# CMS Tracker Phase-2 Upgrade Projects at NCP

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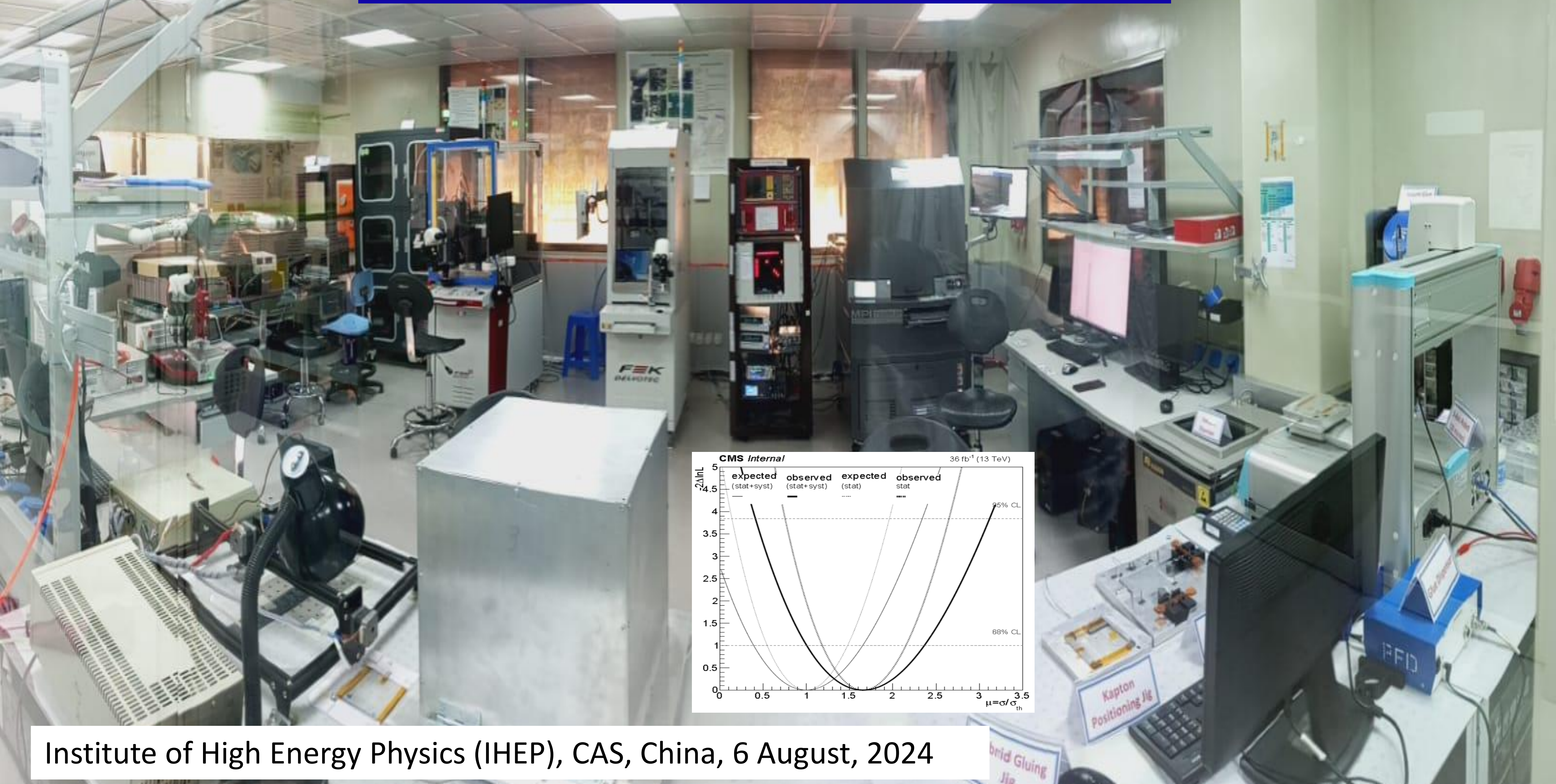



Institute of High Energy Physics (IHEP), CAS, China, 6 August, 2024

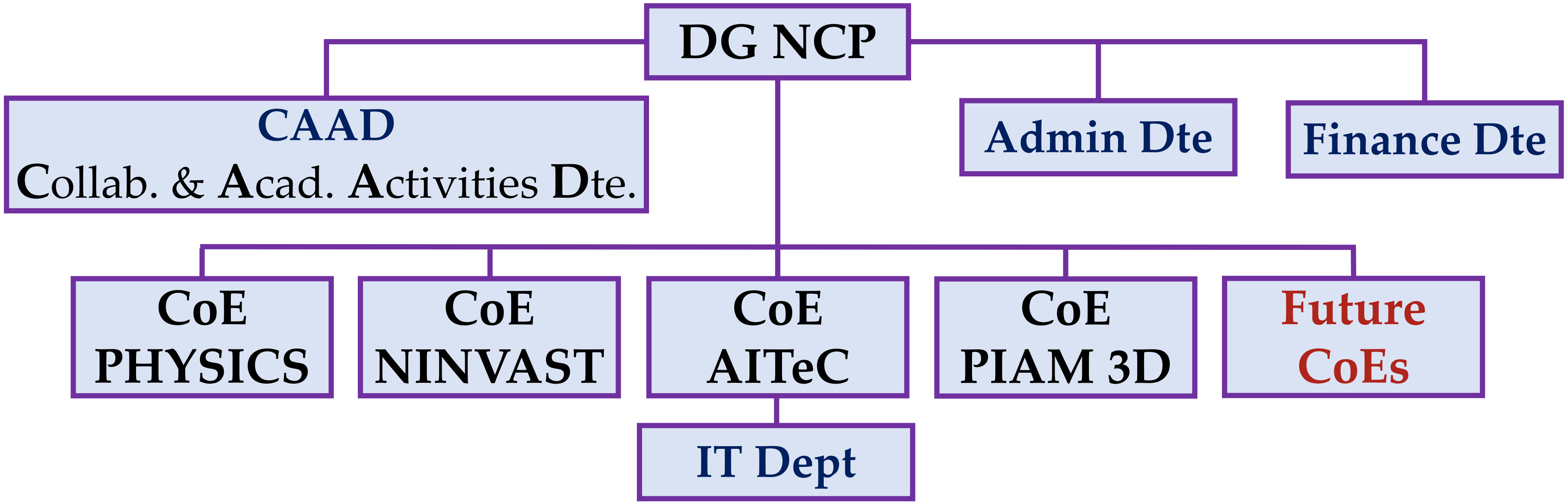
# Introduction

- ➢ Brief Introduction to National Centre for Physics
- ➢ Outer Tracker Phase 2 upgrade

- ➢ Phase 2 upgrade projects at NCP
  - ❑ Ladder Mechanics Project at NCP
  - ❑ Sensor Quality Control project
  - ❑ Assembly, metrology and testing of TB2S modules

- ➢ Summary

# Organogram of NCP




**PHYSICS:** **Exp. HEP, Th. HEP, Accelerator, Laser Physics**
**NINVAST:** **N**ational **In**stitute of **Va**cuum **S**cience and **T**echnology
**AITeC:** **A**rtificial **I**ntelligence **Te**chnology **C**entre
**PIAM-3D:** **P**akistan **I**nstitute of **A**dditive **M**anufacturing

# Panoramic View of NCP

Central part of NCP

**Total Area~ 25 Acre**

# NCP Uniqueness

- One of a kind national research center in Physics & Emerging Techs.
- Breaking the scientific isolation of local researchers by conducting conferences, seminars, workshops.
- Unique Hosted Researcher Program – For Students / Faculty from all national / international universities
- Connected with: CERN, ICTP & TWAS, IHEP, DESY and SESAME

# Hosted Researchers

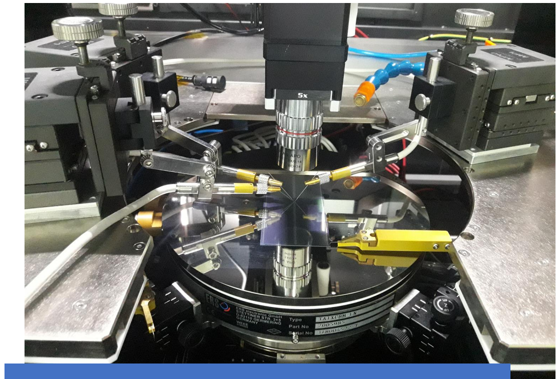
1. **Adjunct Faculty:** Foreign/Local Researchers (Academia & R&D orgs.)
2. **Visiting Scholars:** Foreign / Local PhD Scholars up to 3 months
3. **NCP Associates:** Foreign / Local researchers up to 3 years
4. **Post-Doctoral Fellows:** Foreign / Local PhDs for 6 – 12 months
5. **Research Students:** Foreign / Local M.Phil / PhD 1– 3 years
6. **Internees:** For 3 – 6 months

# Some facilities at NCP

## 5 MV Ion Beam Tandem Accelerator

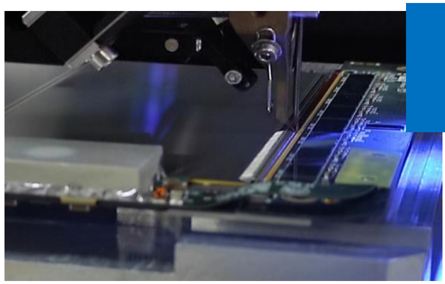

30 meters

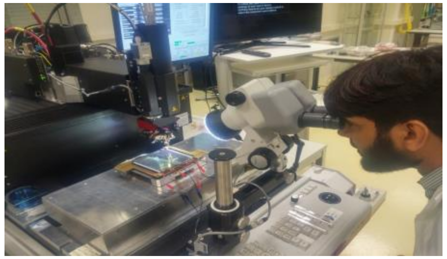
## Probe station



## cleanroom

## Wire/ball bonding machine





## New cleanroom

## LIBS

## PLD

## Ion Implanter

# Logistics Facilities at NCP

1. Auditorium ( 2, Capacity: 285, 70) with Record / Video Conf. Facilities
2. Computer Lab (50 latest general purpose computers)
3. Lecture Theater (Capacity: 60 persons)
4. Lecture Hall (3), Lecture Rooms (4), Conference Rooms (6)
5. Good furnished accommodation for researchers
    1. BoQs (Capacity, 100 guests)
    2. MoQs (Capacity, 50 guests)
    3. Guest House for foreign faculty (Capacity, 50 guests)
6. Cafeteria with seating capacity of 200 persons
7. Wi-Fi throughout the campus

# AS-ICTP like Organization of Scientific Events

Int. Workshop on Tracking Detectors

24-28 October

Ion Beam Application

School on LHC Physics

ISPAD-23

Max Plank Crystallography

Plasma Physics

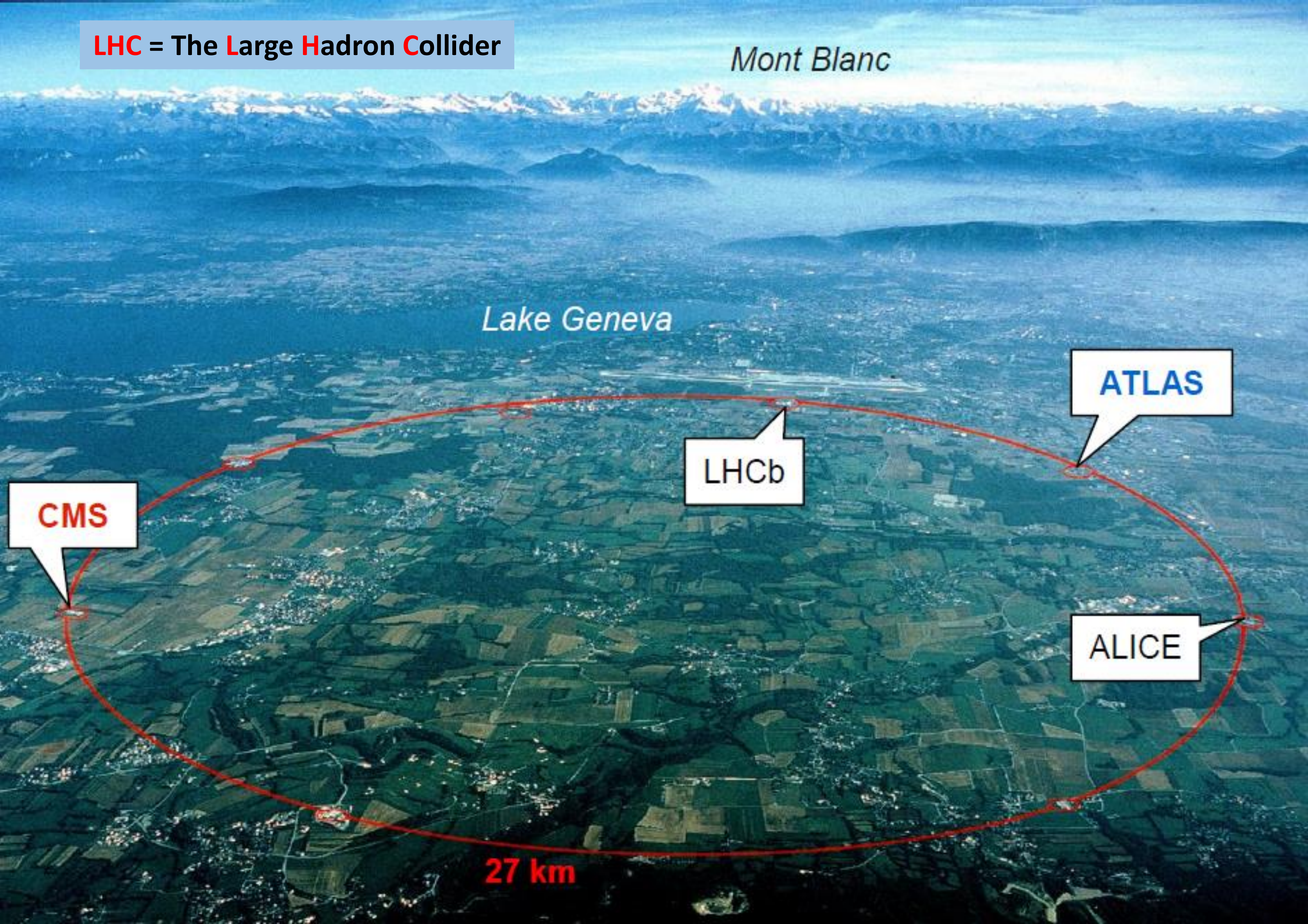
GANDE-China

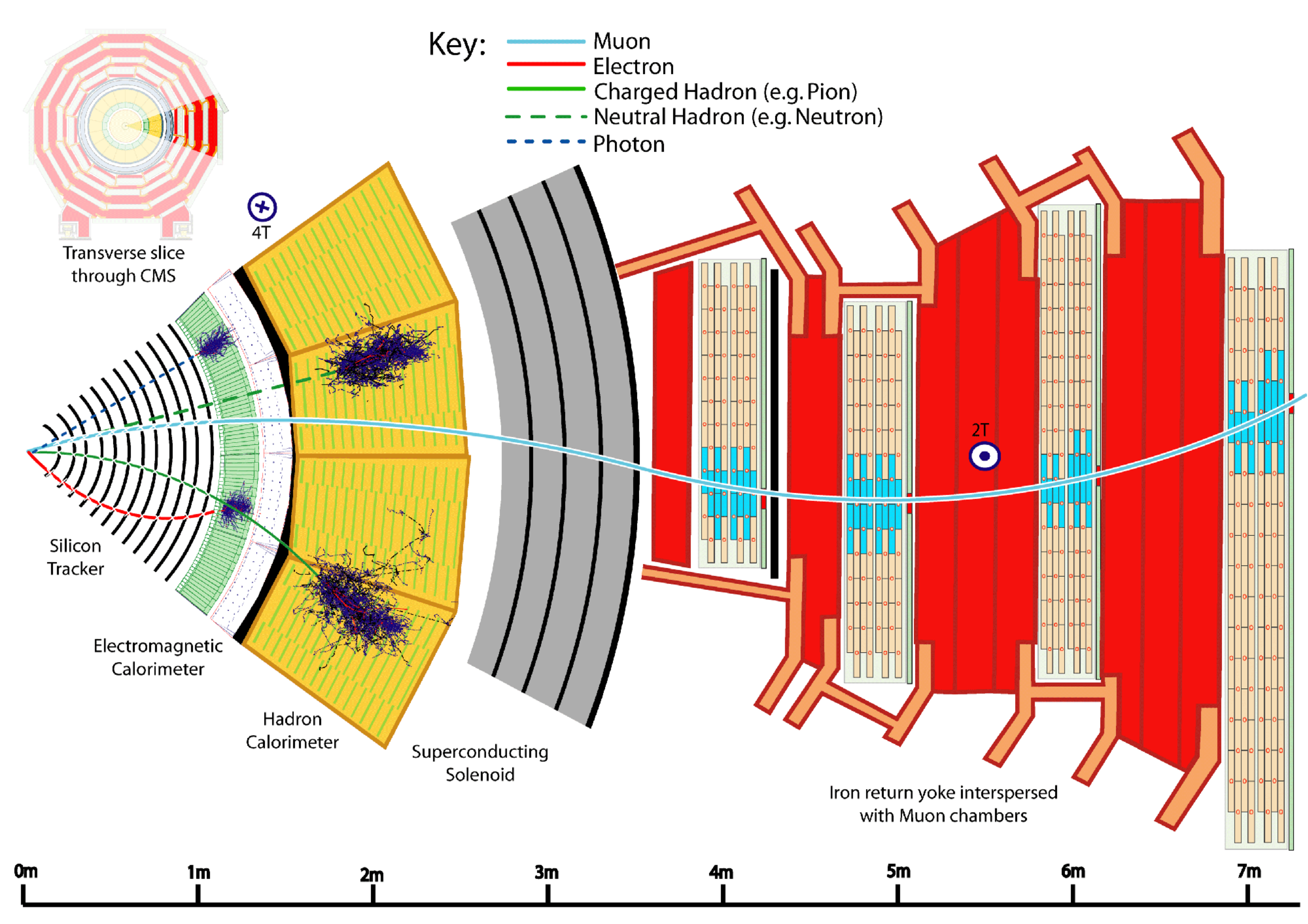
Abdus Salam Sci. Mela

Laser-Matter Interaction

# Annual School on LHC Physics

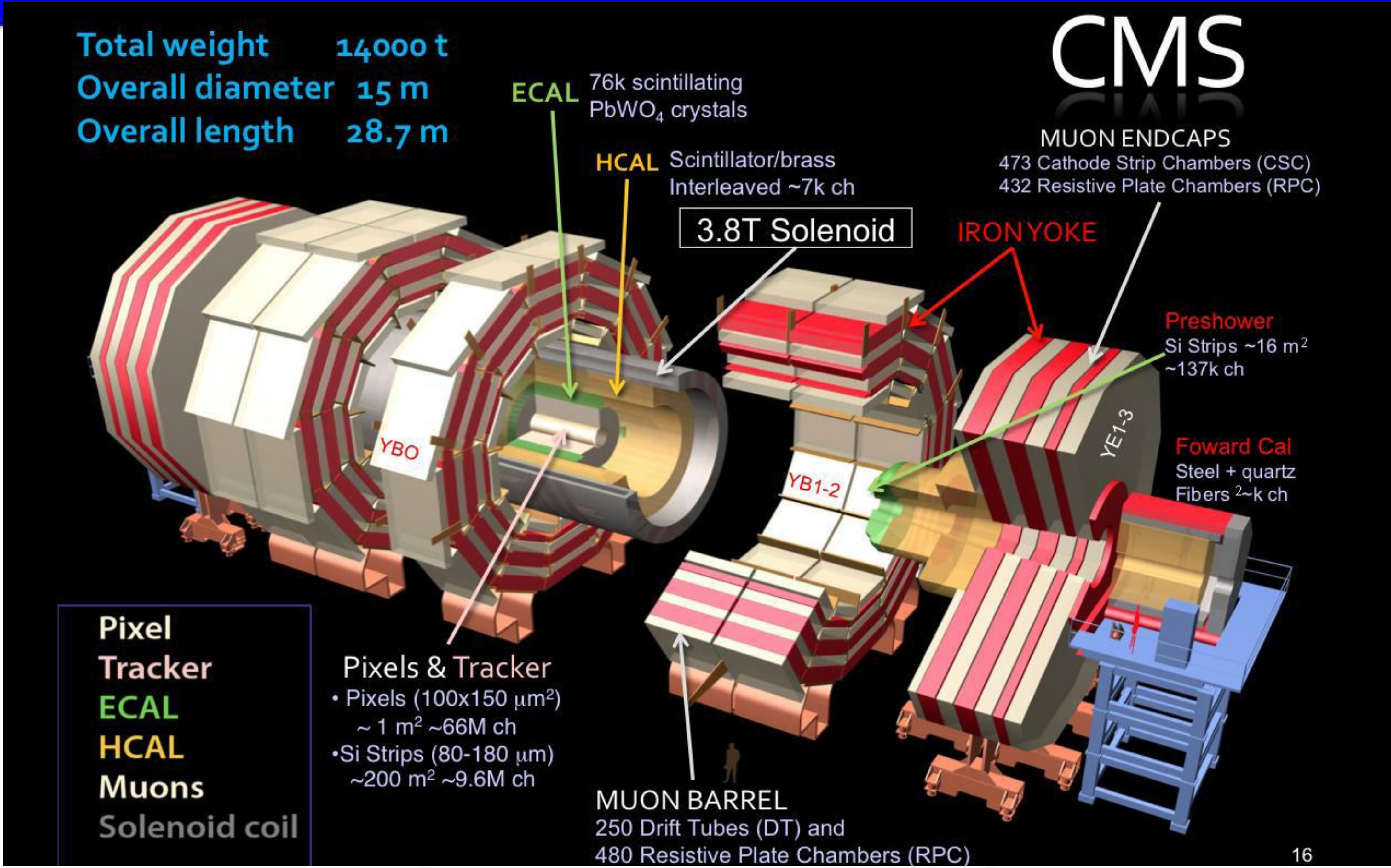
**LHC = The Large Hadron Collider**



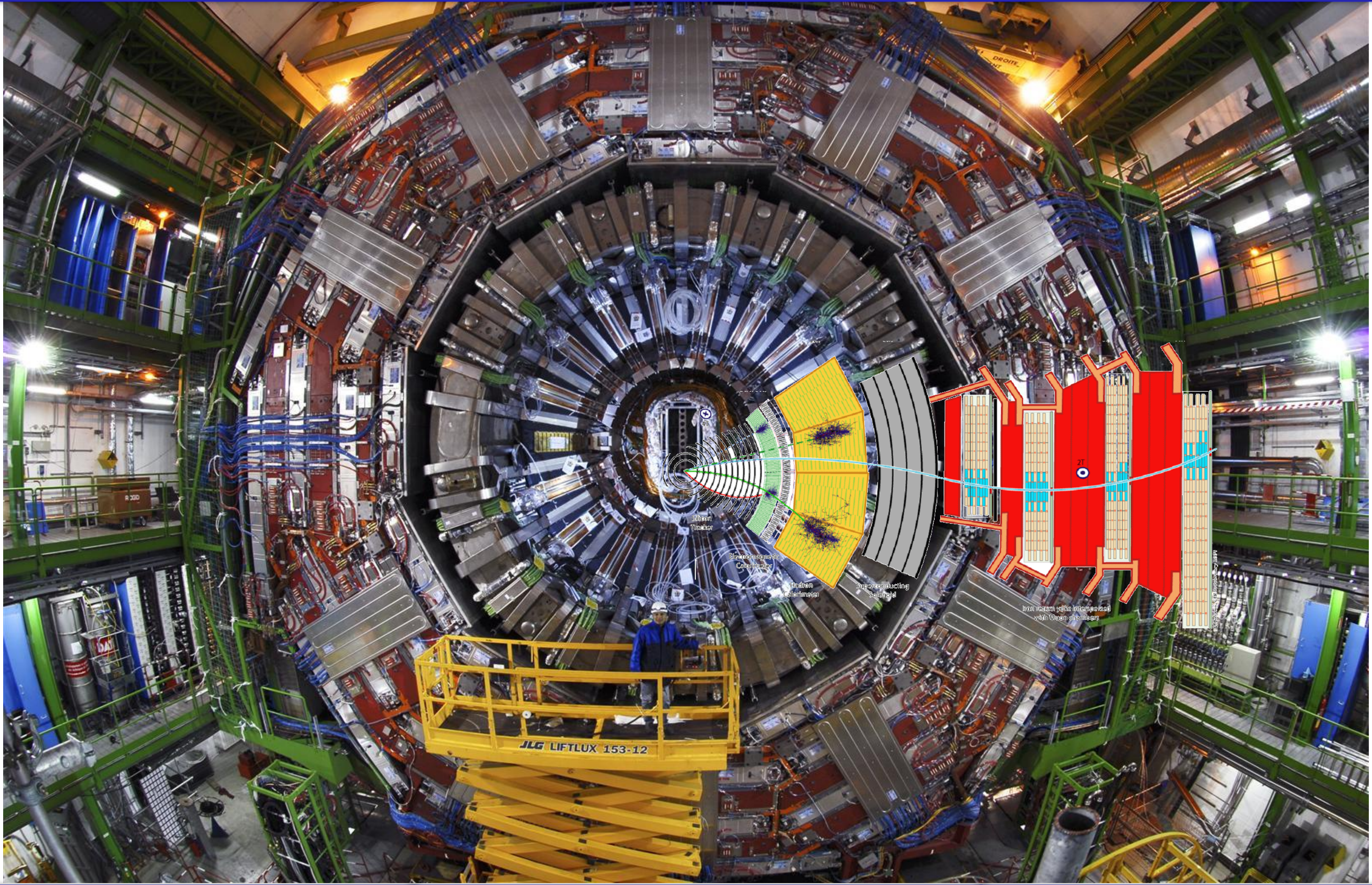


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

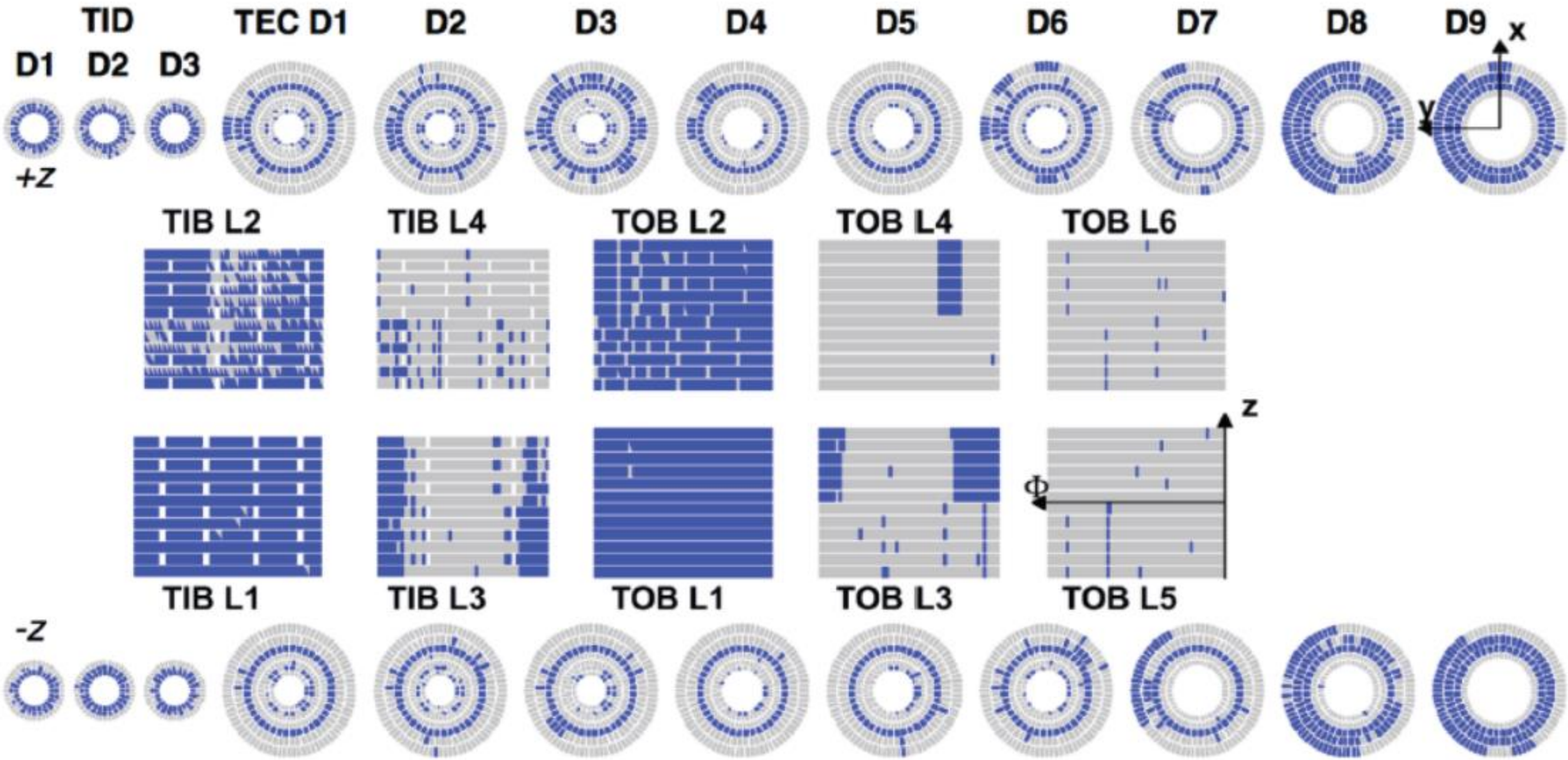
# Compact Muon Solenoid(CMS) Experiment



# The CMS Detector (real!)



# Why we need to upgrade the detector?

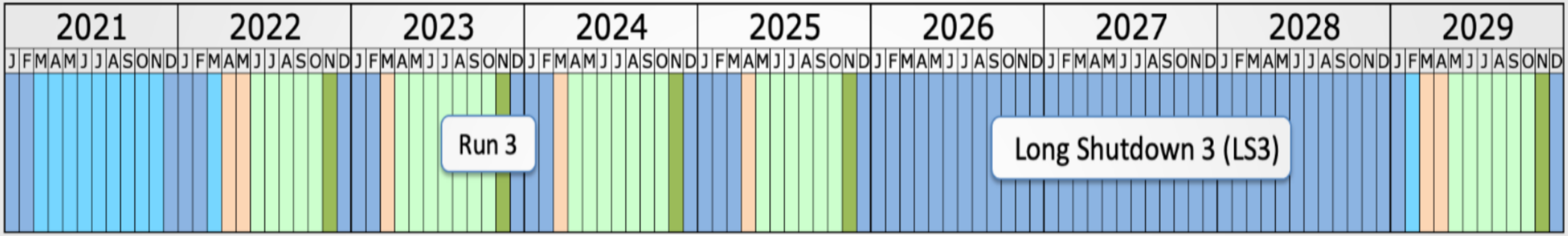



Non-functional modules in CMS after accumulating
1000 $fb^{-1}$ integrated luminosity.

# Motivation for HL-LHC

- **Motivation:** To improve further the physics potential of the LHC for rare standard model and beyond standard model processes. The LHC will be upgraded to deliver an instantaneous luminosity up to 7.5 x $10^{34}$ $cm^{-2}s^{-1}$. Following are the main features of the upgraded detector:
- **Improving luminosity:** from ~500 $fb^{-1}$ to 3000 $fb^{-1}$
- **Radiation tolerance:** Radiation hard technologies to withstand with fluences up to 2.3 x $10^{16}$ $n_{eq}/cm^2$ (in pixel layer 1)
- **Increased granularity:** Occupancy <1% in all tracker regions in order to ensure efficient tracking at high PU(~200)
- **Reduced material budget** in the tracking volume to improve primary vertex reconstruction
- **Extended tracking acceptance** efficient tracking up to $|\eta| = 4$
- **Tracking information** to be made available at trigger level for more selective L1 trigger (contribute to the event selection)
    - will improve the transverse momentum resolution of various objects at L1 (e.g. jets)
    - will allow the exploitation of information on track isolation.
    - will contribute to the mitigation of pileup

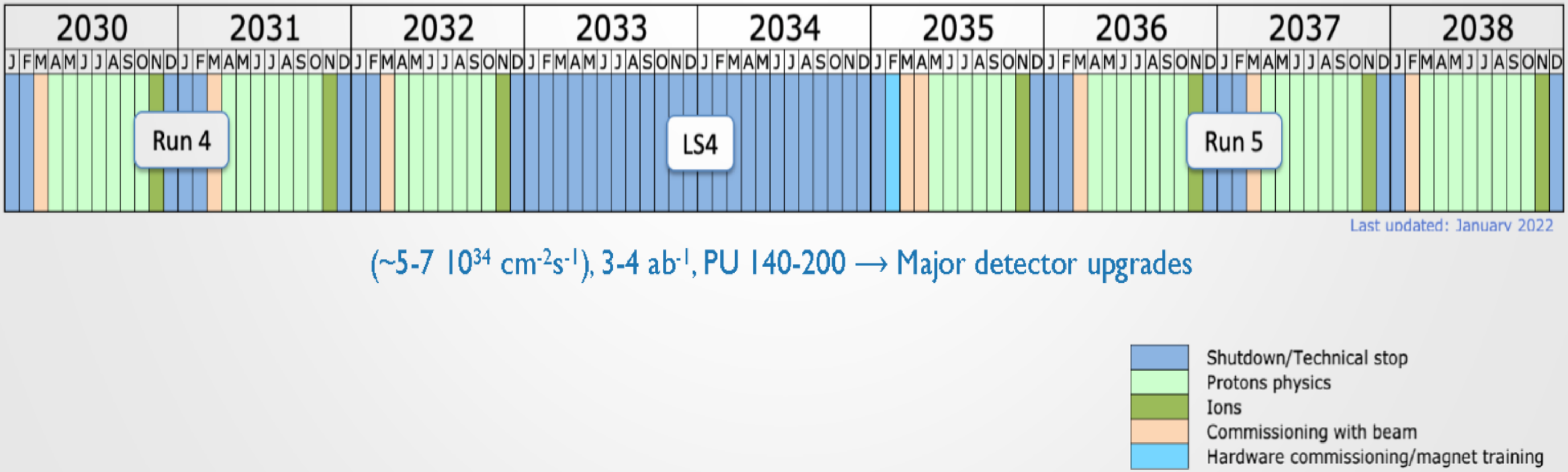
# LHC LONG TERM SCHEDULE




Run (2+)3: 300-350 $fb^{-1}$

($\sim 2\times10^{34}$ $cm^{-2}s^{-1}$), PU 40-60, "last significant low PU run"

→ HL-LHC




($\sim$5-7 $10^{34}$ $cm^{-2}s^{-1}$), 3-4 $ab^{-1}$, PU 140-200 → Major detector upgrades

# CMS Phase 2 Upgrade

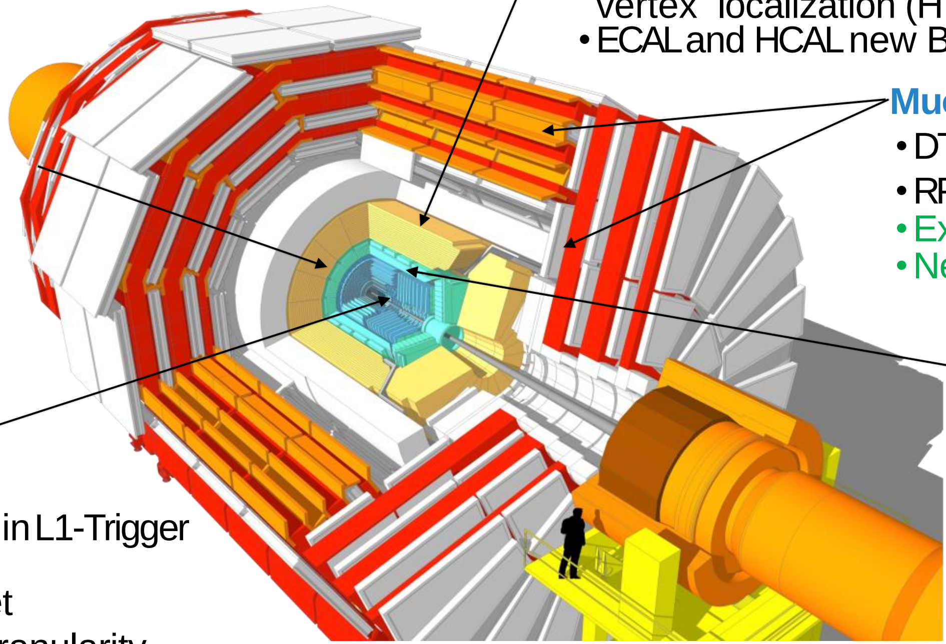
Replacements of existing system/detector
Electronics upgrade/replacement
New detector

**L1-Trigger/HLT/DAQ [CMS-TDR-021 / 022]**
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

**Barrel Calorimeters [CMS-TDR-015]**
- ECAL crystal granularity readout at 40 MHz
- Precision timing for e/γ at 30 GeV, for vertex localization ($H \to \gamma\gamma$)
- ECAL and HCAL new Back-End boards

**Muon systems [CMS-TDR-016]**
- DT & CSC new FE/BE readout
- RPC back-end electronics
- Extended GEM coverage to $\eta \simeq 3$
- New GEM/RPC $1.6 < \eta < 2.4$

