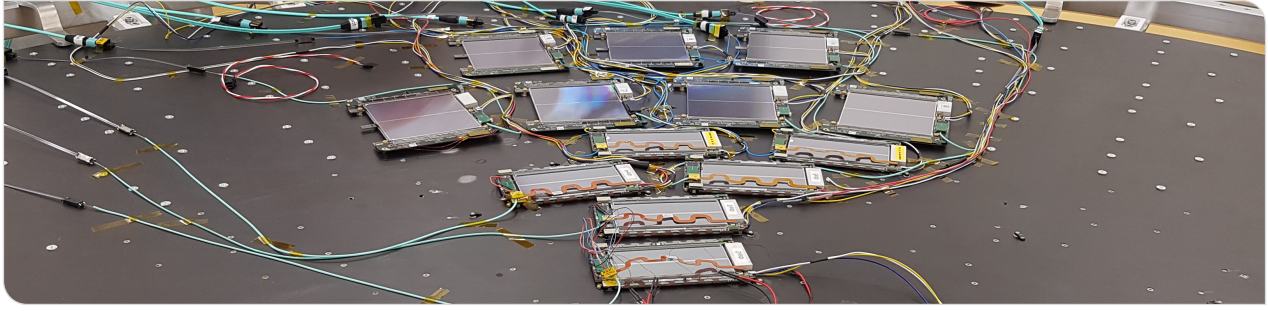
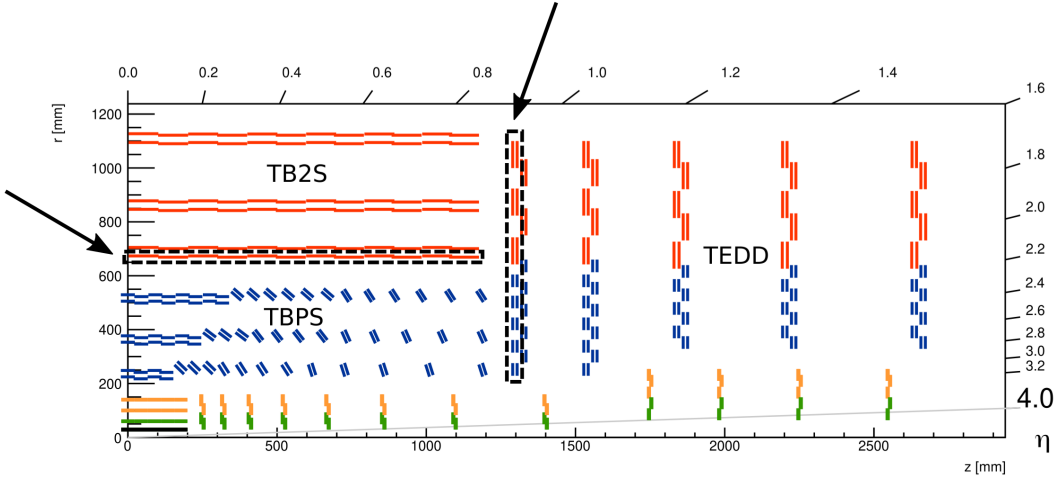
Integration Tests with 2S Module Prototypes for the Phase-2 Upgrade of the CMS Outer Tracker

Technology & Instrumentation in Particle Physics (TIPP2023)

Lea Stockmeier on behalf of the Tracker Group of the CMS Collaboration | September 06, 2023




TB2S
TBPS
TEDD
r [mm]
z [mm]
η
4.0
0.0
0.2
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0.6
0.8
1.0
1.2
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1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
0
200
400
600
800
1000
1200
0
500
1000
1500
2000
2500

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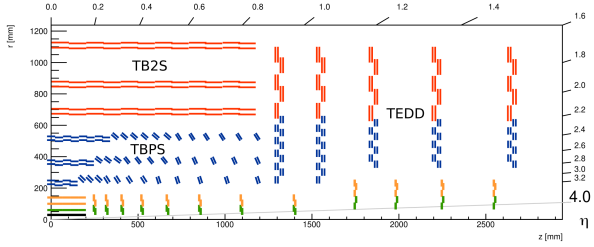
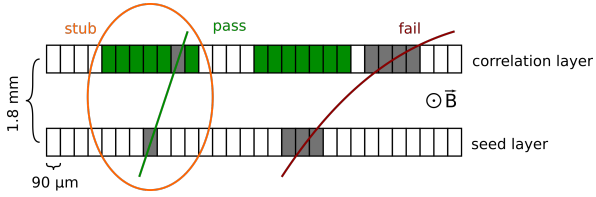
The Phase-2 Upgrade of the CMS Outer Tracker

HL-LHC and CMS Phase-2 Outer Tracker Upgrade

- Accelerator upgrade to reach luminosities up to $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- New tracker for the CMS experiment
  - Improved radiation tolerance
  - Increased granularity
  - Reduced material budget



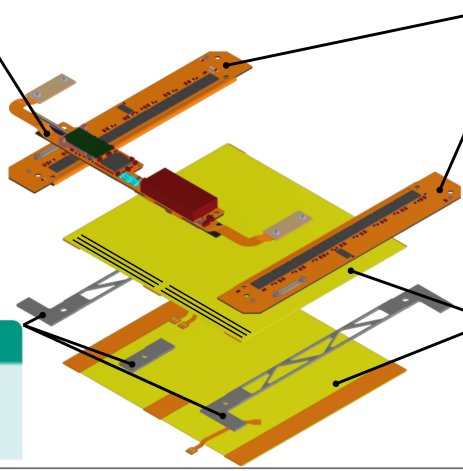
- Outer Tracker (OT) consists of 13 200 p_T-modules
  - 2S: strip/strip sensor
  - PS: pixel/strip sensor
  - Contribution to L1 trigger
  - Two-phase CO_2 cooling to reach a sensor temperature of $\approx -20\,^{\circ}\mathrm{C}$



