Karlsruhe Institute of Technology

Institute of Experimental Particle Physics

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

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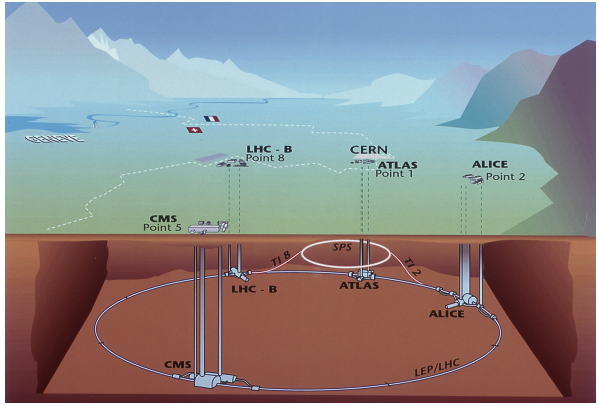
May 09, 2025

The Large Hadron Collider (LHC)

- Particle accelerator
  - Proton-proton collisions with bunch crossing rate of 40 MHz
  - Center-of-mass-energy of 13.6 TeV
  - Four experiments at four interaction points

High Luminosity LHC (HL-LHC) Upgrade

- Increase of instantaneous luminosity by a factor of 3.5
- Exploit full physics potential of LHC
- Begin of data taking in 2030



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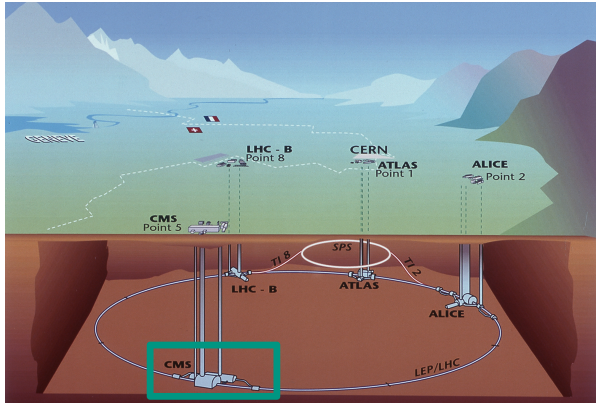
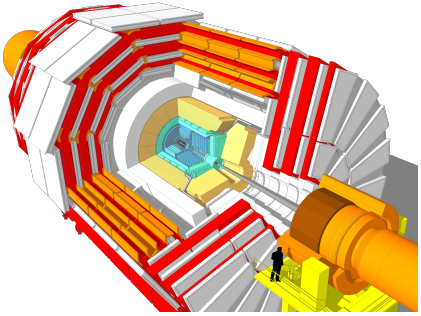
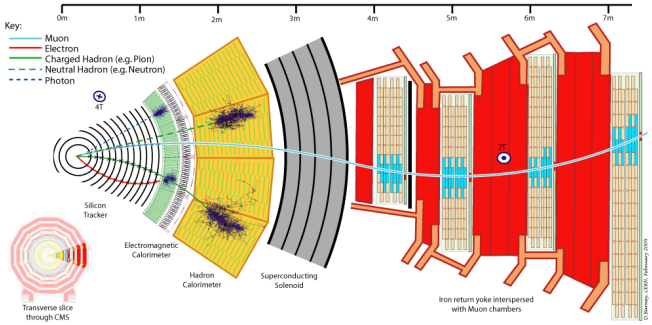


The Compact Muon Solenoid (CMS) Experiment

- Multi-purpose particle detector
- Triggered data readout



- Particle reconstruction by combining charge, energy and momentum information from subdetectors



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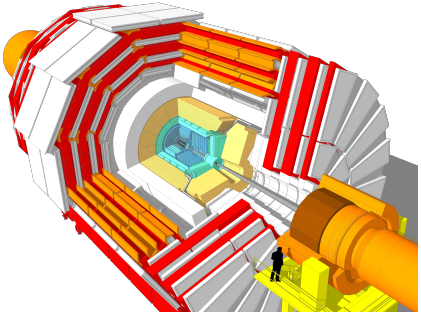

