Thermo-Mechanical Performance of the Local Supports for the ATLAS ITk Pixel Outer Barrel:
Experimental and FEA Studies

Diego Álvarez[1], Sebastien Michal[2], Ricardo Tavares Rego[1], Valery Akhnazarov[1], Christophe Bault[1], Jerome Bendotti[1], Francois Boyer[1], Andrea Catinaccio[1], Alexander Christen[3], Jordan Degrange[1], Neil Dixon[1], Philippe Favre[2], Gilles Grandvaux[1], Coralie Husi[2], Susanne Kuehn[1], Jean-Philippe Logier[4], Mathieu Niclas[4], Nicola Pacifico[1], Alexandre Perez[1], Eric Vigeolas[4], Remus Vrancianu[1].

[1]CERN; [2]Universite de Geneve; [3]University of Bonn, [4]CPPM;

Forum on Tracking Detector Mechanics, Tübingen

1st June 2023

Outline

- Introduction
  - ATLAS ITk Pixel Outer Barrel Local Supports

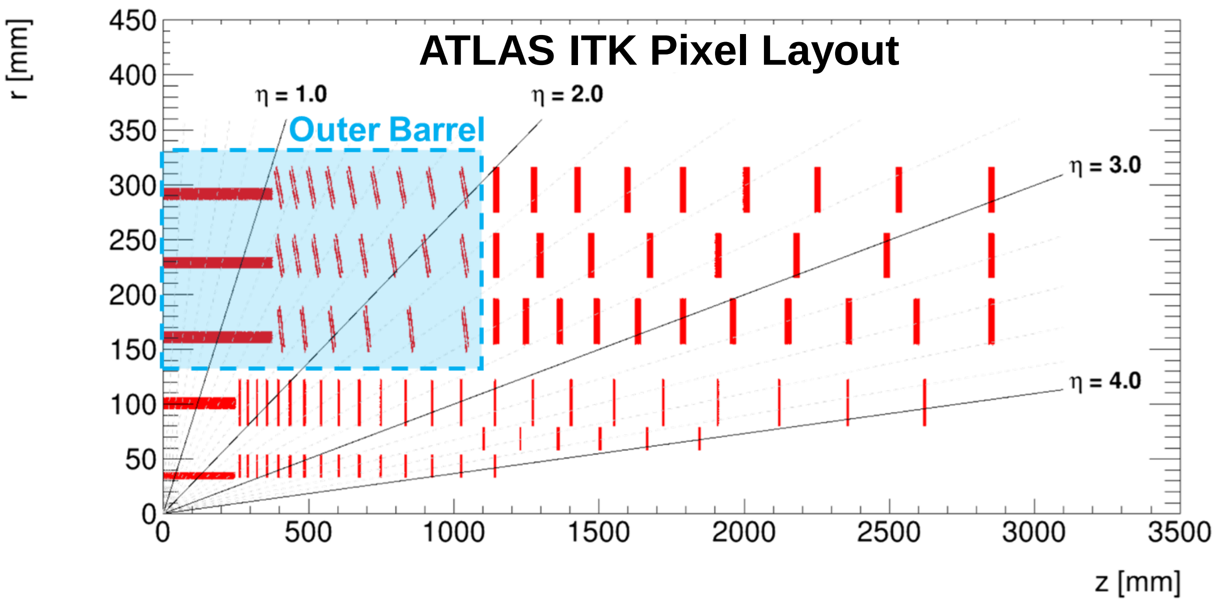
- Thermal Studies
  - Thermal FEA
  - Thermal Prototypes

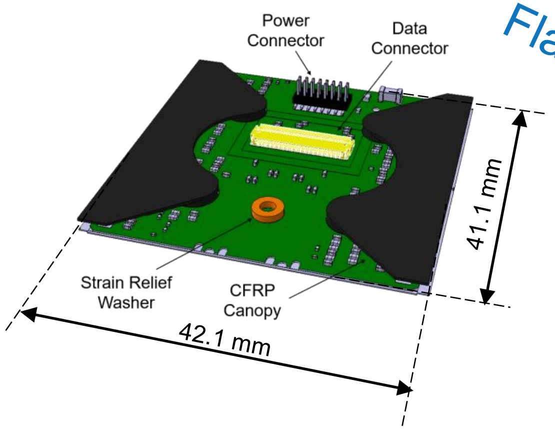
- Thermo-mechanical Studies
  - Thermo-mechanical FEA
  - Thermo-mechanical Prototypes

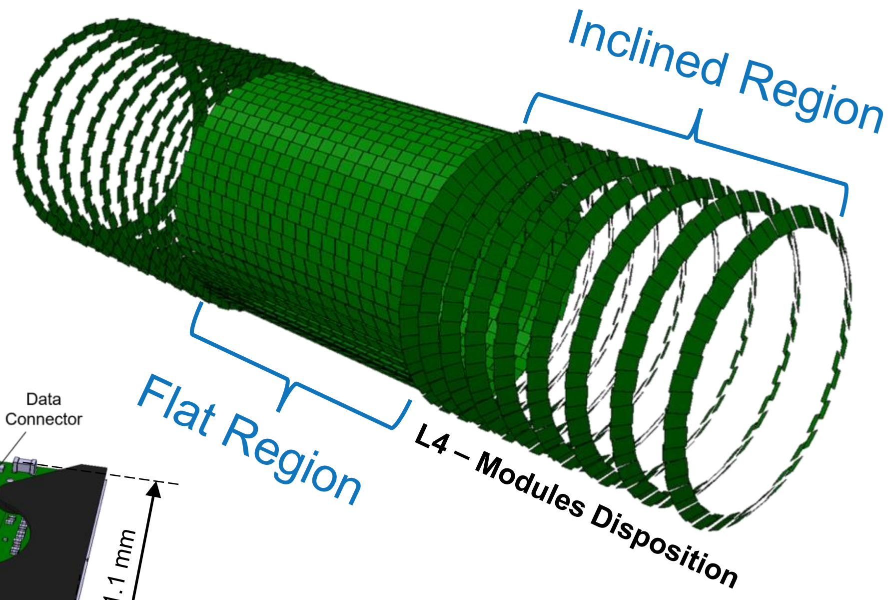
- Summary & Conclusions

Introduction:
Outer Barrel Local Supports

ATLAS ITk Pixel: Outer Barrel Layout







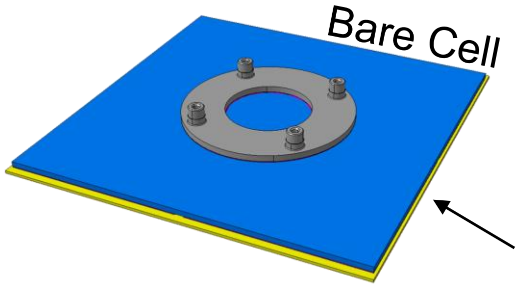
Single QUAD hybrid module type in flat & inclined regions

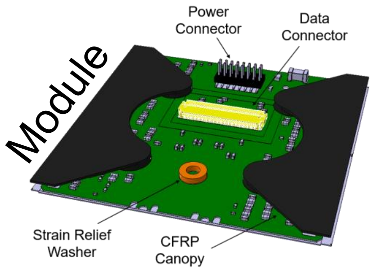
- Pixel Outer Barrel
  - 4472 Pixel Modules
  - Active Area: 6.94m^2 (53.5% of Pixel Detector)
  - >14 Institutes from 5 funding agencies

4 times the area of the current ATLAS ITk Pixel OB!!

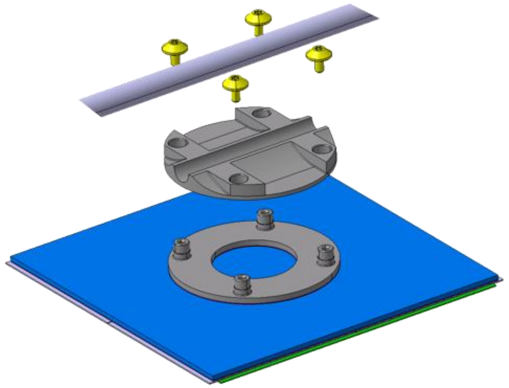
Outer Barrel: Local Supports

Module Cells



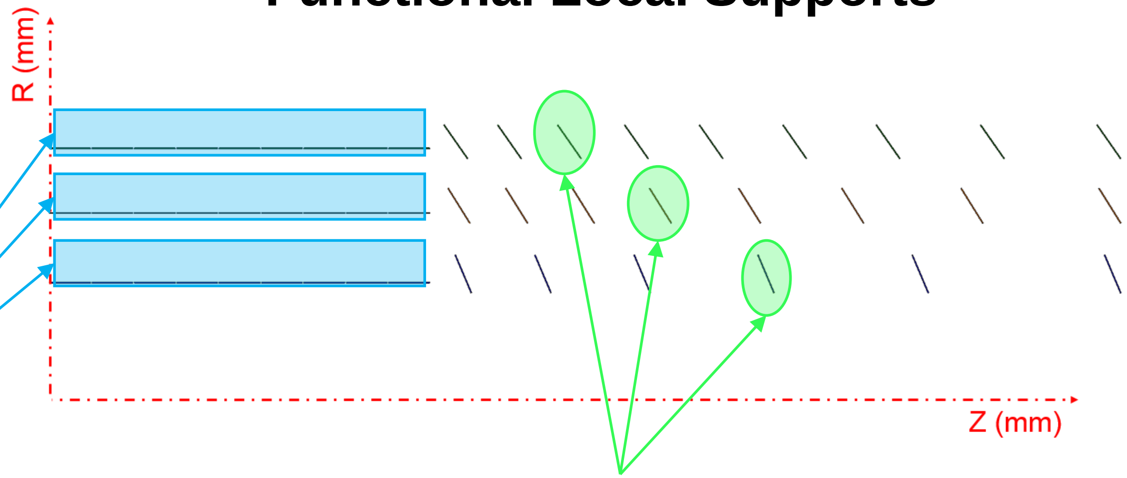


Module glued on Bare Cell



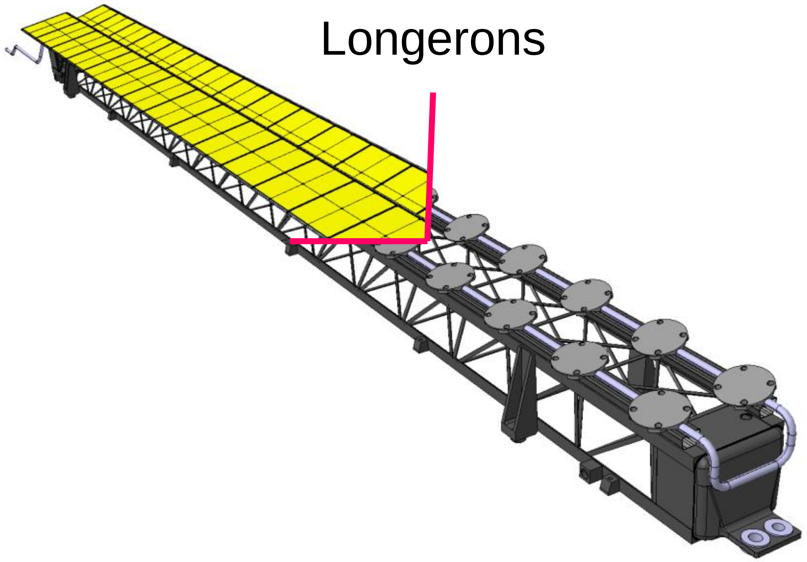
Module Cells screwed to FLS with TIM on the interface (re-workability!)

Functional Local Supports



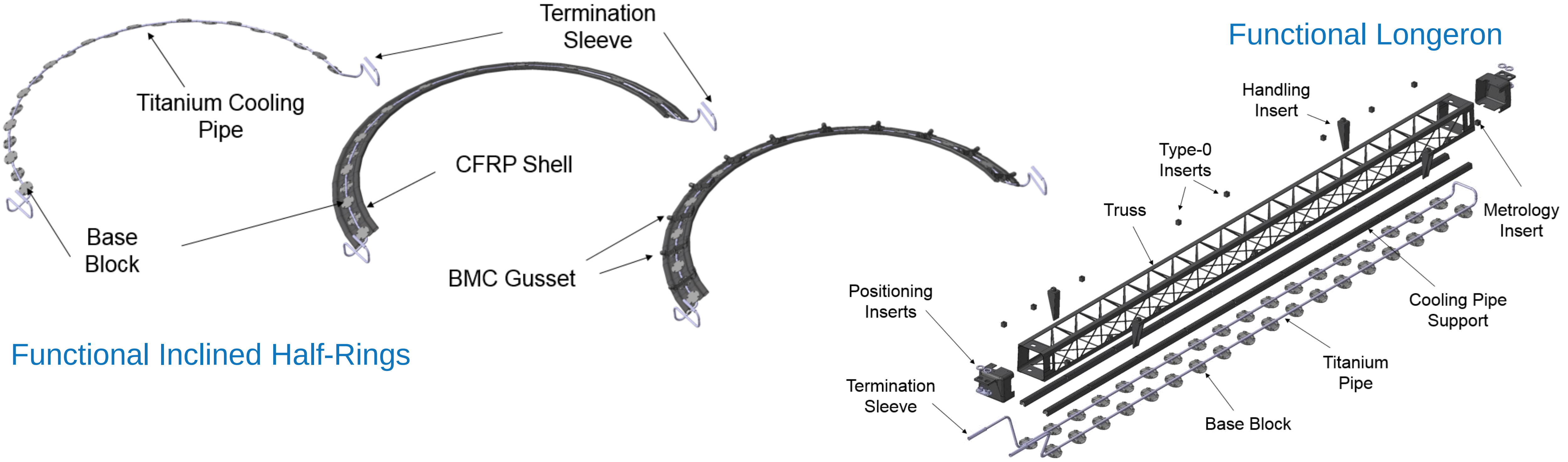
Longerons

Inclined Half-Rings (IHR)



