The Design of Stable, Low-mass Support and Cooling Structures for a CMS Tracker Upgrade

On behalf of the CMS Track-Trigger Group
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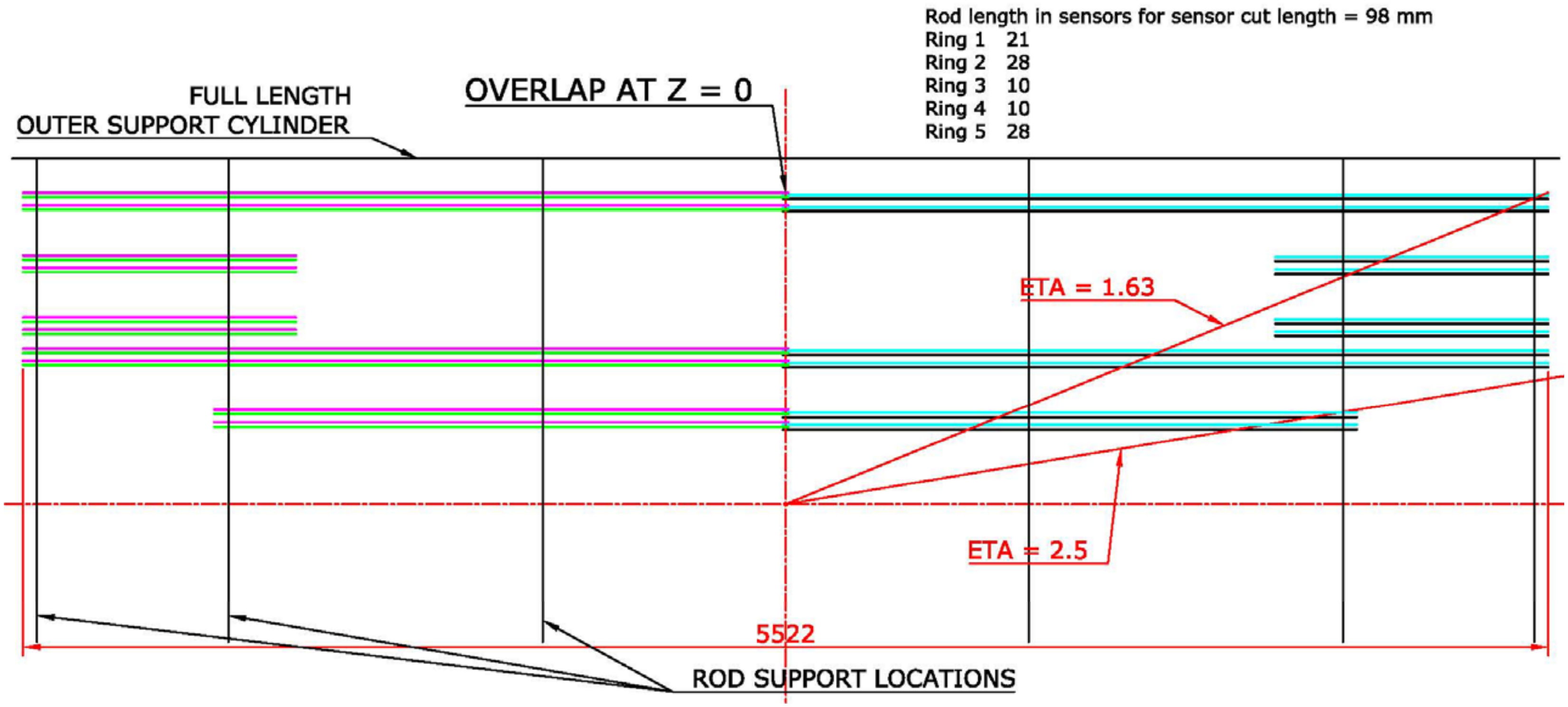
Overall Layout

- Several arrangements of barrels and disks are under consideration.
- One arrangement with barrels only is shown below.
  - It sets an upper limit on the length needed for barrel module support structures.
  - Half-length (~ 2.8 m) rod structures which overlap at Z = 0 reduce deflections and should simplify fabrication and handling.

