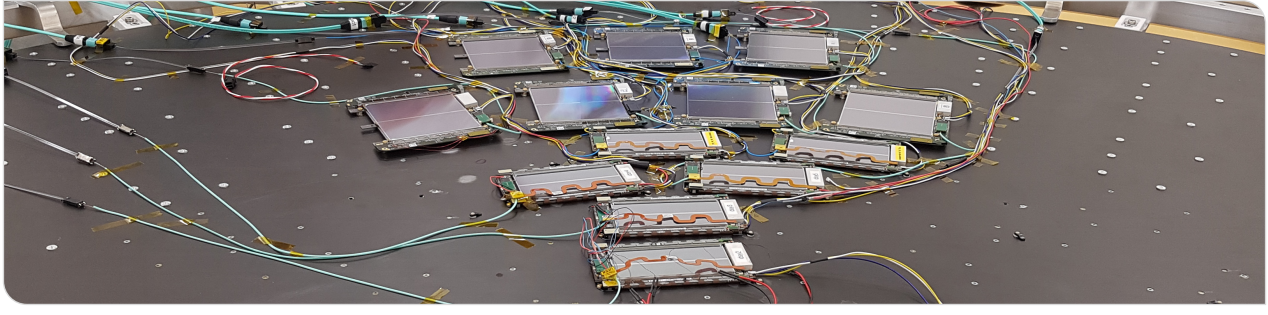
System and Integration Tests with CMS Phase-2 Outer Tracker Module Prototoypes

Lea Stockmeier | March 13, 2024



Outline

- The CMS Experiment and the High Luminosity LHC
- The CMS Phase-2 Outer Tracker Upgrade
- Integration Tests
  - First TB2S ladder integration test
  - Thermal TB2S ladder integration test
  - Full TB2S ladder integration test
  - TEDD dee integration test
- Summary and Outlook

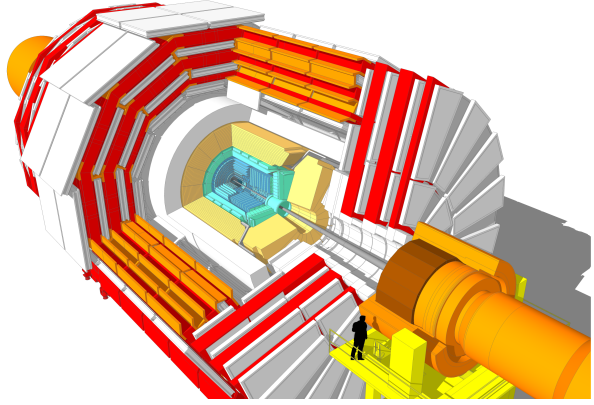
The CMS Experiment

and

The High Luminosity LHC

The Compact Muon Solenoid (CMS) Experiment

- One of the four multi-purpose detectors at LHC
- Subdetectors located cylindrically around beam pipe
  - Silicon tracker
  - Electromagnetic calorimeter
  - Hadronic calorimeter
  - Superconducting solenoid ($B = 3.8\,\mathrm{T}$)
  - Muon chambers
- Particle identification by unique (combined) signature in subdetectors



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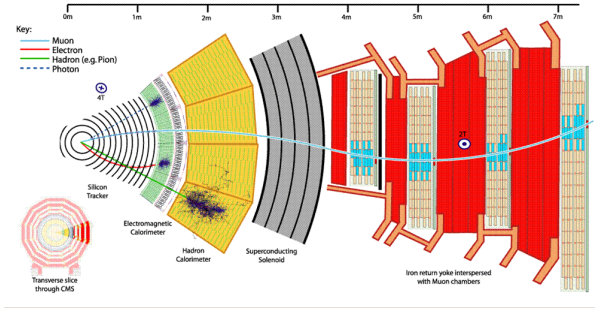


The High Luminosity LHC (HL-LHC)

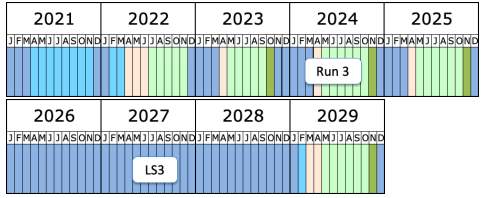
- LHC delivers proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ and 40 MHz bunch crossing rate

