India-JINR Workshop on Particle, Nuclear, Neutrino Physics and Astrophysics

NISER, Bhubaneswar

CMS HL-LHC Outer Tracker Upgrade activities at NISER

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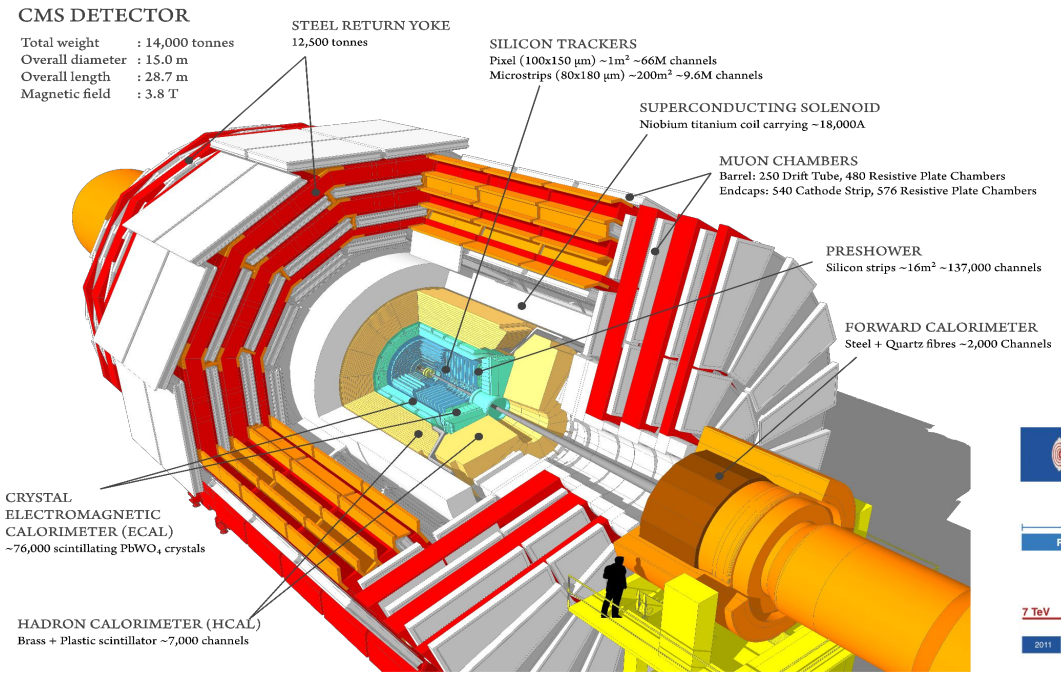
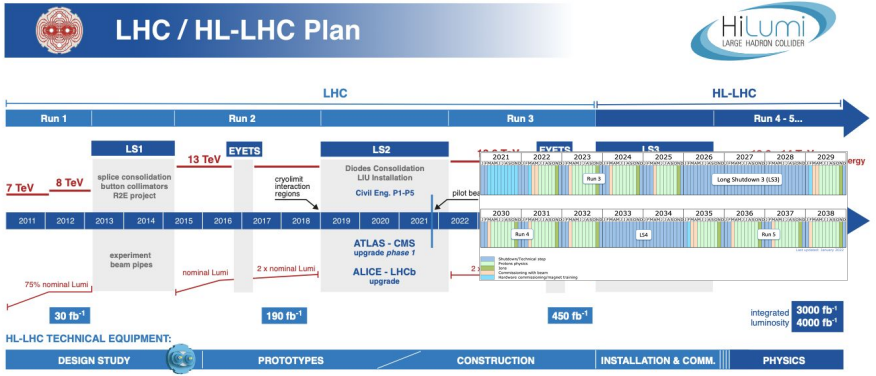
***M. Rahaman**, M. Sahoo, D. Satapathy, S. Shuchi, V. Sinha*

(along with other members of the SINP, IOP and IIT Bhubaneswar)

HL-LHC & CMS Tracker

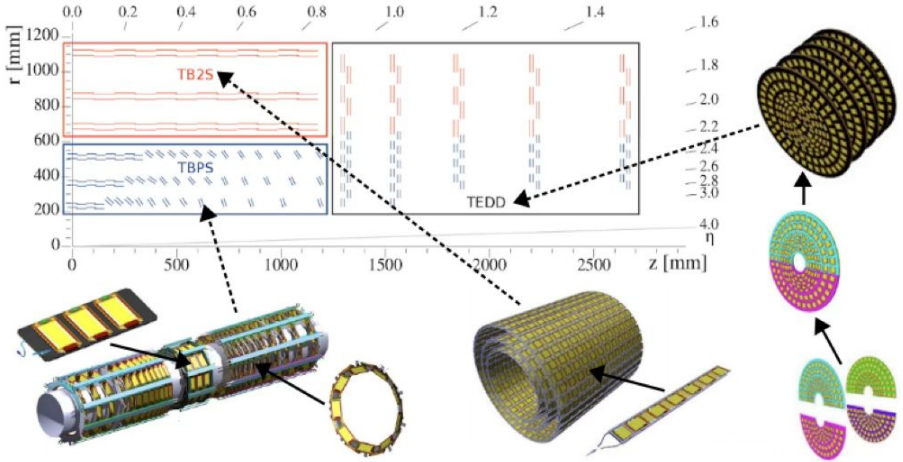


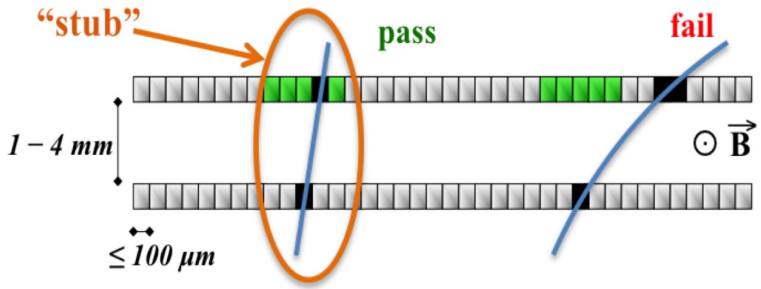
- LHC is planning High Luminosity upgrade to collect high data rate (10x) to probe rare physics.
- CMS Phase-2 upgrade is designed to handle data rates of HL-LHC.
- Higher pile-up, radiation, and data complexity demand advanced detector upgrades.



CMS Phase-2 tracker

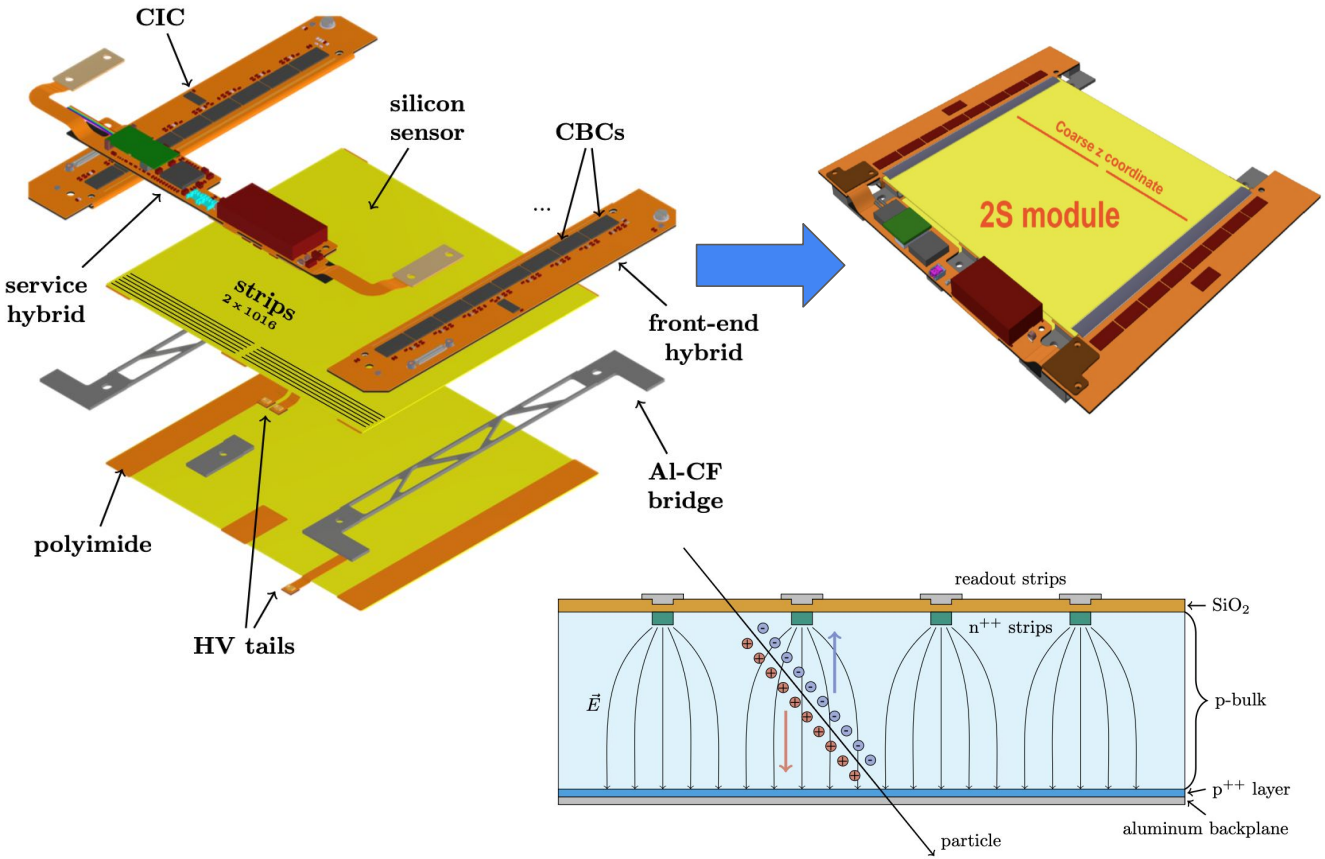
- The Phase-2 CMS detector will feature an upgraded Outer Tracker (OT) with pixel-strip (PS) and strip-strip (2S) modules, equipped with unique feature of **hardware level track triggering capabilities** for the first time in any HEP experiment.
- Each 2S module consists of silicon strip sensors with 2032 strips per sensor, totaling **4064 channels**, and with each strip having dimension of **5 cm × 90 µm** while current OT uses silicon strips measuring **10 cm × 180 µm.**
- NISER is producing **1104 modules** for integration into **92** ladders, which will be installed in the **TB2S** (Tracker Barrel 2S module) **section** of the tracker.



