Thermal Model
of
Pixel Blade Conceptual Design

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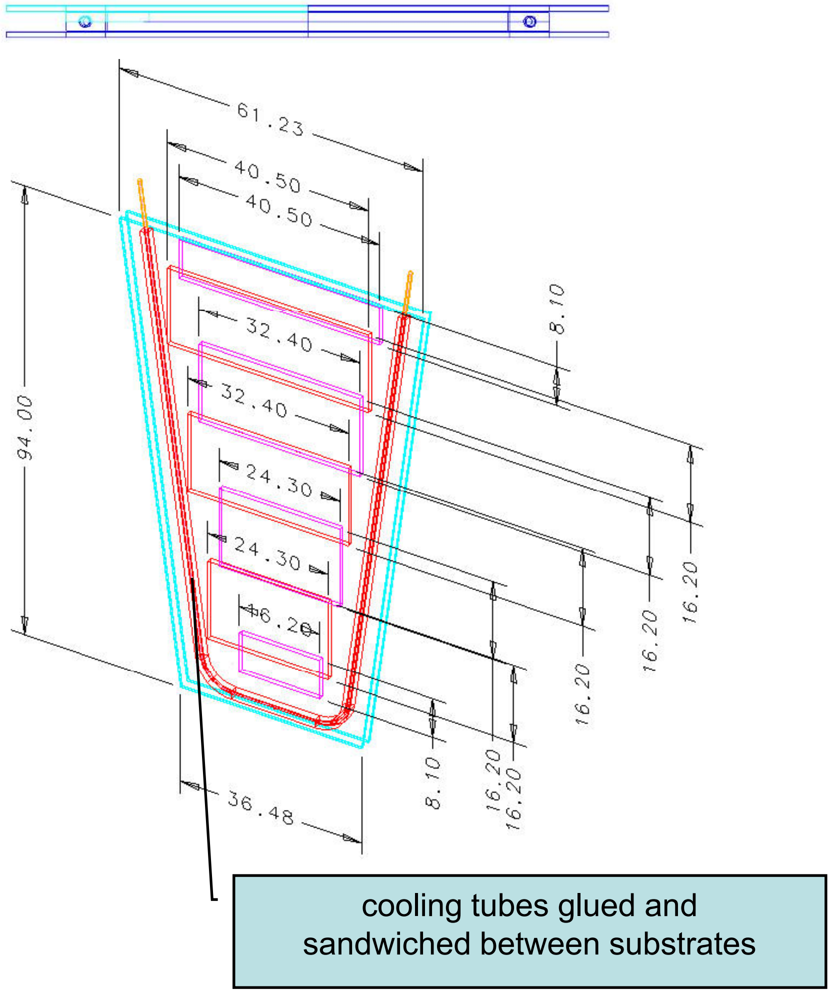
11/20/08

Material Candidates for Substrate

	Density g/cc	Modulus, E_ab Gpa	Modulus, E_c Gpa	Strength Mpa	Thermal K_ab W/m-K	Thermal K_c W/m-K	cte_ab ppm/K	cte_c ppm/K	Rad L, X0 cm
Porous Materials									
fuzzy C, 5% pr	0.11	-	-		-	55	-	1.0	406.7
carbon foam, low density	0.25	0.9			15	20	3.5		170.8
SiC foam, 8% packing ratio	0.26	2.8	2.8		11	11	2.2	2.2	166.1
RVC foam (vitreous C)	0.30	0.1	0.1	0.3	0.5	0.5	2.2	2.2	142.3
carbon foam, medium density	0.35	3.0		-1.6	20	25	3.5		122.0
carbon foam, high density	0.45	5.0		-3.5	25	40	3.5		94.9
poco-foam, 25% pr	0.55	20.7	20.7	-2.07	45	135	2.5	2.5	77.6
rohacell	0.03	0.0	0.0	1	0.0	0.0	37.0	37.0	1497.7
Solid Non-metalic Materials									
pyrolitic graphite, PGS	1				600	15.0	0.9	32.0	42.7
peek	1.32	3.6	3.6	92.9	0.2	0.2	46.8	46.8	35.0
CoolPoly E5101 (PPS)	1.70	13.0	13.0	45.0	20	20	15.0	15.0	26.5
CFRP (M46J-epoxy)	1.61	18.1	7.3		56	0.7	0.0	30.2	26.5
glassy C	1.65	20.0	20.0		5	5	3.0	3.0	25.9
CFRP (K13C2U-epoxy)	1.75	483.0	6.2		320	0.5	-1.0	26.0	24.4
CFRP (K139-EX1515)	1.76	154.0	6.4		63	0.4	-0.8	30.4	24.3
Poco graphite ACF-10Q	1.77	11.0	11.0	69.0	60	60	7.6	7.6	24.1
C-C composite (carbon fiber/carbon matrix)	1.80	152.0	4.8		225	150	2.0	2.0	23.7
SiC	3.21	466.0	466.0	-3900	40	40	3.3	3.3	8.1
G10 (glass fiber/epoxy)	1.8	17.2		262.0	0.3	0.3	11.9	11.9	19.4
pyrolitic graphite, TPG	2.26	18.7*	0.0		1700*	10	-1.0	25.0	18.9
Alumina Silicate	2.80			17.5	1.2	1.2	2.9	2.9	14.2
Vespel SP1 Polyimide	1.43	2.4	2.4	87.3	0.3	0.3	54.0	54.0	31.9
CVD Diamond	3.51	1000.0	1000.0	400.0	2000	2000	1.0	1.0	12.0
DLC (diamond-like carbon) coating									
Solid Metalic									
Be	1.85	290.0	290.0	276	145	145	11.6	11.6	35.4
AlBeMet	2.10	200.0	200.0	192	210	210	13.9	13.9	16.1
BeO	2.90	345.0	345.0	138000	330	330	7.6	7.6	13.3
Aluminum Nitride (AIN)	3.26	331.0	331.0	-2100	165	165	4.5	4.5	10.3
silicon	2.33	110.3	110.3	-120	120	120	2.6	2.6	9.4
aluminum 6061-T6	2.76	69.0	69.0	379	237	237	23.4	23.4	8.9
stainless steel 304	7.86	200.0	200.0	517	16	16	15.1	15.1	1.8
copper 101	8.94	129.7	129.7	350	391	391	17.6	17.6	1.4