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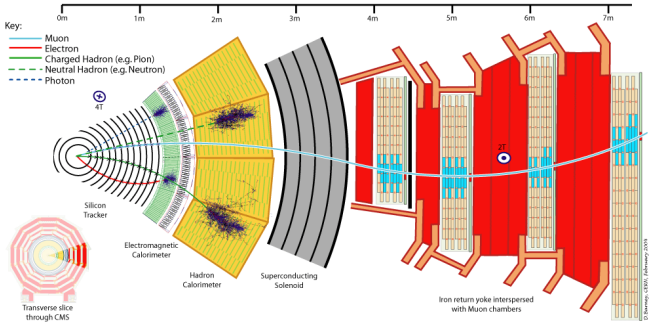
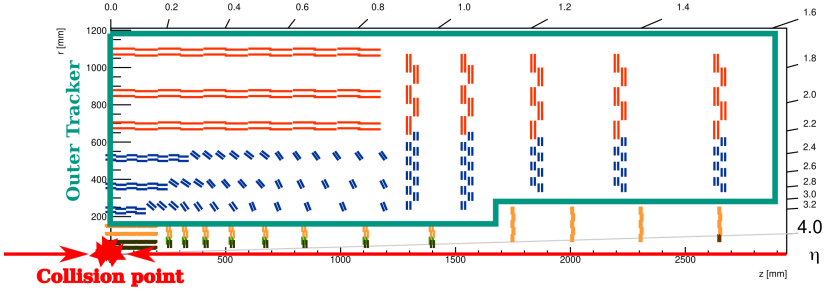


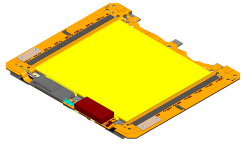
→ **Phase-2 Upgrade** of subdetectors for operation during HL-LHC

The Phase-2 Upgrade of the CMS Tracker

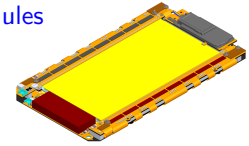
- New silicon tracker for HL-LHC
  - Higher channel density
  - Reduced material budget
  - Improved radiation tolerance
- Outer Tracker: two independent data streams (trigger and physics)



2S modules

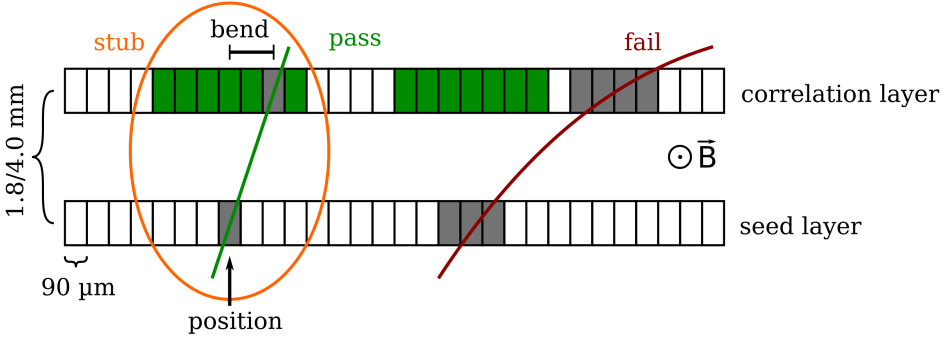


PS modules



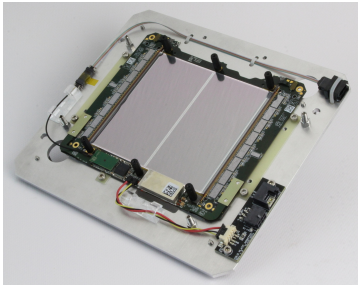
The p_T Module Concept

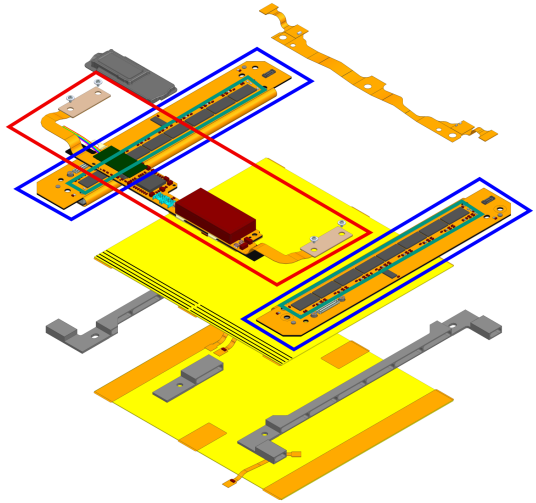
- Contribution of Outer Tracker to L1 trigger system
- Trigger decision within 12 µs



The 2S Module

- **Silicon strip sensors**
- **Al-CF spacers** for mechanical fixation and main cooling path
- **Readout chips** mounted on **frontend hybrids**
- **Service hybrid** for powering and data transmission

