Thermal performance tests of petals for the ATLAS ITk strip end-cap detector

Forum on Tracking Detector Mechanics 2021

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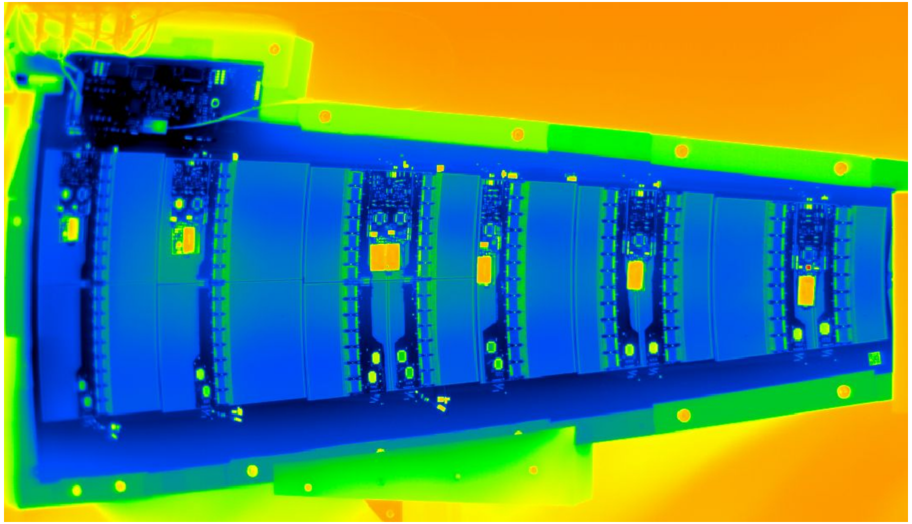
with the help of the ATLAS ITk Strip Community

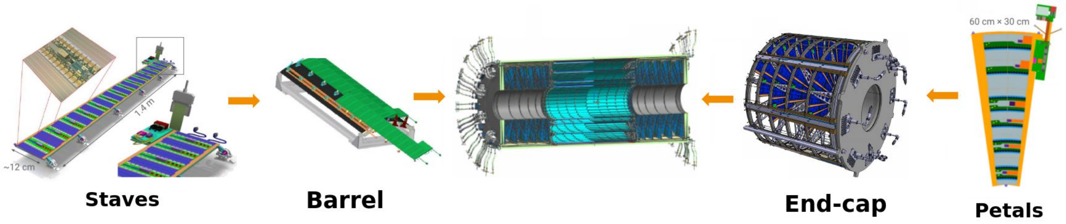


HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

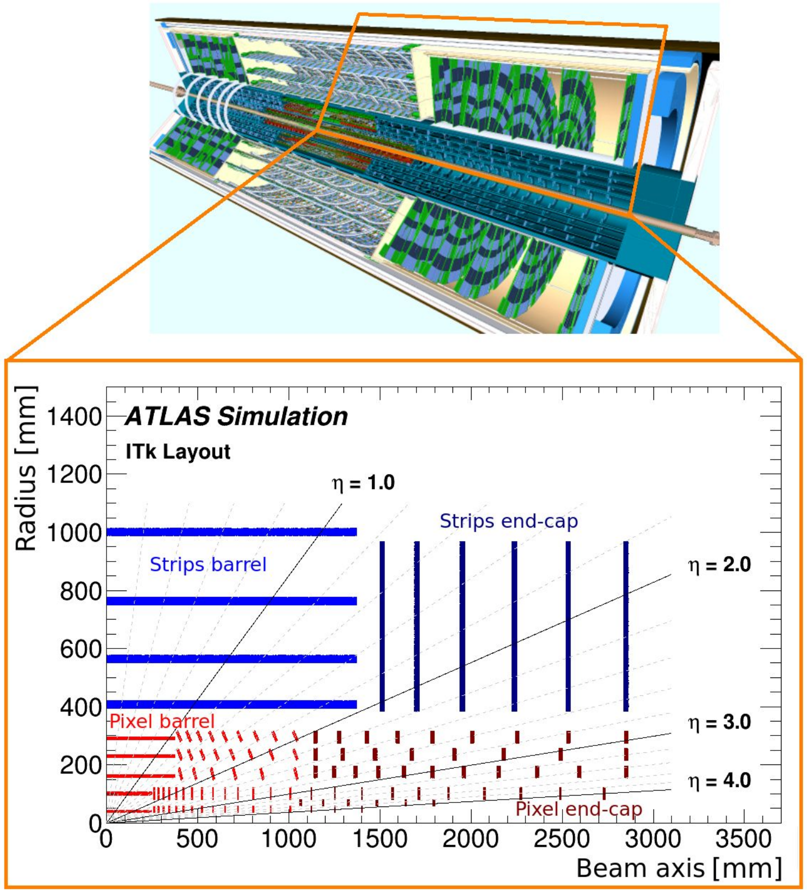
The ATLAS Inner Tracker (ITk)

Design of the new ATLAS tracking detector for HL-LHC

- replacement of the current tracking detector system
  - **all-silicon** tracking detector with total area of ~180 m^2 silicon
  - divided in **pixel** (inner radius) and **strips** systems (outer radius)
  - **barrel** (central region) and **end-caps** (forward regions)

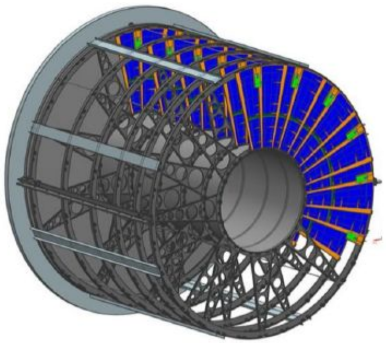


- modular concept of **staves** and **petals** for strip detector
  - similar design approach for barrel and end-caps
  - accommodating their geometries: **rectangular** vs **wedge-shaped**
  - focus in this talk: the petals for the ITk strip end-caps



The ATLAS ITk strip end-caps

Introduction to the “petal” concept



Each end-cap consists of 6 disks

↓

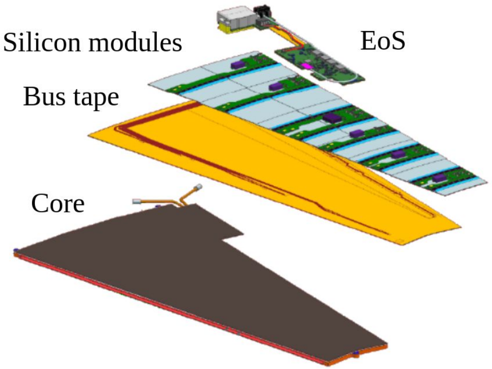
Each disk has 2 layers

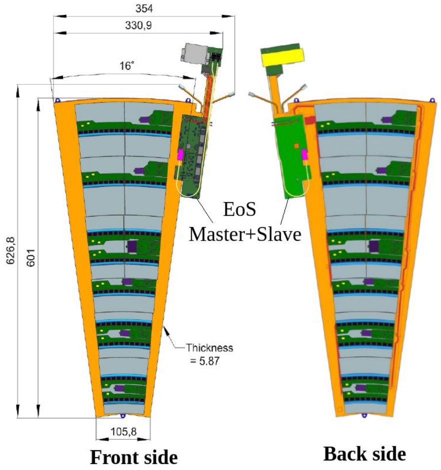
↓

Each layer populated by 16

petals

= support structure loaded with silicon modules



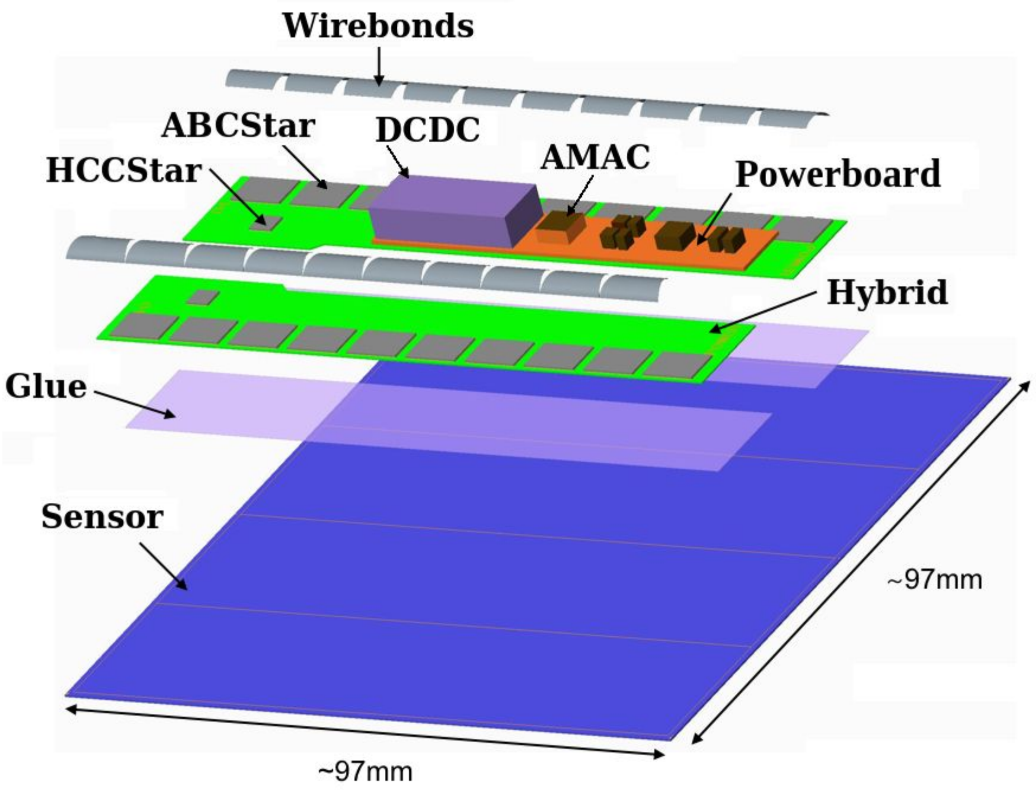


- petals are the building blocks of the strip end-cap detector
  - a **petal** is the wedge-shaped local support structure loaded from both sides with wedge-shaped strip modules
  - a **module** is the assembly of the silicon strip sensor and its readout and power electronics with six different module types
  - a **core** is a lightweight sandwich structure and provides mechanical support, electrical connections and cooling
  - characteristics of concept: minimized material, simplicity for large scale reproducibility and modular testing before assembly

Modules

The silicon strip sensors and their readout electronics

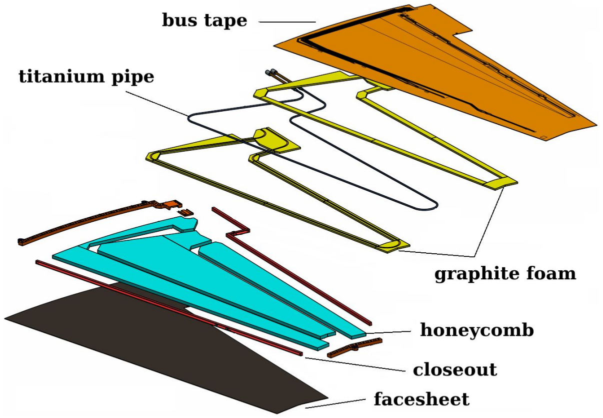
- silicon strip **sensor**
  - n^+-in-p technology, 300 µm thick
  - radial strips (Rφ orientation)
  - 40 mrad stereo angle
- **hybrid** = readout PCB
  - lightweight, polyamide-based PCB
  - readout ASICs (*ABCStar*, *HCCStar*)
  - *wirebonds* for connection to sensor
- **powerboard** = power PCB
  - *DCDC* converter for LV powering
  - sensor biasing via *HVSwitch*
  - monitoring & control ASIC (*AMAC*)