**Calorimeter Endcap [CMS-TDR-019]**
- 3D showers imaging for pattern recognition
- Precision timing for PU mitigation
- Si, Scint+SiPM in Pb/W-SS

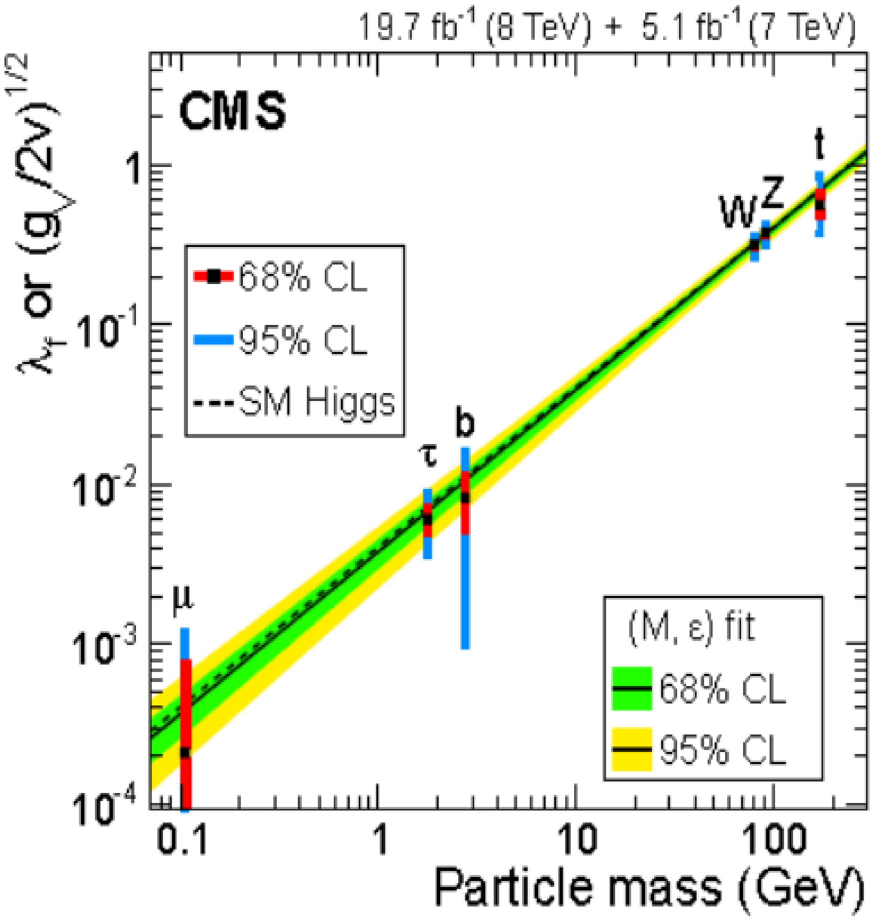


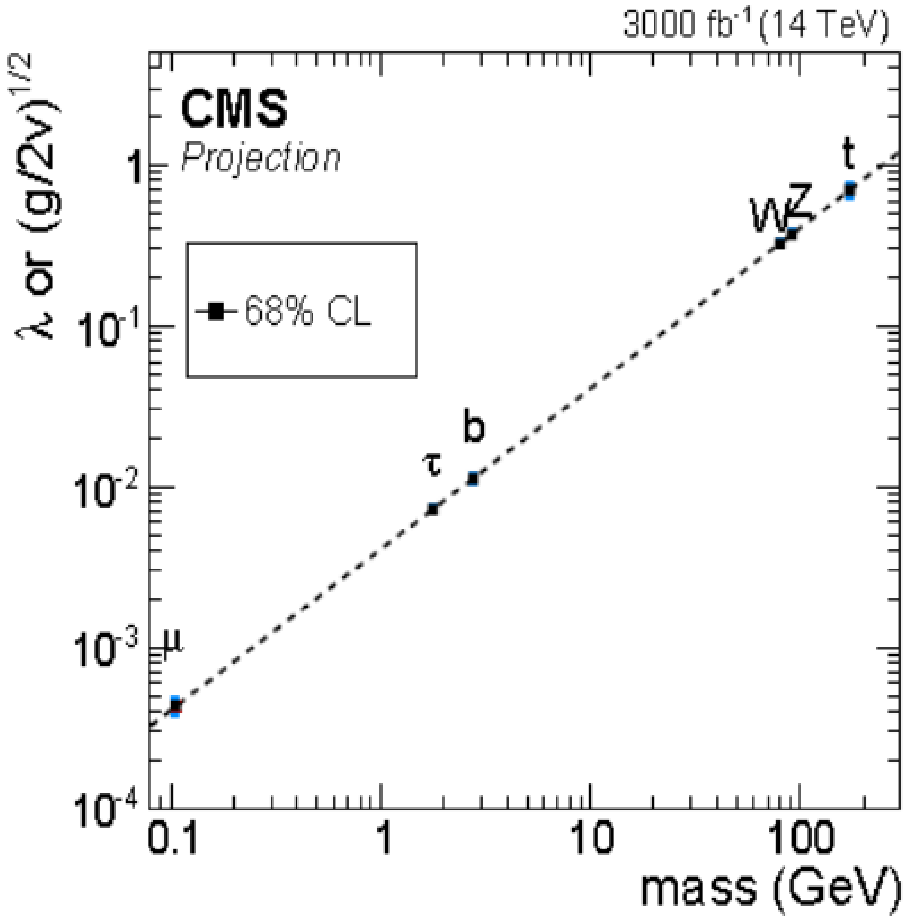
**MIP Timing Detector [CMS-TDR-020]**
- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

**Tracker [CMS-TDR-014]**
- $P_T$ module design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$
- Much reduced material budget
- Si-Strip and Pixels increased granularity

# Physics Motivation for HL-LHC

- Yukawa and boson couplings as function of particle's mass

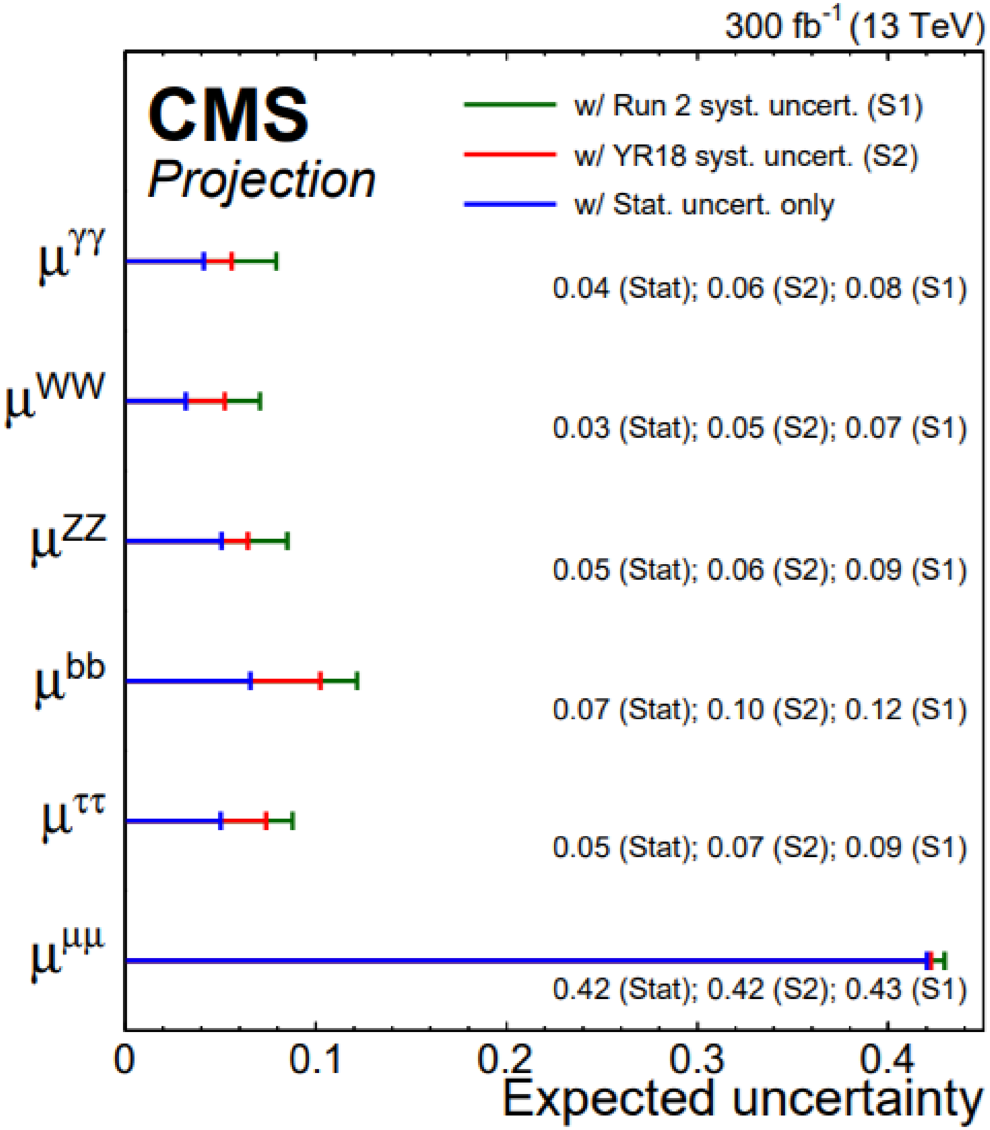


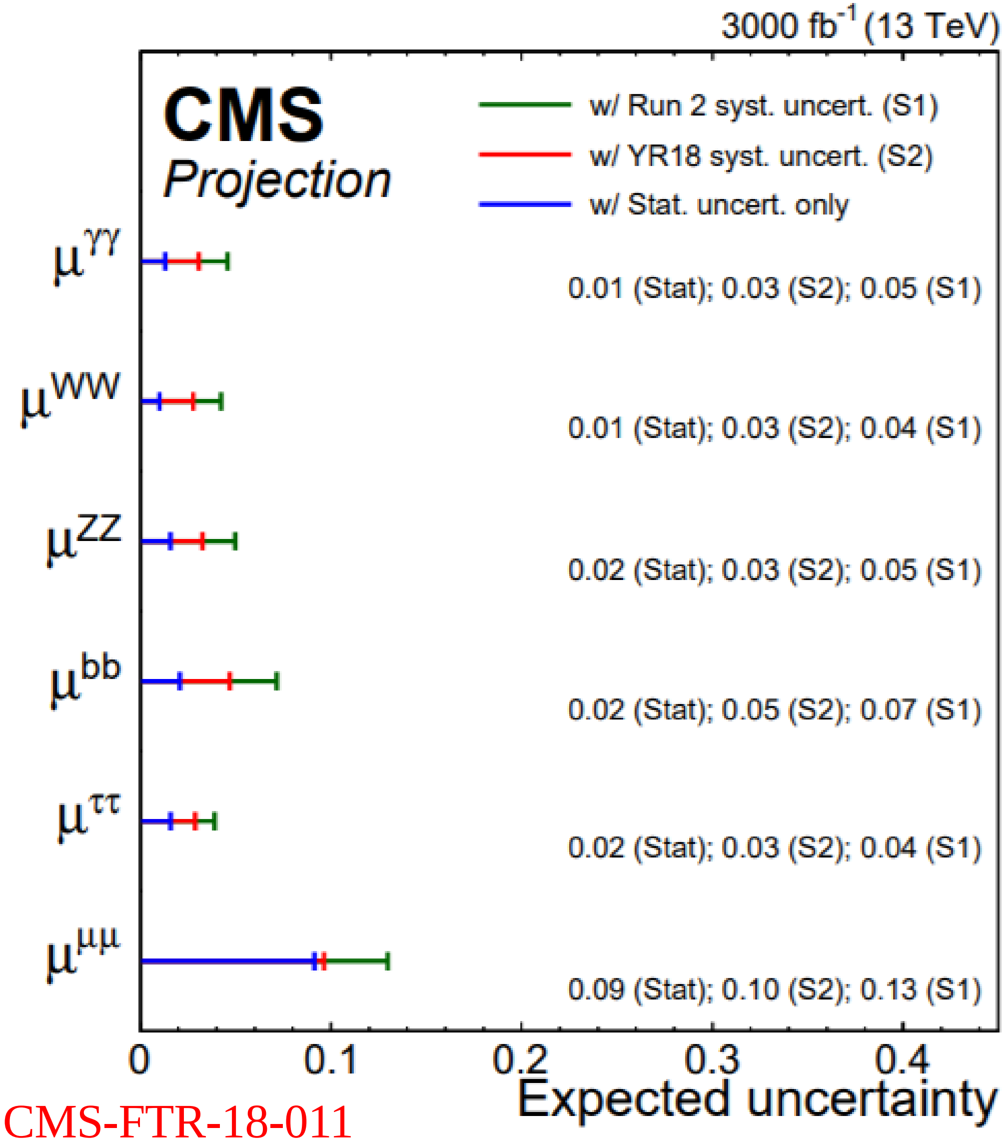




- Run 1 data (left) and projection of the uncertainties(right) (assuming standard model couplings)

# Higgs Coupling Sensitivityat HL-LHC

- Projected HL-LHC uncertainties on Higgs couplings, extrapolated from Run 2 results

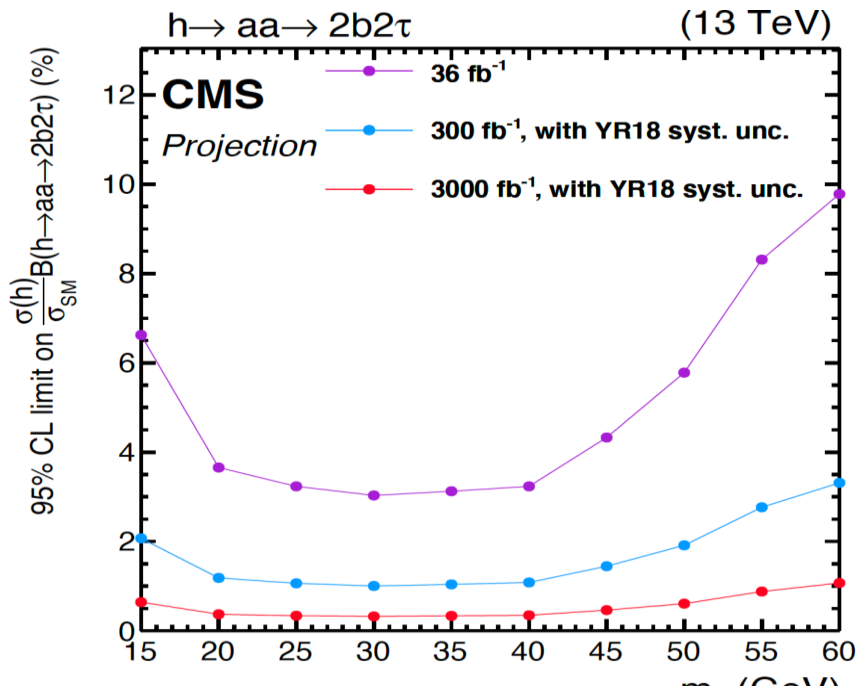


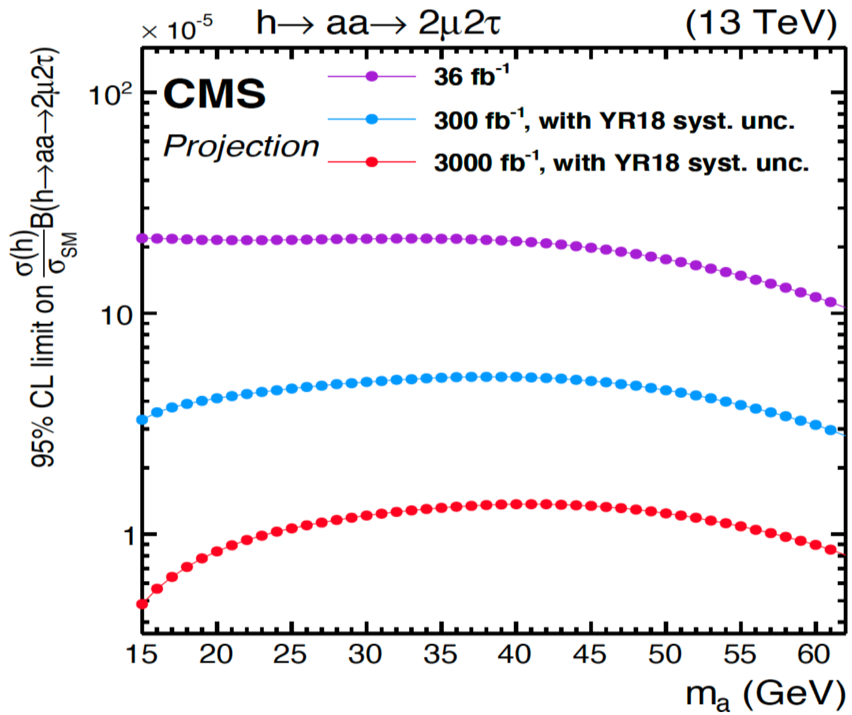

CMS-FTR-18-011

# BSM Higgses: Exotic Higgs boson decays to light Pseudoscalars

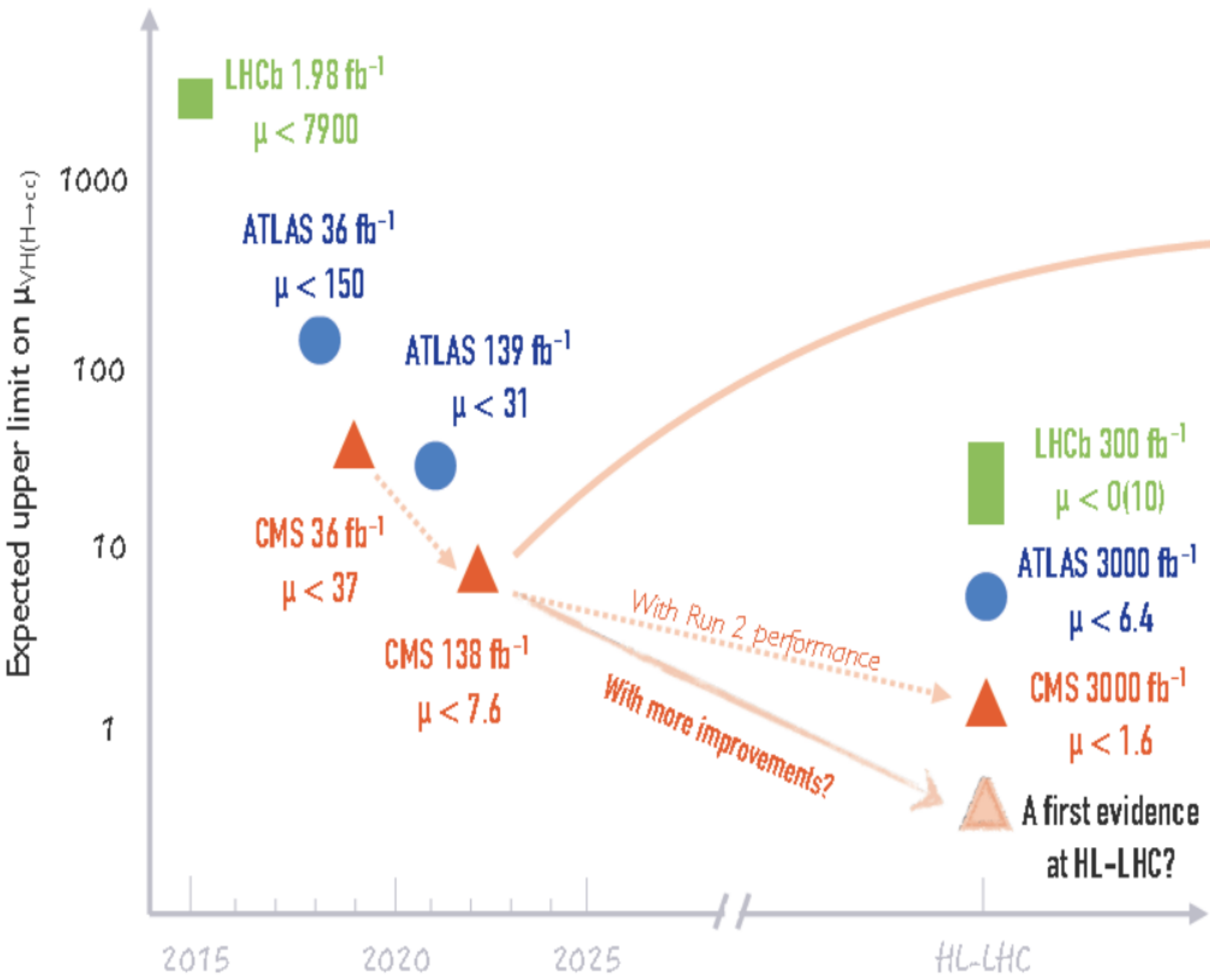
- Light scalar Higgs "a" from NMSSM could decay to hadronic and leptonic τ final states:
  - h —> aa —> bbττ, μμττ (hadronic and leptonic τ decays).
- Searchers are interpreted in two-Higgs-doublet models extended with a scalar singlet (2HDM+S)
- Projected expected limits show increased sensitivity, of the order of SM cross section

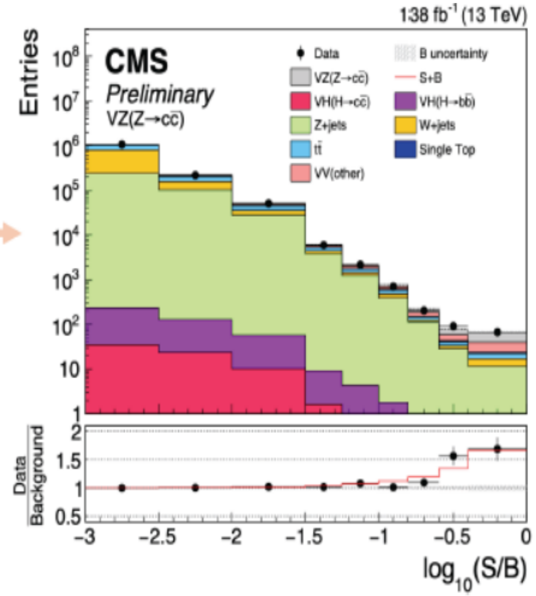



CMS-PAS-FTR-18-035



# Future Expectation




*First observation of $Z \to cc$ at a hadron collider!*
*Opening a new era for future explorations.*

- More channels: ttH(cc), VBF H(cc), indirect constraints, etc.
- Improvements in advanced analysis techniques (e.g., Deep Learning) and instrumentation (e.g., tracker)
- Reduction of systematic uncertainties: c-tagging, event

*CERN LPCC EP-LHC Seminar 1 March 2022*

# Tracker Upgrade

❑ High-Luminosity LHC scenario

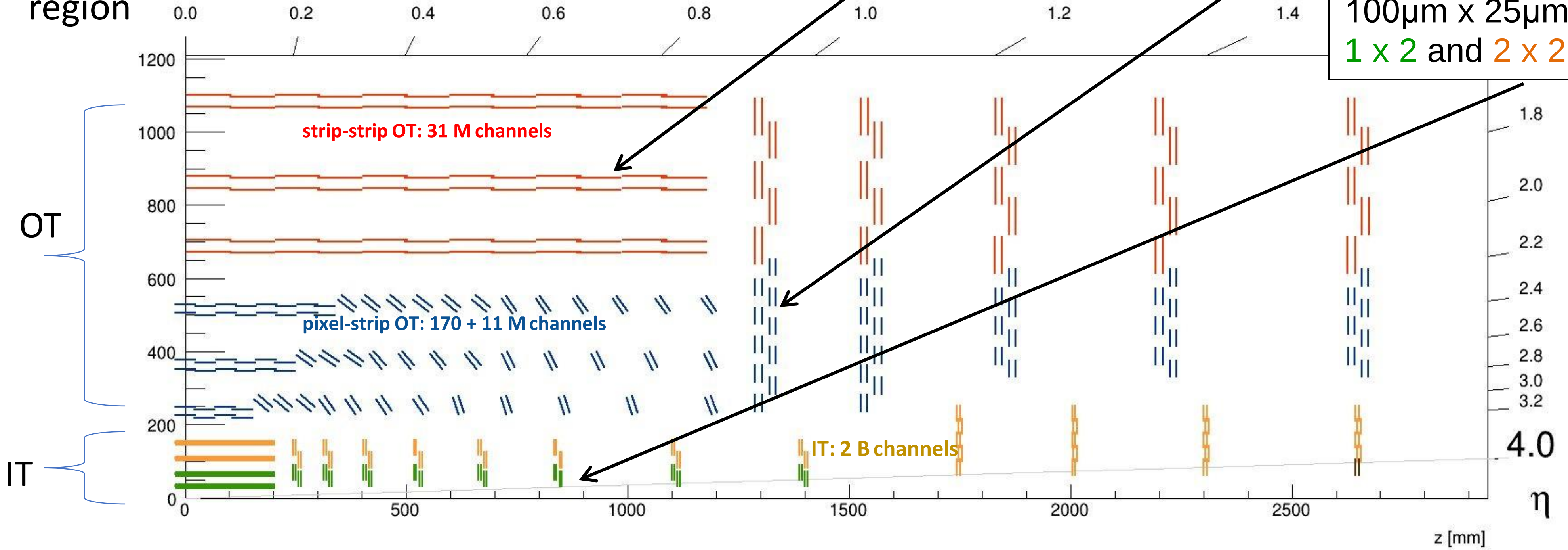
- ➢ Increase (6x) granularity in the innermost detector
- ➢ Outer Tracker TB2S ~ 31 M channels with 7608 modules. For 5592 OT PS modules~ 170+11M channels And for Inner Tracker about 2 billions channels
- ➢ Improve (10x) radiation tolerance of the detectors
- ➢ Easy maintenance and replacement of the innermost region

| 2S module | PS module |
|---|---|
| $\sim 2 \times 90$ cm$^2$ active area | $\sim 2 \times 45$ cm$^2$ active area |
| $2 \times 1016$ strips: $\sim 5$ cm $\times$ 90 $\mu$m<br>$2 \times 1016$ strips: $\sim 5$ cm $\times$ 90 $\mu$m | $2 \times 960$ strips: $\sim 2.4$ cm $\times$ 100 $\mu$m<br>$32 \times 960$ macro-pixels: $\sim 1.5$ mm $\times$ 100 $\mu$m |
| Front-end power $\sim 5$ W<br>Sensor power ($-20\,^\circ$C) $\sim 1.0$ W | Front-end power $\sim 8$ W<br>Sensor power ($-20\,^\circ$C) $\sim 1.4$ W |

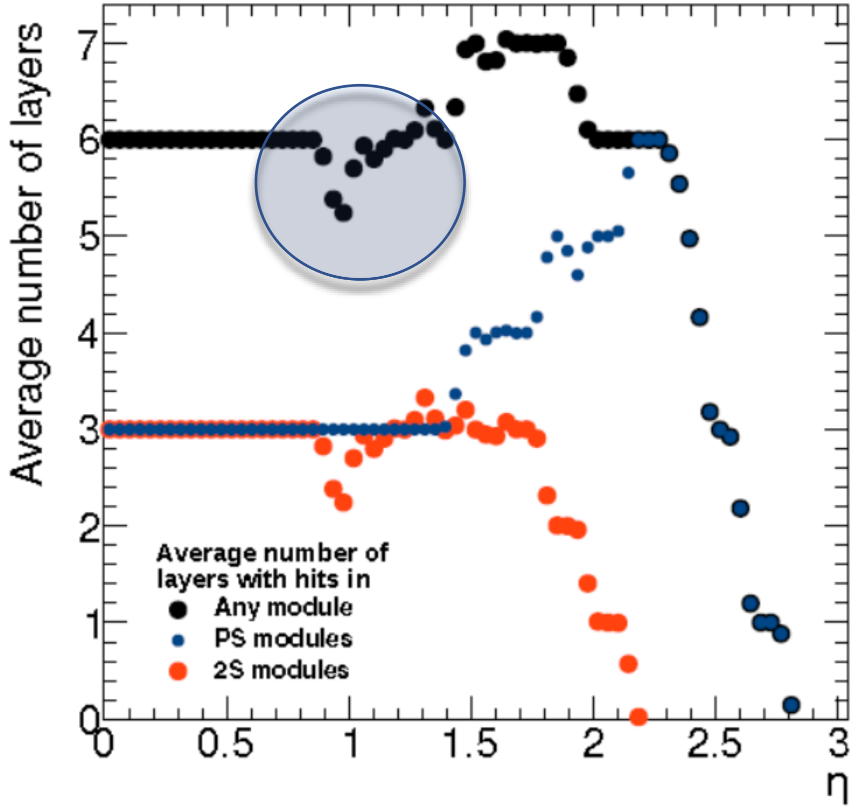
7608 strip-strip modules(2S), with 4464 TB2S modules
5cm x 90μm strips

5592 pixel-strip modules(PS)
2.4cm x 100μm strips
1.5mm x 100μm macro-pixels

3892 pixel modules
100μm x 25μm pixels
1 x 2 and 2 x 2 chips

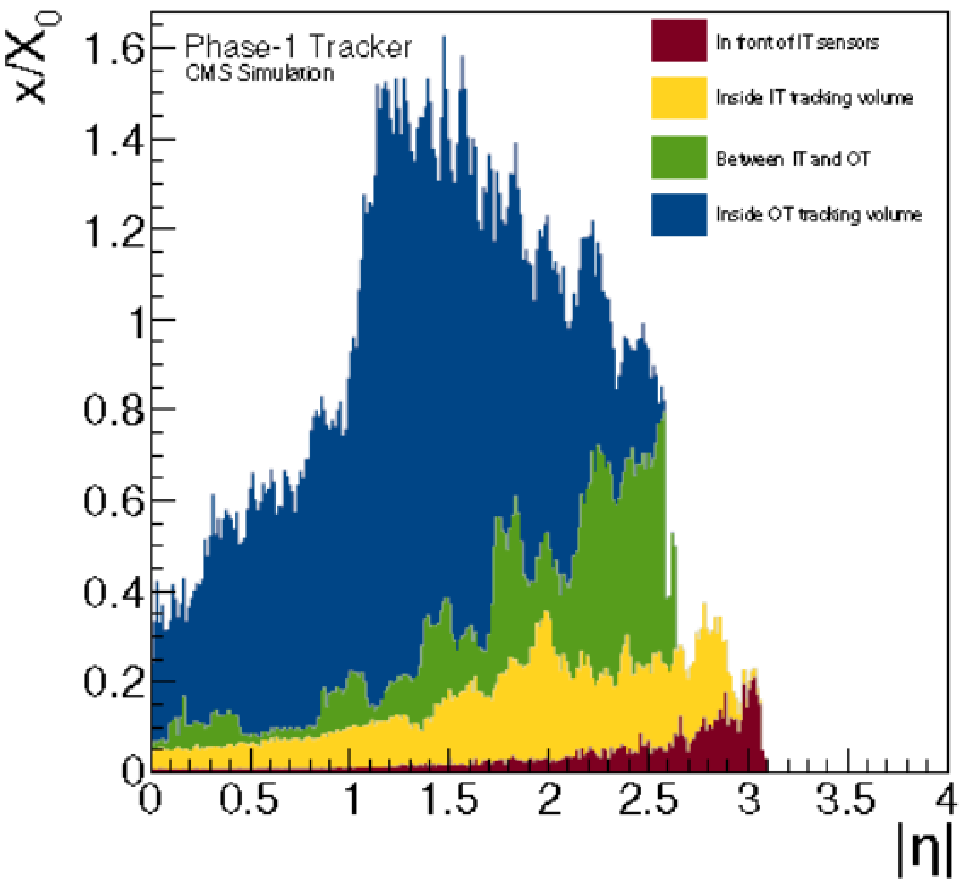


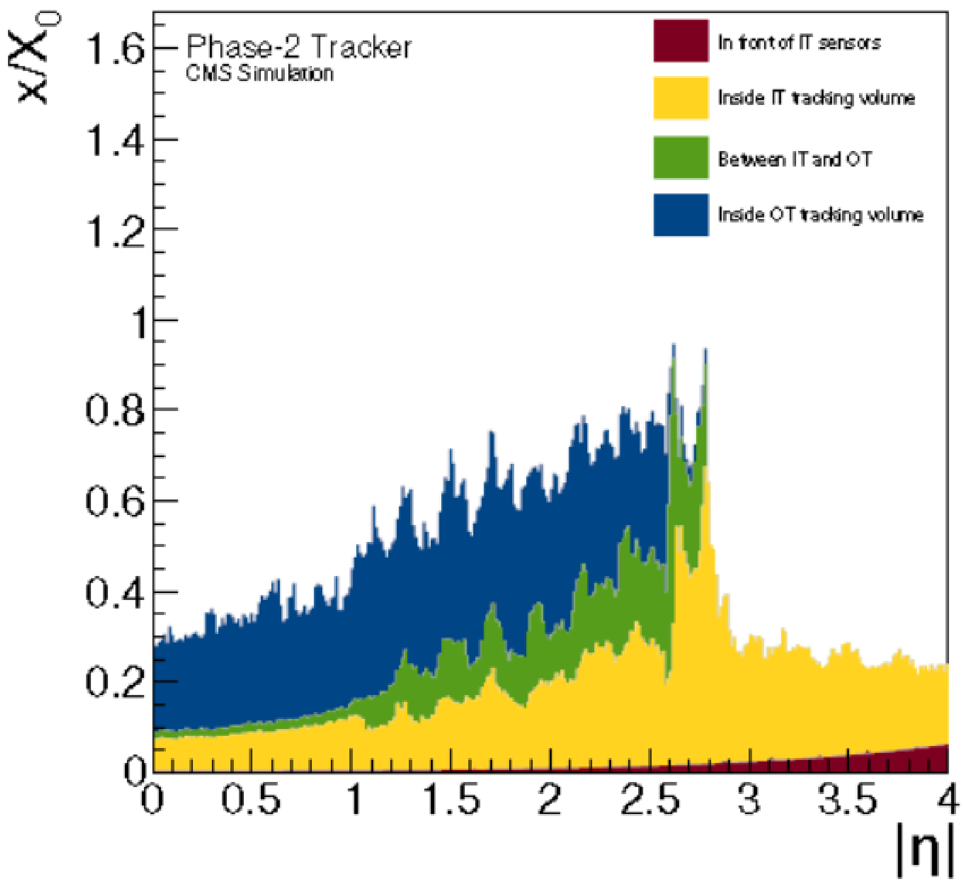
# Module layers crossed by particles




- At least six module layers are crossed by all particles in the rapidity range |η|<2.4 (except in the transition region)
  - These are the minimum that ensures sufficiently robust track finding performance for the L1 trigger

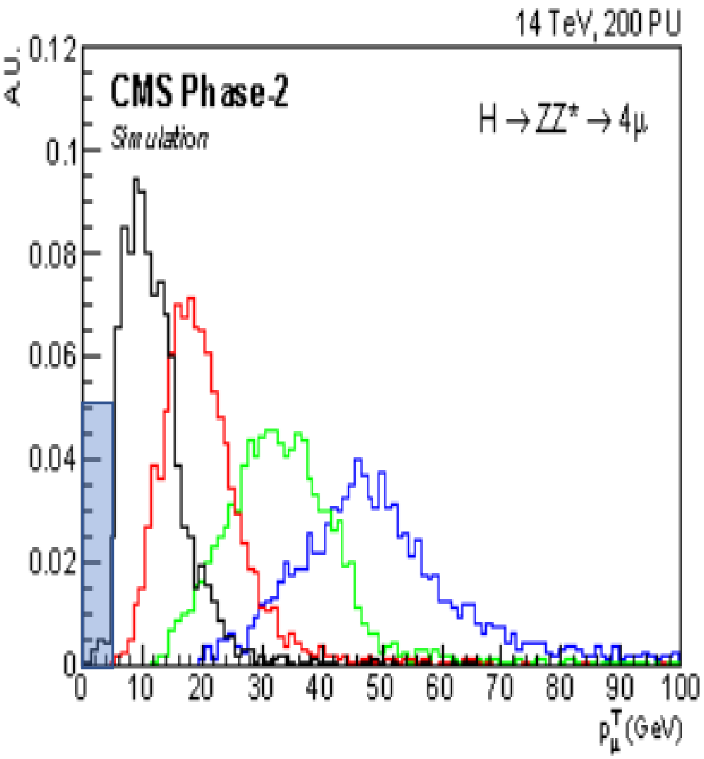
# CMS Tracker Material Budget

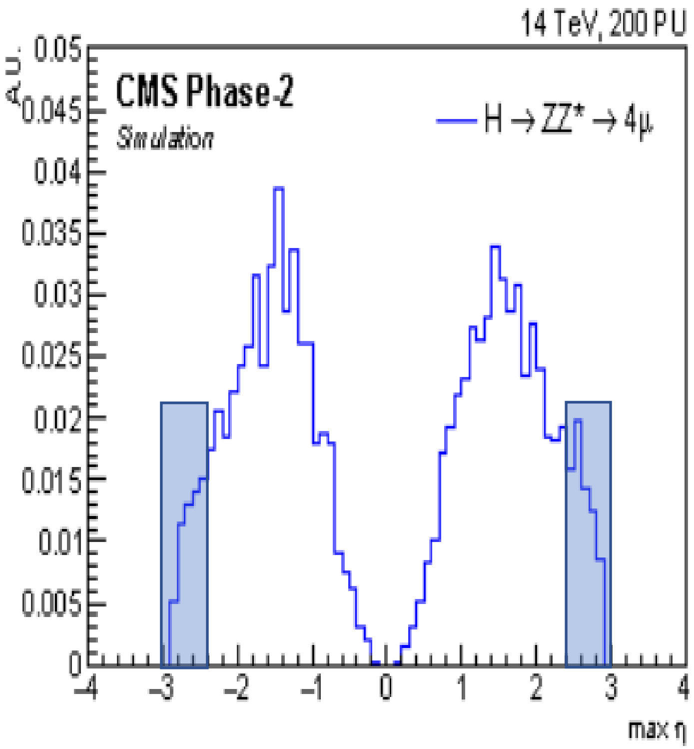


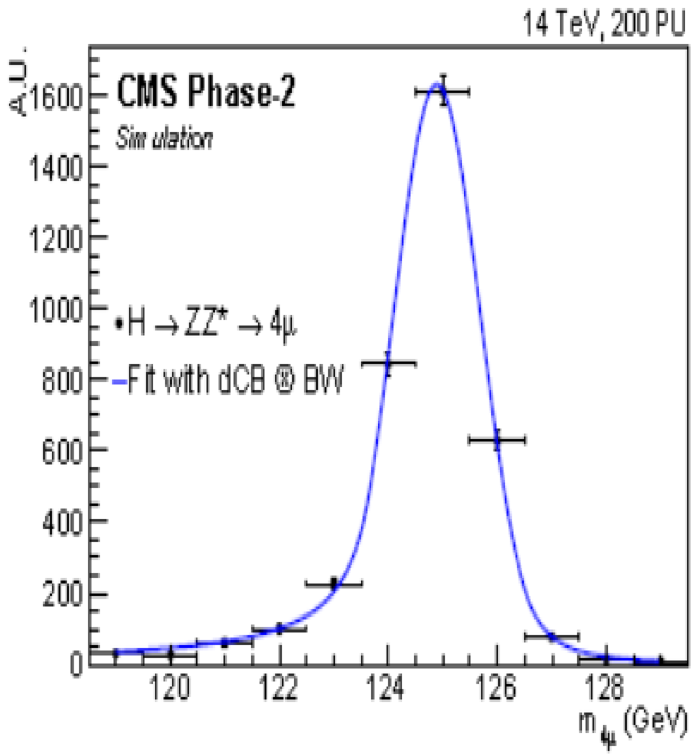




- Reduced material budget in the tracking volume to improve primary vertex reconstruction
- Extended tracking acceptance up to $|\eta|$ = 4

