gas mixture: **55%** CO_2 and **45% n-pentane** (n-CRHC).

TGCs are employed in:

- Part of the Inner Big Wheel as **Triplets** and **Doublets.**
- **small TGC** (sTGC) **Quadruplets** in the New Small Wheel mounted during Phase-1

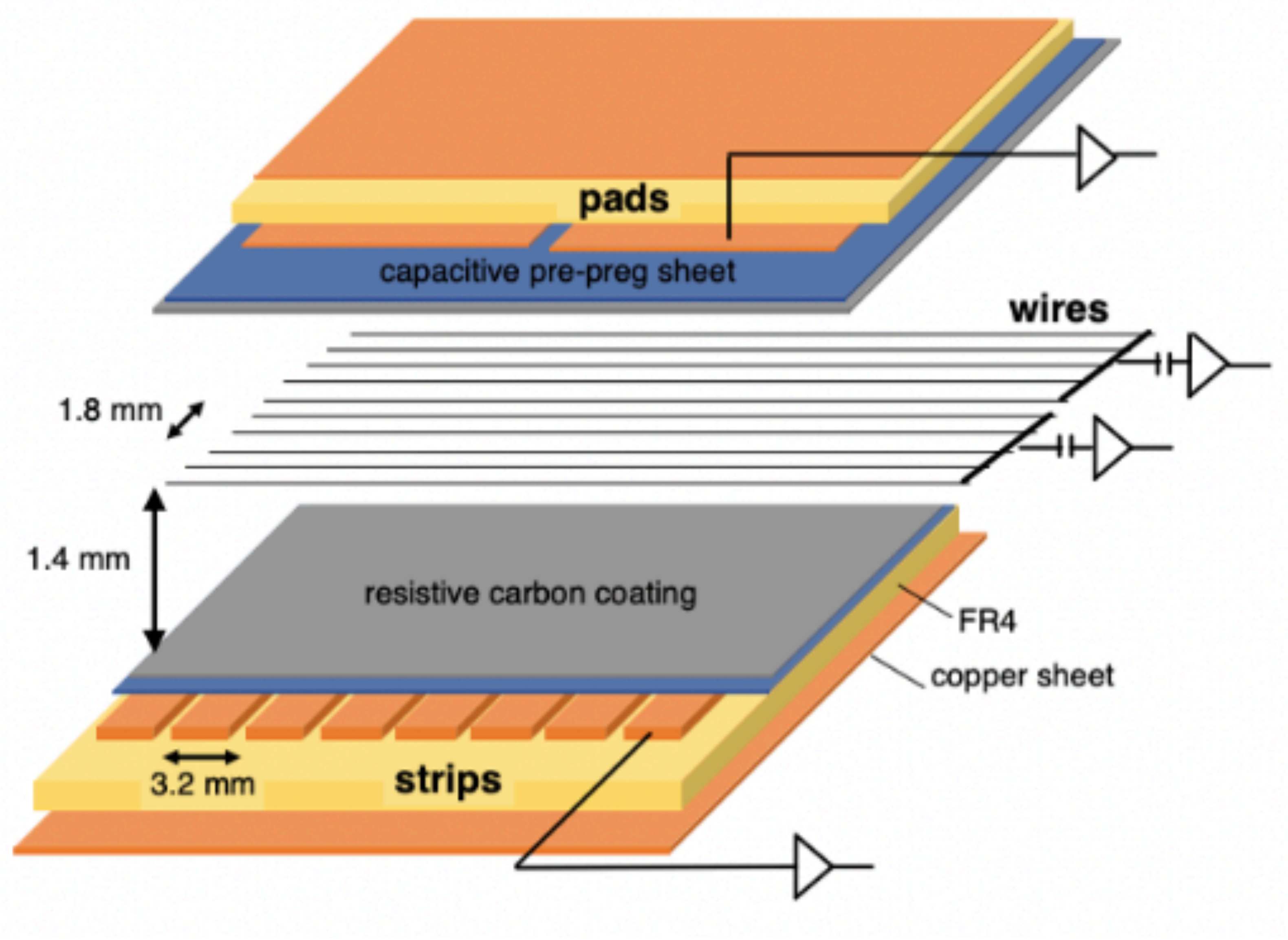
This detectors are fully compliant with the conditions of the HL-LHC.

- **EIL4 TGC Doublets**: This chambers lack sufficient granularity and robustness due to their doublet structure, this limitation could result in excessively high trigger rates.