Functional Local Supports

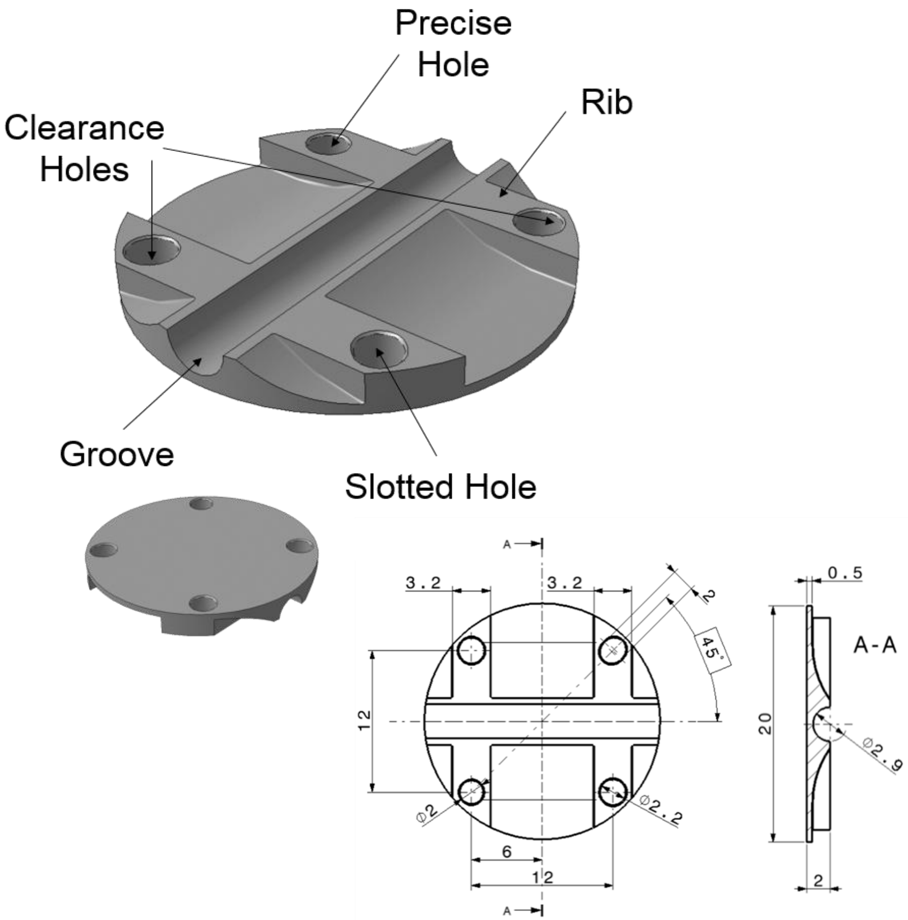
- Comprised of three elements optimised "independently" for specific functions:
    - **CFRP Structure** → mechanical support and stiffness
    - **Inserts and BMC Gussets** → positioning and attachment to interfaces
    - **Functional Cooling Pipe** → thermal management
- All parts joined with electrically conductive epoxy (graphite loaded)

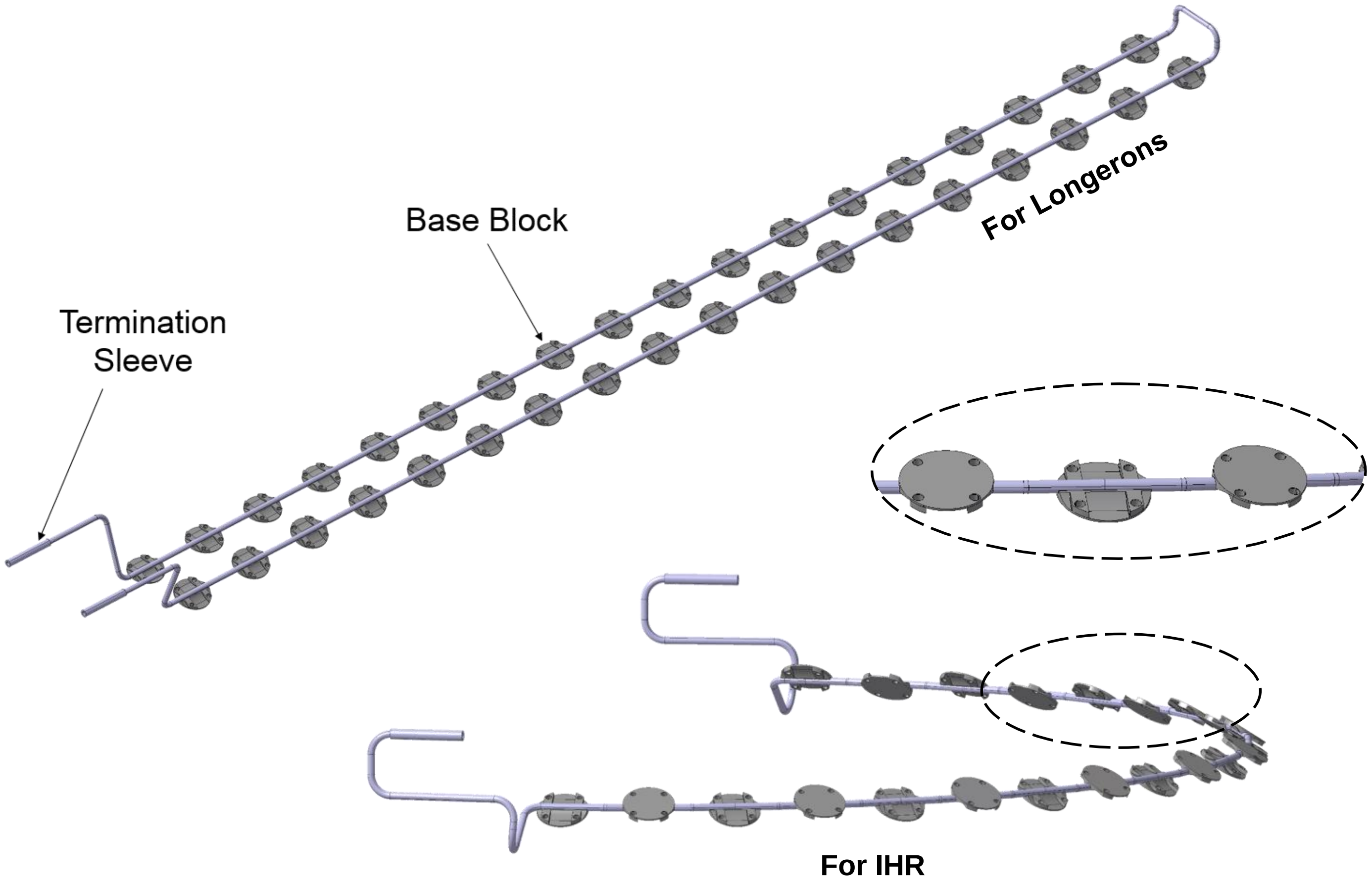


Functional Cooling Pipe

- Ti Cooling Pipe (with brazed termination sleeves)
- Al-Graphite Base Blocks (single design)

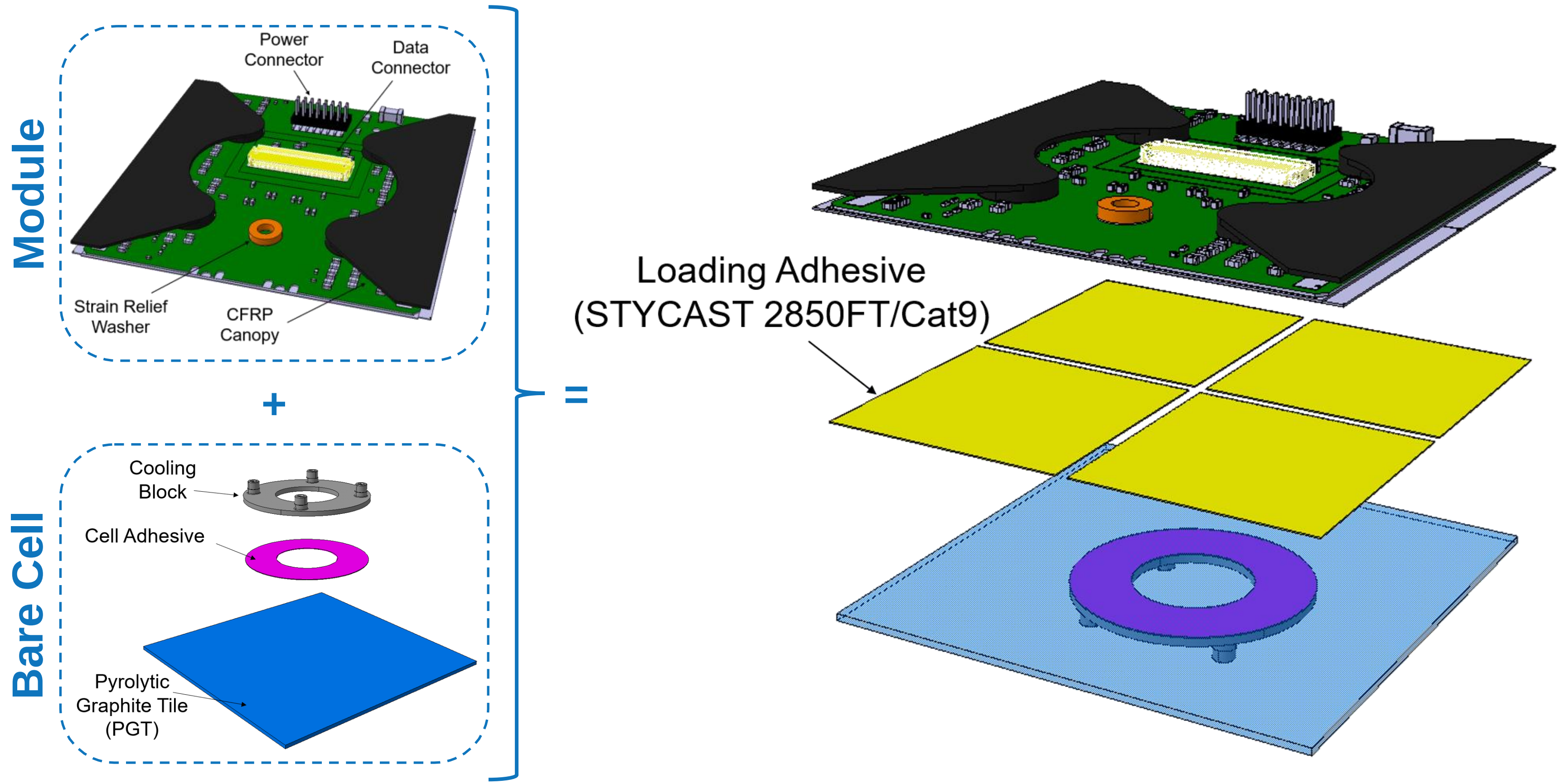
Ni-coating + Soldering

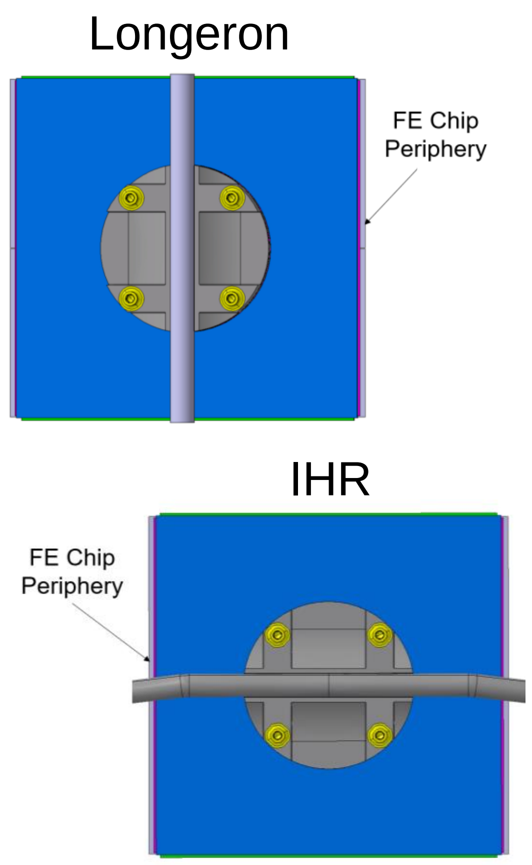




Module Cell

- Single design for longeron & IHRs (90-degree rotation with relation to the cooling pipe)
- Designed for re-workability and distributed production model
  (modules glued on bare cell and tested in 6 institutes around the world)



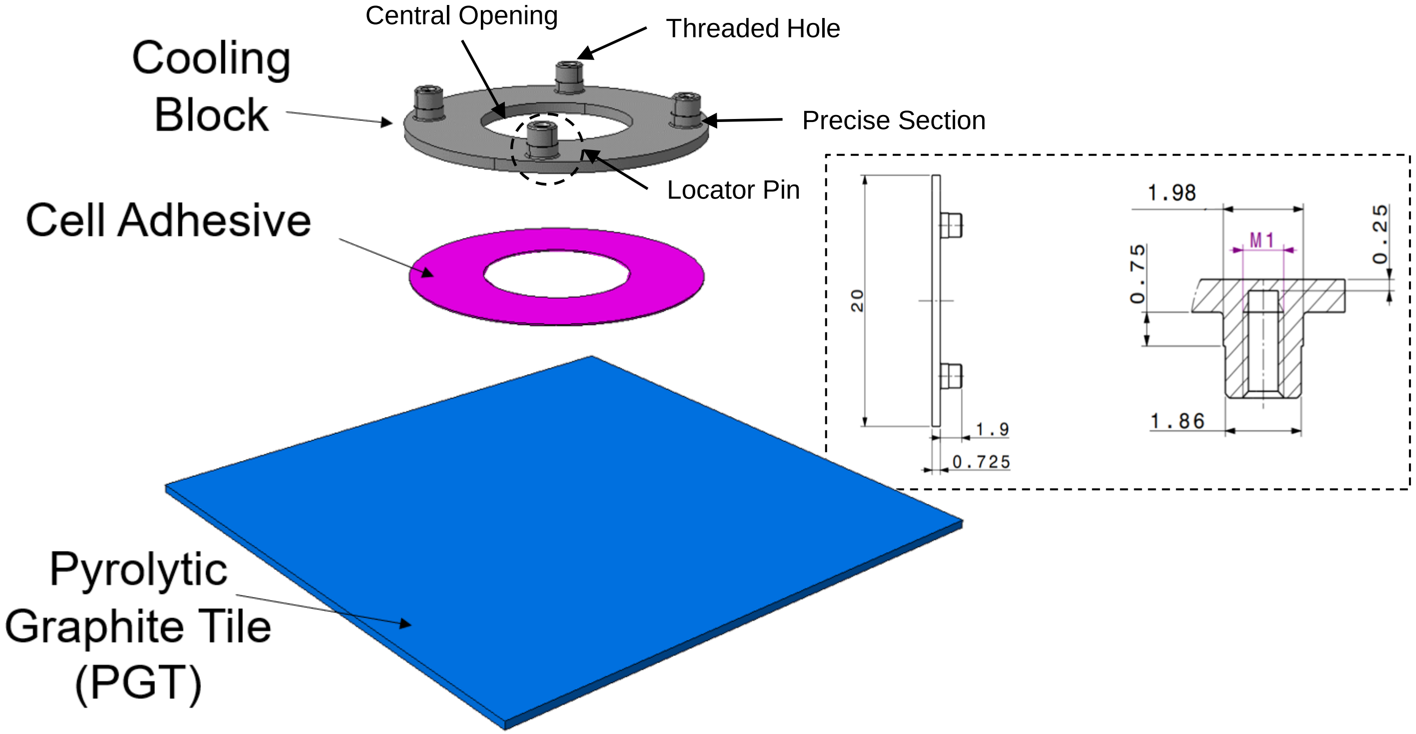


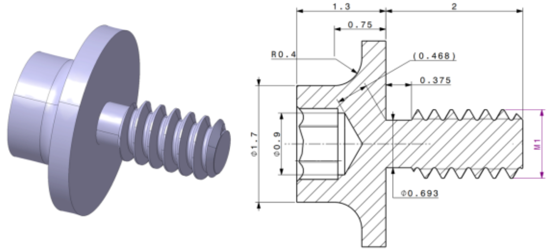
Bare Cell and Module Cell Fixation System