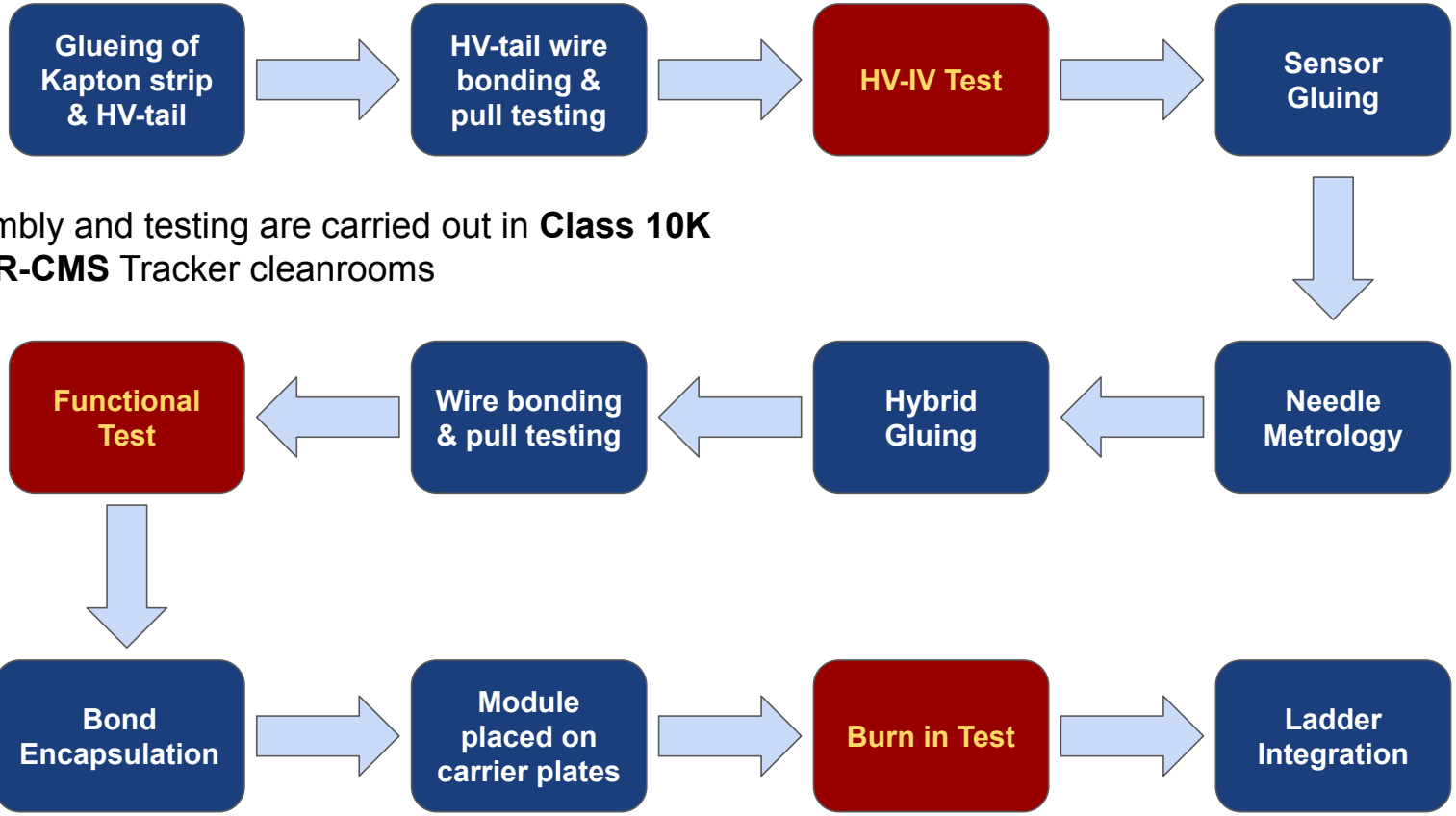


CMS Phase-2 Outer Tracker 2S Module

- **Sensor type:** n-in-p silicon
- **Size:** 145 × 125 × 0.18 mm³
- **Weight:** 37 g
- **Structure:** Two halves with 1016 strips each (5 cm long)
- **Active area:** 10 × 10 cm²
- **Strip pitch:** 90 µm
- **Strip width:** 22.5 µm



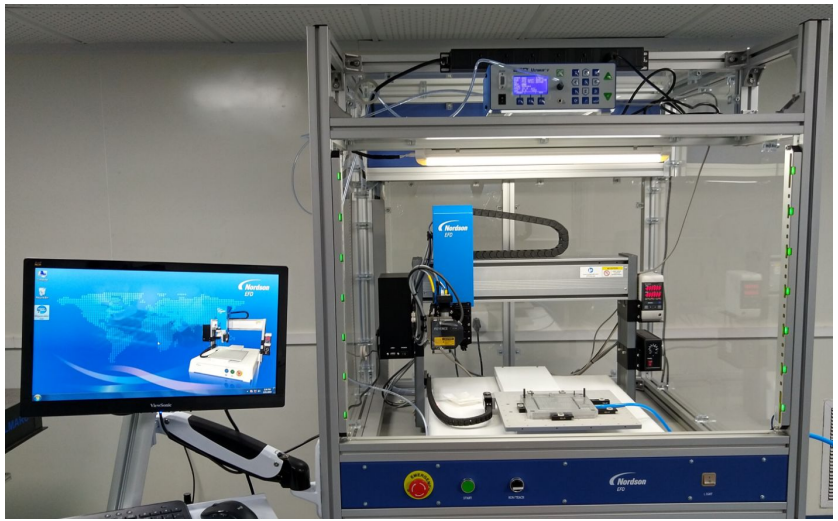
2S Module Standard Integration Procedure



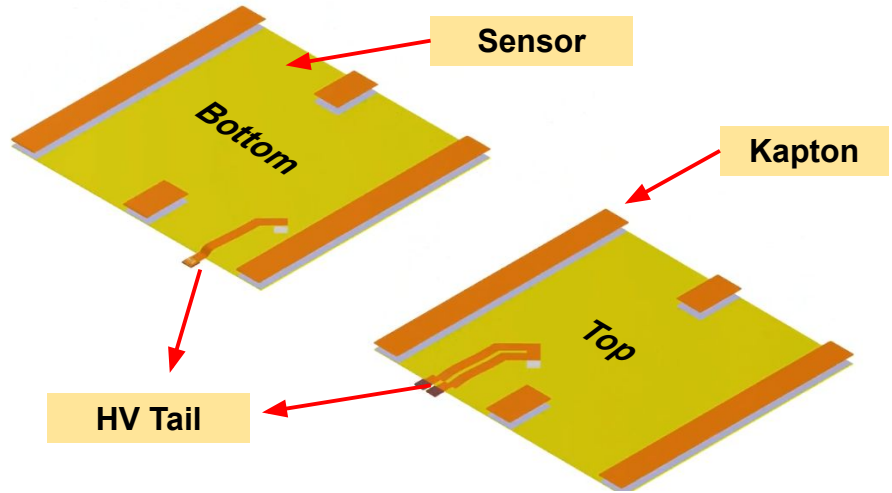
- Assembly and testing are carried out in **Class 10K** **NISER-CMS** Tracker cleanrooms

Kapton Strip and HV Tail Assembly, Inspection & Encapsulation Process

- Kapton strips and HV tails are visually inspected to ensure quality.
- After inspection, the Kapton strips and HV tail are glued to the sensor backplane with a **5–7 µm** layer of low-viscosity insulating glue **(Polytec 601 LV)** applied by the **Nordson Robot.**
- HV tails are wire-bonded for electrical connection and encapsulated with **Sylgard 186** to ensure durability.