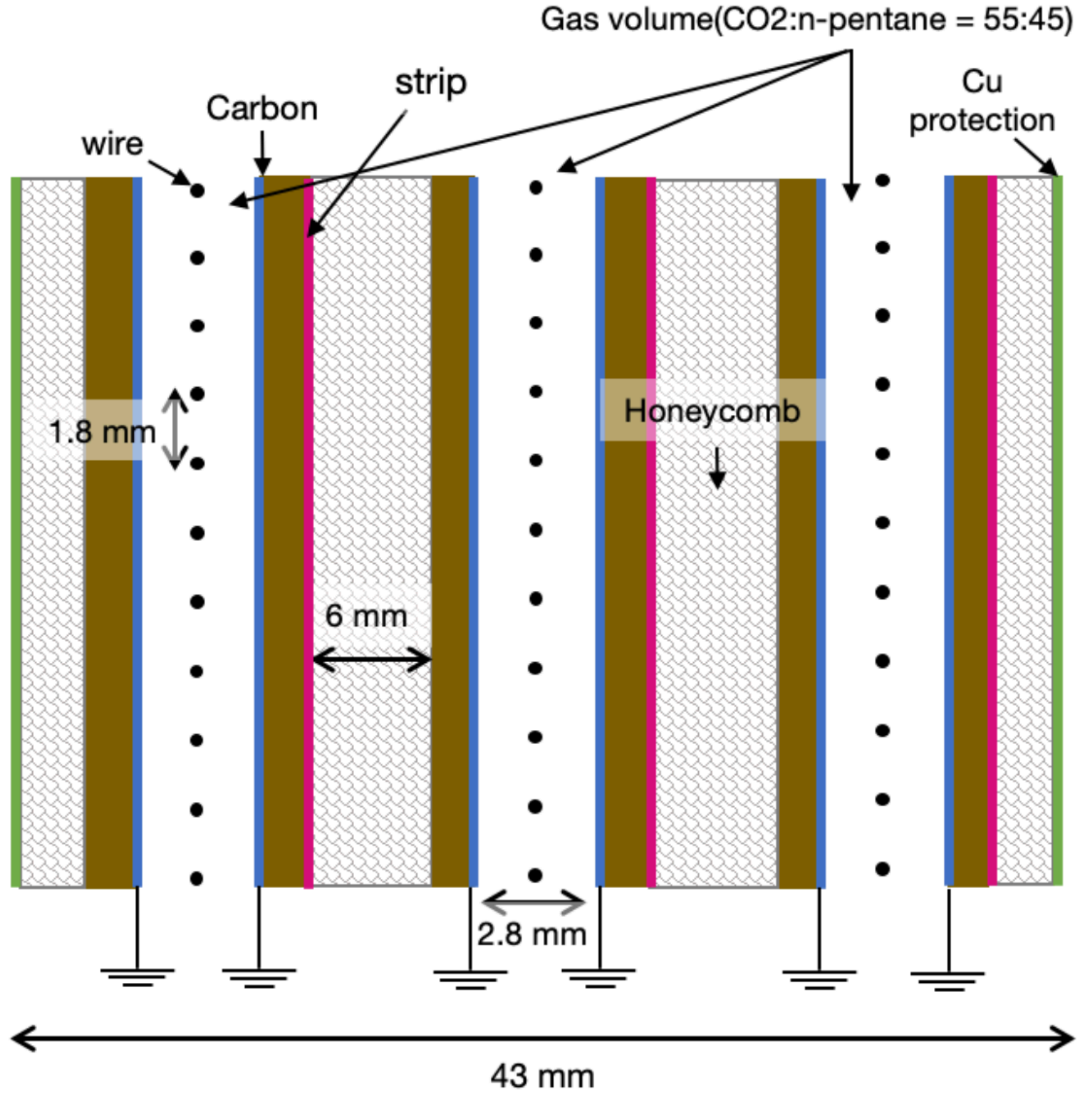
Phase-II upgrade:

- Replace all **EIL4 chambers** with **new TGC triplet chambers** inside the same envelope size as the doublet.
- The triplet structure enables a **2-out-of-3 majority trigger logic** for enhanced reliability.

TGC schematics



TGC EIL4 Triplet structure



EIL4 TGC Status

Production Progress:

- The production of **EIL4 TGC chambers** is progressing well and remains on schedule and will speed up with the implementation of the **Phase-II electronics**.
- **27 out of 50 triplet chambers** have been produced within approximately one year.
- **Mass production of EIL4 TGC single gaps** is also ongoing, with nearly **two-thirds of the planned 150 singlets** already completed.