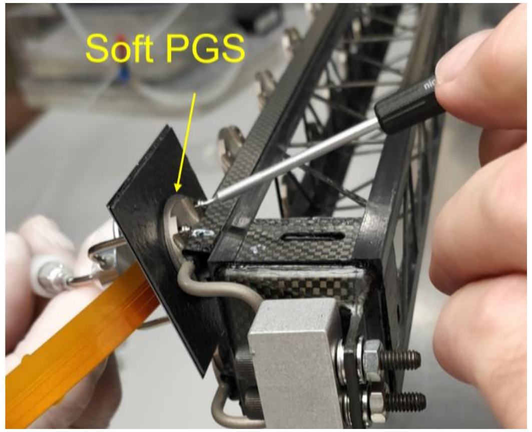
- Pyrolytic Graphite Tile (Pyroid® HT)
- Aluminum Graphite Cooling Block
  - 4x Alignment pins
  - Threaded holes

  } Positioning + fixation on Base Block

- Custom-made Ti M1 screws (Ti Grade 5)
  - Section without thread for preload (12 mN·m)
- TIM between the cooling and base blocks
  - Thermal paste as the baseline (Artic Alumina™)
  - “Soft PGS” as alternative

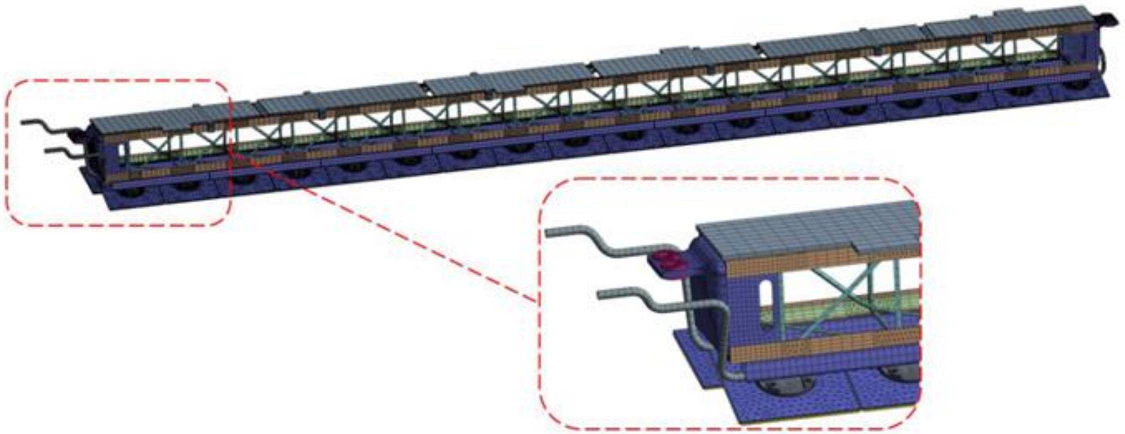


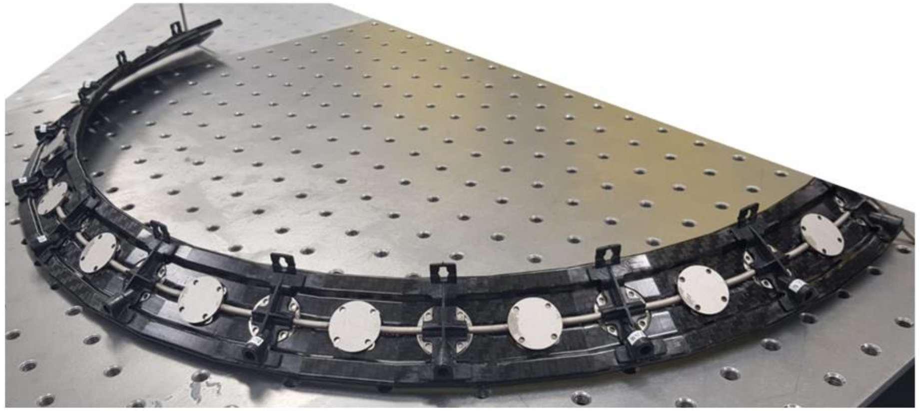


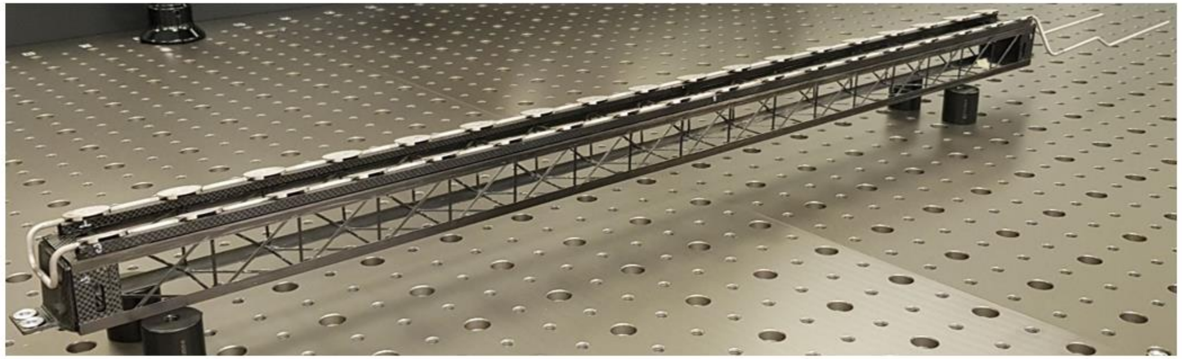


Performance Requirements

- Local Supports Design must comply with stringent thermal, mechanical and stability requirements
  - Ensure minimum gaps to avoid clashes
  - Guarantee hermeticity/minimum overlaps
  - Comply with short- and long-term stability requirements
  - Meet thermal requirements:
    - Avoid thermal runaway
    - Avoid excessive currents per pixel
- Design validation via FEA & Realistic Prototypes



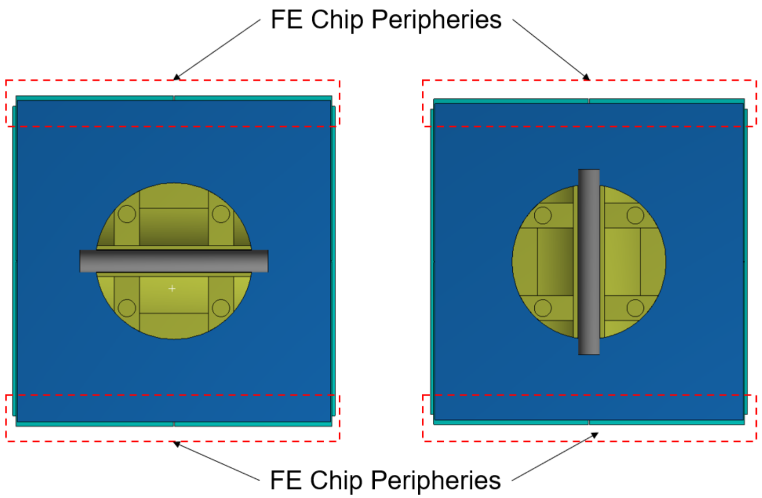




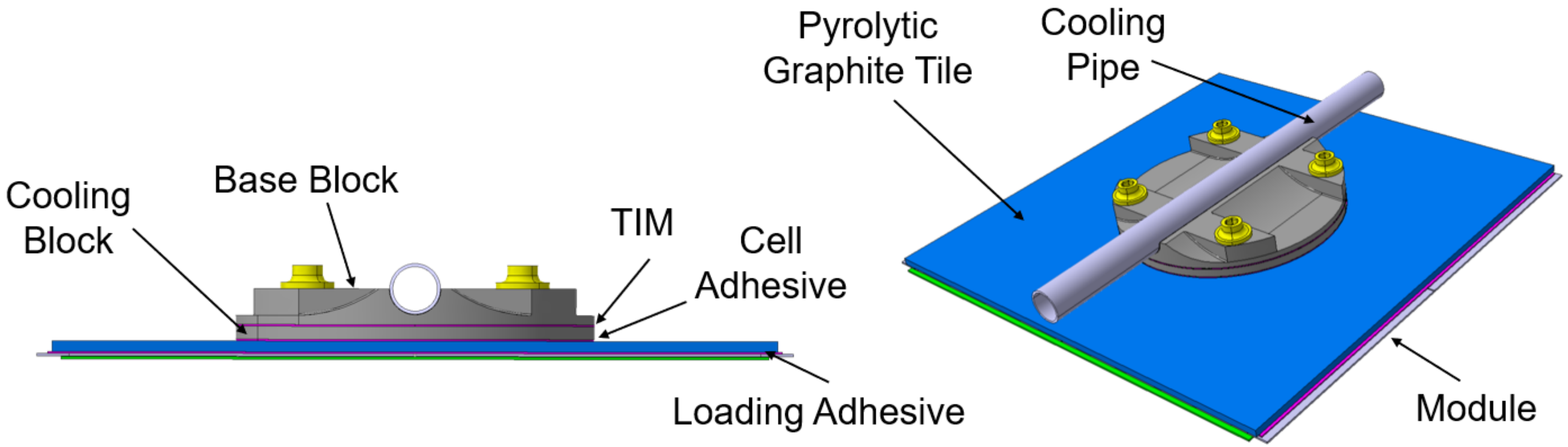
Thermal Studies

Thermal-electric FEA: Introduction

- Thermal-electrical FEA model
- Module Cell + Functional Cooling Pipe (CFRP structures doesn't play any thermal role)
- Three different scenarios:
  - End-of-life performance
  - Thermal runaway behaviour
  - Degraded performance to account for manufacturing variability

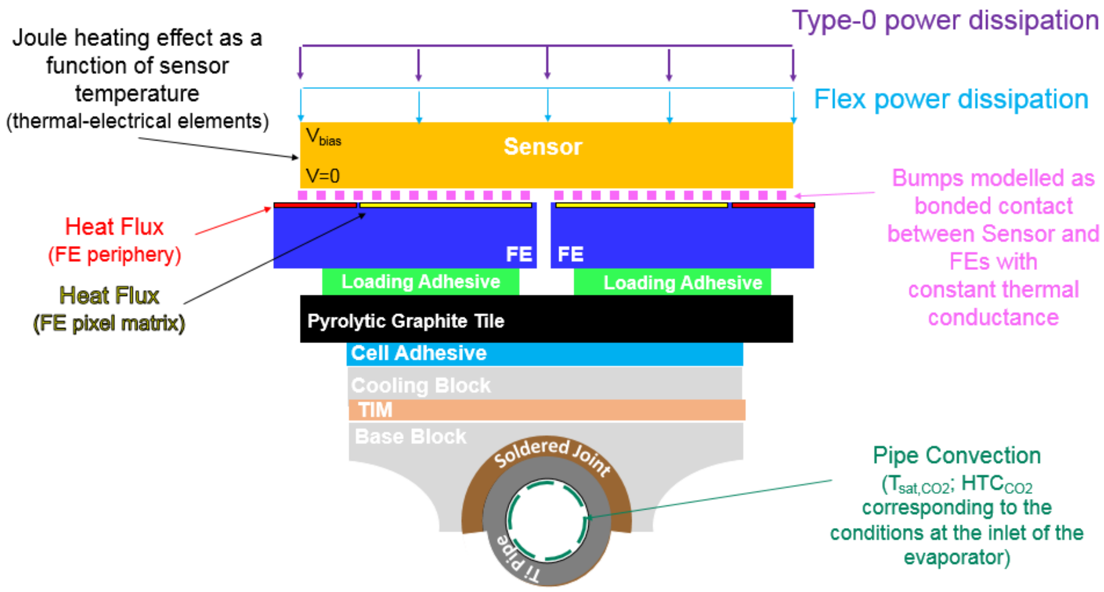


Longeron & IHR Configurations



Thermal-electric FEA: Model Details

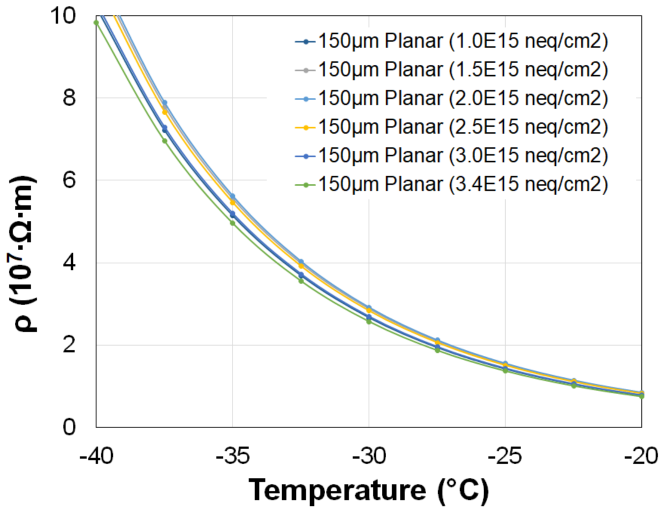
Item	Modelling Comments
Sensor	Power dissipation modelled as Joule Heating Effect using thermal-electrical elements. Resistivity defined as function of temperature for specific fluence
FE Chips	Isotropic, homogeneous silicon; Two separate power dissipation regions for periphery and pixel matrix regions → 5 cases
Bump-bonds	Sensor and FEs "bonded" through a contact with pre-defined conductance
Module Flex	Power dissipated in the module flex applied directly as heat flux to the sensor
Type-0	Up to 100% of the power budget for Type-0 services applied to sensor
CO_2 Behaviour	Convective boundary condition applied to the inner surface of the cooling pipe
Env. Effects	Neglected



