FEA on the Conceptual Design of the FPIX substrate for the CMS upgrade

C. M. Lei
Simon Kwan

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Material Budget

CMS Forward Pixel Blade Radiation Length Estimate

3 Oct 2006

Assumes: Blade mass spread out evenly over area of a 3x substrate face
Normal tracks (20deg camber not accounted for)

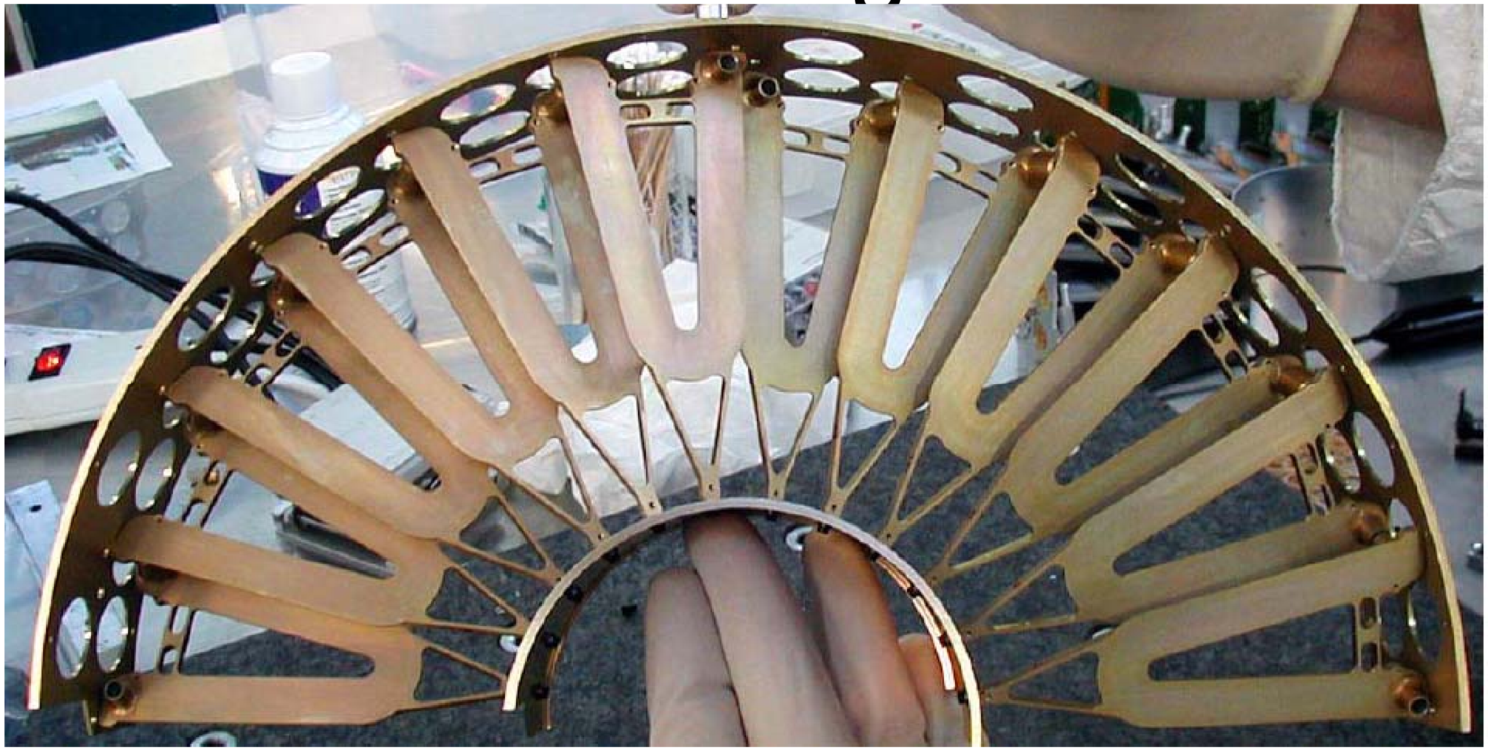
%RL Calc Assumes Mass Averaged over an Effective Area of 42.78 cm^2