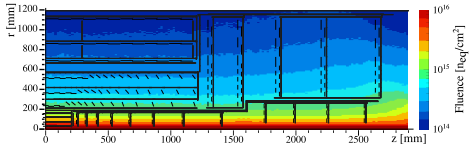
HL-LHC

- Begin of operation in 2029
- Increase of instantaneous and integrated luminosity
  - Smaller uncertainties on precision measurements of physics processes (e.g. Higgs coupling)

Impact on CMS

- Radiation levels increase
- Simultaneous interactions per bunch crossing increase from $\approx$ 30 up to 200
- Trigger system needs to be upgraded due to increased particle density
  - Include track information to trigger decision





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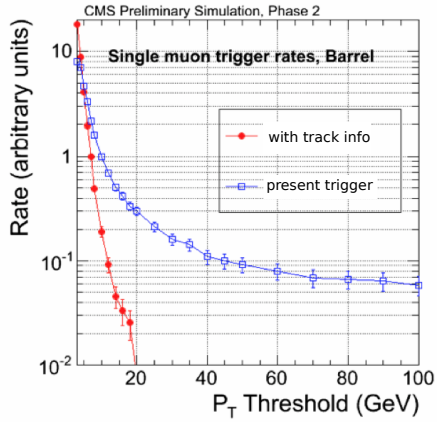
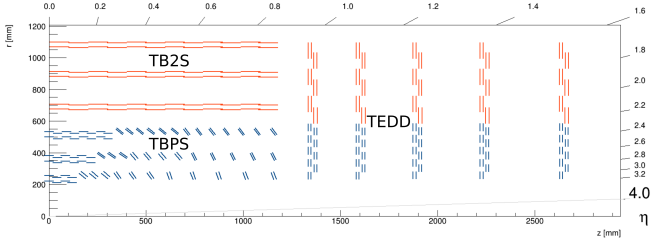


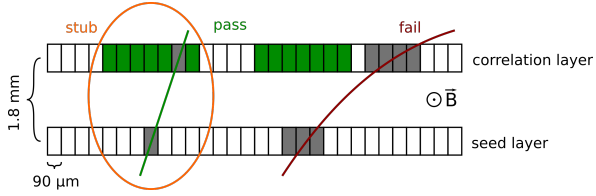
The CMS Phase-2 Outer Tracker Upgrade

CMS Phase-2 Outer Tracker Upgrade

- Full replacement of the CMS silicon tracker
- Features of the new tracker
  - Improved radiation tolerance
  - Increased granularity
  - Reduced material budget



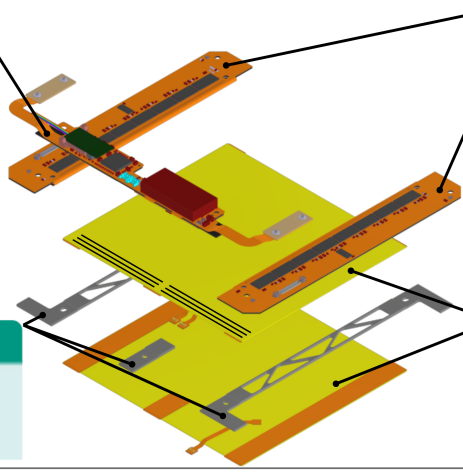
- Outer Tracker consists of 13 200 p_T-modules
  - 2S modules: strip/strip sensor
  - PS modules: pixel/strip sensor
  - Contribution to L1 trigger



2S Module for the CMS Outer Tracker

Service Hybrid

Powering
Data transmission



2 Front-end Hybrids

8 CMS Binary Chips[2] each

- Binary readout of sensor signals
- Fold-over to read bottom channels
- Identification of stubs

1 Concentrator Chip each

Al-CF[1] Spacer

Spacing between sensors
Main cooling path
Mechanical fixation

2 parallel silicon strip sensors

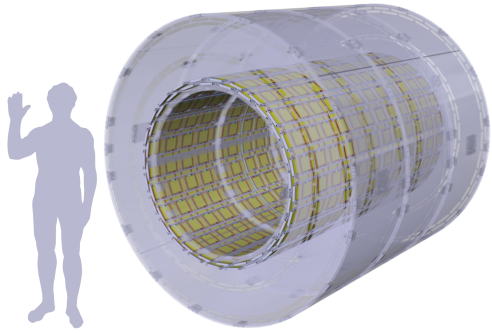
2×1016 strips each
5 cm length, 90 µm pitch