- CO2 Fluid conditions
  - **CO_2 conditions equivalent to inlet of the evaporator ($x \approx 0\%$, 0.01 $g \cdot s^{-1} \cdot W^{-1}$)**
  - Parametric CO_2 HTC model based on Thome's model
  - FEA model run iteratively to take into account the contribution of the sensor power dissipation on the tube heat flux used to compute the correct input HTC (essential to capture correctly runaway behaviour)

Thermal-electric FEA: Model Details (continued)

- **Sensor model**
  - Power dissipated by the sensor
    - Joule heating effect → electrical elements
  - Resistivity → function of the local temperature and fluence (extracted from experimental sensor data)



$$\rho(\Phi,T) = \frac{V_{bias}(\Phi)^2}{t_{sensor}\cdot Q_{ref}(\Phi)\cdot\left(\frac{T}{T_{ref}}\right)^2\cdot exp\left(\frac{-E_g}{2\cdot k_B}\cdot\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)}$$

[Q_{ref}, V_{bias} extrapolated for the fluence of interest]

- **Applied Power**
  - FE Chip with two power dissipation areas
  - 5 different power cases
  - Power dissipation in Module flex and Type-0 services applied uniformly on sensor

Case			OS L2 FE Power Dissipation [W/cm²] Matrix	OS L2 FE Power Dissipation [W/cm²] Periphery	Power Dissipation in Module Flex + Type-0 Services
1	Homogeneous		0.548	0.548	+18% of power delivered to the FE chips Flex: 10%; Type-0: 8%
2	Normal Operation		0.264	3.592	
3	No Configuration		0.000	6.411	
4	One FE Opened		0.264	6.831	
5	No Configuration + One FE Opened		0.000	9.651	

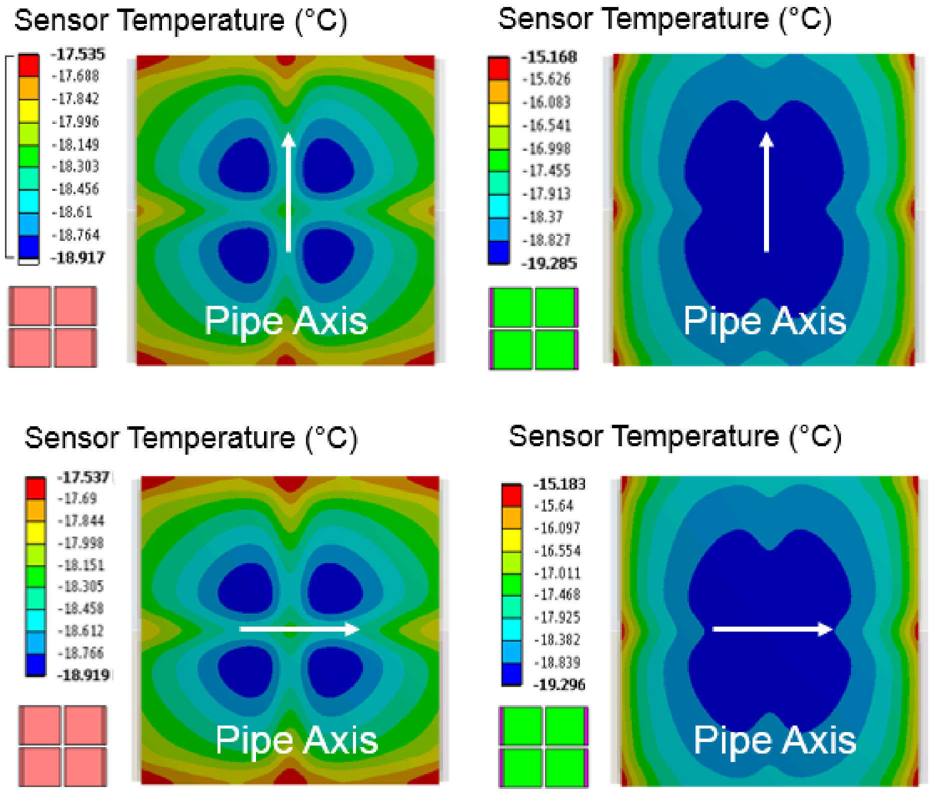
ATLAS ITk

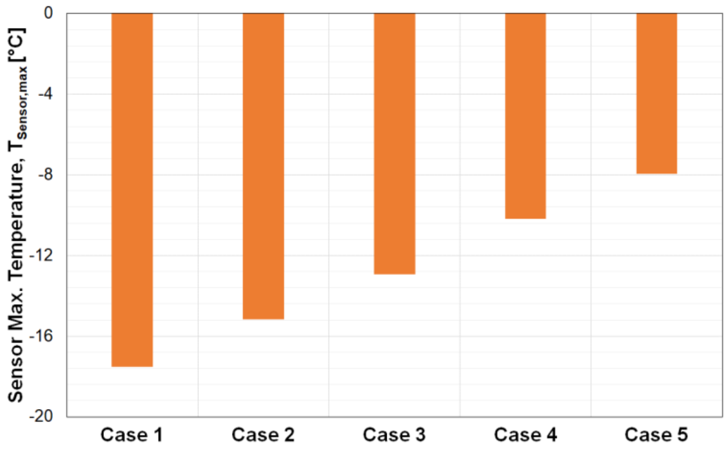
Thermal-electric FEA: End-of-Life Performance

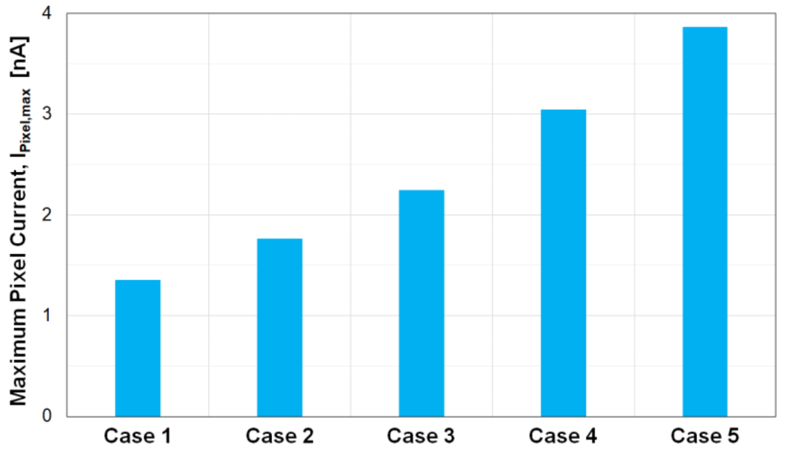
- Results with a fluence of 3.0×10^{15} n_{eq}/cm^2 and T_{CO2}= -35°C
- Equivalent results for Longeron and IHR configurations → expected by design
- TFM predictions compatible with specifications

Longeron

IHR



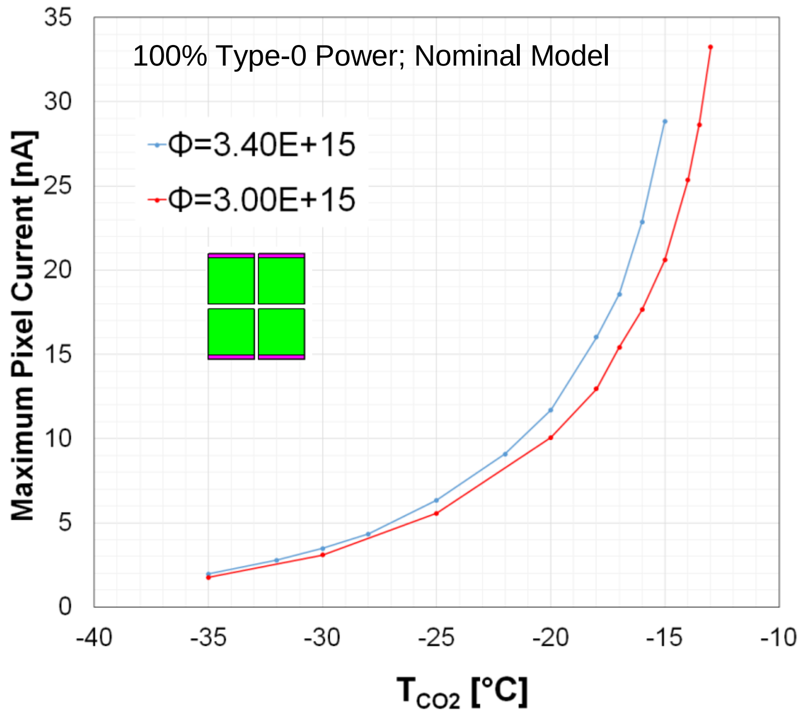




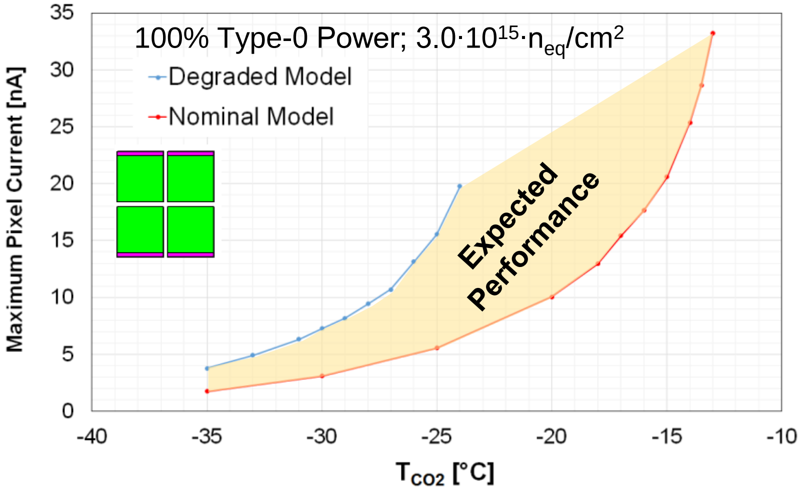
TFM [°C·W-1·cm2] (Case 1; $3.0\cdot10^{15}\cdot n_{eq}/cm^2$)		
Longeron	IHR	L2 Target Value
24.3	24.3	28.85

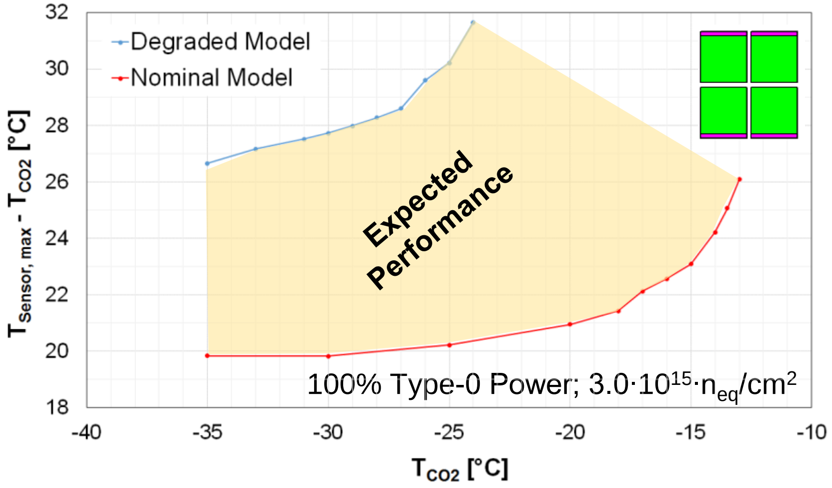
Thermal-Electric FEA: Thermal Runaway

- **Thermal-runaway behaviour** was studied by changing the CO_2 temperature
  - HTC varied accordingly → iterative model to account for sensor power
- **“Degraded” performance** simulated by deliberately worsening the conductive TFM by 50%
  - Account for potential manufacturing variability



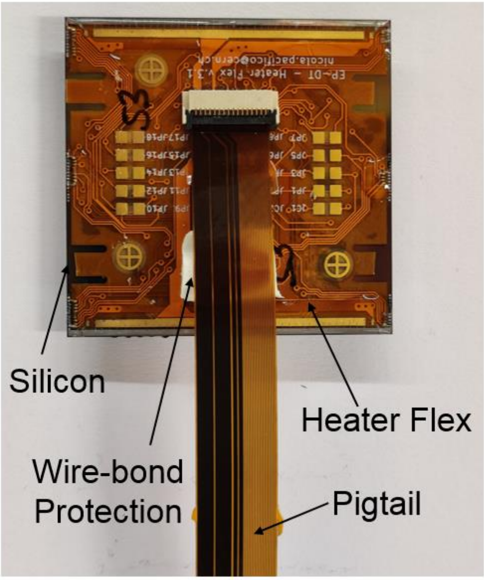
TFM [°C·W^{-1}·cm^2] (Case 1; 3.0·10^{15}·n$_{eq}$/cm^2; TCO2=-35°C)	
Degraded FEA	Layer 2 Design
34.47	38.75



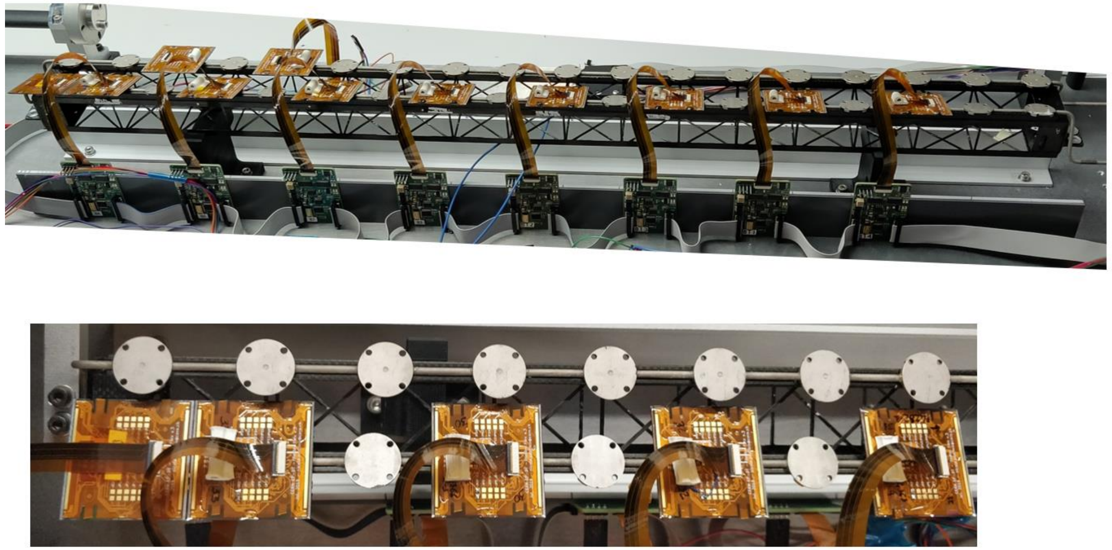


OB Local Supports: Thermal Prototypes

- Longeron & IHRL3 Thermal Prototypes
- Silicon heaters to simulate the heat load of pixel modules
  - Equivalent geometry to pixel modules; with embedded or glued PTs
  - Capable to simulate uniform and non-uniform power dissipation in module matrix/periphery
- Tested with CO_2 (T_{CO2}= 0°C and T_{CO2}= -25°C, 3.8g/s) in a vacuum vessel



