Structure and Cooling for the CMS Phase II Tracker Pixel Detector

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PURDUE UNIVERSITY

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CMS
Compact Muon Solenoid

Outline

- The CMS Experiment Pixel Detector
- The **Thermal** Challenge
  - Cooling the TFPX Dees
  - Measuring through-plane thermal conductivity
  - Measuring in-plane thermal conductivity
- The **Mechanical** Challenge
  - Fabricating the TFPX-TEPX Service Cylinder
  - **Microscopy** for carbon fiber consolidation
  - **Fabricating** the Service Cylinder Mark I
  - Service Cylinder Mark II
- Conclusions

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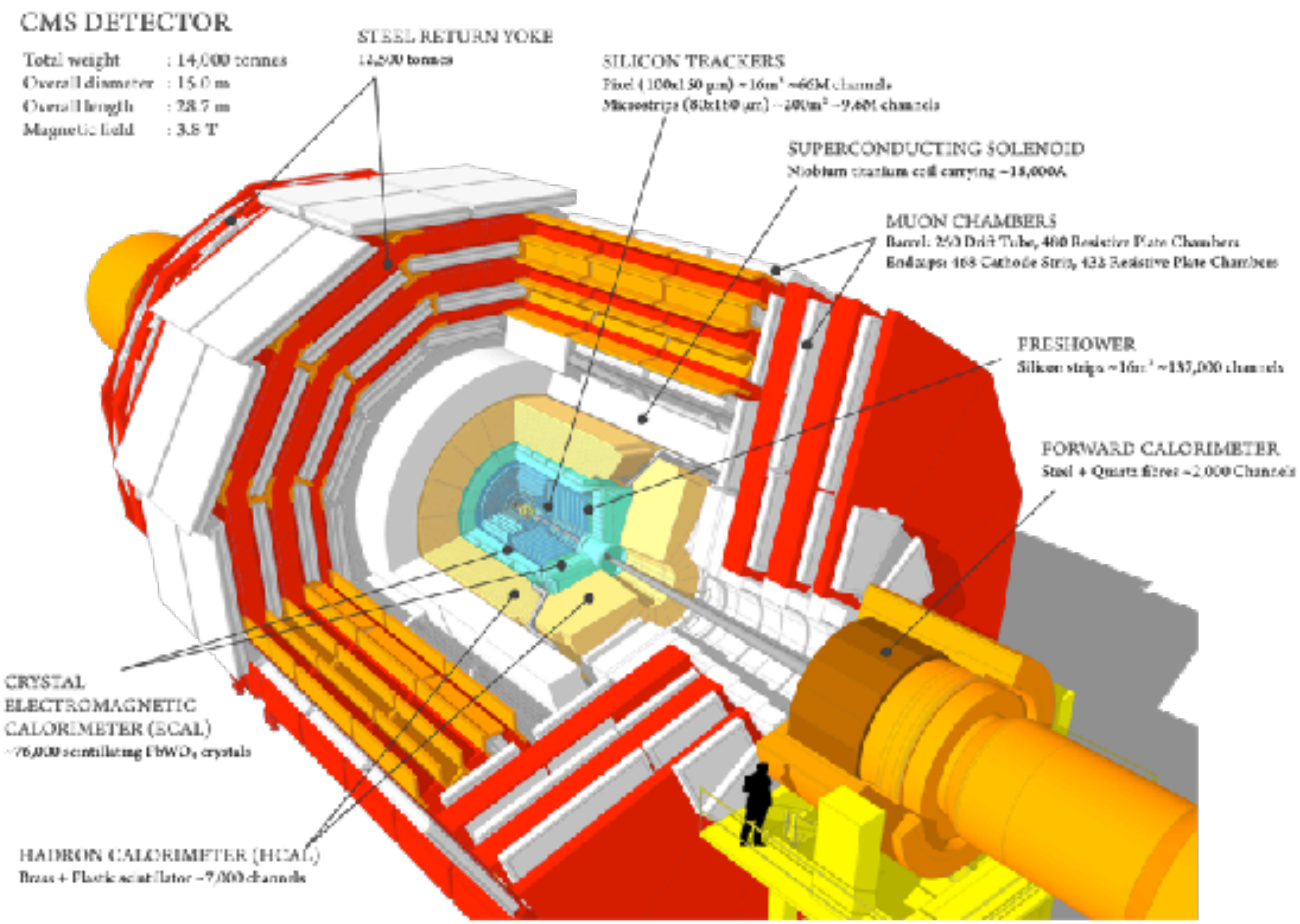
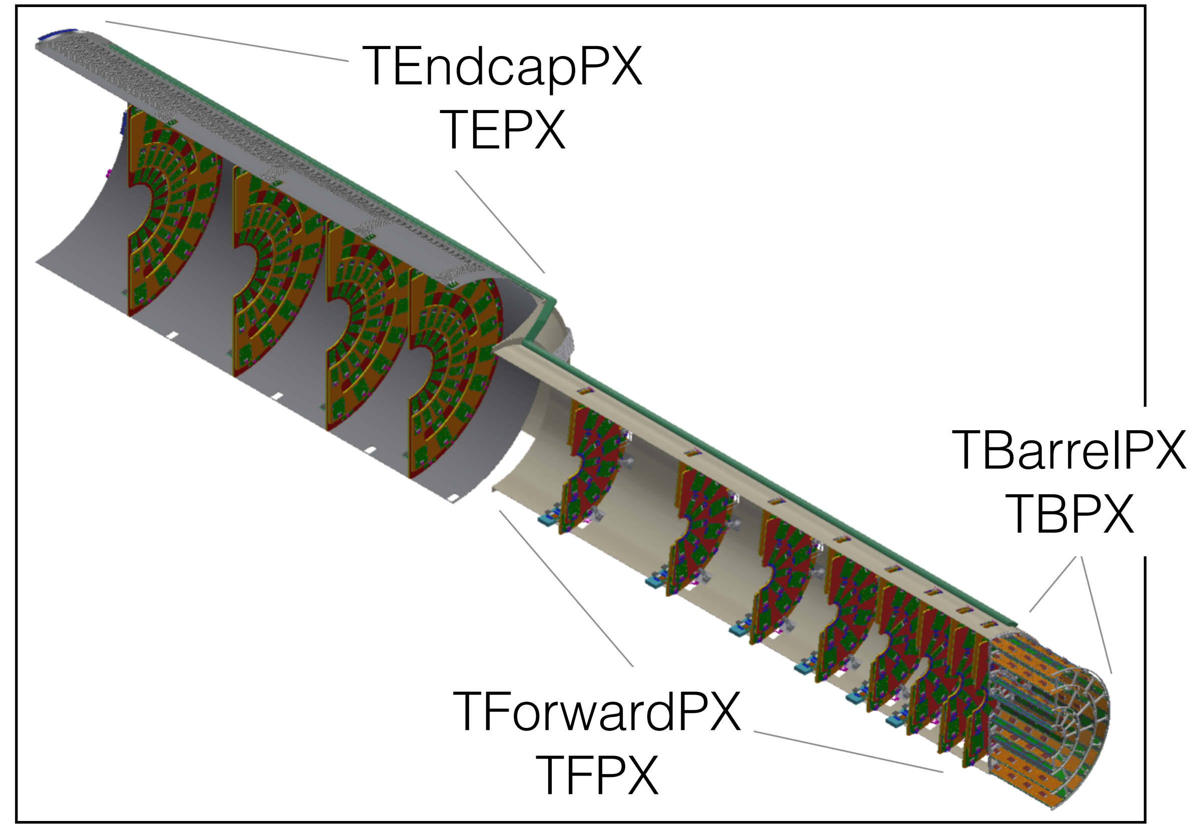
The CMS Experiment Pixel Detector





Phase II Pixel Detector schematic

CMS is a **general purpose detector** at the LHC.
The Pixel Detector is closest to the LHC beam-pipe.

- With LHC —> HL-LHC, instantaneous luminosities will increase x 5
- CMS needs Phase II upgrade to keep up. Pixel detector **needs more granularity**:
  - to limit hit occupancy
  - for higher precision impact parameter measurements, leads to better b-physics

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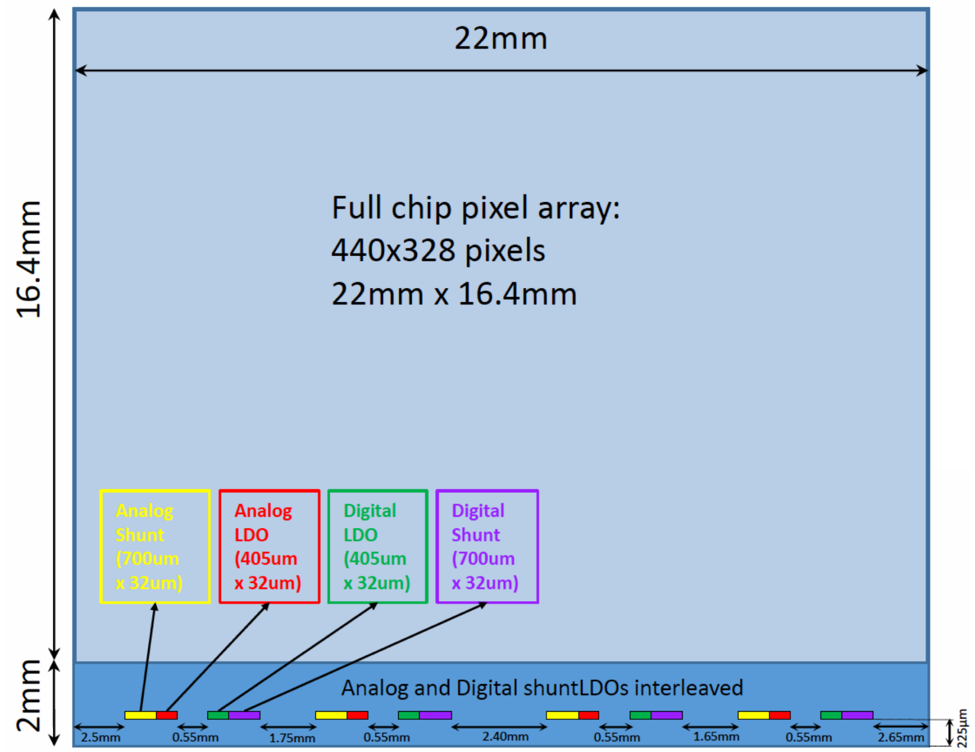
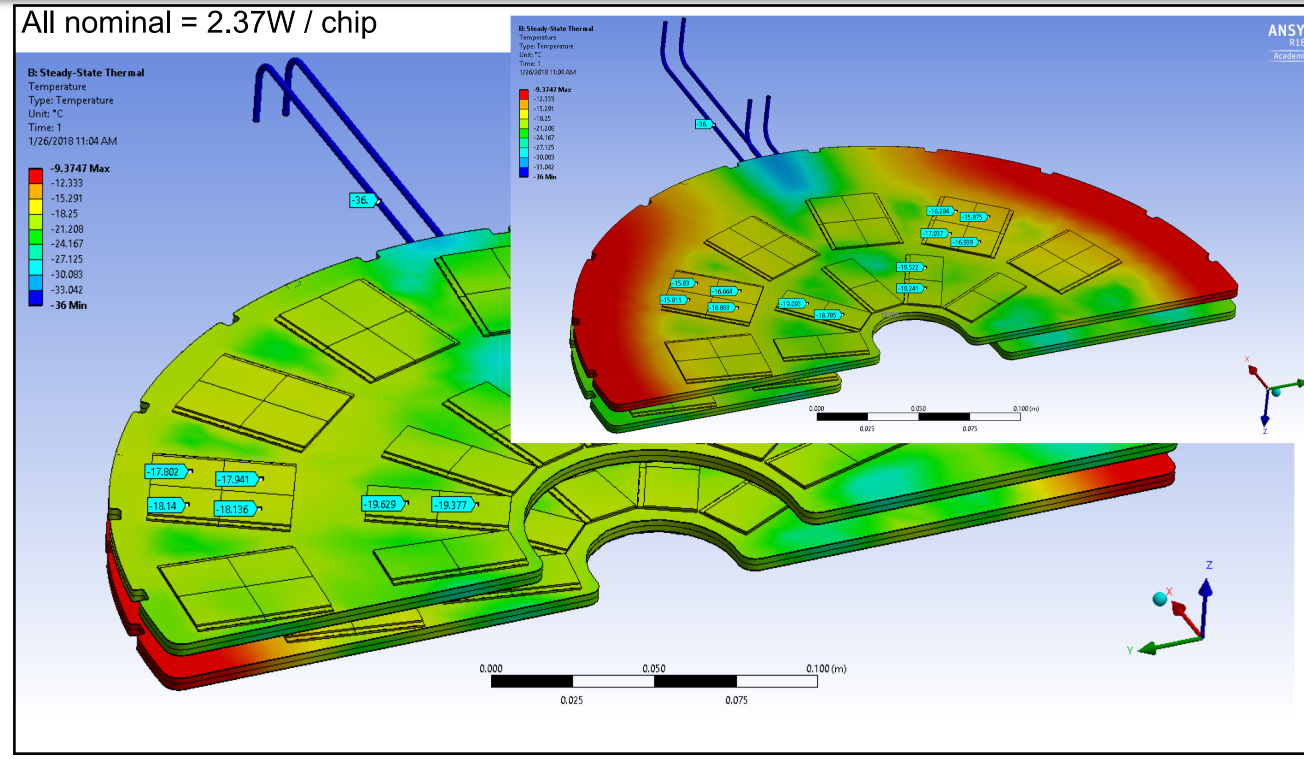
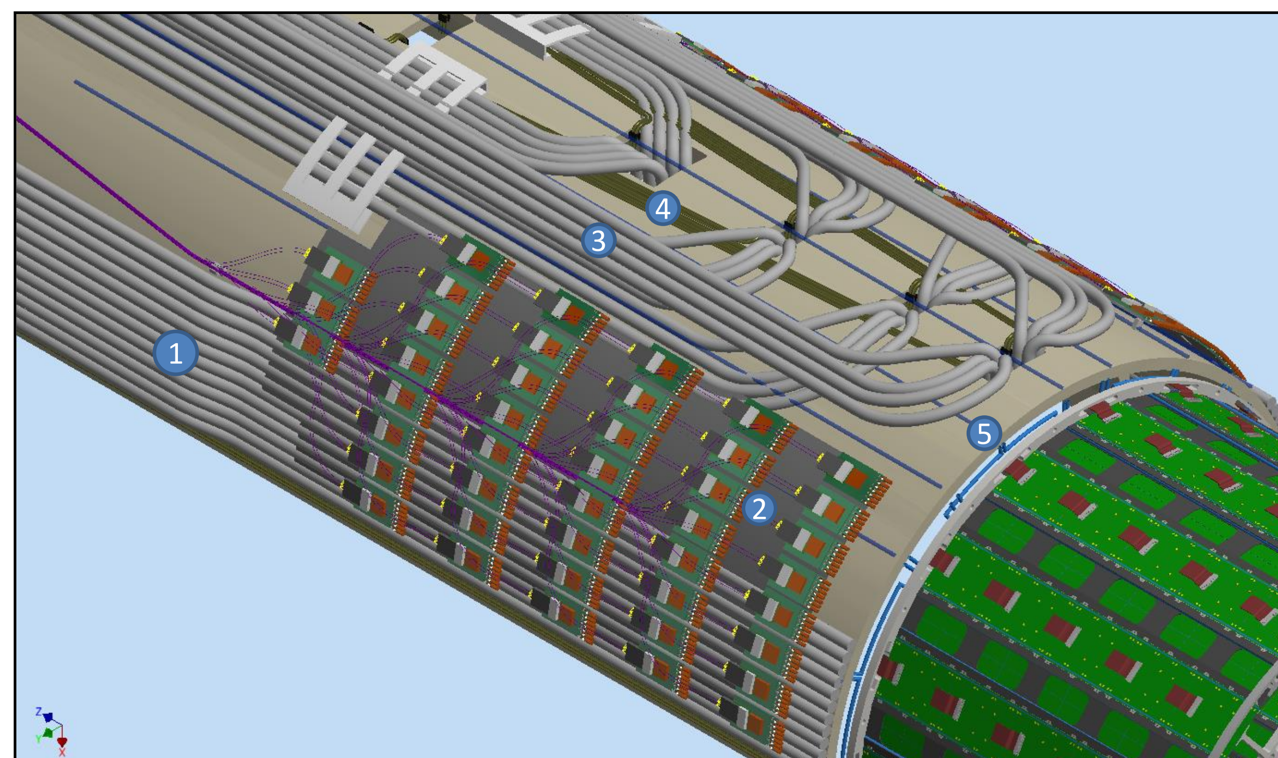
Phase II Forward Pixel Detector Thermal Challenges