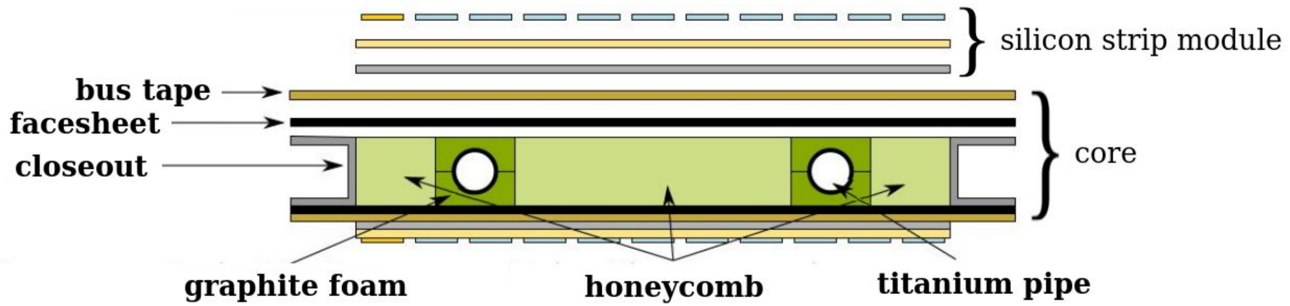


Cores

The local support structure

- goals for design of local support structure
  - minimize **material budget** and complexity
  - provide **mechanical support** and **services** to glued modules
- lightweight sandwich structure of core
  - mechanical stability by **honeycomb**, **closeouts** and **facesheet** (CFK materials)
  - electrical contact for powering, readout and control via co-cured **bus tape**
  - dual-phase CO_2 cooling via embedded **titanium pipe** surrounded by thermally conducting **graphite foam**

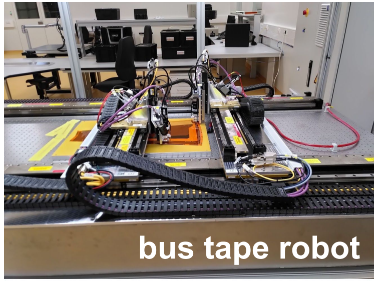


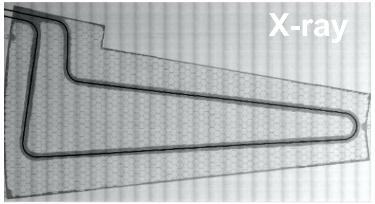


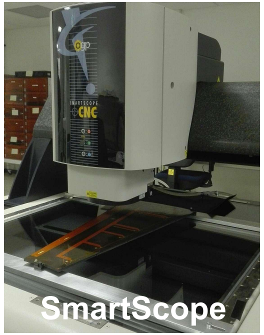
Testing plans

Quality assurance (QA) and quality control (QC)

	Reception	Manufacturing	Assembly	Post-assembly
TESTS	Visual inspection Dimensions Weighing	Visual inspection Dimensions Weighing Pressure test Electrical conductivity HV resistance	Visual inspection Dimensions Weighing Pressure test Leak test Electrical conductivity HV resistance	Visual inspection Metrology X-rays Pressure cycle Thermal cycle Pressure drop Thermography → long cycles → rapid cycles
OBJECT(S)	Pre-preg Honeycomb Bus tape Allcomp foam Titanium pipe	→ C-Channels Co-cured bus tape Half core	→ Core	→ Petal





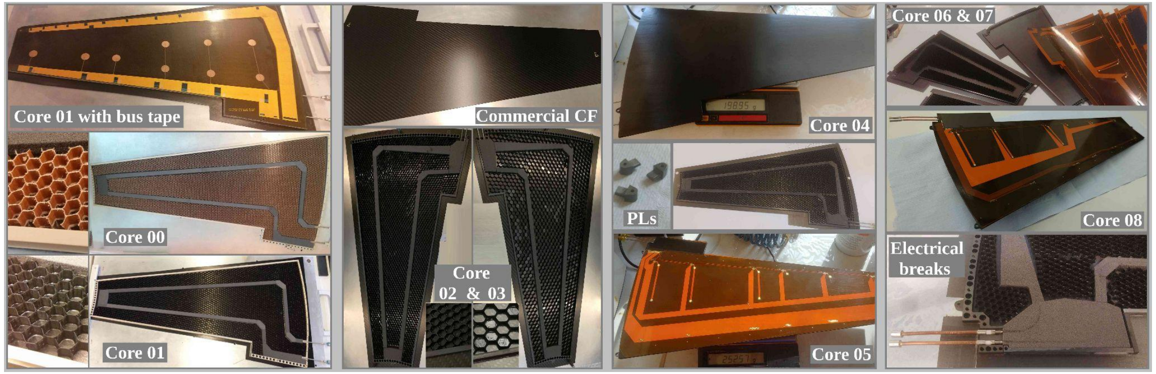


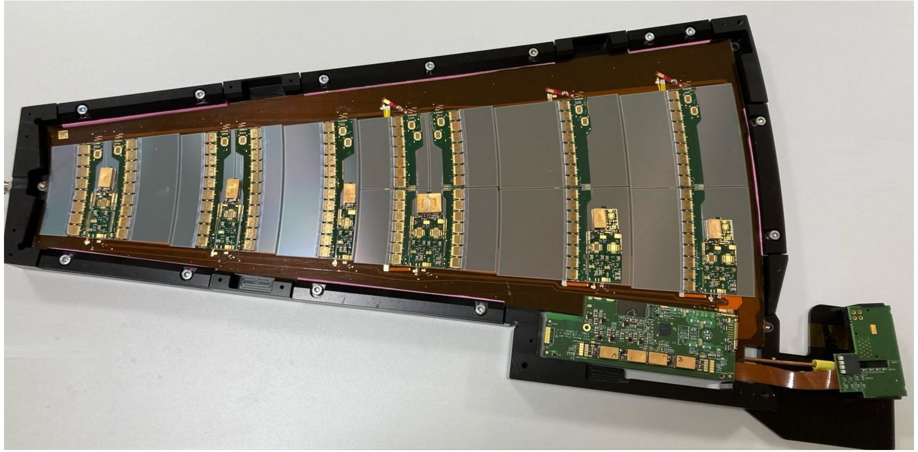
- quality of components and assemblies will be monitored during production phase
  - develop suitable **QA and QC tests** to evaluate required specifications for each object in manufacturing cycle
  - specifications of cores in terms of **geometrical** metrology, **electrical** properties and **thermal** performance
  - focus in this talk: thermal QC tests on core and petal prototypes

Prototyping

Overview of core and petal prototypes

- petal cores
  - several **prototypes** produced at DESY
  - manual **multi-stage assembly** process
  - different **design iterations** (e.g. dimensions, bus tape, pipe routing)





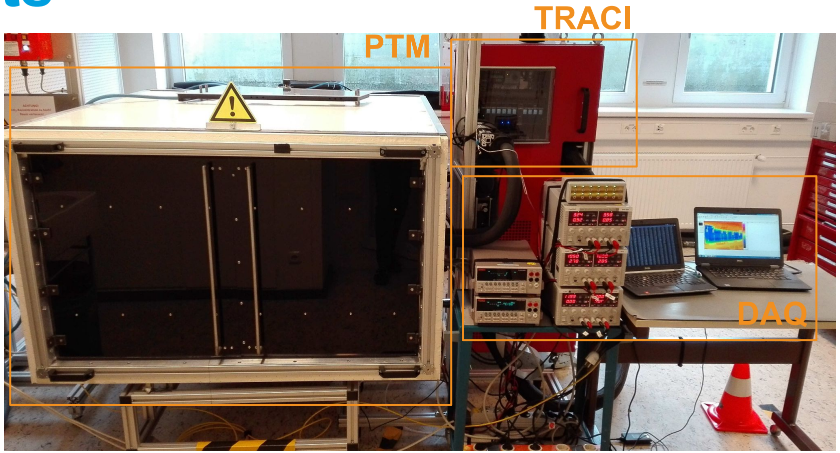
- electrical petal
  - first petal loaded on one side with fully functional silicon strip **modules and EoS card**
  - **electrical readout** possible (e.g. noise studies)
  - realistic **heat load** of sensors and electronics
  - module-on-core loading performed by Uni Freiburg
  - cold testing with CO_2 done at DESY

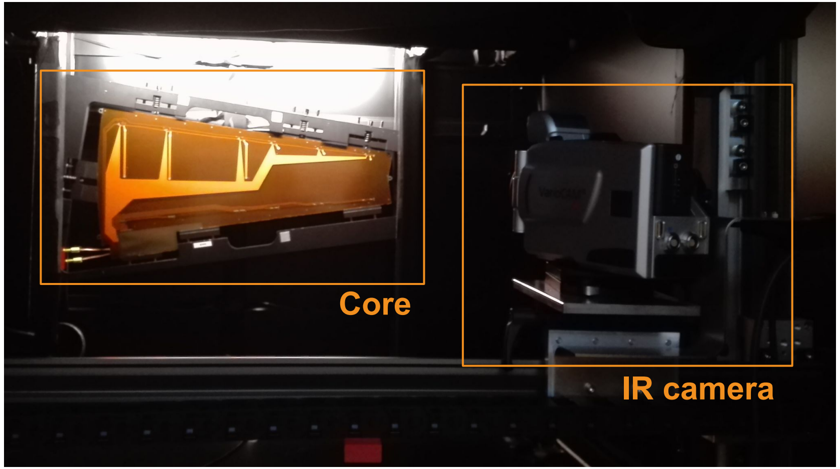
Thermal performance studies on petal cores

Setup for thermal performance tests

Thermal QC of petal cores

- custom-made test box (PTM)
  - **thermally-isolated**, light tight environment
  - rail system for **insertion** of petal cores
  - **dry air** flushing, monitoring of ambient with **SHT sensors**
- infrared thermography as contactless measurement
  - IR camera (**VarioCAM® HD research 875**)
  - readout of thermograms via **IRBIS3 software**
  - tilting angle to avoid **Narcissus effect**
- evaporative CO_2 cooling with TRACI system
  - cooling power up to **100 W**, reaching down to **-25°C**
  - **LabView readout** of system parameters ($\dot{m}$, p, T)
  - additional **diagnostics** of p and T at experiment in- and outlet + visual control of flow state with **sightglasses**

