Thermal Measurements and Modeling of Carbon-Fiber Support Structures for Pixel Detectors

Pau Simpson Crusafon, Benjamin Pulver,
Yuvraj Chauhan, Gasahn Chanikornpradit,
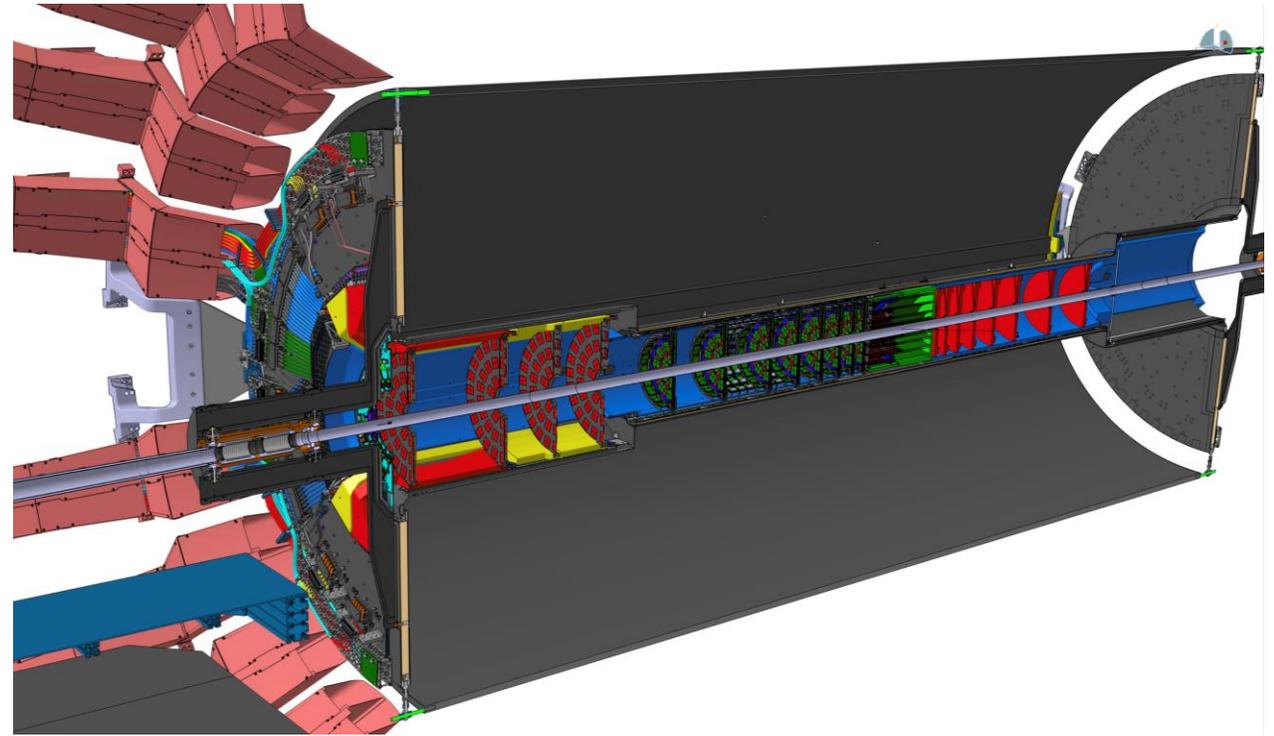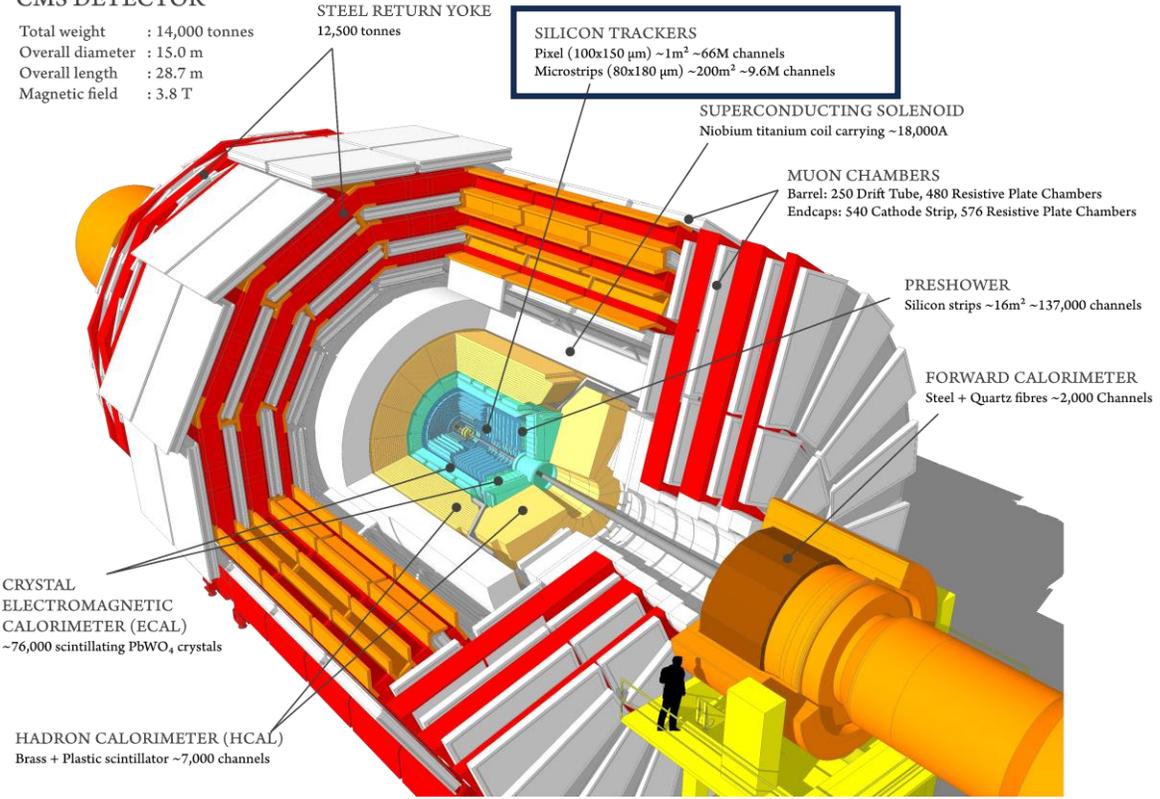Sushrut Karmarkar, Ben Denos, Andreas Jung

09 October 2025

Presented at CPAD 2025 at Penn

⬡ Motivation and Case Study: CMS Phase-II Tracker Upgrade – TFPX Dee Support Structure

⬡ Temperature Dependent Simulations

⬡ Thermal Contact Resistance
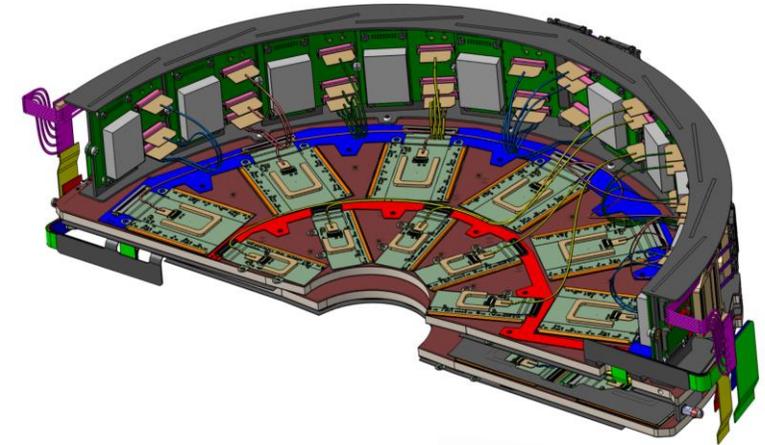
⬡ Conclusions

⬡ Appendix: Thermal Property Measurements

CMS Phase-II Tracker Upgrade

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

- ⬡ Tracker is being upgraded to meet the requirements of higher pile-ups and accumulated radiation dose in the HL-LHC upgrade

- ⬡ Split into the inner (shown) and outer tracker

- ⬡ Near interaction point, the radiation length is critical, so, we need to achieve cooling with a low material budget

3

- The forward pixel is made up of 8 double dees per detector quarter

- The dees are a sandwich structure with a high thermal conductivity carbon fiber facesheet and carbon foam with an embedded titanium evaporator

- Modules are placed on the facesheets, requiring heat to flow through many materials before reaching the heat sink

