Low Mass Materials and Vertex Detector Systems

Bill Cooper (Fermilab)

Goals

- To limit material so that pointing resolution and measurements of momenta are dominated by the inherent resolution of sensors
- To provide a structure and materials for that structure which ensure that distortions due to gravity, temperature, and humidity are negligible or can be tracked and corrected
- To provide a stiff enough structure to minimize the effects of vibration and to address anticipated external forces and moments
- To provide coolants and thermal paths from heat sources to coolants which will ensure that the temperature of sensors, their readout, and their services will be acceptable.

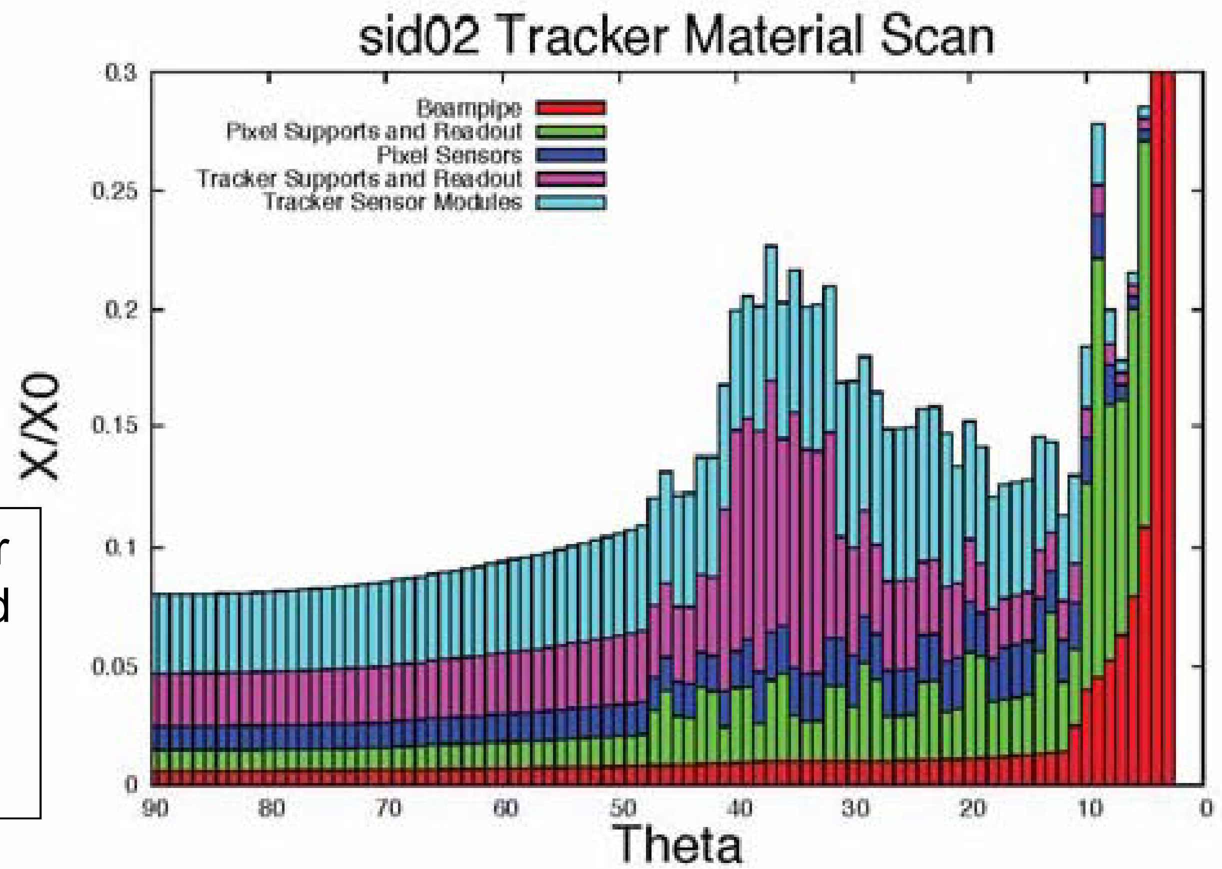
Vertex Detector Radiation Length Goals

- The tightest goals for the vertex detector come from the ILC and CLIC.
- The ILC radiation length goal at normal incidence started at 0.1% X0 per layer plus contributions from the beam tube and cabling.
  - SiD: 0.5% X0 for 5 layers + beam tube + cabling
  - ILD: 0.6% X0 for 6 layers + beam tube + cabling
- Cabling, supports, and services were soon understood to contribute more than had been hoped.
- I'll show the SiD concept for the ILC, since I know it best.
  - There may still be changes, but we think that all material has been taken into account.

Vertex Detector Radiation Length Goals

- Vertex detector and tracker material are shown below for the detailed baseline design of the SiD concept for the ILC (2012).
  - Vertex detector sensors are in dark blue.
  - Vertex detector supports and cables are in green.
  - The beampipe is in red.

Total of the 3 = 2.4% X0 at 90°, or 0.5% X0 per layer (well above the original goal).



The outer support cylinder for the vertex detector and cables and services on it are included in vertex detector material.

Traditional Materials

- Carbon compounds
  - Carbon fiber
    - Unidirectional prepreg with epoxy or cyanate ester resin
  - Carbon-carbon
  - Graphite
  - Thermal pyrolytic graphite (TPG)
- Foams
  - Silicon carbide foam
  - Carbon foams
  - Plastic foams
- Metals
  - Beryllium and its alloys
    - Substrates
    - Beam pipes
  - Titanium and its alloys
    - Cooling tubes
    - Beam pipes
  - Aluminum and its alloys
    - Cooling tubes
    - Substrates
    - Beam pipes
  - Stainless steels
- Ceramics

In a particular application, how do we decide what materials to use?

Beam Equations Allow Calculation of Deflections

- Strength of materials and connections between them must always be checked, but for many low-mass structures, deflection is a governing design concern.
  - Such structures are described as deflection, rather than stress, limited.
- At a given location along the length of a beam, 1/R = M/E/I, where
  - M = applied moment
  - R = radius of curvature,
  - E = elastic modulus
  - and I = moment of inertia about the "neutral axis".

All are evaluated at the z of interest.

We want to minimize M and maximize E & I.

- For z along the beam length and y perpendicular to the length,
  - $d^2y/dz^2 = 1/R = M/E/I$
- y(z) can be determined by evaluating M and I, knowing E, integrating twice, and keeping track of the constants of integration.
- M depends on applied loads (including gravity), support locations, and the method of support.
- I depends on the transverse shape of the beam.

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Example: Simply Supported Beam

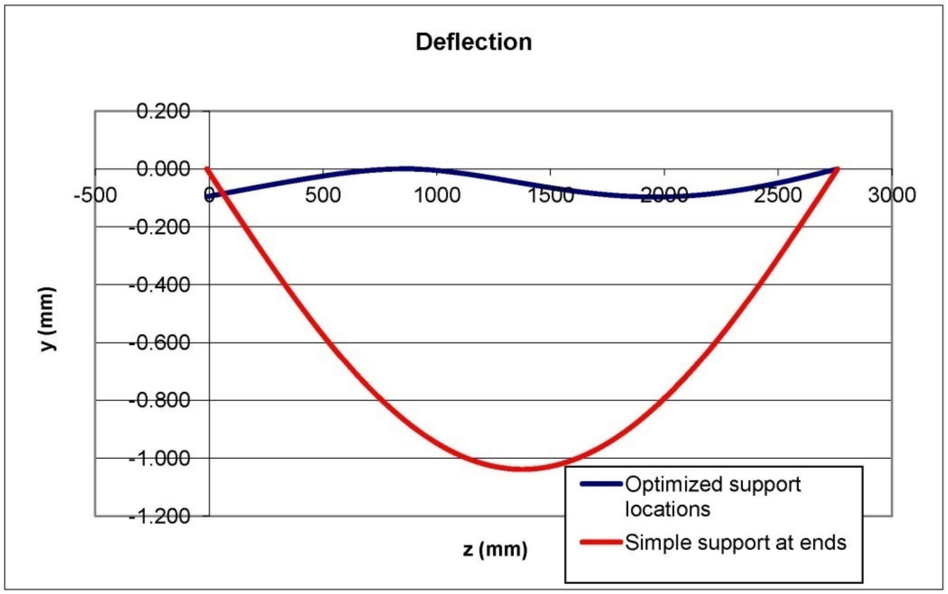
- Simple support means that, at the support location, position is controlled, but slope is free to change.
- For a beam of length L, weight W, constant density and cross-sectional shape, and simple support at its two ends:
- Maximum deflection due to gravity
  - $y_{max} = 5/384*W*L^3/E/I = 5/384*\lambda*L^4/E/I$
  - where $\lambda = W/L$.

