Thermal Studies for the CMS Phase II Forward Pixel Detector

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CMS

Outline

- Through-plane thermal conductivity measurement
  - EBT700 results
- In-plane thermal conductivity measurement
  - Validation with Aluminum
- Thermal FEA of CMS Dee structure
  - Different module scenarios and results
- FEA study on thermal performance improvement
- Conclusion

Through-Plane Thermal Conductivity Measurement – Apparatus

Spring clamp to ensure equal pressure at thermal interfaces

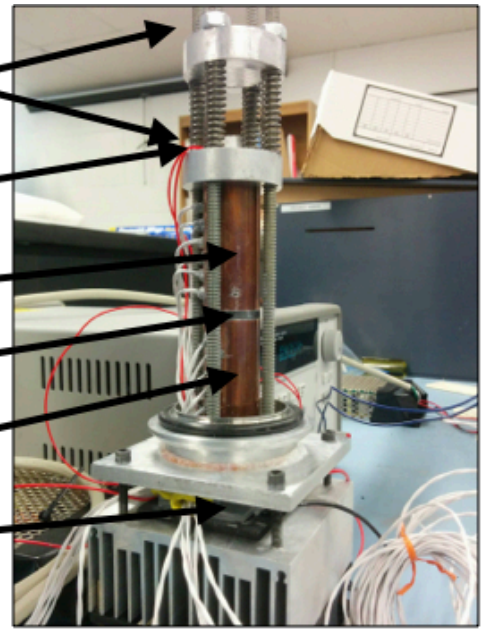
Resistive heating element

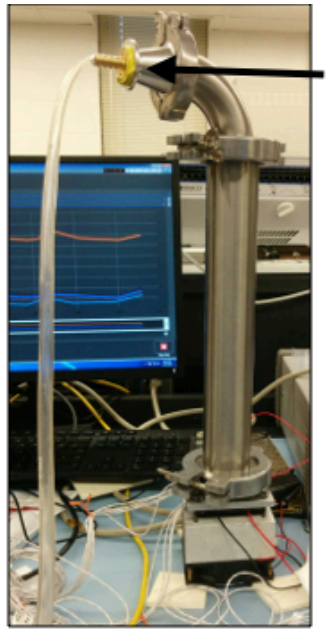
Heating flux-meter made of copper with 6 thermistors

Test material

Cooling flux-meter

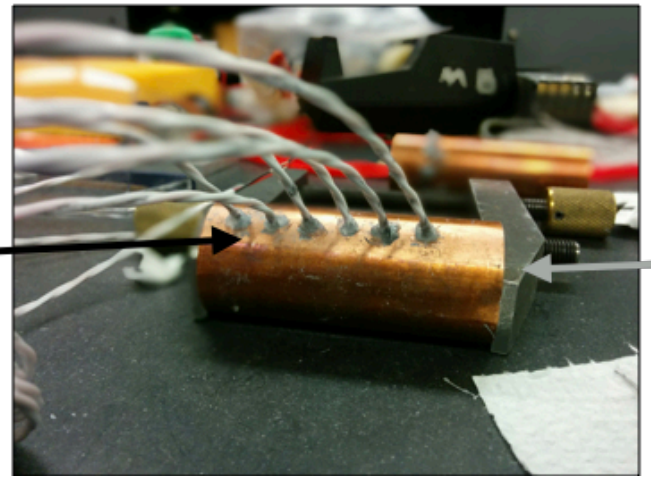
Peltier element with water cooling





Sealed and vacuum of ~ 1 bar maintained to mitigate convective losses

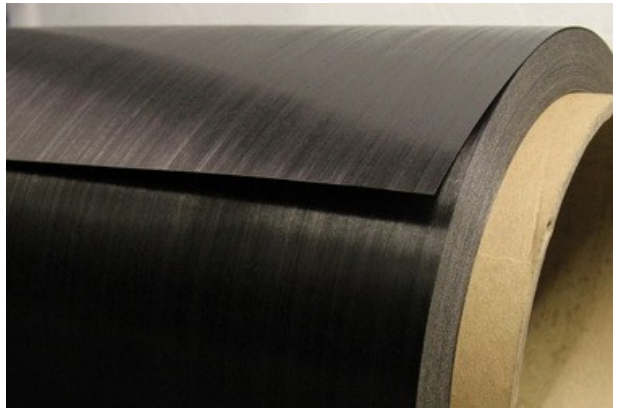
Six equidistant thermistors placed at the center of copper rod and sealed with adequate thermal grease to create a heat flux-meter



Contact surfaces of the flux-meter milled flat with very high tolerance

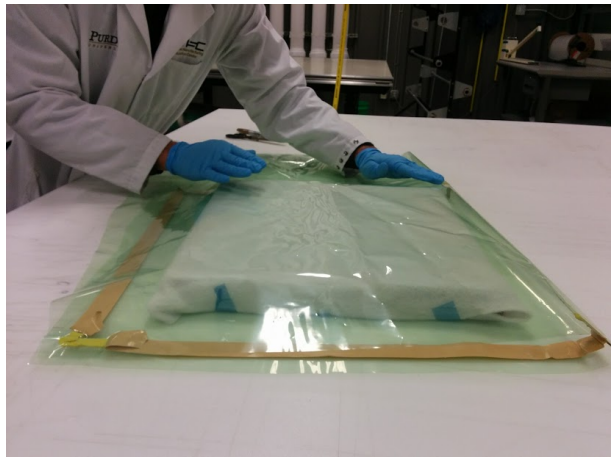
Improving Thermal Conductivity of Carbon Fiber

Four K13D2U / TC275-1 pucks of thicknesses
1.30 mm, 1.95 mm, 2.60 mm, 3.90 mm



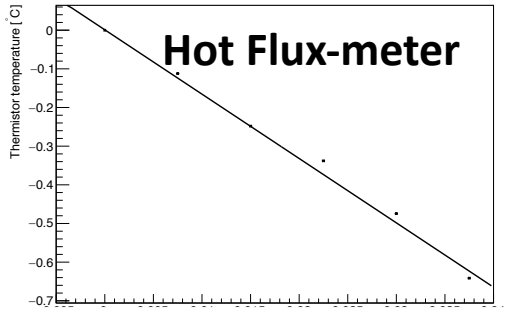
Roll of EBT 700

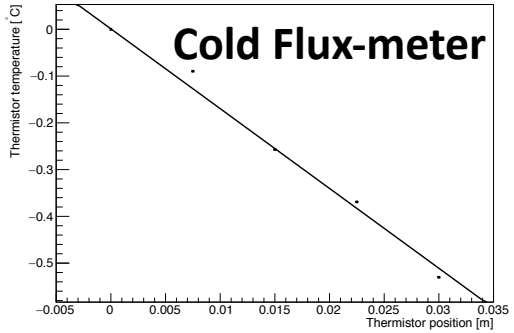
- **$K13D2U_{measured}$ = 1.08 ± 0.01 W/mK**
- How does carbon fiber thermal conductivity change with pressure and graphite?
  - EBT 700 was chosen as cheaper alternative
  - Results in K13D2U are expected to be analogous
- Three cases investigated:
  - **14 psi (1 atm)**
  - **60 psi**
  - **60 psi + graphite**



