Multifunctional Composite Sensor Support Structure with Integrated Cooling

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Outline

1. Motivation and Introduction
2. Hybrid composite design
3. Simulation results
4. First prototypes
5. Summary, conclusions and future work

Why is mechanics design important? - Future colliders (FCC-hh like)

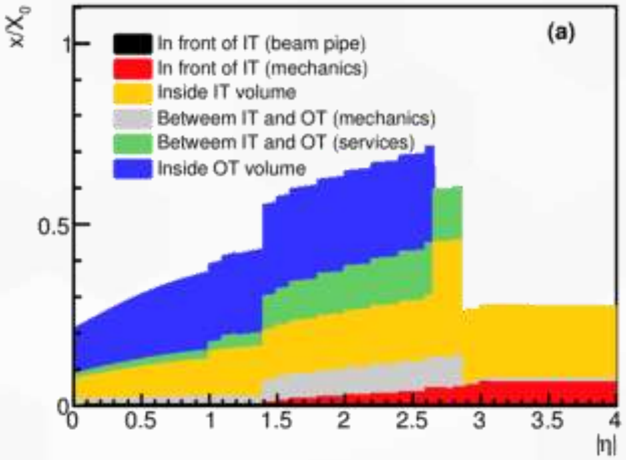
High-luminosity phase of the LHC as example in this talk, but future colliders

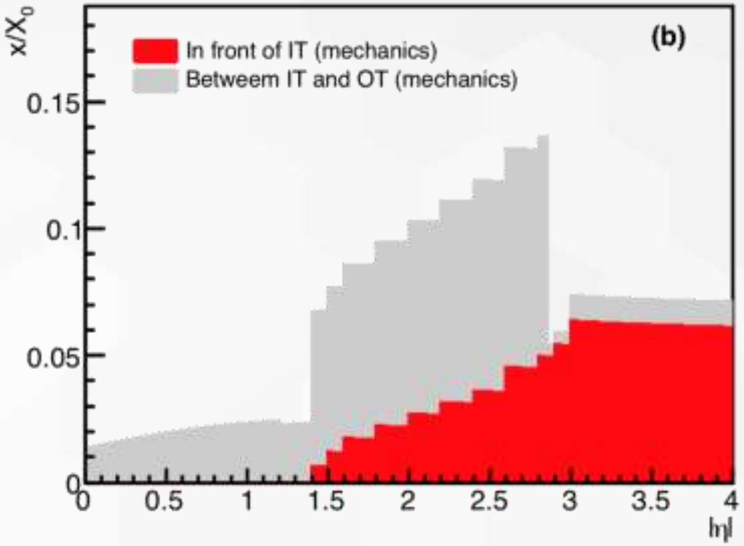
- Momenta and angular ranges up by 10x and 2x
- Challenging for forward tracking/detectors
- Pile-up of a thousand results in very harsh conditions

<u>HL-LHC upgrades as example:</u>

- Support structures need to be optimized, light-weight → minimal mass possible, highly thermally conductive
- CMS HL-LHC upgrades as example

Pixel Layer dose (3.7cm)	HL-LHC $3ab^{-1}$	FCC $3ab^{-1}$	FCC $30ab^{-1}$	FCC (2.5cm) $30ab^{-1}$
$\times 10^{16}\ n_{eq}\ cm^{-2}$	1.5	3	30	70
Dose (MGy)	5	10	100	220



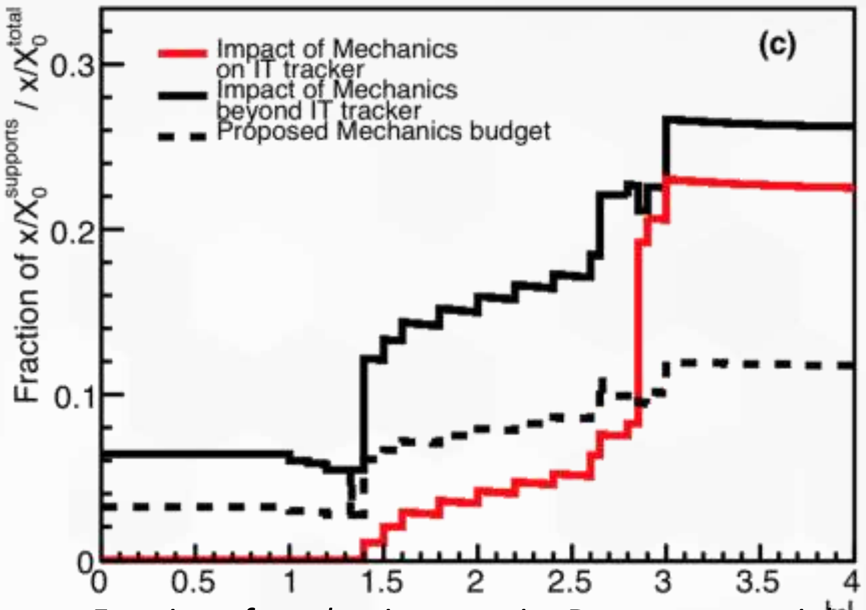


Material budgets and mechanics

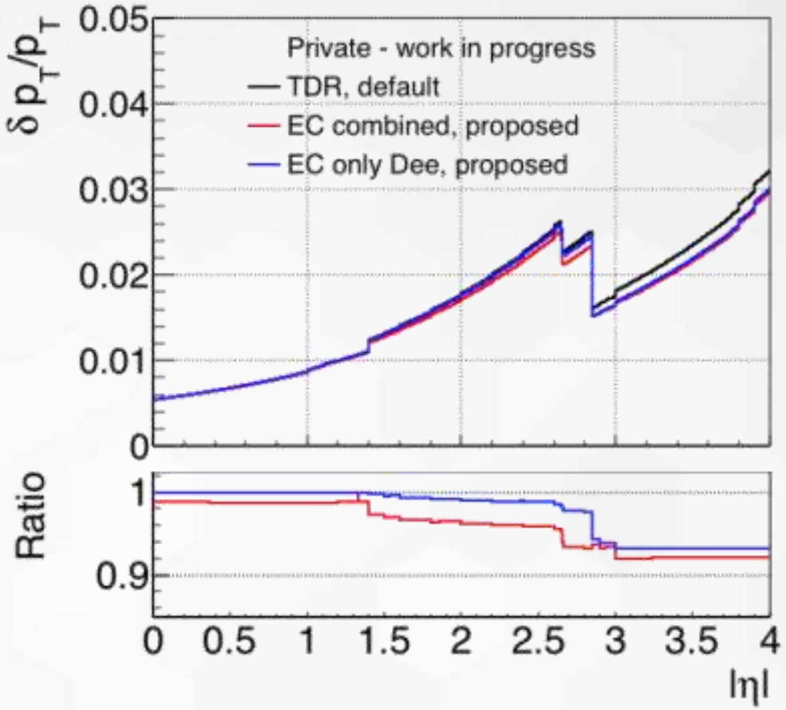
Substantial R&D on all fronts to make a FCC-hh detector a reality

- Support & Cooling constrains Tracker performance, e.g. thermal runaway
- Mechanics is significant fraction of the material budget
- Material testing standardization for irradiation response

- Can improve b-ID efficiencies by 2-3% per b-jet and high b-jet multiplicity ~10-15%
- Significant improvement by novel approach, b-ID relevant for di-Higgs (priority @FCC-hh)



Fraction of mechanics vs entire Detector material

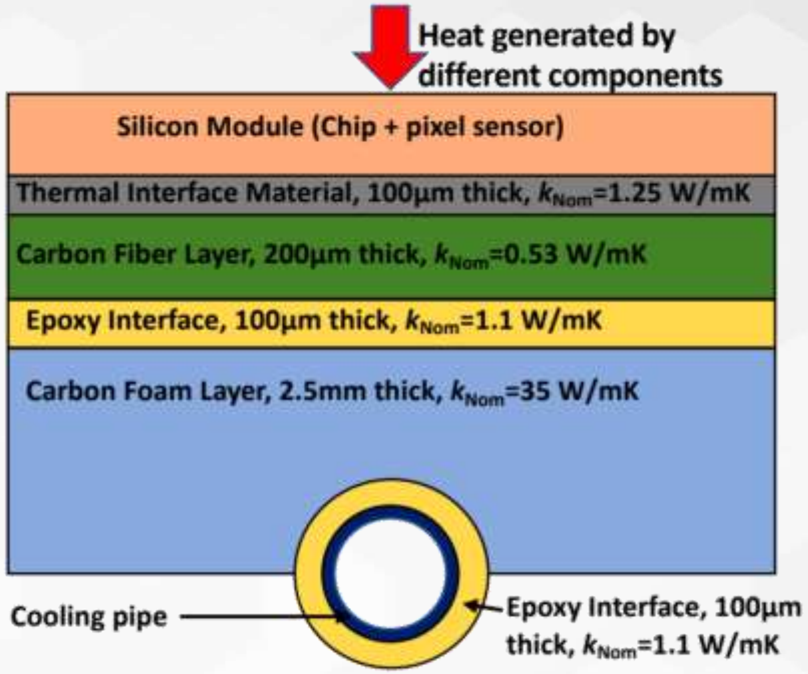


Transverse momentum resolution

Current Architecture of Support Systems

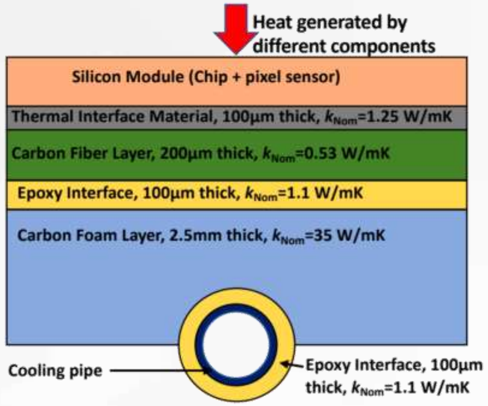
- State of the Art: Multilayer Structure
  - Integrates layers of different material systems with low thermal conductivity (e.g., epoxy interface)
  - Extensive multi-step fabrication process
  - Involves metallic cooling lines
  - Fabrication process poses additional challenges for non-planar geometries
  - Interfaces between layers involve thermal and thermomechanical considerations