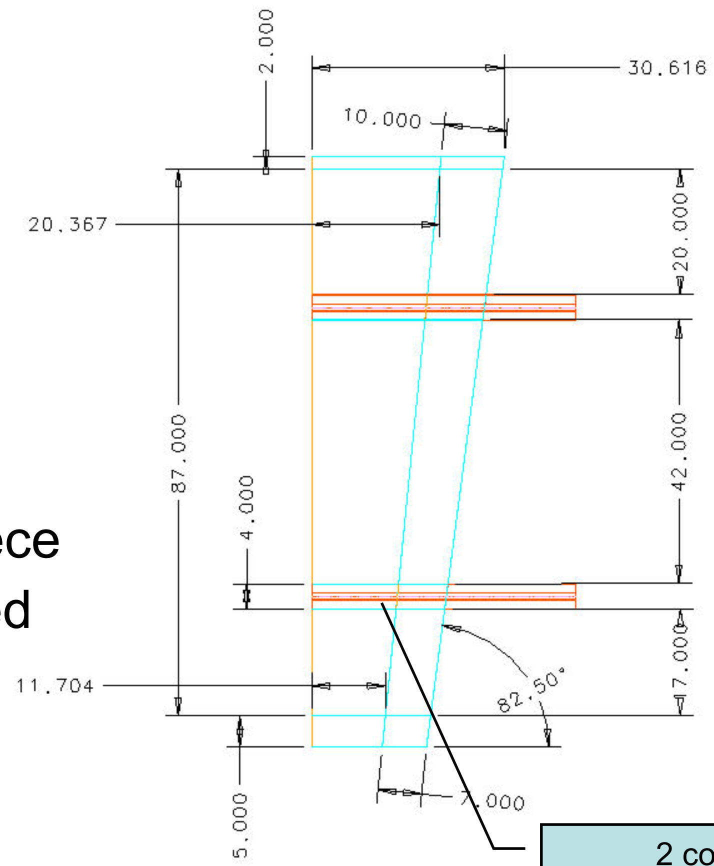
Basic Design of the Pixel Blade

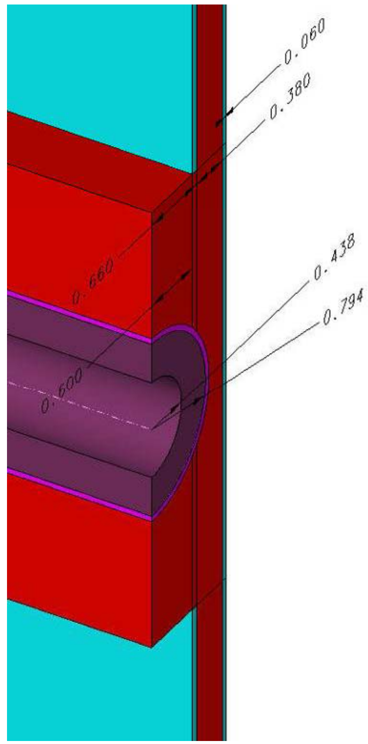
- The tentative basic design of the pixel blade -- 2 substrates with cooling tubing sandwiched in between.
- TPG is tentatively selected for the substrate and it is encapsulated with one ply of CFRP.
- CO2 cooling is selected, and the heat transfer area of the small cooling tube is enlarged by embedding it directly within the TPG substrate.
- The major task is to design the cooling layout and how to bond the cooling tubing to the TPG substrate properly.



Quarter FEA Blade Model (Half Substrate)

- Two tubing running laterally
- Substrate thickness:
  - 0.06 mm 1-ply CFRP
  - 0.38 mm TPG
  - 0.06 mm 1-ply CFRP
- Area spreader and substrate are in one piece
- Regular epoxy was used for the adhesive





2 cooling tubes glued and sandwiched with TPG area spreaders

Some FEA were done

- All 150% heat load, 3.75 W on half substrate;
- All -30C heat sink temperature on tubing inner surface;
- 3 cases reported:
  - 0.88 mm ID ss tubing with 0.66 mm thick TPG spreader (0.6 mm from cf surface)
  - 0.88 mm ID ss tubing with 0.46 mm thick TPG spreader (0.4 mm from cf surface)
  - 0.88 mm ID al tubing with 0.66 mm thick TPG spreader (0.6 mm from cf surface)

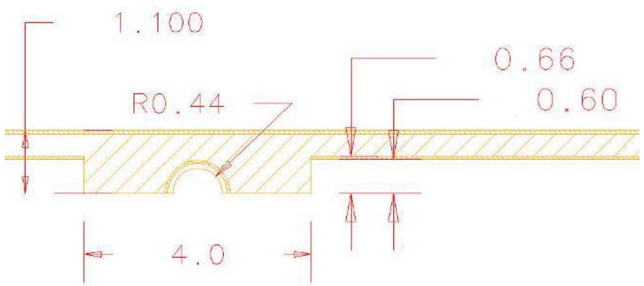
Sensor Dimensions

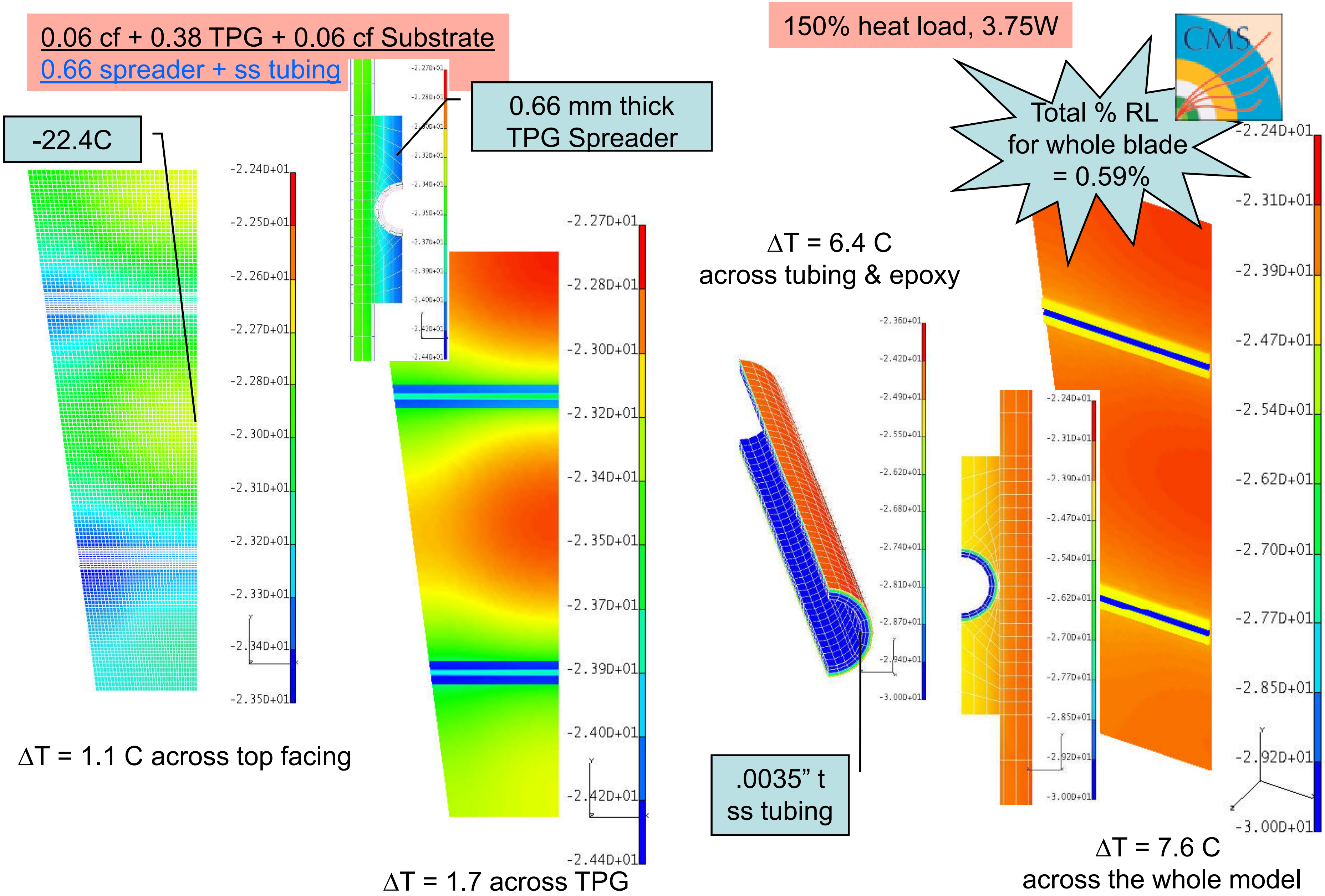
	width, mm	height, mm	area, mm^2
1	40.5	8.1	328.05
2	40.5	16.2	656.1
3	32.4	16.2	524.88
4	32.4	16.2	524.88
5	24.3	16.2	393.66
6	24.3	16.2	393.66
7	16.2	8.1	131.22
		total area =	2952.45 or 29.5245 cm^2

2X3 End Disks	Heat Load, W
ROC	962
control & driver	27
sensors	365
Total	1354

Each end disk has 24 blades, or 48 substrates,
heat load per substrate = 1354/6/48 = 4.701