C Fiber composite lamination

Thermal Conductivity of EBT-700 Carbon Fiber

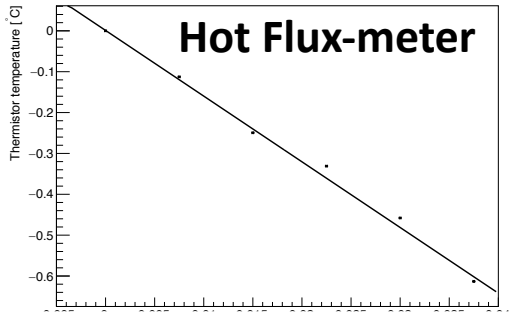


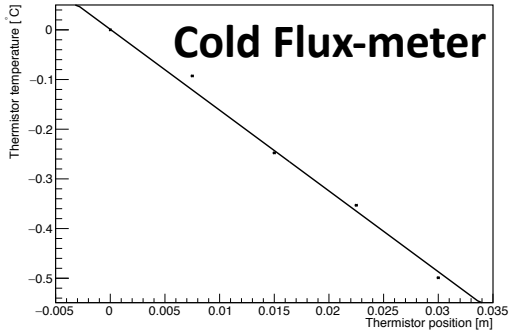


14 psi, without graphite

- ΔT_{sample} = 8.89 +/- 0.02 ^{0}C
- $J_{average}$= 6405 +/- 56 W/m^2

K= 0.532+/-.011 W/mk

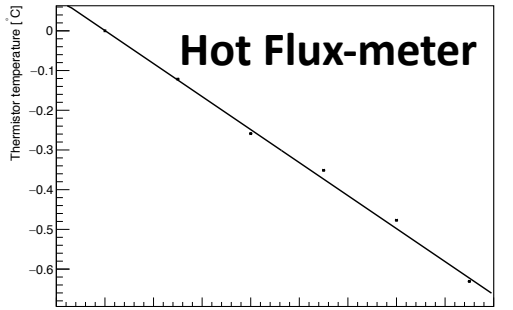


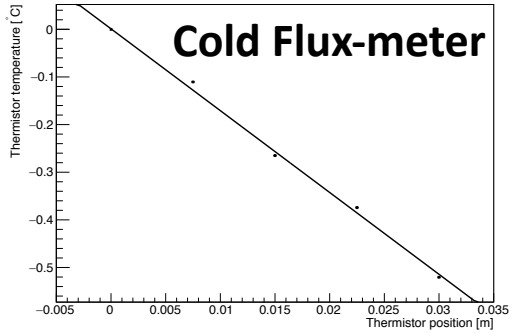


60 psi, without graphite

- ΔT_{sample} = 7.85 +/- 0.02 ^{0}C
- $J_{average}$= 6144 +/- 25 W/m^2

K= 0.594+/-.010 W/mk





60 psi, with graphite

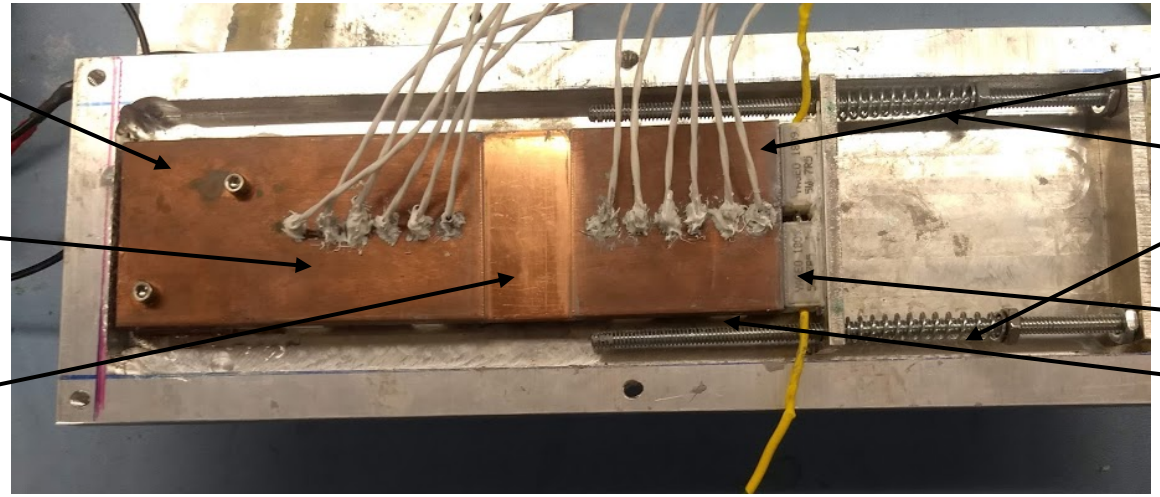
- ΔT_{sample} = 7.75 +/- 0.01 ^{0}C
- $J_{average}$= 6422 +/- 74 W/m^2

K= 0.645+/-.015 W/mk

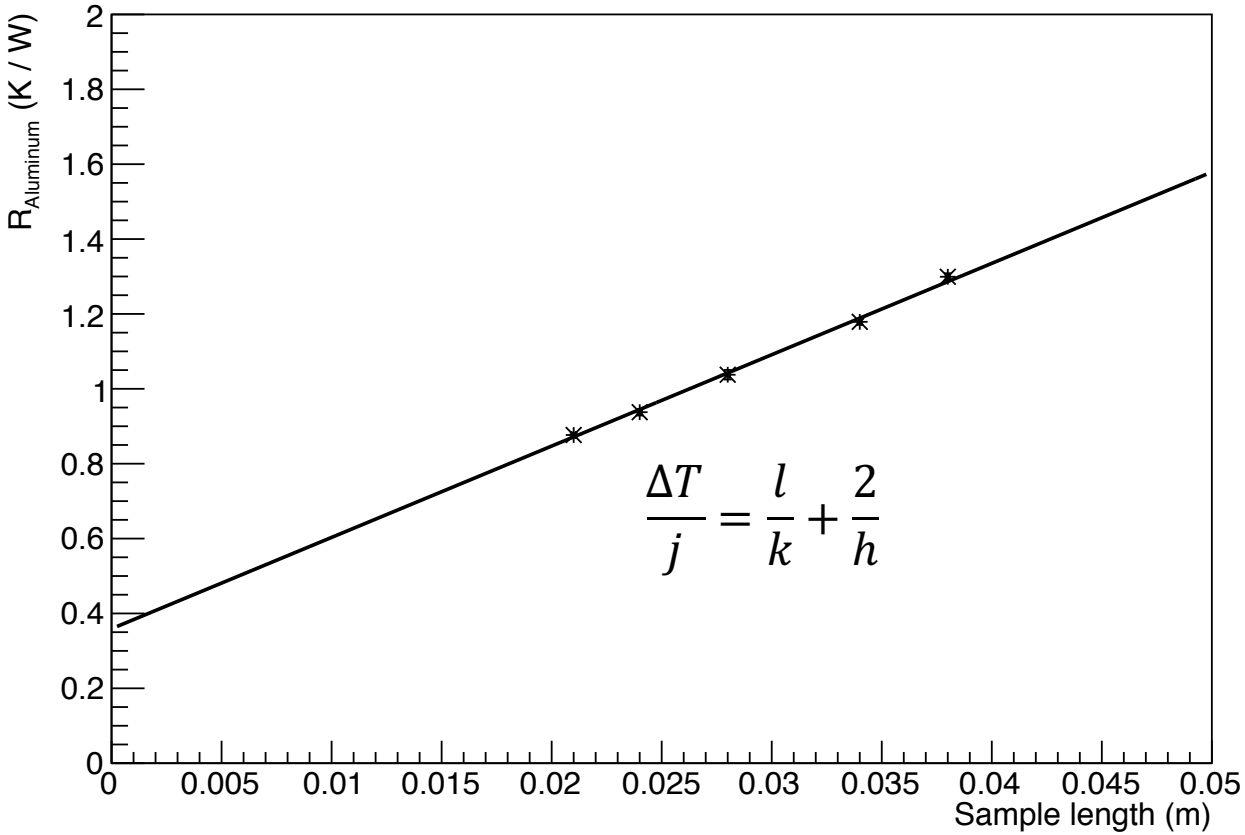
- Thermal conductivity od EBT700 increases by 12 % with pressure and by 21% with pressure and adding graphite.