Multilayer structure

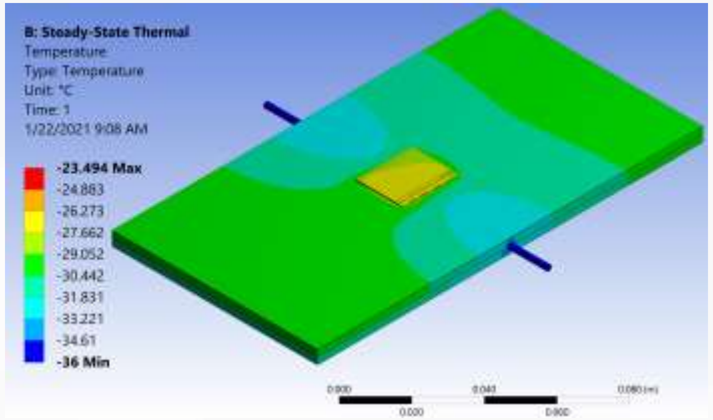


Thermal Performance of Current Architecture of Support Systems

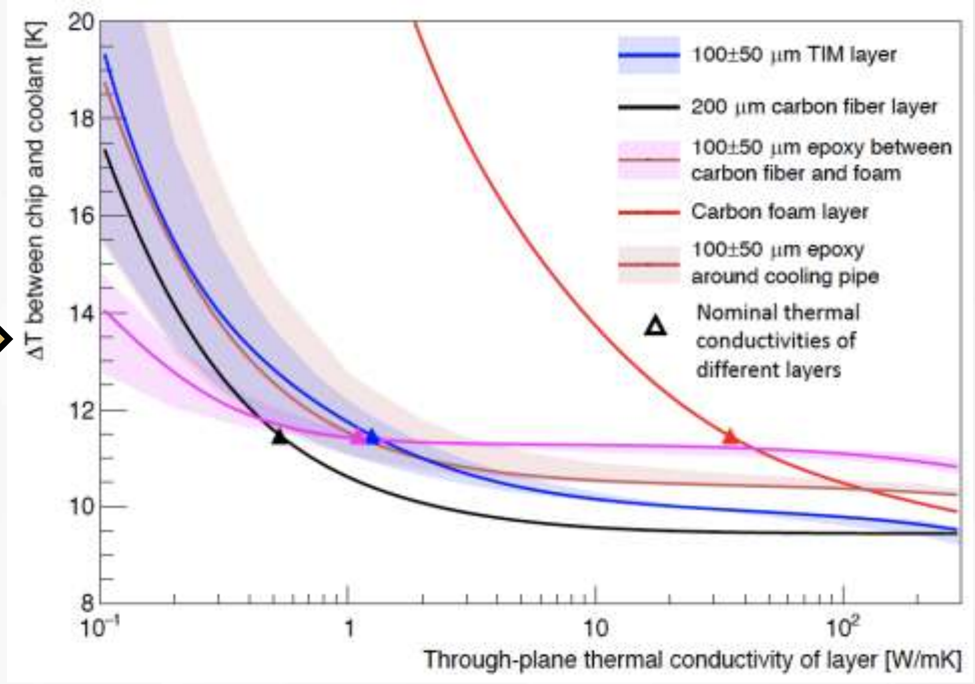
Multilayer Structure



Thermal FEA



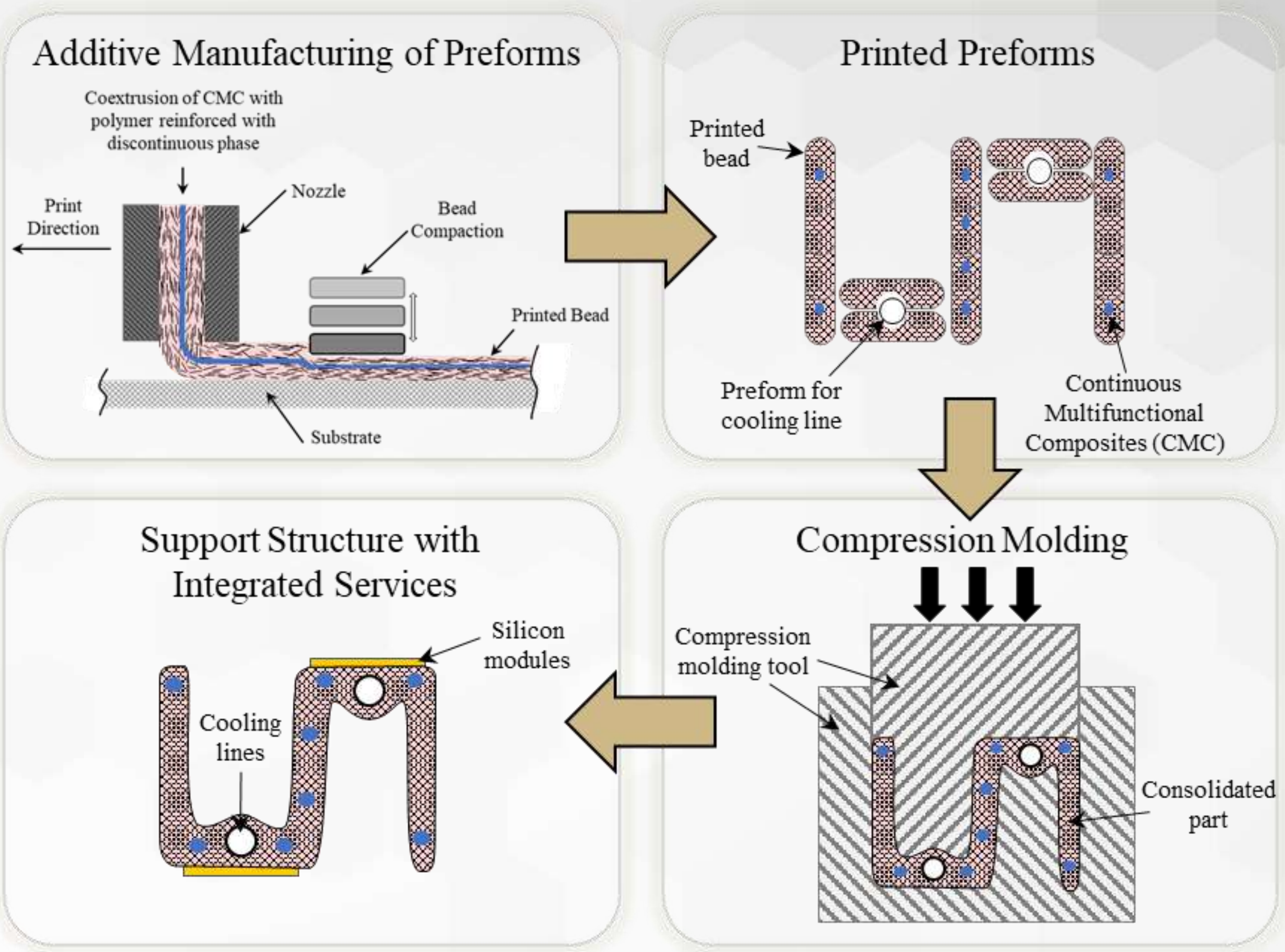
Contribution of Each Layer to Thermal Response



Hybrid Composites for Support Structures with Integrated Services

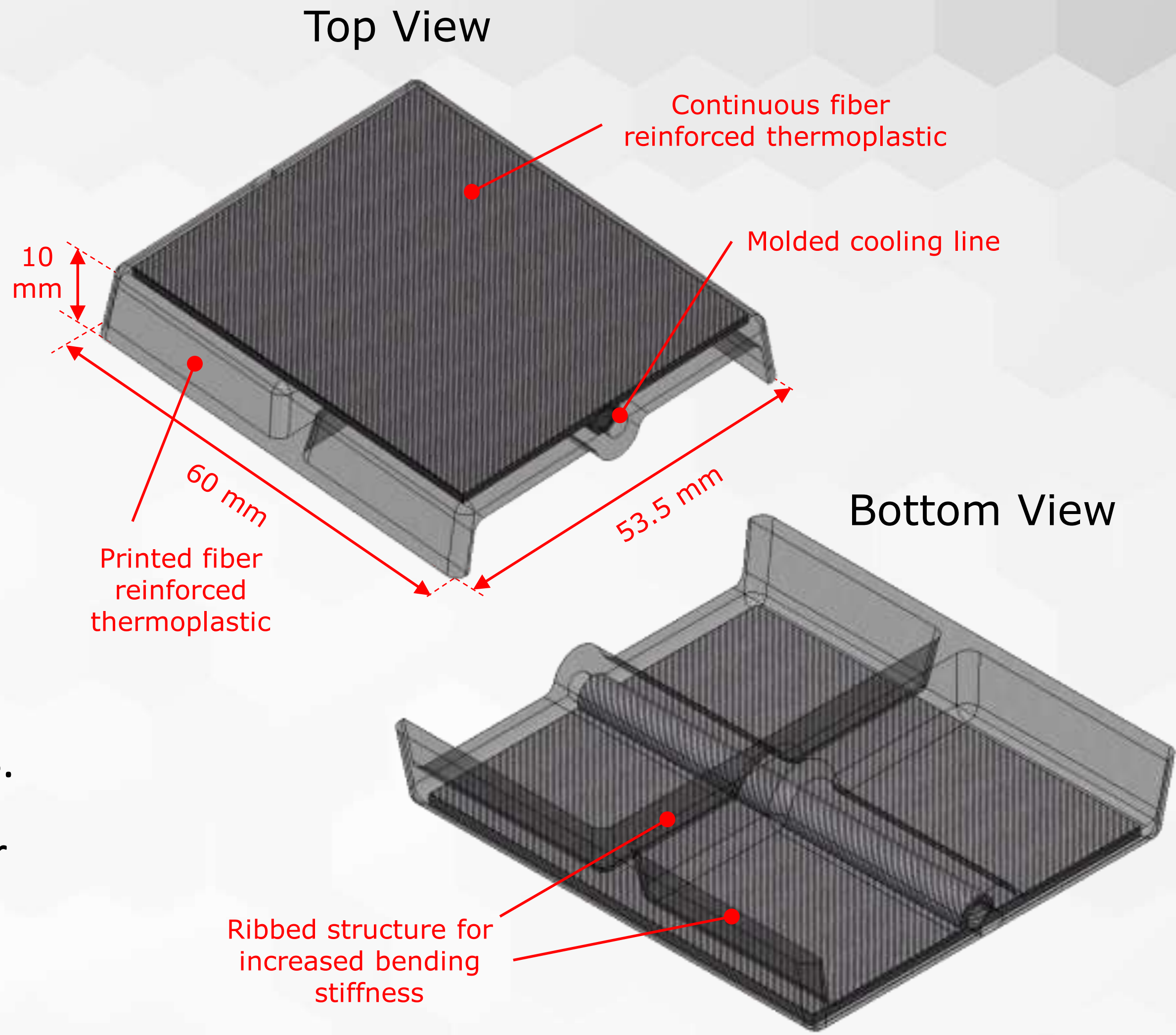
Two-step manufacturing process to produce monolithic hybrid structures with integrated services

