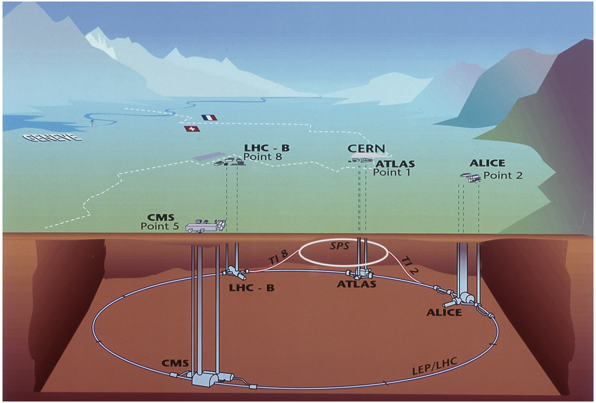
Karlsruhe Institute of Technology
Institute of Experimental Particle Physics

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

Lea Stockmeier
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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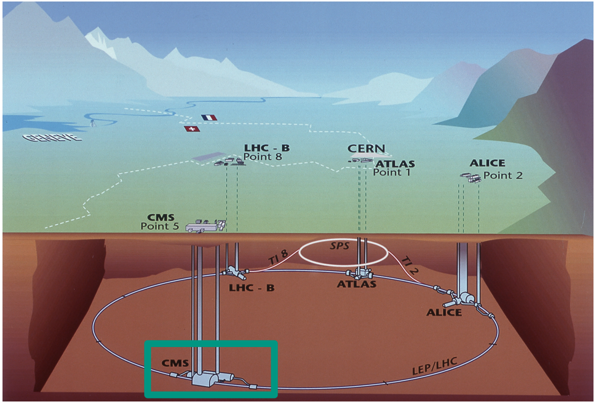
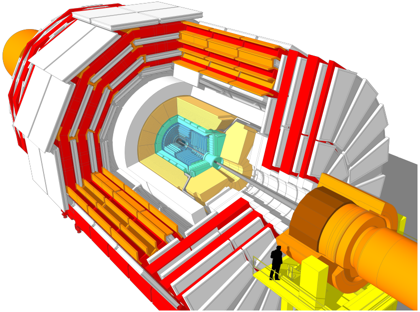
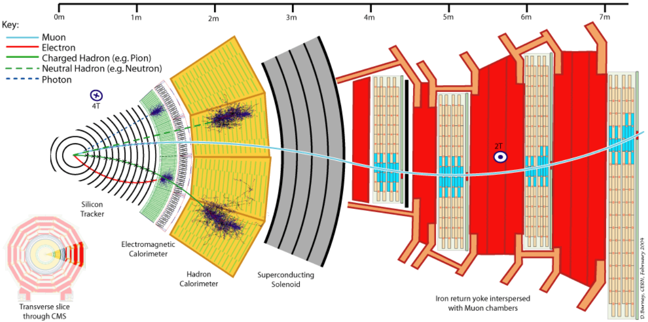


The Compact Muon Solenoid (CMS) Experiment

- Multi-purpose particle detector
- Triggered data readout

- Subdetectors for different purposes
- Particle reconstruction by combining charge, energy and momentum information





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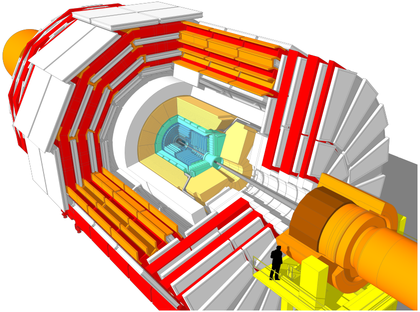
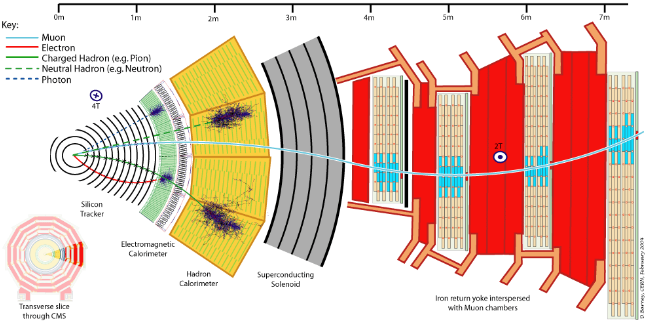
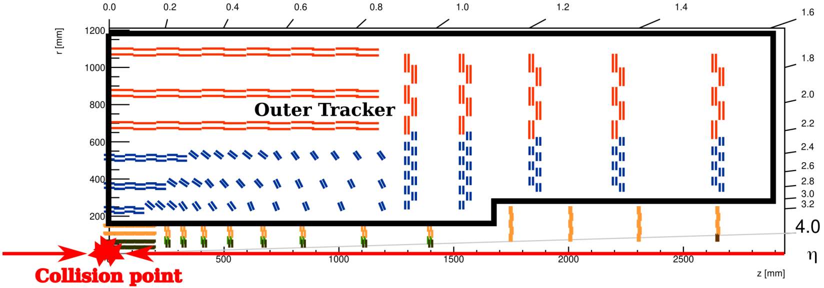




