Summary of Results of

Thermal Measurements for the 2S Module

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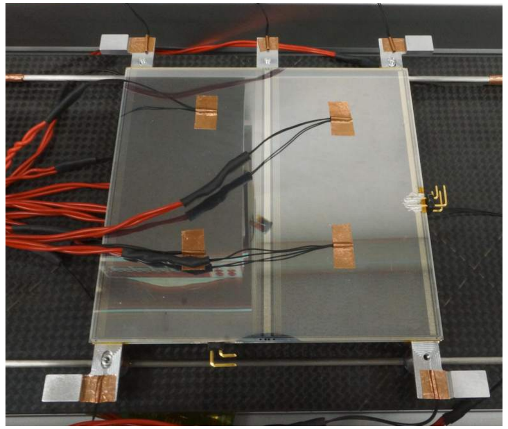
GEFÖRDERT VOM

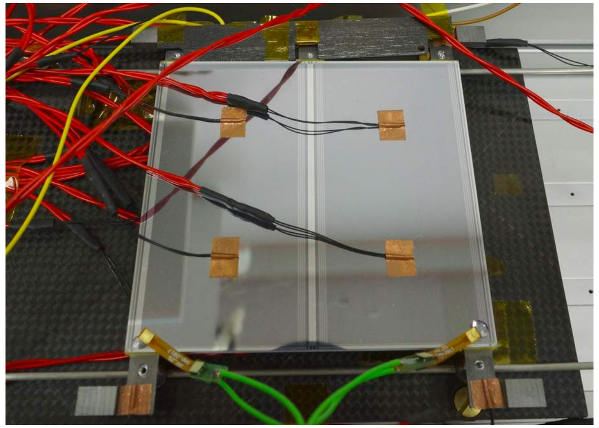
Bundesministerium für Bildung und Forschung

Outline

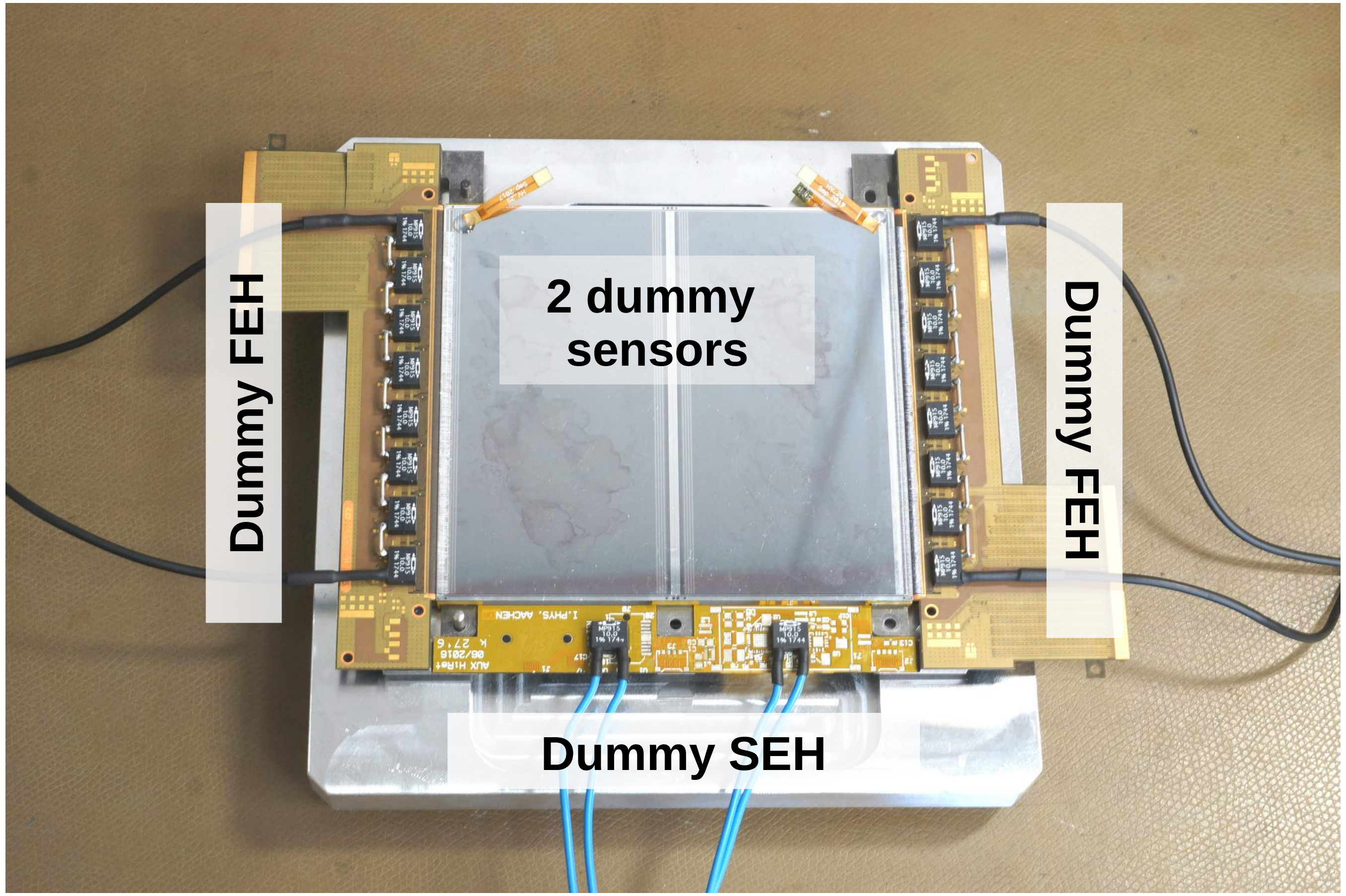
- Reminder on setup, dummy modules, FE model, etc.
- Results with 2S Bare Modules (and comparison with the FE model)
- Results with a 2S Module with Hybrids (and comparison with the FE model)
- Thermal Runaway Measurement (and comparison with the FE model)
- **Measurements were made in the last ~ three years with a continuous process of understanding, cross-checking, re-measuring, …**
- **Real, unavoidable effects have been observed. I want to present the most relevant of them here, qualitatively and as quantitavely as possible. They might also occur in the actual detector, but possibly with different characteristics.**

Thermal Dummy Modules



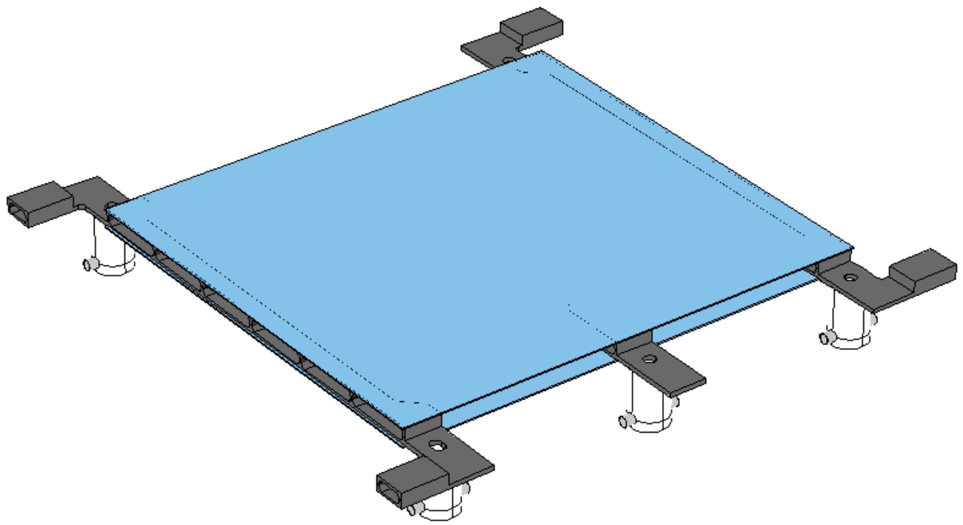


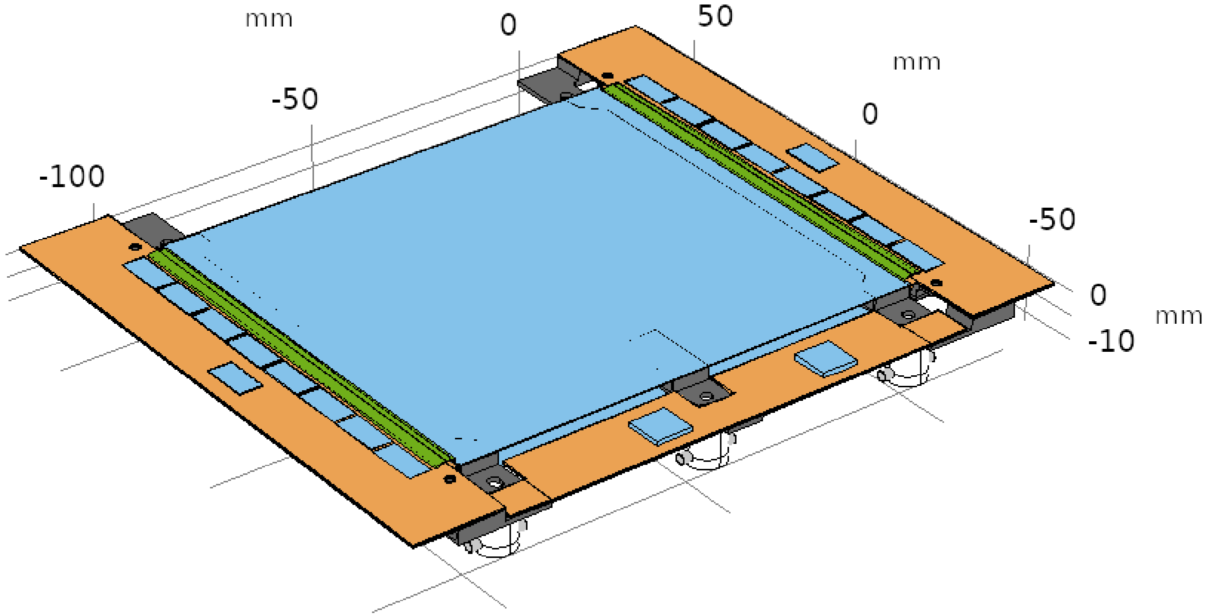
- Two thermal dummy 2S 4.0mm modules
  - thermal dummy silicon sensors powered as Ohmic resistors
- One was equipped with hybrids
  - real flex hybrids, not assembled
  - carbon fiber stiffeners K13D2U (FEH) / K13C2U (SEH)
  - heating resistors
- 2S 4.0mm module was chosen because of the highest expected irradiation for 2S modules in the TEDD forward region

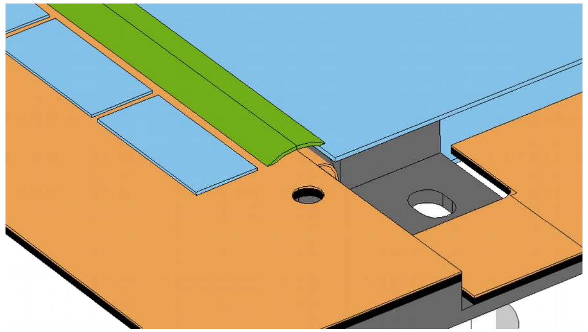


Thermal Finite Element Model

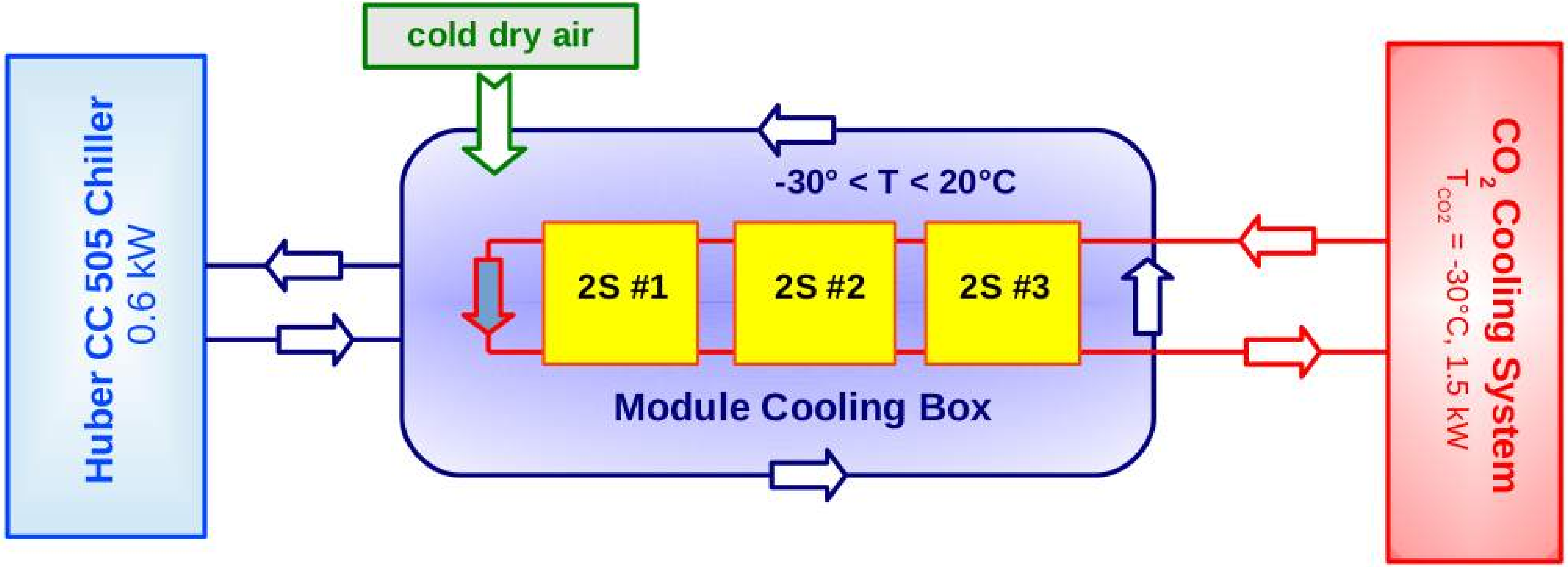
- FE model using COMSOL Multiphysics with properly simplified mechanics
  - Bare module without hybrids
  - Full module with hybrids
- Assumptions on
  - Power production of the single components
  - Heat transfer coefficient of the cooling
  - Thermal conductivity of the materials
    - simplified models for PCB and carbon fiber structures
    - anisotropic assumptions for the AlCF bridges
    - …
  - Glue thicknesses and thermal interfaces
  - Effective models for tiny geometries, e.g. wirebonds, ...





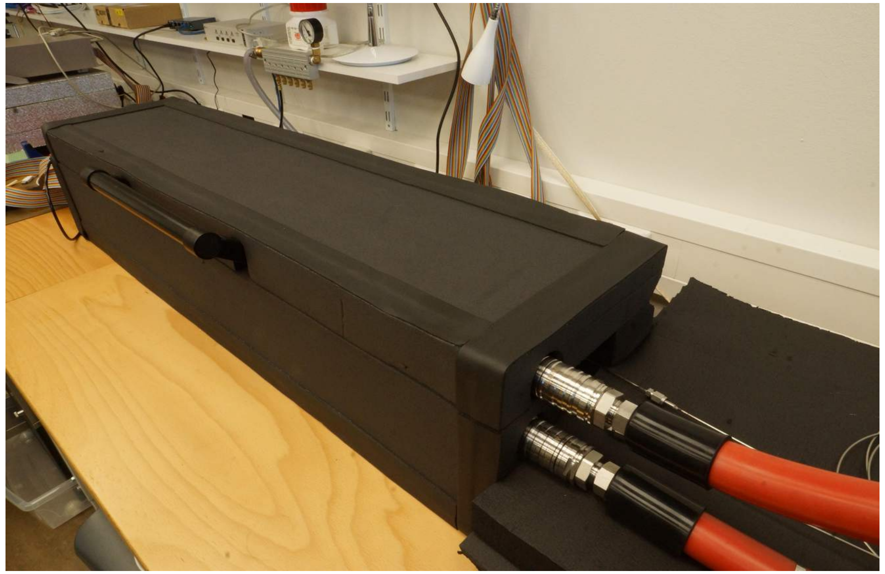


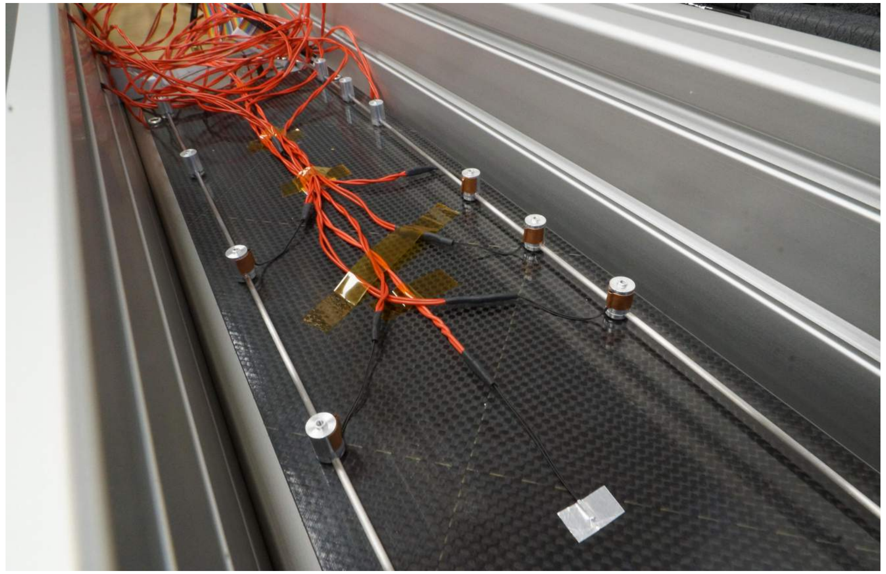
Module Cooling Box Test Setup

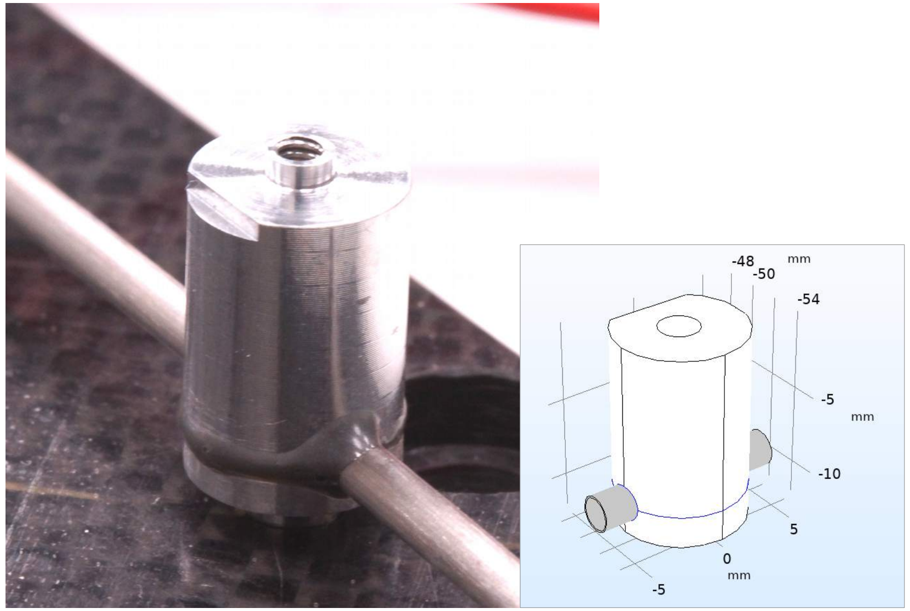


- Closed volume temperated down to -30°C
  - defined ambient temperature in the box → important for controlled measurement conditions
  - cooled with a commercial silicon oil chiller
- CO_2 cooling system
  - two-phase CO_2 cooling system
  - CO_2 standard nominal conditions: T = -30°C, mass flow = 60 g/s
- Three module cooling positions with quasi-realistic cooling blocks