- Additive manufacturing of preforms to provide control of continuous fiber orientation
  - Fiber orientation is driven by thermal and thermomechanical performance requirements
- Compression molding to consolidate printed preforms and to integrate cooling lines
  - Remove voids and reduce effect of interfaces between dissimilar layered materials



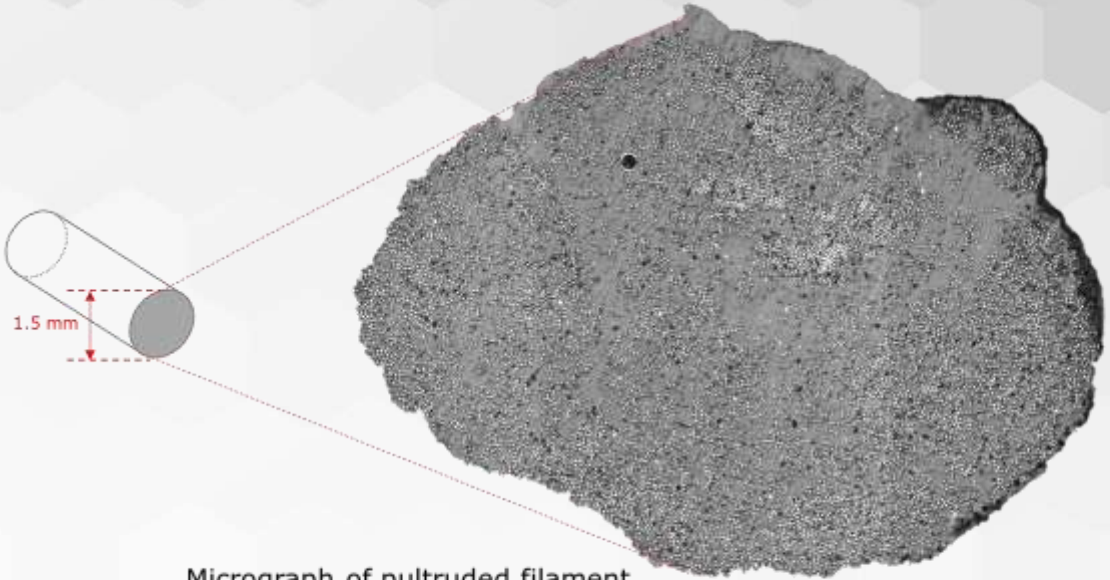
Prototype Support Structure with Integrated Services

- Cooling lines molded in.
- Thermal pathways provided by continuous carbon fibers.
- Stiffness provided by ribbed structure and continuous carbon fiber (Weight 60% < sandwich structure).
- Strength provided by continuous carbon fiber
- Compression molding process included:
  - Preform of continuous fiber impregnated with PPS.
  - Printed continuous and discontinuous carbon fiber reinforced PPS.



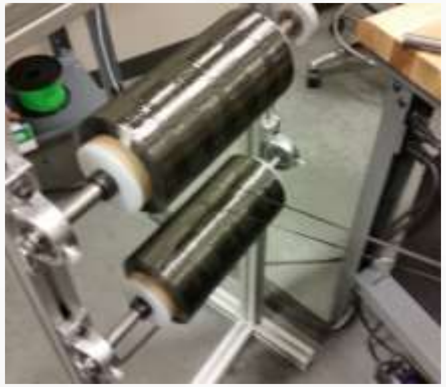
Continuous Carbon Fiber Inclusion in 3D printed preforms

- Continuous carbon fiber filament produced by pultrusion process.
- 40% by volume of carbon fiber
- Average impregnated filament diameter of 1.5 mm
- Achieved high level of impregnation (>95%)
- Commercial grade of carbon fiber compounded with PPS was used for printing (50% wt. CF-PPS).



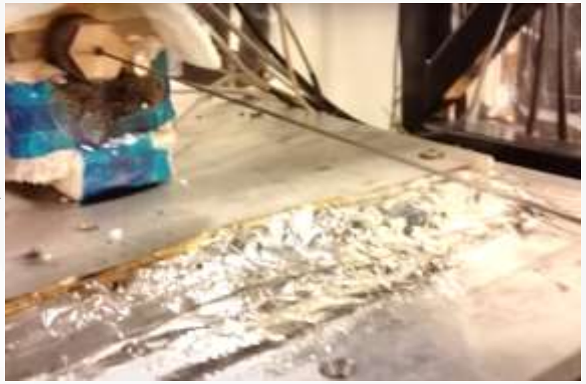
Micrograph of pultruded filament

Spools of Carbon Fiber



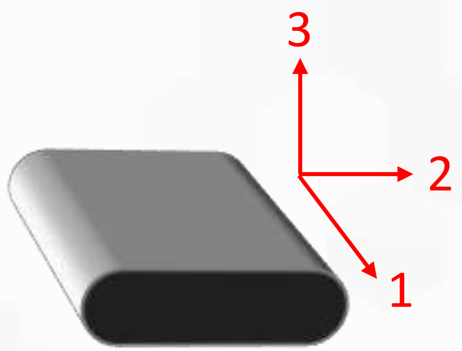
Interior of Impregnation Chamber

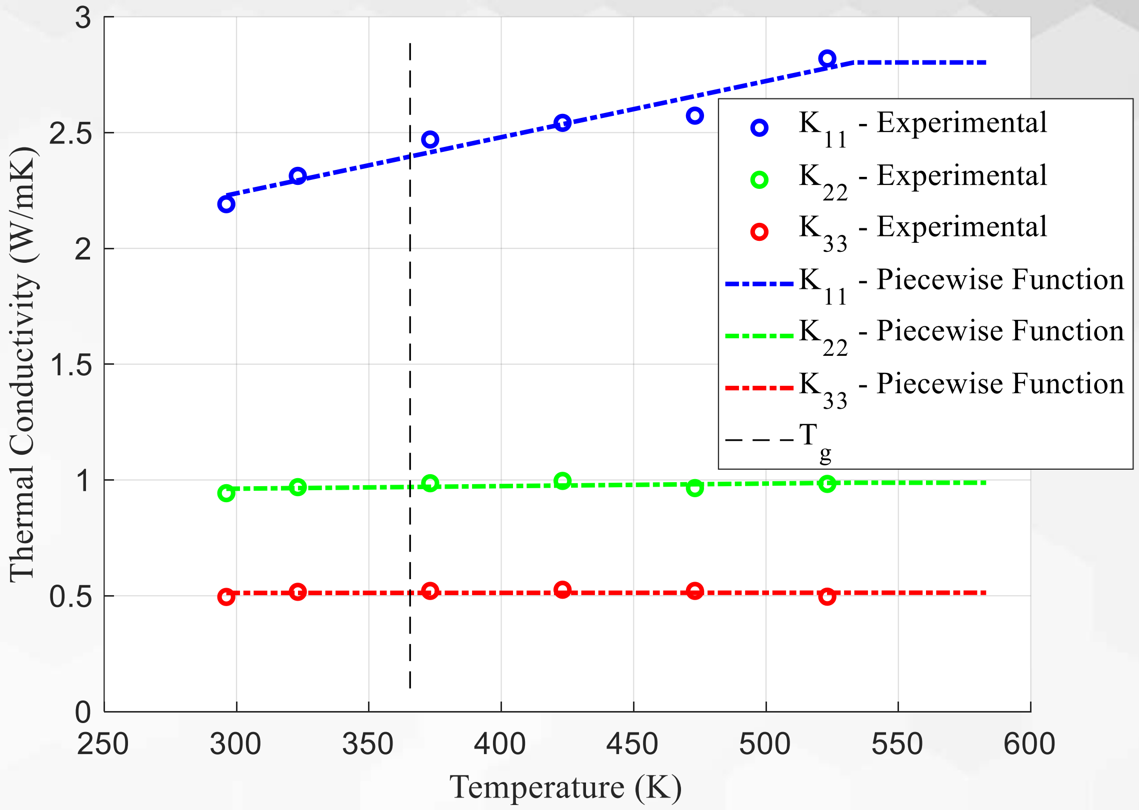
Carbon Fiber Impregnated with PPS



Characterization of Thermal Conductivity

- Laser flash technique (ASTM E1461) used for characterizing thermal conductivity of printed material (50% by wt. of carbon fiber reinforced PPS)
- Micromechanics models to predict thermal conductivity of filament with continuous carbon fiber.





Thermal conductivity in the three principal directions of printed short carbon fiber reinforced PPS.

Characterization of Thermal Conductivity

- Micromechanics predictions of thermal conductivity for 40% by volume of continuous carbon fiber reinforced PPS.
  - Two-step homogenization using Mori-Tanaka method.
  - Types of fiber considered: Hexcel AS4[1] and Nippon CN-90
  - Polymer considered: Celanese Celstran 0203P6 PPS[2]

Hexcel AS4

Direction	Thermal Conductivity (W/mK)
K_{11}	2.918
K_{22}	0.5
K_{33}	0.5

Nippon CN-90

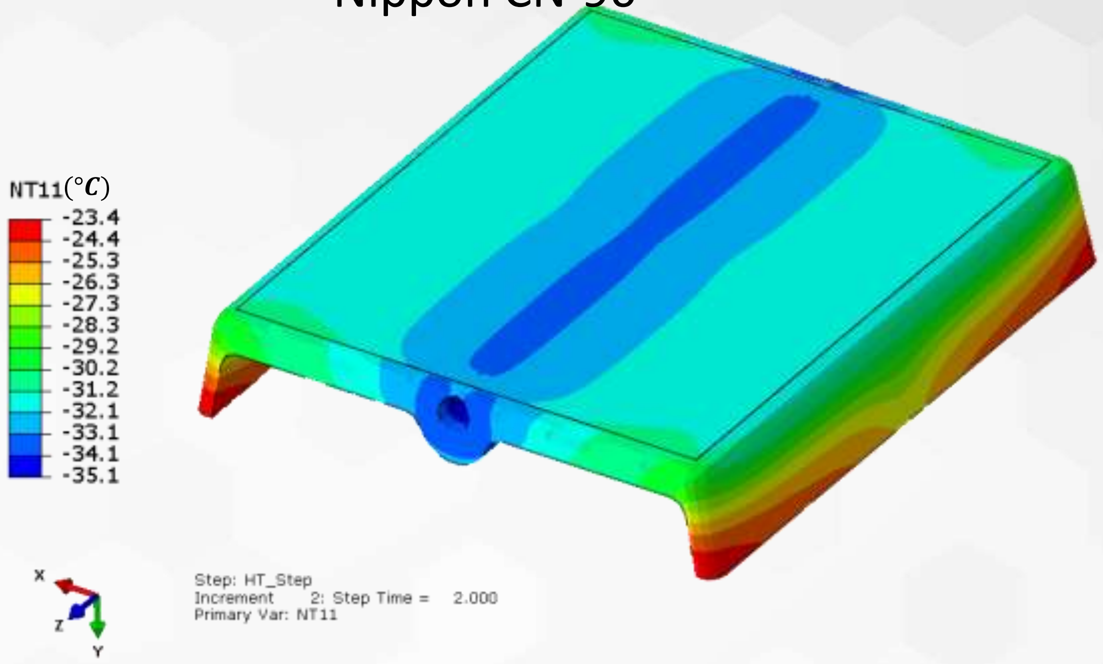
Direction	Thermal Conductivity (W/mK)
K_{11}	200.2
K_{22}	0.72
K_{33}	0.72

1. Hexcel Corporation. HexTow® AS4 Carbon Fiber Product Data Sheet. 2020.
2. Celanese. FORTRON® PPS POLYPHENYLENE SULFIDE (PPS). Short-Term Properties Guide. 2016.