Item	Reference	Material	Volume Fract.	Length (mm)	Width (mm)	Thickness (mm)	SubAssy Volume (mm^3)	Qty	Total Volume (mm^3)	Density (g/mm^3)	Mass (g)	Matl Rad Length (g/cm^2)	%RL	Percent of Total %RL
Sensors											4.9		0.50	12.0
1x2	CMSTKPPE.0001		1.00	18.49	10.39	0.270	51.9	1	51.9	0.00233	0.121	21.82	0.01	0.3
1x5	CMSTKPPE.0002		1.00	42.79	10.39	0.270	120.1	1	120.1	0.00233	0.280	21.82	0.03	0.7
2x3	CMSTKPPE.0003		1.00	26.59	18.49	0.270	132.8	2	265.6	0.00233	0.619	21.82	0.07	1.6
2x4	CMSTKPPE.0004		1.00	34.69	18.49	0.270	173.2	2	346.5	0.00233	0.807	21.82	0.09	2.1
2x5	CMSTKPPE.0005		1.00	42.79	18.49	0.270	213.7	1	213.7	0.00233	0.498	21.82	0.05	1.2
PSI-46 chip	CMSTKPPE.0006		1.00	9.94	8.01	0.190	15.1	45	680.0	0.00233	1.584	21.82	0.17	4.1
Bump Bonds		(63/37 Tin/Lead)	1.00	0.02	0.02	0.025	0.0	187200	2.9	0.00880	0.026	7.72	0.01	0.2
Chotherm1680 (VHDI-to-chip)	See docdb #921	Acrylic	1.00	9.94	8.01	0.025	2.0	45	89.5	0.00110	0.098	40.00	0.01	0.1
		BN powder	0.20	9.94	8.01	0.125	2.0	45	89.5	0.00350	0.313	42.39	0.03	0.4
		Silicone	0.80	9.94	8.01	0.125	8.0	45	357.9	0.00130	0.465	25.13	0.04	1.8
		Polyimide	1.00	9.94	8.01	0.025	2.0	45	89.5	0.00140	0.125	38.39	0.01	0.3
VHDIs											8.7		0.93	22.4
Substrates	CMSTKPPE.0008 & 0009	1 x 2	1.00	21.36	15.05	0.300	96.4	1	96.4	0.00233	0.225	21.82	0.02	0.6
	CMSTKPPE.0010 & 0011	1 x 5	1.00	45.66	15.05	0.300	206.1	1	206.1	0.00233	0.480	21.82	0.05	1.2
	CMSTKPPE.0012	2 x 3	1.00	29.46	27.77	0.300	245.4	2	490.8	0.00233	1.143	21.82	0.12	2.9
	CMSTKPPE.0013	2 x 4	1.00	38.66	27.77	0.300	321.2	2	642.4	0.00233	1.497	21.82	0.16	3.9
	CMSTKPPE.0014	2 x 5	1.00	46.66	27.77	0.300	380.3	1	380.3	0.00233	0.886	21.82	0.09	2.2
3M 9882 tape (VHDI to substrate)	See docdb #921	Acrylic assumed	0.80	Tot Area =	6063.26	0.050	242.1	1	242.1	0.00110	0.266	40.00	0.03	0.4
		Ceramic (BN assumed)	0.20	Tot Area =	6063.26	0.050	60.5	1	60.5	0.00350	0.212	42.39	0.01	0.3
VHDIs	V.C. email 10/3/06	Kapton	1.00	Tot Area =	6063.26	0.090	544.9	1	544.9	0.00140	0.763	38.39	0.05	1.1
		Copper	0.60	Tot Area =	6063.26	0.040	146.3	1	146.3	0.00930	1.361	12.86	0.25	5.9
Capacitors		(BaTiO3 assumed)	1.00	1.00	0.50	0.250	0.1	136	16.9	0.00608	0.103	11.31	0.02	0.5
Resistors		(Alumina assumed)	1.00		Volume =	0.000	0.0	0	0.0	0.00326	0.000	27.46	0.00	0.0
Solder		(63/37 Tin/Lead)	1.00	0.20	0.20	0.500	0.0	270	5.4	0.00880	0.048	7.72	0.01	0.3