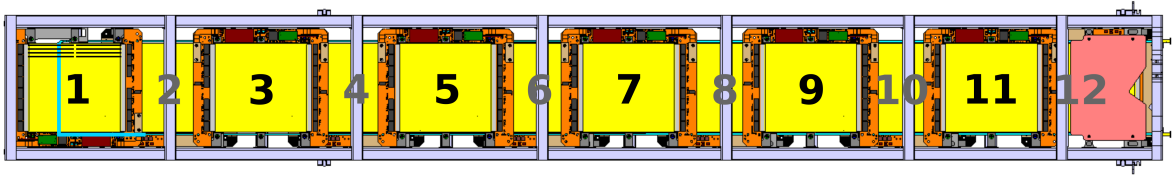
[1] Aluminum / carbon fiber composite

[2] Prydderch et al., *CBC3: a CMS microstrip readout ASIC with logic for track-trigger modules at HL-LHC*, CMS-CR-2017-383

Tracker Barrel with 2S Modules (TB2S) – Design

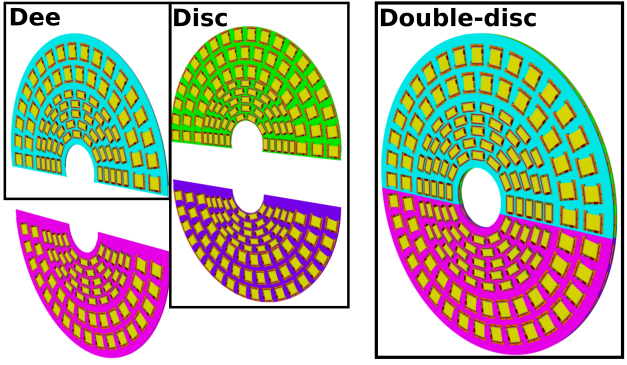
- Tracker barrel made of 372 ladders with twelve 2S modules each
- Length $\approx 2.4\,\mathrm{m}$
- Diameter $\approx 2.3\,\mathrm{m}$
- Two-phase CO_2 cooling to reach a sensor temperature of $\approx -20\,^{\circ}\mathrm{C}$

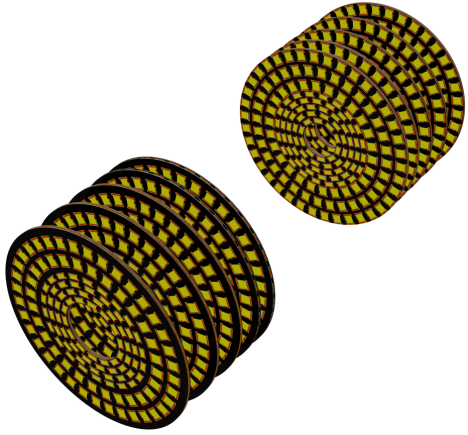




Tracker Endcap Double-Discs (TEDD) – Design

- Each double-disc formed by two discs of two "dees" provides one hermetic detector plane
- 1 TEDD unit formed by 5 double-discs





Module Assembly and Integration

- Production of CMS Phase-2 Outer Tracker
  - Module assembly at “assembly centers“
  - Module integration to detector structures at “integration centers“
  - Mounting of Barrel and Endcaps at CERN
- Performed several integration tests

⇒ This talk covers an overview of TB2S ladder and TEDD dee integration tests

Integration Tests

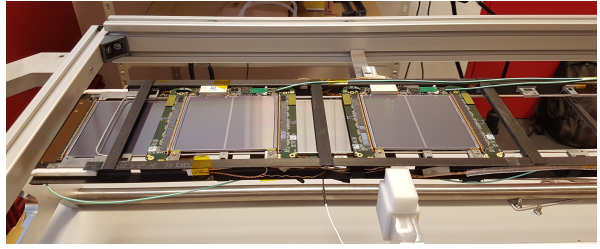
Mounting modules on final detector structures and performing functional tests