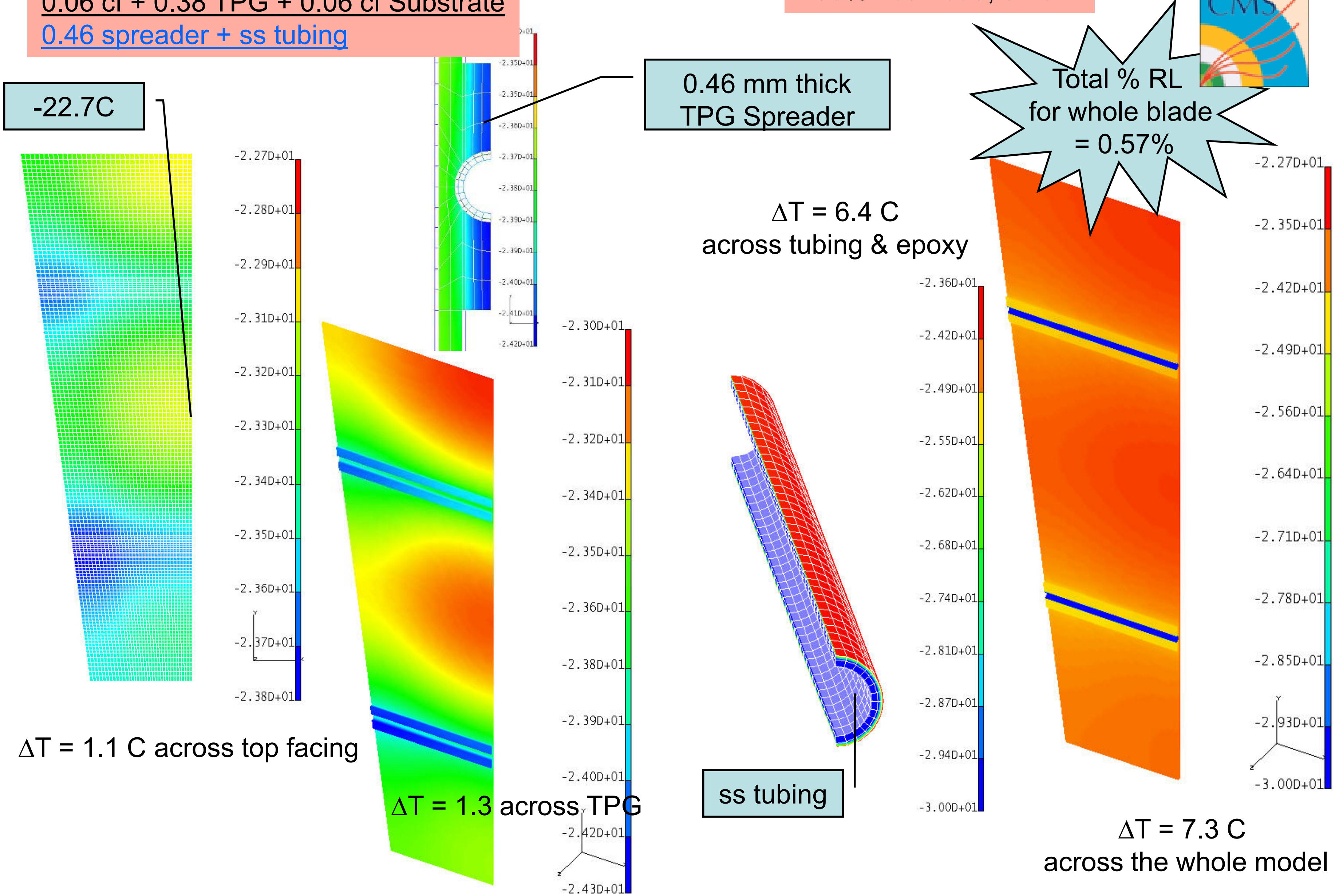
Heat load density = 4.7W/29.5245 =
0.159 W/cm^2




0.06 cf + 0.38 TPG + 0.06 cf Substrate
0.66 spreader + ss tubing
150% heat load, 3.75W
-22.4C
0.66 mm thick TPG Spreader
Total % RL for whole blade = 0.59%
ΔT = 6.4 C across tubing & epoxy
.0035" t ss tubing
ΔT = 1.1 C across top facing
ΔT = 1.7 across TPG
ΔT = 7.6 C across the whole model

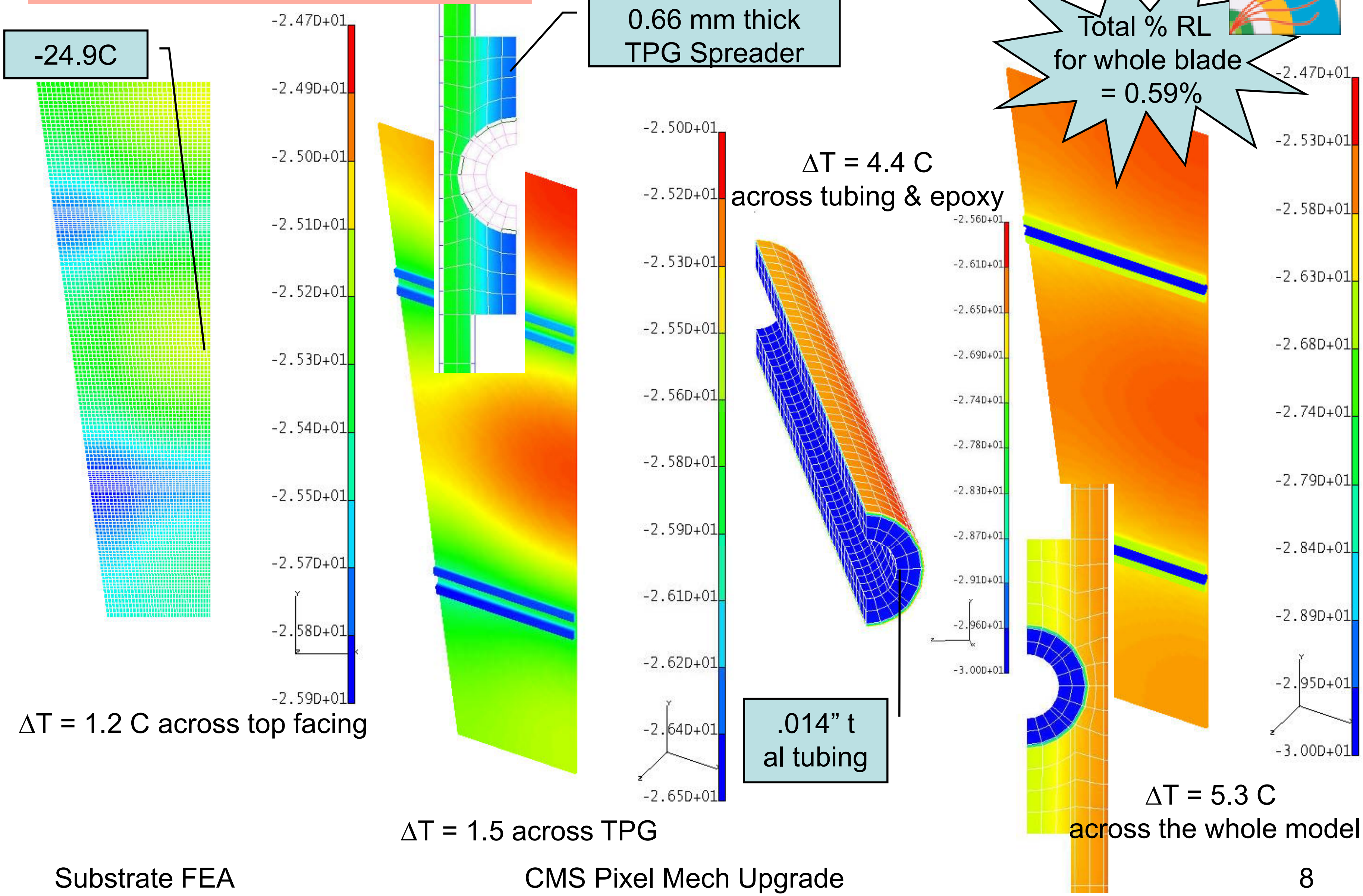
0.06 cf + 0.38 TPG + 0.06 cf Substrate
0.46 spreader + ss tubing

