CMS Pixel CO_2 Cooling

Low-mass Design Studies

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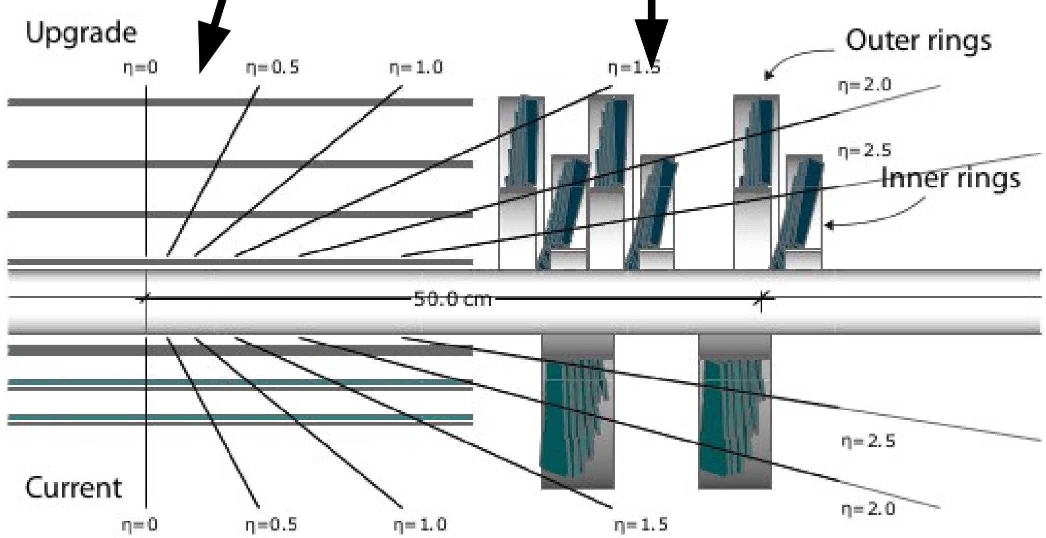
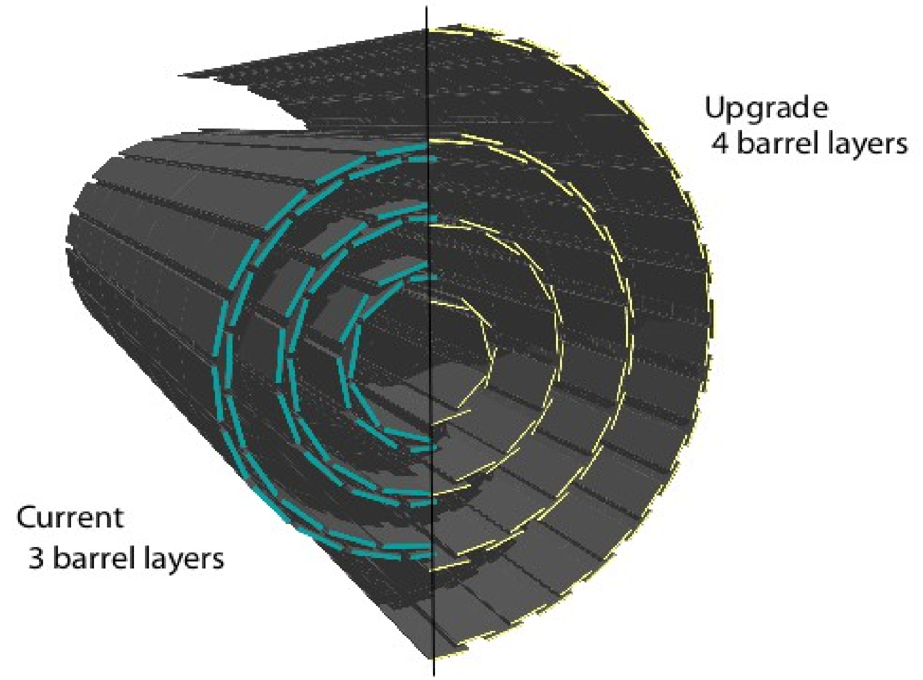
Outline

- CMS pixel detector phase-1 upgrade
  - Replacement of the current detector
  - Two-phase CO_2 cooling
- Low-mass module mechanics
- Cooling studies
  - Thermal resistance of module structure
  - Measurements
  - FE simulations
  - Optimization of the cooling structure
- Conclusions

New Pixel Detector

Barrel part (BPIX) **Forward part (FPIX)**



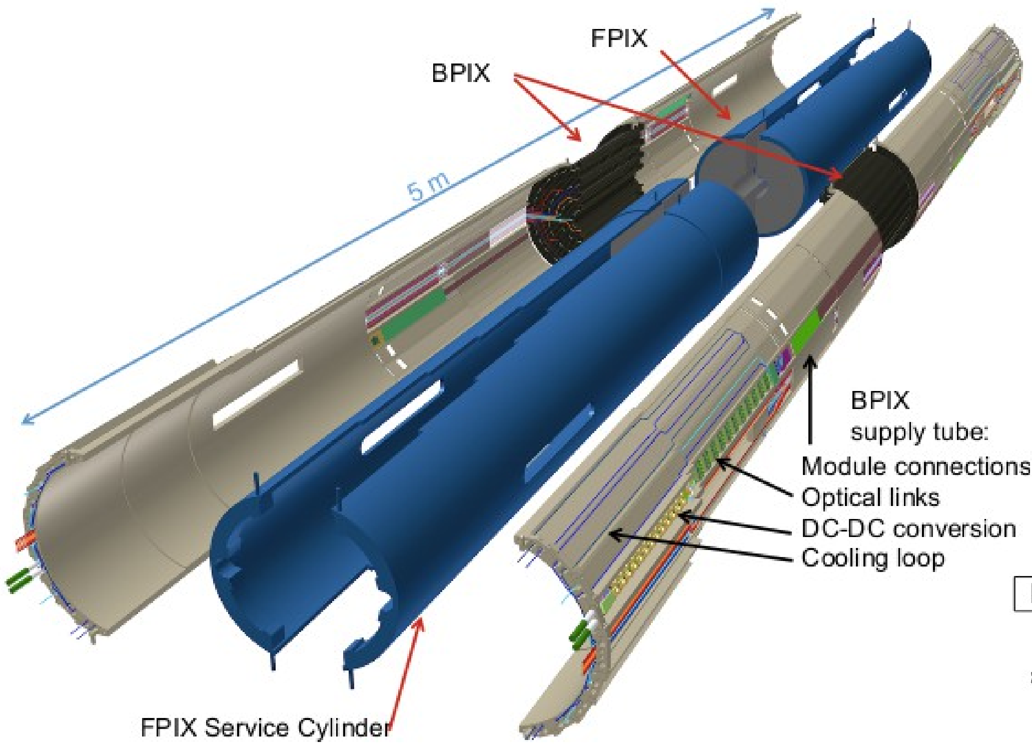


➔ Will be installed during extended year-end technical stop 2016/2017

- A 4th outer layer is added to the barrel detector part (BPIX)
- The inner layer is moved closer to the interaction point (from 4.4cm to 3.0cm)
- A new digital read-out chip (ROC) has been designed

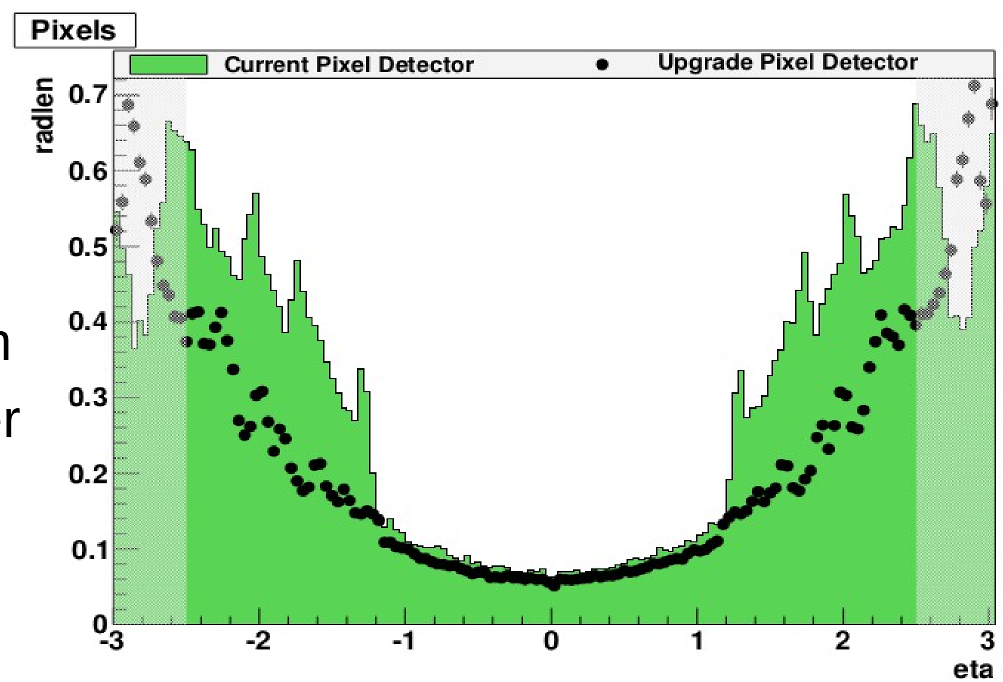
Expected data loss	$1 \times 10^{34}\ cm^{-2}\ s^{-1}$ @ 25ns	$2 \times 10^{34}\ cm^{-2}\ s^{-1}$ @ 25ns	$2 \times 10^{34}\ cm^{-2}\ s^{-1}$ @ 50ns
Current Layer1	4.0 %	16.0 %	50.0%
Upgrade Layer1	1.1 %	2.4 %	4.8 %

Material Budget



BPIX	Current	Upgrade
#Modules	672	1184
Mass	16.8 kg	6.7 kg

FPIX	Current	Upgrade
#Modules	672	672
Mass	8.6 kg	7.0 kg

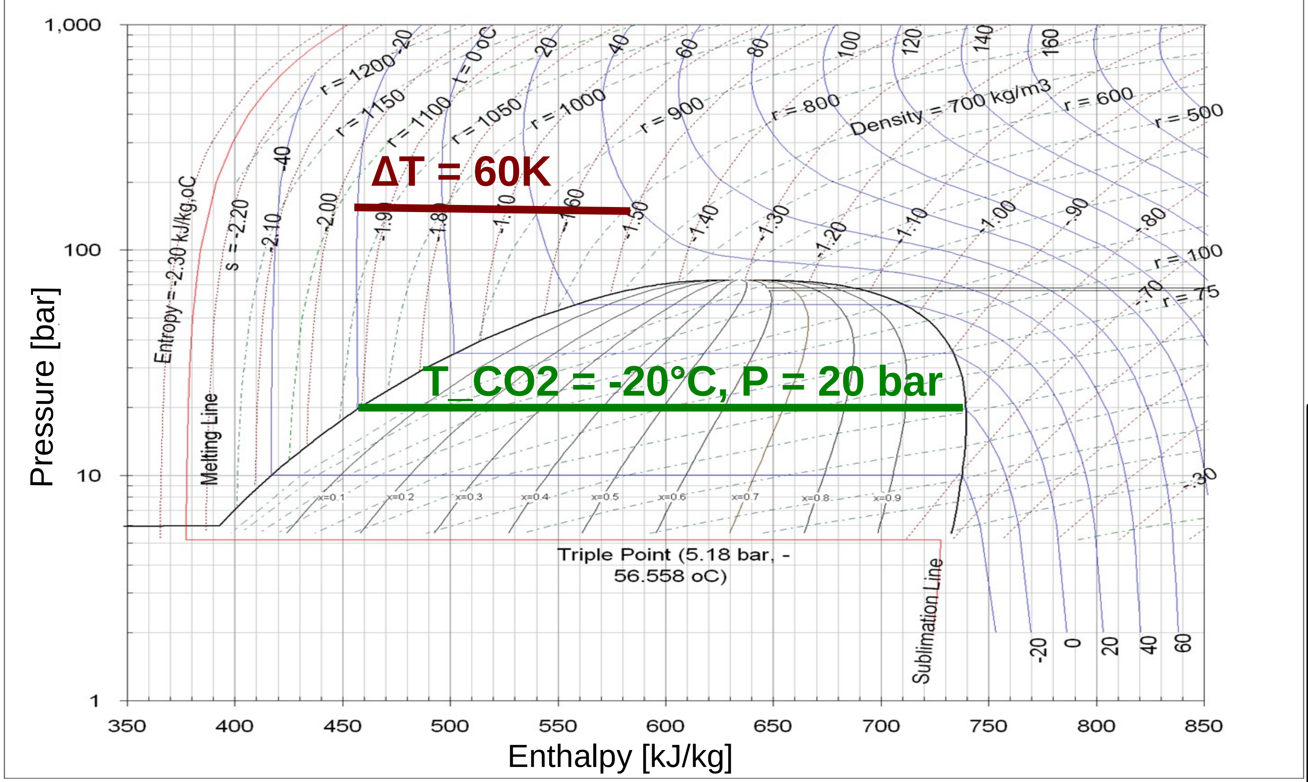


- Reduction of material budget by
  - using a low-mass CO_2 cooling system
  - using an ultra light-weight carbon fiber support structure
  - moving electronics to high |η|