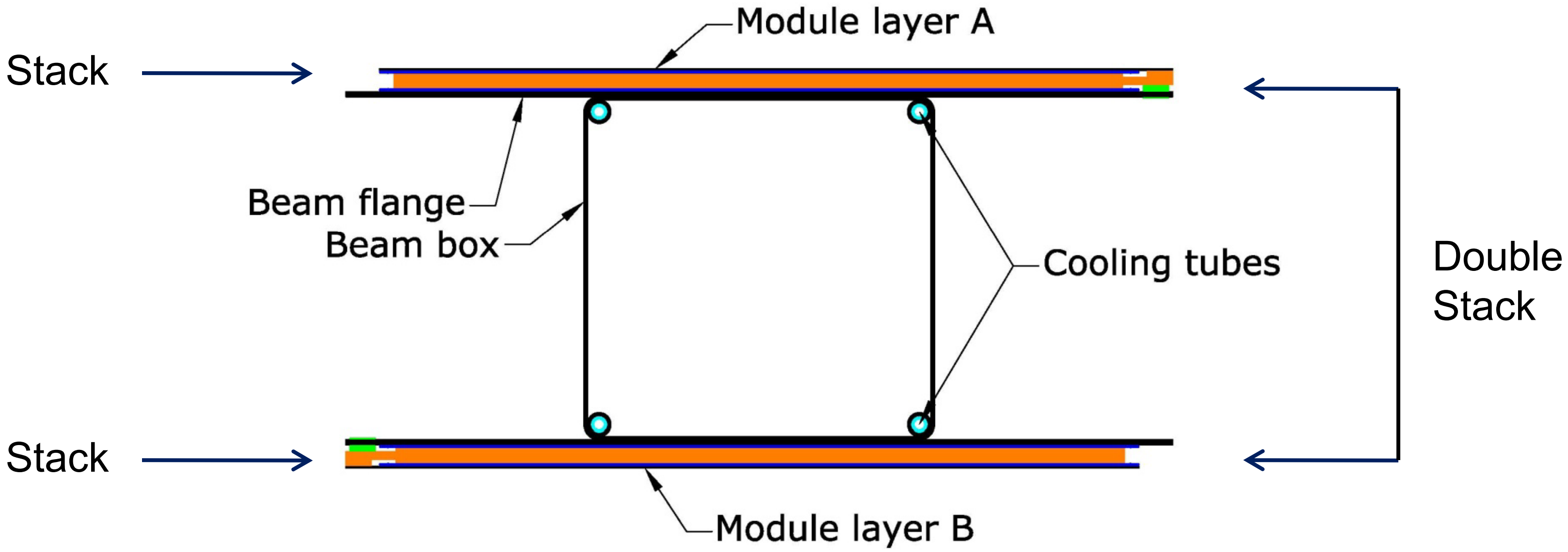


Rod length in sensors for sensor cut length = 98 mm

Ring 1	21
Ring 2	28
Ring 3	10
Ring 4	10
Ring 5	28

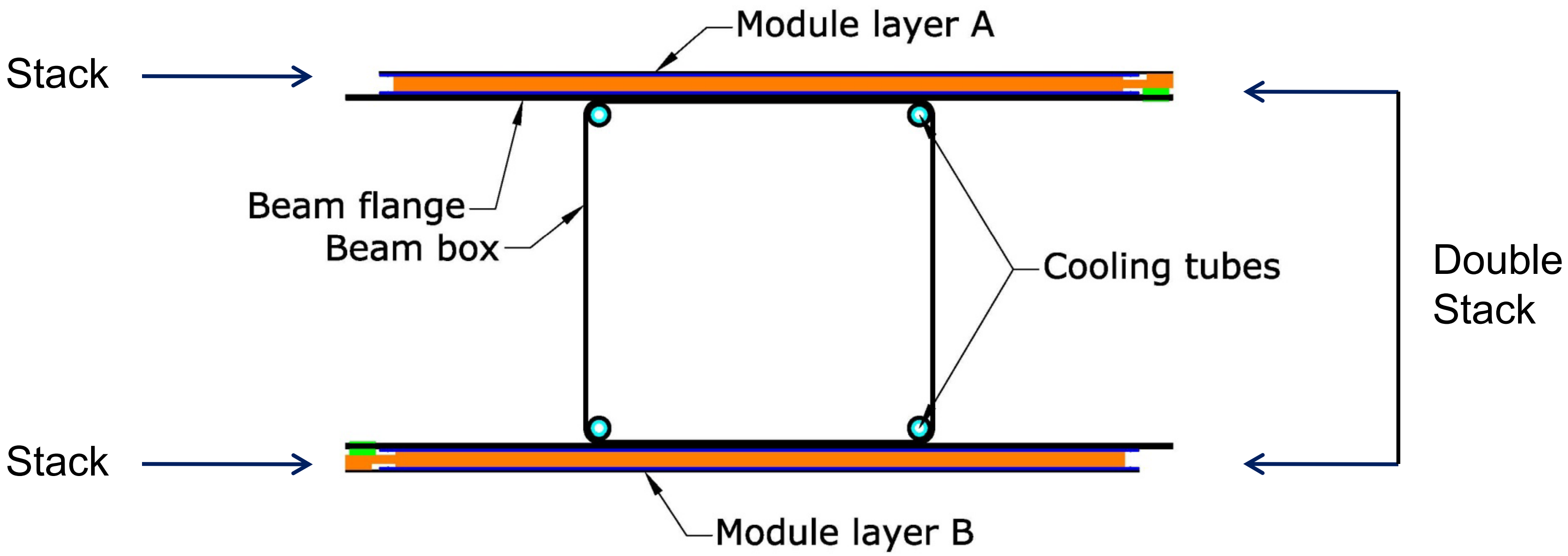
Rod Layout

- Within barrels, modules of a layer are proposed to be supported by beam structures called rods.
- To allow local trigger formation, each module would include two sensor layers separated radially by 0.5 – 2.0 mm to form a “stack”.
- A rod would position stacks at locations separated radially by 40 – 60 mm to form “double-stacks”.



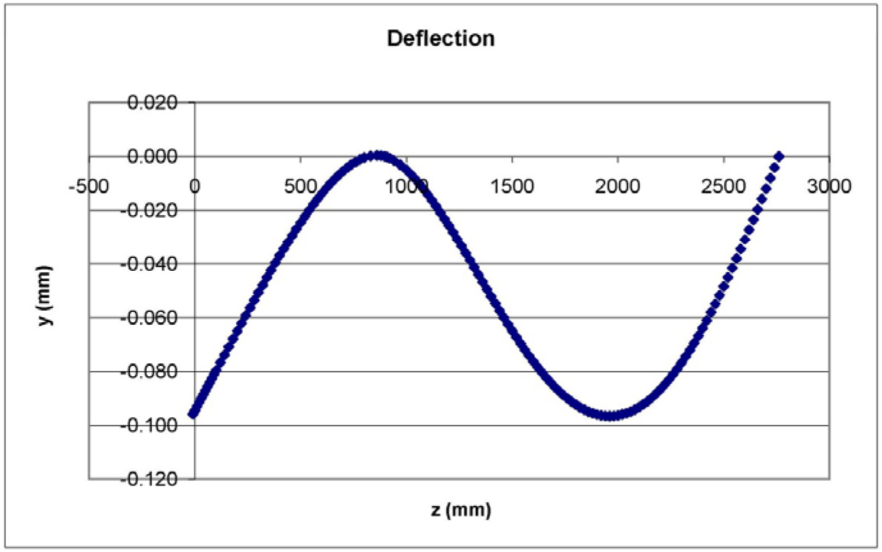
Mechanical Motivation for Using Rods

- Using rods to support modules is similar to what was done with the existing CMS detector.
- In principle, the strengths and weaknesses of this approach are known.
- For a double-stack geometry, rods are even more attractive because the increased height of the core structure reduces deflections.
- In principle, rod dimensions can be chosen so that the stiffness of a rod is independent of its azimuthal orientation.



Rod Deflection

- An analytic calculation was made of deflection under gravity for rods based upon laminate made from Mitsubishi K13C2U carbon fiber.
  - Simple support was assumed with no contributions to stiffness from the modules.
  - The weights of support structures, major modules components, and cooling were included.
  - Support points were adjusted in increments of 1 mm to minimize deflection.
- Maximum deflection was a little less than 100 μm.
- Full length rods were also investigated, but deflections were too great.
- For weight distributed uniformly in Z, deflection scales linearly with rod weight and as the fourth power of rod length.



Rod Deflection

- Items included in deflection calculation:

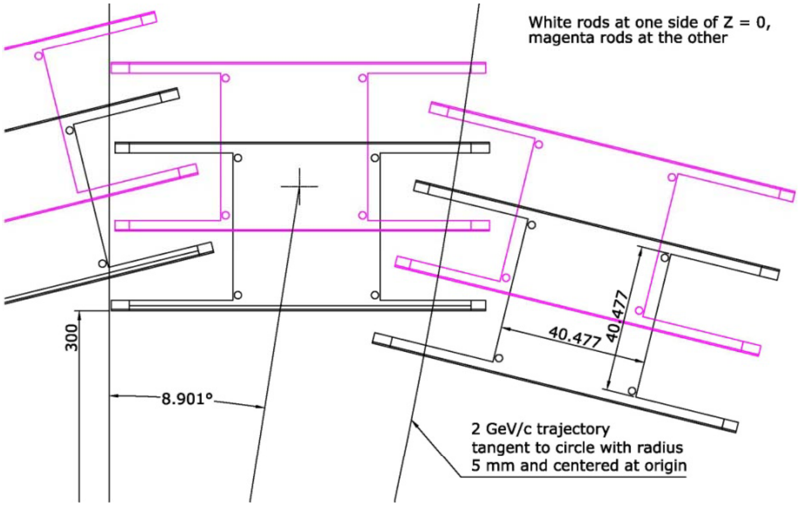
Item	Weight (g)
Sensors + interposers	1918
Cooling	123
Support structures	1305
Total	3346

- Weights for readout, DC-DC converters, cables, optical fibers, etc. were not yet known.

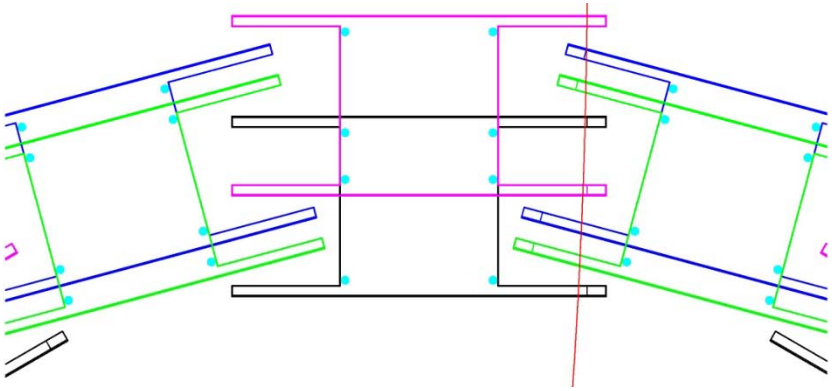
Rod Azimuthal Arrangement

- The height of rods, providing overlap in phi, overlap at Z = 0, and a desire to have a common rod geometry in all layers, and the need to have sufficient clearance to rod support structures severely constrain rod geometry.
- Both pinwheel and staggered geometries were considered.
- The R-Phi arrangement is intended to be hermitic for PT > 2 GeV/c.
- A staggered geometry was provisionally chosen.