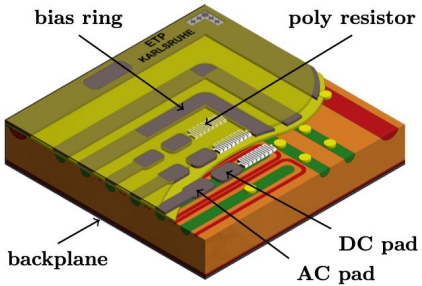


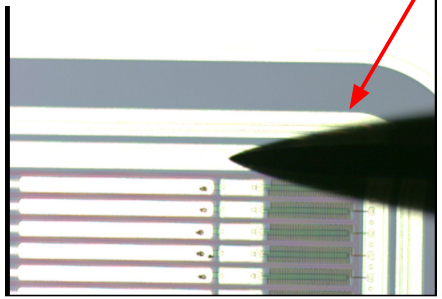
Nordson Robot



HV-IV Test for Individual Sensor

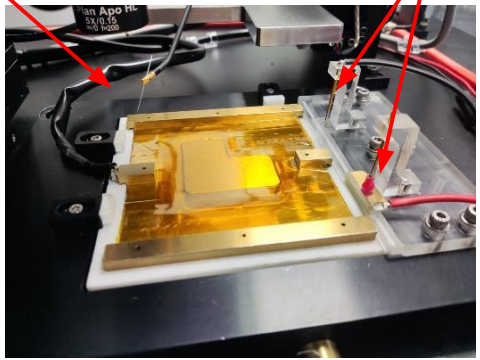
- After wire bonding and encapsulating the HV tail on the sensor backplane, an **HV test** checks electrical isolation up to **1000 V.**
- The sensor's bulk **IV characteristics** are measured using a probe needle and Keithley power supply up to **800 V.**
- This Quality Control step is essential to ensure successful Kapton gluing.



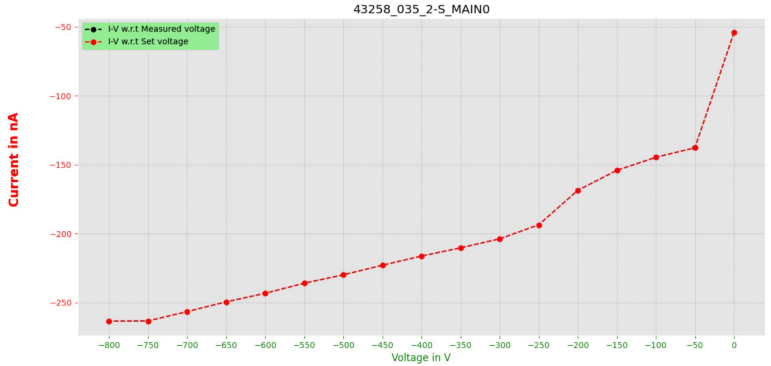


Needle

HV tail connector



Brass rail inside the probe station

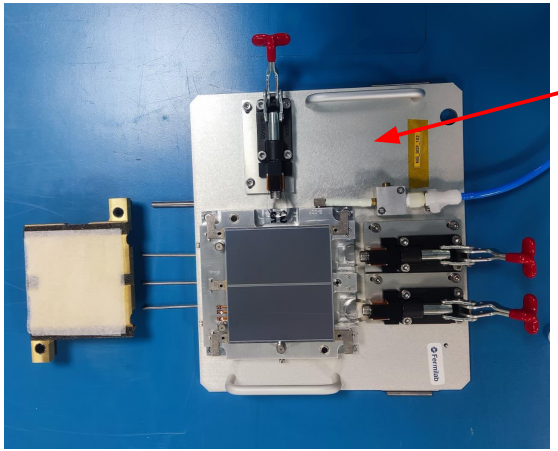


IV Result

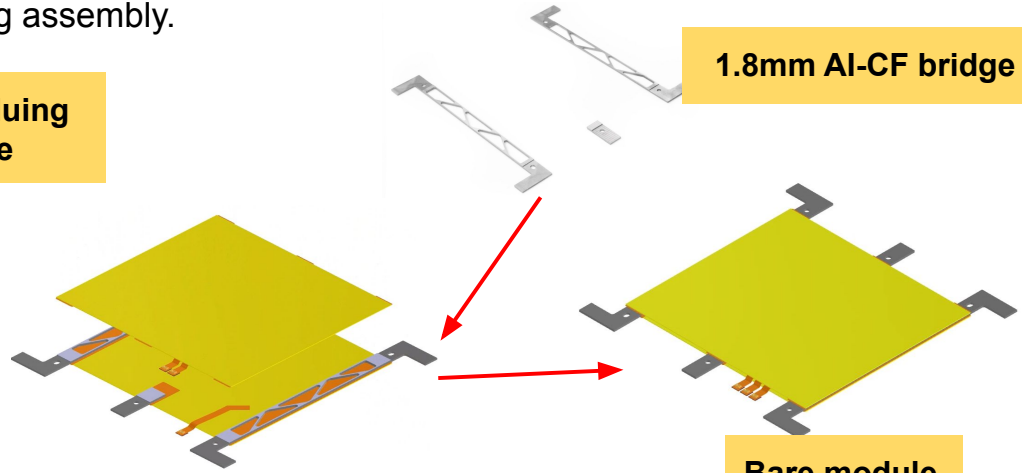
Sensor-Sensor Gluing

Once both the top and bottom sensors pass the HV and IV tests, **Al-CF** (aluminum–carbon fiber) spacers are used with **Polytec 437** glue to precisely align and bond them into a bare module. These spacers, or **“bridges”** not only maintain sensor separation but also serve three main purposes:

- They provide the module’s support structure with tabs for hybrid attachment.
- They include holes for mounting the module onto the tracker’s cooling and support system.
- They ensure precise module positioning during assembly.

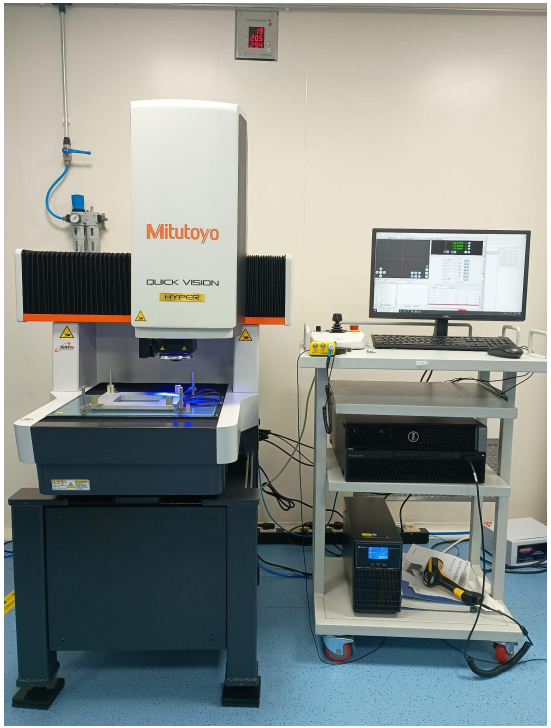


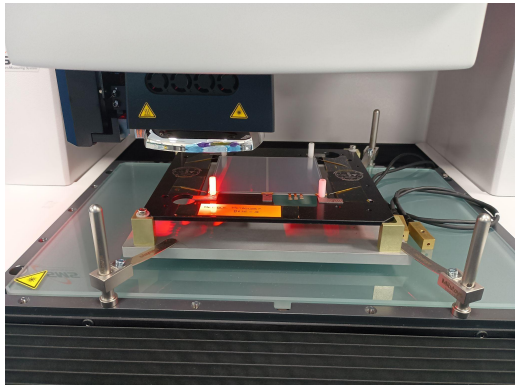
Sensor Gluing Fixture

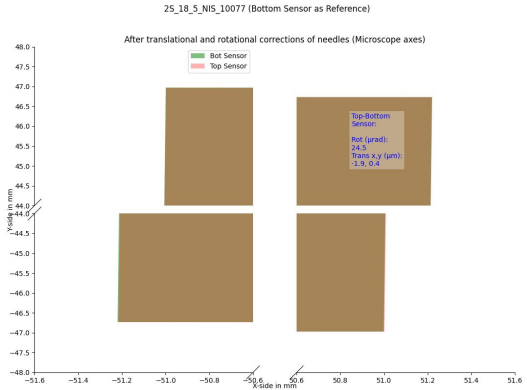


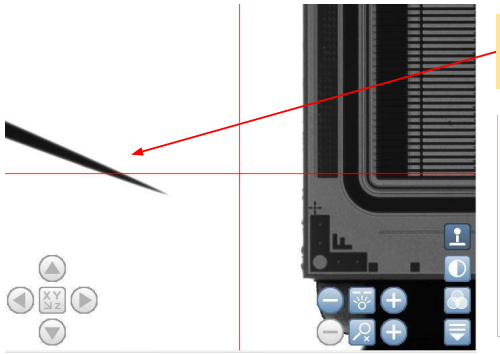
Needle-Based Metrology

- It verify the alignment of the top sensor with respect to the bottom sensor of the bare module
- 16 coordinates (8 from each sensor) are taken — 4 from the needle and 4 from the fiducial marks.
- The code calculates **Δx** (along the strips), **Δy** (perpendicular to the strips), and the **rotation** between the strips.