- Power dissipation of the sensors increases with temperature

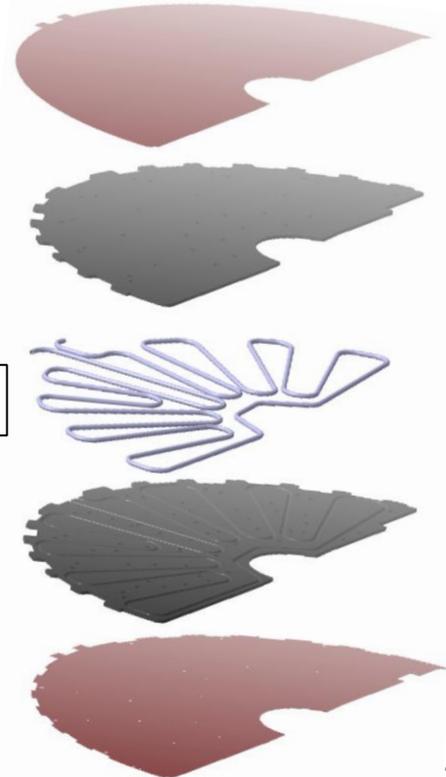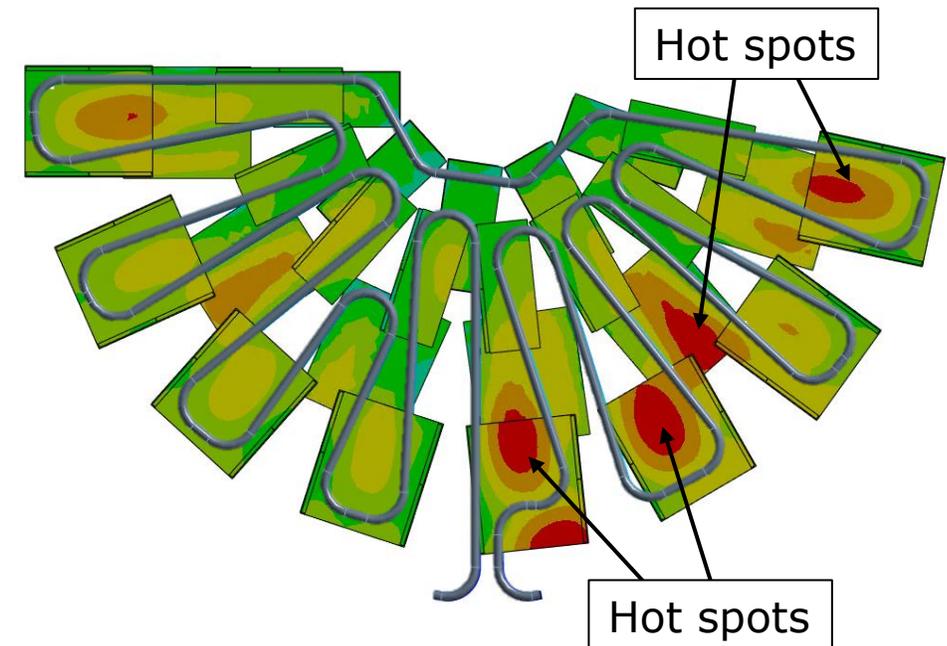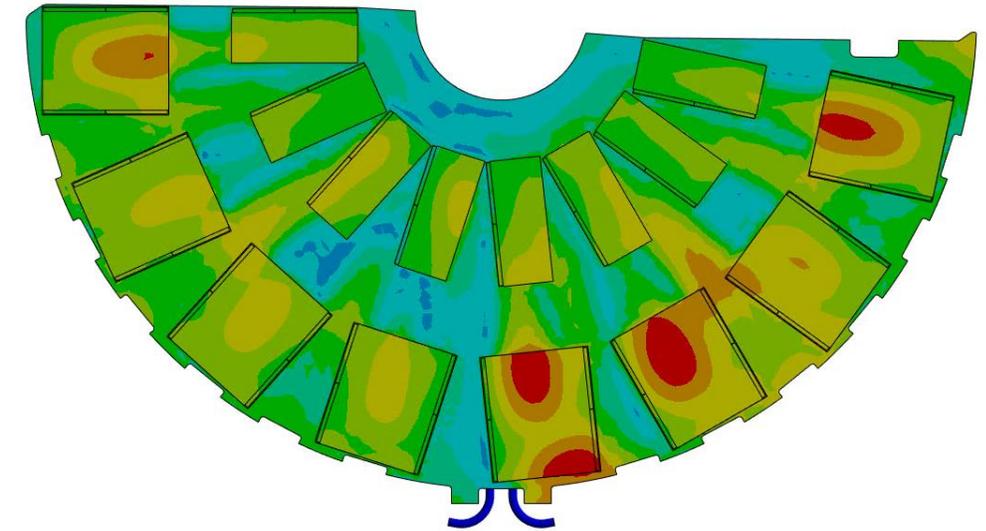 - Thermal runaway is a large concern for the cooling of TFPX

Carbon Fiber Facesheet

Carbon Foam

Titanium Pipe Evaporator

Carbon Foam

Carbon Fiber Facesheet

⬡ ANSYS model

- Full read-out chip and high-density interconnect heat sources

- Applied convection profiles to cooling pipe

- Ambient surfaces have been developed

⬡ Near outside of the dee where pipe density is lower, locations with modules on both sides see a hotspot

    ⬡ These will be the points where thermal runaway can nucleate and thus must be predicted accurately

⬡ This is considered a "first order" model and more investigation is needed to verify accuracy of FEA predictions

⬡ Robust FEA models require temperature dependent properties for accurate predictions

Hot spots

Hot spots

- Materials experience and change in properties with their temperature

- A Netzsch LFA467 and TA DSC Q100 are used to measure thermal diffusivity and specific heat capacity respectively

- Multiplying these properties with the density yields the thermal conductivity

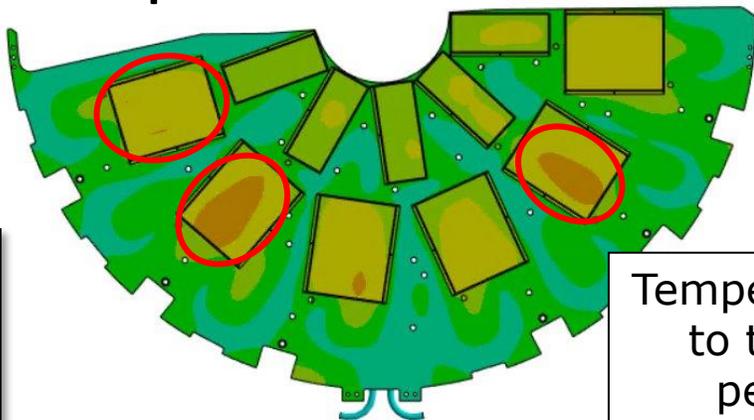- These instruments have precise temperature control, allowing property measurements at detector conditions (-35C)
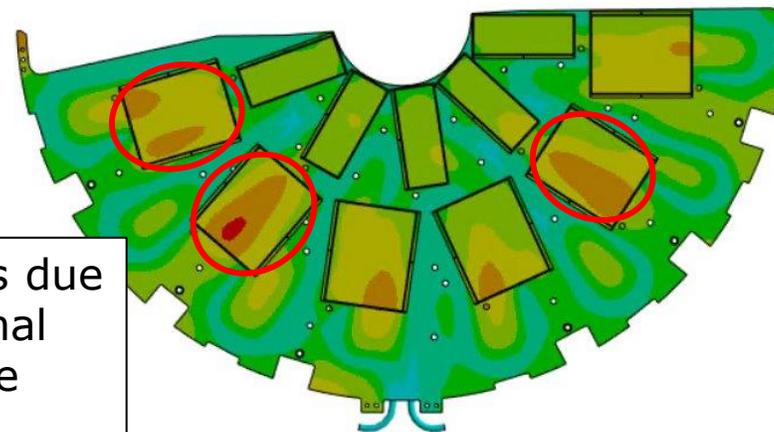
$$k = \rho \alpha c_p$$

⬡ All materials of the dees have been characterized for temperature-dependent thermal properties

⬡ EX1515-K13D2u, the facesheet material, is the limiting factor in the thermal stack-up of the dees

⬡ It has a ~25% degradation in thermal conductivity from room temperature down to operation temperature of -35C

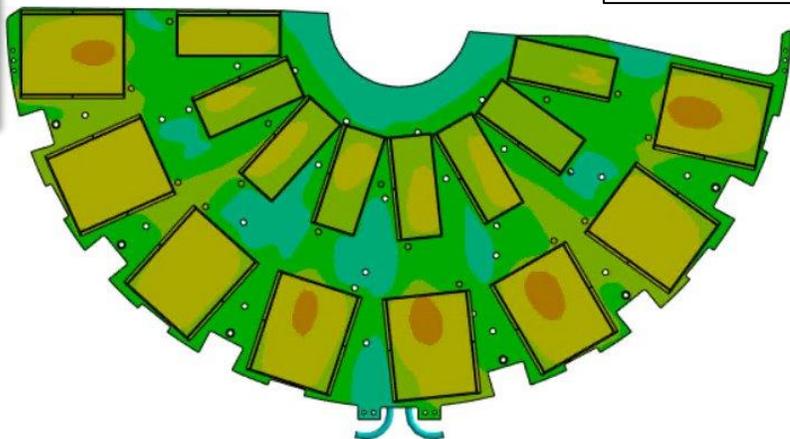⬡ Without temperature dependence, the simulation will over-predict the thermal performance of the dee

Thermal Conductivity vs. Temperature of EX1515-K13D2u

Constant Properties:

Temperature-dependent Properties:

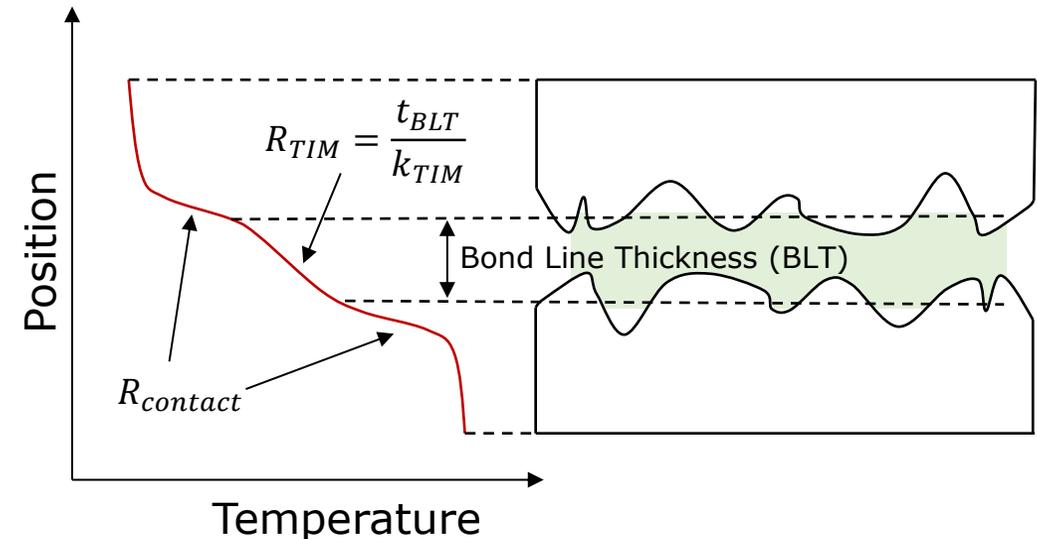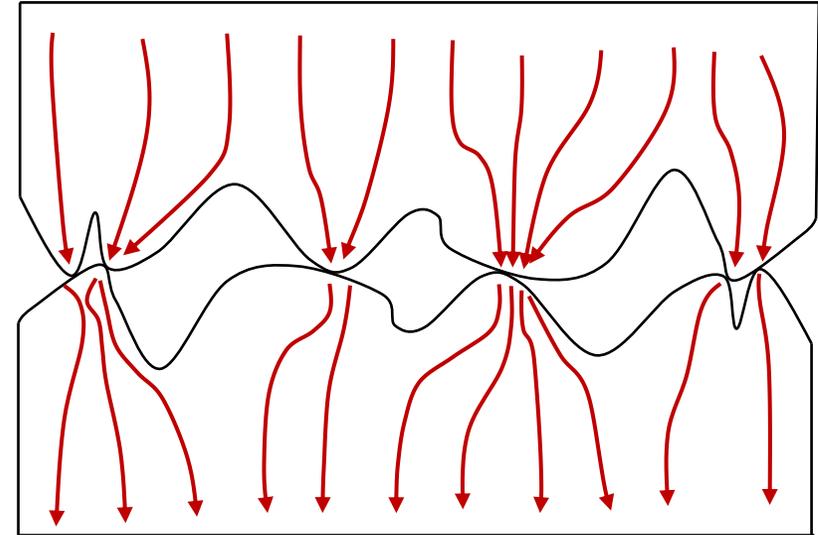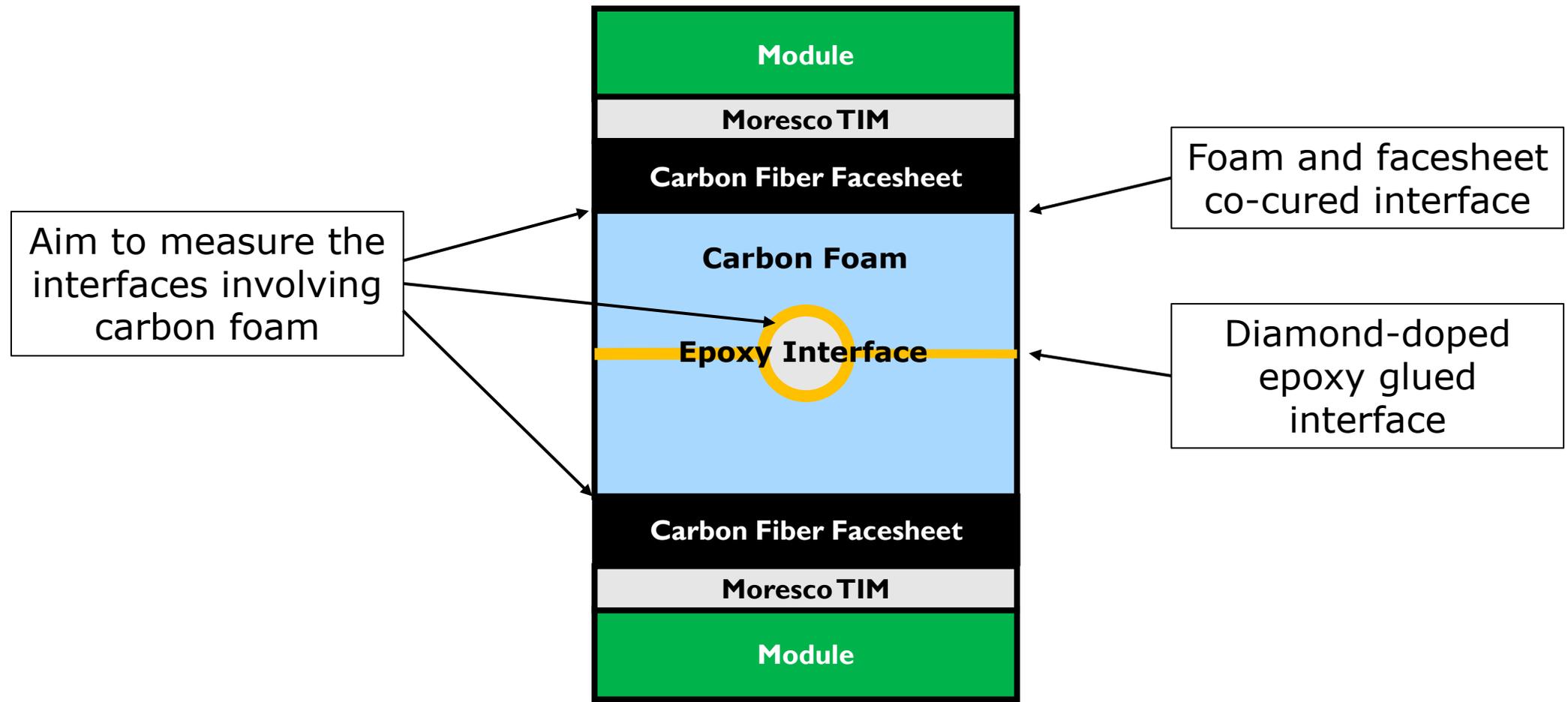Temperature increases due to the limited thermal performance of the facesheet

- ⬡ Because the power dissipation of the modules is dependent on the temperature, hotter modules means the cooling system must remove more heat.

- ⬡ With the 64 dees in TFPX, a slight increase in power dissipation of a module has a large effect on the total amount of heat required to be removed from the detector
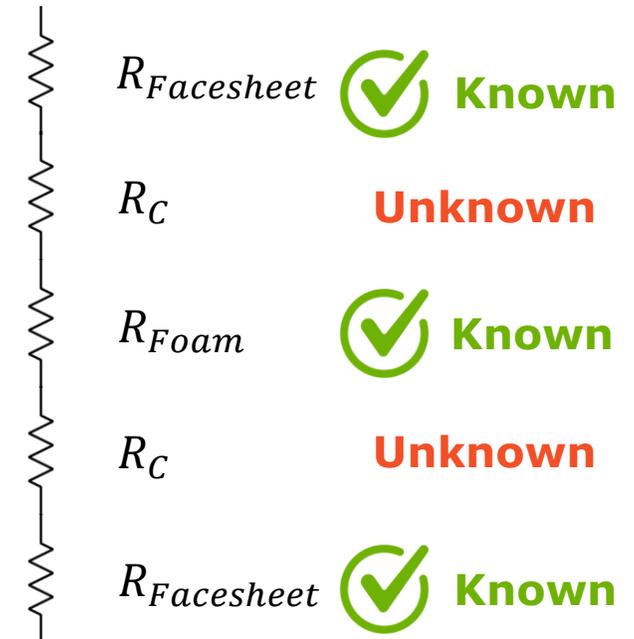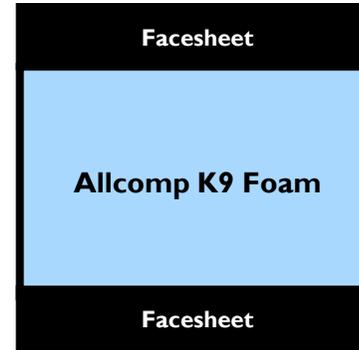
8

Thermal Contact Resistance

⬡ At all real interfaces, there is not a perfect thermal contact, causing heat to constrict, causing additional temperature rise

⬡ This can dominate thermal systems if not handled properly

⬡ Thermal interface materials (TIMs) are used to fill the gap and improve thermal contacts

⬡ Thermal conductivity does not tell the whole story with TIMs; there is still an interfacial resistance must be measured to be characterized

$$R_{TIM} = \frac{t_{BLT}}{k_{TIM}}$$

Bond Line Thickness (BLT)

$R_{contact}$

Position

Temperature

◆ Using LFA technique, due to the porous nature of foam, the laser flash penetrates the thickness of the sample causing a faster-than-normal temperature rise

◆ This can be accounted for in a single-layer sample, but gets complicated for an interface

　　◆ Thus, a three-layer samples is used for any interface measurement involving foam

　　◆ Foam thickness is varied to make sure the contact resistance is independent of geometry

◆ The interface is taken to have zero thickness for this case

◆ Note: If you are not using porous material, a two-layer sample simplifies this significantly

Facesheet

Allcomp K9 Foam

Facesheet

$R_{Facesheet}$ ✅ **Known**

R_C **Unknown**

R_{Foam} ✅ **Known**

R_C **Unknown**

$R_{Facesheet}$ ✅ **Known**

- Assume 1D heat transfer, so all resistance is normalized by area

- Find the ideal thermal resistance from conduction through all three layers of the sample ignoring contact resistance

$$R_{ideal}^{''} = \sum \frac{t_i}{k_i}$$

- Find the effective heat capacity of the three-layer sample

$$(\rho c_p)_{eff} = \frac{1}{t_{tot}} \sum t_i (\rho c_p)_i = \frac{1}{m_{tot}} \sum m_i (\rho c_p)_i$$

  - Must include mass of glue if present

- Using the LFA, measure the effective diffusivity of the three-layer sample

$$R_{actual}^{''} = \frac{t_{tot}}{\alpha_{eff} * (\rho c_p)_{eff}}$$

- Find the actual thermal resistance as measured by LFA

$$R_c^{''} = \frac{1}{2}(R_{actual}^{''} - R_{ideal}^{''})$$

- Compare to the ideal case for the resistance the interfaces contribute

R_{L1}

R_C

R_{Foam}

R_C

R_{L1}

⬡ There is a relatively significant thermal interface resistance even with a co-cure

⬡ Plane wall conduction through 200μm of diamond-doped epoxy is also plotted to give context on order of magnitude

⬡ Results are mostly independent of foam thickness (to a limit)