Spiral geometry



Staggered geometry

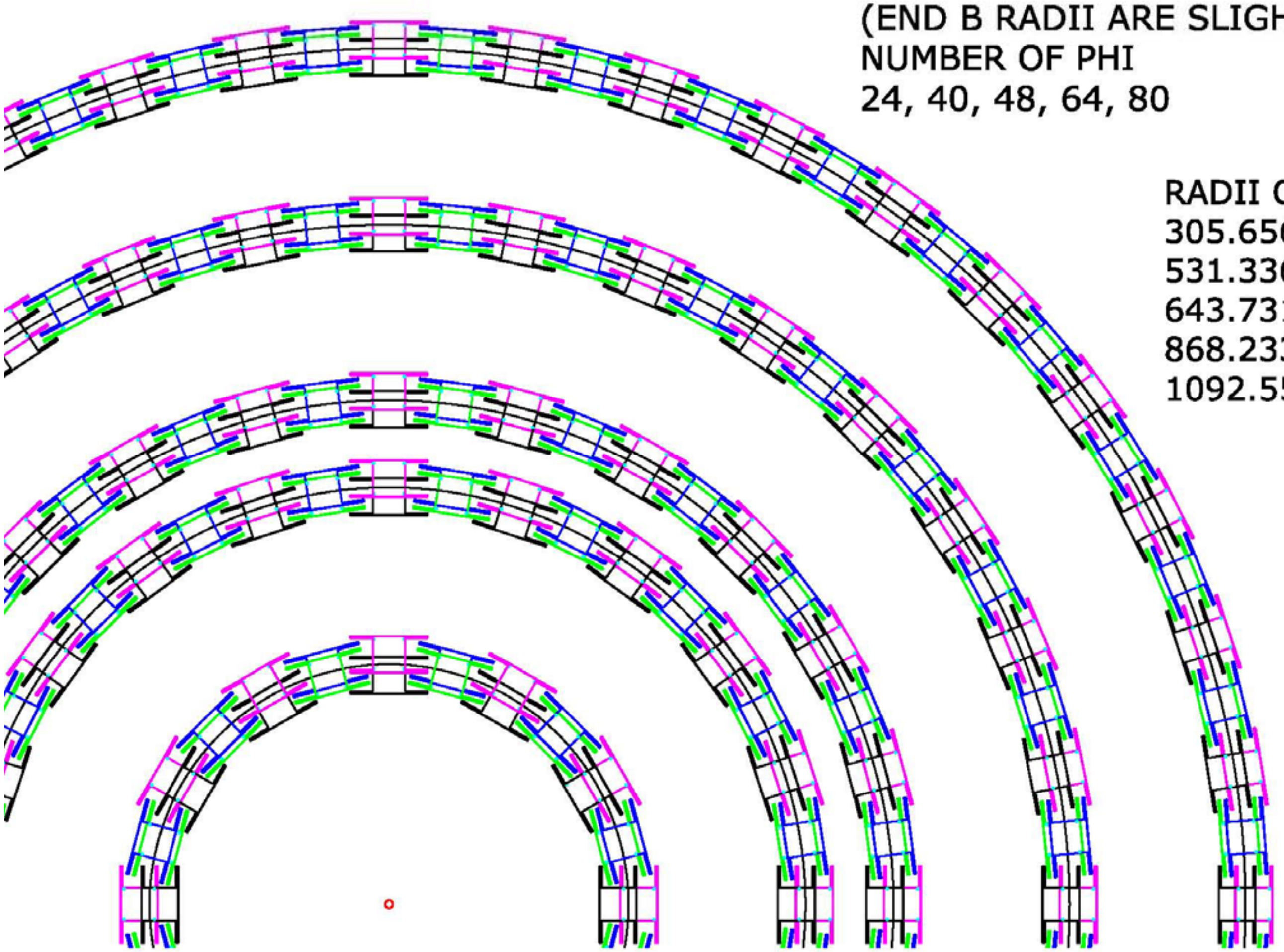


Rod Azimuthal Arrangement

- A pinwheel geometry allows partial compensation of Lorentz drift.
  - Compensation varies with the radius of a layer and over the phi extent of a sensor.
  - Acceptance cut-off at low P_T is different for positive and negative tracks.
- A staggered geometry gives nearly identical acceptance for tracks of either sign.
- Either geometry can probably be made to work, though I didn’t find a pinwheel geometry that worked well in the Z = 0 overlap region.