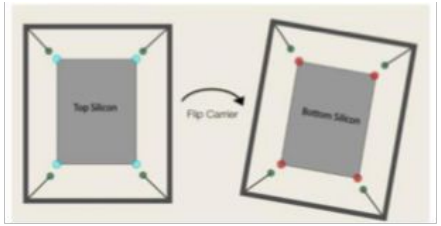








Needle



Qualifying standards:

Δx < 100 μm ,

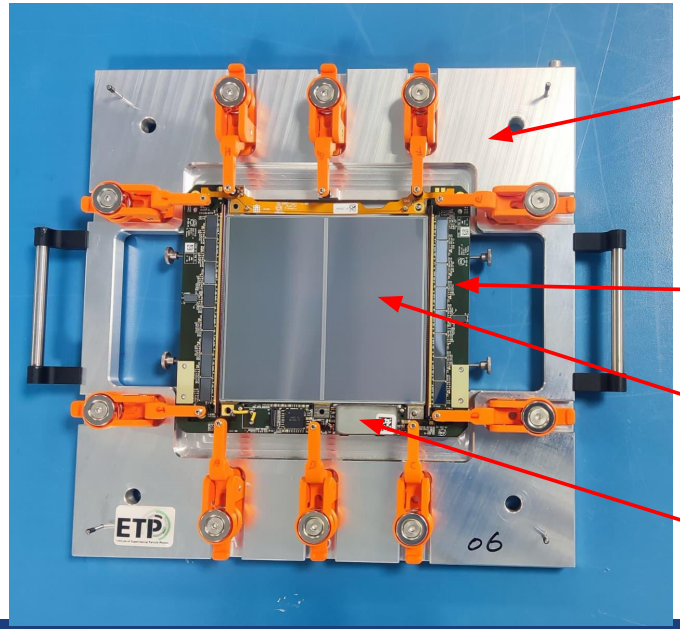
Δy < 50 μm,

Rotation

< 400 μrad

Hybrid(s) Gluing

- A functional test is carried out before attaching the hybrid to the bare module.
- The hybrid is then carefully mounted onto the structure, followed by functional tests to verify its performance.
- Glue is applied in small dots on the support structure, and the skeleton is precisely aligned and placed onto the sensor using special alignment pins.

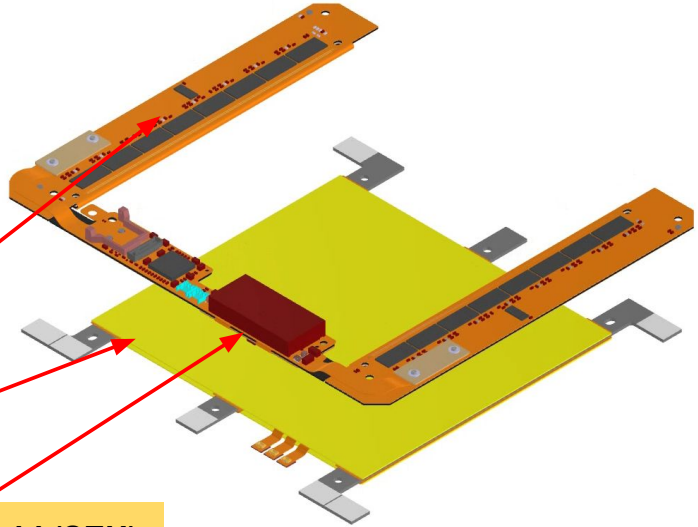


Hybrid Gluing Fixture

Front-end Hybrid (FEH)

Bare Module

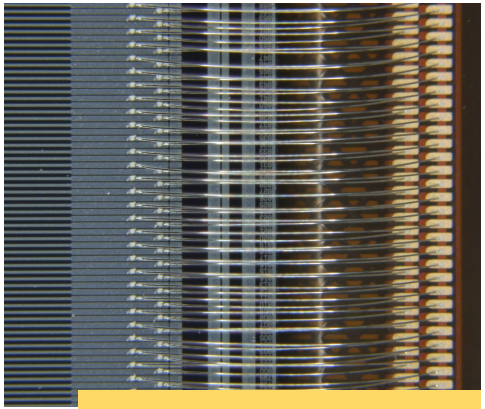
Service Hybrid (SEH)



Automatic Ultrasonic Wire-Bonding

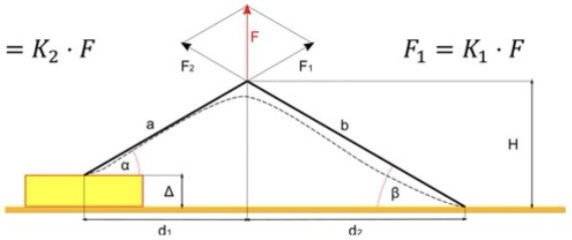
- Sensor channels are connected to the **FEH** using a **Delvotec wire bonder**, forming **4064 bonds** in total (1016 bonds on each of four sides).
- Around **10** bonds are pull-tested using a **Nordson Dage pull tester** to ensure bond quality.
- Functional tests are carried out after bonding, then the wirebonds on both sides are **encapsulated**. Once the glue has cured, the tests are done again to confirm stable performance.

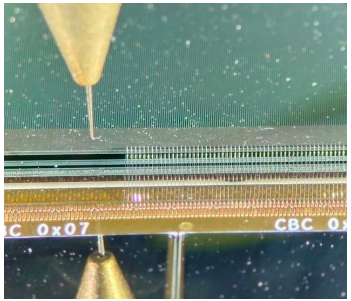
Delvotec ultrasonic wire-bonder



FEH & sensor bonding

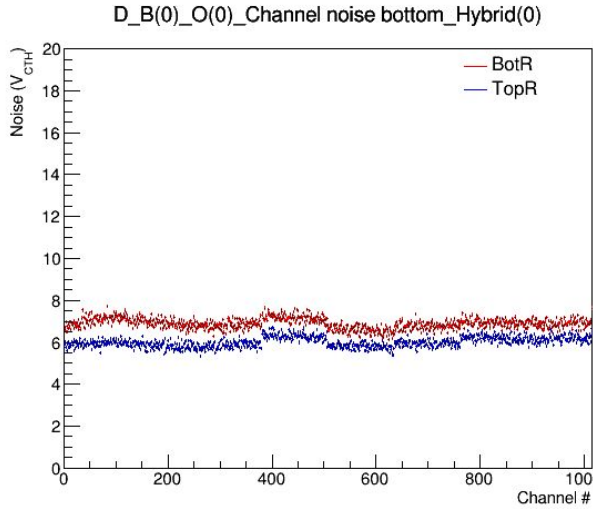
$$F_2 = K_2 \cdot F \qquad F_1 = K_1 \cdot F$$