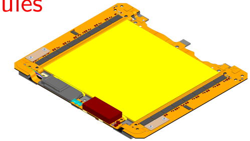
→ **Phase-2 Upgrade** of subdetectors for operation during HL-LHC

The Phase-2 Upgrade of the CMS Tracker

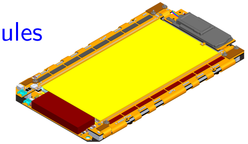
- New silicon tracker for HL-LHC
  - Higher channel density
  - Reduced material budget
  - Improved radiation tolerance
  - Binary readout



2S modules

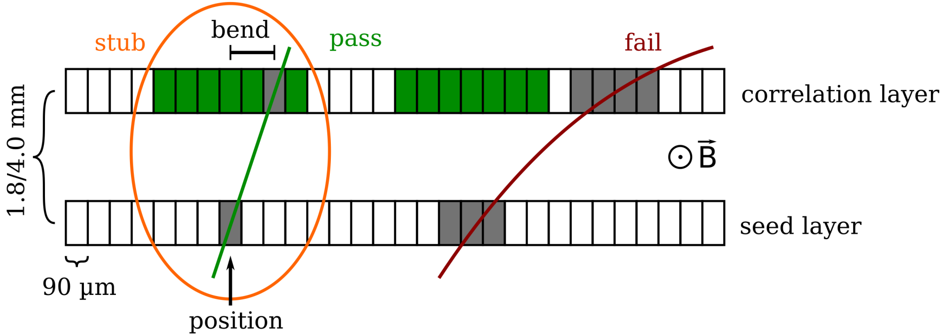


PS modules



The p_T Module Concept

- Contribution of Outer Tracker to L1 trigger system



The 2S Module

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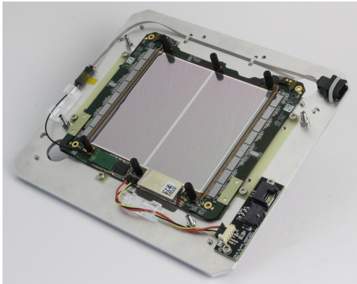
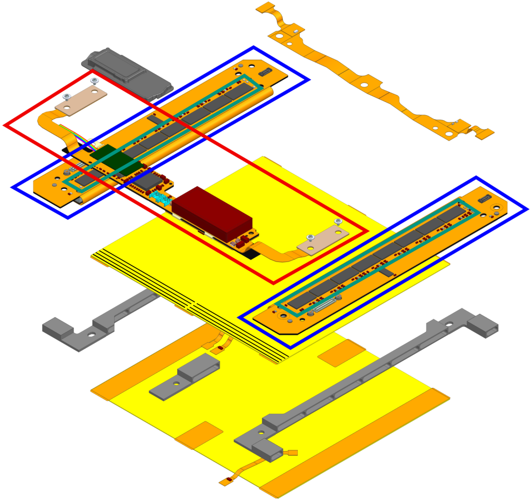
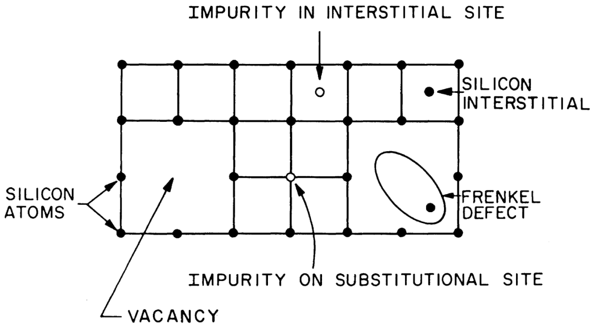
- Silicon strip sensors
- Al-CF spacers for mechanical fixation and main cooling path
- Readout chips mounted on frontend hybrids
- Service hybrid for powering and data transmission