CO_2 Two-Phase Cooling

- In monophase cooling systems, the liquid is heated up by the power of the detector component
  - ➔ A large amount of cooling liquid is needed
- CO_2 is in the two-phase regime → liquid and gaseous state exist simultaneously
- Heat removal by evaporating liquid CO2 at constant temperature and pressure

CO_2 Pressure-Enthalpy-Diagram



CO_2 advantages

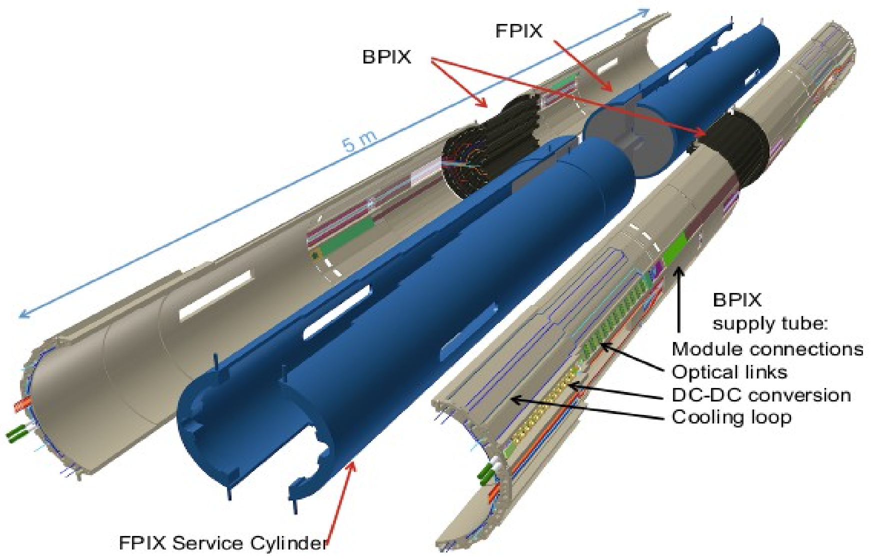
- High enthalpy of vaporization:
  - ➔ 280 kJ/kg @ -20°C
- Low density:
  - ➔ Order of 1 g/cm3
- High vapour pressure → pipes with small diameters
- Non-toxic, relatively low-cost material

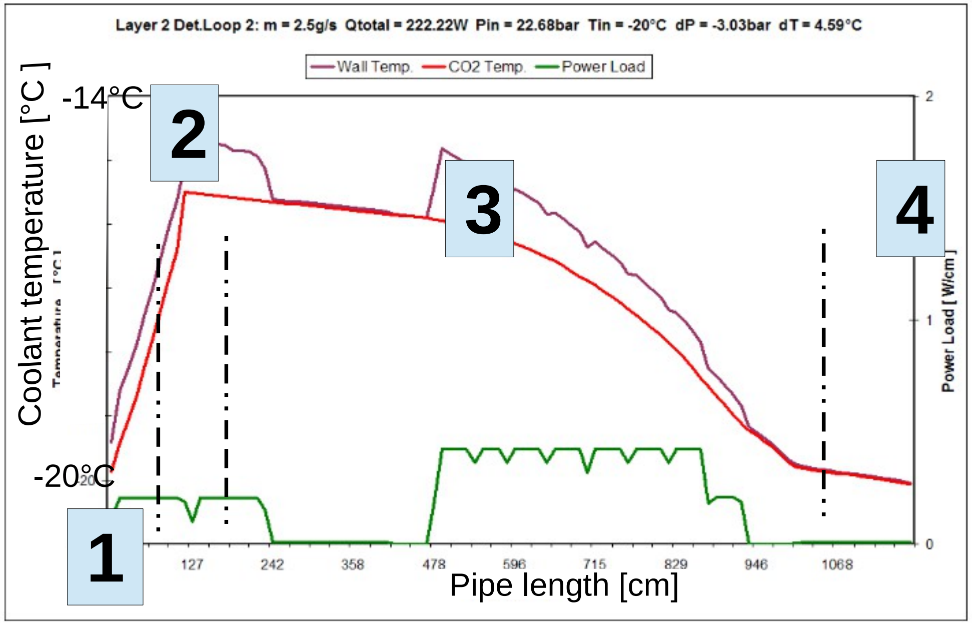
CO_2 challenges

- Operation at high pressure and thin pipes with wall thickness ~50µm
  - ➔ 20bar @ -20°C
  - ➔ 55bar @ 20°C
- Need to guarantee the two-phase state, otherwise “dryout”

CO_2 two-phase cooling is an efficient concept for low-mass detectors.

CO_2 Cooling Loop in the CMS Pixeldetector



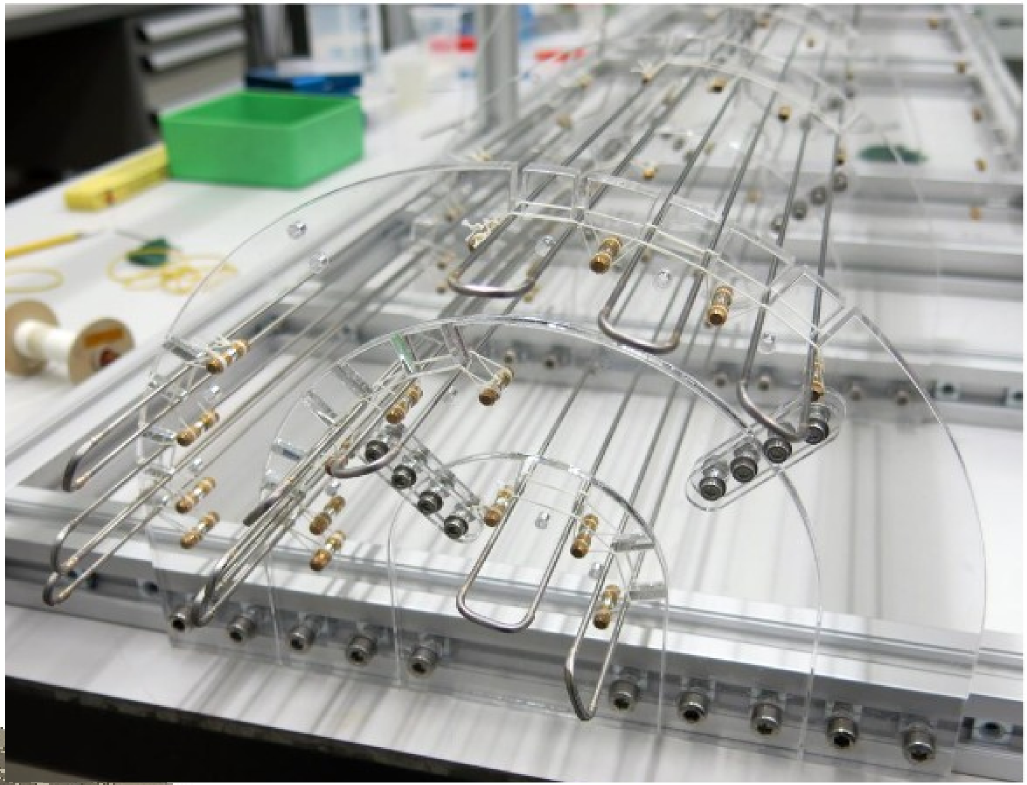


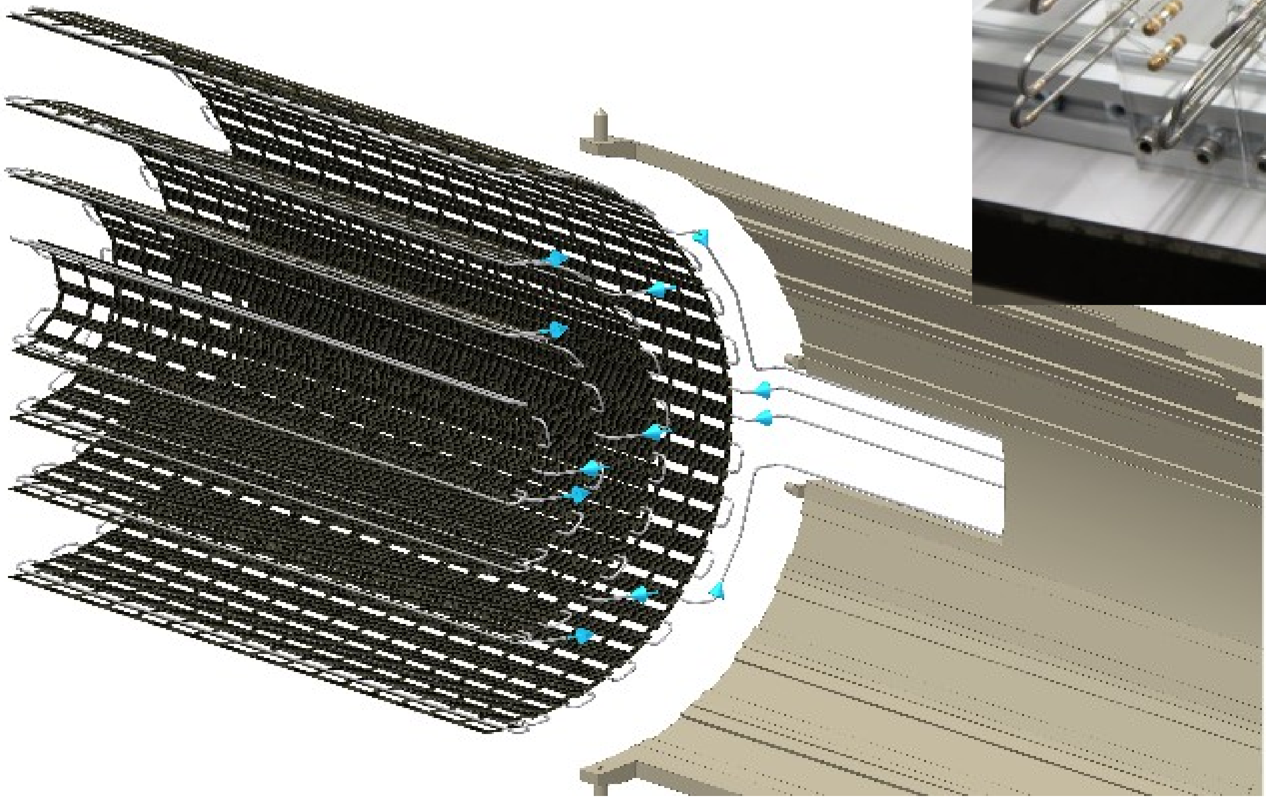
- Length of one cooling pipe is up to 11.2m
- Heat load of supply tube components is used as preheater
  - i.e. DC-DC-converters, opto-hybrids
- For Layer1 a total heat load of up to 170W per pipe is expected (Layer2, 240W)

1. CO2 enters the cooling loop at a temperature of -20°C
2. Preheating section in the supply tube
3. Section of cooling the detector by evaporization
4. Return to cooling plant through heat exchanger