Dissipative elements in a pixel ROC



Simulation snapshot for a Dee in ANSYS



1: TBPX power bundle scheme. 2: TBPX port card mount. 3: TFPX first 4 double-dee power bundle scheme. 4: TFPX cooling tube routing. 5: TBPX cooling tube routing.

Service Cylinder with cooling lines to extract heat

- A pixel Readout Chip (ROC) will nominally dissipate 2.37 W and maximally 4.06 W
- The ROCs will need to be at - 20 C
- **50 kW** to be dissipated from the Pixel Detector

Scope of this talk: Experimental methods for material choices for the Dees

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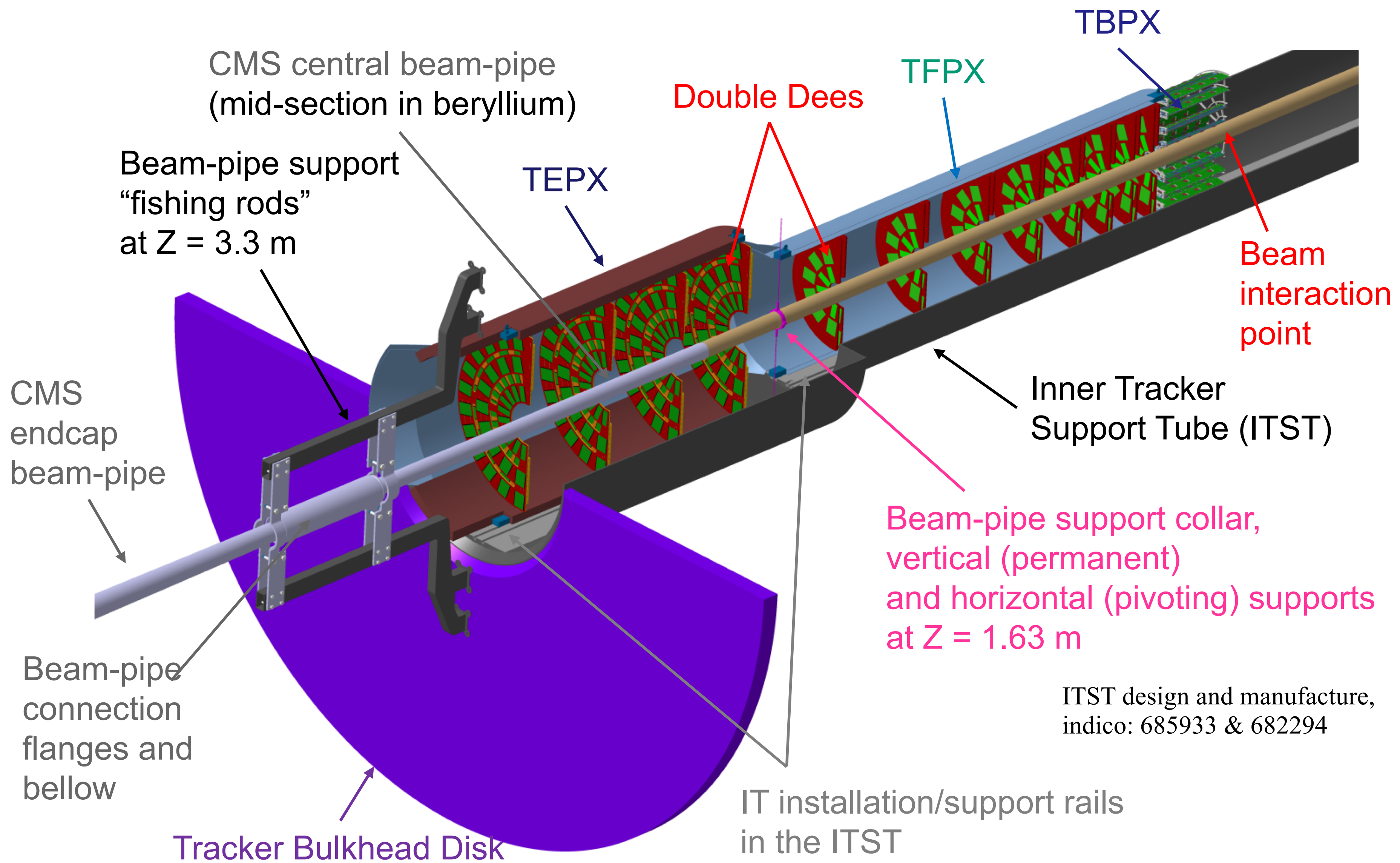
Phase II Forward Pixel Detector Mechanical Challenges



- 4 pieces of the Service (half-) Cylinder will be inserted into the Support Tube
- Support Tube is attached to the Tracker Bulkhead Disk
- Dees affixed to the Service Cylinder
- **Minimal deflection with minimum material** required

Scope of this talk: Fabrication of the Service Cylinder

Thermal Challenge

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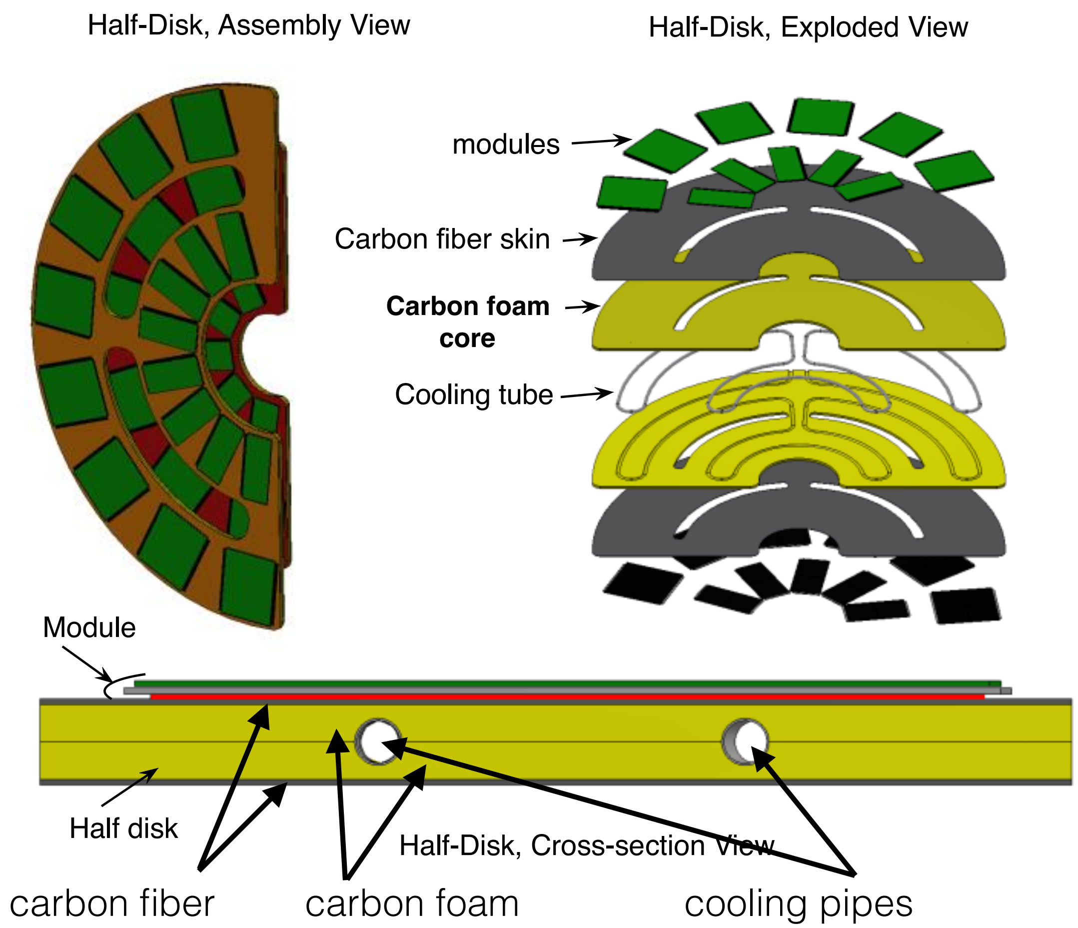
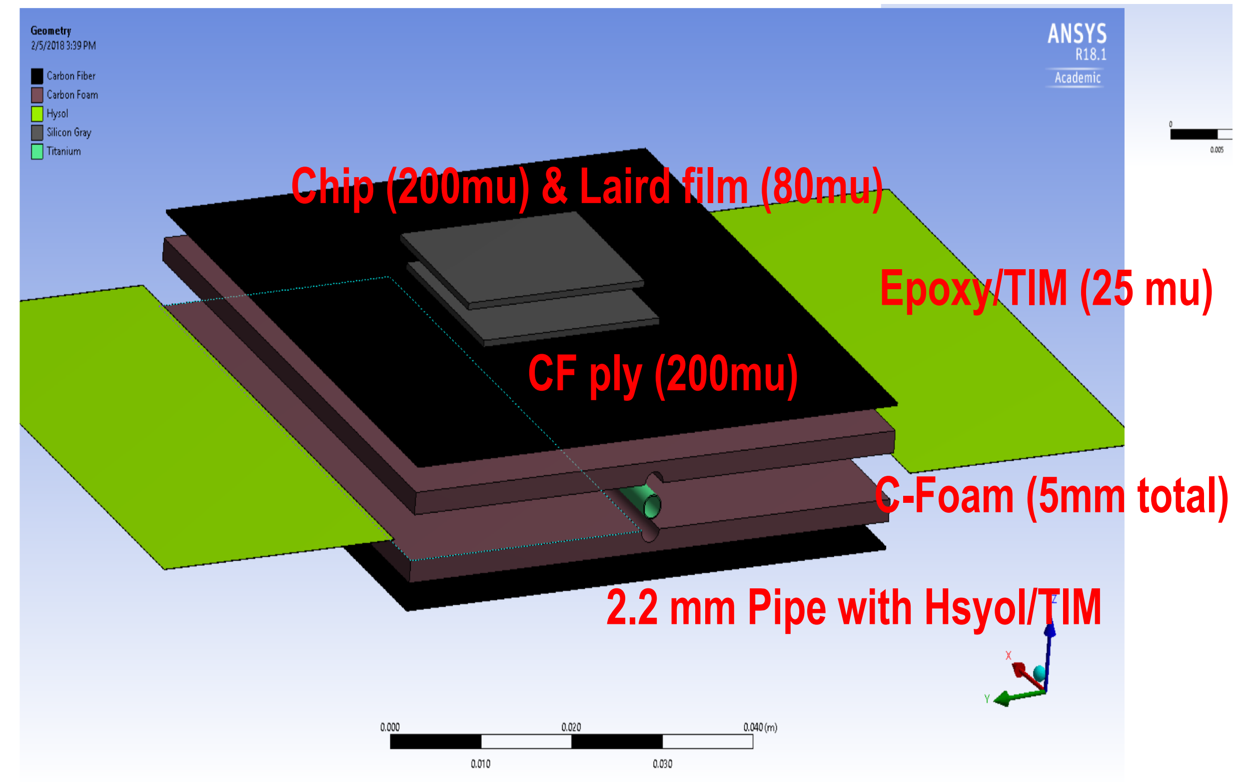
Cooling the TFPX Dees