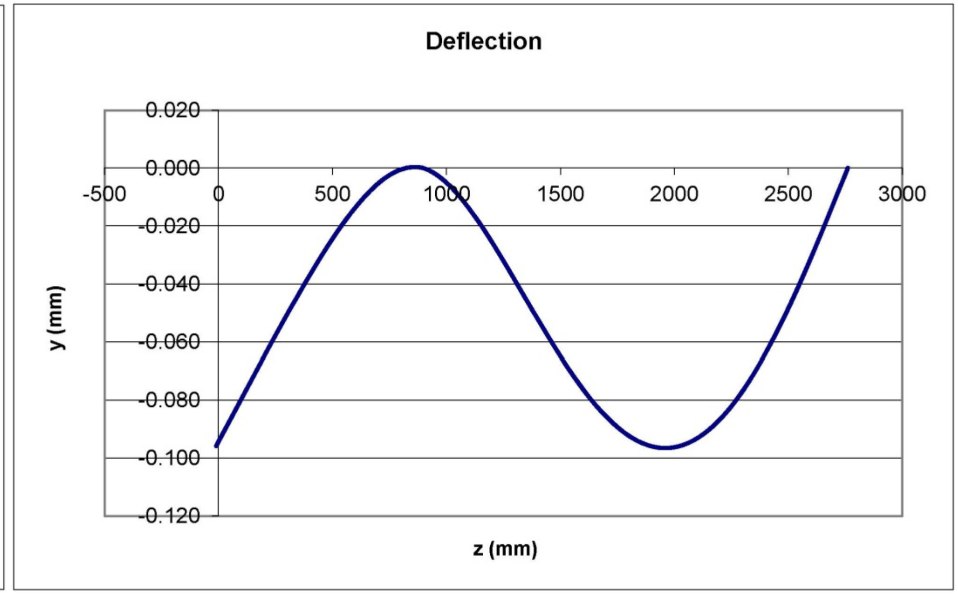
Generally applicable when F/L = constant ="λ".

- The variation of y_{max} with L^4 is the main reason deflections are difficult to control as structures become long.
- Tools at our disposal to limit deflections include:
  - Selecting materials with large elastic modulus (E)
  - For gravitational deflections, selecting materials with small density (ρ)
  - Choosing cross-sectional geometries with large moment of inertia (I)
  - Optimizing the number of supports and their locations
  - Evaluating the possibility of angular constraint at each support.
- The last three tools are at least as important as the first two in the effective use of materials.

Example: Support Locations

- Simple support at ends compared with simple support at one end and at an optimized, intermediate location:
  - No changes in materials
  - More than a factor of 10 reduction in gravitational deflection!





Thermal and Environmental Stability

- Coefficients of thermal and moisture expansion of materials in structures must be sufficiently well matched.
- Silicon properties set the scale.
  - CTE = 2.5 to 2.6 ppm/^{o}C near room temperature
  - CME is negligible
- Otherwise, stresses can become unacceptably large and unbalanced sandwich structures can bow or potato-chip.
- Most metals have a CTE (9 to 25 ppm/^{o}C) noticeably larger than that of silicon; plastics (including adhesives) have much larger CTE's (20 to 60 ppm/^{o}C); and carbon fiber laminate has a noticeably lower CTE (-0.8 ppm/^{o}C).
- Issues with plastics are tempered by a relatively low elastic modulus, but must be addressed.
- In principle, carbon (or carbon fiber laminate) can be combined with other materials to achieve a CTE sufficiently close to that of silicon.
  - Not so easy in practice

Representative Properties of a few Materials

Material	ρ g/cm^3	X0 cm	X0 g/cm^2	k W/m-K	T_U MPa	E GPa	E/ρ GPa/(g/cm^3)	E*X0 GPa*cm	CTE ppm/deg C	Poisson's ratio
G-10	1.7	19.41	33	0.288	517	18.6	10.9	361	9.9	0.12
304 SS	8.03	1.71	13.7	16.3	505	200	24.9	341	17.3	0.29
Ti	4.54	3.56	16.16	21.9	434	116	25.6	413	11.4	0.32
Titanium Ti-6Al-4V	4.43	3.69	16.344	7.3	1000	113.8	25.7	420	8.6	0.342
Al 6061-T6	2.7	8.90	24.01	152	310	68.9	25.5	613	23.6	0.33
Al 1100-H14	2.71	8.90	24.01	220	124	68.9	25.4	613	23.6	0.33
MetGraf 4-230 alum.-carbon	2.4	11.56	27.75	225	103	98.6	41.1	1140	4	
(100) Si wafer, (110) direction	2.329	9.37	21.82	149	120	169	72.6	1583	2.6	0.22
(100) Si wafer, (100) direction	2.329	9.37	21.82	149	120	130	55.8	1218	2.6	0.22
Carbon-carbon	1.7	25.12	42.7	40	18.5	95	55.9	2386	3	
AlN	3.25	7.55	24.53	140	197	330	101.5	2491	4.5	0.24
AlN	3.25	7.55	24.53	140	270	330	101.5	2491	4.5	0.24
SiC	3.21	8.00	25.68	150	250	450	140.2	3600	2.77	0.21
K13C2U quasi-isotropic laminate	1.71	30.70	52.5	95.3		137	80.0	4200	-0.8	0.335
Beryllium	1.848	35.28	65.19	151	345-517	303	164.0	10689	11.4	0.037
Boron fiber	2.37	22.23	52.69	27.4		478	201.7	10627	6	
K13C2U fiber	2.2	19.41	42.7	620	3800	900	409.1	17468	-1.1	0.39
Kapton 100 HN	1.42	28.58	40.58	0.12	231	2.5	1.8	71	20	0.34
PEEK 450g (unfilled)	1.23	10.42	12.812	0.24	100	3.7	3.0	39	50	0.4
ERG Duocel SiC 8% foam	0.257	100	25.68	5.28	2.76	2.76	10.7	276	2.2	0.22
ERG Duocel 3% carbon foam	0.051	837.3	42.7	0.033	0.17	0.102	2.0	85	2.2	
ERG Duocel 3% carbon foam	0.051	837.3	42.7	0.05	0.34	0.102	2.0	85	2.2	

Actual values can differ substantially from "representative" values.

Representative Properties

- Please notice that E/ρ and E*X0 provide figures of merit.
  - Deflection of a support structure itself under gravity (no sensors, cables, etc.) scales inversely as E/ρ. (The higher E/ρ the better).
  - E*X0 adds physics impact of the material. (The higher the better).
- The first six rows of the preceding table represent materials often used in structures which are stress, rather than deflection, limited.
  - Often used as a matter of convenience, but maybe not the best materials for low-mass support
- The next eight rows have higher figures of merit.
  - These, or similar materials, are reasonable to link sensor structures to their outside support or to augment the stiffness of sensor structures.
  - Please note that silicon is in this batch.
    - Sensors must be present in any case, contribute to structural stiffness, have good thermal conductivity, provide natural support for many heat sources (readout chips), and provide a natural substrate for local power distribution.
    - Incorporating additional features into sensors must be balanced against the possibility of lower yields during sensor production.
  - Carbon fiber is often used due to its versatility.

Representative Properties

- The next three rows have noticeably better figures of merit.
  - Beryllium seems an obvious choice.
    - However, It is toxic, expensive, brittle, difficult to machine, the number of suppliers is limited, and its CTE doesn't match silicon very well.
    - It may be the best material for some applications and is normally used in the most critical regions of beam pipes.
  - Except for CTE, unidirectional properties of raw fibers look great.
    - The difficulty is in combining fibers into three dimensional objects while maintaining their good properties.
    - For example, when carbon fibers are combined with resins to build 3-D objects, net properties are degraded by the resins.
- The next two rows represent materials for cables or small components.
- The last batch represents foams commonly used as spacers in multi-layer structures or for low-load structural purposes.

Carbon Fiber Laminates

- High performance support structures often rely upon laminates made from unidirectional carbon fiber because of its favorable elastic modulus, long radiation length, and low density.
- A common fiber for low-mass structures is Mitsubishi K13C2U.
  - Fiber elastic modulus = 900 GPa (4.45 that of stainless steel).
  - Normally obtained as “prepreg” with either epoxy or cyanate ester resin.
  - K13D2U has a slightly higher modulus, but is more difficult to handle.
- Unidirectional prepreg of width 15 to 30 cm is normally “layed up” in several layers (6-8) to form laminate.
  - The angle of each layer is chosen to control laminate properties.
  - Cure at 250 - 275 ^{o}F and 1 - 5 atmospheres pressure.
  - Cured laminate is roughly 50% fiber and 50% resin by volume.
  - Laminate elastic modulus $\approx$ 137 GPa for a quasi-isotropic lay-up (~67% that of stainless steel).
- Typically, cured fiber ply thickness is 57-63 μm for K13C2U fiber.
  - Depends on the amount of resin removed during cure.
- X/X0 per ply $\approx$ 0.0185%.