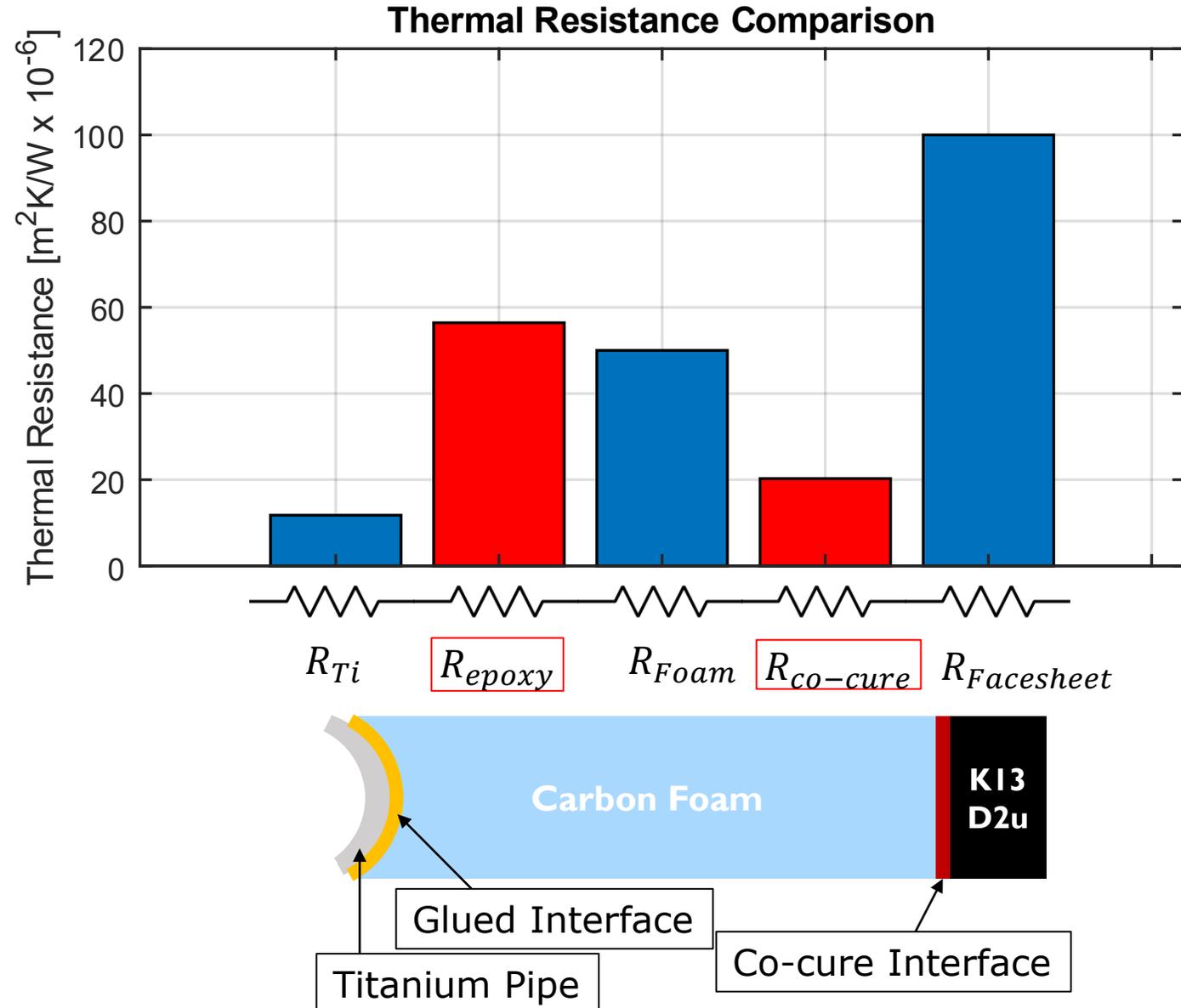   ⬡ Sample 3 shows non-physical results that stem from foam thickness being too large

ID	Thickness
Sample 1	1.3mm
Sample 2	1.1mm
Sample 3	4.2mm
Sample 4	2.0mm

Interfacial Contact Resistance of K13D2u to K9 Foam

Interfacial Contact Resistance of Titanium to K9 Foam using 70% Doped EA9396

Interfacial Contact Resistance of Titanium to K9 Foam using 0% Doped EA9396

- ⬡ Undoped epoxy caused a large spread in contact resistance
    - ⬡ This is likely due to the low viscosity epoxy wicking into the pores of the foam and causing poor adhesion
- ⬡ More data at 0% doping and new data at intermediate doping fractions is needed

- Comparing these measured interface resistances (red) to the conduction thermal resistance of the materials (blue), one can see interfaces are very important to consider in simulation

- Due to poor through-plane conductivity, the limiting thermal factor is the facesheet, but the epoxy interface is very close in magnitude

- ANSYS allows for contact resistances to be entered at interfaces, so these measurements can be easily added to simulations

Thermal Resistance Comparison

R_{Ti} R_{epoxy} R_{Foam} $R_{co-cure}$ $R_{Facesheet}$

Glued Interface

Titanium Pipe

Carbon Foam

K13 D2u

Co-cure Interface

○ Visualizing the thermal resistance through analysis was carried out using a representative plaquette, with the thermal performance compared through two approaches:

  ○ Explicit modelling of epoxy

  ○ Resistance equivalent placeholders

○ Results:

  ○ Maximum temperature difference of 0.2 C

  ○ Subtle variations in temperature distribution as carbon foam is overall warmer

○ Full model comparisons still underway

Conclusions and Future Work

- From a 1D thermal resistance perspective, the interfaces are a significant contributor to temperature rise
  - Further validation of LFA models is underway at Purdue

- Co-cure interface is not accounted for in the simulations. While it is small, adding it will improve the simulation's fidelity
  - This is being added into thermal simulations at Purdue

- Measured diamond-doped epoxy interface matches well with the 1D conduction prediction value
  - A CT scan and micrograph is being done on the samples to make sure the bond line thickness of the samples matches the actual TFPX dees

- Very careful attention is needed when assembling the TFPX Double Dees to ensure good thermal performance at interfaces

- Proper characterization of materials and thermal interfaces is essential for the design of support structures and cooling systems for future detectors
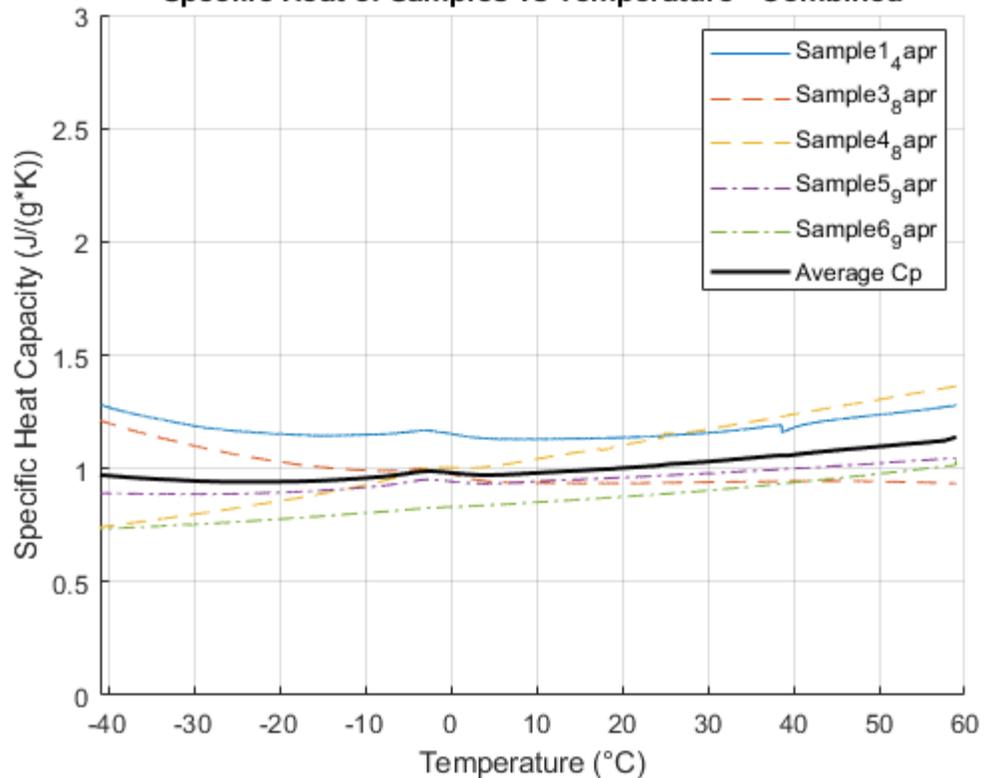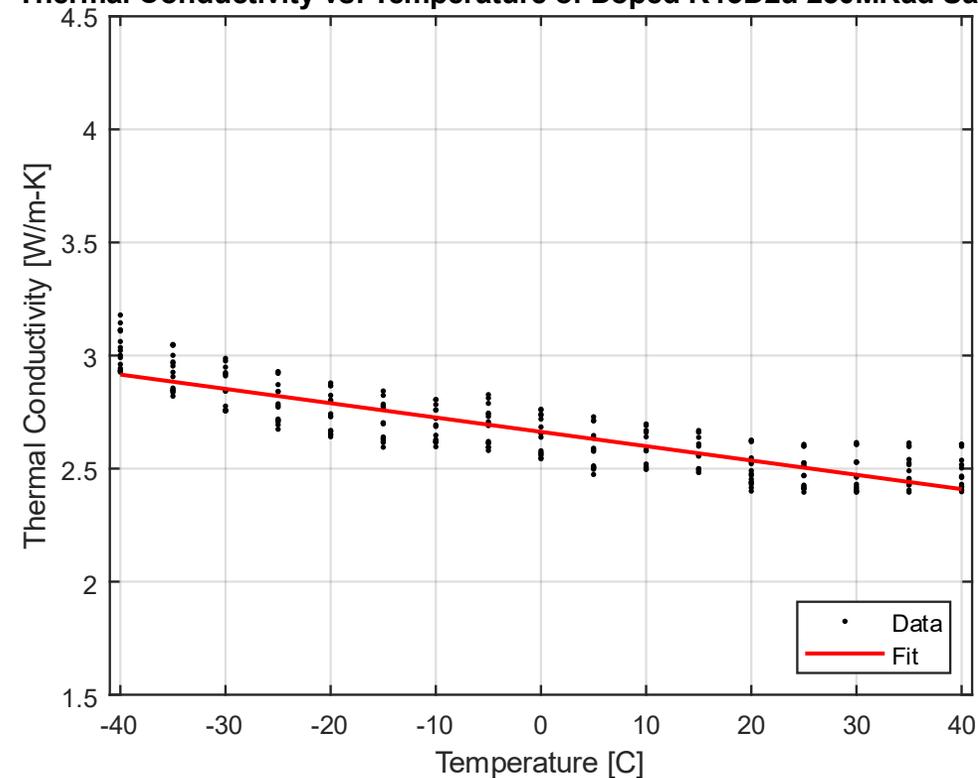
THANK YOU FOR YOUR ATTENTION