InPlane Thermal Conductivity -Apparatus

- **Goal**: To measure in-plane thermal conductivity of anisotropic CF-like composite materials.
- **Design** an apparatus to measure TC of rectangular sheet-like samples.



Validation of apparatus using Aluminum



Plot of thermal resistance vs sample length

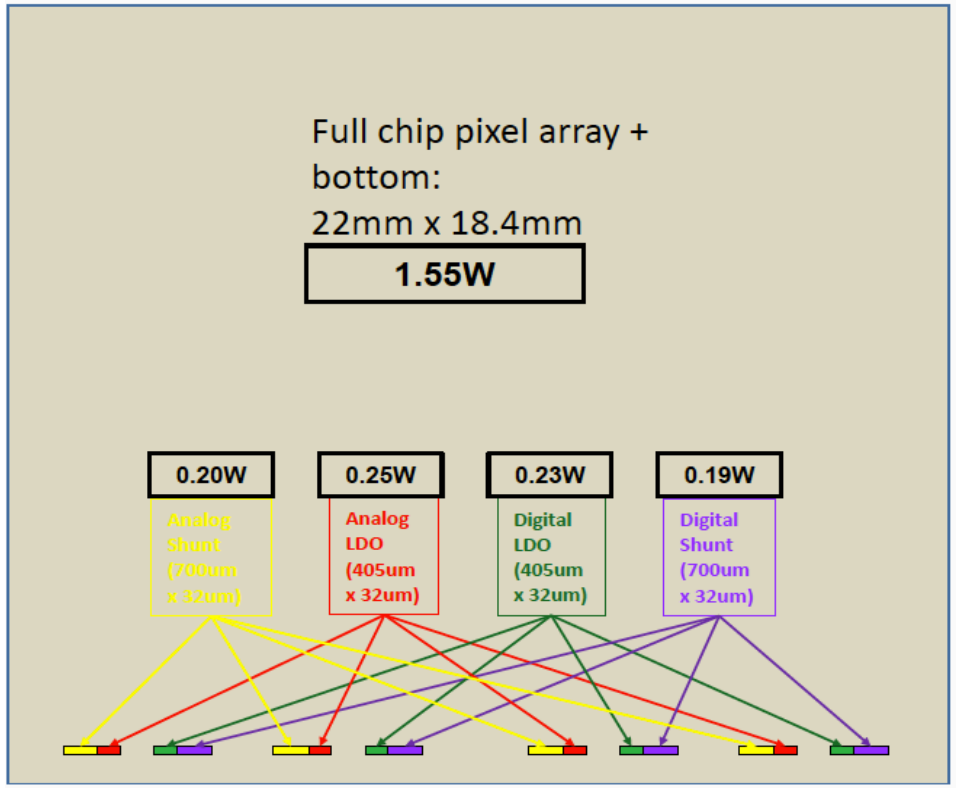
- Thermal resistances of 2.1cm, 2.4cm, 2.8cm, 3.4cm and 3.8cm samples are measured.
- From the 'meta-slope' fit, the inverse of the slope gives, $K_{measured}$ = 196 ± 4W/mK.
- 2% correction (from FEA) to heat flux is applied to account the convection and radiation losses.
- $K_{reference}$ for T6-6061 Aluminum = 170 W/mK.
- The measured value is 15% higher than the reference value.
- To mitigate systematic uncertainties, ratio of conductivities to copper will be reported.

Thermal loads in CMS Dee structure

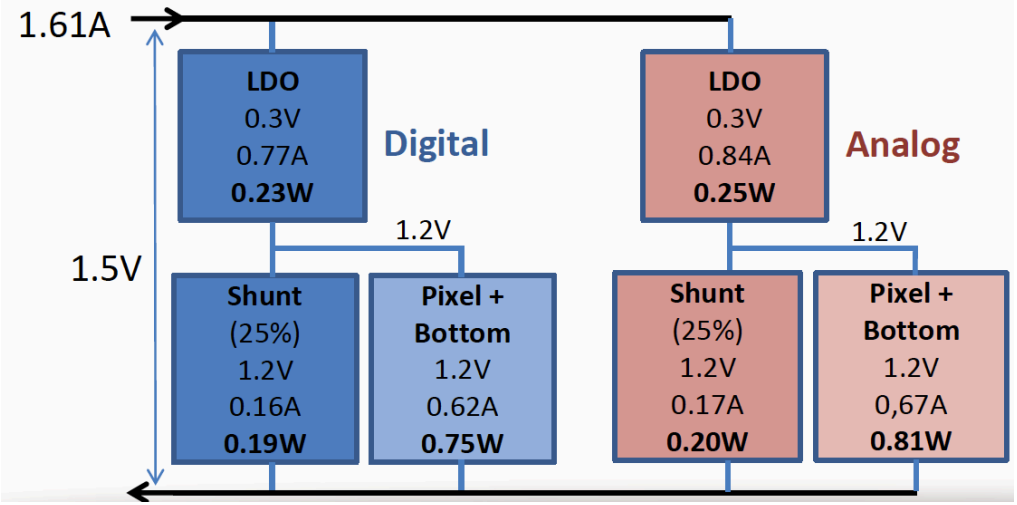
- Heat is generated by Read Out Chips(ROCs), Shunts & Load Drop Outs (SLDOs) and High Density Interconnects (HDIs).