Cooling Pipes

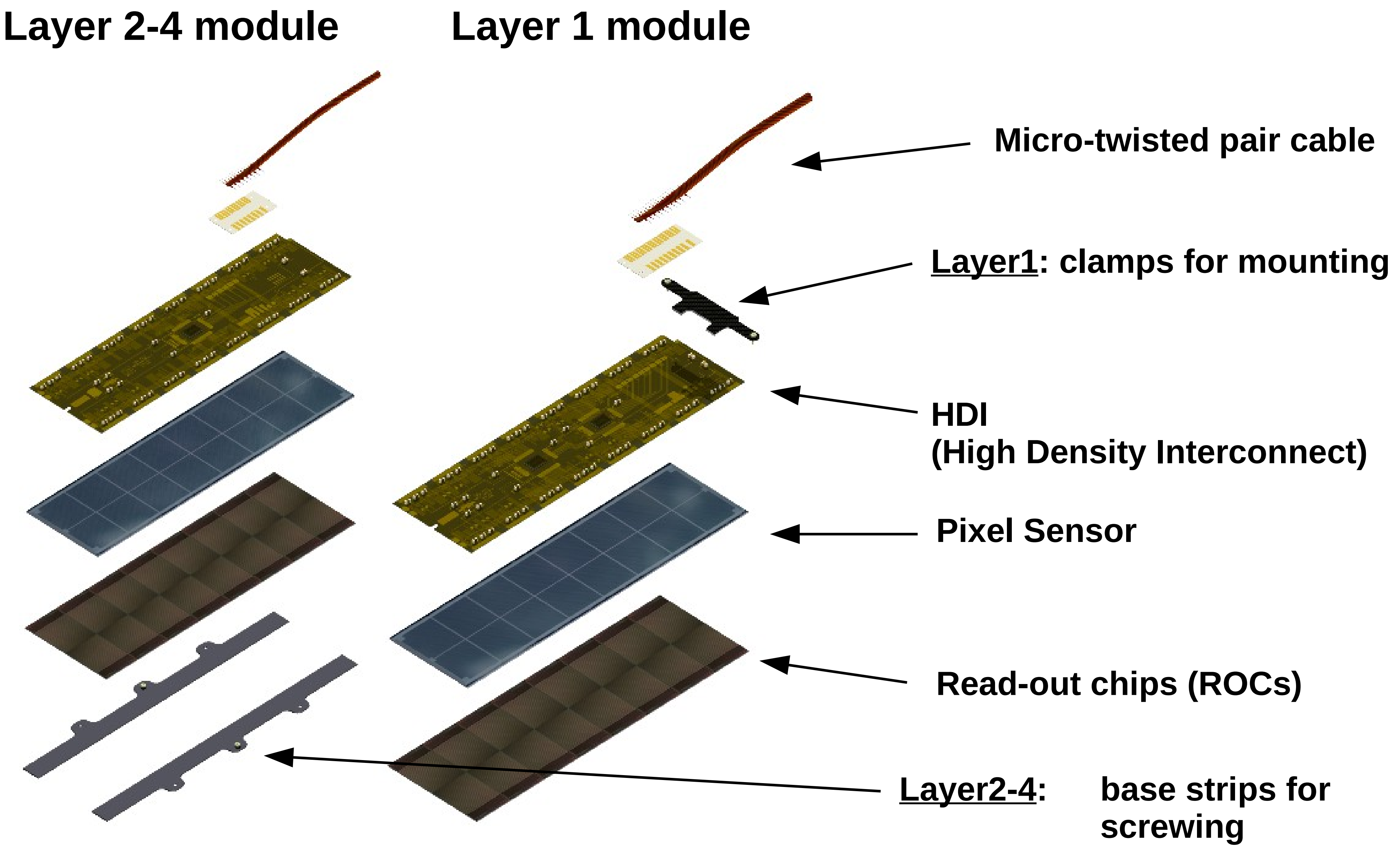
Prototype for the pipe routing
in the pixel detector





Connection between supply tube and BPIX detector

Pixel Module Components

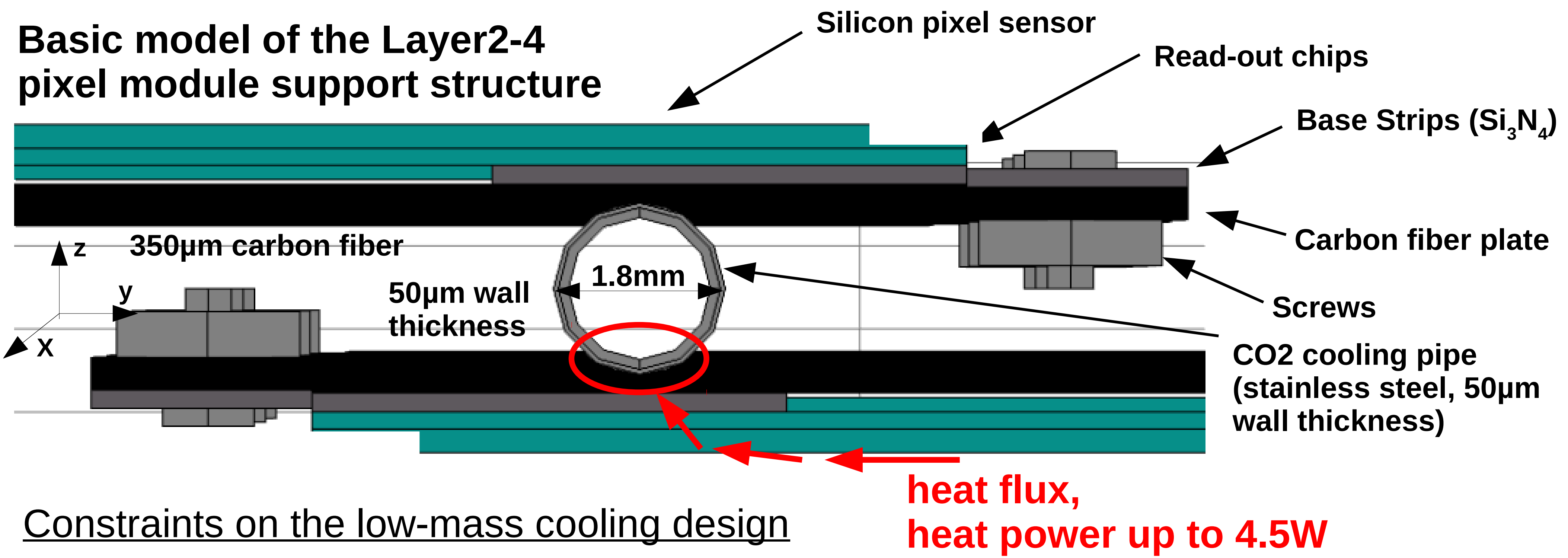


Structure of BPIX Detector

Module positions and mounting
on the cooling loops

Ultra light-weight carbon fiber support structure

Basic Module Mechanics



Constraints on the low-mass cooling design

- No massive cooling blocks can be installed
- Small contact surfaces between carbon fiber structure and cooling pipe
- Limited thermal conductivity of carbon fiber plates
  - Relatively good conductivity in x-y-direction (k_{xy} > 10 W/mK)
  - Bad conductivity in z-direction (k_z < 1 W/mK)

Critical point: How to get the heat into the pipe?

Optimization of the cooling performance is very challenging

Heat Transfers in the System

- Heat load of the module is produced by ROCs and the leakage current of the pixel sensor

Ambient temperature T_a

$\Delta Q/\Delta t = \gamma\,(T_{module} - T_{ambient})$

Heat load on module (0W - 7W)

$\Delta Q/\Delta t = \beta\,(T_{module} - T_{CO2})$

CO_2 cooling system T_{CO2}

$$P_{\text{module}} = \beta(T_{\text{module}} - T_{CO2}) + \gamma(T_{\text{module}} - T_{\text{ambient}})$$

Expression for module temperature

$$\Rightarrow T_{\text{module}} = \frac{1}{\beta+\gamma} P_{\text{module}} + \frac{\beta T_{CO2} + \gamma T_{\text{ambient}}}{\beta+\gamma}$$

Linear relation

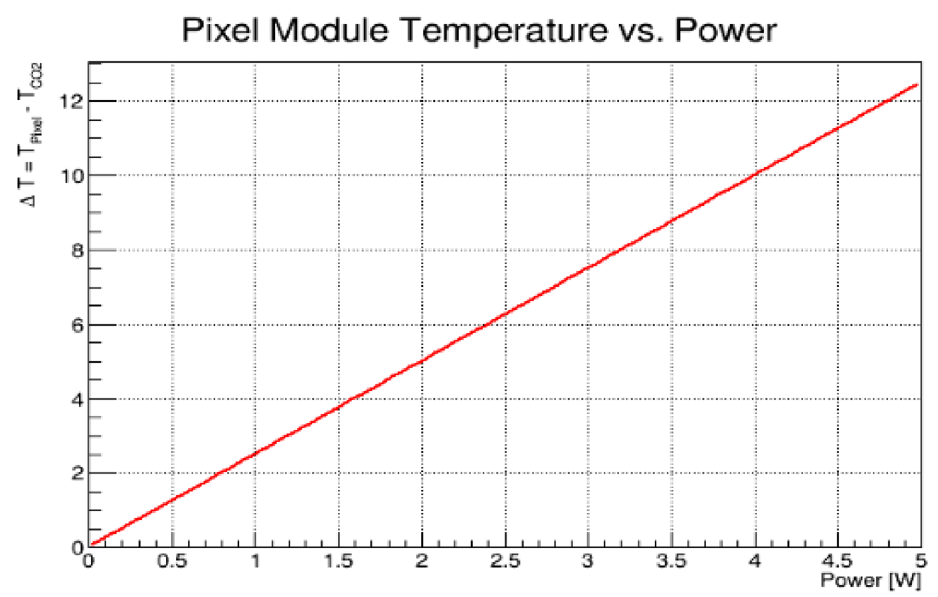
$$\Rightarrow T_{\text{module}} = c P_{\text{module}} + T_0$$

Heat exchange to ambient

- γ is estimated to be 0.1 W/K
- Total heat exchange in the order of 0.5W

Thermal resistance $\alpha = \Delta T/\Delta P$ [K/W]

- Property of module mechanics
- In this model: $\alpha = 1/\beta$



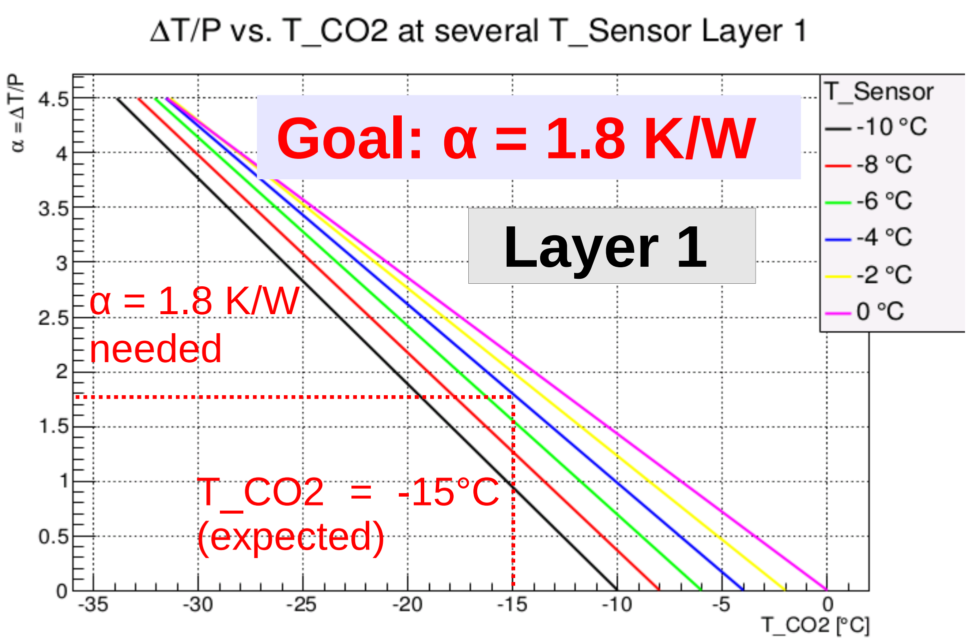
Power of the Pixel Modules

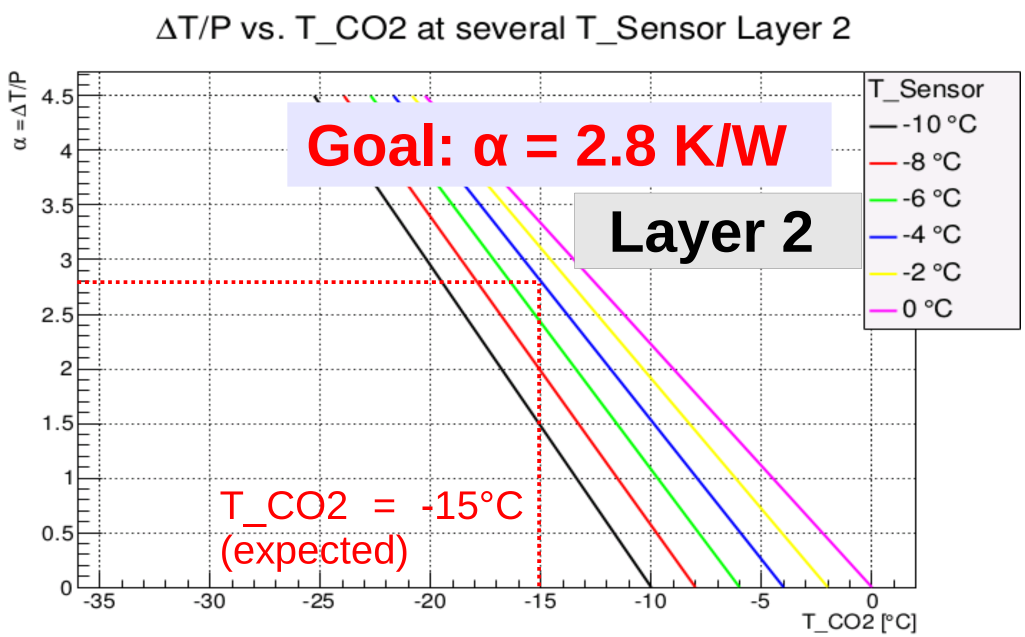
- Power consumption of the ROCs depends on position in the detector (hit rate)
- Leakage current of the sensor depends on collected irradiation and sensor temperature

$$P_{\text{leak. current}} \propto T_{\text{sensor}}^2 \, e^{-\frac{\Delta E}{2k}\frac{1}{T_{\text{sensor}}}}$$