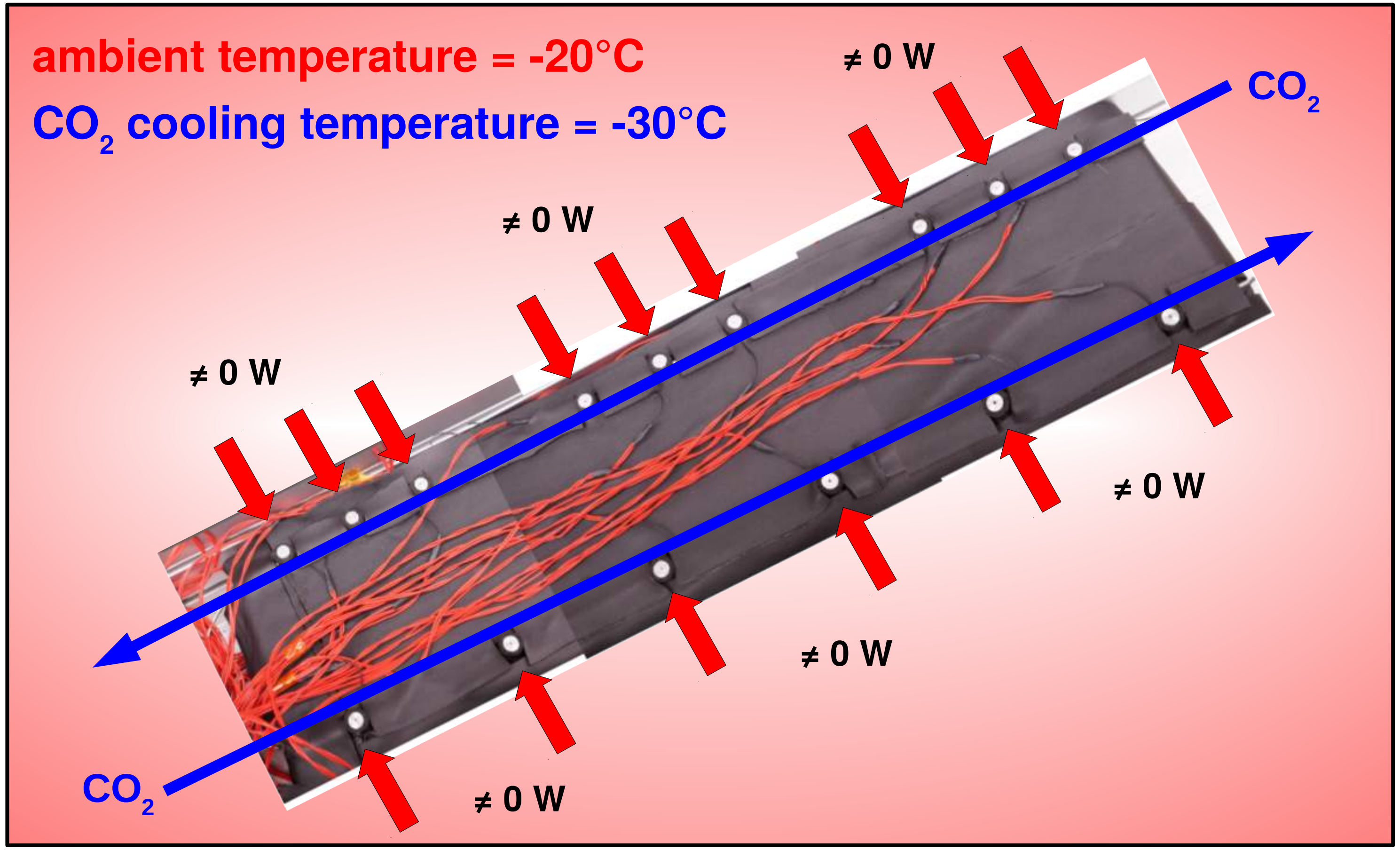
Module Cooling Box Test Setup

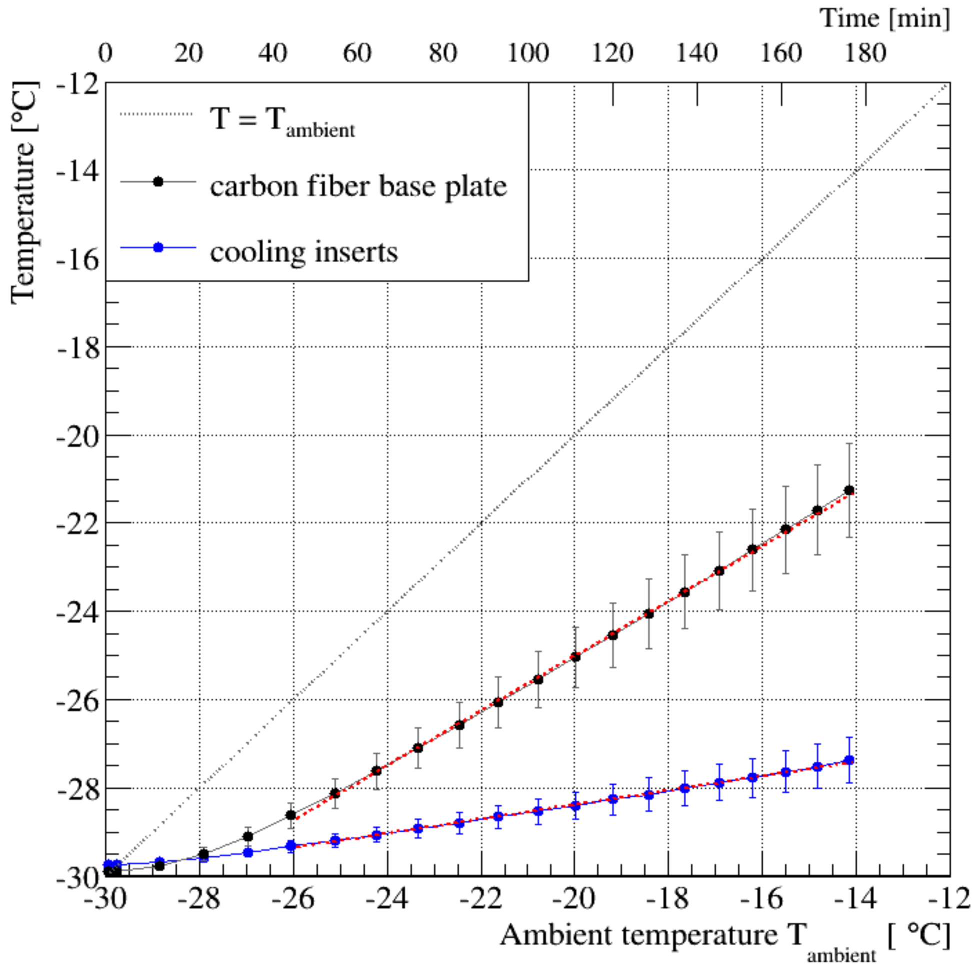






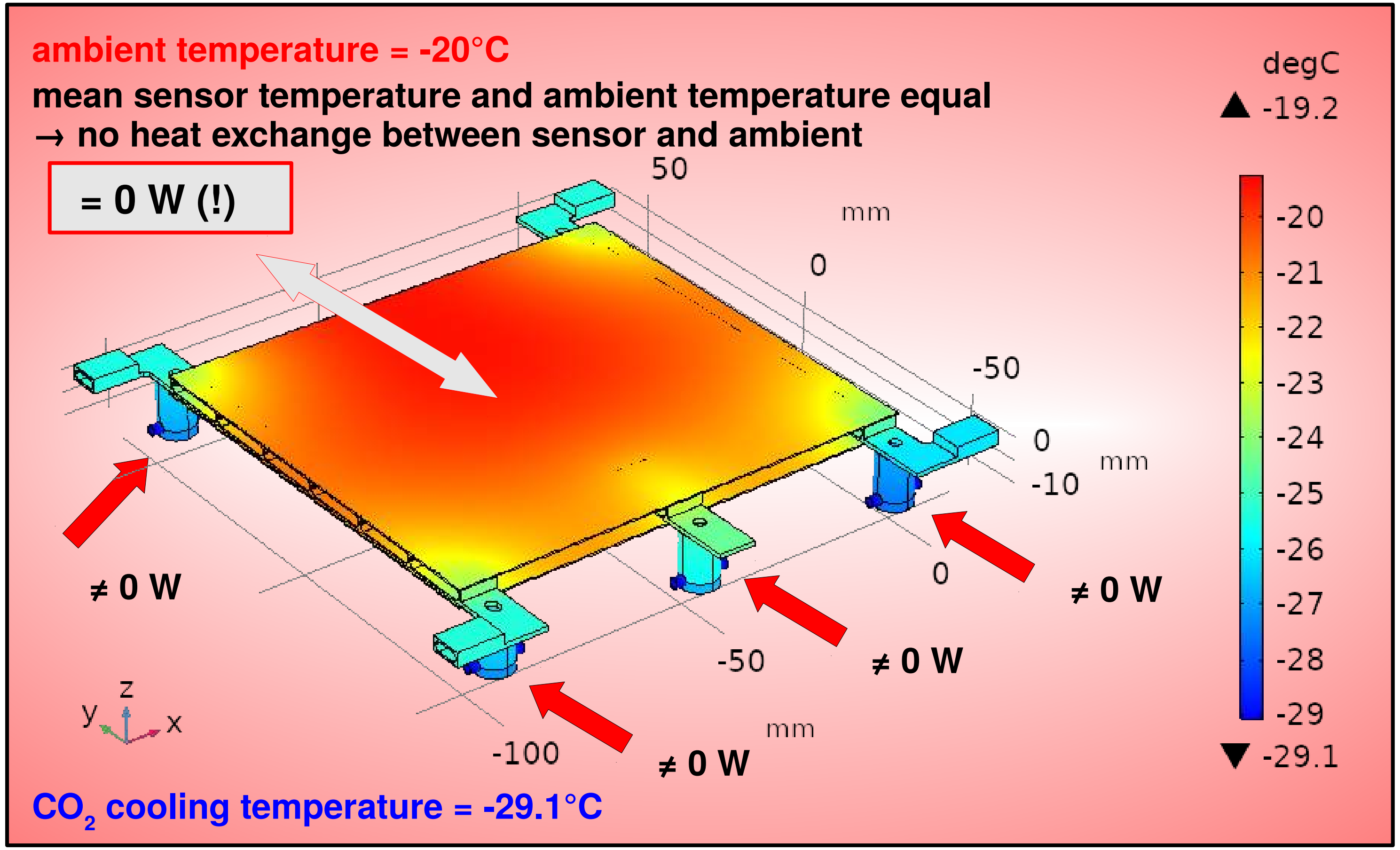
Heat Impact from the Ambient

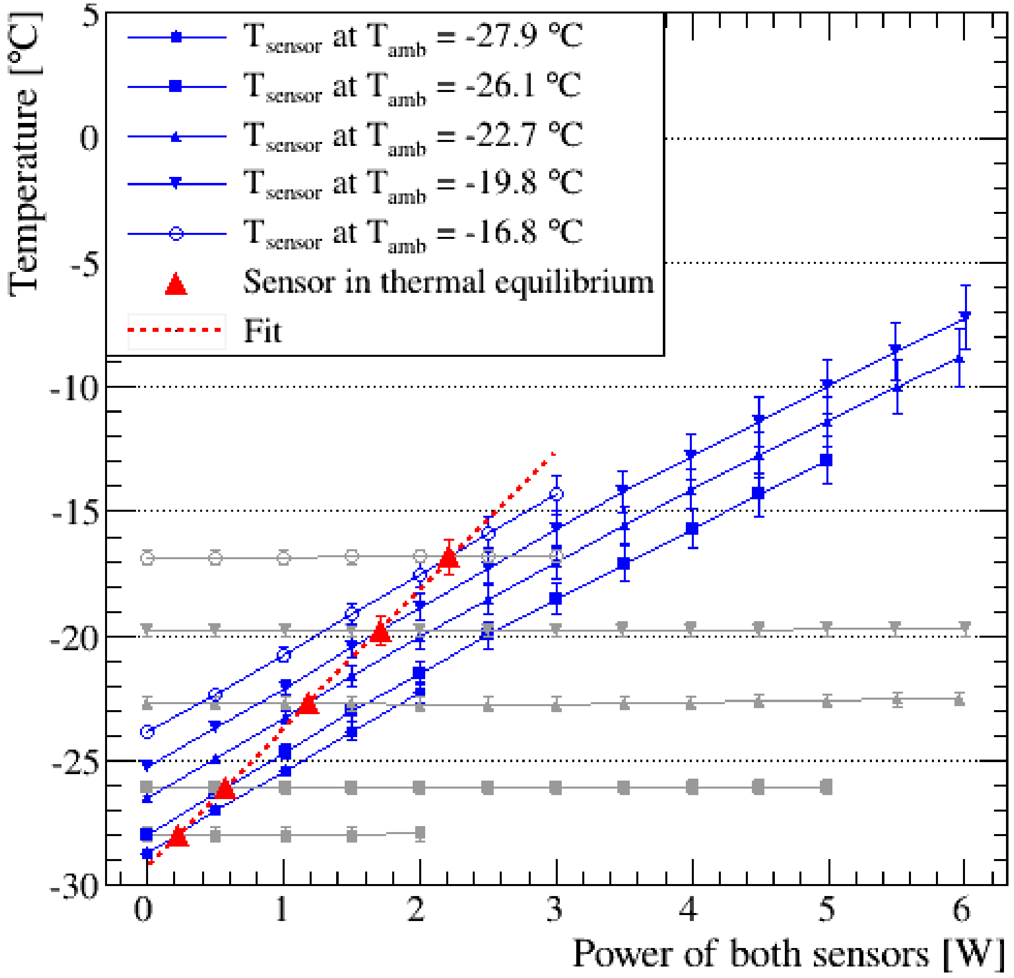




- Heat input from the warmer ambient to the colder cooling inserts → unavoidable effect
- Insert temperatures are raised without any heat load applied
- Linear calibration function → in our setup: $T_{\text{inserts}} = 0.16\left(T_{\text{ambient}} - T_{\text{CO2}}\right) + T_{\text{CO2}}$
- **All temperature data have to be corrected with this calibration for comparison with the FE analysis**

Concept of Thermal Equilibrium





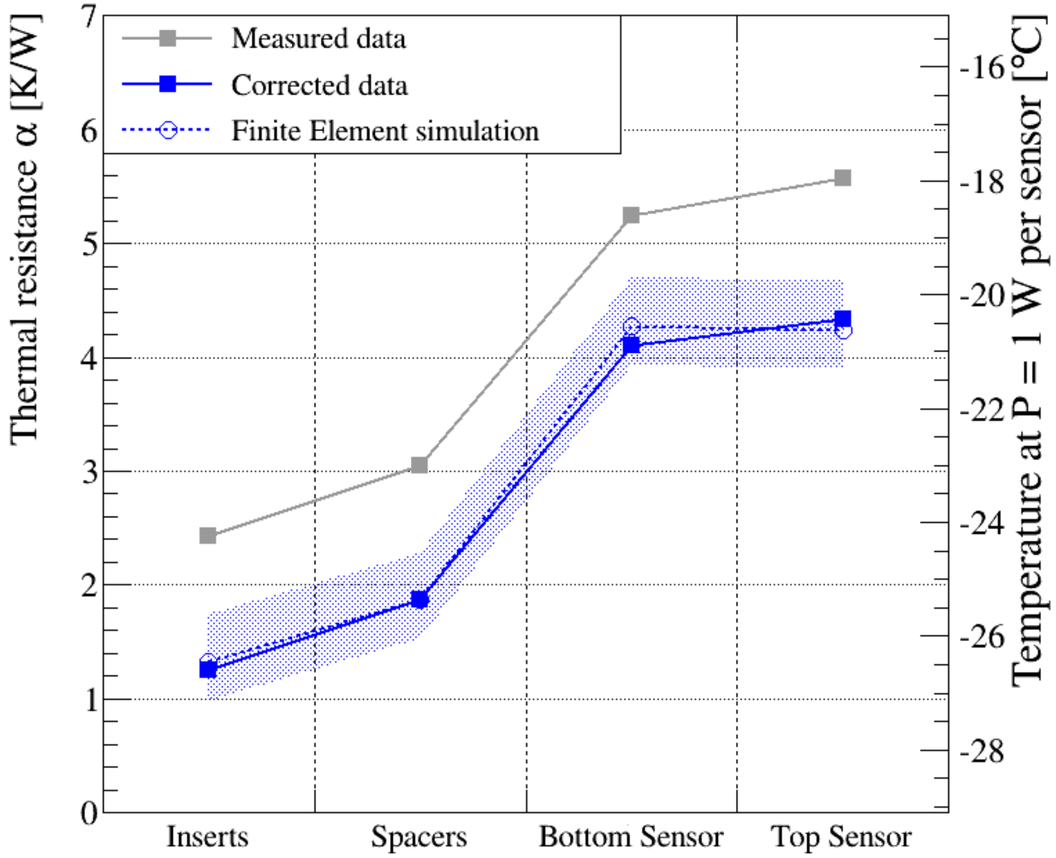
$$P_{\mathrm{amb}} + P_{\mathrm{cooling}} = P = \underbrace{\lambda_{\mathrm{ambient}}\,(T - T_{\mathrm{ambient}})}_{=\text{ heat exchange with the ambient}} + \underbrace{\lambda_{\mathrm{cooling}}\,(T - T_{\mathrm{cooling}})}_{=\text{ heat removed by cooling system}}$$

- Produce thermal equilibrium between sensor and ambient → sensor power is fully removed by the CO_2 system
- Extract thermal resistance of module and cooling structure mechanics → $\overline{\alpha}^{\mathrm{corrected}}_{\mathrm{top\ sensor}} = 4.3\,\mathrm{K/W}$

Results for the Bare Module

Thermal FE model of the bare module validated with measurements

- Averaged temperatures per component are offset corrected for the ambient effects
- Comparison with Finite Element model
- Very good agreement between data and simulation
  - average deviation smaller than 10%



Component	$\alpha_{\text{equil}}\,[\mathrm{K/W}]$	$\alpha_{\text{corrected}}\,[\mathrm{K/W}]$	$\alpha_{\text{FE model}}\,[\mathrm{K/W}]$	$(\alpha_{\text{corrected}} - \alpha_{\text{FE model}})/\alpha_{\text{corrected}}$
Top sensor	5.6	4.3	4.2	-6 %
Bottom sensor	5.3	4.1	4.3	0 %
Spacer	3.1	1.9	1.9	-5 %
Insert	2.4	1.3	1.3	2 %

Results for the Bare Module

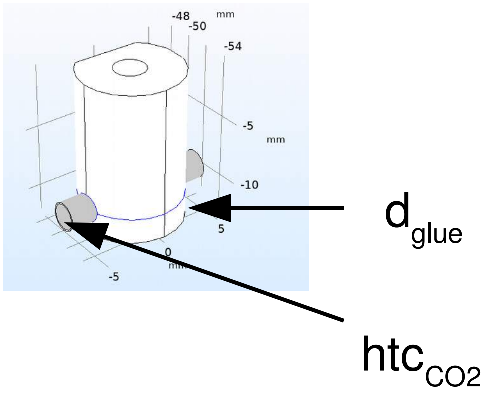
- Blue error band shows sum of
  - variation of insert glue thickness ± 50%:

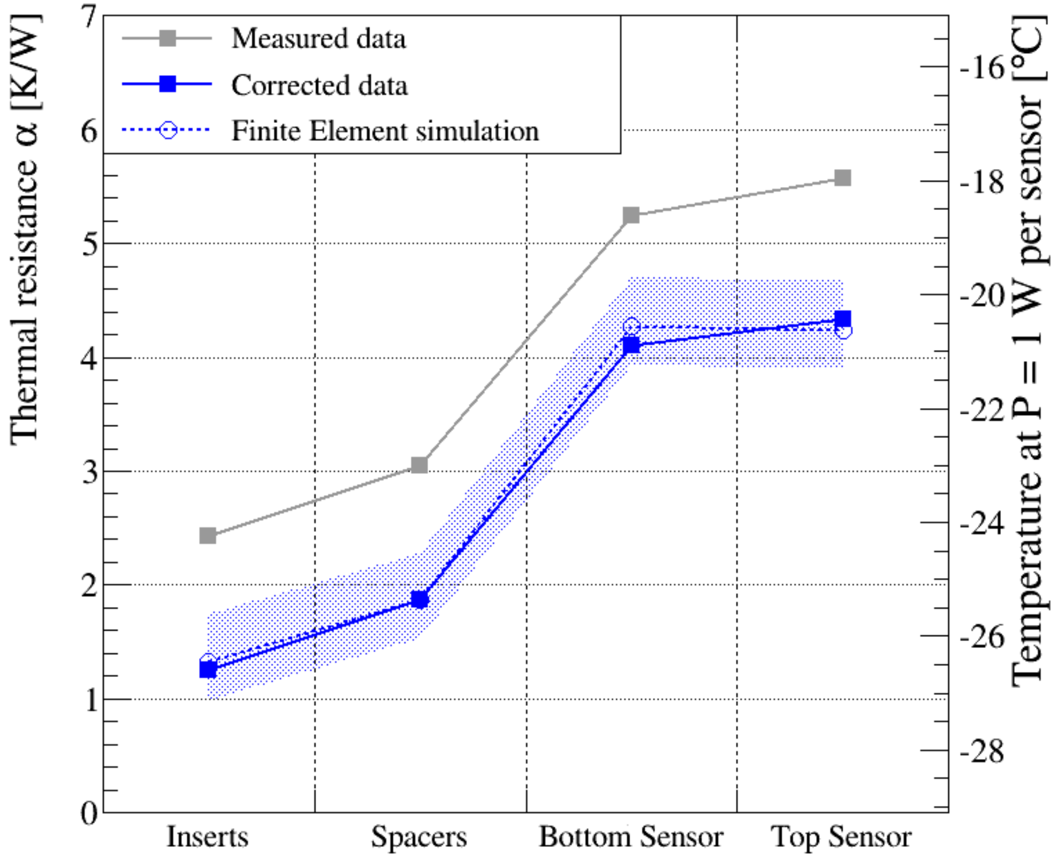
$$11\,\mu\mathrm{m} < \bar{d}_{\mathrm{glue}} < 33\,\mu\mathrm{m}$$

  - variation of CO_2 heat transfer coefficient ± 25%:

$$3.75\,\frac{\mathrm{kW}}{\mathrm{m}^2/\mathrm{K}} < \mathrm{htc}_{\mathrm{CO2}} < 6.25\,\frac{\mathrm{kW}}{\mathrm{m}^2/\mathrm{K}}$$

  - **inserts -25% / +30%**
  - **spacers -18% / +22%**
  - **sensors 8 - 13%**





Results for the Bare Module

- Blue error band shows sum of
  - variation of HV Kapton isolator overall glue thickness ± 20µm

$$20\,\mu\text{m} < \overline{d}_{\text{glue}} < 40\,\mu\text{m}$$

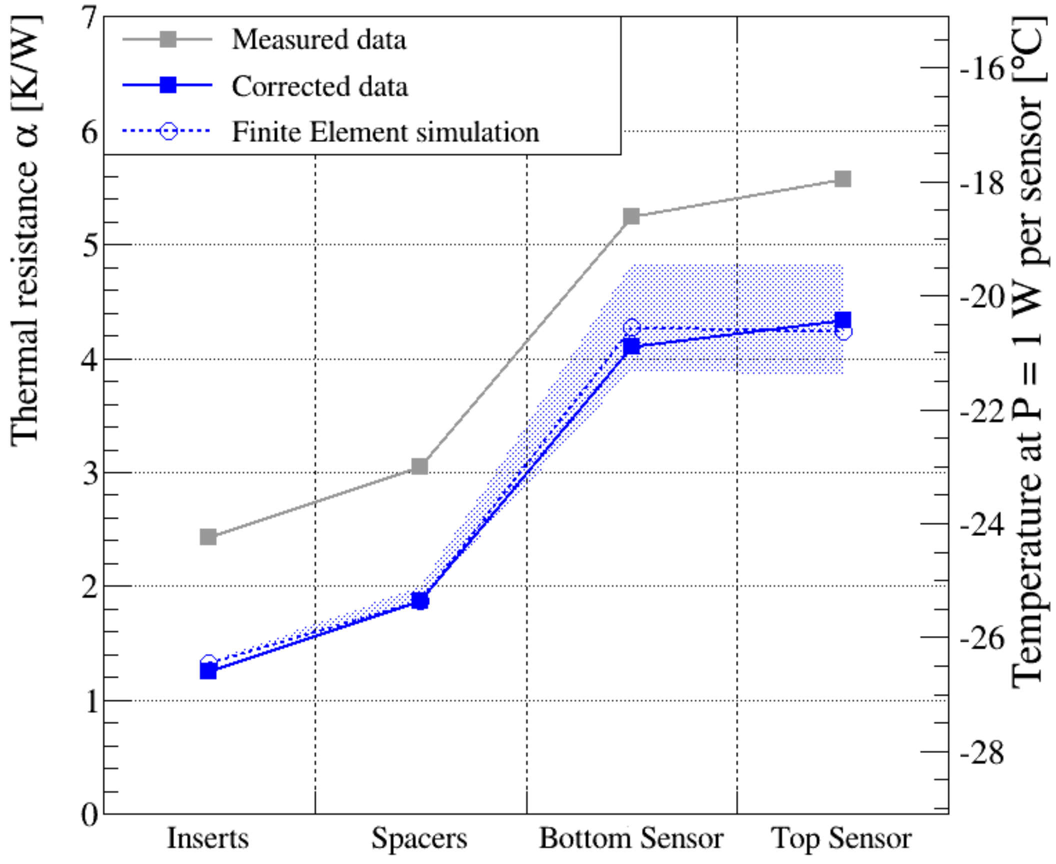
  - variation of spacer screw point heat transfer coefficient ± 25%

$$7500\,\frac{\text{W}}{\text{m}^2/\text{K}} < \text{htc}_{\text{screw point}} < 12500\,\frac{\text{W}}{\text{m}^2/\text{K}}$$