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

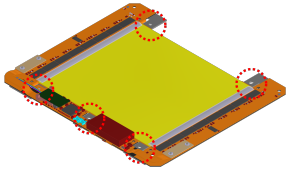
[1] Aluminum / carbon fiber composite

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

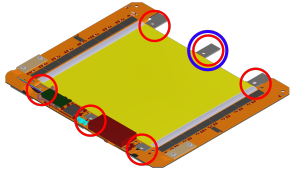
Module Thermal Performance Simulation

- Finite Volume Model (FVM) simulations
  - Simulate cooling performance after irradiation
  - Adiabatic model
  - For some module positions, thermal runaway sets in at CO_2 temperatures below $-35\,^{\circ}C$

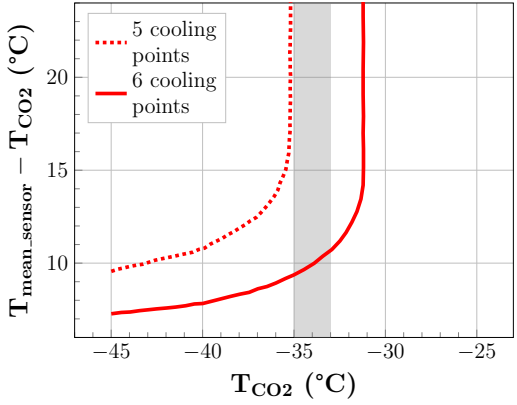
$\Rightarrow$ 2nd stump bridge inserted to improve module cooling at these critical positions



5 cooling points

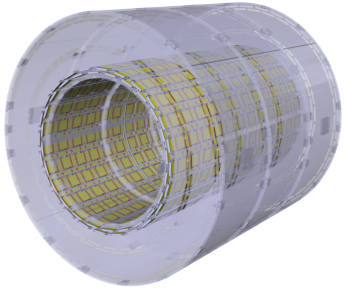


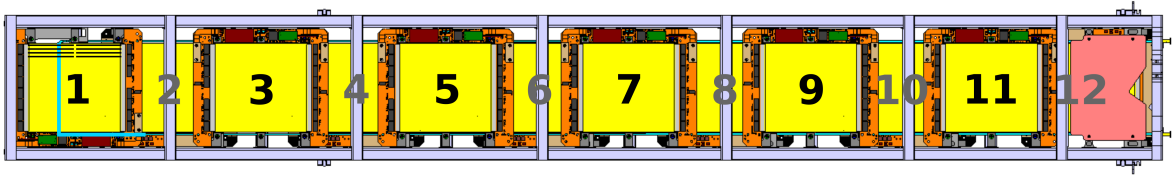
6 cooling points



Tracker Barrel with 2S Modules (TB2S) Design

- 372 ladders with 12 modules each
  $\Rightarrow$ 4464 2S modules in total
- Two-phase CO_2 cooling to reach a sensor temperature of $-20\,^{\circ}C$
- Layer 2 and 3:
  - Module at position 1 with 6^{th} cooling point at long cooling insert
- Layer 1:
  - Innermost layer
  - All modules with 6^{th} cooling point





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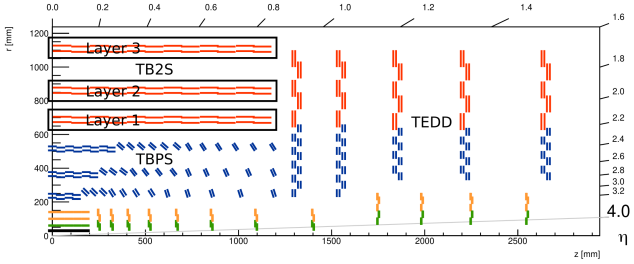
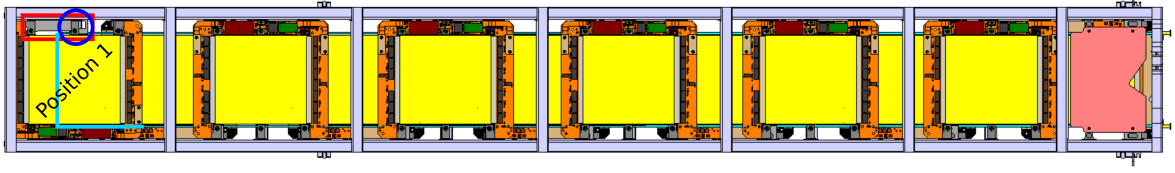
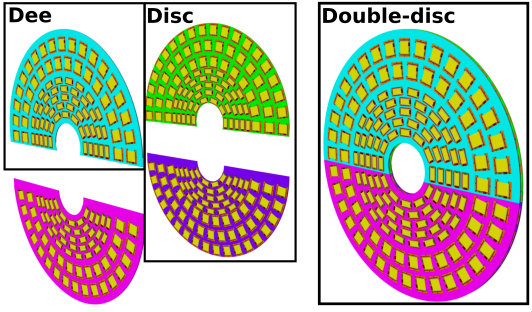
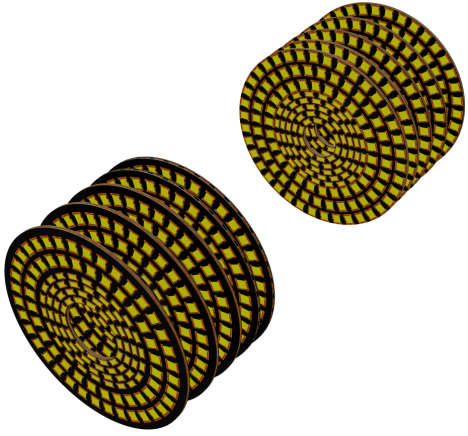