# Acceptance enhancement



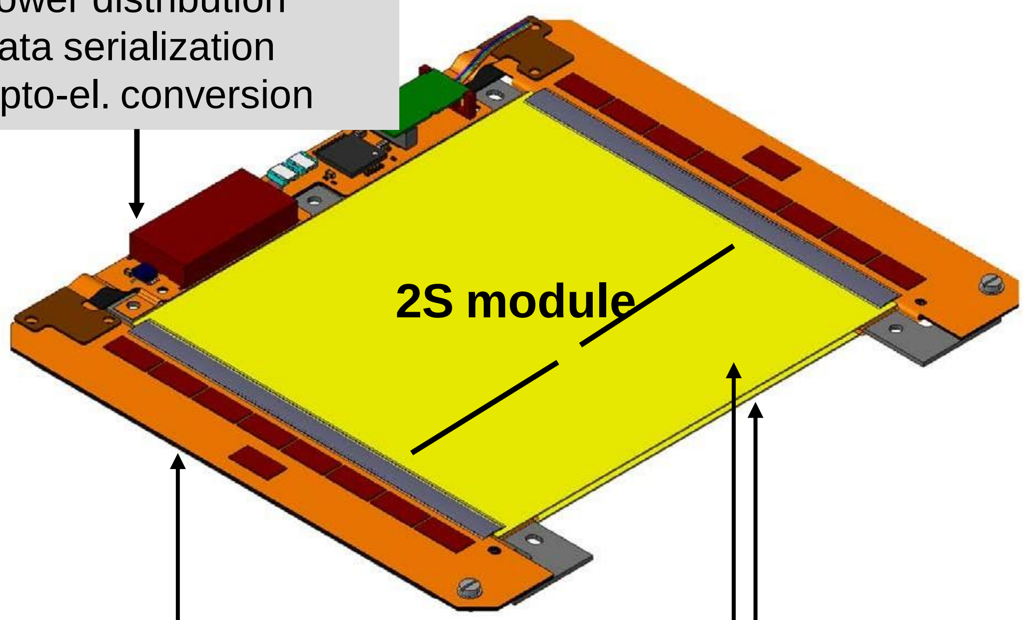




- Lowering pT threshold for triggering and increase in eta coverage maximize the acceptance
- Increase in acceptance from 2.4 to 3 corresponds to an increase in acceptance of about 15% for four leptons from Higgs decay with respect to Run II detector acceptance
- No worsening of the mass resolution due to increase in pileup

# TB2S Modules

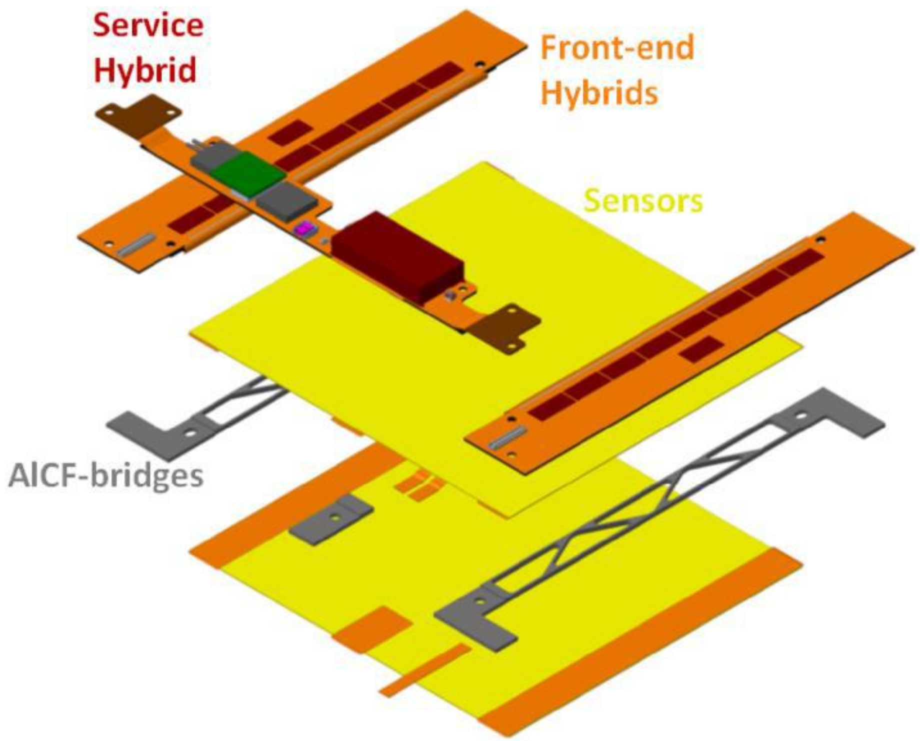
- The pT module concept relies on the fact that the strips of the top and bottom sensors of a module are parallel to each other
- Stringent alignment constraints between top and bottom sensors in modules
- Should be below 400 µrad for 2S module and below 800 µrad for PS modules

**Service hybrid (SEH)**
Power distribution
Data serialization
Opto-el. conversion



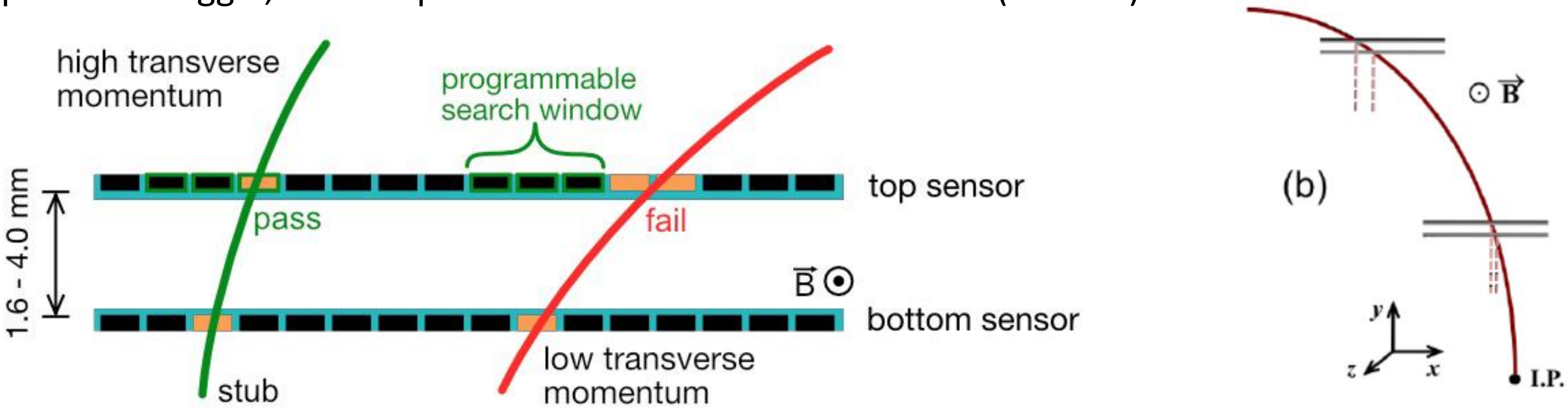

**Front-end hybrids (FEH)**
8 CBC3 readout ASICs
1 Concentrator (CIC) ASIC

**Strip sensors (top & bottom)**
10cm x 10cm
5cm x 90µm cell size



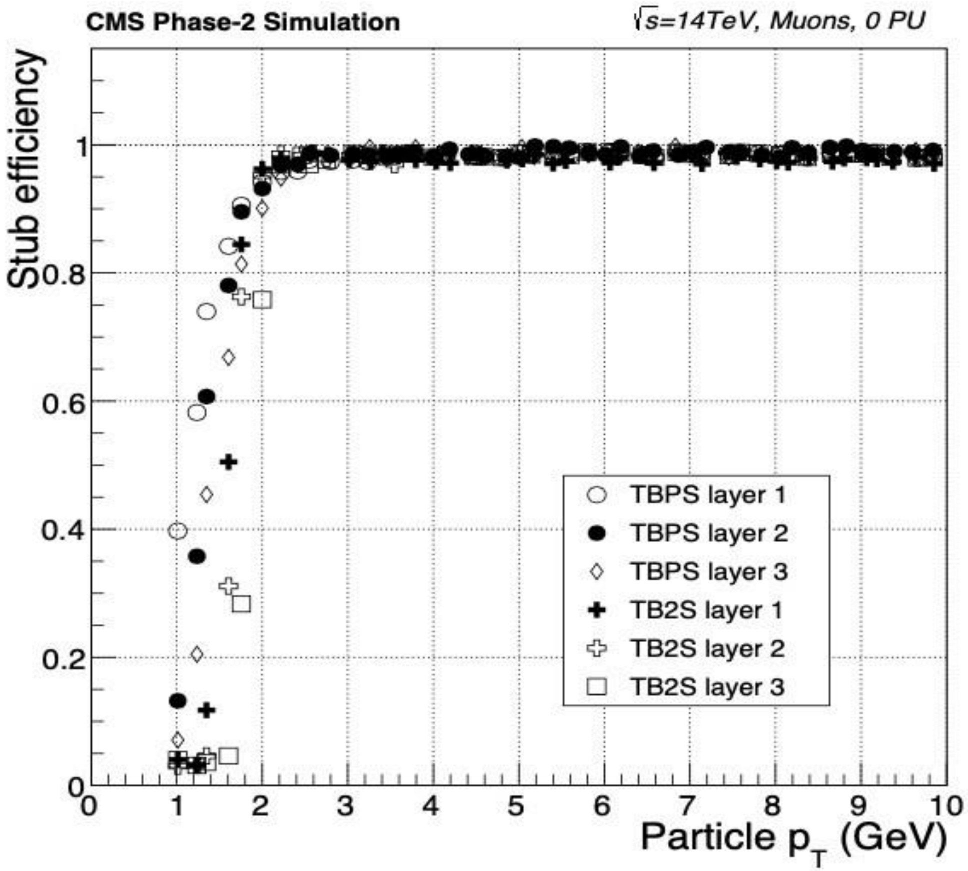
# Outer Tracker pT modules

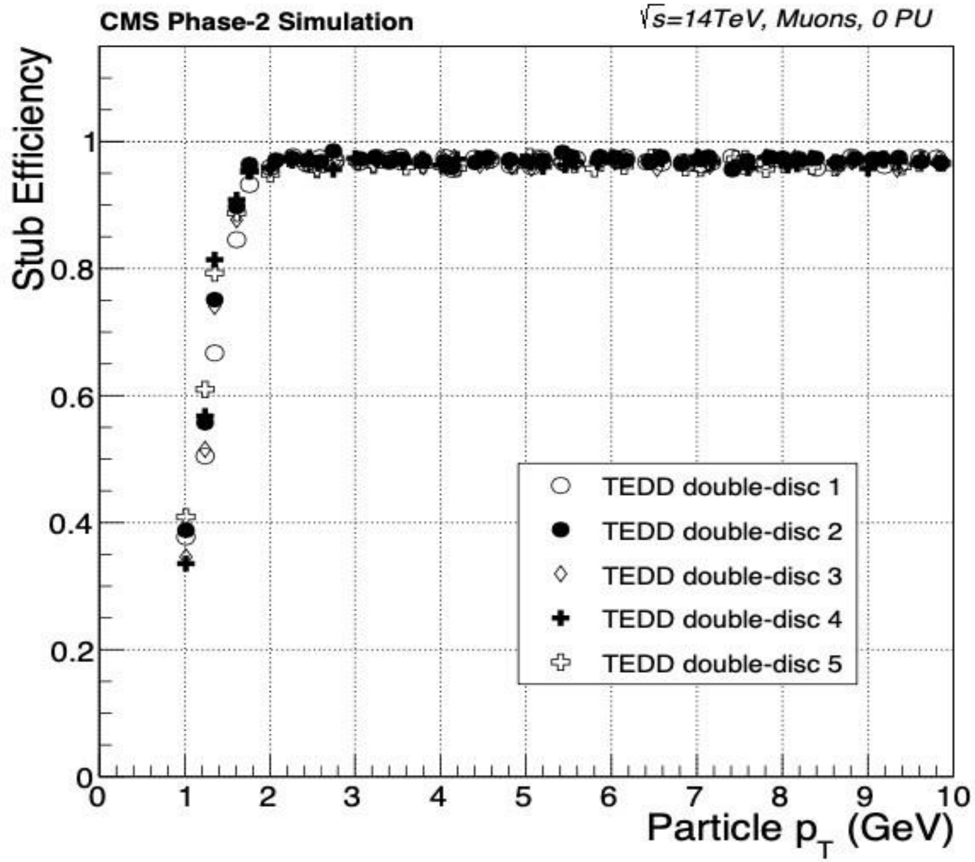
- ❑ pT module concept:
  - Exploit bending of charged particle tracks in CMS 3.8T B-field
  - Correlate hits from 2 closely spaced sensors to form "stubs" compatible with a track $p_T > 2$ GeV (stub is pair of hits in closely spaced sensors of the same module)
  - Space/offset between two sensors and stub window is tuneable for $p_T$ threshold throughout the Outer Tracker
- ❑ Use of Tracking Information at L1 Trigger
  - Provision of tracking information at L1 trigger will enhance performance (currently only muon and Calo.)
  - Can't read out all information at 40MHz → reduction of data volume at front-end needed
  - majority of hits are from low $p_T$ tracks → select hits from tracks with $p_T$ >2GeV (reduction by factor of 10)
  - "Stubs" are sent to the back-end at 40MHz → track reconstruction → L1 trigger decision
  - On receipt of a L1 trigger, the complete event information is read out (750kHz)



# Phase 2 Tracker Performance

➢Stubs well reconstructed with about 99% efficiency



# Tracker and GEM Upgrade Funding by Govt of Pakistan

- Two Exp. HEP related PC-1's approved by Govt. of Pakistan, namely,
  1. The upgrade of the Compact Muon Solenoid (CMS) Silicon Strip Tracker and GEM detectors
     - Project Cost: **PKR 275.75 +41 Million (~1.7 M CHF)** (from 2018-onward)
  2. Upgrade of the Exp. HEP laboratory and IT infrastructure at NCP
     - Project Cost EHEP Lab Upgrade: **PKR 95.94 Million** (from 2018-2020)

- Total funding of ~2.5 M CHF

# GE1/1 Project: Assembly and testing of GEM detectors

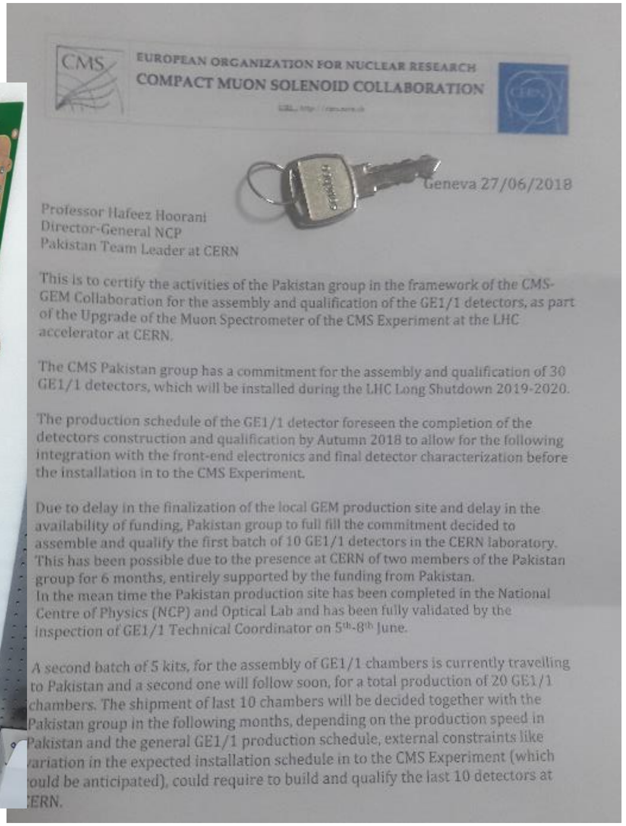
**GE1/1 assembly and testing in Pakistan**

- GE1/1 detector assembly inside Clean room of class 10k
- Our assembly/testing sites were validated by CERN team in June 2018
- GEM detectors were assembled and tested successfully
- After Quality Control, the GEM detectors were shipped to CERN and installed as part of CMS experiment
- Worked on development of GEM software database


Site validation


QCs setup at NCP


QCs (3,4,5) test


CMS EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
COMPACT MUON SOLENOID COLLABORATION

Geneva 27/06/2018

Professor Hafeez Hoorani
Director-General NCP
Pakistan Team Leader at CERN

This is to certify the activities of the Pakistan group in the framework of the CMS-GEM Collaboration for the assembly and qualification of the GE1/1 detectors, as part of the Upgrade of the Muon Spectrometer of the CMS Experiment at the LHC accelerator at CERN.

The CMS Pakistan group has a commitment for the assembly and qualification of 30 GE1/1 detectors, which will be installed during the LHC Long Shutdown 2019-2020.

The production schedule of the GE1/1 detector foreseen the completion of the detectors construction and qualification by Autumn 2018 to allow for the following integration with the front-end electronics and final detector characterization before the installation in to the CMS Experiment.

Due to delay in the finalization of the local GEM production site and delay in the availability of funding, Pakistan group to full fill the commitment decided to assemble and qualify the first batch of 10 GE1/1 detectors in the CERN laboratory. This has been possible due to the presence at CERN of two members of the Pakistan group for 6 months, entirely supported by the funding from Pakistan.
In the mean time the Pakistan production site has been completed in the National Centre of Physics (NCP) and Optical Lab and has been fully validated by the inspection of GE1/1 Technical Coordinator on 5th-8th June.

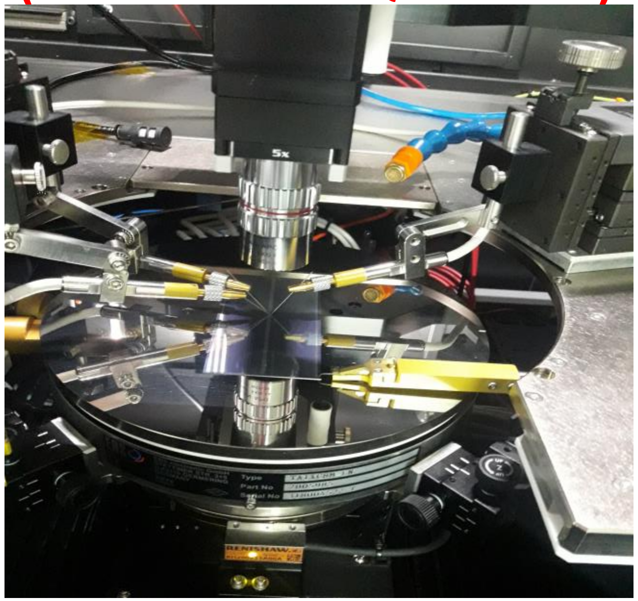
A second batch of 5 kits, for the assembly of GE1/1 chambers is currently travelling to Pakistan and a second one will follow soon, for a total production of 20 GE1/1 chambers. The shipment of last 10 chambers will be decided together with the Pakistan group in the following months, depending on the production speed in Pakistan and the general GE1/1 production schedule, external constraints like ariation in the expected installation schedule in to the CMS Experiment (which ould be anticipated), could require to build and qualify the last 10 detectors at ERN.

# R&D for Phase II upgrade of CMS Tracker

- Project started from scratch
- Major sub-projects:

1. Lab development 2. Training of Manpower
3. Qualification and testing of silicon sensors and modules. NCP is SQC Center

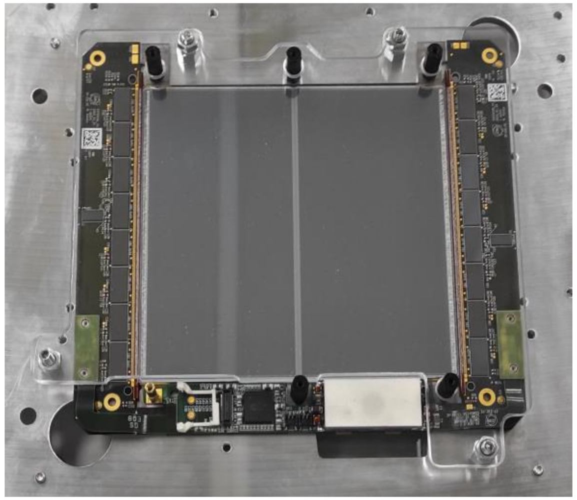
(total six CMS SQC centers)



4. Assembly/testing of silicon modules at NCP. Prototyping finished. Built, tested and validated

NCP is silicon module assembly center

(total eight CMS 2S module assembly centers)



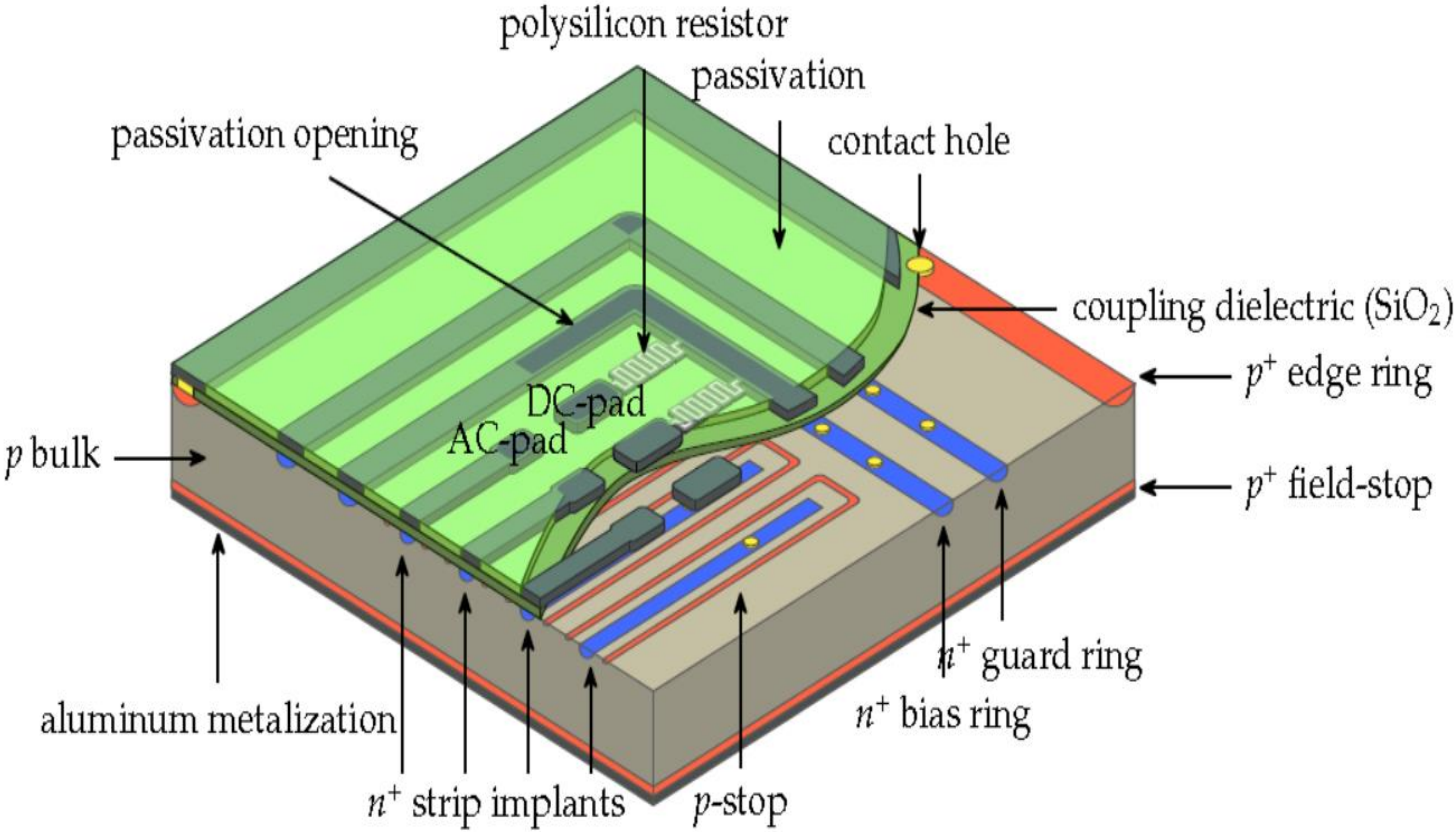

5. Building 410 Al-CF TB2S ladders at NCP. Three prototypes successfully built at NCP and validated at CERN.

For production, has been awarded to a local company. The first three pre-production ladders have been built and senr to CERN. Pre-production ongoing.

(NCP is the only center building TB2S Ladders for CMS)

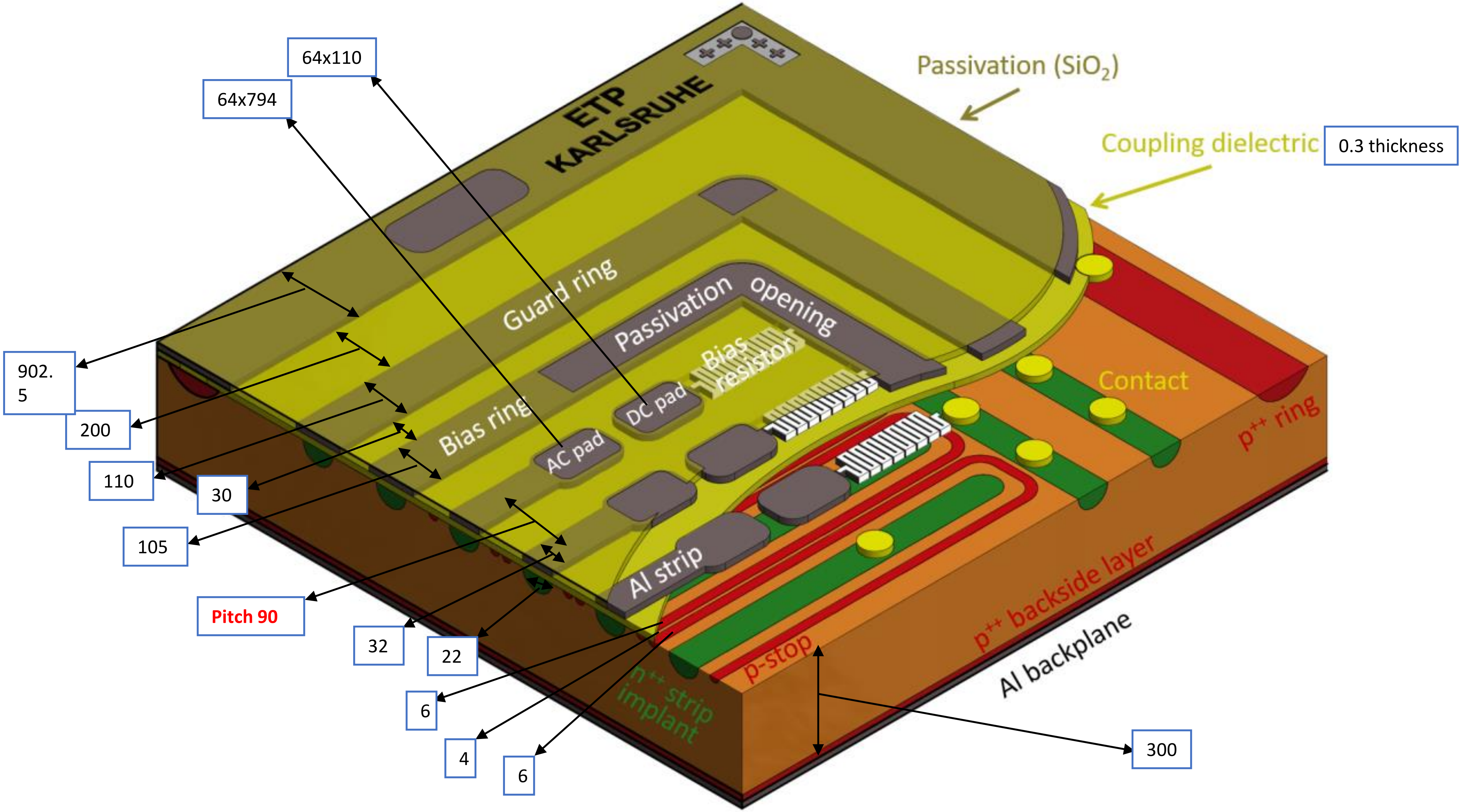
# Silicon Sensor Qualification

# 3D Model of n-in-p Silicon Sensor



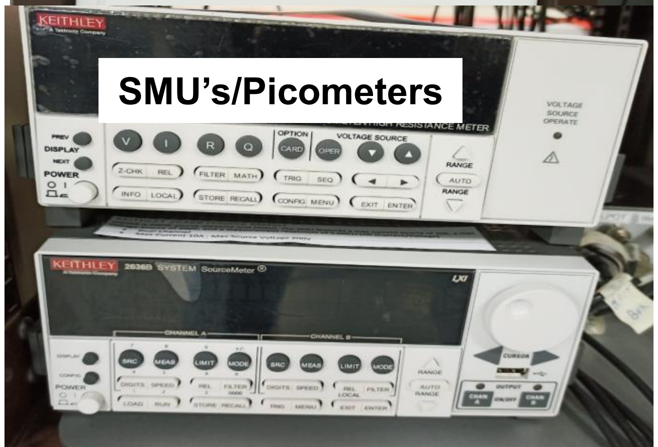
# CMS Strip Silicon Sensor

dimensions in µm

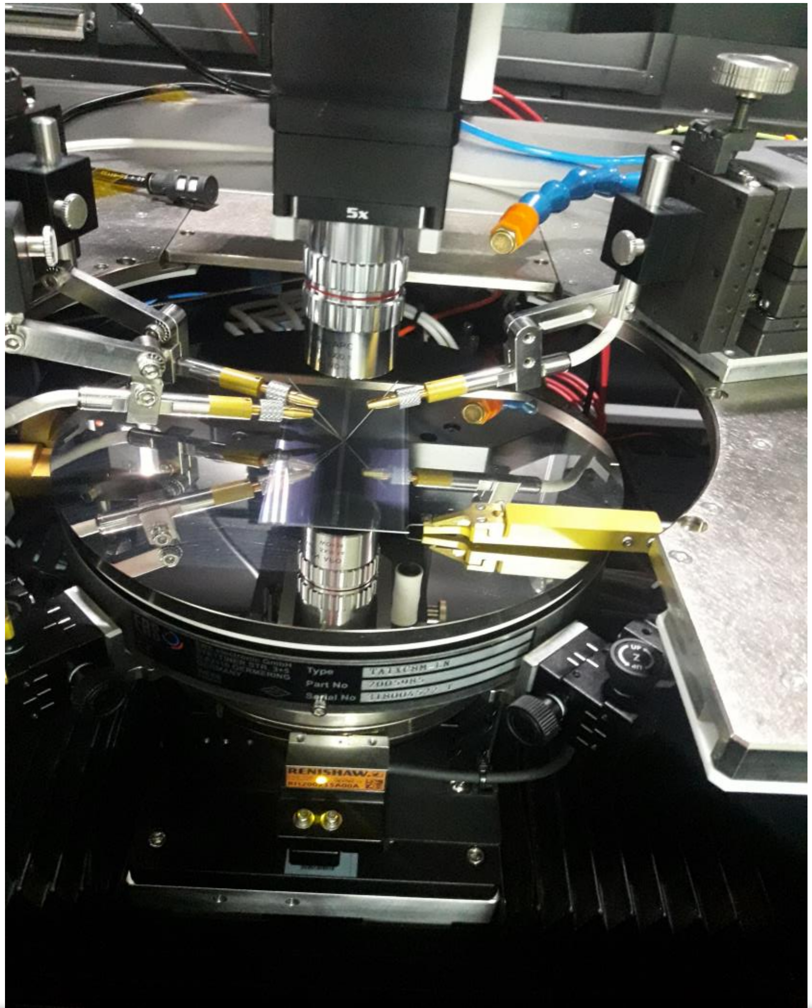


# Sensors Qualification Lab Setup

- SQC setup is operational: MPI Probe Station with motorized chuck with 2µm precision.
  1. Six micro positioners installed. 2. Switching matrix system (crate and cards)
  3. SMU's and pico-ammeters (Keithley 2636B, 2470 and 6517B) 4. LCR meter (Keysight-4980A)
- Fully automized with indigenously developed LabVIEW programs/vi's
- **NCP is validated silicon sensor qualification center of CMS!**

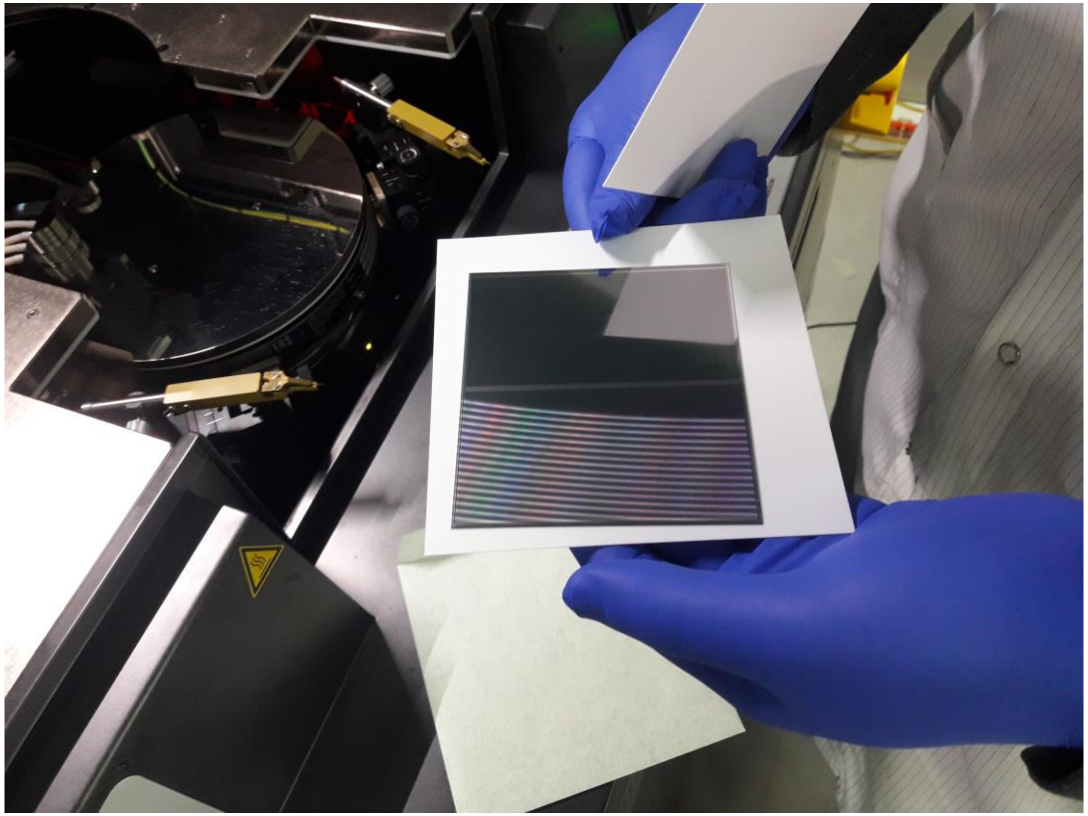


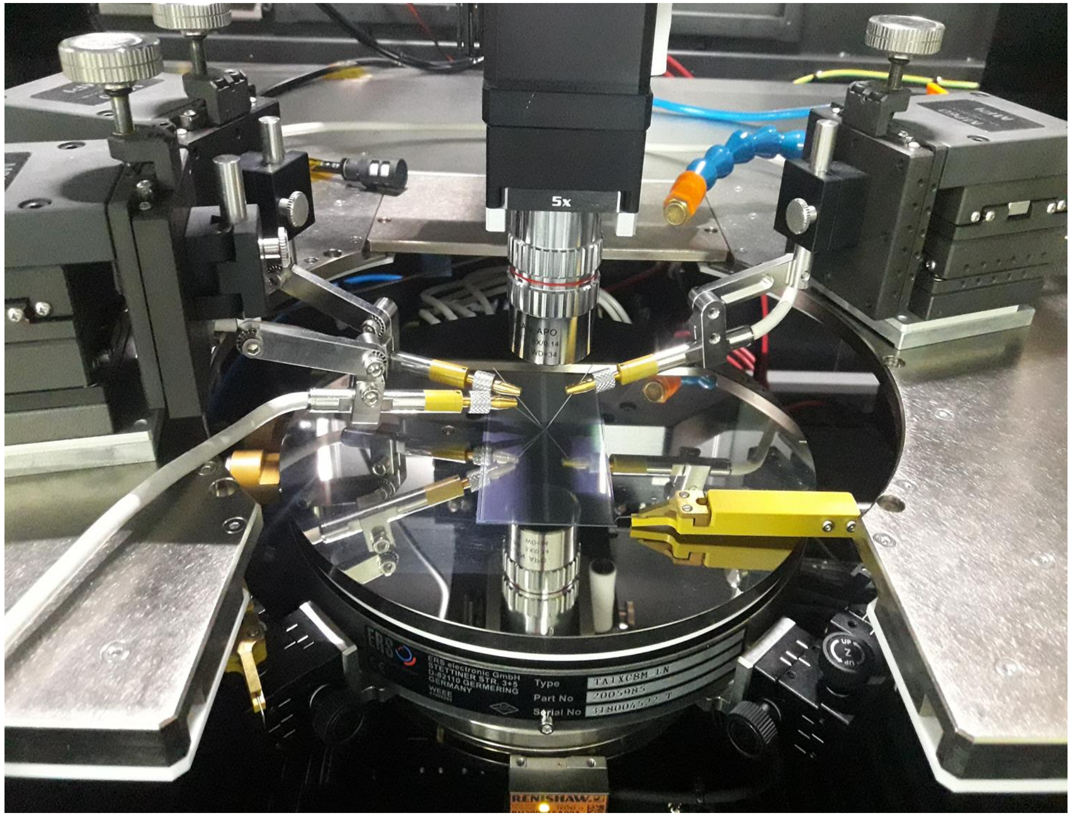



# Silicon Sensors Quality Control setup at EHEP Lab, NCP


About 2000 CMS Silicon Sensors have been qualified so far.