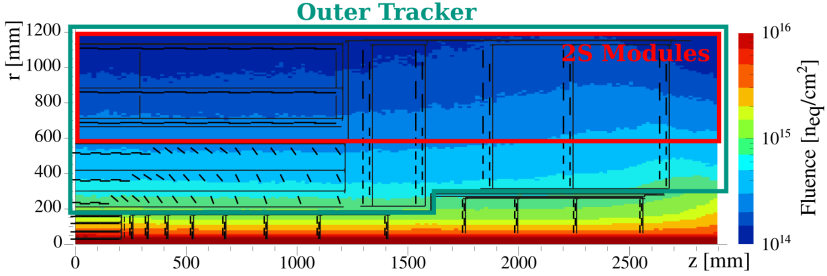




Radiation Damage in Silicon

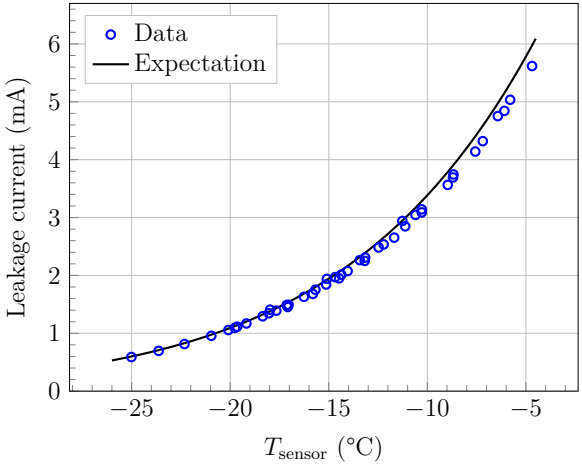
- Detector operation at LHC environment
  ⇒ **Radiation damage**
  - Microscopic defects in silicon lattice
- Change in sensor parameters, e.g., higher leakage current
- **Annealing** of crystal defects at temperatures above 0 °C

- Expected radiation environment known from simulation
  → Irradiate sensors with protons and neutrons to level expected at the end of HL-LHC data taking



Cooling and Thermal Runaway

- Heat sources
  - Module electronics
  - Silicon sensors: temperature and irradiation dependent leakage current
    $I_{\text{leak}} \propto T^2 \cdot \exp\left(-\frac{1}{T}\right)$
    $\Delta I_{\text{leak}}(21\,^\circ\text{C}) = \alpha \cdot \Phi_{\text{eq}} \cdot V_{\text{sensor}}$



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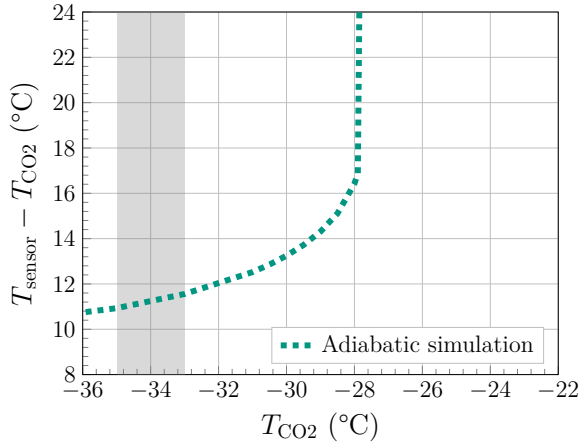
- **Thermal runaway**
  - Silicon sensors enter uncontrolled self-heating loop
  - Operation of detector impossible
  - Finite Volume Method (FVM) simulations to predict thermal runaway temperature



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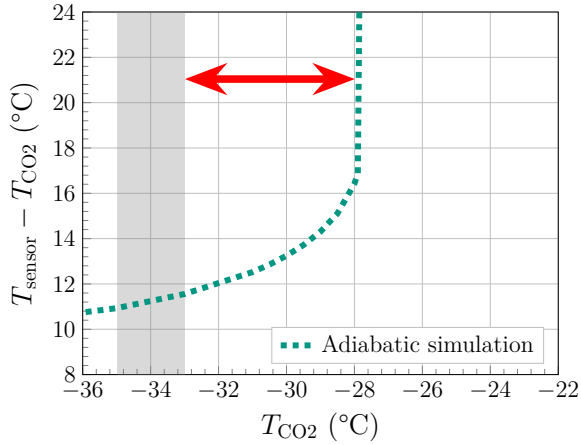
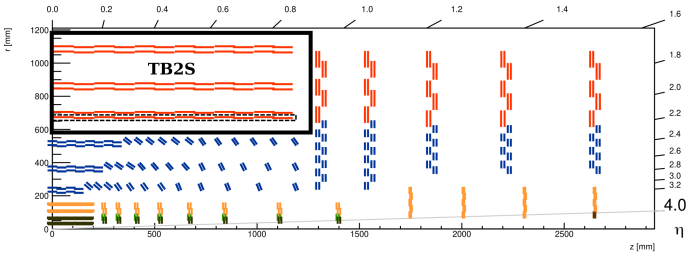
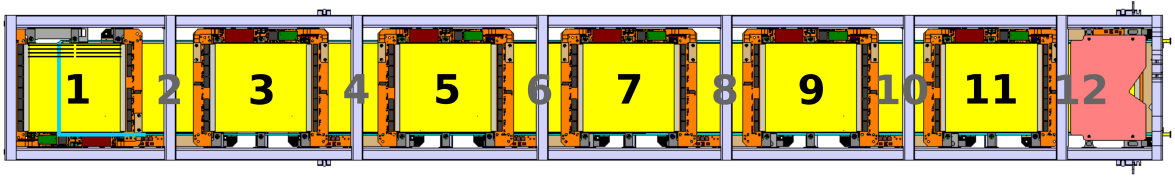
  - Finite Volume Method (FVM) simulations to predict thermal runaway temperature
  - Safety margin: Difference between operation and thermal runaway temperature