Carbon Fiber

- Mitsubishi uni-directional carbon fiber

1.Fiber properties (Typical data)

GRADE	Tensile Strength		Tensile Modulus		Elongation	Density	Yield		Thermal Conductivity	Filament Diameter	Filament Count
	MPa	KSI	GPa	MSI	%	g/cm^3	g/1,000m	Yard/lb	W/m·K	μ	-
K1352U	3600	530	620	90	0.6	2.12	270	1800	140	10	2000
K1392U	3700	540	760	110	0.5	2.15	270	1800	210	10	2000
K13B2U	3800	550	830	120	0.5	2.16	270	1800	260	10	2000
K13C2U	3800	550	900	130	0.4	2.20	270	1800	620	10	2000
K13D2U	3700	535	935	135	0.4	2.20	365	1340	800	11	2000
K13A1L	3700	540	790	114	0.5	2.15	66	7500	220	7	1000

2.Laminate properties (Measureed by MCC)

GRADE	Longitudinal											Transverse			
	Tensile Strength		Tensile Modulus		Compressive Strength		Compressive Modulus		Shear		CTE (Temp. 50-125℃)	Tensile Strength		Tehsile Modulus	
	MPa	KSI	GPa	MSI	MPa	KSI	GPa	MSI	MPa	KSI	$\times 10^{-6}/K$	MPa	KSI	MPa	KSI
K1352U	2000	280	380	55	450	65	250	46	75	11	-1.1	40	5.5	6200	900
K1392U	2100	300	460	67	400	58	420	61	70	10	-1.2	35	5.0	6000	870
K13B2U	2200	310	490	71	380	55	450	65	60	9	-1.2	30	4.0	5500	800
K13C2U	2200	310	560	81	380	55	560	81	50	7	-1.2	30	4.0	5400	780
K13D2U	2000	290	560	81	350	50	560	81	40	6		30	4.0	5100	740

Carbon Fiber Pre-preg

- Epoxies and cyanate esters (or a mixture of them) are the most common resins.
- Cure temperature ranges from 250°F to 375°F (120°C to 190°C).
  - Low temperature cure often leads to better control of flatness.
  - High temperature cure often leads to a stronger material and normally leads to a greater tolerance for elevated temperature.
- Each group tends to develop expertise with a few resins and to rely upon them.
- Within the US, pre-preg carbon fiber is routinely obtained from either Tencate
  - http://www.tencate.com/emea/aerospace-composites/default.aspx

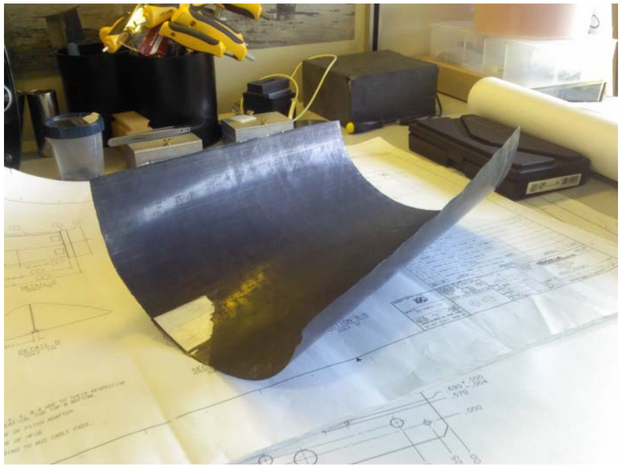
  or from a newer supplier, Renegade Composites
  - http://www.renegadematerials.com/.
- Cost ~$1500 per pound for 50 pounds
- Each supplier can provide pre-preg based on a wide variety of carbon fiber and resin systems.

Carbon Fiber Pre-preg

- Curing is often done with pre-preg layers applied to a mandrel covered with a mold release layer.
  - Breather material and vacuum bagging assist in absorption/removal of excess resin.
  - An autoclave can be used to provide pressure (typically 3 to 7 atmospheres) during the cure process.
  - Alternatively, for planar products, pressure can be applied by clamping between flat plates.
  - Cure time is usually an hour or less, but a substantially longer time can be used for temperature ramp-down.
- For quasi-cylindrical objects, thermal expansion of the mandrel during the cure is an issue if carbon fiber ply angles are too small.

Carbon Fiber Pre-preg

- A quasi-isotropic laminate provides in-plane properties which are independent of angle.
- Typical angles are 0°/60°/-60° (3 plies) or 0°/45°/-45°/90° (4 plies).
- To avoid bowing and "potato chipping", lay-ups are usually symmetric.
  - 0°/60°/-60°/-60°/60°/0° (6 plies) or 0°/45°/-45°/90°/90°/-45°/45°/0° (8 plies)
  - Not necessary for cylindrical structures



Bowing of a 3-ply (asymmetric) lay-up

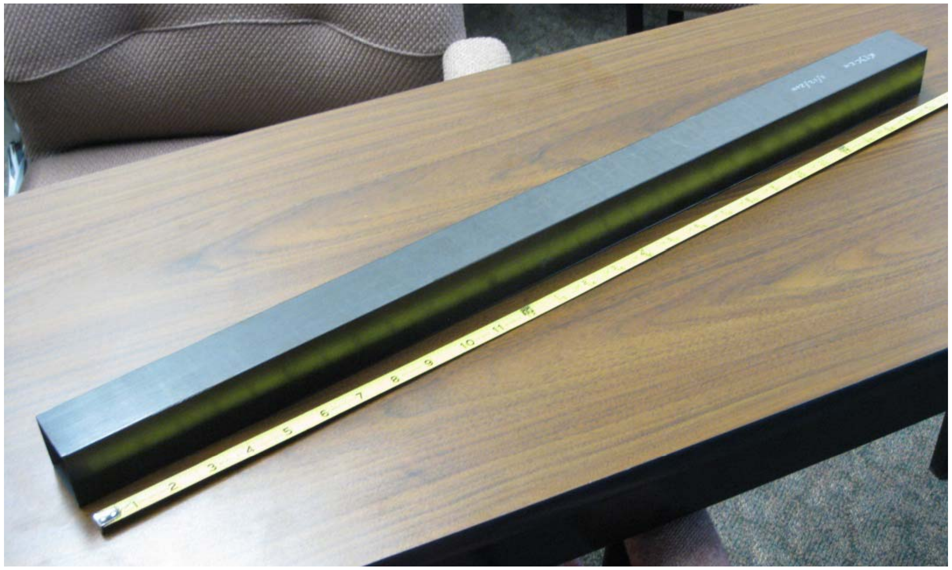
Representative Carbon Fiber Parameters

- Input parameters are in blue. Some are batch dependent.
- Resin bleedout, laminate ply thickness, and other laminate parameters depend on cure pressure and bleed material.
- "Quasi-isotropic" layups have uniform in-plane properties.
- Out-of-plane and in-plane properties differ.
- Laminate ply angles can be chosen to favor per-formance in one direction.

Relationships for carbon fiber lay-up (typical) K13C2U carbon fiber			
		Epoxy resin	Cyanate ester resin
Fiber areal weight (FAW)	gsm = g/m^2	61	61
Resin density	g/cm^3	1.24	1.18
Fiber density	g/cm^3	2.2	2.2
Fiber content by weight (FCW)	%	60	60
Resin content by weight (RCW)	%	40	40
Volumetric resin bleedout during cure	%	10	10
Fiber content by volume (FCV)	%	45.81	44.58
Resin content by volume (RCV)	%	54.19	55.42
Laminate fiber content by weight	%	62.50	62.50
Laminate resin content by weight	%	37.50	37.50
Laminate fiber content by volume	%	48.44	47.20
Laminate resin content by volume	%	51.56	52.80
Laminate density	g/cm^3	1.705	1.661
Prepreg ply thickness	mm	0.0605	0.0622
Laminate ply thickness	mm	0.0572	0.0587
X0_CF	g/cm^2	42.7	42.7
X0_resin	g/cm^2	83.6	83.6
X/X0_CF (per laminate ply)	%	0.0143	0.0143
X/X0_resin (per laminate ply)	%	0.0044	0.0044
X/X0 (per laminate ply)	%	0.0187	0.0187
X0_laminate	g/cm^2	52.29	52.29
X0_Fiber	cm	19.41	19.41
X0_Resin	cm	67.42	70.85
X0_Laminate	cm	30.67	31.48

Carbon Fiber Pre-preg

- Lay-ups which are not quasi-isotropic are often chosen to enhance properties in a particular direction or to avoid fiber bending radii which are too small.
  - $0^o/\phi^o/-\phi^o/-\phi^o/\phi^o/0^o$
  - Minimum bending radius to avoid fiber fracture ~8 mm for K13C2U.

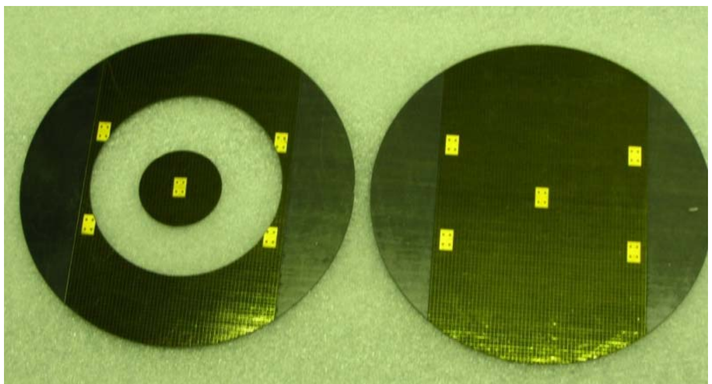


Prototype box structure for CMS Track-Trigger module support

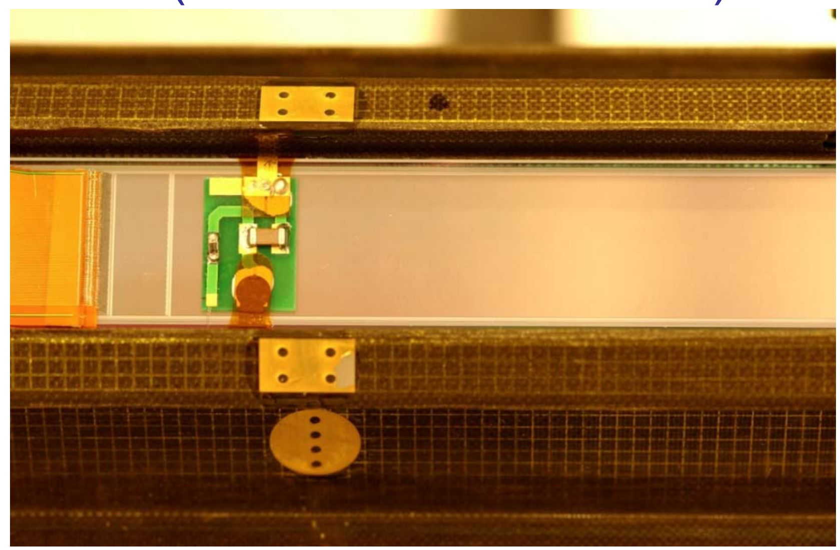
Lay-up =
$90^o/-15^o/+15^o/+15^o/-15^o/90^o$
Dimensions =
42.2mm x 42.2mm x 729mm x 0.28mm wall