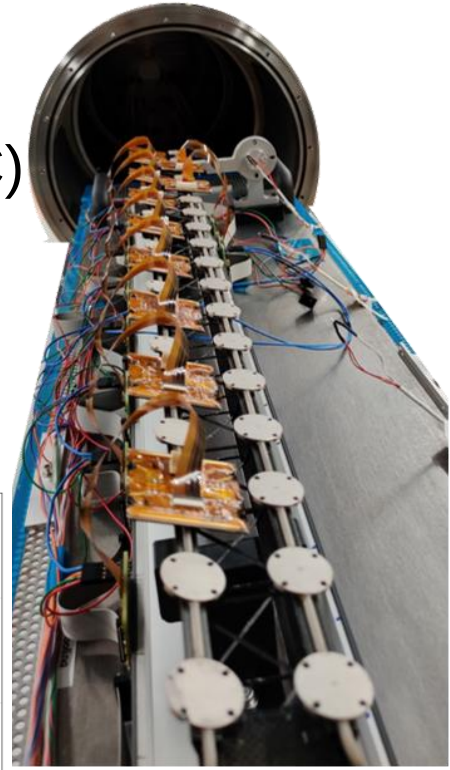
Bare Cell + Si-heater

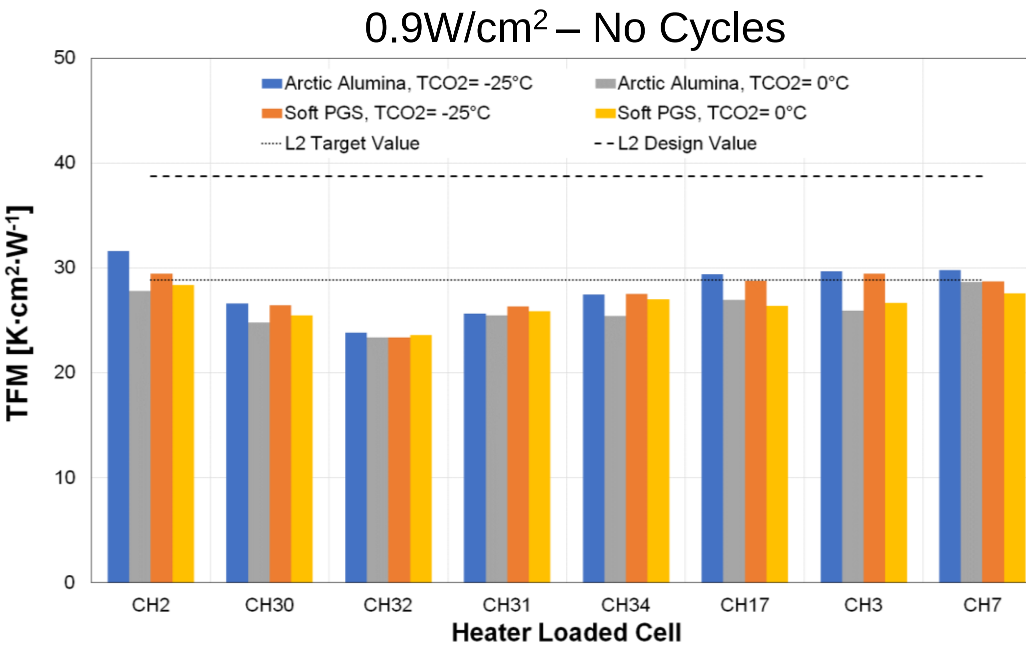

Longeron Thermal Prototype

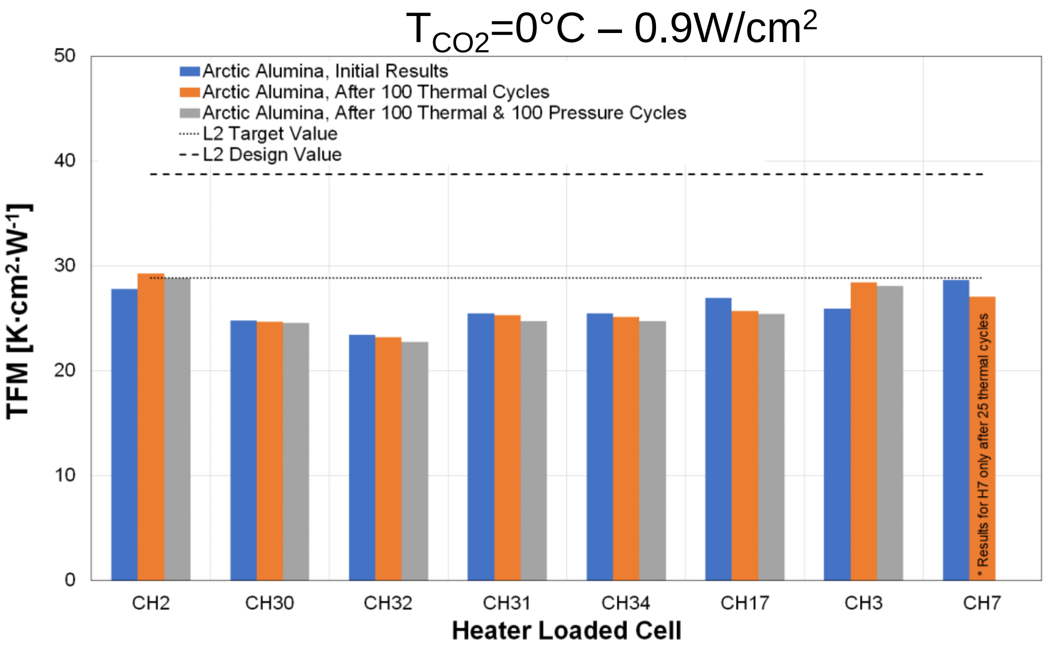

IHRL3 Thermal Prototype

Longeron Thermal Prototype

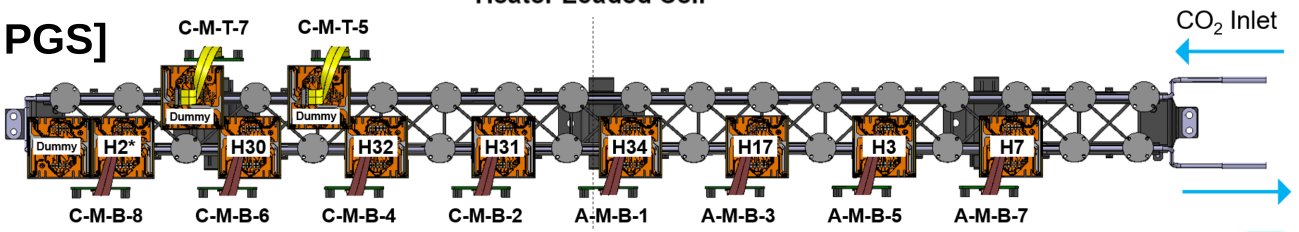
- Tests carried out before and after thermal cycling (100cycles ,-55°C and +60°C) and pressure cycling (100 cycles, 0-162bar)
- Results well within the design specification for the OB innermost layer
- No performance degradation after thermal and pressure cycles





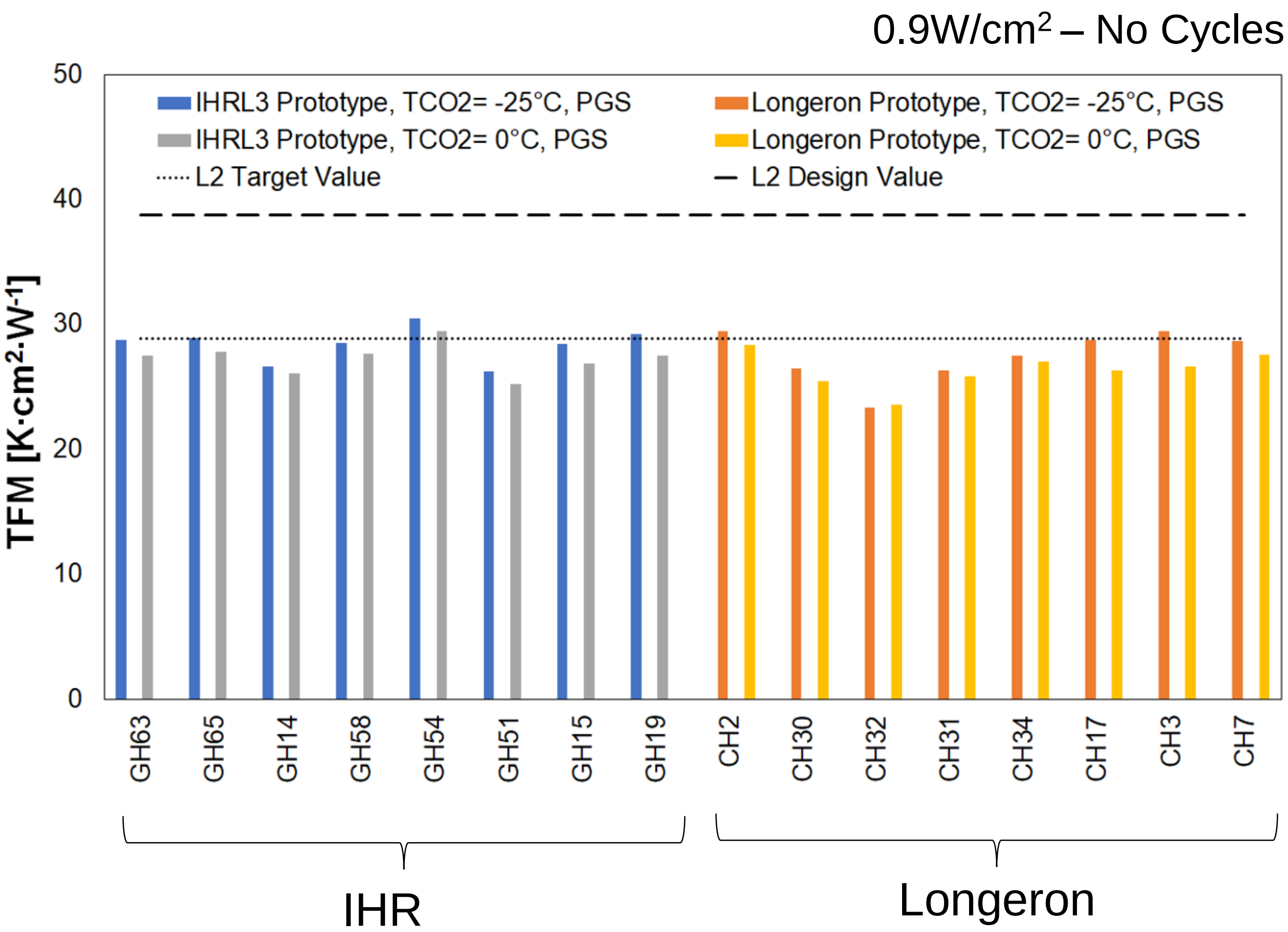


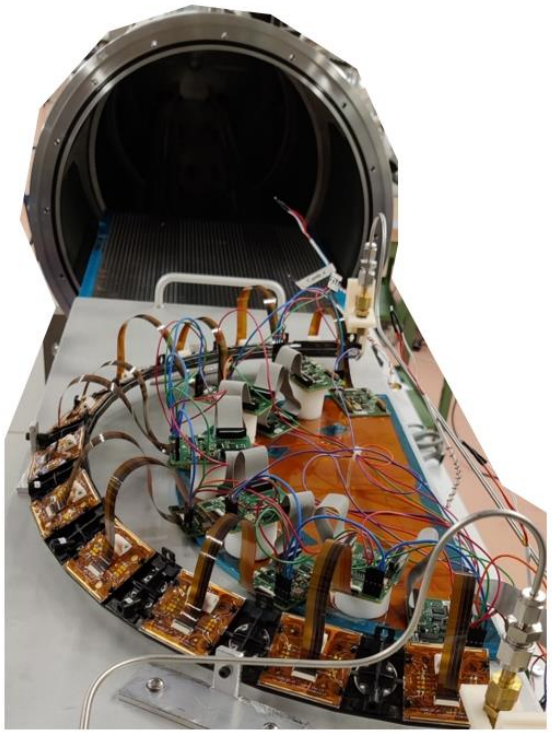
[Equivalent performance for Arctic Alumina & Soft PGS]

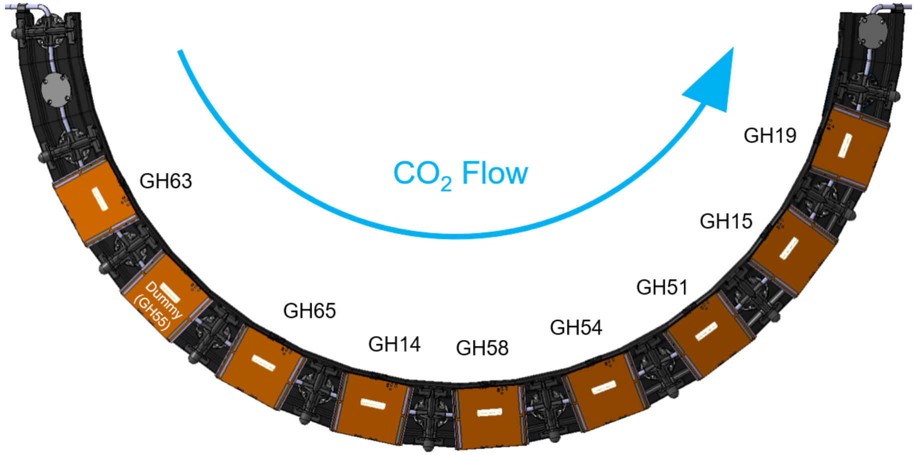


IHRL3 Thermal Prototype

- Equivalent performance for IHR and Longeron configurations
  - Expected by design and from FEA results
- Small manufacturing variability