- Test module integration itself
  - Module handling
  - Tooling
- Test optical and electrical services
- Test power supplies
- Test cooling performance
  - Validate Finite Volume Method (FVM) simulations
- Test electrical performance of the modules on the structure

Integration Tests

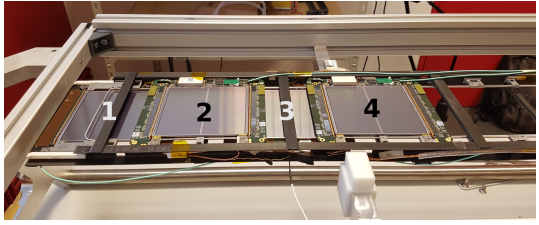
First TB2S Ladder Integration Test – Overview

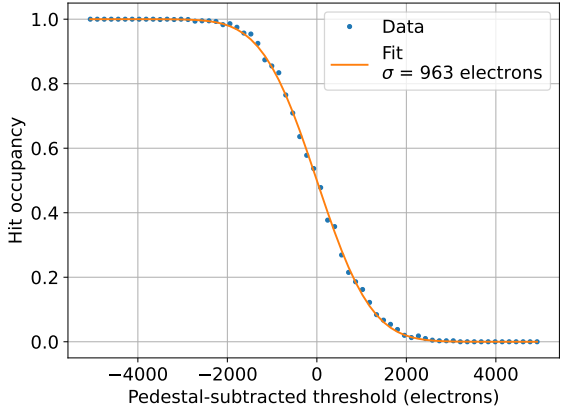
- December 2021 at IPHC in Strasbourg
- Four 2S modules integrated on a TB2S ladder prototype
  - First time of mounting 2S modules on subdetector structures
- Test of electrical module performance
- No final electrical and optical services



First TB2S Ladder Integration Test – Results

- Module noise extracted from S-curves of binary readout
- No significant increase of module noise encountered on ladder





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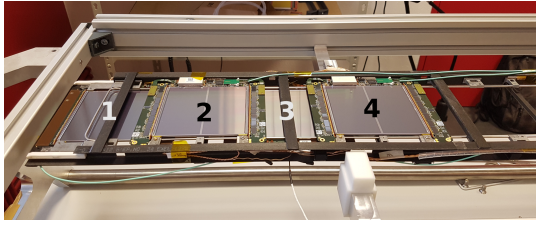

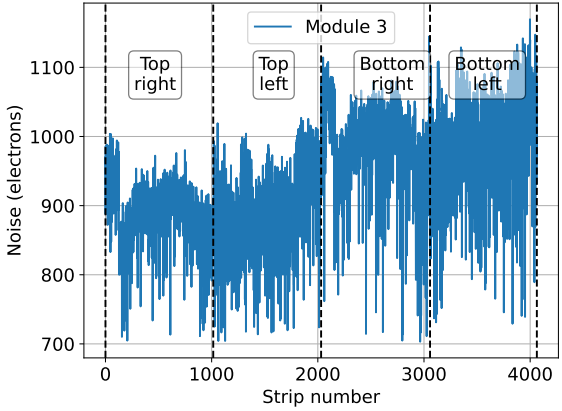

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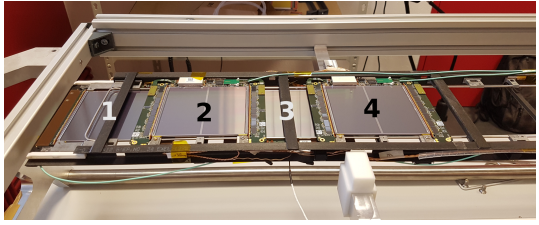