Tracker Endcap Double-Discs (TEDD) Design

- 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

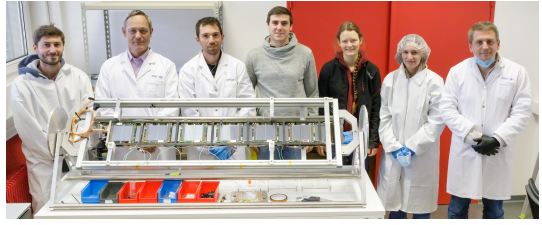




Integration Tests

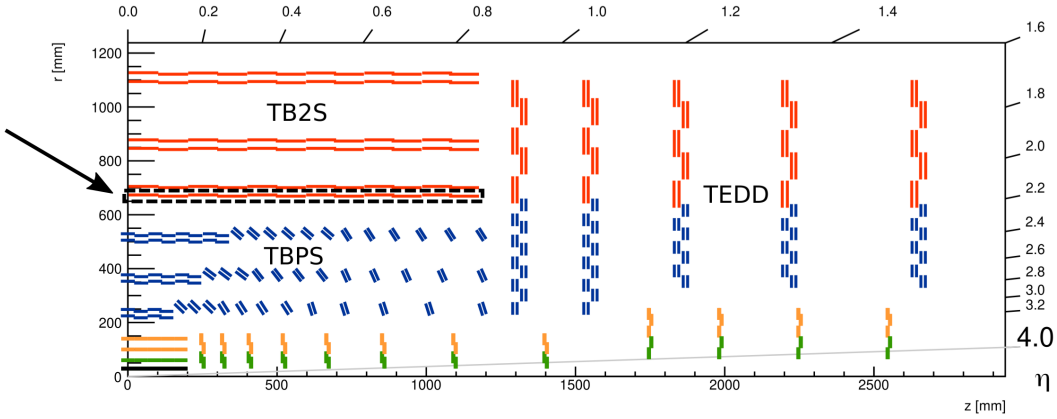
Mounting modules on final detector structures and performing functional tests

- Test module integration itself
  - Module handling
  - Tooling
- Test optical and electrical services
- Test power supplies
- Test cooling performance
  - Validate Finite Volume Method (FVM) simulations
- Check for possible crosstalk between modules



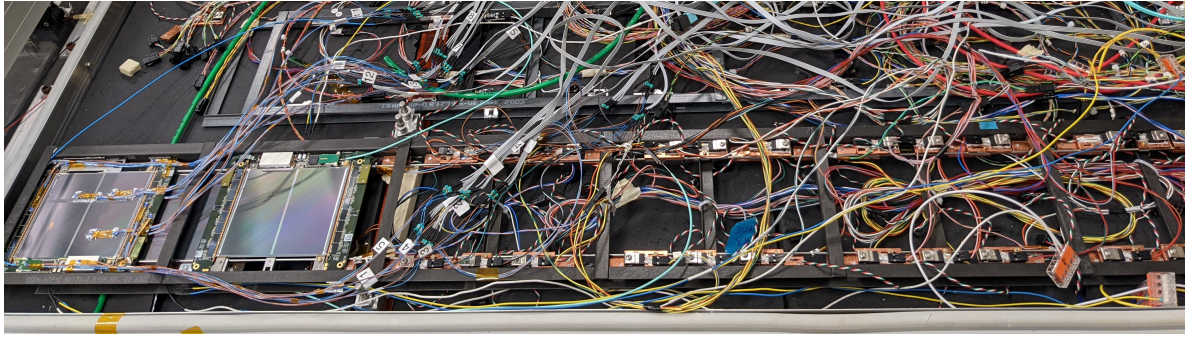
⇒ This talk covers an overview of
TB2S and TEDD integration tests

Thermal TB2S Integration Test



Thermal TB2S Integration Test – Overview

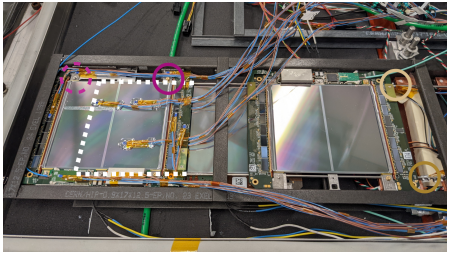
- March 2022 in cold room at CERN
- 3 modules mounted on a TB2S ladder prototype cooled using two-phase CO_2 cooling system
  - One module with irradiated sensors (equipped with 16 temperature sensors)
- Cooling of air around modules unavoidable ⇒ effect has to be estimated with thermal simulation