Appendix: Thermal Property Measurements

Specific Heat of Samples vs Temperature - Combined

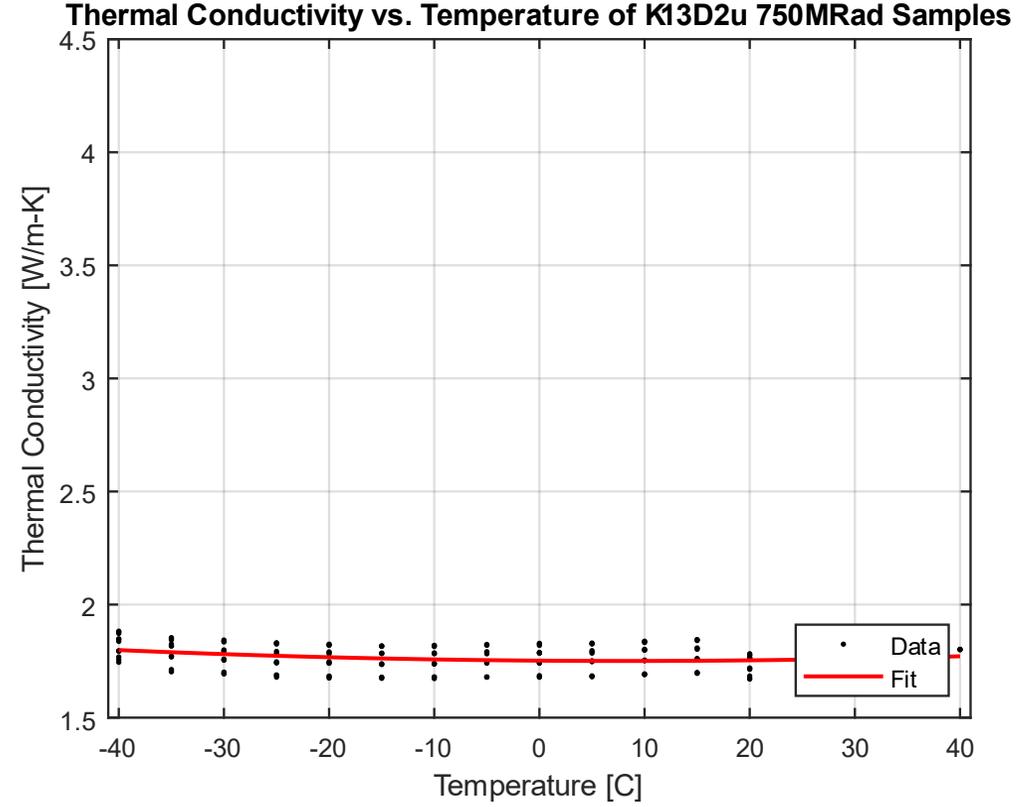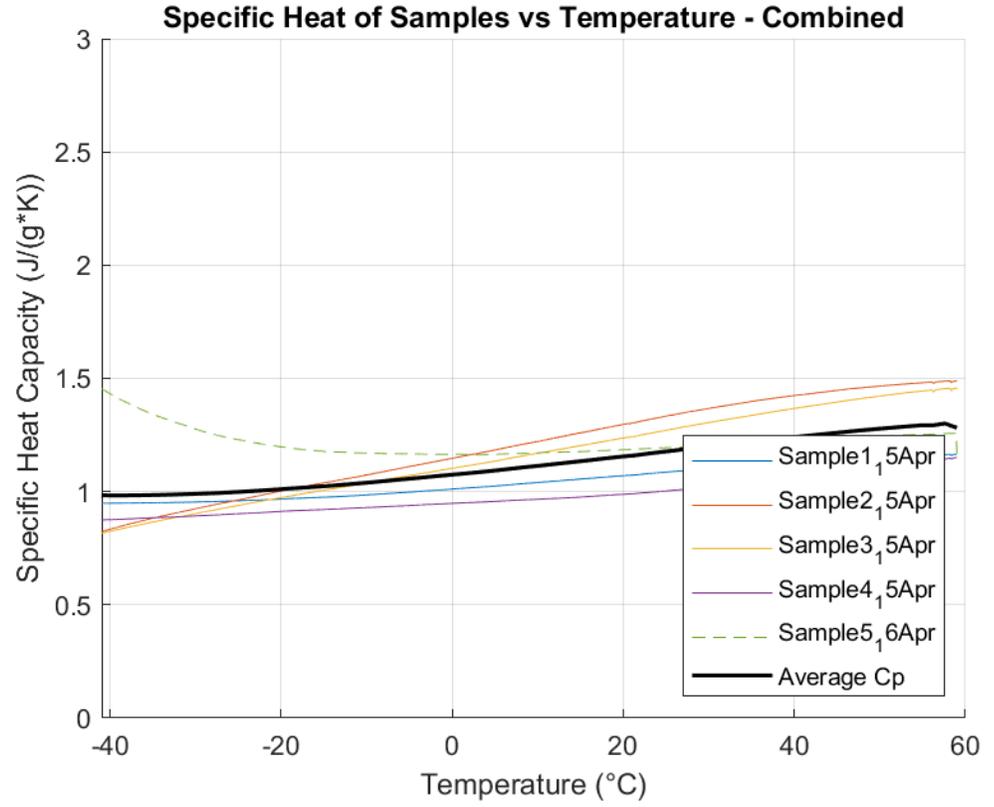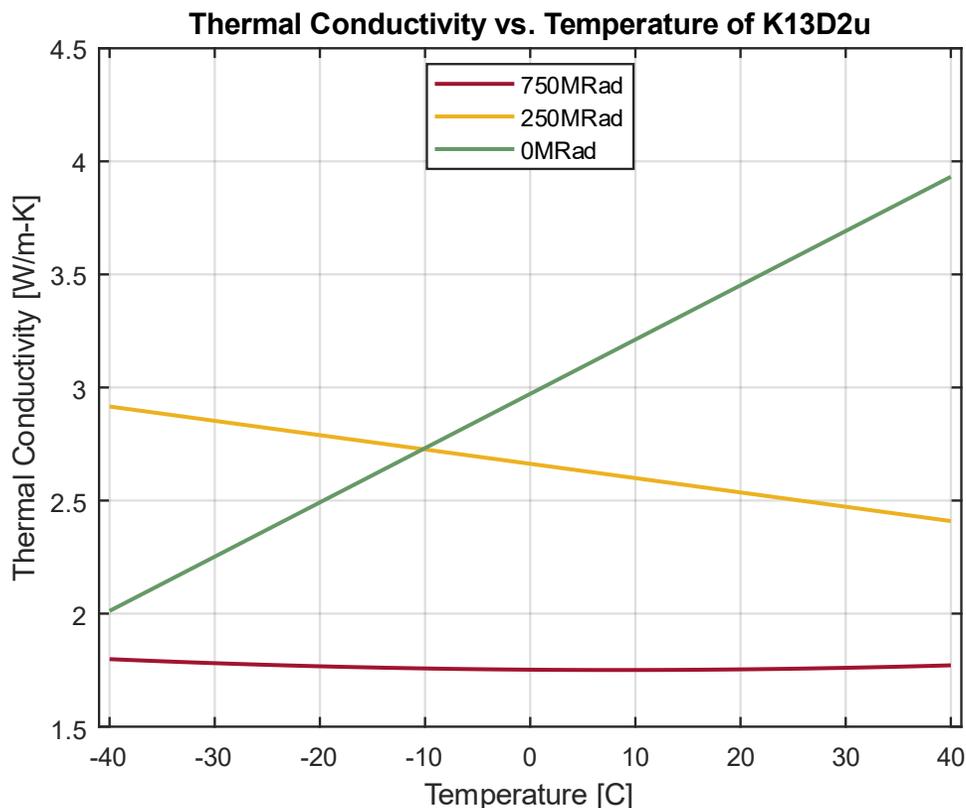Thermal Conductivity vs. Temperature of Doped K13D2u

