Thermal Measurements and FEA of the 2S Module for the CMS Phase-2 Tracker Upgrade

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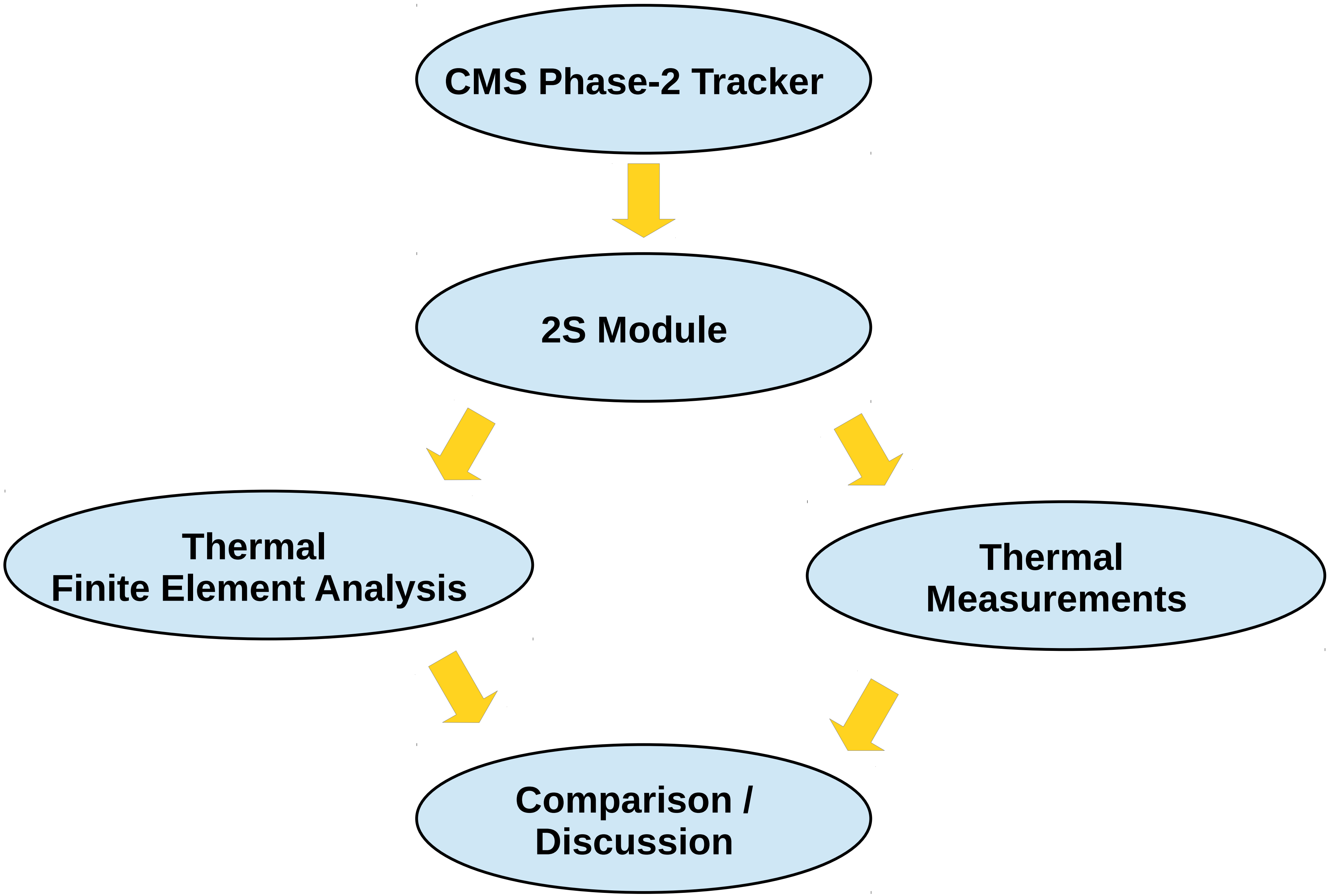
3th July 2017

Forum on Tracking Detector Mechanics 2017, Marseille

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Outline



CMS Phase-2 Tracker
2S Module
Thermal
Finite Element Analysis
Thermal
Measurements
Comparison /
Discussion

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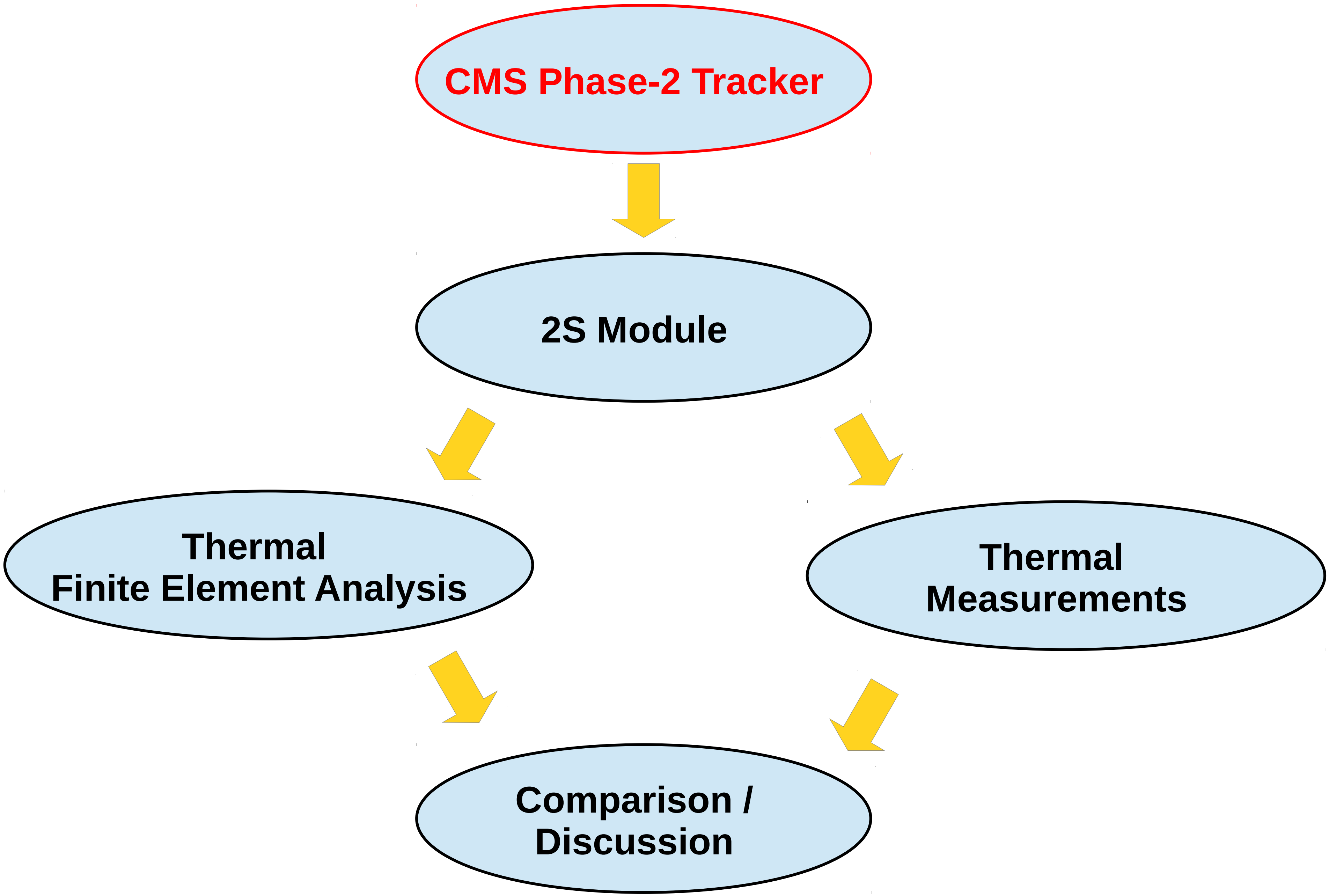
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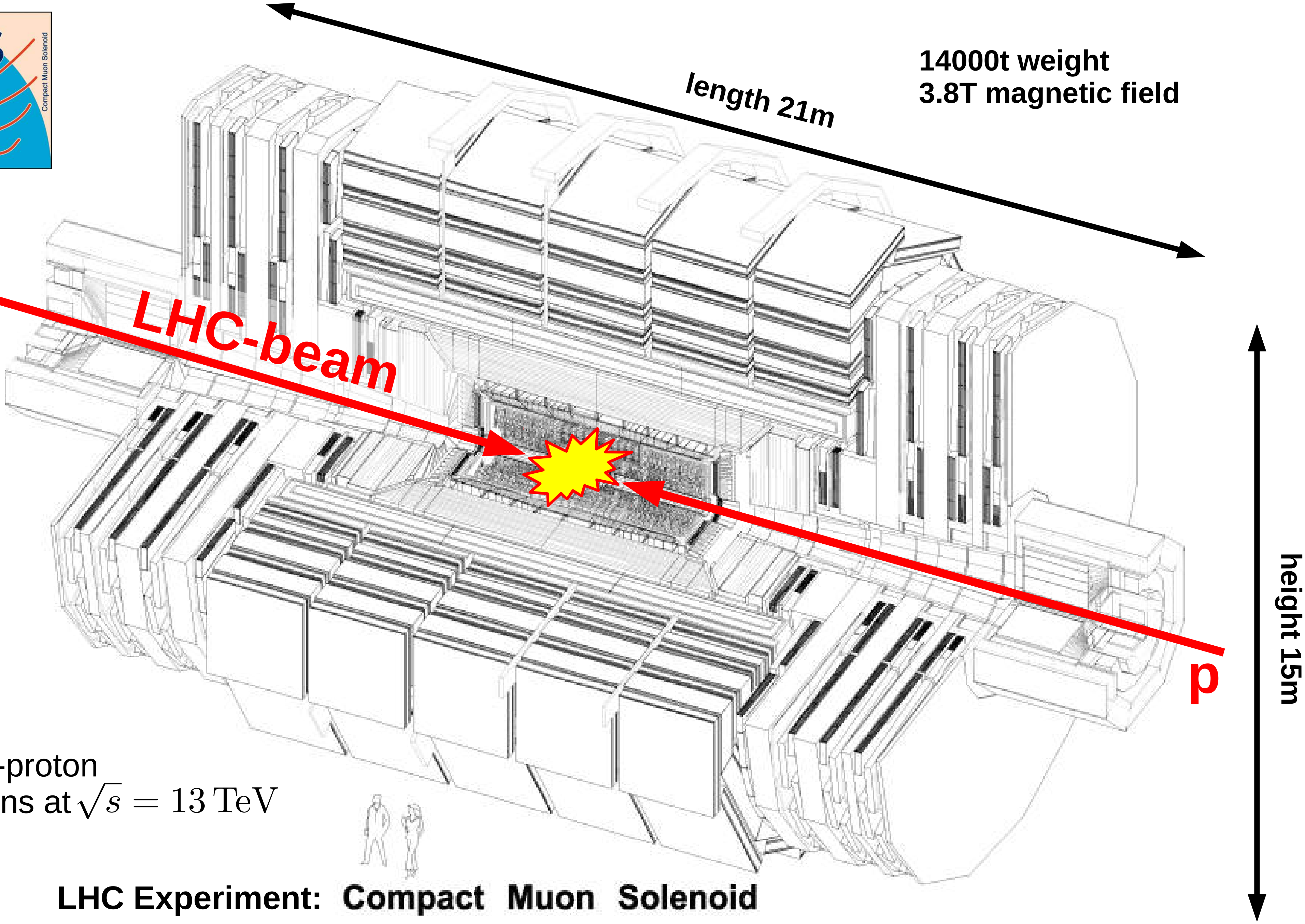
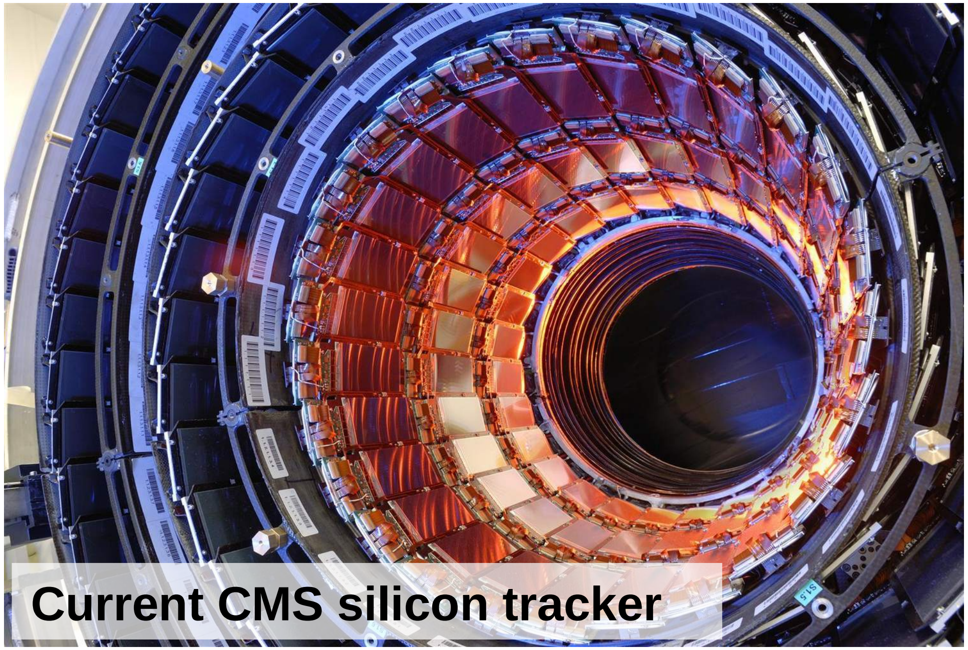
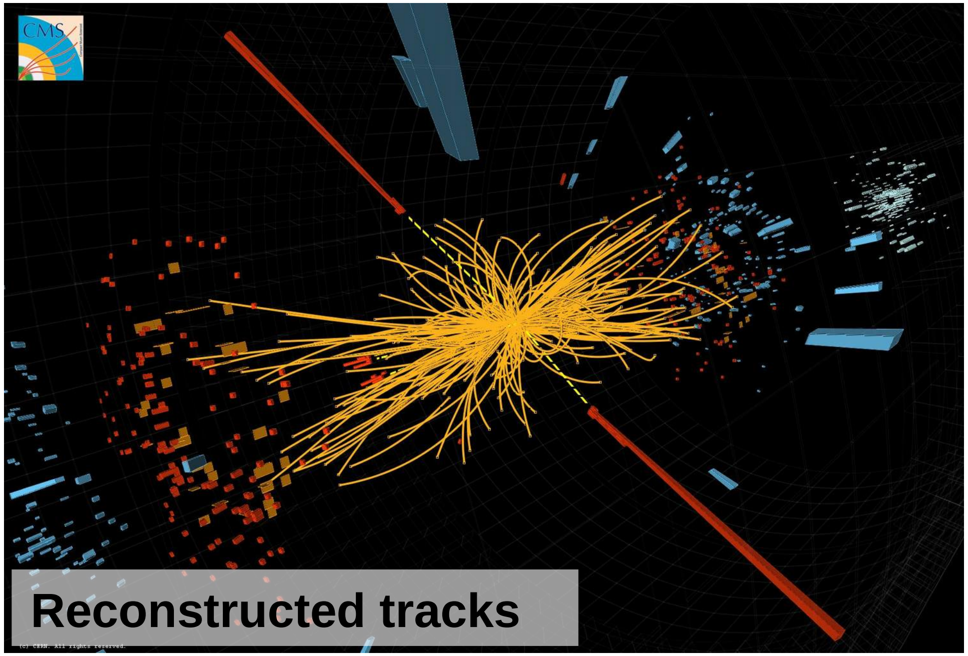
Compact Muon Solenoid

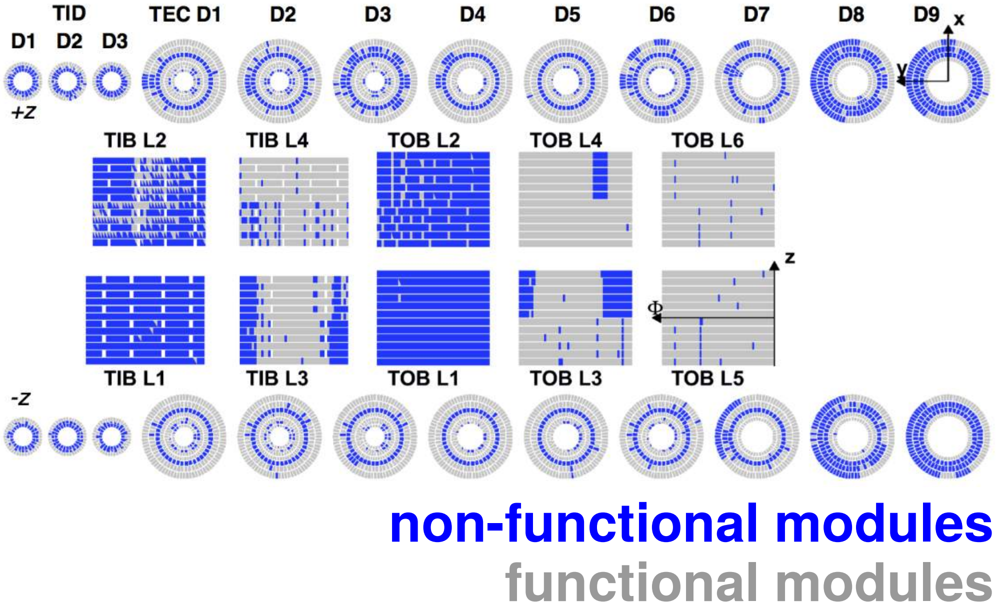


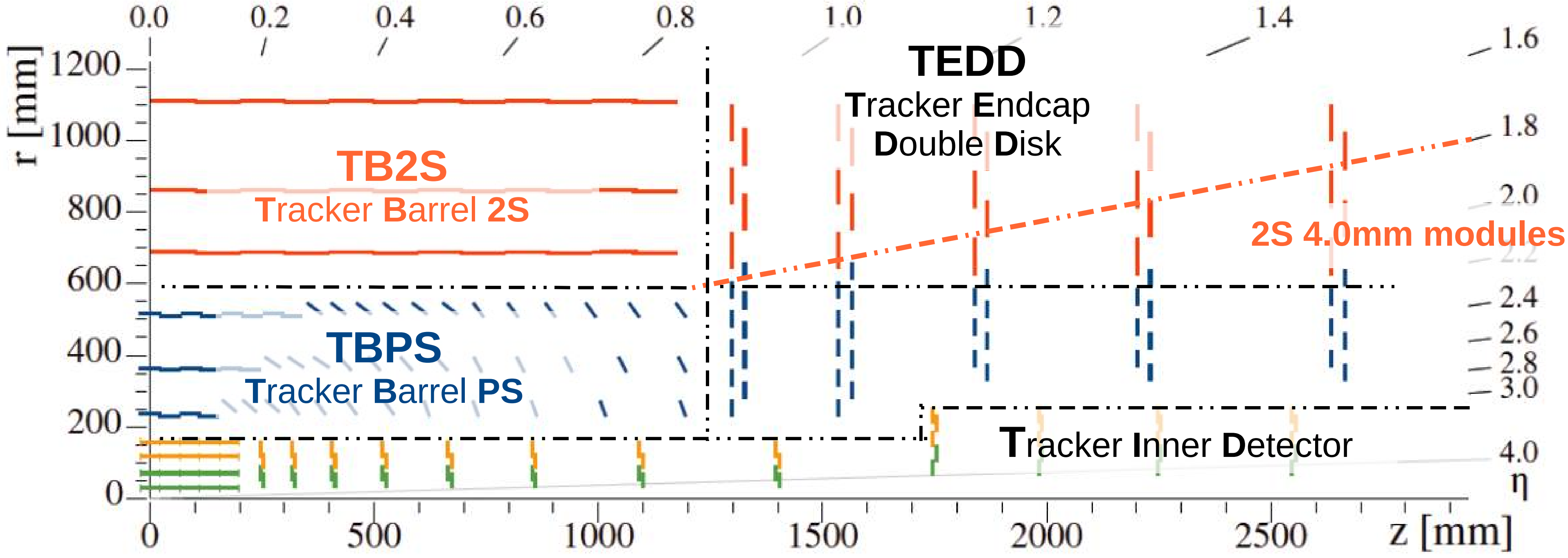
proton-proton
collisions at $\sqrt{s} = 13\,\mathrm{TeV}$





- upgrade from LHC to HL-LHC
  - up to 5 times higher luminosity
  - up to 10 times more integrated luminosity
- **insufficient cooling** of irradiated silicon sensors at HL-LHC
- full replacement of the current tracker detector with an **upgrade in 2024** planned





Inner Tracker

two types of hybrid pixel modules (1x2 and 2x2 chips), 4.9m², 2G channels

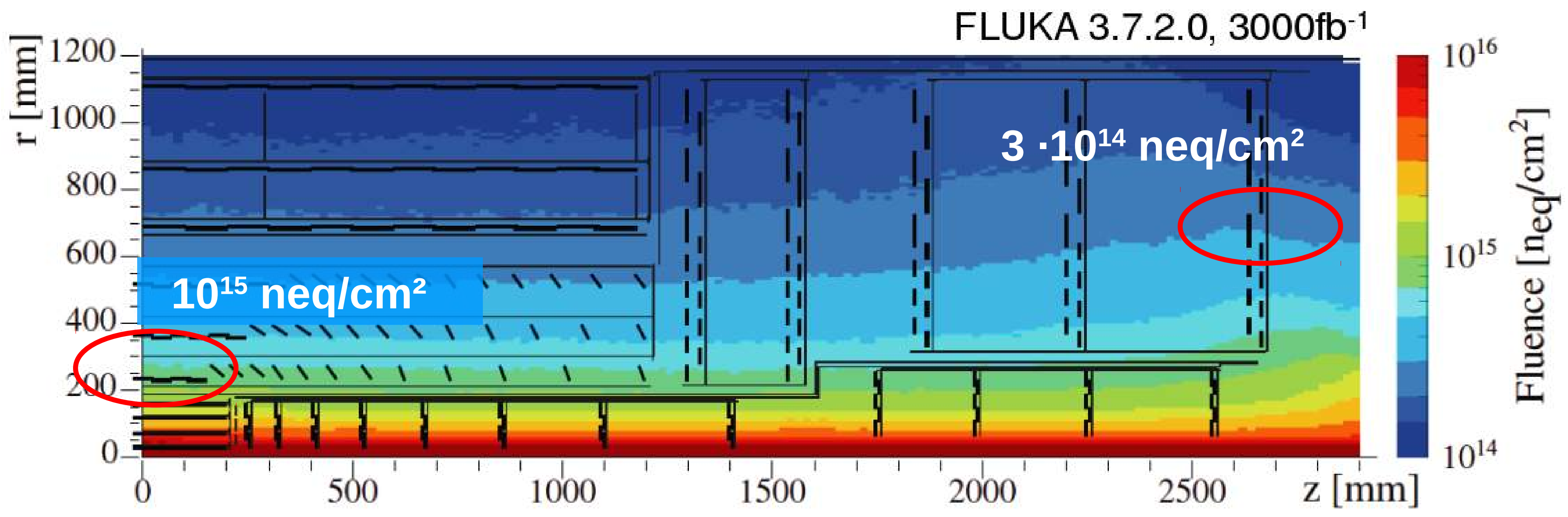
Macro-Pixel Sensor Modules:

5500 modules, 11M strip channels, 170M macro-pixels, different sensor spacings, upto 10^{15} neq/cm²