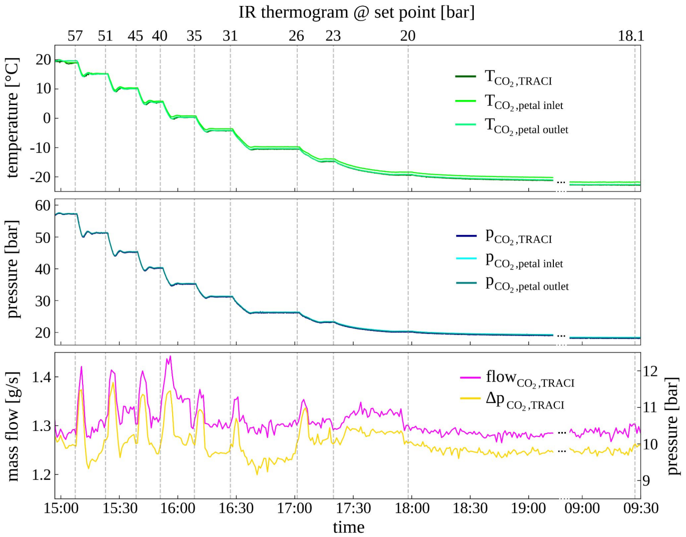


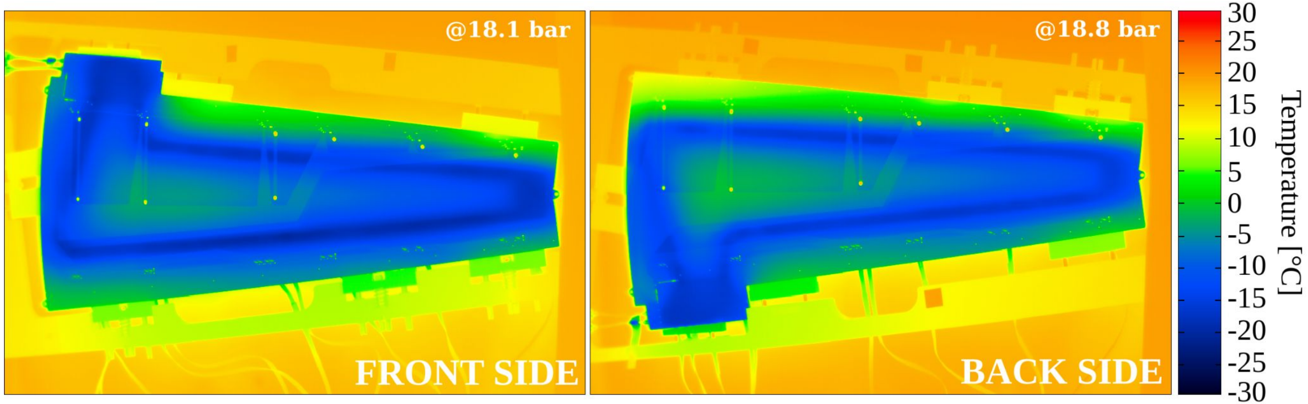


Results of thermal performance test

Testing of petal core prototypes

- thermal testing of cores at different CO_2 set points
  - recording IR thermograms between warmest up to lowest reachable CO_2 temperature (from **+20°C** down to **-25°C**)
  - stabilizing CO_2 **mass flow** and system **pressure drop** over test cycle
  - **logging** of CO_2 state data as well as ambient conditions in PTM
  - example: **IR thermograms** of core front and back side at lowest point



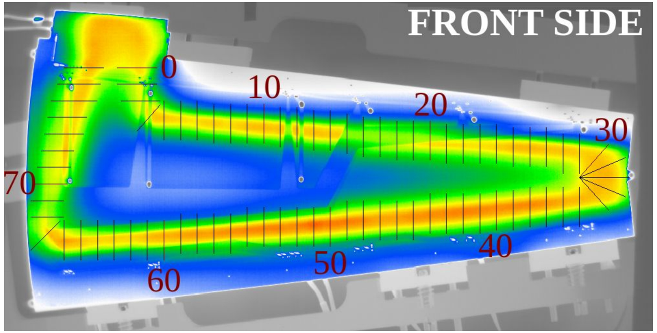


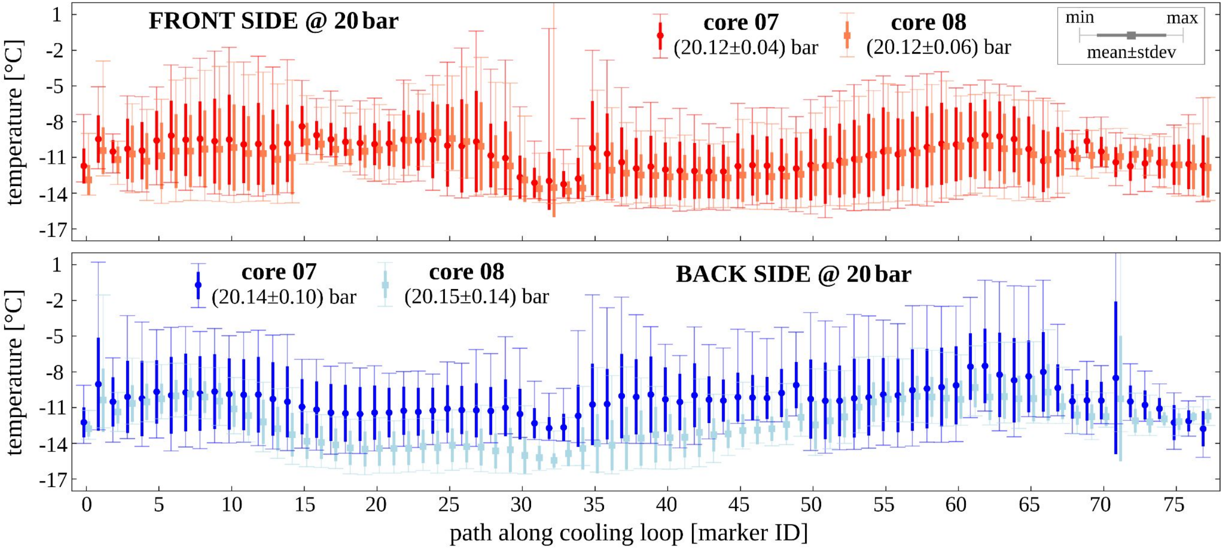
- qualitative evaluation of IR thermograms of petal core
  - good visibility of cooling loop due to high thermally conducting foam →**cooling path** in petal concept
  - no **emissivity correction** applied →gold pad openings as well as buried copper layers in bus tape visible as warmer contours

Analysis of IR thermograms

Temperature distribution along cooling loop

- investigation of temperature distribution along cooling loop
  - define equidistant **linear markers** of defined length in software
  - **comparison** of two core prototypes on front and back side
  - evaluate at different **CO_2 set points** (here: 20 bar ≈ -20°C)



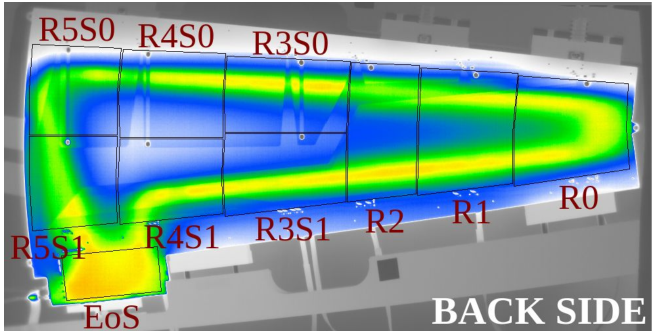


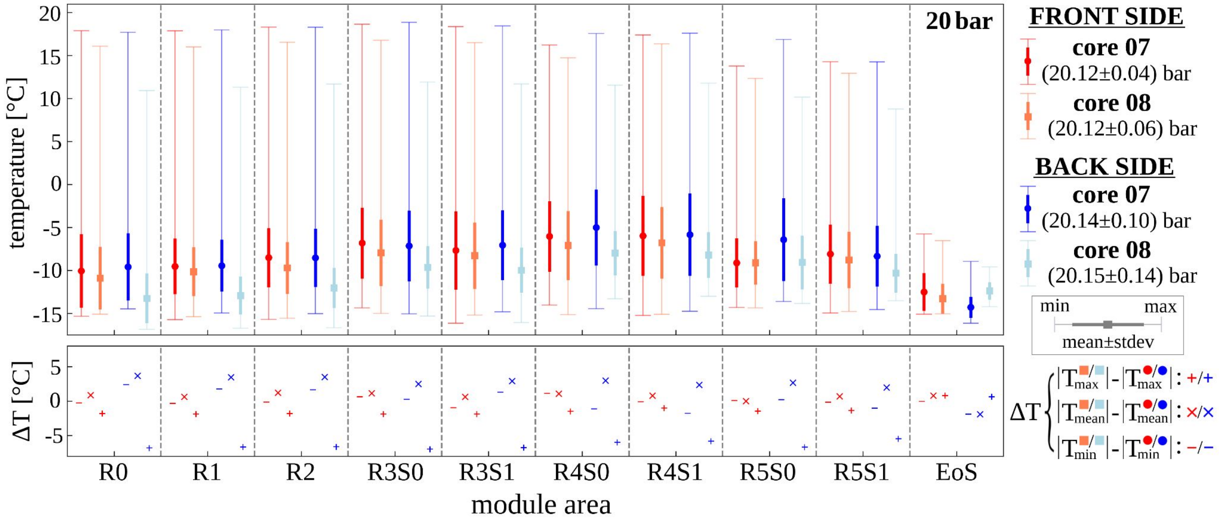
- thermal performance comparison
  - good agreement for the **front** side
  - larger discrepancy for the **back** side
  - independent test cycles can result in non identical **CO_2 states (ṁ, p, T)**
  - different conditions in the ambient cause difference due to **uncorrected emissivity** of core surface

Analysis of IR thermograms

Temperature distribution over module areas

- investigation of temperature distribution over module areas
  - define **polygonal markers** according to module shape in software
  - **comparison** of two core prototypes on front and back side
  - evaluate at different **CO_2 set points** (here: 20 bar ≈ -20°C)





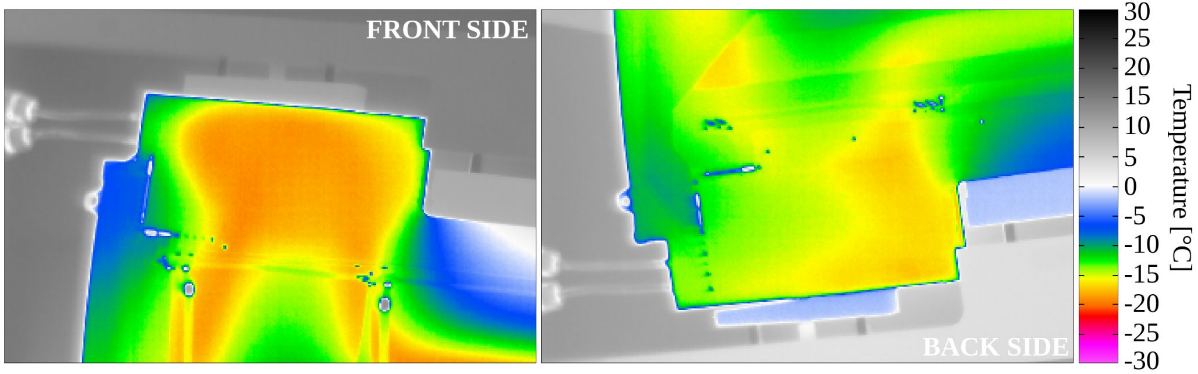
- thermal performance comparison
  - same observation as before: back side of core 08 is observed colder than core 07 → effect of different **test conditions**
  - but: EoS region for core 08 warmer than core 07 contrary to overall trend → indicates a **delamination defect**!

Thermal performance comparison between cores shows overall good agreement.