150% heat load, 3.75W



0.06 cf + 0.38 TPG + 0.06 cf Substrate
0.66 spreader + al tubing

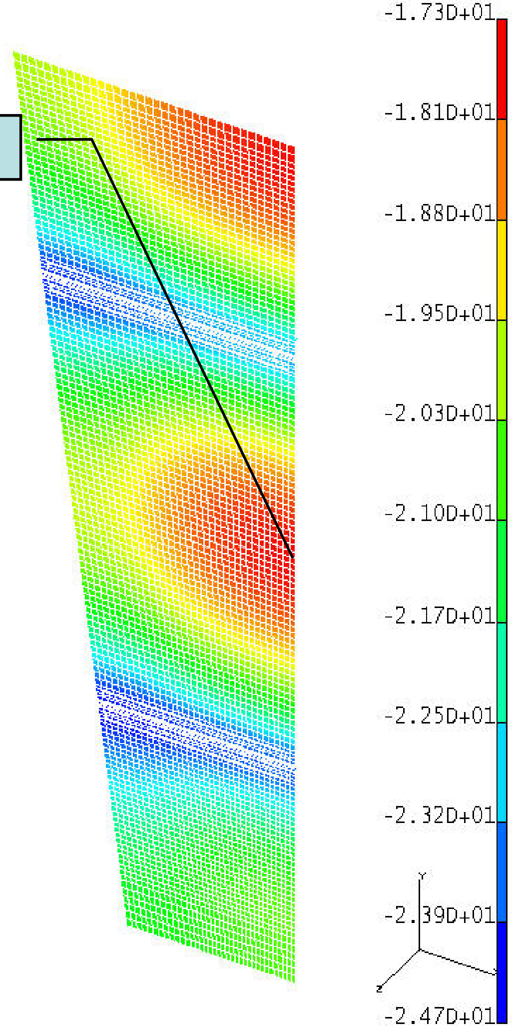
150% heat load, 3.75W



0.50 Beryllium Substrate
0.46 spreader + ss tubing

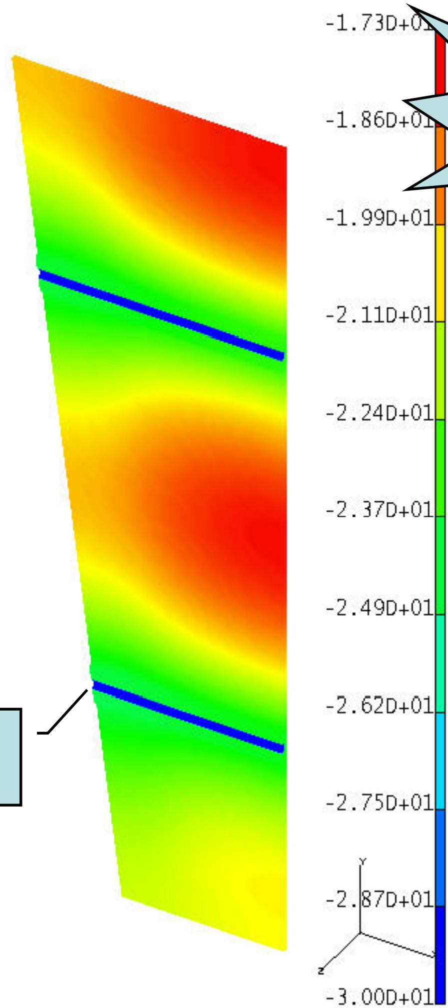
150% heat load, 3.75W

-17.3C



ΔT = 7.4 C (6.1 C more)
across Be substrate

0.46 mm thick
Be Spreader



Total % RL
for whole blade
= 0.34%

ΔT = 12.7 C (5.4 C more)
across the whole model

Two Tubing were considered in this FEA

	OD, inches	t, inches	OD in mm	ID in mm	t, mm	Pressure, bar with SF = 3	per half tube X2 mass, g	X0, g/cm^2	Eff. % Rad L
SS 316L	0.0415	0.0035	1.0541	0.8763	0.0889	112	0.103	14.1	0.02%
Al 3003 H14	0.0625	0.014	1.5875	0.8763	0.3556	299	0.185	24.6	0.02%

Both tubing have the same ID and
basically the same effective % rad L over the substrate area.

% RL Details and Summary

<< Masses are evenly distributed over the substrate area 4592 mm^2 >>

Configuration	B-T1, 2 horizontal tubing with TPG area spreader thickness in mm =				0.66				
Whole substrate	material	t or l, mm	area, mm^2	volume, mm^3	density, g/cc	mass, g	X0, g/cm^2	Eff. % Rad L	Heat
TPG	TPG	0.380	4592.488	1745.146	2.260	3.944	42.7	0.20%	150%
CF	CF	0.120	4592.488	551.099	1.760	0.970	42.8	0.05%	
Area Spreader	TPG	97.469	2.400	233.926	2.260	0.529	42.7	0.03%	
epoxy	for substrate								
tube, half	ss 316L	97.469	0.135	13.137	7.860	0.103	14.1	0.02%	
epoxy, half	for tubing	97.469	0.083	8.069	1.200	0.010	42.6	0.00%	
Coolant, half	CO2 liq.	97.469	0.302	29.392	1.030	0.030	36.2	0.002%	
Total % RL for half blade								0.30%	ΔT
Total % RL for whole blade								0.59%	7.6

Configuration	B-T1, 2 horizontal tubing with TPG area spreader thickness in mm =				0.46				
Whole substrate	material	t or l, mm	area, mm^2	volume, mm^3	density, g/cc	mass, g	X0, g/cm^2	Eff. % Rad L	Heat
TPG	TPG	0.380	4592.488	1745.146	2.260	3.944	42.7	0.20%	150%
CF	CF	0.120	4592.488	551.099	1.760	0.970	42.8	0.05%	
Area Spreader	TPG	97.469	1.600	155.951	2.260	0.352	42.7	0.02%	
epoxy	for substrate								
tube, half	ss 316L	97.469	0.135	13.137	7.860	0.103	14.1	0.02%	
epoxy, half	for tubing	97.469	0.083	8.069	1.200	0.010	42.6	0.00%	
Coolant, half	CO2 liq.	97.469	0.302	29.392	1.030	0.030	36.2	0.002%	
Total % RL for half blade								0.29%	ΔT
Total % RL for whole blade								0.57%	7.3

Configuration	B-T1, 2 horizontal tubing with TPG area spreader thickness in mm =				0.66				
Whole substrate	material	thickness, mm	area, mm^2	volume, mm^3	density, g/cc	mass, g	X0, g/cm^2	Eff. % Rad L	Heat
TPG	TPG	0.380	4592.488	1745.146	2.260	3.944	42.7	0.20%	150%
CF	CF	0.120	4592.488	551.099	1.760	0.970	42.8	0.05%	
Area Spreader	TPG	97.469	2.400	233.926	2.260	0.529	42.7	0.03%	
epoxy	for substrate								
tube, half	al 3003	97.469	0.688	67.069	2.760	0.185	24.6	0.02%	
epoxy, half	for tubing	97.469	0.125	12.153	1.200	0.015	42.6	0.00%	
Coolant, half	CO2 liq.	97.469	0.302	29.392	1.030	0.030	36.2	0.002%	
Total % RL for half blade								0.30%	ΔT
Total % RL for whole blade								0.59%	5.3

Configuration	B-T1, 2 horizontal tubing with TPG area spreader thickness in mm =				0.46				
Whole substrate	material	thickness, mm	area, mm^2	volume, mm^3	density, g/cc	mass, g	X0, g/cm^2	Eff. % Rad L	Heat
Be	Be	0.380	4592.488	1745.146	1.850	3.229	65.2	0.11%	150%
Be	Be	0.120	4592.488	551.099	1.850	1.020	65.2	0.03%	
Area Spreader	Be	97.469	1.600	155.951	1.850	0.289	65.2	0.01%	
epoxy	for substrate								
tube, half	ss 316L	97.469	0.135	13.137	7.860	0.103	14.1	0.02%	
epoxy, half	for tubing	97.469	0.083	8.069	1.200	0.010	42.6	0.00%	
Coolant, half	CO2 liq.	97.469	0.302	29.392	1.030	0.030	36.2	0.002%	
Total % RL for half blade								0.17%	ΔT
Total % RL for whole blade								0.34%	12.7

Note: The total % RL for the existing whole blade design = 0.29% + 0.86% + 0.31% (2 Be substrates + al channel + coolant) = 1.46%