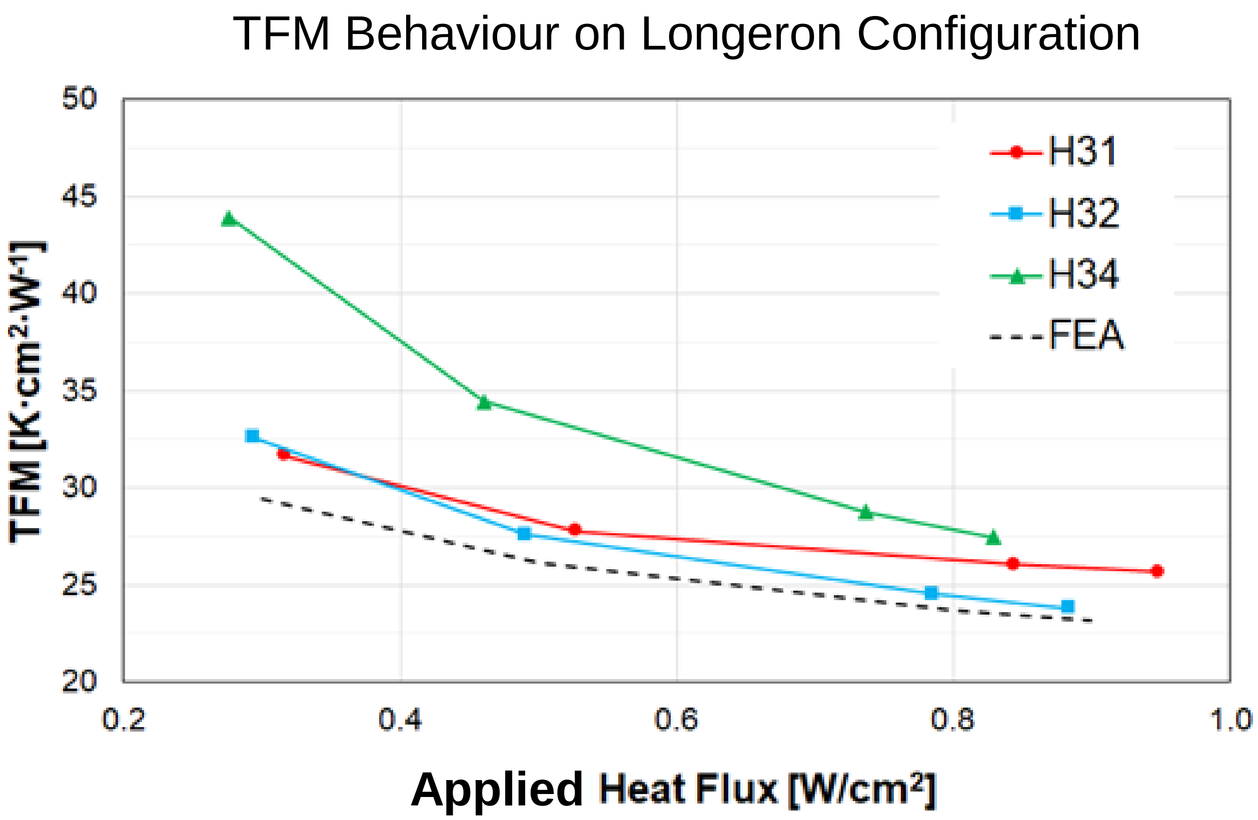




ATLAS ITk

Thermal FEA Model Validation

- Comparison of experimental and FEA results for loaded cells with silicon heaters installed in the thermal prototypes (nominal properties used in FEA model)
- Good agreement between the experimental and FEA results



Thermo-mechanical Studies

Thermo-mechanical FEA: Introduction

- Coupled thermo-mechanical simulations
  - Check minimum gaps and hermeticity
  - Assess short- and long-term stability

1. Steady-state Thermal Analysis	
Power Dissipation	FE Power (Case 2) + Sensor Power (end-of-life) + Module Flex + Type-0 Services
Convective CO_2 BC	- Linear T_{CO2} variation along evaporator - HTC from Thome's model (x_{max}=33%, 0.01 $g \cdot s^{-1} \cdot W^{-1}$)

T(X,Y,Z) →

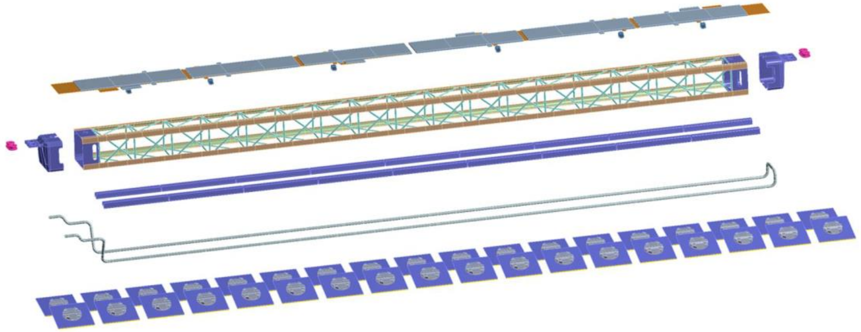
2. Coupled Thermal-Mechanical Analysis
- Gravity & distributed masses for missing components (e.g. SMDs, connectors) - Pipe internal pressure - **T(X,Y,Z)** = Temperature distribution obtained in Steady-state Thermal analysis - Changes in moisture content (ΔM)
Output: Nodal Displacements U(X,Y,Z)

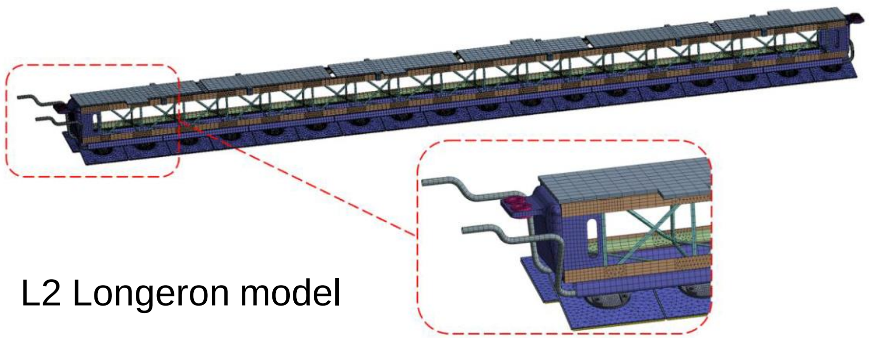
Repeat Steps 1&2 Run for different T_{CO2}, power dissipations and moisture contents →

Combine results to extract relative deformations
U_r(ΔT, ΔPower, ΔM); U_φ (ΔT, ΔPower, ΔM); U_z(ΔT, ΔPower, ΔM)

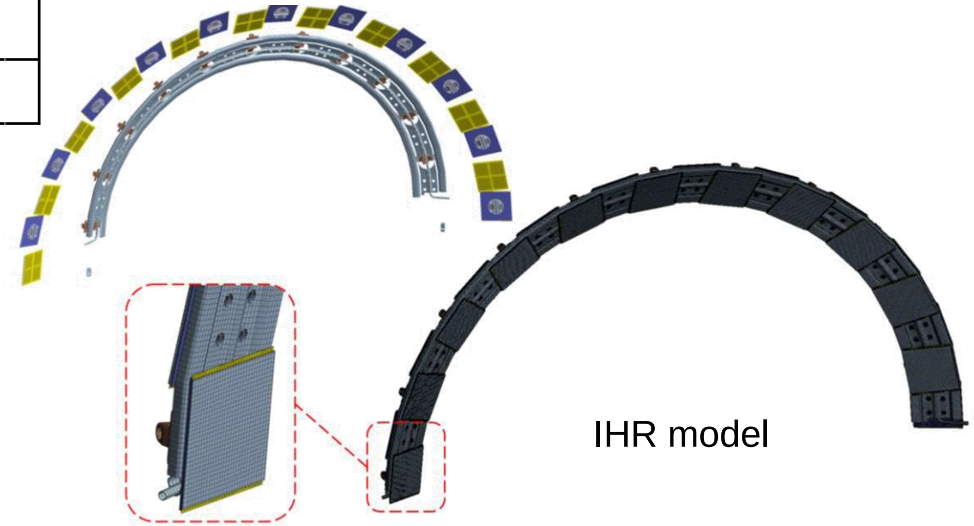
Thermo-mechanical FEA: Model Details

Item	Modelling Comments
Functional Local Support	CFRP structures, functional pipes, inserts modelled with solid elements (ACP and element orientations to define correct fibre and ply directions)
Bare Cells	PGT, Cooling Block modelled with solid elements
Module	- Sensor and FE chips modelled as isotropic, homogenous silicon - Flex modelled as solid layered structure - SMD components and connectors simulated as masses
Longeron PP0s	- Modelled explicitly as solid layered structure - SMD Components and connectors modelled as distributed masses - Joints to link rigid board with inserts; Frictionless contact with truss
Glued & Soldered interfaces	Bonded contacts with specified stiffness/thermal conductance values
Type-1 Services	Longeron: Distributed masses applied on PP0s. IHR: not applicable



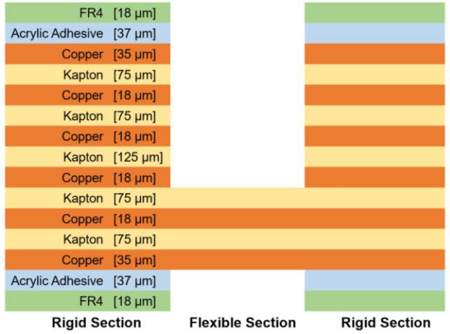


L2 Longeron model



IHR model

Module Flex

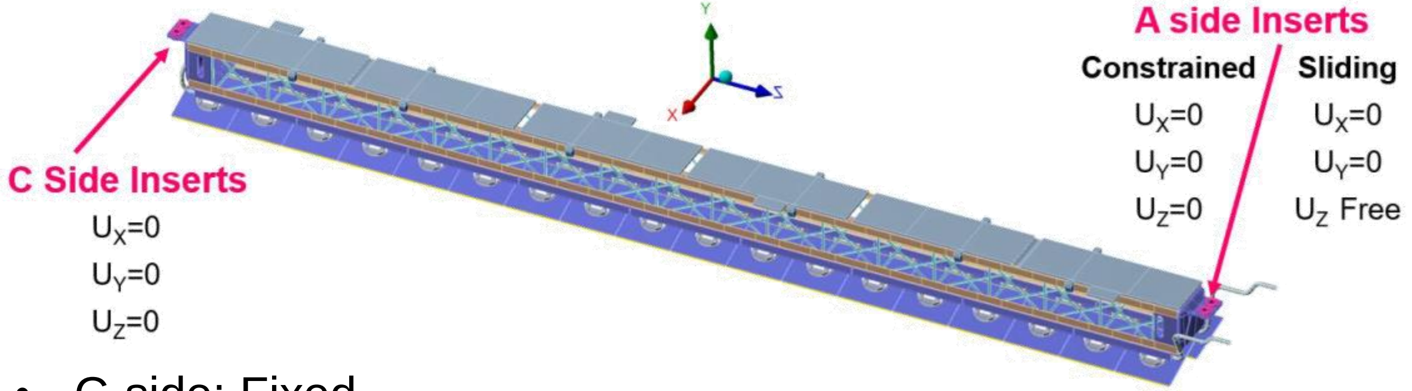


Longeron PP0 rigid-flex

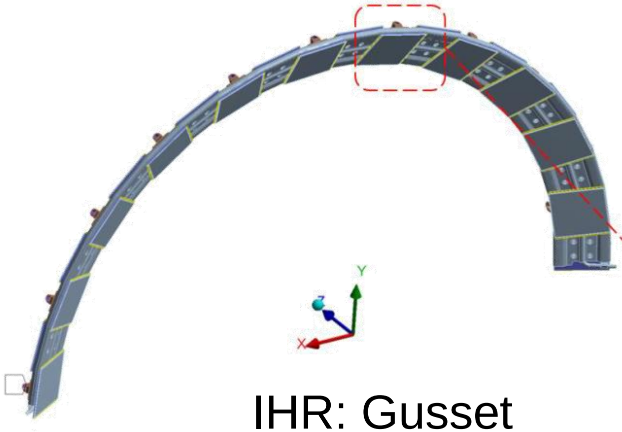
Thermo-mechanical FEA: Loads & BCs

Item	Modelling Comments
CO_2 Behaviour	Convective BC applied to the inner surface of the cooling pipe - Thome's model to compute HTC: - Linear variation of temperature (2.5°C) and vapour quality (1% - 33%) along evaporator; $\dot{m}$= 0.01 g·s^{-1}·W^{-1}
CO2 pressure	11bar (equivalent to saturation T_{CO2}= -37.5°C)
Module & Services Power	- Sensor: Q_{sensor} extracted from thermal-electric model at the end-of-life - FE Chips: Non-uniform power dissipation (Case 2) - Flex: 10% of the power delivered to FE chips (uniformly applied on sensor) - Type-0: 8% of the power delivered to FE chips (applied on sensor)
Moisture Uptake	Uniform moisture content in each body; Modelled via equivalent thermal analysis (CME - CTE and ΔM%-ΔT with consistent units)

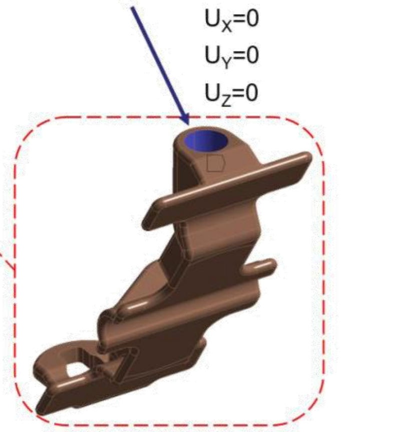
Stability Case	Loads
Short-Term	• ±1°C Variation of T_{CO2} • ±10% Variation FE and service power
Long-Term	• ±3°C Variation of T_{CO2} • Up to 40% change in the moisture content



- C-side: Fixed
- A side: Fixed or Sliding (more realistic due to global OB behaviour)