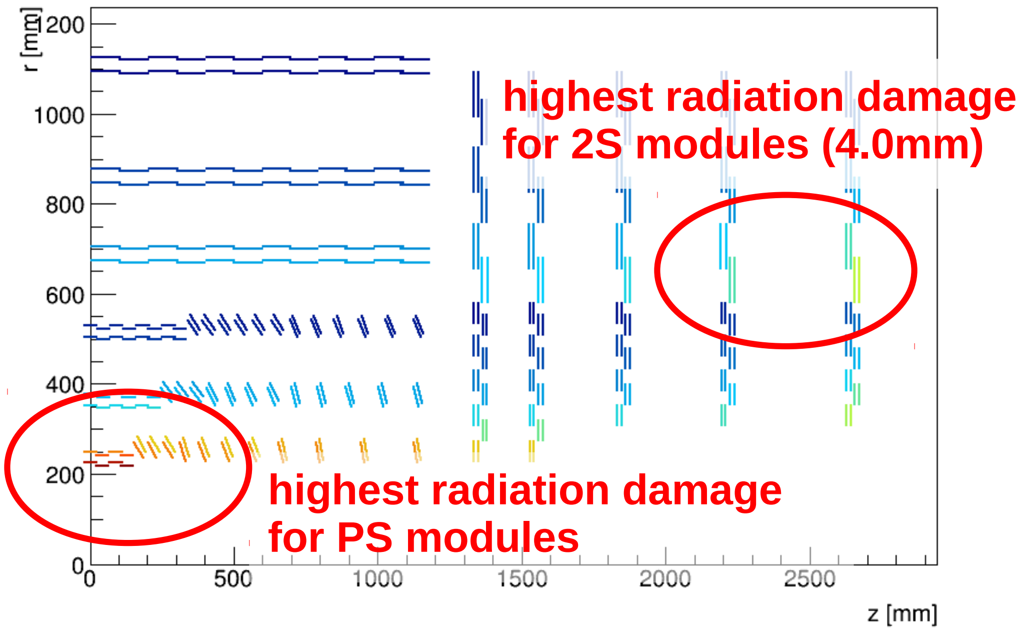
2 Strip Modules:

7500 modules, 30M strip channels, 1.8mm and 4.0mm sensor spacing, up to $3 \cdot 10^{14}$ neq/cm^2

Radiation Damage



- silicon sensors will suffer from damage due to irradiation at HL-LHC conditions
  - instantaneous luminosities of 1 $\cdot 10^{35}$ $cm^{-2}s^{-1}$
- leakage current (power) increases
  - with radiation damage
  - with temperature
- **goal:** keep the silicon sensor temperatures at lowest possible temperatures
- **challenge:** Outer Tracker will have an overall power of 100kW



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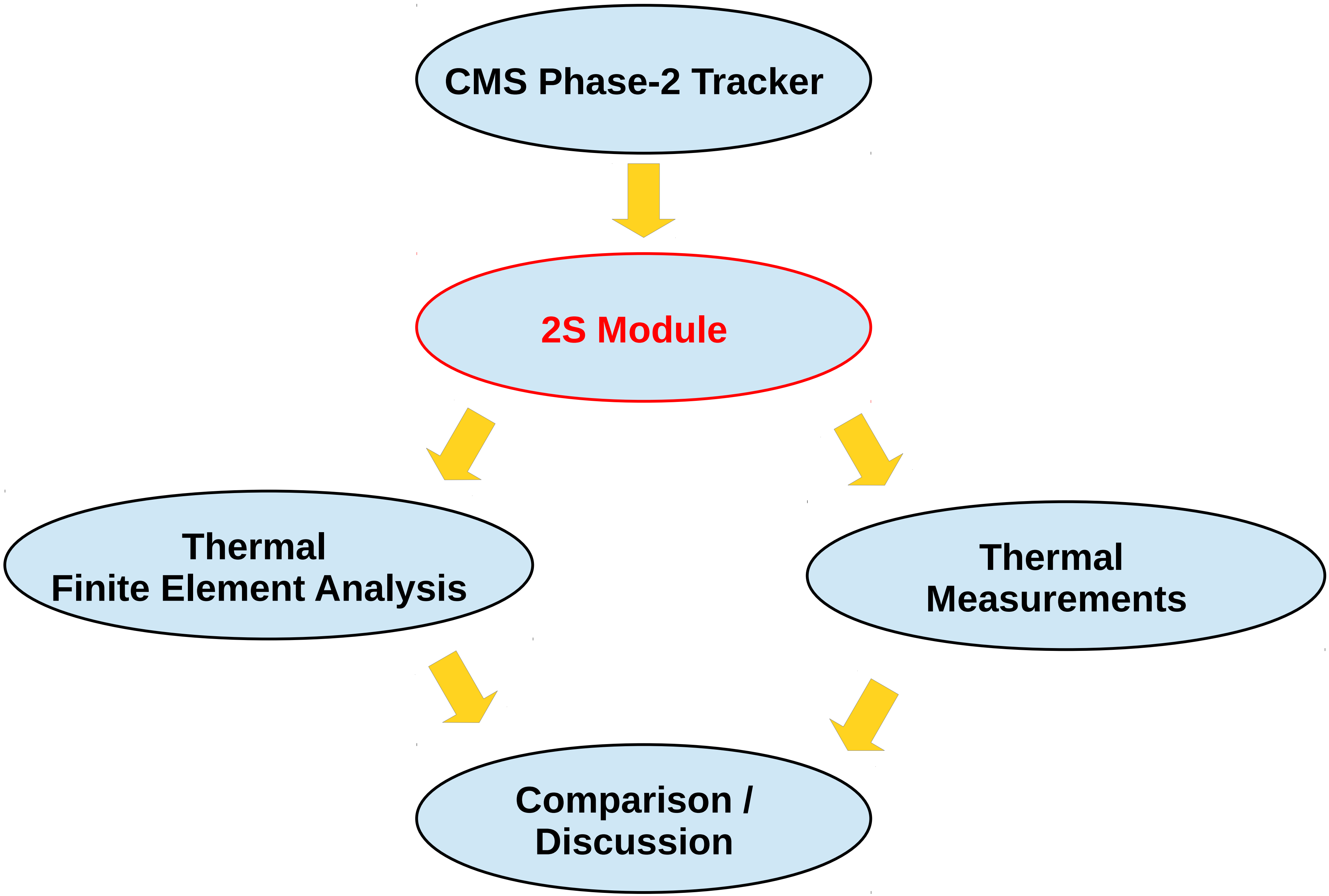
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The CMS 2S Module

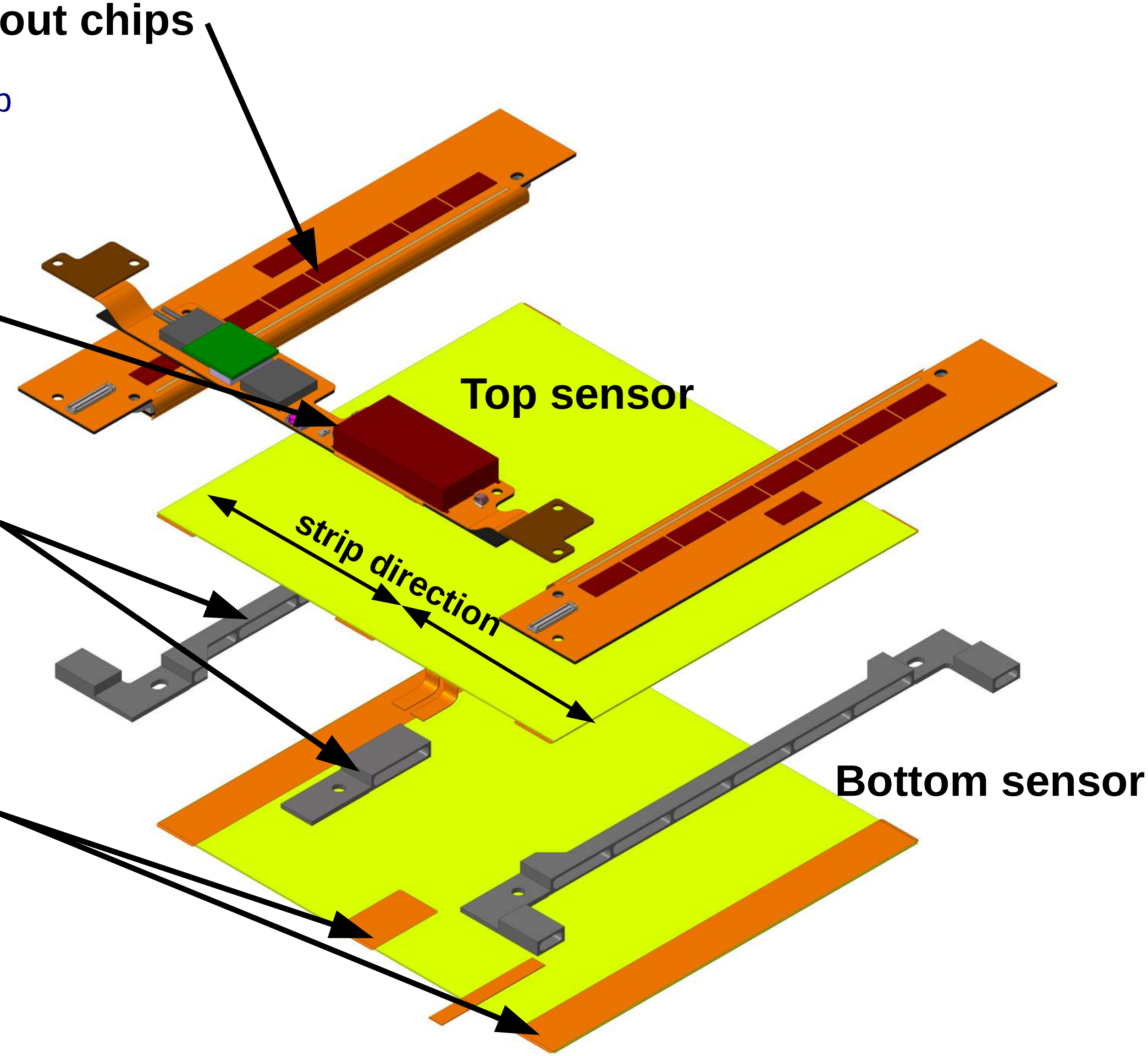
2 Front-end flex-hybrids with read-out chips
- 2032 channel
- chips receive signals from both bottom and top sensor

Service hybrid with DC-DC-converters and opto-module
- 2 stage DC-DC-converter (from 11V to 2.5V and from 2.5V to 1.2V)
  → power efficiency about 50%

Aluminum carbon-fiber stiffeners
- carbon-fiber re-enforced aluminum for the CTE (≈4ppm/K) match between silicon sensors and spacers
- screwing holes for fixture and cooling

Kapton strips for the high-voltage isolation of the sensor
- carbon-fiber re-enforced aluminum for the CTE (≈4ppm/K) match between silicon sensors and spacers

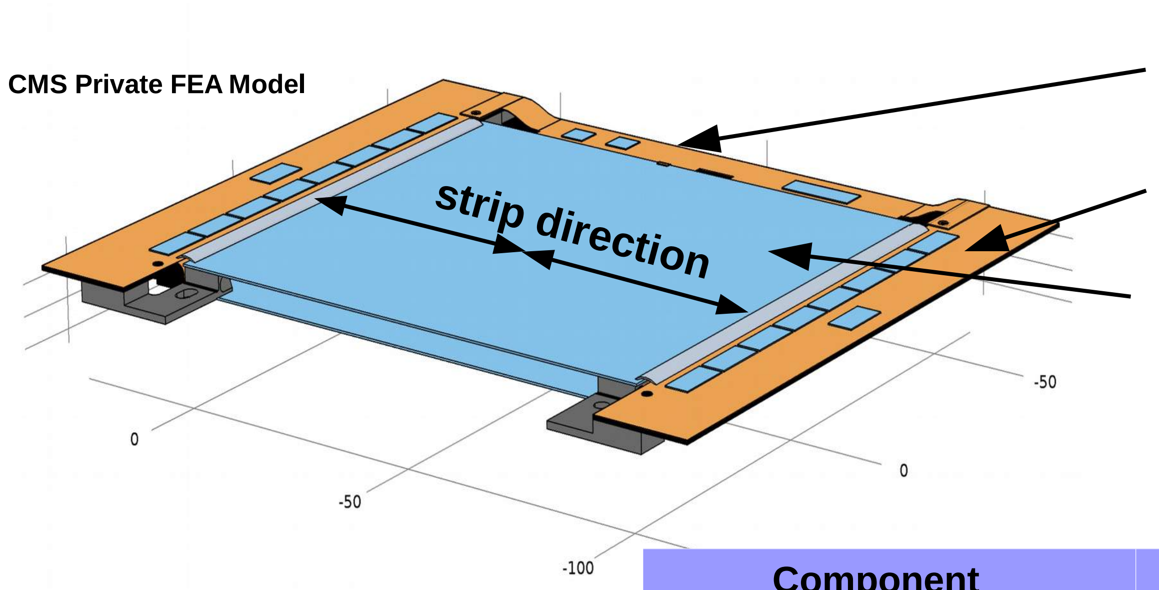
2 n-in-p silicon strip sensors
- 10cm x 10cm, 2 x 5cm strip length,
- 90µm pitch
- 320µm thickness, 200µm active thickness



mass ca. 40g

size roughly 14cm x 12cm

Power of the 2S Module



service hybrid: **2.6 W**

2 front-end hybrids: **2.8 W**

2 silicon strip sensors after 3000fb^{-1}: **1.2 W**

Component	Part	Power [W]
Service hybrid	DC-DC-converters	1.8
	opto-components	0.8
Front-end hybrids	2 x 8 CBC chips	2.2
	2 CIC chips	0.6
Sensors at -20°C	top	0.6
	bottom	0.6
	Sum	**6.6**

6.6W per module!

Thermal Runaway

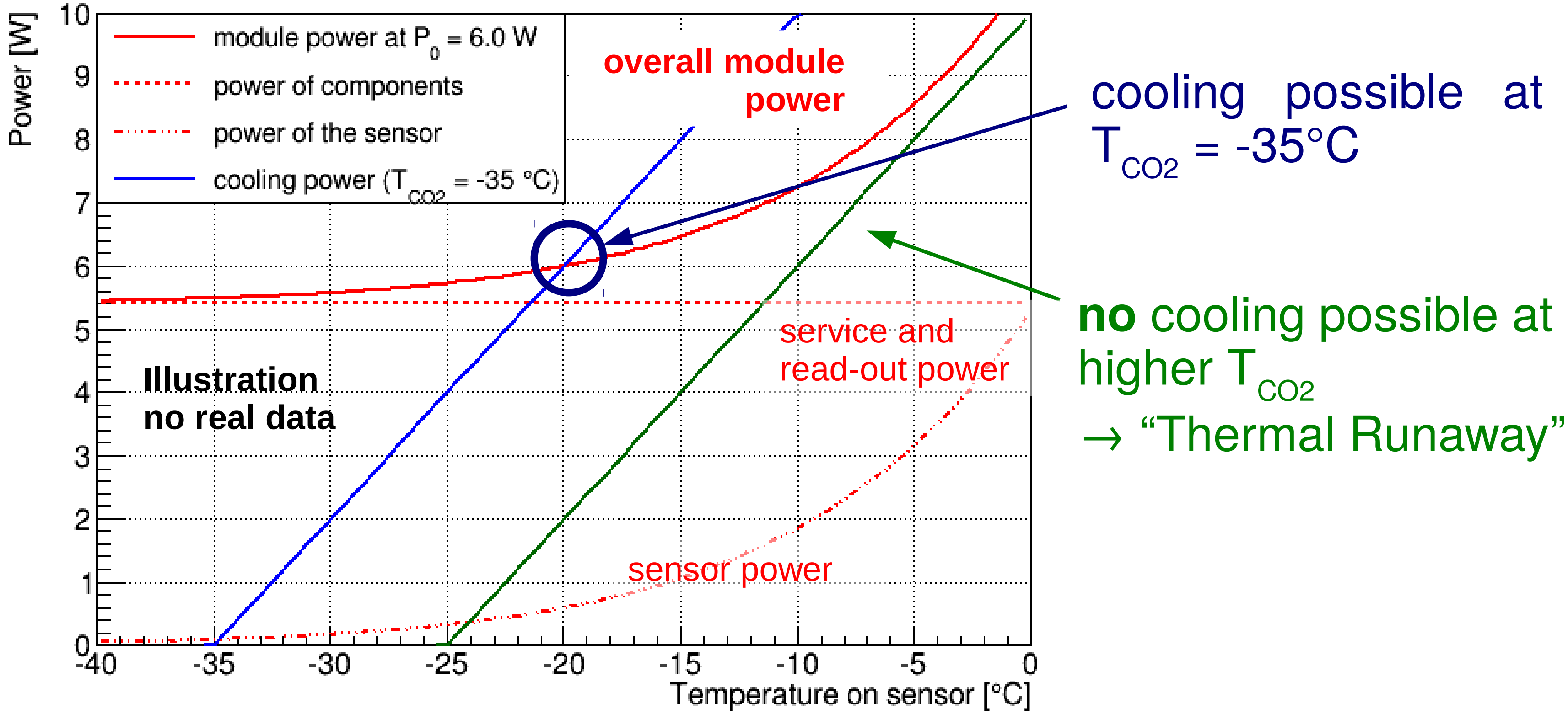
- Some components (read-out chips, DC-DC converters, ...) produce a constant power

$$P_{\text{components}} = \text{const.}$$

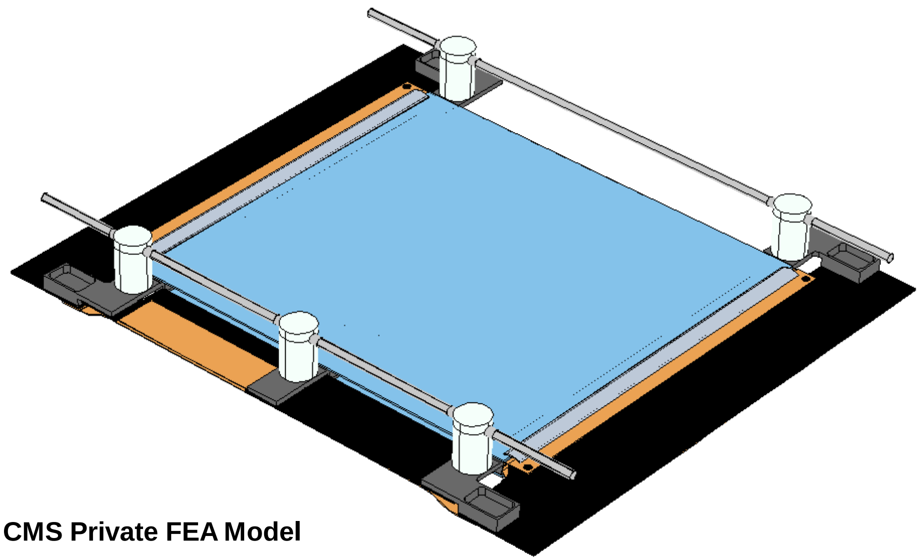
- Irradiated silicon sensors generate temperature dependent leakage current

$$P_{\text{sensor}} \propto P_0 \frac{T^2}{T_0^2} \exp\left[-\frac{\Delta E}{2\,k_B} \left(\frac{1}{T} - \frac{1}{T_0}\right) \right]$$

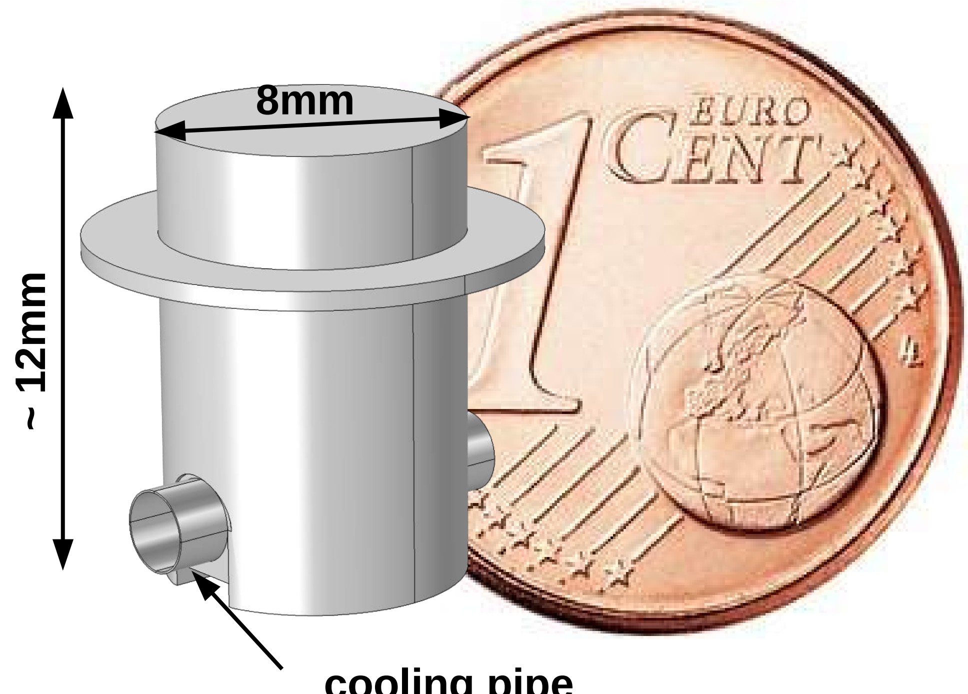
- Linear dependence of the cooling power $P_{\text{cooling}} \approx \frac{1}{\alpha}(T_{\text{module}} - T_{\text{coolant}})$



- cooling fluid CO_2 enters the detector in the 2-phase state (2PACL system)
  - 12 bar at a temperature of -35°C
  - CO_2 is evaporated at constant temperature → heat removal
- many advantages with respect to low-material tracking detectors
  - cooling pipes: stainless steel, inner diameter 2.0mm, 100µm wall thickness
  - high heat transfer coefficients in boiling CO_2 (5000 W/m²/K or higher)
- 2S modules in TEDD mounted on five cooling contacts