# Sensors Visual Inspection and Placement



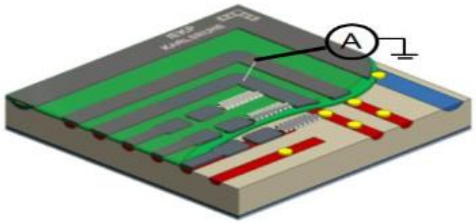


# Sensor Storage in environmentally controlled cabinet

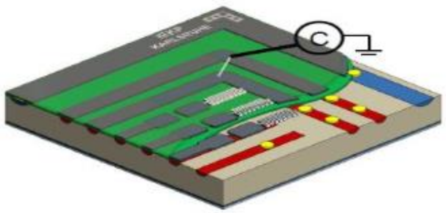
- Sensors storage cabinet is available to store sensor with control T and RH
- T~ 20-25C  and RH ~ 10-15%
- To keep stable environment in the cabinet, only it is opened for a short time just to put in and out the sensors
- Cleanroom T and RH is continuously controlled monitored at 20-25 C and 40-45% respectively

# Silicon Sensor Qualification

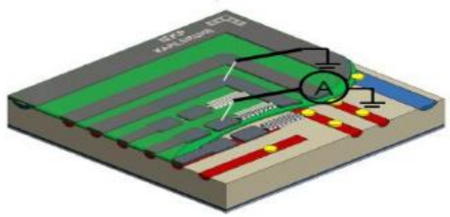
**1. IV**
**Sensor current vs Bias**



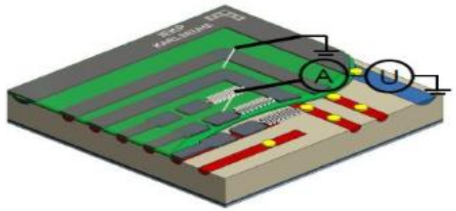

**2. CV**
**Sensor capacitance vs Bias**



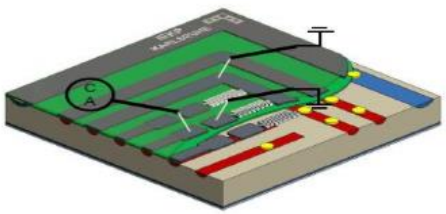

**3. $I_{leak}$**
**Strip leakage current**



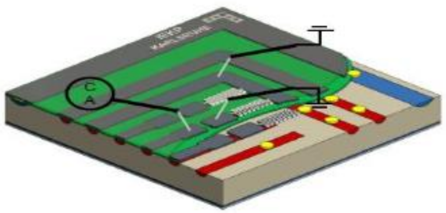

**4. $R_{bias}$**
**Strip bias resistor**



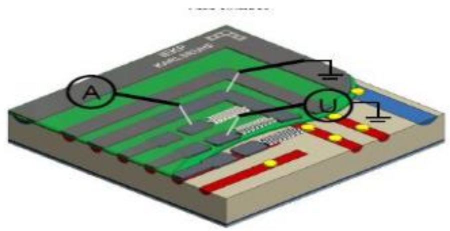

**5. $C_{Coup}$**
**Coupling capacitance**



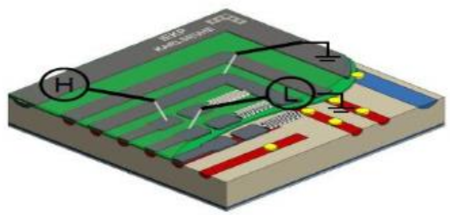

**6. $I_{diel}$**
**Dielectric current**




**7. $R_{int}$**
**Interstrip resistance**




**8. $C_{int}$**
**Interstrip capacitance**

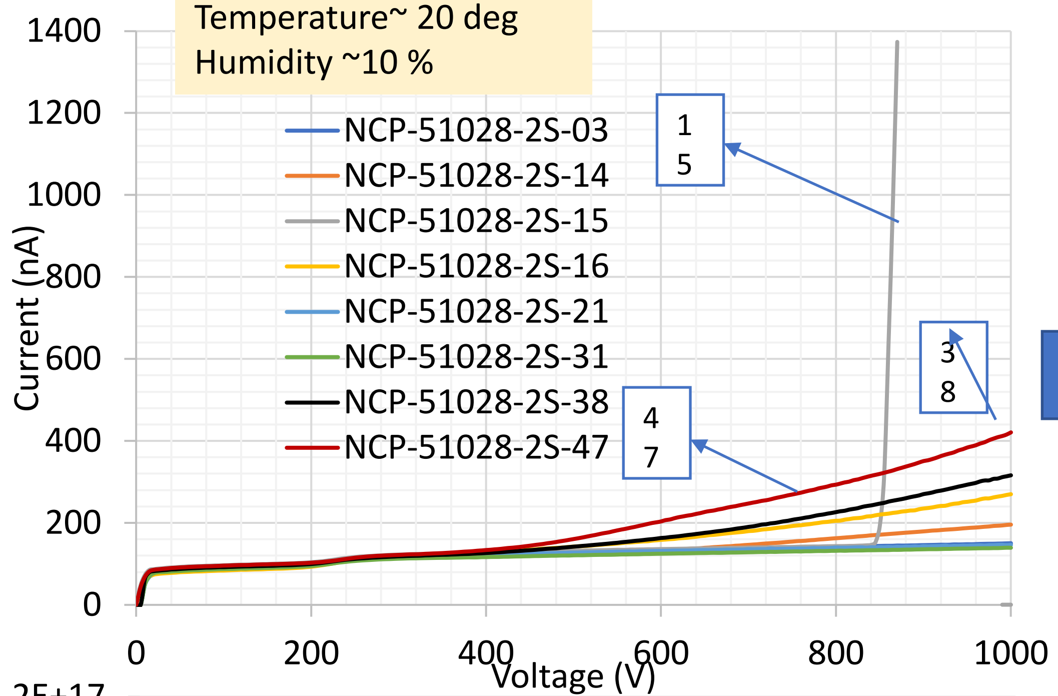


# SQC Requirements

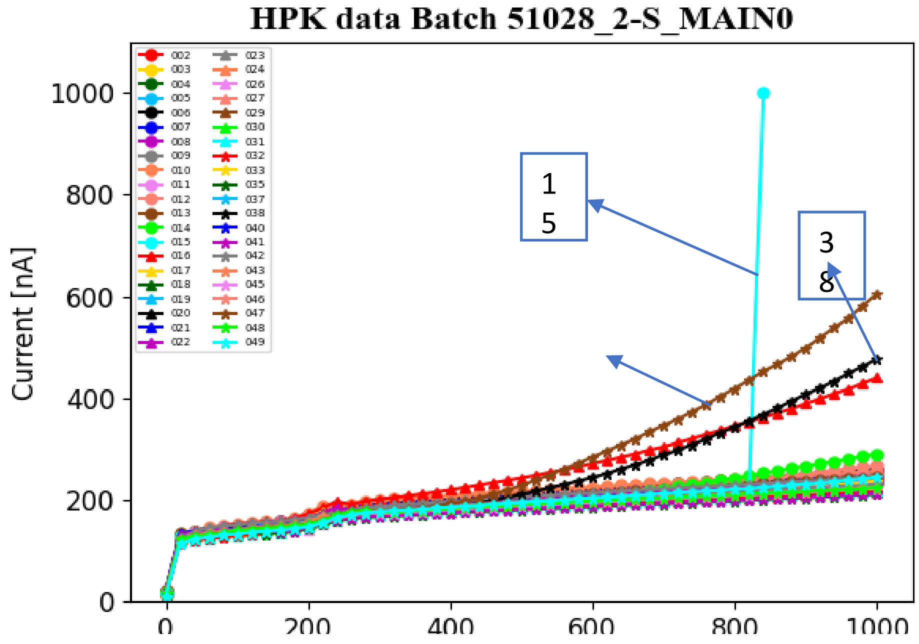
| # | Parameters | Limits |
|---|---|---|
| 1 | Global IV | 600V@7.5μA (upper limit)<br>800 V, I800 < 2.5 x I600<br>1000 V, I1000 < 2.5 x I800 |
| 2 | Global CV | ~ 3-4 nF |
| 3 | Strip Current | 50nA @ 600V |
| 4 | Coupling Capacitance | ~ 132 pF |
| 5 | Inter-strip Capacitance | < 0.5 pF/cm |
| 6 | Dielectric current | < 10 nA@10 V |
| 7 | Inter-strip Resistance | > 50 GΩcm |
| 8 | Polysilicon resistance | ~ 1.5± 0.5 MΩ |

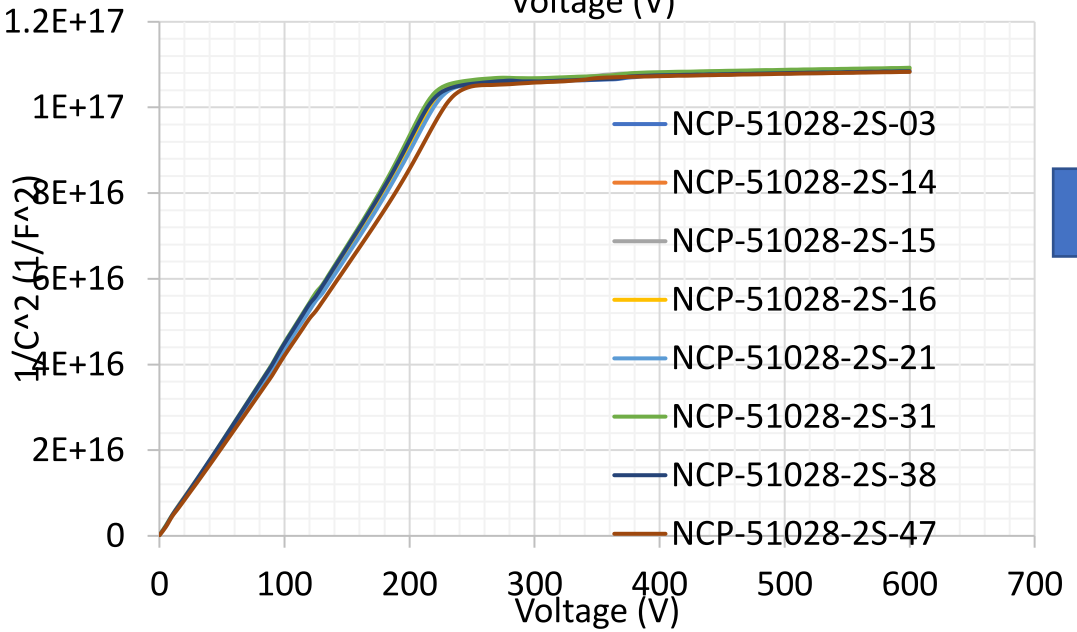
# IV and CV  (Batch no. 51028)

**NCP**
Temperature~ 20 deg
Humidity ~10 %

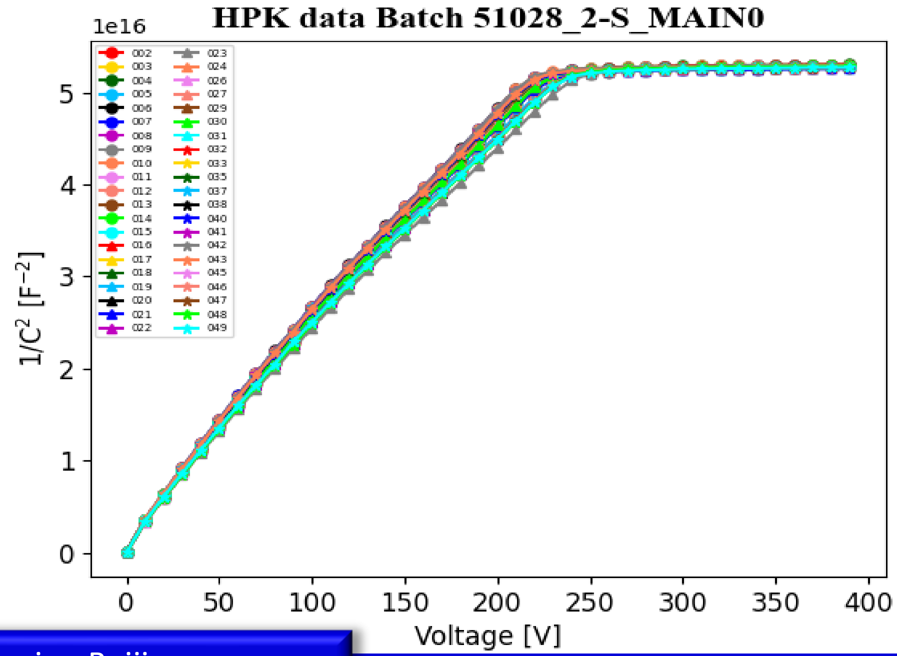



IV



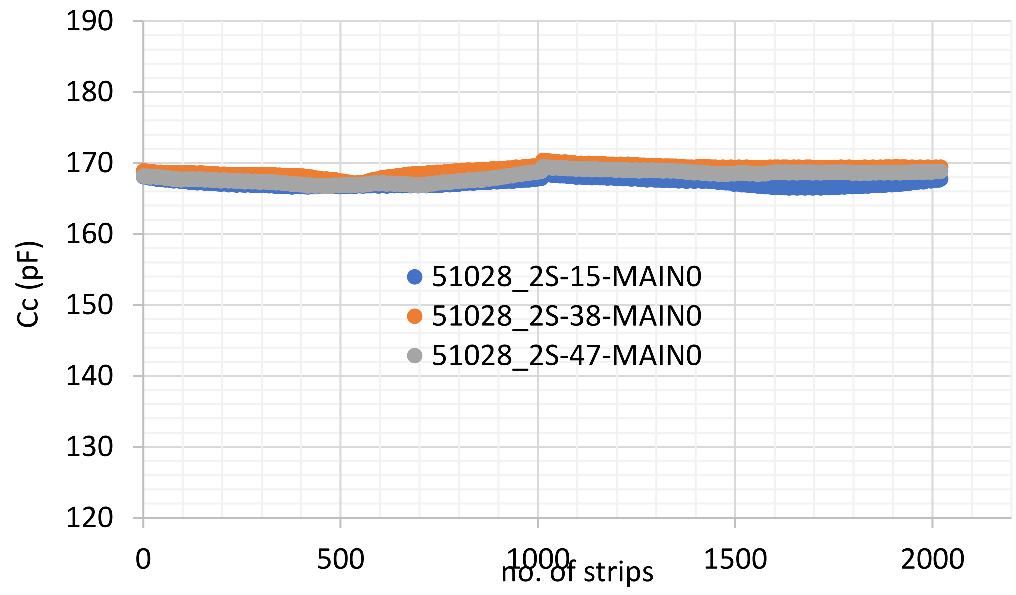



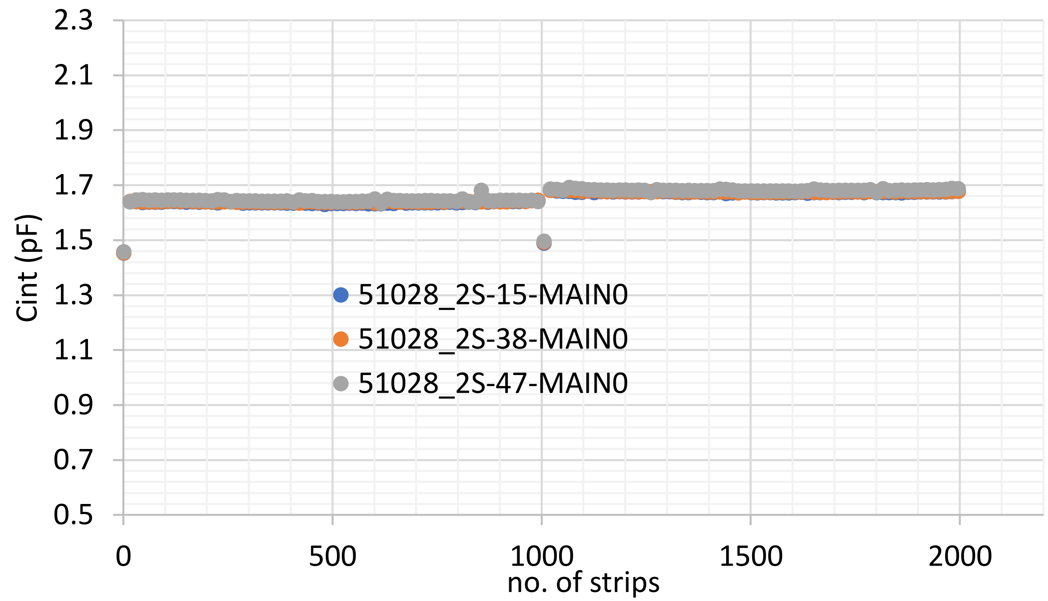

CV

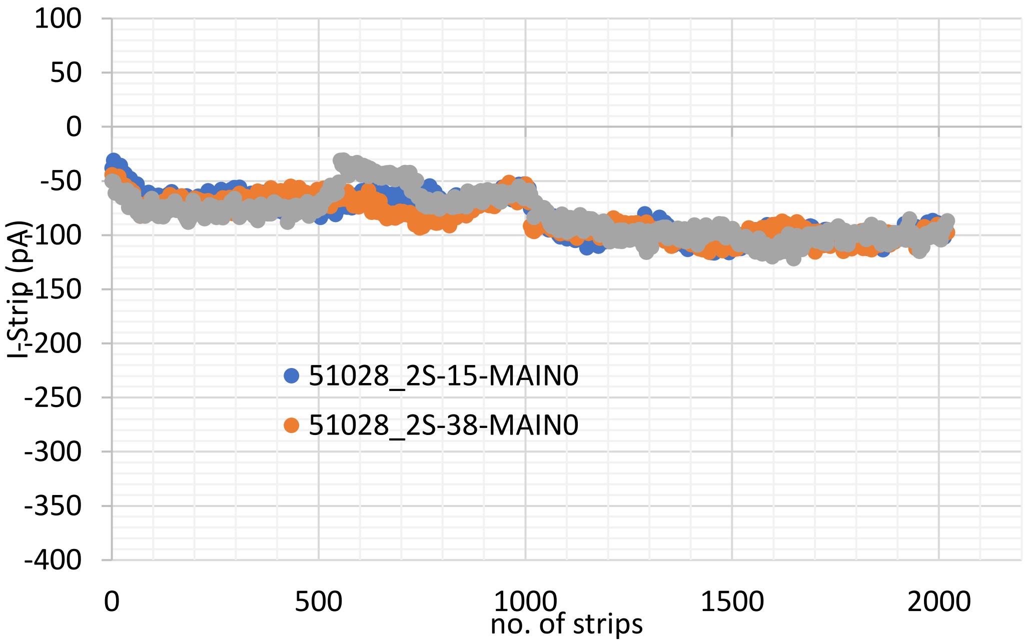


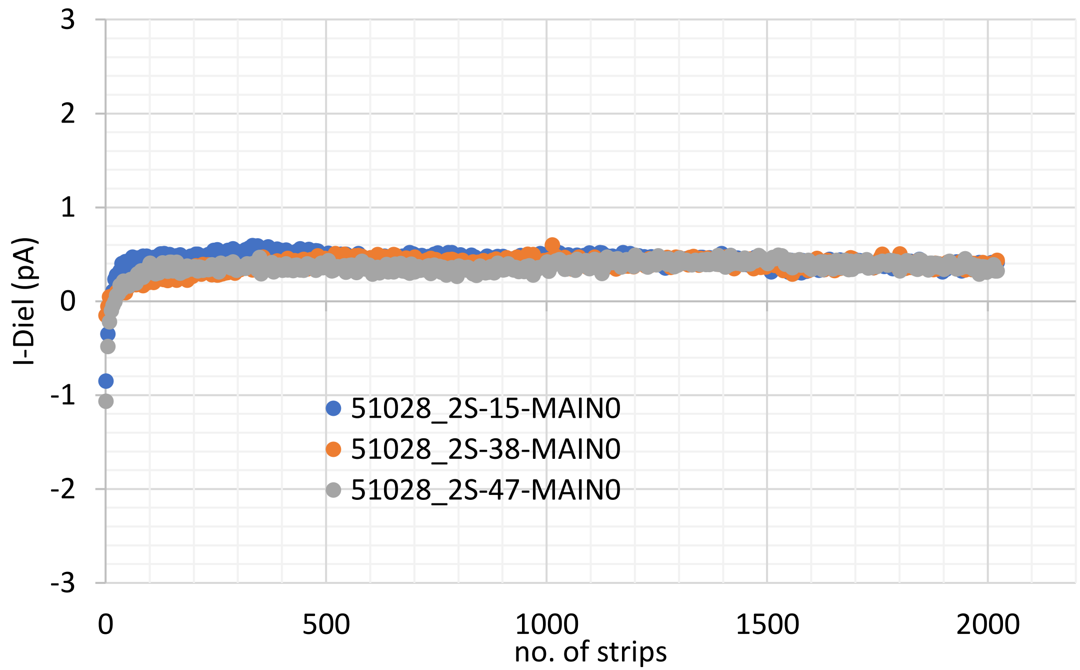
# $C_c$ , $C_{int}$ , $I_{strip}$ and $I_{diel}$

## Batch no. 51028

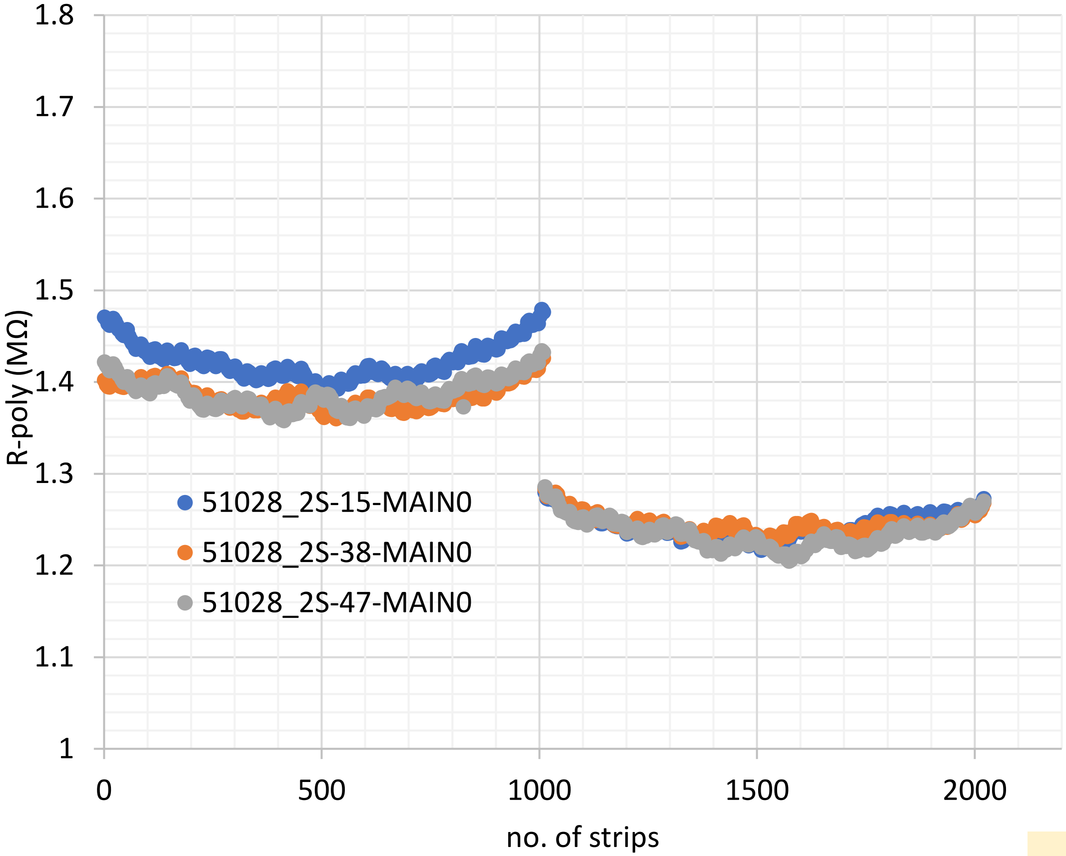


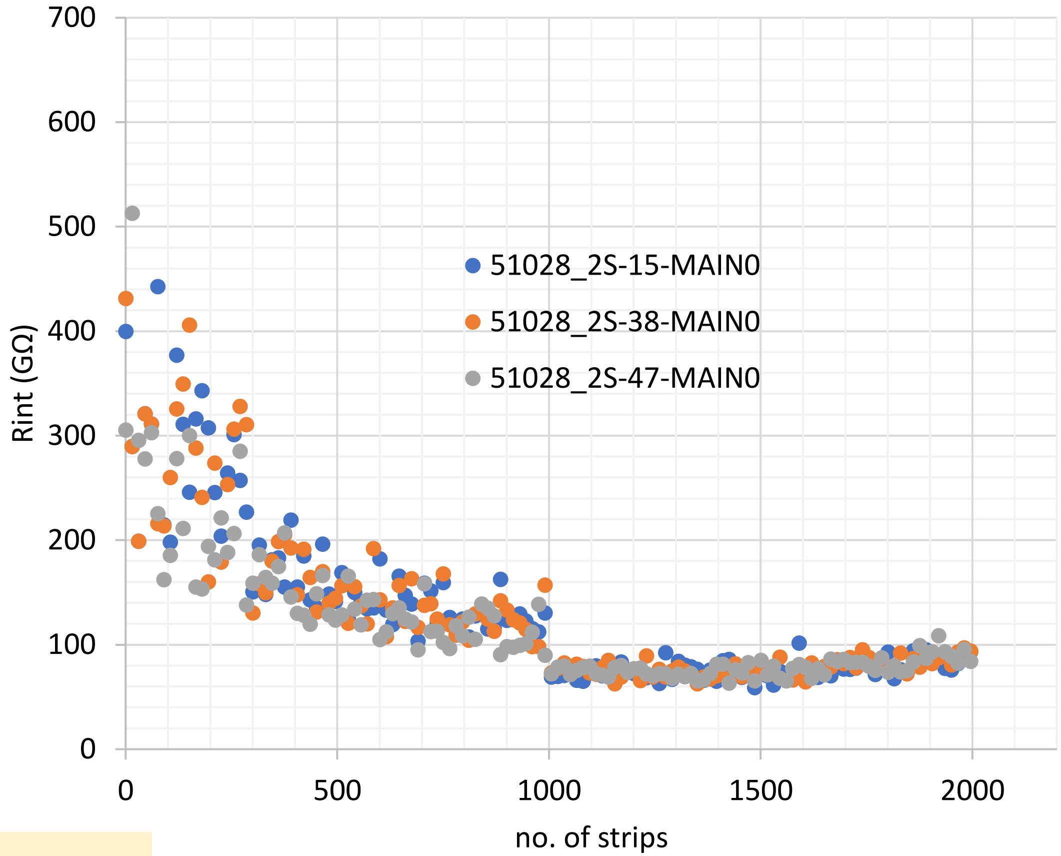



# $R_{poly}$ and $R_{int}$ (Batch no. 510280)




## Summary

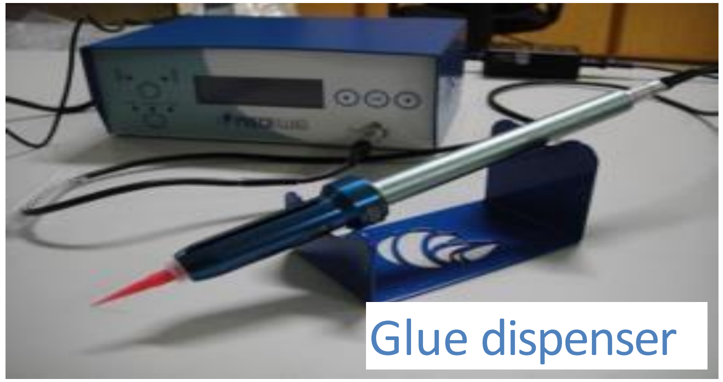
| Sensor no. | I@600 (nA) | I@800 (nA) | I800/I600 | Vfd | I-strip (pA) | Rpoly (MΩ) | Cac (pF) | Cint (pF) | Rint (GΩ) |
|---|---|---|---|---|---|---|---|---|---|
| 51028_2S_15 | -135.84 | -143.01 | 1.05 | ~225 | -82.19 | 1.33 | 167.20 | 1.65 | 131.76 |
| 51028_2S_38 | -163.38 | -226.48 | 1.38 | ~225 | -81.82 | 1.31 | 168.99 | 1.63 | 130.63 |

**54 batches with about ~2000 silicon sensors have been qualified at NCP**

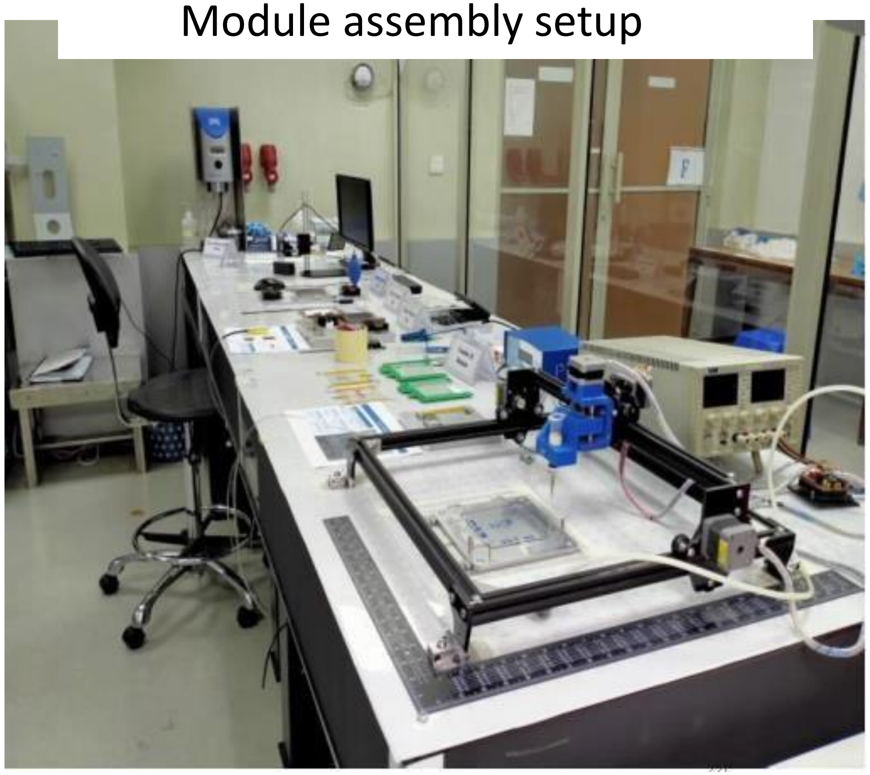
# Silicon Module Assembly Setup

- Developed Lab Setup for module assembly and testing
  - Build 8 mechanical modules to validate dimensional accuracies and refine/fix locally made assembly jigs
- Built eight silicon modules(including kickoff modules). Tested, validated and presented in CMS meetings.
- **NCP is one of the eight silicon module assembly center**