  - variation of AlCF material thermal conductivity ± 25%

$$173\,\frac{\text{W}}{\text{mK}} < k_{\parallel} < 288\,\frac{\text{W}}{\text{mK}};\quad 98\,\frac{\text{W}}{\text{mK}} < k_{\perp} < 163\,\frac{\text{W}}{\text{mK}}$$

  - **inserts ± 0.2%**
  - **spacers -4% / +7%**
  - **sensors -9% / +13%**



Interaction of Sensors with Ambient

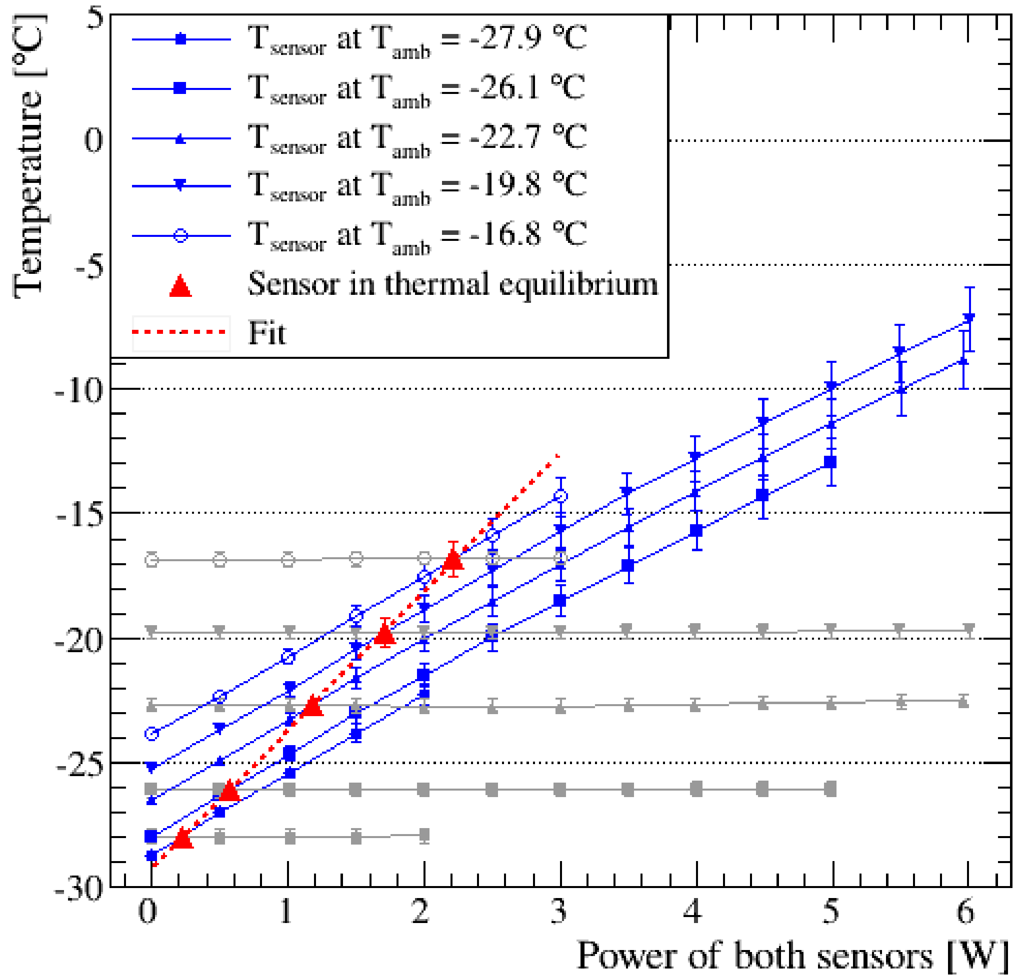
$$P_{\text{amb}} + P_{\text{cooling}} = P = \underbrace{\lambda_{\text{ambient}}\,(T - T_{\text{ambient}})}_{=\text{ heat exchange with the ambient}} + \underbrace{\lambda_{\text{cooling}}\,(T - T_{\text{cooling}})}_{=\text{ heat removed by cooling system}}$$

- Thermal resistance $\alpha_{\text{cooling}} = 1/\lambda_{\text{cooling}}$ determined by producing thermal equilibrium
- Slope of equilibrium data is higher than of raw data

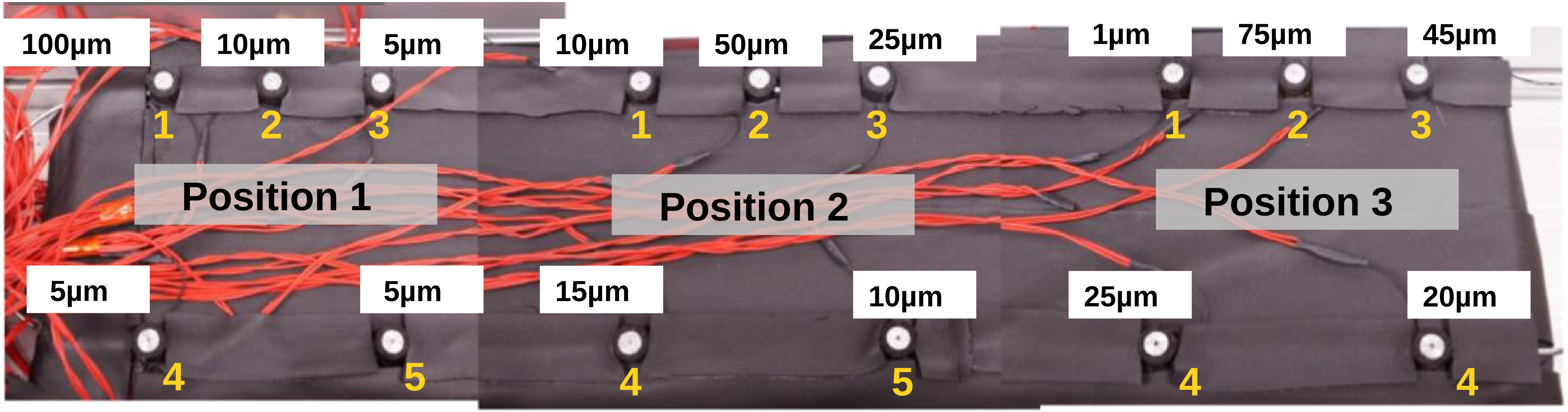
$$\Delta T \propto \frac{1}{\alpha_{\text{top}}} \propto \frac{1}{\lambda_{\text{ambient}} + \lambda_{\text{cooling}}} P$$

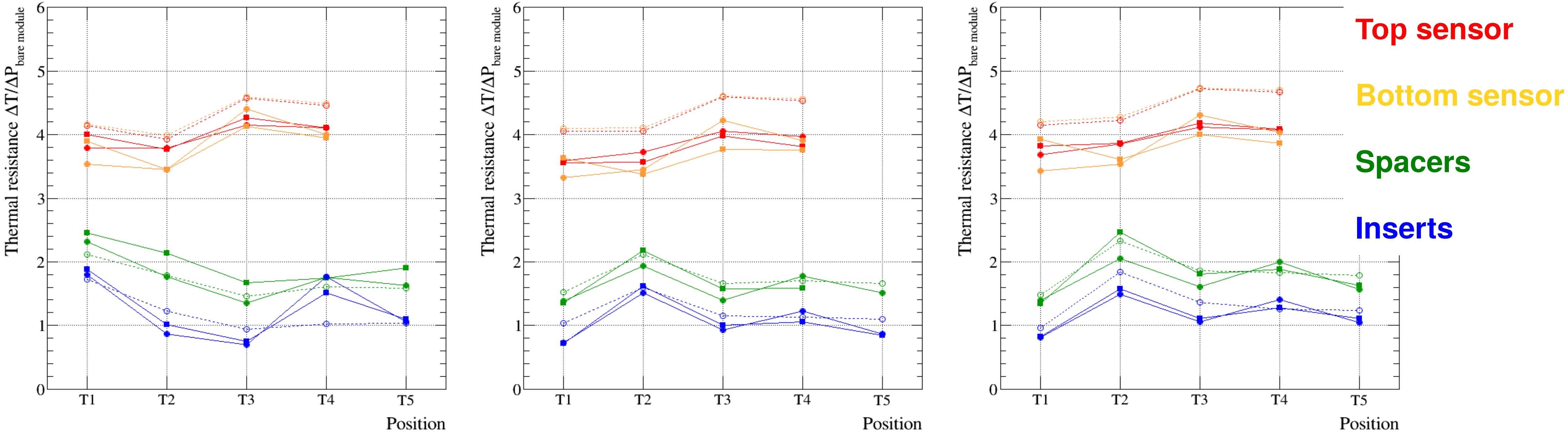
- Measurement of λ_{ambient} possible
- **$\lambda_{\text{ambient, top}}$ = 81 mW/K (top sensor)**
- **$\lambda_{\text{ambient, bottom}}$ = 58 mW/K (bottom sensor)**

T_{ambient} [°C]	α^{top} [K/W]	λ^{top} [mW/K]	α^{bottom} [K/W]	λ^{bottom} [mW/K]
-27.9	3.28	68	3.46	52
-26.1	3.14	81	3.38	59
-22.7	3.09	87	3.33	63
-19.8	3.10	86	3.35	61
-16.8	3.15	81	3.44	53
Average	3.15	81	3.39	58

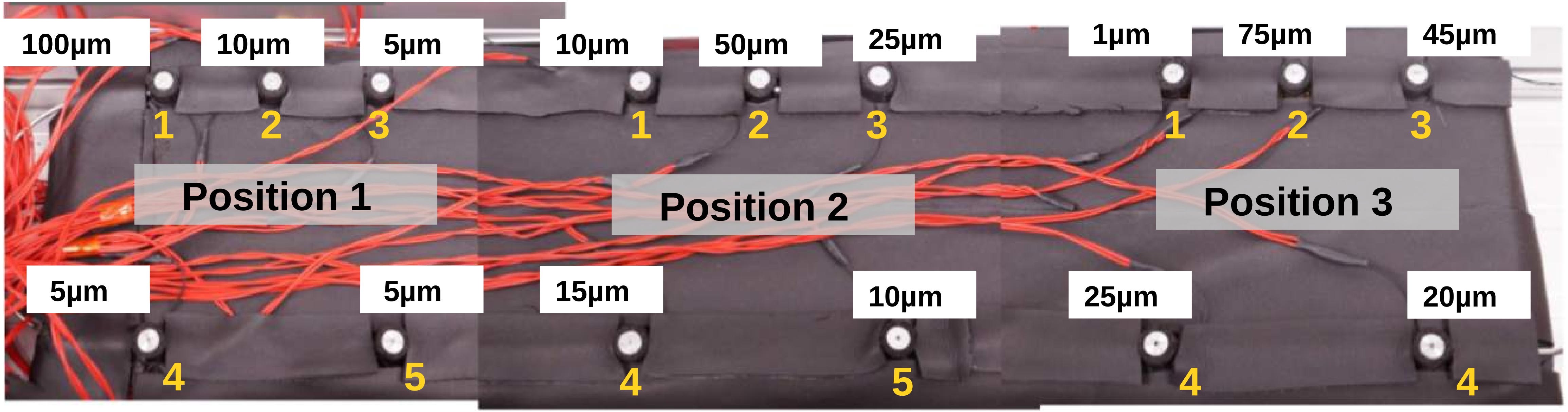


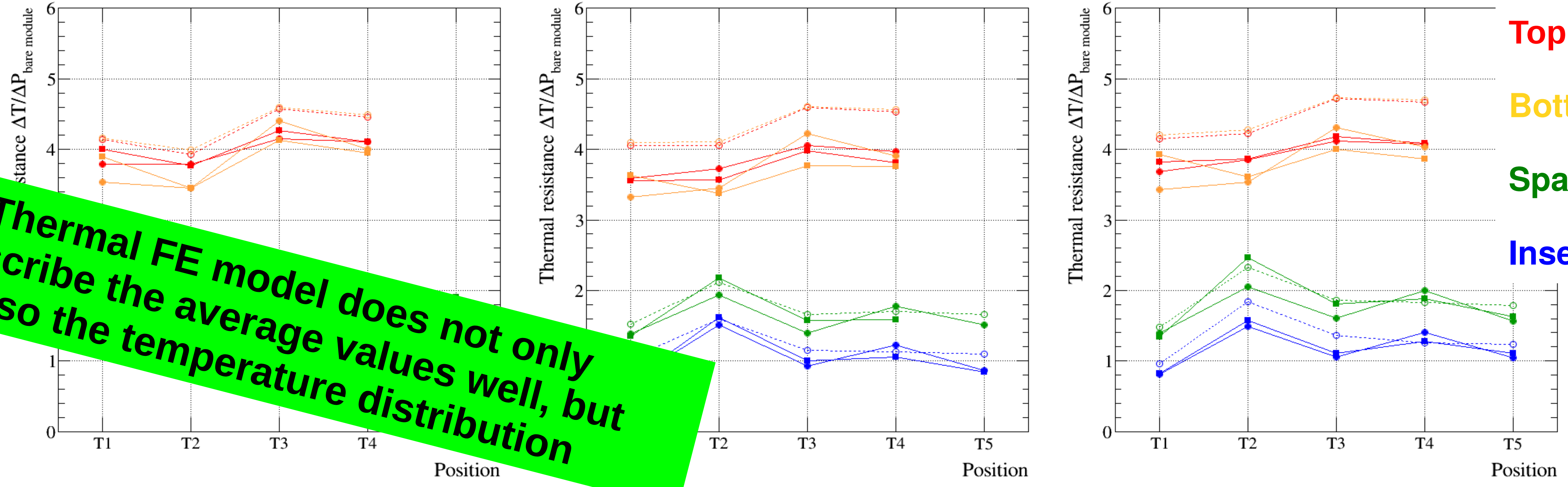
Results for the Bare Module





Results for the Bare Module





Thermal FE model does not only describe the average values well, but also the temperature distribution

Thermal Dummy with Hybrids

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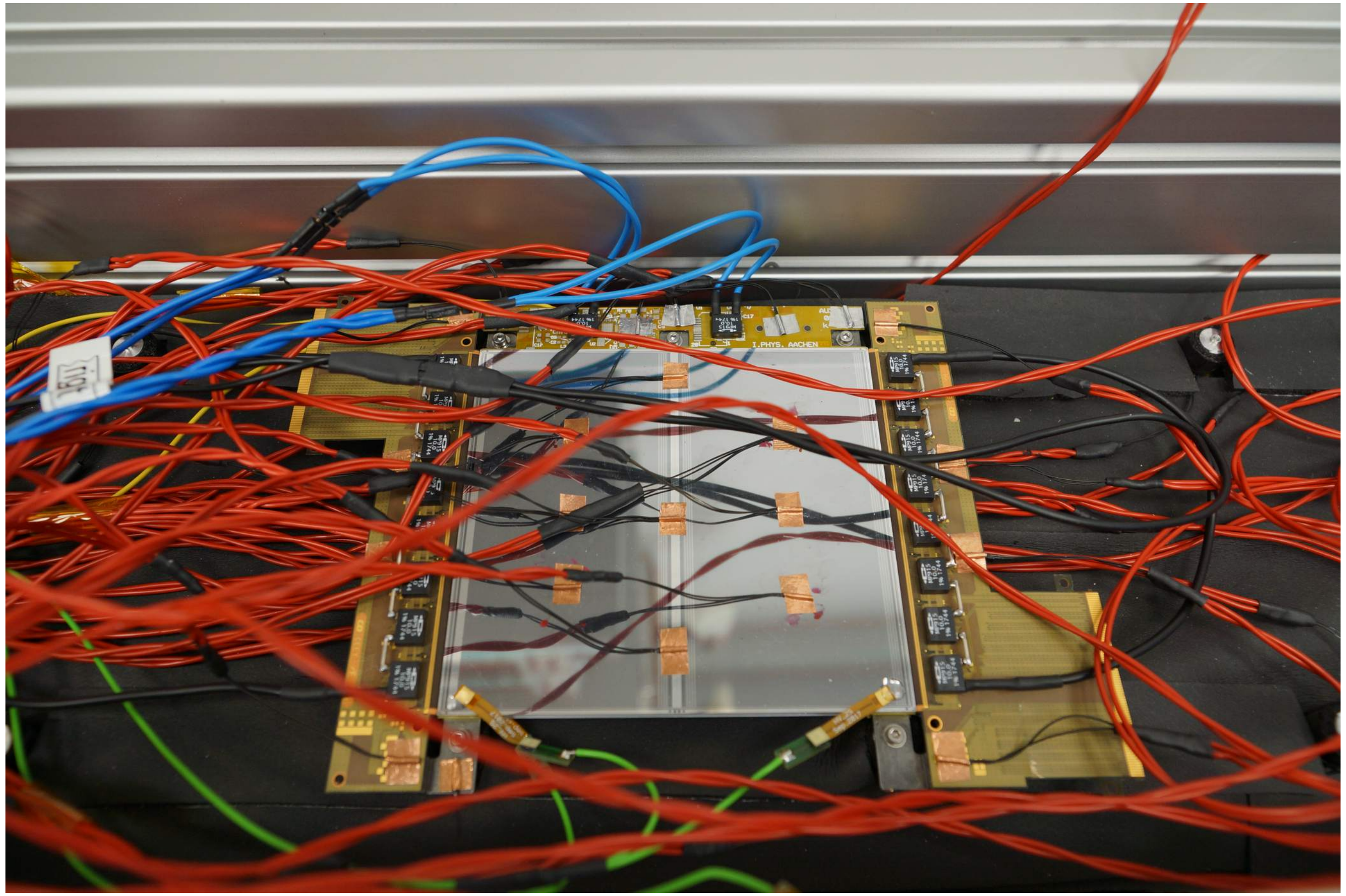
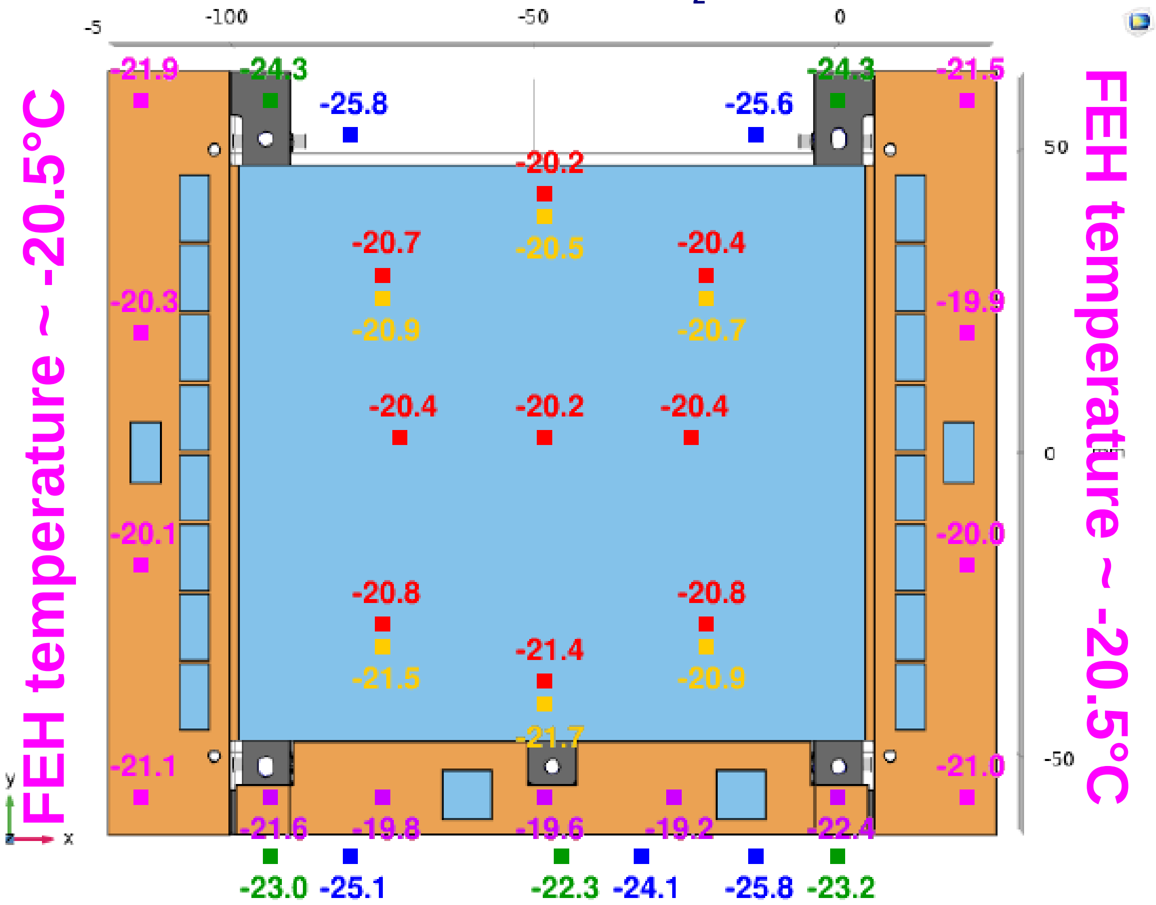


power top sensor = 0.74 W
power bottom sensor = 0.73 W
T_{amb} = -20.97 °C

power SEH = 0.80 W
power FEHs = 0.80 W
CO_2 temperature -29.8 °C



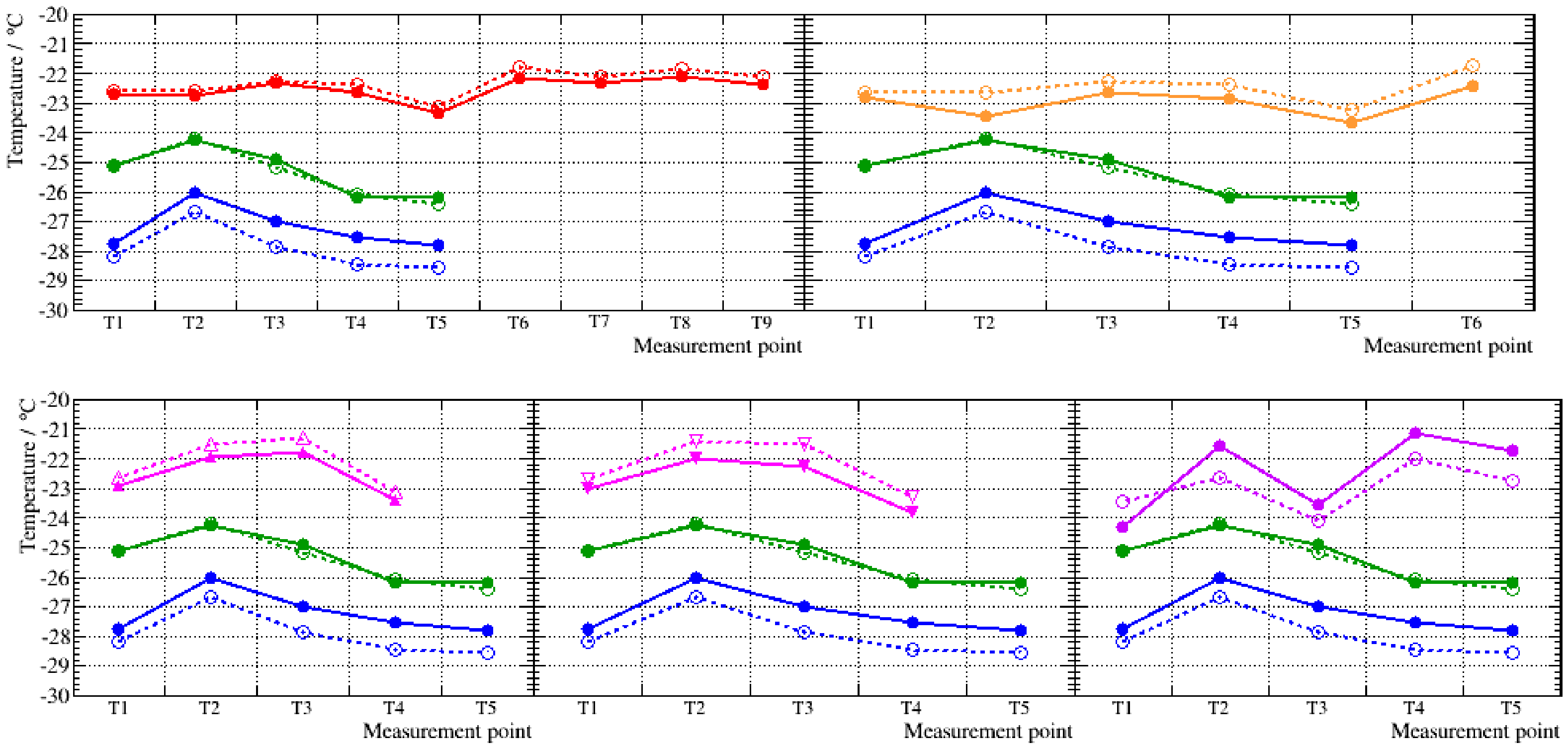
- Two dummy FE hybrids
  - folded flex circuit
  - AlCF spacers
  - K13D2U carbon fiber stiffener
  - heating resistors
- Dummy Service hybrid
  - folded flex circuit
  - K13C2U stiffener
  - heating resistor