Exploded snapshot of FEA using ANSYS

- Modules on Dee consist of ROC, sensor, HDI. Prototypes being constructed
- Modules affixed on carbon fiber using Laird (580 series) film. 3.8 W/mK
- Carbon fiber is TENCATE K13C2U / TC-275-1
- Carbon foam is AllComp K9 foam
- Cooling tube is stainless steel. Two phase CO_2 at -36 C is the coolant
- Loctite EA 9396 (Hysol) to glue foam to foam, foam to fiber, foam to pipe
- FEA suggest temperature drop most sensitive to through-plane conductivity of carbon fiber
- **Need to measure** through-plane, in-plane conductivities of materials to feed into simulations

Apparatus for Through-Plane Thermal Conductivity Measurements

Spring clamp to ensure equal pressure at thermal interfaces

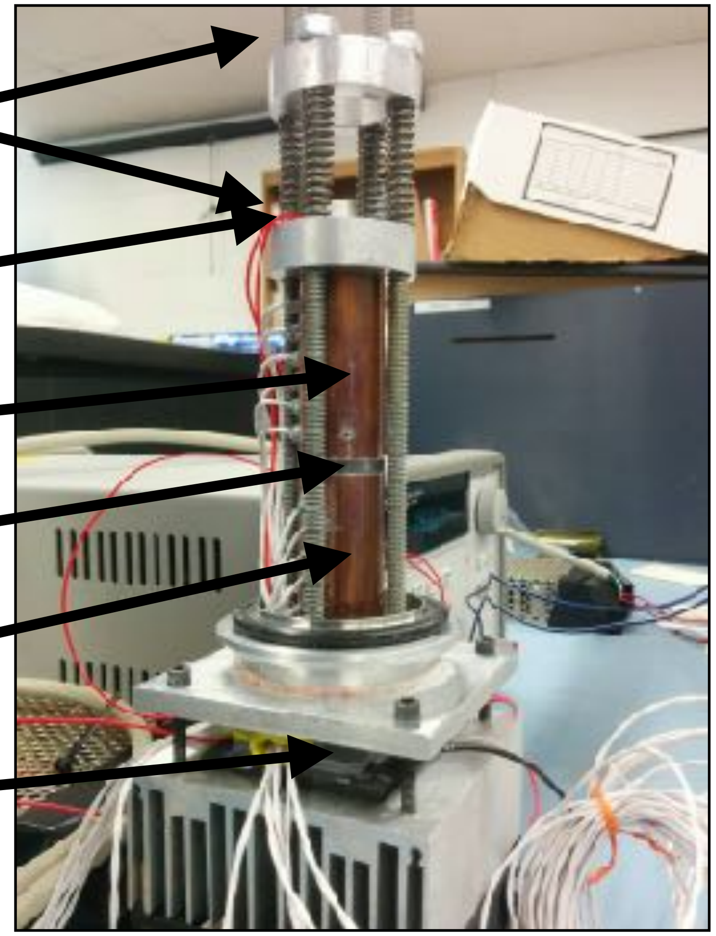
Resistive heating element

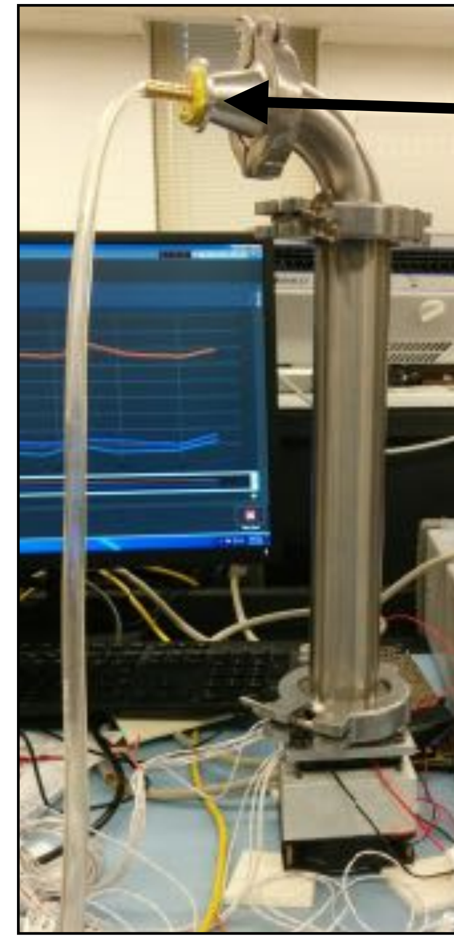
Heating flux-meter made of copper with 6 thermistors

Test material

Cooling flux-meter

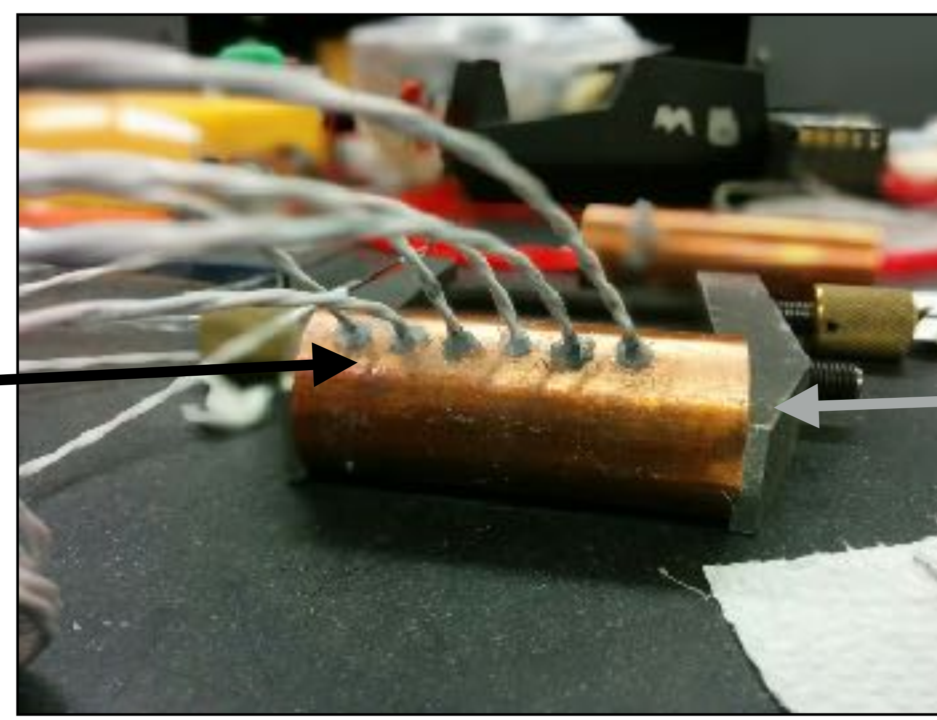
Peltier cooling element





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

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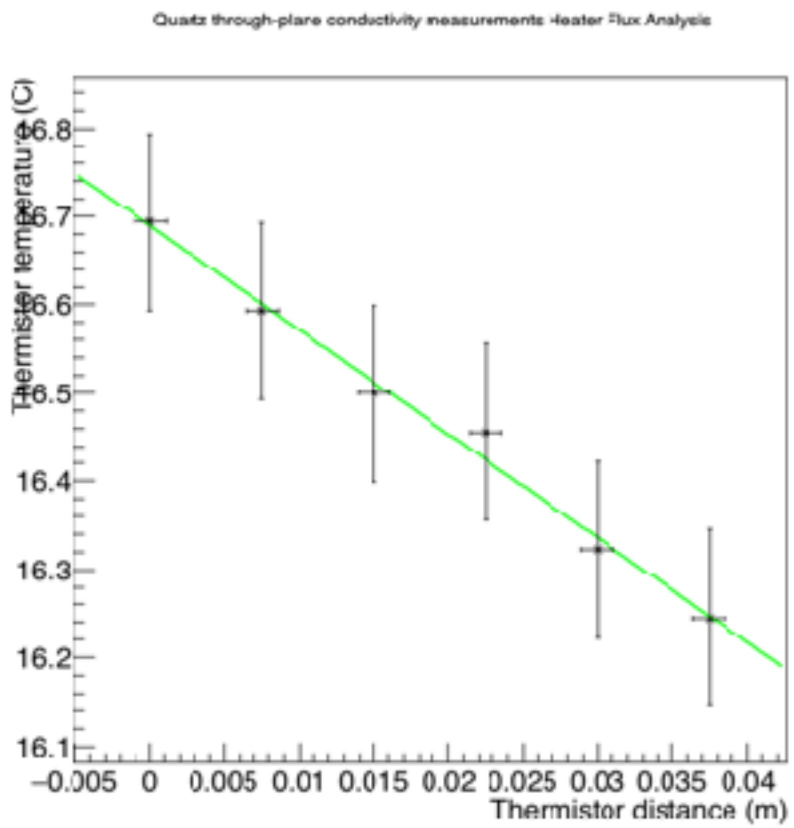
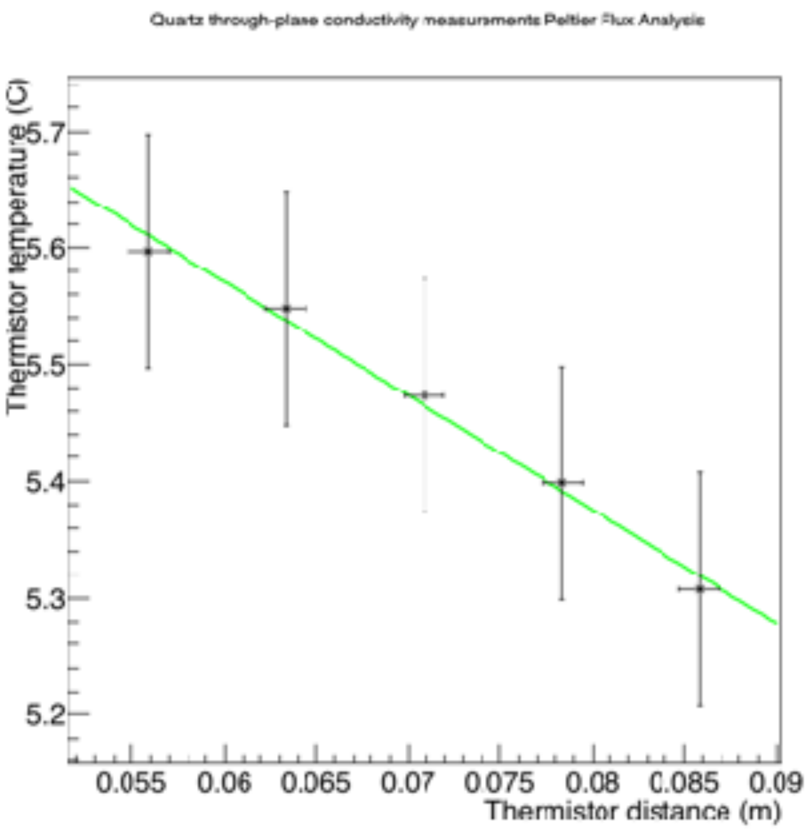
Through-Plane Apparatus Calibration with Quartz