Specific Heat of Samples vs Temperature - Combined

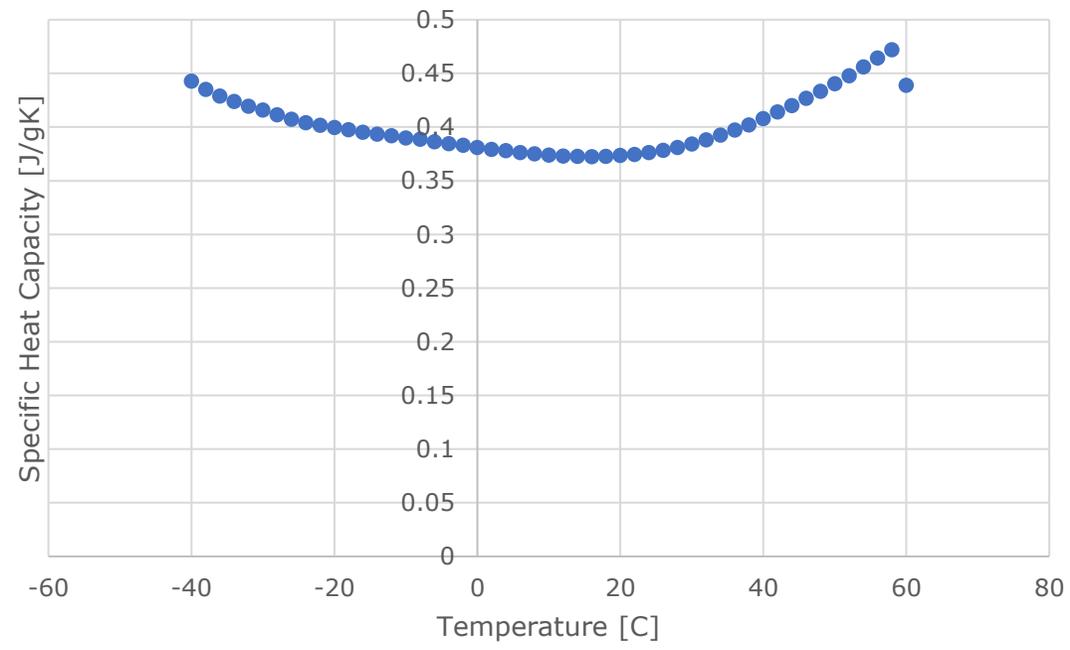Thermal Conductivity vs. Temperature of Doped K13D2u 250MRad Samples

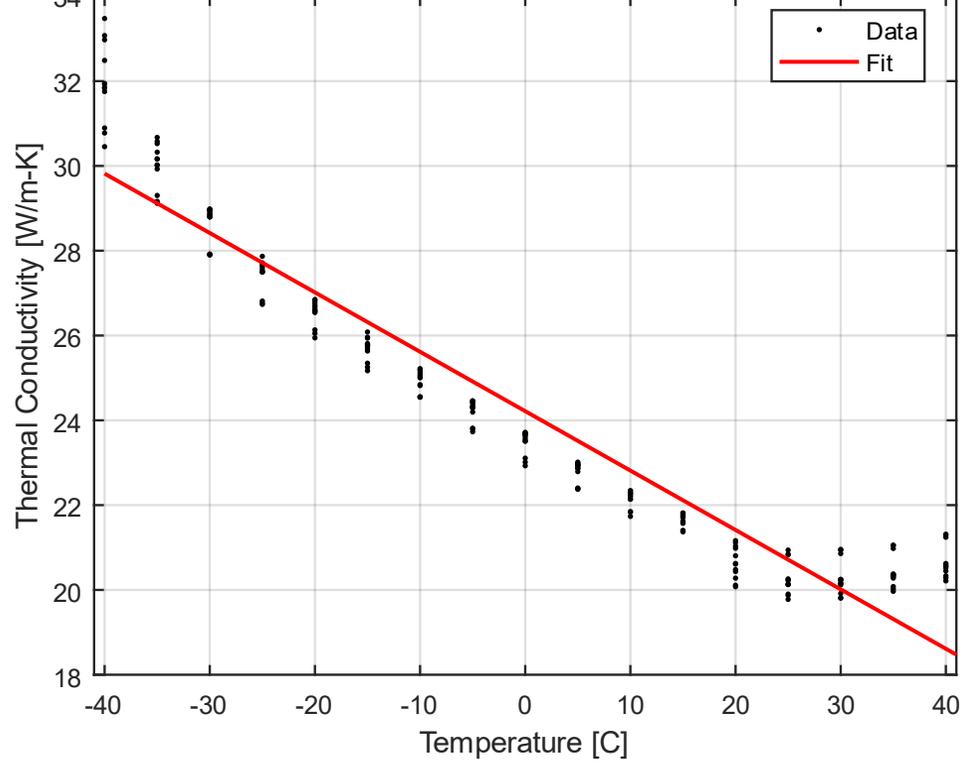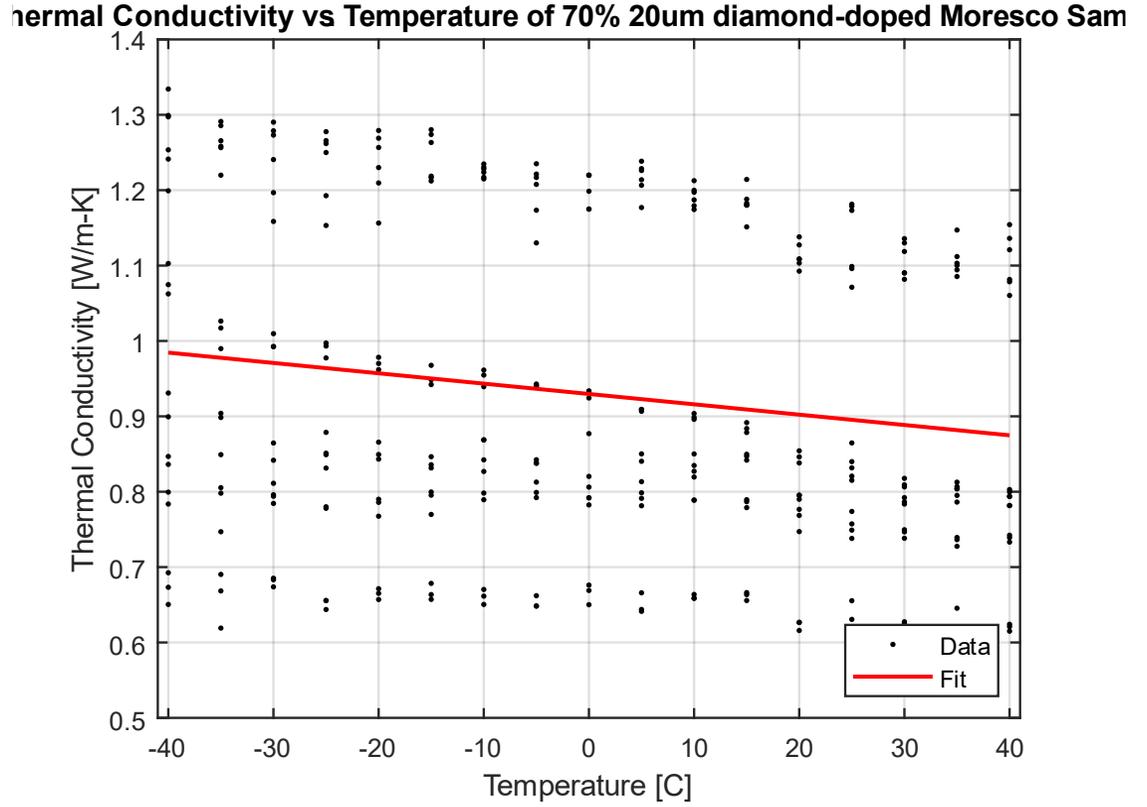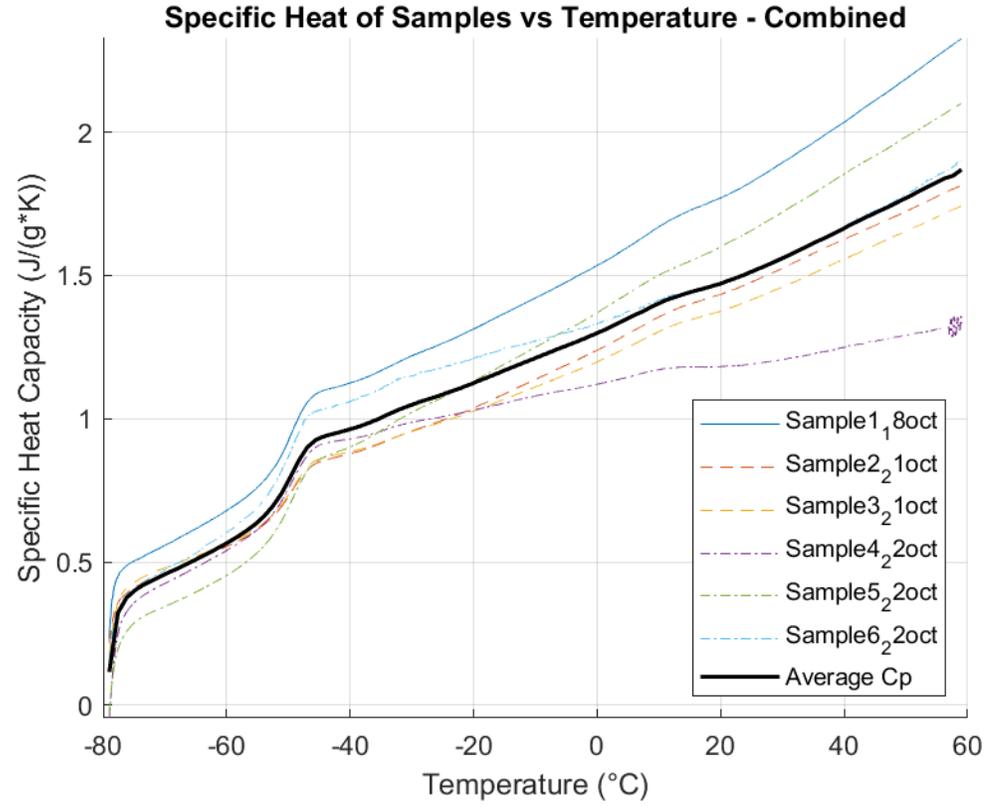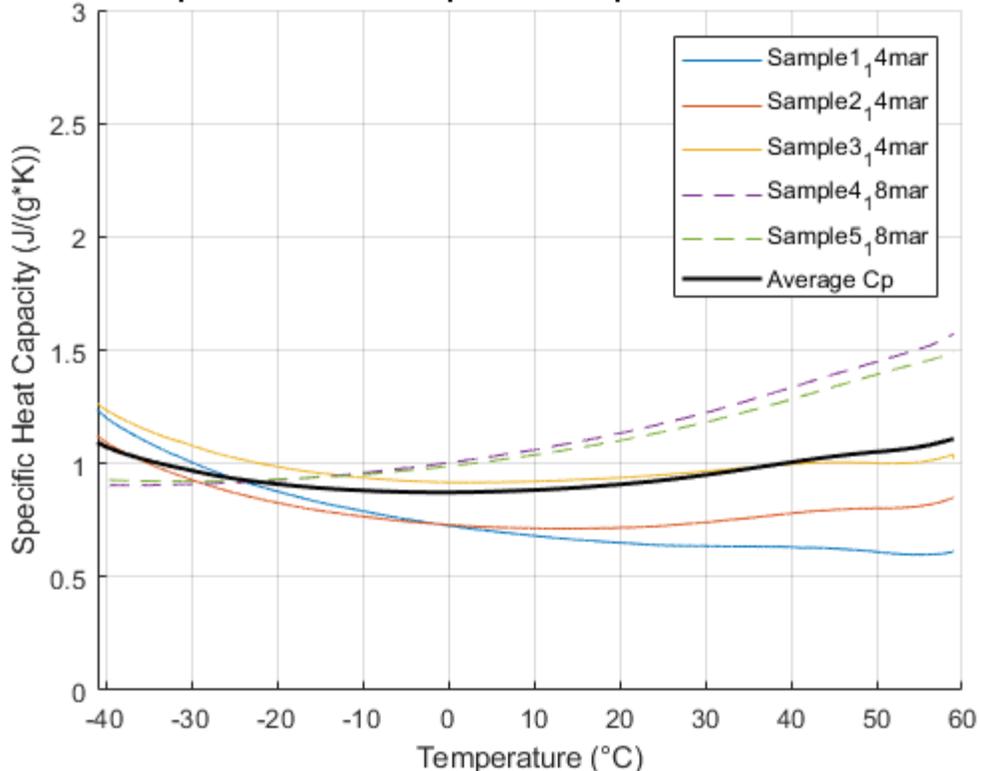Thermal Conductivity vs. Temperature of K13D2u