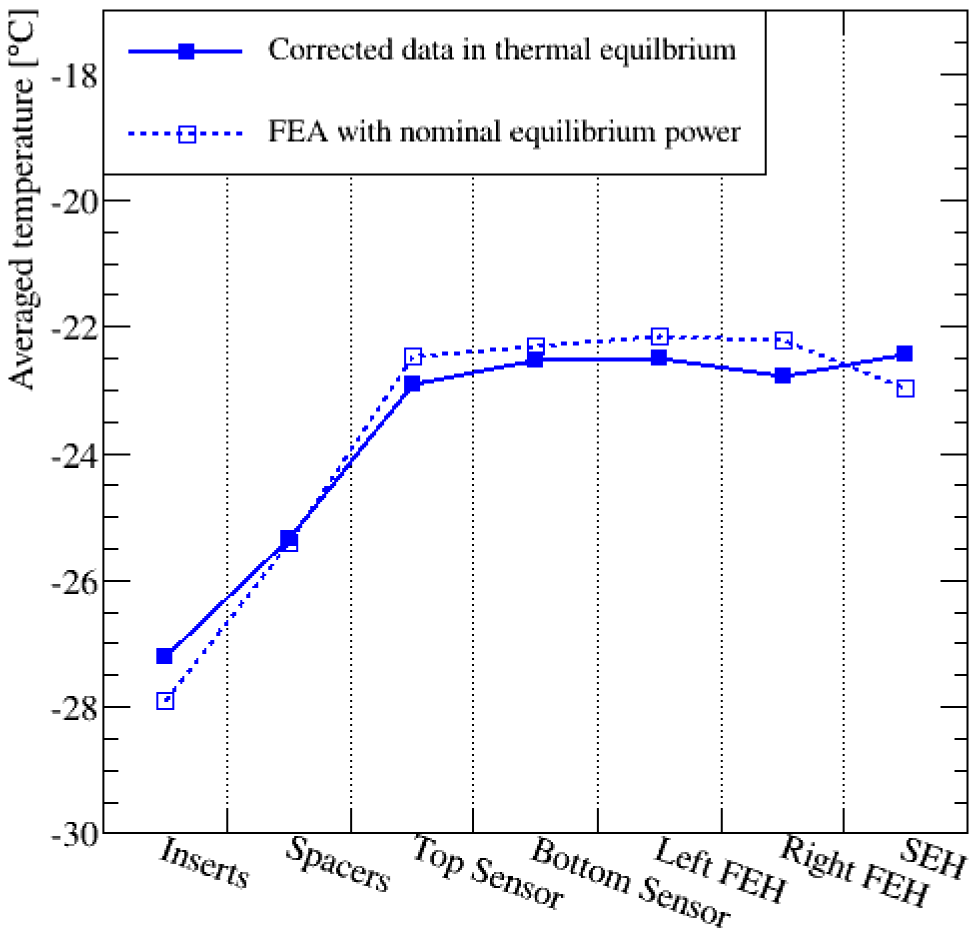
SEH temperature ~ -20.5°C

Top sensor ~ -20.5°C, Bottom sensor ~ -21°C

→ Thermal equilibrium (T ~= -21°C) between module and ambient!

Results with the Full 2S Module



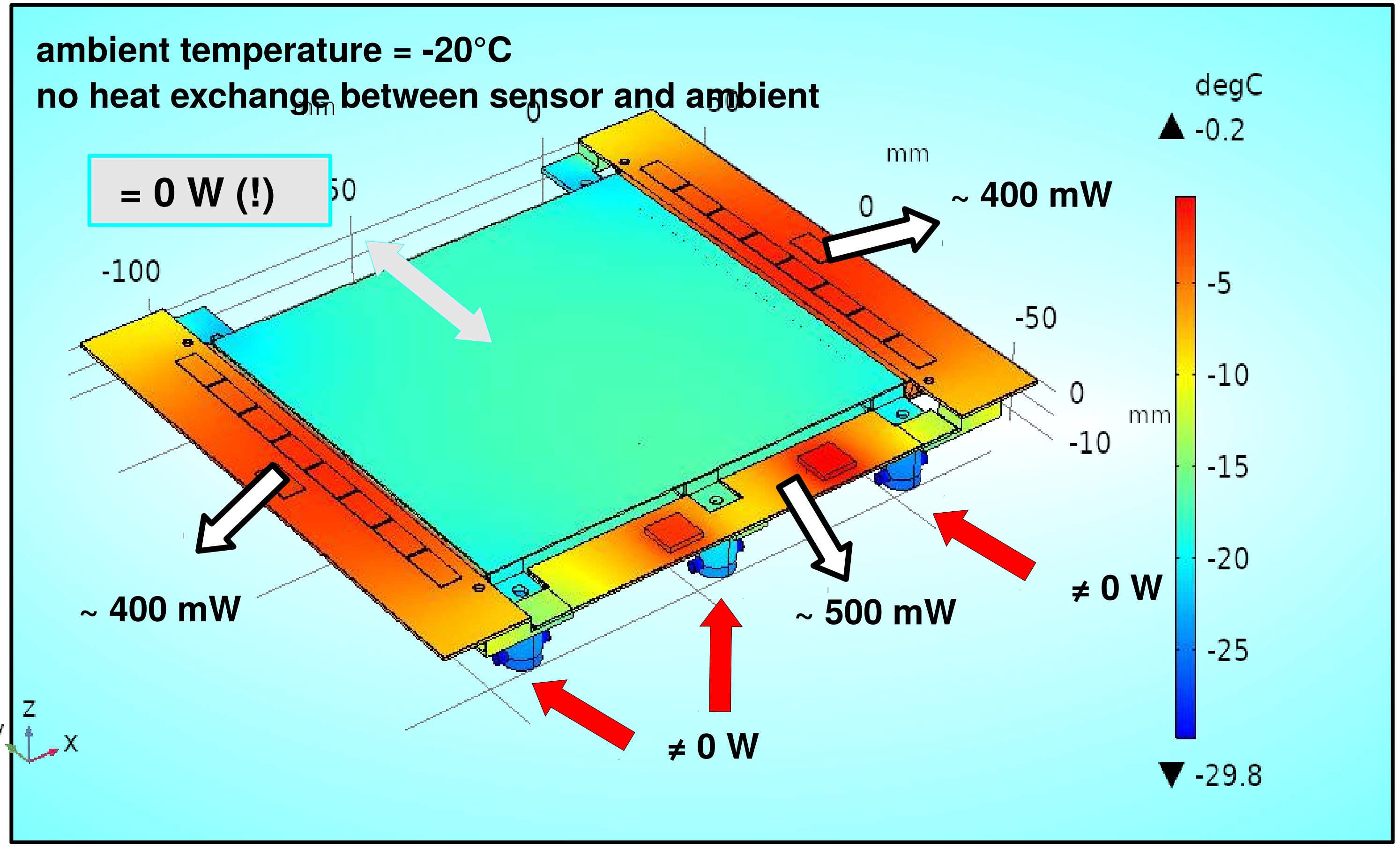


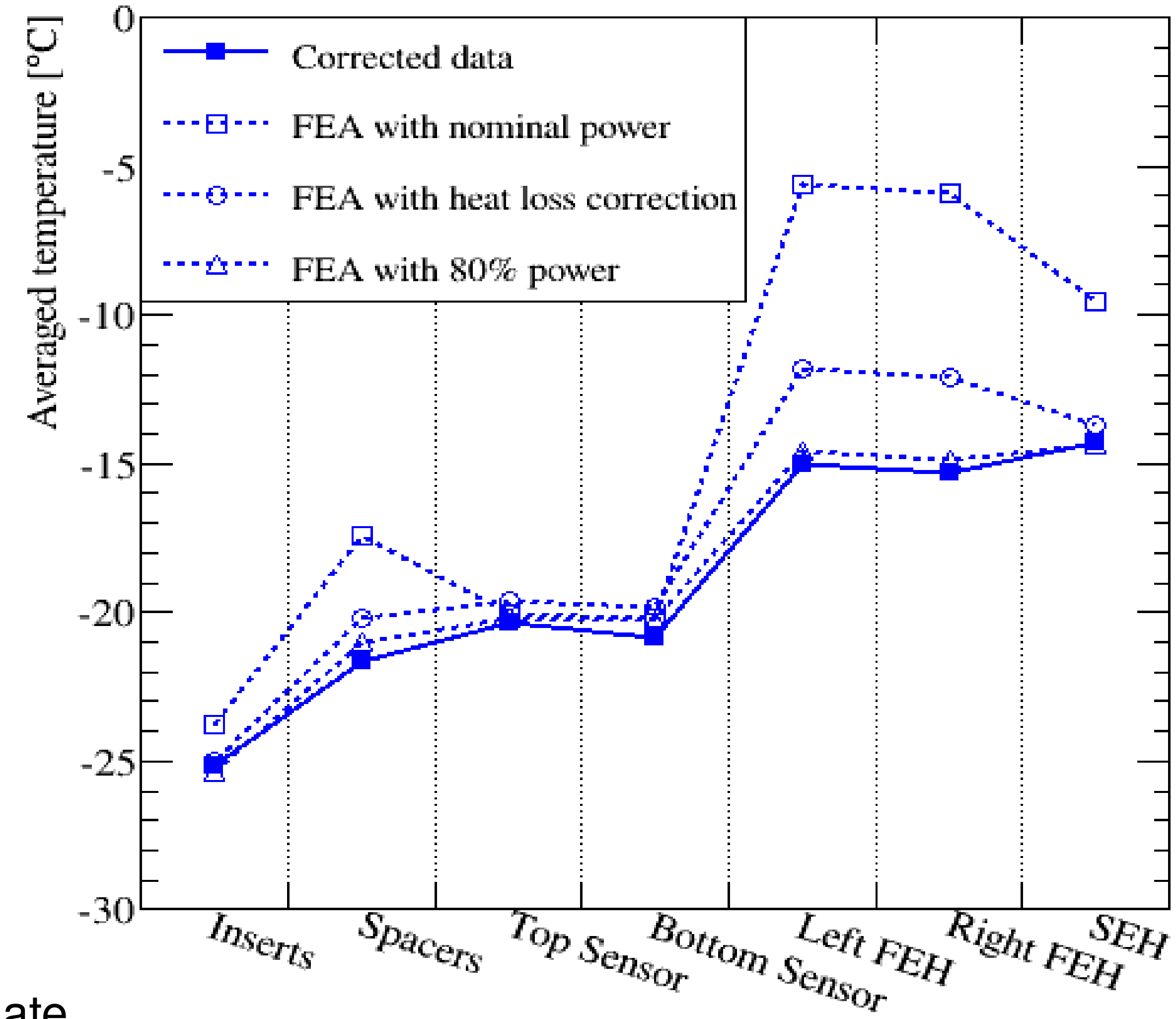
Nominal powers

Front-end hybrids:	0.8 W
Service hybrid:	0.8 W
Top sensor:	~ 0.74 W
Bottom sensor:	~ 0.73 W
Spacers	
Inserts	

Thermal FE model of the full 2S module validated with measurements

Realistic Load of the Full 2S Module

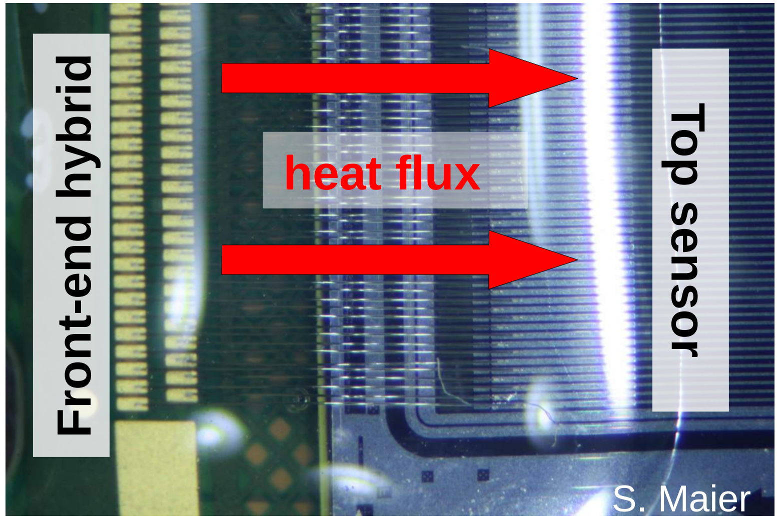


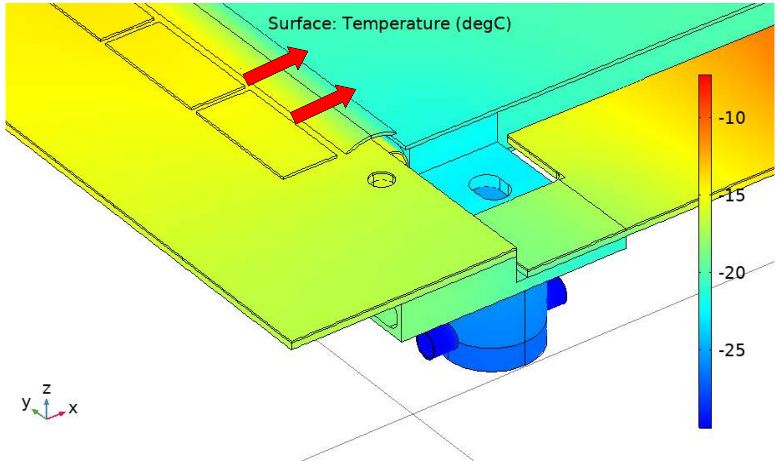


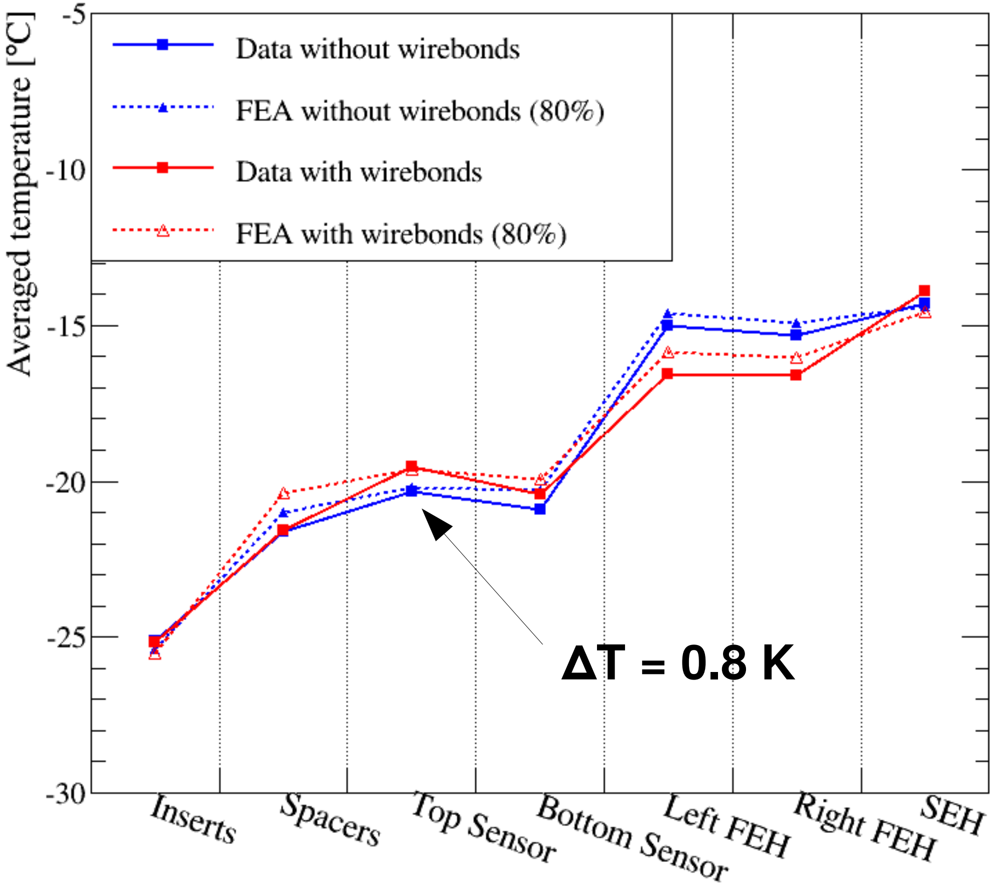
- Generate thermal equilibrium between sensor and ambient to eliminate heat exchange
- Heat loss from the warmer hybrids to the colder ambient
- Heat loss is estimated from data → order of 400 mW per hybrid
- Corrections implemented in Finite Element Analysis

Nominal powers (realistic values !)	
Front-end hybrids:	2.8 W
Service hybrid:	2.5 W
Top sensor:	~ 0.4 W
Bottom sensor:	~ 0.4 W

Heat Flux through Wirebonds





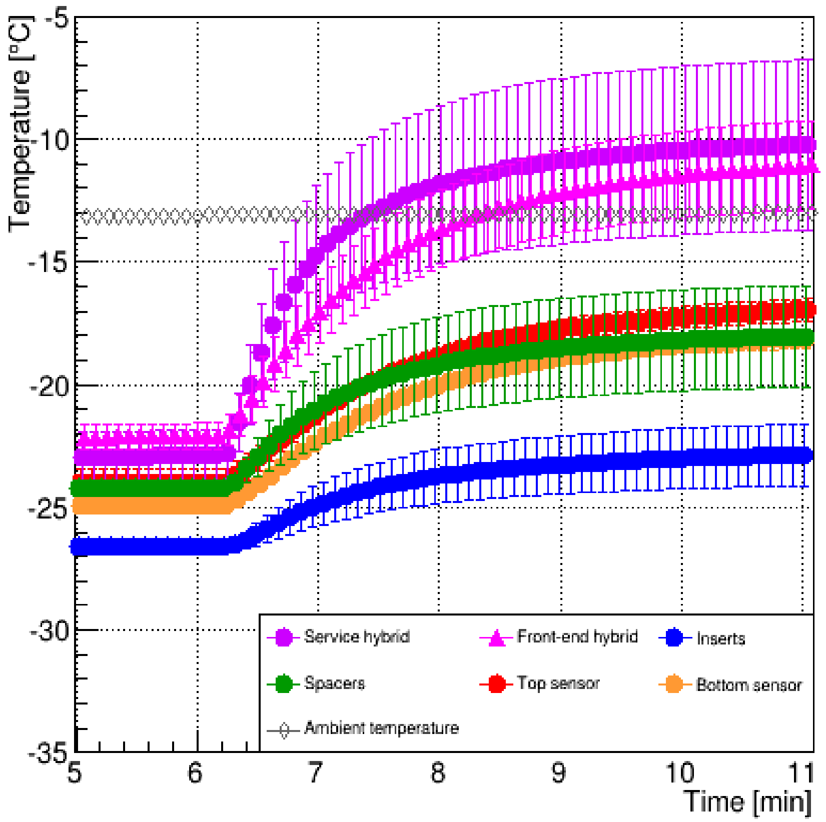


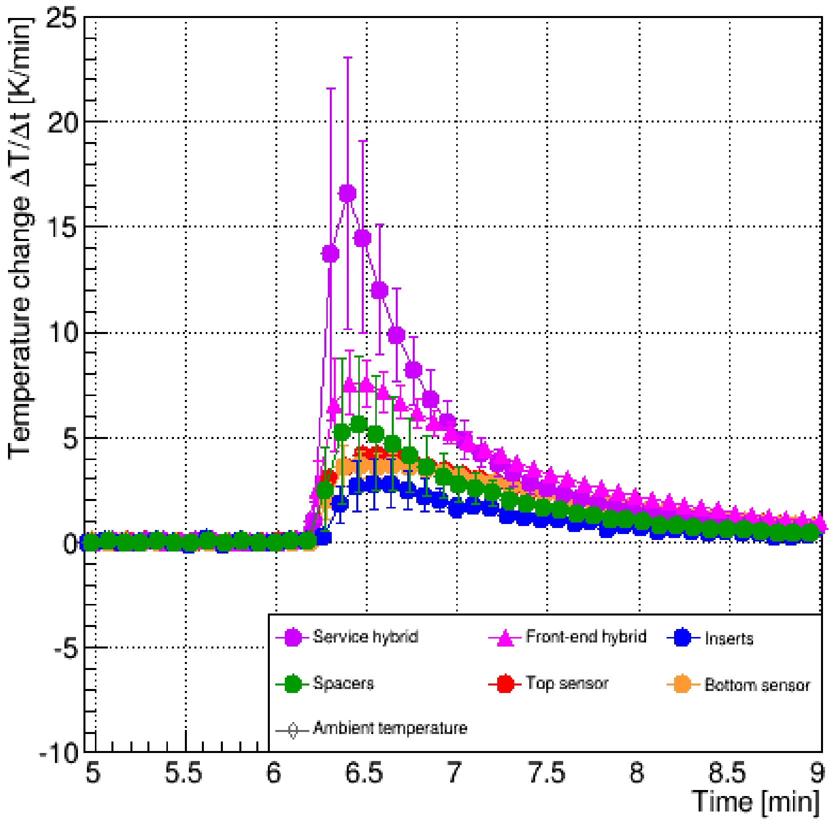
- Heat flux from hybrids to sensor through wirebonds and encapsulation material, expected from simulation
- Top sensor is wirebonded and encapsulated
  - bottom sensor could not be wirebonded for technical reasons
- Same measurement peformed as before
- Effect of wirebonds is clearly visible for the top sensor
  - top sensor warmer
  - front-end hybrids colder
- Estimation from data **$\Delta T/\alpha_{sensor}$ = 0.8 K / (4 K/W) = 200mW**
- Extracted from simulation: 340 mW per sensor