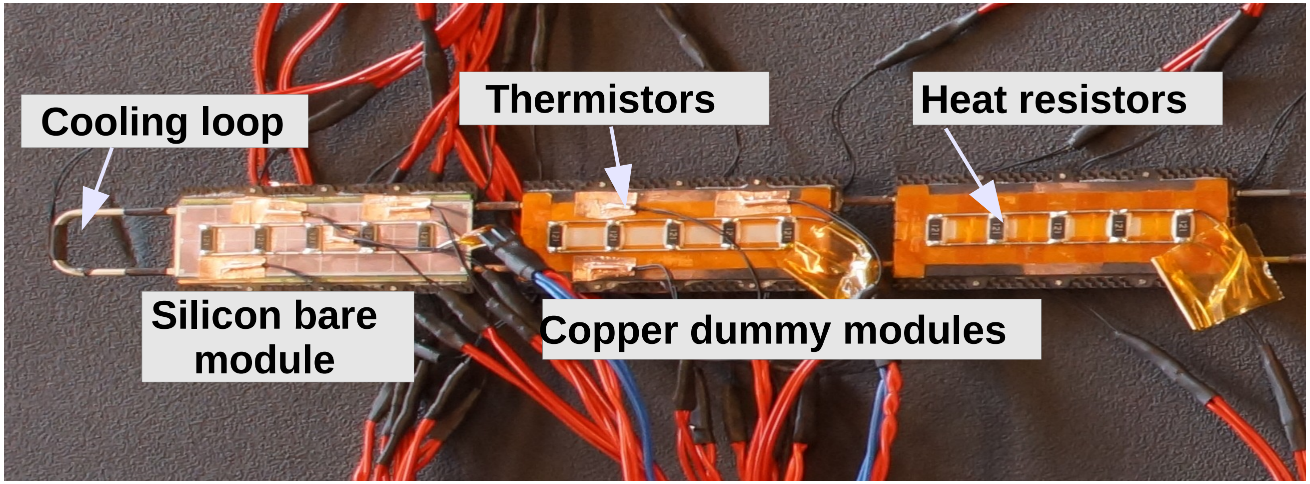
  - ➔ i.e. the leakage current doubles if the temperature increases by about 7K
  - ➔ Leakage current is limited by High-Voltage power supplies
- Design goal is a sensor temperature of -4°C at coolant temperature T_CO_2 = -15°C

Layer	Int. Lumi	Sensor	ROCs	Power	α
Layer 1	250 fb^{-1}	2.6W	4.4W	7W	1.8 K/W
Layer 2	500 fb^{-1}	1.7W	2.8W	4.5W	2.8 K/W





BPix Thermal Mock-Up



- CO_2 cooling system in RWTH laboratory
  - Temperatures between -20°C and 20°C
  - CO_2 flow up to 1.5 g/sec

- A thermal mock-up is used for simulating the thermal properties of the modules

- Heating resistors are used for applying heat loads between 0W and 7W

- Measurements are made with copper dummy modules

Measurement of the Thermal Resistance

- A heat load 0W – 5W is applied in steps of 0.1W

- Temperature is measured redundantly on several components
  - on top of the module
  - on the carbon fiber plate
  - on the cooling pipe

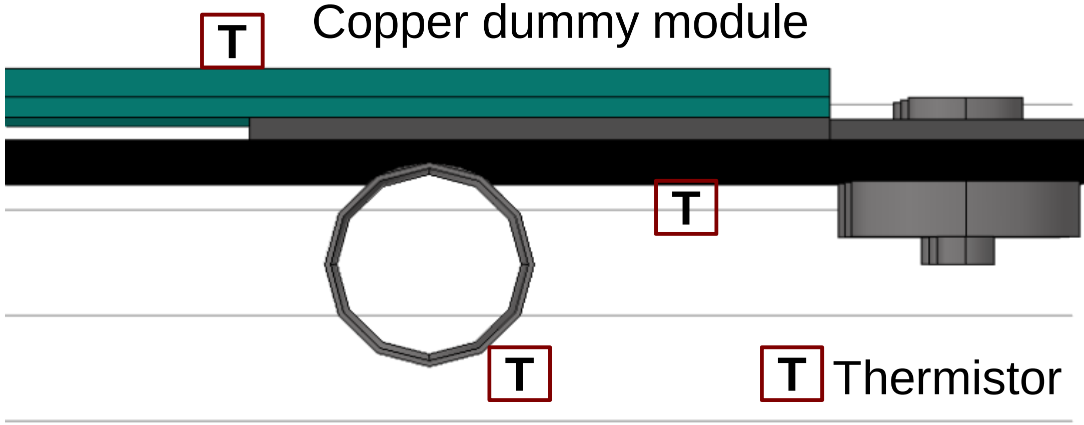
- For every component the thermal resistance to the CO_2 can be measured

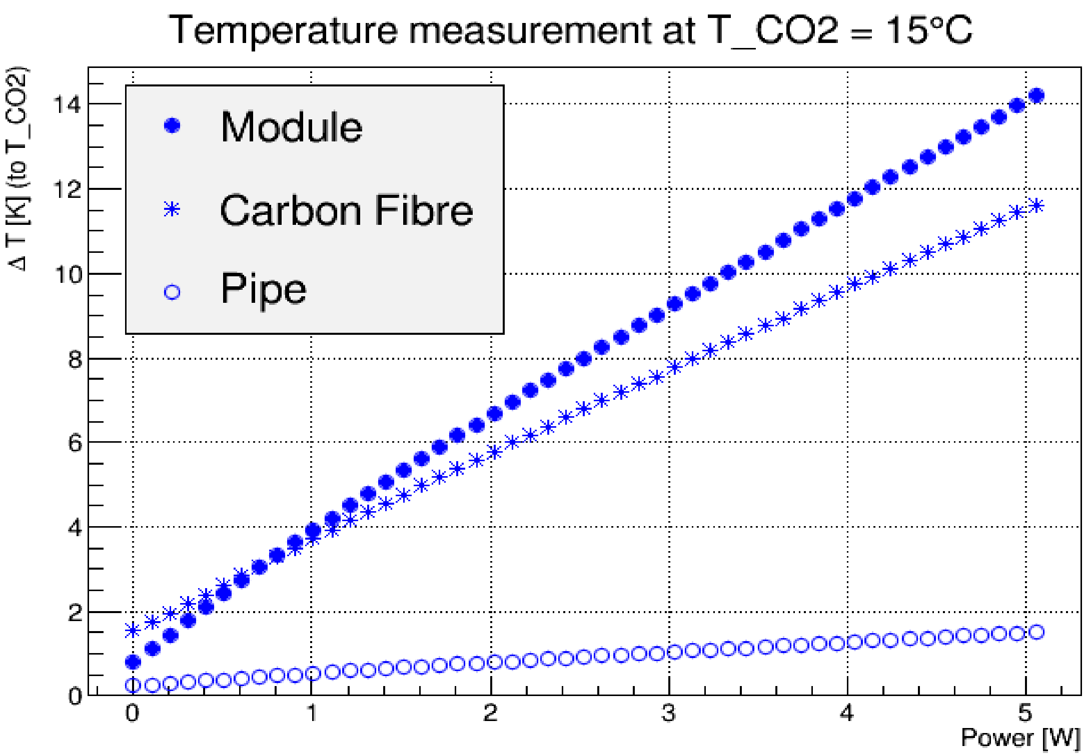
Component	Top	CF	Pipe
α [K/W]	3.7	3.2	0.3
Δα [K/W]	0.5	2.9	0.3

- Main contributions to the thermal resistances can be read off

- Largest contributions stems from the transition carbon fiber plate to pipe

Position of the thermistors on the module





Comparison between different Glues

- The glueing between carbon fiber support and cooling pipe is tested with several glues
  - **EPO-TEK T7110**
  - **Araldite Standard**
  - **EPO-TEK 301**

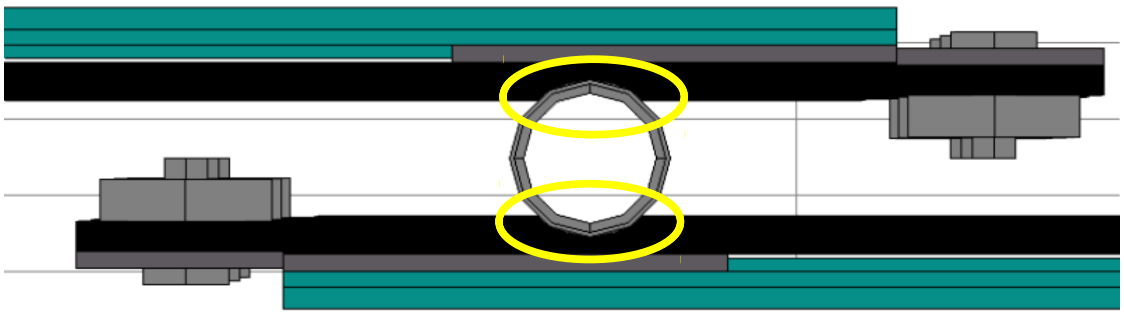
- **EPO-TEK T7110** is
  - a thermally conductive glue
  - rather viscous

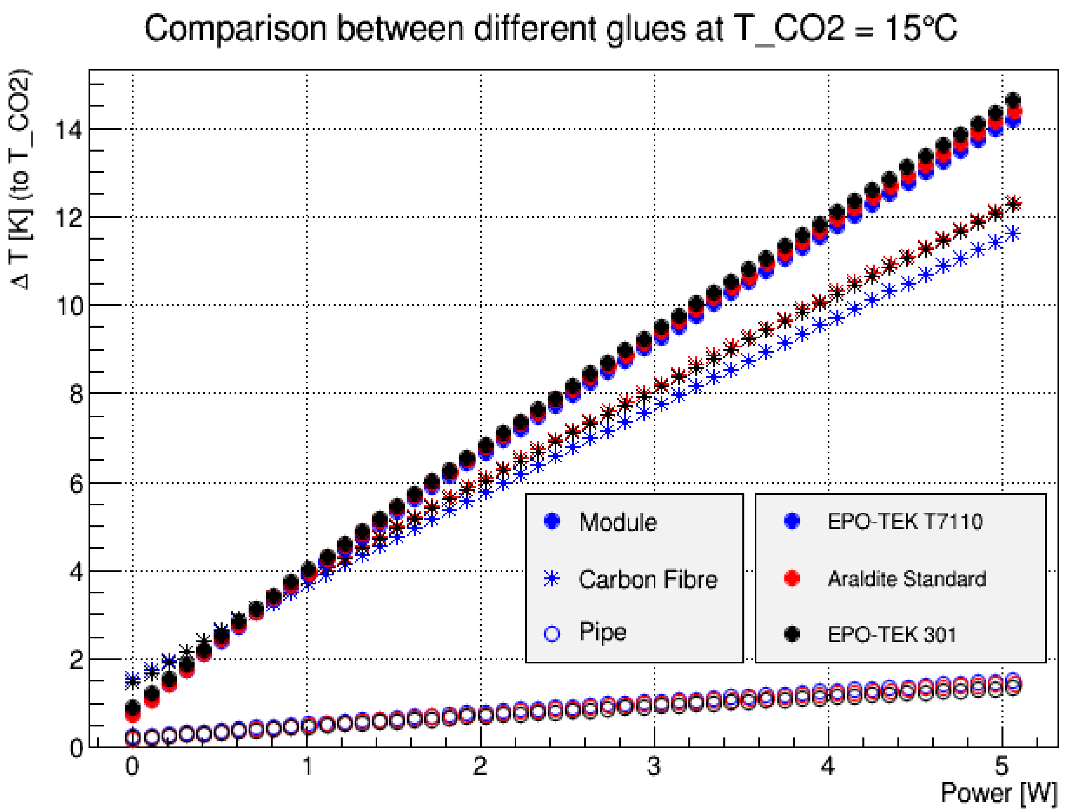
- **EPO-TEK 301** is
  - a standard 2-component glue
  - low-viscous and easy to handle

Thin layers of low-viscosity glues have same properties than rather viscous thermal glues

→ May use the glue which is the easiest to handle.