The Tracker Barrel with 2S Modules (TB2S)

- TB2S provided by ladders equipped with twelve 2S modules each
- Two-phase CO_2 cooling to reach a sensor temperature of $\approx -20\,^{\circ}C$





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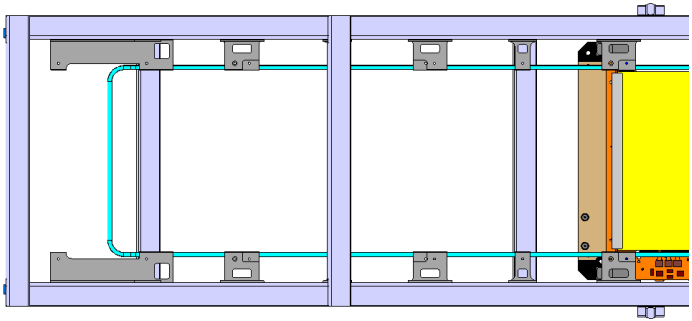

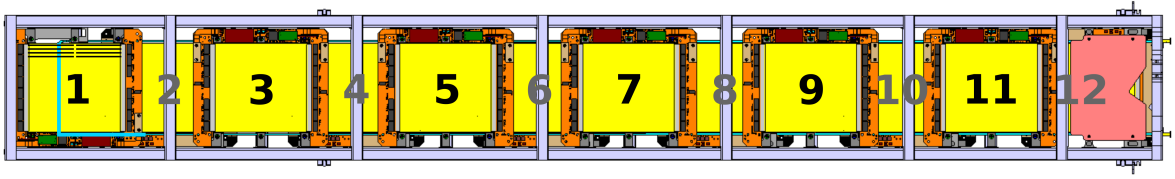

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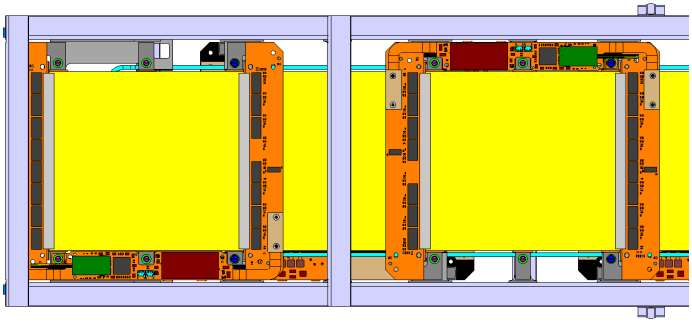
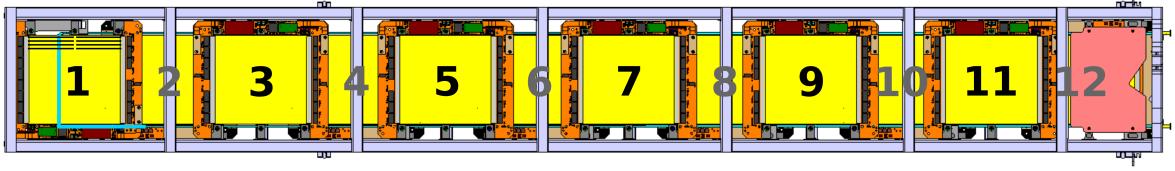
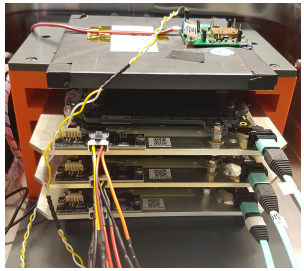


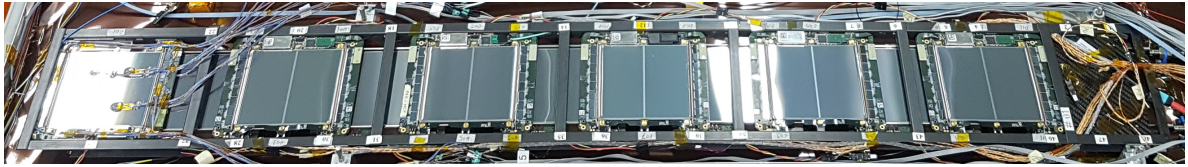


Goals of My Thesis

- System tests
  - Single module measurements as a baseline for comparing with multi-module results
  - Particle detection in the laboratory with a 2S module stack
  - Characterization of final 2S module prototypes in a beam test