CMS Private FEA Model



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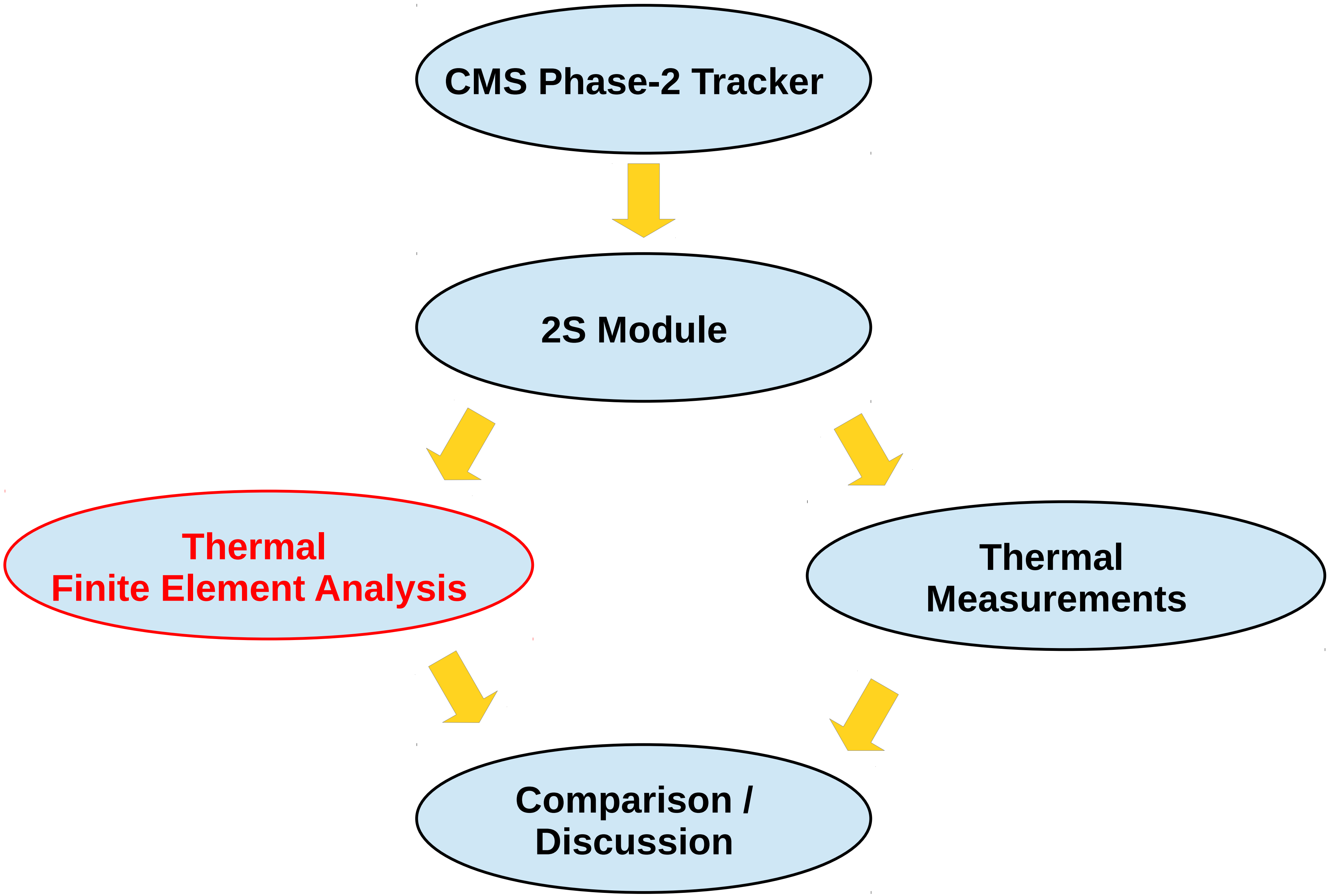
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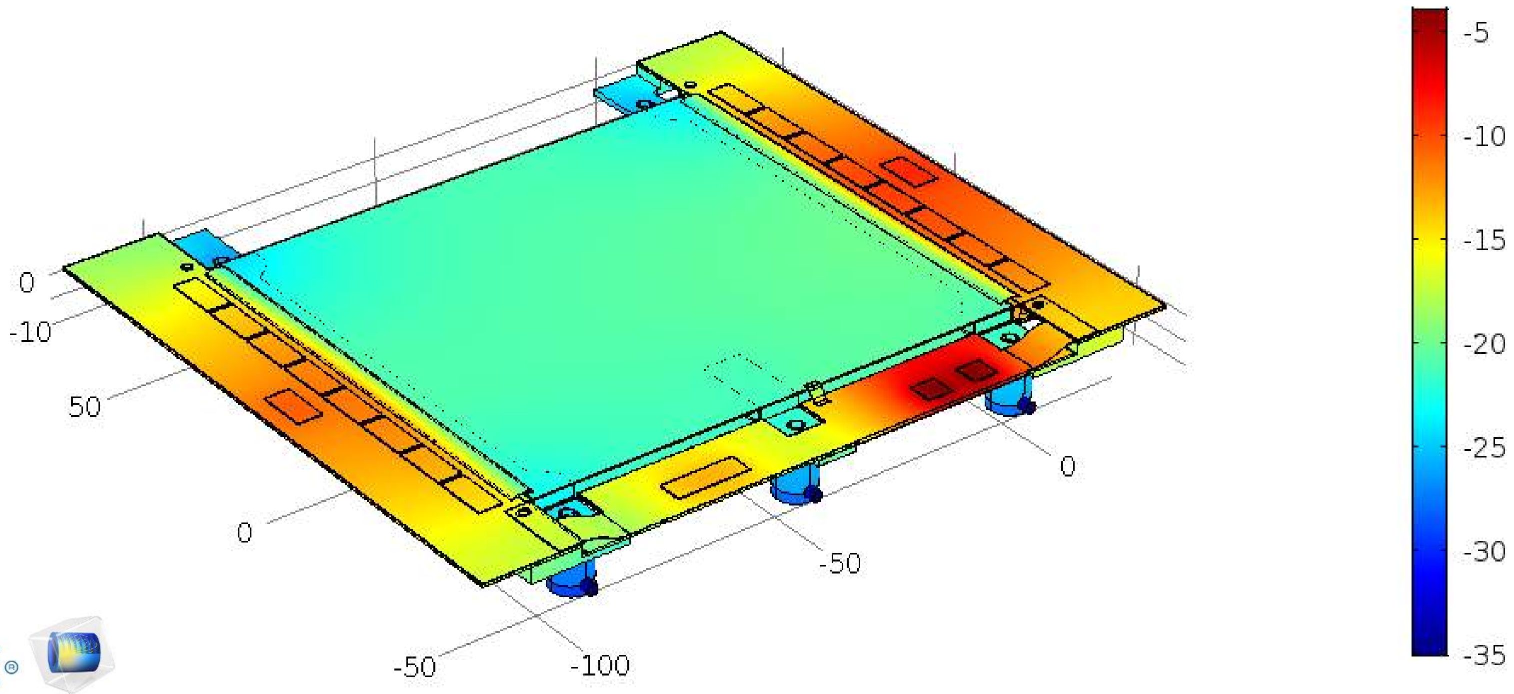
Thermal Finite Element Analysis

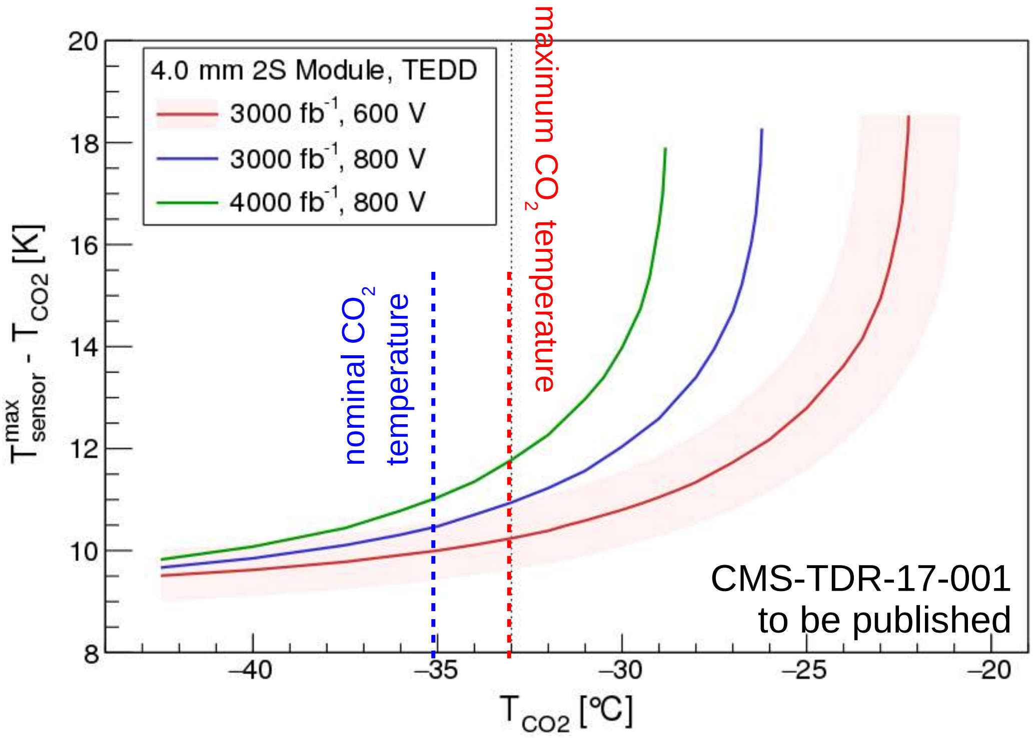
- Thermal FE analyses are made with COMSOL Multiphysics → Heat Transfer Module
- CO_2 temperature of -35°C is assumed in the cooling pipes
- Heat load is generated in the specific volumes
  - constant heat load for ASICs: 5.4W overall
  - temperature dependent leakage current of irradiated silicon sensors (Boltzmann distribution)
    - P_0 = 0.6W at -20°C after 3000 fb^{-1}
    - maximum U_{bias} assumed is -800V

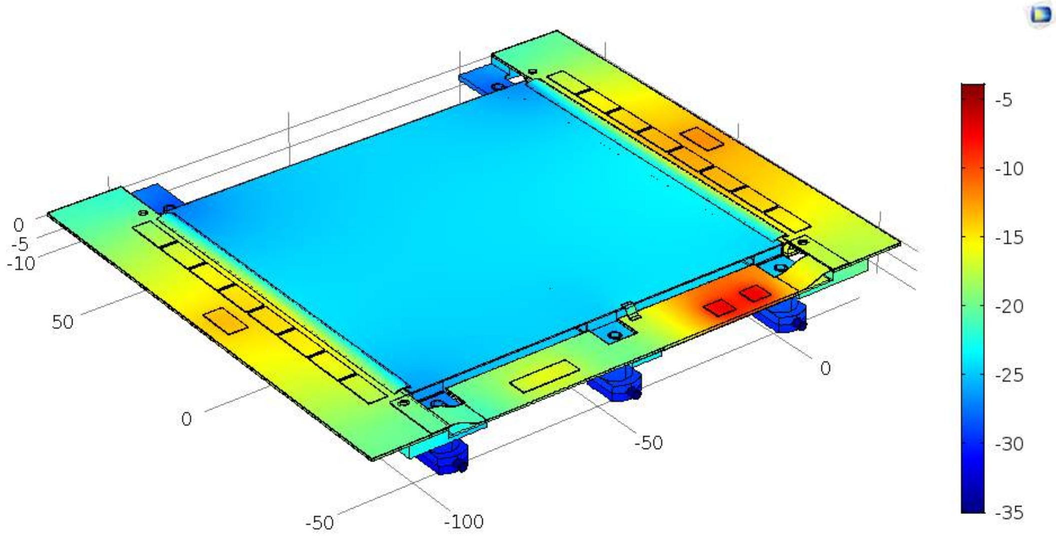
$$U_{\text{bias}} \cdot I(T) = U_{\text{bias}}\, I_0 \left(\frac{T}{T_0}\right)^2 \exp\left(-\frac{\Delta E}{2k_B}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right)$$



COMSOL MULTIPHYSICS®

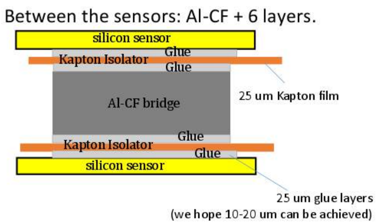
Predicted Thermal Runaway





- Maximum sensor temperature is computed as a function of the CO_2 temperature
- Difference between maximum sensor temperature and CO_2 temperature is calculated
- Sensor temperature stays in safe regimes
  - for the nominal CO_2 temperature -35°C → sensor temperature -25°C
  - for the maximum CO_2 temperature -33°C → sensor temperature -23°C
- Good margin between thermal runaway and the maximum CO_2 temperature
  - 4K for the scenario at 4000fb^{-1} and a bias voltage of 800V

Thermal Interfaces

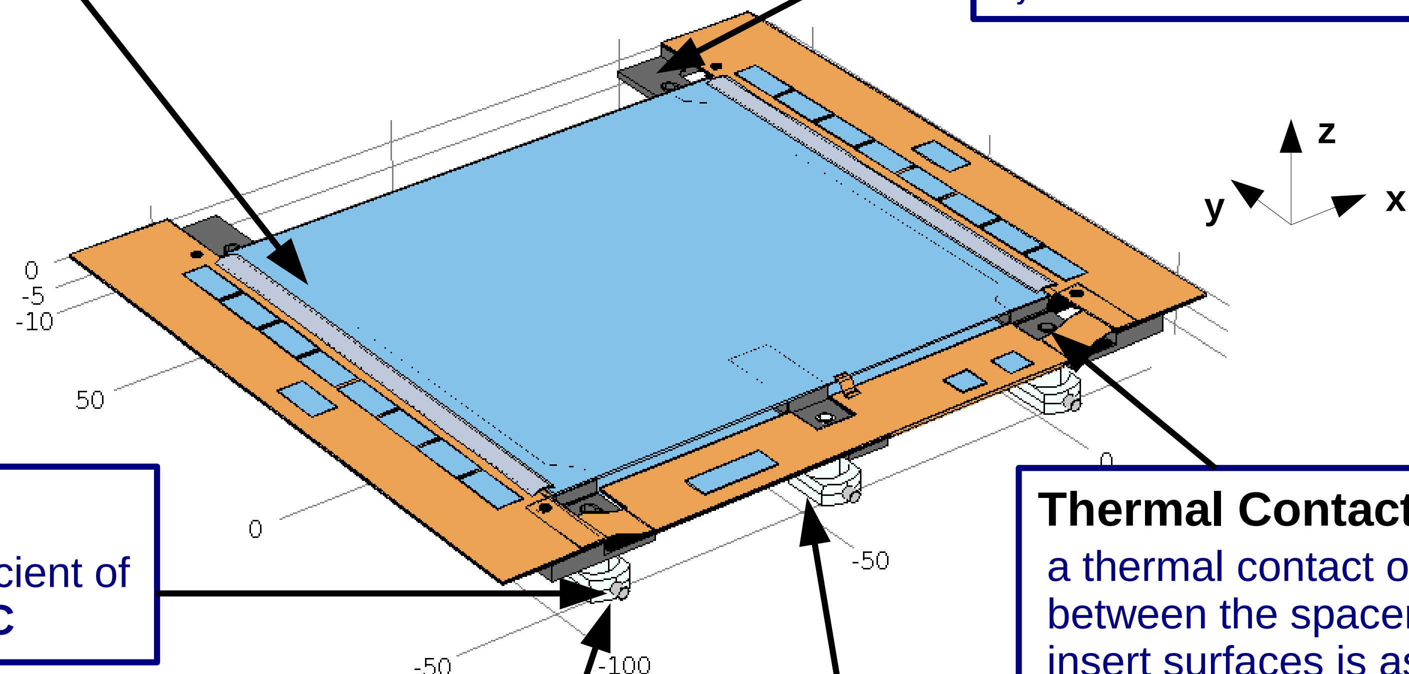


Epoxy-Kapton-Epoxy Layer

described with effective thermal through-plane conductivity 0.3 W/m/K and with **65µm** thickness

AlCF-Spacer

anisotropic thermal conductivity due to carbon fiber orientation:
k_{yz} = 230 W/m/K; k_x = 120 W/m/K



CO_2 Heat Flux

heat transfer coefficient of **5 kW/m²/K** at **-35°C**

Thermal Contact

a thermal contact of **10kW/m²/K** between the spacers and in the insert surfaces is assumed

Cooling Pipe

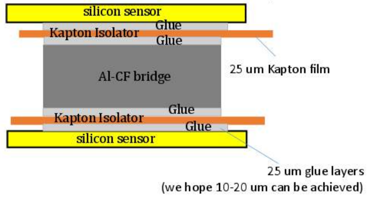
stainless steel (**12 W/m/K**)
2mm inner diameter
100µm wall thickness

Cooling Pipe Contact

epoxy layer with **20µm** thickness and **0.2W/m/K**

Thermal Interfaces

Between the sensors: Al-CF + 6 layers.



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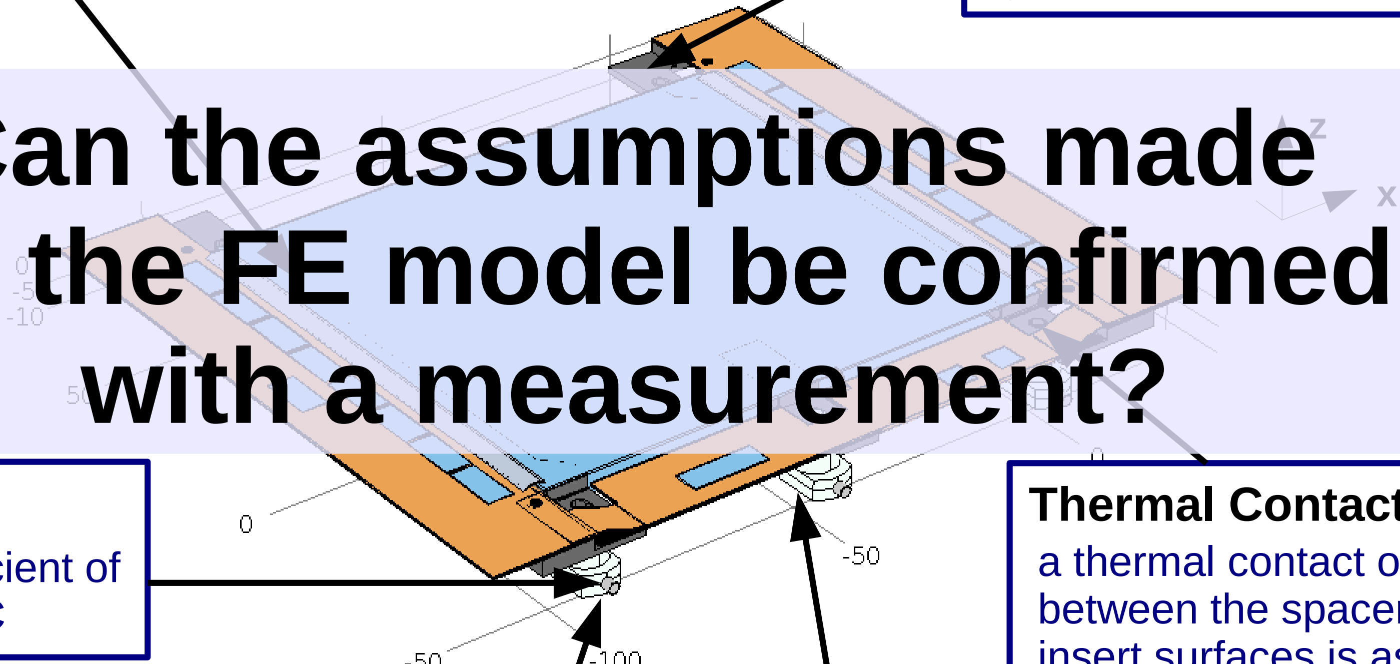

Can the assumptions made for the FE model be confirmed with a measurement?

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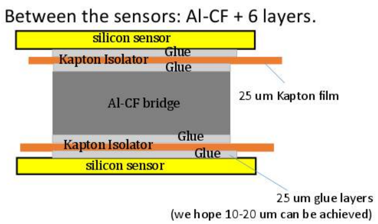
Thermal Dummy Module



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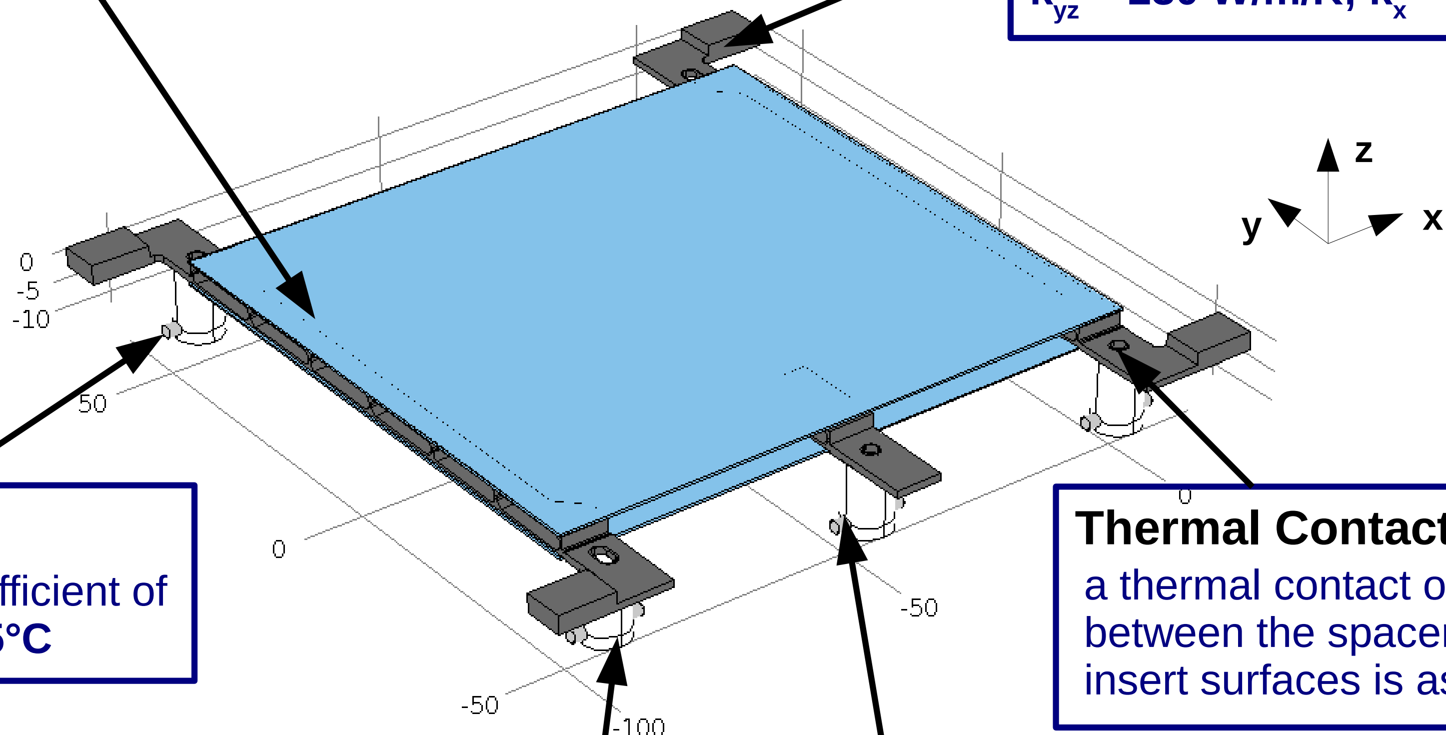

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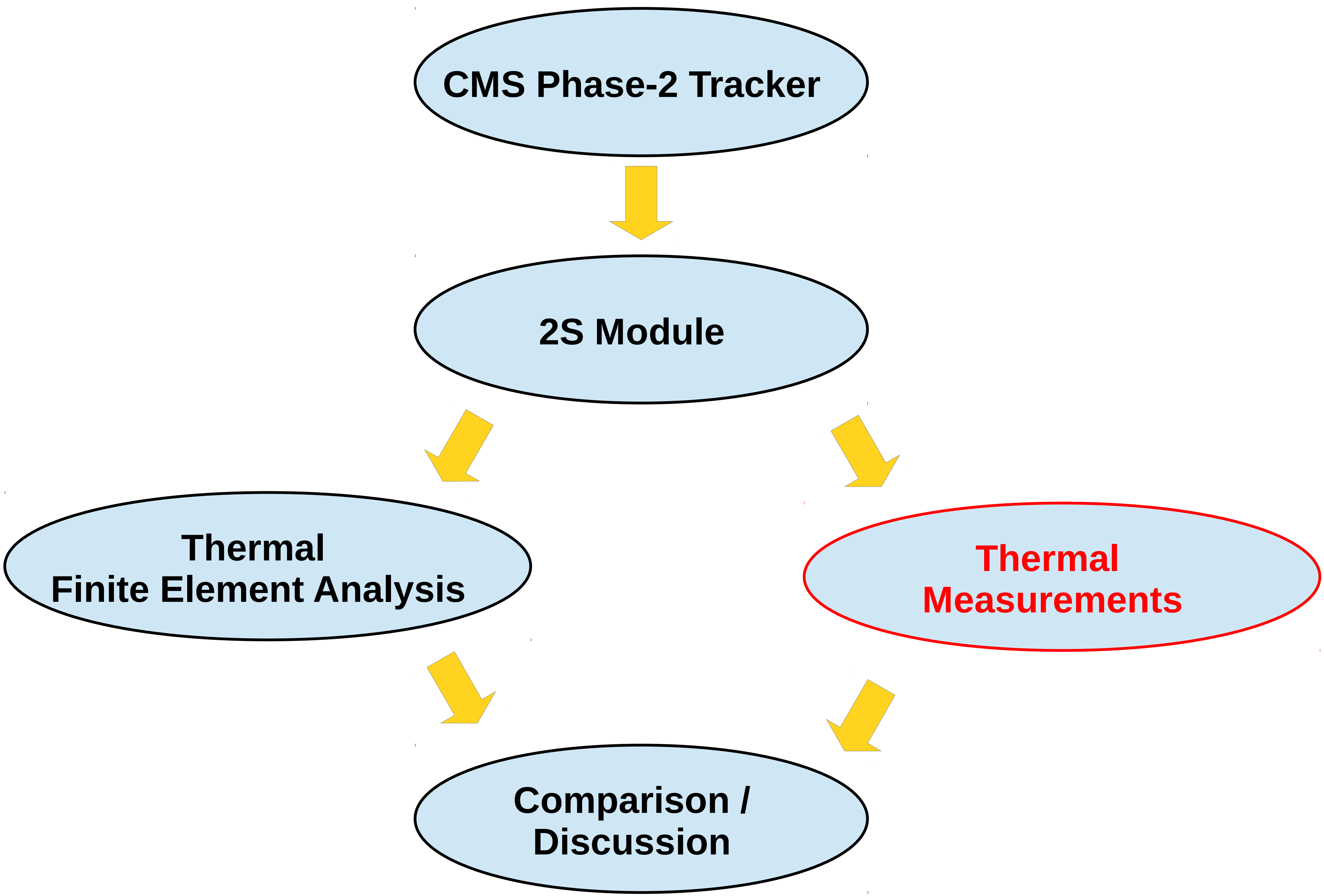