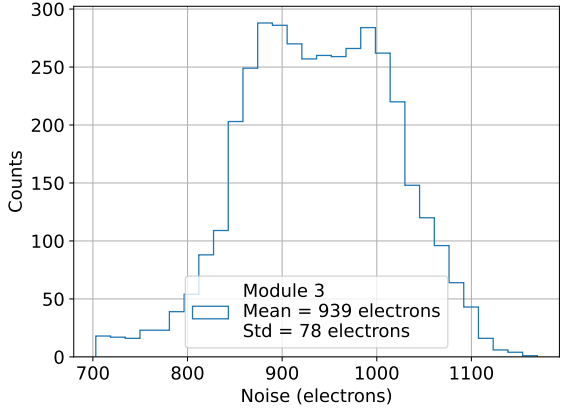

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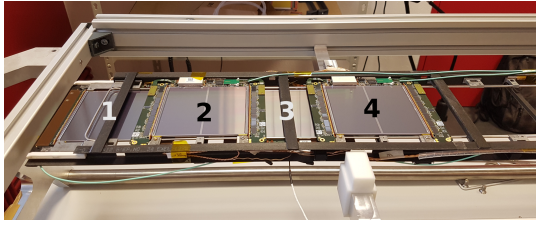
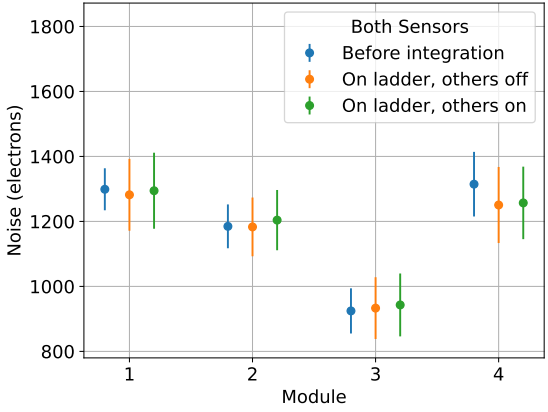
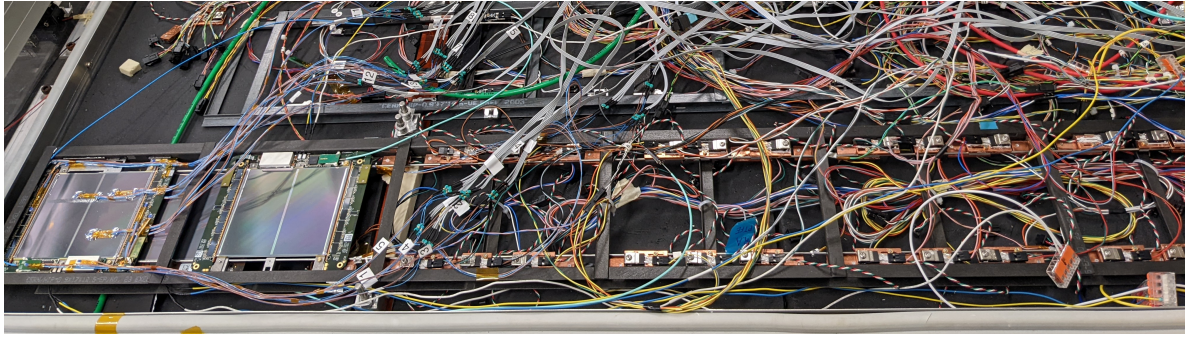




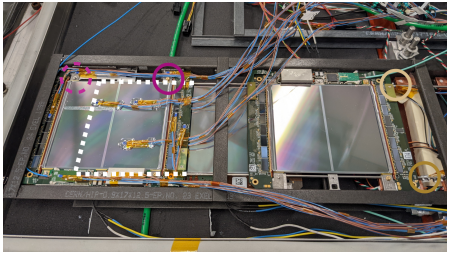
Thermal TB2S Integration Test – Overview

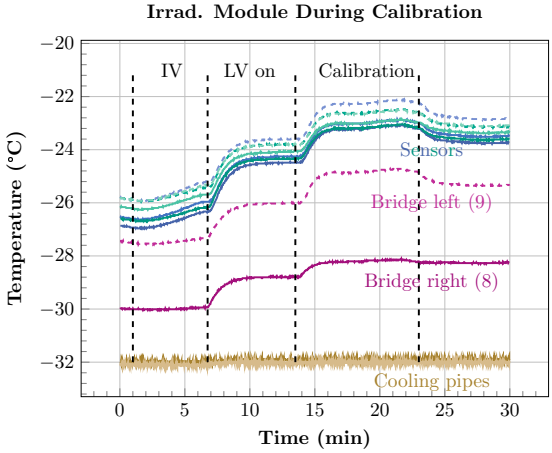
- March 2022 in cold room at CERN
- 3 modules mounted on a TB2S ladder prototype cooled using two-phase CO_2 cooling system
  - One module with irradiated sensors (equipped with 16 temperature sensors)
- Cooling of air around modules unavoidable ⇒ effect has to be estimated with thermal simulation