} **well compatible**

Nominal powers	
Front-end hybrids:	2.8 W
Service hybrid:	2.5 W
Top sensor:	~ 0.4 W
Bottom sensor:	~ 0.4 W

Turn-on & Turn-off Behavior

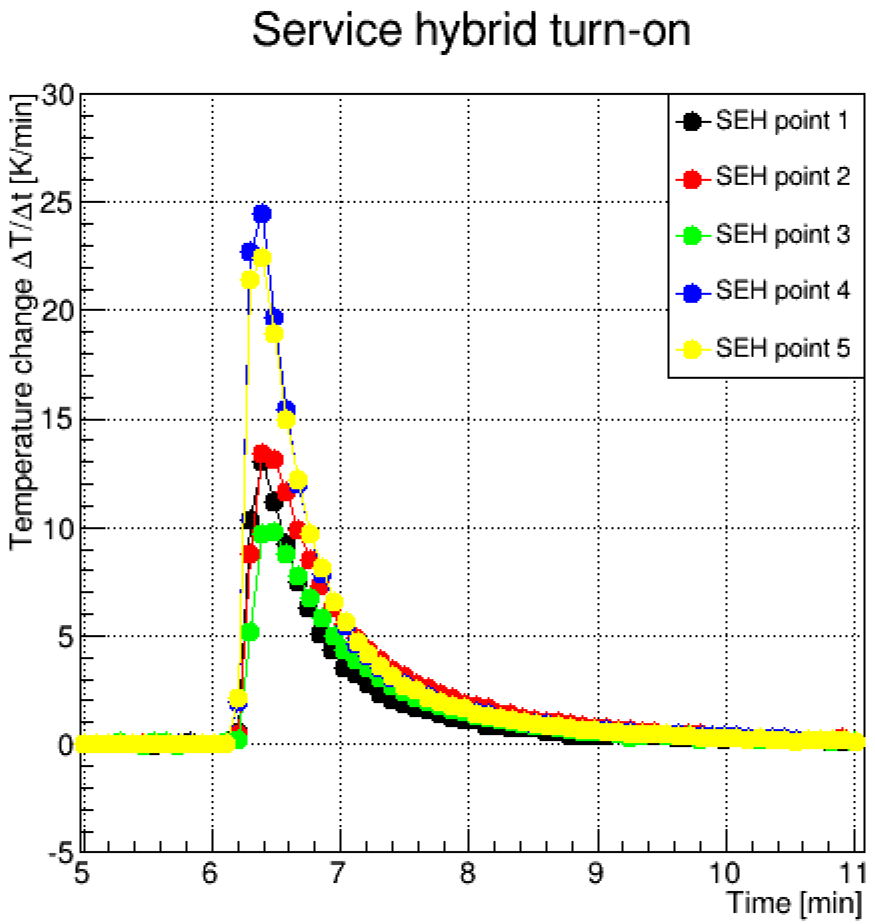


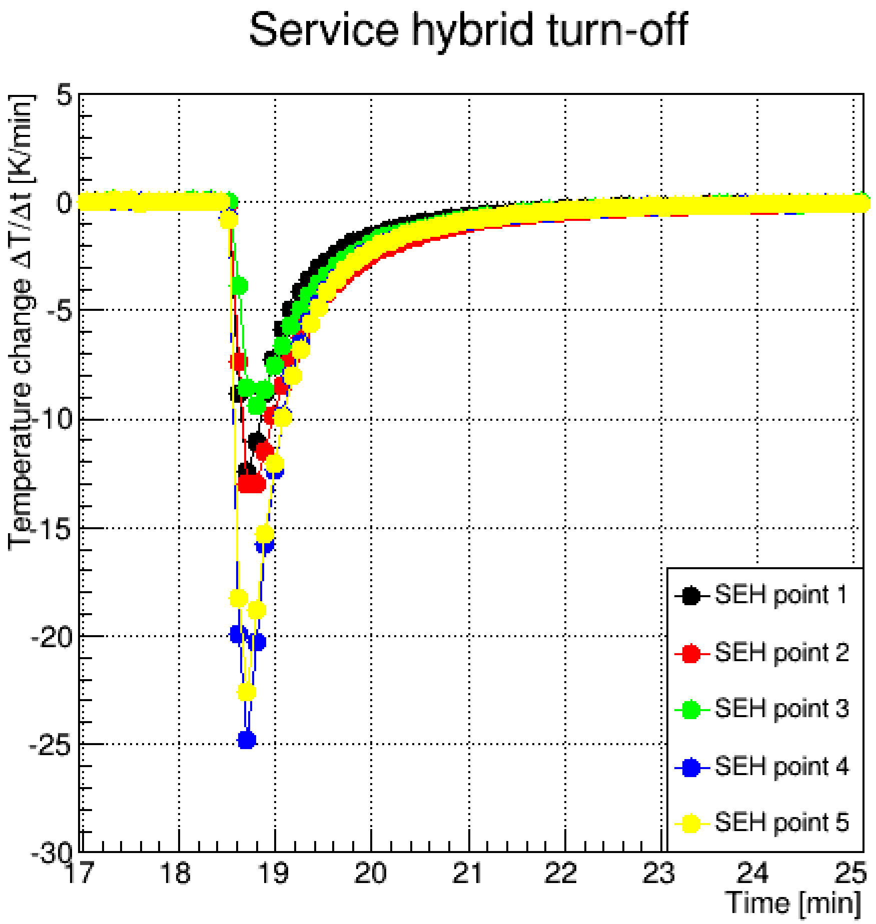


- Switching on all powers of the module of all components
- Not realistic for high-voltage ramping
- Probably realistic for the DC-DC converters and all LV-powered parts
- Temperatures level out after approx. 3 minutes
- Highest temperature change rates on SEH of up to 17 K/min

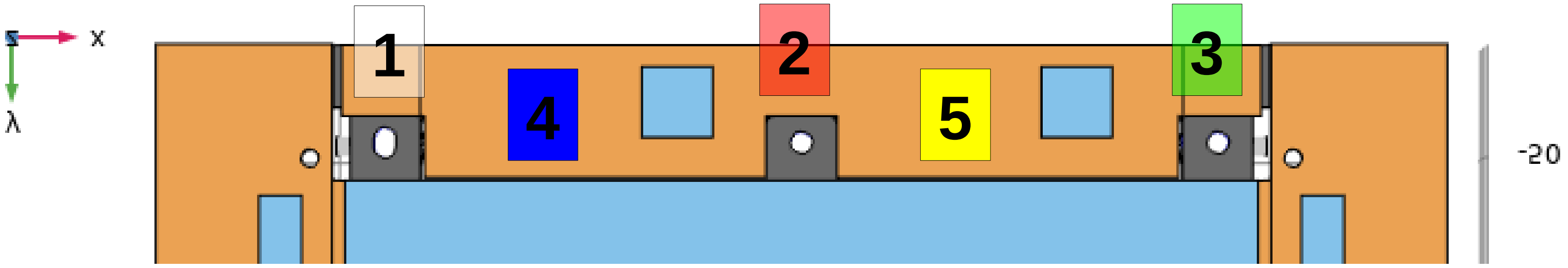
Nominal powers	
Front-end hybrids:	2.8 W
Service hybrid:	2.5 W
Top sensor:	~ 0.4 W
Bottom sensor:	~ 0.4 W
Spacers	
Inserts	

Turn-on & Turn-off Behavior (SEH)



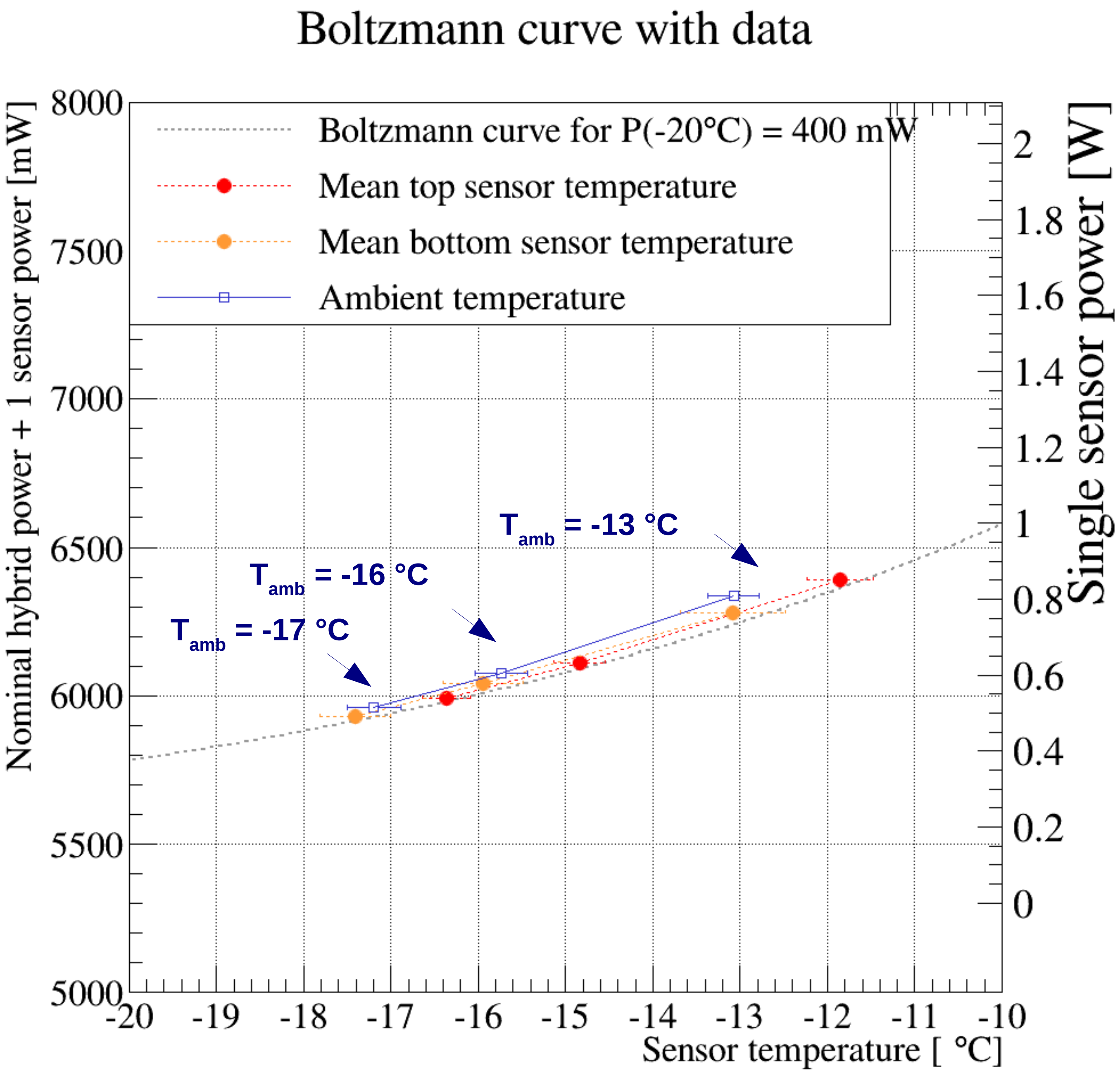


- Temperature change rates on SEH up to **10 to 14 K/min** near cooling contacts
  - **1**, **2**, **3**
- Temperature change rates up to 25 K/min between cooling contacts
  - **4** and **5**



Measurement of Thermal Runaway

- Attempt to measure the thermal runaway of the 2S module with the thermal dummy module
- Assumption: P_{sensor} (-20°C) = 400 mW
  - approx. sensor power after 3000 fb^{-1} at $|V_{bias}|$ = 600 V
- Record measurement points at situation where sensor temperatures and ambient temperatures are roughly equal



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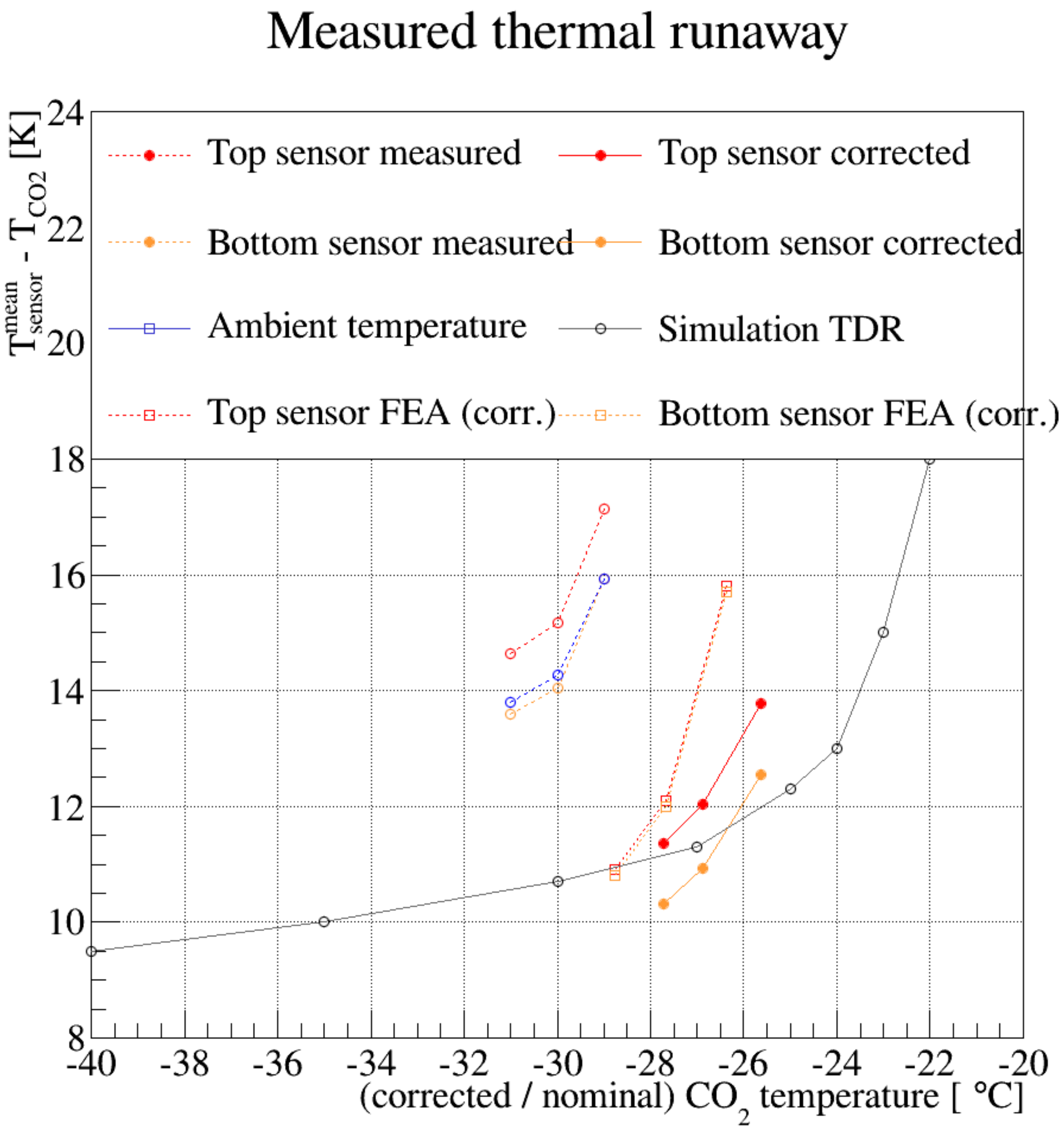
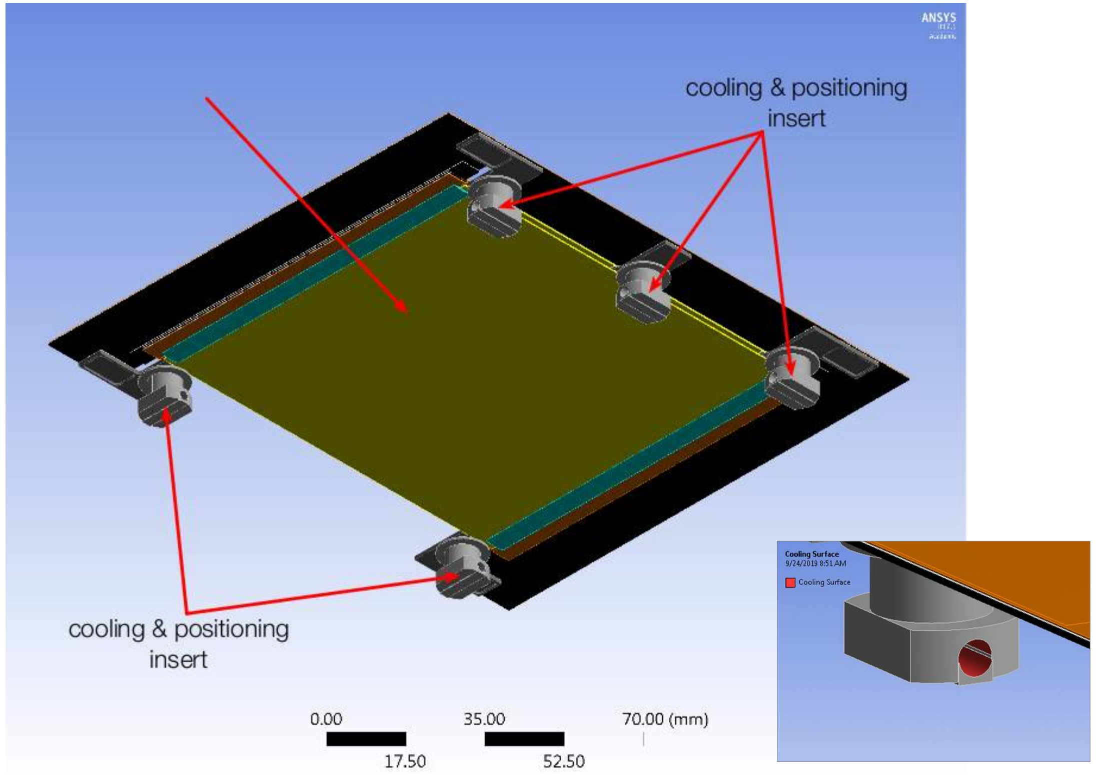
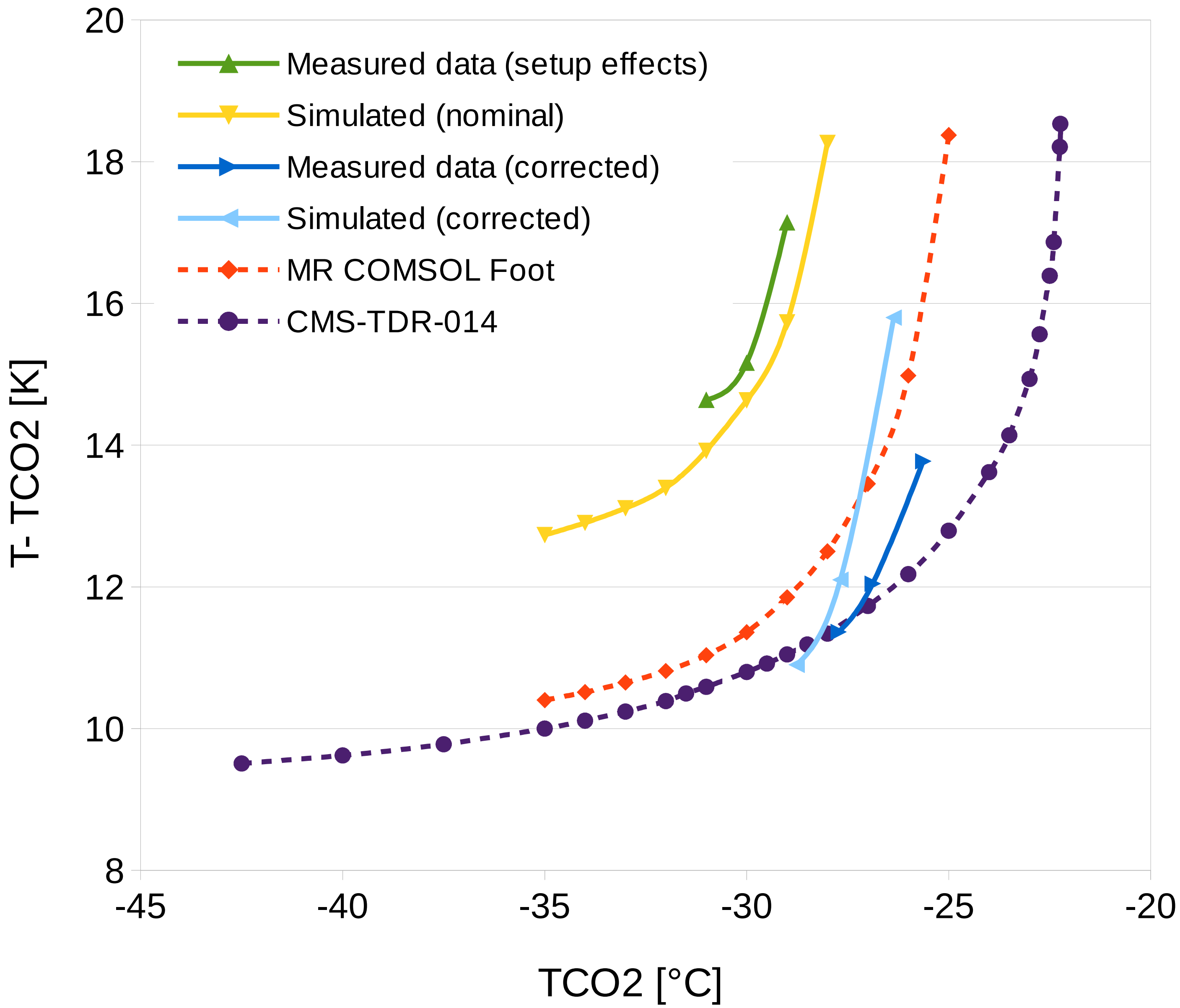
- Record measurement points at situation where sensor temperatures and ambient temperatures are roughly equal
- Actual thermal runaway measured in the setup occurs at T_{CO2} = -29°C / -28°C
- Corrected thermal runaway occurs at T_{CO2} = -26°C / -25°C
- FE simulation with COMSOL compatible
  - offset corrected
  - power values of hybrids corrected