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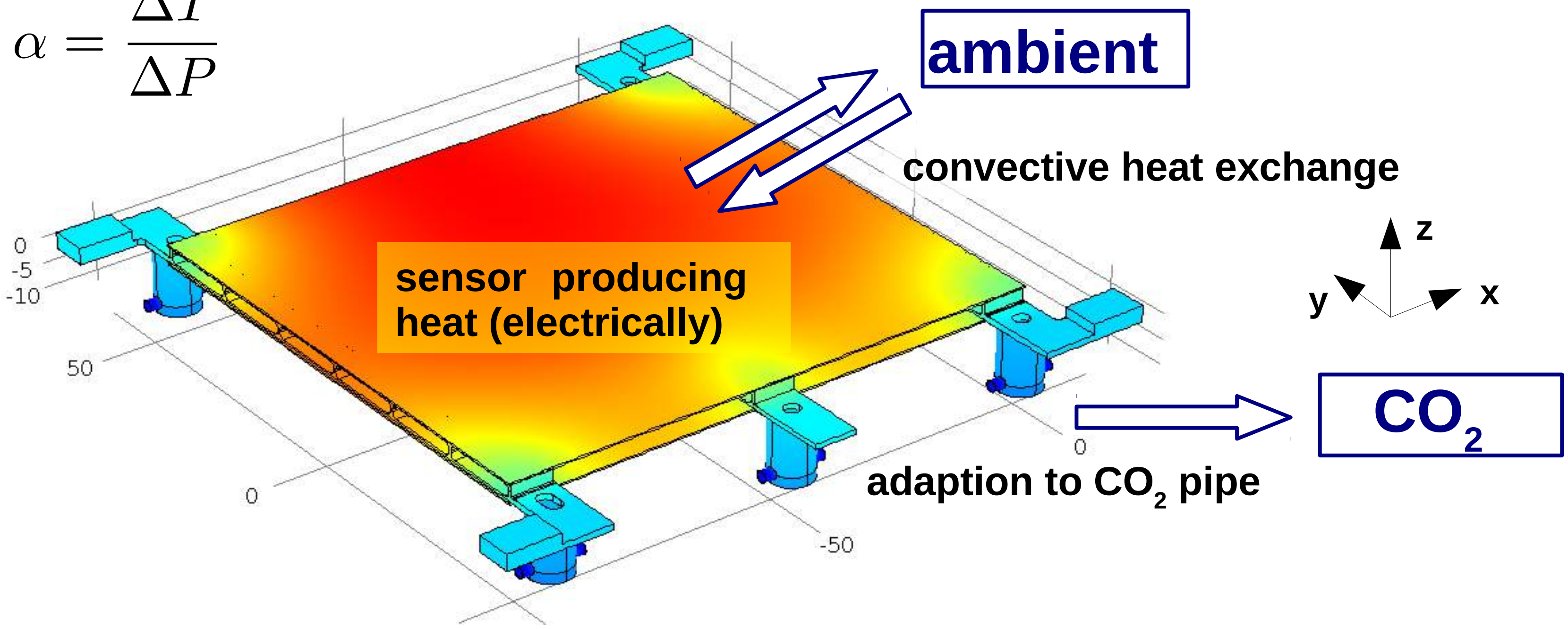
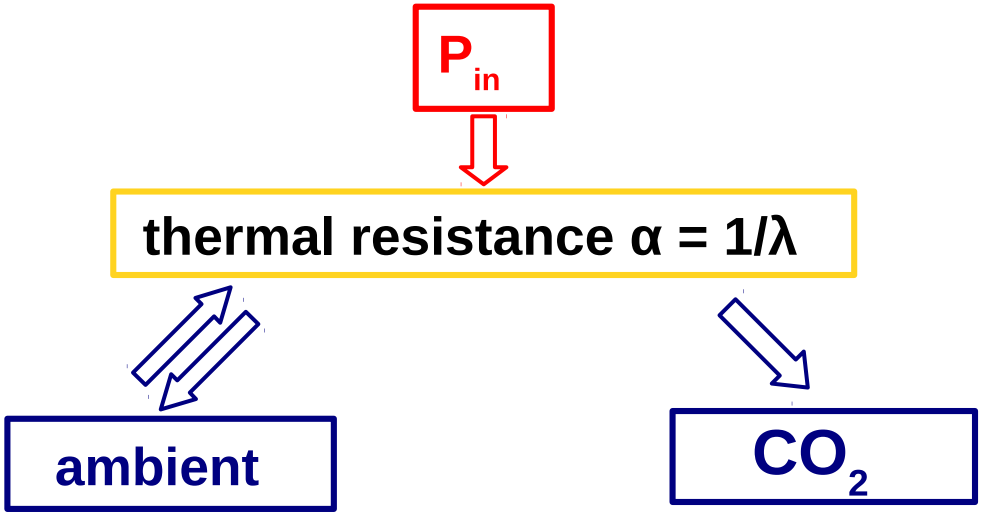
Concept of Thermal Tests

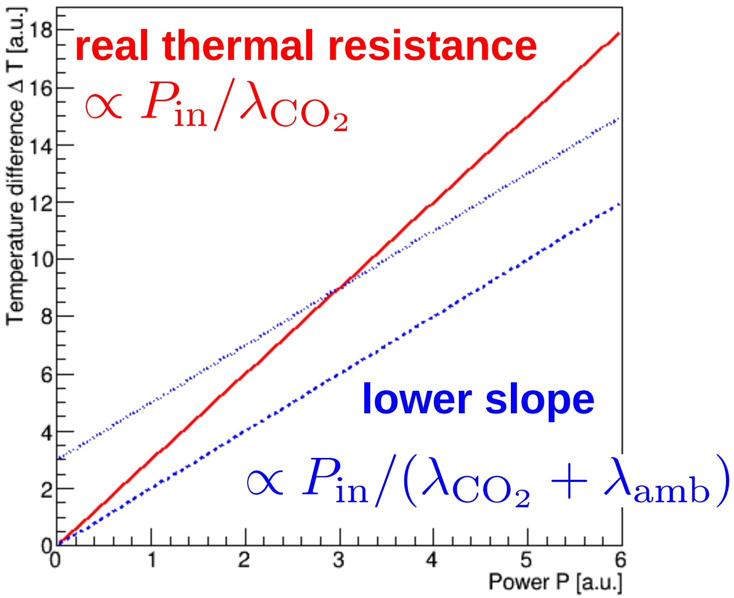
Thermal resistance $\alpha = \frac{\Delta T}{\Delta P}$



- Requirements on a reliable thermal test setup
  - Feed the measured heating power fully into the sensor/module
    - difficult with heating resistors, heating foils, …
  - Control the heat exchange with the ambient
- Generate thermal equilibrium between sensor and the ambient
  - FE simulations do not take into account the heat exchange with the ambient
  - 200m² of silicon in the detector → silicon dominates the entire volume
    - silicon sensors and ambient will be at the same temperature

Model of Heat Fluxes





- Mathematical model (equation of continuity)

$$P_{\mathrm{in}} = \underbrace{\lambda_{\mathrm{amb}(T_i)}(T_i - T_{\mathrm{amb}})}_{=\text{heat exchange with the ambient}} + \underbrace{\lambda_{\mathrm{CO_2}}(T_i - T_{\mathrm{CO_2}})}_{=\text{heat removed by CO}_2\text{, linear}}$$

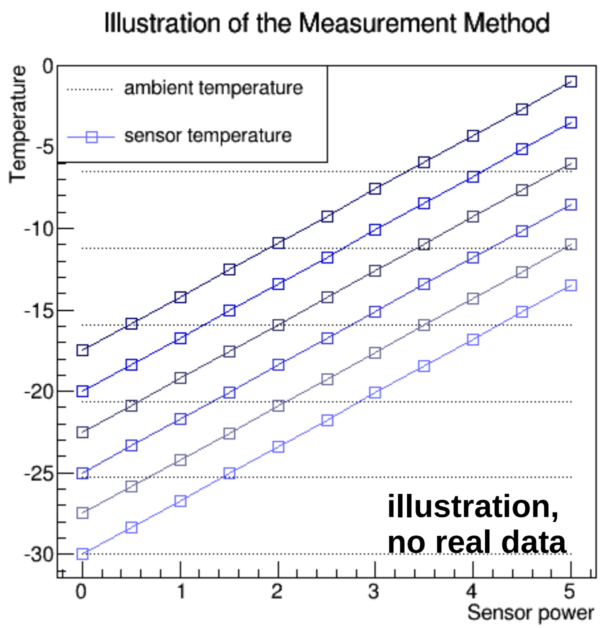
- Solution of the equation

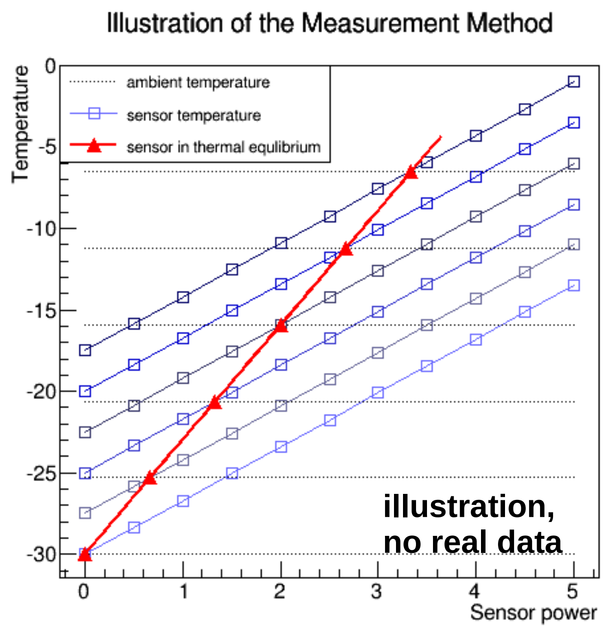
$$T_i = \frac{P_{\mathrm{in}} + \lambda_{\mathrm{amb}} T_{\mathrm{amb}} + \lambda_{\mathrm{CO_2}} T_{\mathrm{CO_2}}}{\lambda_{\mathrm{amb}} + \lambda_{\mathrm{CO_2}}} \Rightarrow \frac{1}{\lambda_{\mathrm{amb}} + \lambda_{\mathrm{CO_2}}} P_{\mathrm{in}} < \frac{1}{\lambda_{\mathrm{CO_2}}} P_{\mathrm{in}}$$

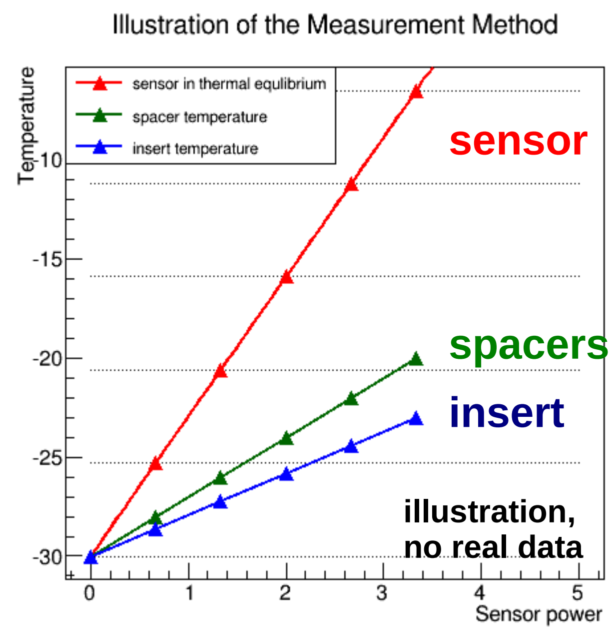
Find thermal equilibrium state where

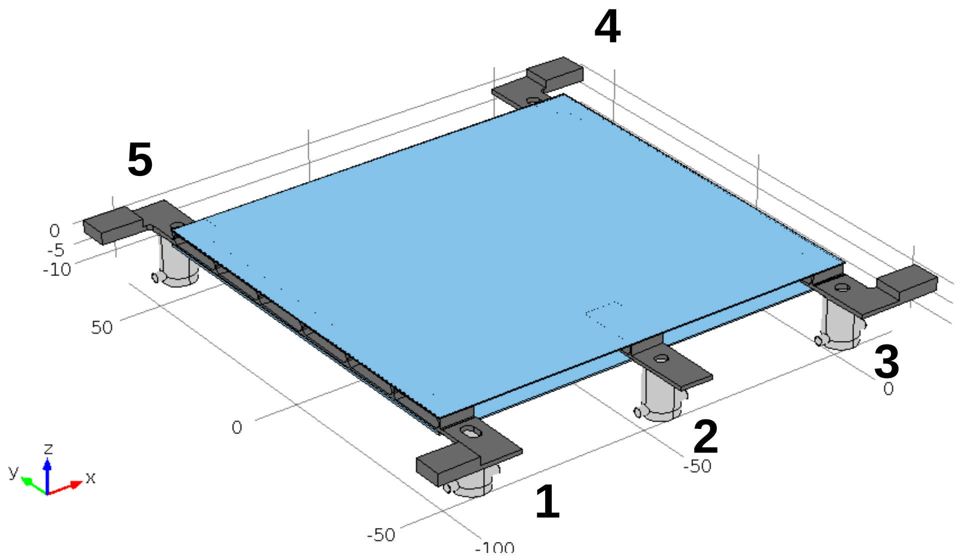
$$P_{\mathrm{in}} = \lambda_{\mathrm{CO2}}(T_i - T_{\mathrm{CO2}}) \Rightarrow T_i - T_{\mathrm{amb}} = 0\,\mathrm{K}$$

Measurement Method





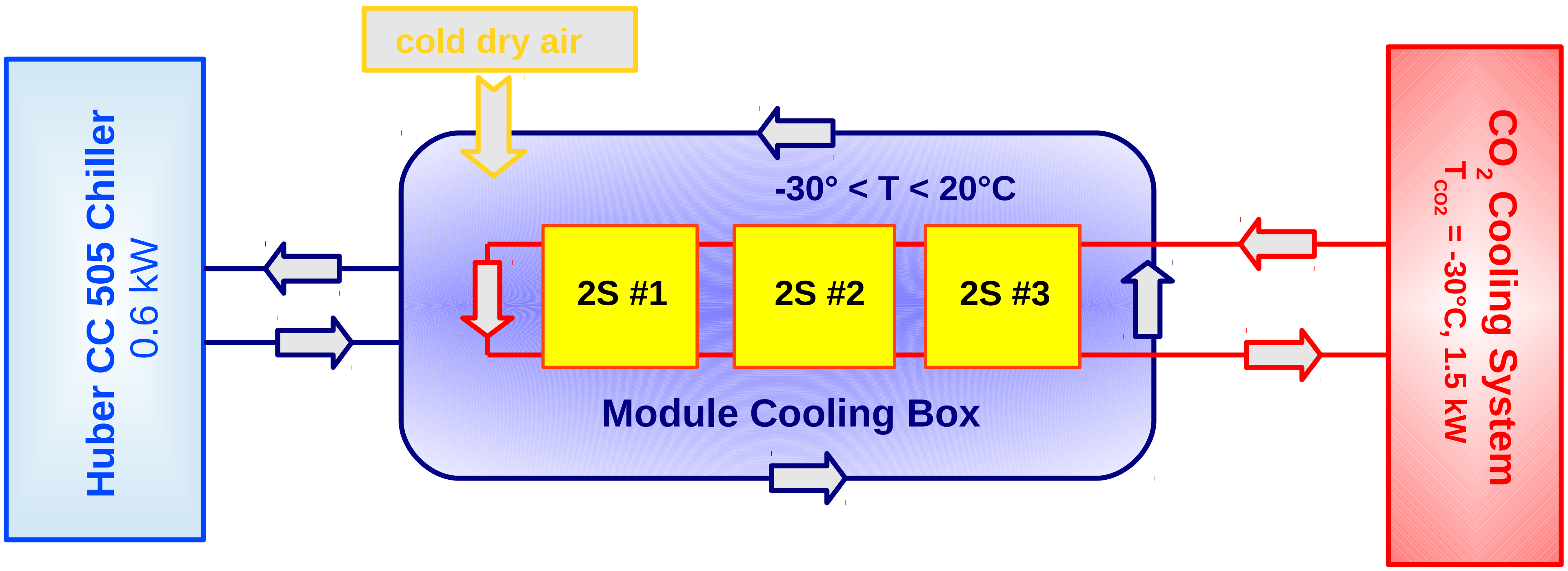




Thermal resistance $\alpha_{\mathrm{sensor}} = \frac{\Delta T_{\mathrm{equilibrium}}}{\Delta P_{\mathrm{equilbrium}}}$

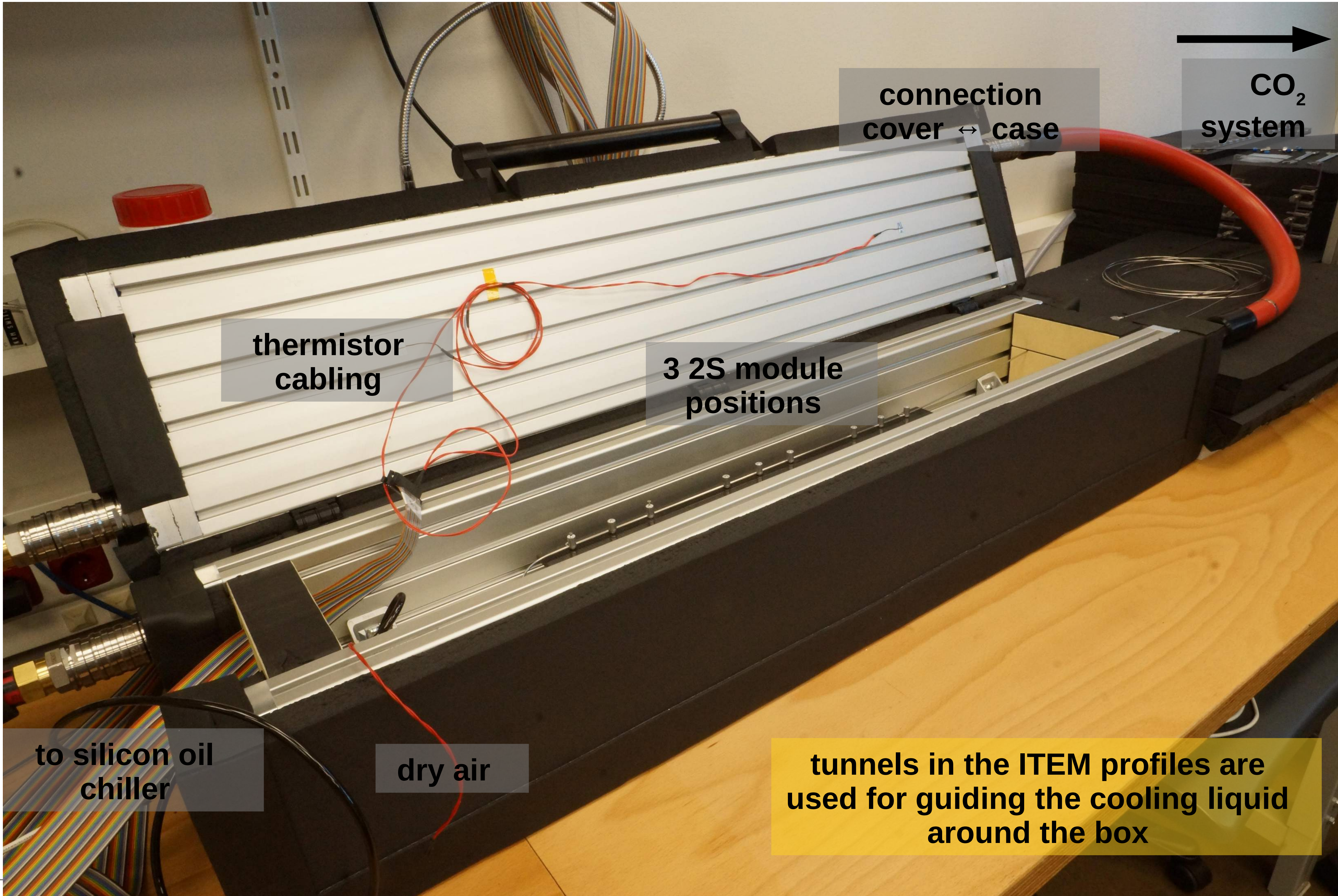
- is used for characterization of the thermal properties
- comparison of measured and simulated data
- **goal: confirm, validate or improve parameters assumed in the FE model**

System Design

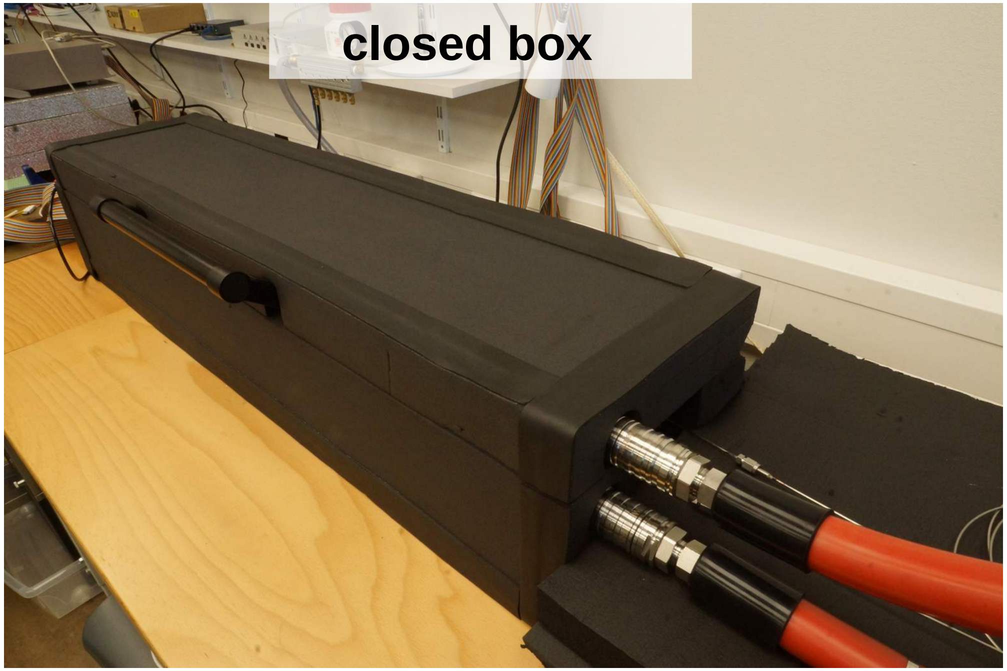


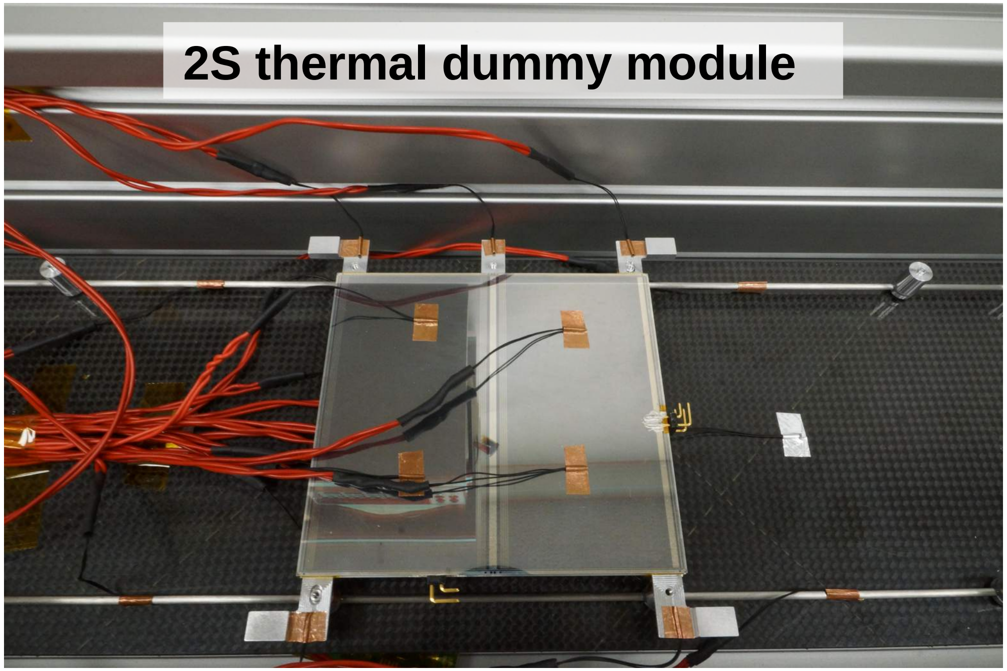
- Three positions for the 2S modules in a cooling box
- A CO_2 cooling system is available for cooling the modules: **T_{CO2} = -30°C**
- The ambient temperature of the box is controlled by a silicon oil chiller: **-30°C ≤ $T_{ambient}$**
- Cold dry air with the same temperature as the cooling box is injected