Copper dummy module

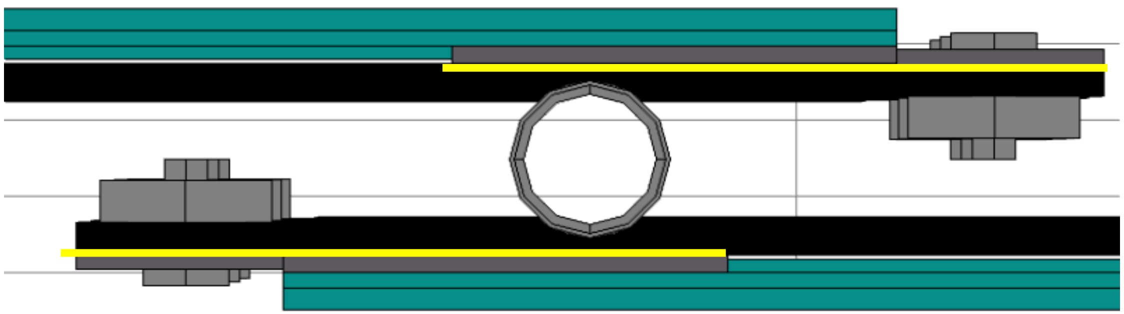




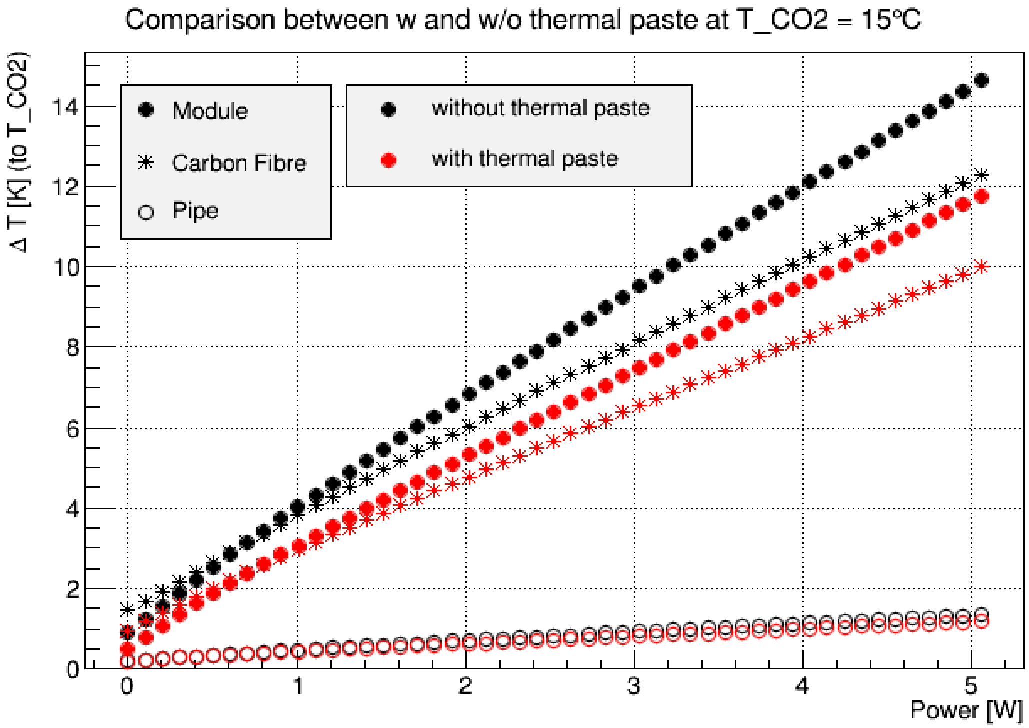
Thermally Conductive Paste

- Thermally conductive paste is brought between base strips and carbon fiber plate
- Keratherm KP 98
- Thermal improvement due to better thermal contact and higher conductivity

Copper dummy module



α [K/W]	Top	CF	Pipe
w/o thermal paste	3.7	3.2	0.3
w thermal paste	2.8	2.4	0.2



Disadvantage

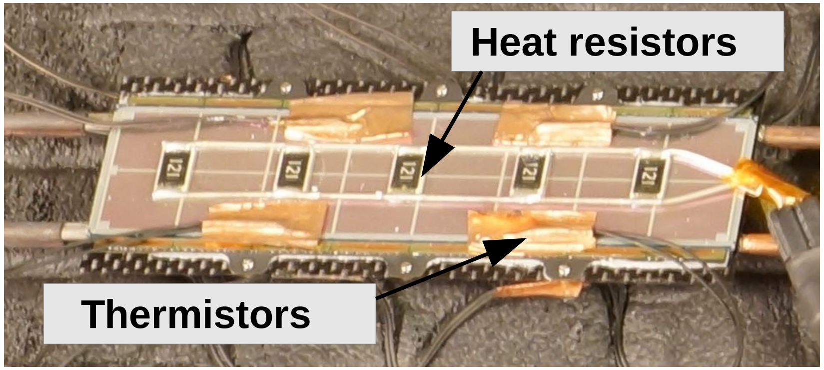
Removement and replacement of pixel modules becomes more difficult

→ base strips “stick” at the carbon fibre

→ possibility of destroying the module

Results - Overview

Bare silicon module



Measurements at a CO_2 temperature of -20°C

T_CO_2 = 15°C	"Sensor"	Carbon fiber
α (Si) [K/W]	3.3	2.4
α (Cu) [K/W]	2.8	2.4
Δα (relative) [%]	**15%**	-

T_CO_2 = -20°C	"Sensor"	Carbon fibre
α (Si) [K/W]	3.6	2.6
α (Cu) [K/W]	3.2	2.6
Δα (relative) [%]	**12%**	-
α (design value) [K/W] Layer 2-4	**2.8**	-
α (design value) [K/W] Layer 1	**1.8**	-

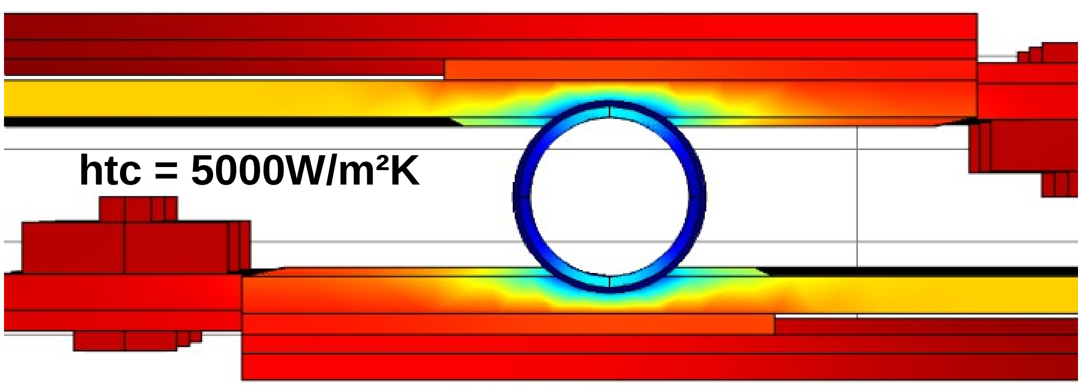
- All measurements were done with thermally conductive paste
- α (silicon) was measured 12% - 15% higher than for copper
  - better thermal conductivity of the copper modules
- The main contribution still stems from α("carbon fibre → CO_2")
  - considered to have the best potential for improvement

→ FE simulations

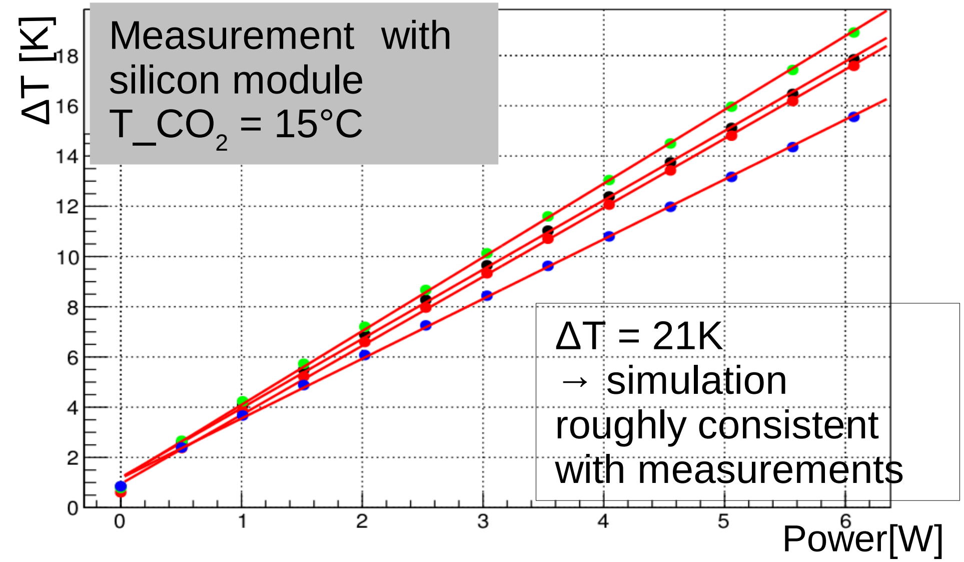
Thermal FE Simulation

- Thermal FE simulations are made with COMSOL® Multiphysics
- The most relevant components of the mechanics have been taken into account
- Pixel module development is finalized, production is going to start very soon
- Carbon fiber plate has been identified as only realistic parameter which can be optimized

Heat load 7W **ΔT = 21K**



htc = heat transfer coefficient

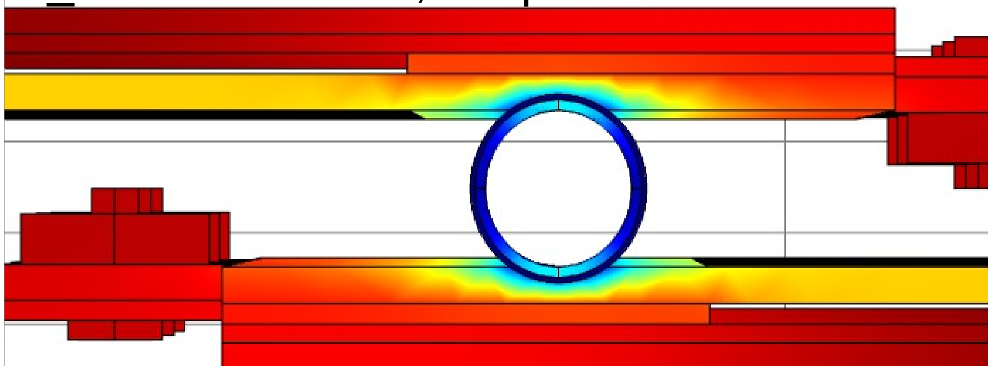


Parameter	Meaning	Unit	Current standard value (estimated)	Reachable/realistic value
k_CF	thermal conductivity in x-y-direction	[W/mK]	~ 10	100
k_CFz	thermal conductivity in z-direction	[W/mK]	<< 1	0.5
h_CF	thickness of the carbon fibre plate	[µm]	350	550

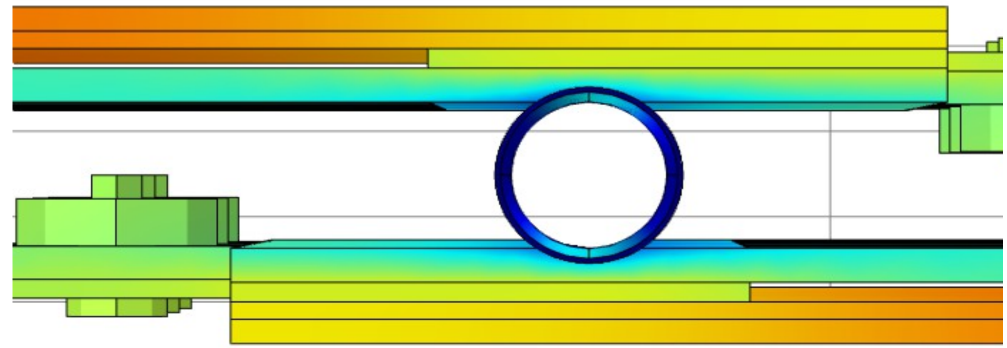
Optimization of the Carbon Fiber Structure