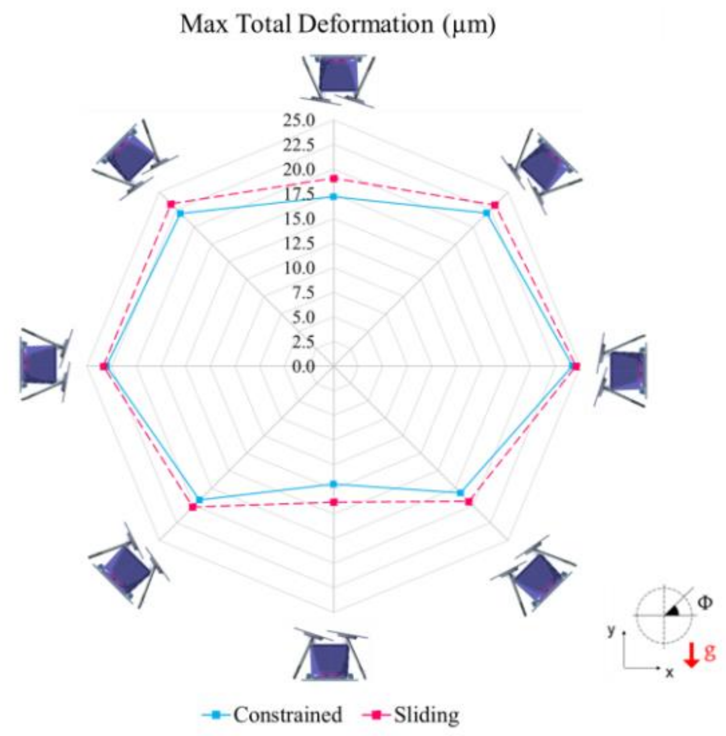
IHR: Gusset locators fixed



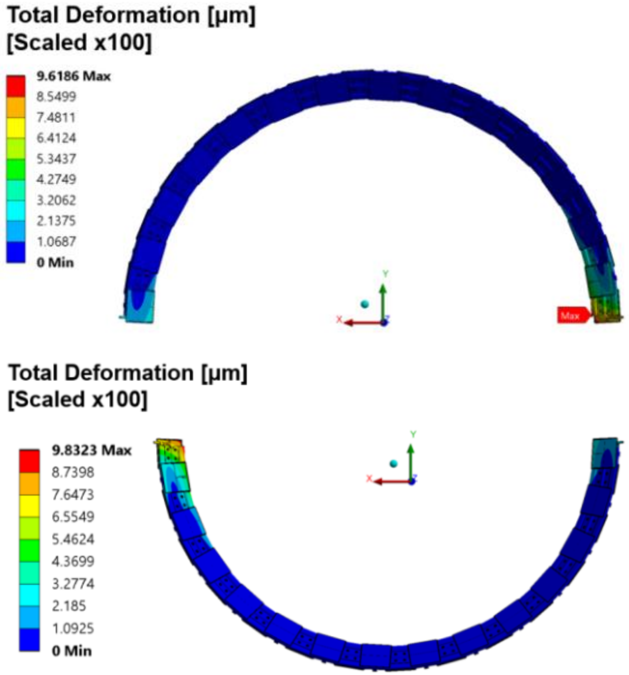
Thermo-mechanical FEA: Gravity Effect

- Design meets specs for max. gravitational sag (<100µm) and min. resonance frequency (>50Hz)
- No significant impact due to local support orientation

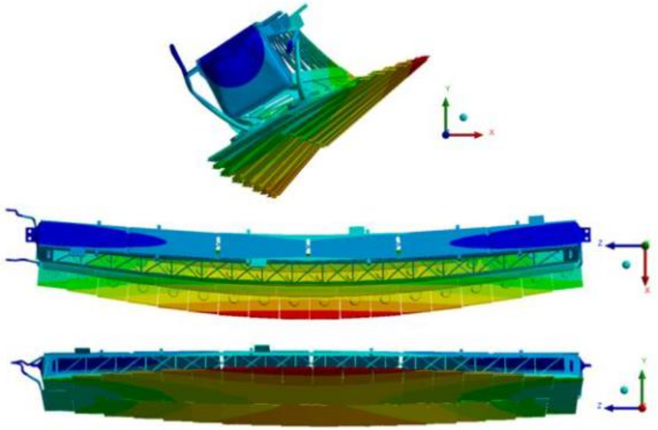
Gravitational Sag – Longeron



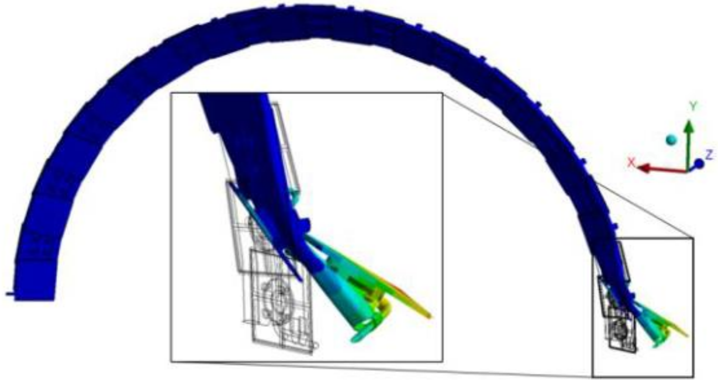
Gravitational Sag – L4 IHR



First mode shape – L2 Longeron & L4 IHR



Sliding → 115 Hz



557.3 Hz

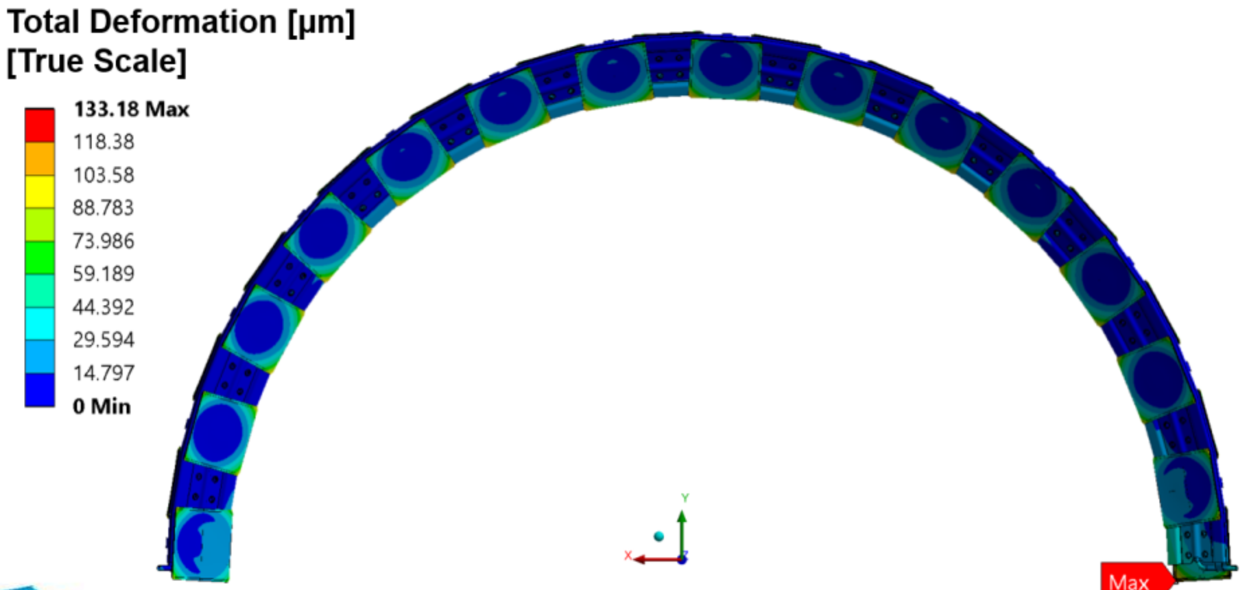
Thermo-mechanical FEA: Gravity and Thermal Effect

- No minimum clearance issues (no clashes)
- No hermeticity issues (minimum overlap in deformed LS >> 5pixels)

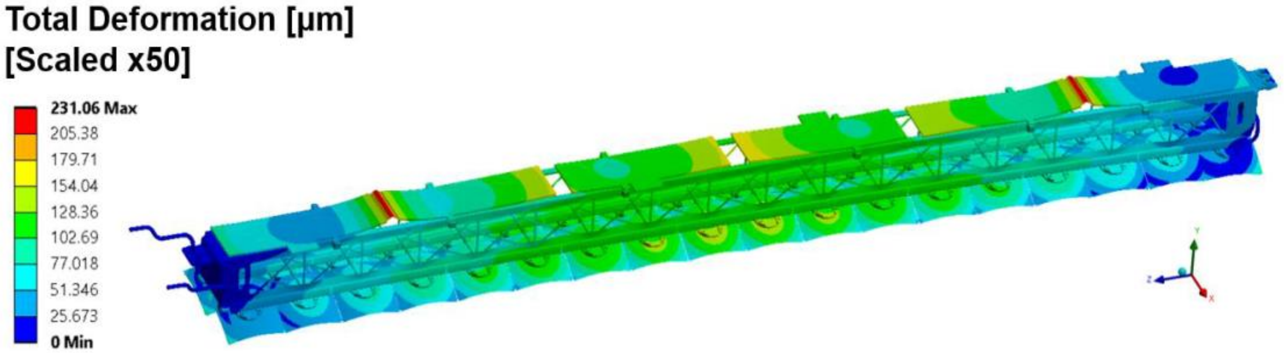
Max. direction displacements at the modules

		Longeron L2 (φ=90°)		Inclined Half Ring		
		Constrained	Sliding	Layer 2	Layer 3	Layer 4
Absolute Maximum Directional Displacement in Modules [μm]	$\lvert U_{r,max} \rvert$	94.4	135.5	39.3	54.5	61.4
	$\lvert U_{\varphi,max} \rvert$	30.9	36.3	18.0	32.7	32.2
	$\lvert U_{z,max} \rvert$	19.4	34.5	94.8	106.8	104.5

L4 IHR



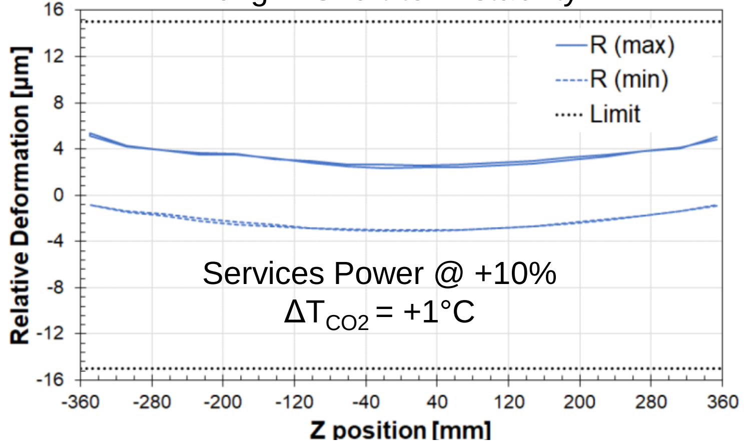
L2 Longeron



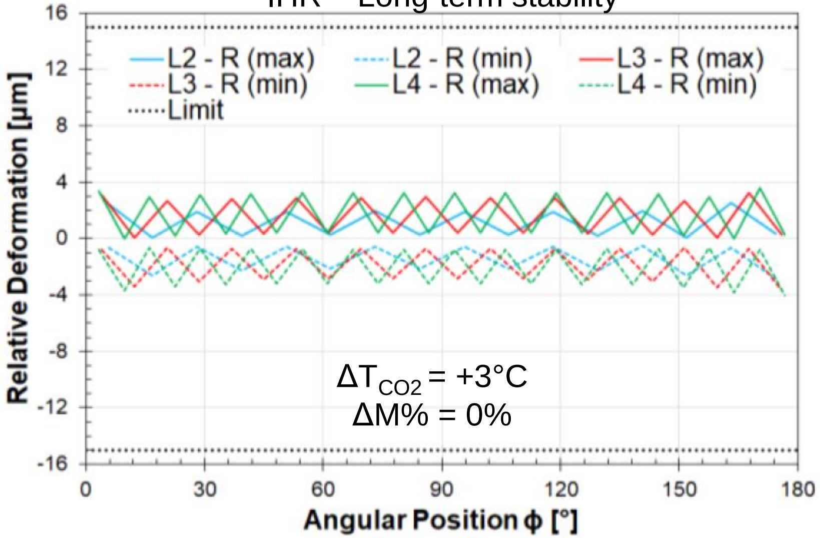
Thermo-mechanical FEA: Short- & Long-Term Stability

- Results within specifications for both short- and long-term stability (for both Local Supports)
  - Short-term → biggest margins to specifications
  - Long-term → changes in moisture content is the dominant effect (hygro-mechanical loads)