Thermal Runaway

- CMS-TDR-014 Andreas Mussgiller's FE simulation
  - ANSYS Thermal Electric
  - inserts with “foot”
- My model:
  - COMSOL Multiphysics Heat Transfer Module
  - pure cylindrical inserts like in thermal test setup
- Comparison between the models and the measurement results shows large differences between the inserts





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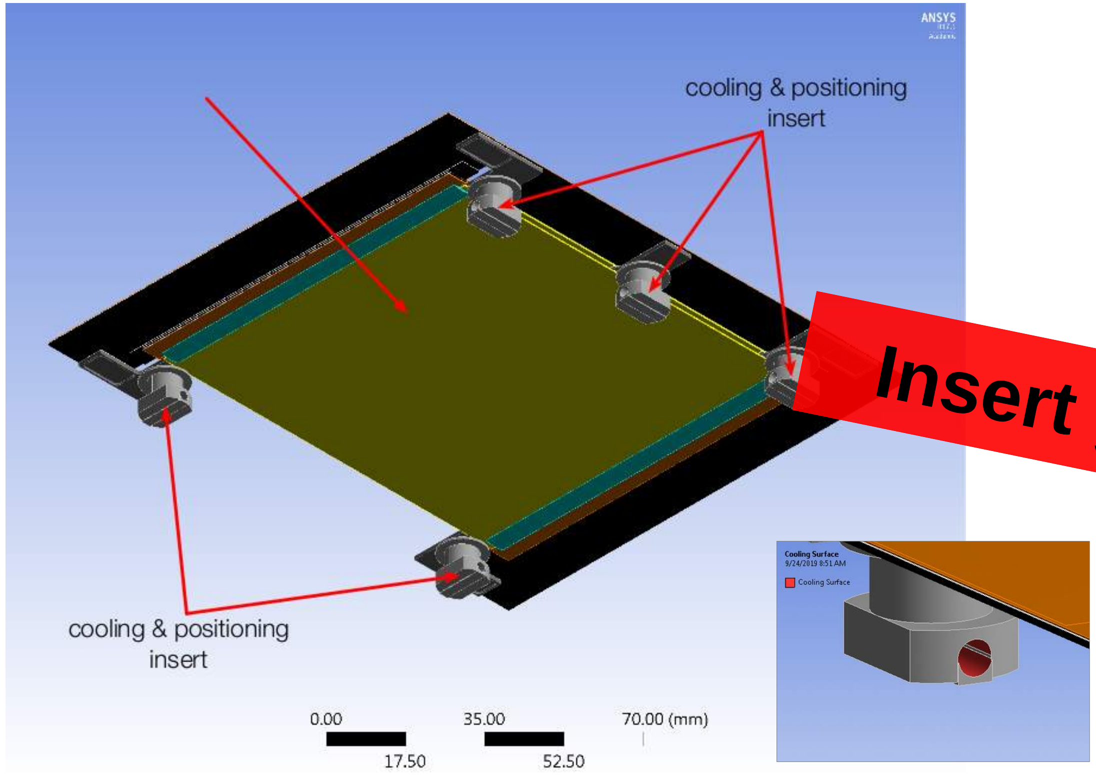
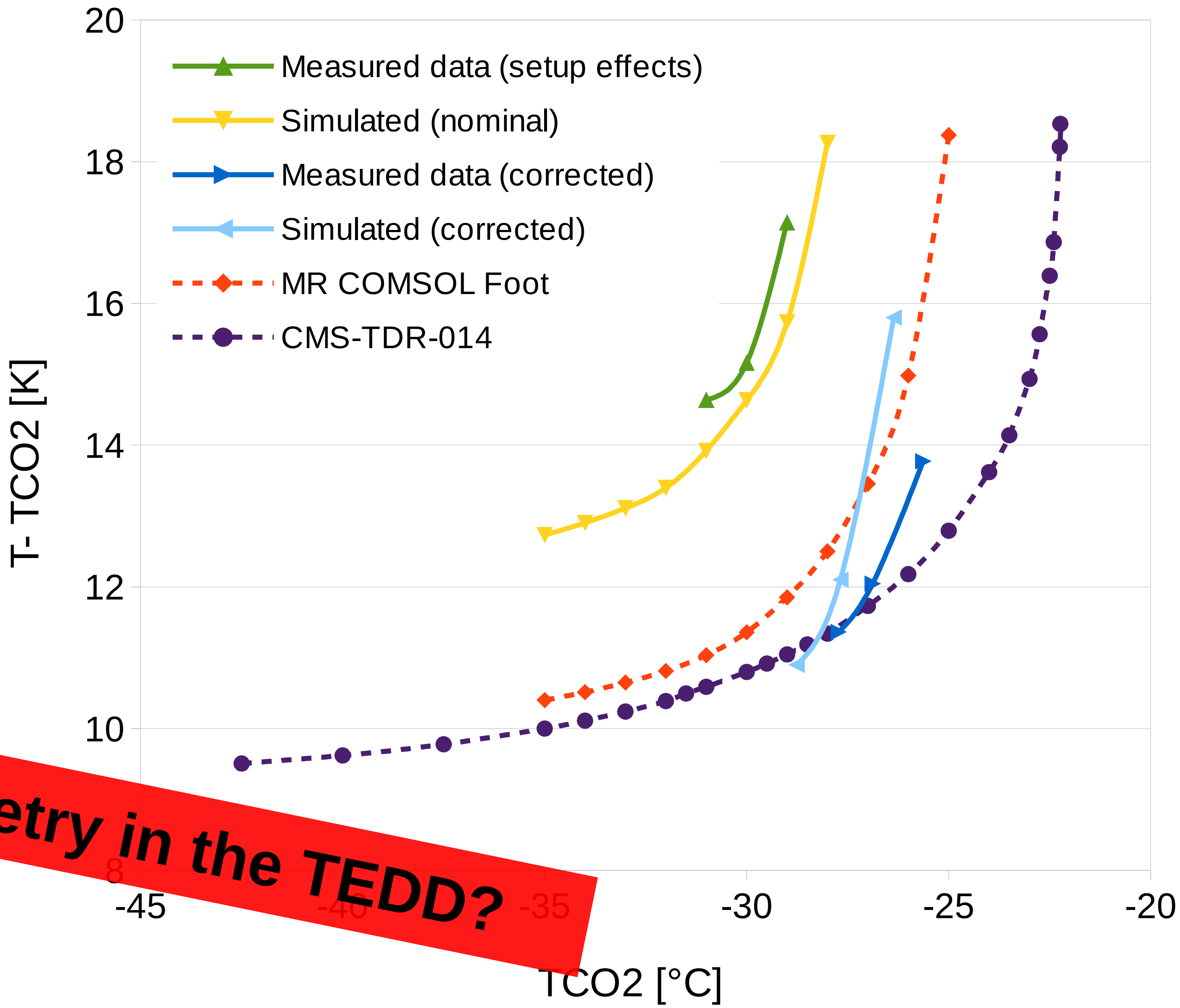
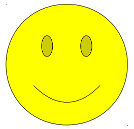




Conclusion

- Thermal measurements with 2S dummy modules have been conducted
- Comparison with FE analyses
- Temperatures and heat fluxes estimated from measurements
  - impact from the ambient
  - thermal interaction of sensors and hybrids with the ambient
- Thermal model for the wirebonds
- Measurement of thermal runaway and comparison with FE analyses



In an intensive and involved measurement program, it was shown that the assumptions for the mechanics of the 2S modules made in the FE models withstand the measurement under defined ambient conditions.

Ambient effects affecting both the modules and the test setup could be described and partly quantified.

? **The extrapolation of these results to the real detector geometry and mechanics (e.g. where modules sit back to back and e.g. an FEH could radiate heat to an opposite sensor) seems very hard.**

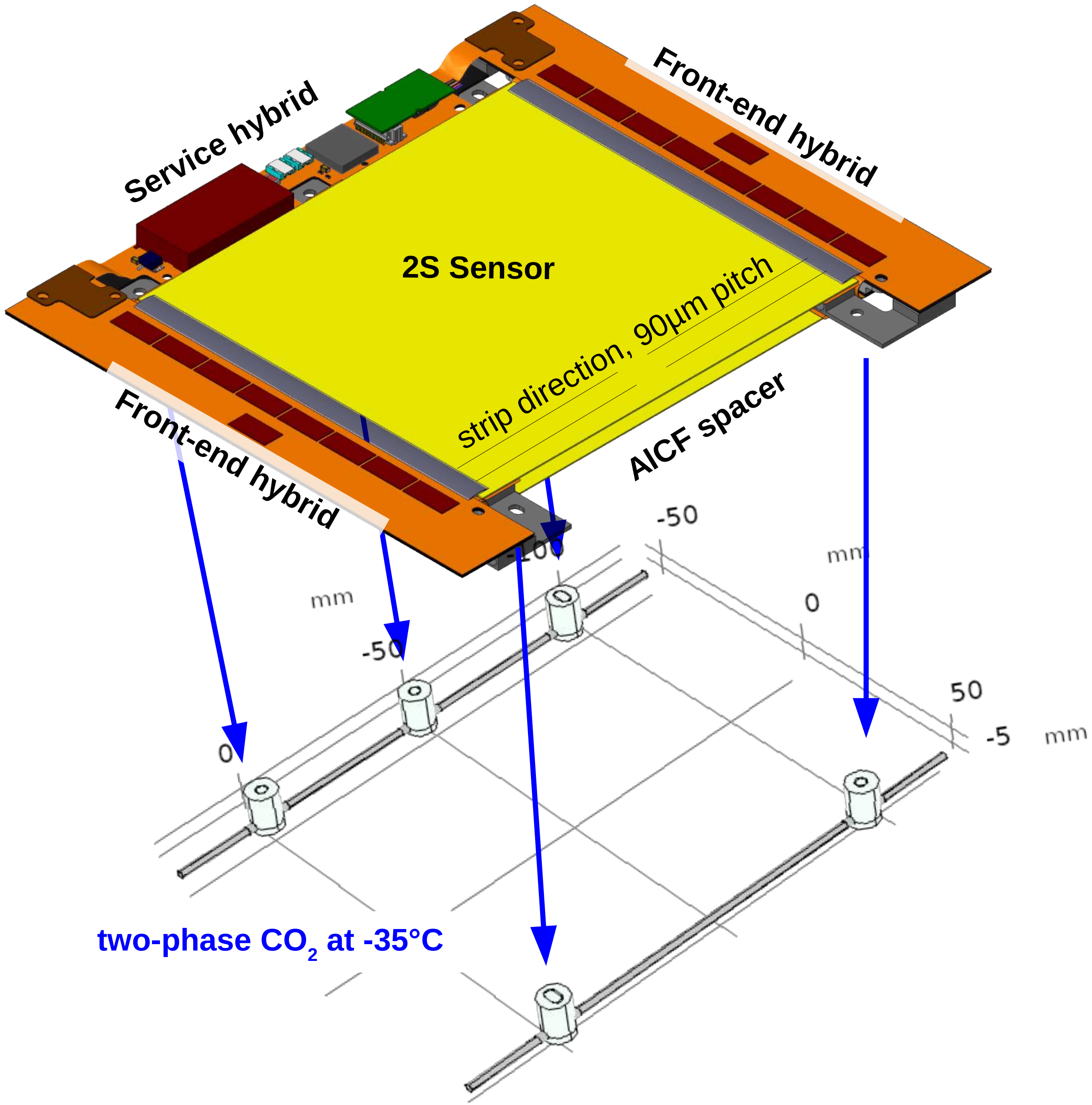
Additional Material

2S Module Overview

- Power consumption of the 2S module
  - Front-end hybrids: 2.8 W
  - Service hybrid: 2.5 W
  - Top sensor: ~ 0.4 W
  - Bottom sensor: ~ 0.4 W
  - **Full 2S module ~ 6.1 W**

estimates for 3000 fb^{-1} at -20°C

- Heat load is cooled with an evaporative CO_2 cooling system
  - nominal temperature of -35 °C
  - maximum expected temperature -33 °C



Thermal Runaway

- Silicon sensors suffer from irradiation
  - ➔ increase of the leakage current
  - ➔ higher power consumption after irradiation
- Volume leakage current increases linear with radiation damage:

$$\Delta I_{\mathrm{leakage}} = \alpha_{\mathrm{damage}} \cdot \Phi_{\mathrm{neq}} \cdot V_{\mathrm{sensor}}$$

- Temperature dependence of the leakage current with Boltzmann function:

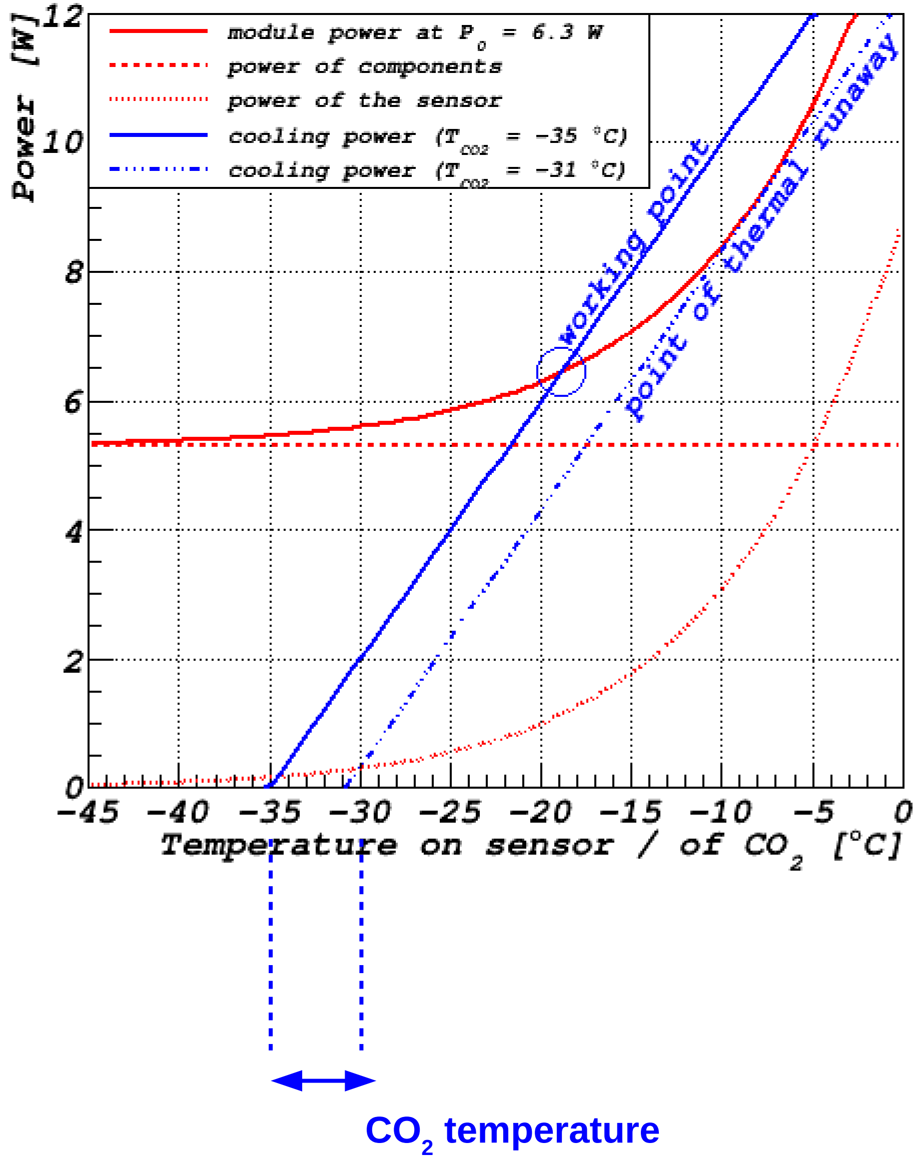
$$I_{\mathrm{leakage}}(T) \propto I_{\mathrm{leak,0}} \left(\frac{T}{T_0}\right)^2 \exp\left(-\frac{\Delta E}{2k_B}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$$

- Linear cooling power defined by the mechanical structure:

$$T_{\mathrm{sensor}} \approx \alpha_{\mathrm{cooling}} P + T_{\mathrm{cooling}}$$

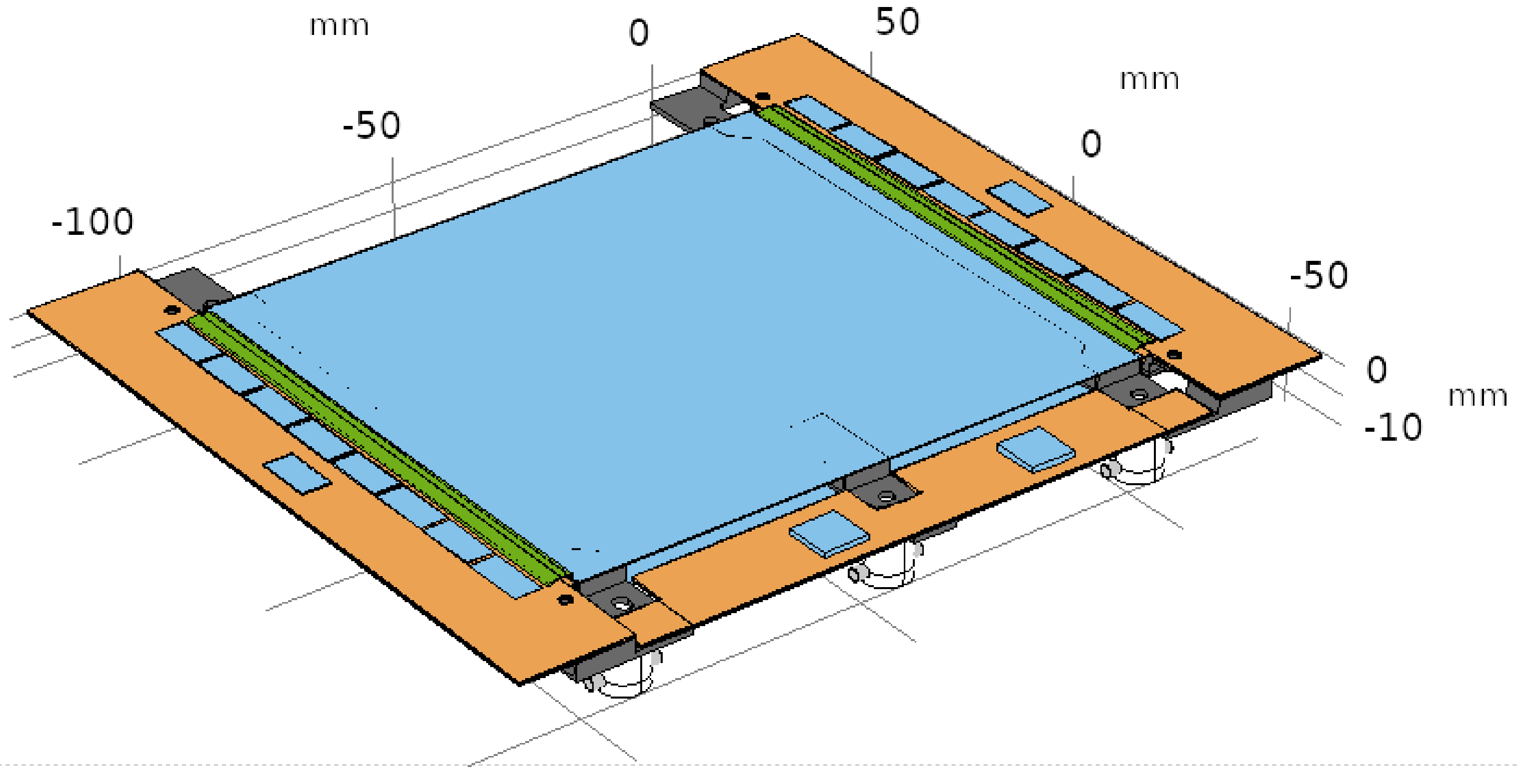
thermal resistance α

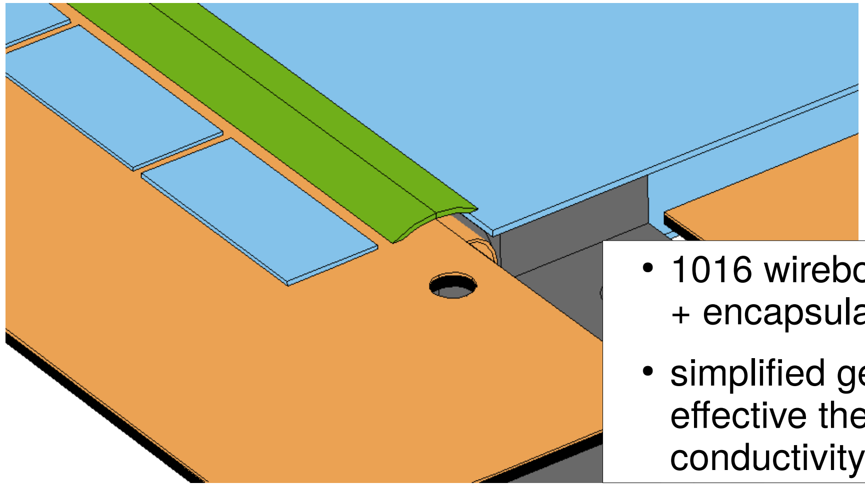
- Working point of the module must exist for the operation of the module → otherwise: "thermal runaway"



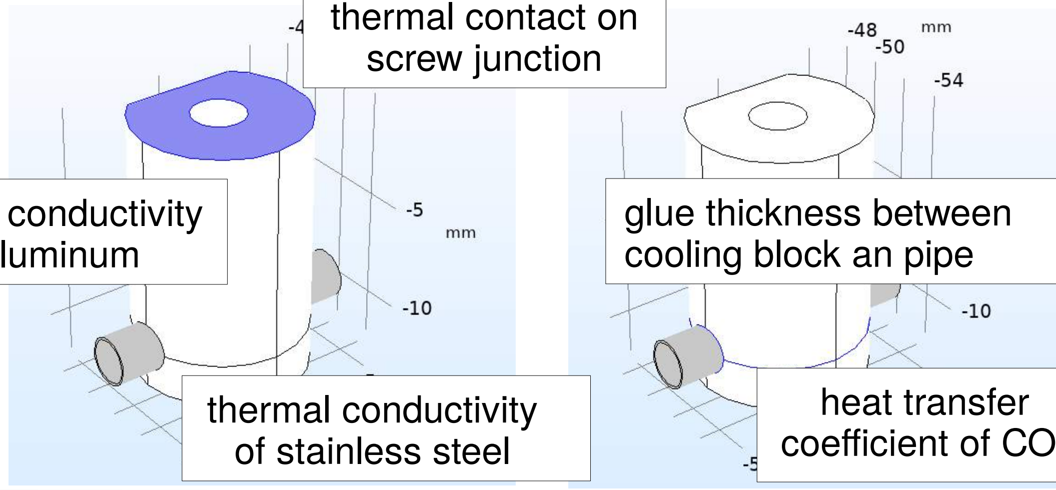
Thermal Finite Element Model

- FE model using COMSOL Multiphysics with properly simplified mechanics
- Assumptions on
  - Power production of the single components
  - Heat transfer coefficient of the cooling
  - Thermal conductivity of the materials
    - simplified models for PCB and carbon fiber structures
    - anisotropic assumptions for the AlCF bridges
    - …
  - Glue thicknesses and thermal interfaces
  - Effective models for tiny geometries, e.g. wirebonds, ...