Schematic of RD53A

TOTAL CHIP POWER = 2.43W HDI = 0.6 W

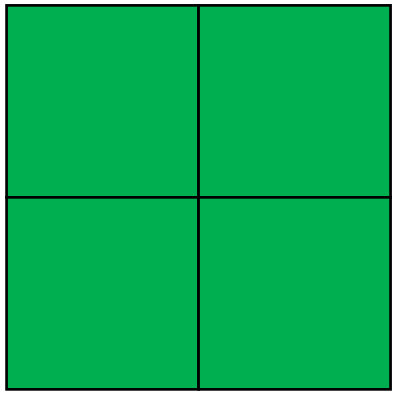


Element	Opt	Nom	Cons
Per pixel analog	3.1 µA	3.6 µA	4.2 µA
Per pixel digital	3.1 µA	3.6 µA	4.2 µA
Analog Chip bottom	130 mA	150 mA	180 mA
Digital Chip bottom	70 mA	100 mA	150 mA
TOTAL 440x328 chip	**1.10 A**	**1.30 A**	**1.54 A**
+10% SLDO headroom (to be tested)	1.21 A	1.43 A	1.70 A
+25% SHUNT-LDO Headroom	**1.38 A**	**1.61 A**	**1.93 A**



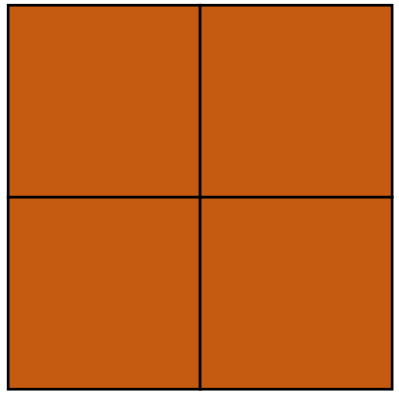
CMS Dee Module Scenarios - Heat Dissipation

Normal



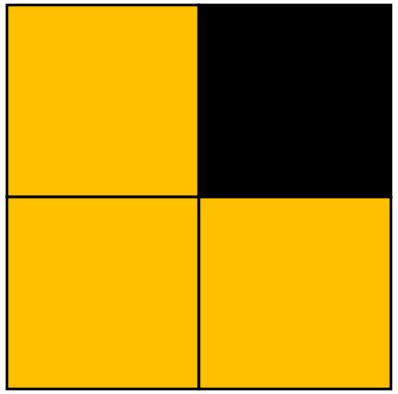
2.42 W per chip

Conservative



2.90 W(20% margin) per chip

Failure of 1/4 chip



3.51 W on neighboring chips

Failure of 1/2 chip

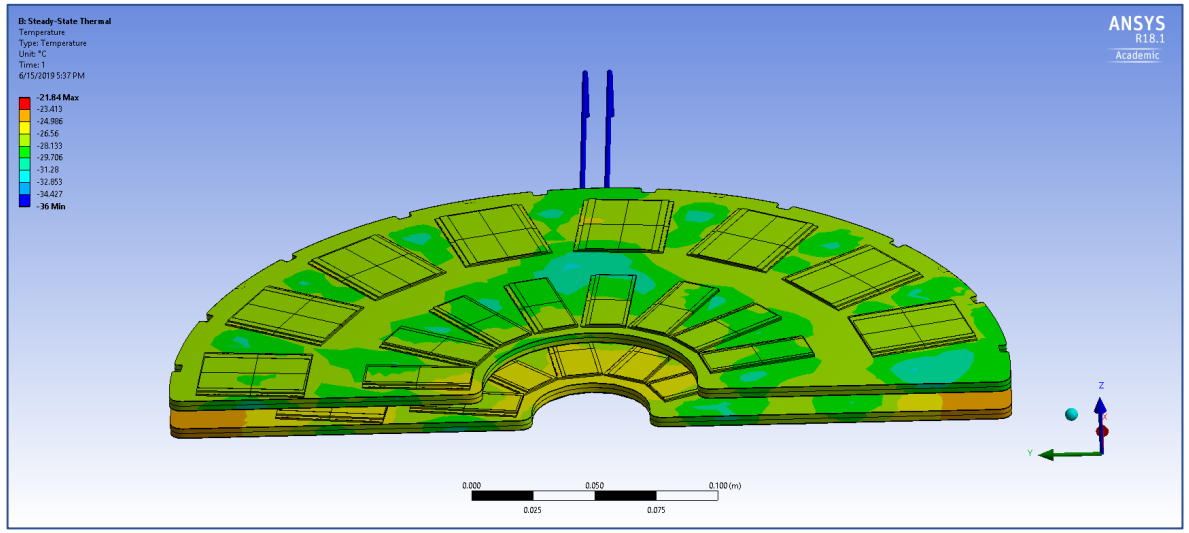
6.12 W on neighboring chips

Parameters used for FEA

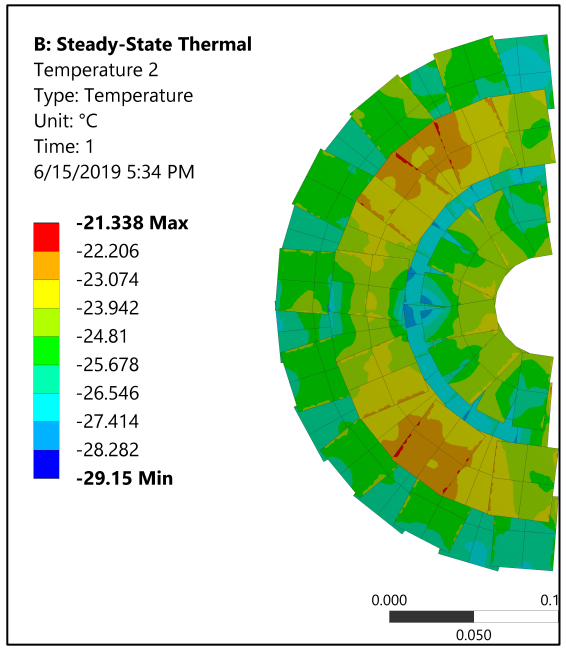
1. Thermal conductivity values(W/mK): CFoam=20, Silicon=150, Cfiber=<200,200,1>, HDI= 0.12, Titanium=21.
2. Conductance values($W/m^2 .^0C$): Epoxy = 40,000, Laird film = 500,000, Bumpbonds = 800,000.
3. Convection coefficients ($W/m^2 .^0C$): Air=5 to 22 ^0C, Active cooling via CO_2 = 5000 to -36^0C.

CMS Dee results

Preliminary FEAs of Read On Chips without taking account of thermal runaway.