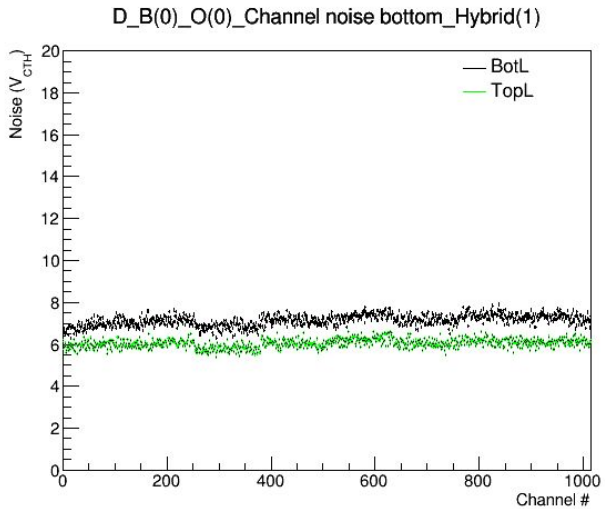


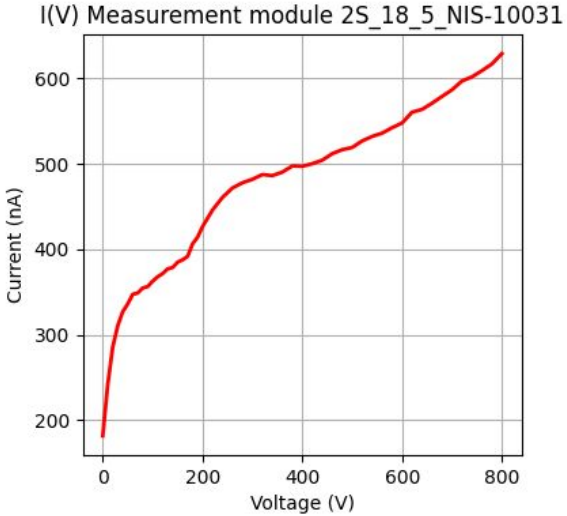


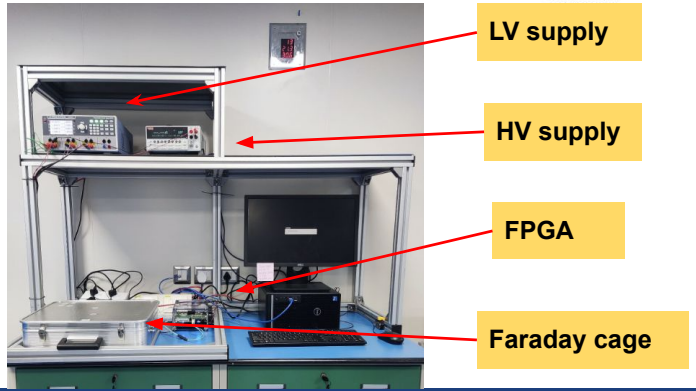
Pull testing
Hook diameter 75 µm
Maximum force applicable 100 gm
Specification Needed:
Mean > 8g
RMS <10% × Mean
Grade <20% liftoff

Functional Test





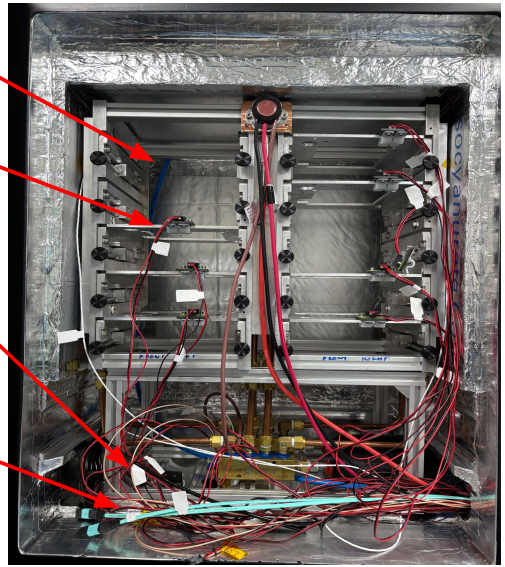




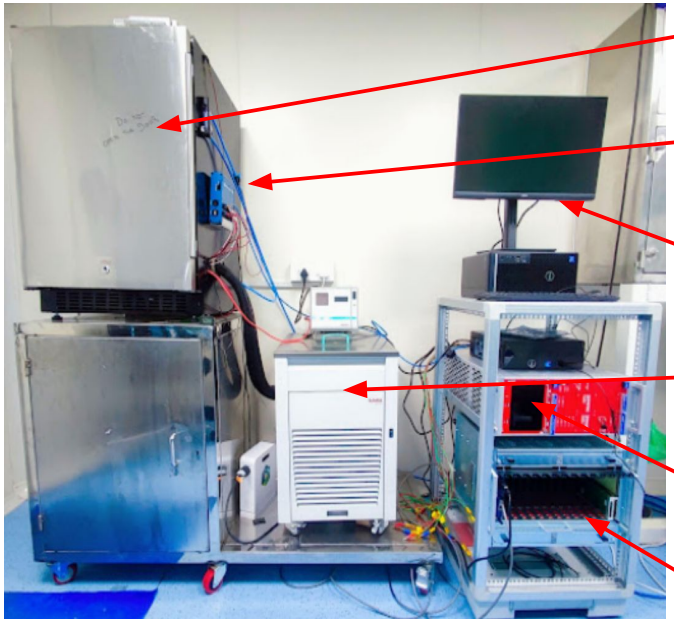
- Only IV & noise test shown here
- For each module functional test would reveal any problem in any of the **4 × 1016 channels**.

Multi-module Burn-In Test & Set-up

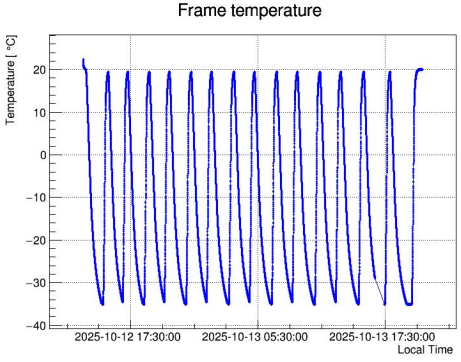
- Ten modules are placed in a **burn-in setup** for controlled thermal cycling between **20 °C** and **−35 °C**, with functional tests performed at each temperature.
- The entire procedure is automated using **OTSDAQ** (CMS detector control software) and the Phase-2 Acquisition and Control Framework **(Ph2ACF)** for temperature cycling and module readout.