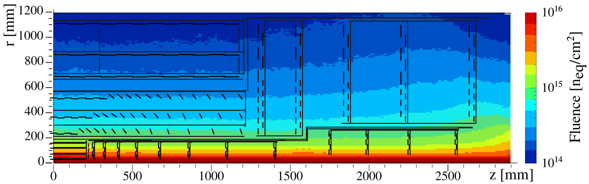




Radiation Damage in Silicon

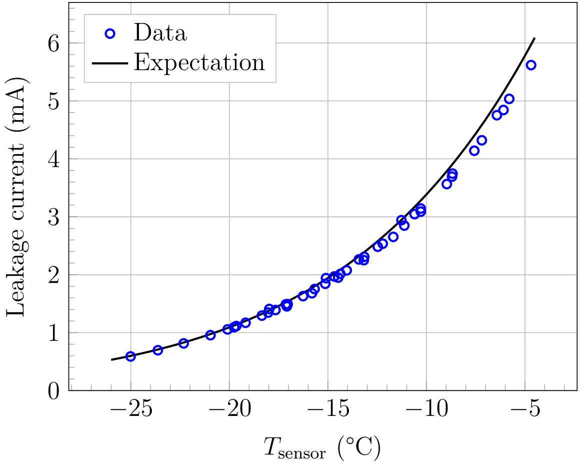
- Detector operation at LHC environment
  ⇒ **Radiation damage**
  - Microscopic defects in silicon lattice
- Change in sensor parameters, e.g., higher leakage current
- **Annealing** of crystal defects at temperatures above 0 °C
- Expected radiation environment known from simulation
  → Irradiate sensors with protons and neutrons to level expected at the end of HL-LHC data taking





Cooling and Thermal Runaway

- Contributions to heat dissipation
  - 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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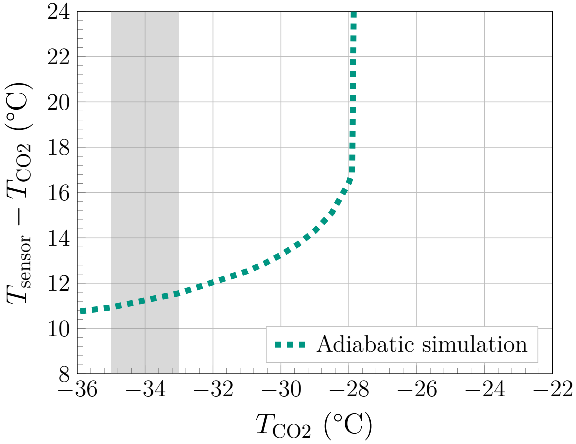
  - Operation of detector impossible
  - Finite Volume Method (FVM) simulations to predict thermal runaway temperature



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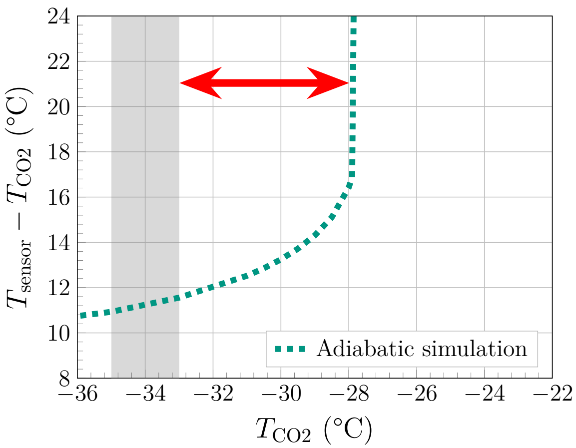
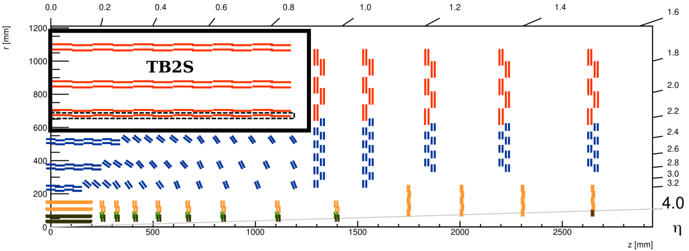
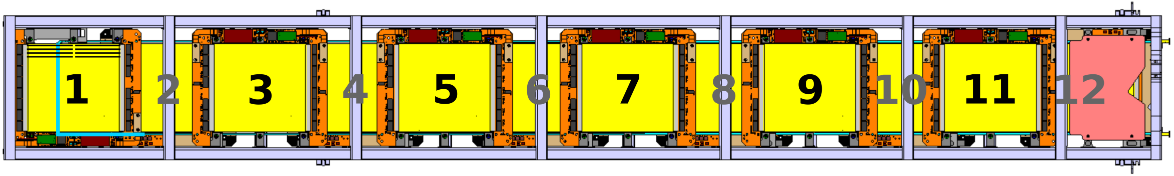
  - Safety margin: Difference between operation and thermal runaway temperature