◇ Note: Each radiation value comes from different sample batches; each of them were manufactured at different thicknesses varying from 200um to 2mm. Direct comparison of thermal conductivity likely violates isotropic material assumptions of the LFA

Allcomp K9 Carbon Foam

Specific Heat Capacity of K9 Carbon Foam

Thermal Conductivity vs. Temperature of Foam Samples

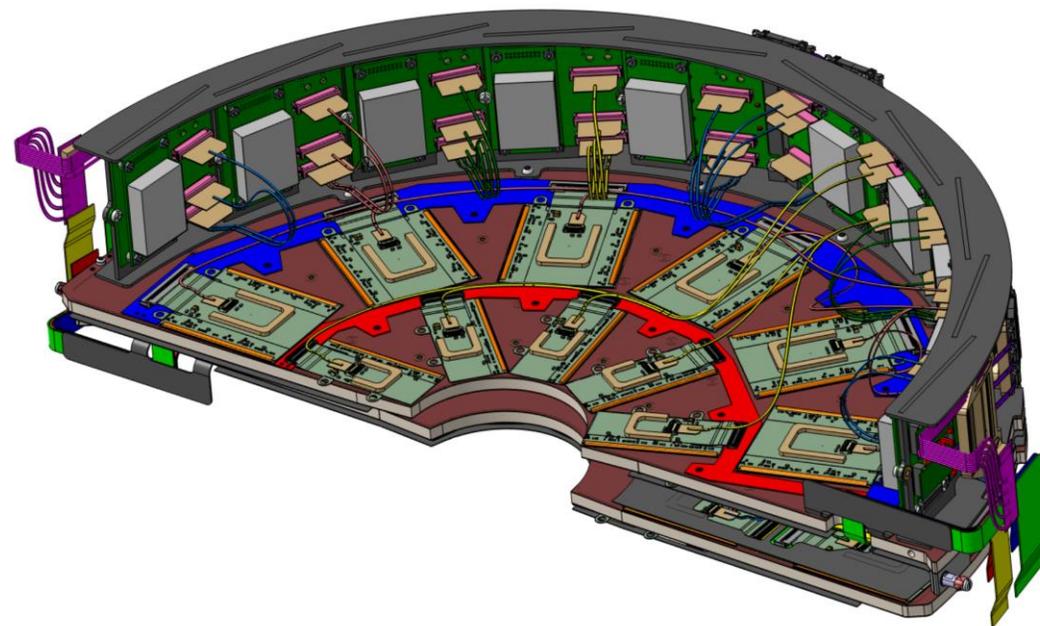Thermal Conductivity vs. Temperature of Titanium Samples (McMaster Carr)

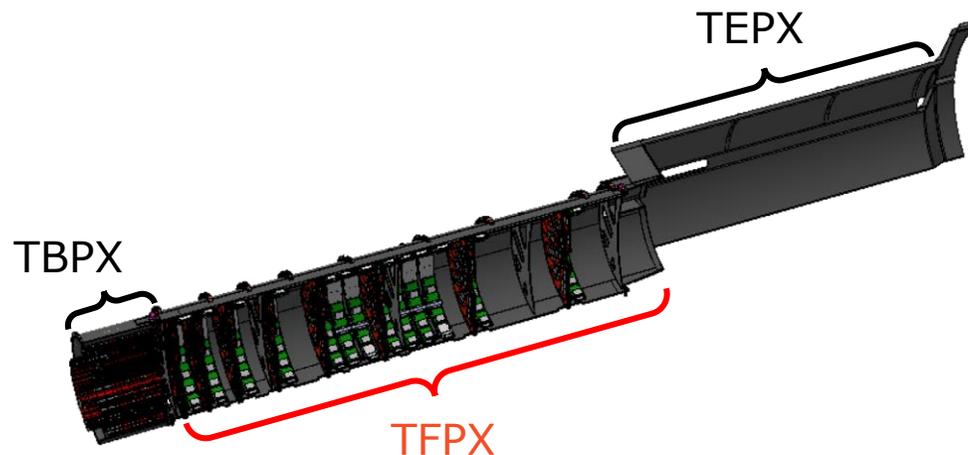⬡ This was used for the 3-layer thermal resistance tests presented in this talk

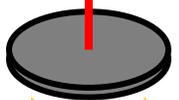# Backup

TEPX

TBPX

TFPX

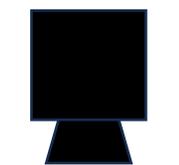- ⬡ The phase-II inner tracker consists of the barrel, forward, and end cap pixels along with the service cylinder

- ⬡ It is split into four quarters each supported by the Inner Tracker Support Tube

- ⬡ This talk focuses on the **Tracker Forward Pixel (TFPX)** double dees

  - ⬡ Each TFPX quarter has 8 double dees

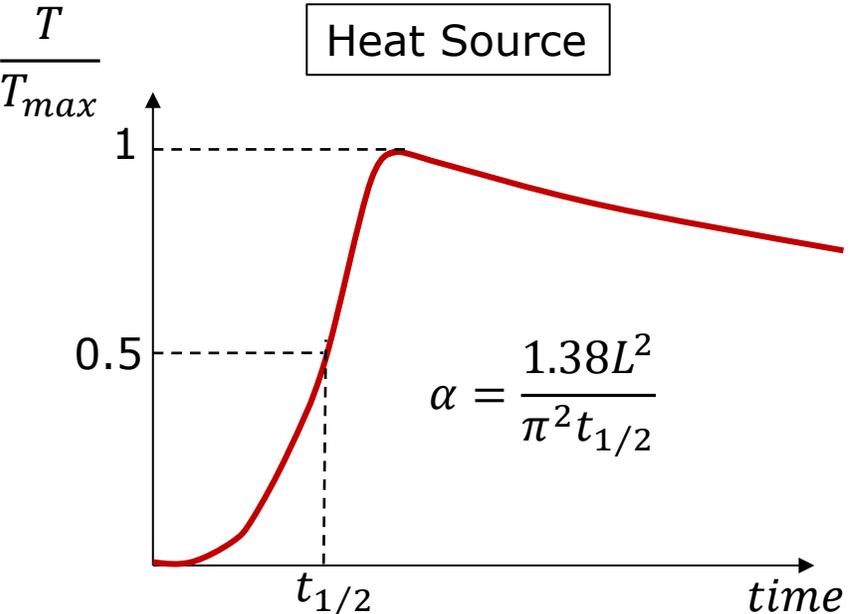- ⬡ The dees consist of two, double-sided 'D' shaped support structures and a portcard assembly

31

Measuring Strategies

$$\alpha = \frac{1.38L^2}{\pi^2 t_{1/2}}$$

$$c_{p,s} = c_{p,sap} \frac{Q_s * m_{sap}}{Q_{sap} * m_s}$$

32

⬡ To confirm the validity of the conductivity measurements, two "Sapphire" Al_2O_3 discs from MSE Supplies were measured and compared to datasheet values

⬡ Manufacturer quotes thermal conductivity of 40W/m-K at 20C

⬡ Matches temperature dependency trends from literature of similar materials

⬡ Yields confidence in further measurements with methodology

Y.S. Touloukian et al., Thermophysical Properties of Matter - The TPRC Data Series. Volume 2

Glued Samples

- ⬡ Titanium-Foam-Titanium samples are manufactured with grade 2 titanium sheets and 2mm thick foam using 70% diamond-doped EA9396 epoxy

- ⬡ All layers of the sample are weighed to have a measurement of glue mass

- ⬡ Weights were placed on top of samples during curing

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Titanium Top	1.167g	1.173g	1.164g	1.174g	1.162g
Foam	0.218g	0.220g	0.203g	0.209g	0.221g
Titanium Bottom	1.170g	1.170g	1.164g	1.172g	1.165g
Total Mass	3.915g	3.820g	3.727g	3.528g	3.861g
Mass of Epoxy	1.360g	1.257g	1.196g	0.973g	1.313g

⬡ The measured thermal resistance is relatively independent of temperature

⬡ The conduction prediction is quite close to the measured value, but does not predict correct trend

 ⬡ Contact resistance depends more on glue quantity rather than conductivity of the glue