Steady State FE Heat Transfer Analysis

- Heat transfer analysis used to drive design of continuous fiber and to investigate effects of fiber thermal conductivity
- Surface heat flux (0.1 - 1 W/cm^2) applied over detector's surface (heat flow of 2.5 – 25.85 W)
- Cooling line set to $-35\ °C$
- Convection ($h = 7.5\,\frac{W}{m^2 °C}$) and radiation ($\epsilon = 0.92$) from exposed surfaces to ambient temperature
  of $-20\ °C$
- Assumed ideal bonding between material systems (no thermal resistance)

Nippon CN-90



Finite Element Mesh

Continuous Fibers Reinforcements:

- Hexahedron element mesh (DC3D8)
- Thermophysical properties of continuous carbon fiber reinforced PPS (investigated Hexcel AS41 and Nippon CN-90)
- Considered orthotropic elastic properties and thermal conductivity based on material orientation (Fibers oriented across cooling line)

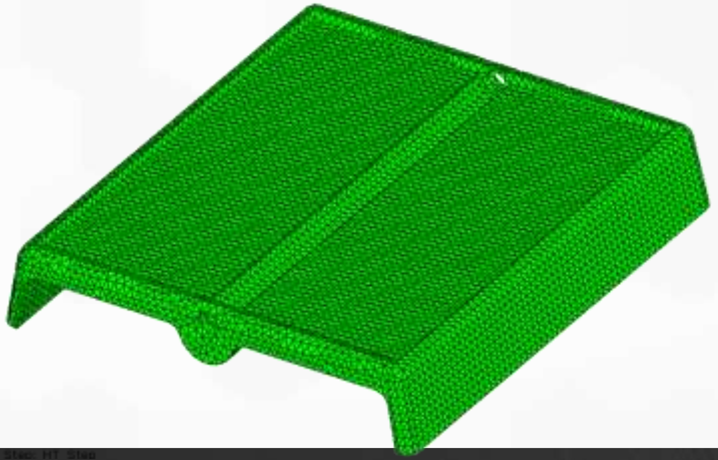
Discontinuous Fibers Structure:

- Tetrahedral element mesh (DC3D4)
- Considered properties of short-carbon fiber reinforced PPS (measured experimentally)
- Neglects anisotropic thermal conductivity

Continuous Fiber System

+

Discontinuous Fiber System



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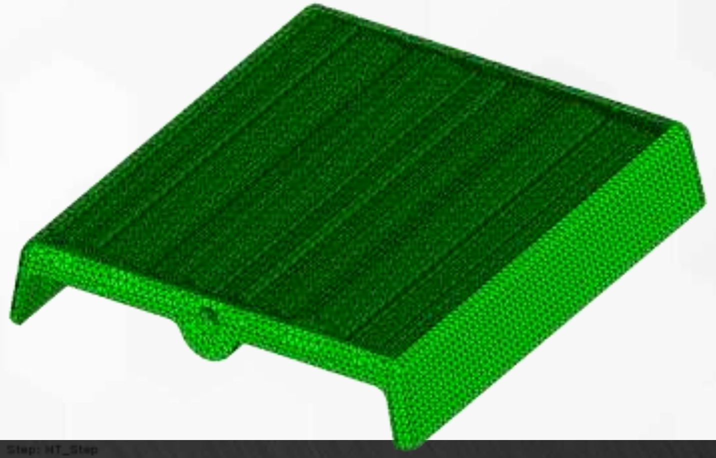
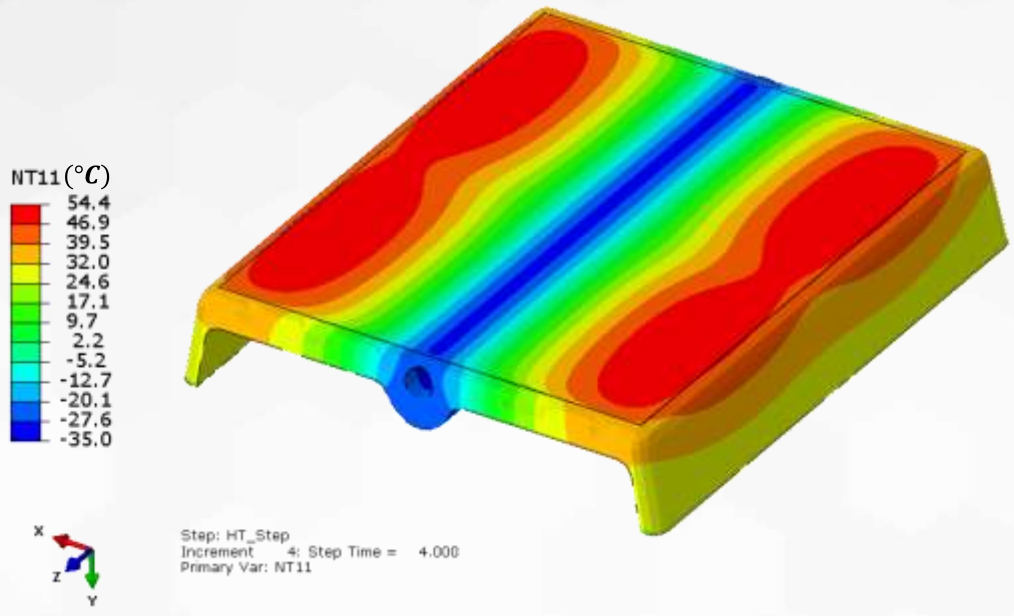
Hybrid Compression Molded Structure



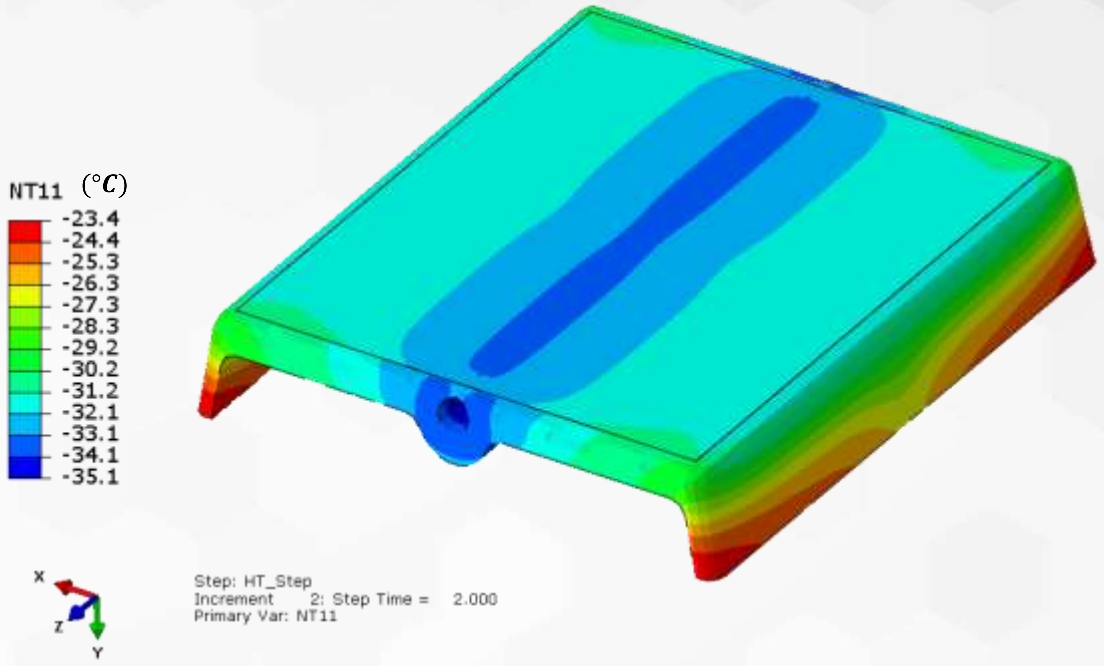
Temperature Field with Different Fiber Systems