Connections to K13C2U Carbon Fiber Laminate

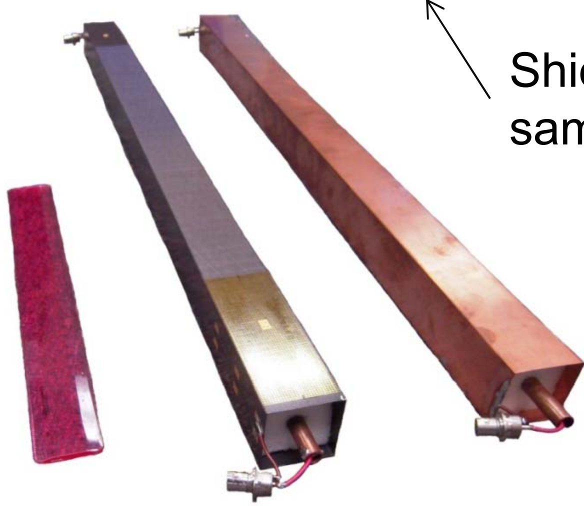
- Good, reliable connections have routinely been made by co-curing copper mesh on kapton circuits as the outer laminate layer.
- Vias through the kapton connect 5 mm x 8 mm pads to the mesh.
- CF – Cu < 0.2 db from 10 Hz to 78 MHz (transmission line tests).



Shielding test samples

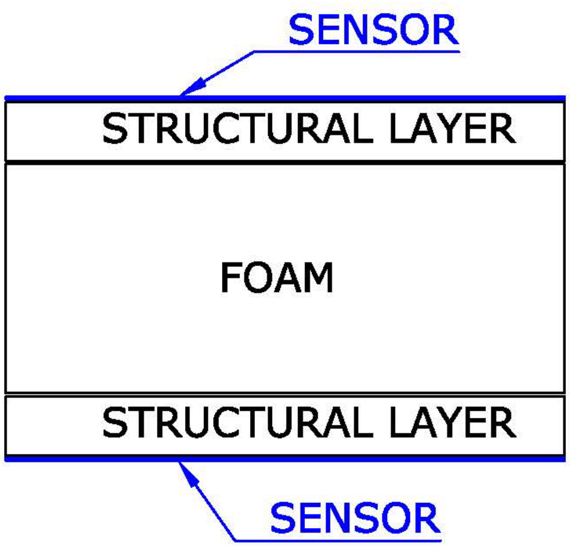


A portion of the D0 Layer 0 support cylinder with contacts for sensors

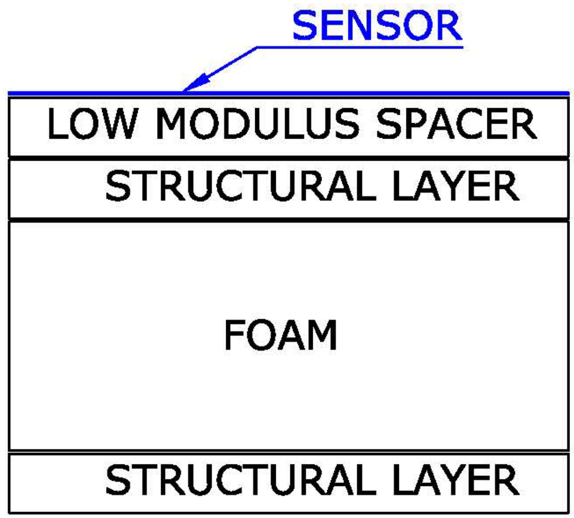


CF laminate and copper samples for transmission line testing. Laminate DC resistance = 280x that of copper.

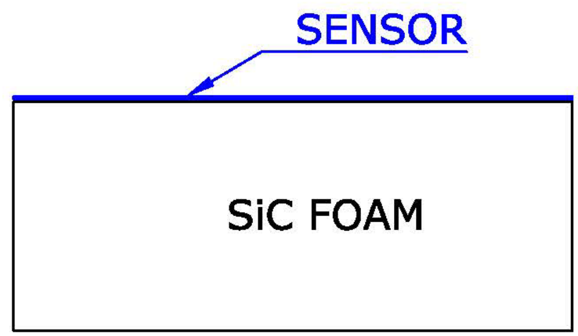
Ladder Geometries to Reduce Thermal Distortions



Make symmetric



Start with a stiff, symmetric core; mount sensors via a low modulus spacer or posts

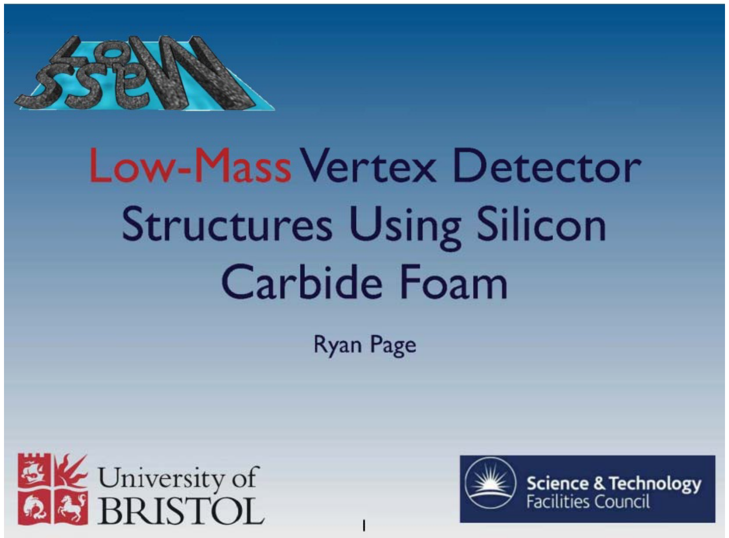


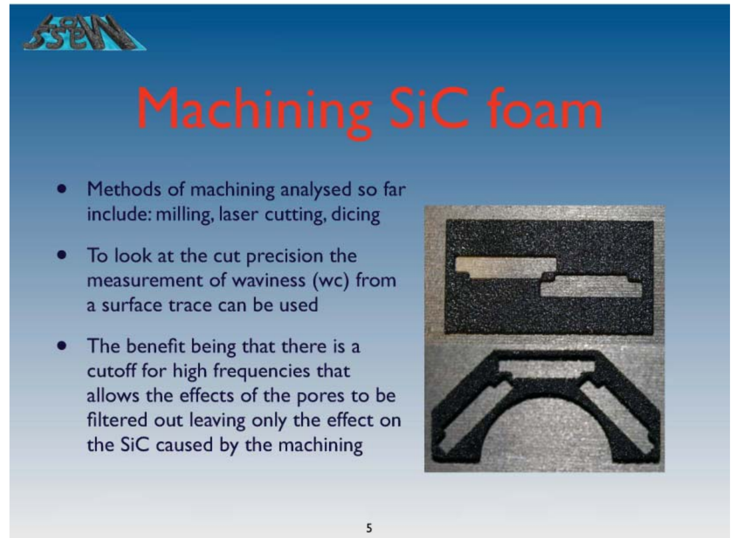
Match coefficients of thermal expansion (See next slide)

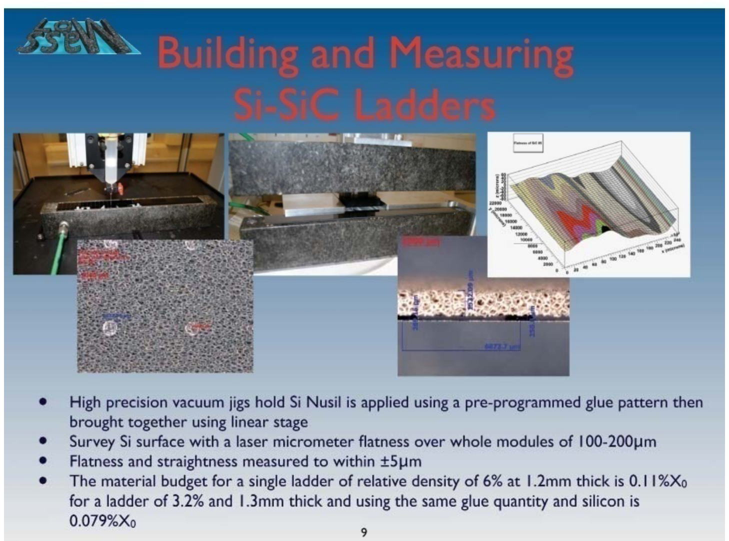
Sensor module core for CLAS12 upgrade at JLab:
Sandwich of copper/kapton printed circuit - carbon fiber - Rohacell - carbon fiber - printed circuit
Three sensors per core surface