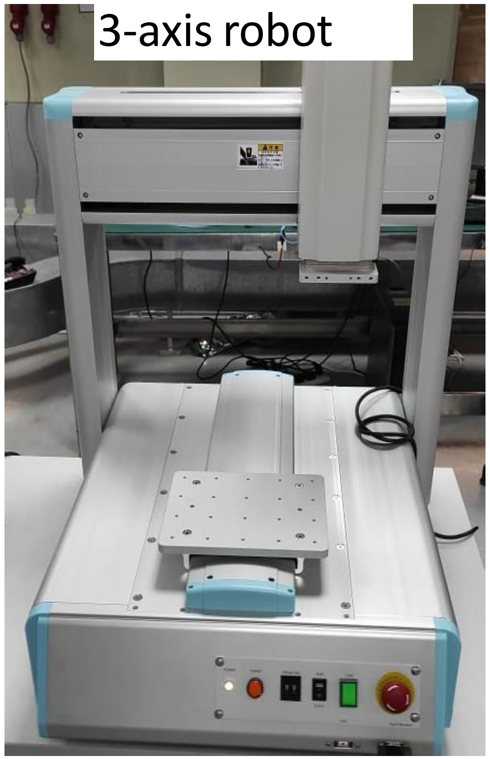

Glue Mixer


Glue dispenser

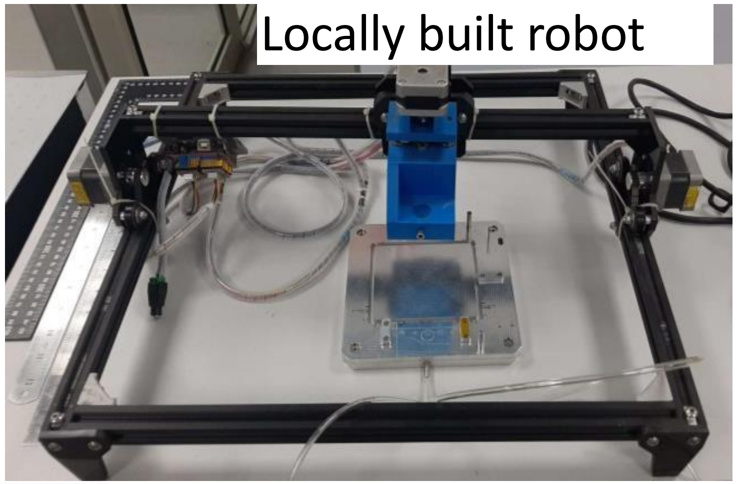
Module assembly setup



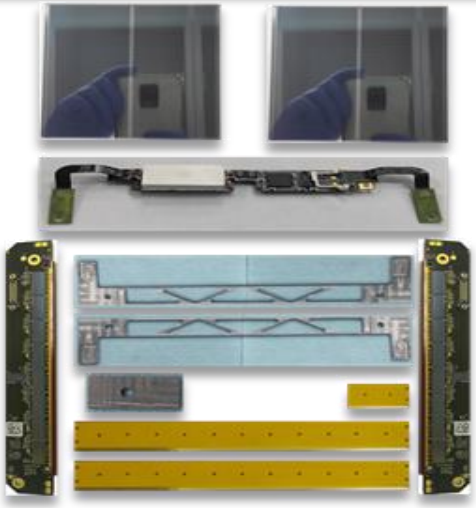
LH-300T Robot
3-axis robot



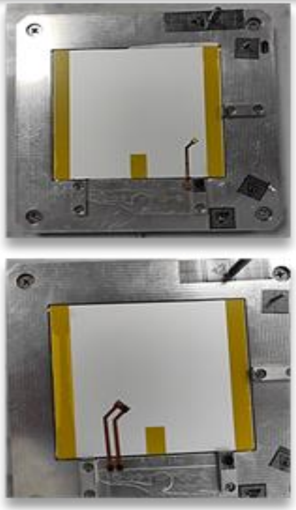
Locally built robot



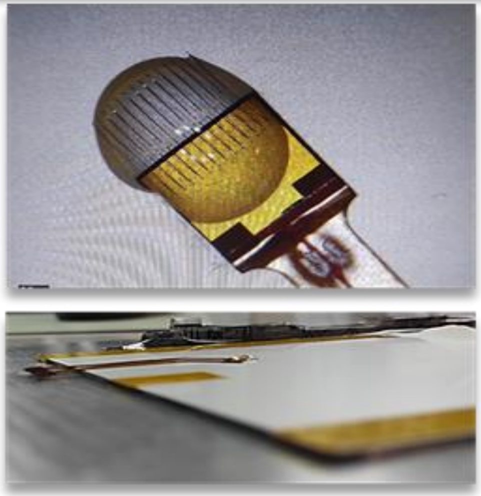
# Module Assembly Flow Chart



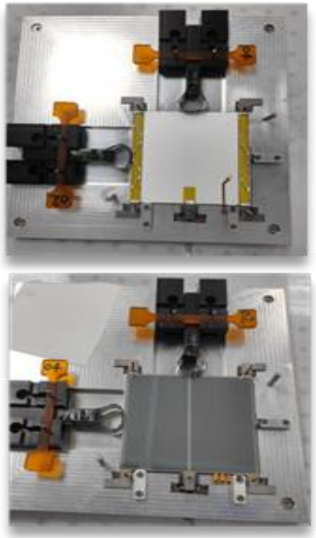
**STEP 1:** Optical Inspection



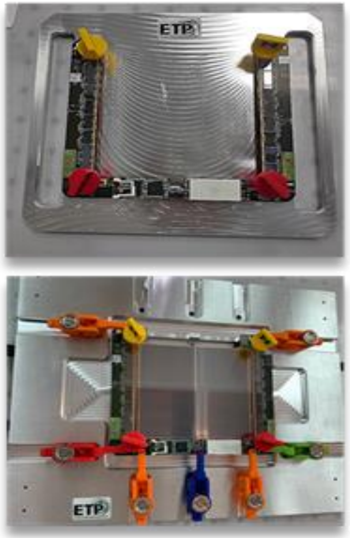
**STEP 2:** PI-Strips & HV-tail Gluing



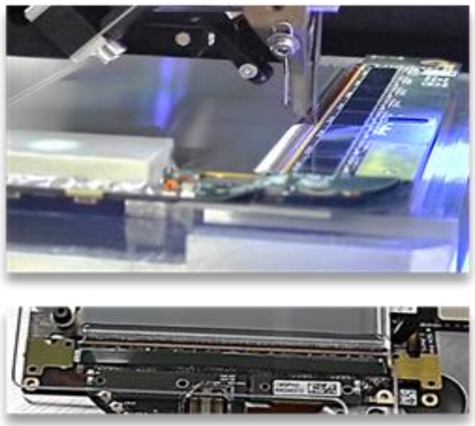
**STEP 3:** HV-tail Wire-bonding & Encapsulation



**STEP 4:** Bare-Module Assembly



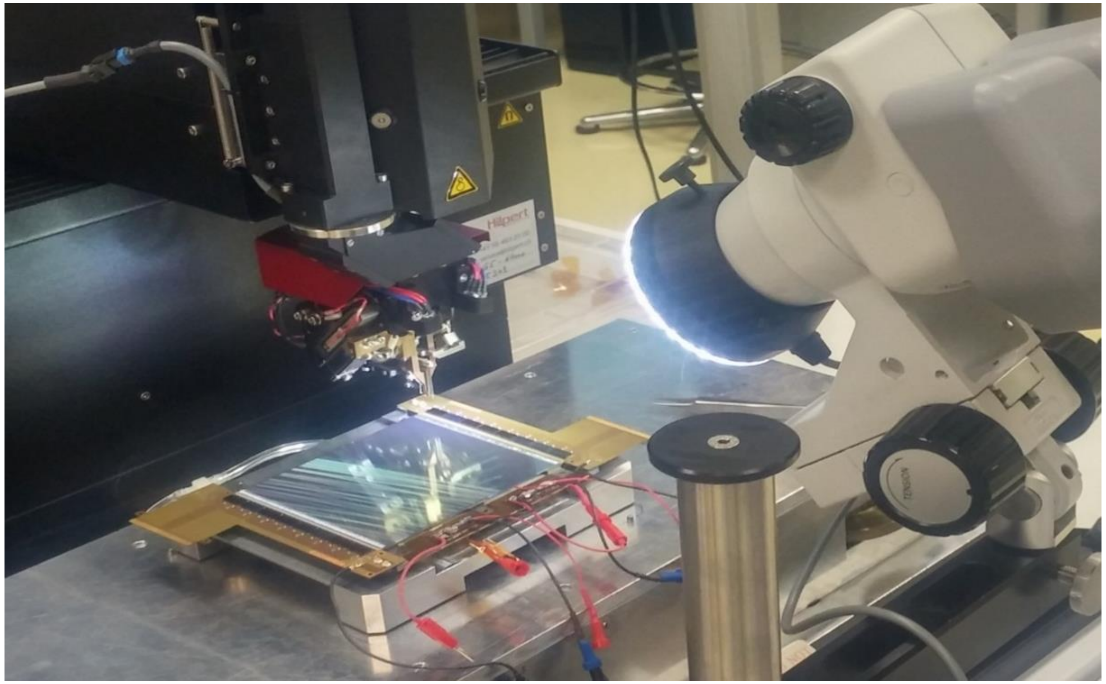

**STEP 5:** Hybrid Gluing



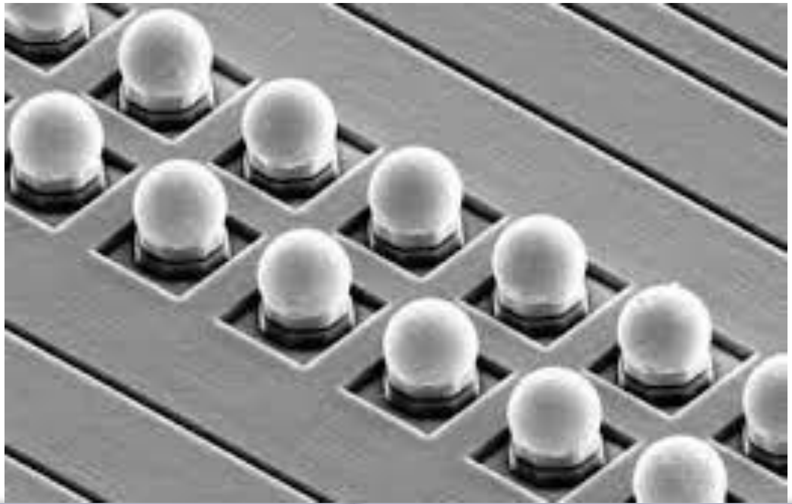
**STEP 6:** Sensor-to-FEH Wire-bonding & Encapsulation

# Wire/ball Bonding Setup for Silicon Modules

Wire bonding setup is operational at NCP



Ball-wedge bonding machine is being installed



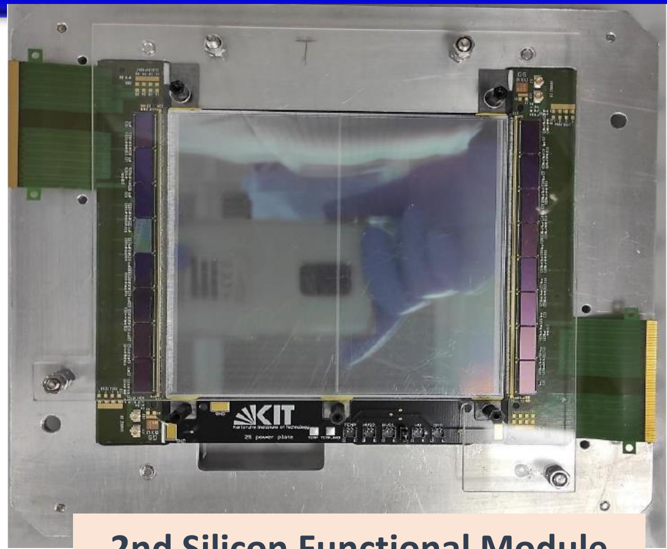
A unique facility

Wire bonding machine-1

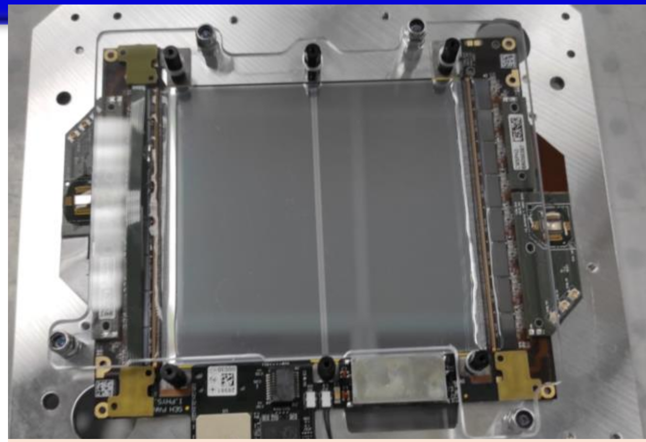
Wire bonding machine-2

# Outer Tracker Modules Assembly at NCP

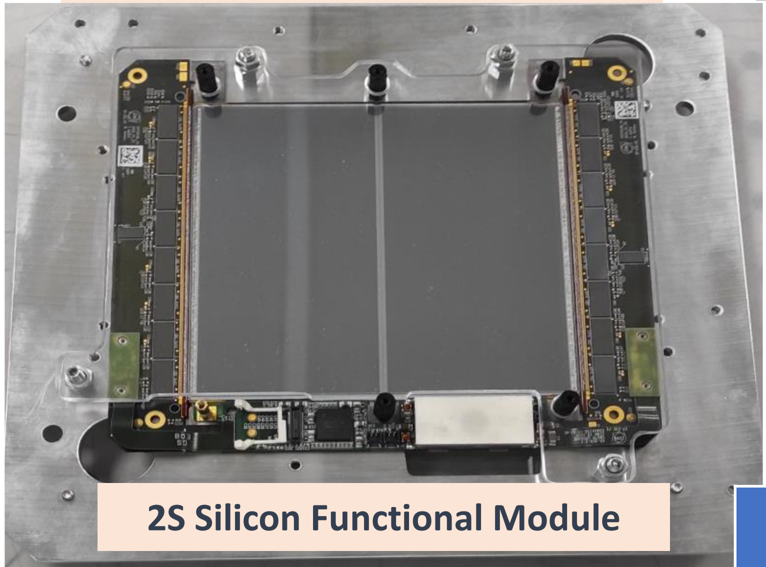
1st Silicon Module



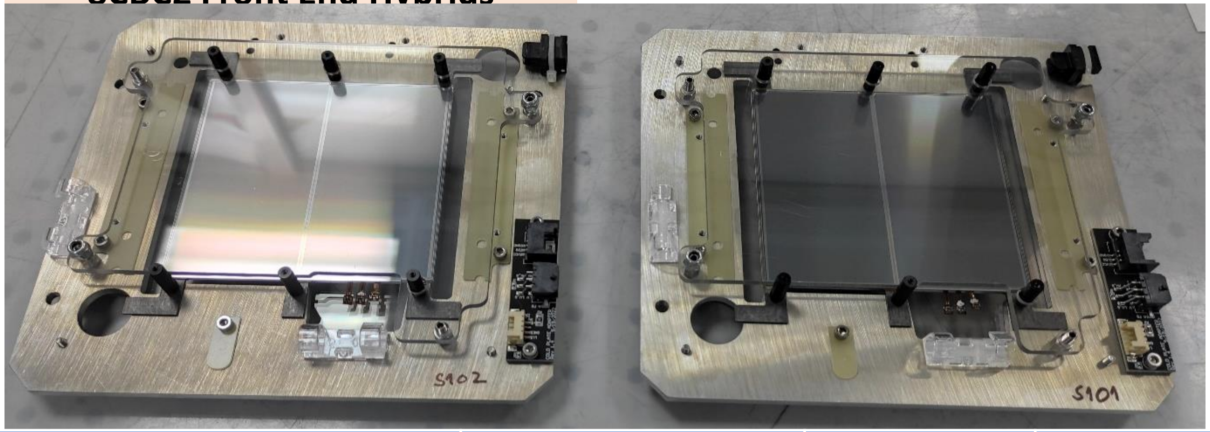
2nd Silicon Functional Module
8CBC2 Front End Hybrids



3rd Silicon Functional Module
8CBC3 Front End Hybrids
Module has been validated at CERN.



2S Silicon Functional Module

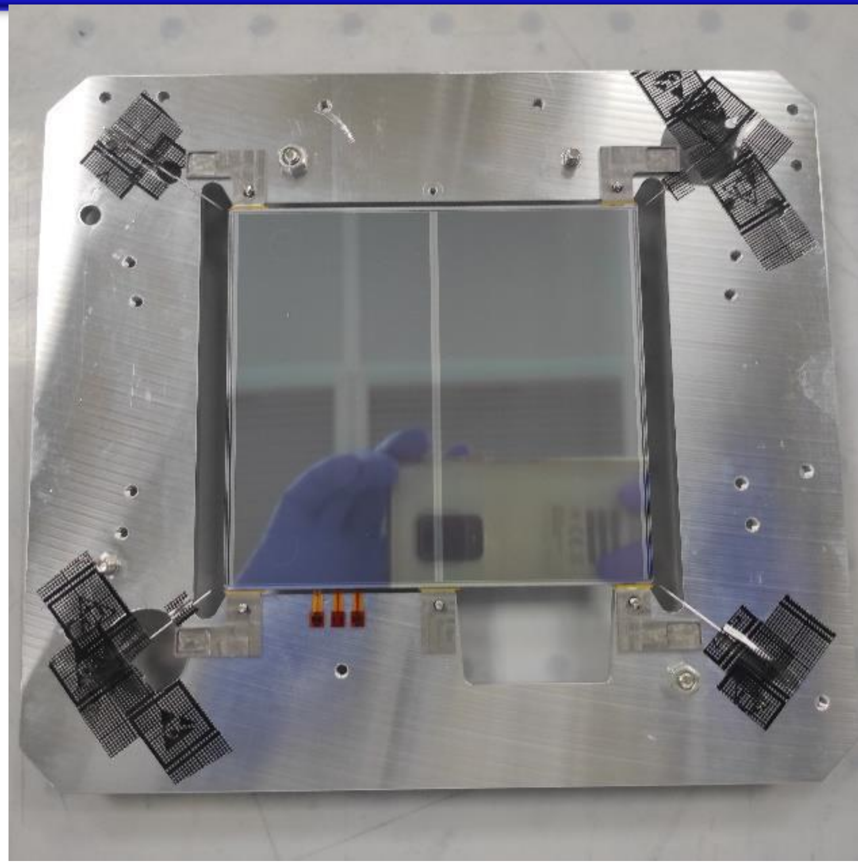


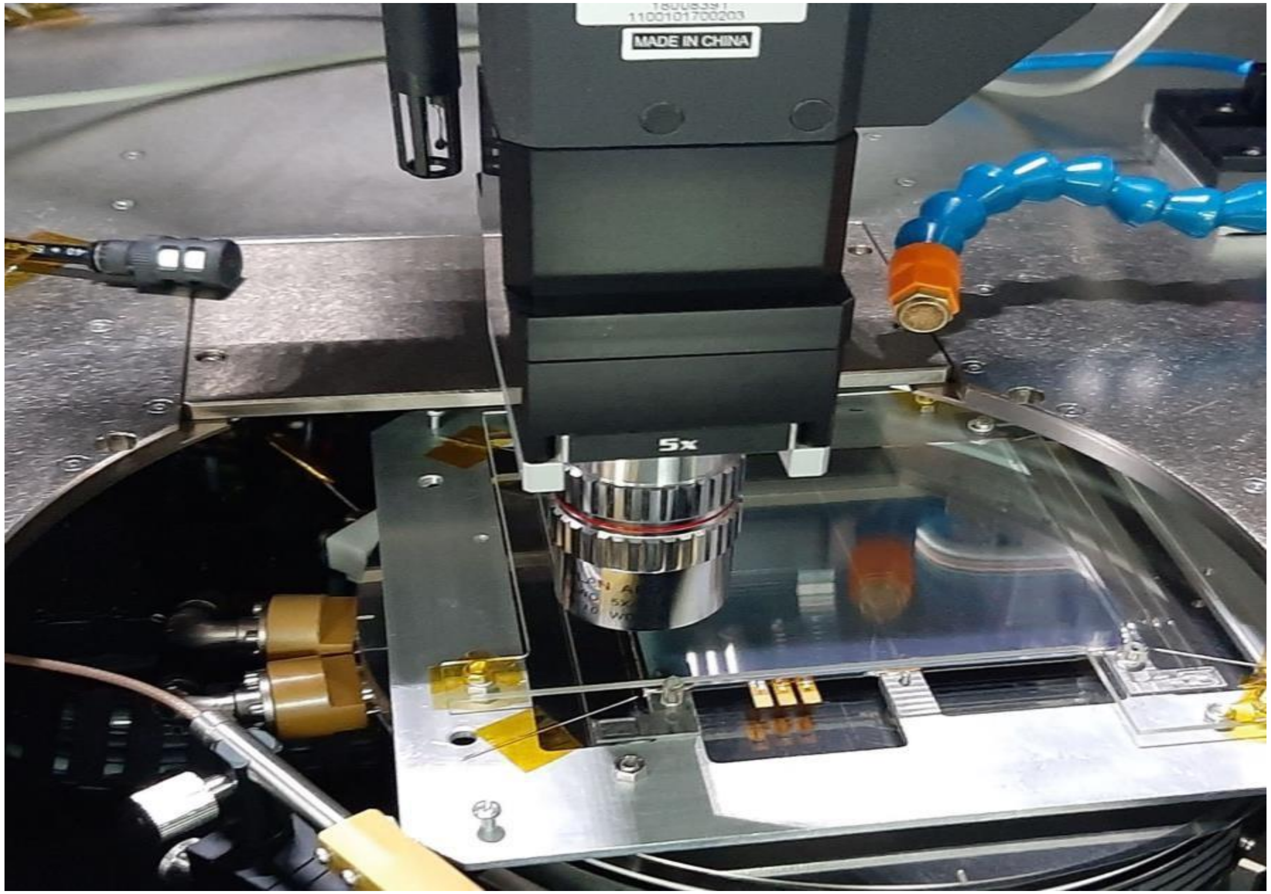
Eight modules built at NCP so far!

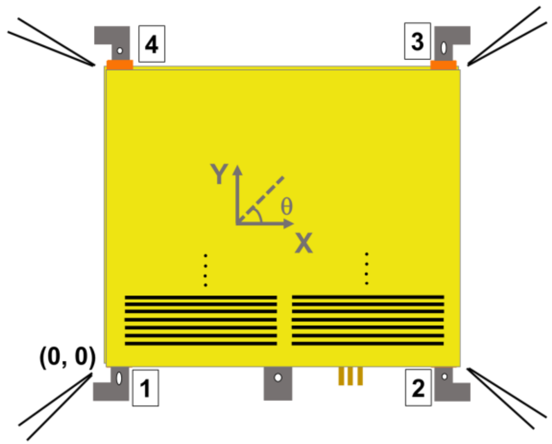
| Module | Δθ (μrad) Required < 400 μrad | Δx (μm) Required < 100 μm | Δy (μm) Required < 50 μm |
|---|---|---|---|
| 2S_18_5_NCP-00101 | 51 ± 10 | -7 ± 5 | -1 ± 5 |
| 2S_18_5_NCP-00102 | 30 ± 10 | -6 ± 5 | -1 ± 5 |

# Module Metrology

- Needle method locally developed to perform metrology of modules using probe station
- Validated by measuring misaligned module



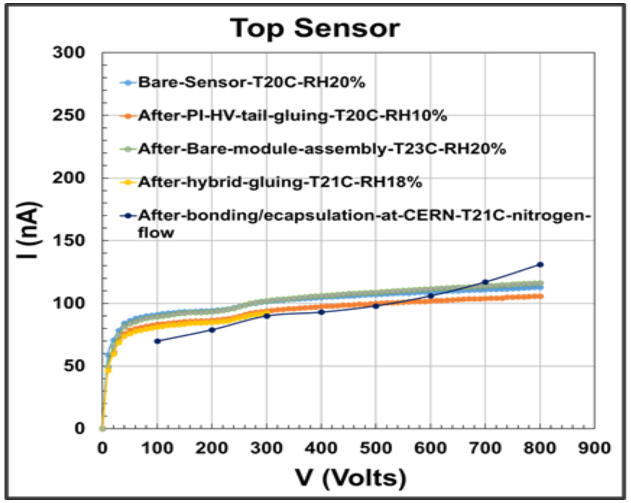


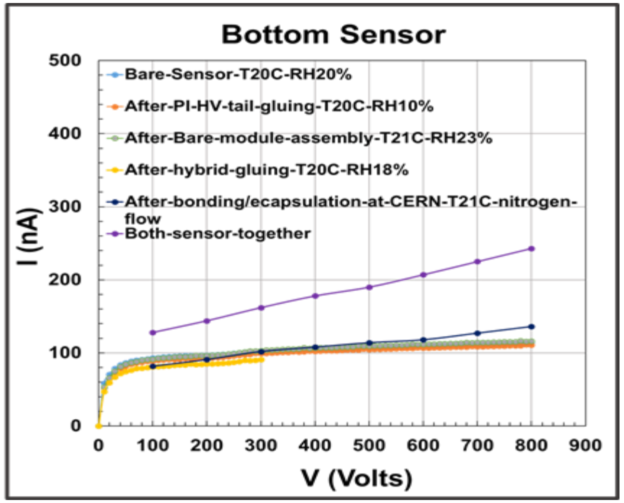



# Metrology summary Module Assembled

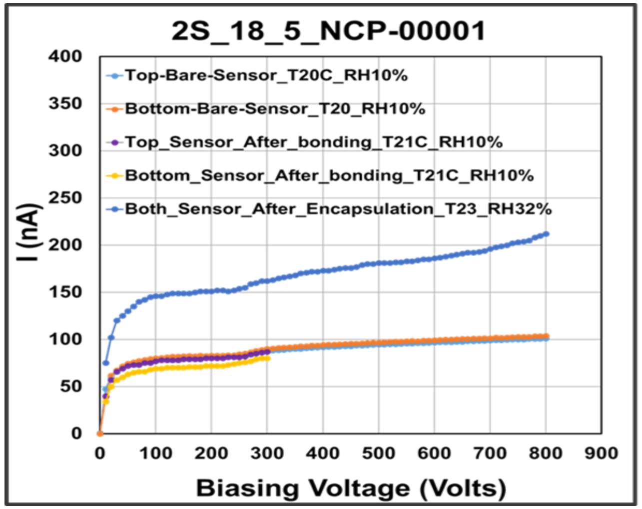
| Module Name | Module Type | Module Batch | Δx (μm) tolerance < 100 (μm) | Δy (μm) tolerance < 50 (μm) | Δϴ (μrad) tolerance < 400(μrad) |
|---|---|---|---|---|---|
| **NCP - F01** | 8CBC2 | Prototype | 54 | 14 | 374 |
| **NCP - F02** | 8CBC3 | Prototype | -13 | -4 | -22 |
| **2S_18_5_NCP-00001** | 2S | Prototype | -15 | -13 | -22 |
| **2S_18_5_NCP-00002** | 2S | Prototype | -1 | -9 | -31 |
| **2S_18_5_NCP-00003** | 2S | Prototype | 3 | 3 | 24 |
| **2S_18_5_NCP-00101** | 2S | Kick-off | -7 | -1 | 51 |
| **2S_18_5_NCP-00102** | 2S | Kick-off | -6 | -1 | -30 |

# IV Measurements at different assembly steps

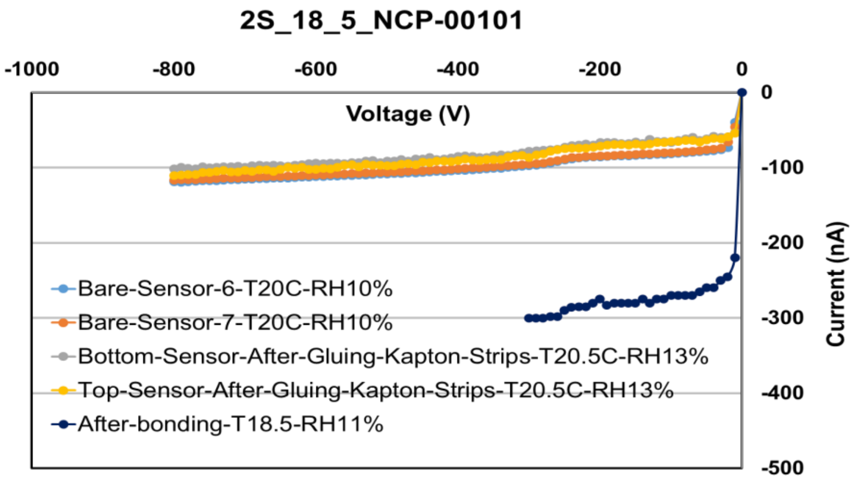


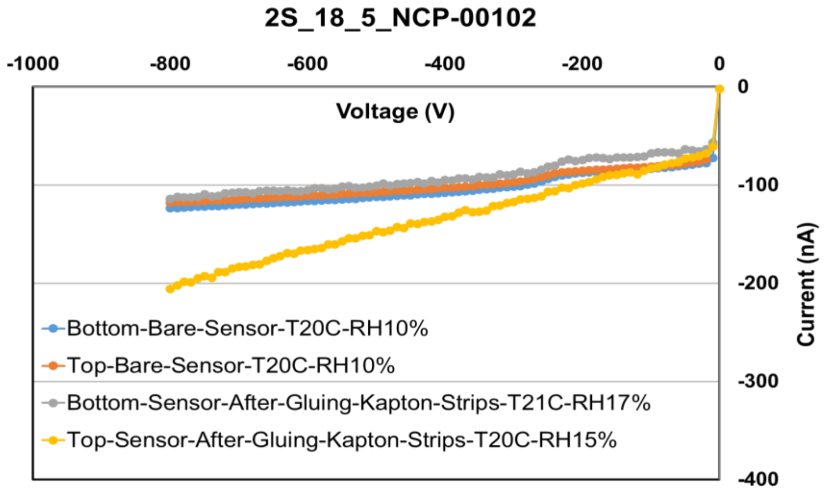




**8CBC3 Prototype Module**



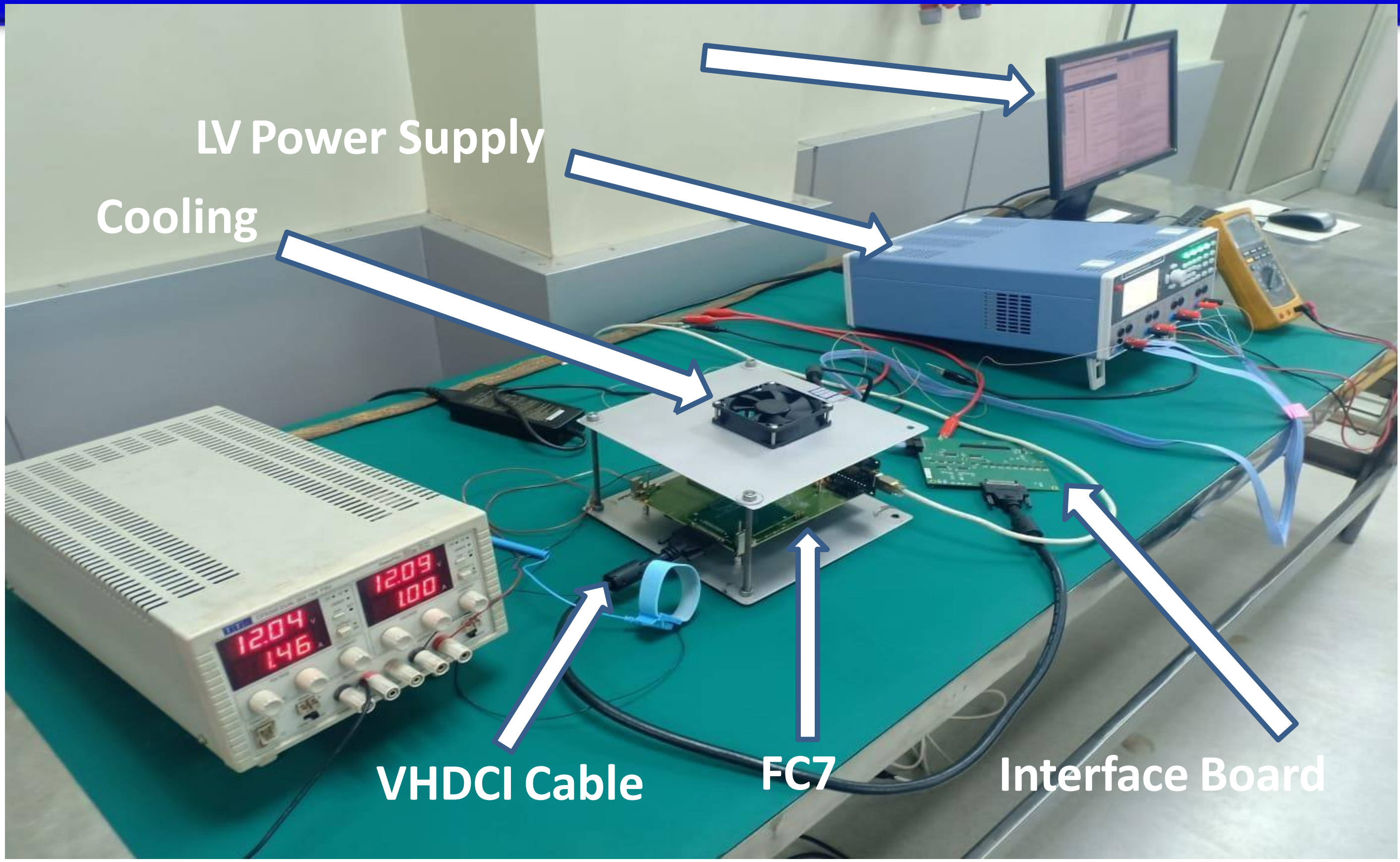

**2S Prototype Module**



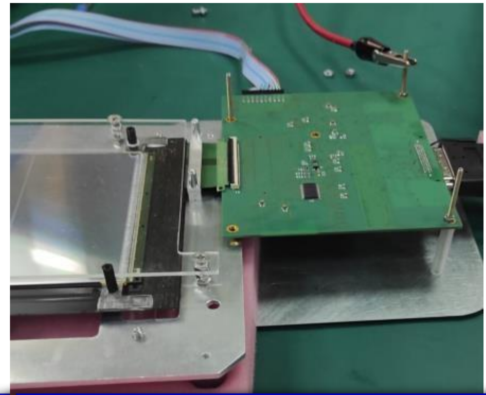

**Kick-off Batch Modules**

# Module Test Setup – 8CBC2/CBC3/2S




Micro TCA Crate

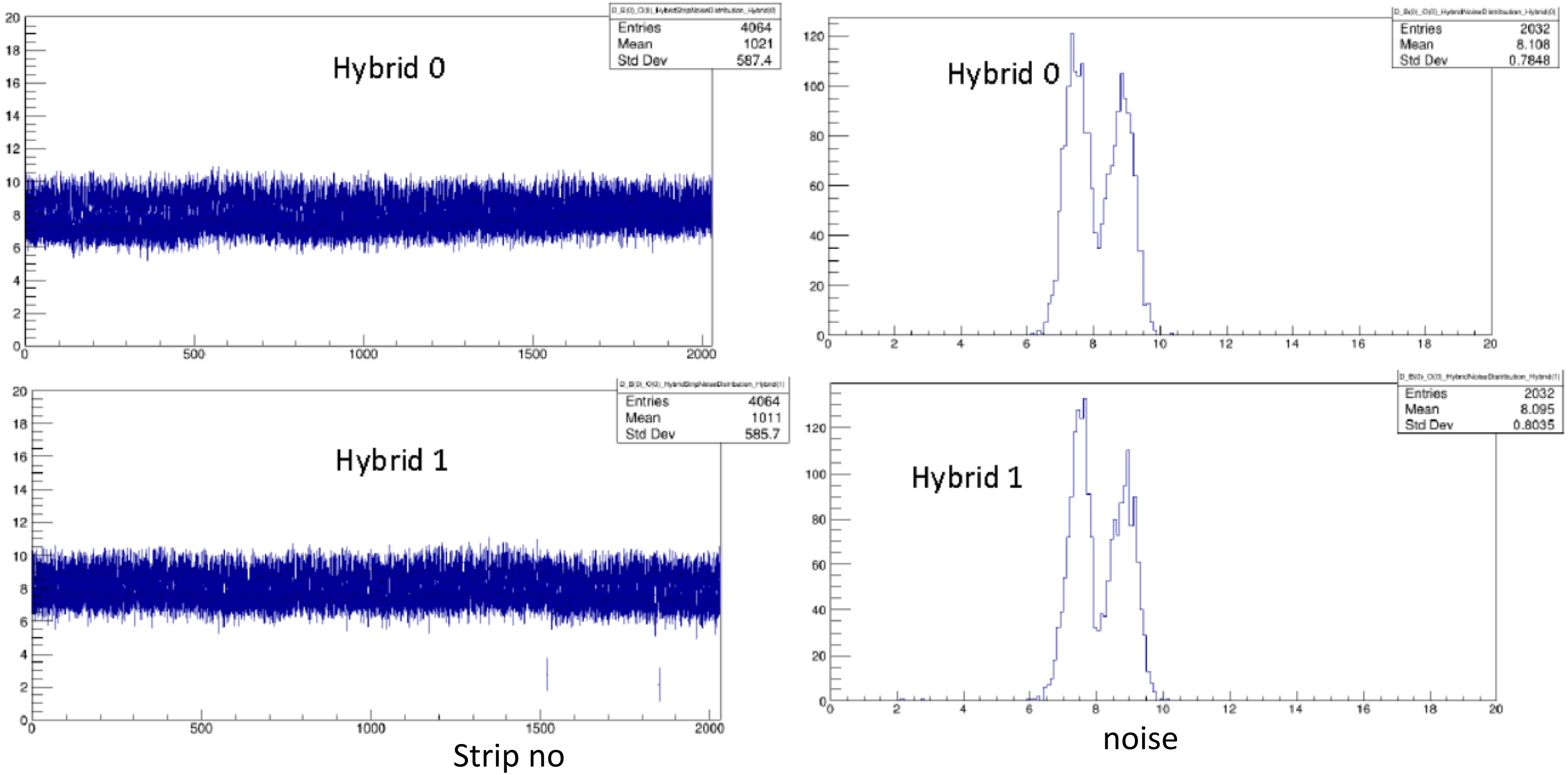
- 8CBC2, 8CBC3 and 2S modules testing setups are operational
- Burn-in testing setup is operational



Thermoelectric Plate

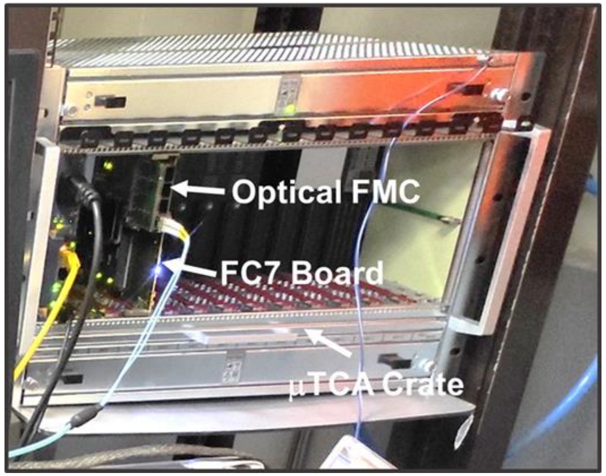
Chiller

# 2S module Functionality Test @ 300V

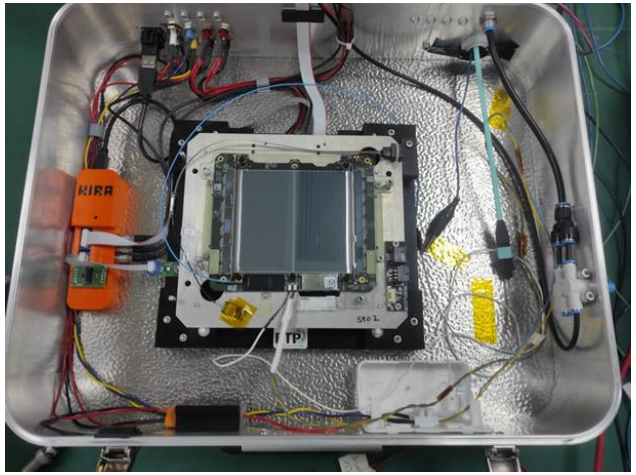


# 2S Module Testing Setups

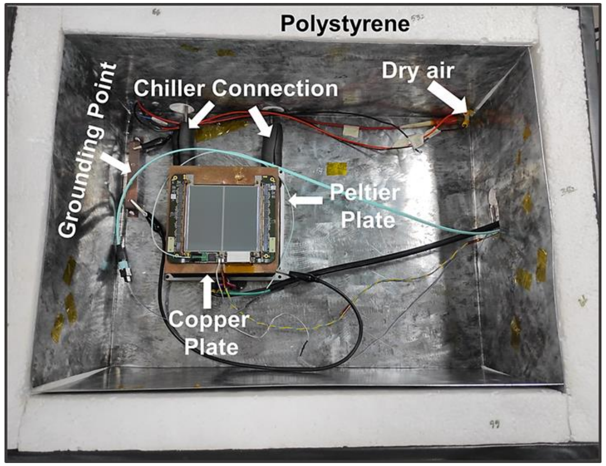
- **Noise Test Measurement Setup**
  - FC7 Board in µTCA is used
  - PH2_ACF algorithm developed by CMS collaboration is used for noise measurement
- **Cold test Setup**
  - Cold test box for testing single module
  - Burn-in setup used to load and operate 10 modules at the same time