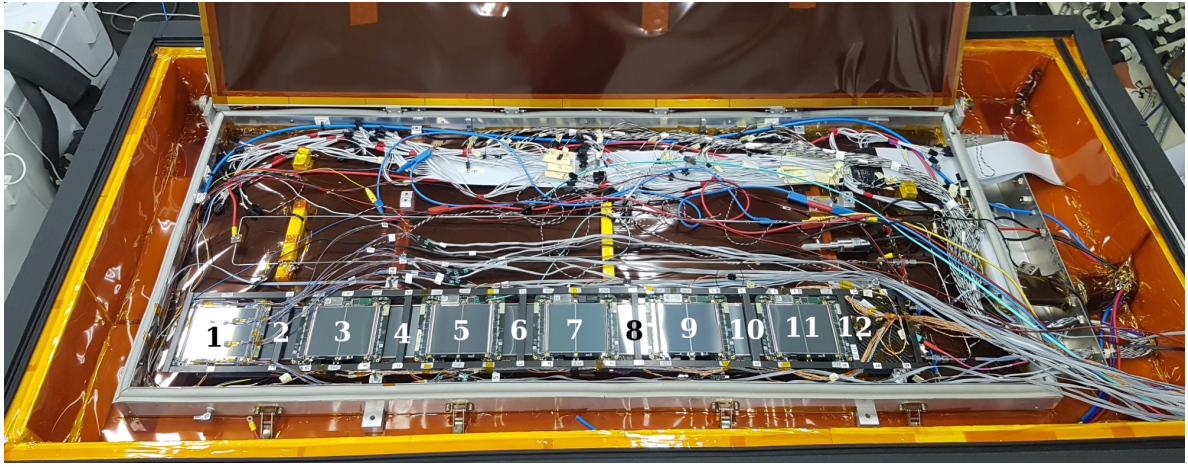


- Integration tests
  - First tests with modules mounted on subdetector structures
  - Test module integration with handling and tooling
  - **Thermal performance studies**
  - **Electrical performance studies**



Thermal Performance – Experimental Setup

- TB2S ladder with twelve 2S modules connected to an evaporative CO_2 cooling system



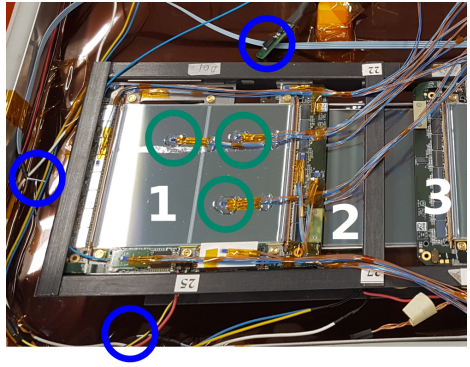
Thermal Performance – Experimental Setup

- Study module performance at the end of HL-LHC data taking with irradiated sensors

- Position 1: Irradiated module (23 MeV protons at KIT)
  - Top sensor: $\Phi_{eq} = 1.01 \times \Phi_{eq,\,max}$
  - Top sensor: $\Phi_{eq} = 1.4 \times \Phi_{eq,\,max}$

- Positions 2 to 12: Unirradiated modules

- Temperature probes
  - On irradiated module
  - In air
  - On cooling pipe



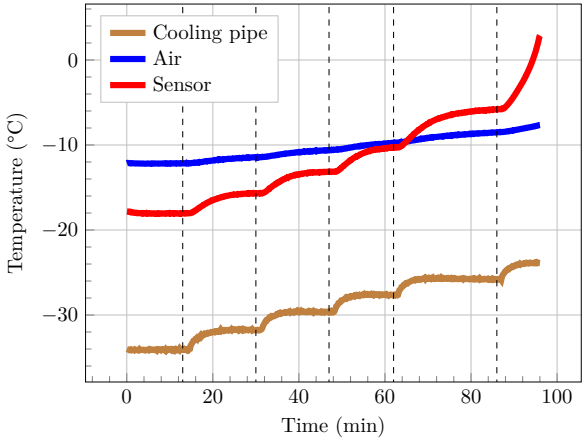
Thermal Runaway – Measurements

- Change CO_2 pressure (temperature) in steps
- Wait at each point until silicon sensor temperature stabilized