Steady state temperature field at heat flow of 10.34 W

Hexcel AS4



Nippon CN-90

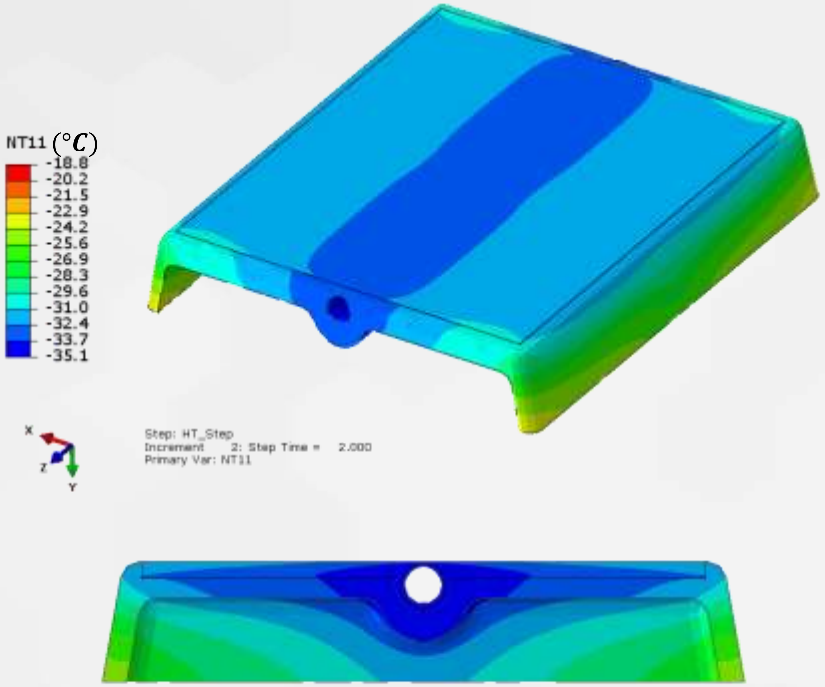


NOTE - Temp scale is different between the two plots

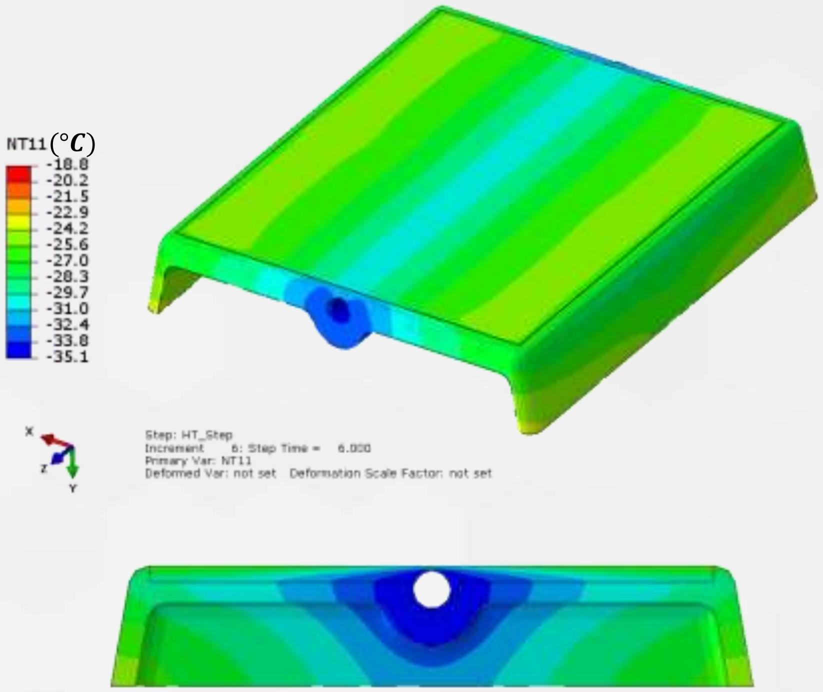
Temperature Fields at Different Heat Flows

- Fiber system considered: 40% vol. Nippon CN-90 reinforced PPS

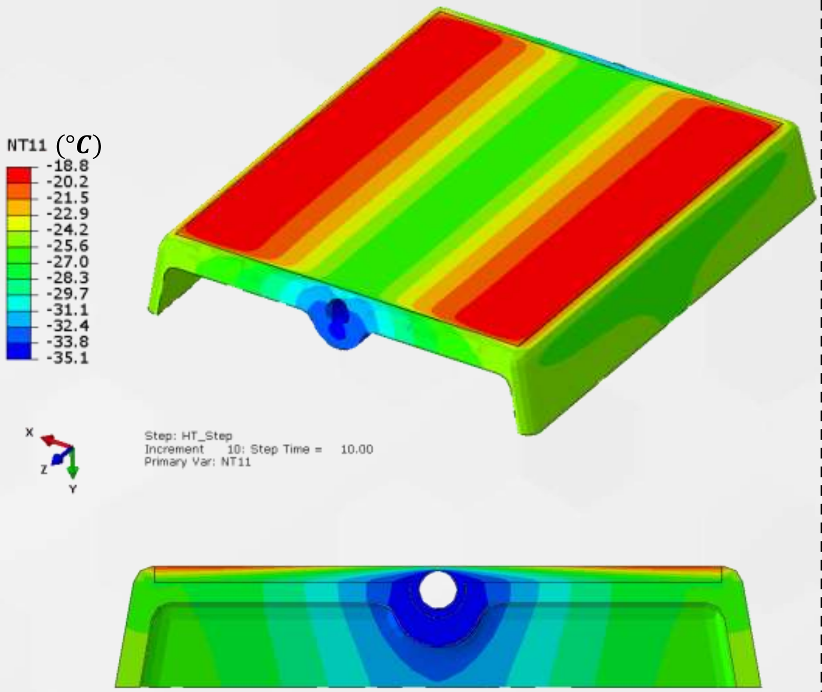
Heat flow = 5.17 W $(0.2\, W/cm^2)$



Heat flow = 15.51 W $(0.6\, W/cm^2)$

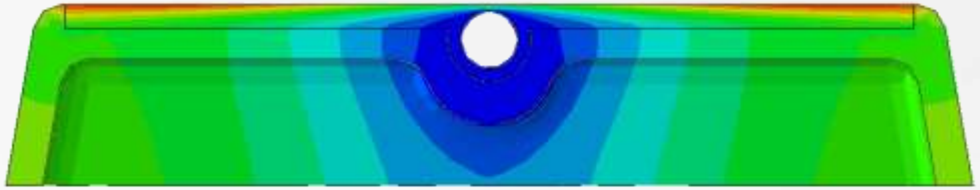


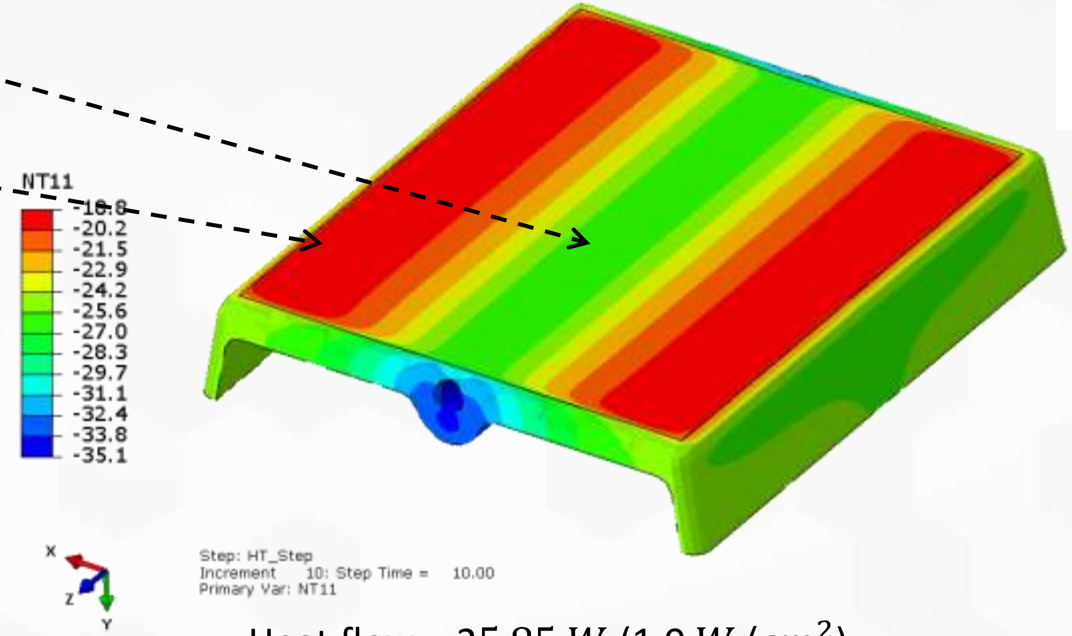
Heat flow = 25.85 W $(1.0\, W/cm^2)$



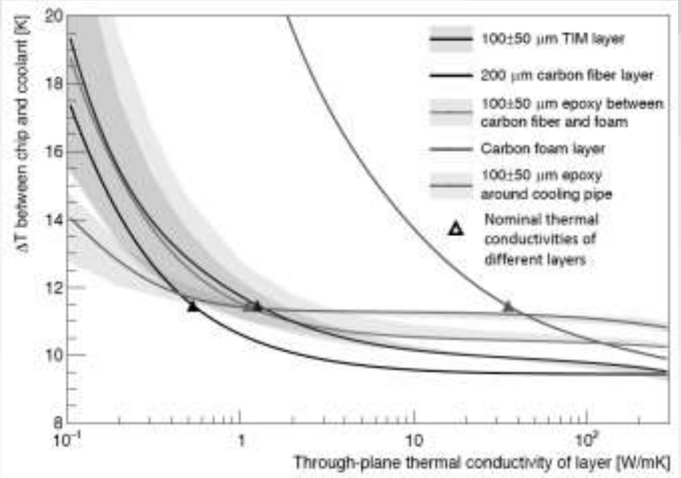
Temperature Difference Between Detector and Coolant

- Temperature difference between detector and coolant varies between $4.2\ °C$ and $15\ °C$ across the detector