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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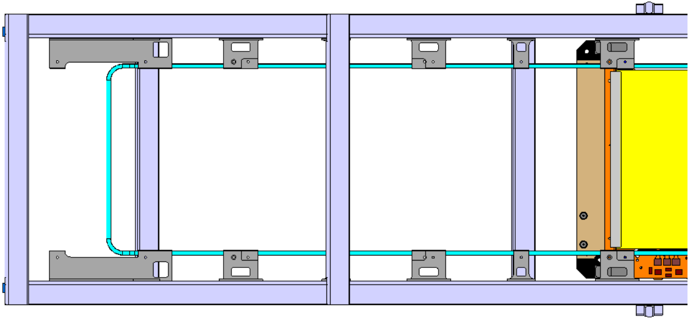
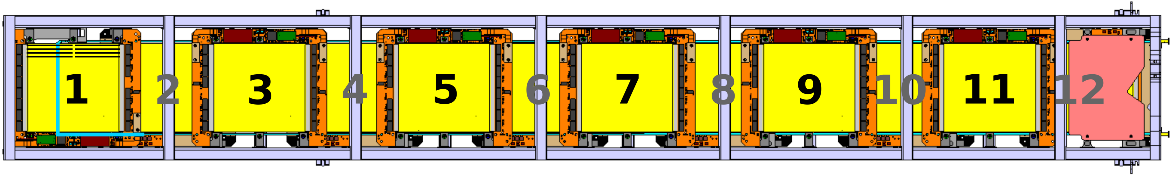
- Mounting of 2S modules on cooling inserts
  - Worst cooling contact at position 1
  - Sixth cooling point added due to special inserts





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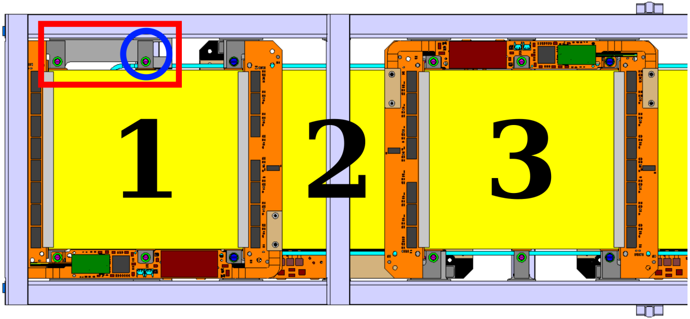
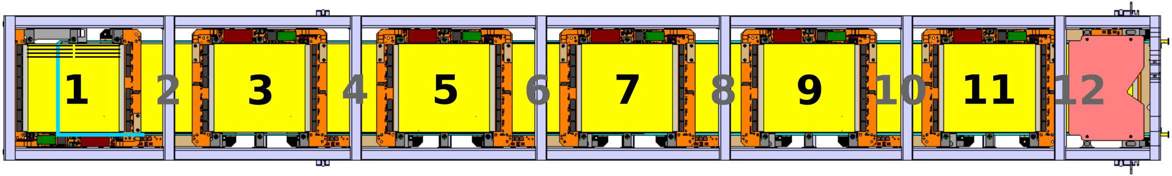
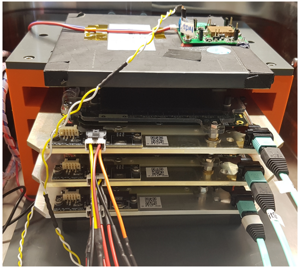