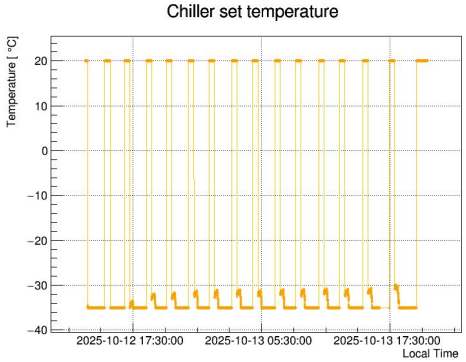


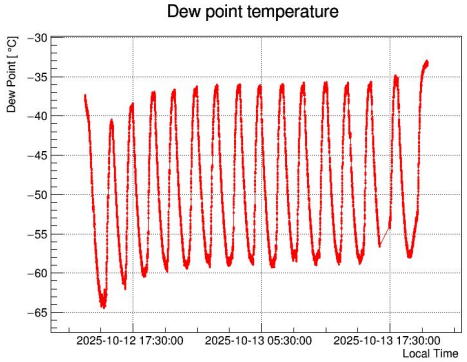
Inside view of BurnIn-box

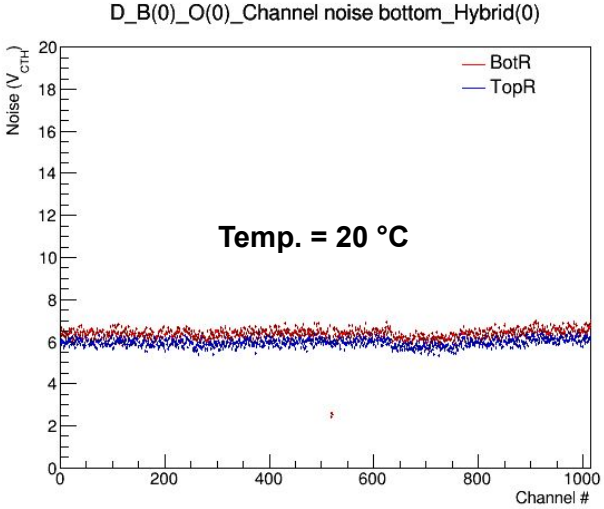


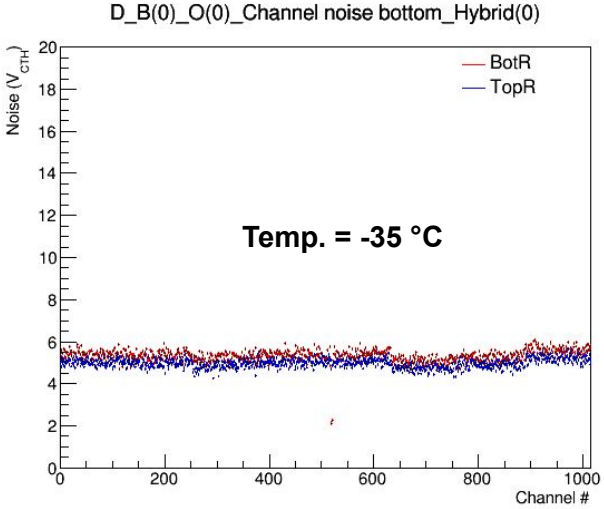
2S_18_5_NIS-10056 BurnIn Cycle Results





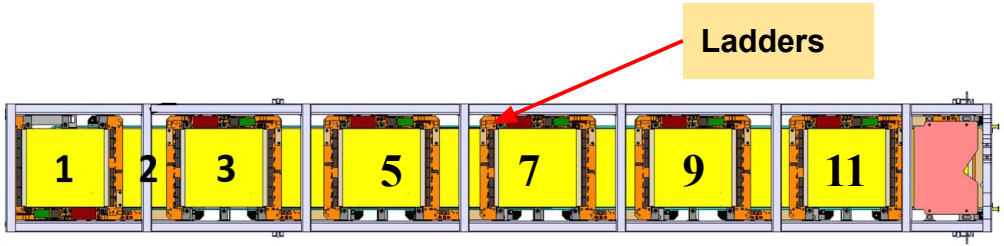


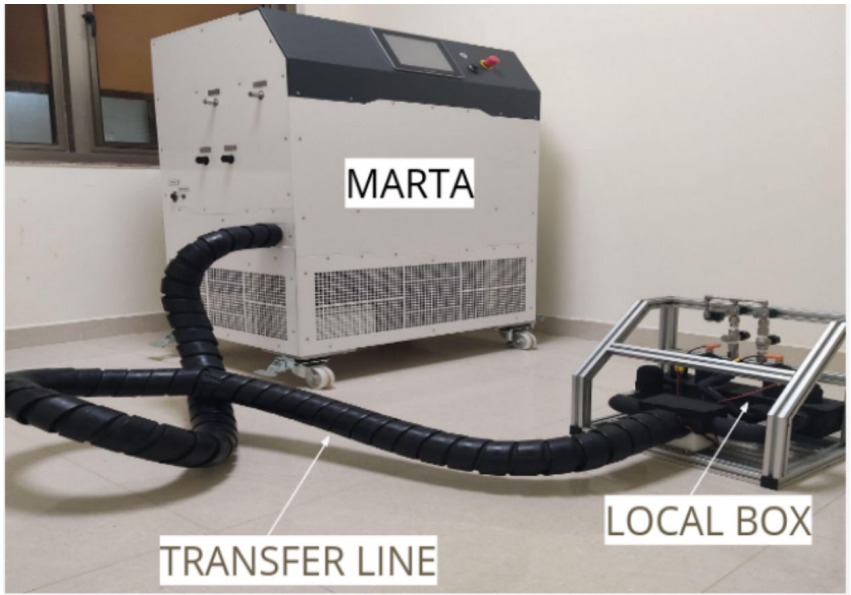




Ladder Integration

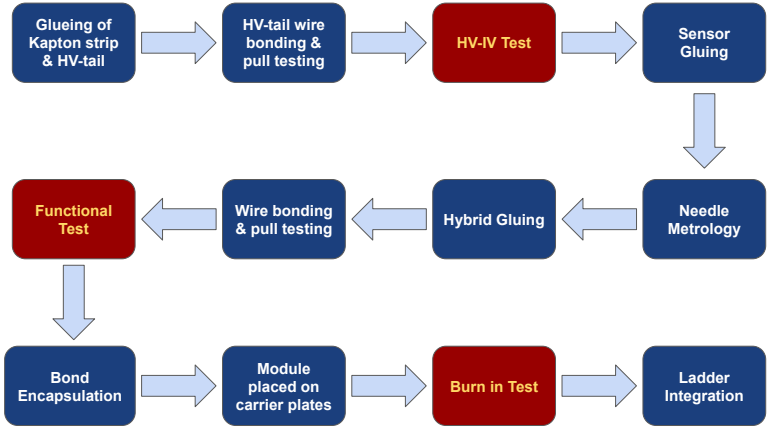
- **92 ladders** will be integrated into the tracker barrel **(TB2S)**, each carrying **twelve** 2S modules.
- A **CO_2**-based **Marta cooling plant** is used for temperature cycling.
- The collective noise profile of all **TB2S ladder** modules will be measured at different temperatures.

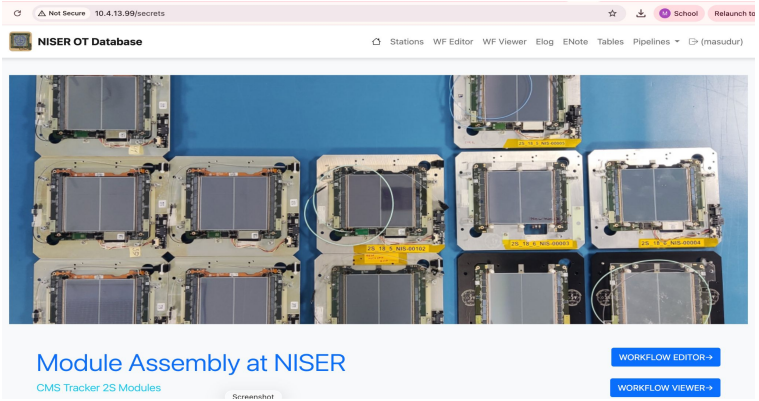




NISER OT Database

- To support the Outer Tracker Module Assembly process we built a local database management system for storing and tracking assembly data.
- Complex Assembly Workflow
  - Over 10+ production and testing steps
  - Each steps requires precise tracking parameters & status
- Manual Data Handling Issues
  - Paper logs and scattered spreadsheets are inconsistent
  - Risk of human error and data loss
- Ensures efficient Workflow management, Quality control
- Provides easy access to production history
- Supports real-time monitoring of the entire workflow assembly
- Enables precise tracking and traceability





Summary

- The CMS Tracker upgrade is vital for the HL-LHC upgrade for achieving the CMS physics goals and objectives with 3000 fb-1 HL-LHC dataset by 2024
- The NISER Module Assembly Center has been qualified early Jan 2025 for production readiness, and the quality control standards are maintained at other CMS Tracker assembly centers across the world.
  - CERN has been continuously monitoring the activities of NISER's work
- Skilled personnel ensure smooth module assembly, integration, and testing.
- More than 60 final modules have been tested as per the stringent quality control criteria for OT, while integration of first ladder is yet to be completed
- The assembly, testing and integration are to be completed at the CMS centers by **December 2027**
  - The commissioning and installation at CERN is to be completed by 2029

For the very first time the Indian HEP experimental community have taken the responsibility of assembly and integration of sophisticated silicon-based tracking detector in India

→ Great patience and support requested to make the journey successful!


Ulrich Heintz, CMS OT Modules Group
co-convener visited in March, 2023


Frank Hartmann, CMS Phase 2 Upgrade
Coordinator visited in February, 2023

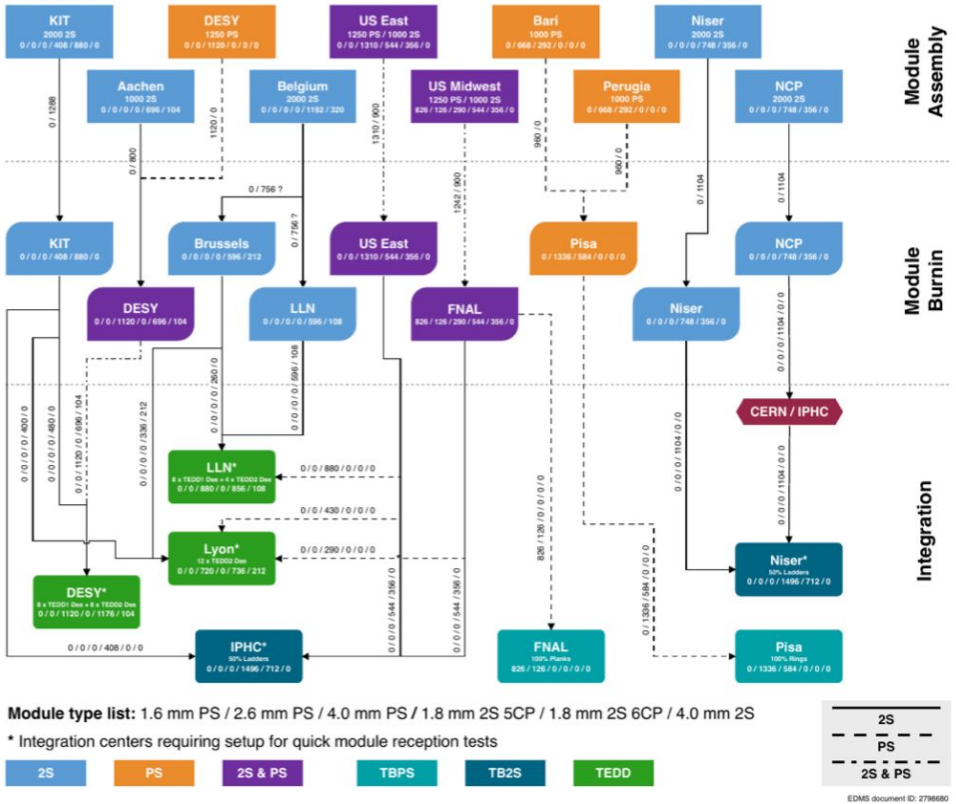

Visit by the CMS Tracker Team
(October 14-15, 2024)


CMS Spokesperson Team Visit
(Feb 25, 2025)