- Various configurations have been simulated for a heat load of 7W

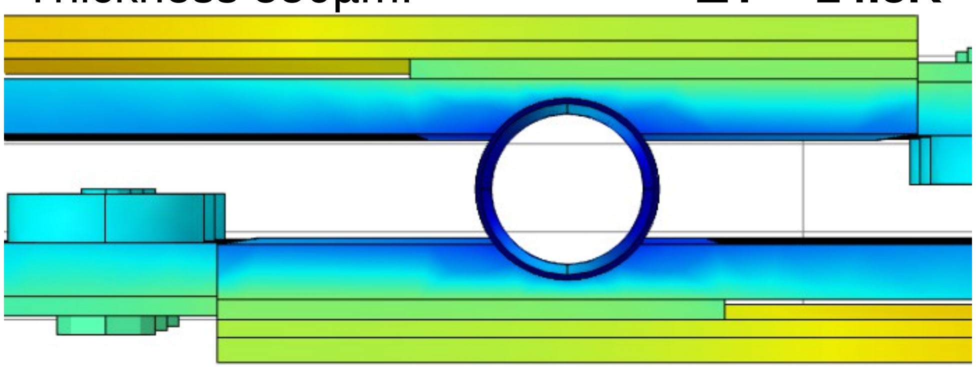
Standard geometry: k_CF = 10W/mK,
k_CFz = 0.5W/mK, 350µm **ΔT =21.1K**



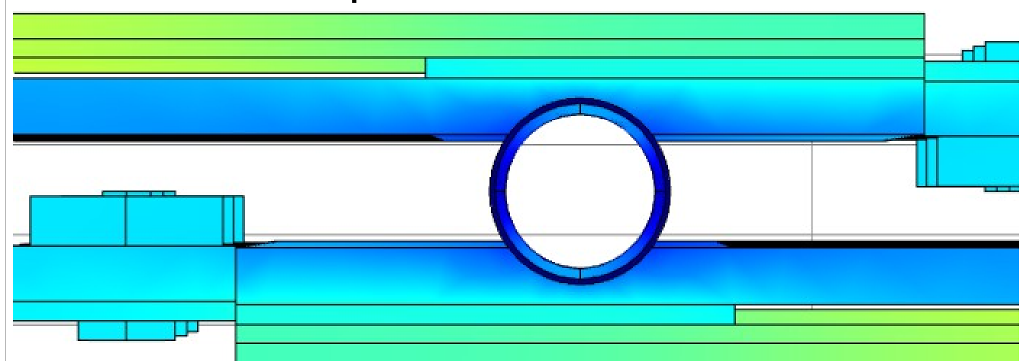
k_CF = 100W/mK,
Thickness 350µm: **ΔT = 16.2K**



k_CF = 100W/mK,
Thickness 550µm: **ΔT = 14.5K**



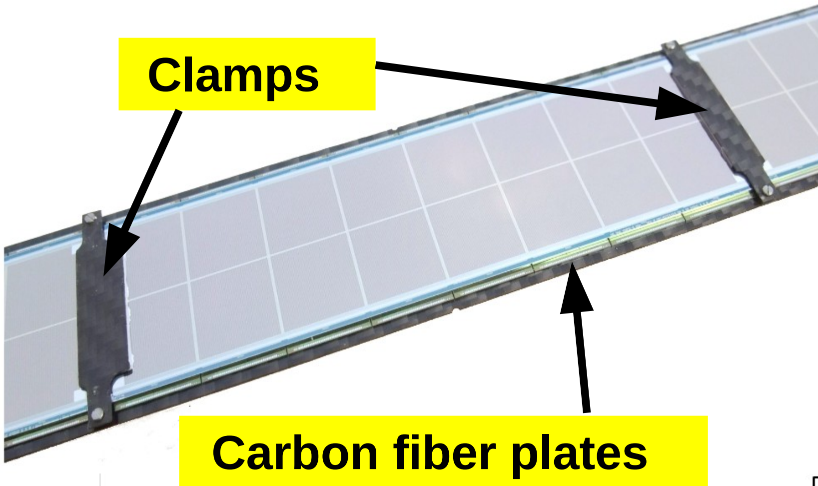
k_CF = 100W/mK, k_CFz = 1W/mK
Thickness 550µm: **ΔT = 12.1K**



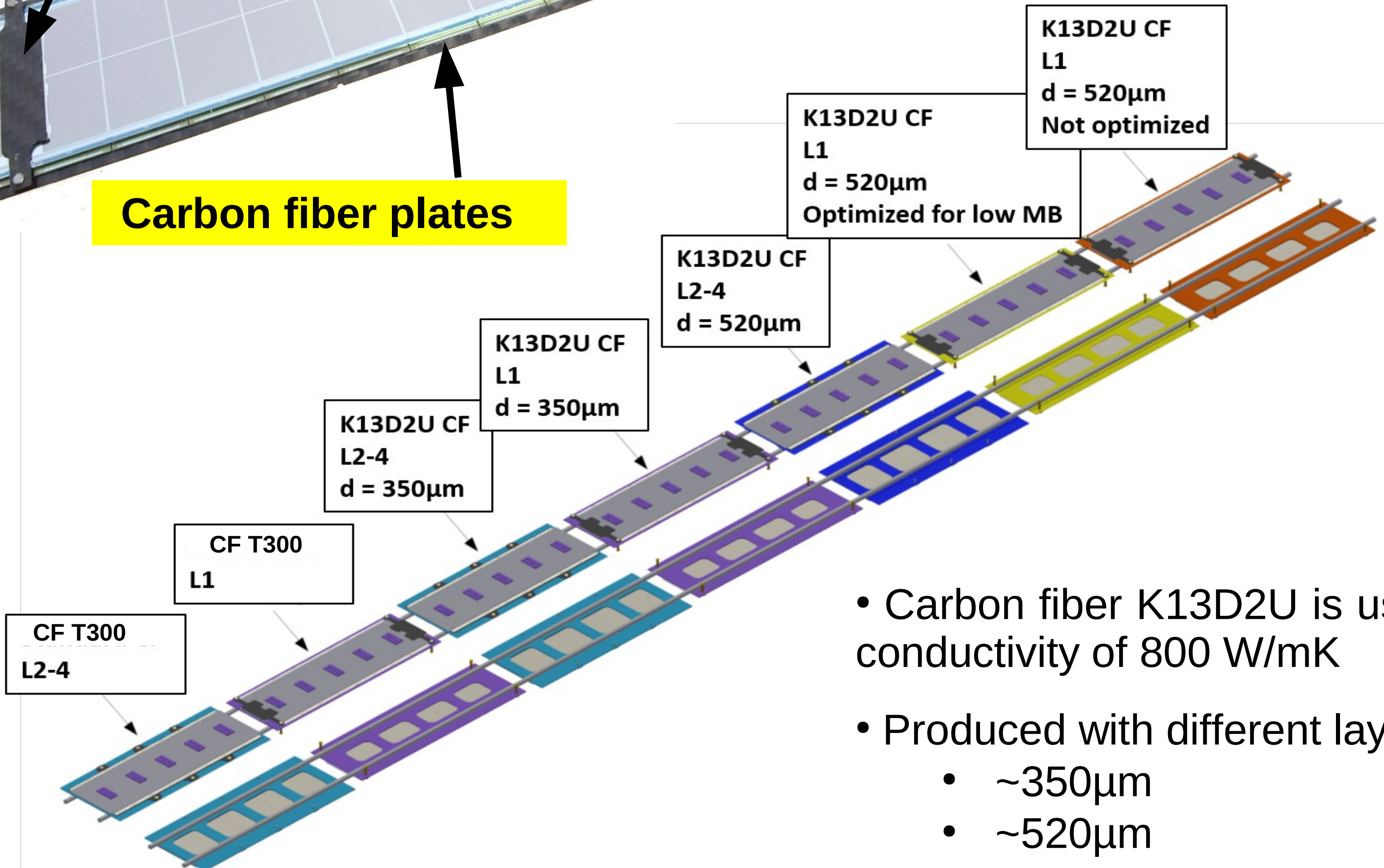
Improvements on the carbon fiber structure are promising for better thermal properties

New Thermal Mock-Up

Layer1 module mechanics



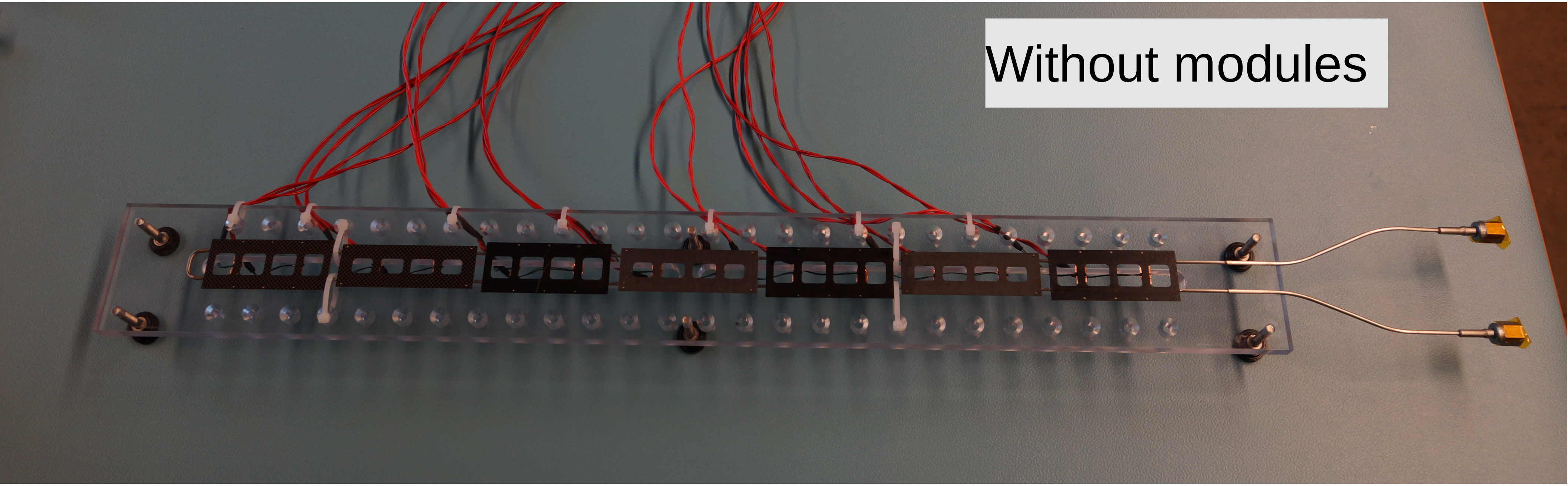
- Realization of the thermal FE simulation results
- Seven additional configurations
- Measurement with a Layer1 module
  - not screwed with base strips, but clamped

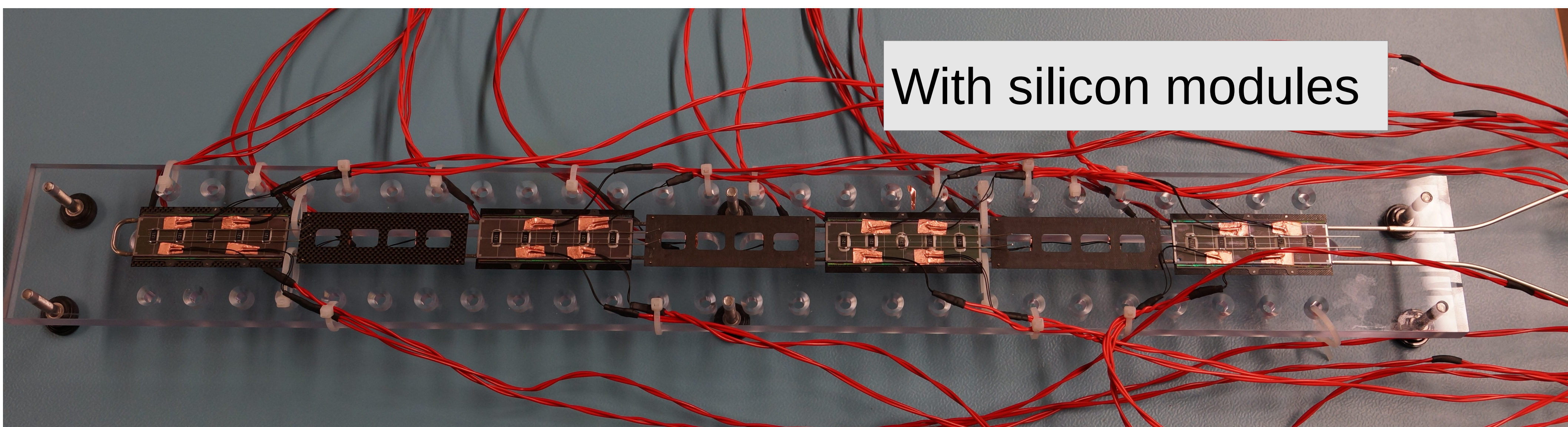


- Carbon fiber K13D2U is used with a thermal conductivity of 800 W/mK
- Produced with different layer thicknesses
  - ~350µm
  - ~520µm