Chotherm1680 (HDI-to-plaquette)	See docdb #921	Acrylic	1.00	Tot Area =	6063.26	0.025	151.3	1	151.3	0.00110	0.166	40.00	0.01	0.2
		BN powder	0.20	Tot Area =	6063.26	0.125	151.3	1	151.3	0.00350	0.530	42.39	0.03	0.7
		Silicone	0.80	Tot Area =	6063.26	0.125	606.3	1	606.3	0.00130	0.787	25.13	0.07	1.8
		Polyimide	1.00	Tot Area =	6063.26	0.025	151.3	1	151.3	0.00140	0.212	38.39	0.01	0.3
HDIs											12.5		0.80	19.2
Substrates	CMSTKPPE.0007	(Be)	1.00	Area =	4278.00	0.508	2173.2	2	4346.4	0.00185	8.032	65.19	0.29	6.9
HDI	V.C. email 10/3/06	Kapton	1.00	Area =	4278.00	0.100	427.8	2	855.6	0.00140	1.198	38.39	0.07	1.8
		Internal flex adhesive	1.00	Area =	4278.00	0.050	213.9	2	427.8	0.00125	0.535	40.00	0.03	0.8
		Copper	0.29	Area =	4278.00	0.057	67.5	2	134.9	0.00930	1.255	12.86	0.23	5.5
Capacitors		(BaTiO3 assumed)	1.00	0.75	0.50	0.640	0.2	9	1.9	0.00608	0.012	11.31	0.00	0.1
Resistors		(Alumina, RTD added as 2 extra)	1.00	0.75	0.50	0.640	0.2	9	2.2	0.00326	0.007	27.46	0.00	0.0
Solder		(63/37 Tin/Lead)	1.00		Volume =	0.540	0.5	17	8.5	0.00880	0.075	7.72	0.03	0.5
TBM Chip		Silicon	1.00	4.42	3.20	0.600	0.6	2	1.2	0.00233	0.003	21.82	0.00	0.0
3M 9882 tape (HDI to substrate)	See docdb #921	Acrylic assumed	0.80	Area =	4278.00	0.050	171.1	2	342.2	0.00110	0.376	40.00	0.03	0.5
		Ceramic (BN assumed)	0.20	Area =	4278.00	0.050	42.8	2	85.6	0.00350	0.299	42.39	0.03	0.4
Bias / Ground Wires	CMSTKPPE.0112	Copper	1.00	Area =	0.08	80.000	6.0	6	36.2	0.00930	0.337	12.86	0.06	1.5
		Kapton	1.00	Area =	0.23	80.000	18.1	6	108.7	0.00140	0.152	38.39	0.01	0.3
		Solder (63/37 Tin/Lead)	1.00		Volume =	1.000	1.0	12	12.0	0.00880	0.106	7.72	0.03	0.8
		Epoxy	1.00		Volume =	15.000	15.0	2	30.0	0.00110	0.033	40.00	0.00	0.0
		In Solder (52In 48Sn)	1.00		Volume =	3.000	3.0	2	6.0	0.00730	0.044	8.93	0.01	0.3
Support Hardware											20.9		1.92	46.3
Panel + Channel Screws		(Ti, M1.6)	1.00		Volume =	13.624	13.6	9	122.6	0.00454	0.557	16.17	0.08	1.9
Cooling Channel	CMSTKPSP.0115 & 0131	(Al, includes 1 jumper)	1.00		Volume =	3261	3261.0	1	3261.0	0.00270	8.805	24.01	0.86	20.6
Outer Ring	CMSTKPSP.0128-A	(Al, model vol. / 12)	1.00		Volume =	1774	1773.9	1	1773.9	0.00270	4.790	24.01	0.47	11.2
Inner Ring	CMSTKPSP.0126	(Al, model vol. / 12)	1.00		Volume =	796	796.1	1	796.1	0.00270	2.150	24.01	0.21	5.0
Coolant		(C6F14 -- volume from V.R.)	1.00		Volume =	15530	15530.0	0.1667	2588.3	0.00179	4.638	34.82	0.31	7.3