Module Temperatures During Calibration

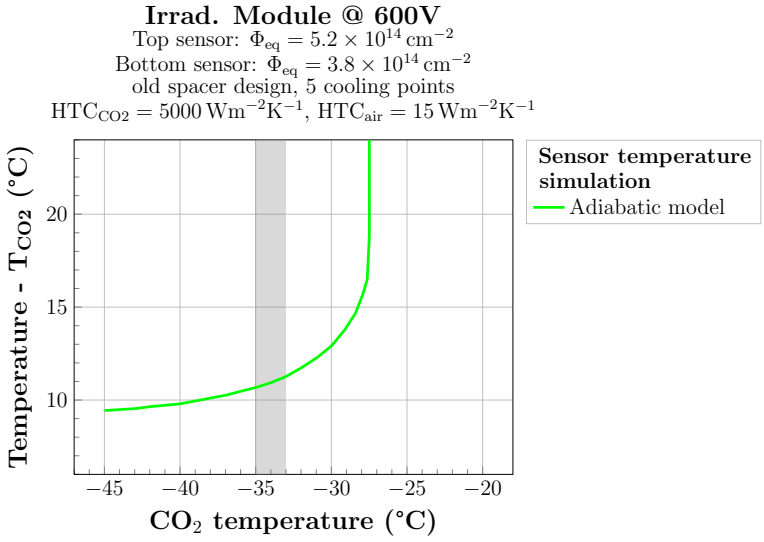
- Measurements
  - Minute 1 to 6: IV curve (0 V to 800 V)
  - Minute 7: Set HV to 600 V, switch on LV
  - Minute 14 to 23: Calibration of module
- Long cooling insert and missing 6th cooling point
  - Higher temperature at left bridge
  - All temperatures on left side higher than on right
- Spread of sensor temperatures within 1 °C





Module Thermal Performance

- Current limit of 5 mA reached during measurements
  ⇒ Thermal runaway not observed during measurements
- Difference between measurements and simulations with reasonable choice of heat transfer coefficient for air convection $< \pm 1\,^{\circ}\mathrm{C}$



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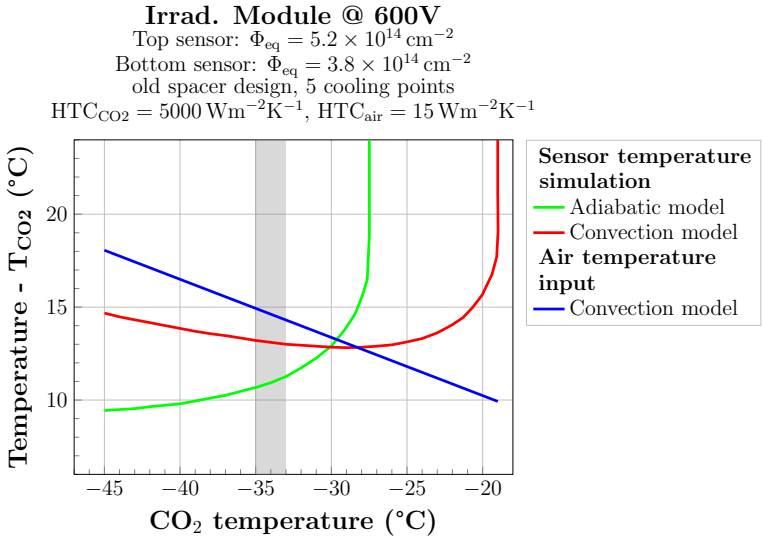