- Temperature gradients in the heating and cooling flux-meters estimate heat flux through the system
- Extrapolating the two curves, we estimate temperature at the two ends of the quartz sample
- We estimate the thermal conductivity of this piece of quartz to be:

  Preliminary: k = 1.4 ± 0.5 W/mK

  manufacturer datasheet = 1.3 W/mK

  independent test using laser flash = 1.2 W/mK
- Major sources of uncertainty: Loss of 1 thermistor in cooling flux-meter, 0.1 K systematic uncertainty in thermistor readings
- We measure thermal conductivity of *carbon fiber through-plane*, *carbon foam*, *Laird film interface*, and *carbon fiber - foam hysol interface*
- Exploring the use of Few Layers Graphite thermal interface materials (FLG-TIMs)

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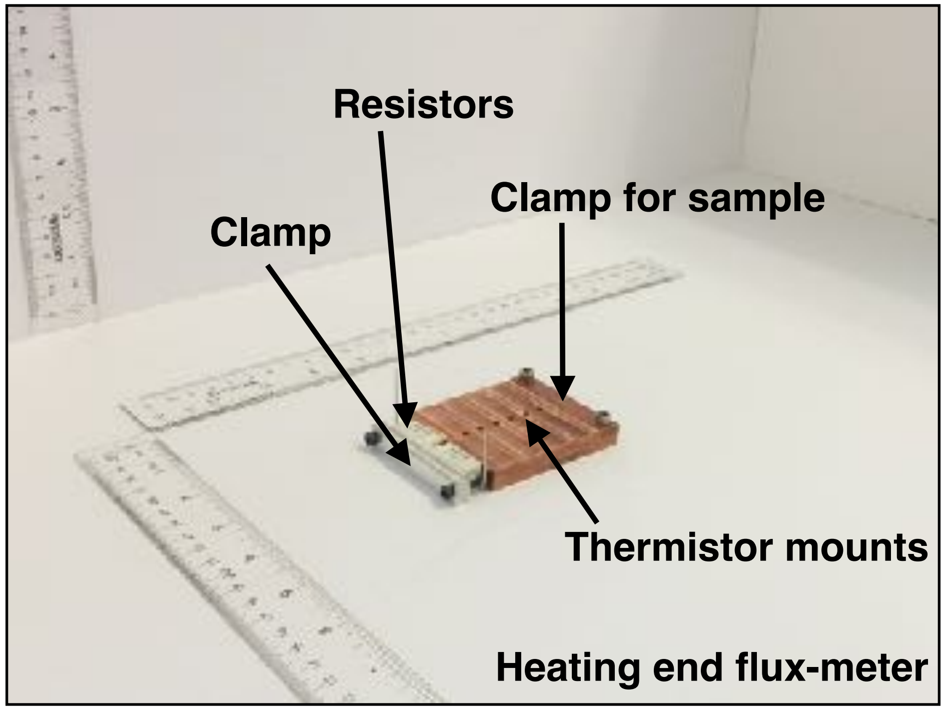
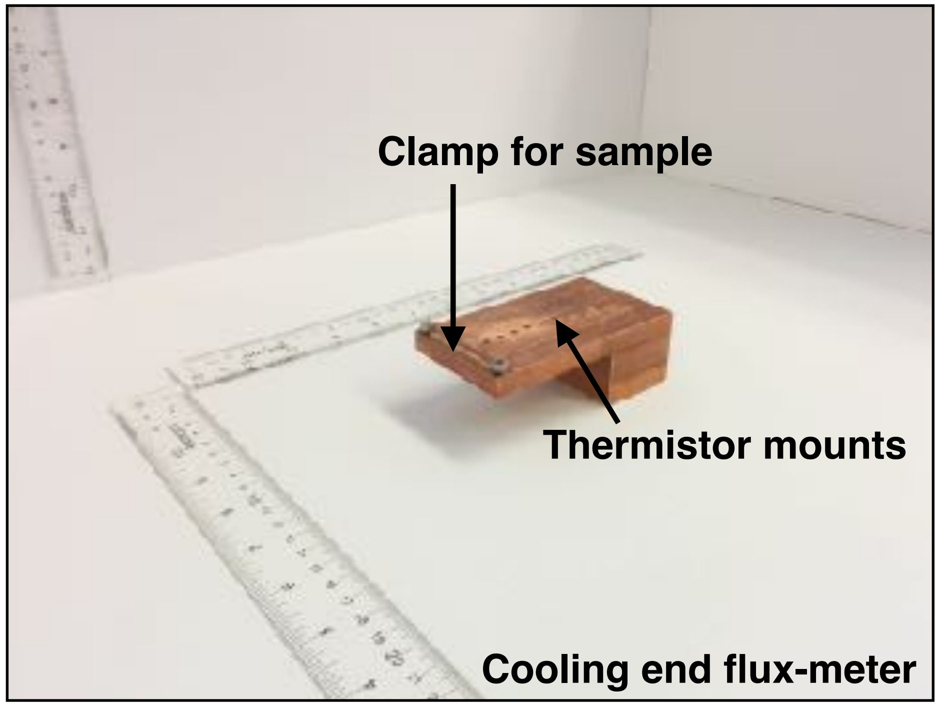
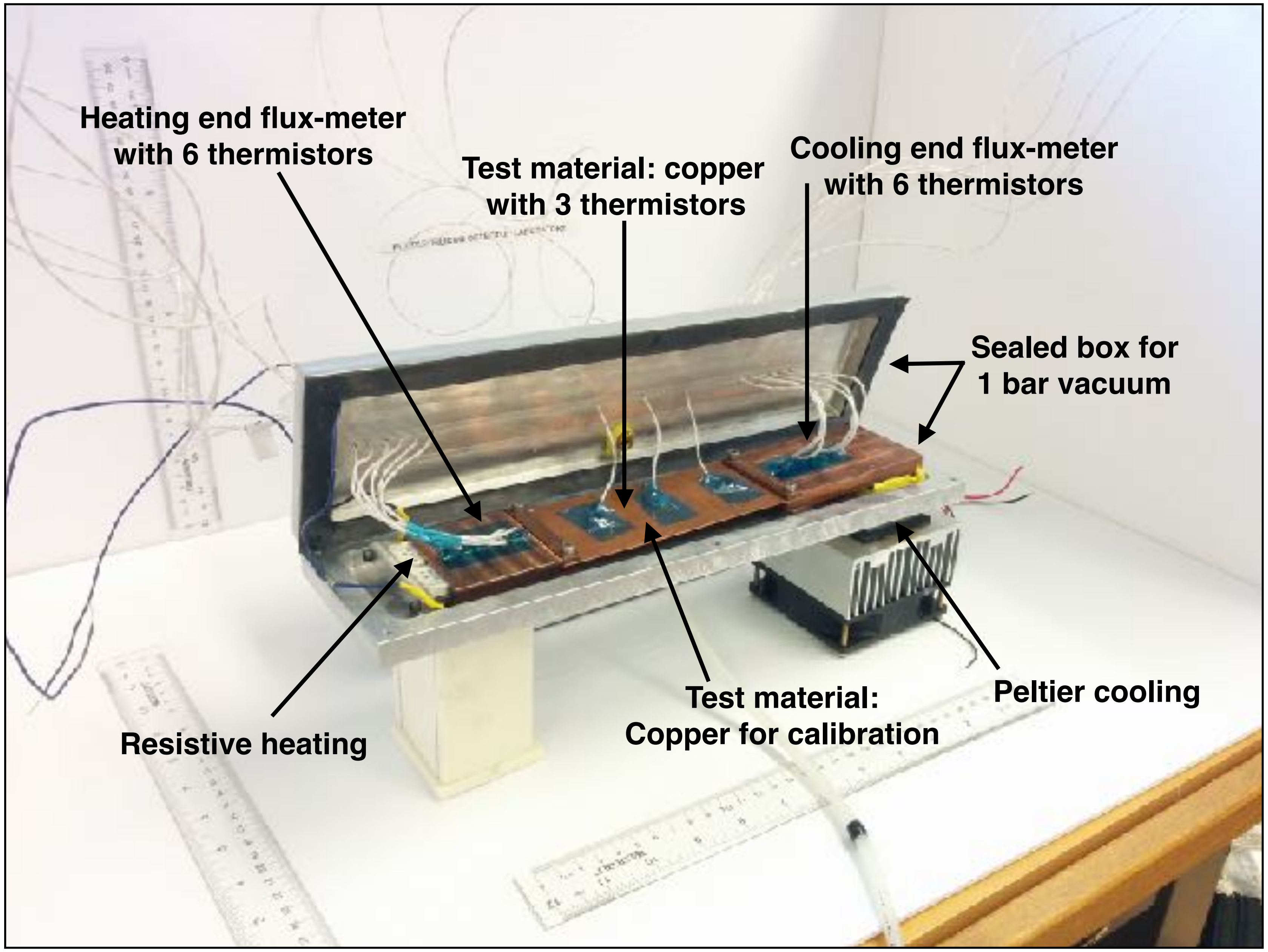
Apparatus for In-Plane Thermal Conductivity Measurements