DOES NOT INCLUDE:
Adapter Board
Other plumbing hardware
Survey Balls

Total = 4.16 %RL
Total = 47 grams

The Al cooling channel



They are the most complicated component of the Disk. They are made out of 2 blocks of Al aluminum brazed together.
It took 5 prototyping submissions, with Bodycote, over 5 years to develop a reliable process.

1st Brazing U. Miss.	Dec 2000 - Sep 03	Data Base #	xxxxxxx
2nd Brazing FNAL	Nov 02 - May 03	Data Base #	xxxxxxx
3rd Brazing FNAL	Mar 03 - Jun 03	Data Base #	xxxxxxx
4th Brazing FNAL	Jun 03 - Apr 04	Data Base #	xxxxxxx
5th Brazing FNAL	Feb 05 – Dec 05	Data Base #	xxxxxxx

Prototypes from last subm. have been used to assemble the first ½-Disk

For each of the ± z sides 3 types of channels are needed!

Material Candidates

	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	600.0	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	1050.0	36.0		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

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 ~ 1600 W/mK at room temperature

- Cooling selected for Substrate
  - High-pressure CO_2 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.

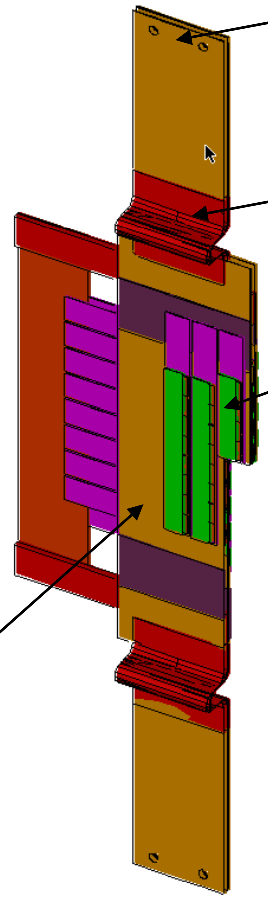
Thermal Pyrolytic Graphite (TPG)

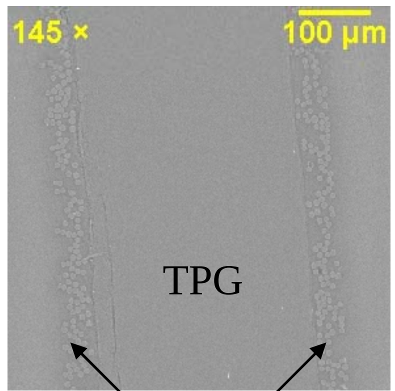
- A unique form of pyrolytic graphite
- Made by the decomposition of a hydrocarbon gas within vacuum furnace
- High thermal conductivity (in-plane k = up to 1700 W/m-K, out-of-plane k = 10W/m-K at room temperature)
- Low CTE (in-plane = -1 ppm/C, out-of-plane = 25 ppm/C)
- Low density = 2.26 g/cc
- X0 = 18.9 cm (X0*k = 321 W/K vs 51 W/K of Be)
- Friable, needs encapsulation; carbon fiber composite is chosen for needed rigidity within material budget constraint.
- Extensive studies performed by BTeV from 2002-2005. Also used by ATLAS (strips) and LHCb.
- Vendors:
    - Momentive Performance Materials (http://advceramics.com/)
      Quote: TPG0044
      TPG .38MM THKx90mmx150mm LG
      .38MM +/-.03mm
      20-50pc's 203.50ea.