Temperature heat map of **CMS Dee nominal case**



ROC chips in conservative case

Constraints on temperature and gradient

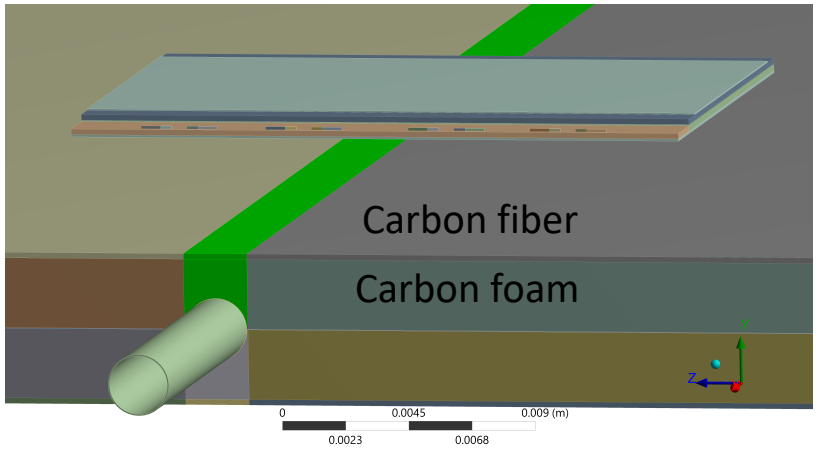
	Max SLDO temp	Max Chip gradient
Normal Operation	0^0C	15^0C
Failure mode	20^0C	20^0C

RESULTS

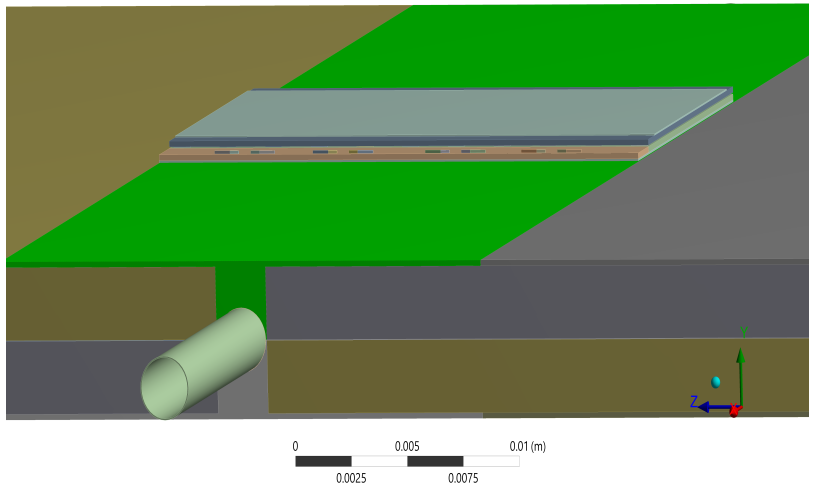
Case	Maximum temperature(^{0}C)	Variation in chips(^{0}C)
Nominal	-21.8	-30.0 to -23.2
Conservative	-19.6	-29.2 to -21.3
¼ failure	-18.8	-30.0 to -21.5
½ failure	-13.0	-30.4 to -19.9

Effect of AlNi on thermal performance of Dee structure

- Thermal wing, a representative unit of Dee is used for FEA
- Replaced C.Foam and C.Fiber layers under the chip with AlNi (k=285W/mK) to calculate the thermal performance.



AlNi upto width of pipe



AlNi upto width of chip

	Unmodified thermal wing	AlNi upto width of pipe	AlNi upto width of chip
Av. Chip temp(^{0}C)	-29.6	-30.8	-31.7

Only 2^{0}C decrease in the average temperature of the chip -> Not worth changing the geometry drastically.

Conclusions/Future Work

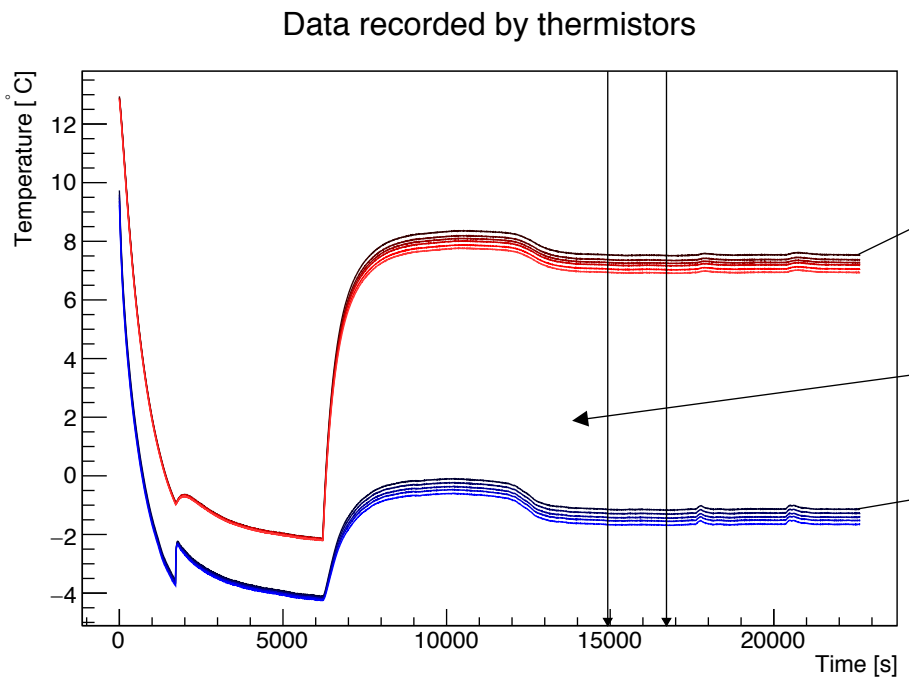
- **Through Plane thermal conductivity measurement:**
  - Apparatus is working and samples important to CMS detector upgrade are measured.
- **In Plane thermal conductivity measurement:**
  - Validation with the updated geometry is done.
  - Need to finish carbon fiber samples measurement.
- **FEA of CMS Dee structure is done**
  - Preliminary FEAs indicate detector is safe within the temperature and gradient constraints during normal working of detector.
- **FEA of thermal wing**
  - Including AlNi does not improve the thermal performance much.

BACKUP

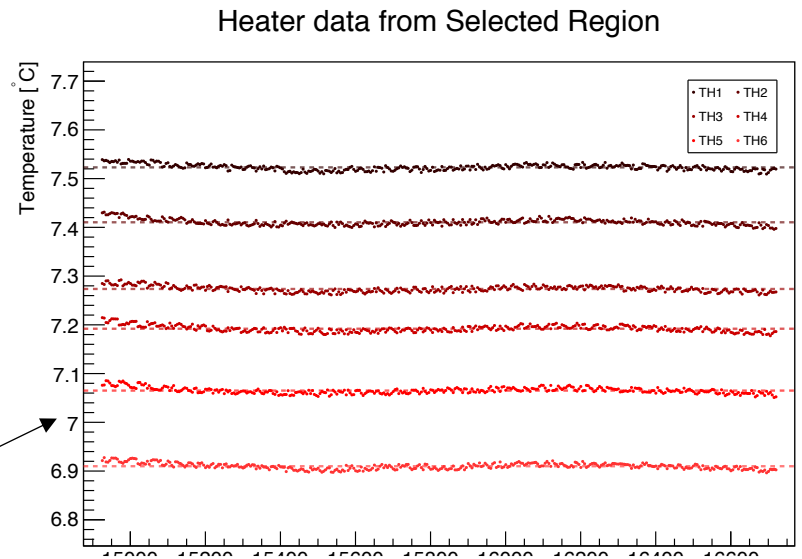
Thermal Conductivity of EBT-700 Carbon Fiber