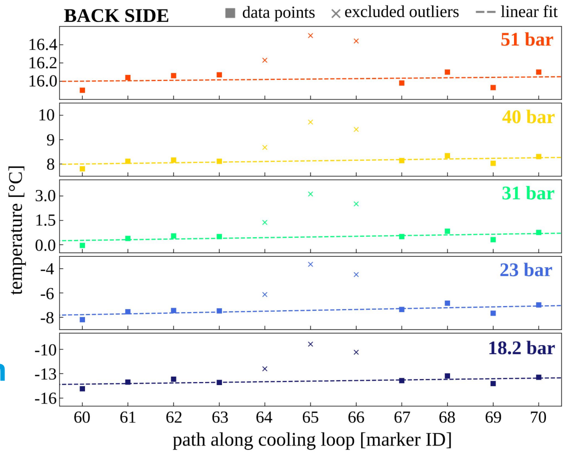
Thermal QC criteria

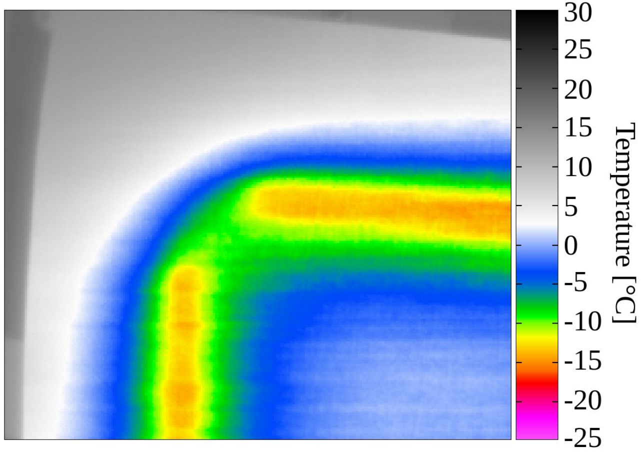
Detection of delamination defects

- observation of delamination defect in EoS region
  - **delamination** between CF **facesheet** and graphite **foam** breaks good thermal path
  - result is a higher surface temperature compared to the intact interface



- observation of delamination defect along cooling loop
  - evaluation of linear markers in this region indicates a **temperature increase** for all investigated CO_2 set points →relative increase up to 33% for lowest CO_2 temperature



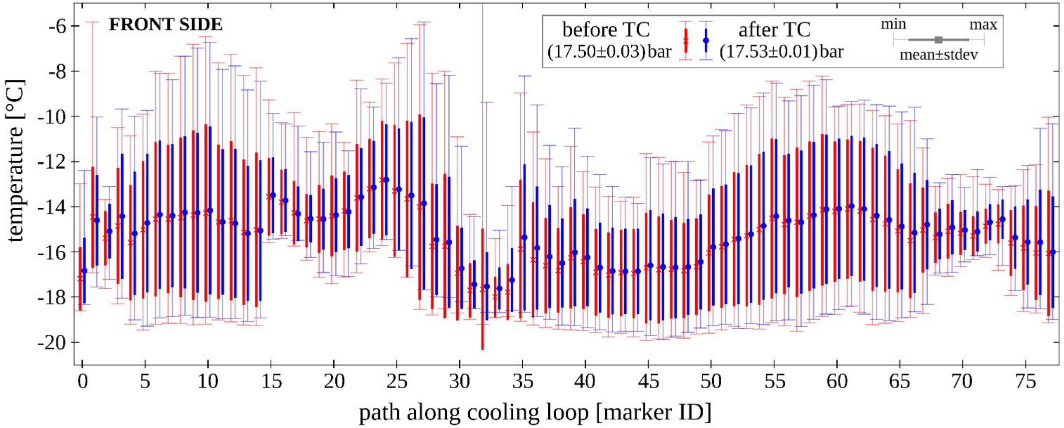


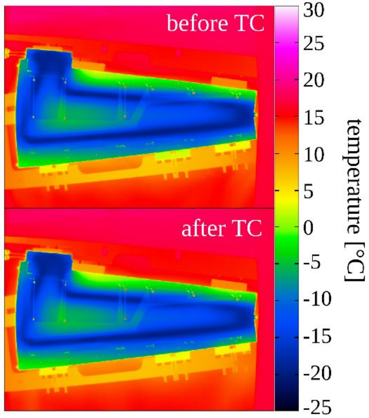
Thermal QC allows to detect delamination defects in critical thermal path.

Thermal cycling of petal cores

Performance comparison after cycling 100 times

- investigate possible degradation of thermal performance over experiment's lifetime
  - **O(100)** thermal cycles between **+40°C** and **-40°C** are expected over full detector lifetime
  - perform fast thermal cycling with **climate chamber**
  - compare **thermal performance** with IR thermography before and after thermal cycling





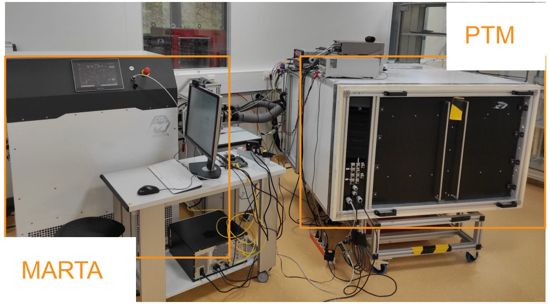
No degradation of thermal performance of cores is observed after thermal cycling.

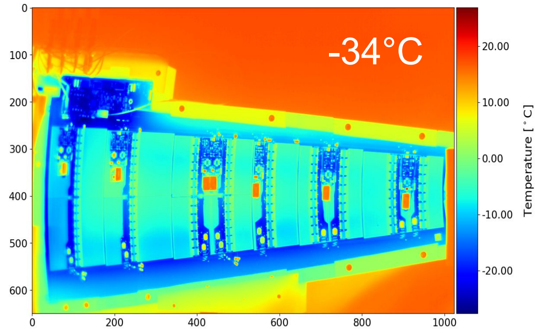
Thermal analysis on electrical petal

Infrared thermography on electrical petal

Not only a debugging tool

- same setup used as for the thermal analysis of cores
  - electrical petal placed into the **PTM chamber**
  - **power cables** and **optical fibers** connected to the EoS
  - power supplies (low and high voltage) for **electronics**
  - total power consumption for one side: **<45 W**
  - **IR camera** located inside the box to observe modules
  - temperature and humidity **monitoring**
  - **MARTA** CO_2 cooling system → from RT to -34°C
- IR thermography can be used for several purposes
  - checking the **functionality** of single electrical component (heat dissipation = working)
  - investigation of **power consumption** for ASICs (comparison to nominal values)
  - **thermal analysis** of single modules, comparison for different CO_2 temperatures