⬡ The amount of glue used can affect the thermal resistance

 ⬡ Sample 4 is the lightest sample that also has the largest resistance

Interfacial Contact Resistance of Titanium to K9 Foam

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Titanium Top	1.167g	1.173g	1.164g	1.174g	1.162g
Foam	0.218g	0.220g	0.203g	0.209g	0.221g
Titanium Bottom	1.170g	1.170g	1.164g	1.172g	1.165g
Total Mass	3.915g	3.820g	3.727g	3.528g	3.861g
Mass of Epoxy	1.360g	1.257g	1.196g	0.973g	1.313g

Assumptions

- HDI Thickness = 50 μm
- Chip Thickness = 150 μm
- 2.4 W per Chip (highlighted in green)
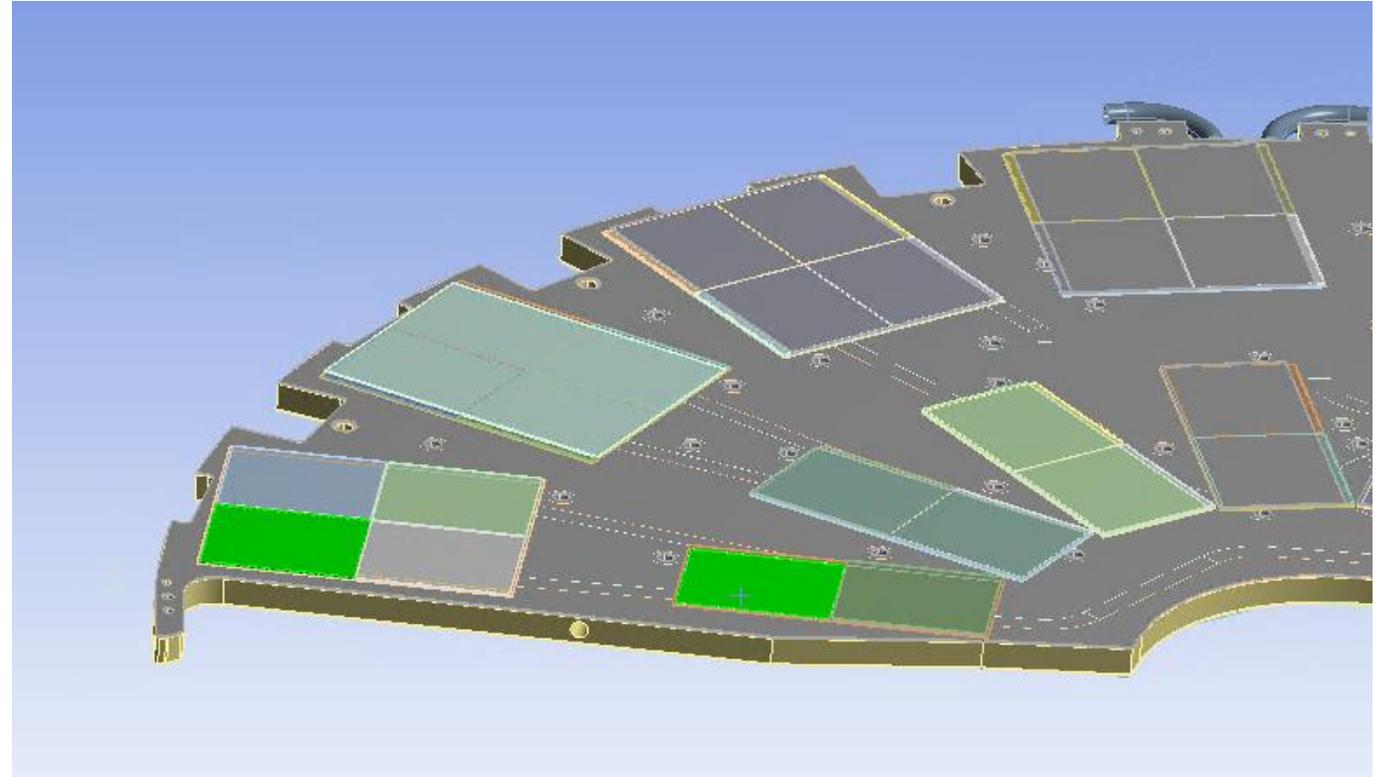- Chip Area = $402.78\ mm^2$

Determining unit heat values

- $\dfrac{2.4\ W}{402.78\ mm^2} = 5958.6\ \dfrac{W}{m^2}$

Calculating Chip Internal Heat Generation

- $\dfrac{958.587\frac{W}{m^2}}{150e^{-6}\ m} = 6.39e6\ W/m^3$

Calculating HDI Internal Head Generation

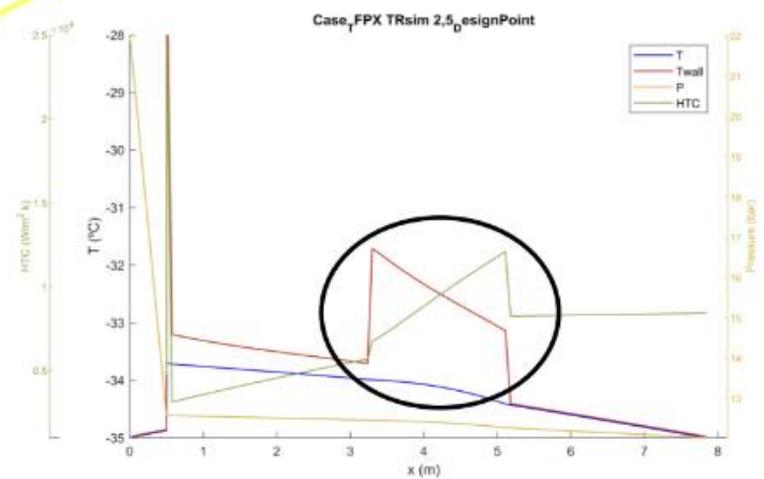- $\dfrac{5000\frac{W}{m^2}}{50e^{-6}\ m} = 100e6\ W/m^3$

⬡ Individually selected and placed convection conditions as shown

⬡ Linear interpolated between given section 1 and 21 conditions

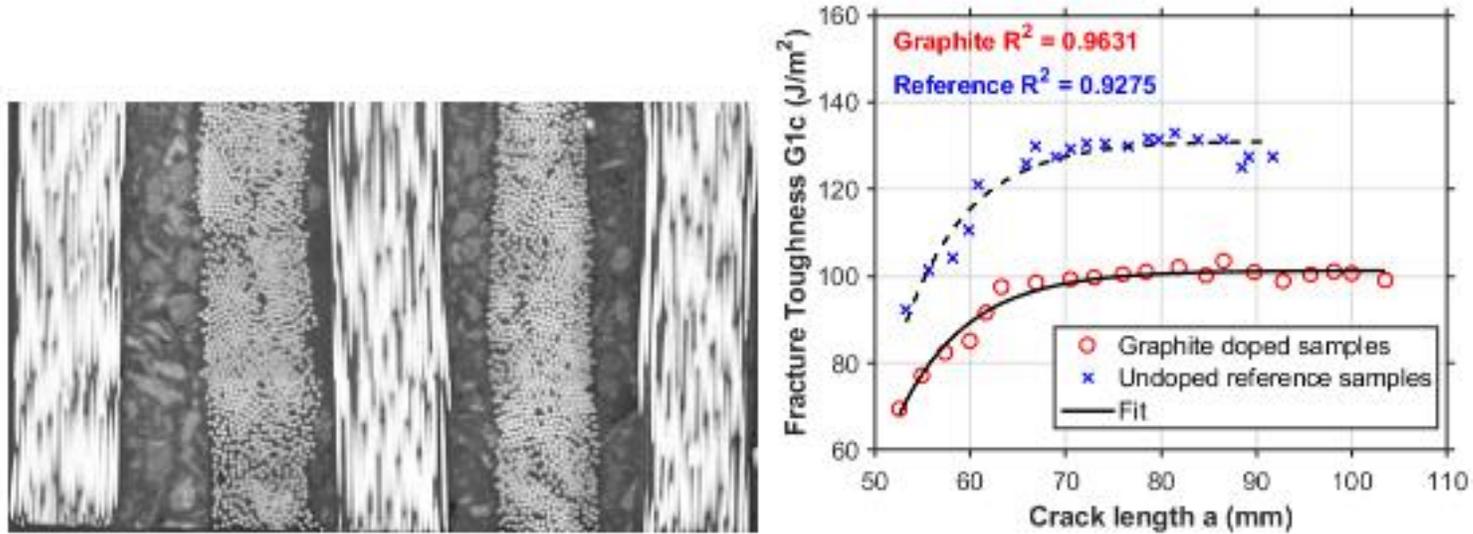| Section	HTC	Temp
A	7300	-33.8
B	7570	-33.825
C	7840	-33.85
D	8110	-33.875
E	8380	-33.9
F	8650	-33.925
G	8920	-33.95
H	9190	-33.975
I	9460	-34
J	9730	-34.025
K	10000	-34.05
L	10270	-34.075
M	10540	-34.1
N	10810	-34.125
O	11080	-34.15
P	11350	-34.175
Q	11620	-34.2
R	11890	-34.225
S	12160	-34.25
T	12430	-34.275
U	12700	-34.3

Cooling loop is splitted in 21 parts to give different HTC (and T) along the pipe considering the CO_2 flow results
The parts are between 8-10 cm long.

1. HTC = 7300 W/m^{2}K – T_{CO2} = - 33.8°C

21. HTC = 12700 W/m^{2}K – T_{CO2} = - 34.3°C

Case_FPX TRsim 2,5_DesignPoint

Figure 2. An example of a micrograph (a) with graphite (10 micron flake size) introduced during the manufacturing process of the composite sample for TC characterization - flakes are clearly visible in the resin (dark gray) regions between plies. Results of an earlier delamination study using ASTM D5528/D5528M-21 : Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites are shown in (b).

* Paper in preparation for publishing in JINST – Purdue University