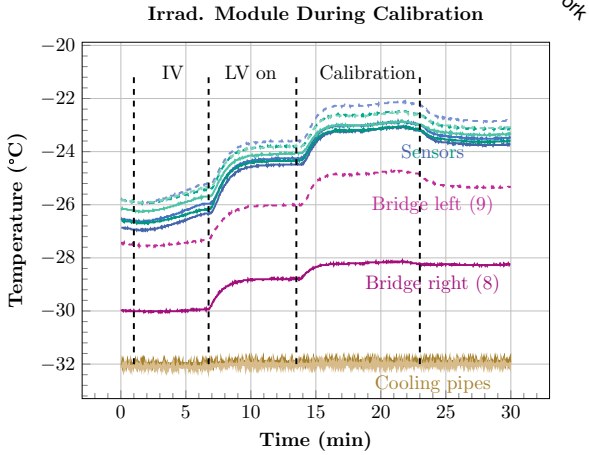


Module Temperatures During Calibration

Private work

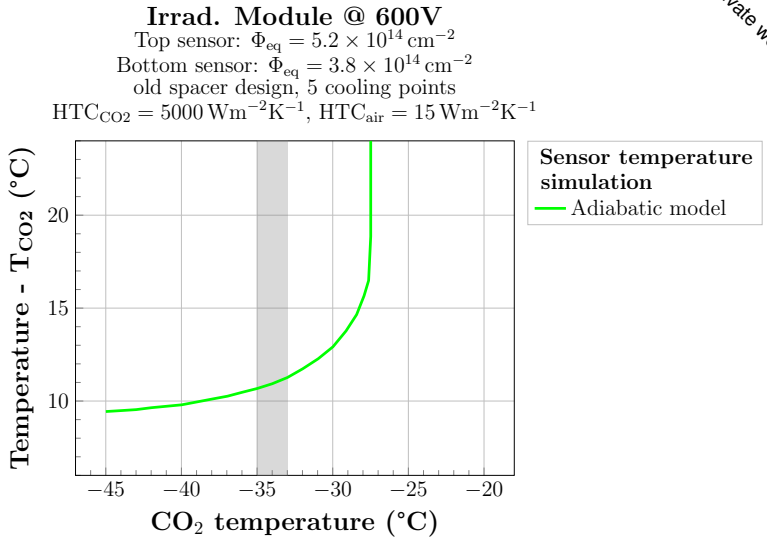
- Measurements
  - Minute 1 to 6: IV curve (0 V to 800 V)
  - Minute 7: Set HV to 600 V, switch on LV
  - Minute 14 to 23: Calibration of module
- Long cooling insert and missing 6th cooling point
  - Higher temperature at left bridge
  - All temperatures on left side higher than on right
- Spread of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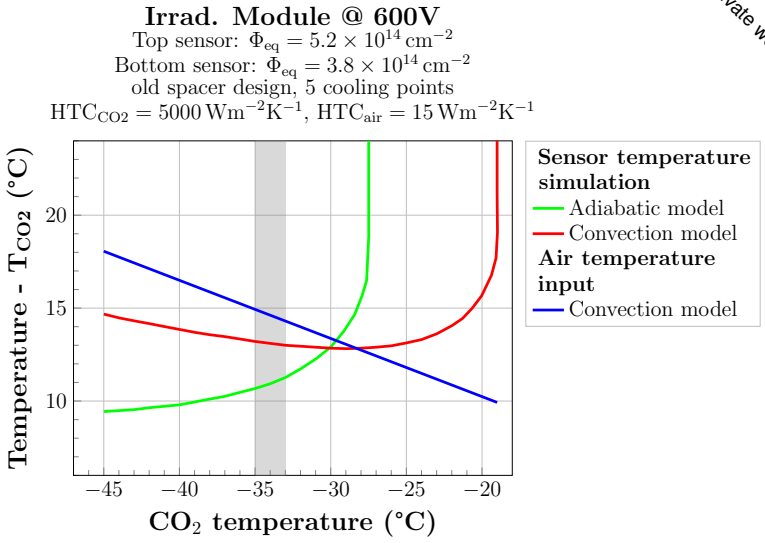

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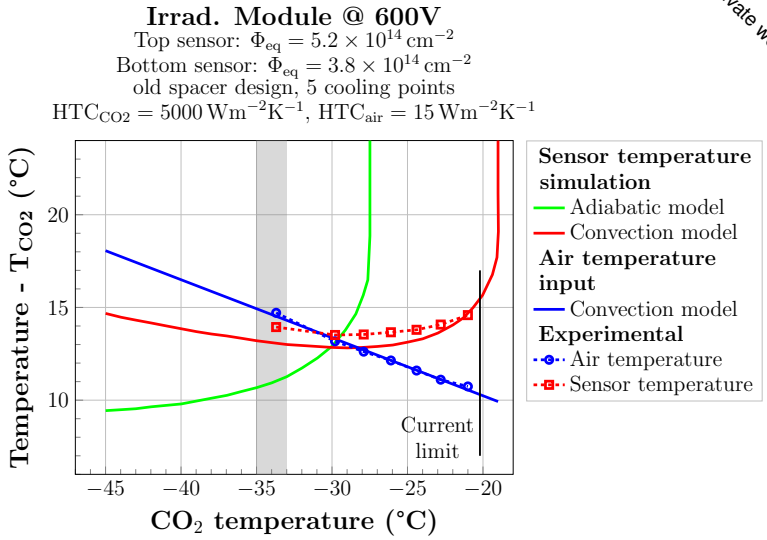
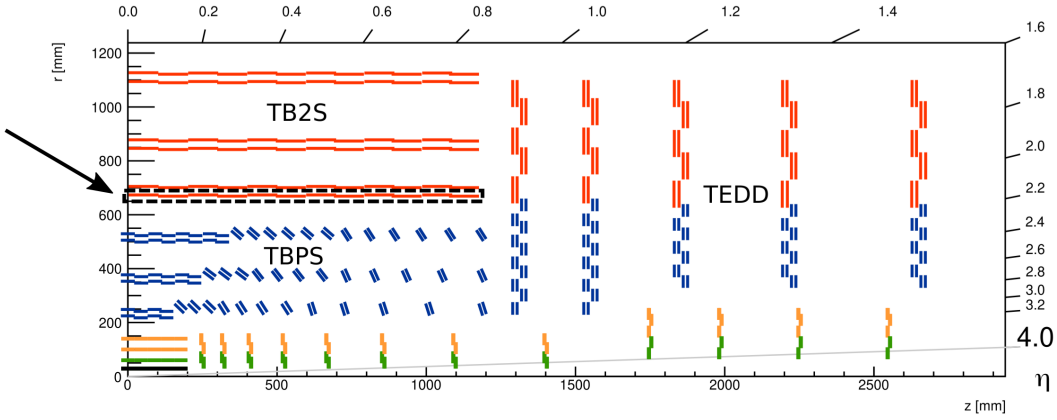