    - MiNTEQ (http://pyrographite.com/)

TPG Experience at FermiLab

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

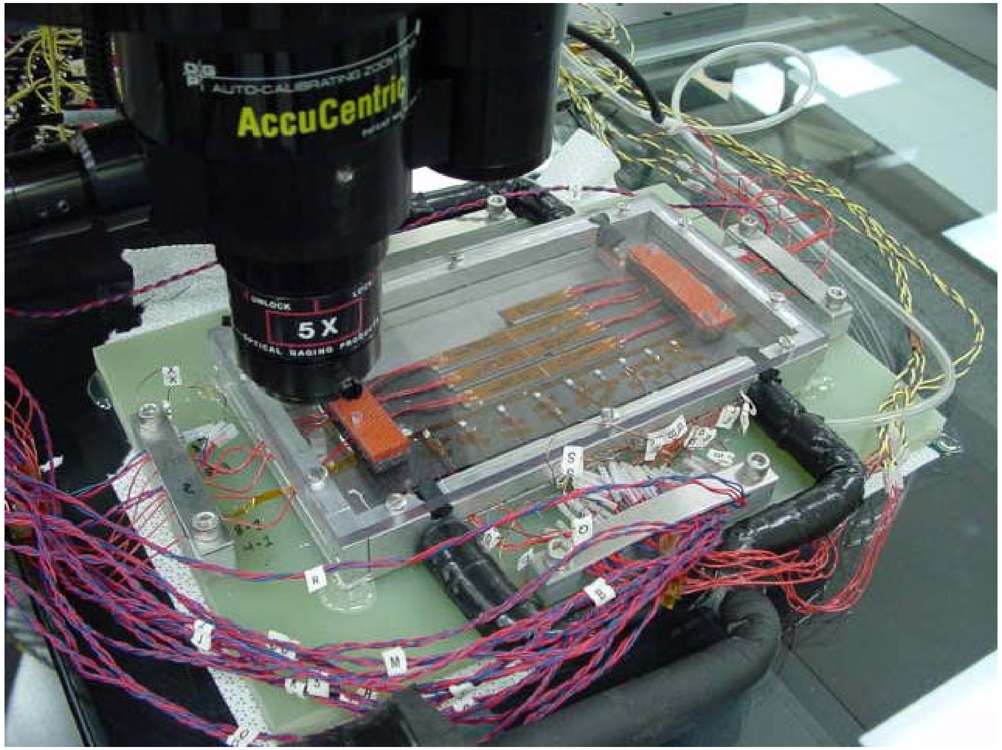




TPG Experience at FermiLab …continued (1)