Comparisons between TPG and Beryllium

Results Comparison

	Eff. % Rad L	ΔT overall	ΔT substrate	cte
TPG/CF	0.57%	7.3	1.3	-1
Be	0.34%	12.7	7.4	11.6
Difference	-0.23%	5.4	6.1	10.6
% toTPG	-41%	74%	469%	-1060%

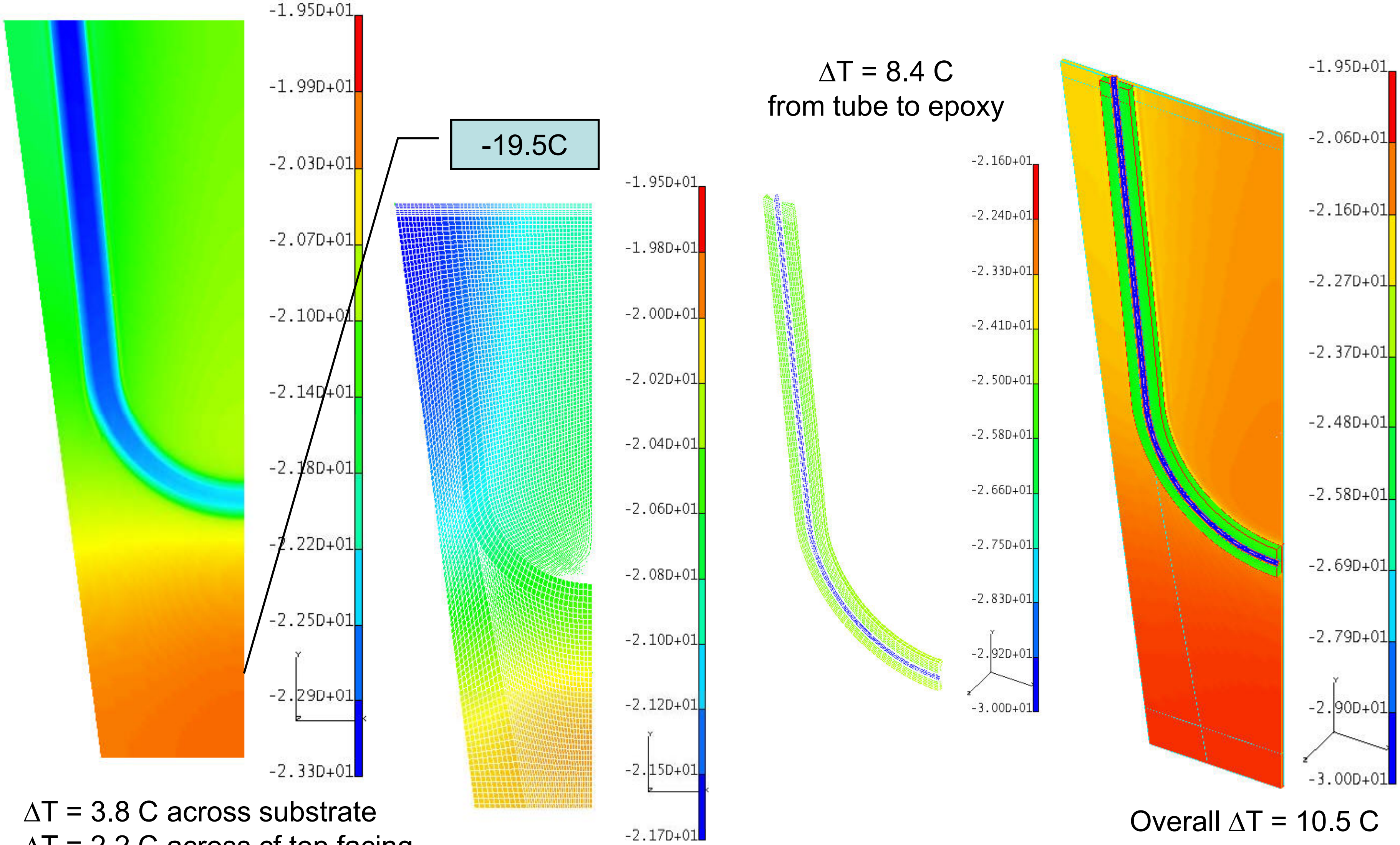
**** It should be noted that this cooling arrangement, with cooling tube directly under the modules, is favorable to beryllium as it has much better thermal conductivity in out of plane direction.**

Properties Comparison

	Thermal K_ab W/m-K	Thermal K_c W/m-K	Rad L, X0 cm	K_ab*Rad L W/K	K_c*Rad L W/K
CFRP - 1ply	126	0.6	24.3	30.6	0.1
TPG @ -20C	1960	10	18.9	370.4	1.9
Be	145	145	35.4	51.3	51.3

Conf. A-T1: 0.06 cf + 0.50TPG + 0.06 cf Substrate

200% heat load (0.318 W/cm^2)
4.44 W on this half substrate

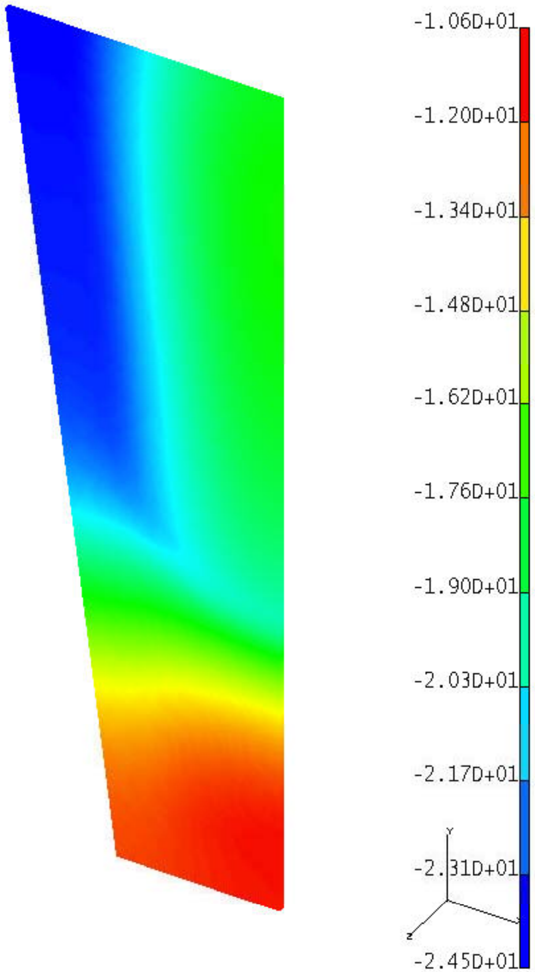


ΔT = 3.8 C across substrate
ΔT = 2.2 C across cf top facing

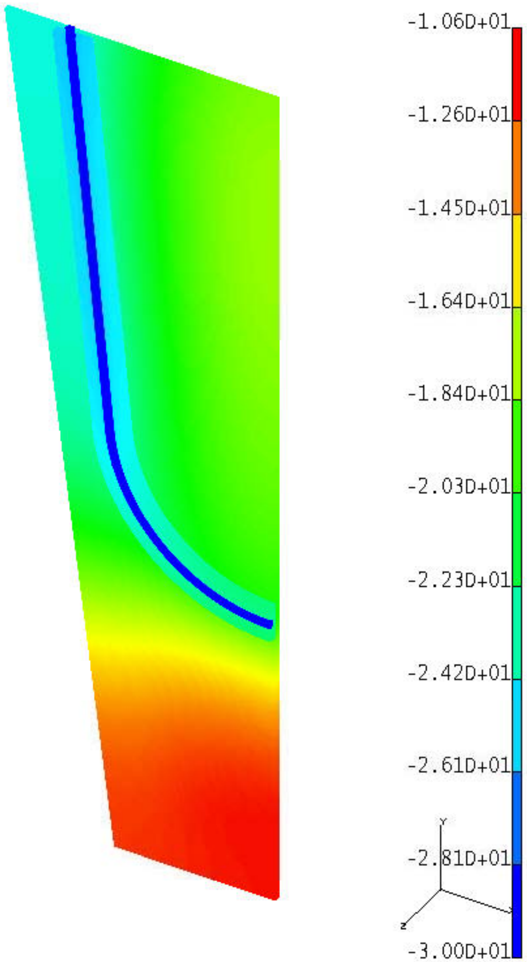
Overall ΔT = 10.5 C

Conf. A: 0.62 mm thick Beryllium Substrate

200% heat load (0.318 W/cm^2)
4.44 W on this half substrate



ΔT = 13.9 C (10.1C more)
across substrate



Overall ΔT = 19.4 C (8.9C more)

Preliminary Conclusions

- Although beryllium substrate could offer the least % Rad L, the large temperature distribution over the substrate is thermally inferior than that of TPG.
- Using TPG as substrate in incorporating with small-size CO_2 tubing appeared positive and offered an overall material saving and outstanding thermal performance at a reasonable cost. (120mm x 100mm x 1.04mm ~$200 per piece)
- Further FEA checks on thermal stresses and displacements with module glued on substrate is needed and will be followed.