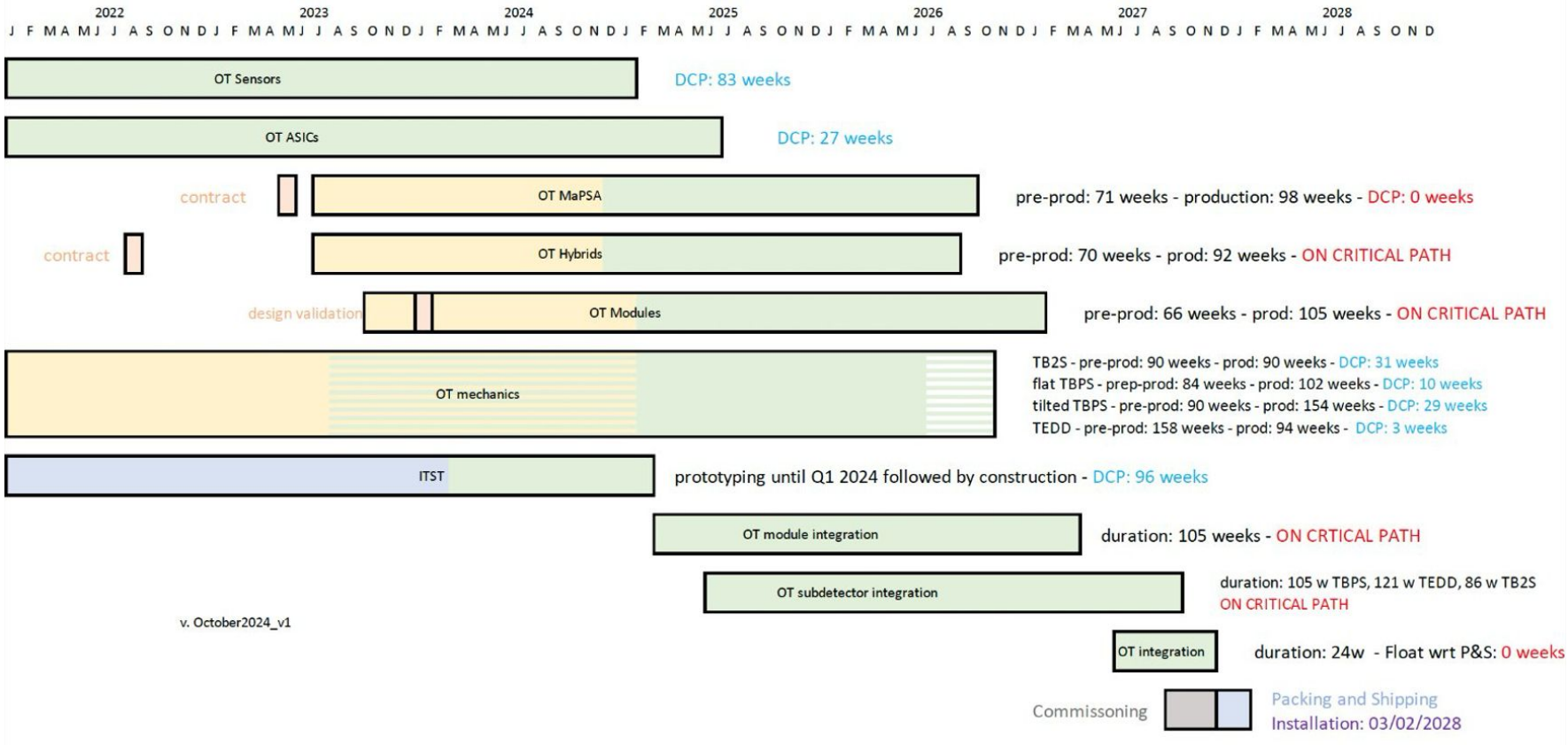
Thank you !

Flow of modules : from assembly to integration

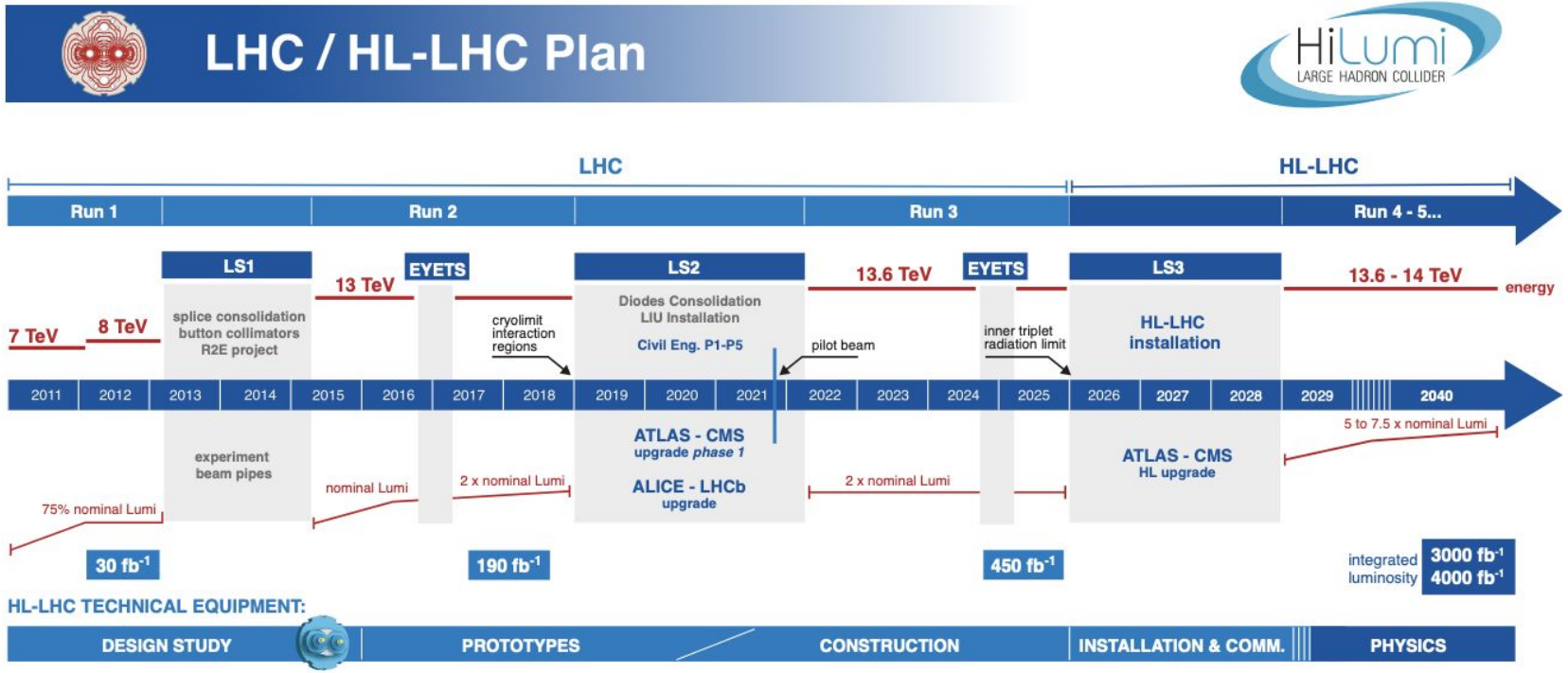
- A detailed plan for module distribution exists, and is used as an input to the production model.
  - Given amount of modules of a given type in each center
  - Predefined destination
    - Sometimes a 1:1 relation between assembly and integration.
    - Sometimes more intricate.
- Could be tuned, but gives already a rather optimal scheme.