Rod Azimuthal Arrangement

- Radial locations and azimuthal arrangement

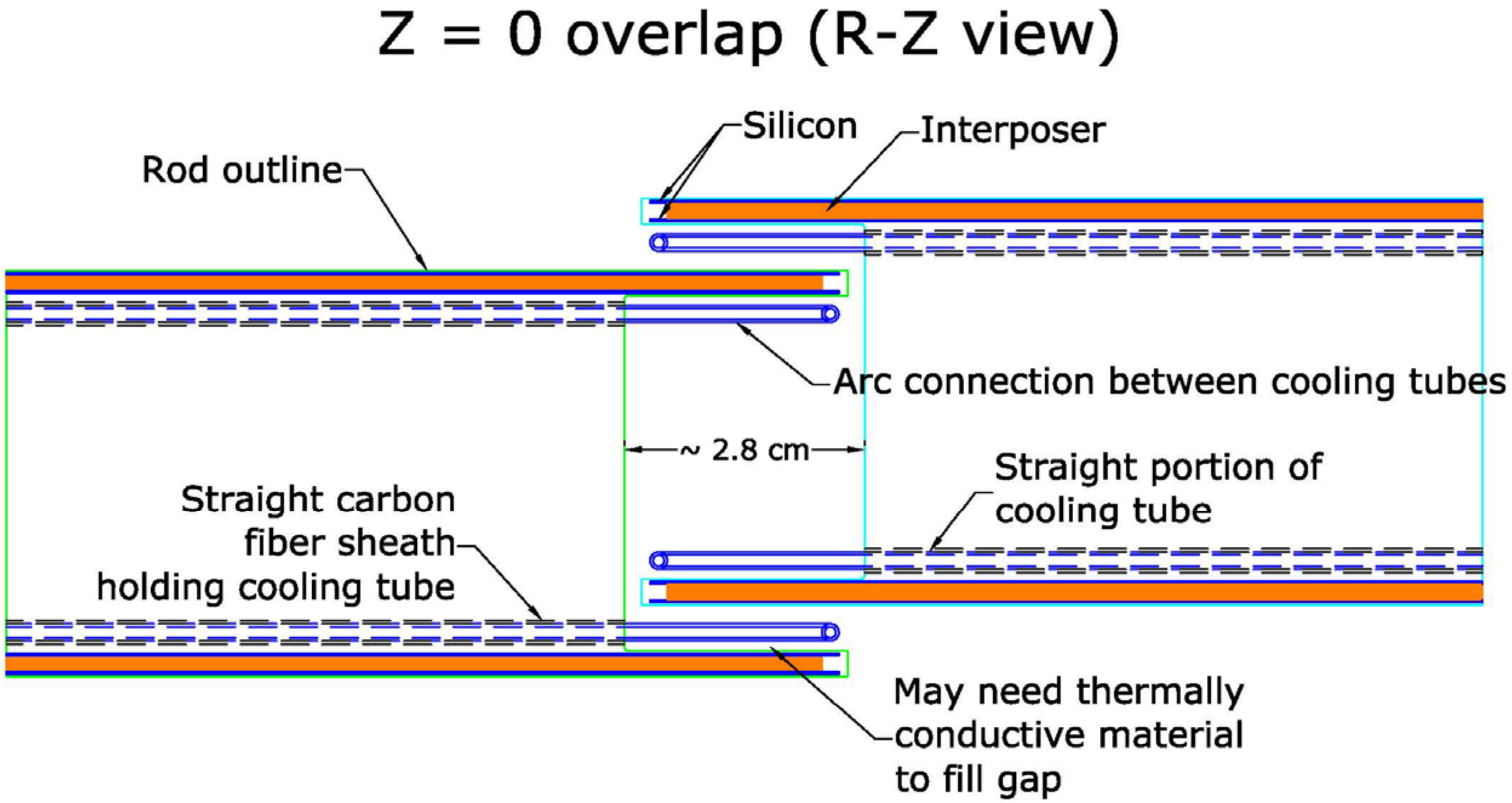


END A
(END B RADII ARE SLIGHTLY DIFFERENT)
NUMBER OF PHI
24, 40, 48, 64, 80

RADII OF CIRCLES
305.656
531.336
643.731
868.233
1092.557

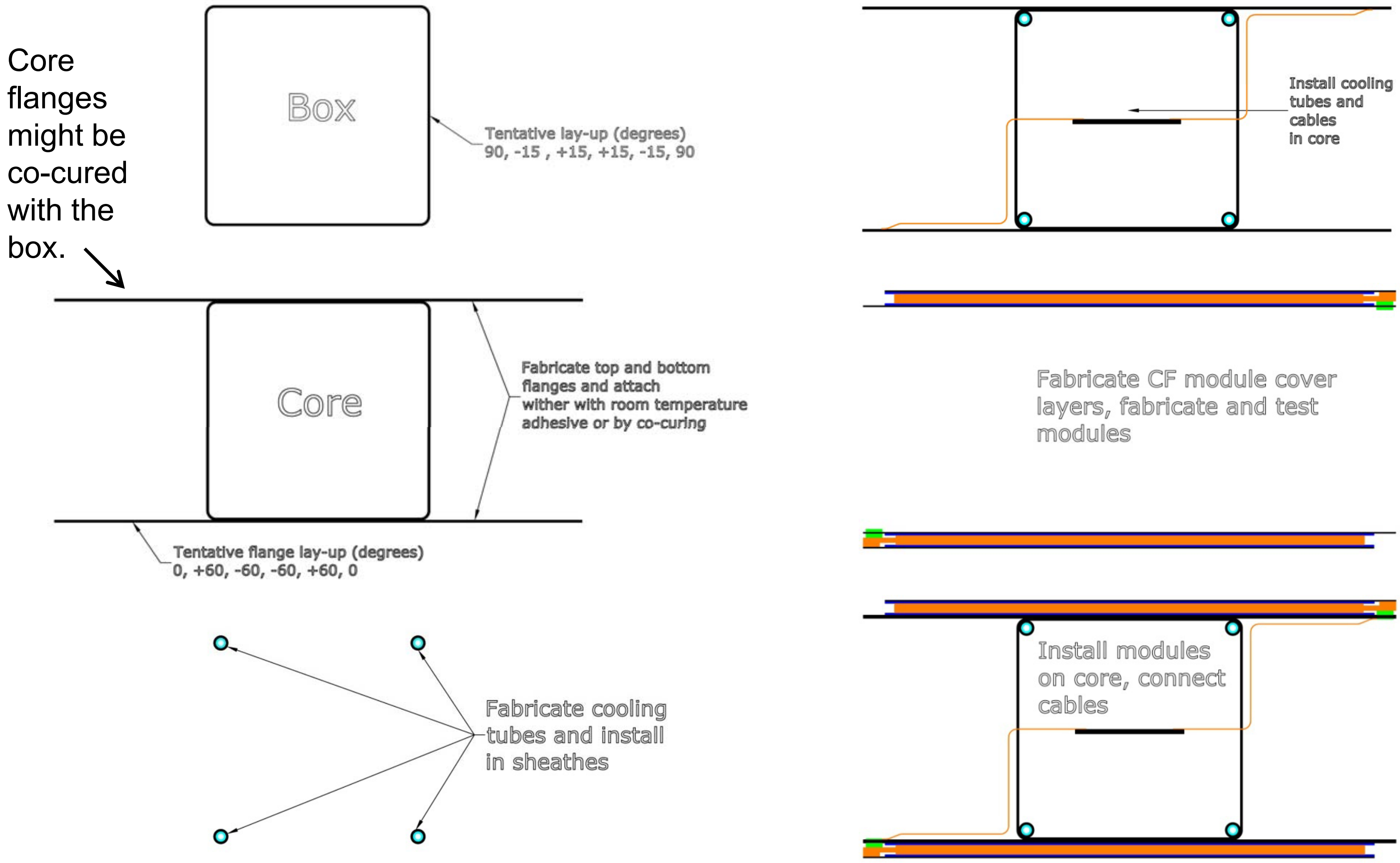
Arrangement at Z = 0

- Overlap ensures trigger information can be available at both ends of the tracker for tracks originating within the interaction diamond.
- Cooling tubes are enclosed in sheaths to allow the tubes to slide and accommodate longitudinal differential contraction.



Rod Mechanical Fabrication Sequence

- Each piece needs to be prototyped and tested.
- The assembly needs to be prototyped and tested at each stage.



Core flanges might be co-cured with the box.

Tentative lay-up (degrees)
90, -15 , +15, +15, -15, 90

Fabricate top and bottom flanges and attach wither with room temperature adhesive or by co-curing

Tentative flange lay-up (degrees)
0, +60, -60, -60, +60, 0

Fabricate cooling tubes and install in sheathes

Install cooling tubes and cables in core

Fabricate CF module cover layers, fabricate and test modules

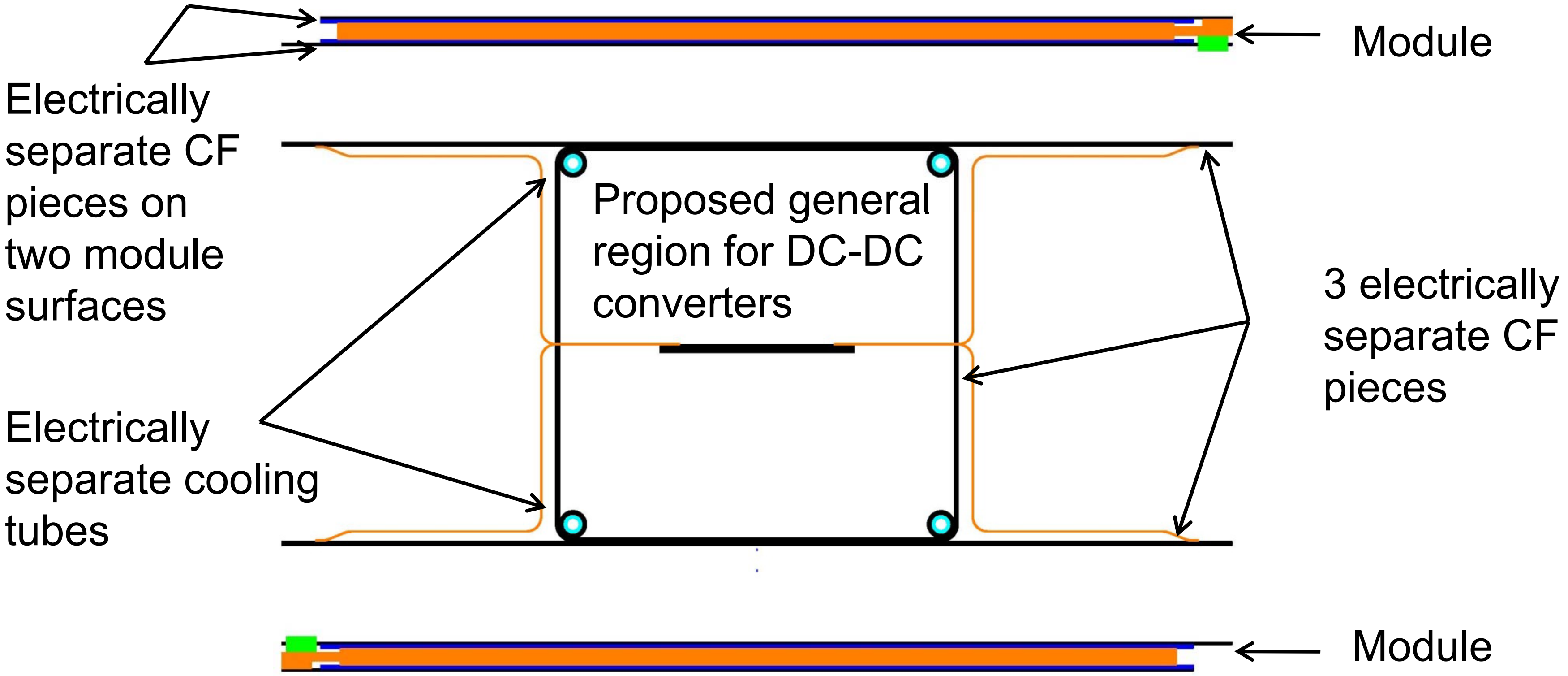
Install modules on core, connect cables

Carbon Fiber Lay-ups

- The major support structures assume laminates of Mitsubishi K13C2U fiber.
- The number of plies and ply angles were proposed to minimize mass and distortions while maintaining acceptable deflections.
  - They are given on the previous slide.
- Most of the structures have a six ply symmetric lay-up.
  - The box includes plies at $\pm 15^o$ to give good longitudinal stiffness.
  - The 90^o plies help with thermal conductivity to the cooling tubes and help with box integrity.
  - The symmetric lay-up reduces twisting during curing and use.
  - The quasi-isotropic lay-up of flanges minimizes thermal distortions.
  - For the modules, we propose a quasi-isotropic, 6 ply lay-up with three plies on each surface of the sensor-interposer-sensor structure.
  - That will need to be tested.
  - Electrical insulation, grounding, and connections will need to be understood.

Electrical Connectivity

- In the absence of specific measures, CF laminate pieces may not be well-connected electrically.
- Conducting CF pieces couple signals capacitively into structures, which can contribute significantly to noise.
- We need to understand which pieces should be electrically connected and how good the connections will be.