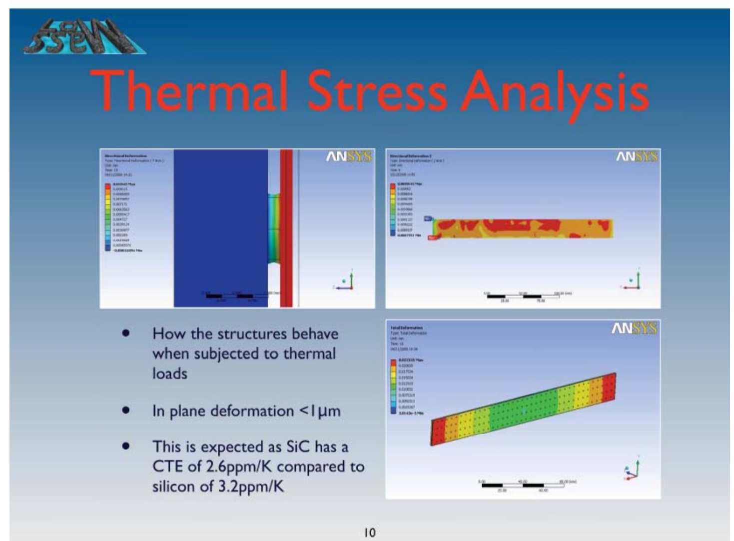
SiC Sensor Support

- LCWA2009, Ryan Page





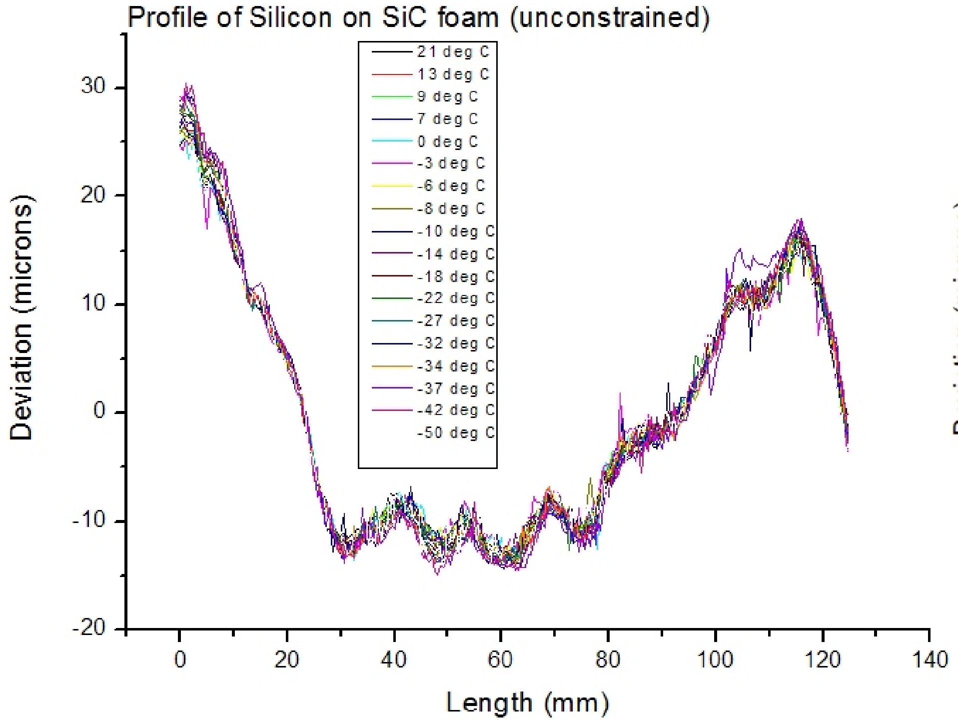


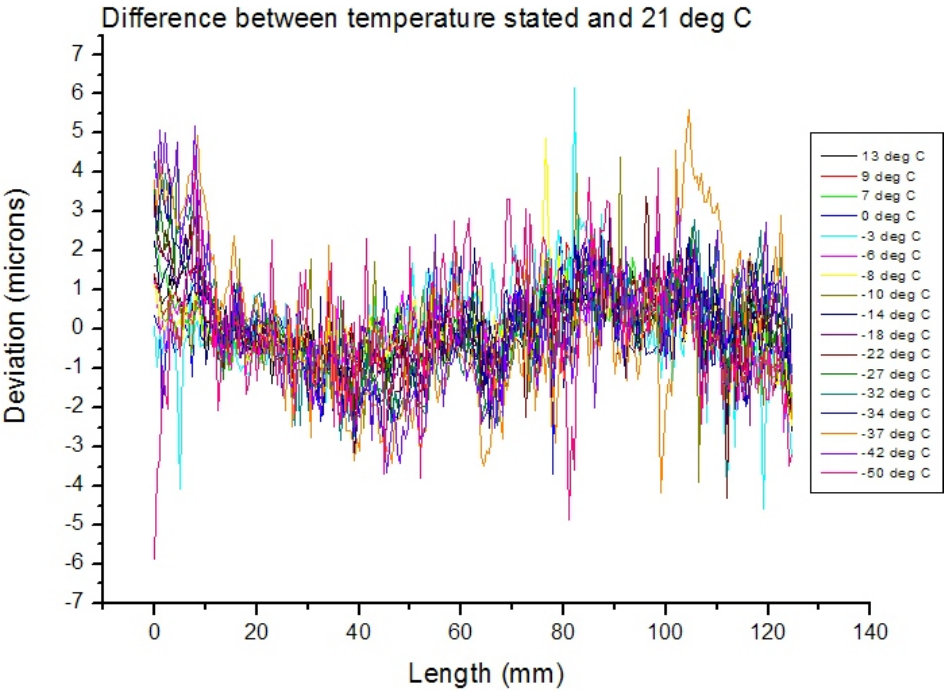


SiC Sensor Support

- Joel Goldstein et al. (LCFI)

- 8% ERG SiC foam: 25 μm silicon on one surface of 1.5 mm foam



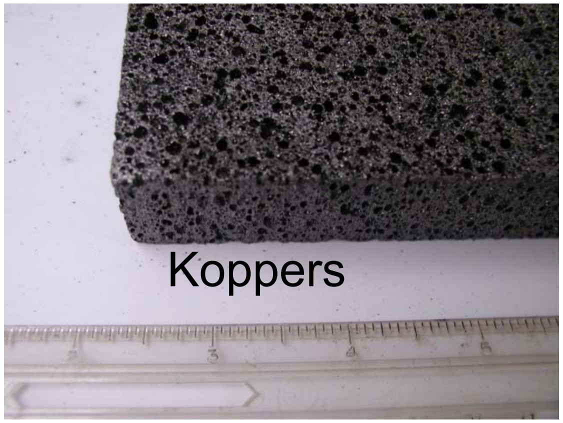


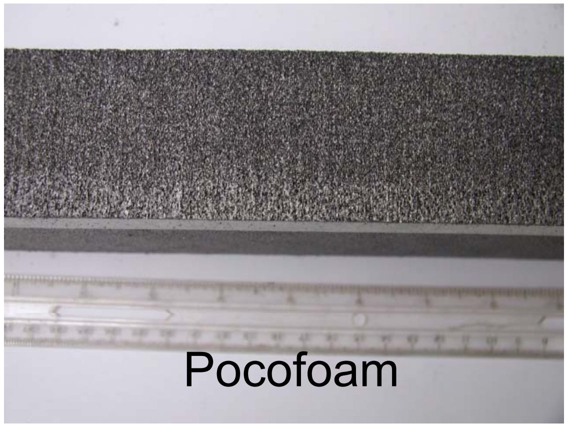
- *Studies were aimed at a vertex detector, but length is consistent with LHC modules.*
- *Flatness is reasonable and indicates what can be expected.*
- *6% to 8% SiC foam was obtained from ERG.*
  - *~ 3% foam was desired for the ILC, but hard to obtain.*
  - *Thermal conductivity, large quantities, and costs are likely issues.*

CF Foams

- In the US, substantial R&D has been done on CF foams at LBNL (Gilchriese, Haber), at BNL and affiliated institutions, & by AllComp (Wei Shih, Bill Miller). A glimpse from one talk follows.
- **"Experiences and Issues with Carbon Foam at BNL & Yale"**
  - BNL: David Lynn, Marc-Andre Pleier, Anatoli Gordeev, Russ Burns, Ken Sexton
  - Yale: Paul Tipton, Will Emmet, Tom Hurteau

•Koppers is closed-cell and has an extremely non-uniform cell size
•Poco varies in density through thickness
•Allcomp is open-cell, has a fairly uniform pore size-easiest to machine and can manufactured in different densities
•All are more-or-less comparable in cost





Carbon-Carbon

- Comments from Stefan Gruenendahl (Fermilab)(CMS forward pixel upgrade):
- High elastic modulus and high strength at high temperatures; low coefficient of thermal expansion
- Production:
  - Blank made from carbon fiber layup with carbon (e.g. graphite) filler
  - Pyrolytically transformed into pure carbon (with degree of conversion depending on temperature)
  - Voids filled by heat treatment in carbon-forming gas (e.g. acetylene), or repeated cycles of (vacuum) impregnation with carbon-carrying liquid (resin, carbon cement) and heat treatment
- Properties depend on fiber layup and treatment; often anisotropic
  - 3D: fibers run in all three directions
  - 2D and 3D: planes can be made from woven cloth or unidirectional fibers
  - Layup largely determines strength and failure mode(*)

(*): low fiber/matrix interface strength, in particular in 3D CC, believed to lead to higher toughness, higher yield strains, low thermal CTE

Carbon-Carbon

- Typical density ~1.5-2 g/cm^3
- Typical CTE ~0.5*10^{-6}/ºK (in fiber directions)
- Elastic modulus ~10s of GPa (in fiber directions)
- Strength often lower than expected from fiber content
- Thermal conductivity up to several 100 W/mK

- Untreated surface can shed carbon particles
  - Encapsulate with epoxy or conformal coating (e.g. parylene)
- Epoxies adhere well
- Prototype composite structures consisting of CC with embedded stainless tubing, bonded to carbon fiber sheet and to pyrolytic graphite blades continue to perform well after 20 thermal cycles -40ºC to +40ºC

Representative C-C Properties

Properties of Allcomp / FMC C-C Composites		
Fiber		PAN
Fabric		Pseudo 3D
Fabric		needled
Grade		Hi-k
density	g/cc	1.75-1.80
Tensile - modulus	msi	5.6
Tensile - strength	ksi	10.1
Failure strain	%	0.24
Poisson Ratio		0.24
compression - modulus	msi	4
compression - strength	ksi	9.8
Failure strain	%	0.33
Interlaminar Shear	psi	na
Interlaminar Tensile	psi	>1750
Conductivity x	W/m.K	215
conductivity y	W/m.K	200
conductivity z	W/m.K	125
CTE x	10^{-6}/°F	0.5
CTE y	10^{-6}/°F	0.5
CTE z	10^{-6}/°F	4

Measured:
>300 W/m-K !