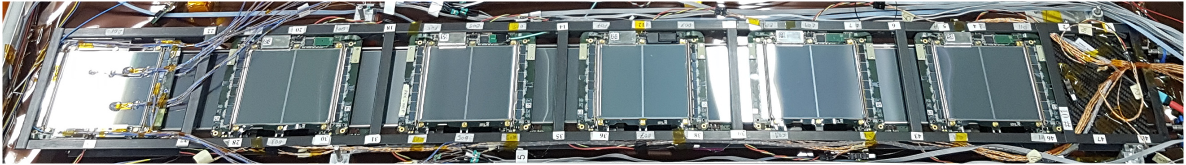


Goals of My Thesis

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

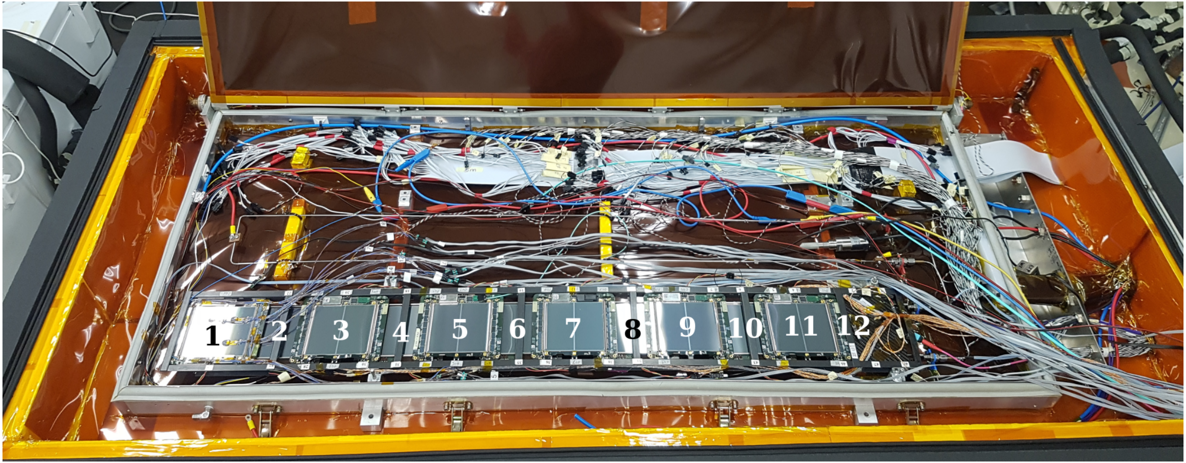


- Integration tests
  - First tests with modules mounted on subdetector structures
  - Test module integration with handling and tooling
  - **Thermal performance studies**
  - **Electrical performance studies**



Thermal Performance – Experimental Setup

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



Experimental Setup

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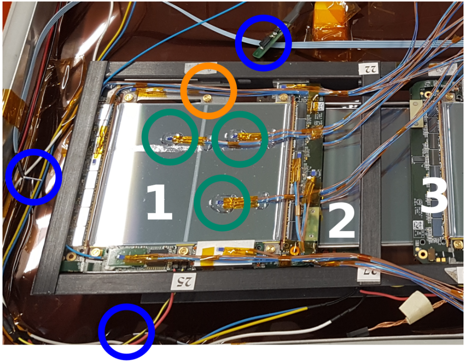
Study module performance at the end of HL-LHC data taking

At $4000\,\text{fb}^{-1}$: maximal fluence of $\Phi_{\text{eq}} = 3.7 \times 10^{14}\,\text{cm}^{-2}$ for 2S modules mounted in the TB2S

- Position 1: Irradiated module (23 MeV protons at KIT)
  - Top sensor: $\Phi_{\text{eq}} = 5.2 \times 10^{14}\,\text{cm}^{-2}$
  - Bottom sensor: $\Phi_{\text{eq}} = 3.8 \times 10^{14}\,\text{cm}^{-2}$
  - No additional sixth cooling point (foreseen at position 1)
  - No extra mass in spacers (preliminary design)
- Positions 2 to 12: Unirradiated modules
- Temperature probes
  - On irradiated module
  - In air
  - On cooling pipe