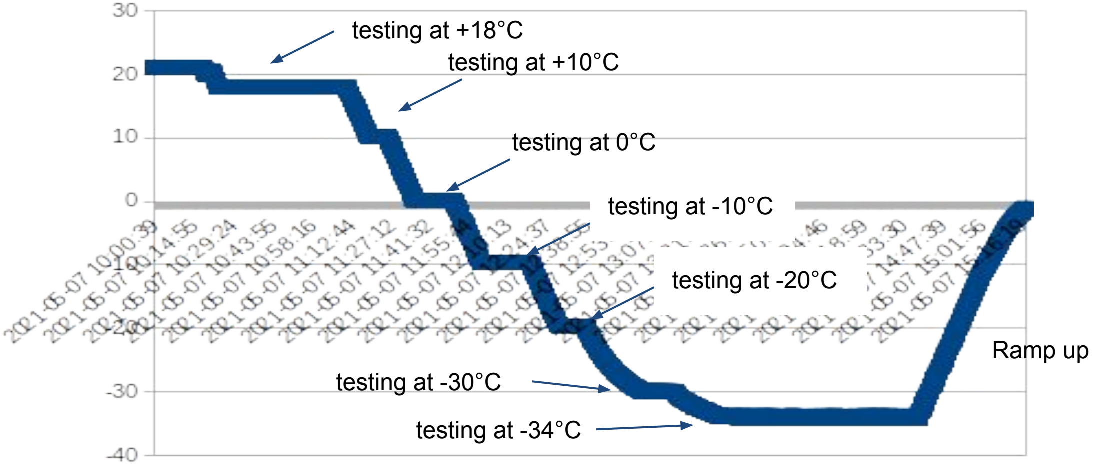


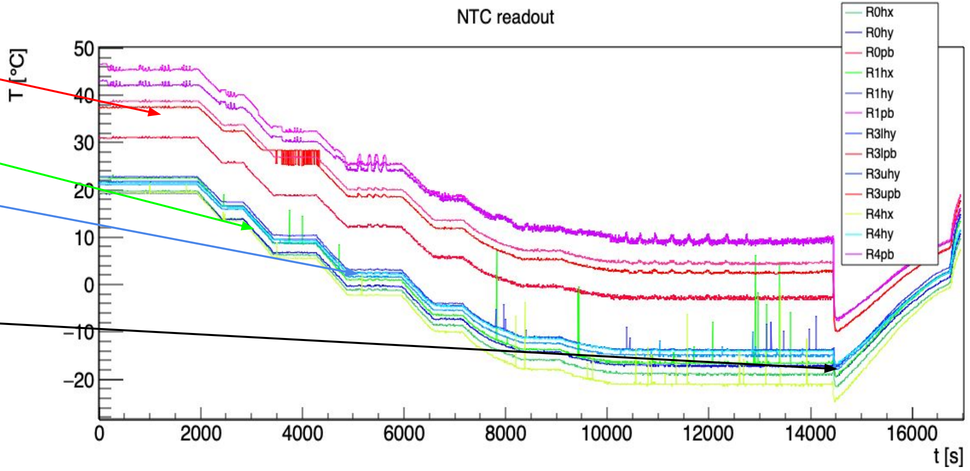


CO_2 cooling cycle

From room temperature to -34°C

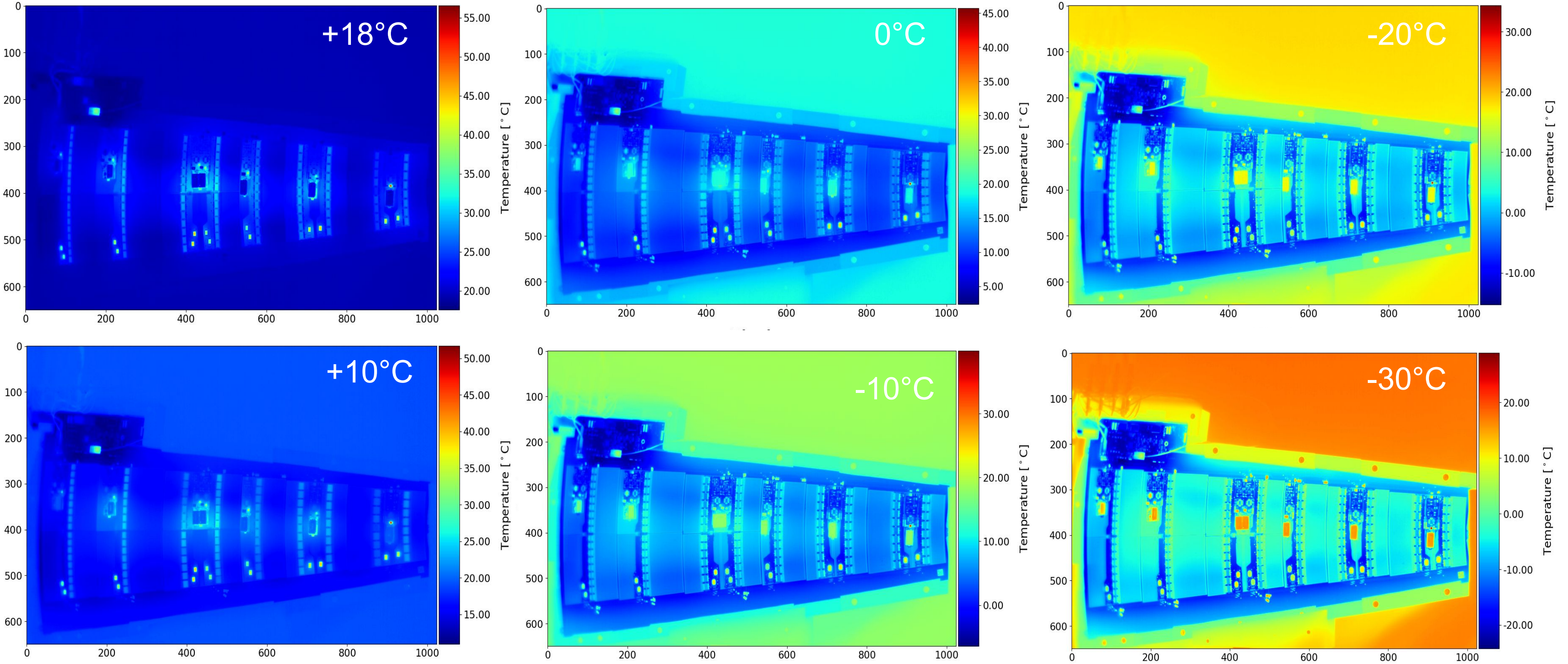
- monitoring of complete test cycle
  - from **highest** to **lowest** possible CO_2 set point
  - here: CO_2 temperature measured at **petal inlet**
- monitoring of electronics temperature with three NTCs on each module
  - NTC on **power board** (red colors)
  - NTC on **hybrid X** (green colors)
  - NTC on **hybrid Y** (blue colors)
  - electrical tests on modules shows as **ripples** on the temperature curve
  - for ramp up: module power **turned off** (except AMAC powering to allow monitoring)





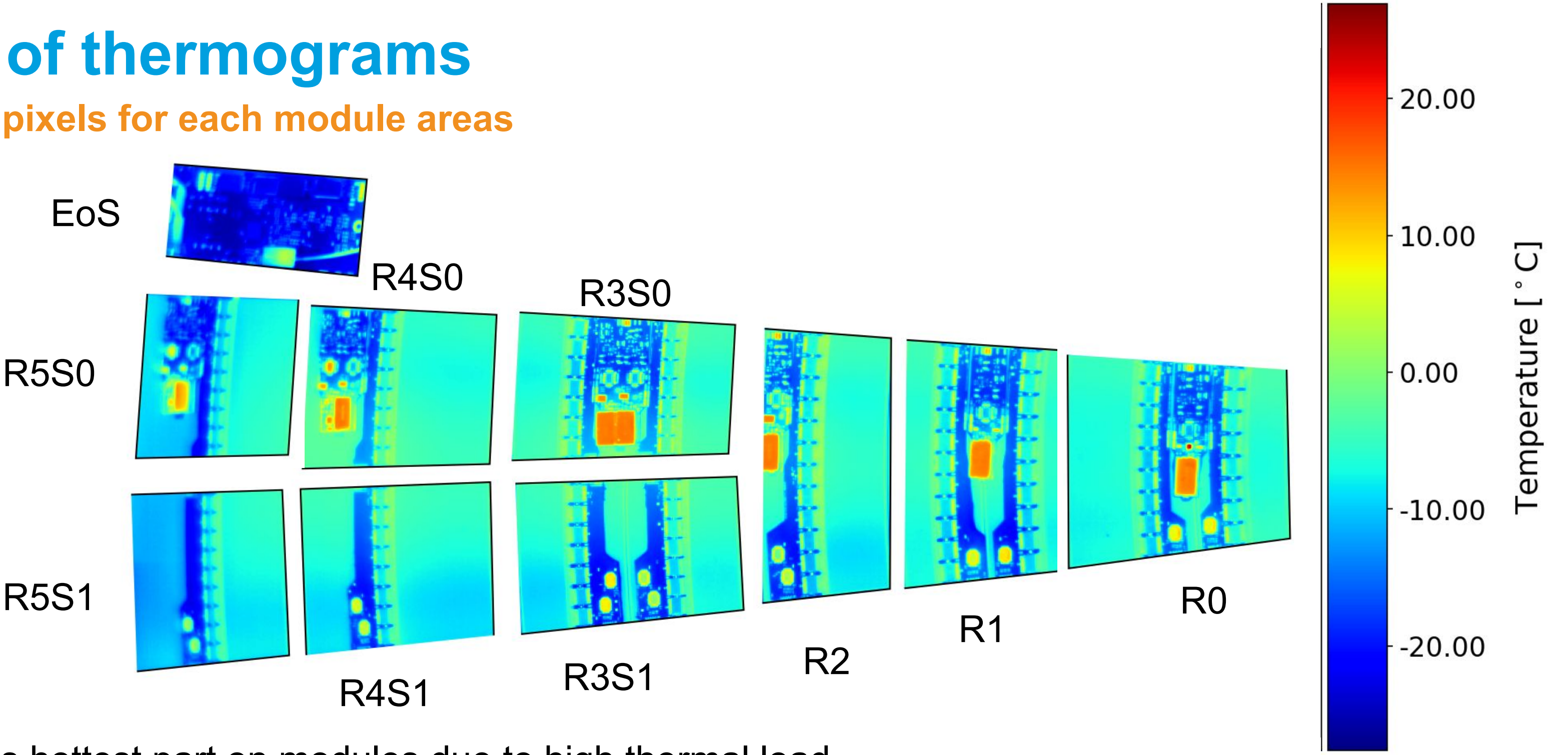
Thermograms of electrical petal

Cooling performance for fully powered modules



Analysis of thermograms

Identifying the pixels for each module areas

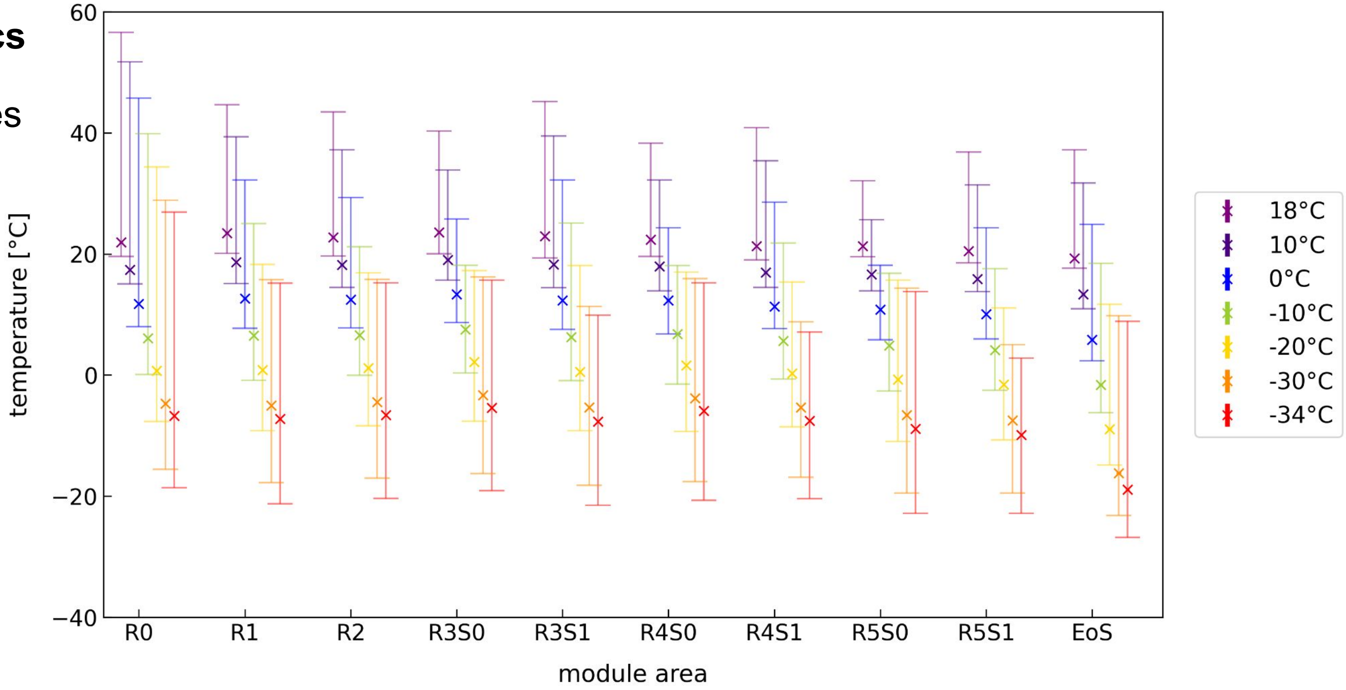


- power board is hottest part on modules due to high thermal load
  - heat load from **DCDC converter** not visible in IR due to copper **shield boxes** (but NTC reading available)
- EoS board well cooled due to CO_2 in/outlet as well as big foam block
  - previously, concerns about **heat dissipation of active EoS components** (lpGBT, DCDCs)

Temperature distribution for different CO2 setpoints

Average and span over the module areas

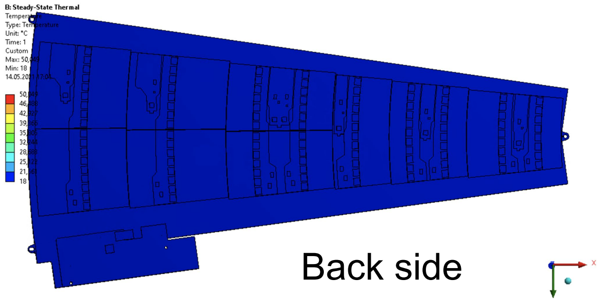
- for fixed CO_2 set points, every module has a similar temperature **characteristics**
- absolute temperature values do not correspond to real temperature
  - no **emissivity correction** applied (e.g. silicon, ASIC chips, PCBs)
- in-depth analysis of thermograms ongoing
  - **studies of ΔT** as subtraction of thermograms to minimize emissivity effects