Full TB2S Ladder Integration Test

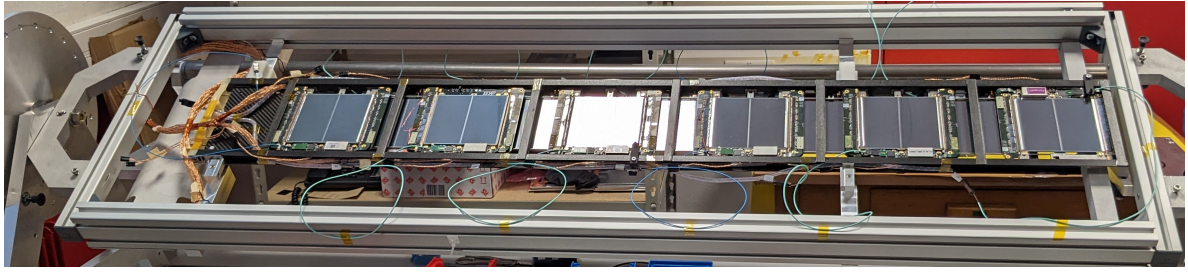


Full TB2S Ladder Integration Test – Overview

- January 2023 at IPHC in Strasbourg
- 12 2S modules from 5 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

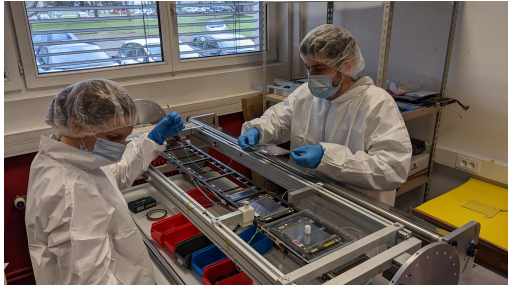
Tests Performed

- I(V) curves
- **Noise measurements**
- High-statistics measurements
  - High rate trigger studies
  - Common mode noise studies



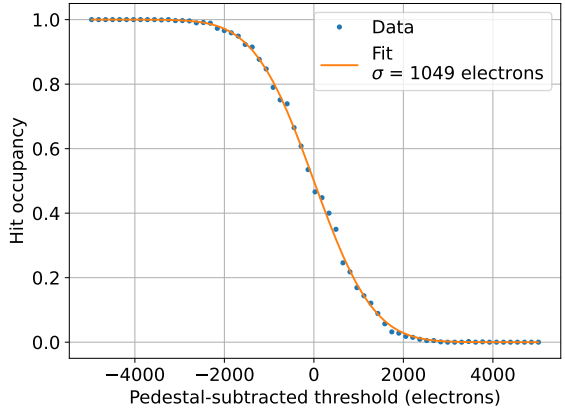
Module Handling and Integration Tooling

- Test of module handling and integration tooling during ladder integration
- Tooling worked fine
- Ideas for minor changes came up



Noise Comparison Test Bench - Ladder - Power Supplies

- Module noise extracted from S-curves of binary readout
- 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



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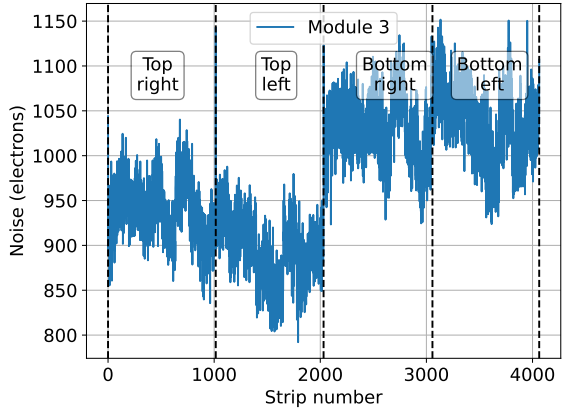

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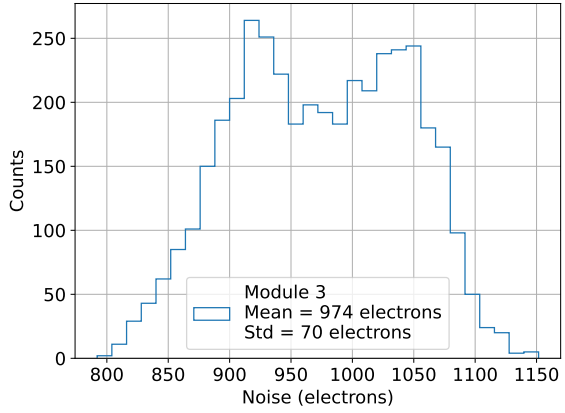