CMS Forward Pixel Upgrade

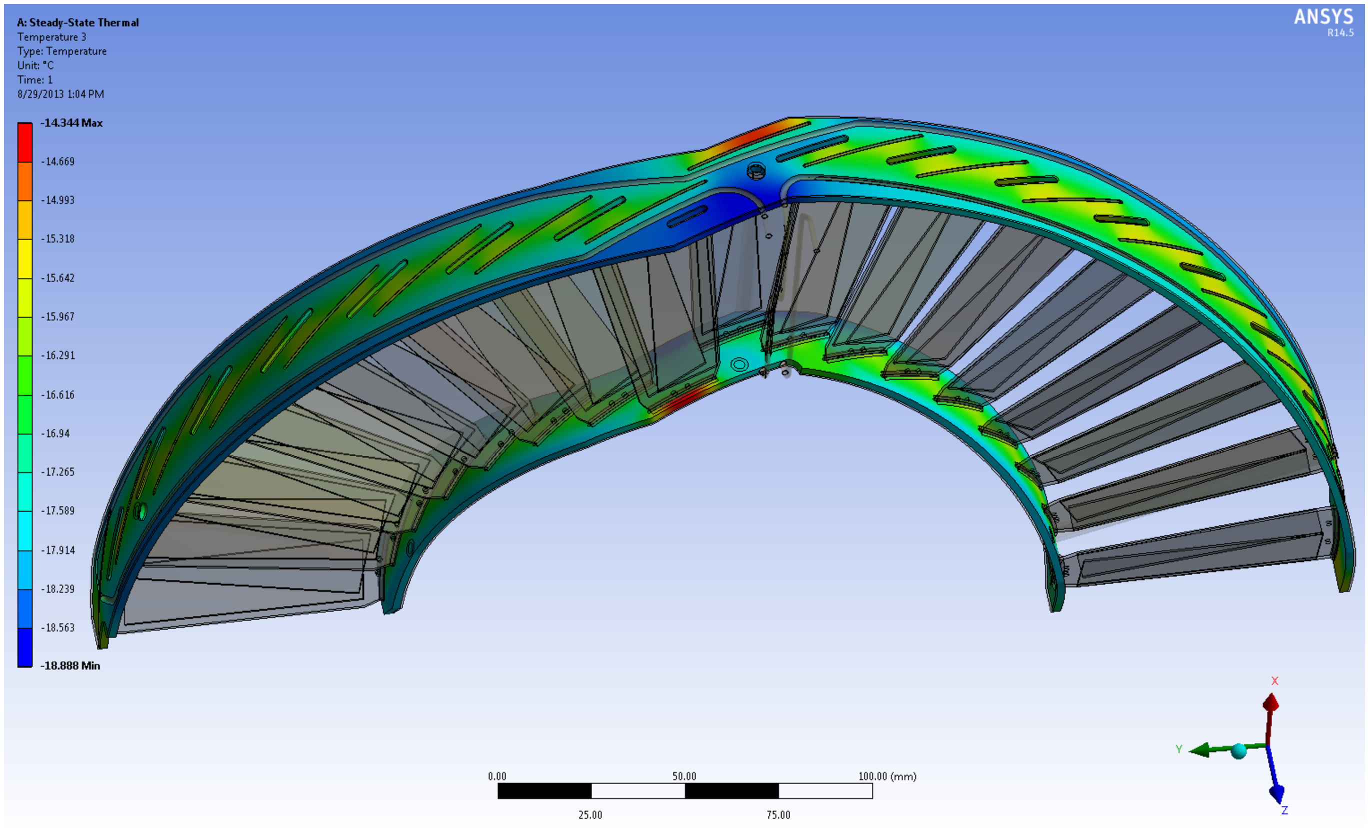
- Ring structure prototypes for mechanical support and cooling initially made from ‘3D’ carbon-carbon
- Properties and cost comparison 3D CC vs 2D CC vs graphite:
  - 2D CC even better than 3D for our thermal requirements (higher in-plane conductivity)
  - Graphite (Mersen extruded type 5607) thermally equivalent, structurally good enough, and much cheaper

Thermal FEA showing graphite ring temperature

Heat source: 100W on blades

Heat sink: embedded stainless tubes carrying two-phase CO_2 at -20ºC

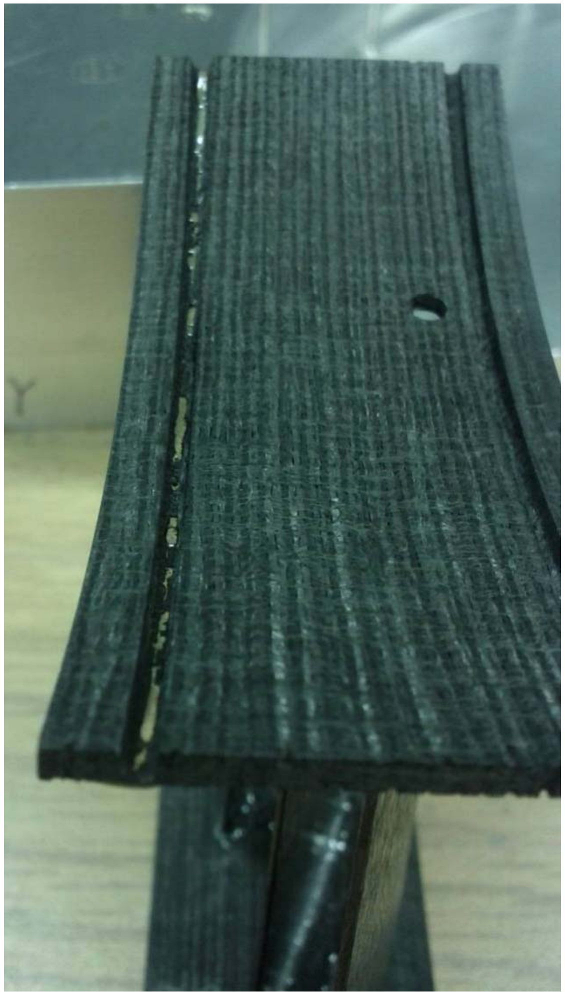
ΔT a little over 4 ºC in rings



Bill Cooper

Machining

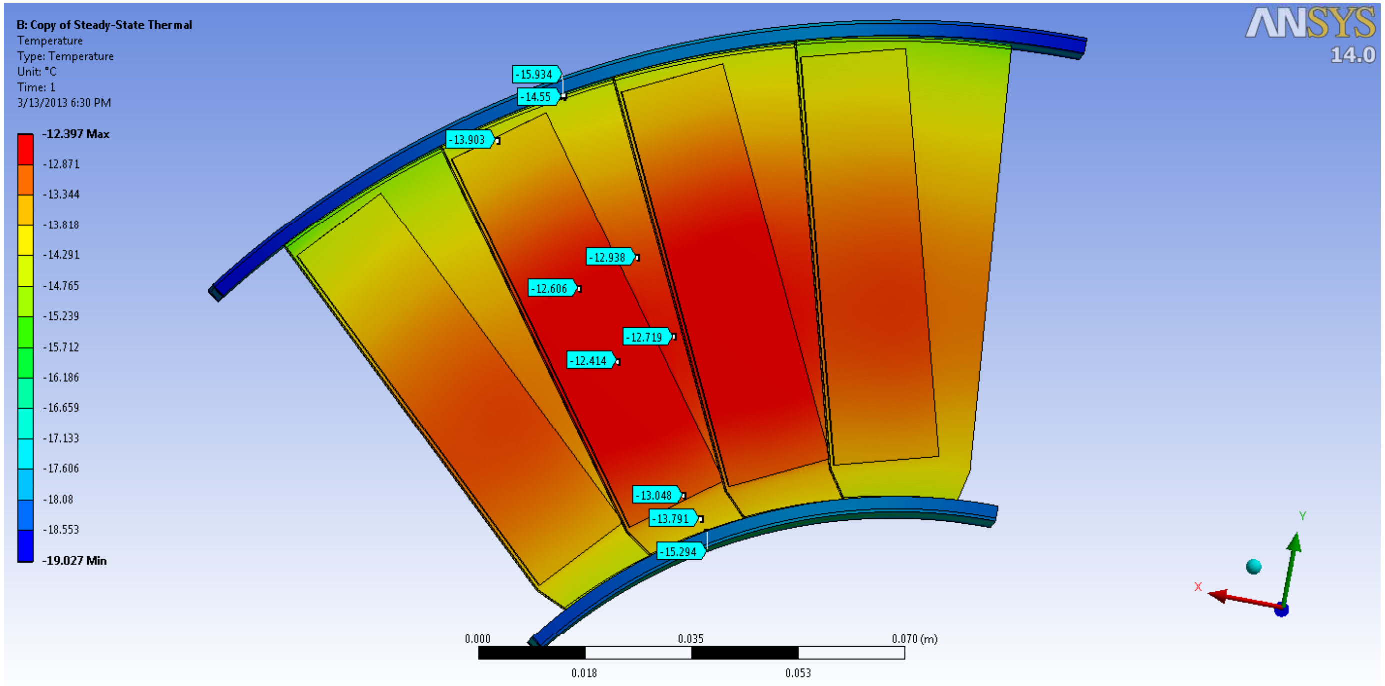
- Caveat: layup structure limits feature size
- Pin holes observed in layer of thickness 0.2mm