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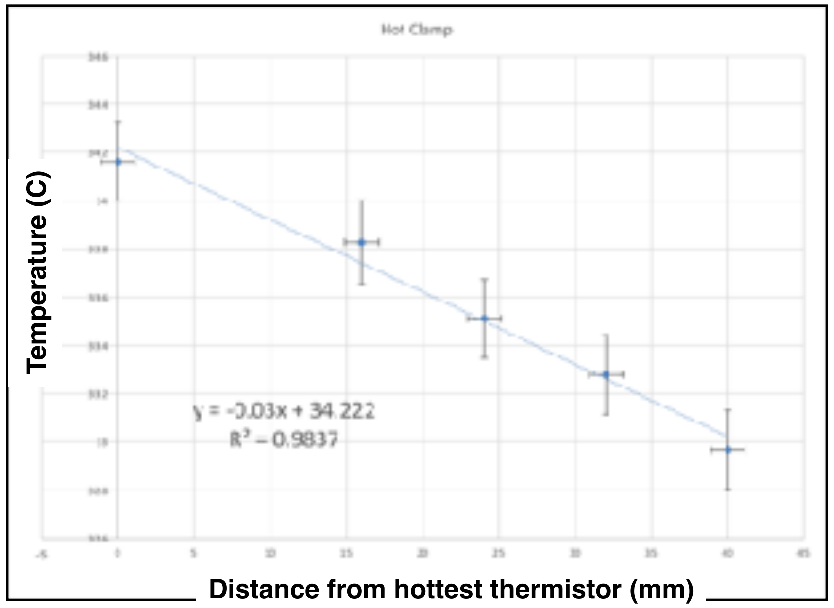
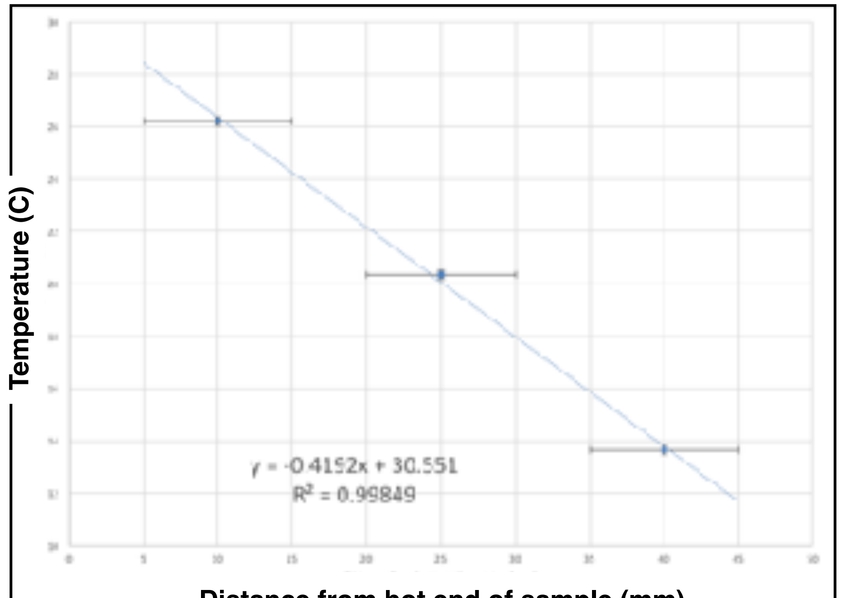
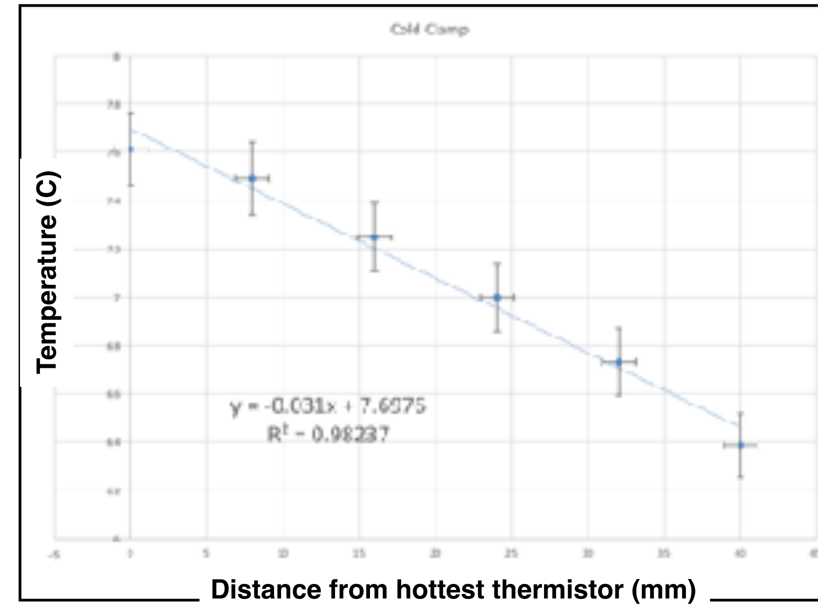
In-Plane Apparatus Calibration with Copper



Temperature gradient in Heating End Flux-meter



Temperature gradient in Copper Sample



Temperature gradient in Cooling End Flux-meter

- Similar principle as the through-plane apparatus. We also have temperature gradient across sample
- We estimate the thermal conductivity of this piece of copper to be:

Preliminary: k = 450 ± 50 W/mK

textbook value = 400 W/mK

- We measure thermal conductivity of *carbon fiber in-plane*, *along fiber* direction and *across fiber* direction
- Exploring pyrolitic graphite (PGS) cured within the carbon fiber laminate to increase these conductivities

Mechanical Challenge

Fabricating the TFPX-TEPX Service Cylinder

Service Cylinder will be made of **carbon fiber**

- Purdue works closely with Cornell and UC Davis on the Service Cylinder
- Purdue HEP now has close ties with the Purdue **Composites and Simulations Center** (CMSC) completed in 2016
- 32,000 ft^2 building, **13,000 ft^2 for composite manufacturing**
- CMSC has **highly qualified** full time staff. Graduate students work on our project. Weekly talks with the Executive Director

- Besides deep expertise with carbon fiber manufacturing, they **spearhead simulation** with express aim of "modeling composites with the accuracy and ease of metals"
- Simulation suite *cdmHub* sponsored by Boeing, Rolls Royce, Cytec, Dassault, Henkel and DARPA

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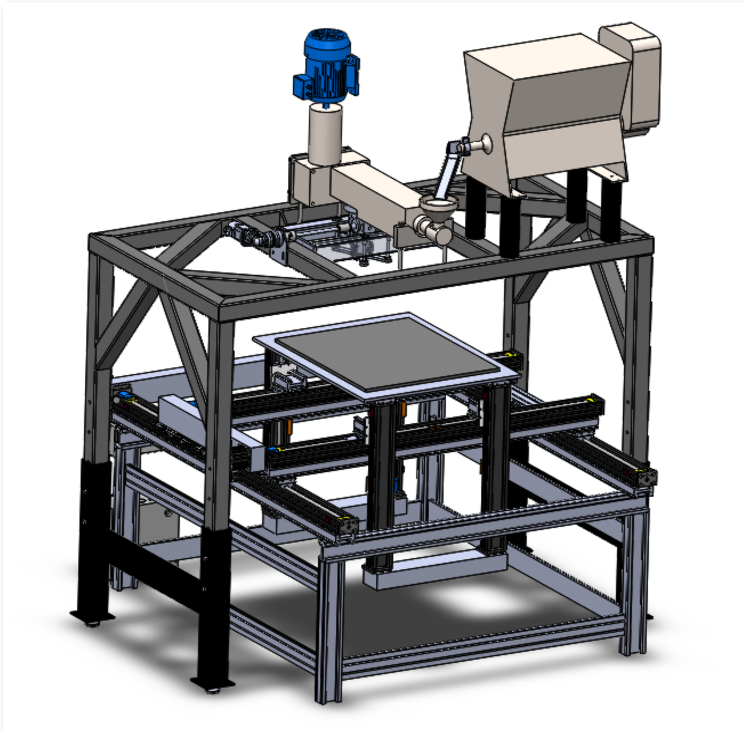
Fabricating the TFPX-TEPX Service Cylinder



CMSC carbon fiber 3D printer

CMSC autoclave

Large clean room workspaces

Main instruments relevant to Service Cylinder fabrication:

- Shredded carbon fiber **3D Printer** with 20” x 20” x 20” print volume
- **Autoclave** that reaches 5.9 bar
- 2 more **large vacuum ovens**
- Access to industry-scale autoclaves in Indianapolis
- **Gerber cutting tool** for fiber layup
- Large **clean room** workspaces
- FARO **laser arm scanner** CMM
- Large **CNC** tool for machining

FARO laser arm

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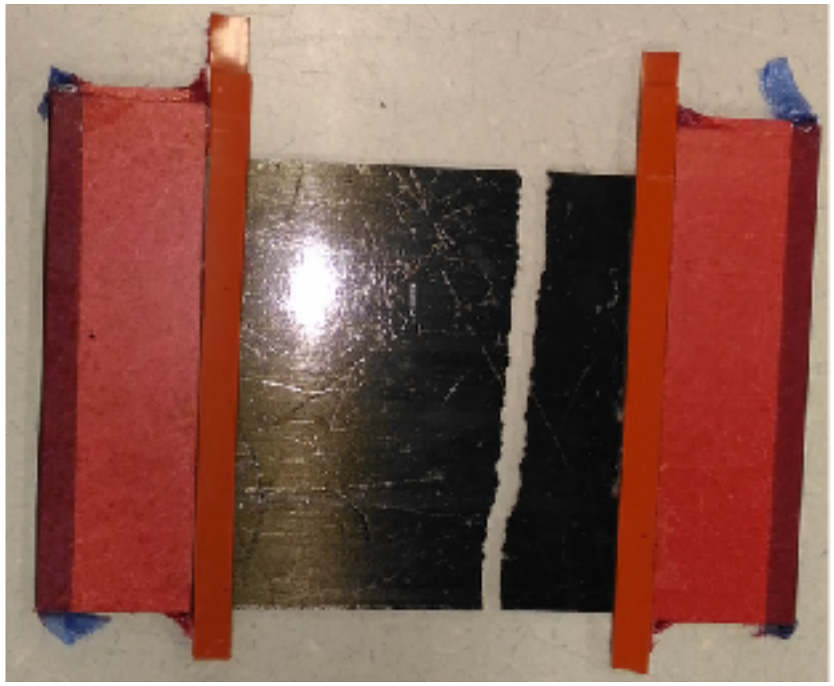
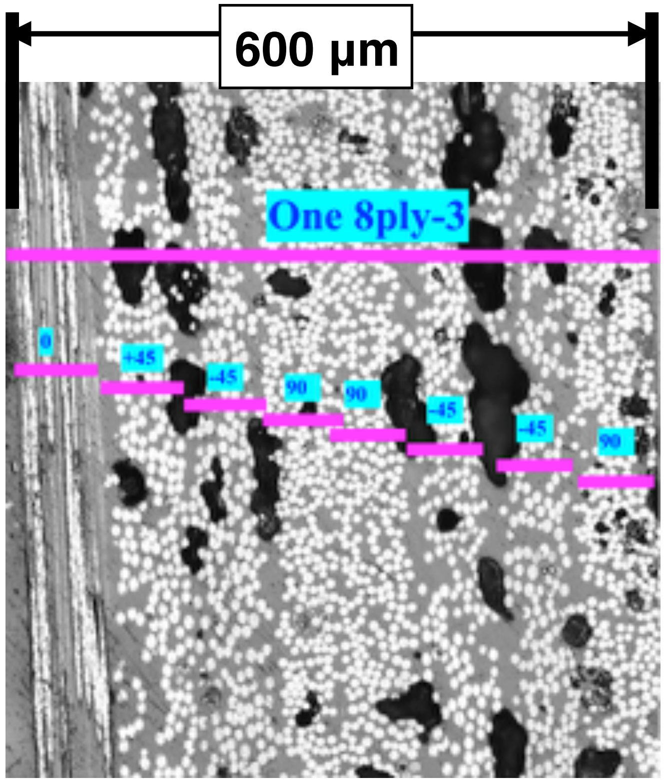
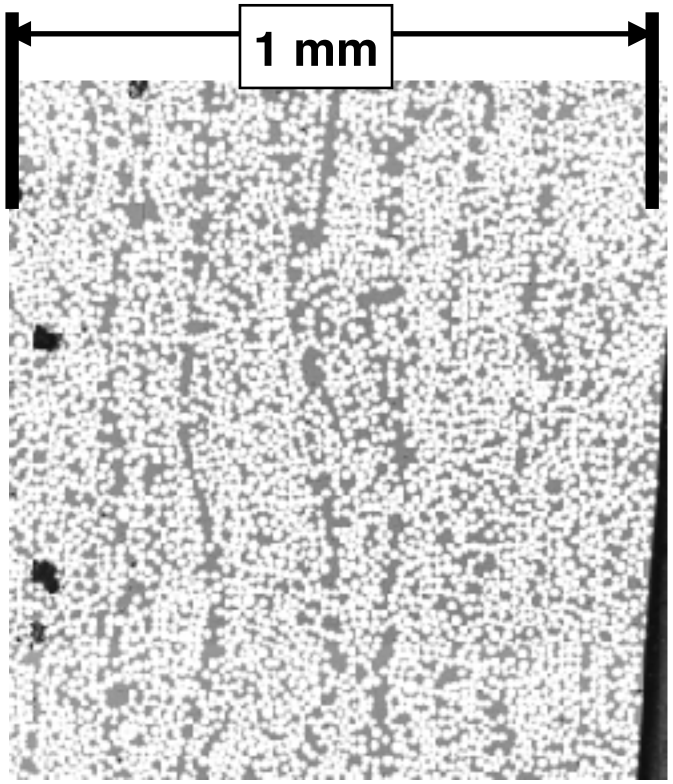
Microscopy to study carbon fiber consolidation