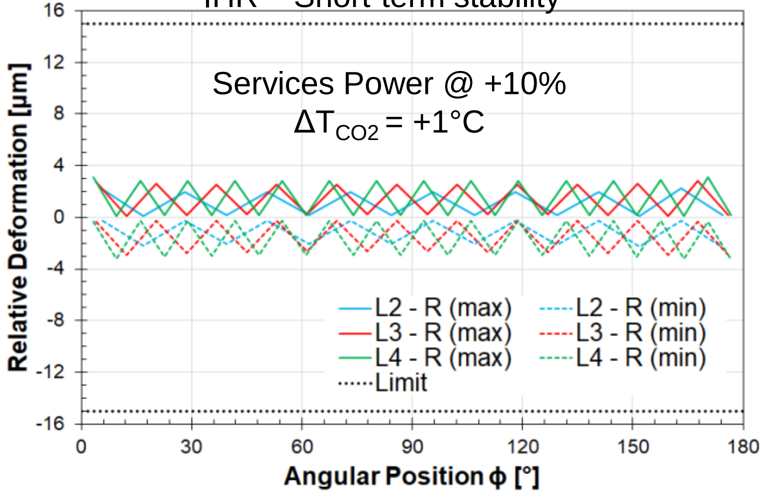
L2 Long. – Short-term stability



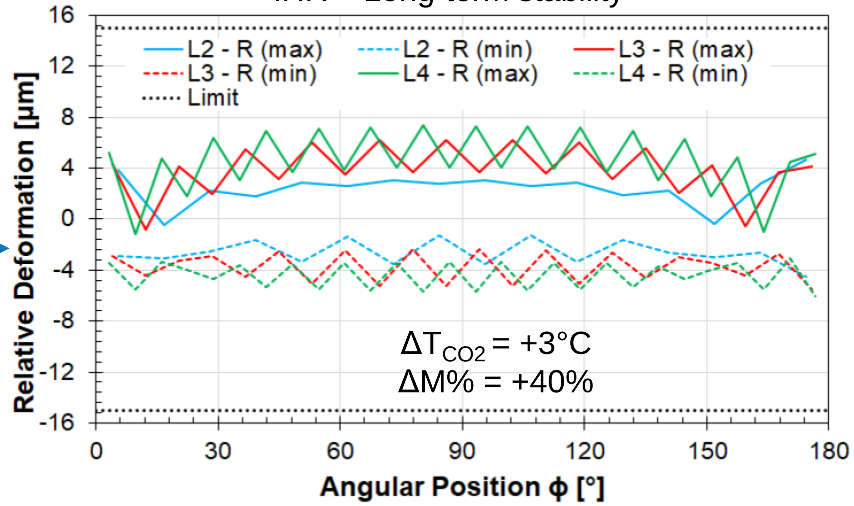
IHR – Long-term stability



IHR – Short-term stability

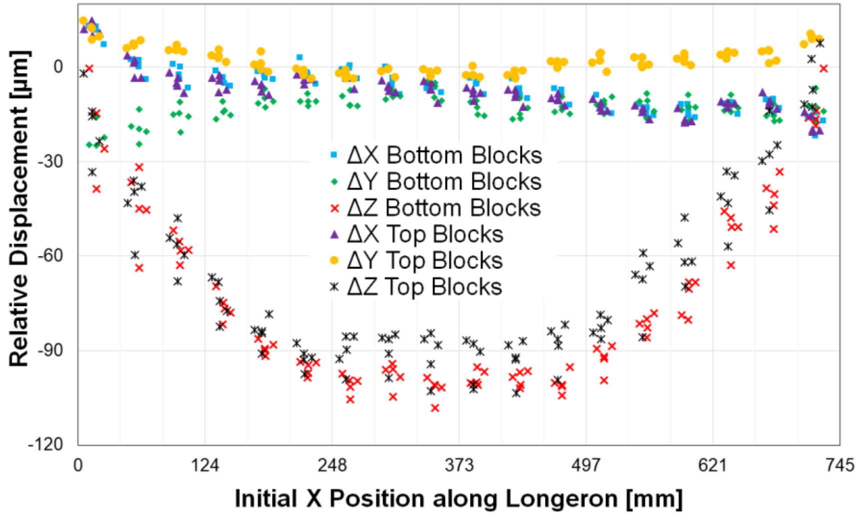


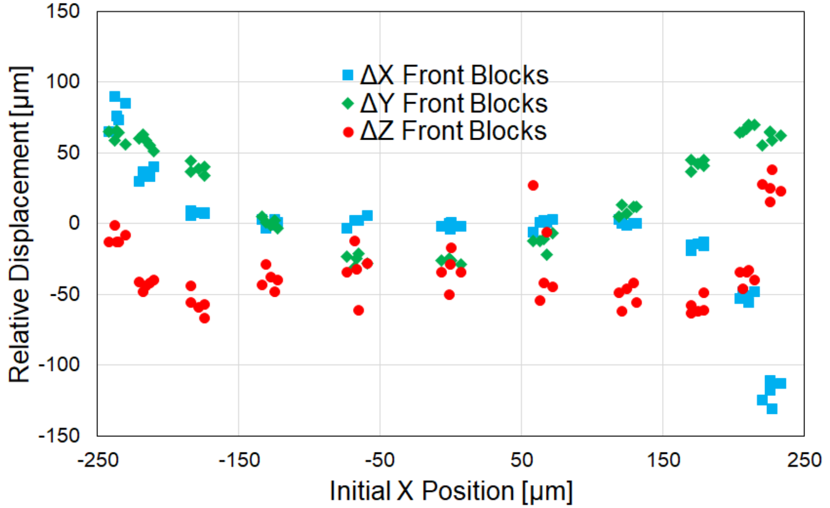
IHR – Long-term stability

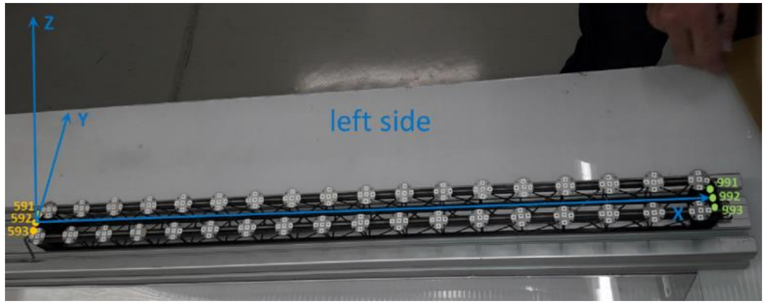


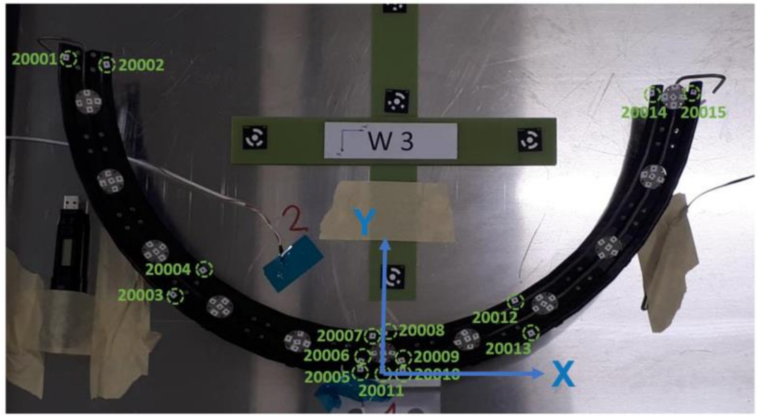
Thermo-mechanical Prototypes

- Two full-size prototypes: Functional Longeron; and Functional IHRL3
- Photogrammetry used → 5 targets per Base Block
- Temperature change → 21°C to -18°C
- 1-σ precision in the measurements (warm vs cold):
  - Longeron: 10µm and 15µm
  - IHR: 15µm and 20µm





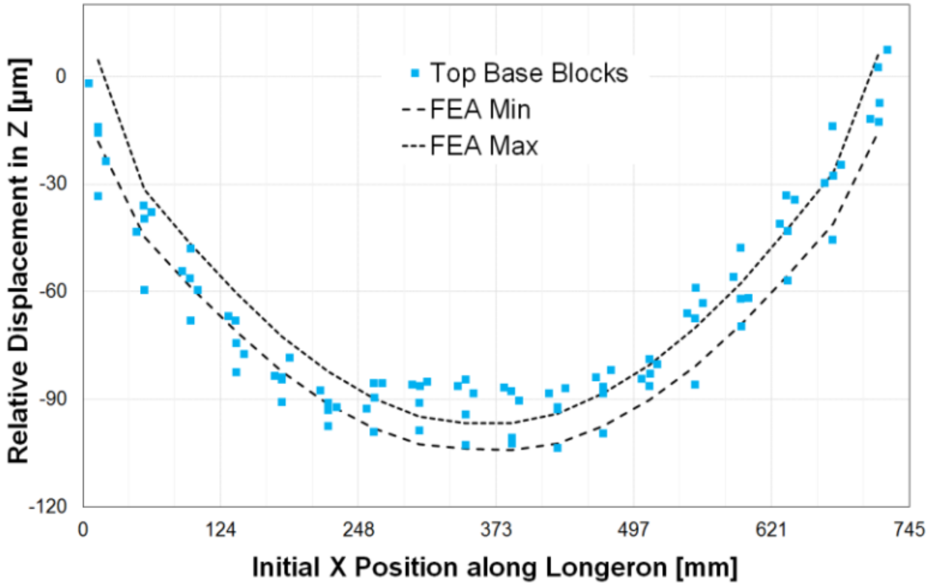


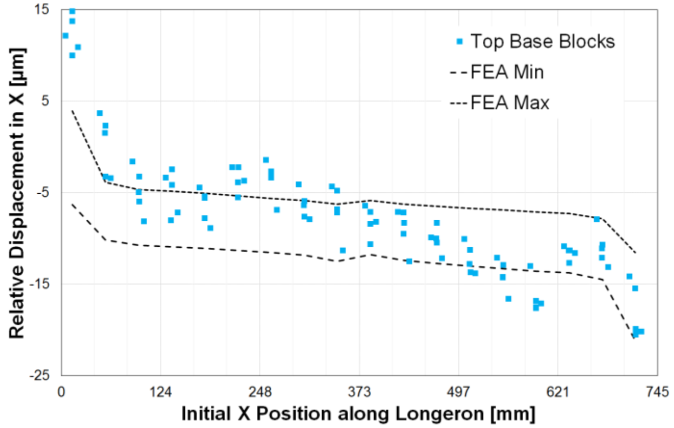


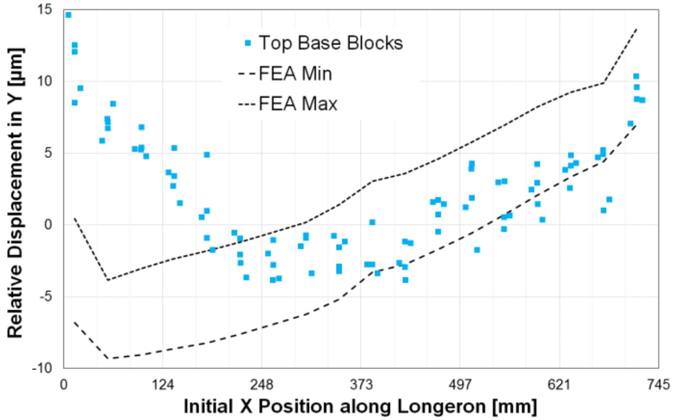
Thermo-mechanical FEA Model Validation

- Relative displacement obtained in cold tests of the functional local supports used to validate thermo-mechanical FEA models
  - Results from FEA models that replicated the test conditions
- Good agreement between experimental and numerical results

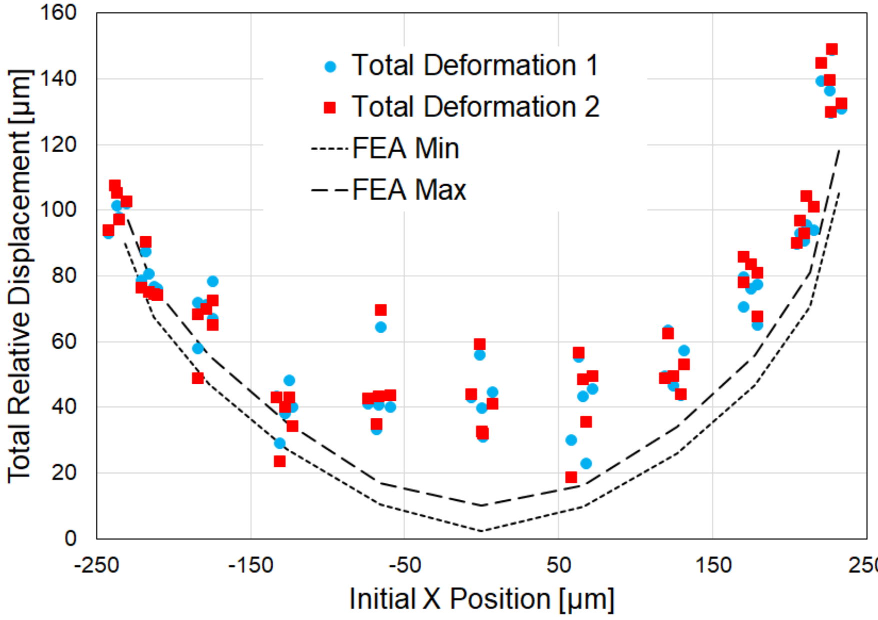
Longeron







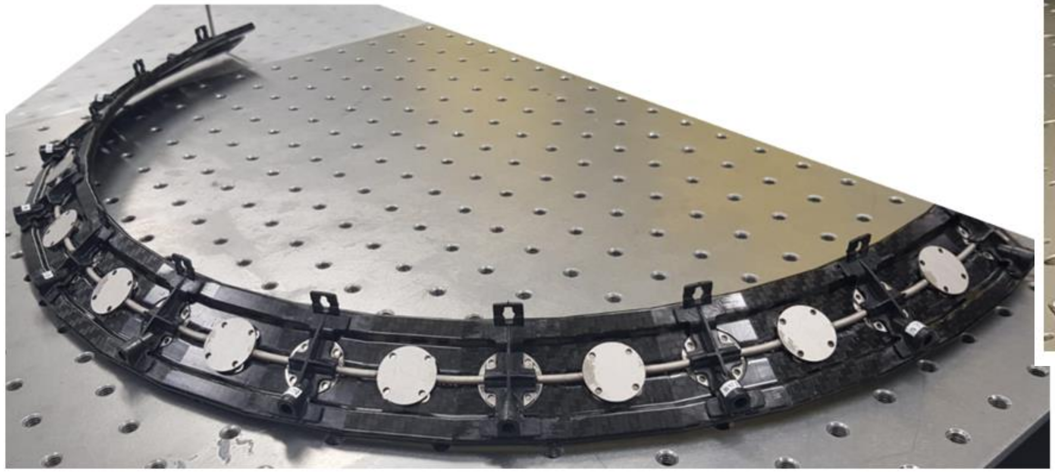
IHR

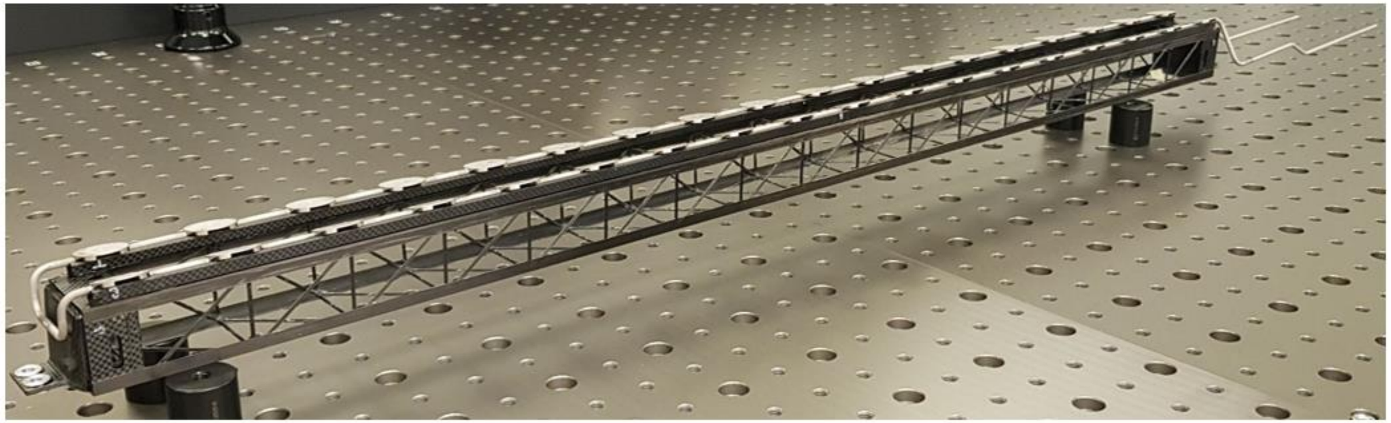


Summary and Conclusions

Summary and Conclusions

- Local Support concept compatible with the tilted layout of the ATLAS ITk Pixel OB
- Design based on a new solution → functional local support + module cell
- Design Qualification based on thermal and thermo-mechanical prototypes and FEA models
  - Performance compatible with specs for the most stringent layer
  - Good agreement between experimental and numerical results
- Bare Local Supports pre-production is almost completed; Production to begin this summer





Thank you for your attention!
Questions?