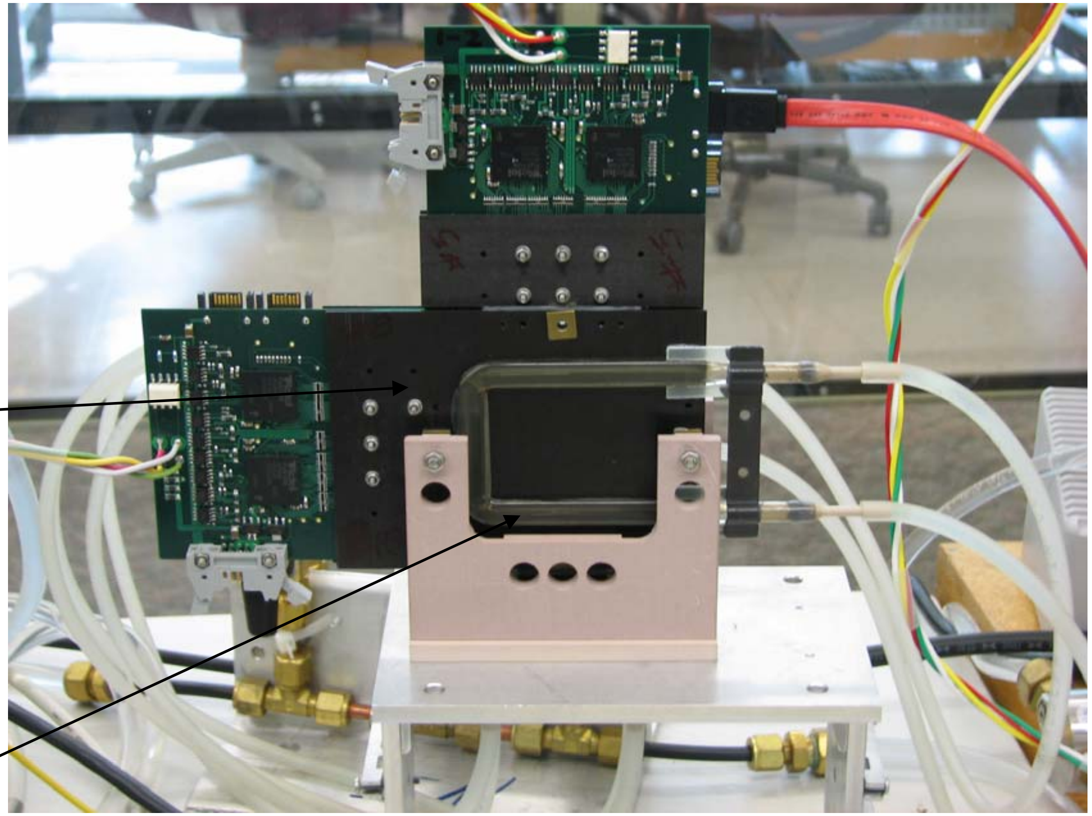
The BTeV prototype was made and thermal cyclic tests with heaters and cooling on and off were conducted. Results were satisfactory, no alarming problem was found.

- 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 (2008)