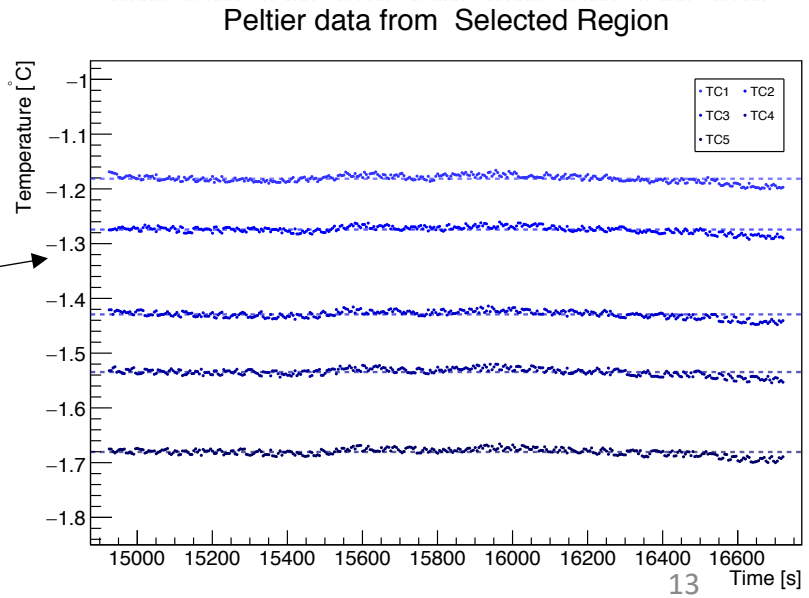
	Without graphene	With graphene
14 psi	✓	
60 psi	✓	✓

Readings from 60 psi, without graphene is shown here. (CMS work in progress)



30 min





Through Plane Thermal Conductivity of K13D2U

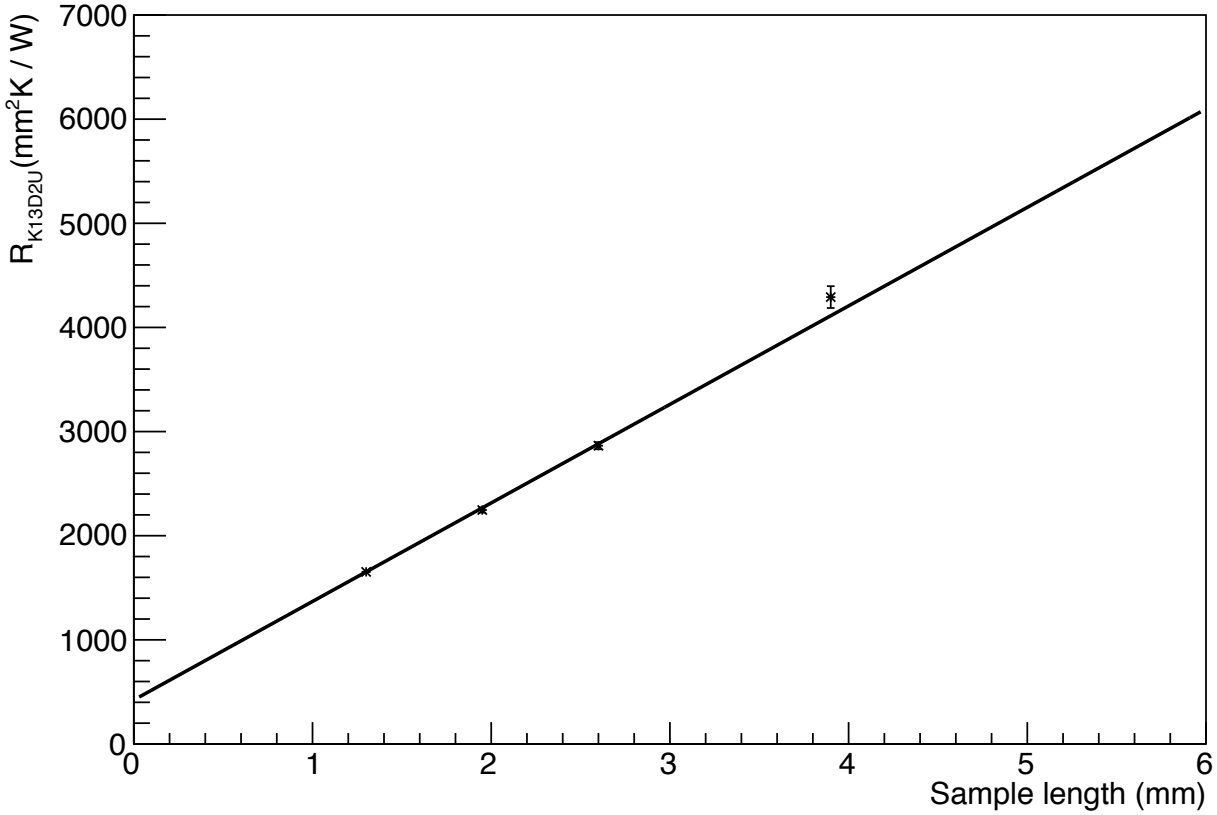
Four K13D2U / TC275-1 pucks of thicknesses 1.30 mm, 1.95 mm, 2.60 mm, 3.90 mm

K13D2U samples from 12 to 36 plies were created for this measurement.

Our measurement:

k = 1.08 ± 0.01 W/mK

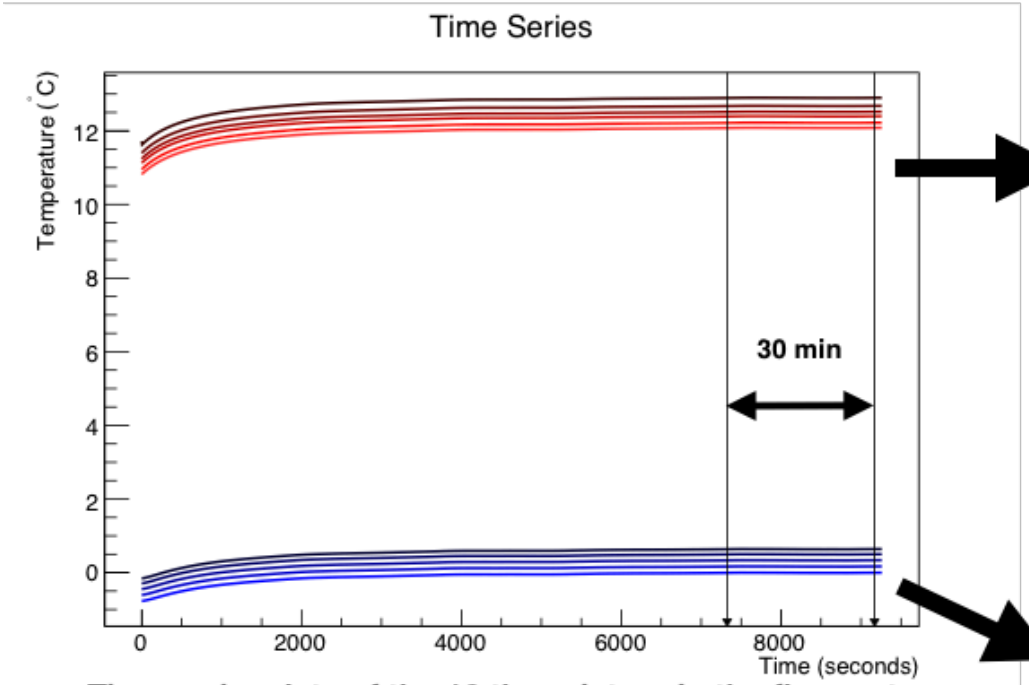
- This value was used for CMS Dee thermal FEAs.
- Can we increase the conductivity of Carbon Fiber?