Module

Electrically separate CF pieces on two module surfaces

Proposed general region for DC-DC converters

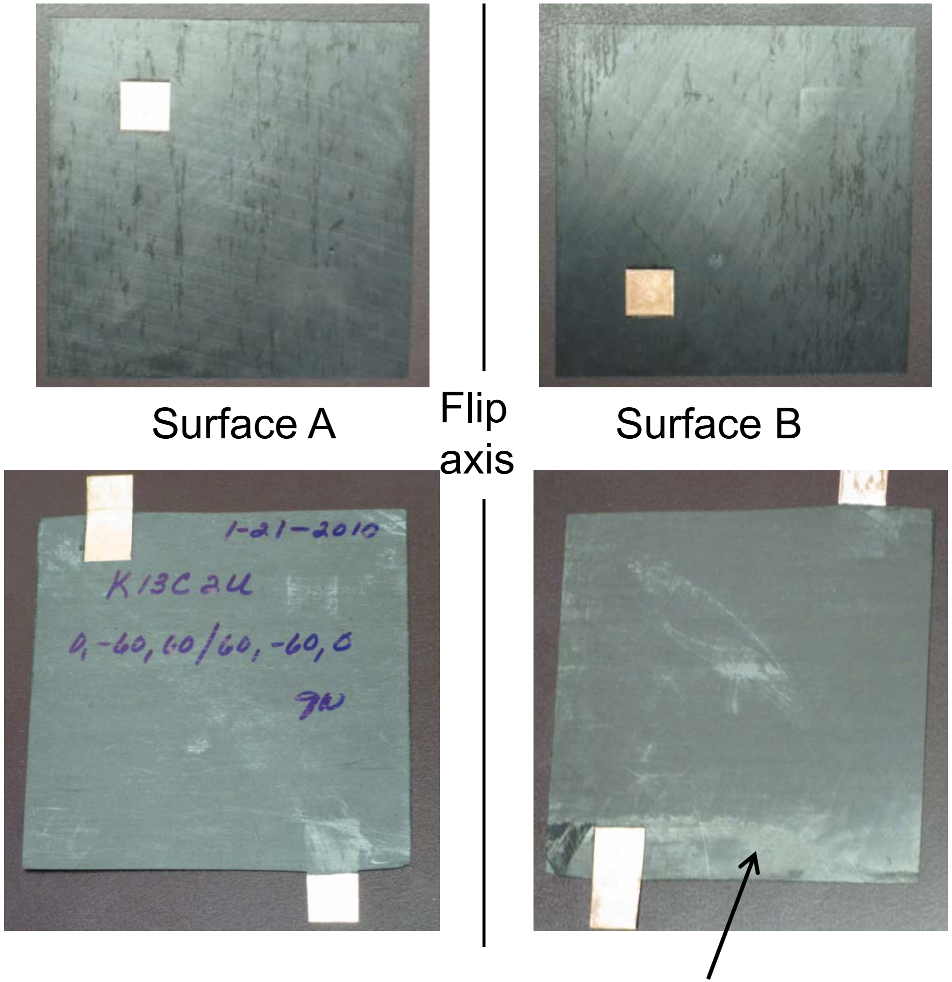
3 electrically separate CF pieces

Electrically separate cooling tubes

Module

Carbon Fiber Laminate

- Initial resistance measurements were made between copper contacts co-cured into two samples of K13C2U laminate.
- Both samples were 101.6 mm x 101.6 mm x 0.33-0.35 mm and had 6 plies.
- Both samples were intended to have a quasi-isotropic lay-up (possibly not achieved in the top sample).
- Cure pressure = 80 psig
- Contacts were 12.7 mm x 12.7 mm x 0.127 mm.
- Both were measured by Mike Matulik and Marvin Johnson.
- In a DC measurement, the top sample gave ~ 40 milli-Ω.
- The bottom sample gave ~ 80 milli-Ω.



Stuck to curing plate

Carbon Fiber Laminate

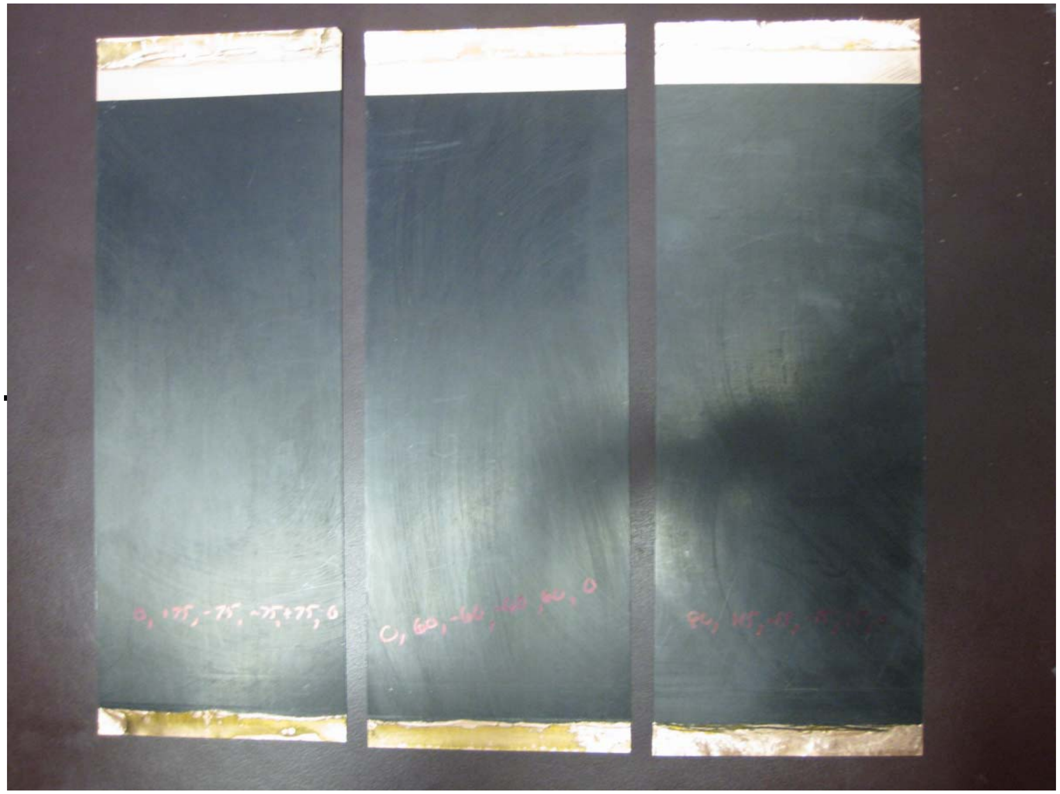
- Three additional 6-ply K13C2U samples ~ 4” x 9” x 0.0133” were prepared with lay-ups consistent with proposed structures:
- Cure pressure was reduced to 40 psig to limit the extent 0.0014” thick copper contacts imbedded into laminate.
- Geometry was chosen to simplify the determination of resistance per square.

Carbon Fiber Laminate

- The center sample has a quasi-isotropic lay-up (applies to flanges and modules).
- The outer two samples test resistance in longitudinal and transverse directions of the box portion of a rod.
- DC results (milli-Ω): 71, 77, 41
- Based on laminate theory, the ratios of resistances should be 72.4, 73.8, 44.1 (reasonable agreement).