⇒ Exponential increase of sensor temperature during thermal runaway

- Extract relevant data from stable points

⇒ Compare with simulation



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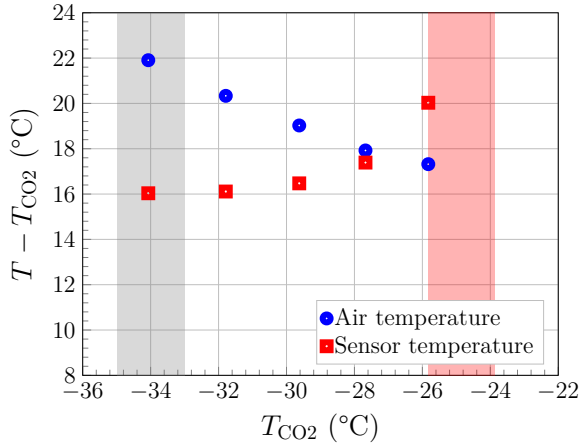
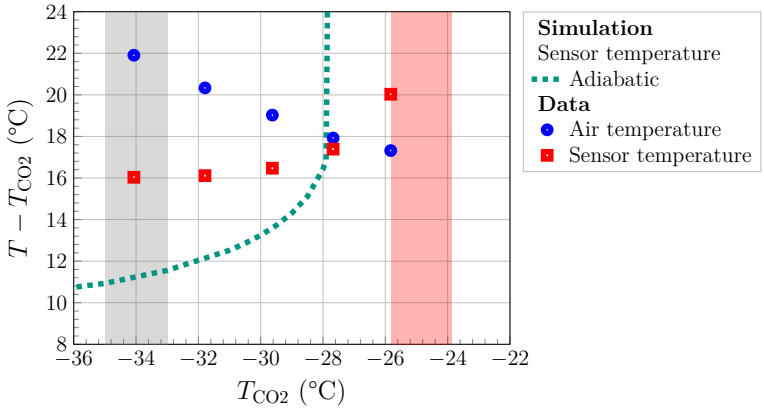


Thermal Runaway – Simulation

Adiabatic simulation

- Without heat transfer to the surrounding air



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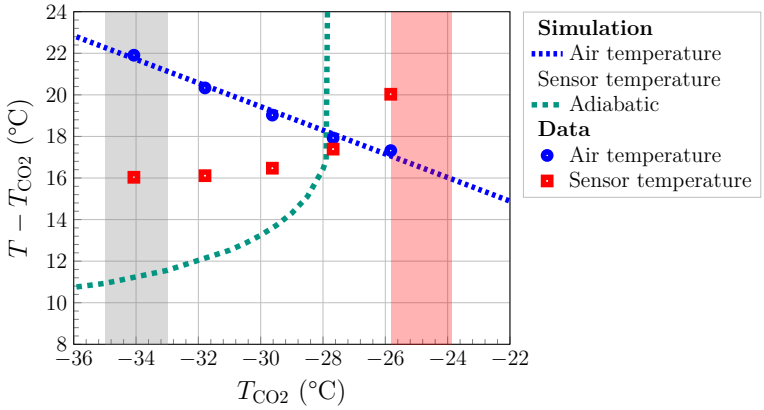
Convection simulation

- Linear air profile as input



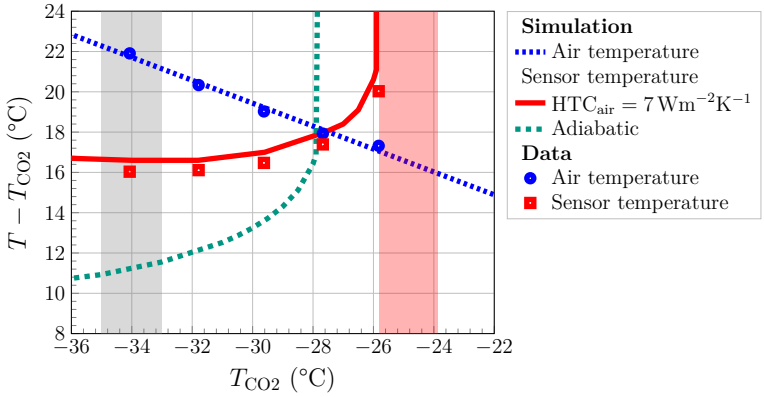
Thermal Runaway – Simulation

Adiabatic simulation

- Without heat transfer to the surrounding air

Convection simulation

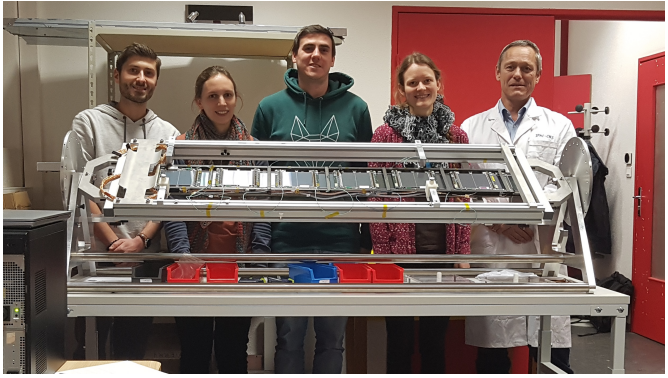
- Linear air profile as input
- Tuned heat transfer coefficient ($\mathrm{HTC_{air}}$) to match measurement conditions
  → Reasonable value for natural air convection