K13C2U laminate failed early in strength testing



K13C2U found damaged by humidity, past shelf life



K13D2U well consolidated

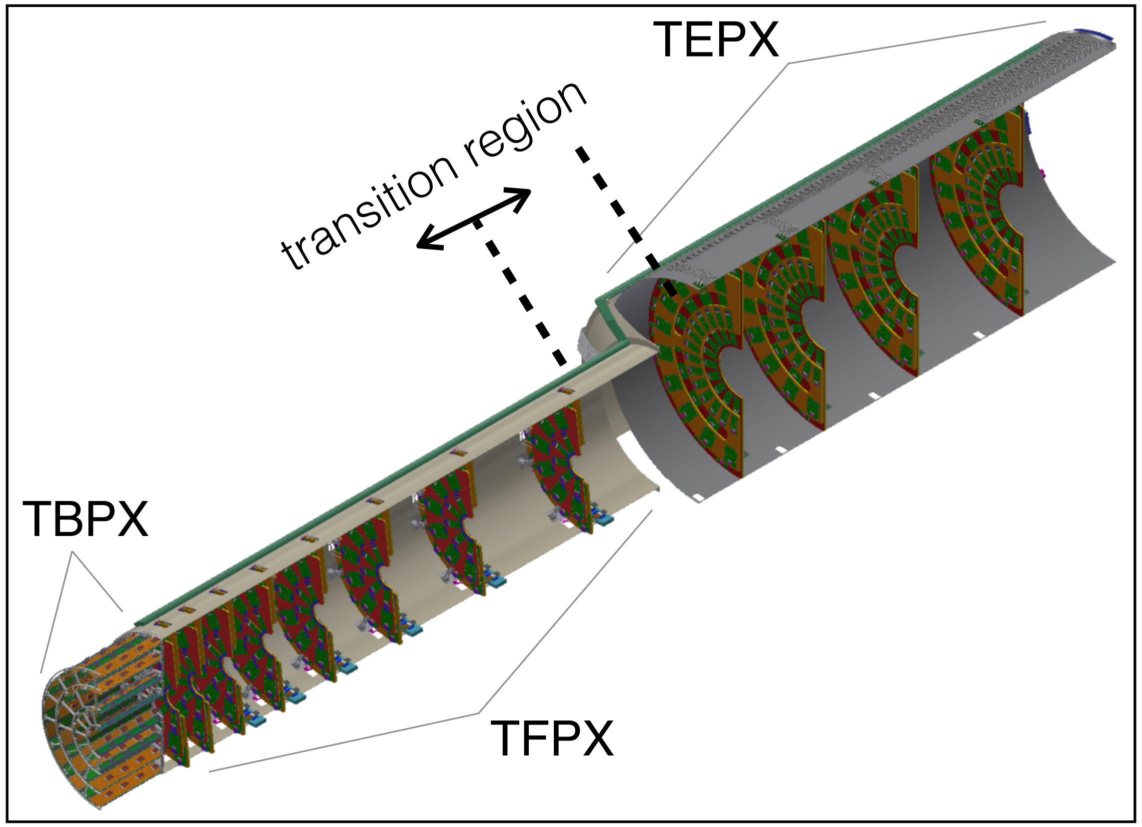
- To create precision structures with carbon fiber, it is necessary to **measure** several thermo-mechanical properties, one of which is **tensile strength**.
- Pull tests with old K13C2U/TC-275-1 in early 2017 resulted in *half* the expected strength.

Why?

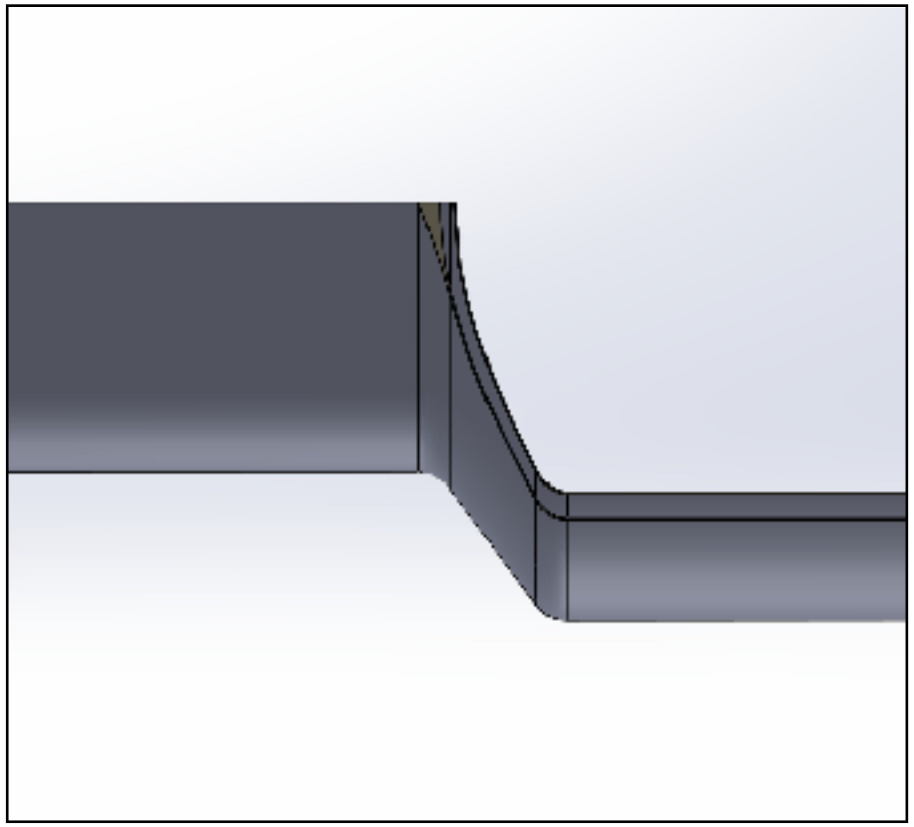
- Microscopy revealed humidity damage, broken fibers, insufficient consolidation, resin past shelf life.
- Enforced **new Standard Operating Procedures** to prevent humidity damage.
- Well stored samples of K13D2U now reveal minimal humidity damage.

Earned expertise in carbon fiber microscopy

Fabricating the Service Cylinder Mark I



Nominal design of the Service Cylinder



Smoothened transition region

- Design of Service Cylinder based on CAD files from Antti and Axel
- Modified design at Purdue for **monolithic build** with smooth edges. Within geometrical constraints of Support Tube
- A monolithic build can add strength but is tricky to fabricate. Two orthogonal curvatures at transition region. Decided to prove concept by just fabricating the transition region first: **Service Cylinder Mark I**

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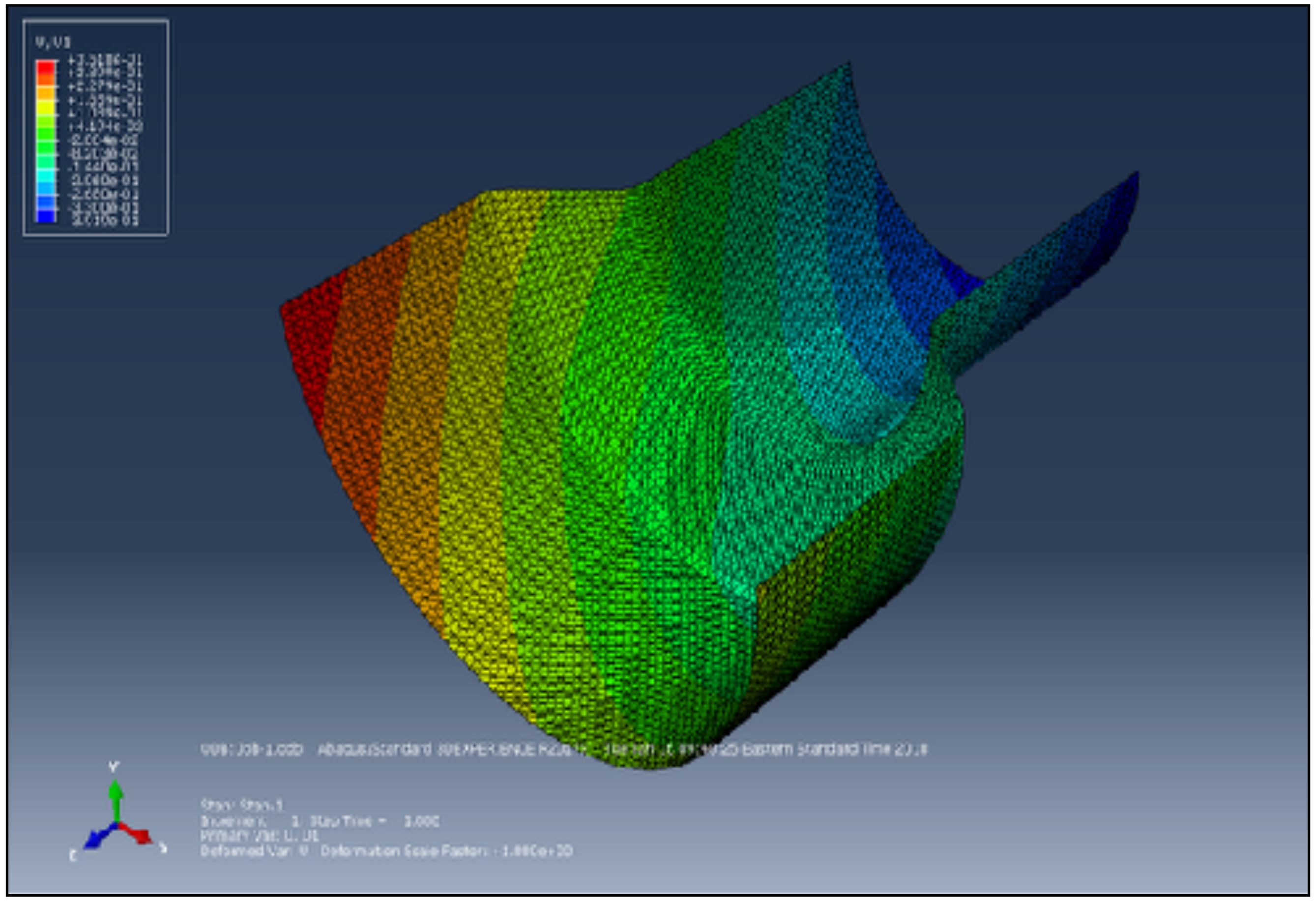
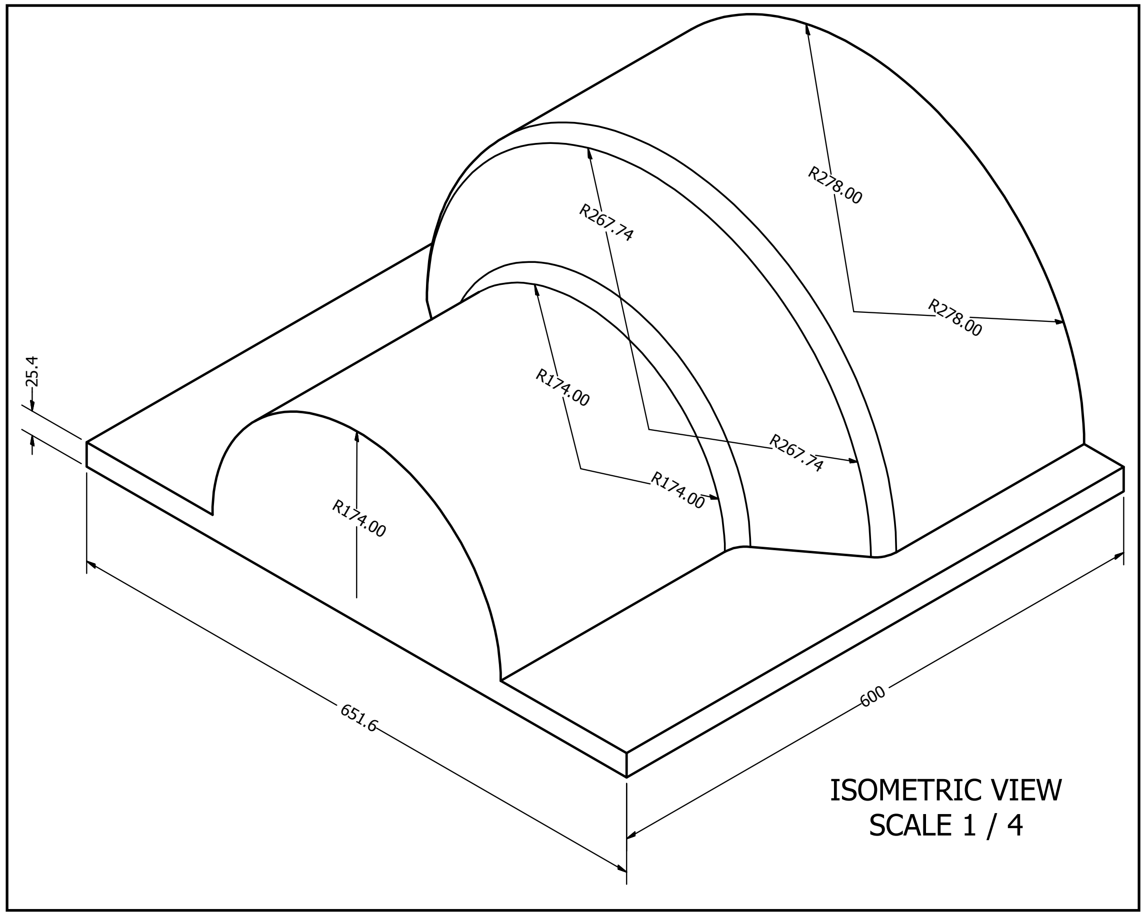
Fabricating the Service Cylinder Mark I