S. Streuli

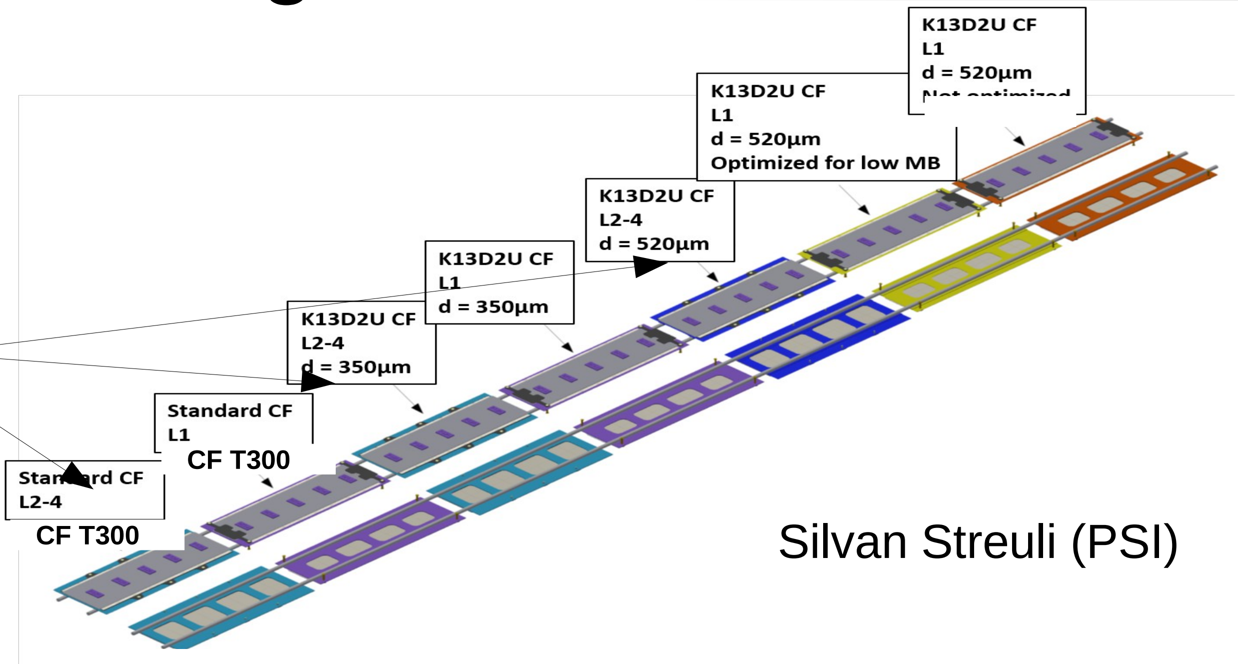
Photos of the new mock-up





First Results with Optimized Configuration

- Recent measurement at a CO_2 temperature of 15°C
- Measurements with Layer2-4 bare silicon modules
- No thermal paste is used
- Qualitative results
- New carbon fiber plates improve the results

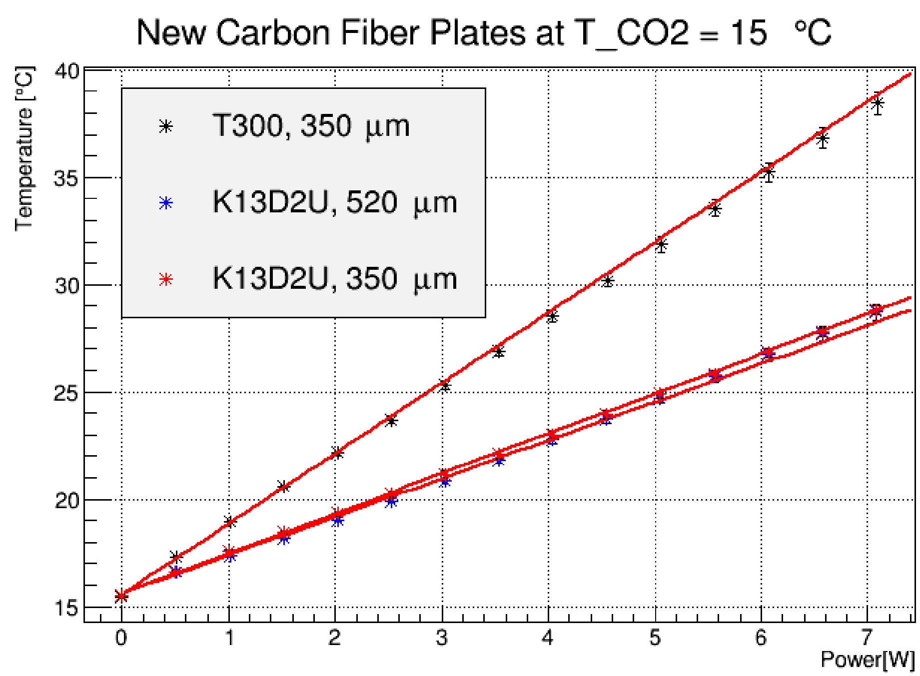


Silvan Streuli (PSI)

α = 3.6 K/W for T300, 350µm

α = 2.0 K/W for K13D2U, 520µm

α = 2.0 K/W for K13D2U, 350µm

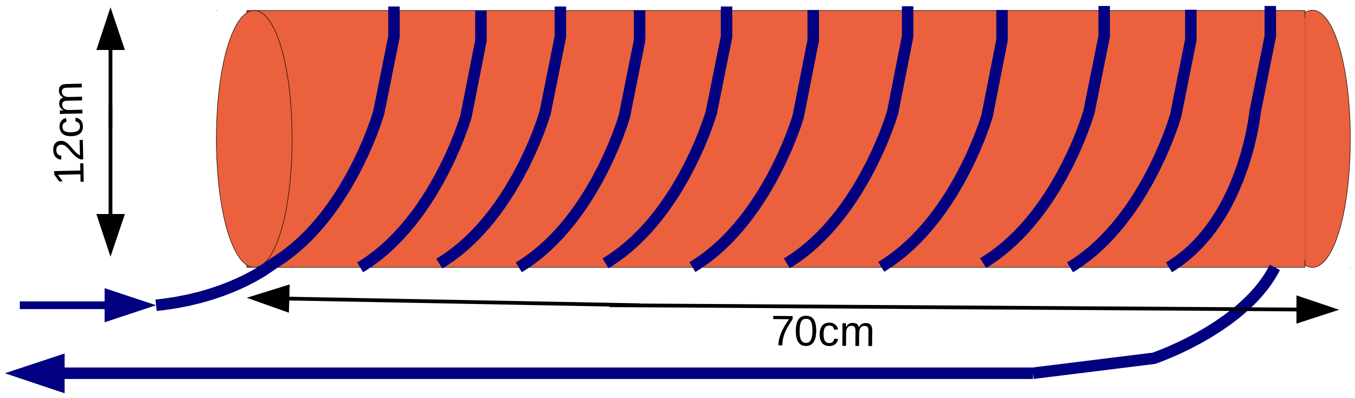


Defined Ambient Temperature

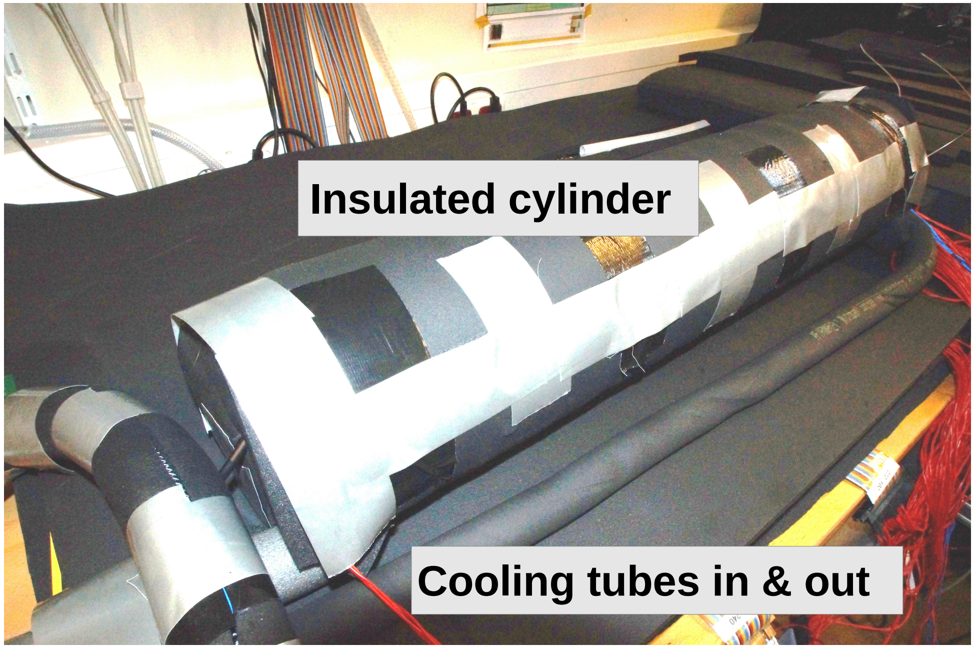
- Measurements so far are done for qualitative characterization

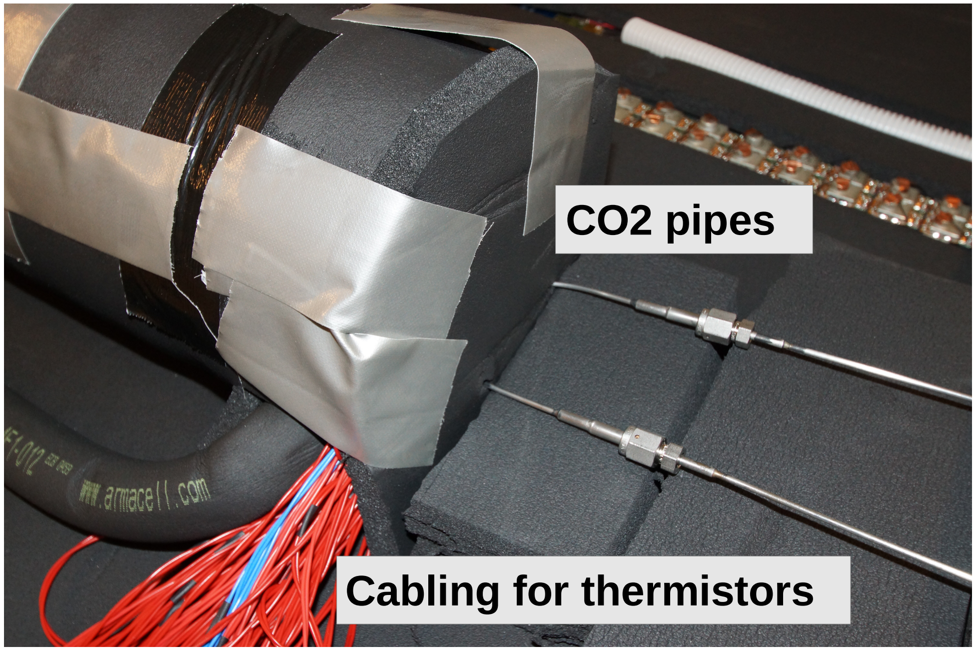
- Next step: quantitative measurements will be done in defined ambient temperature