⇒ Thermal model validated with measurements
→ First and only thermal TB2S ladder tests with modules before production

Electrical Performance – Experimental Setup

- First fully integrated TB2S ladder
- Powering with prototype power supply for the Phase-2 Outer Tracker
- Synchronous readout of twelve 2S prototype modules on the ladder



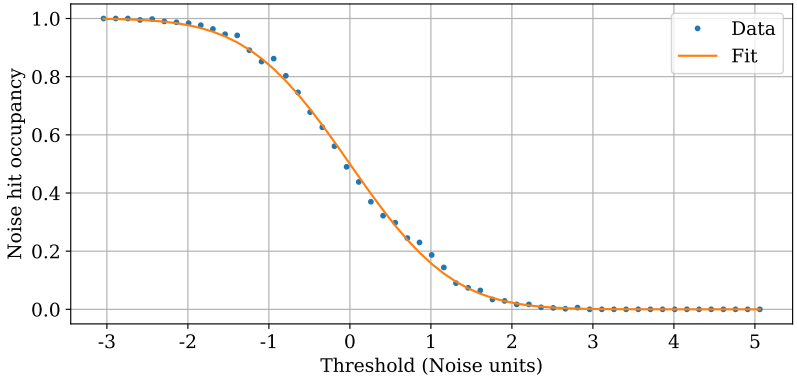
Noise Measurements

Threshold scan at 100 kHz with 1000 events at each threshold step

Noise hit occupancy η

$$\eta = \frac{\#\text{ noise hits}}{\#\text{ events} \cdot \#\text{ channels}}$$

- Tracker operation aims for $\eta < 10^{-5}$ at thresholds above 5 noise units
  $\Rightarrow$ Fulfilled for all modules on ladder



→ First and only high rate readout test with modules mounted on subdetector structures

Noise Measurements

Threshold scan at 597 kHz with about 100 000 events at each threshold step

Noise hit occupancy η

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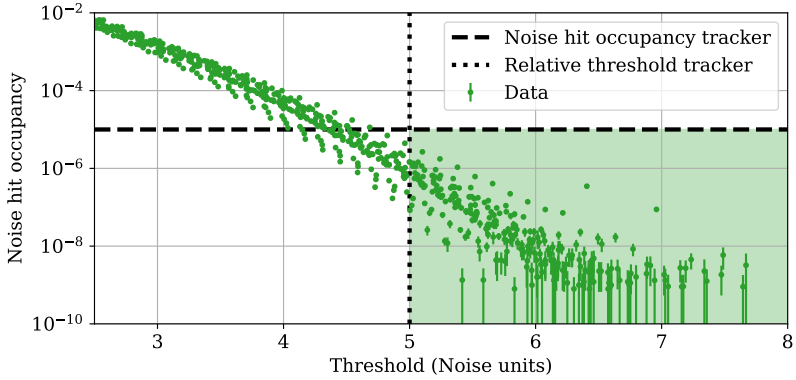
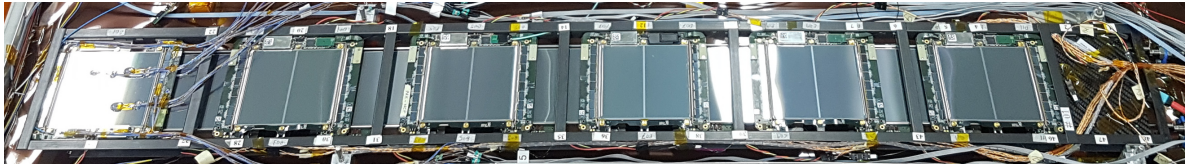


→ First and only high rate readout test with modules mounted on subdetector structures

Summary

- Replacement of the CMS silicon tracker for the HL-LHC by completely new device

- First integration tests with Outer Tracker module prototypes on subdetector structures
- Validation of thermal simulations
  - Cooling performance as expected from simulation
  - Proceeding for the conference “Technology and Instrumentation in Particle Physics 2023” pre-published
- Tests of electrical performance
  - Excellent performance of 2S modules on subdetector structures