FEA for post-cure deformation



Mold design [mm]

- Choice of carbon fiber:
  - Initial: IM7/8552 uni-directional prepreg. Well characterized. Very difficult to layup
  - Current: **Cycom 5320/AS4 satin weave**. Easy to layup. Needs some characterization
- Carbon fiber deforms after curing due to thermal contraction from cooling and thermal expansion from exothermic curing reaction
- **Mold design has to compensate** for this. We need to characterize carbon fiber's: Young's moduli, Poisson's ratios, coefficients of thermal expansion, fiber diameter, fiber volume fraction, and curing enthalpy

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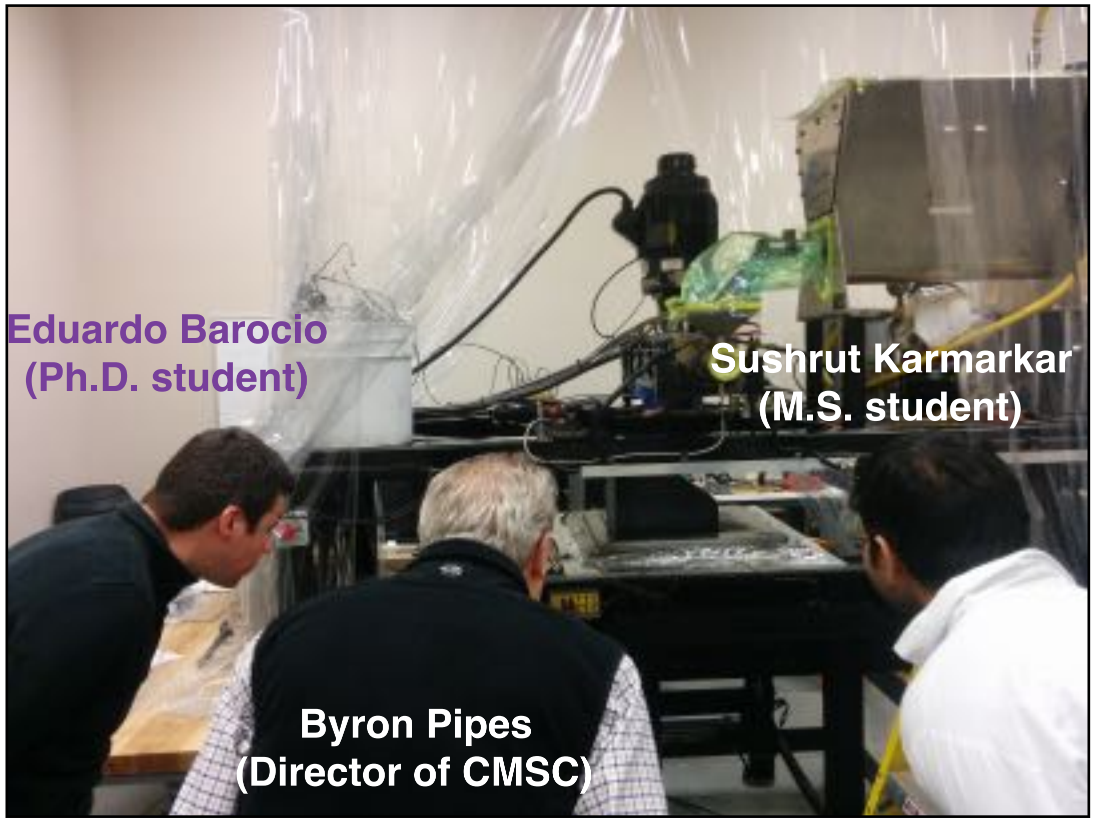
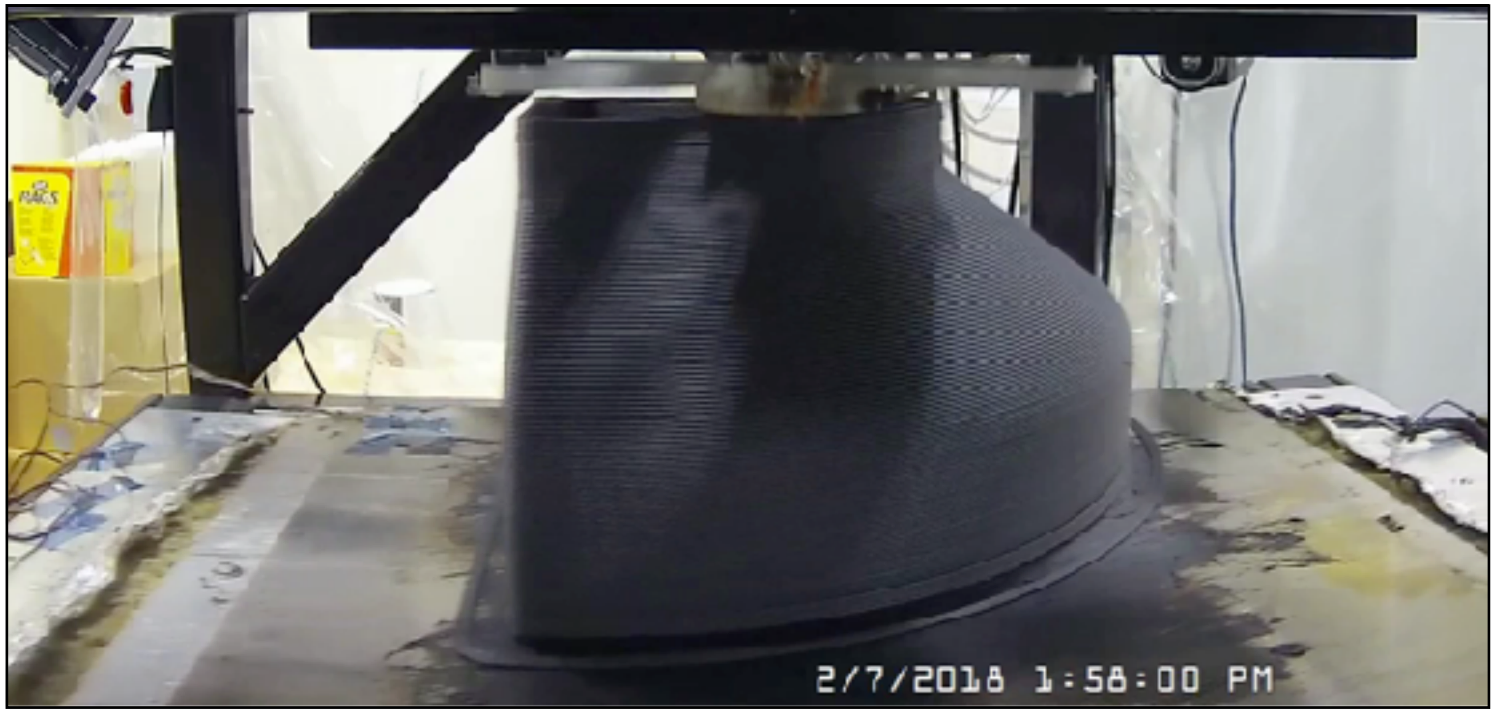
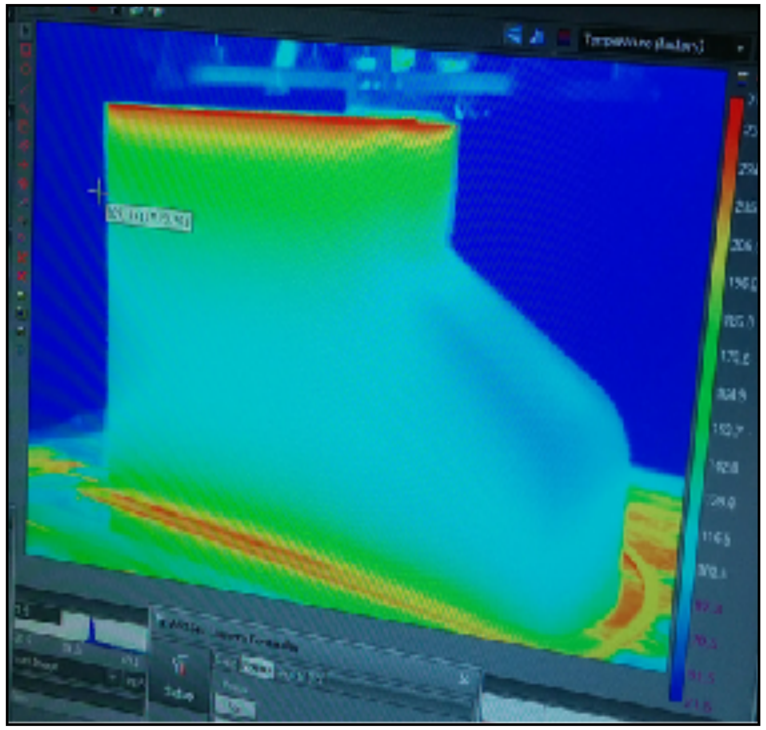
Fabricating the Service Cylinder Mark I



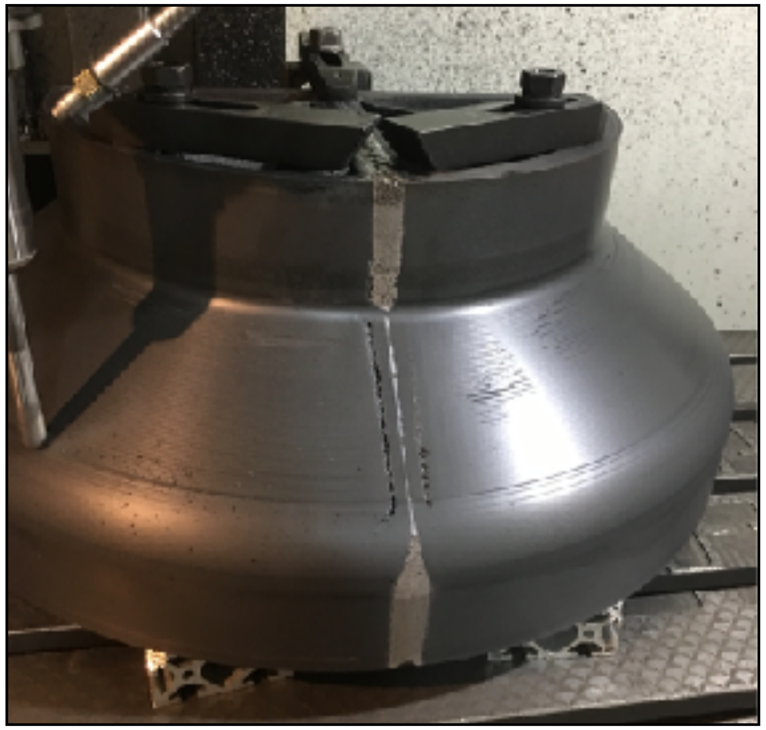


3D printing the Mark I mold

- Mold designed to keep inner surface smooth to mount Dees
- Mold printed at CMSC with shredded carbon fiber and PPS resin (1:1). Minimal CTE mismatch with part
- Mold machined commercially. We will do this in house for Mark II
- Finally, hand polished before layup



Heat signature of part during printing
Essential for predicting behavior during cure