Back Up Slides

Items Selected for the Conceptual Design

- Material selected for Substrate
  - TPG laminated with carbon-fiber reinforced plastic
  - Low mass (X0 = 18.9 cm)
  - Radiation hard
  - Dimensionally stable
  - Very high thermal conductivity ~ 1700 W/mK at room temperature

- Cooling selected for Substrate
  - High-pressure CO2 with small tubing
  - Low mass
  - Radiation hard
  - High thermal performance

  >> small cooling tube will be used.

The major task is thus to design the cooling layout and how to bond the cooling tubing to the TPG substrate properly.

K Values used in this FEA

Thermal Conductivities K of TPG, In-Plane

Temp in K	K in W/m-K
70	2920
80	3432
90	3784
100	3984
150	3624
200	2600
250	1960
273.2	1784
300	1600
350	1352
400	1168
500	904
600	744

Thermal K of TPG, Out-of-Plane = 10 W/mK

0^0 Carbon-Fiber Facing, In-Plane = 126 W/mK
0^0 Carbon-Fiber Facing, Out-of-Plane = 0.6 W/mK
epoxy (3M DP190 Gray) = 0.38 W/mK

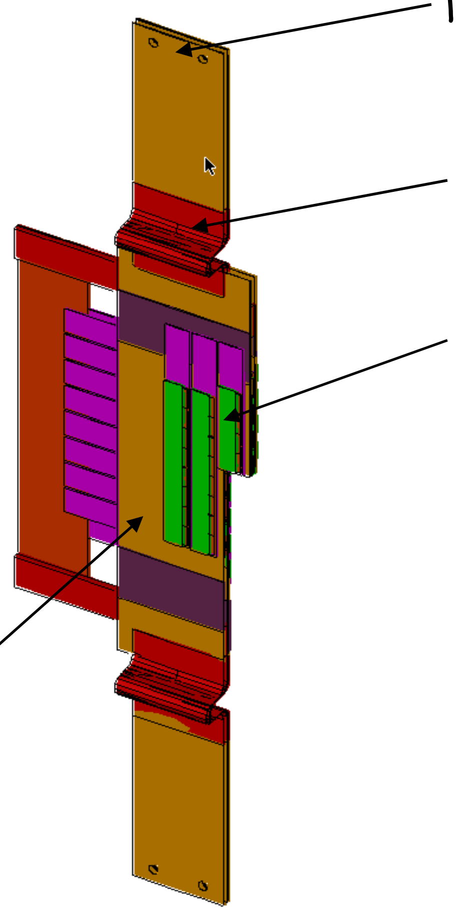
Thermal Pyrolytic Graphite (TPG)

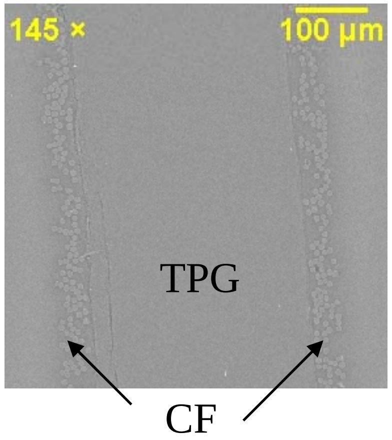
- A unique form of pyrolytic graphite
- Made by the decomposition of a hydrocarbon gas within vacuum furnace
- Exceptionally high thermal conductivity (in-plane k = up to 1700 W/m-K, out-of-plane k = 10W/m-K at room temperature)
- Low CTE (in-plane = -1 ppm/C, out-of-plane = 25 ppm/C)
- Low density = 2.26 g/cc
- Long X0 = 18.9 cm (X0*k = 321 W/K vs. 51 W/K of Be)
- Only available in rigid but brittle sheet, non-bendable.
- Friable, needs encapsulation; carbon fiber composite is chosen for needed rigidity within material budget constraint.

- Vendors:
  - Momentive Performance Materials (http://advceramics.com/)
  - MiNTEQ (http://pyrographite.com/)

TPG Experience at FermiLab

TPG was firstly proposed to use for BTeV pixel detector in 2003.

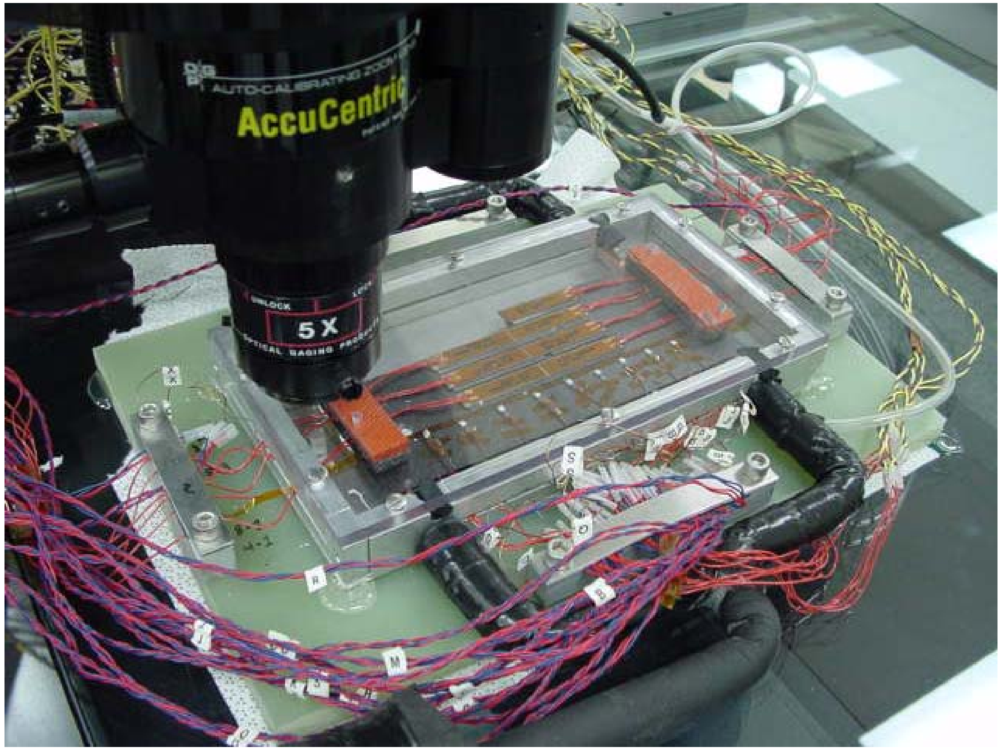




TPG Experience at FermiLab …continued (1)