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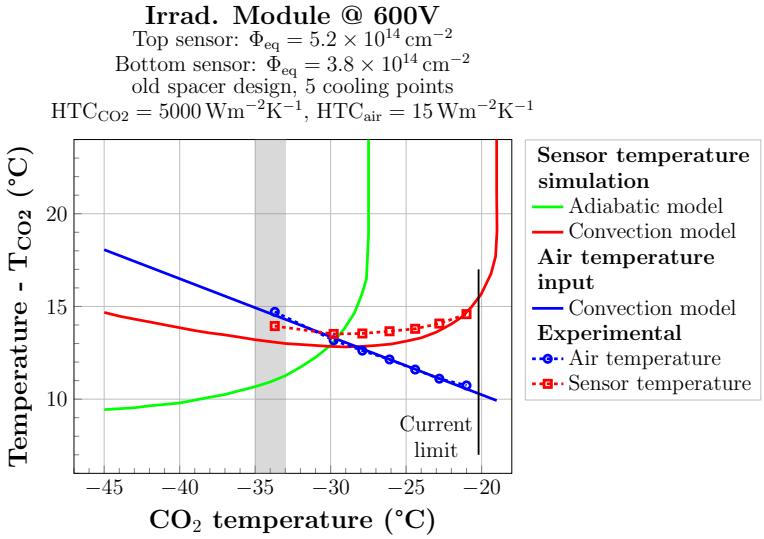
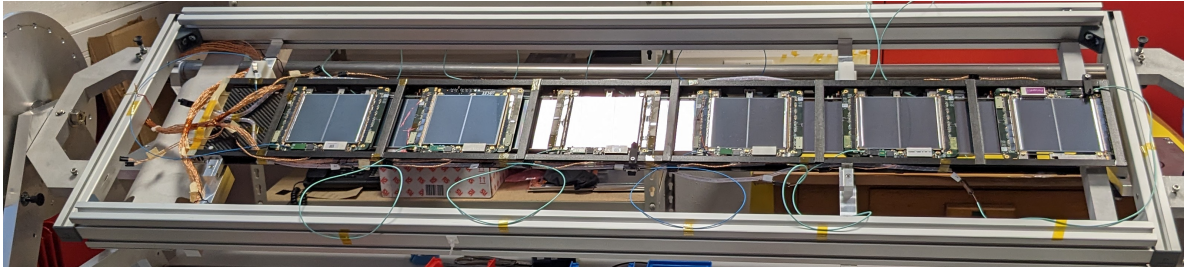


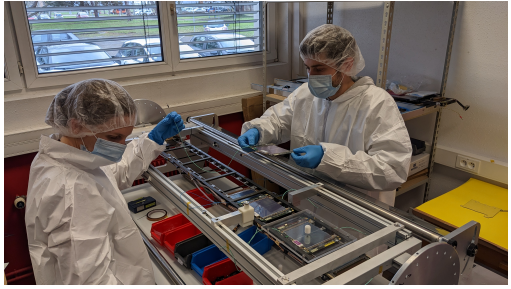
Full TB2S Ladder Integration Test – Overview

- January 2023 at IPHC in Strasbourg
- Twelve 2S modules from five assembly sites
- Prototypes of electrical and optical services
- Two powering possibilities
  - Lab power supply
  - Prototype power supply for the Phase-2 tracker with 60 m long cable



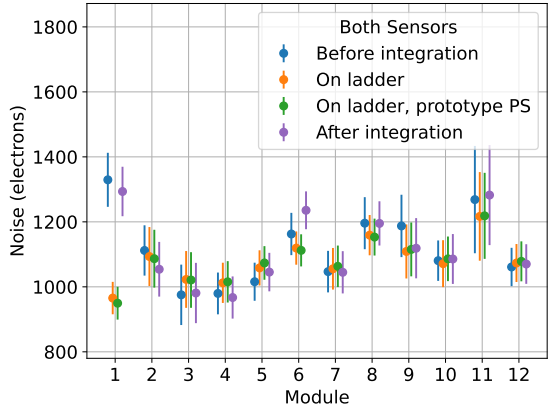
Module Handling and Integration Tooling

- Manual placing of modules
- screwed to inserts with a fixed torque
- Tooling worked fine (ideas for minor changes came up)



Noise Comparison: Test Bench – Ladder – Power Supplies

- Module noise shows no significant increase on the ladder compared to the measurement before integration
- Noise level independent of power supply powering the modules
- No noise degradation throughout integration test



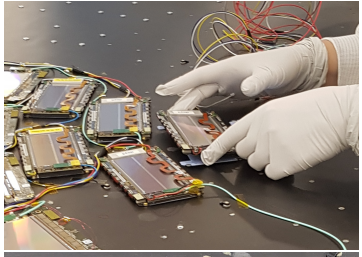
Module 1: Only top sensor noise shown
Reduced noise on ladder due to a lost soldering connection