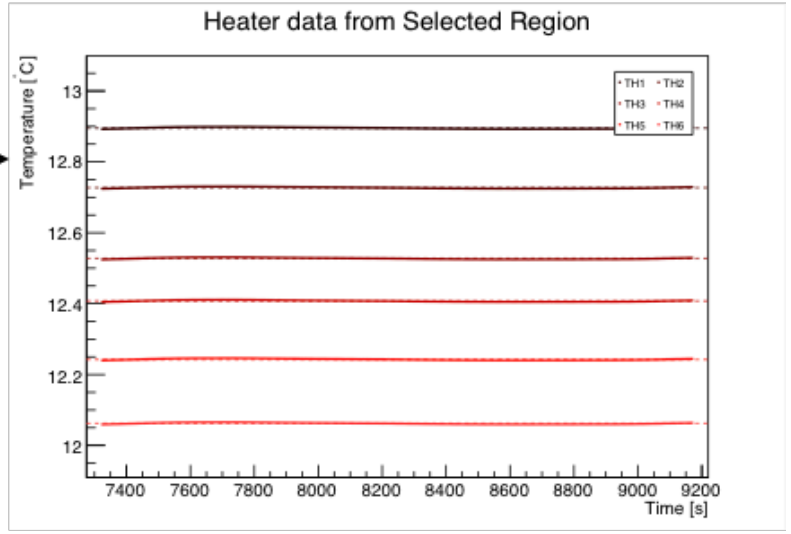
Fit of thermal resistance against carbon fiber sample thicknesses to eliminate contact conductance

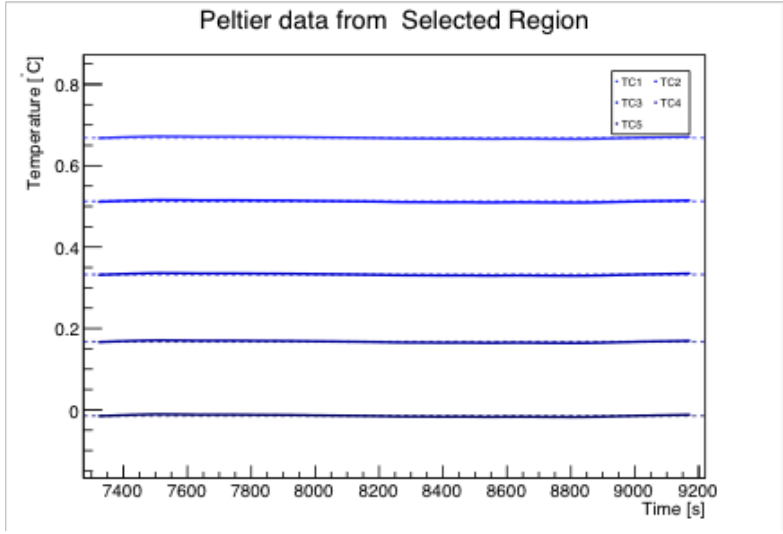
Measurement for validation: Thermal Conductivity of Fused Quartz

Three thickness samples of fused quartz are used, 1.70, 3.40, 6.40 mm, to eliminate contact conductance
Readings from the 1.70 mm sample shown below



Time series data of the 12 thermistors in the flux-meters

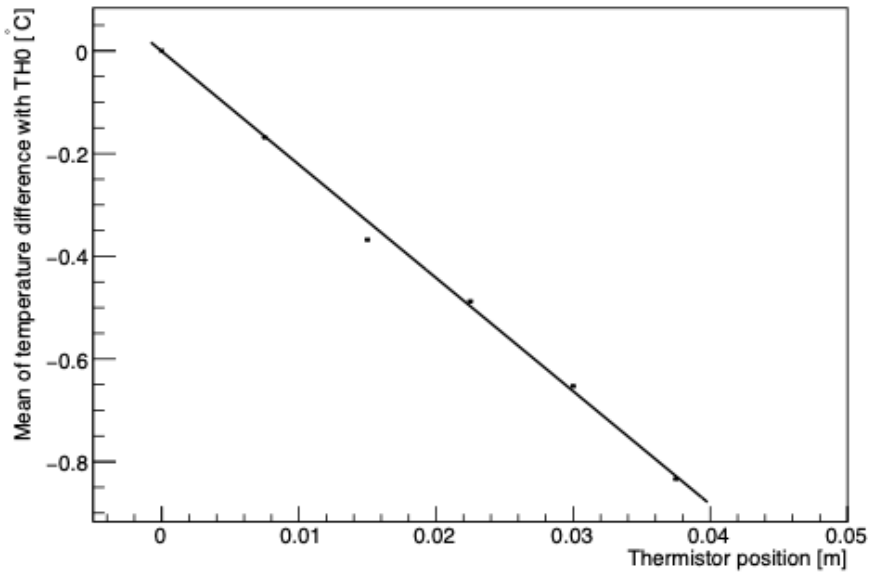




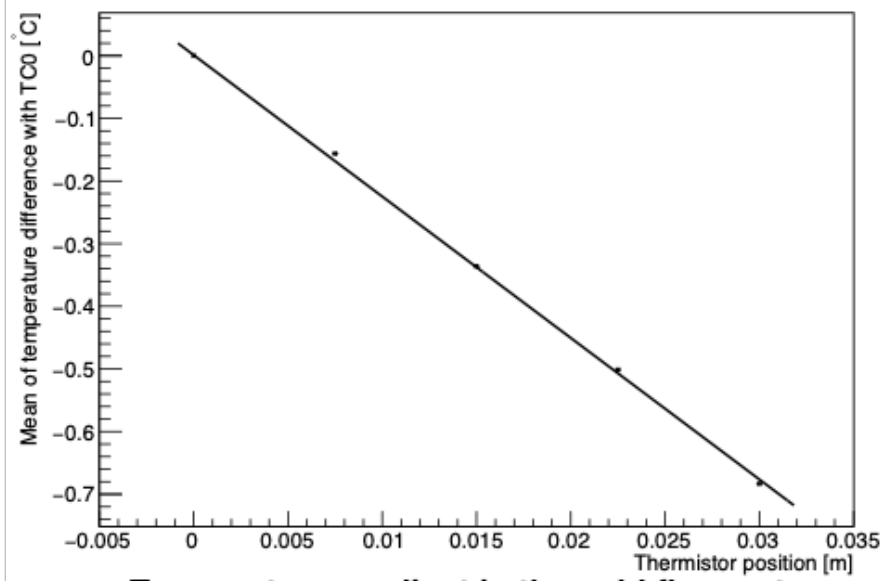
- We ensure flux readings in the hot and cold flux-meters are close
- To get non-equilibrium steady state data, a 30 min window is chosen that has minimum fluctuation (defined as the quadrature sum of standard deviations of all 12 thermistors)