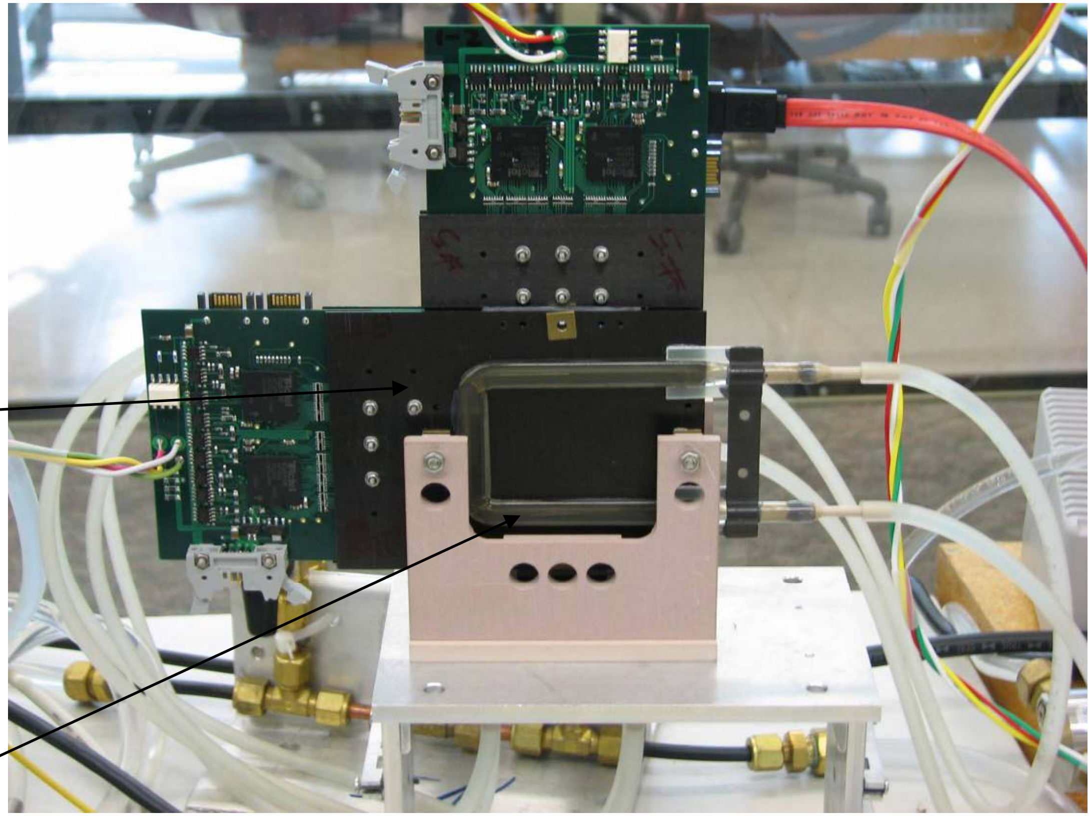
The BTeV prototype was made and thermal cyclic tests with heaters and cooling on and off were conducted. Results were satisfactory, no alarming problem was found.

- Test was conducted within a dry box with small amount of nitrogen flowing
- Kapton heaters on dummy silicon were used to simulate module heat load
- Cooling contacts were provided at ends
- An optical camera was used to observe the target displacements
- RTDs were glued on substrate to record thermal data
- Pin & hole engagement at large end
- Pin & slot engagement at small end



TPG Experience at FermiLab - continued (2)

It was successfully used for MTest Pixel Detector this year.

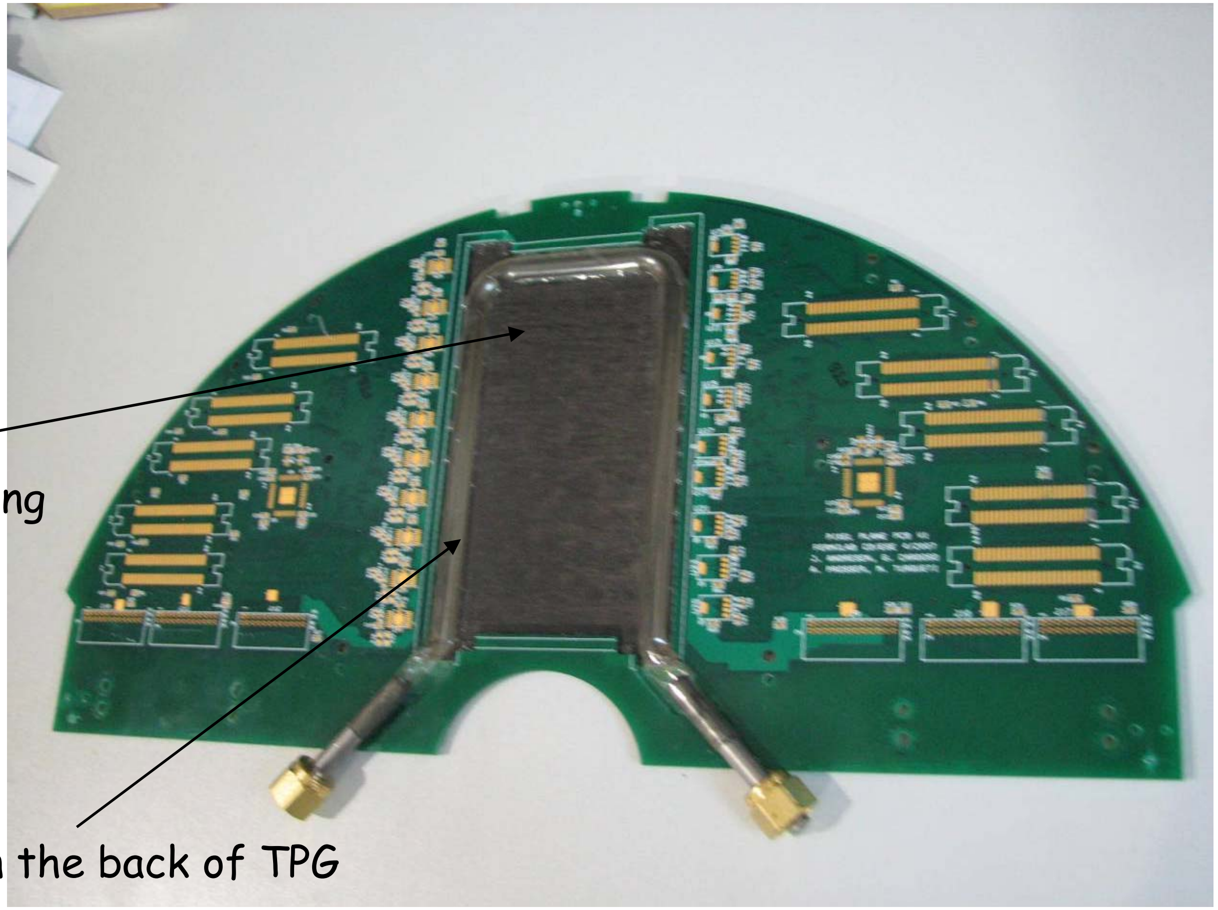


TPG encapsulated with two plies of CFRP for the facing

PEEK Cooling tube glued on the back of TPG

TPG Experience at FermiLab - continued (3)

It is planned to use for the PHENIX pixel detector as well.

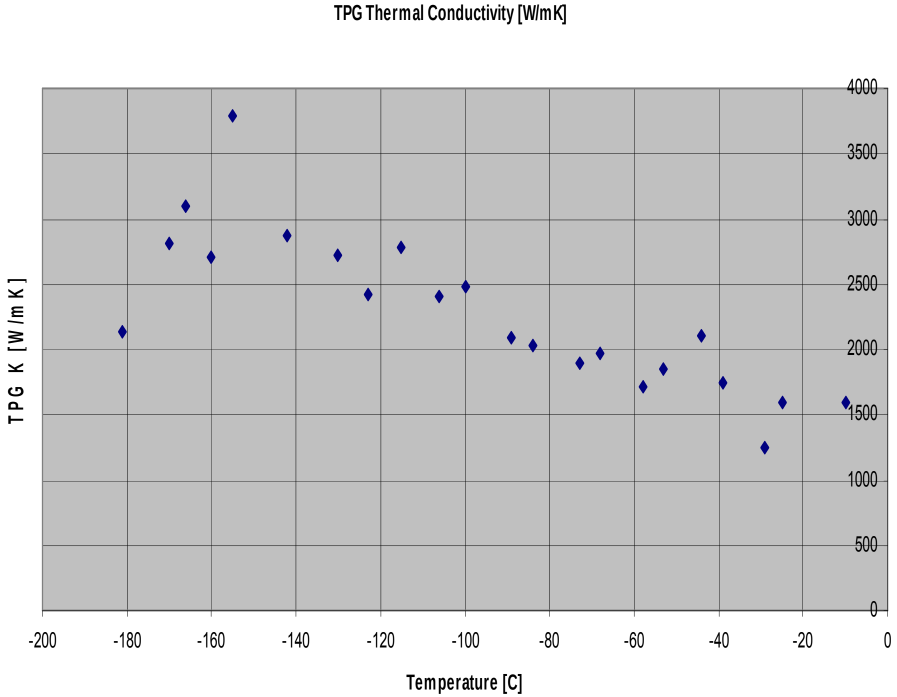


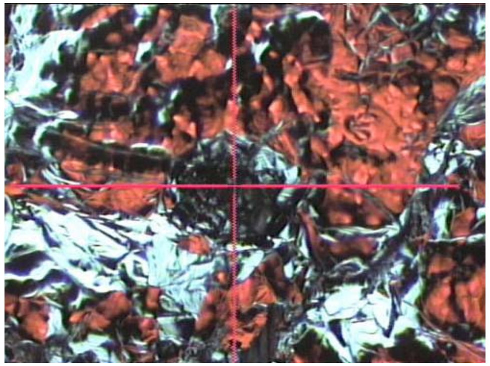
TPG encapsulated with
two plies of CFRP for the facing

