Thermal Studies for the CMS Phase II 
Forward Pixel Detector

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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

- **K13D2U\textsubscript{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
Thermal Conductivity of EBT-700 Carbon Fiber

14 psi, without graphite
- $\Delta T_{sample} = 8.89 \pm 0.02 \, ^{\circ}C$
- $J_{\text{average}} = 6405 \pm 56 \, \text{W/m}^2$
- $K = 0.532 \pm 0.011 \, \text{W/mk}$

60 psi, without graphite
- $\Delta T_{sample} = 7.85 \pm 0.02 \, ^{\circ}C$
- $J_{\text{average}} = 6144 \pm 25 \, \text{W/m}^2$
- $K = 0.594 \pm 0.010 \, \text{W/mk}$

60 psi, with graphite
- $\Delta T_{sample} = 7.75 \pm 0.01 \, ^{\circ}C$
- $J_{\text{average}} = 6422 \pm 74 \, \text{W/m}^2$
- $K = 0.645 \pm 0.015 \, \text{W/mk}$

- Thermal conductivity of 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.

- Heating flux-meter made of copper with 6 thermistors.
- Two spring-system
- Resistive heater
- Copper flux-meters are thermally isolated from the case using airex.

Heat sink(water-cooled)
Cooling flux-meter made of copper, has 6 equidistant thermistors
Testing material

Pressure to ensure good contact
1mm lip to hold sample
Thermal Paste
Validation of apparatus using Aluminum

- 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, $K_{\text{measured}} = 196 \pm 4 \text{W/mK}$.
- 2% correction (from FEA) to heat flux is applied to account for convection and radiation losses.
- $K_{\text{reference}}$ 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.

\[ \Delta T = \frac{l}{j} \left( \frac{2}{k} + \frac{2}{h} \right) \]
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

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

- Full chip pixel array + bottom: 22mm x 18.4mm
  
  **1.55W**
CMS Dee Module Scenarios - Heat Dissipation

Normal

Conservative

Failure of 1/4 chip

Failure of 1/2 chip

2.42 W per chip

2.90 W (20% margin) per chip

3.51 W on neighboring chips

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/m².°C): Epoxy = 40,000, Laird film = 500,000, Bumpbonds = 800,000.
3. Convection coefficients (W/m².°C): Air=5 to 22 °C, Active cooling via CO₂ = 5000 to -36°C.
CMS Dee results

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

Temperature heat map of CMS Dee nominal case

Constraints on temperature and gradient

<table>
<thead>
<tr>
<th></th>
<th>Max SLD0 temp</th>
<th>Max Chip gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Operation</td>
<td>0°C</td>
<td>15°C</td>
</tr>
<tr>
<td>Failure mode</td>
<td>20°C</td>
<td>20°C</td>
</tr>
</tbody>
</table>

RESULTS

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum temperature(°C)</th>
<th>Variation in chips(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>-21.8</td>
<td>-30.0 to -23.2</td>
</tr>
<tr>
<td>Conservative</td>
<td>-19.6</td>
<td>-29.2 to -21.3</td>
</tr>
<tr>
<td>¾ failure</td>
<td>-18.8</td>
<td>-30.0 to -21.5</td>
</tr>
<tr>
<td>½ failure</td>
<td>-13.0</td>
<td>-30.4 to -19.9</td>
</tr>
</tbody>
</table>
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 ($k=285\text{W/mK}$) to calculate the thermal performance.

<table>
<thead>
<tr>
<th></th>
<th>Unmodified thermal wing</th>
<th>AlNi upto width of pipe</th>
<th>AlNi upto width of chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. Chip temp($^\circ$C)</td>
<td>-29.6</td>
<td>-30.8</td>
<td>-31.7</td>
</tr>
</tbody>
</table>

Only $2^\circ$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

<table>
<thead>
<tr>
<th></th>
<th>Without graphene</th>
<th>With graphene</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 psi</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>60 psi</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Readings from 60 psi, without graphene is shown here. (CMS work in progress)
Through Plane Thermal Conductivity of K13D2U

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

\[ k = 1.08 \pm 0.01 \text{ W/mK} \]

- 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

- 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

\[
\text{Average flux} = 8,480 \pm 70 \text{ W/m}^2
\]
- Extrapolating the two lines, we estimate temperature difference between two ends of the sample

\[
\Delta T = 11.06 \pm 0.05 \text{ C}
\]
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: \( k = 1.48 \pm 0.01 \text{ W/mK} \)
- Manufacturer: \( k \approx 1.5 \text{ W/mK} \)
- Thermo-Physical Research Laboratory in West Lafayette (laser flash): \( k = 1.2 \text{ W/mK} \)

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