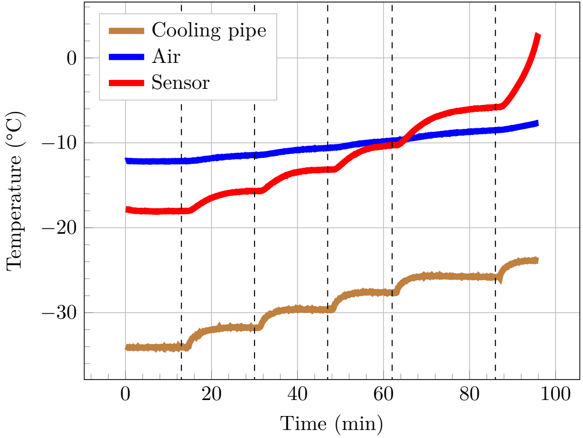
Thermal Runaway – Measurements

- 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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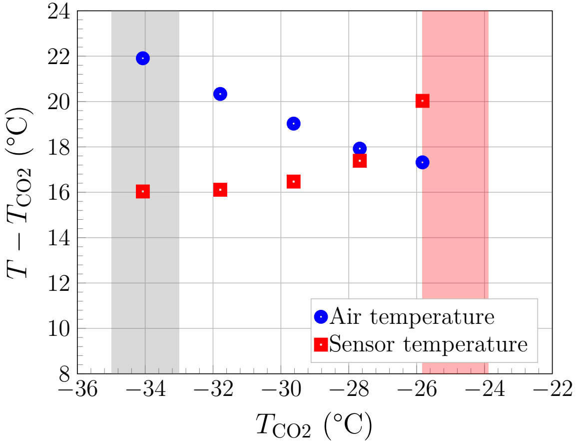
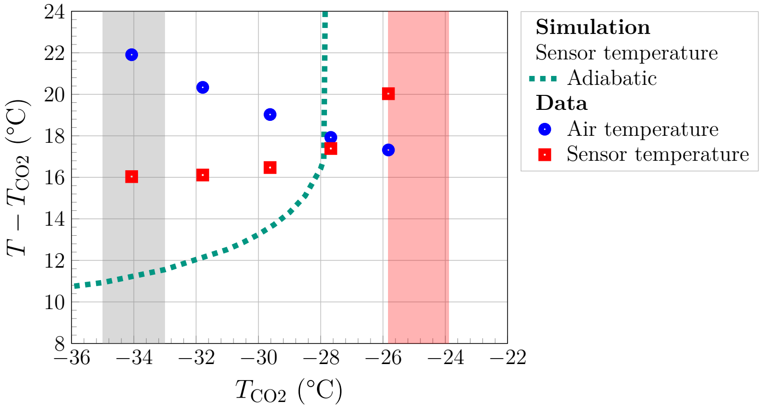


Thermal Runaway – Simulation

Adiabatic simulation

- Without heat transfer to the surrounding air



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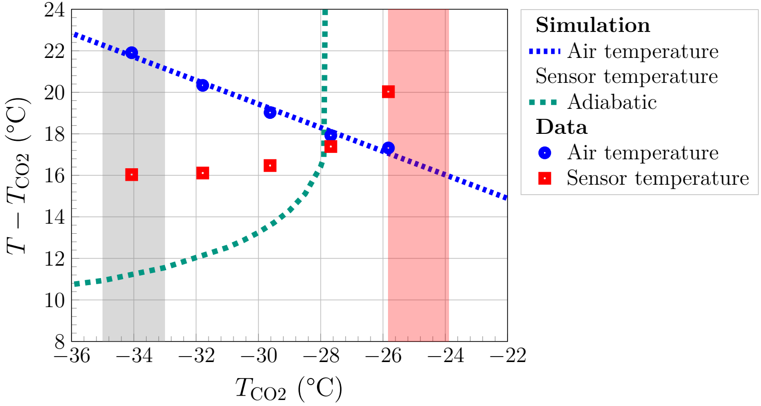