PEEK Cooling tube glued on the back of TPG

TPG Experience at FermiLab - continued (4)

- No alarming problems were found.
- Perforated holes drilling on TPG was needed before encapsulation. It would improve the rigidity of the substrate.
- Tensile pulling test on encapsulated TPG samples were done, and the improved strength was verified.
- Thermal conductivity measurement of TPG were checked and its high thermal K characteristic at low temperatures was verified.
- Plasma cleaning on the CFRP encapsulated TPG was checked, the thermal performance could be slightly improved as a thin layer of the impregnated epoxy was removed.
- TPG might not be very flat due to the relief of internal stress when made at the factory. It could be flatten somewhat when CFRP was added.





This perforated hole was basically filled up completely with epoxy

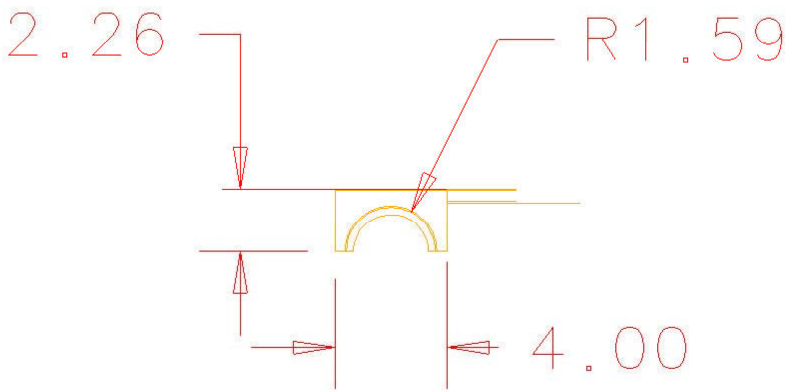
Distance between substrate to substrate within the blade

This distance should be as small as possible so that minimum material is effectively used to provide an hermitage coverage of tracking.

Existing design = 4.52 mm

Using this distance as the limiting guideline, it is possible to increase tubing size without thickening the TPG substrate.

Largest possible OD = 1/8” (3.175 mm).



% Rad L of Tubing and corresponding TPG Area Spreader per Substrate

Tubing ss 316L OD, inches	t, inches	Pressure, bar with SF = 2	**Half Tubing** area, mm^2	mass, g	Rad L due to t	Per Substrate Rad L over A	**TPG** Sp area, mm^2	mass, g	Per Substrate Rad L over A	**Total/Subs** Rad L over A	**Total/Blade** Rad L over A
0.125	0.01	160	1.165	0.893	1.41%	0.14%	3.049	0.672	0.03%	0.17%	0.34%
0.119	0.007	118	0.795	0.609	0.99%	0.09%	3.118	0.687	0.04%	0.13%	0.26%
0.108	0.009	167	0.903	0.692	1.27%	0.11%	3.195	0.704	0.04%	0.14%	0.28%
0.094	0.009	191	0.775	0.594	1.27%	0.09%	3.204	0.706	0.04%	0.13%	0.25%
0.094	0.005	106	0.451	0.345	0.71%	0.05%	3.204	0.706	0.04%	0.09%	0.18%
0.082	0.008	195	0.600	0.460	1.13%	0.07%	3.133	0.690	0.04%	0.11%	0.21%
0.082	0.0055	134	0.426	0.327	0.78%	0.05%	3.133	0.690	0.04%	0.09%	0.17%
0.0715	0.006	168	0.398	0.305	0.85%	0.05%	3.010	0.663	0.03%	0.08%	0.16%
0.0715	0.004	112	0.274	0.210	0.56%	0.03%	3.010	0.663	0.03%	0.07%	0.13%
0.0645	0.009	279	0.506	0.388	1.27%	0.06%	2.897	0.638	0.03%	0.09%	0.18%
0.0645	0.006	186	0.356	0.273	0.85%	0.04%	2.897	0.638	0.03%	0.07%	0.15%
0.0645	0.004	124	0.245	0.188	0.56%	0.03%	2.897	0.638	0.03%	0.06%	0.12%
0.0615	0.005	163	0.286	0.219	0.71%	0.03%	2.841	0.626	0.03%	0.07%	0.13%
0.0575	0.008	278	0.401	0.307	1.13%	0.05%	2.759	0.608	0.03%	0.08%	0.16%
0.0575	0.005	174	0.266	0.204	0.71%	0.03%	2.759	0.608	0.03%	0.06%	0.12%
0.0575	0.003	104	0.166	0.127	0.42%	0.02%	2.759	0.608	0.03%	0.05%	0.10%
0.0555	0.005	180	0.256	0.196	0.71%	0.03%	2.715	0.598	0.03%	0.06%	0.12%
0.0495	0.0085	343	0.353	0.271	1.20%	0.04%	2.570	0.566	0.03%	0.07%	0.14%
0.0495	0.006	242	0.265	0.203	0.85%	0.03%	2.570	0.566	0.03%	0.06%	0.12%
0.0495	0.004	162	0.184	0.141	0.56%	0.02%	2.570	0.566	0.03%	0.05%	0.10%
0.0455	0.0065	286	0.257	0.197	0.92%	0.03%	2.464	0.543	0.03%	0.06%	0.12%
0.0415	0.0075	361	0.258	0.198	1.06%	0.03%	2.349	0.518	0.03%	0.06%	0.11%
0.0415	0.005	241	0.185	0.142	0.71%	0.02%	2.349	0.518	0.03%	0.05%	0.10%
0.0415	0.0035	169	0.135	0.103	0.49%	0.02%	2.349	0.518	0.03%	0.04%	0.08%
0.0385	0.006	312	0.198	0.151	0.85%	0.02%	2.258	0.497	0.03%	0.05%	0.10%
0.0355	0.006	338	0.179	0.137	0.85%	0.02%	2.162	0.476	0.02%	0.05%	0.09%
0.0355	0.005	282	0.155	0.118	0.71%	0.02%	2.162	0.476	0.02%	0.04%	0.09%
0.0355	0.004	225	0.128	0.098	0.56%	0.02%	2.162	0.476	0.02%	0.04%	0.08%
0.034	0.004	235	0.122	0.093	0.56%	0.01%	2.113	0.465	0.02%	0.04%	0.08%
0.032	0.006	375	0.158	0.121	0.85%	0.02%	2.045	0.450	0.02%	0.04%	0.08%
0.032	0.005	313	0.137	0.105	0.71%	0.02%	2.045	0.450	0.02%	0.04%	0.08%
0.032	0.002	125	0.061	0.047	0.28%	0.01%	2.045	0.450	0.02%	0.03%	0.06%
0.03	0.0035	233	0.094	0.072	0.49%	0.01%	1.975	0.435	0.02%	0.03%	0.07%
0.028	0.006	429	0.134	0.102	0.85%	0.02%	1.903	0.419	0.02%	0.04%	0.07%
0.028	0.004	286	0.097	0.075	0.56%	0.01%	1.903	0.419	0.02%	0.03%	0.07%
0.028	0.0025	179	0.065	0.049	0.35%	0.01%	1.903	0.419	0.02%	0.03%	0.06%