Machining part at Accutech, LLC

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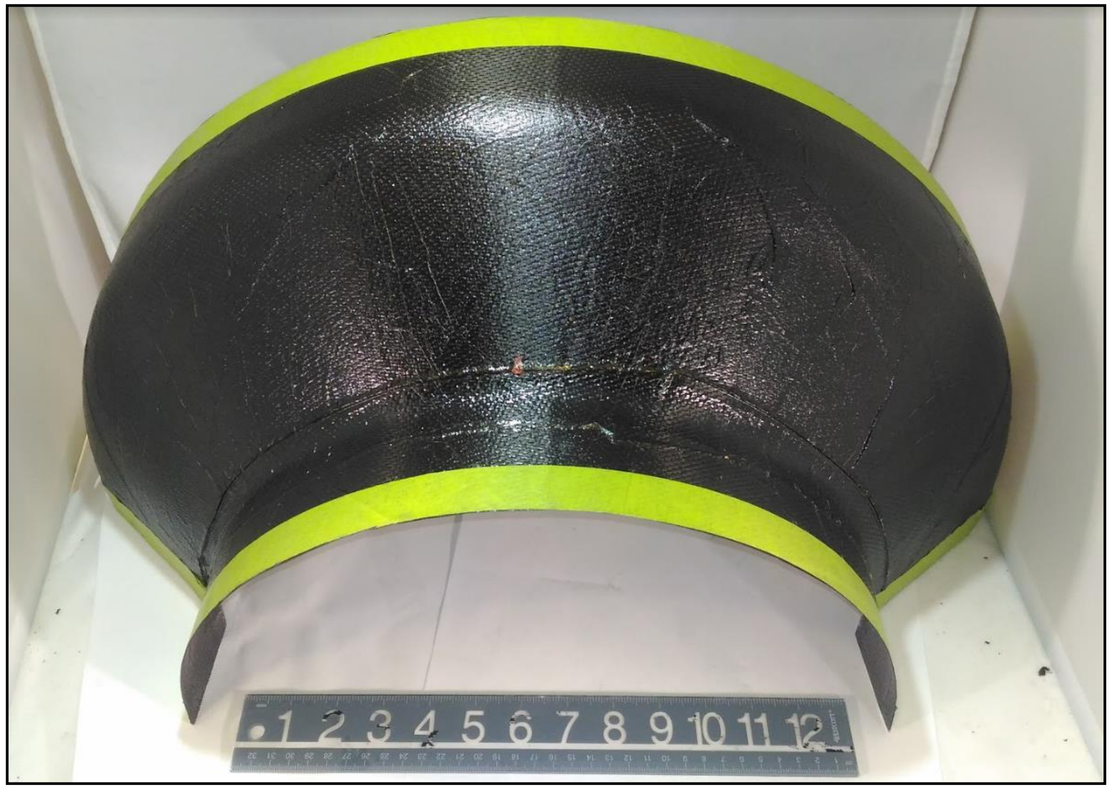
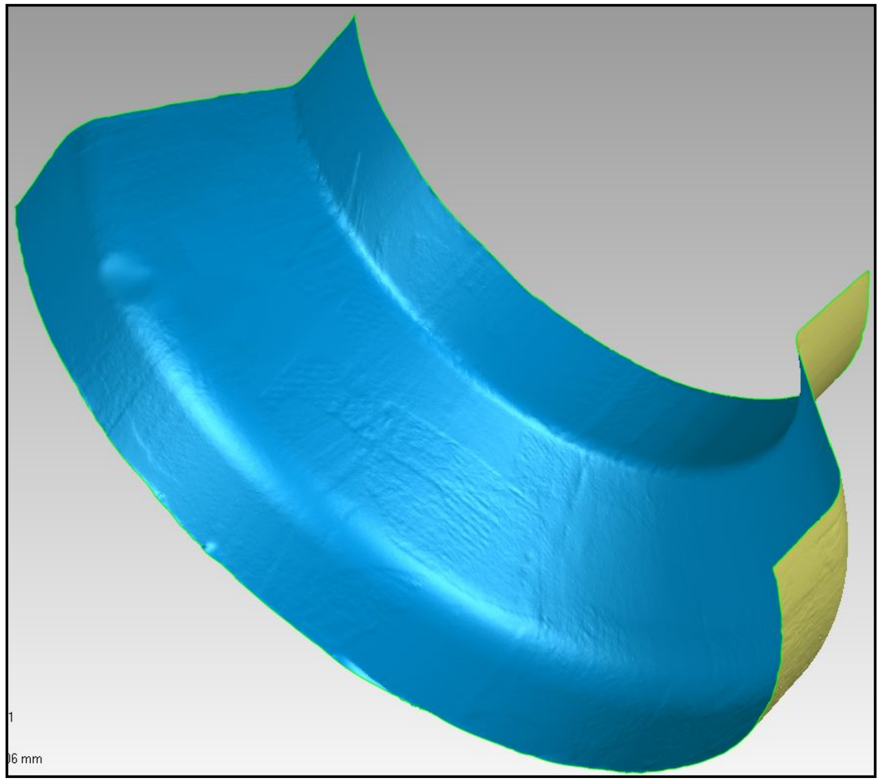
Fabricating the Service Cylinder Mark I

Layup bagged for the oven



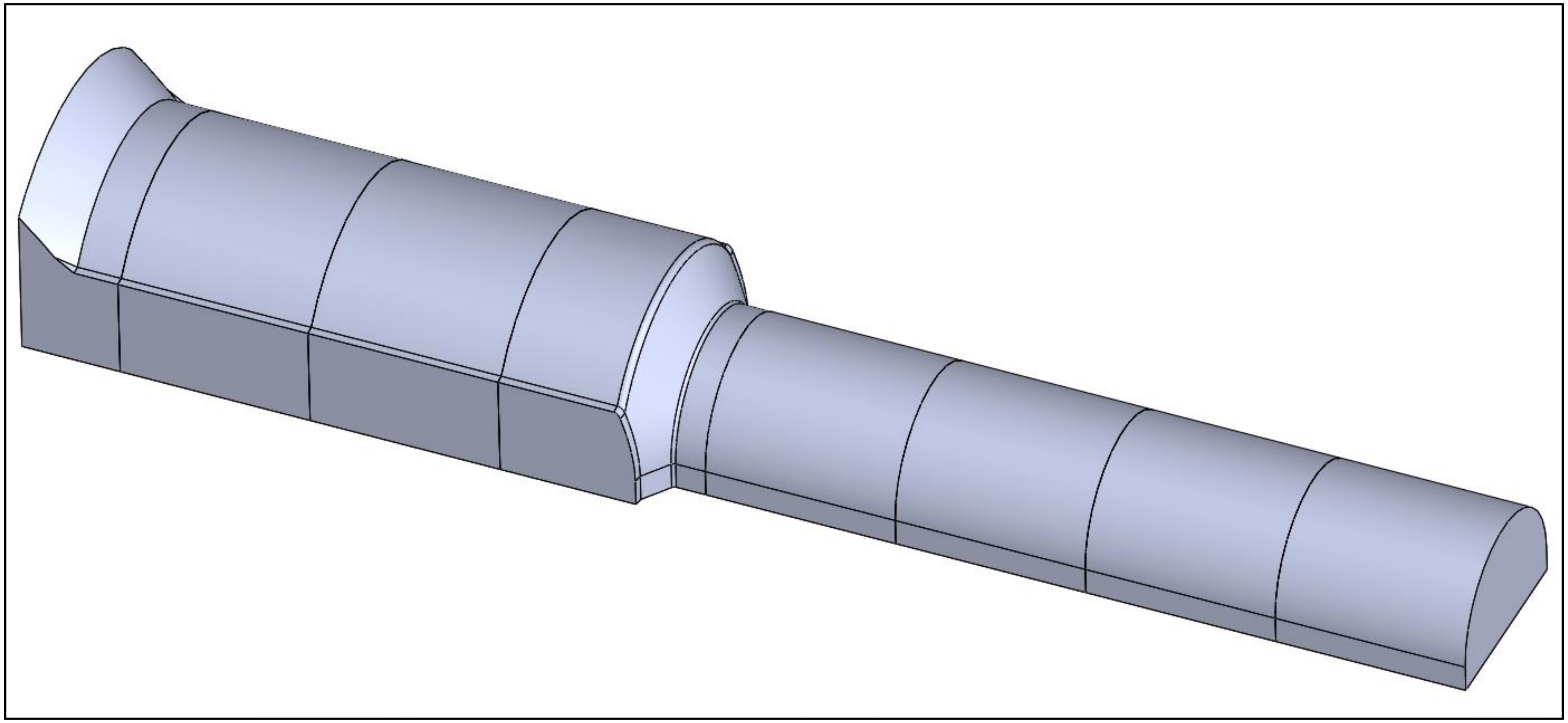
Service Cylinder Mark I

- Satin weave carbon fiber proved easier to layup. Created a 2 ply
- **Service Cylinder Mark I came out nicely.** Fairly firm
- Studying it with the laser arm for deviations and deformations
- Mark II will have 4 plys.



Laser scan coordinates

Fabricating the TFPX-TEPX Service Cylinder



Service Cylinder Mark II — Mold design in 8 parts

- The mold for Mark II will be created in 8 parts and glued together
- All parts will be printed and machined at CMSC, Purdue
- The part will be made of 4 ply satin weave (~ 1 mm in thickness)
- Mold design will account for weight deflections of the Dees and services in addition to post-cure deformations of the carbon fiber
- Mark II will be used for mock "insertion test" into the Support Tube. Will be designed with wheels and rails in mind

Expected completion: end of summer 2018

Conclusions

Summary

- Close collaboration between **Purdue and Cornell** for material choices and design of the TFPX Dees based on simulation and experiment
- **Thermal transport measurement apparatuses** built at Purdue will be used to guide material choices
- Close collaboration between Purdue, Cornell and UC Davis for prototype Service Cylinder structure, Support Tube, rails and **preliminary insertion tests**
- Purdue has strong carbon fiber expertise at **CMSC**
- **First prototypes of the Service Cylinder** are being built

END

BACKUP

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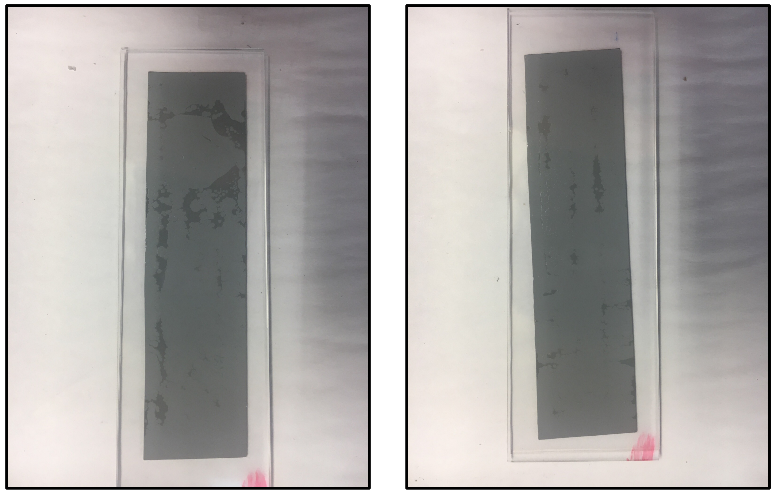
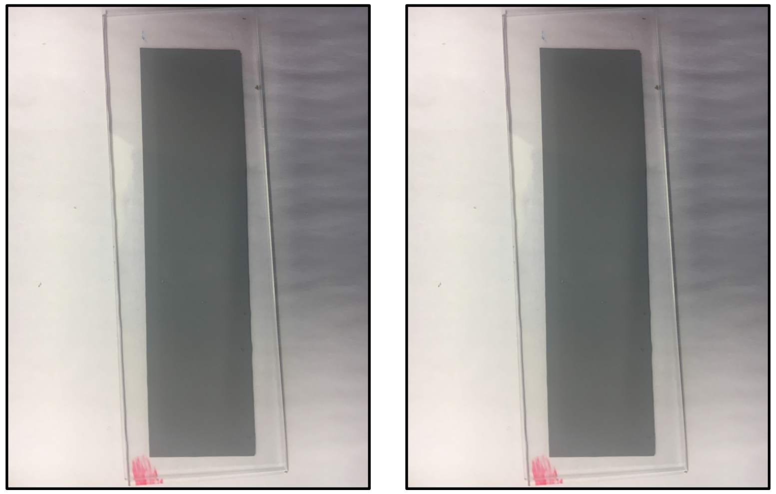
Mounting ROC with Laird Film

1. Clean surfaces with acetone and Kimwipes
    1. Wet wipe (for smudges and oil)
    2. Dry wipe (for dust and drying)
2. Take Laird Film and peel plastic backing on one side
3. Place exposed film on surface and apply heat gun at 200°F (~93°C)
4. Roll laird film with roller.
5. Peel off final layer of plastic film and set in oven at 60-75 °C
6. Wait 30 minutes
7. Remove sample and place clean glass slide delicately
    1. Apply light pressure lengthwise
    2. Place back in oven with ~73g weight on top
    3. Turn on vacuum pump
8. Wait 20 minutes
9. Remove sample and press lightly over whole surface.



Silicon Detector Side



Cooling Side