Thermal FEA

- 315 W/m-K measured for 3D CC
- Very good agreement with prototype measurements in our thermal FEAs

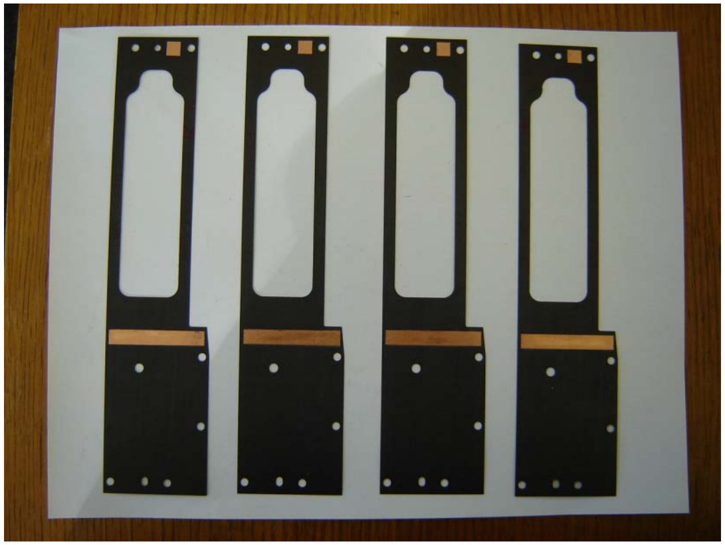
ΔT from CO_2 to ring (next to blade interface):
- 2.9-4.1 K experimental
- 3.1-3.8 K predicted



A Few Photos

- CMS:
- Measurement of flatness of a MetGraf 4-230 plate sample
- Nominal CTE = 4 ppm/°C
- Plate size ≈ 150mm x 150mm x 12.5mm
- Std dev = 8.5μm over surface
- Module parts would be machined from plate

- HPS experiment at JLab:
- K13C2U window frames for sensor support
- Micro-strip sensors are placed on both sensor surfaces and aligned to provide small angle stereo
- Copper electrical contacts are co-cured with the K13C2U



CO2 Cooling Worries

- Corrosion associated with moisture in the coolant
  - More of a concern with aluminum lines / structures
- Growth of micro-cracks in structures and tubing
- Erosion of cooling line inner surfaces over many years (leaks)
  - A serious concern with very thin walls (50 μm?)
- Leaks in connections
  - Less of an issue if connections are welded
  - Can lead to impaired control of pressure, hence temperature
- Differences in CTE between cooling tubes and structures to which they attach
  - Can fracture glue joints
  - Can fracture spacers (for example, carbon foam) intended to provide thermal contact
- Changes in geometry due to insufficient compliance in cooling tube connections to the outside world.

CO2 Cooling Worries

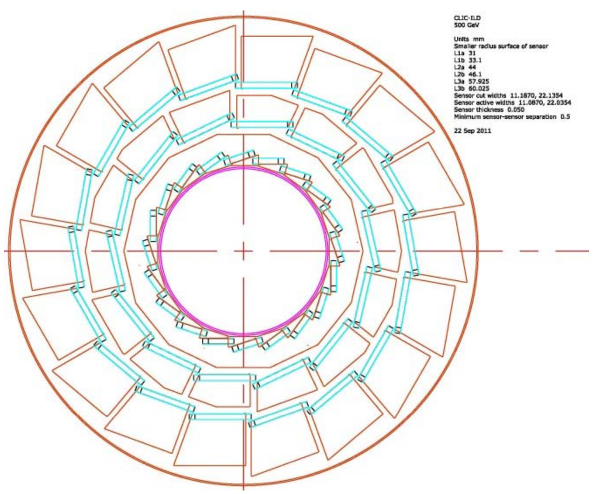
- Damage associated with insufficient pressure relief during a coolant evaporation incident
  - Structures, not just the cooling tubes themselves, need to designed to withstand the effects of high pressure.
  - Pressure rise tends to force cooling tube paths towards a circular shape, which can damage support structures and sensors attached to them.

Dry Gas Cooling

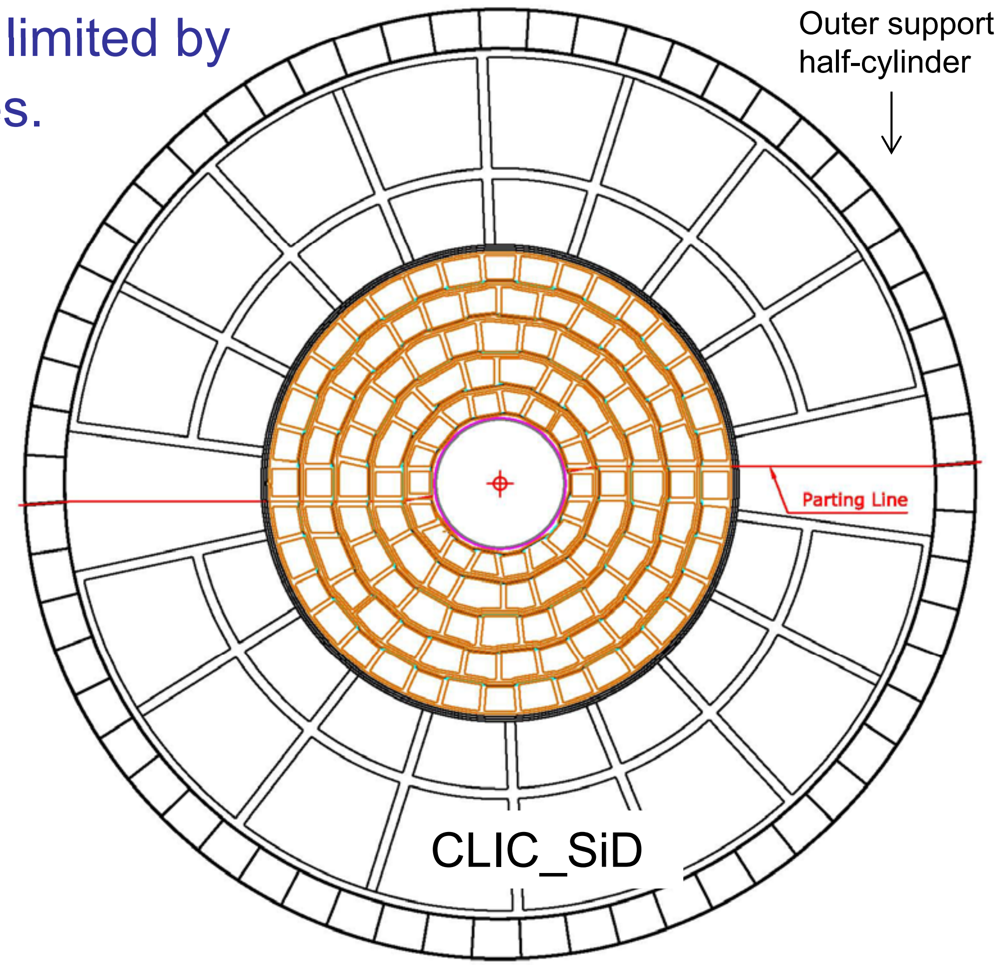
- Five considerations designs should address:
  - Ensure flow paths are effective and without stagnant regions
  - Ensure that pressure differences associated with flow don’t distort structures
  - Ensure that vibrations aren’t induced by cooling gas flow
  - Ensure that flow will not be obstructed or lost
  - Ensure cooling gas is delivered at the proper temperature.
- Prescriptions can be easier to write than to fulfill.

Example Barrel End Views

- In CLIC_ILD, ladders are inserted as units through end support disks.
- In CLIC_SiD, VTX structures are built as top and bottom halves with ladders already in each half.
- For both, gas flow paths are limited by support structures and cables.