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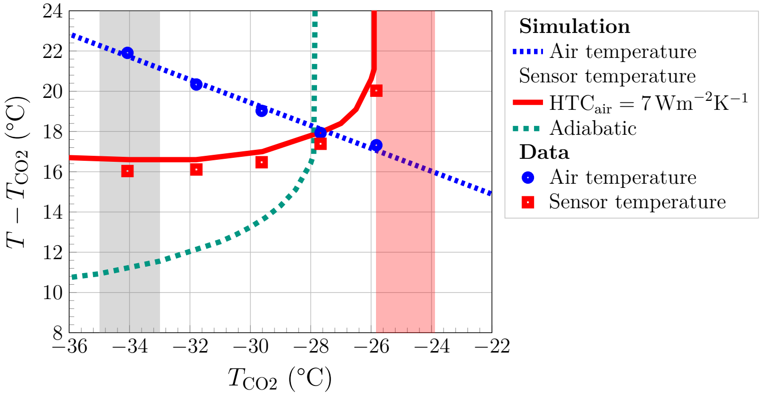
- Linear air profile as input
- Tuned heat transfer coefficient ($\mathrm{HTC_{air}}$) to match measurement conditions
  → Reasonable value for natural air convection



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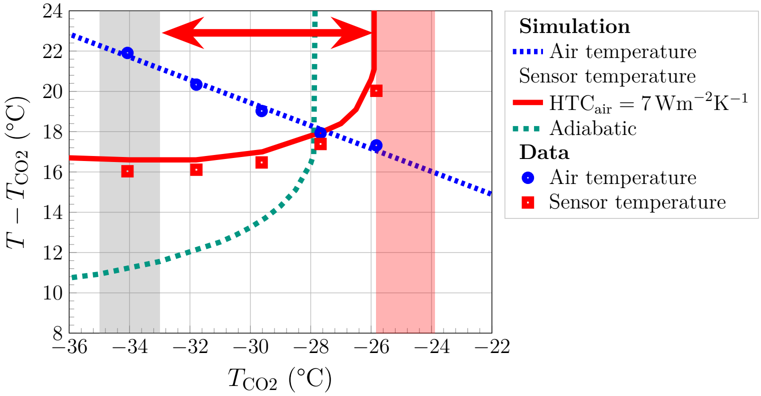
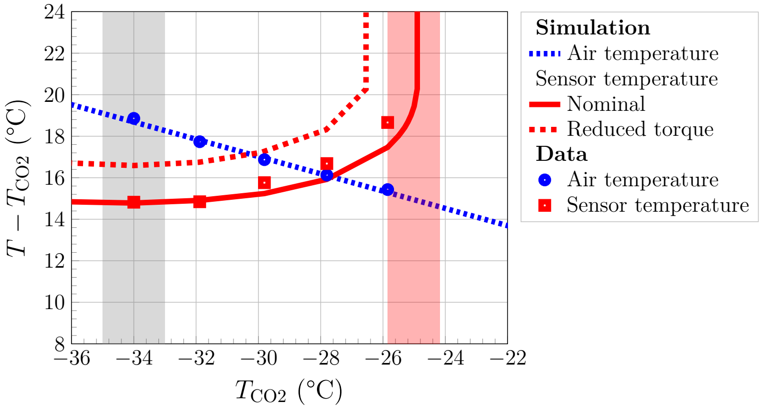
⇒ Thermal model validated with measurements



Thermal Runaway – Torque Reduction

- Reduced torque on all inserts
  - Effect not as pronounced as expected from simulation

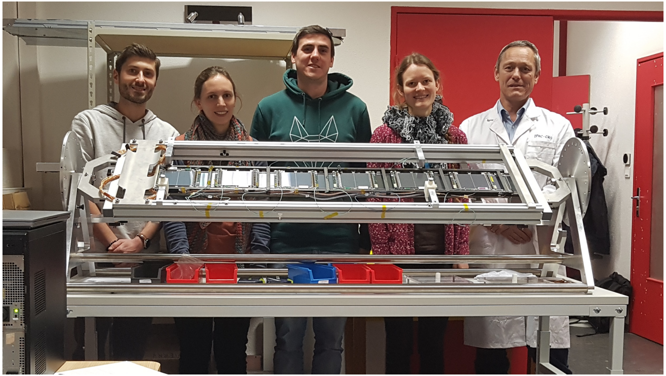
⇒ Torque can be reduced to avoid thread breakage in fragile ladder inserts