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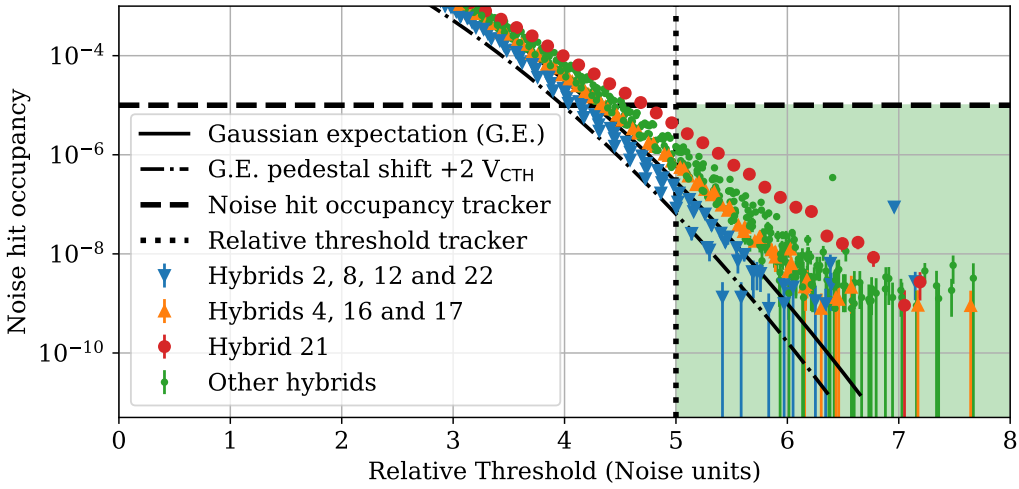
Backup

Noise Measurements



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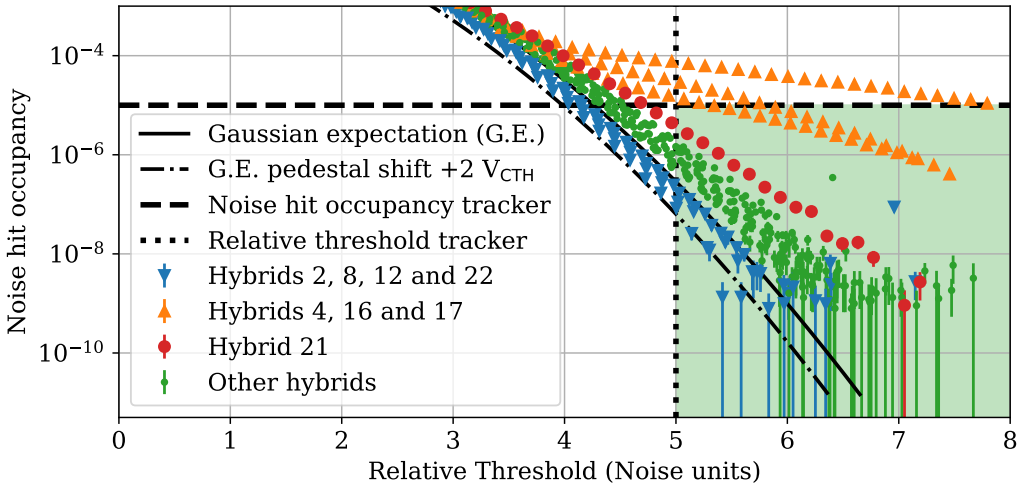
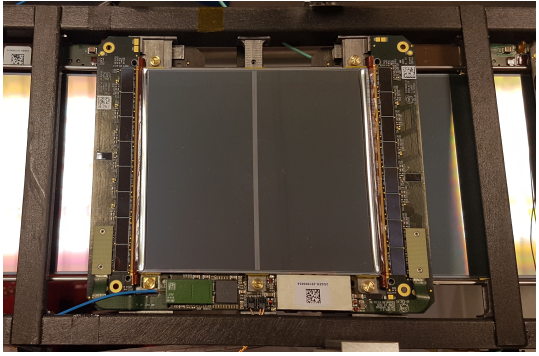
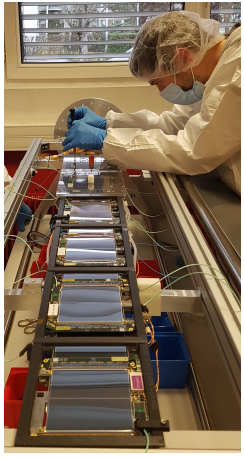


Thermal Runaway – Torque Reduction

- Modules are screwed to ladder inserts





Thermal Runaway – Torque Reduction

- Modules are screwed to ladder inserts
- Reduced torque on all inserts
  - Effect not as pronounced as expected from simulation

⇒ Torque can be reduced to avoid thread breakage in fragile ladder inserts