Ply angles (degrees) with respect to long. direction

0, 75, -75, -75, 75, 0 **0, 60, -60, -60, 60, 0** **90, 15, -15, -15, 15, 90**

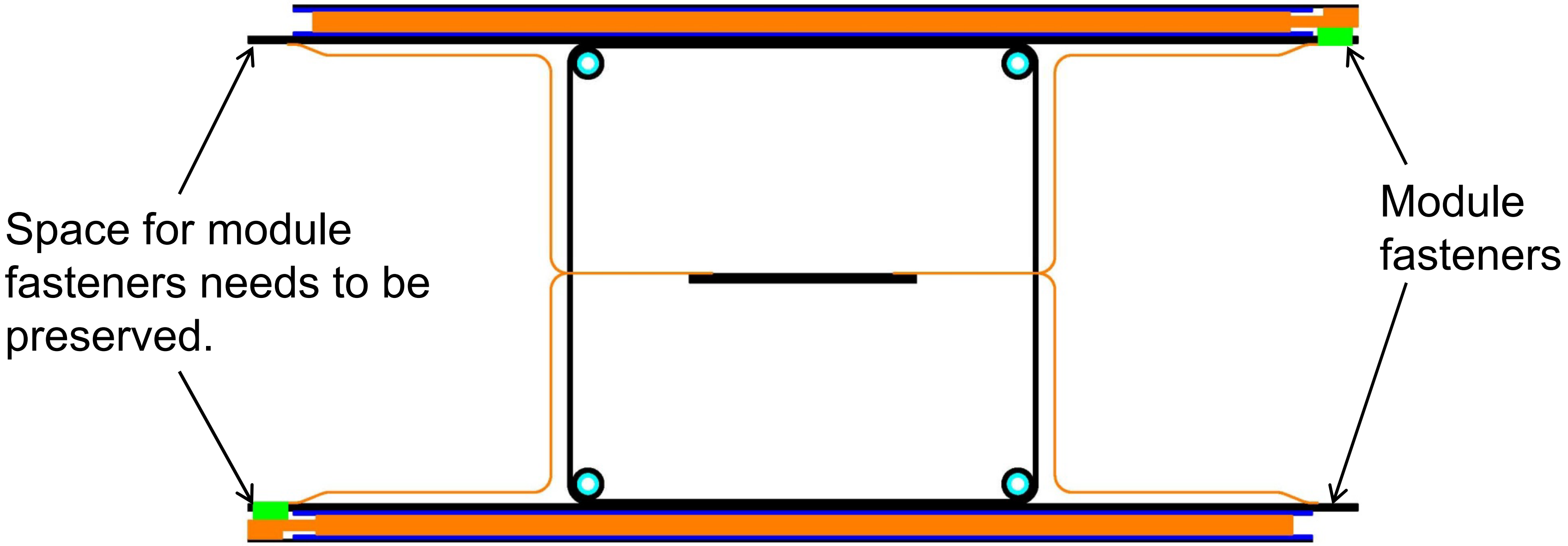


Carbon Fiber Laminate

- Based upon a fit between measured and expected values, end-to-end resistance of a 2.8 m long rod box should be roughly 0.34 Ω.
  - For the box, L/P = 17.7, input R/square = 0.0194 Ω.
- Including the conductance of core flanges would reduce the end to end resistance to roughly 0.20 Ω.
  - For two flanges, L/W = 14.3, input R/square = 0.0321 Ω.
- Both end-to-end values are quite low compared with folklore values.
  - Similar structures have often been said (even by us at one time) to have an end-to-end resistance ~ 10 Ω.
  - Our guess is that the higher values were the result of poor contact to the carbon fiber.
- Initial measurements of the impedance of samples versus frequency have also been made as a start of an investigation of high frequency effects.
  - Not yet ready to report

Module Installation and Grounding

- Clear regions will be needed at edges to hold modules in place.
- Provisions for grounding will be needed.
  - Carbon fiber laminate may provide good high and low frequency shielding and connectivity.
  - Given the results of measurements of carbon fiber samples, the carbon fiber may be fine by itself provided contacts to it are good.
  - In the past, we've used co-cured copper mesh on kapton to enhance conductivity and allow good connections.



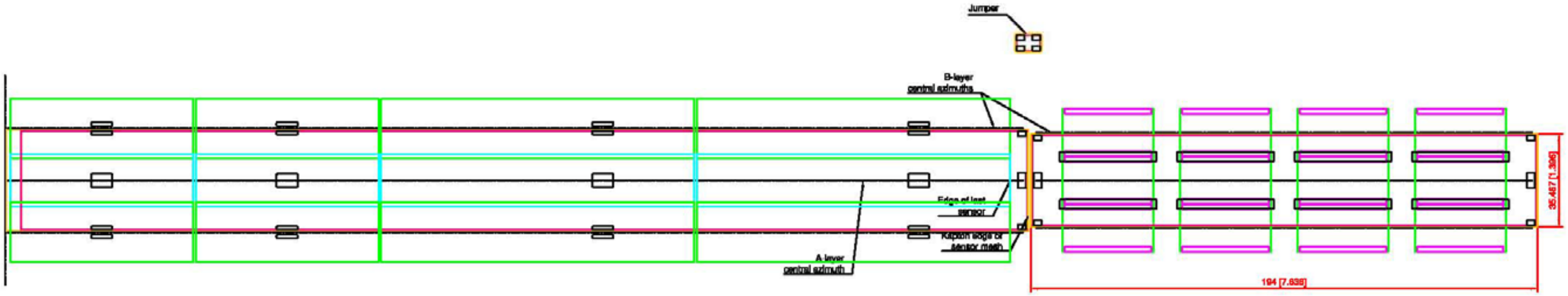
Space for module fasteners needs to be preserved.

Module fasteners

Methods for Making Electrical Connections

- Resin forms an insulating layer on the surface of carbon fiber laminate.
- On D0 L0, we used copper mesh on kapton for shielding and ground connections with excellent results.
  - Co-cured with the carbon fiber support cylinder
  - 5 μm copper, ~30% copper fill factor, 25 μm thick polyimide

- Analogue flex-cables connected sensors to hybrids.
- In the sensor and hybrid regions, copper mesh on kapton circuits covered roughly 180^o of the support cylinder circumference.
- Sensor and hybrid mesh circuits were connected with three jumpers.
- Two of the three jumpers also connected the two mesh circuits of a region.
- Vias made contacts accessible. Via pads were gold plated.



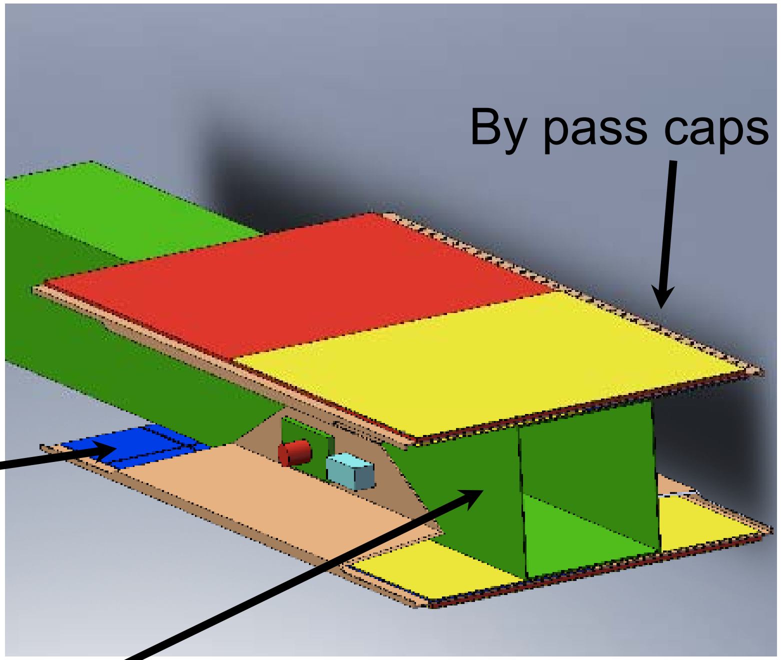
Sensor region

Hybrid region

From Marvin Johnson's October 2009 CMS Talk

- Don't need full bandwidth over entire rod
  - Rate drops by half at half distance from IP in inner layer
- Design optic chip with 4 inputs
  - use one chip to read 4 half sensors in outer part of inner layer
  - one chip per 8 half sensors in outer layers
    - Connector through carbon f rod
  - Minimizes mass