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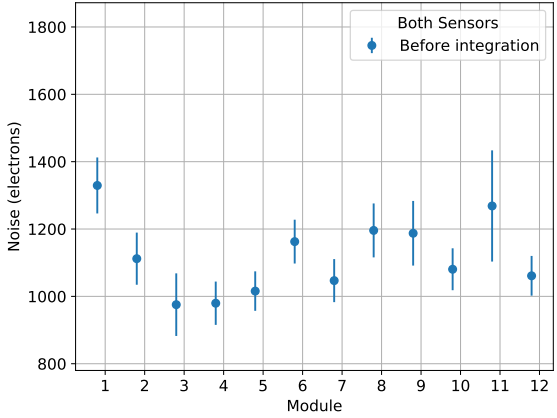

Module 1: Only top sensor noise shown
Reduced noise on ladder due to a lost soldering connection

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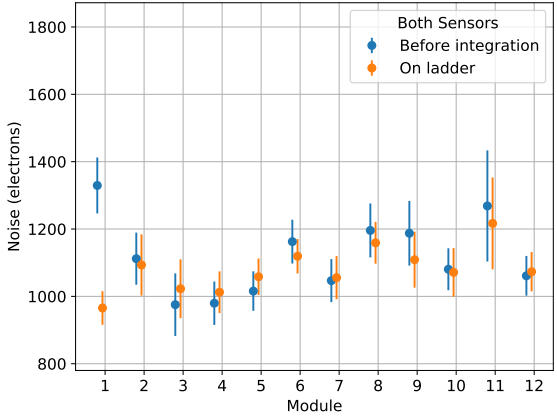

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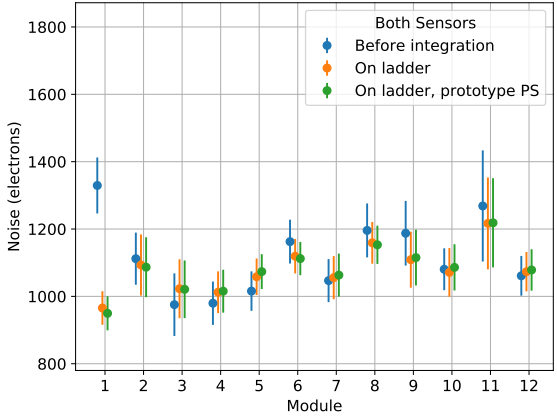

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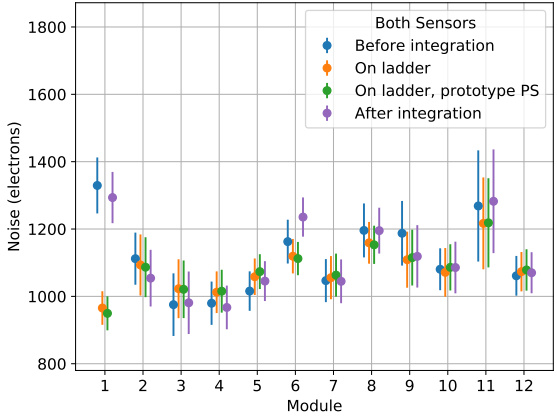

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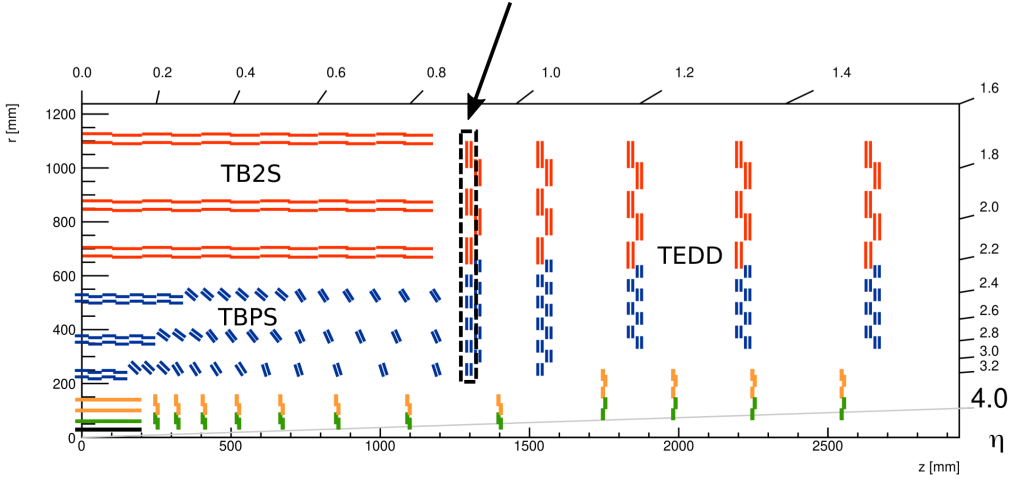
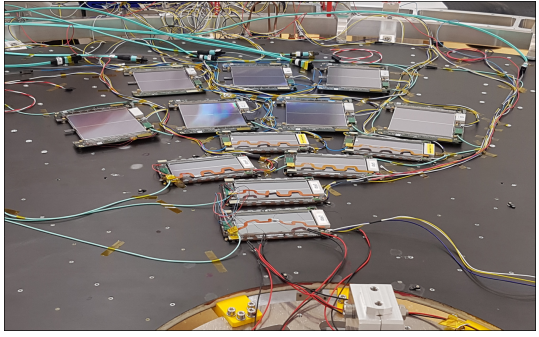
TEDD Dee Integration Test



TEDD Dee Integration Test – Overview

- June 2023 at DESY in Hamburg
- 13 2S and PS modules from 4 assembly sites
- First integration test with 2S and PS modules
- First time mounting 2S modules on a dee prototype