**FC7 and µTCA**



**Single Module test bench**

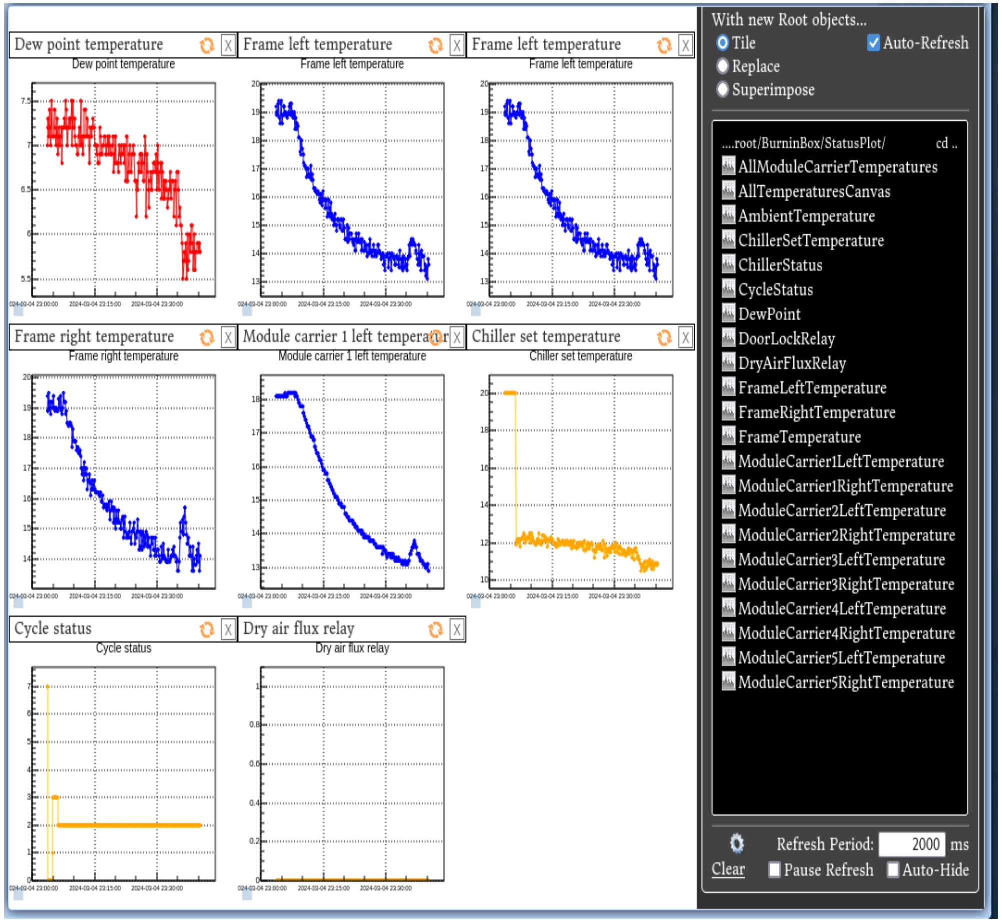



**Single module cold test setup**

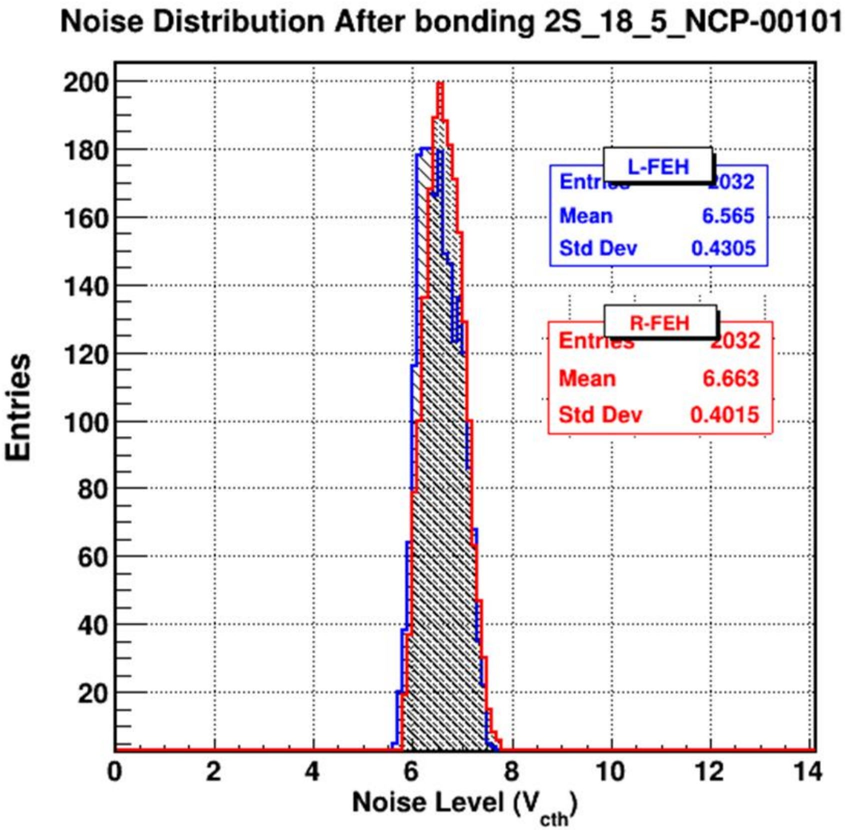
**Multi module cold test burn-in setup**

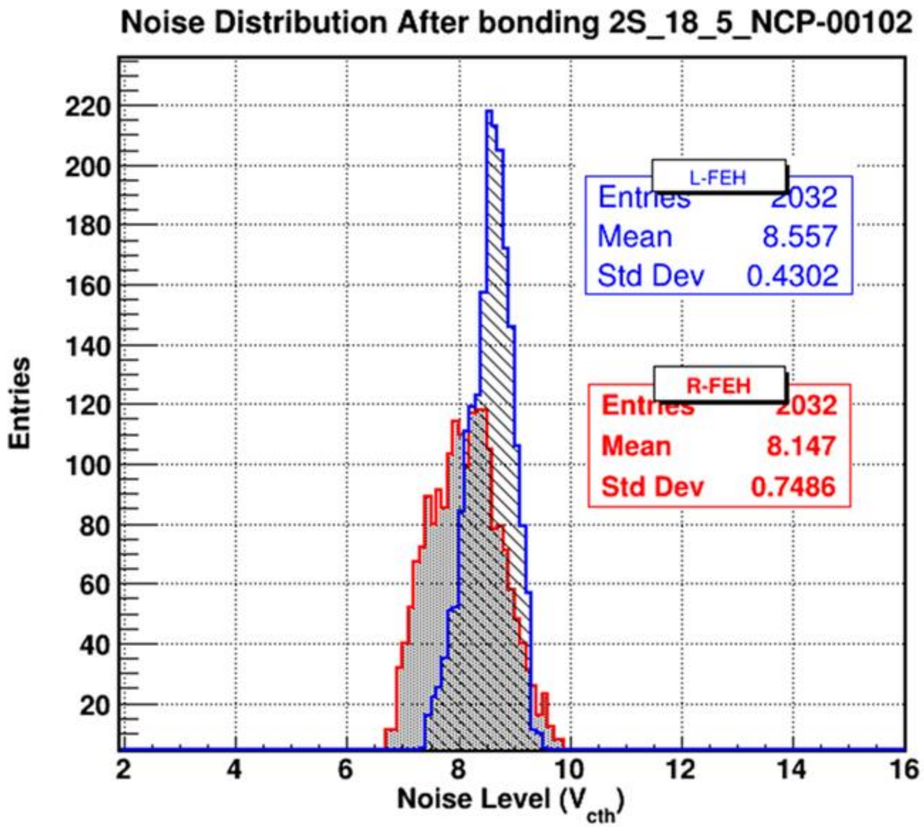
# Burn-in Setup

- Ready for testing 10 modules in parallel



# Noise Measurements



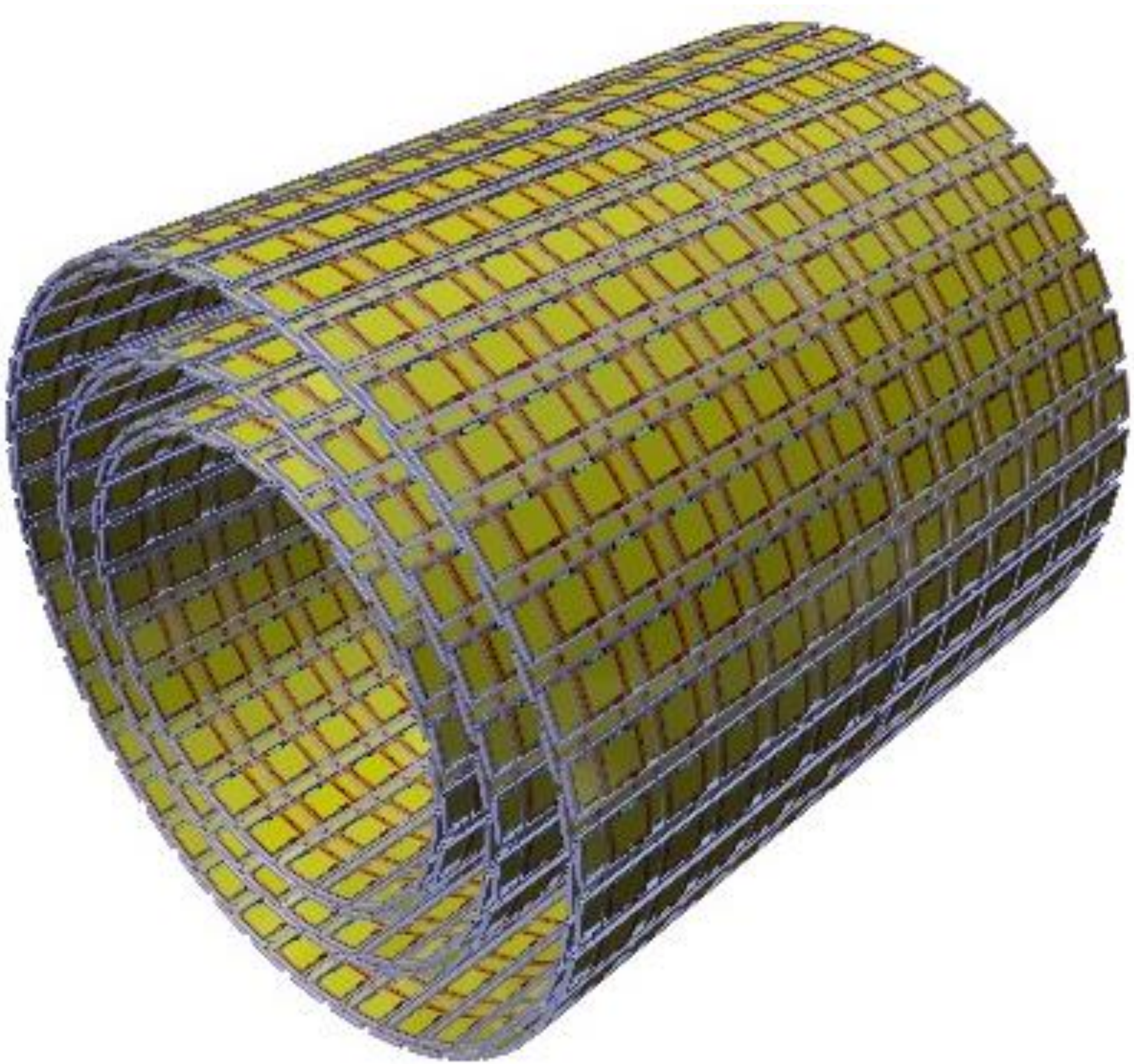




**Noise Level distribution for Kick-off Batch Modules**

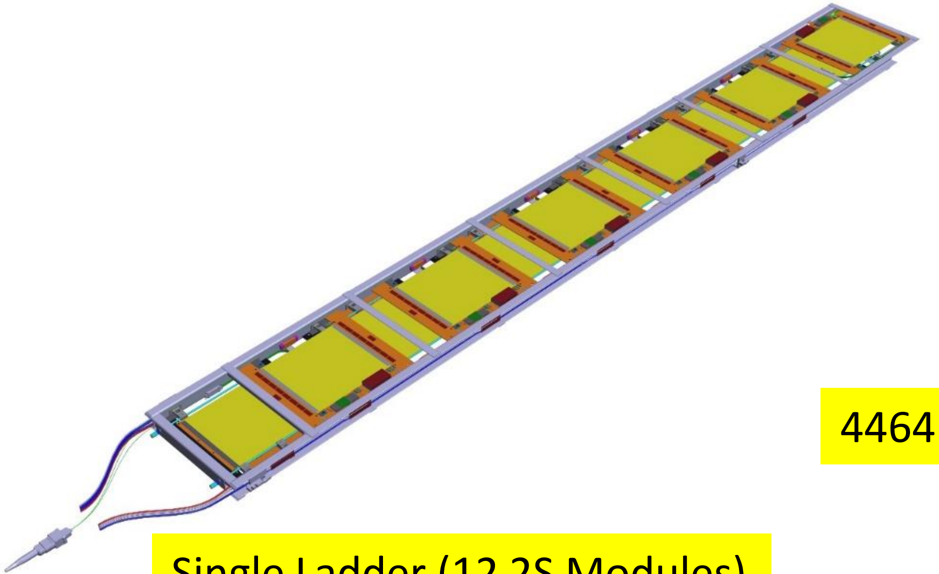
# Module Production Card Board Exercise in new Cleanroom

# Fabrication and Assembly of TB2S Ladders

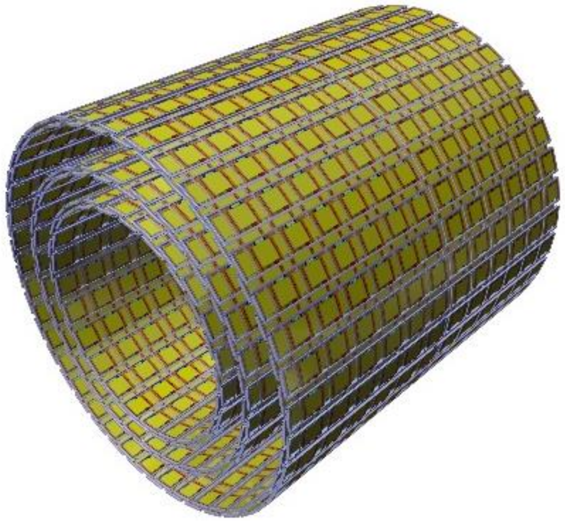
# CMS Outer Tracker Barrel



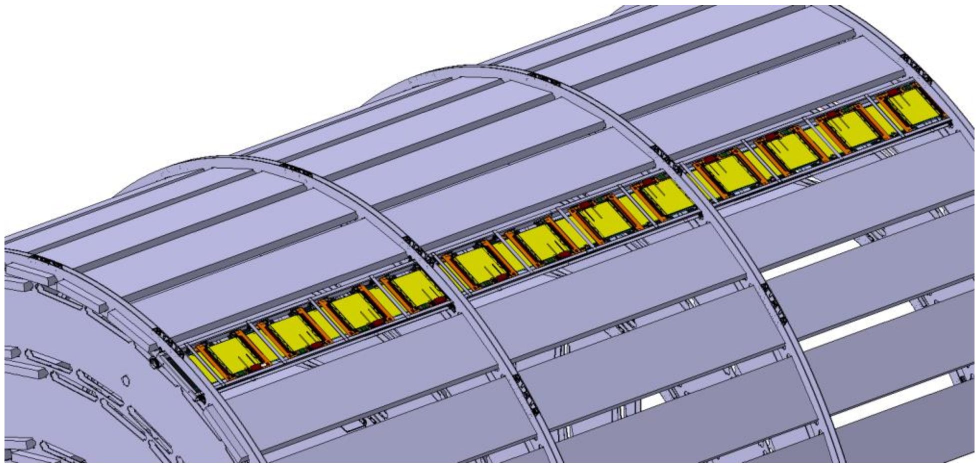
# TB2S Ladder Mechanics at NCP



Single Ladder (12 2S Modules)

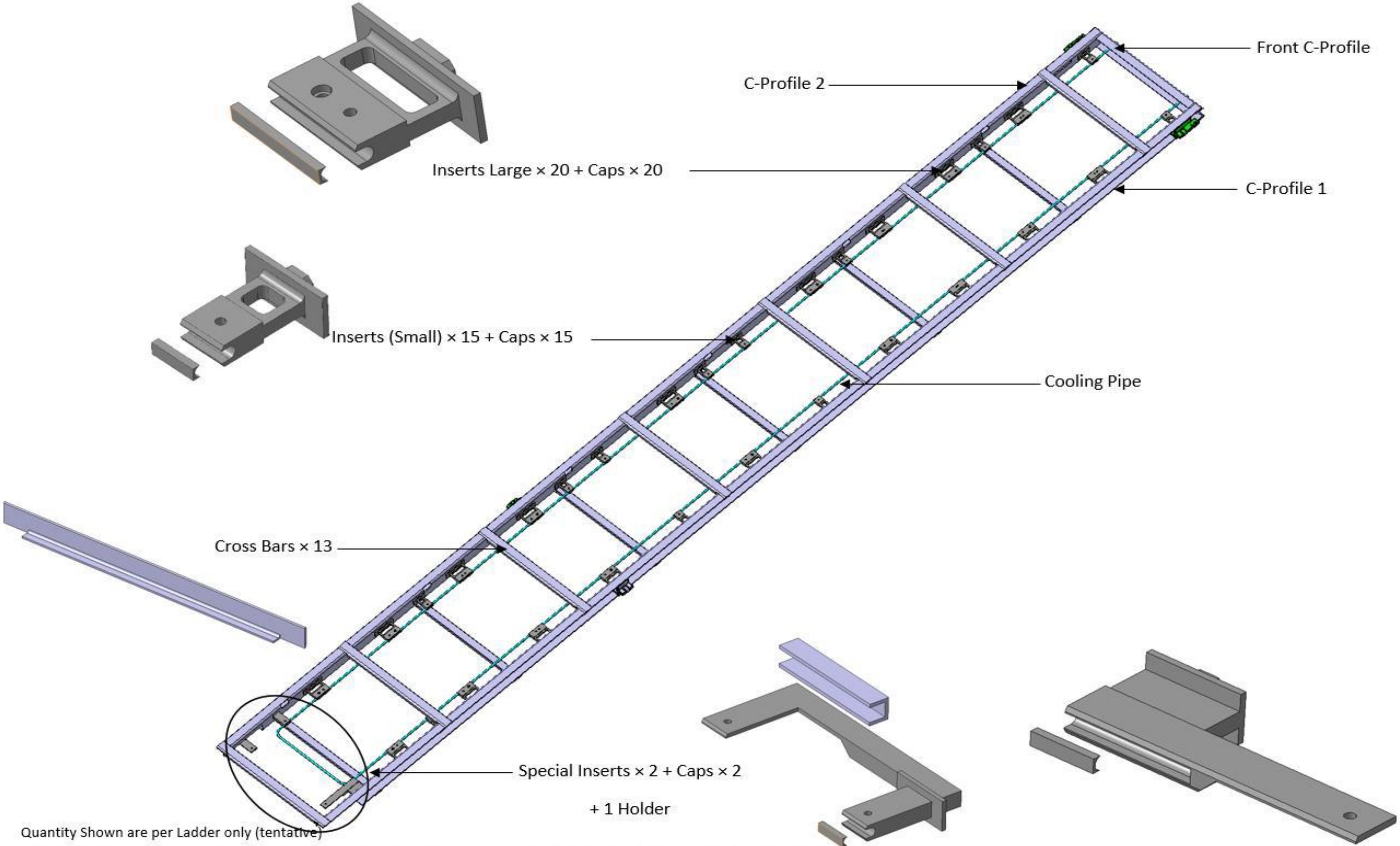


4464 2S Modules = (368 Ladders Arranged in 3 Layers)



NCP Scope of Work = build about 400 ladders including spares

# TB2S Ladder Mechanics




* Quantity Shown are per Ladder only (tentative)

** All the numbers are based on the +ve side of the TB2S (The quantities may vary as the –ve side of the TB2S is still in design process)

*** Cooling pipe is a part of the ladder assembly but it is not in NCP's scope of work

# Water Jet Cutting

- Different Industrial Setups were Explored
- Experienced Setups for CF cutting = 2
- R&D was done in one of the Setups;
  - Fixtures were designed to hold the Profile at 3 Locations
  - Different Cutting Pressures were tested (30 to 70 kpsi)
  - Nozzle Dia = 0.5 mm

Fixture for C-Profiles

# Tracker Mechanics Project: TB2S Ladders

- Three ladder prototypes were designed, fabricated and assembled successfully at NCP
- Jigs, inserts fabricated and water jet cutting in a local company

**1st Prototype Ladder** – Proof of Concept
sent to CERN in **April 2019**

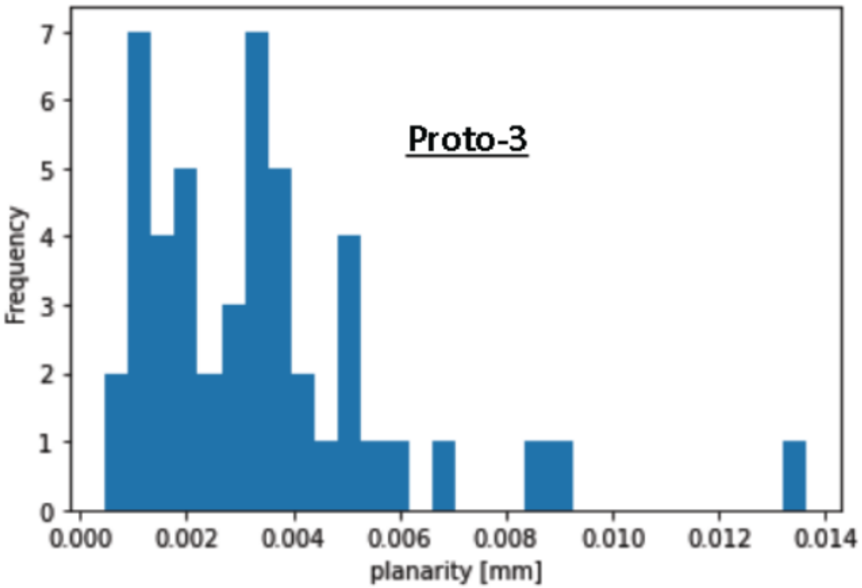
**2nd Prototype Ladder** – planarity < 30 microns
Sent to CERN in **August 2020**, validated and tested at CERN/Strasbourg, well appreciated!

**3rd Prototype Ladder** – planarity < 10 microns)
shipped to CERN on **14 October, 2021**
Tested for performance at CERN/Strasbourg, well appreciated!

- Production of TB2S ladders will be done in local company

# Metrology of 3rd and 2nd prototypes ladders at Strasbourg/France

## Insert planarity

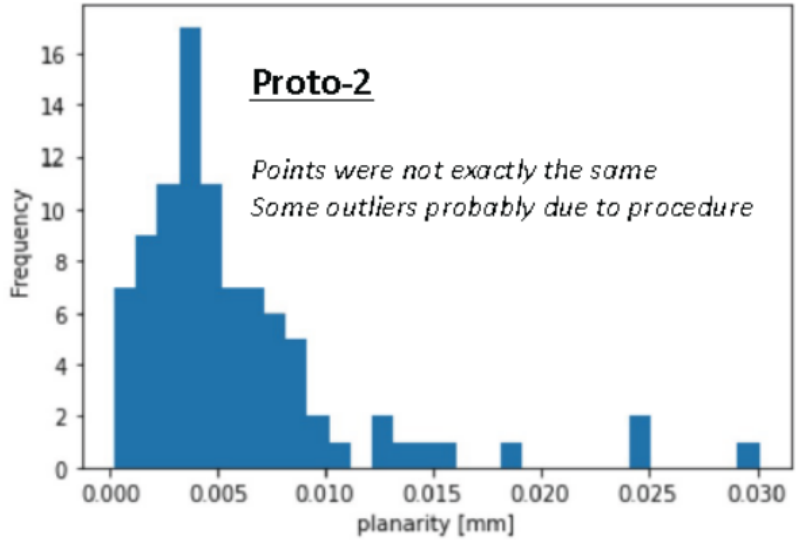


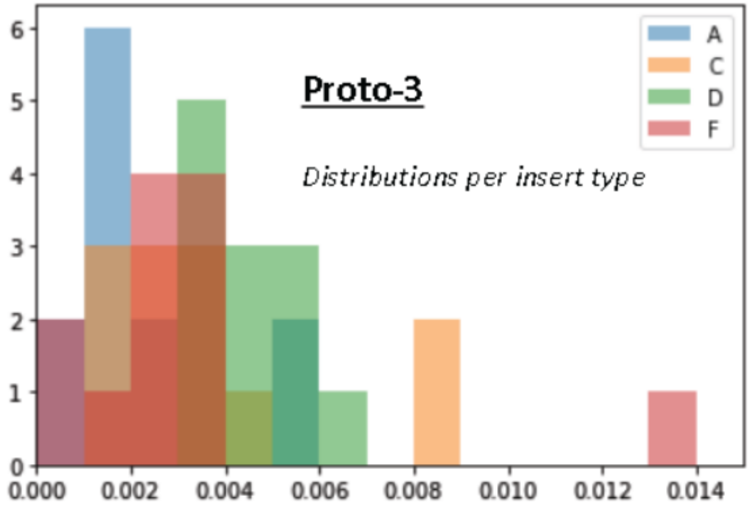

**Observations:**

- Measurement of the top surface, close to the hole
- Small inserts were not measured
- Mean planarity: ~ 3.5 µm
- 90% of inserts with planarity < 5 µm

**Remark**: CMM accuracy/repeatability of about 3.5 µm

**Conclusion: measurement show good planarity for the inserts**

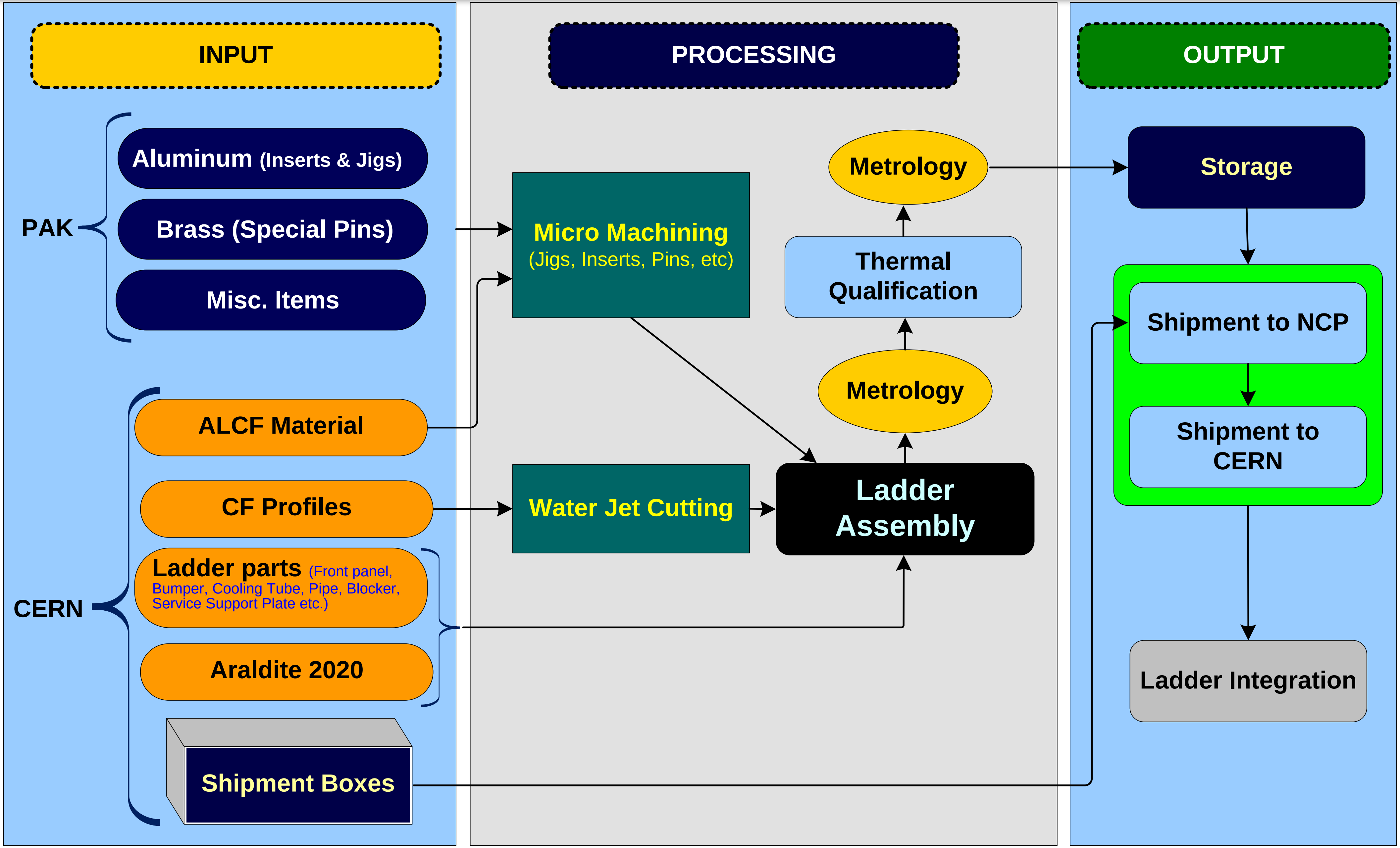


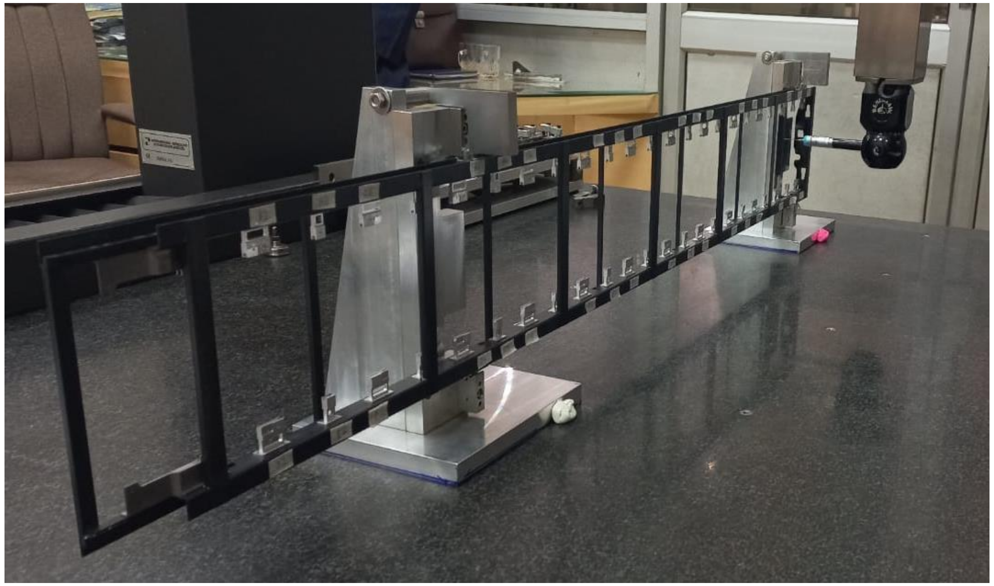

Slide from Eric Chabert, presented on 24/11/2021 at CERN

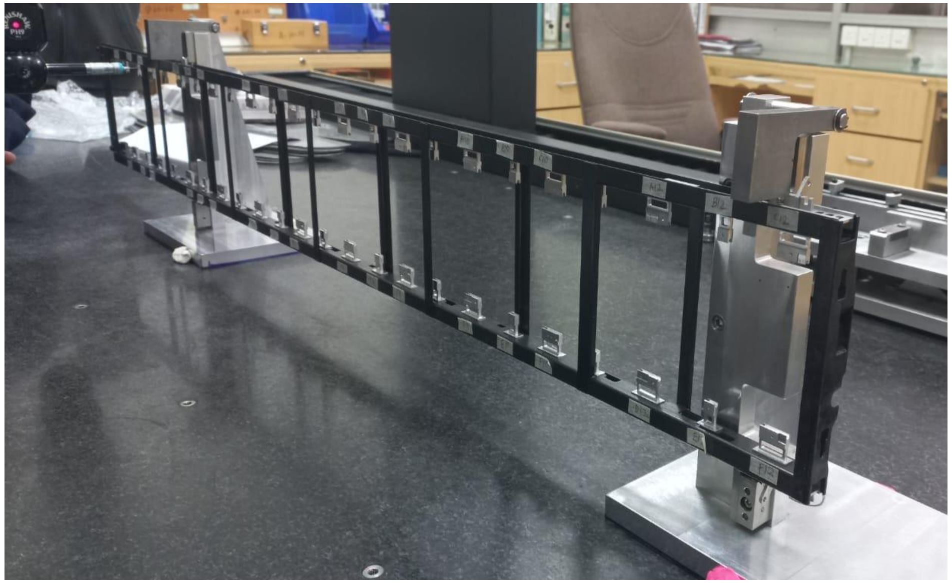
# TB2S Ladders Pre-Production/Production

# TB2S Ladders Assembly Workflow

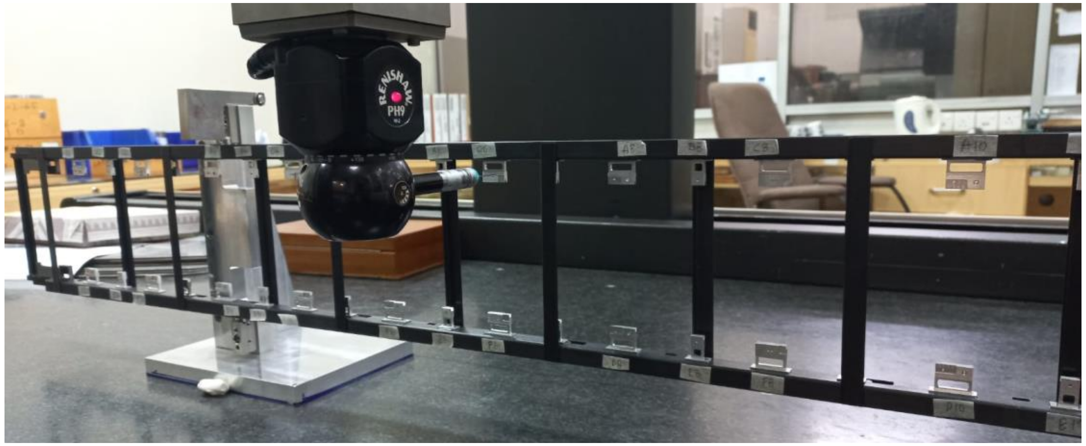


# Pre-Production: Metrology at CMM (dedicated setup)

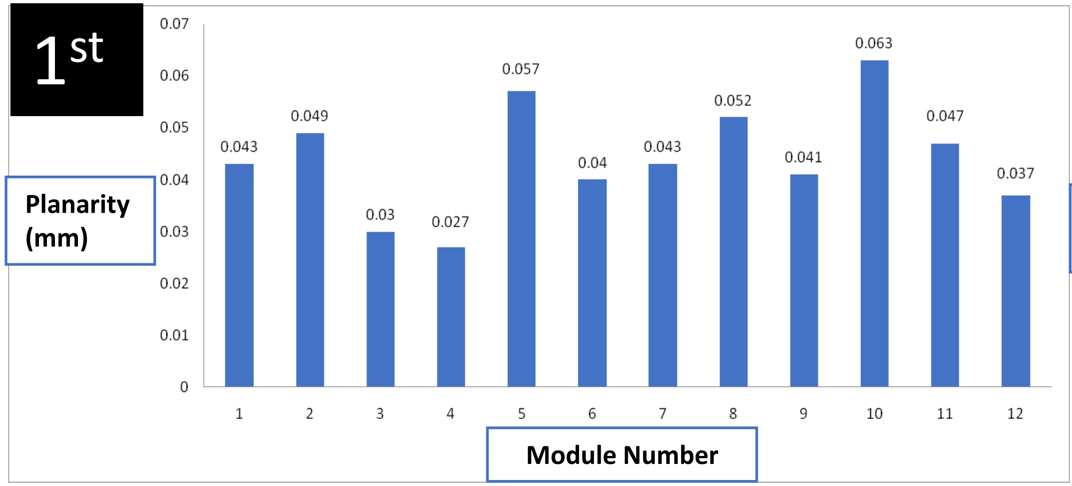


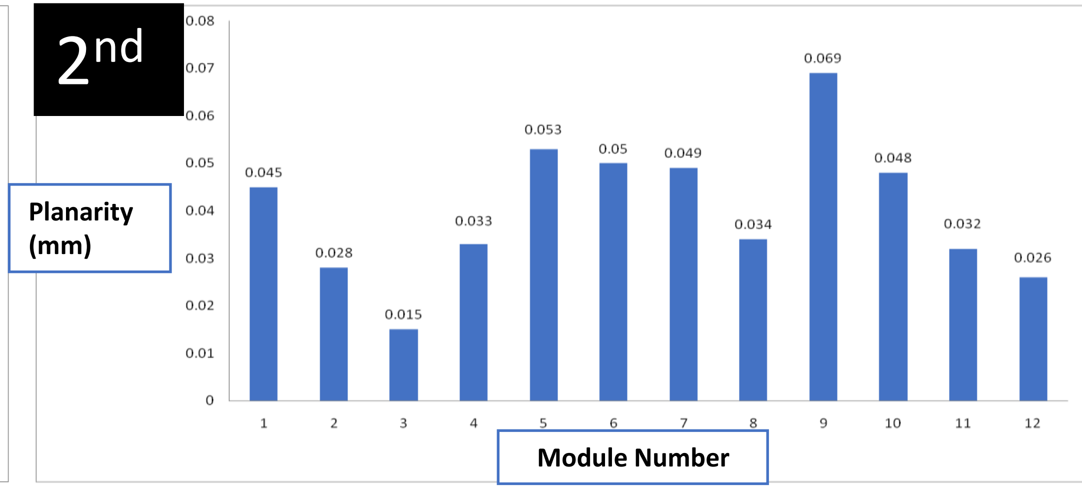


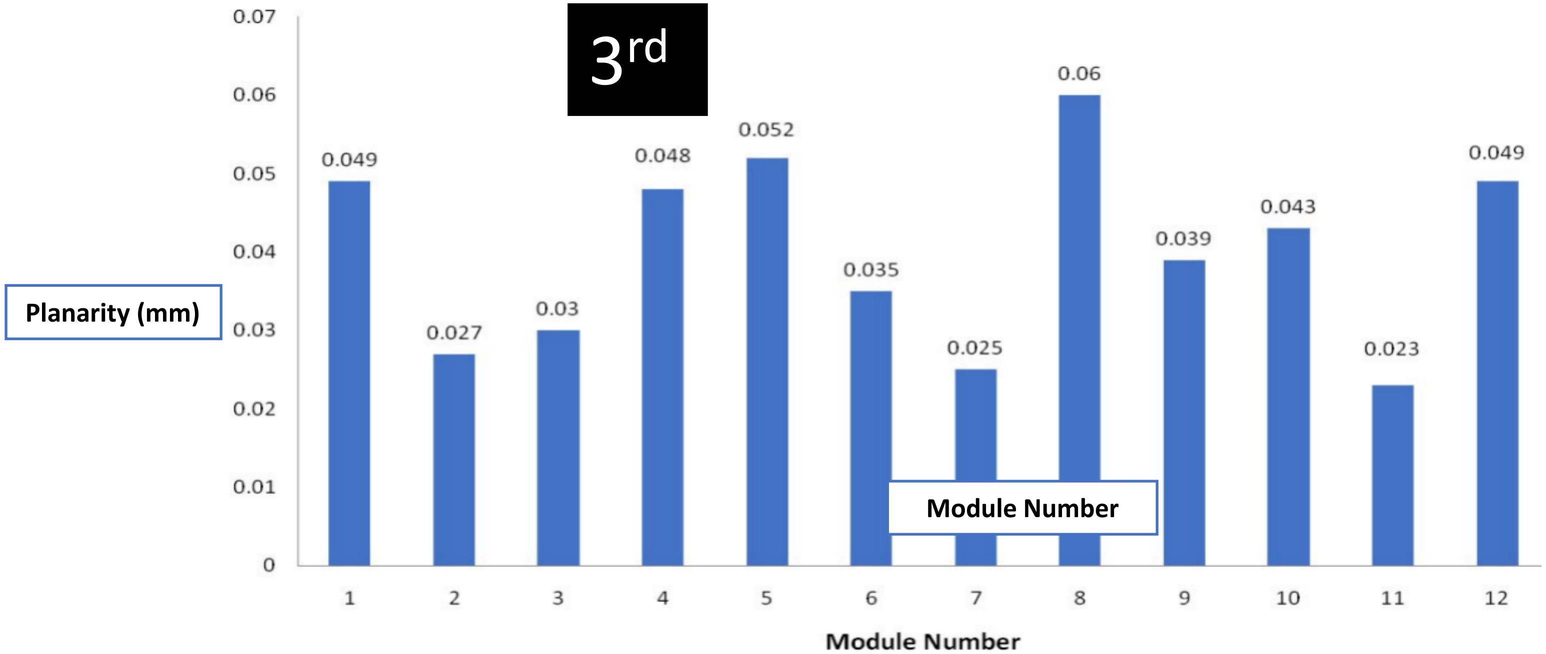
- The dedicated metrology setup is prepared
- It has already been utilized to perform metrology on the three pre-production ladders.