Heat flow = $25.85\ W\ (1.0\ W/cm^2)$

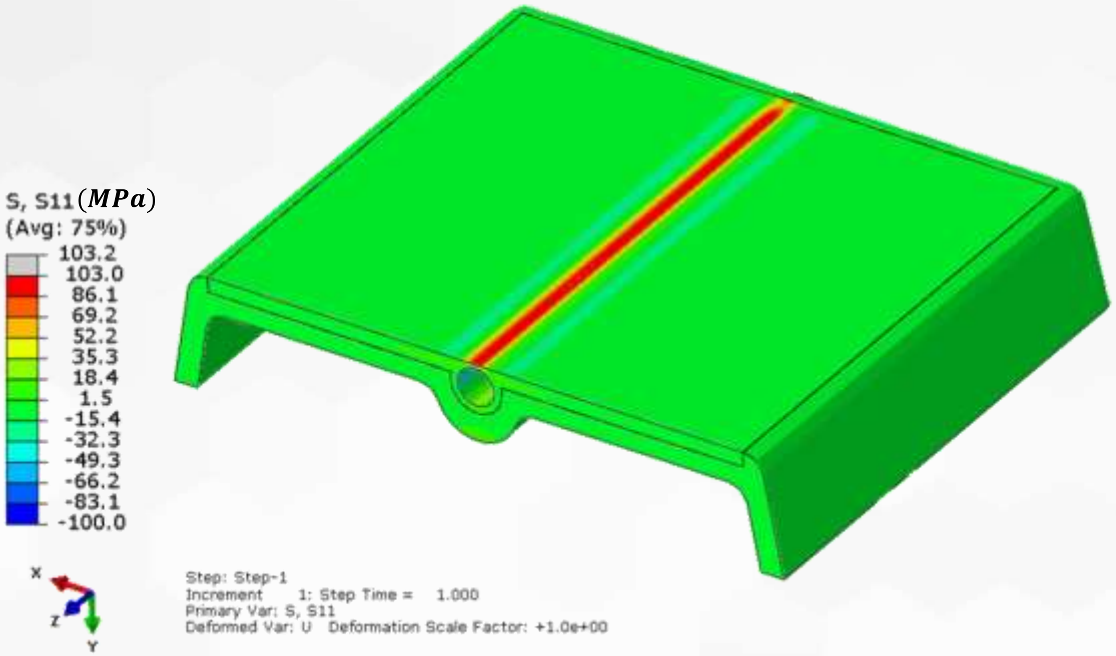


State of the art – CMS-Phase II Upgrade has $\Delta T \sim 12\ to\ 17\ °C$

Stress Analysis of Hybrid Structure Under Pressure

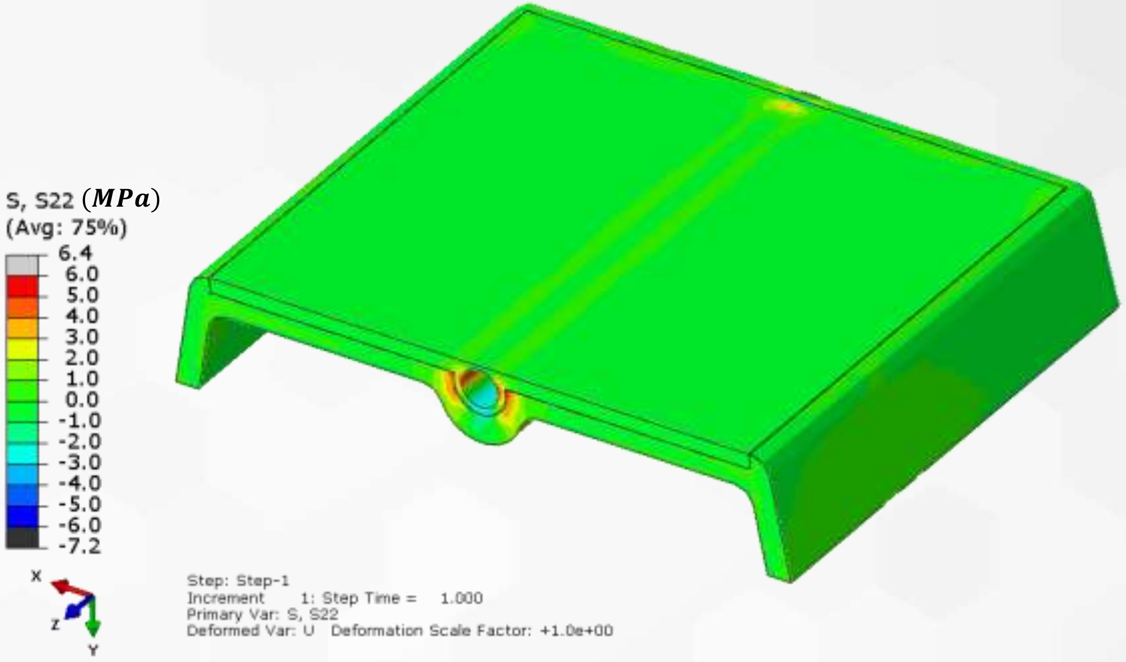
- Cooling line pressurized at 68.9 Bar

Stress in Fiber Direction



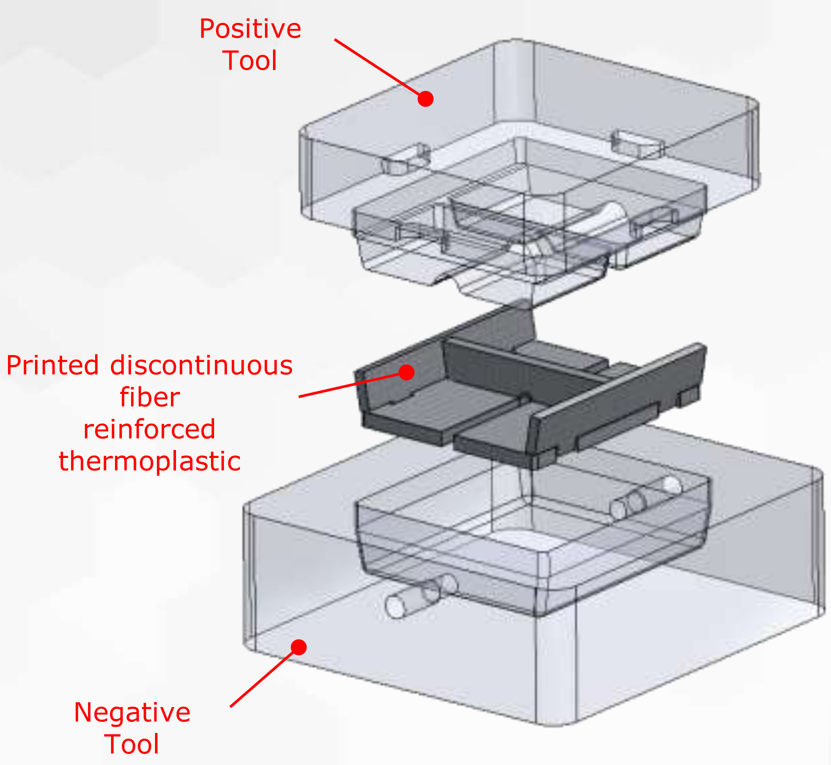
$\sigma_{11} \ll X_1^T \sim 300 - 500\ MPa$

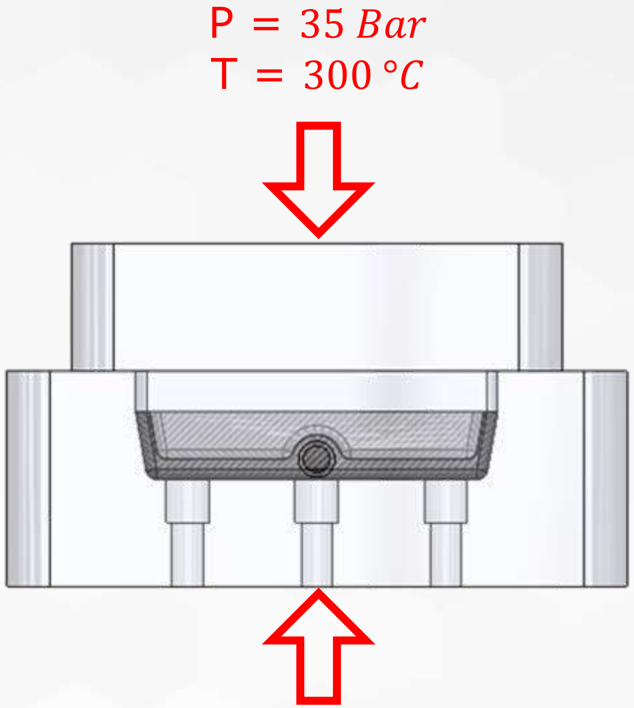
Stress Transverse to Fiber Direction



$\sigma_{22} \ll X_2^T \sim 30 - 50\ MPa$

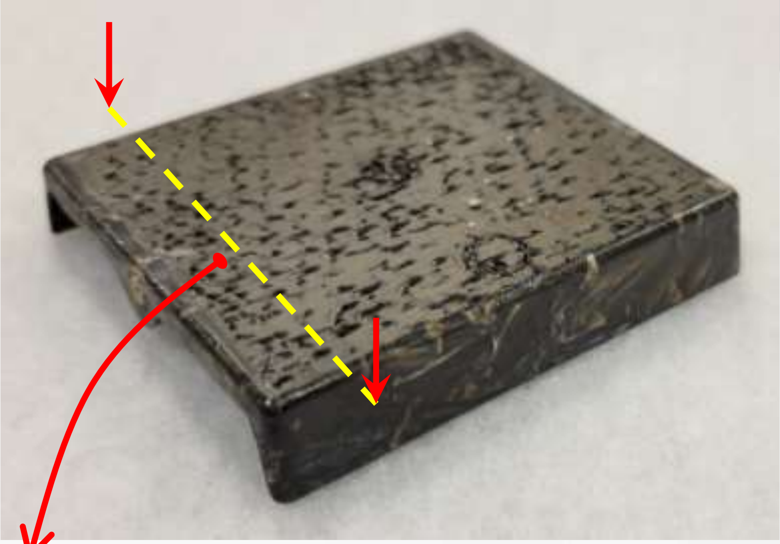
Compression Molding Process

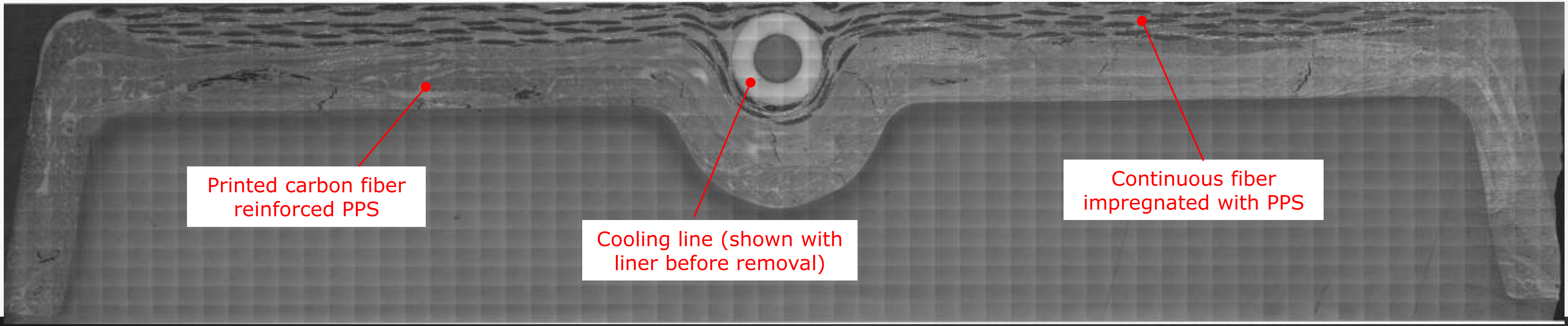




Prototype Support Structures with Integrated Services – AS4 fiber

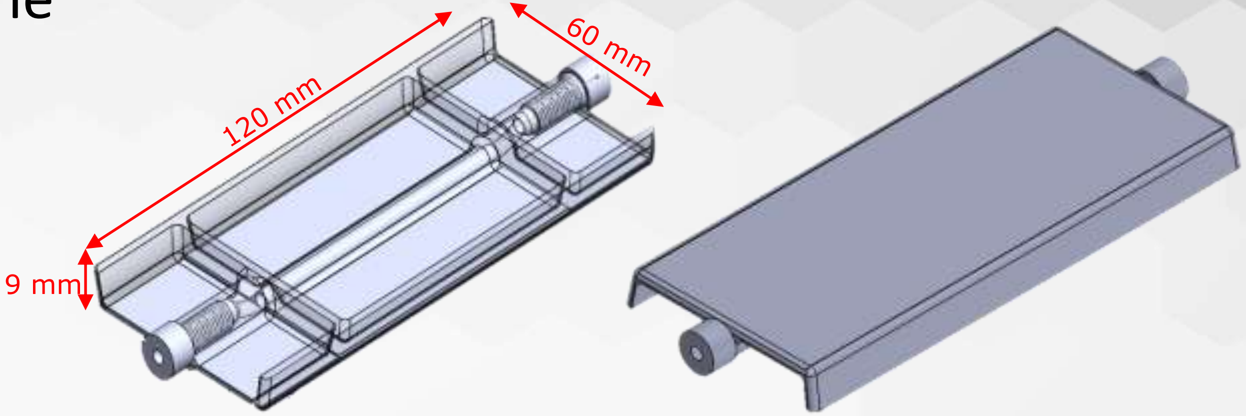
- Cross section of molded prototype demonstrates:
  - Feasibility of integrating cooling line with non-metallic liners
  - Hybrid continuous and discontinuous fiber architecture
  - Consolidation of multiple material systems through compression molding