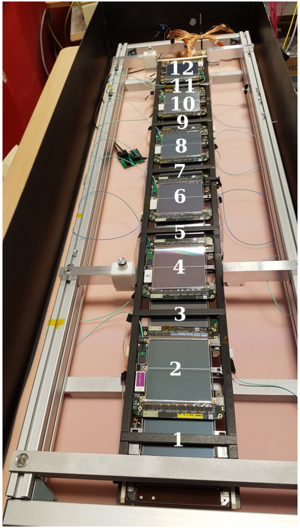


→ Only thermal TB2S ladder tests with modules before production

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





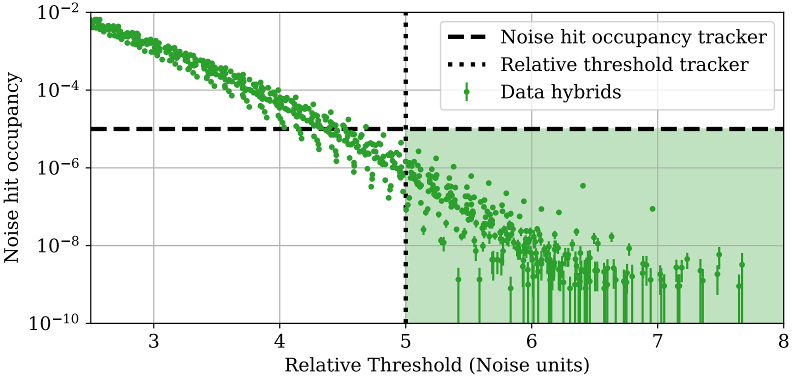
Noise Measurements

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

Noise hit occupancy η

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

- Tracker operation requires $\eta < 10^{-5}$ at thresholds above $5\,\sigma$
  $\Rightarrow$ Fulfilled by all hybrids

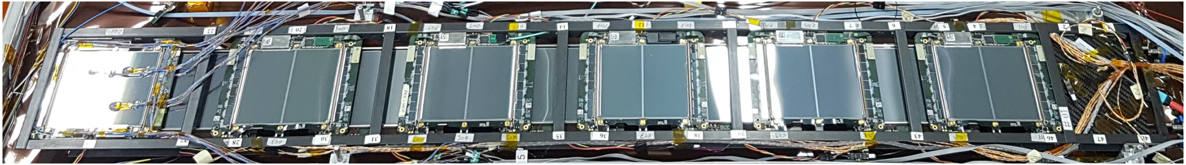


$\rightarrow$ First and only high rate readout test with modules mounted on subdetector structures

Summary

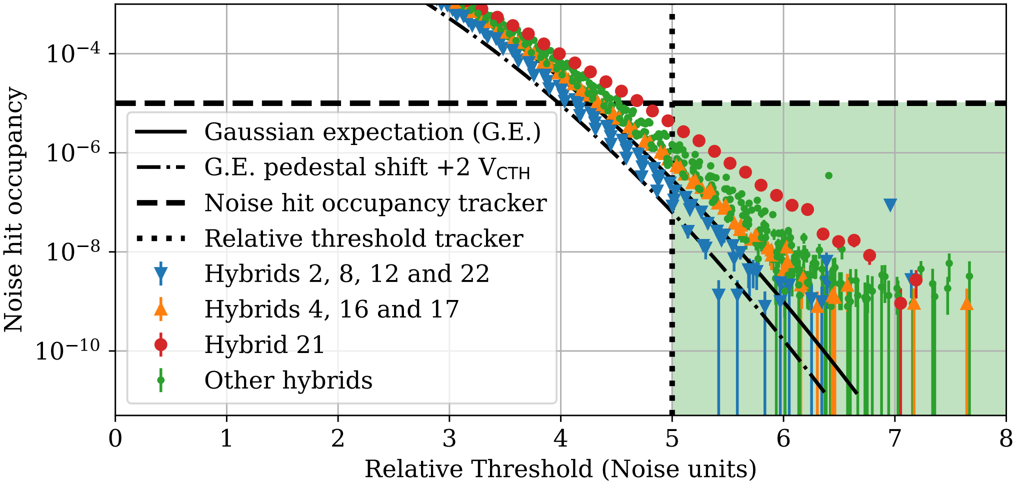
- Replacement of the CMS silicon tracker for the HL-LHC by completely new device

- First integration tests with Outer Tracker module prototypes on subdetector structures
- Validation of thermal simulations
  - Cooling performance as expected from simulation
  - Submitted proceeding to PoS for the conference "Technology and Instrumentation in Particle Physics 2023" (TIPP2023)
- Tests of electrical performance
  - Excellent performance of 2S modules on subdetector structures



Backup

Noise Measurements



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