# Planarity of Pre-Production Ladders

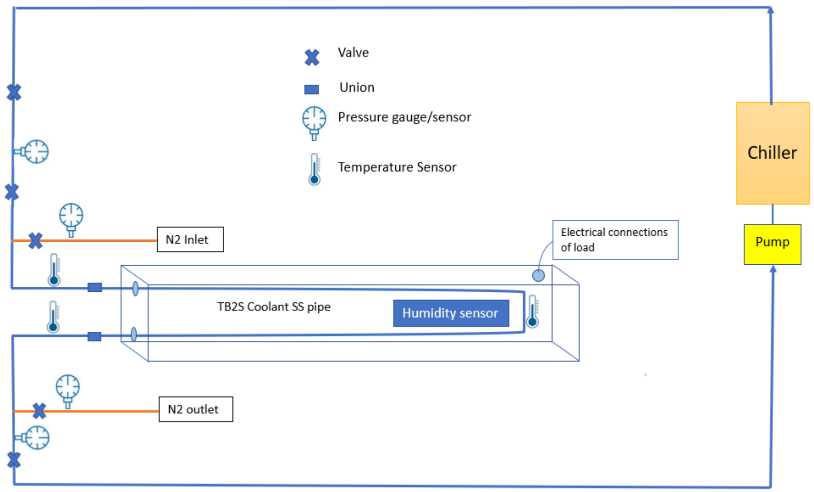


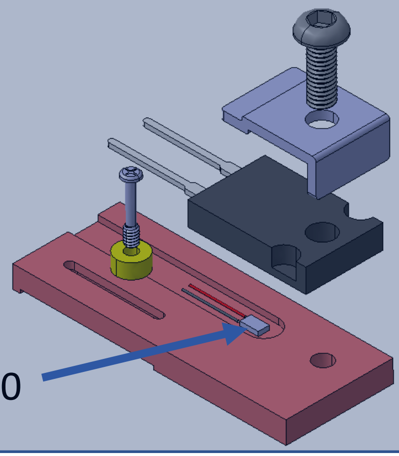



# Thermal Qualification setup

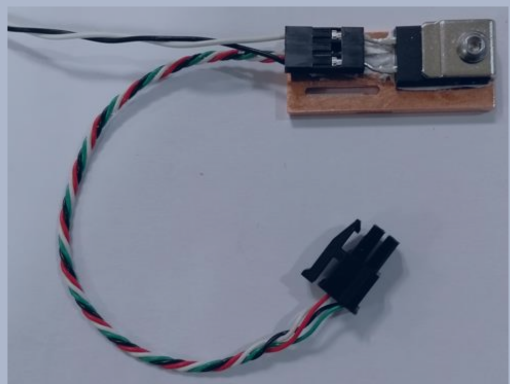
- A dedicated thermal qualification setup has been built at NCP and relocated to the company.
- A comprehensive thermal qualification procedure document has been drafted.
- To study the thermal performance of the ladder, equivalent twelve 2S modules load is applied by using heating elements

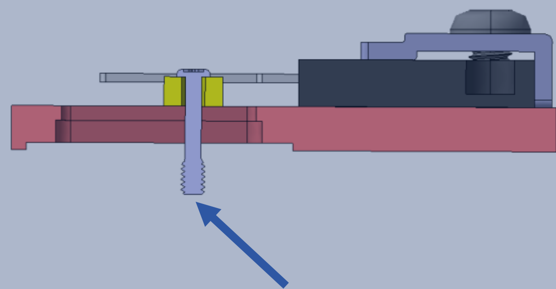


PT1000


Arcol series AP851 resistor, 120 Ω, ± 1%, 50W

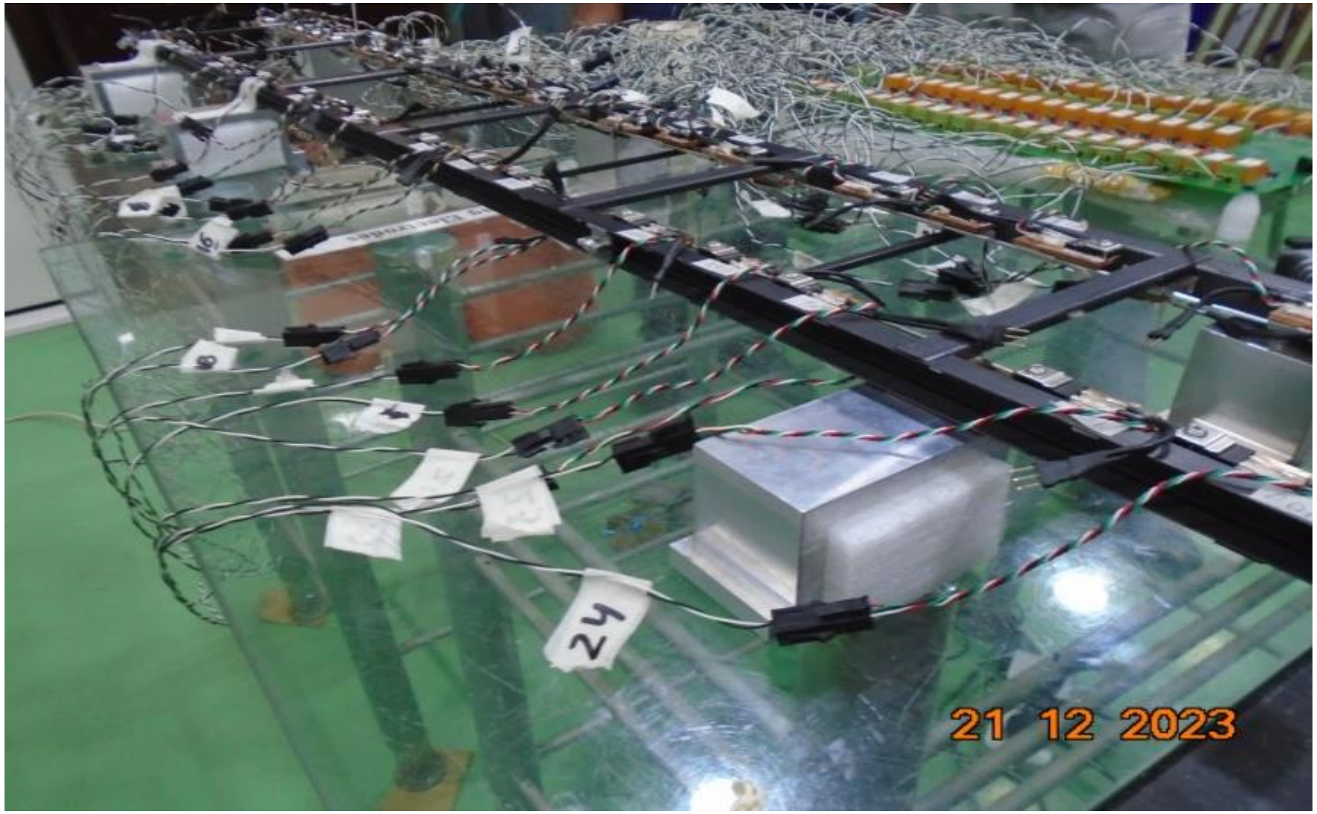




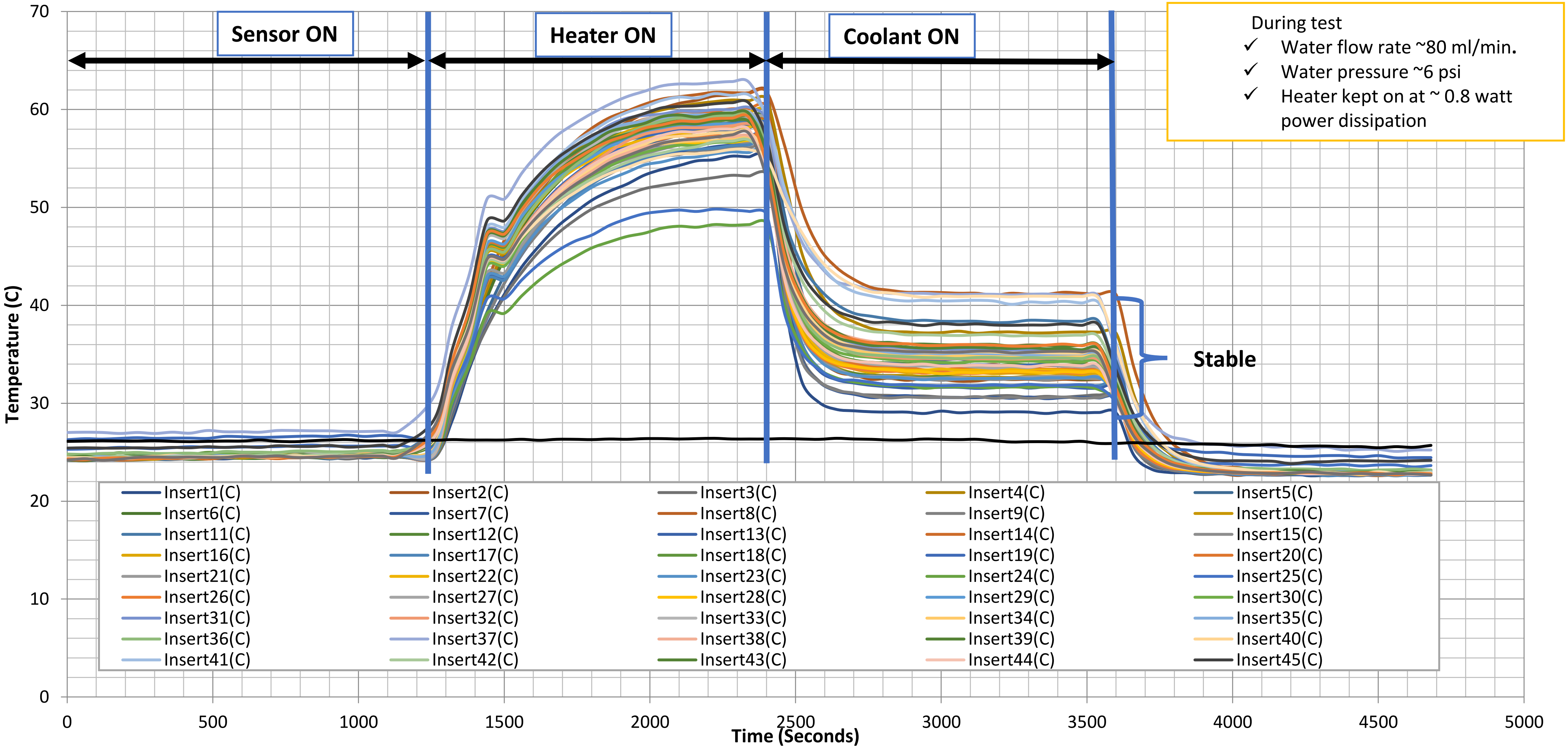
Captive Screw

# Thermal Qualification of the Pre-Production Ladder

- Forty-eight heating elements installed
- Each heater dissipating approximately 0.8 Watts
- The thermal response is monitored
- Torque ~6cNm
- **Three pre-production** ladders qualified



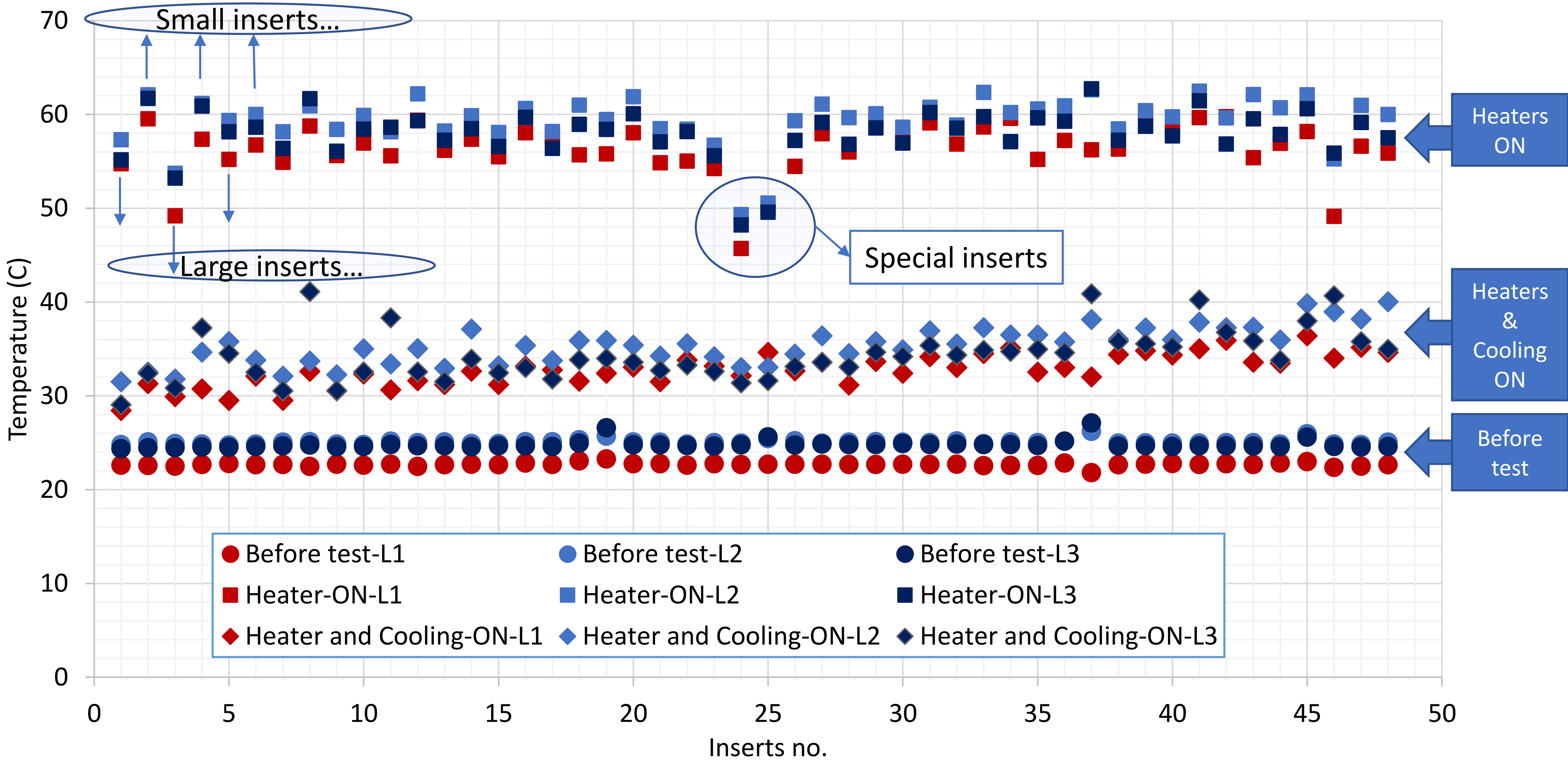
# Thermal QC of the 3rd Pre-Production TB2S Ladder




During test

- ✓ Water flow rate ~80 ml/min.
- ✓ Water pressure ~6 psi
- ✓ Heater kept on at ~ 0.8 watt power dissipation

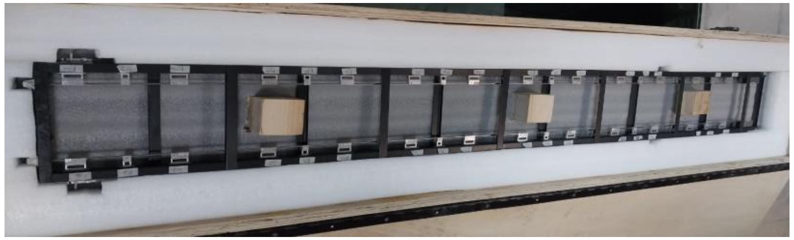
# Thermal QC of three Pre-Production Ladders



# Pre-production ladders

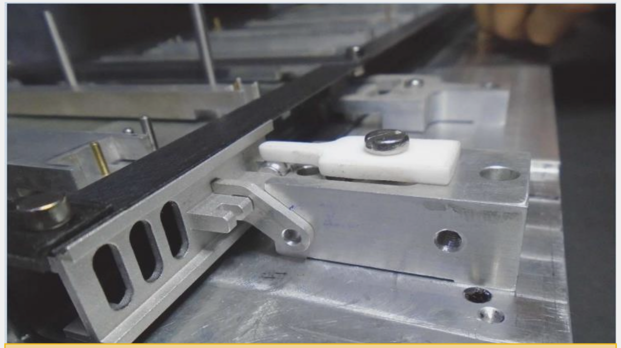
**Fourth pre-production** ladder assembly is in progress with modified Jig design.

First pre-production ladder shipped to CERN on Jan. 10, 2024



2nd and 3rd pre-production ladder shipped to CERN on 16 May 2024

Support sphere Type II Fitment Trials



Support sphere Type I Fitment Trials

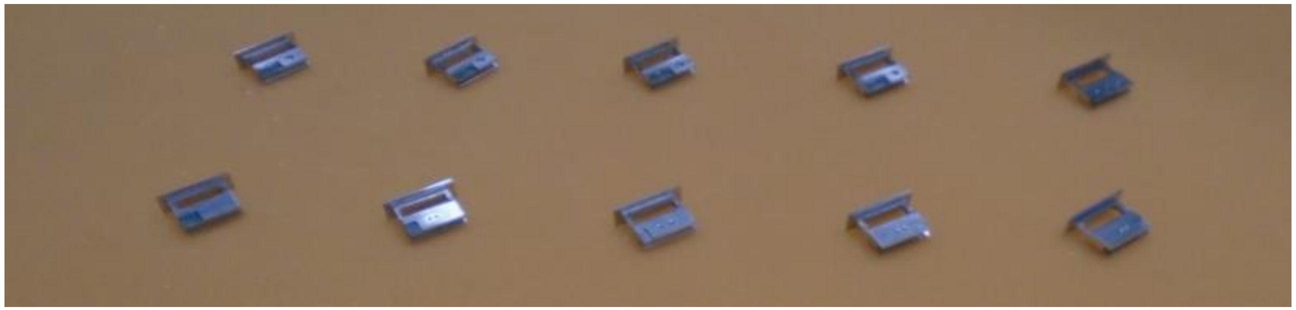
Six precision granite control tables added for assembly on Jig 1.

# Inserts Manufacturing Summary

| | Qty Completed | Enough for no. of ladders |
|---|---|---|
| Small Insert | 1336 | ~61 |
| Special Insert | 97 | ~49 |
| Large Insert Z-ve | 1635 | ~68 |

Design for Z+ ladders is being finalized at CERN





# Cold Test of 1st Pre-production Ladder at CERN

## Test with 2S_18_5_NCP-00102

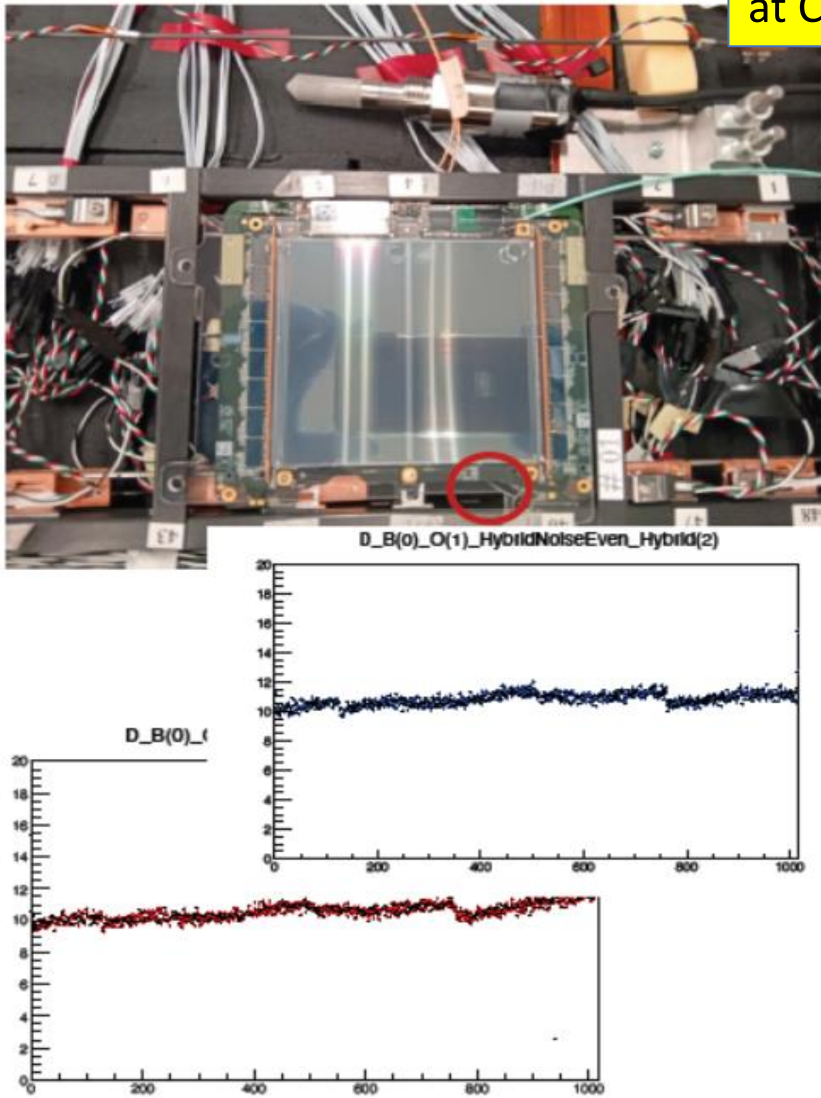
NCP module on NCP Ladder at CERN

- Ground balancer not connected.

- Module tests :
  - At room temperature in the single test box and on the ladder,
  - on the ladder, without screwing => verify the module works in cold,
  - On the ladder with screws at nominal torque 10cNm.

- During the test :
  - Pedenoise taken at about 15°C, 0°C, -15°C, -20°C, -25°C, -30°C, -35°C,
  - One wire bond connection a bit loose FIXME chip+strip numbers, working and not working a bit randomly,
  - One wire bond stopped to work at some point.

- After the test and the module is removed from the ladder, and removing the electrical pigtail => service hybrid mechanically disconnected.
  - not glued in the first place,
  - Should we glue for the full ladder test ?




8

Slide from Jeremy Andrea

# Cold test of Ladder with 12 2S Modules (first test!)

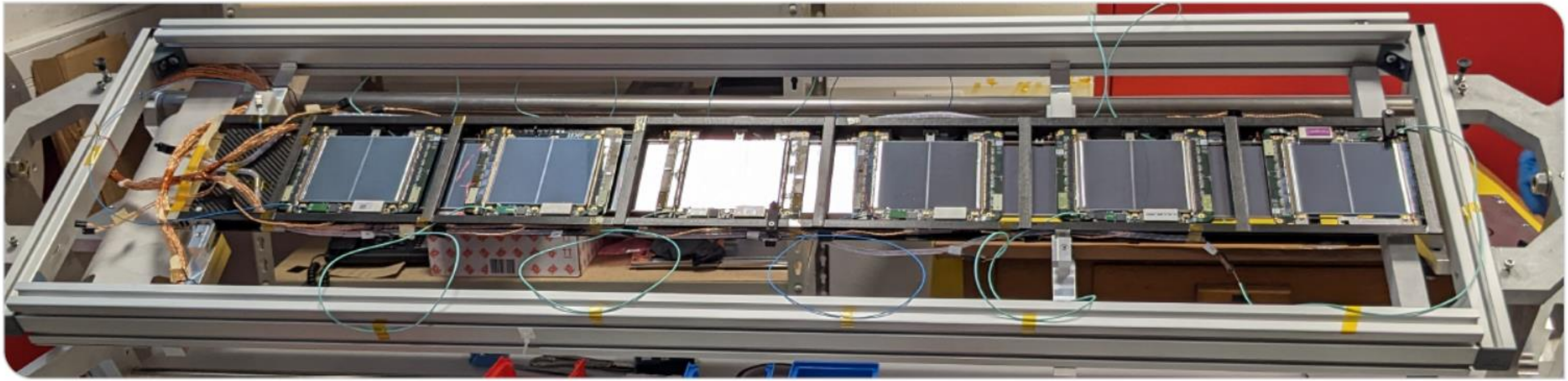
KIT
Karlsruhe Institute of Technology

CMS Germany

ETP
Institute of Experimental Particle Physics

## Preparation of TB2S Ladder Cold Test at CERN

Mohsin Abbas (CERN), Jeremy Andrea (IPHC), Irfan Asghar (NCP), Pier Filippo Cianchetta (CERN), Laurent Gross (IPHC), Clément Hass (IPHC), **Lea Stockmeier** (KIT), Cristiano Turrioni (Perugia), Giovanni Zevi Della Porta (CERN), | June 13, 2024

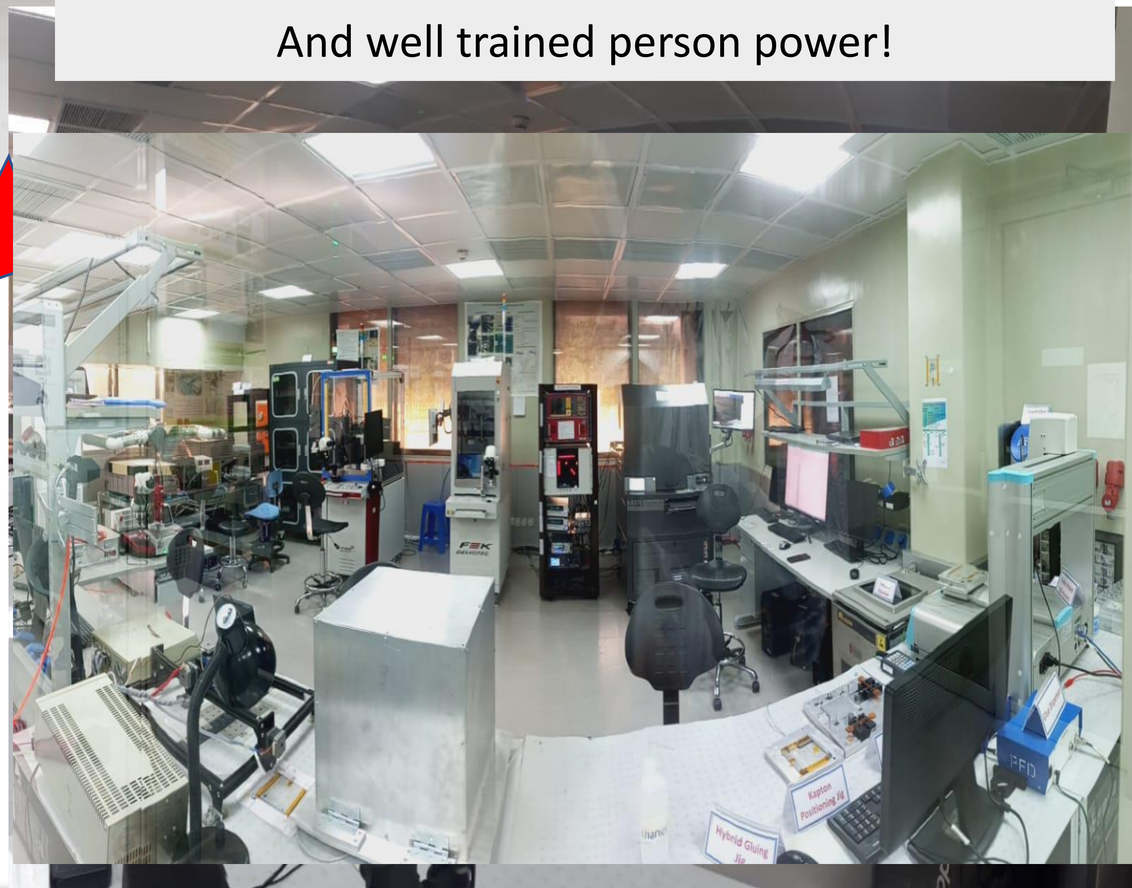


KIT – The Research University in the Helmholtz Association

www.kit.edu

GEM QC Setup in 2018

Well-equipped Semiconductor detectors Lab in 2023!
And well trained person power!

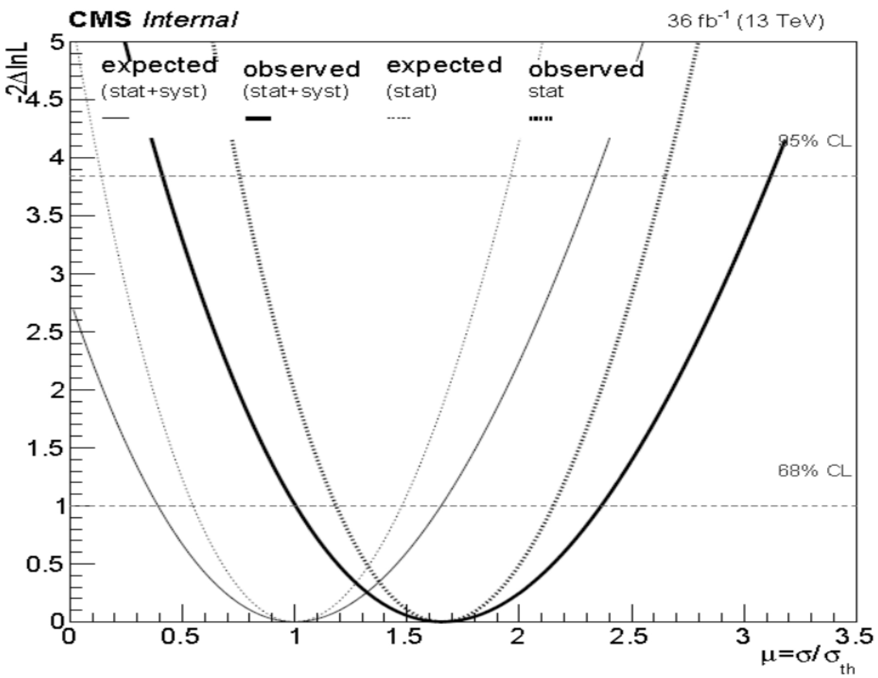


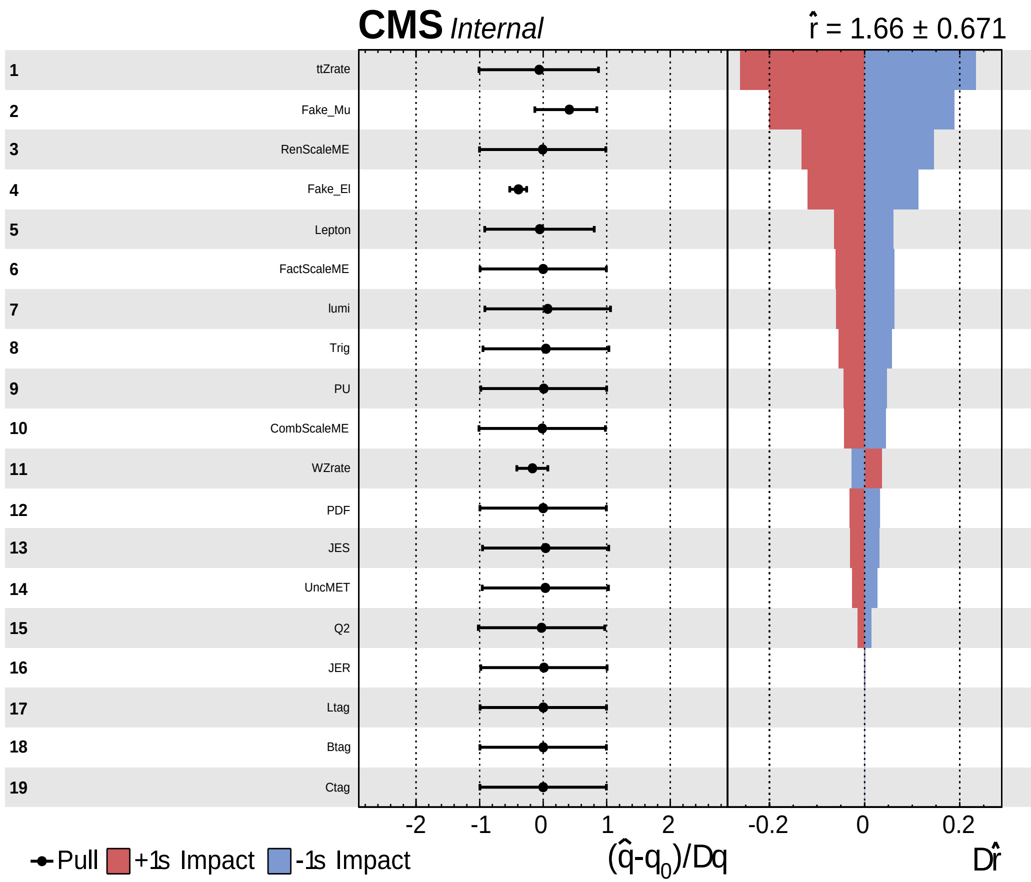
# Physics Projects: Some Physics Analysis Projects Finished at NCP

- The cross section measurement of top quark in association with Z boson (Measured for the first time in any HEP experiment)
  - Analysis Note: CMS/AN-14-182 and CMS/Top-12-039 (published in JHEP, arxiv.org/abs/1702.01404)
  - Analysis at 13 TeV, Note: CMS/AN-16-285, CMS/Top-16-020 (published in PLB)
- Measurement of ttabr cross-section in l+jets channel at 13 TeV
  - Documented in CMS Paper: Top-16-006
- Search for Microscopic Black Holes with the Early Run 2 CMS Data
  - Documented in CMS Paper: EXO-15-007
- Measurement of CKM matrix elements in single top quark t-channel production in proton-proton collisions at sqrt (s) = 13 TeV
- Measurement of the single top quark and antiquark production cross sections in the t-channel and their ratio in proton-proton collisions at sqrt{s}= 13 TeV
- Measurement of the inclusive single top t-channel cross section at 13TeV (2016 data) CMS-TOP-17-001

# tqZ Results @ 13 TeV

## Signal Strength Calculated by simultaneously.
## Fitting tZq and ttZ region




**Expected Signal Strength : 1.66 $^{+0.66}_{-0.60}$**

**Expected Significance : 1.95 ± 0.09 σ**

**Observed Significance : 2.81 σ**

$$\sigma_{tZq}(measured) = 156^{+47}_{-42}(stat)^{+40}_{-34}(syst)fb$$

First measurement of tqZ!