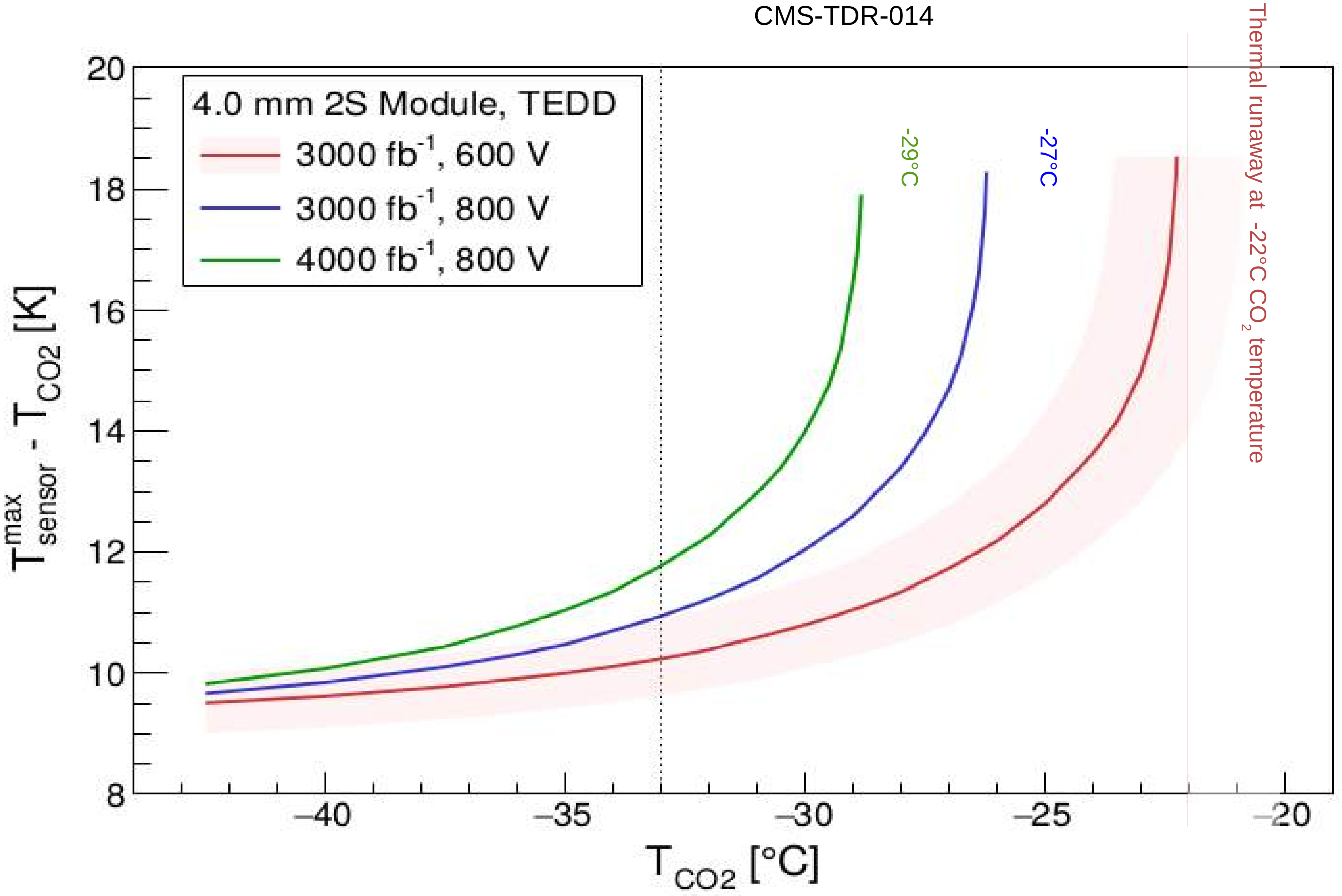


- 1016 wirebonds of ⌀25µm + encapsulation material
- simplified geometry with effective thermal conductivity of 5 W/m/K

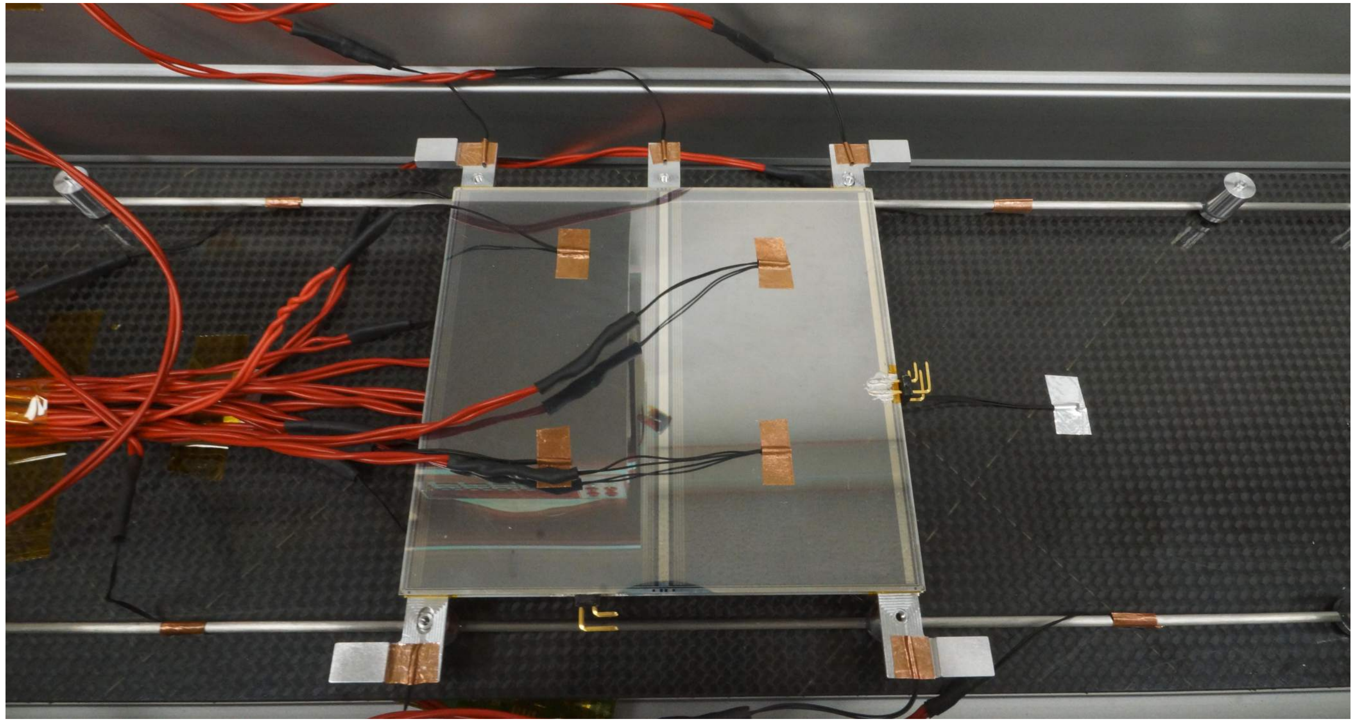


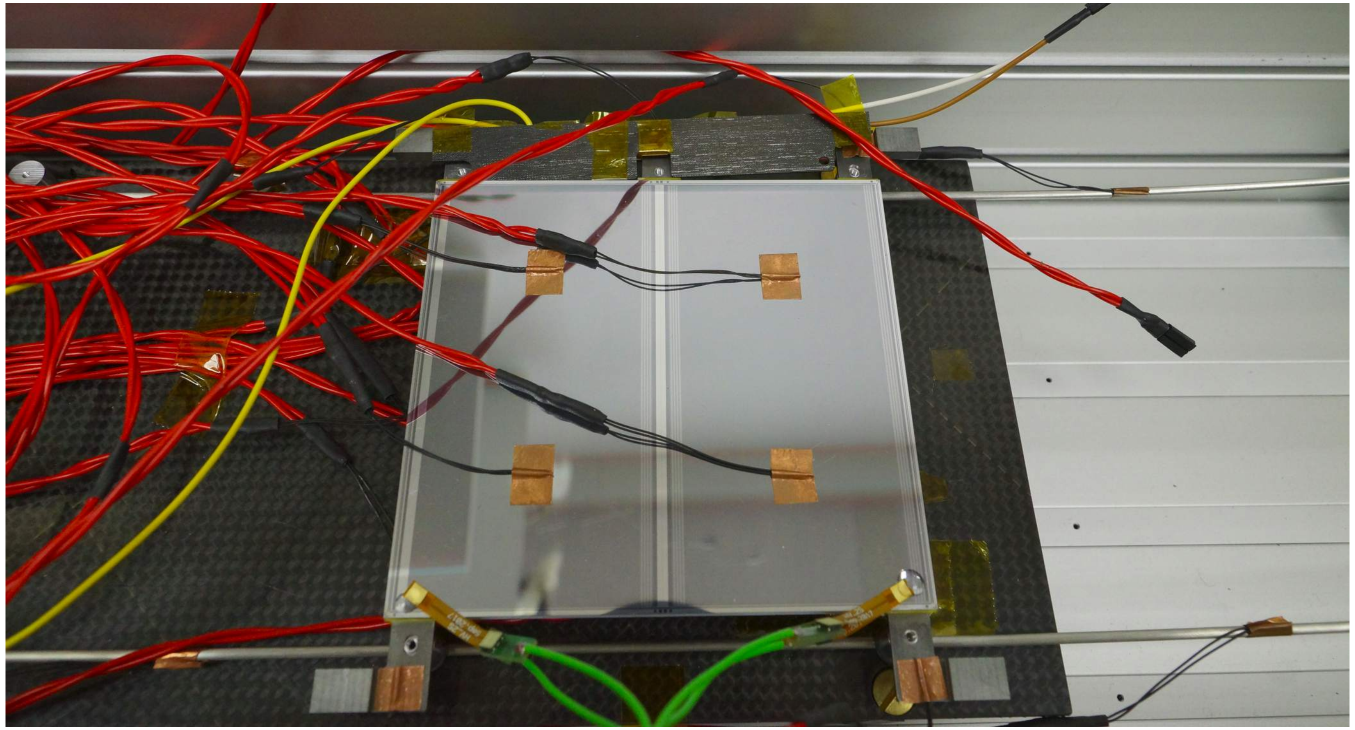
Prediction of Thermal Runaway

CMS-TDR-014



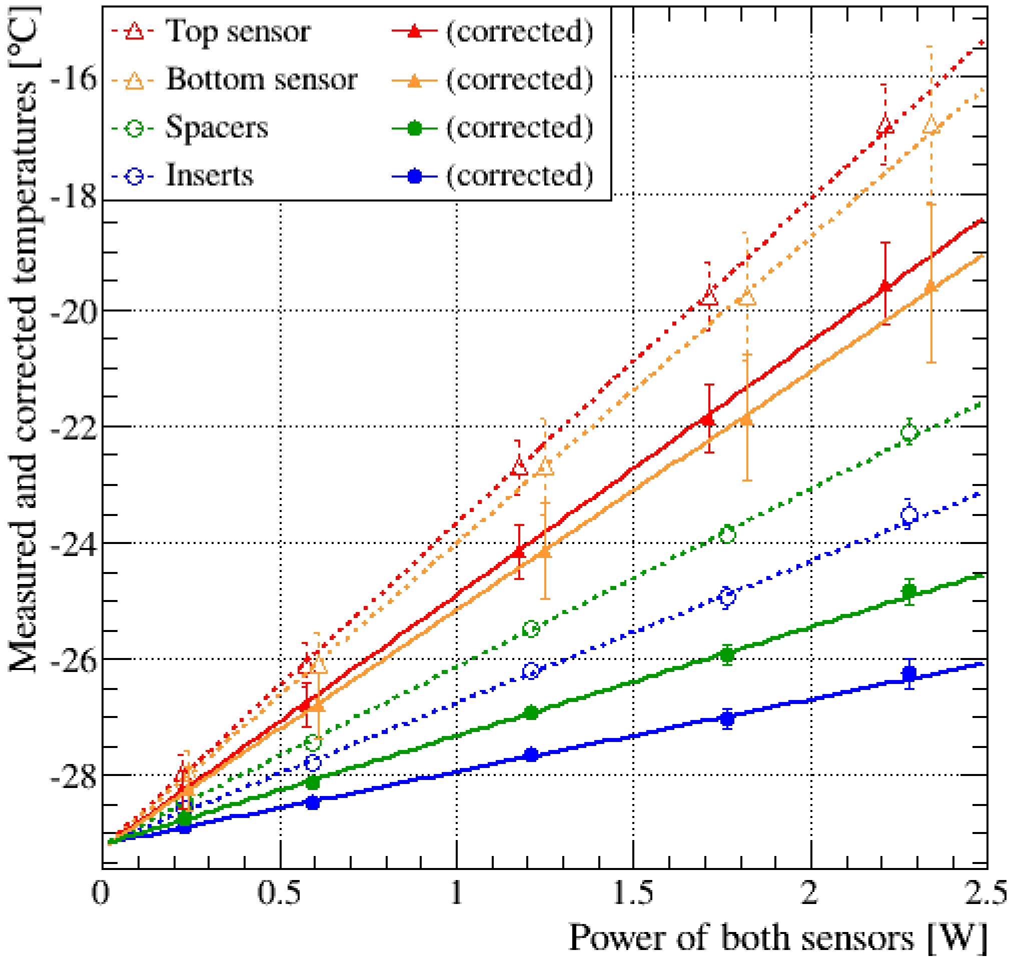
2S Dummy Bare Modules



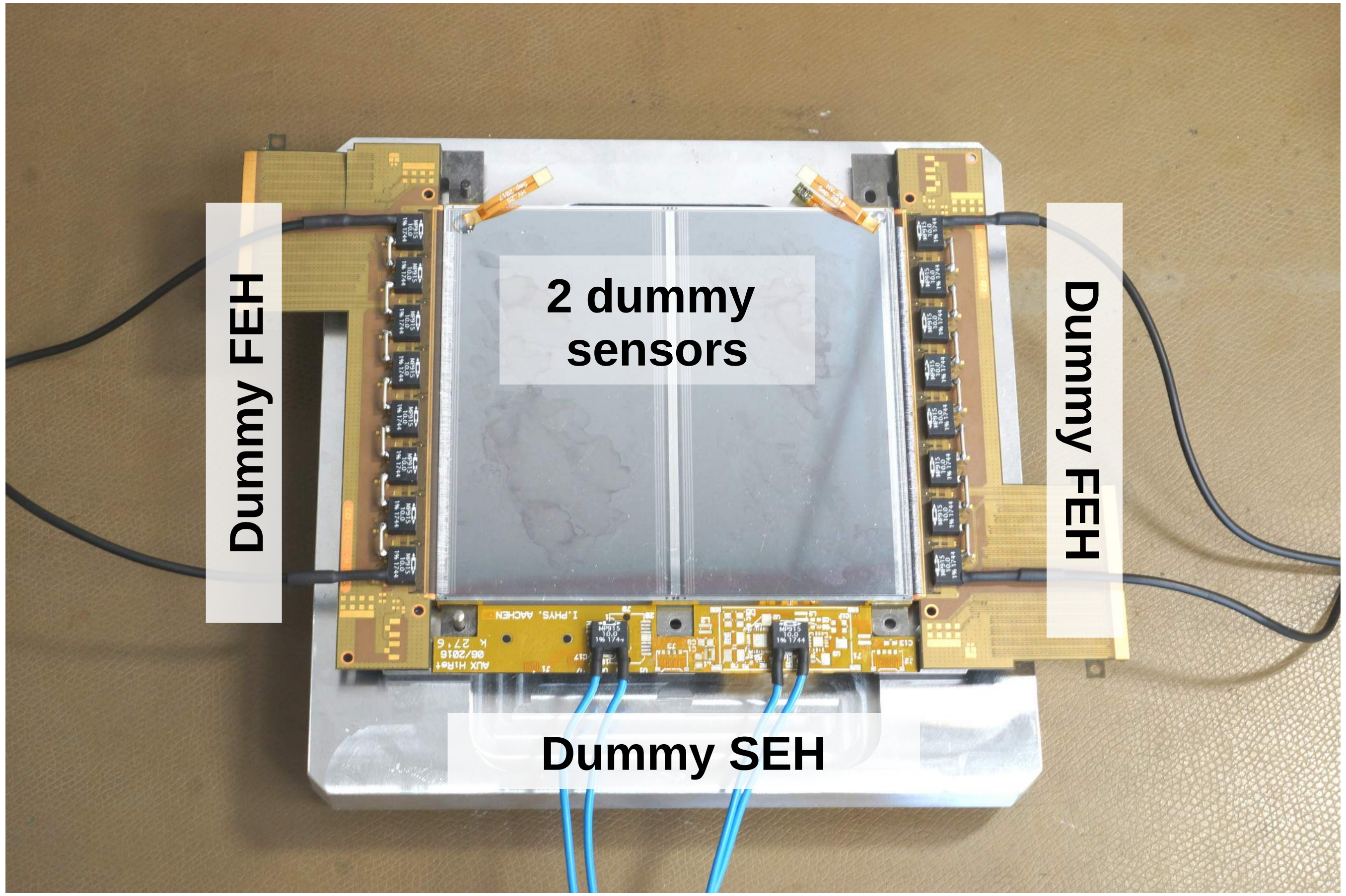


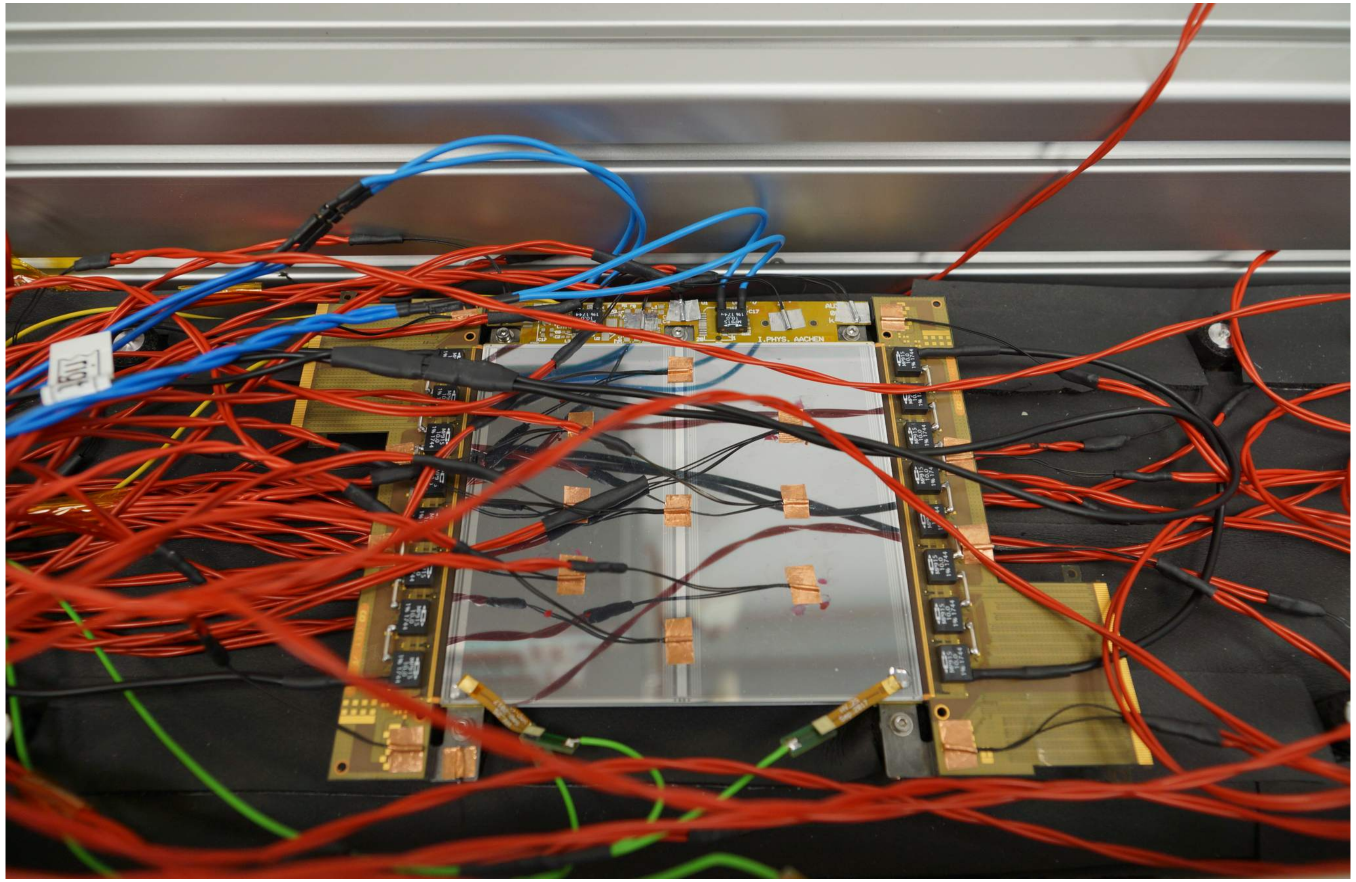
- First step: measurements with 2S bare modules
  - only dummy sensors and AlCF bridges
  - no hybrids
- Check of the thermal connection between sensor and cooling system
  - important test as sensors are the crucial component in terms of thermal runaway
- Dummy modules are ”elegant” test devices
  - dummy sensors can be used as Ohmic resistors → no additional heat source needed
  - temperature measurement with low-mass NTC thermistors