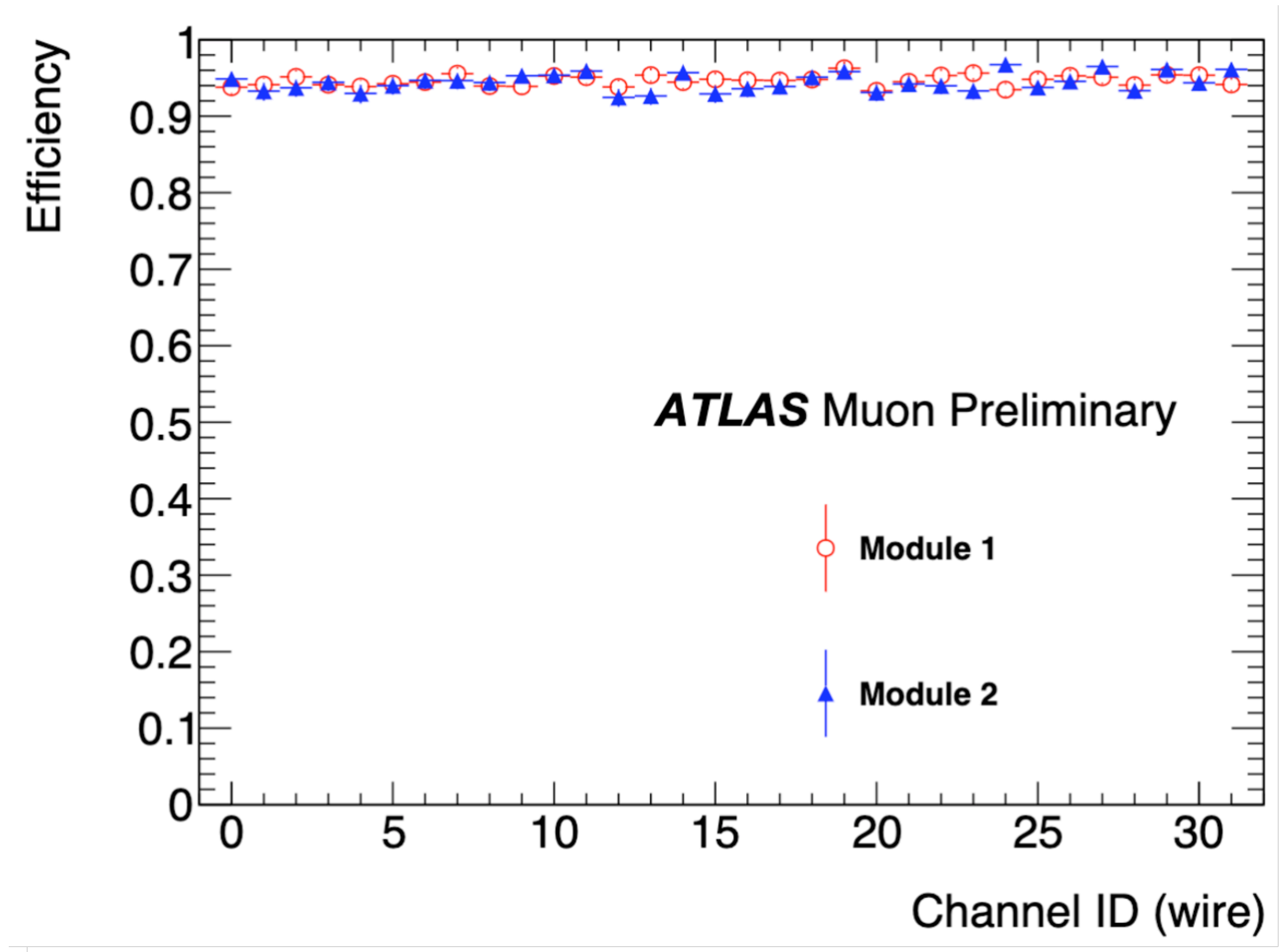
Quality and Performance:

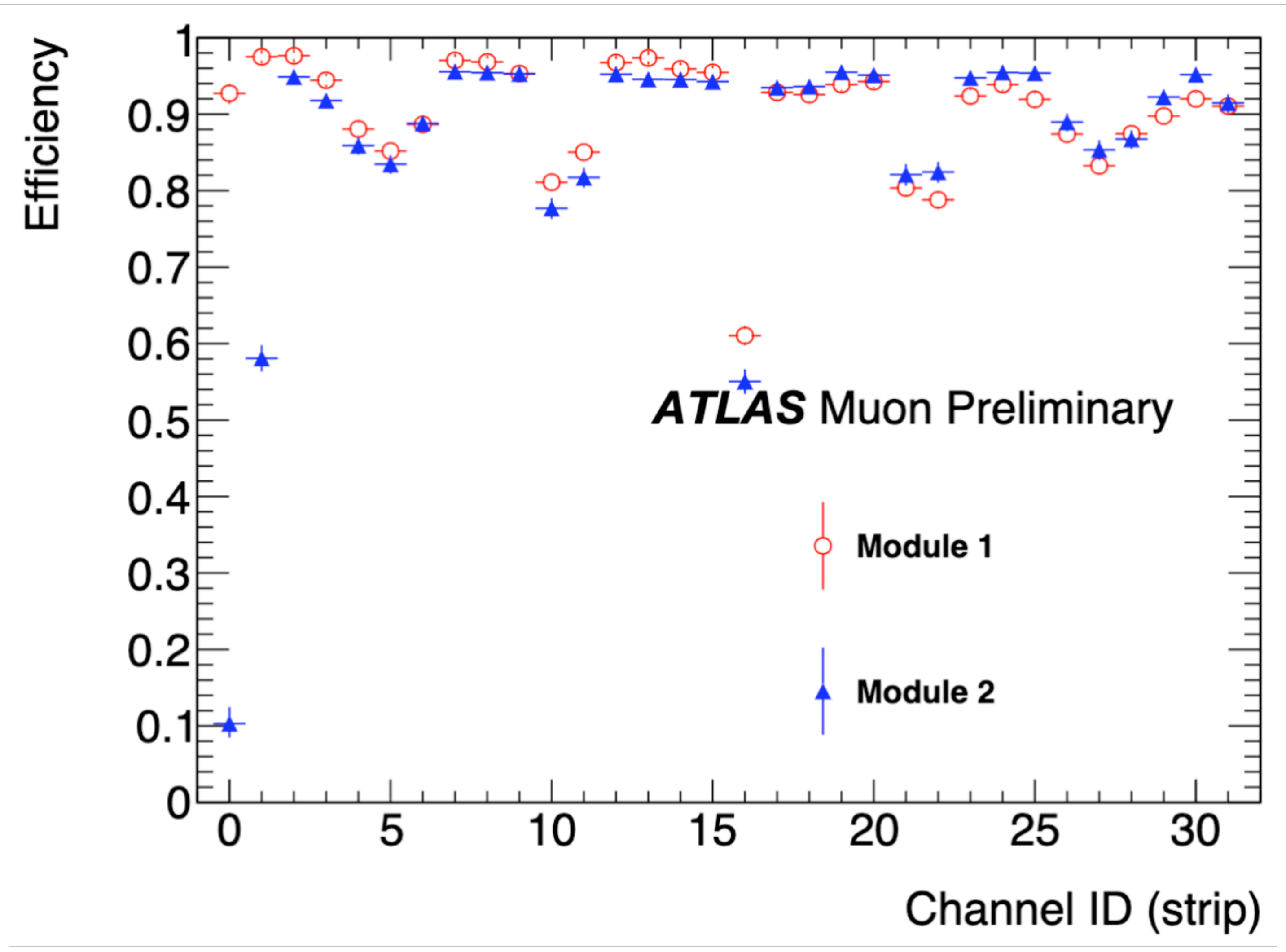
- The quality of the produced detectors has been stable over time, with effective quality assessment and control processes in place.
- Measured hit detection efficiencies are **94% for wires** and **92% for strips**, meeting performance expectations.

Pilot Installation:

- A pilot installation of one of the **Sectors** was successfully completed during the **2024-25 YETS**, demonstrating readiness for future deployment.