Copper cyclinder surrounded by cooling pipes



Cooling with silicon oil -20°C < T < 30°C, with huber chiller



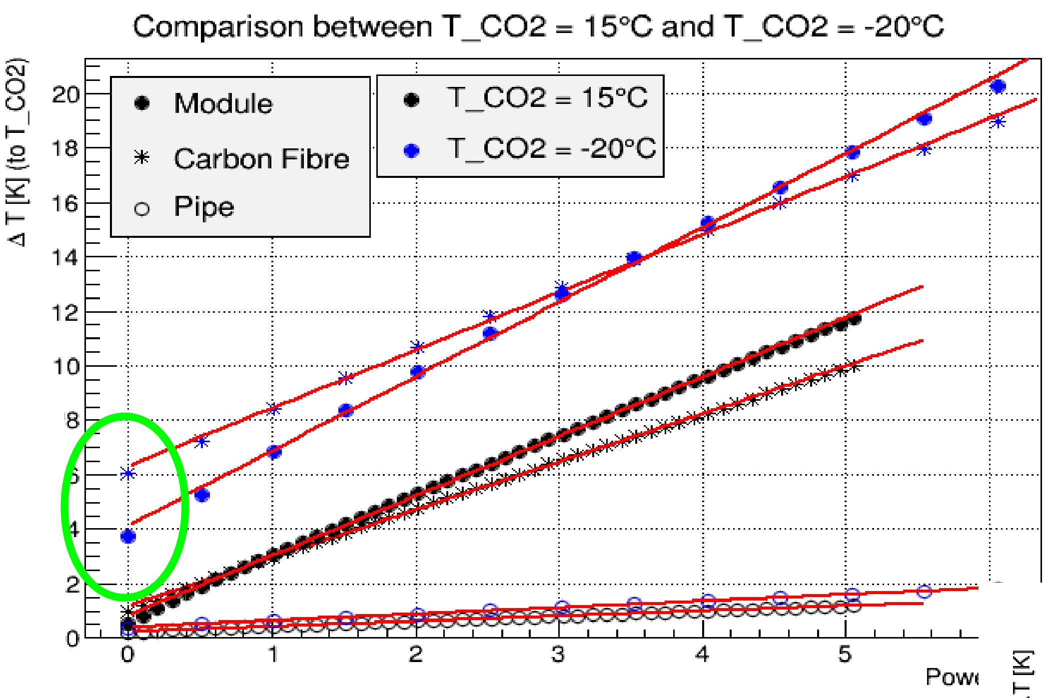


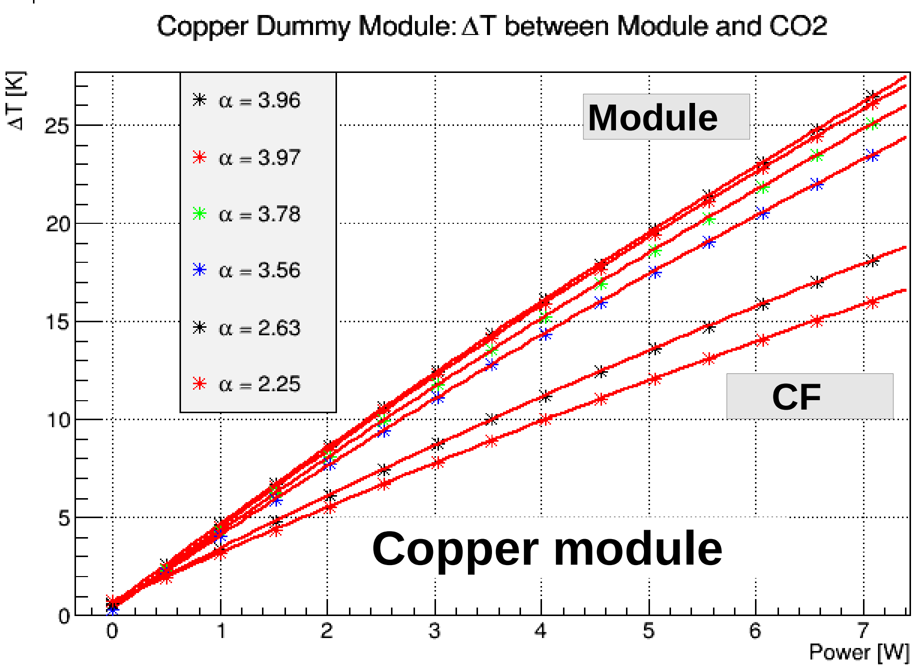
Conclusions

- Low-mass design of detectors requires an involved cooling system
  - ➔ CO_2 cooling is a promising solution
- CMS phase-1 pixel detector uses CO_2 cooling system
  - ➔ Cooling of heat loads > 100W with only one thin cooling pipe
- Requirement for low material budget brings challenges
  - ➔ Ultra light-weight support structures, no massive cooling blocks
  - ➔ Small contact surfaces between detector and pipe
- Carbon fiber plates can be used as support structure
  - ➔ Optimization of thermal conductivity seems necessary for good performance
  - ➔ Improved carbon fiber plates promise better thermal characteristics

Additional Material

Measurements at -20°C





Specification CF

K13D2U

COAL TAR PITCH-BASED CARBON FIBERS

TYPICAL PROPERTIES

Tensile Strength	*535 Ksi*
Tensile Modulus	*135 Msi*
Ult Elongation	*.40 %*
Yield	*1360 yard/Lb*
Density	*2.2 g/cm³*
Electrical Resistivity	1.5×10^{-6} ohm·m
Thermal Conductivity	*800 W/m·K*
Sizing Amount (Epoxy Type)	*2 %*
Number of Filaments	*2 K*
Filament Diameter	*11 u*
Twist	*0 untwisted type*
Carbon Content	*over 99 %*

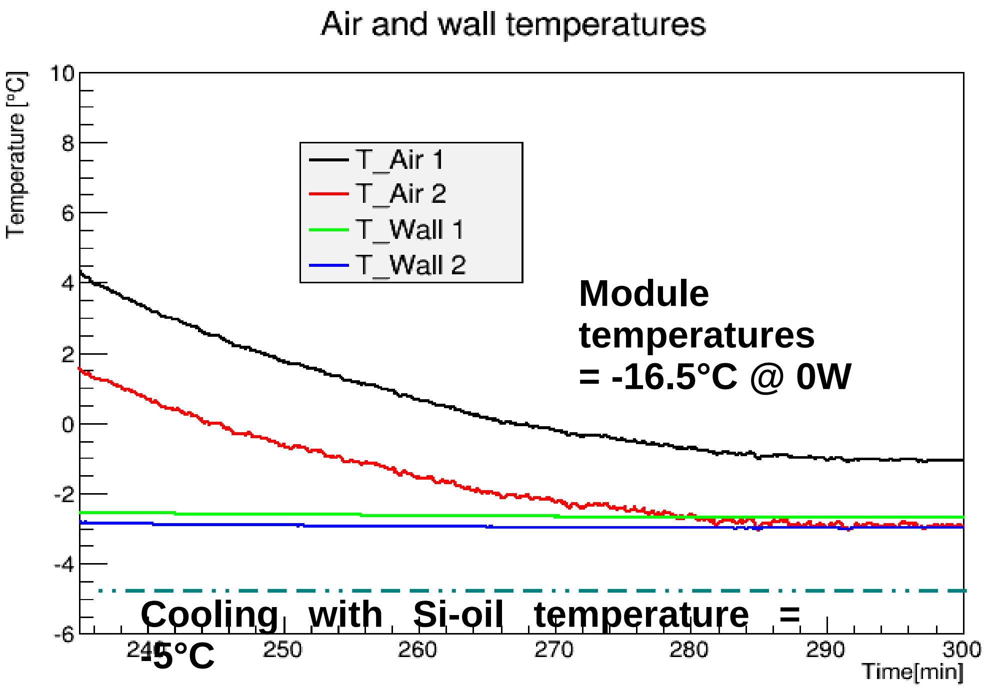
Condition in pixel detector

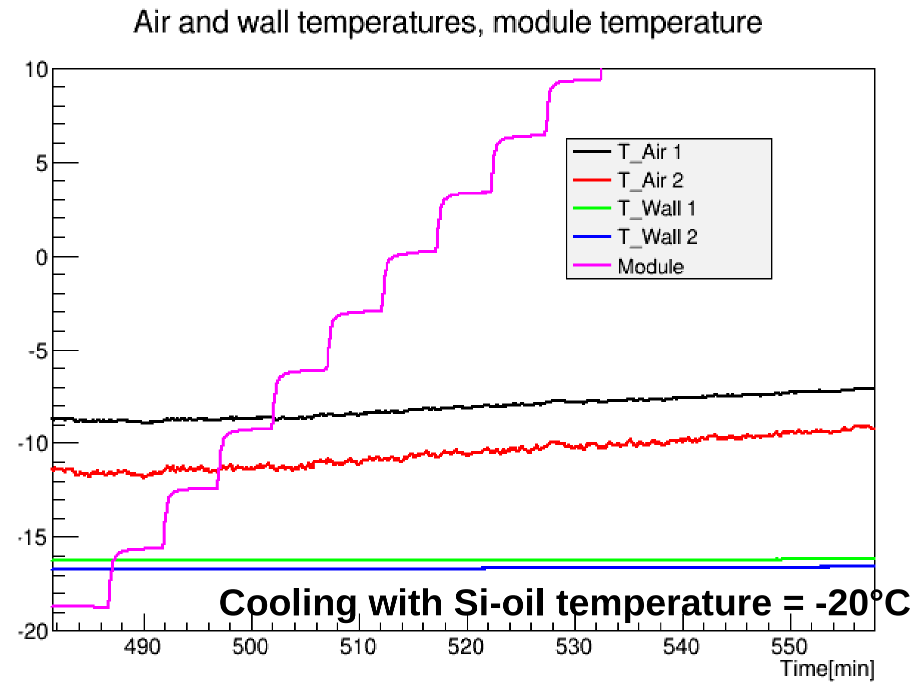
- The pixel detector is filled with nitrogen
- Nitrogen pipes are parallel to CO_2 cooling pipes → nitrogen temperature when entering the detector is expected to be equal to T_{CO2}
- 3 complete nitrogen volume exchanges per 1 hour → cooling effect of nitrogen negligible
- Assume a module temperature of -4°C and good thermal insulation of the detector with respect to the external volume
    - ➔ Temperature (Nitrogen) approximately equal to module temperature

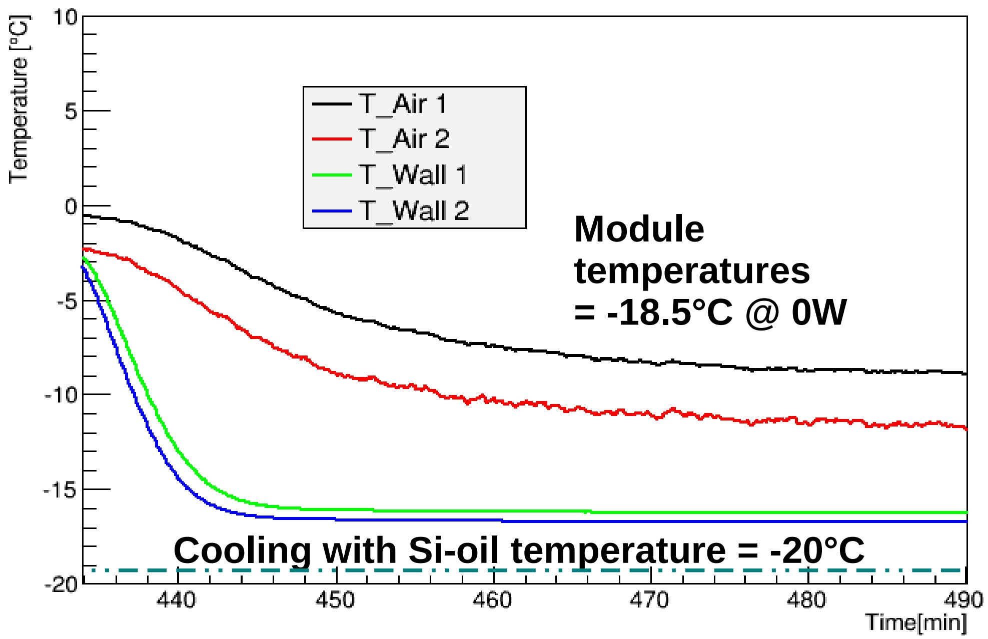
➔ Idea:

- ➔ Construct a volume with an air temperature of about -4°C
- ➔ But keep cooling power which stems from air as low as possible
- ➔ Build a “fridge” which does not actively regulate the temperature of the air surrounding the pixel modules

Air and Wall Temperatures







- CO_2 cooling operated at -20°C
- Air temperatures < 0°C degrees can be reached
- When applying heat load to the modules, the temperature rises about 2K

→ Air temperature in the system is roughly constant

Evaporation

- Applied preheating of up to 100W → no change in temperatures observed