Module Cooling Box

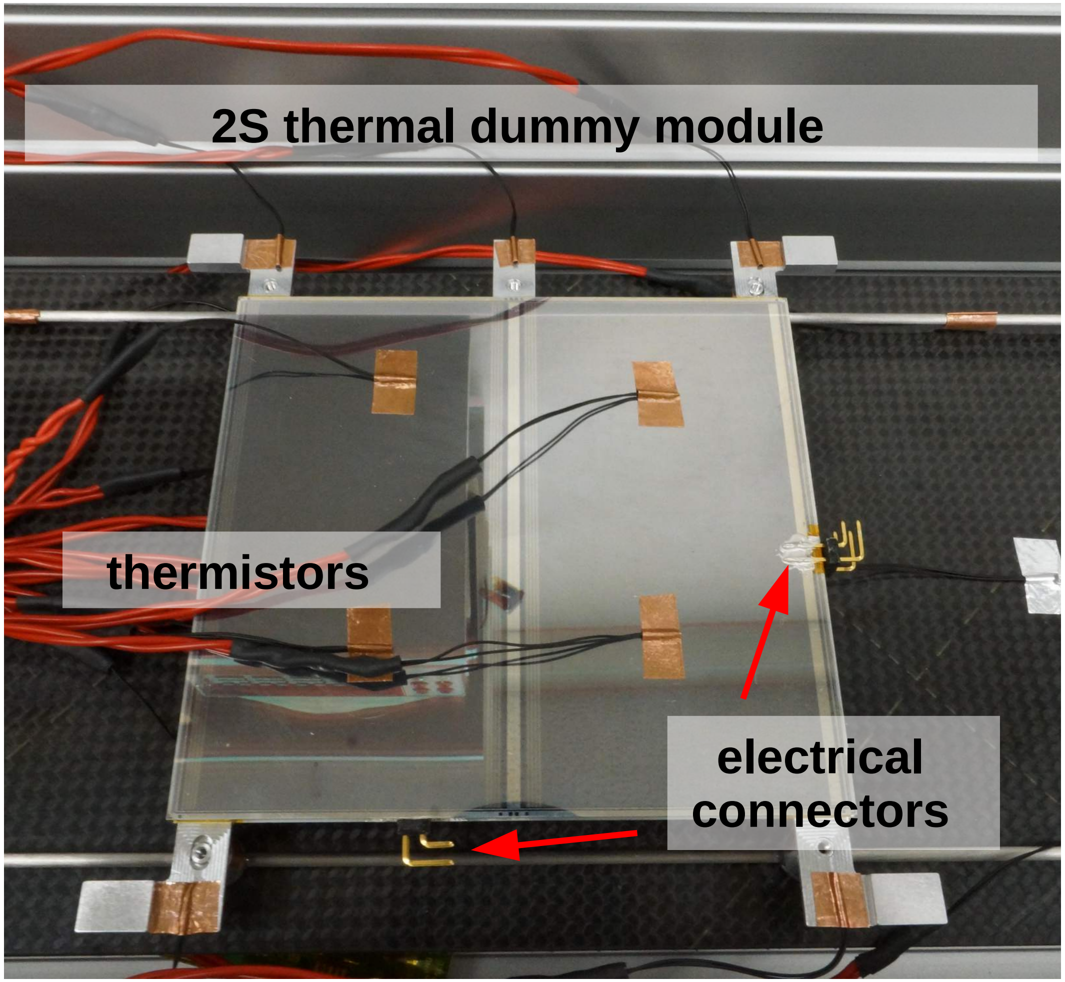


Module Cooling Box





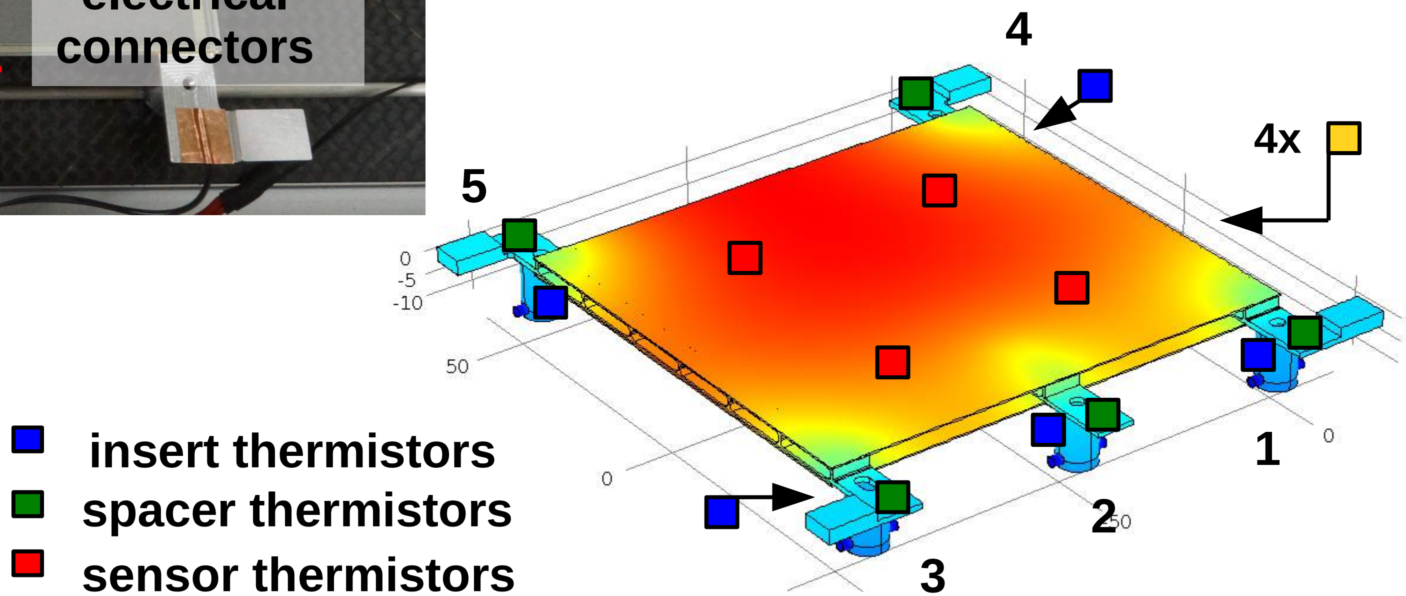
Thermal Dummy Module



- Thermal dummy module
  - strips of the sensors not doped
  - resistance between strip side and back plane in the order of 4 Ohm
- Electrically connected with silver-based, electrically conducting glue
- Voltage sensing

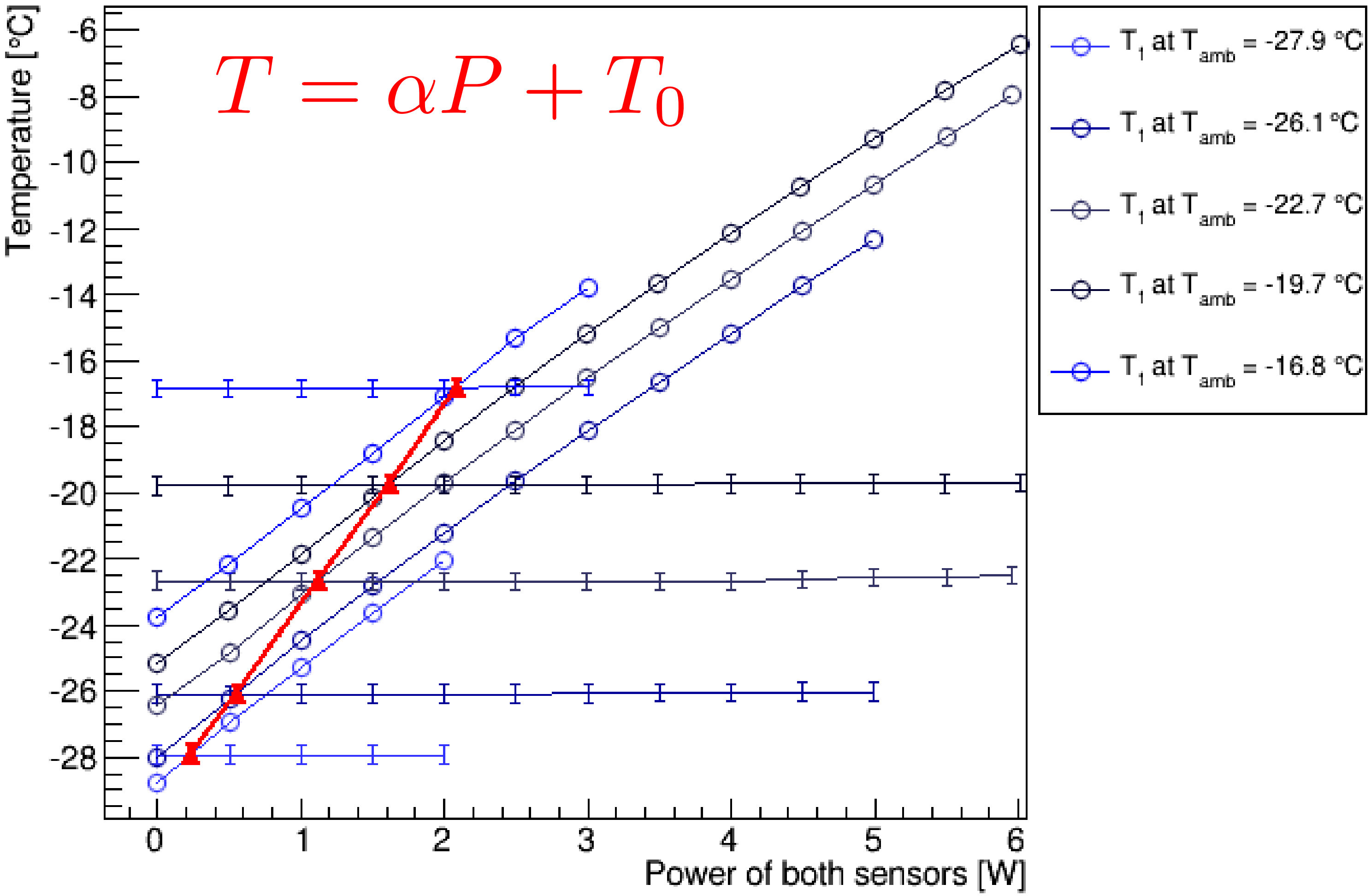
➔ the power is completely produced <u>in</u> the sensor → current through the bulk

➔ power ramp up to 3W per sensor



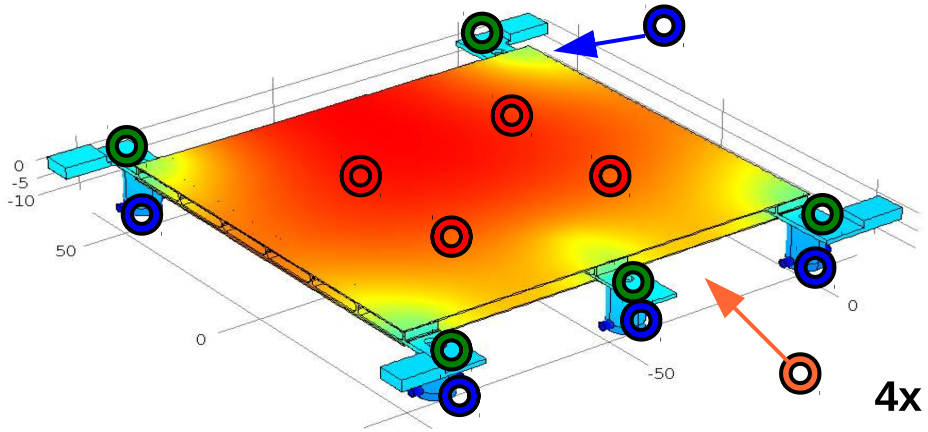
Measurement

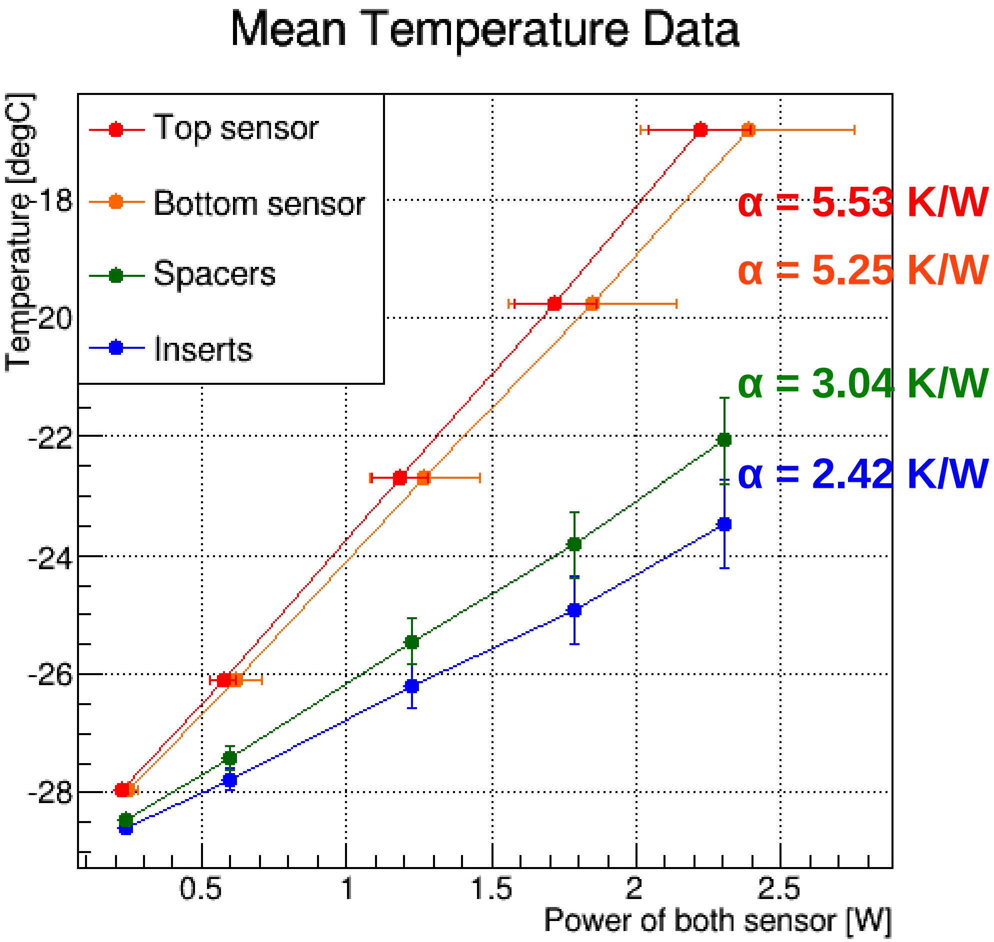
Measurement Series at five different T_{amb} – Sensor Temperature



- sensor temperature differs for same power values, but different ambient temperatures
- thermal equilibrium is determined by the intersection of T_{amb} and T_{sensor}
- much higher linear slope is obtained for the thermal resistance

Extraction of Thermal Resistances





- mean values of thermal equilibrium of the single thermistors is calculated
- temperature for every single spacer and insert thermistor is evaluated
  - linear interpolation between real data points
  - mean values are plotted
- thermal resistances α = ΔT/ΔP are determined by a linear fit
- comparison with FE simulated temperatures

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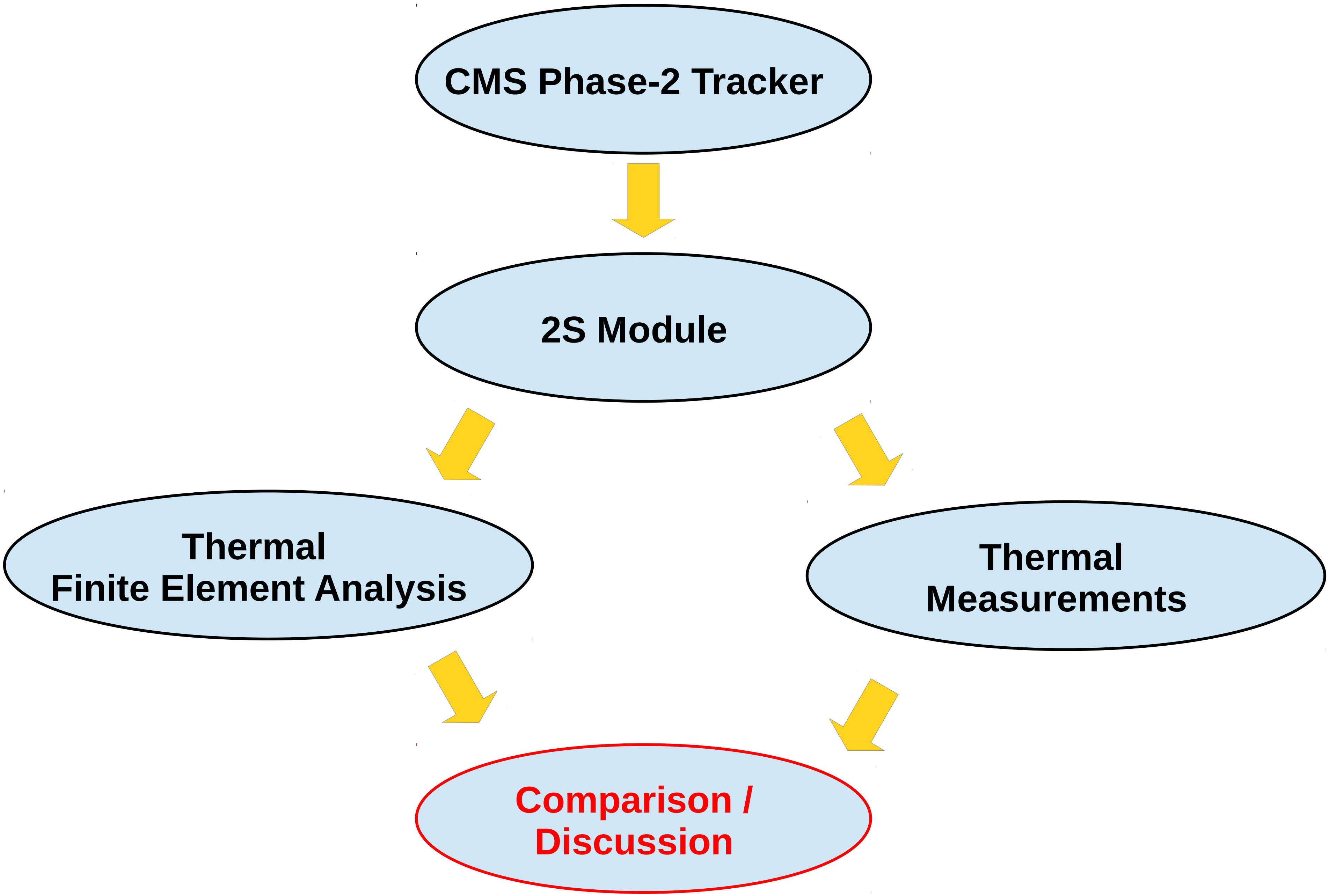
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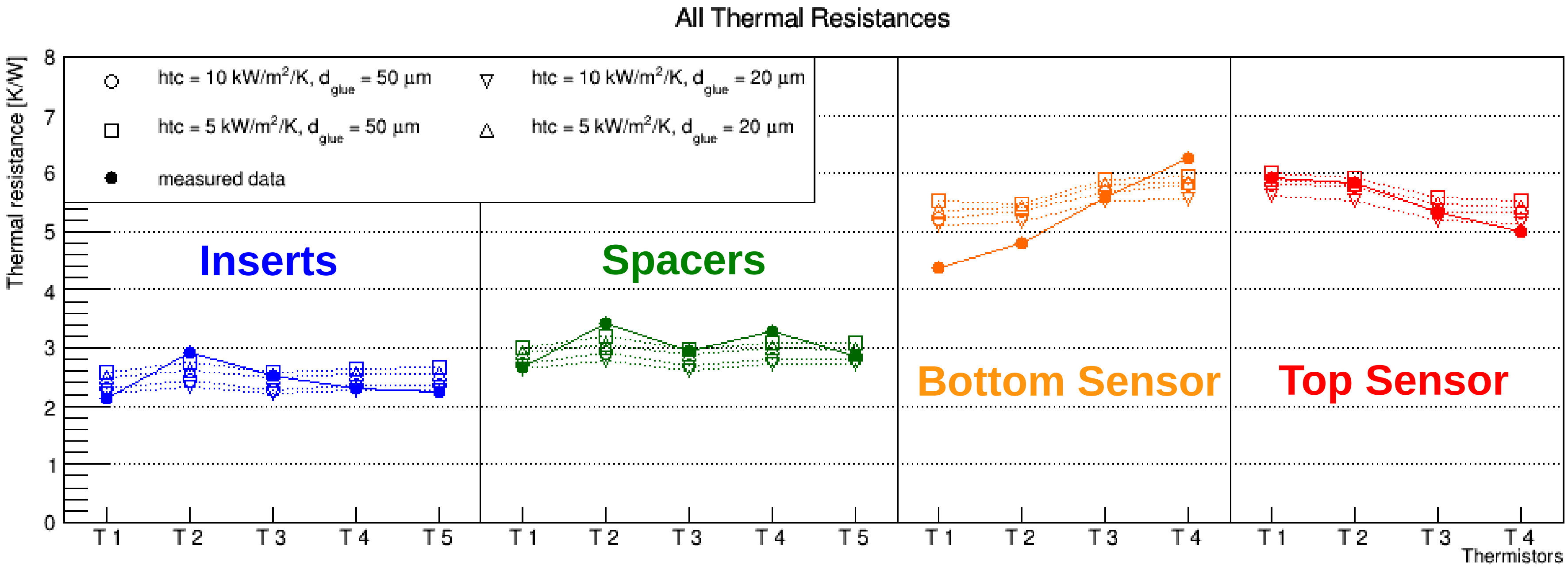
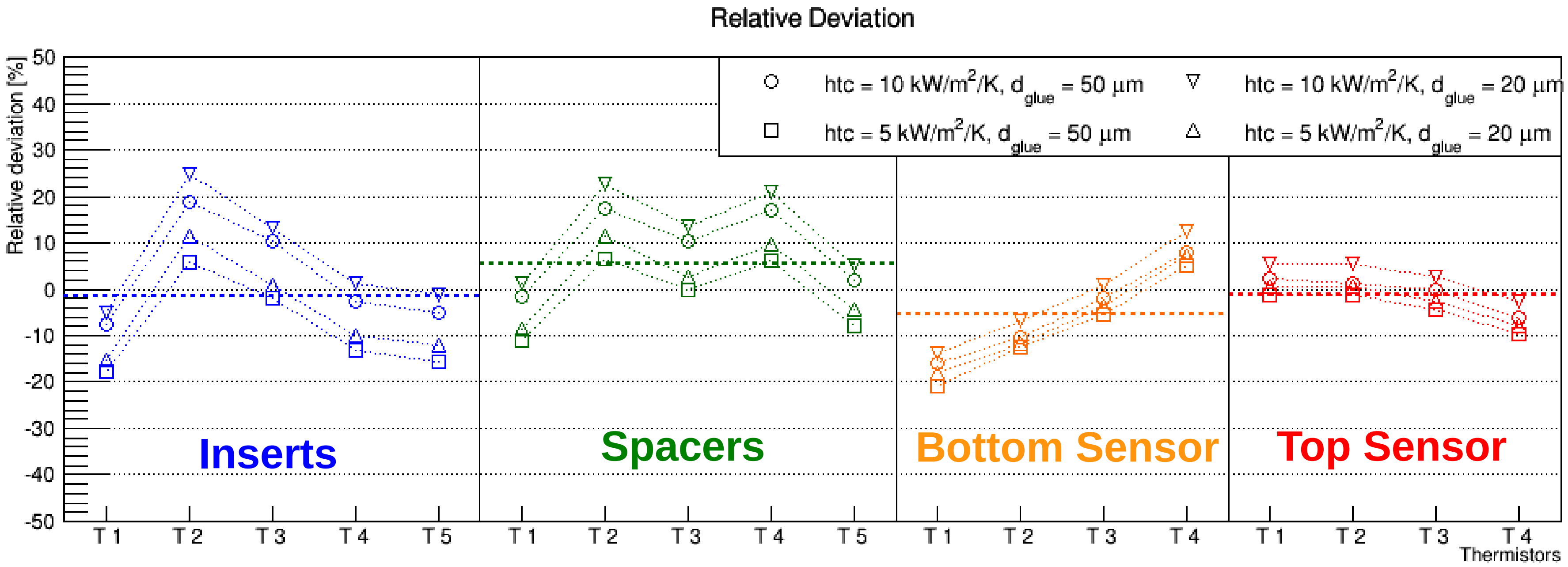
Absolute Measurements