Measurement for validation: Thermal Conductivity of Fused Quartz

Flux-meter readings of 1.70 mm sample used below



Temperature gradient in the hot flux-meter



Temperature gradient in the cold flux-meter

- To ignore covariant temperature fluctuations, we consider mean of the temperature difference with the first flux-meter thermistor (TH0, and TC0)
- The thermistor measurements are corrected by systematic biases measured in a climate chamber. Uncertainty for each measurement is the standard error on the mean for N readings, combined with uncertainty in the systematic correction
- Temperature gradients in the heating and cooling flux-meters estimate heat flux through the system

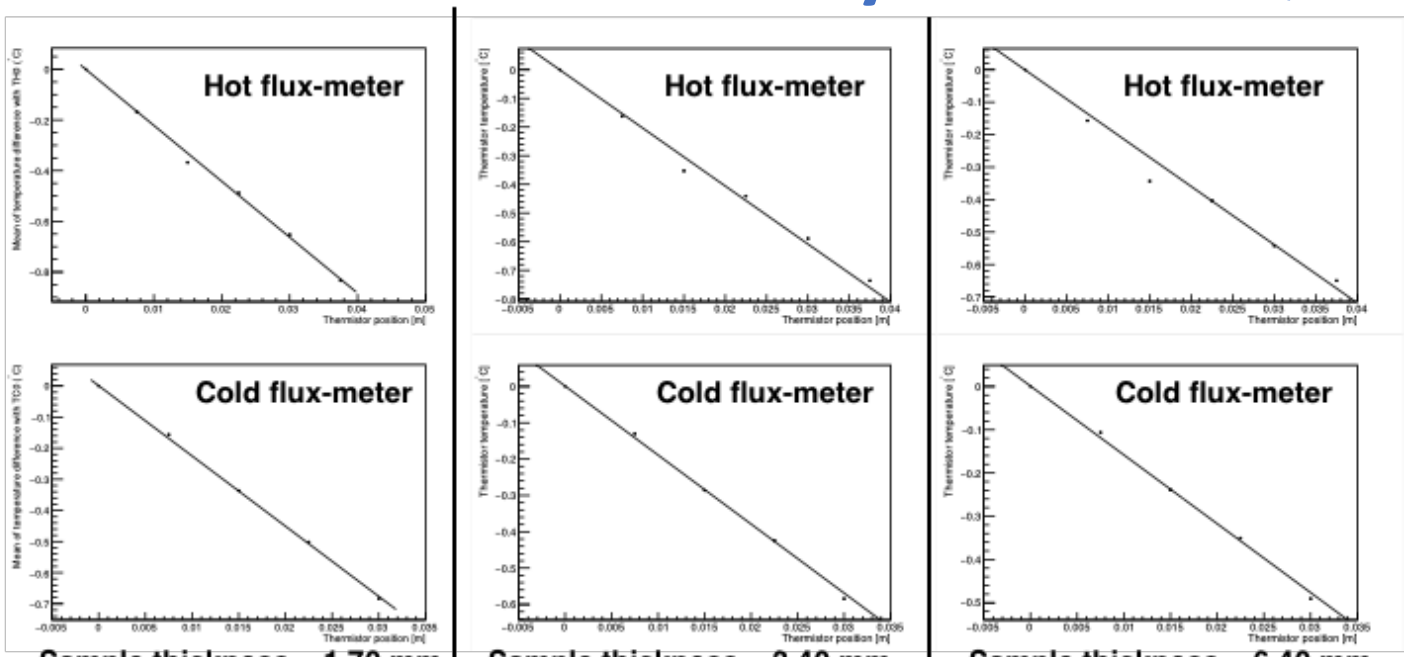
  Average flux = 8,480 ± 70 W/m^2
- Extrapolating the two lines, we estimate temperature difference between two ends of the sample

  $\Delta T = 11.06 \pm 0.05$ C

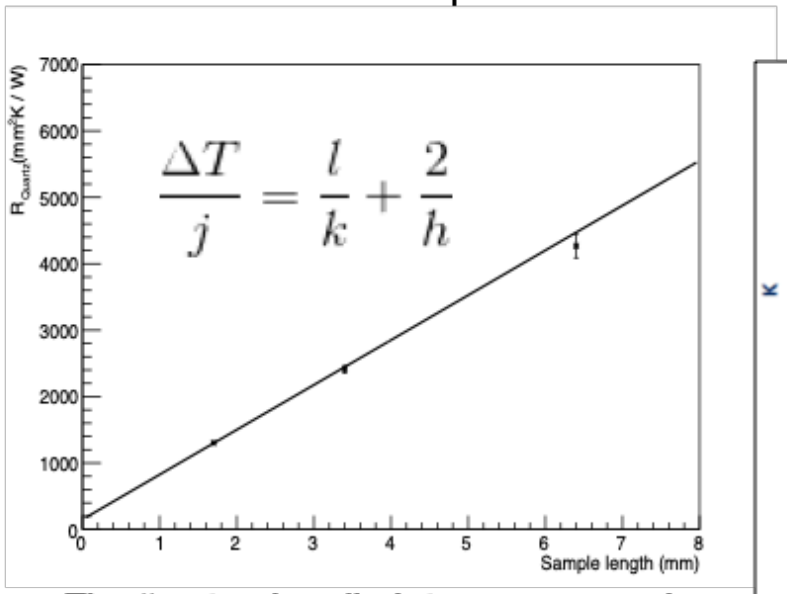
Measurement for validation: Thermal Conductivity of Fused Quartz

- A fit of the thermal resistance against sample thickness screens out interface conductance as the intercept.
- Thermal conductivity is inverse of the slope
- Our measurement:
  k = 1.48 ± 0.01 W/mK
- Manufacturer: k ~ 1.5 W/mK
- Thermo-Physical Research Laboratory in West Lafayette (laser flash): k = 1.2 W/mK

Enough precision to detect variations in carbon fiber and adhesives with pressure and additives



Sample thickness = 1.70 mm | Sample thickness = 3.40 mm | Sample thickness = 6.40 mm



The "meta-slope" plot across samples