Temperature Correction



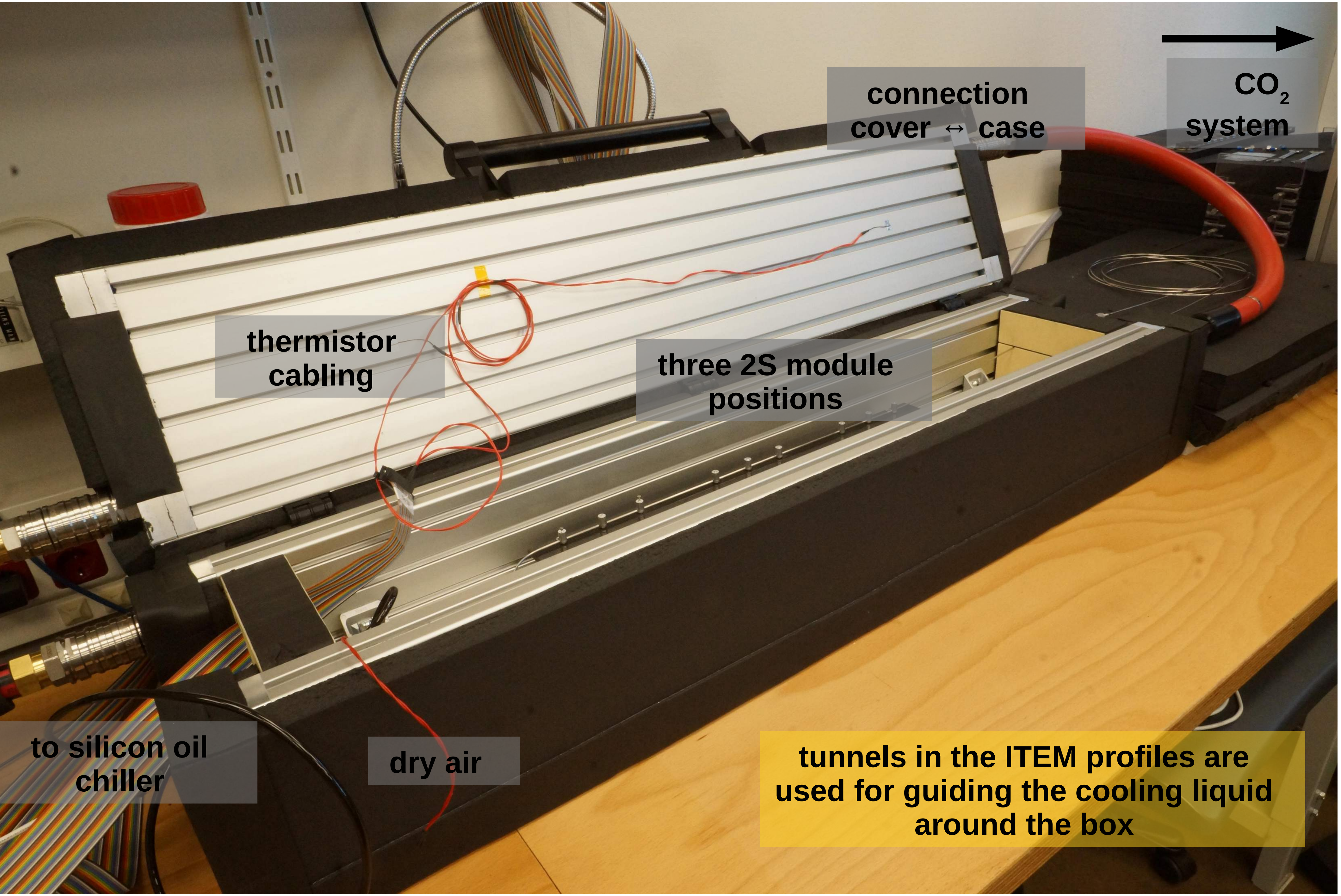
Full Thermal 2S Dummy Module





- Thermal test 2S 4.0mm module with dummy components
  - silicon sensors used as ohmic resistor (~ resistance approx. 5 Ω, power up to 1 W)
  - front-end hybrids with eight heating resistors (“CBC-chips”, power ~ 0.2 W per resistor)
  - service hybrid with two heating resistors (“DC-DC-converter” and “VTRX+”, power ~ 1.3 W per resistor)
- Temperature measurement at 33 positions on the module with NTC thermistors

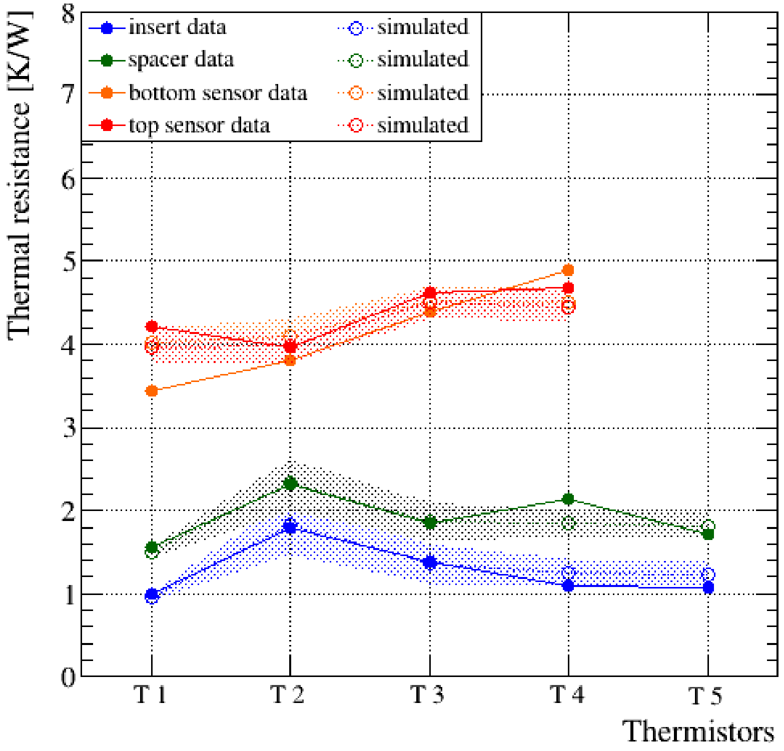
Module Cooling Box Test Setup

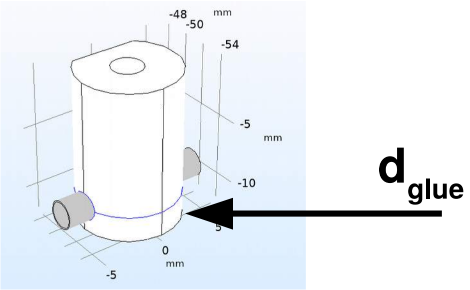


Comparison with Finite Element Model

Variation of
insert glue thickness ± 50%

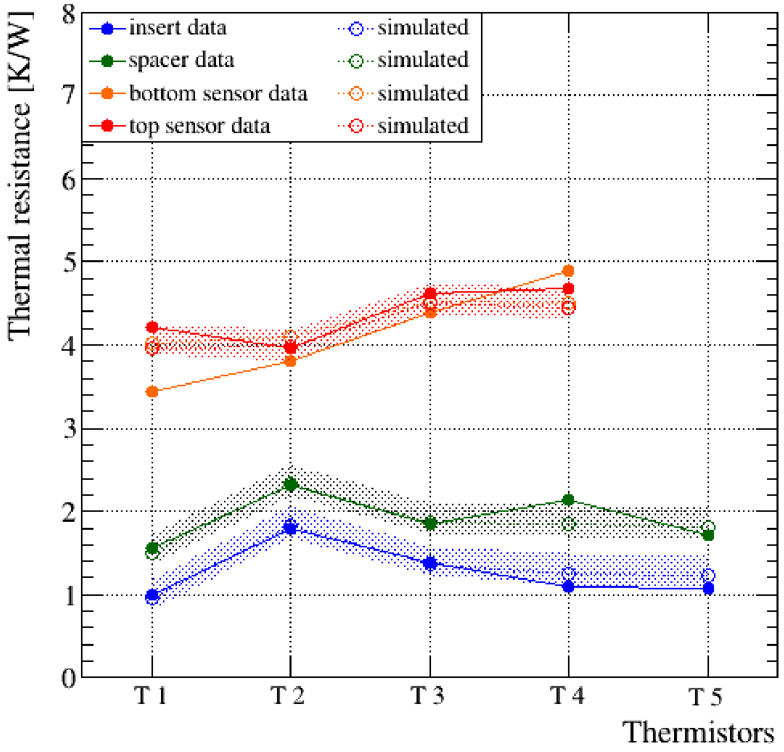
$$11\,\mu\mathrm{m} < \bar{d}_{\mathrm{glue}} < 33\,\mu\mathrm{m}$$

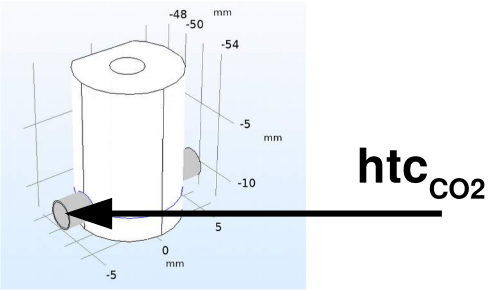




Variation of
CO_2 heat transfer coefficient ± 25%

$$3.75 < \mathrm{htc}_{\mathrm{CO2}} < 6.25\ \frac{\mathrm{kW}}{\mathrm{m}^2/\mathrm{K}}$$

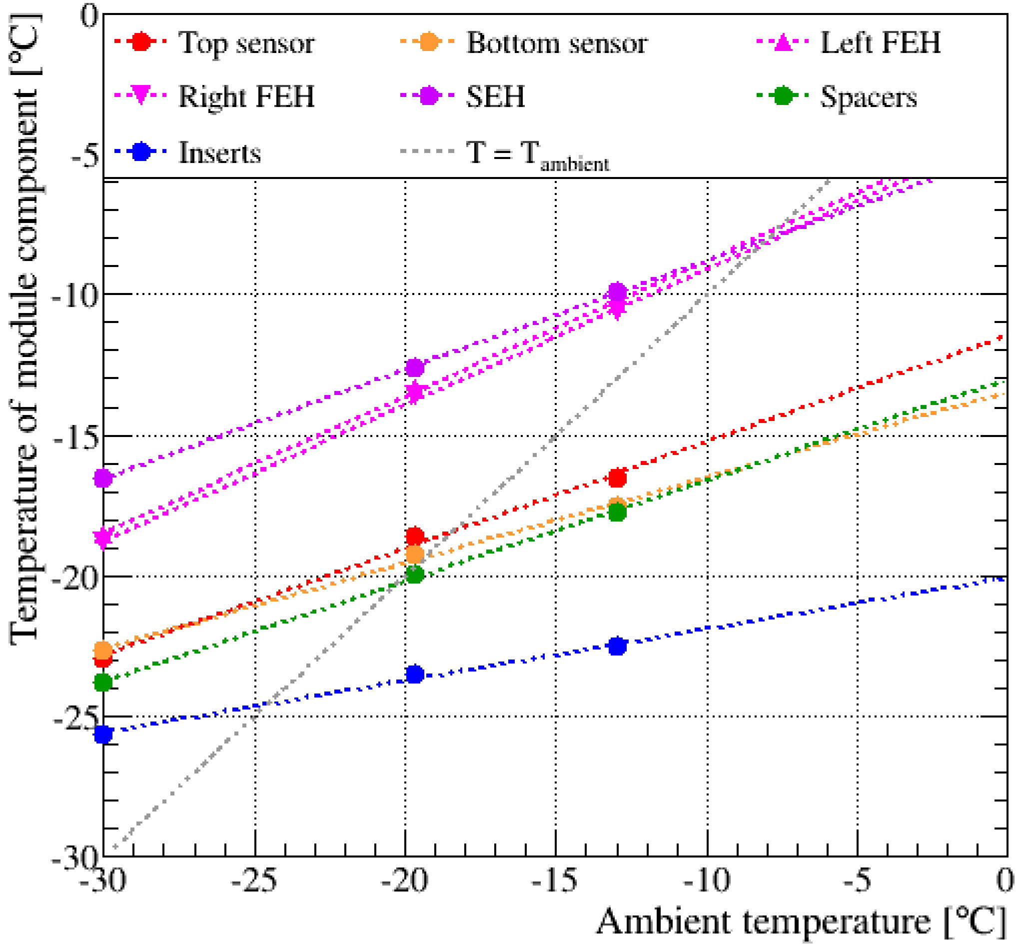




Estimation of Heat Loss

- Principle of thermal equilibrium for each component
- Extrapolation of component temperatures to thermal equilibrium
- Calculation of thermal resistance
- Calculation of actual heat removed with the cooling system

Component	P_{nominal}	$P(T_{\text{amb}} = -30\,^\circ\text{C})$[W] no WB	WB	$P(T_{\text{amb}} = -20\,^\circ\text{C})$[W] no WB	WB	$P(T_{\text{amb}} = -13\,^\circ\text{C})$[W] no WB	WB
Top sensor	0.49	0.28	0.29	0.45	0.44	0.54	0.54
Bottom sensor	0.48	0.32	0.33	0.46	0.46	0.54	0.54
Left FEH	1.40	0.68	0.73	0.99	1.08	1.22	1.35
Right FEH	1.40	0.69	0.76	1.00	1.11	1.20	1.32
SEH	2.50	1.55	1.26	1.99	1.75	2.31	2.10
Full Module	6.3	3.5	3.4	4.9	4.8	5.8	5.8



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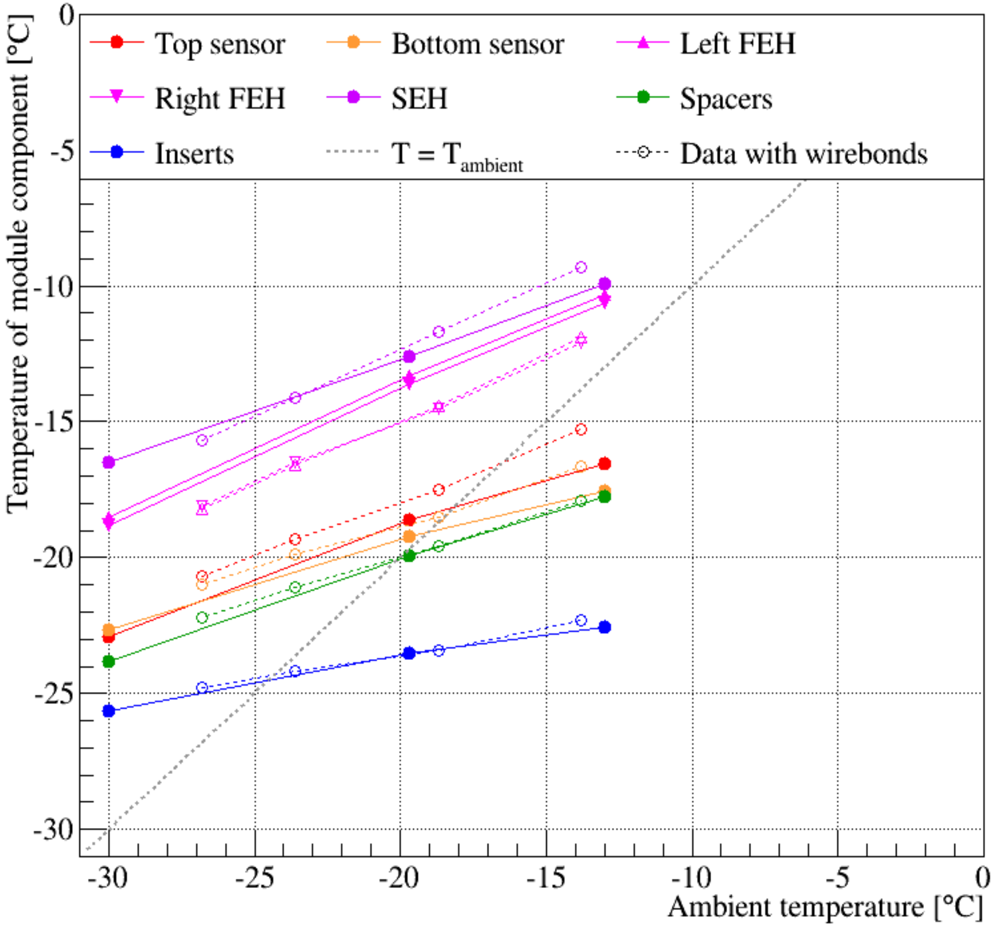

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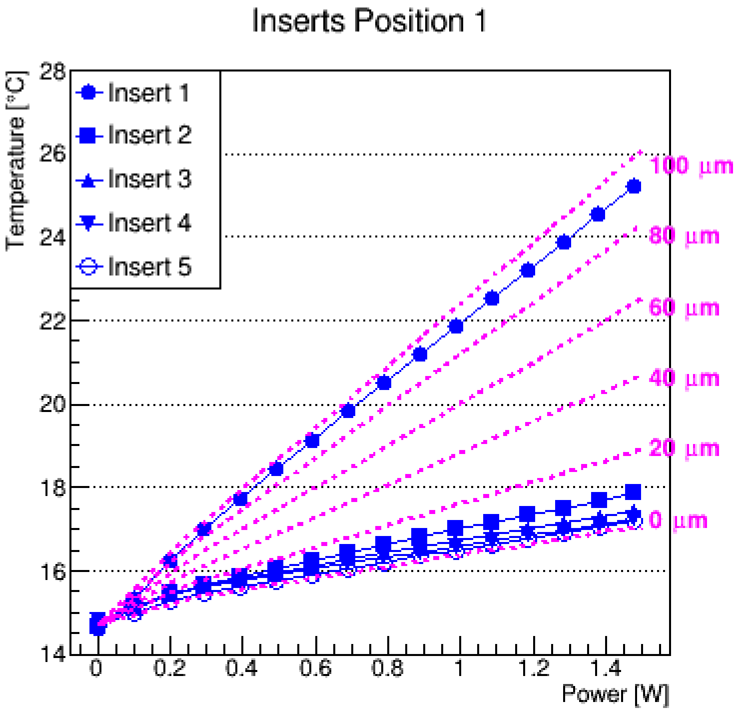
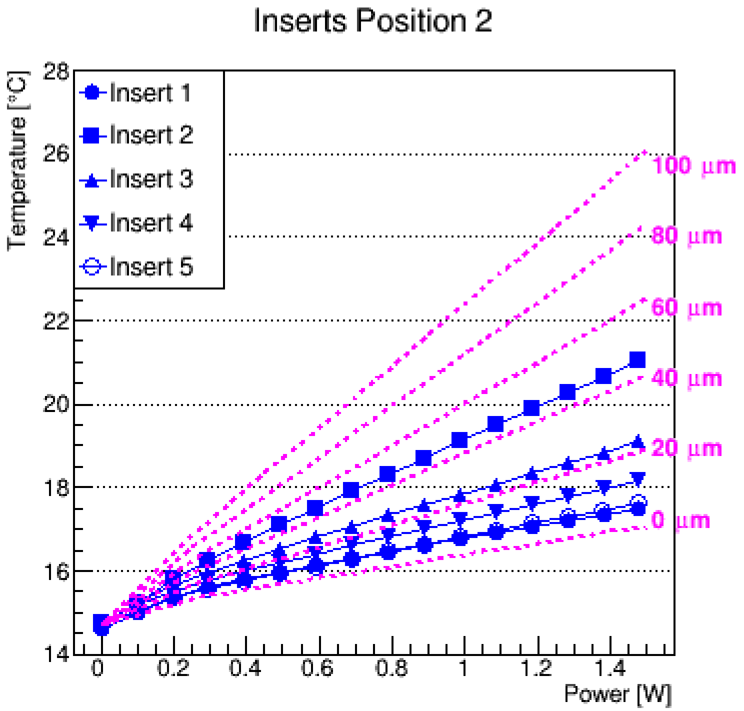
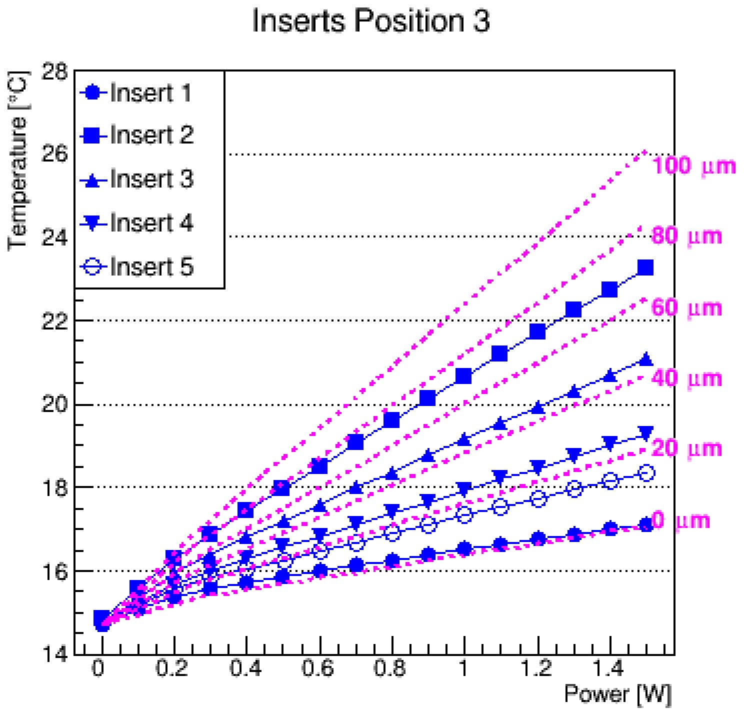
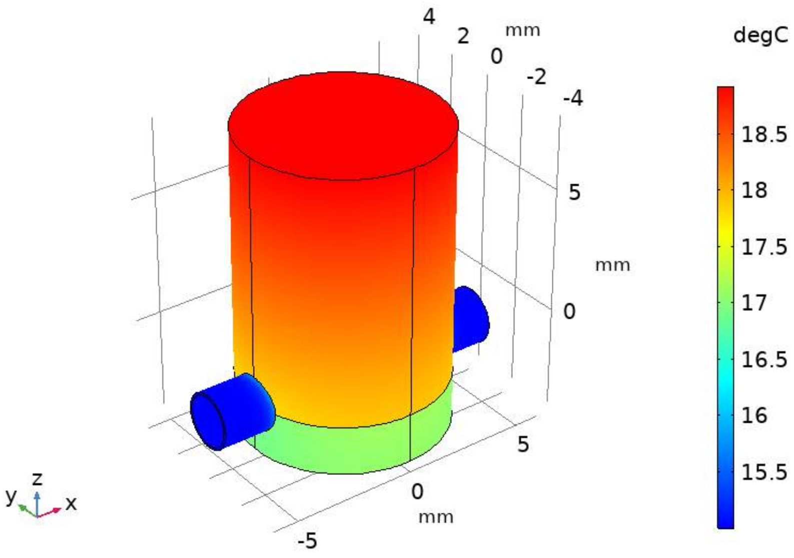
Insert Characterization









- Characterization of the inserts in terms of glue thicknesses

Insert number	Position 1	Position 2	Position 3
1	100 μm	10 μm	0 μm
2	10 μm	50 μm	75 μm
3	5 μm	25 μm	45 μm
4	5 μm	15 μm	25 μm
5	5 μm	10 μm	20 μm
Average	25 μm	20 μm	35 μm