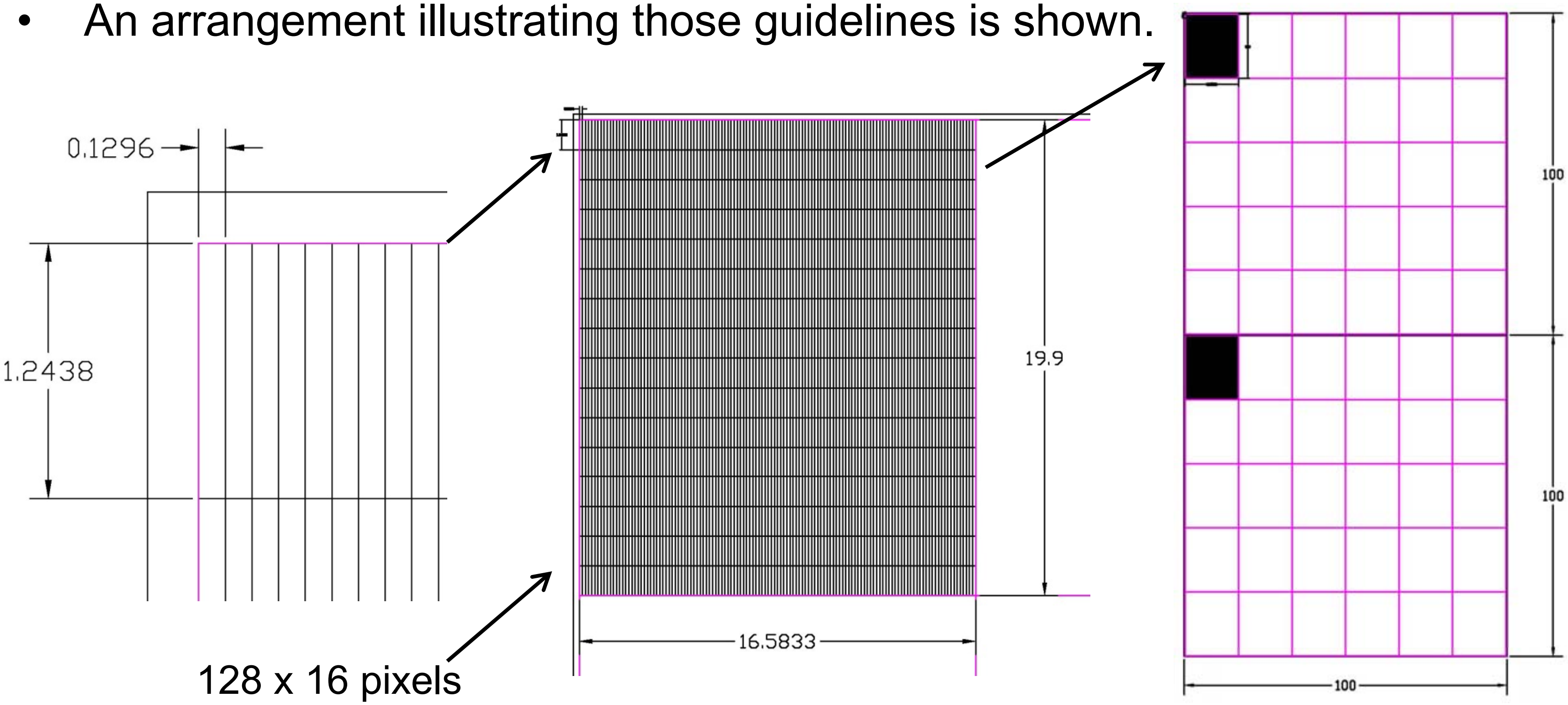
Green is carbon fiber support
Yellow is sensor
Red is interposer
Blue is read out chip



Tan is Kapton buss
Green-red is DC-DC
Cyan is fiber driver

Sensors

- Sensor dimensions are proposed to be roughly 100 mm x 100 mm x 0.25 mm.
- Two sensor – interposer sets per module
- It’s too early to say what the arrangement of reticles of a sensor would be.
- Pixels are proposed to be roughly 0.1 mm x (1 or 2) mm.
- An arrangement illustrating those guidelines is shown.



128 x 16 pixels

Note that 8 reticles over the sensor width would give a trace pitch of about 97 µm.

Cooling

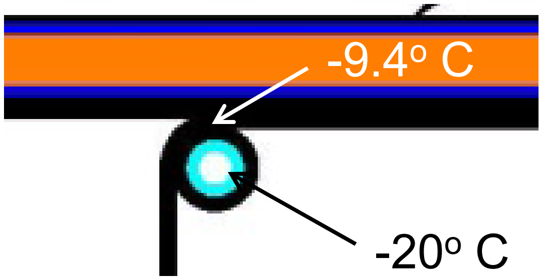
- Evaporative CO2 cooling is planned.
- An early proposal was that cooling tubes would be stainless steel tubing with 1.5 mm ID and 0.25 mm wall.
- Uniformity and ease of fabrication may set the wall diameter.
  - MAWP for that size tubing (SA-213 TP303L) is ~ 295 Atm., well above the roughly 80 Atm. needed in a CO2 system.
  - For aluminum tubing (SB-241 6061-T6) of the same dimensions, MAWP ~ 263 Atm.
- More recent proposals have been to use aluminum for cooling tubes.
  - Aluminum has the advantage that the number of radiation lengths represented by a tube (ignoring coolant) would be reduced from 0.026 X0 to 0.0092 X0.
  - Aluminum has at least two disadvantages: tubes are more difficult to form and corrosion may be induced in aluminum in contact with carbon fiber.
- Methods to make reliable end connections to tubing would need to be developed for either choice.
- Results from CERN tests last fall suggested that flow regimes were difficult to control in tubing with ID in the range 1.3 – 1.5 mm.
- For that reason, we have tentatively increased tube ID to 1.8 mm.
  - Testing will be needed.

Cooling

- An initial cooling estimate is based on 3.4 W per module half-length and 80% DC-DC conversion efficiency.
- Then power into one cooling tube is 3.4 W / 2 / 0.8 / 100 mm = .02125 W/mm.
- Assume the cooling tube ID = 1.8 mm and power is evenly distributed in Z.
- Then heat flux into a tube is 5.3 x 10^{-3} W/mm^2.
- Over a tube length of 5600 mm, power is 119 W.
- For a heat of vaporization = 293 j/g, flow must exceed 0.41 g/s.
- To ensure that a tube is wetted over more than 50% of its surface, assume that actual flow is 1.0 g/s which corresponds to flow rate / area = 0.393 $g/s/mm^2$.
- Measurements have been conducted on a 1.4 mm ID tube of length 5.5 m with a heat input of 144 W.
  - Reported by Hans Postema at a CMS workshop last May.
- Based upon those measurements and our flow conditions and heat input, we expect a temperature change < 2.7° C over the length of a cooling tube with an average cooling tube temperature of -20° C. That should be OK.

Module Temperature

- Conduction from the cooling tube inner wall to the start of the core flange contributes a temperature increase of ~ 10.6^{o} C due to:
  - A relatively small cooling tube diameter
  - Imperfect contact between the outer wall of the tube and sheath (air gap)
  - Epoxy in the conduction path.



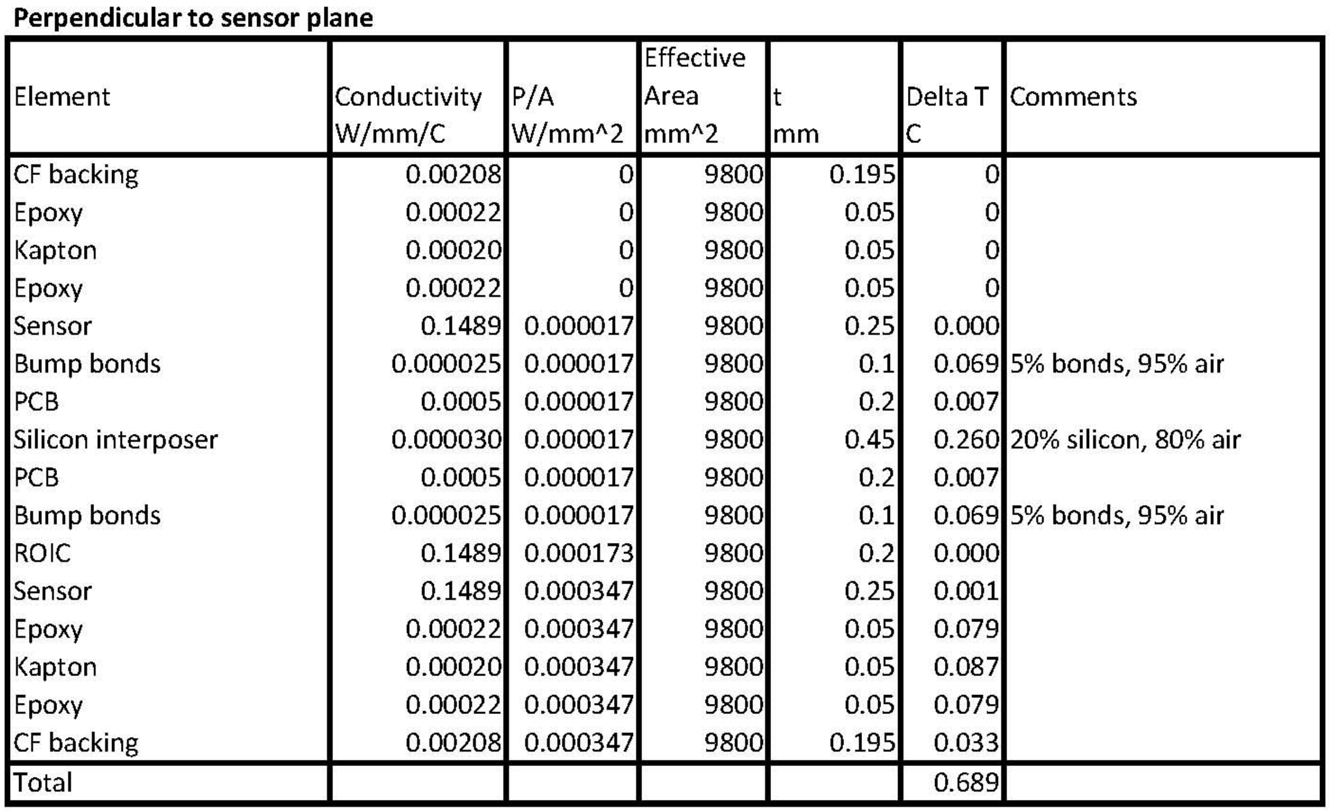
Power at one tube per 100 mm length	2.125 W
Portion of that from sensors & RO	1.7 W
Portion transmitted through interposer	0.17 W
P/A at cooling tube inner wall	0.007516 W/mm^2