- Thermal resistances are extracted from data and compared to simulation $\alpha = \frac{\Delta T_i}{P_{\text{module}}}$
- Configuration of the FE model
  - different CO_2 heat transfer coefficients
  - different pipe glue layer thicknesses
- Absolute deviation between data and FE simulation is maximum 1.2 K/W, mostly smaller
- Average deviation per component is smaller than 0.4 K/W

Relative Deviations



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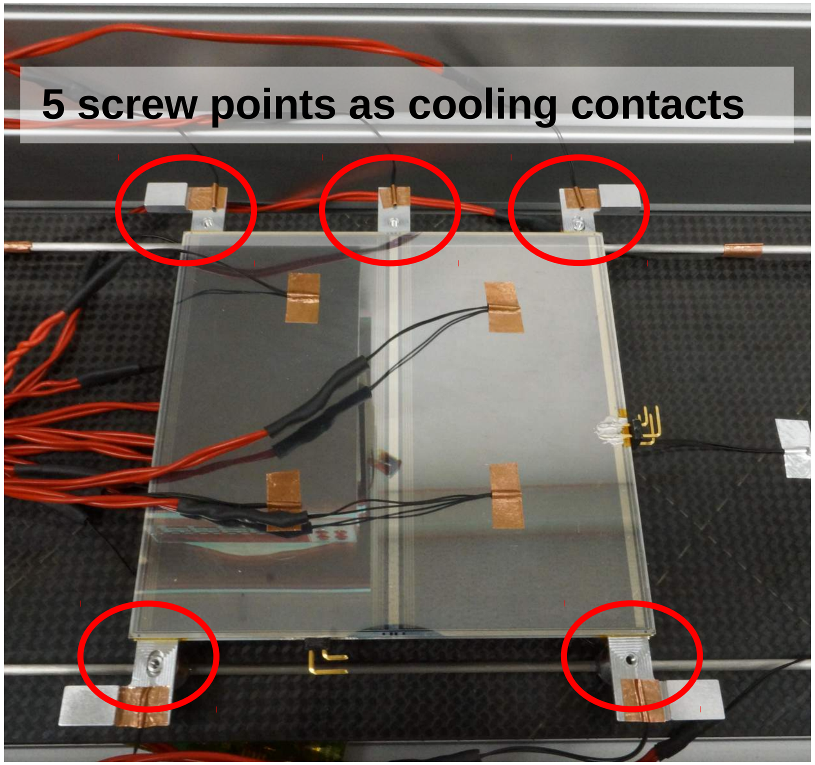
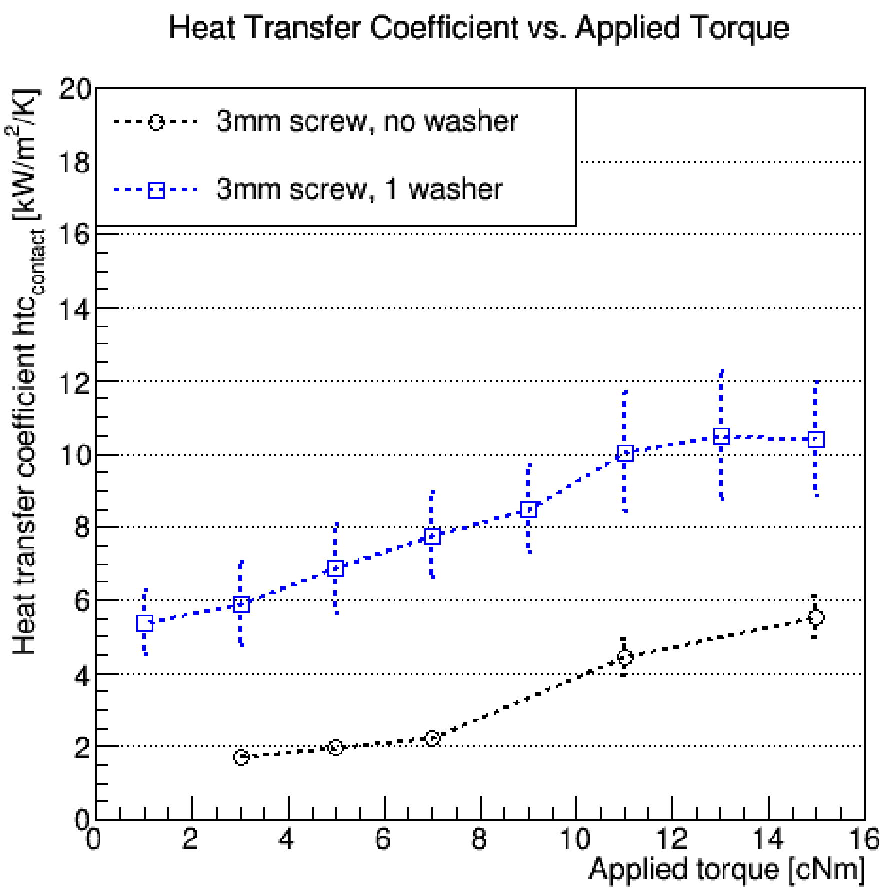
- Absolute deviation between data and FE simulation is maximum 1.2 K/W, mostly smaller
- Average deviation per component is smaller than 0.4 K/W
- On average the FE simulated data can be confirmed with data better than 10%
- Maximum about 20% deviation for certain measurement points

Torque and Thermal Contact

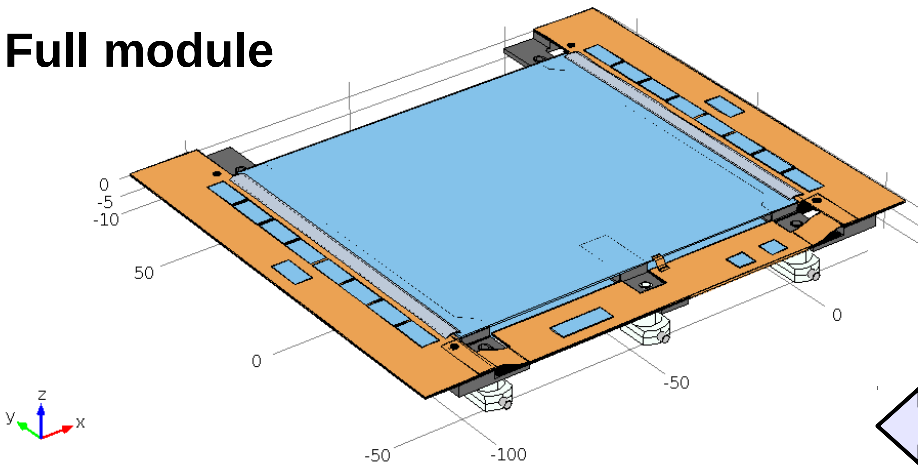




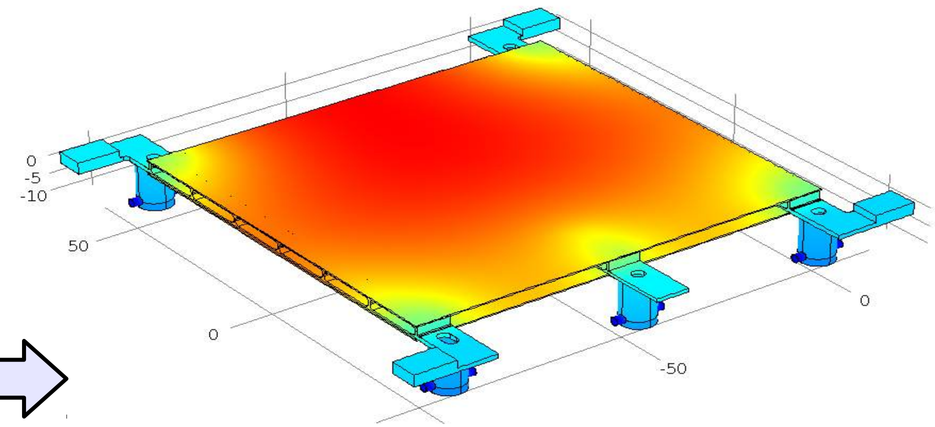
- M2 screws, 3mm long, are tested with an without washer
- heat transfer coefficient is measured
  - **significant dependence on torque**
- in FE simulation, 10kW/m²/K is assumed
  - ➔ plateau of 10kW/m²/K reached with 11cNm
  - ➔ **confirmation by measurement**

What have we learned?

Full module



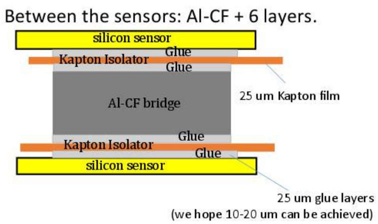
Bare module



- not a full module was tested, but a bare module
  - ➔ bare module contains all thermal interfaces relevant for cooling of the sensor
  - ➔ in full modules, the hybrids are glued on other parts of the spacers
- critical parameter is the silicon sensor power ↔ temperature of the silicon sensor
- good understanding of the adaption to the cooling system is important
  - ➔ prediction of thermal runaway with FE simulations
- thermal interfaces between sensor and cooling system could be measured
- good compatibility with values assumed in FE simulations for all measured data

➔ reliability of FE simulations

Thermal Interfaces

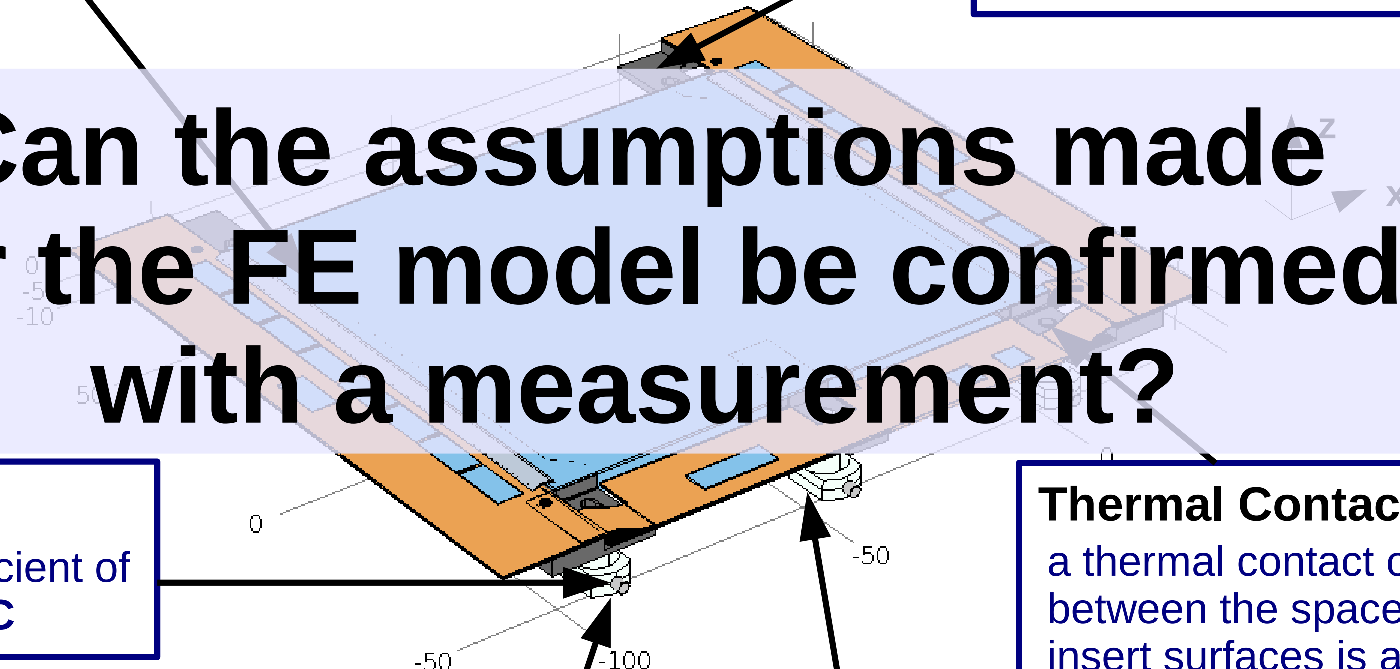


Epoxy-Kapton-Epoxy Layer

described with effective thermal through-plane conductivity 0.3 W/m/K and with **65µm** thickness

AlCF-Spacer

anisotropic thermal conductivity due to carbon fiber orientation:
k_{yz} = 230 W/m/K; k_x = 120 W/m/K



Can the assumptions made for the FE model be confirmed with a measurement?

CO_2 Heat Flux

heat transfer coefficient of **5 kW/m²/K** at **-35°C**

Thermal Contact

a thermal contact of **10kW/m²/K** between the spacers and in the insert surfaces is assumed

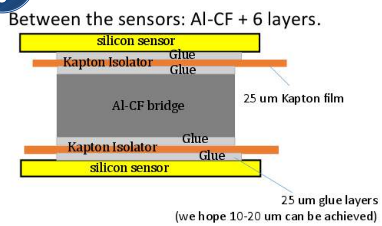
Cooling Pipe

stainless steel (**12 W/m/K**)
2mm inner diameter
100µm wall thickness

Cooling Pipe Contact

epoxy layer with **20µm** thickness and **0.2W/m/K**

Thermal Interfaces



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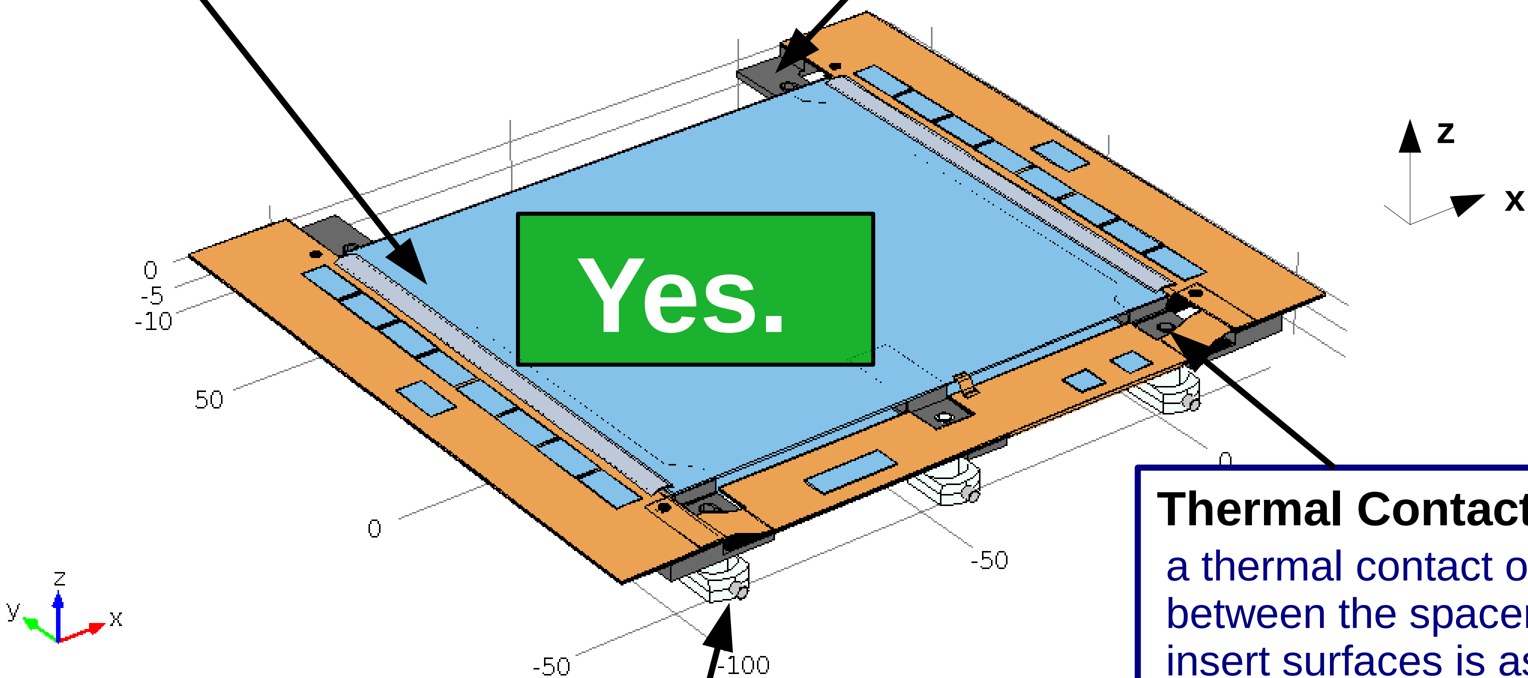

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100μm wall thickness

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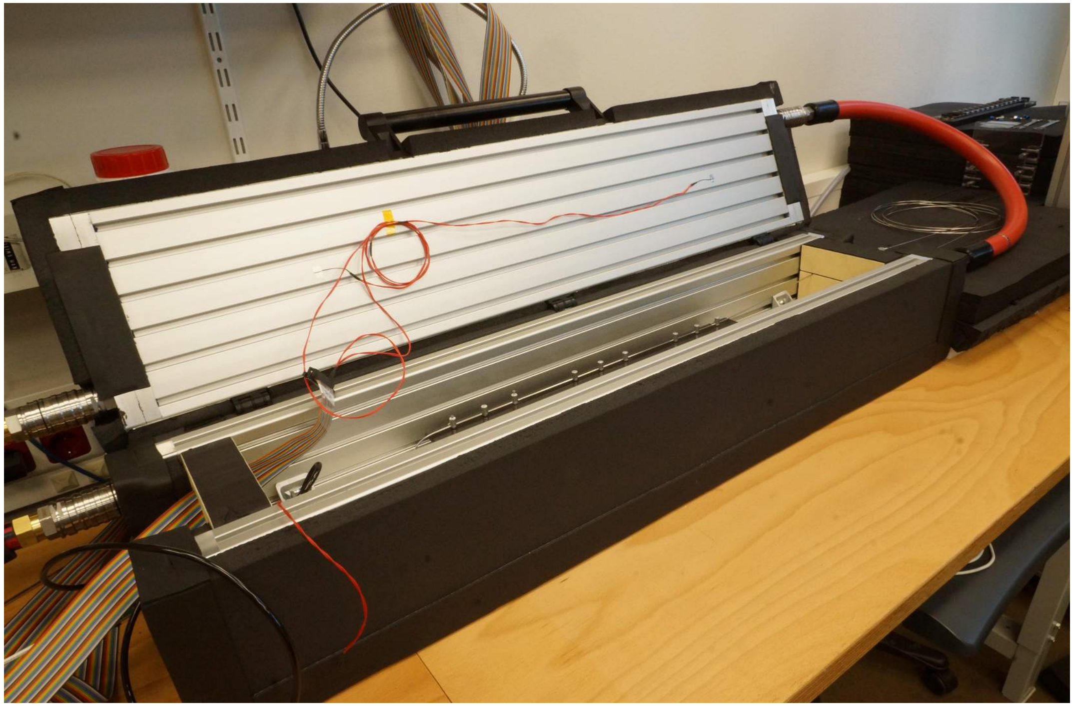
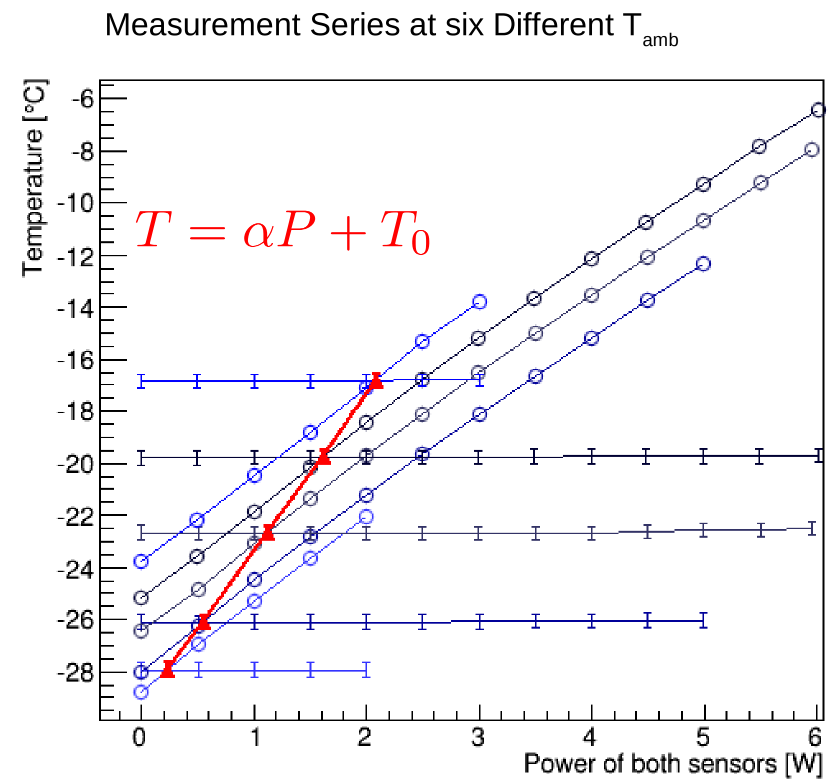
epoxy layer with **20μm** thickness and **0.2W/m/K**

Summary

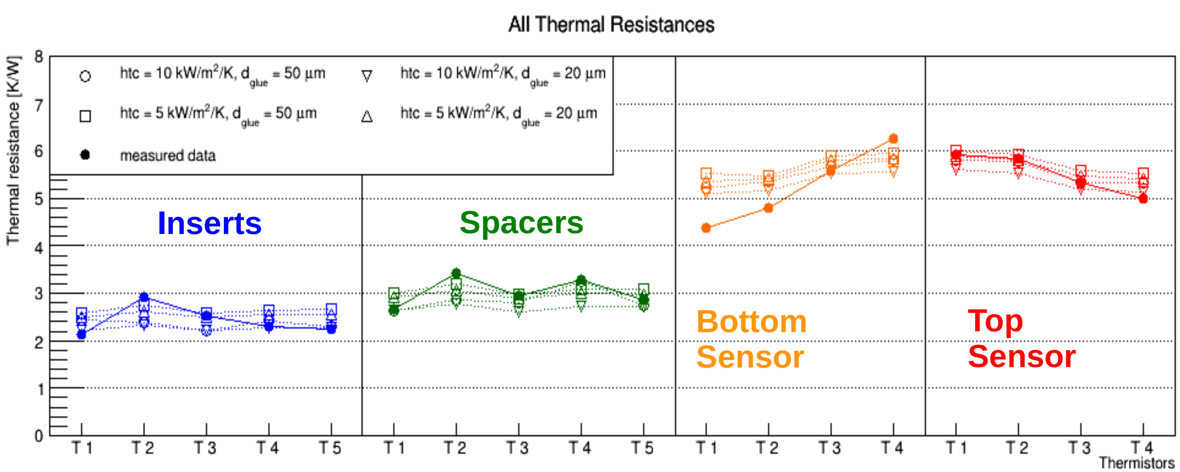
- description and understanding of the thermal properties of silicon sensors is important for detector development in the HL-LHC detector environment
  - radiation damage, sensor power, thermal runaway, …
- FE simulations are used to estimate the thermal performance of the detector modules
  - assumptions are made for thermal interfaces like glue layer, heat transfer coefficients, …
- thermal measurements are necessary to confirm or adjust assumptions made in the FEA
  - many systematic uncertainties and non linearities: convection, heat input from the ambient, …
- a setup was developed and built which allows to understand and avoid a lot of systematic uncertainties
  - control of the ambient temperature
  - controlled heat input into the silicon sensors
- linear behavior of temperature in dependence on heat load can be measured
- thermal resistances assumed in FE simulations could be confirmed with good accuracy

Thank you!