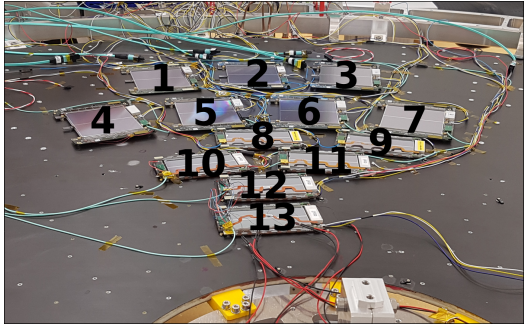
TEDD Dee Integration Test – Overview

- June 2023 at DESY in Hamburg
- People from TEDD dee integration centers and 2S and PS module assembly centers
- 13 2S and PS modules from four assembly sites
- First integration test with both 2S and PS modules
- First time mounting 2S modules on a dee prototype

Module Integration

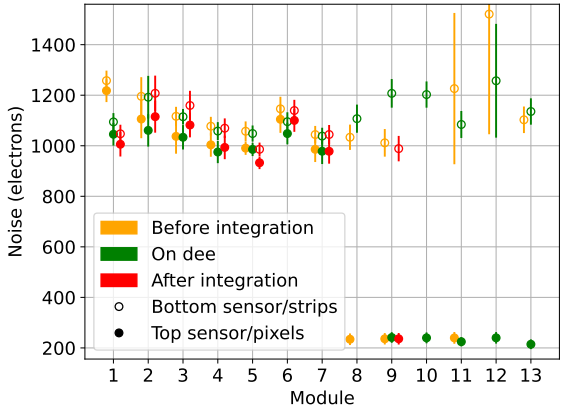
- Manual positioning of modules on the dee
- Module 1 to 7: 2S modules
- Module 8 to 13: PS modules





Noise Comparison: Test Bench – Dee

- PS module noise different in some cases due to prototype-specific known issues
  - Grounding of the modules to the dee is very important
- 2S module noise shows no significant increase on the dee compared to the measurement before integration
  - Module 1: Differences before and after integration due to different grounding during measurements



Module 1 to 7: 2S modules
Module 8 to 13: PS modules

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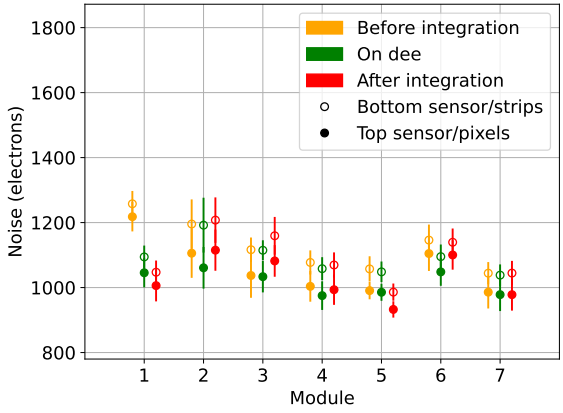
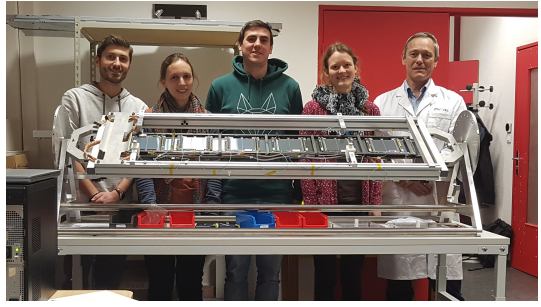


Module 1 to 7: 2S modules

Summary and Outlook

Summary

- CMS Outer Tracker upgrade moving from R&D to production phase
- Integration tests with CMS Phase-2 Outer Tracker module prototypes on barrel and endcap detector structures
  - First exercises of mounting these modules on larger structures
  - No increase of noise and no crosstalk between modules observed
  - Thermal simulation results fit data



Outlook

- Further integration tests are planned
  - With final modules
  - With final support structures

Karlsruhe Institute of Technology

Backup

Tracker Endcap Double-Discs (TEDD) – Design

- Each double-disc formed by two discs of two "dees" provides one hermetic detector plane
- 1 TEDD unit formed by 5 double-discs
- Seven cooling circuits per dee
  - Cooling inserts for 2S modules
  - Carbon foam blocks for PS modules