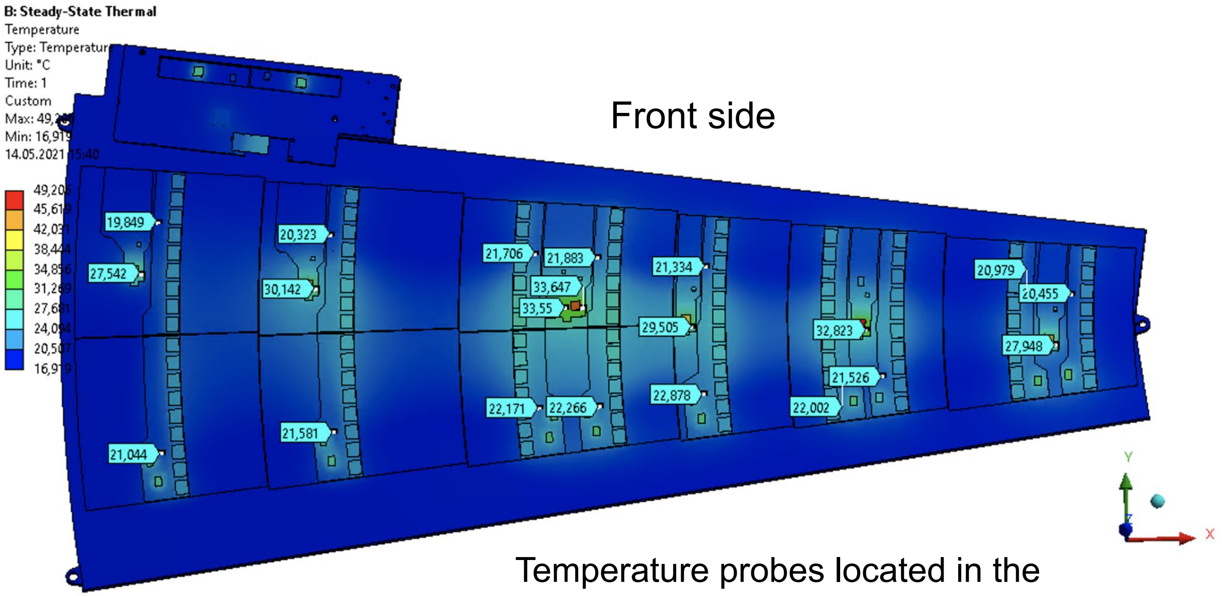
FEA simulation for the electrical petal

Simulation of half a petal

- FEA (Ansys) simulation of half loaded petal allows to estimate the temperature of the NTCs sensors
  - petal is **half loaded** (simulation only takes into account the front side of the petal)
  - CO_2 temperature of **18°C**
  - contact of the air with **10 W/m²K**
  - temperature of the air **20°C**
  - estimated **position of NTCs**
  - simulation without **shield box**
  - further **FEA details** in backup



Back side



Front side

Temperature probes located in the estimated position of the NTCs.

Comparison of the NTCs with the simulation

CO_2 cooling at 18ºC

	R0 NTC	R0 FEA	R1 NTC	R1 FEA	R3l NTC	R3l FEA	R3u NTC	R3u FEA	R4 NTC	R4 FEA
Hybrid 1	20.0	21	22.8	22	nan	22	nan	22	19.3	20
Hybrid 2	19.4	20	22.9	22	21.9	22	21.1	22	21.5	22
Power Board	31.3	28	46.1	33	37.9	34	39.1	34	42.6	30

- NTCs from R2 and R5 are **not working**, some others give **misreadings** (R3l and R3u hybrid1)
- most of the simulation shows a good **agreement** with the reading of the NTCs
  - power board NTCs shows higher values than the simulation, probably from a **heating of the shield box** or maybe not gluing it appropriately (production tool set not yet machined)
  - simulation was not taking into account the **glue pattern** between modules and core → future simulations with it could bring improvement

Conclusion & Outlook

Conclusions

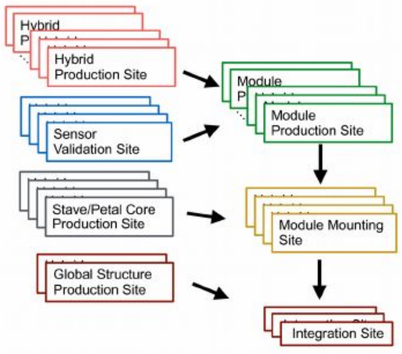
Result of thermal analysis of cores and petals

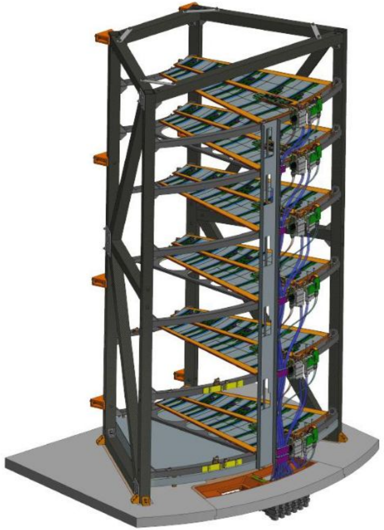
- thermal performance of petal cores is evaluated by IR thermography and dual-phase CO_2 cooling
  - developed a **thermal QC test** procedure for cores during production → possible to detect **delamination defects**
  - expected **cooling performance** with no degradation for different temperature scenarios (e.g. **thermal cycling**) observed
  - a **“golden image” comparison** should be used for thermal QC→ define good performing core and check for differences
  - reproducible and stable **test conditions** (e.g. CO_2 state, ambient) are very important
- IR thermography is a useful tool during electrical tests of petals
  - significant change of temperature on **electrical components** is observed depending on the CO_2 temperature
  - investigation on single module’s temperature showed **comparable temperature values** among them
  - thermal analysis allows to **validate the cooling concept** for petals → almost ready for production phase
- FEA simulation shows good agreement at 18°C for NTC sensors, except of power board NTCs
  - possible reason could be the **effect of the shield boxes** (not included in simulation)
  - **NTC calibration** need to be understood, possible offsets in absolute values from experiment
  - more studies will be conducted for other CO_2 set points to **check agreement over full working range**

Outlook

Production plans and further testing

- petal **core production** will be outsourced to industry
  - alternative assembly process with higher throughput than in-house prototyping
  - next step: qualify industry prototypes on their specifications to kick-off production
  - QA and QC testing of cores will be performed by the collaboration
- finalizing **QA and QC** plans for modules, cores and fully-loaded petals
  - validate developed test stands for QA and QC testing of components
  - site qualification of worldwide-distributed assembly sites
  - automatic tracking of test results by ATLAS ITk production database
- planning and performing end-cap detector **system test**
  - building ⅛ slice of end-cap global structure with 12 petals and electrical and cooling services
  - performing realistic testing of full system design (electrical performance, cooling, DAQ)
  - evaluating tracking performance with cosmic muons





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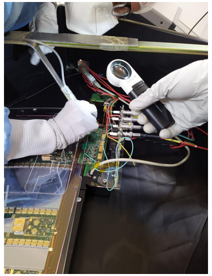


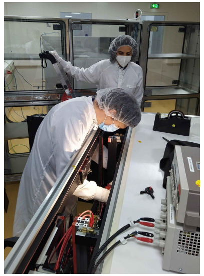

Further references

Technical Design Report for the ATLAS Inner Tracker Strip Detector, ATLAS Collaboration, ATLAS-TDR-025

Detection and Identification of Electrons and Photons, Jan-Hendrik Arling (*PhD thesis*), DESY-THESIS-2020-022

Thermo-electrical modelling of the ATLAS ITk Strip Detector, Kurt Brendlinger *et al.*, arXiv:2003.00055

BONUS

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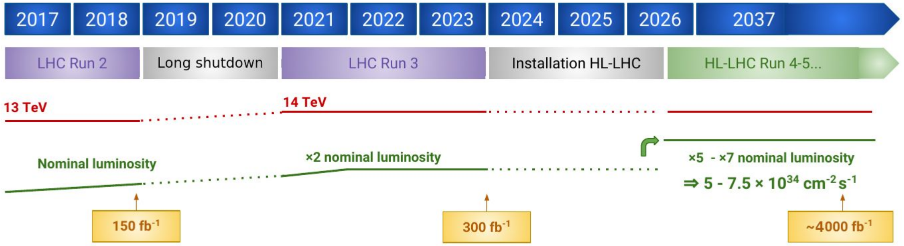
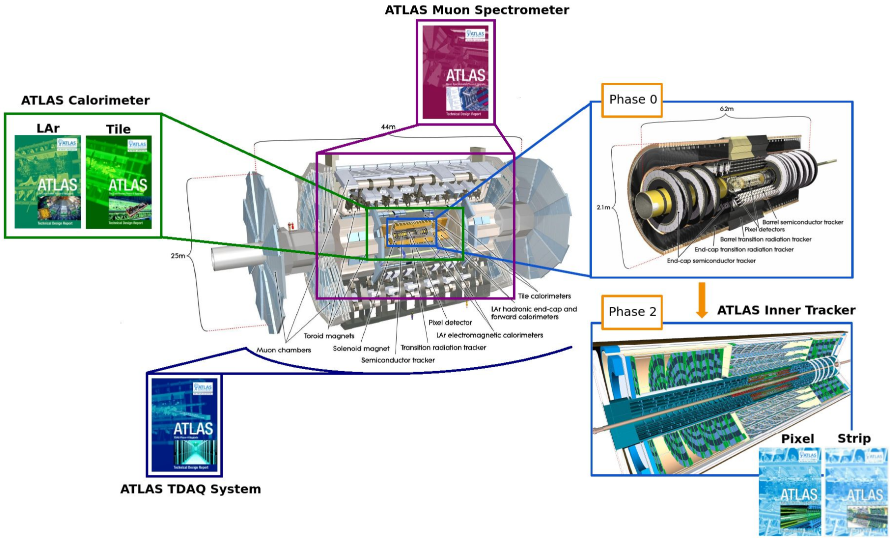
The ATLAS Phase-II Upgrades for the High-Luminosity LHC

New detectors for the challenges of the HL-LHC

- high-luminosity phase of the LHC
  - planned start of operation in 2026
  - increase of **nominal luminosity** by factor 5-7
  - collection of factor 10 more **integrated luminosity**



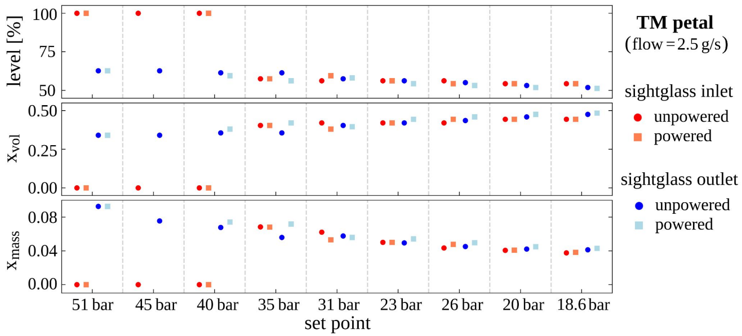


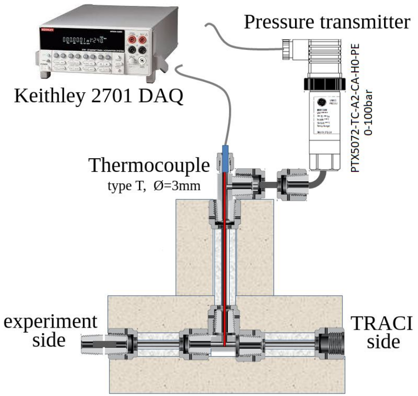
- challenges for detectors under HL-LHC conditions
  - **pile-up** increases from ~60 to ~200
  - **radiation levels** are by a factor of 10 higher
  - faster **readout** & higher **bandwidth** for improved triggering
- ATLAS phase-II upgrade programme
  - **upgrades** of detector subsystems needed to resume good performance of LHC data taking
  - focus in this talk: the new **tracking detector system**