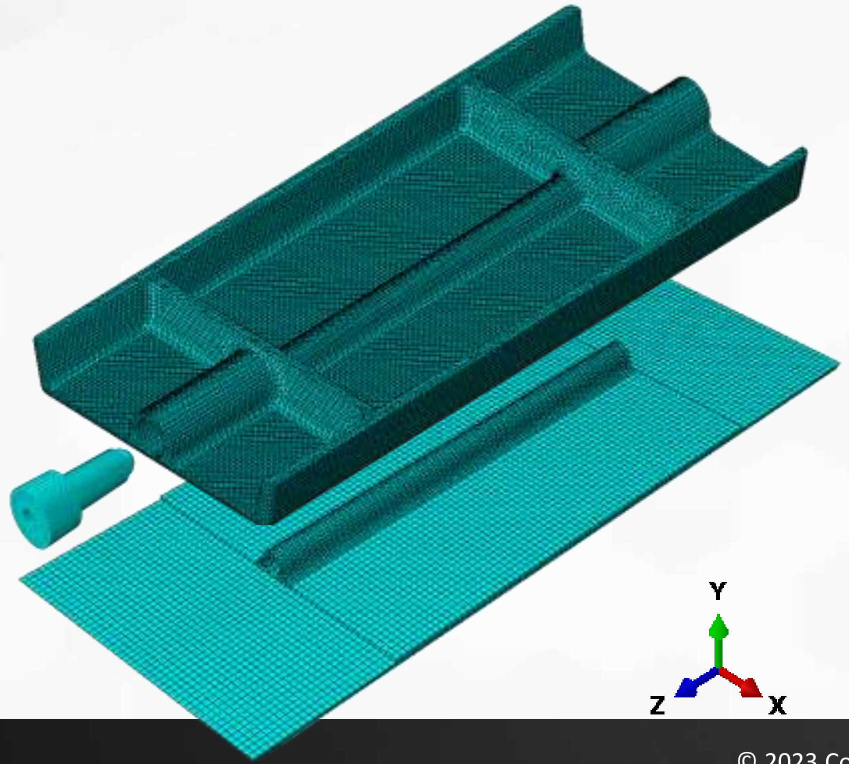




Extended Multifunctional Test Structure – AS4 fiber

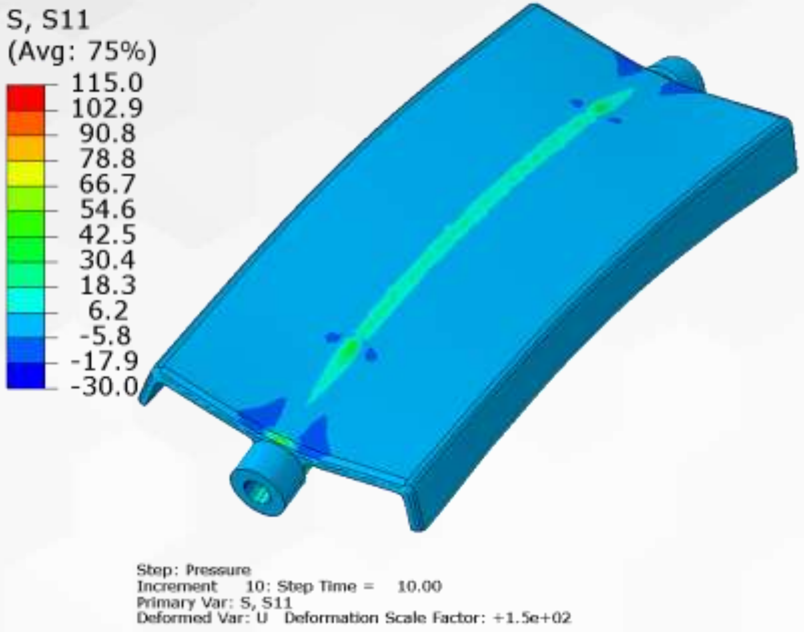
- Aim to show scale up capabilities of the manufacturing method
- Validate the structure with pressure and temperature testing





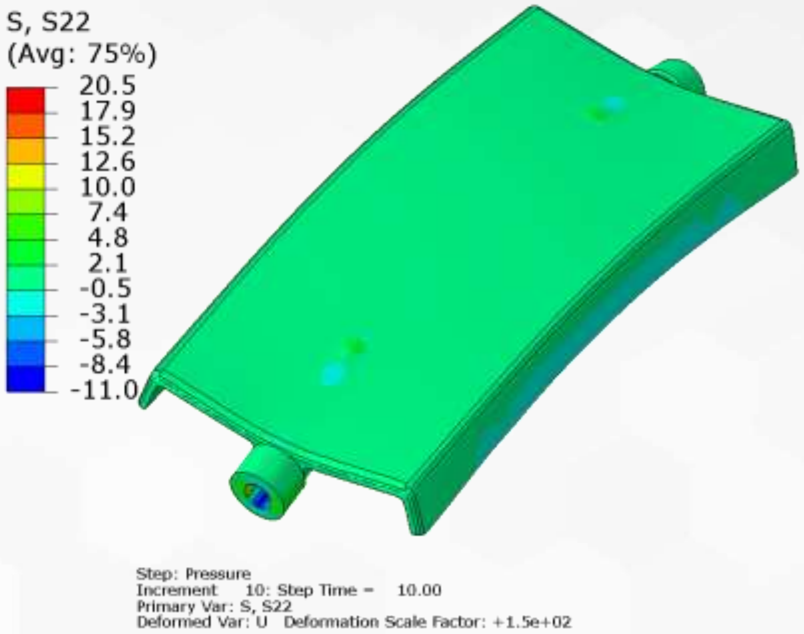
Part Performance Simulation for Pressure Test at 600 psi (41.3 bar) Coolant Pressure – AS4 fiber

Stress in Fiber Direction



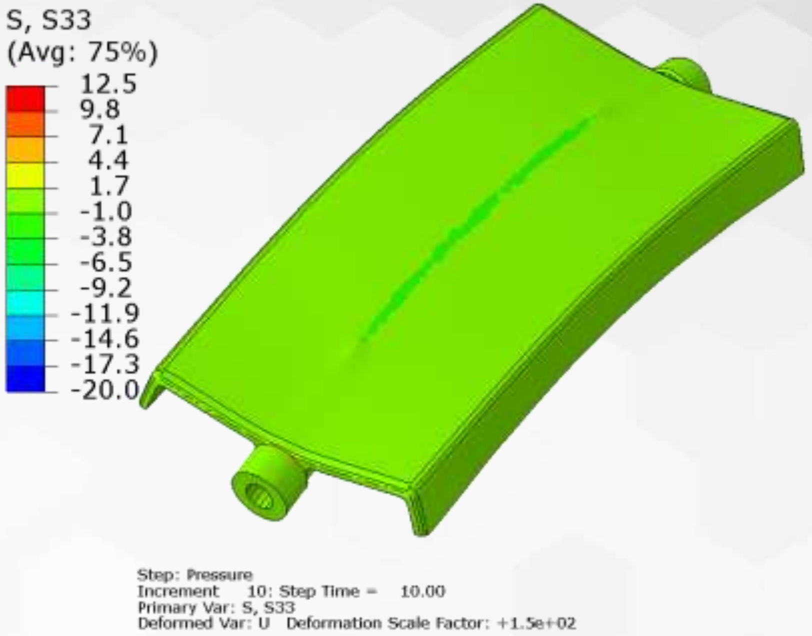
$\sigma_{11} \ll X_1^T \sim 300 - 500\ MPa$