The efficiency per wire and per strip for each channel





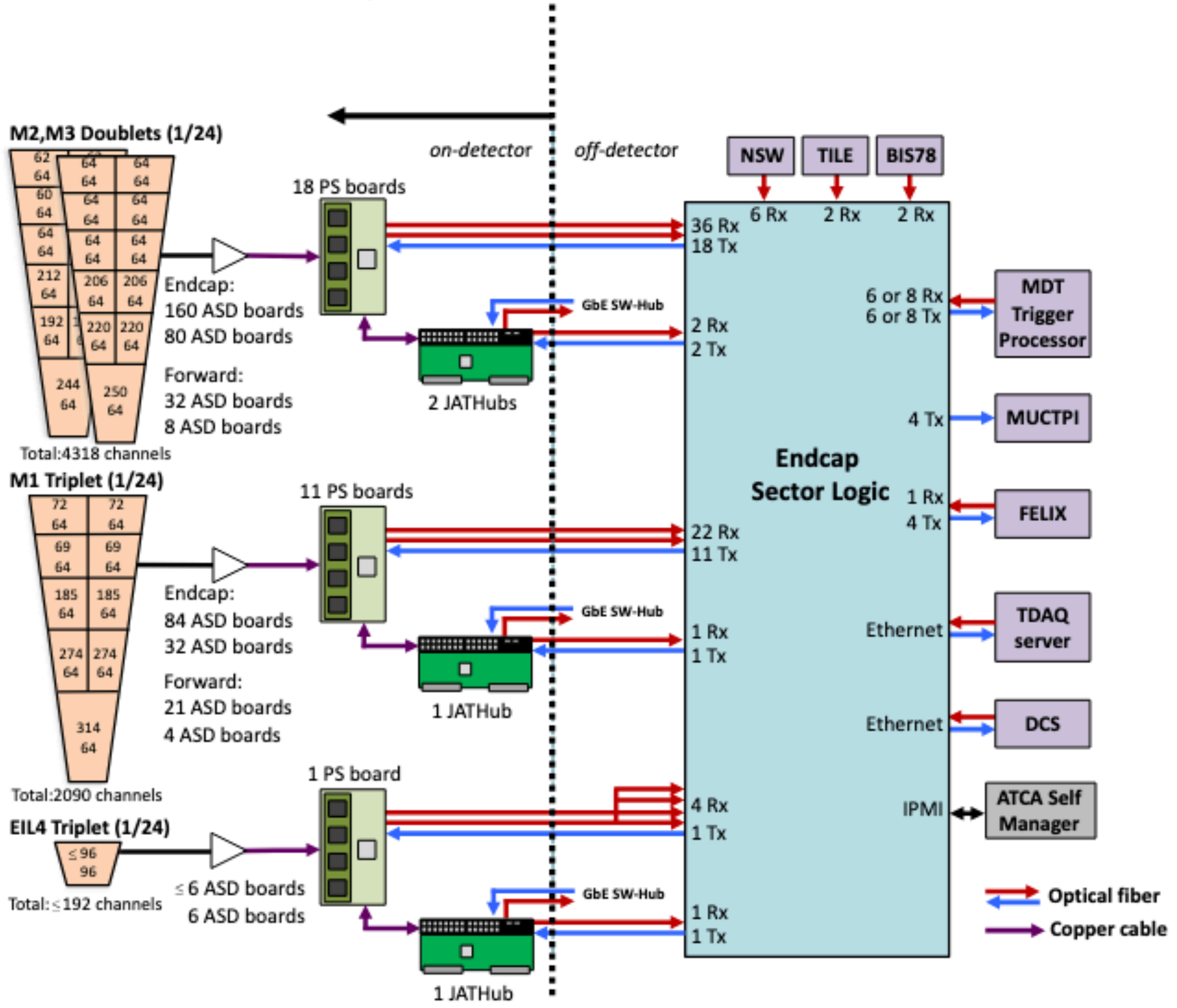
Early replacement of 3 new EIL4 chambers of sector 9 on side C on during end-of-year technical stop 2024-25

TGC Phase-II Electronics

- To meet the **Phase-2 Trigger DAQ specifications**, the entire electronics system for both the **frontend** and **backend** of the TGC trigger/readout will be upgraded.
- The on-detector trigger boards will be substituted with **off-detector electronics** (Endcap Sector Logic) based on **FPGA** capable of more complex trigger logics.
- **New Components** like the Patch Panel ASIC, the PS Board and the JATHub Board have all been **produced and tested**. Soon they will be shipped to CERN.

Phase-2 L0 Endcap Muon Trigger System

Muon Projects



Schematic diagram of Phase2 TGC/L0 muon system

Conclusions

The upgrade of the ATLAS Muon detectors, along with their electronics and power systems, ensures the preservation and enhancement of the Spectrometer's exceptional triggering and tracking capabilities at High Luminosity-LHC, all while maintaining the current kinematic thresholds for physics triggers.

- This presentation covered the **Phase-2 upgrades** for Monitored Drift Tubes (MDTs), Resistive Plate Chambers (RPCs), Thin Gap Chambers (TGCs), and their associated electronic systems.
- The upgraded **MDTs** and new **sMDTs** will play a role in the **Muon hardware trigger**.
- A new generation of **RPCs** will be integrated into the **inner layer of the Muon Barrel**
- **New TGC chambers** will complete the **Muon End-cap hardware trigger** in the EIL4 region.

The ATLAS Muon community has made remarkable progress over the years, advancing significantly toward the completion of the **Phase-2 upgrade program** for Muon Detectors.