Measurement Series at six Different T_{amb}
$T = \alpha P + T_0$
Temperature [°C]
Power of both sensors [W]

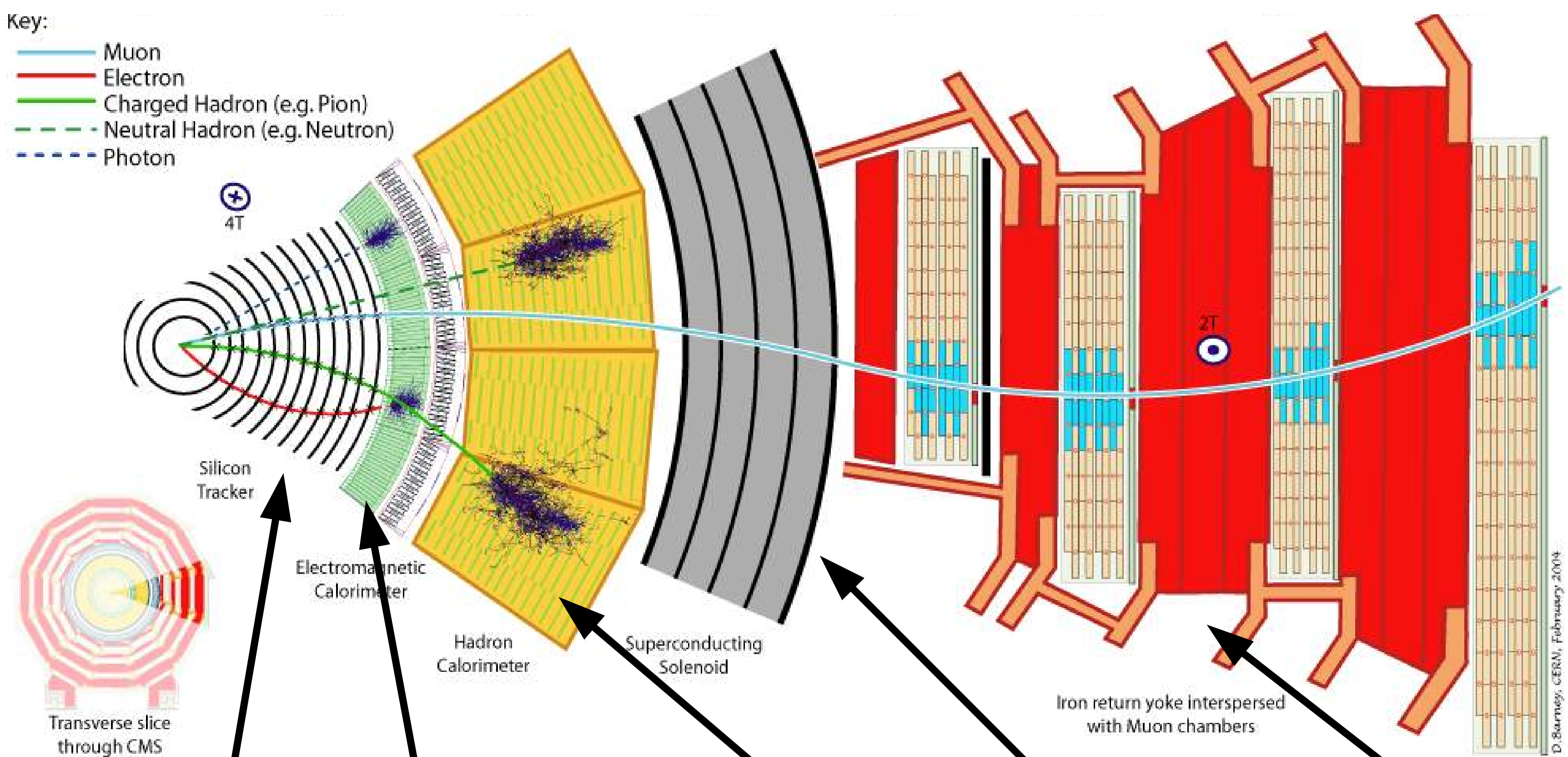


All Thermal Resistances
htc = 10 kW/m²/K, d_{glue} = 50 µm
htc = 10 kW/m²/K, d_{glue} = 20 µm
htc = 5 kW/m²/K, d_{glue} = 50 µm
htc = 5 kW/m²/K, d_{glue} = 20 µm
measured data
Inserts
Spacers
Bottom Sensor
Top Sensor
Thermal resistance [K/W]
Thermistors

Additional Material

Compact Muon Solenoid

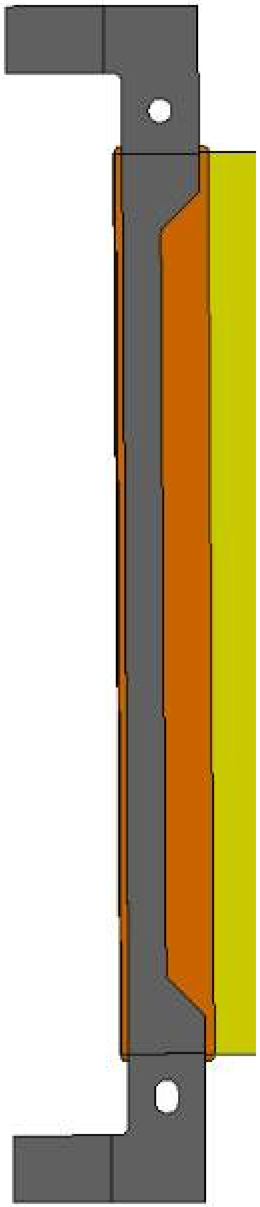
radius 7.5m

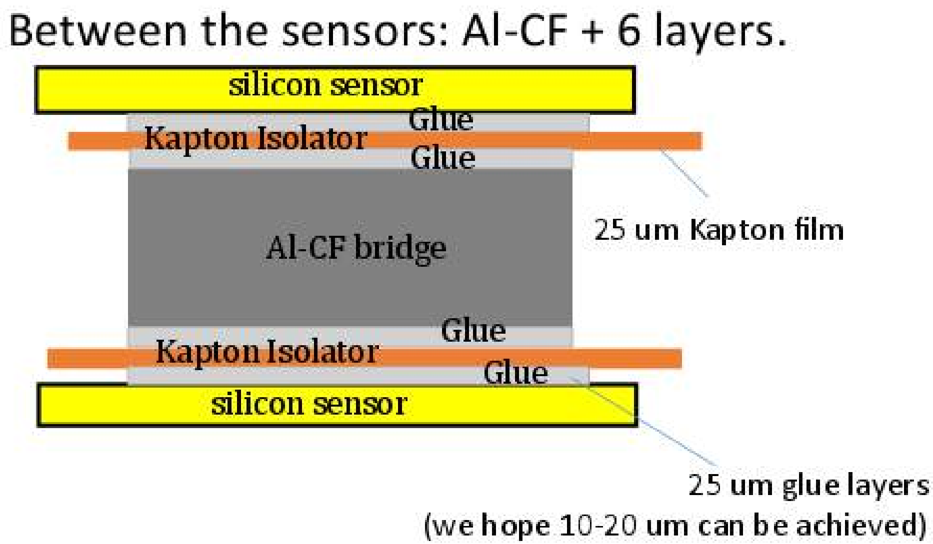


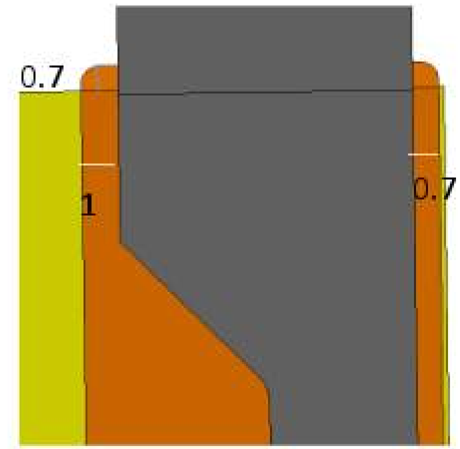
silicon pixel detector silicon strip tracker | **electromagnetic calorimeter** | **hadronic calorimeter** | **superconducting solenoid magnet** | **muon system**

- multipurpose detector with various detector components
- silicon strip tracker is an important part for the particle and event reconstruction

HV Isolation of the Sensors







- Back plane of the sensors (inner plane) is on high voltage: -600V
- Electrical isolation of the sensor is necessary
  - Solution is gluing 25µm thick Kapton strips between sensor and spacer
    - Kapton MT+ with 0.8 W/m/K, thickness 25µm
  - thermally worse contact between sensor and cooling system
  - two layers of glue
    - Epoxy (Polytec 601-LV) with 0.2W/m/K and 20µm thickness
- Effective thermal through-plane-conductivity of the glue-Kapton-glue sandwich: 0.3 W/m/K

Thermal Runaway

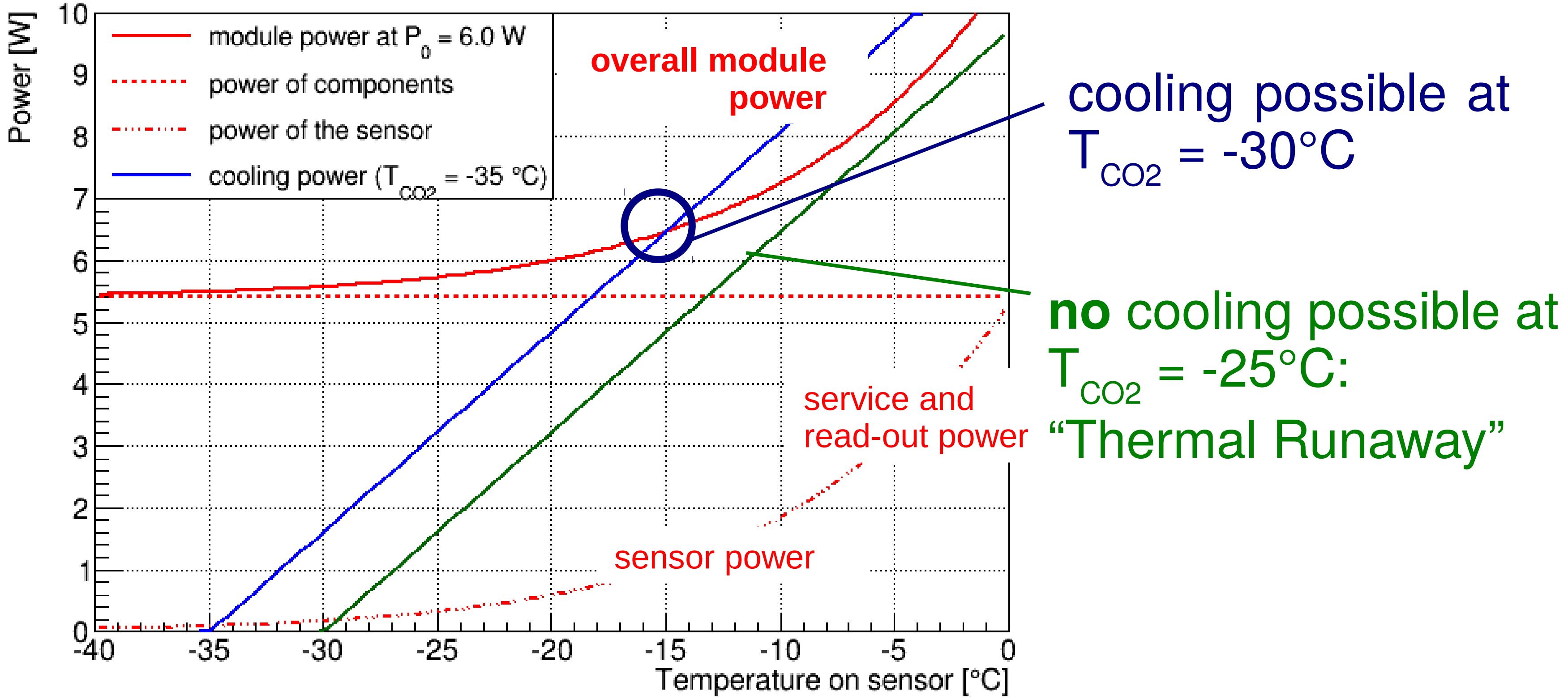
- Irradiated silicon sensors generate temperature dependent leakage current and thus power

$$P_{\mathrm{sensor}} \propto P_0 \frac{T^2}{T_0^2} \exp\left[-\frac{\Delta E}{2\,k_B}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]$$

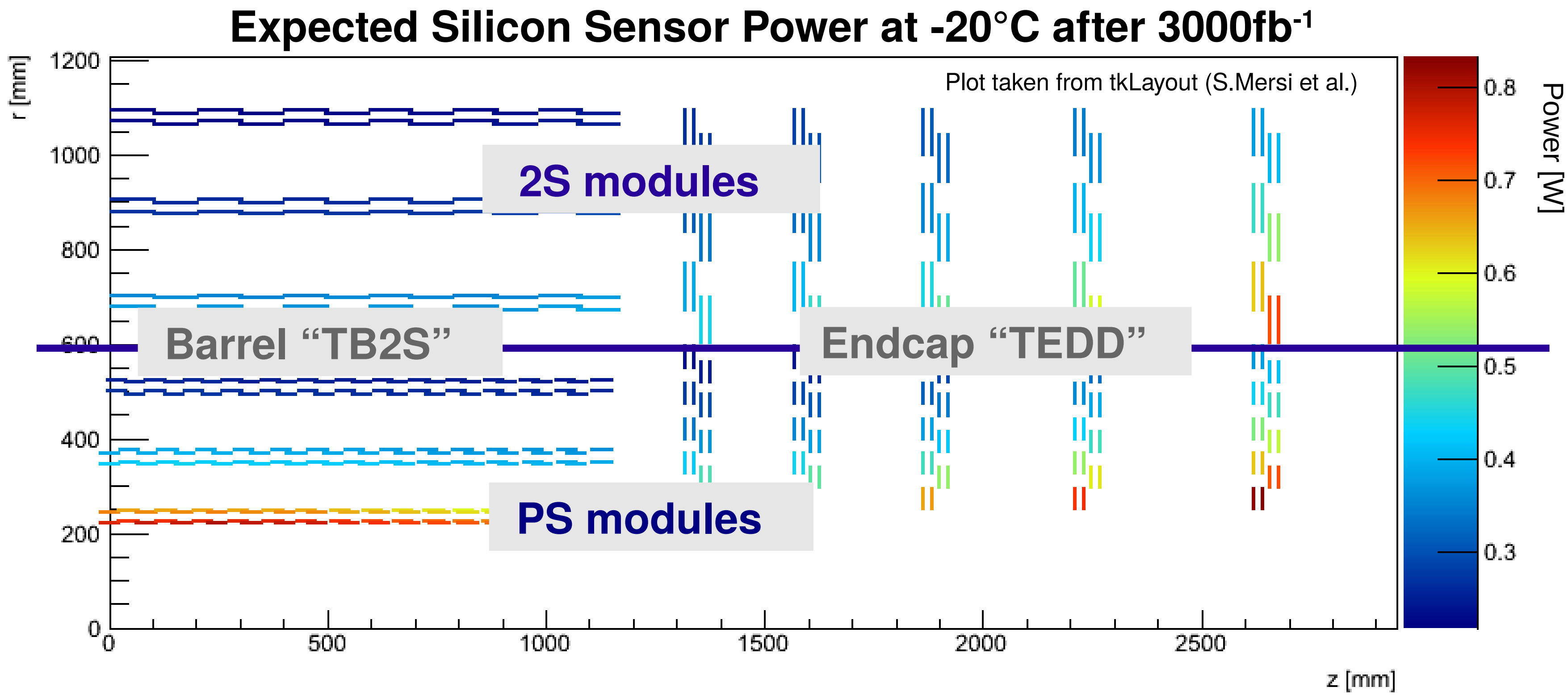
- Other components (read-out chips, DC-DC converters, ...) produce a constant power

$$P_{\mathrm{components}} = \mathrm{const.}$$

- Linear dependence of the cooling power $P_{\mathrm{cooling}} \approx \alpha(T_{\mathrm{module}} - T_{\mathrm{coolant}})$

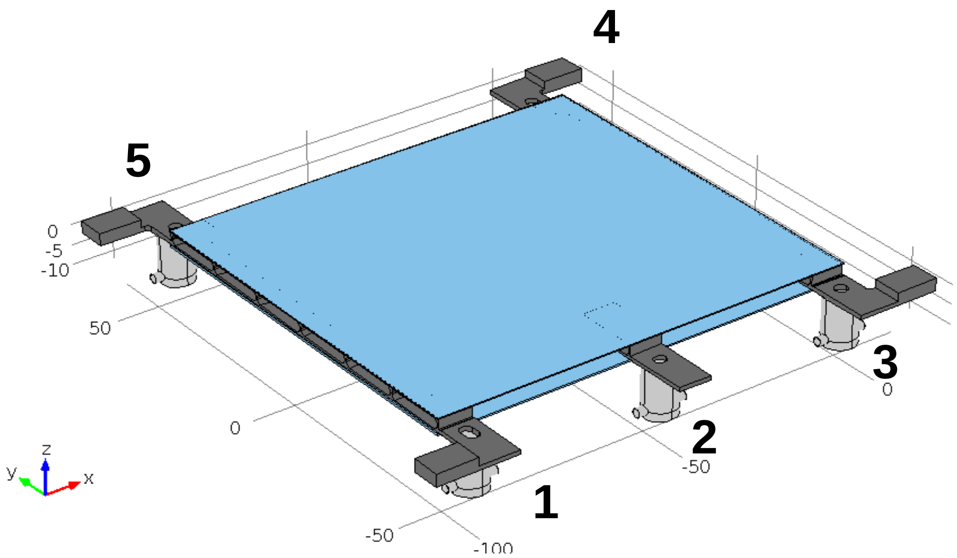


Sensor Power after 3000fb^{-1}

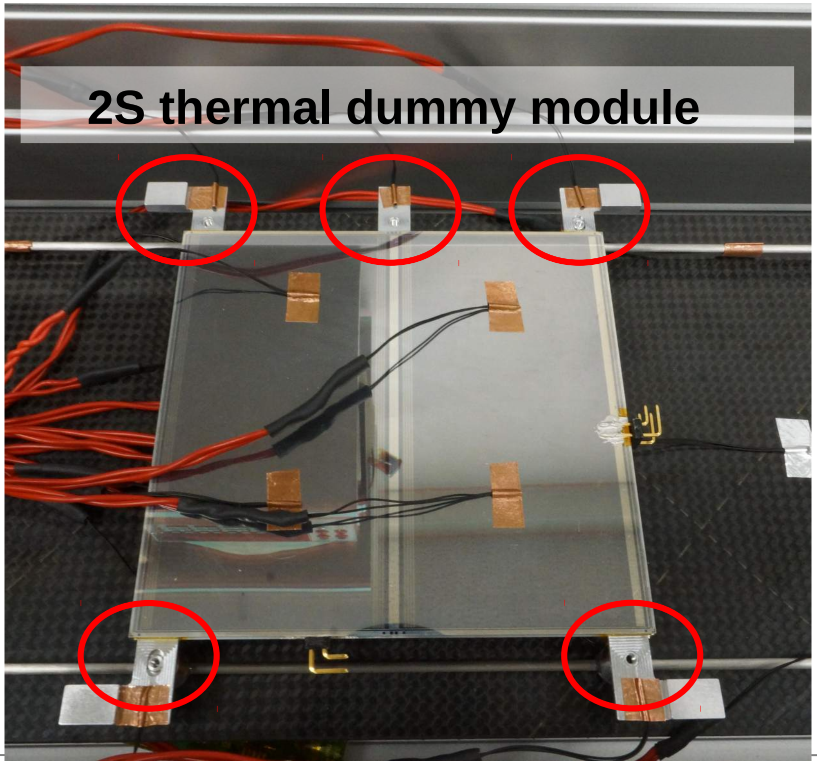


- Sensor power increases linearly with radiation damage
- highest irradiation for the 2S modules in the forward regions
- Technical Design Report value for -20°C sensor temperature:
  - ➔ maximimum expected power is 570mW for 2S modules in the endcap

Torque and Thermal Contact



- For the five screwing junctions a heat transfer coefficient of 10 kW/m²/K is assumed
  - ➔ confirmed with measurements
- M2 screws fastened with a torque of 9cNm were used
- Question: How does the thermal contact depend on the applied torque?
  - ➔ Answer: Measurement!