Stress Transverse to Fiber Direction



$\sigma_{22} \ll X_2^T \sim 30 - 50\ MPa$

Stress Transverse to Fiber Direction

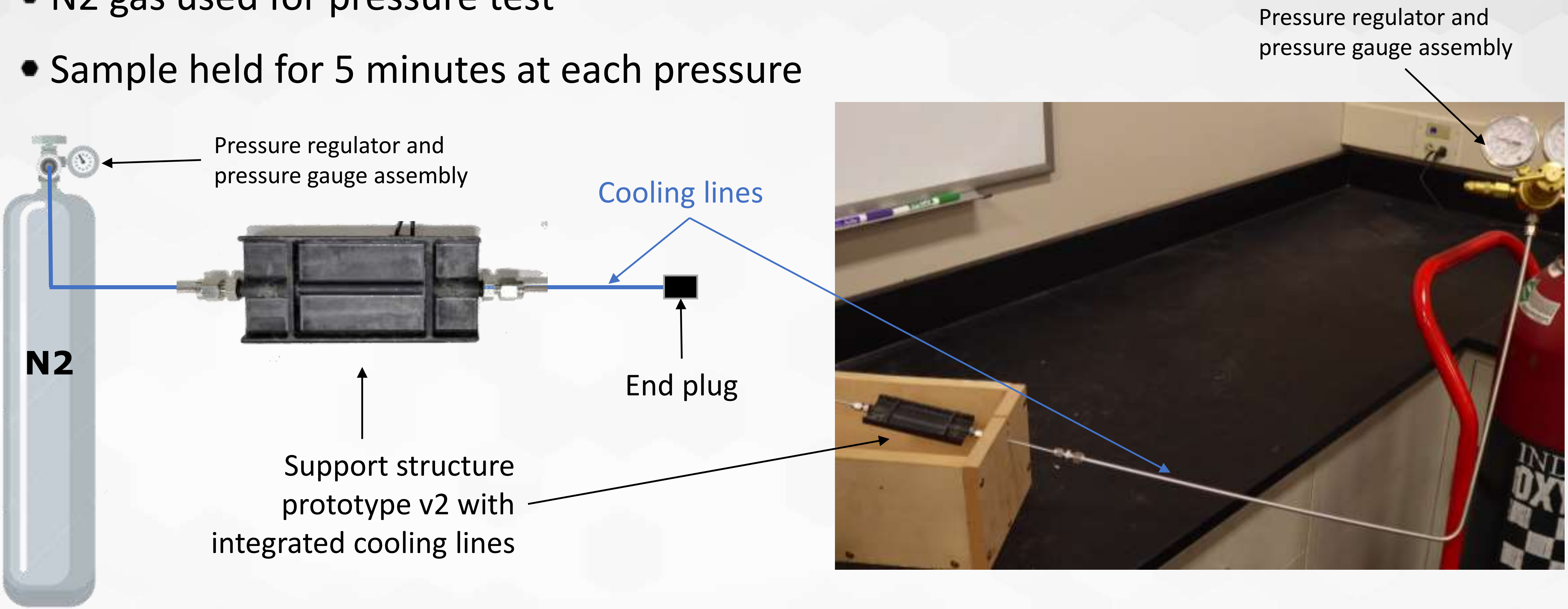


$\sigma_{33} \ll X_3^T \sim 30 - 50\ MPa$

Deformation Scale Factor: 150x

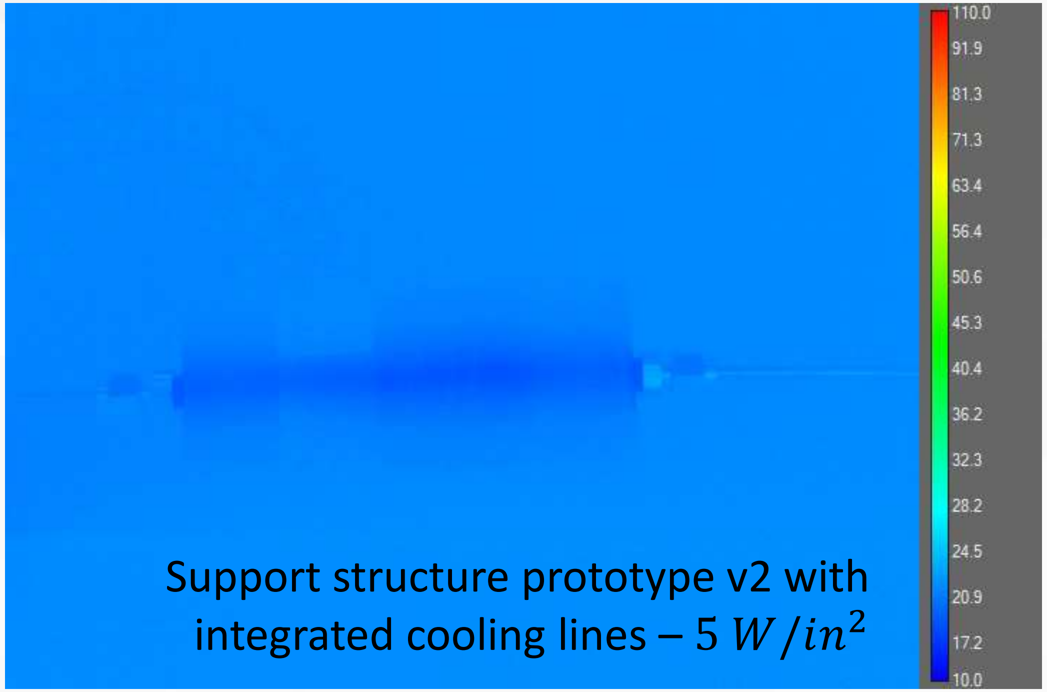
Preliminary Results – Pressure Test – AS4 fiber

- Pressure test carried out at increments of 3.4 Bar up to 48.3 Bar
- N2 gas used for pressure test
- Sample held for 5 minutes at each pressure

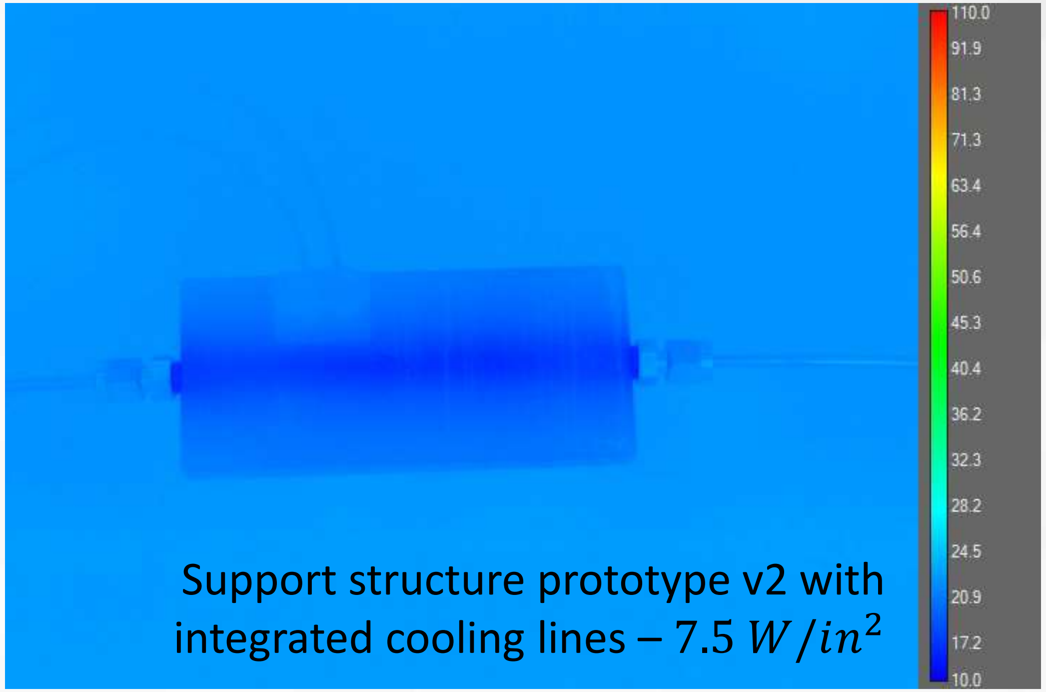


Preliminary Results – Thermal Response – AS4 fiber

- Thermal response test carried out with room temperature coolant and film heaters to mimic sensors mounted on the surface of the structure
- Transient response recorded for 5 W/in^2 and 7.5 W/in^2 heating



Support structure prototype v2 with integrated cooling lines – 5 W/in^2

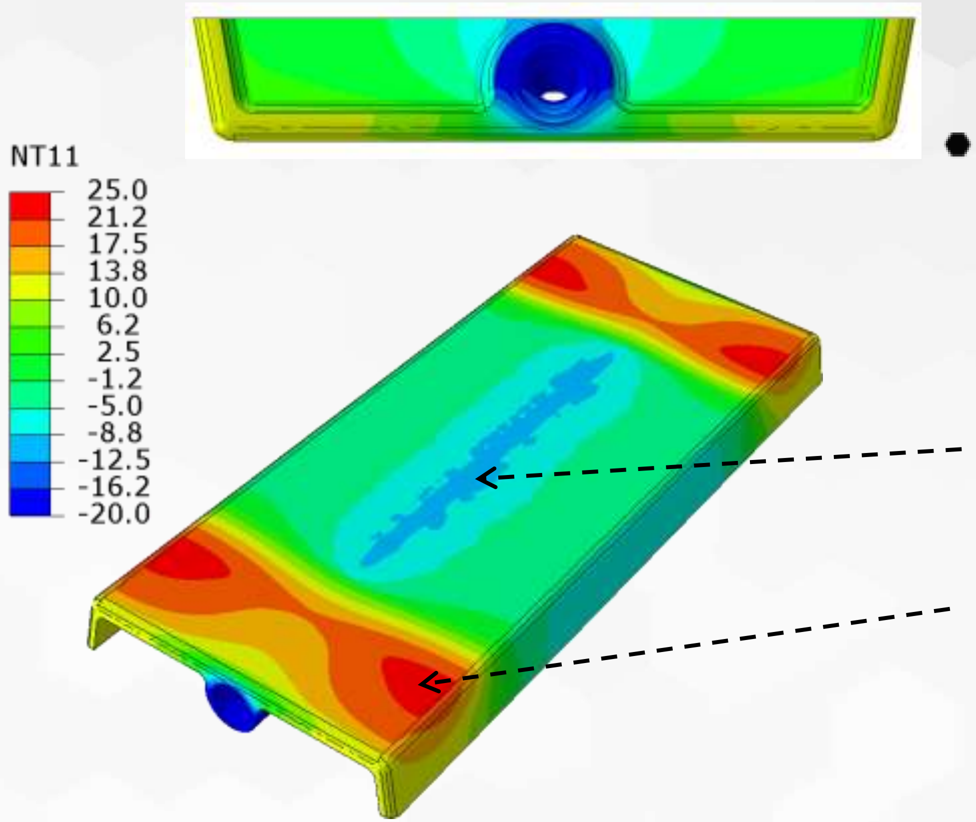


Support structure prototype v2 with integrated cooling lines – 7.5 W/in^2

Preliminary Results – Thermal Response – AS4 fiber

- Upcoming tests –

Thermal response with coolant at -20°C



Heat flow = 25.85 W

Convection Coefficient = 3000 $[W/m^2K]$

- Temperature difference between detector and coolant varies between
10 $°C$
and
42.5 $°C$
across the detector
(-20 $°C$ cooling line temperature)

Summary and Conclusions

1. The hybrid structures with integrated services offer the potential to reduce manufacturing time, cost, and to improve thermal performance.
   - Reduces the number of thermal interfaces
   - Provides engineered thermal paths through microstructures printed with highly thermally conductive fibers
   - Offers the potential to remove metallic liners used in traditional designs
   - Allows for complex non-planar designs
2. The heat transfer and structural analyses showed the potential to meet the thermal and structural requirements of support structures
3. The prototype demonstrated the feasibility of manufacturing support structures with integrated cooling

Future Work

1. Conduct experimental validation on prototype v2
   - Structural integrity of structure under cooling's line pressure with scale up potential
   - Integrity of custom developed non-metallic cooling line connections
   - Thermal performance at sub-zero coolant temperatures
   - Verify simulation predictions for temperature fields in representative conditions
2. Apply technology to full size support structure
   - Potential for modular designs
   - High thermal conductivity fibers to improve thermal response

Acknowledgments

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Thank You!