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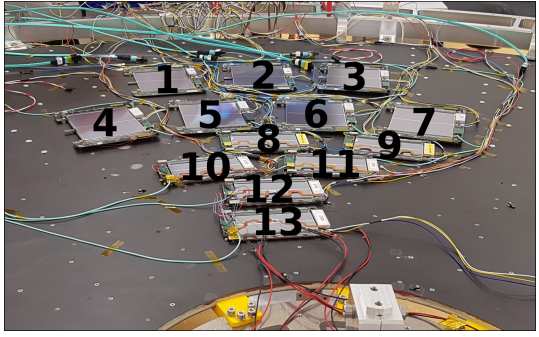
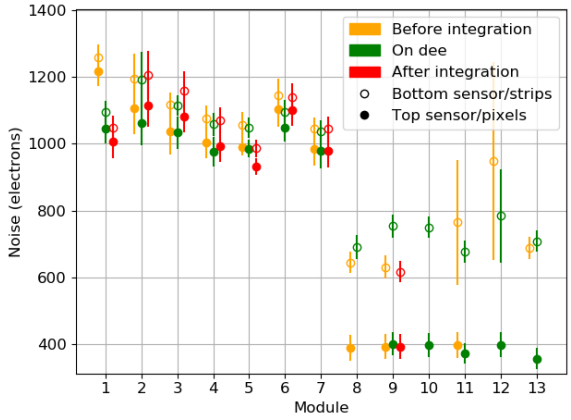


Noise Comparison Test Bench - Dee

Private work

- PS module noise different in some cases due to prototype-specific known issues
- 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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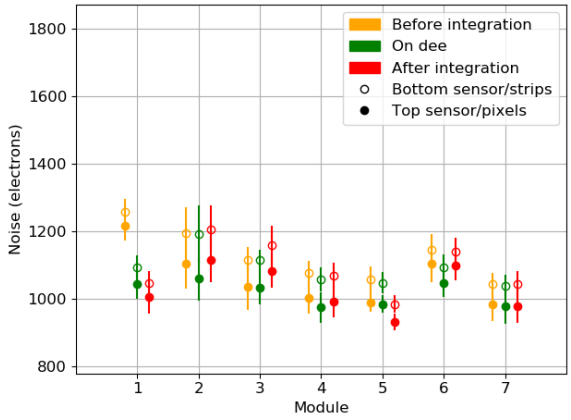

Module 1 to 7: 2S modules
Module 8 to 13: PS modules

Summary and Outlook

Summary

- CMS Outer Tracker upgrade moving from R&D to production phase
- Integration tests with 2S and PS module prototypes on a TB2S ladder and TEDD dee
  - First exercises of mounting CMS Phase-2 Outer Tracker modules on larger structures
  - No increase of noise and no crosstalk between modules observed
  - Thermal simulation results fit measurements for a reasonable choice of heat transfer coefficient for air convection

Outlook

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

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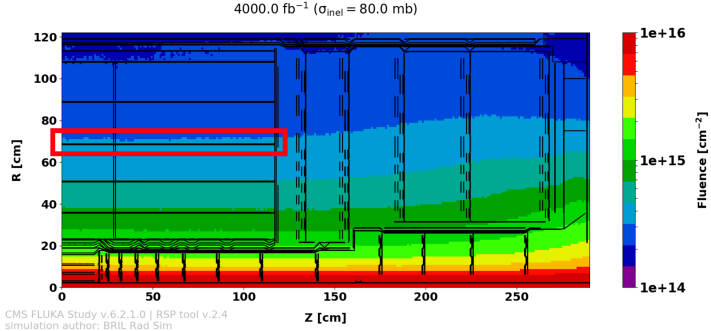
Backup

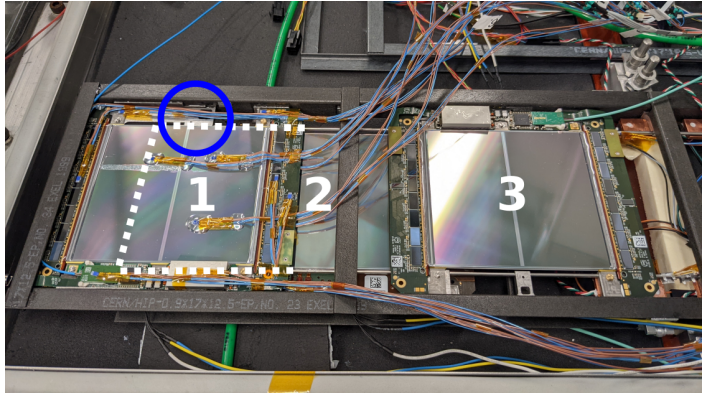
Irradiated Module

- Study module performance at the end of HL-LHC
  - At 4000 fb^{-1}: maximal fluence of $\Phi_{eq} = 3.7 \times 10^{14}$ cm^{-2} for modules mounted on a ladder
- Module components irradiated (before module assembly) with 23 MeV protons at KIT
  - Top sensor: $\Phi_{eq} = 5.2 \times 10^{14}$ cm^{-2}
  - Bottom sensor: $\Phi_{eq} = 3.8 \times 10^{14}$ cm^{-2}
  - Total sensor annealing: 154 d at room temperature
  - Front-end hybrids: $\Phi_{eq} = 1 \times 10^{14}$ cm^{-2} (dose of 150 kGy)