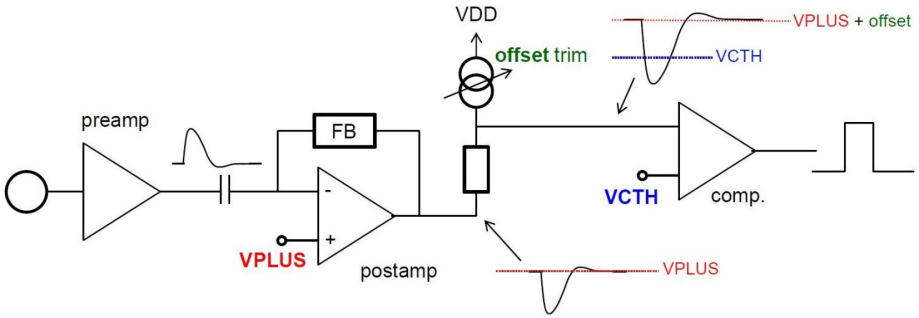
Outer Tracker Schedule



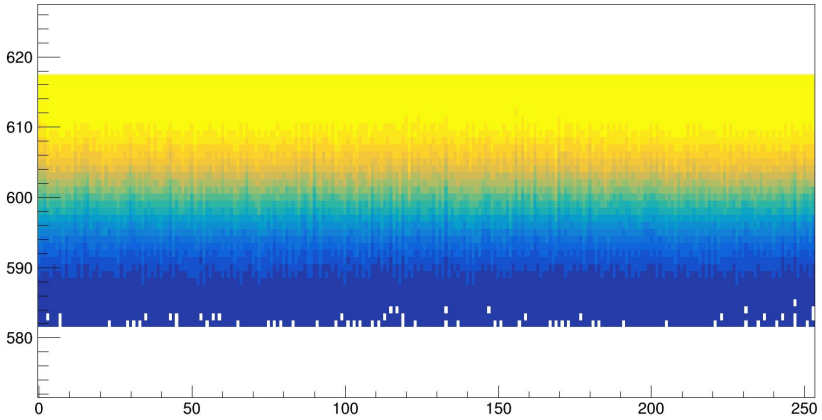
Backup

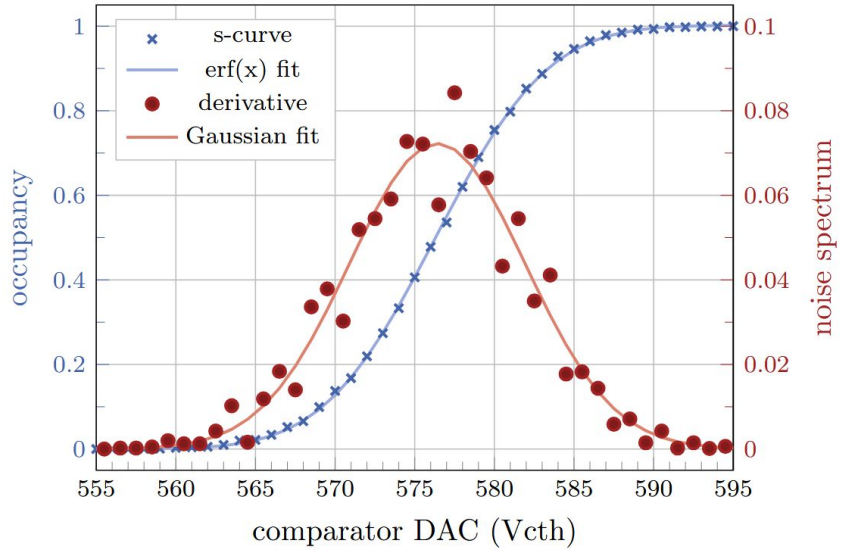

LHC / HL-LHC Plan
HiLumi
LARGE HADRON COLLIDER
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
LS2
LS3
EYETS
EYETS
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
inner triplet
radiation limit
HL-LHC
installation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
5 to 7.5 x nominal Lumi
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1
HL-LHC TECHNICAL EQUIPMENT:
DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS

Backup

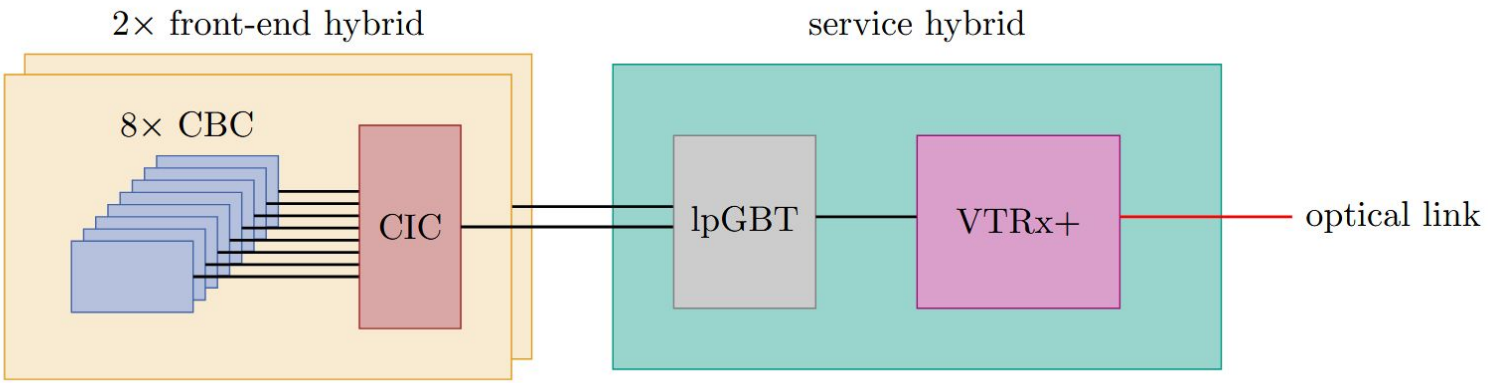


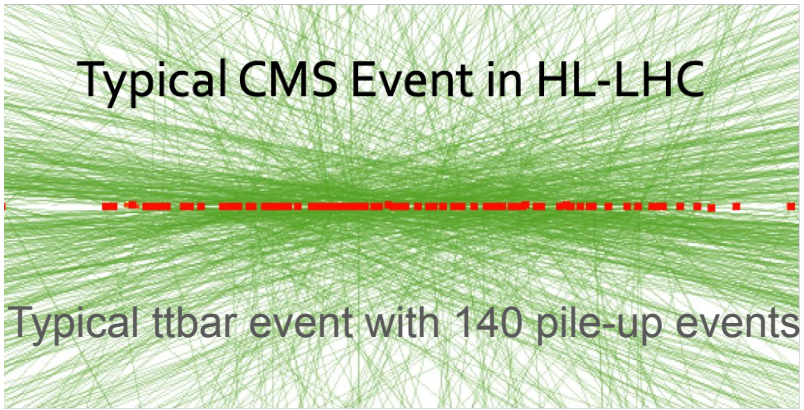
D_B(0)_O(0)_H(0)_SCurve_Chip(0)





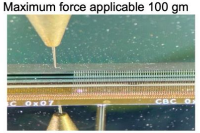
Backup





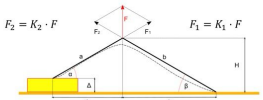
2S Module Assembly: Pull-testing

Bond pull test :
. Hook diameter 75µm
. Maximum force applicable 100 gm



correction factors :
.Simple (2D geometric considerations)
.K^s_1 = cosβ/sin(α+β)
.K^s_2 = cosα/sin(α+β)

Specification Needed:
.Mean > 8g
.RMS < 10% x Mean
.Grade: < 20 % liftoff



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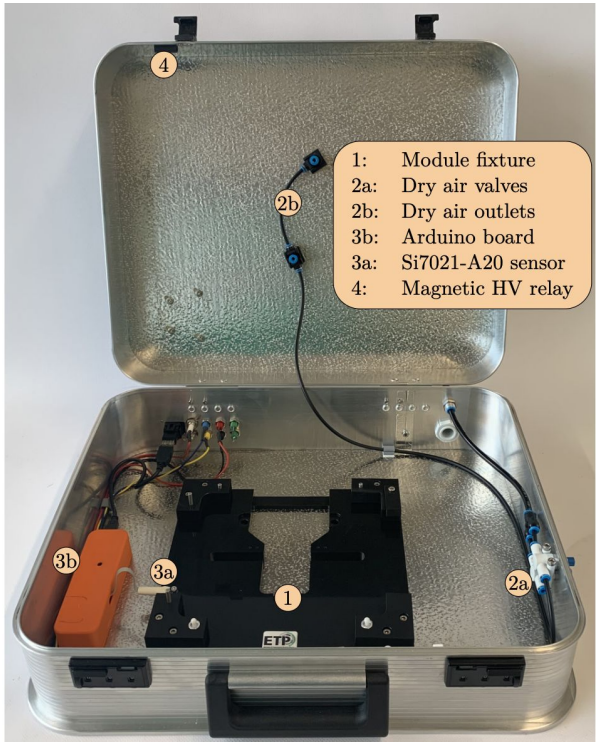
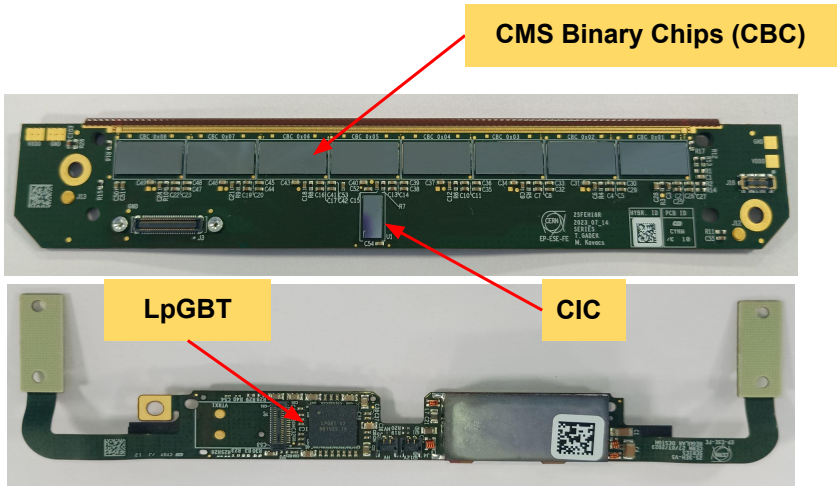

4
2b
3b
3a
1
2a
ETP
1: Module fixture
2a: Dry air valves
2b: Dry air outlets
3b: Arduino board
3a: Si7021-A20 sensor
4: Magnetic HV relay


CMS Binary Chips (CBC)
LpGBT
CIC