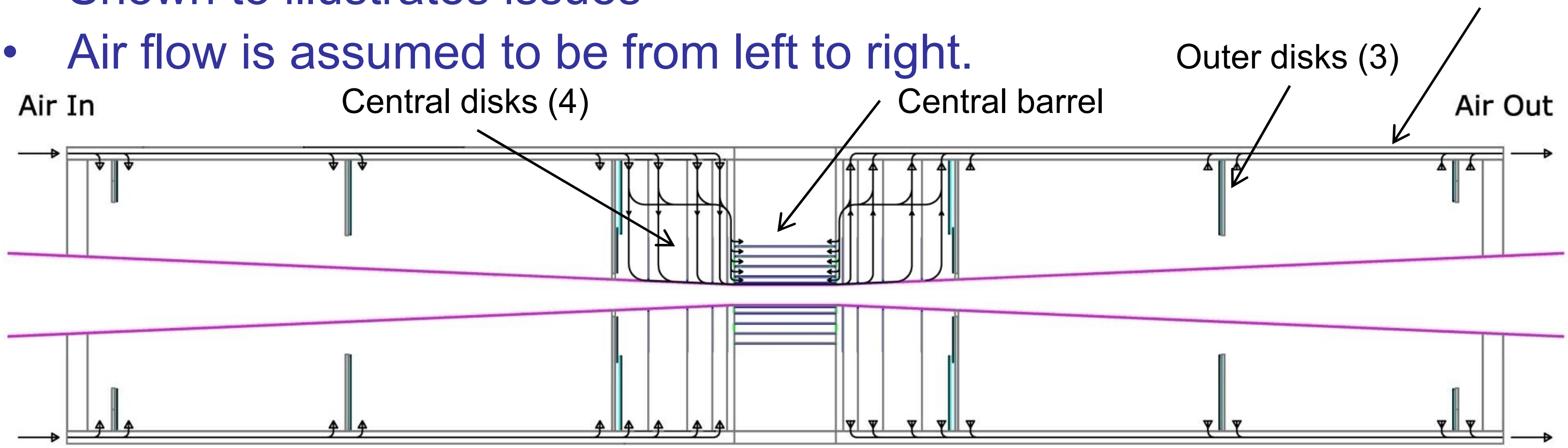
CLIC_ILD



CLIC_SiD

Side View of SiD

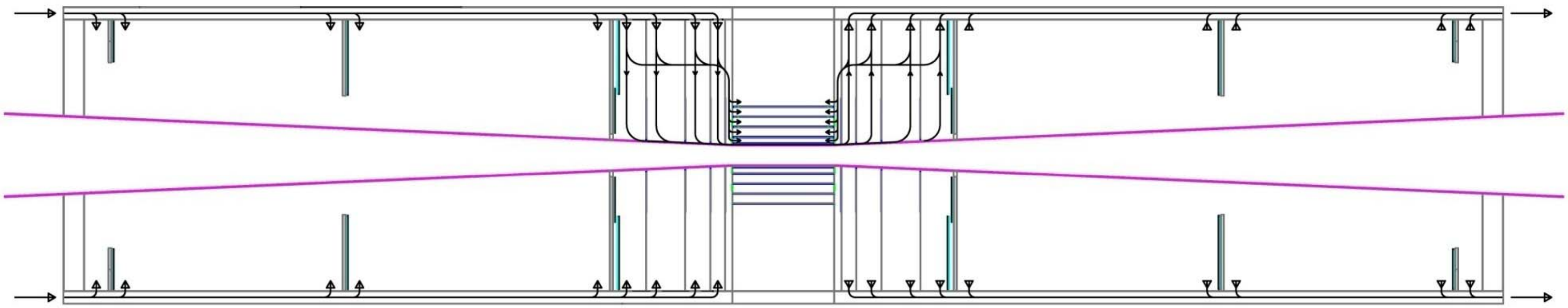
- Shown to illustrates issues
- Air flow is assumed to be from left to right.



- Support membranes for the barrel and the disks must be stiff enough to resist the pressure of air flow.
  - They probably either need to be double-walled sandwiches or they need to have conical shapes.
- Disks close to the barrel obstruct barrel flow.
- Cabling will obstruct flow and can move (if inadequately anchored) and block flow passages.
- The outer disks appear to be adequately cooled by convective heat transfer into the overall flow stream.

SiD Barrel with Normal Power

SiD VTX Barrel.
0.014 W/cm^2



- Dry air was assumed to enter the barrel at a temperature of -15^o C. (Results with dry nitrogen would be nearly identical)
- We assumed no heat transfer from the beam pipe to the innermost layer, that is, the beam pipe would have thermal intercepts.
- A total power dissipation of 20 watts was assumed for the barrel.
  - Based upon the results, that seems reasonable.

Reynold's number	Total barrel flow (g/s)	Ave. ΔT air (^{o}C)	Max sensor T (^{o}C)
800	9.0	2.21	-2.44
1200	13.5	1.47	-4.61
1800	20.2	0.98	-6.36

- For N_{Re} = 1800 and maximal openings in end membranes, average velocity = 1.7 m/s; maximum velocity (between L1 and the beam tube) = 4.6 m/s.
- Vibration should not be an issue with this range of Reynold's numbers.

SiD Barrel with High Power

SiD VTX Barrel.
0.13 W/cm^2

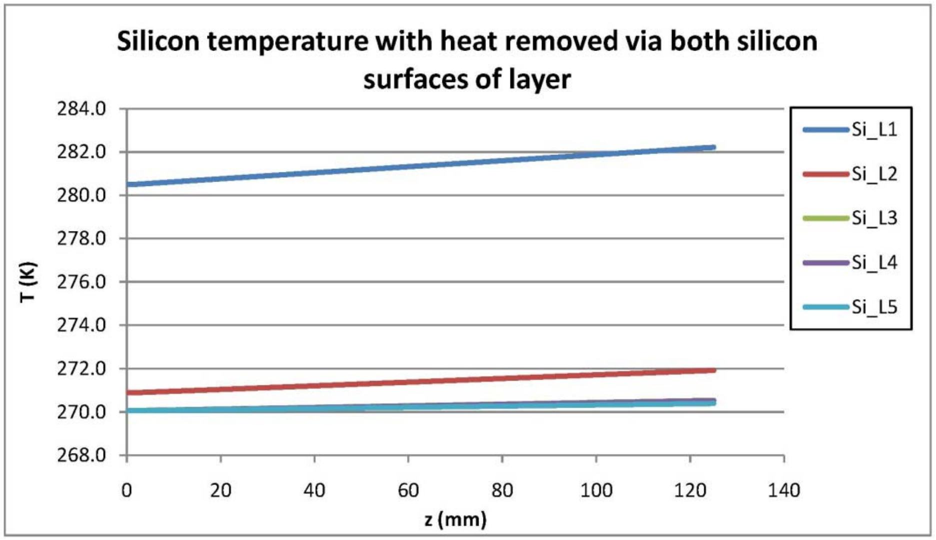
- Shown to illustrates issues

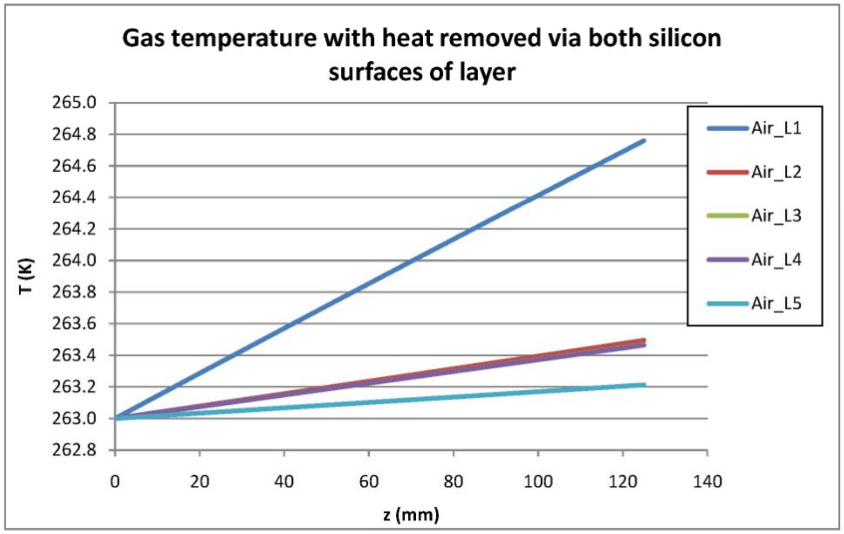
End-to-end pressure	7.72 Pa 0.00112 psi		SiD Heat removed via both surfaces	0.13 W/cm^2		
Gap	Flow g/s	Reynold's number	Flow velocity m/s	Heat removed W	Average T_silicon - T_gas K	T_rise of gas K
Beam pipe to L1	0.21	307	1.19	0.19	15.95	0.87
L1 to L2	6.21	6766	6.04	27.15	15.03	2.73
L2 to L3	28.40	19719	9.43	25.98	10.18	0.71
L3 to L4	41.81	19719	9.43	41.39	12.81	0.85
L4 to L5	55.21	19719	9.43	54.44	12.83	0.87
L5 to outer shell	68.62	19719	9.43	30.94	12.94	0.45
Totals	200.46			180.08		

Vibrations are a worry with high flow velocity.

Flow between the beam pipe and L1 is too low for significant heat removal.

L1-L2 flow carries away most of L1 and a portion of L2 heat.





US Future for New Materials

- The Instrumentation Frontier of the Snowmass 2013 process identified power and mass as one of seven technology areas having broad impact on current and future HEP detectors.
- The draft executive summary noted that :
  - “Experiments, especially those at the energy frontier, are characterized by high radiation, huge interaction rates, and serious constraints on power and mass budgets”.
- It called for:
  - Better strong and low-mass structural materials, including materials with ultra-low intrinsic radioactivity
  - Electrical power distribution and cooling systems, which can deliver services with low-mass in a high radiation environment
  - Innovative solutions.
- This indicates support for R&D on materials within the US HEP community.
- We hope that support will extend to funding agencies.
- Thank you!