Heat flow near the cooling tube

Location	Conductivity W/mm/C	P/A W/mm^2	R mm	L mm	Delta T C	T Deg C	Comments
Inner cooling tube wall		0.00752	0.9			-20	Assumes that inner tube wall is at average coolant temperature
Outer cooling tube wall	0.163000	0.00588	1.15	0.250	0.010	-19.99	Assumes SS cooling tube (worst case)
Air gap outer wall	0.000024	0.00587	1.1525	0.013	3.109	-16.88	Assumes 0..0127 mm air gap
Outer sheath wall	0.002080	0.00502	1.3475	0.390	1.021	-15.86	Assumes 3 ply sheath (might be reduced to 2 plies) and pessimistic estimate of conductance
Epoxy outer surface	0.000220	0.01902	1.4225	0.05	4.323	-11.54	Assumes 0.05 mm epoxy over 1/4 of circumference
Box mid-thickness	0.002080	0.01673	1.6175	0.195	1.568	-9.97	Assumes 1/4 circumference, 6 ply box, and pessimistic estimate of conductance
Start of flange	0.102770	0.04359	1.6175	1.270	0.539	-9.43	Assumes P2, (0, +15, -15, -15, +15, 0) box lay-up, and conductance over 1/8 circumference
Total					10.570		

Sensor Temperature

- Consider conduction normal to the sensor plane and parallel to the sensor plane separately.
- ΔT through the module thickness is small (0.69^o C) with ROIC's placed so that their power does not pass through the interposer.



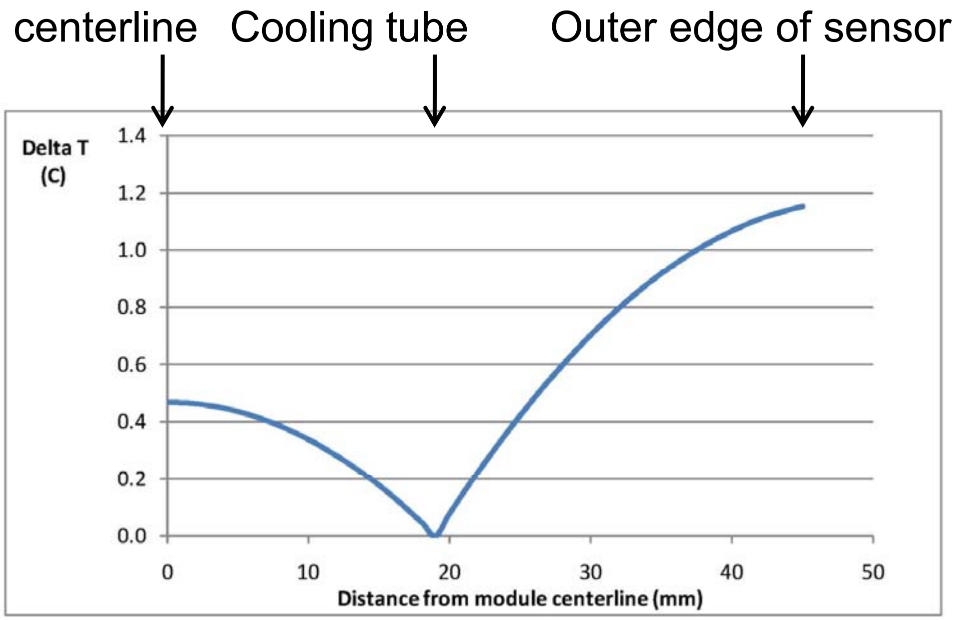
Perpendicular to sensor plane

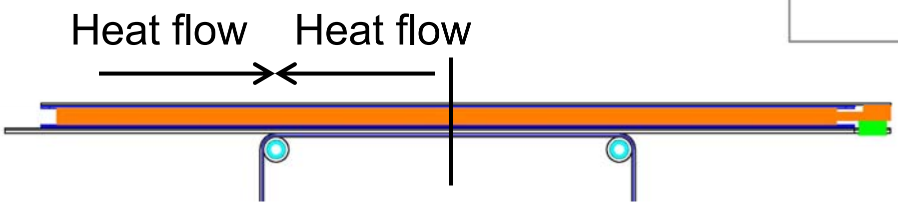
Element	Conductivity W/mm/C	P/A W/mm^2	Effective Area mm^2	t mm	Delta T C	Comments
CF backing	0.00208	0	9800	0.195	0	
Epoxy	0.00022	0	9800	0.05	0	
Kapton	0.00020	0	9800	0.05	0	
Epoxy	0.00022	0	9800	0.05	0	
Sensor	0.1489	0.000017	9800	0.25	0.000	
Bump bonds	0.000025	0.000017	9800	0.1	0.069	5% bonds, 95% air
PCB	0.0005	0.000017	9800	0.2	0.007	
Silicon interposer	0.000030	0.000017	9800	0.45	0.260	20% silicon, 80% air
PCB	0.0005	0.000017	9800	0.2	0.007	
Bump bonds	0.000025	0.000017	9800	0.1	0.069	5% bonds, 95% air
ROIC	0.1489	0.000173	9800	0.2	0.000	
Sensor	0.1489	0.000347	9800	0.25	0.001	
Epoxy	0.00022	0.000347	9800	0.05	0.079	
Kapton	0.00020	0.000347	9800	0.05	0.087	
Epoxy	0.00022	0.000347	9800	0.05	0.079	
CF backing	0.00208	0.000347	9800	0.195	0.033	
Total					0.689	

Temperature drop through the bump bonds and the effects of removing a portion of the interposer silicon need to be checked.

Transverse Temperature Distribution

- Due to the relatively low ΔT normal to the sensor, essentially all module elements contribute to in-plane conduction.
- Effective thermal conductivity (~ 0.058 W/mm/C) is dominated by the two carbon fiber stiffeners, the two sensors, and the interposer.
  - Contributions to conductance from the core flange have been ignored.
- Max transverse ΔT ~ 1.15° C





Comments on Temperatures

- Conduction both normal to and parallel to the sensor plane contributes to the sensor temperature distribution..
- For a reasonable module design, conduction in the vicinity of the cooling tubes dominates sensor temperatures.
- Finite element analysis can be used to develop a proper 3D (really 2D) picture of conduction.
  - However, knowledge of power spatial distributions, bump bond geometry, and interposer geometry are critical.
  - Without that knowledge, either a hand estimate or FEA can give incorrect answers.
- Temperatures rise quickly and become less uniform if:
  - Significant power must flow through the bump bonds
  - Heat sources are concentrated transversely
  - Interposer material is removed in a non-uniform way.

Plans

- Continue with DC resistance and AC impedance measurements of carbon fiber laminate samples.
- Expand those to include measurements of thermal conductivity.
- Fabricate prototype rod structures.
- Measure their AC, DC, and thermal properties.
- Begin finite element analyses of module heat flow.
- When a CO2 cooling system is available, measure heat transfer to cooling tubes.
- When prototype modules are available, populate and test rod structures.
- Meanwhile, update module and support structure drawings and continue to assist with the overall design.

- Thank you!