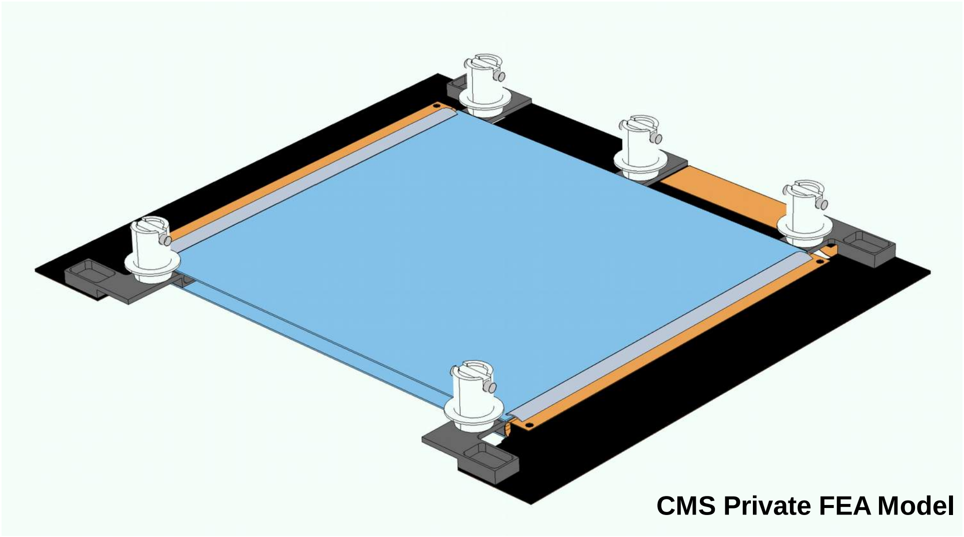


Three Measurement Series

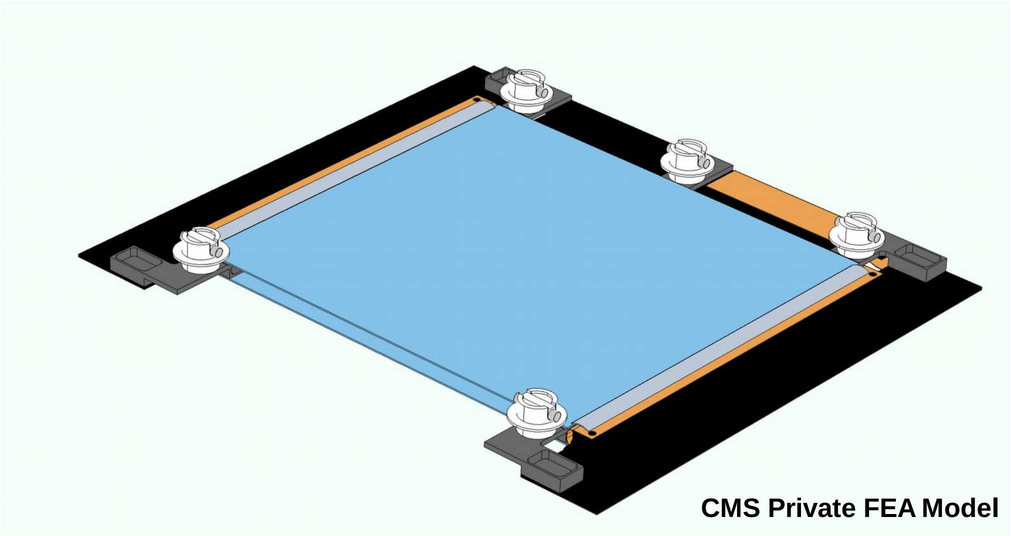
- Serie #1:
  - M2 screws, 4mm long thread, 2 washers
- Serie #2:
  - M2 screws, 3mm long thread, 1 washer
- Serie #3:
  - M2 screws, 3mm long thread, no washer

Cooling Contacts Endcap

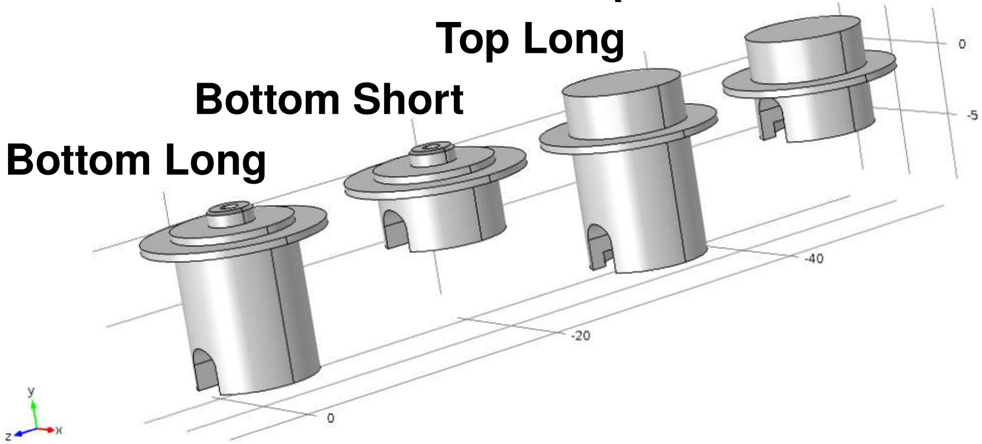
2S Module with "Long Inserts"



2S Module with "Short Inserts"



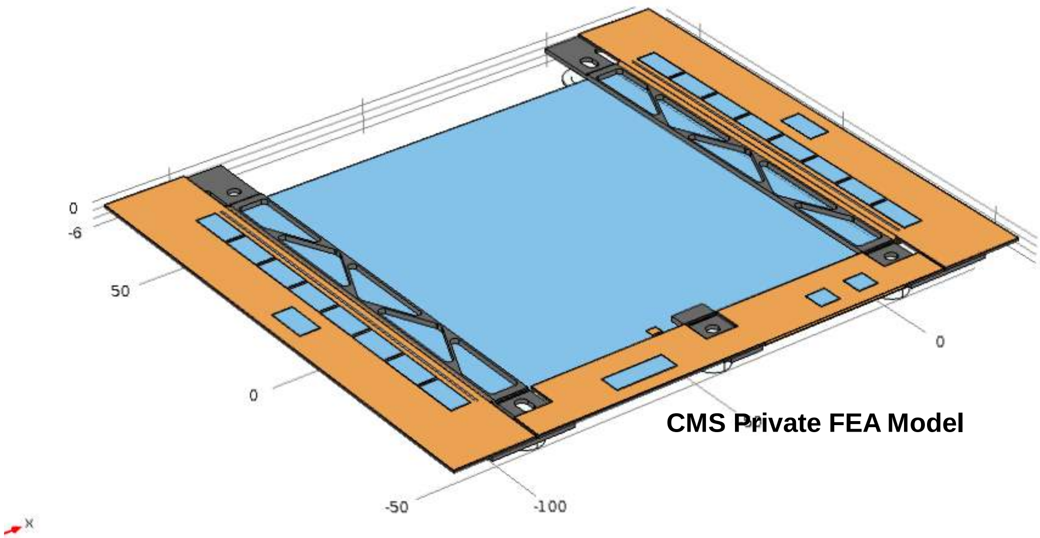
- two types of cooling inserts "Long" and "Short" due to the cooling pipe routing



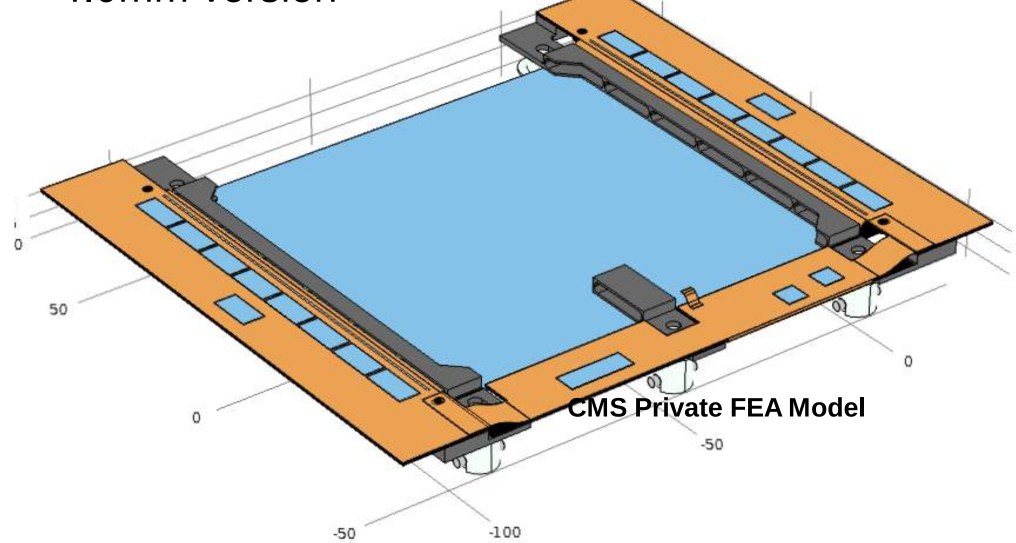
2S 1.8mm and 2S 4.0mm

Two versions of the module for different sensor spacings

1.8mm version



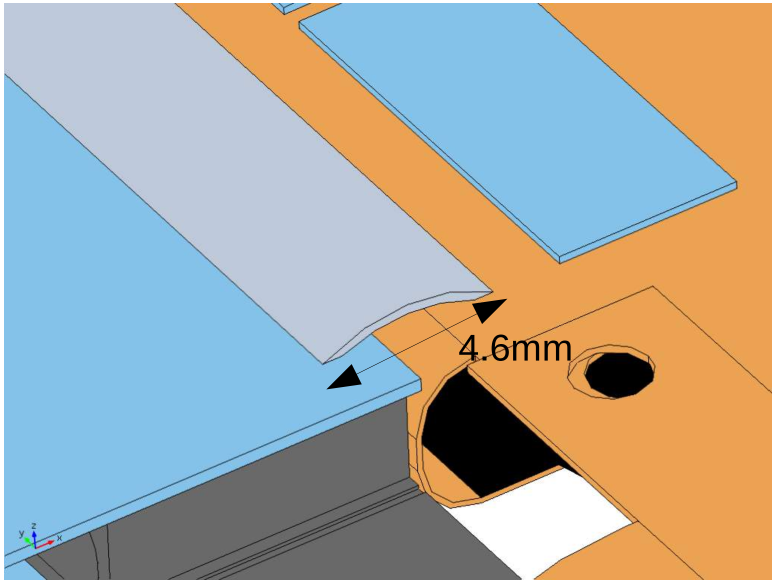
4.0mm version



Materials

Material	Component	Therm. conductivity [W/m/K]
Silicon	sensor, chips, opto dummy	140
Aluminum-Carbon Fiber (AlCF)	sensor spacer, TB2S Ladder cooling contacts	k_{xy} = 240 ; k_z = 120
K13D2U carbon fiber	carbon fiber stiffener	k_{xy} = 250 ; k_z = 0.5
PCB-Material	service hybrid, read-out hybrid	50
Stainless steel	cooling pipes	12
Aluminum alloy	TEDD cooling inserts	130

- All **glue layers** are simulated with
  - the COMSOL function "Thin Layer"
  - a thickness of 20µm
  - a thermal conductivity of 0.2 W/m/K
- For the **wire bonds** an effective model is created
  - length 4.6mm, thickness 250µm
  - thermal conductivity 5 W/m/K
- The model corresponds to 1016 aluminium wire bonds
  - diameter per wire bond 12.5µm



TEDD Cooling Inserts

- Temperature difference between CO_2 and inner cooling pipe

$$\Delta T_{\text{pipe}} \approx \frac{P}{h \cdot A_{\text{contact}}} = \frac{1.1\,\text{W}}{5000\,\text{W/m}^2/\text{K}\ \pi\ 2.2\,\text{mm}\ 8\,\text{mm}} = 4.0\,\text{K}$$

- Temperature gradient across cooling block:

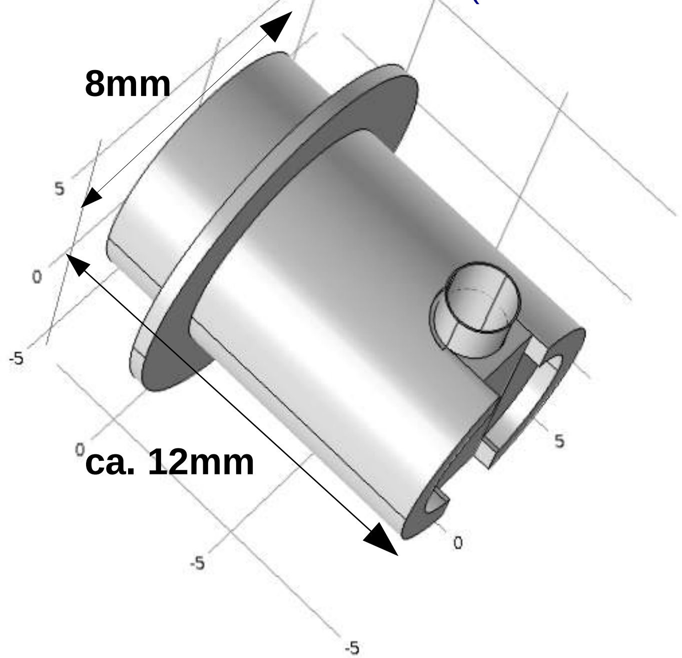
$$\Delta T_{\text{block}} \approx \frac{P \cdot h_z}{\lambda \cdot A_{\text{x-section}}} = \frac{1.1\,\text{W} \cdot 10\,\text{mm}}{240\,\text{W/m/K} \cdot \pi (4\,\text{mm})^2} = 0.9\,\text{K}$$

- Overall temperature difference, ΔT_{glue} is not negligible:

$$\Delta T_{\text{overall}} \approx \Delta T_{\text{block}} + \Delta T_{\text{pipe}} + \Delta T_{\text{glue}}$$

- Simulated $\Delta T_{overall}$ is
  - 5.0K without glue layers
  - 7.9K with 20µm glue layers (0.2 W/m/K)

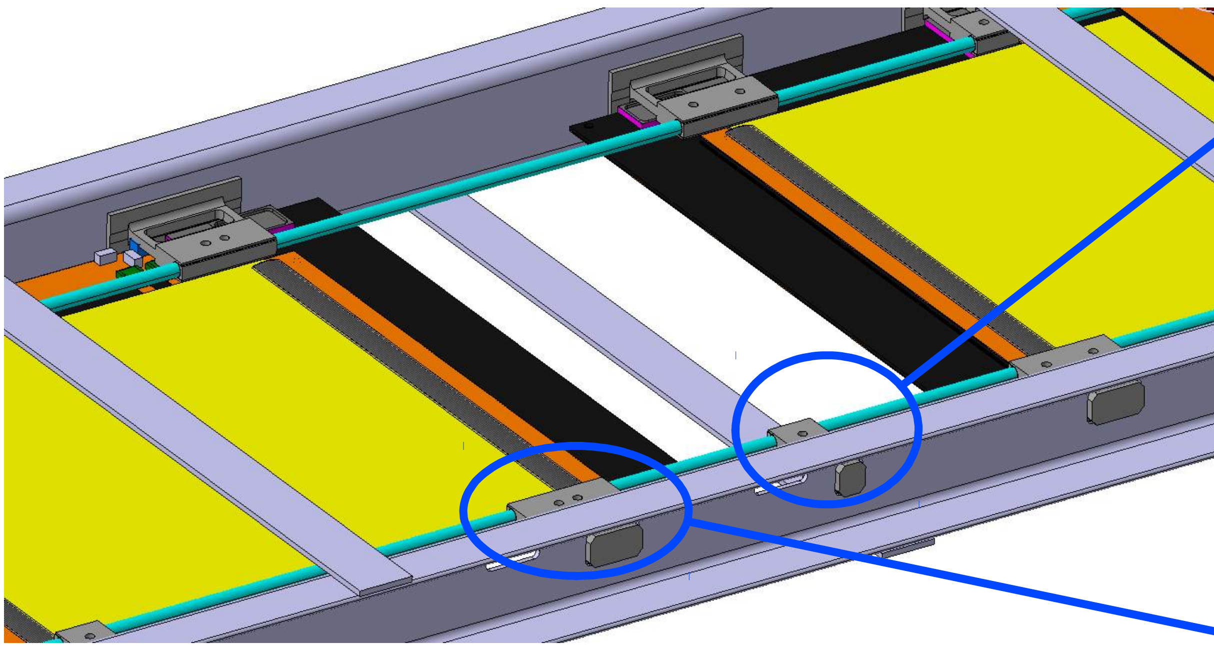
Cooling insert design DESY (Oskar Reichelt)



TB2S Ladder Cooling Blocks

• 2S 1.8mm modules are mounted in the TB2S Ladder structure
• Modules are mounted back-to-back onto the AlCF (?) cooling contacts

2S 1.8mm Modules on the ladder

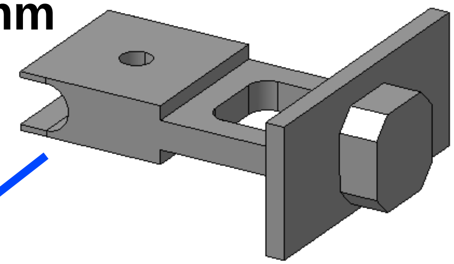


Pierre Rose

• cooling support for the 5th thermal contact

• cooling pipe contact length 8mm

8mm

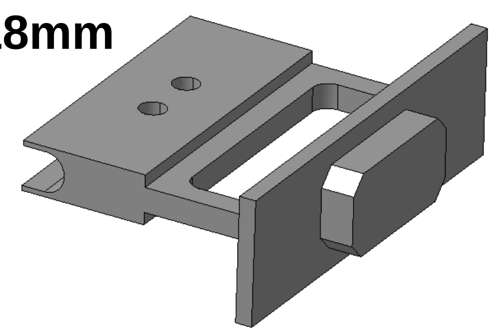


• cooling support for the four corners of the 2S modules

• cooling pipe contact length 18mm

• heat input on top and bottom side from two modules mounted to the cooling contact

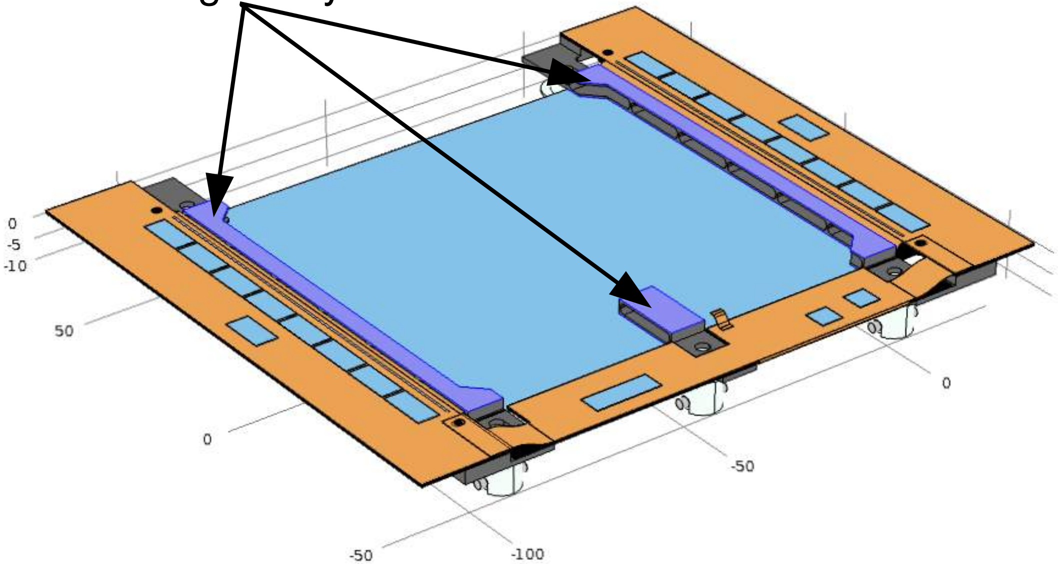
18mm

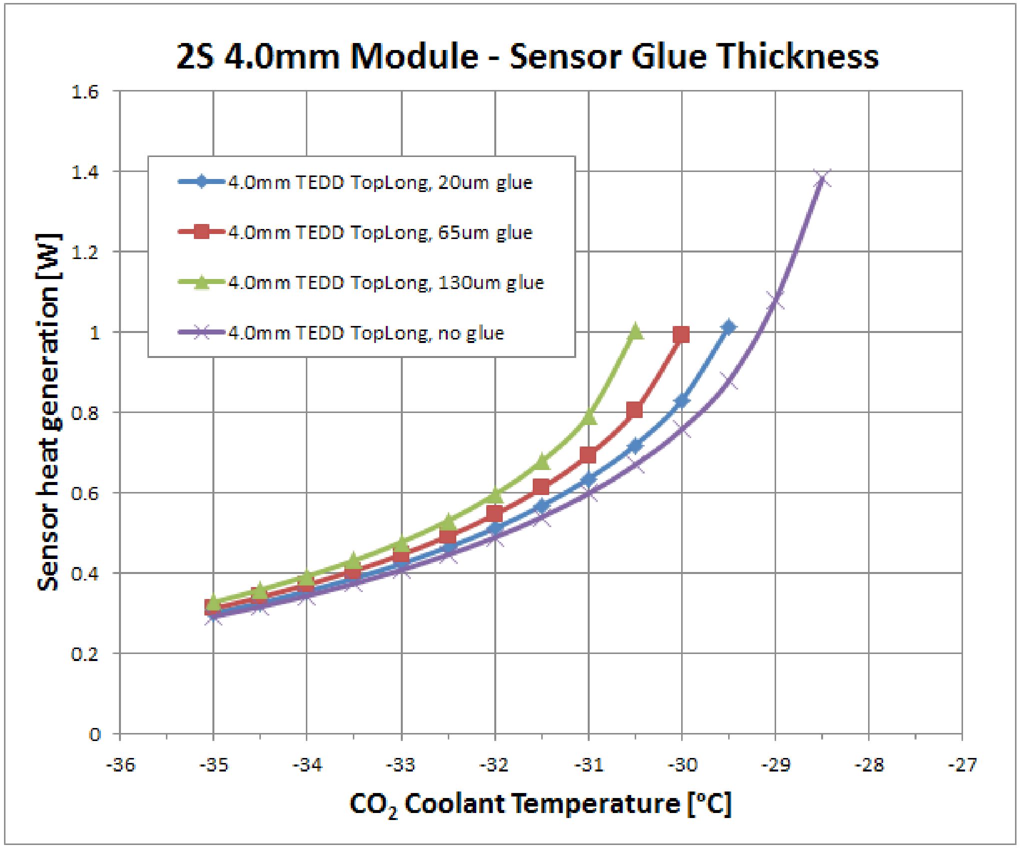


➔ The factor 2 of heat input of two modules has to be taken into account in the FE simulation

Thickness of the Sensor Glue Layer

Sensor glue layers



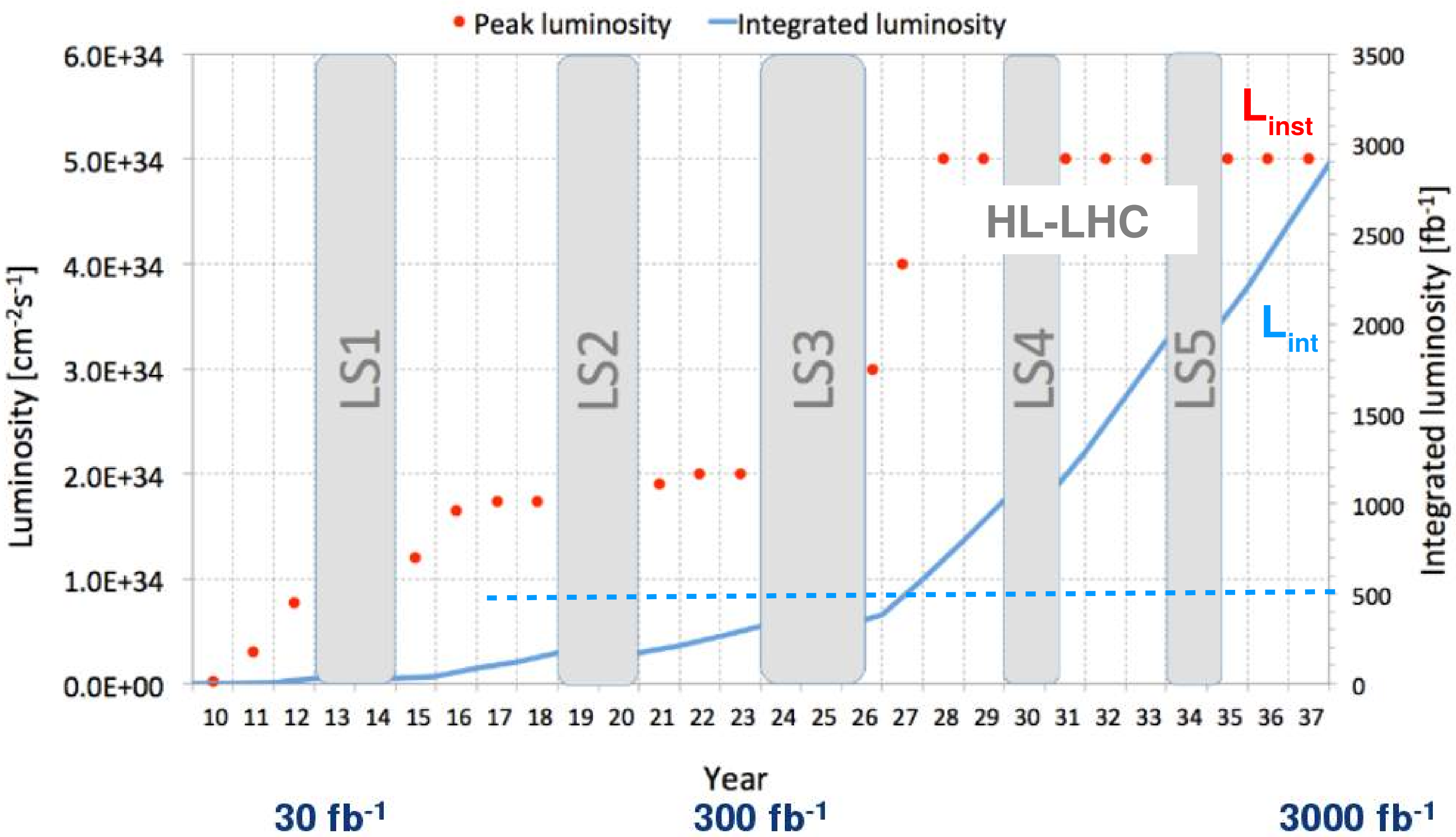


- Glue layer thicknesses of 0µm, 20µm, 65µm, and 130µm are simulated
- Thermal conductivity 0.2 W/m/K
- Thermal runaway at 1-2K lower temperatures 130µm thick glue layer

From LHC to HL-LHC

- High-luminosity LHC (HL-LHC) will operate
  - at an instantaneous luminosity of $5 \cdot 10^{34}\,cm^{-2}s^{-1}$ (pileup up to **200**)
  - deliver an integrated luminosity of **3000fb^{-1}**
- Current CMS Outer Tracker is designed to operate up to **500fb^{-1}** and pileup of **50**

Plot from Frederick Bordry (June 2015)



TB2S Ladder Cooling Contacts

- backside heat inputs into cooling blocks have to be applied diagonally due to module arrangement in the TB2S Ladder

- no additional heat input necessary for the 5th cooling contact

➔ can be implemented with COMSOL functions