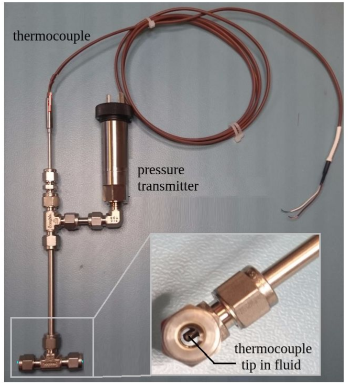
CO_2 diagnostics

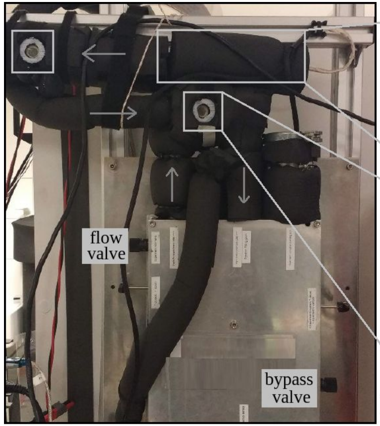
Additional measurement of p and T + visual inspection with sightglasses

- pressure and temperature measurement at petal in- and outlet
  - custom-made **pT-probe** with pressure transmitter + thermocouple (type T)
  - readout via **Keithley DAQ** and python monitoring
- additional heater (Watlow, up to 200 W)
  - can be used for triggering **CO_2 boiling** (not used here)
- sightglasses at in- and outlet for visual inspection of flow state
  - observing **bubbles** in outlet can hint to bi-phase state
  - **quantitative analysis** not really conclusive

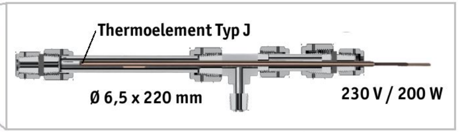




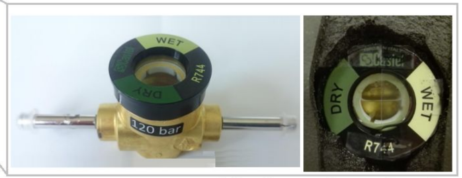




local box



heating element

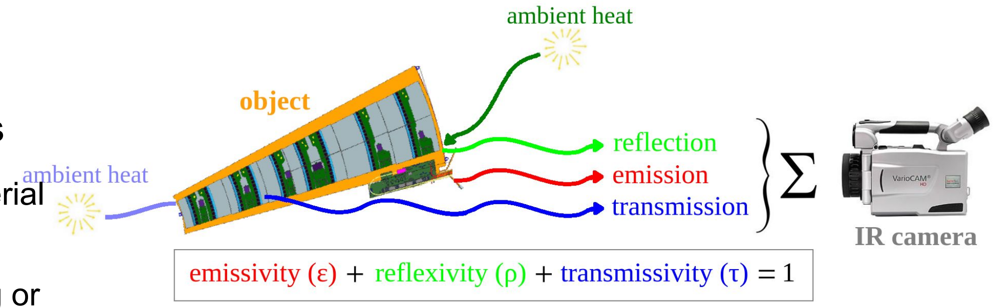


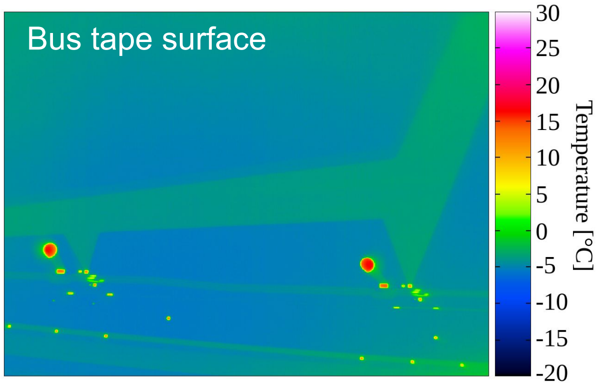
sightglass at in- and outlet

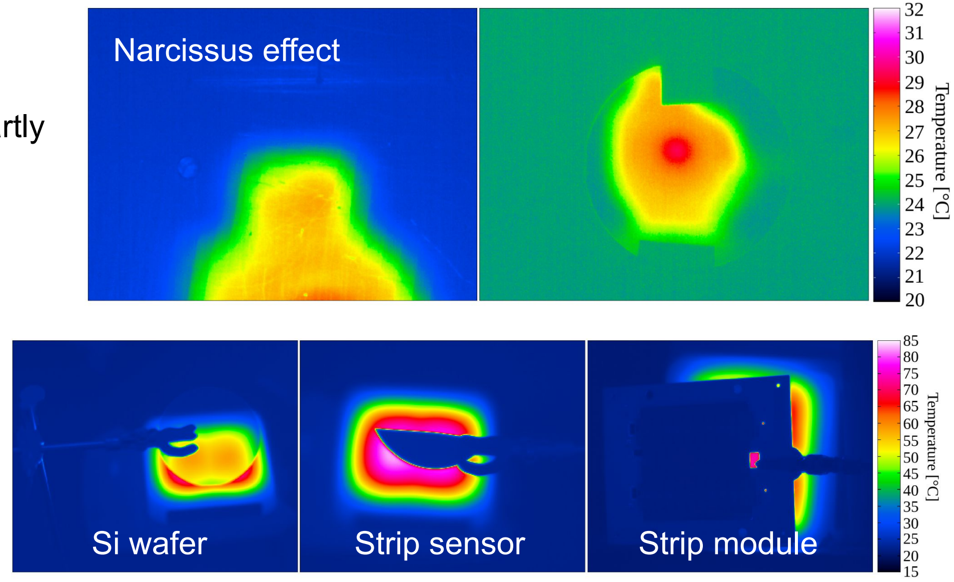
101 of infrared thermography

Emissivity as critical measurement parameter

- IR camera is collecting heat from several sources
  - objects have **emissivity < 1** →depending e.g. on material properties, surface manufacturing
  - **emissivity correction** possible → e.g. painting, taping or contact temperature probe
  - camera itself can have influence →**Narcissus effect**
  - objects under investigation (bus tapes, silicon) have partly very poor emissivity →**measured ≠ real** temperature



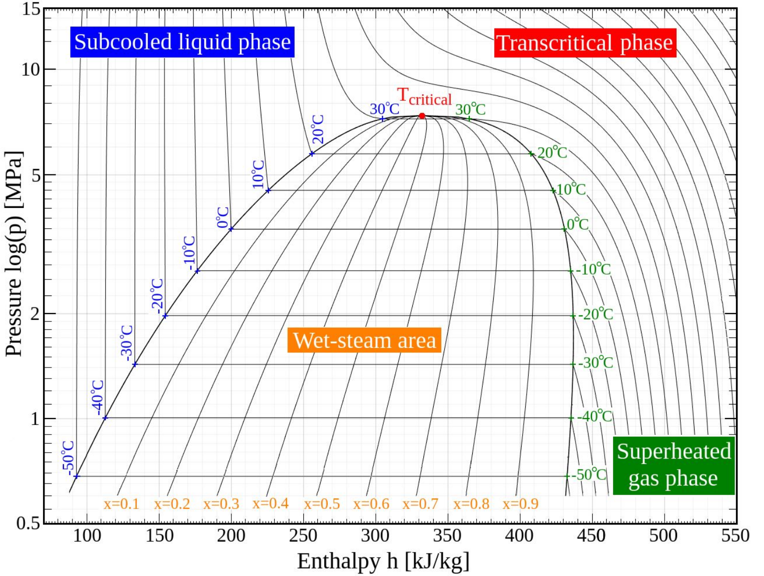


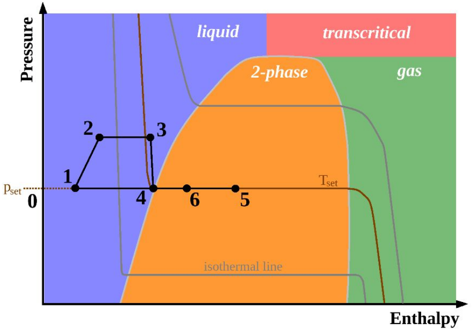


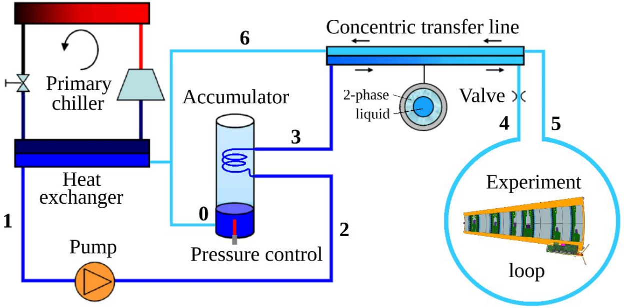
101 of dual-phase CO_2 cooling

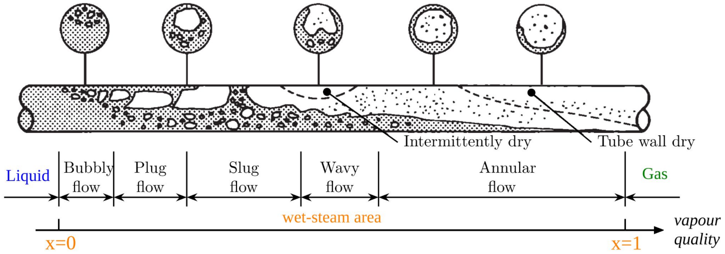
Thermodynamics of evaporative cooling & 2-PACL systems

- evaporative CO_2 cooling
  - typical **log(p)-h diagram** of CO_2 →operation in **wet-steam area**
  - use of evaporative **cooling capacitance** →very effective
  - actual CO_2 **flow pattern** important →avoid **dry-out** with poor cooling
- 2-Phase Accumulator Controlled Loop (2-PACL) systems
  - **TRACI** and **MARTA** cooling machines operate use 2-PACL method
  - **cooling cycle** is shown in log(p)-h diagram and on system level