Feasibility studies of further rare top processes are in progress.

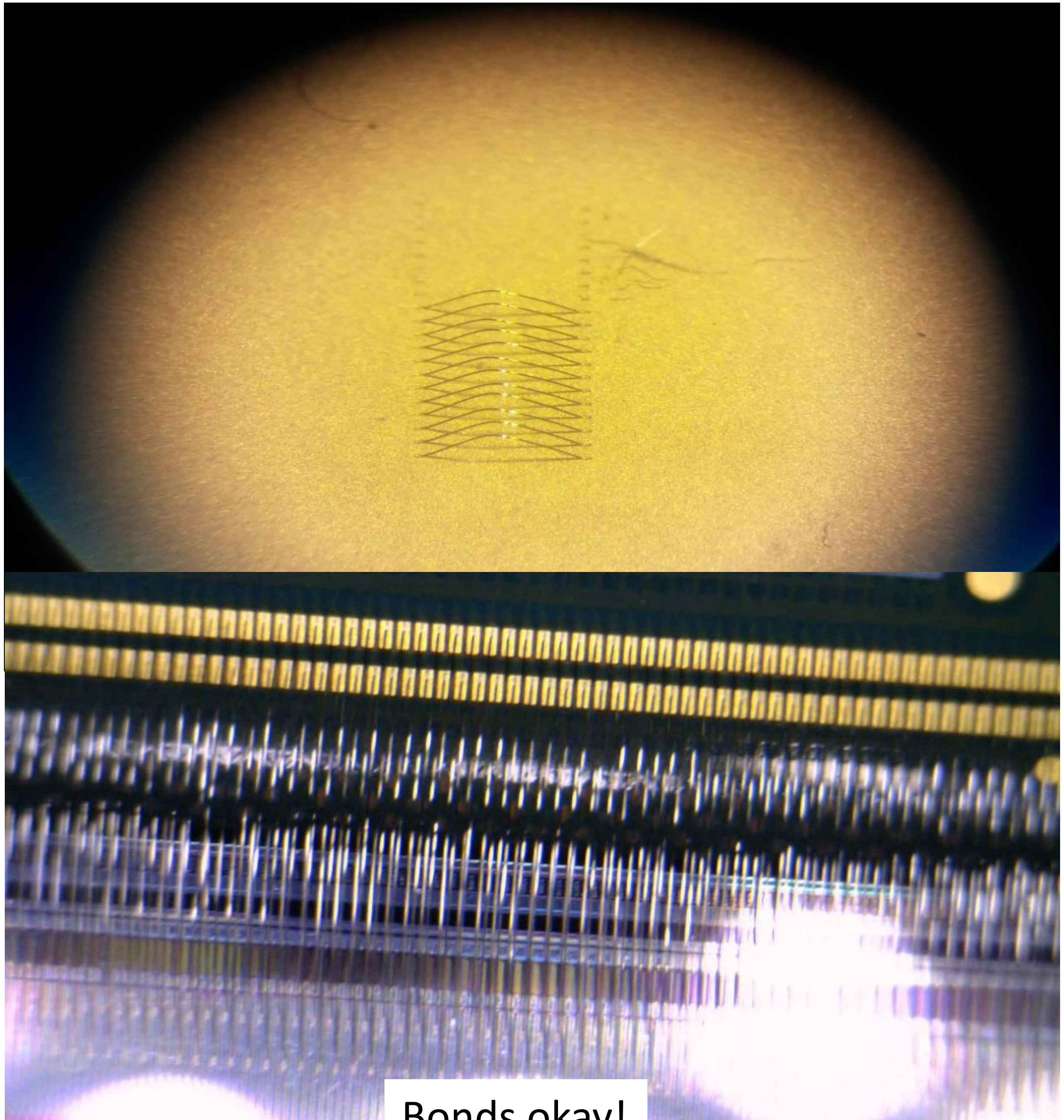
# Summary

➢ The three main Phase-2 upgrade projects are progress well

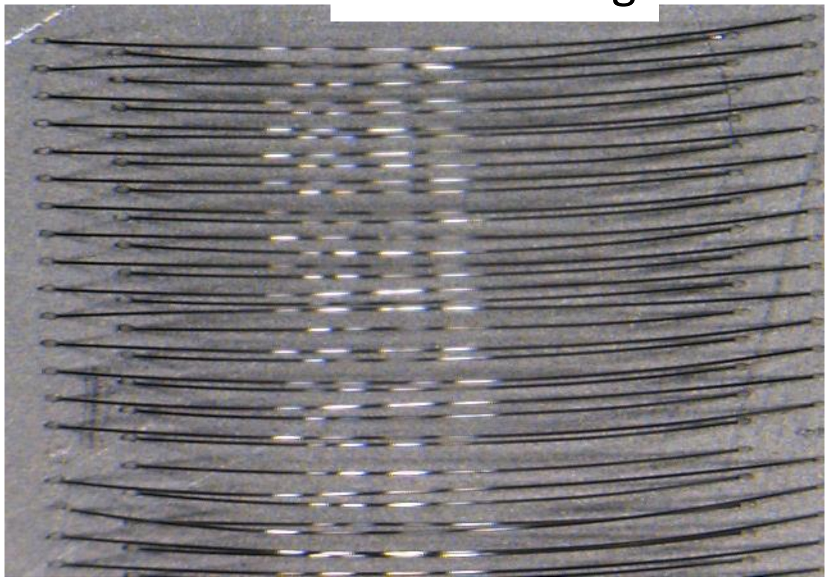
1. SQC status: The last batches of Silicon sensor qualification are being tested. The project is going to finish this month
2. Module Production: Ready for production, kickoff modules assembled and tested. One kickoff module is at CERN now. Production will commence as soon as module components arrives.
3. Ladder production: In progress in a local company
4. GEM (GE1/1) project successfully finished

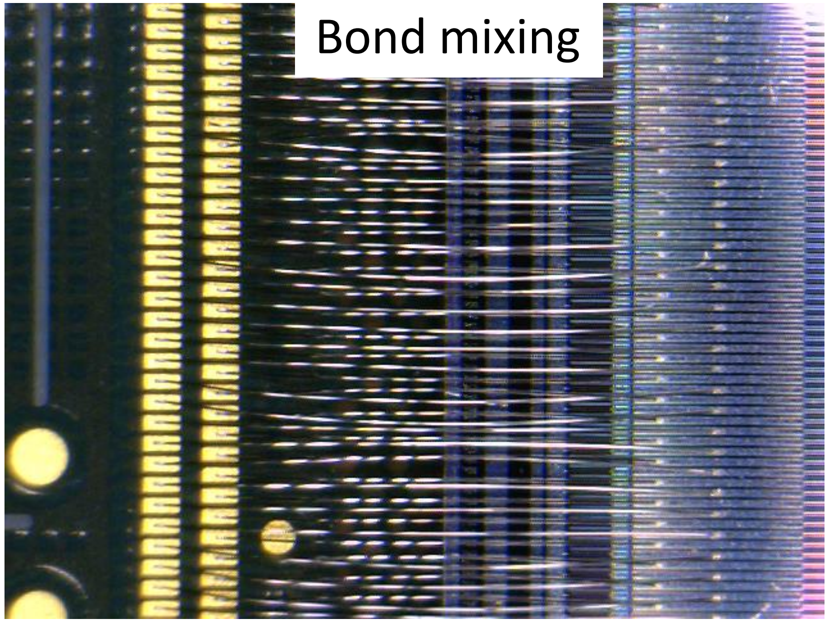
# Thank You!

# Some wire bonds silicon and hybrid!




Bonds mixing





# Outer Tracker R-Z view

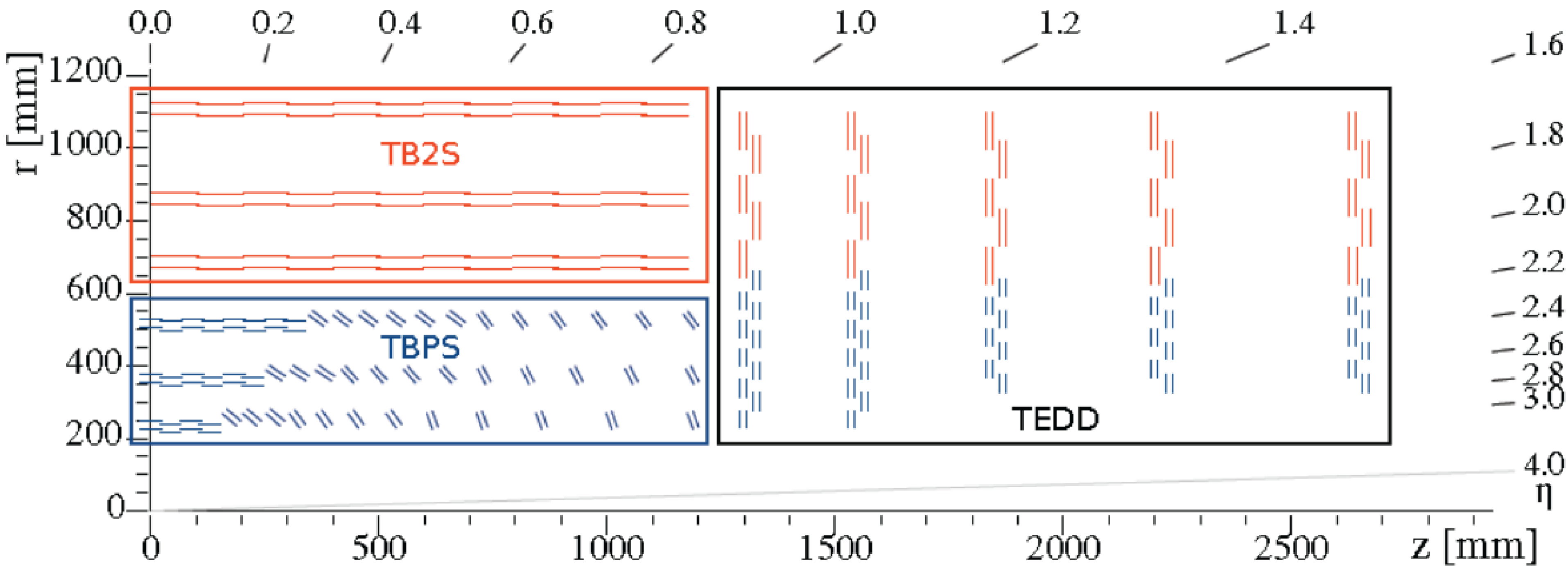
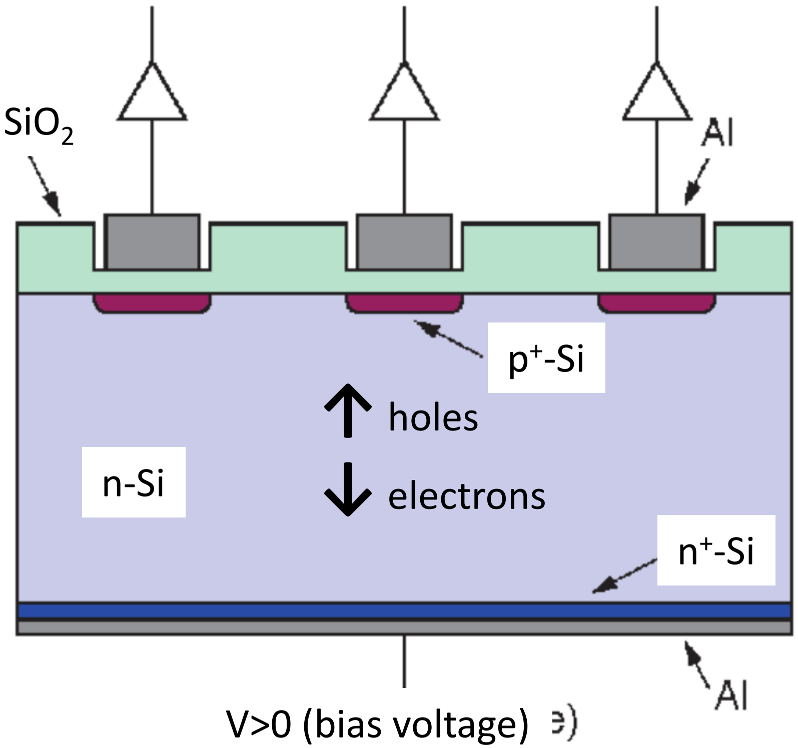
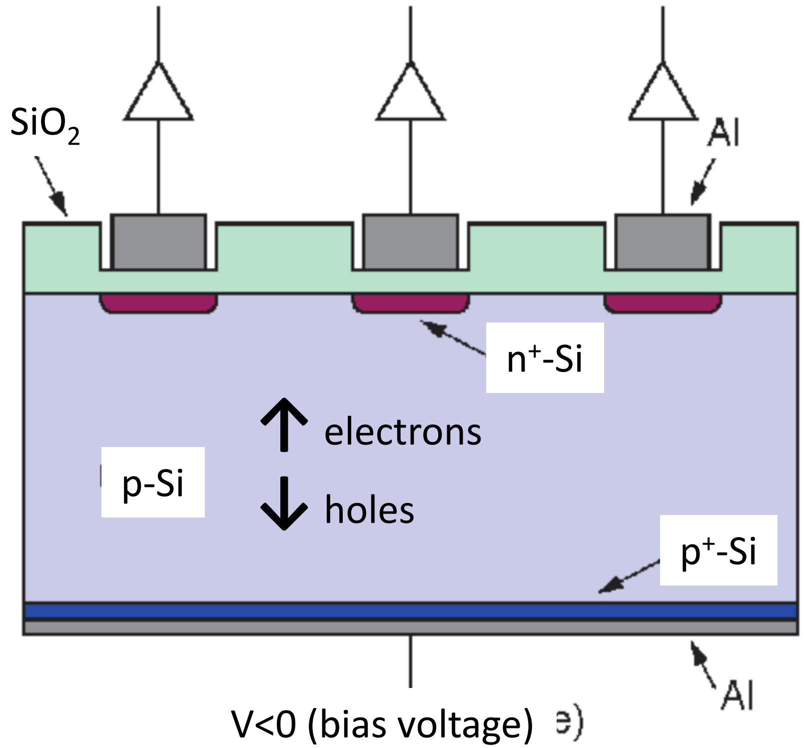



Figure 3.1: Sketch of one quarter of the Outer Tracker in *r*-*z* view. Blue (red) lines represent PS (2S) modules. The three sub-detectors, named TBPS, TB2S, and TEDD, are indicated. All overlapping layers are shown separately, while in Fig. 2.3 the mean positions are shown.

# Other designs



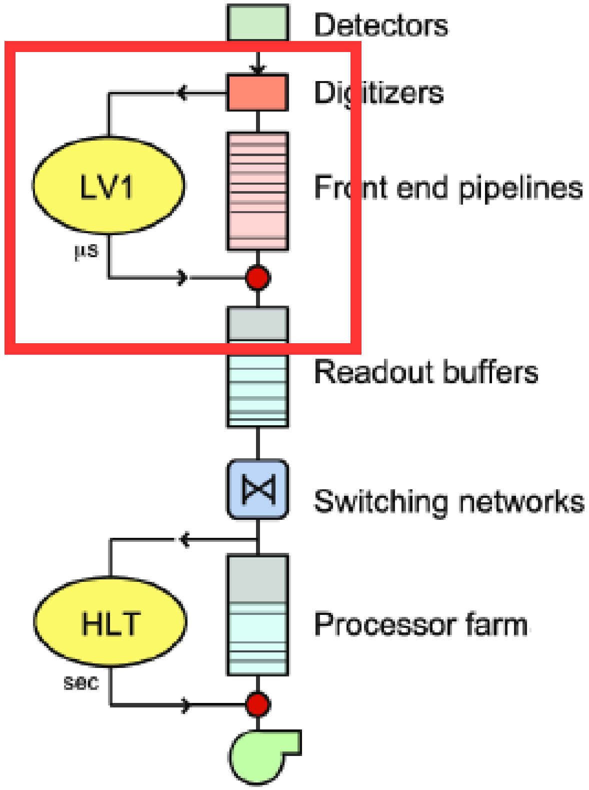

**p-in-n, AC coupled**




**n-in-p sensors**

# Two Level Trigger System

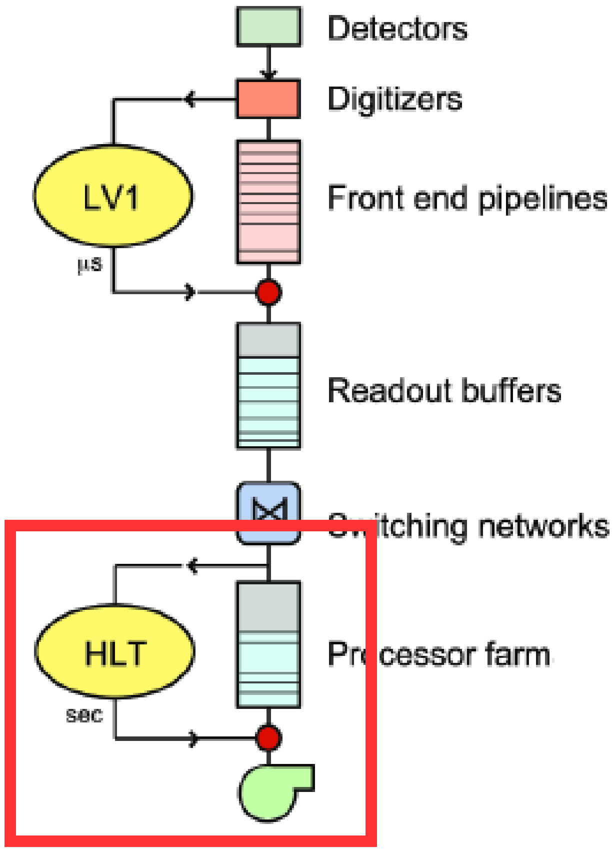
- **Level-1 Trigger (L1T)**
  - Hardware-based Trigger
  - Uses low-res detector information from calorimeter and muon
  - No tracker in the trigger decision
- Data stored in on-detector buffers
  - 3.8 μs to take a decision
  - Limited by tracker buffer size




- Data bandwidth reduced from 40 MHz (as delivered by detector) to 100 kHz (~ 100 GB/s)

# High-Level Trigger (HLT)

- Dedicated Computer farm with ~ 26000 cores
  - Using full-detector information
  - Two-stage event selection
    - Only calorimeter, ~ 50 ms
    - Full-detector, w/ tracking & PF, ~ 1 sec
- Data rate is reduced from 100 kHz -> 1kHz
  - ~ 1 GB/sec, which is stored on disk
- Plan to use tracker at LVL1 in HL-LHC
  - Improved resolution, identification, pile-up rejection
  - Max rate 100 → 750 kHz
  - Latency 3.8 → 12.5 μs
- HLT
  - Output rate 1 kHz → 7.5 kHz
  - Even higher computing power would be needed

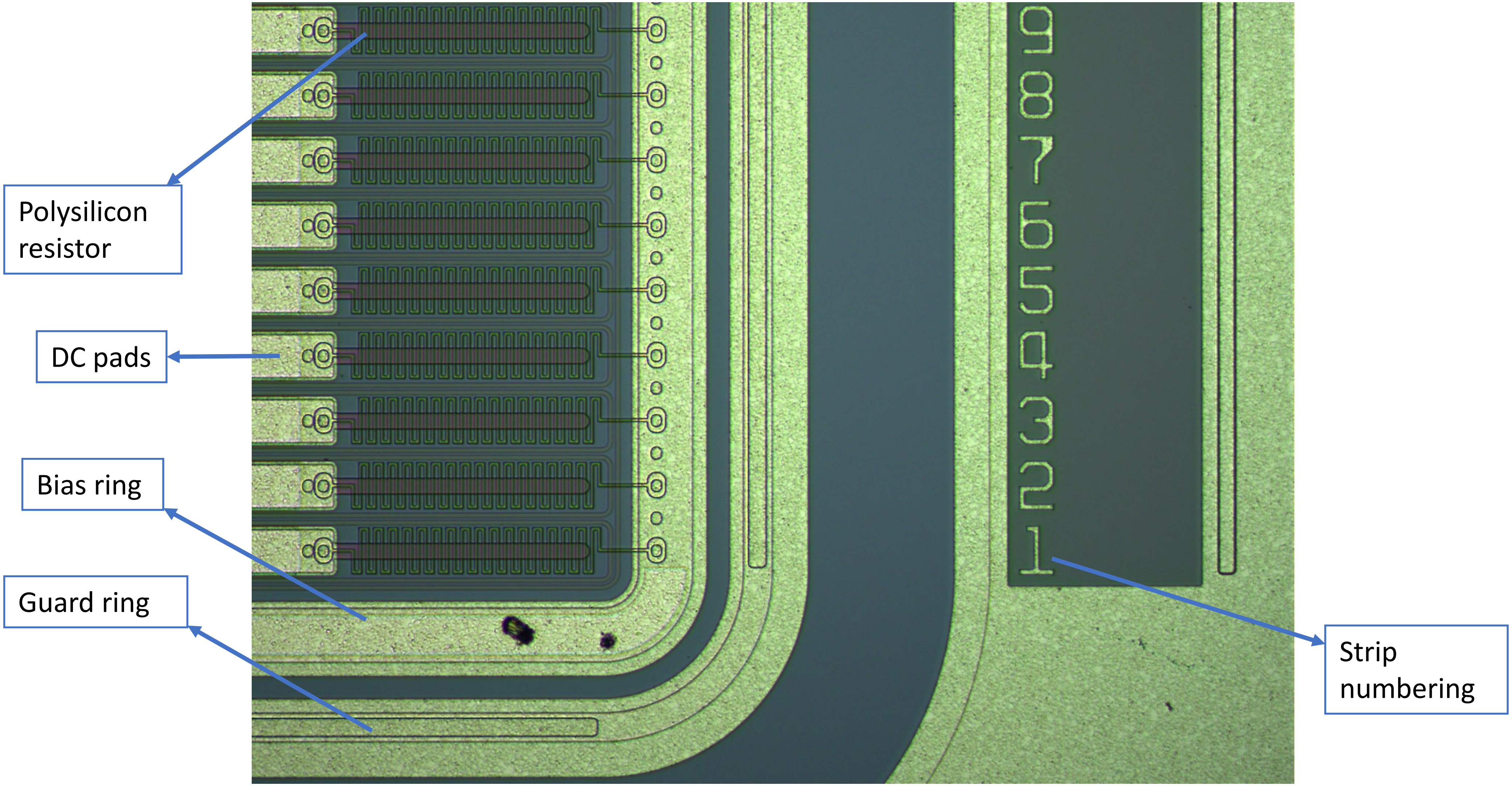


# Sensors to qualify for the CMS phase-II upgrade project

| Type | Outer | | Active | | Strip/Pixel Cell | | Quantity needed |
|---|---|---|---|---|---|---|---|
| | width | length | width | length | pitch | length | |
| **2S** | **94 183** | **102 700** | **91 488** | **100 703** | **90** | **50 260** | **15 216** |
| **PS-s** | 98 140 | 49 160 | 96 055 | 47 163 | 100 | 23 479 | 5 592 |
| **PS-p** | 98 740 | 49 160 | 96 055 | 47 163 | 100 | 1 467 | 5 592 |

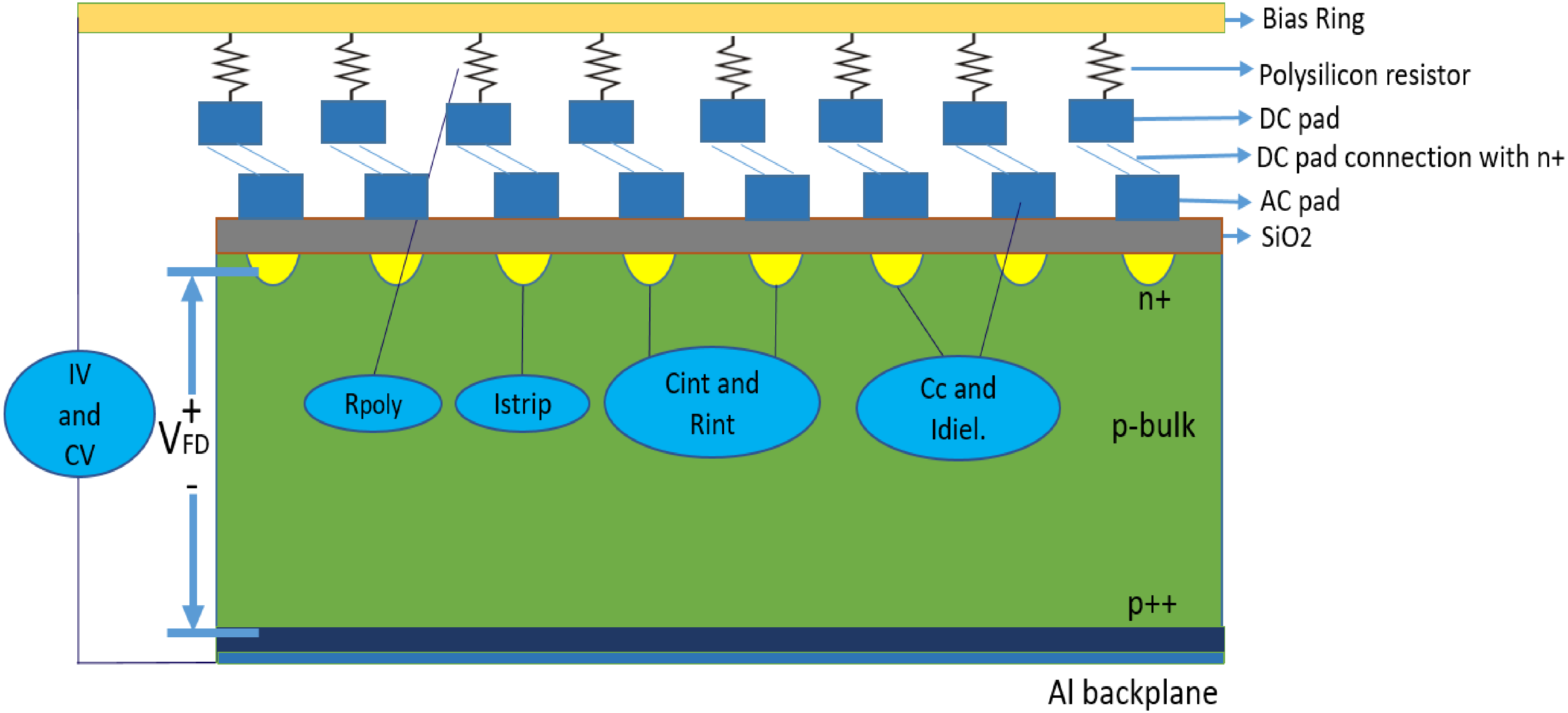
## At NCP SQC site- 2S sensors

The 2S and PS-s strip sensors share a common design of the periphery (bias, guard and edge ring) and also the active strip area is identical with exception of the strip pitch and length

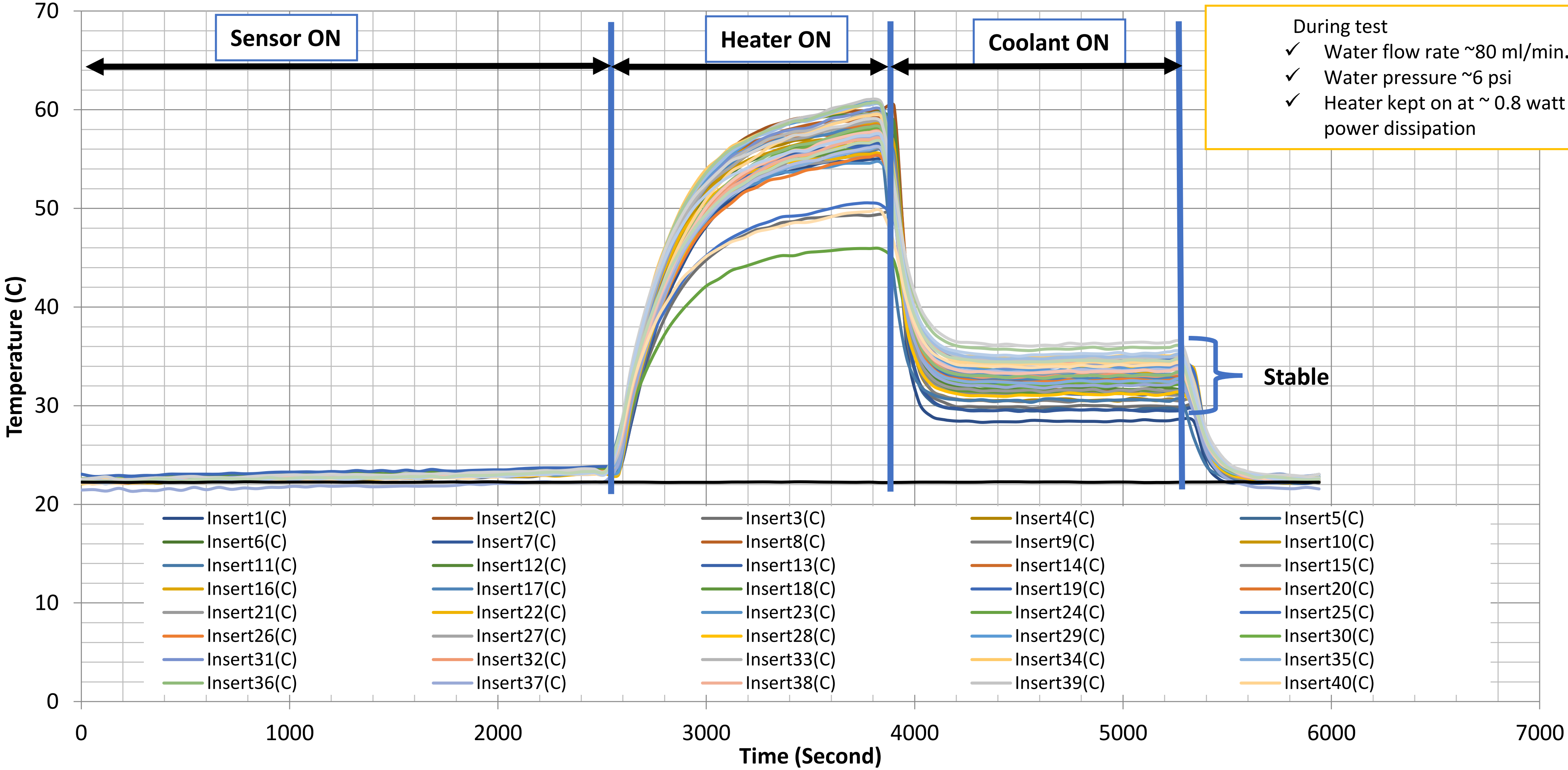


Polysilicon resistor
DC pads
Bias ring
Guard ring
Strip numbering
9
8
7
6
5
4
3
2
1

# SQC proposed tests

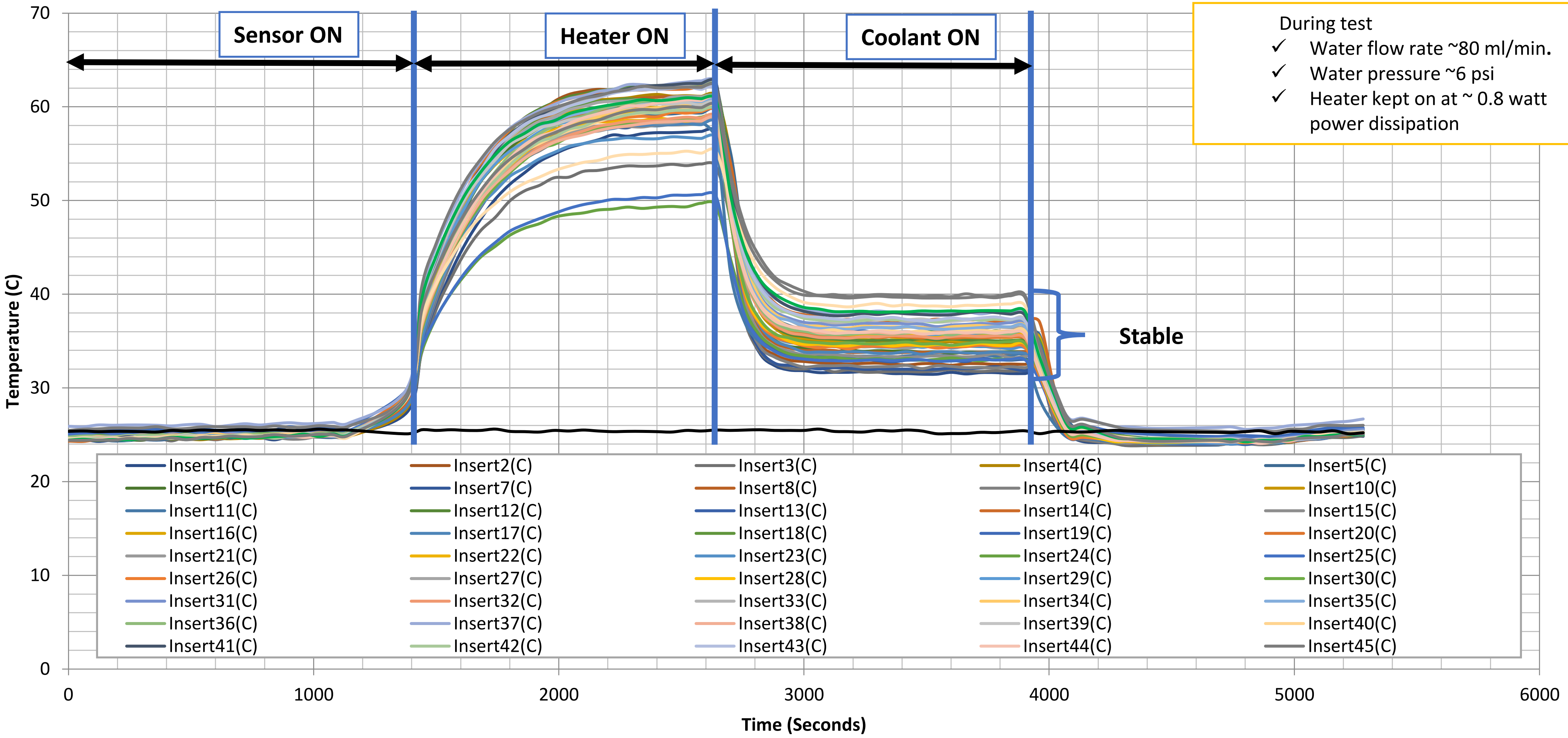


# Thermal QC of the 1st Pre-Production TB2S Ladder




During test
- ✓ Water flow rate ~80 ml/min.
- ✓ Water pressure ~6 psi
- ✓ Heater kept on at ~ 0.8 watt power dissipation

# Thermal QC of the 2nd Pre-Production TB2S Ladder




During test

- ✓ Water flow rate ~80 ml/min.
- ✓ Water pressure ~6 psi
- ✓ Heater kept on at ~ 0.8 watt power dissipation