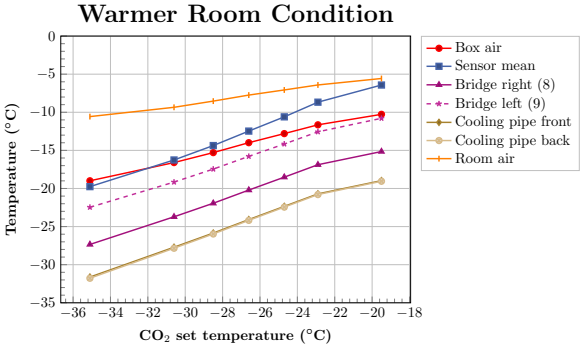
Module Arrangement

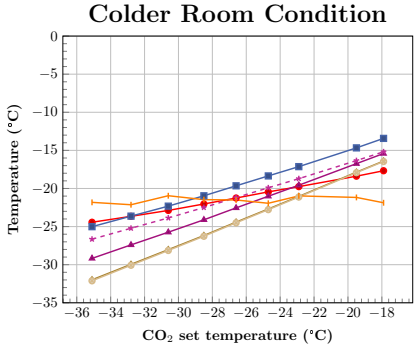
- Position 1 (left): Irradiated module
  - **No additional 6th cooling point** (foreseen at position 1)
  - **No extra mass in spacers** ("old" design)
- Position 2 and 3: Non-irradiated modules
- Heating resistors at ladder inserts of the other positions:
  - Powered to have a total power consumption of ≈ 70 W across full ladder



Module Thermal Performance

- Changing CO_2 set temperature by adjusting pressure
- All modules: HV = 600 V
- Heating resistors with summed power of 70 W
- Two different environmental conditions during measurements

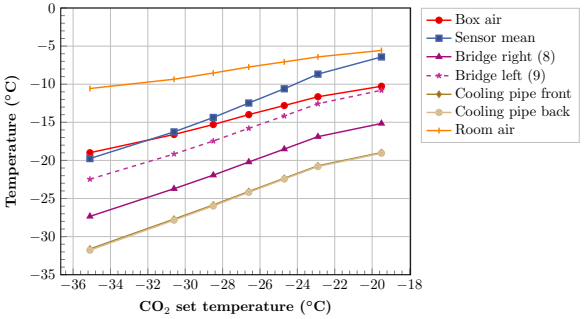




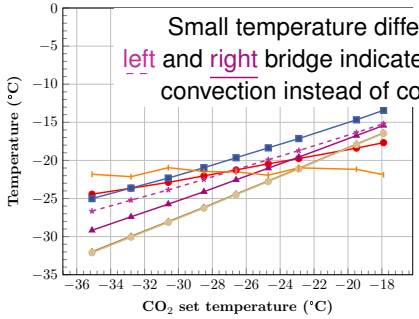
Module Thermal Performance

- Changing CO_2 set temperature by adjusting pressure
- All modules: HV = 600 V
- Heating resistors with summed power of 70 W
- Two different environmental conditions during measurements

Warmer Room Condition



Colder Room Condition



Small temperature difference at left and right bridge indicates cooling by convection instead of conduction

⇒ Compare with thermal Finite Volume Model (FVM) simulations (Take convection into account)

Thermal FVM Simulation

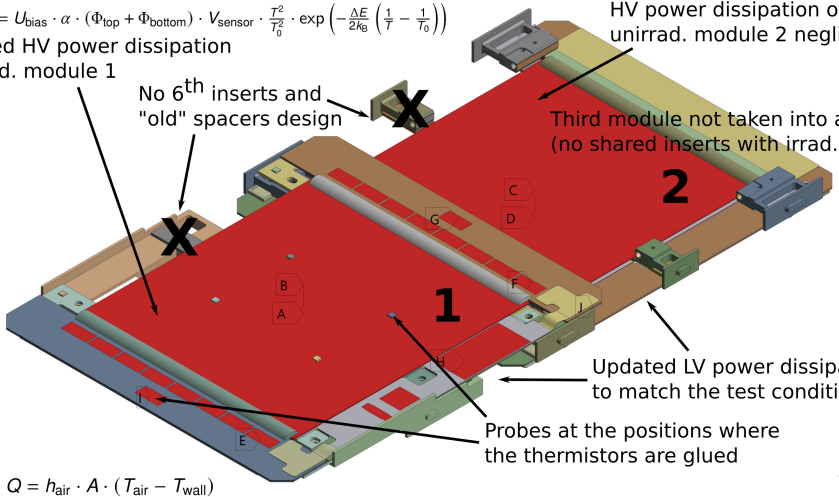
$$P_{\mathrm{HV,mod1}} = U_{\mathrm{bias}} \cdot \alpha \cdot (\Phi_{\mathrm{top}} + \Phi_{\mathrm{bottom}}) \cdot V_{\mathrm{sensor}} \cdot \frac{T^2}{T_0^2} \cdot \exp\left(-\frac{\Delta E}{2k_B}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$$

Updated HV power dissipation for irrad. module 1

No 6th inserts and "old" spacers design

HV power dissipation of unirrad. module 2 negligible

Third module not taken into account (no shared inserts with irrad. module 1)



Updated LV power dissipation to match the test conditions

Probes at the positions where the thermistors are glued

$$Q = h_{\mathrm{air}} \cdot A \cdot (T_{\mathrm{air}} - T_{\mathrm{wall}})$$

Convective boundary conditions → Effect of convection with air to the modules' external surface

Detailed presentation of simulation in Cristiano Turrioni's talk

Results: Colder Room Condition

- Lower air temperature and different LV power dissipation with respect to the case on slide 13
- Thermal runaway not seen in the range $-45\,^{\circ}\mathrm{C} < T_{CO2} < -18\,^{\circ}\mathrm{C}$