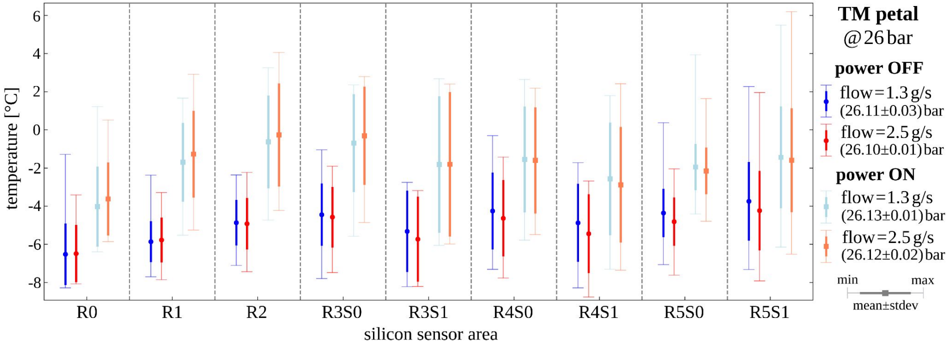


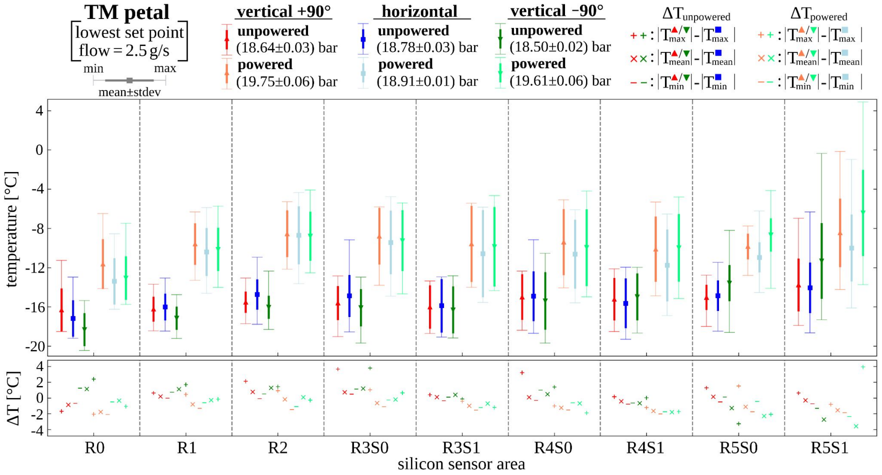


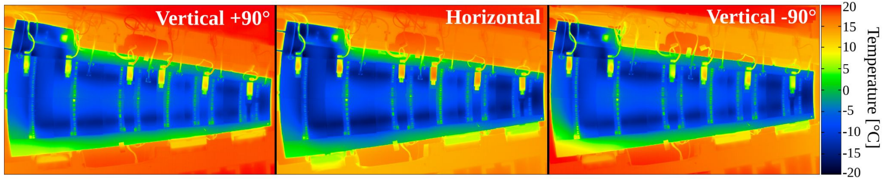
Influence of CO_2 cooling on thermal performance

Study on mass flow and orientation with TM petal

- performed influence studies with **thermo-mechanical petal** prototype
- studied influence of the selected CO_2 mass flows
  - compared nominal flow (**1.3 g/s**) with highest possible flow with TRACI (**2.5 g/s**) + **ON** and **OFF** petal state
  - **no influence** observable
- studied influence of petal orientation
  - compared **horizontal**, **vertical +90°** and **vertical -90°** configuration (extremes in end-cap setup)
  - overall, **no influence** observable; but for **R0 and R5** a possible effect can be seen (under investigation)







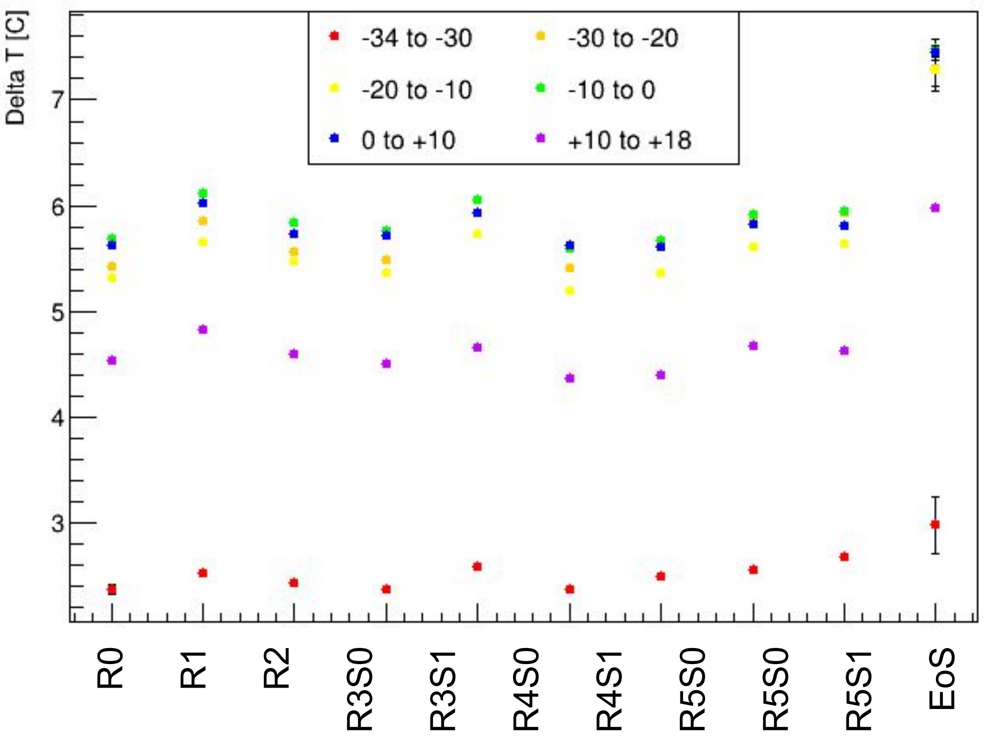
Delta T

Comparison of two temperatures from the thermogram

To bypass the **emissivity** property of each component, the area of same module can be compared with different CO_2 temperatures (from -34°C to +18°C)

PRELIMINARY

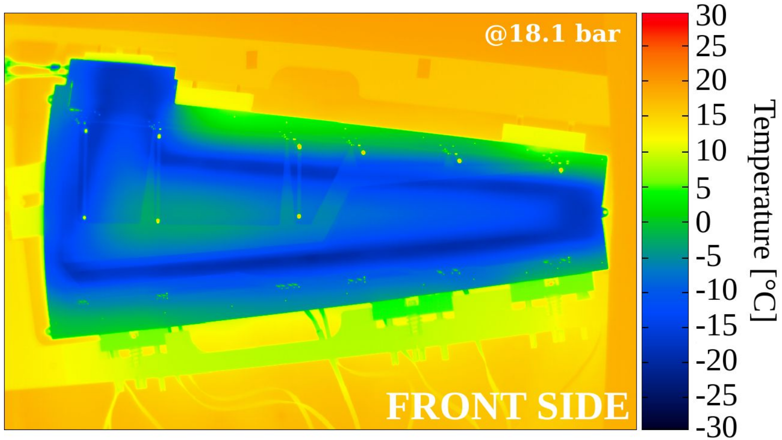
Further analysis and interpretation of results ongoing.

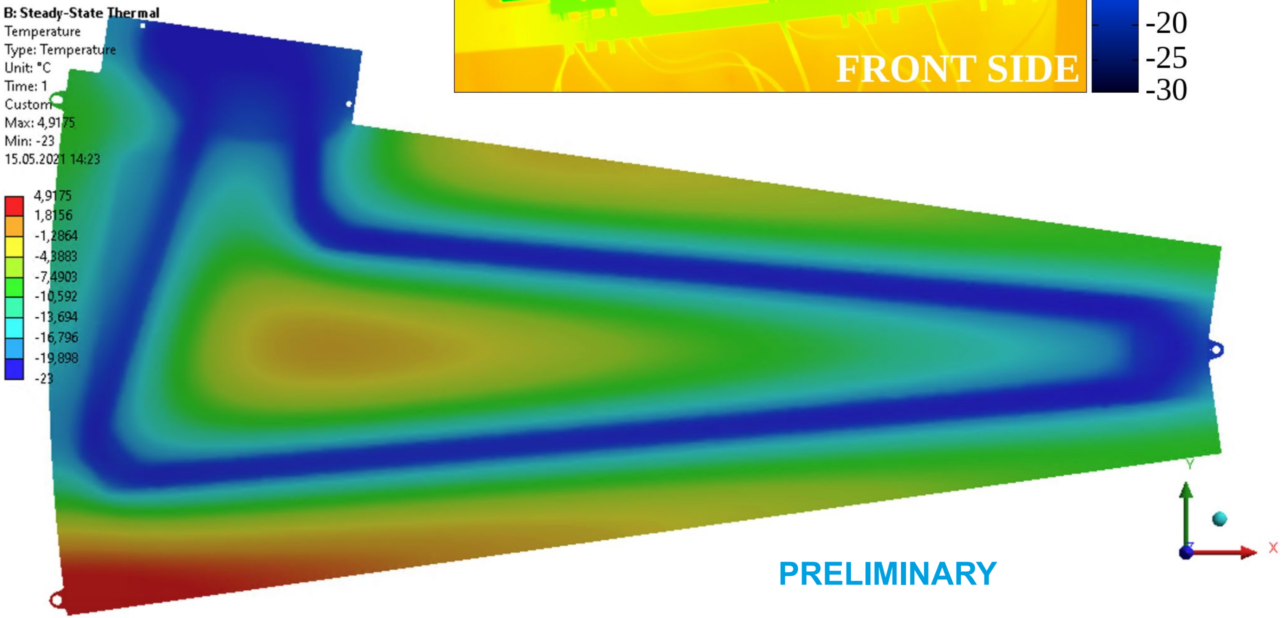


FEA of petal cores

Simulation of thermal QC of cores

- FEA simulation of petal core
  - CO_2 temperature of -22C (TRACI set point: 18 bar)
  - contact of the air with 10 W/m^{2}K
  - temperature of the air 20°C
- generally, good agreement with experimental IR results
  - high thermal conductance of foam interface to surface visible
- possible improvements
  - simulation of bus tape surface (partly emissivity effects)





FEA values

Power load

Values from Kurt Brendlinger

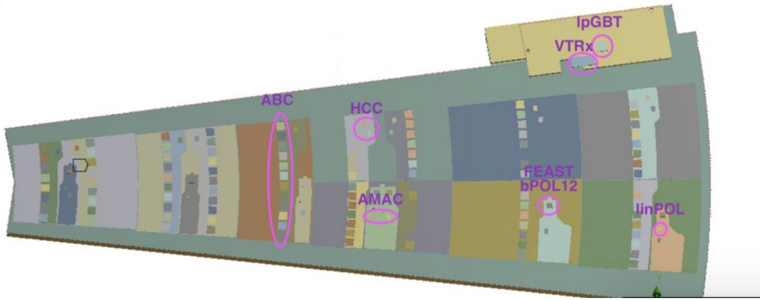
Electrical load

Core

Component	Power [W]
AMAC	0.068
ABC	0.1425
HCC	0.315
bPOL12V R0	1.212
bPOL12V R1	1.433
bPOL12V R2	0.935
bPOL12V R3	1.045
bPOL12V R4	1.156
bPOL12V R5	1.267
linPOL12V	0.033

EoS

Component	Power [W]
lpGBT	0.38
VTRx	0.338
bPOL2V5	0.056
bPOL12V	0.633



FEA values

Contact values

Part or contact	Material	$K_x/K_y/K_z[\mathrm{W\,m^{-1}\,K^{-1}}]$	Thicnkess [mm]	Coverage
ASIC	Silicon	191 (250 K)-148 (300 K)	0.30	
ABC to hybrid	UV cure glue	0.5	0.08	50%
HCC to hybrid	UV cure glue	0.5	0.08	75%
Hybrid PCB	Cu/polymide	72/72/0.36	0.2	
Power PCB	Cu/polymide	120/120/3	0.3	
PBC to sensor	FH5313 Epolite	0.23	0.12	75 %
Sensor	Silicon	191 (250 K)-148 (300 K)	0.30	
Sensor to bus	DC SE4445	2.	0.1-0.2	100%
Bus tape	Polymide/Cu/Al	0.17/0.17/0.17	0.24	
Bus to CF	ideal			
CF	0-90-0 CFRP	180/90/1	0.15	
CF to allcomp	Hysol 9396 + graphyte	1	0.1	
Allcomp	Allcomp 2 g/cm3	17	5	
Allcomp to pipe	Hysol 9396 + graphyte	1	0.1	
Pipe	Titanium	16.4	0.14-0.15	