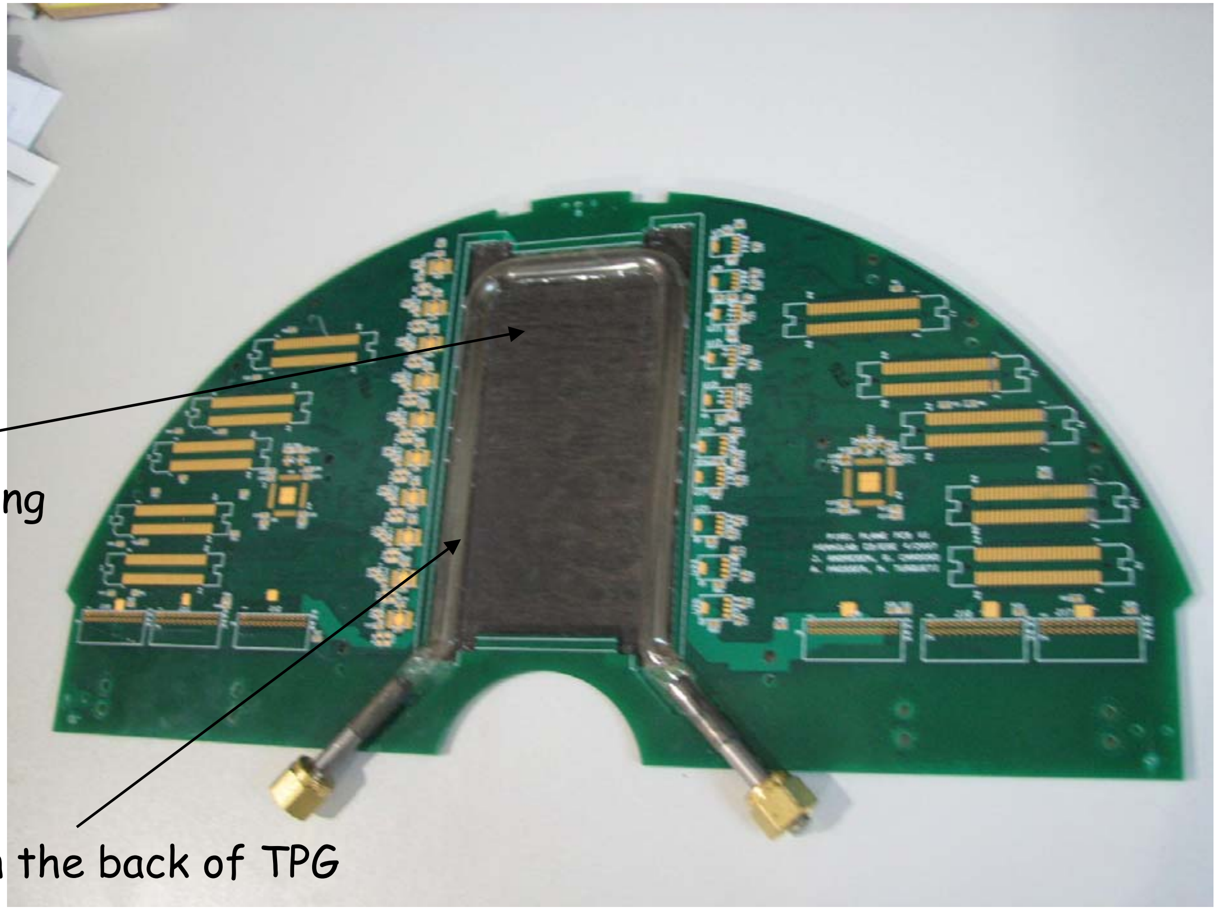


TPG encapsulated with two plies of CFRP for the facing

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.

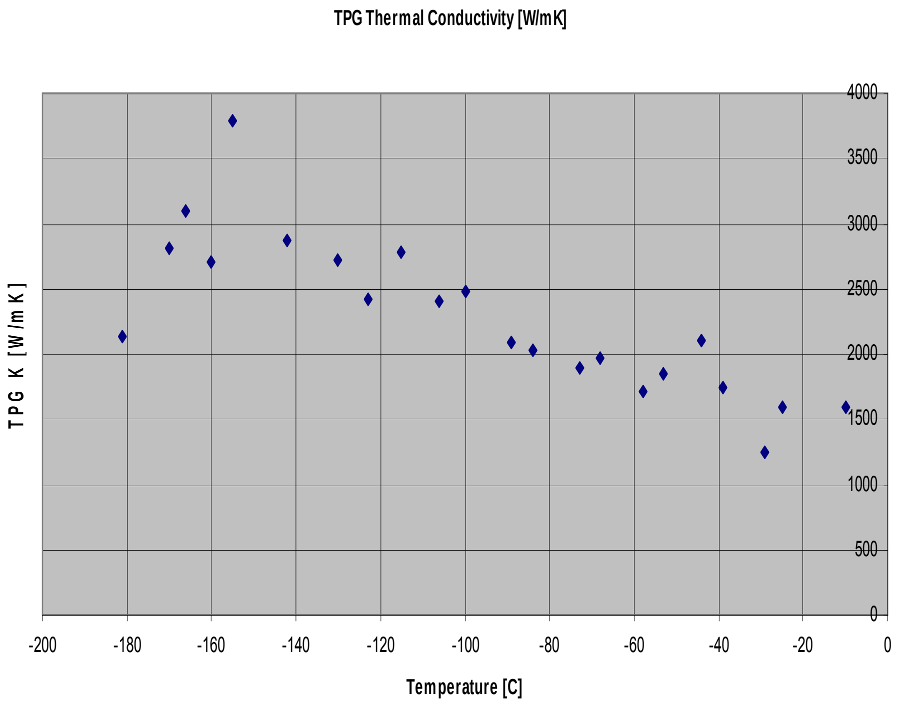


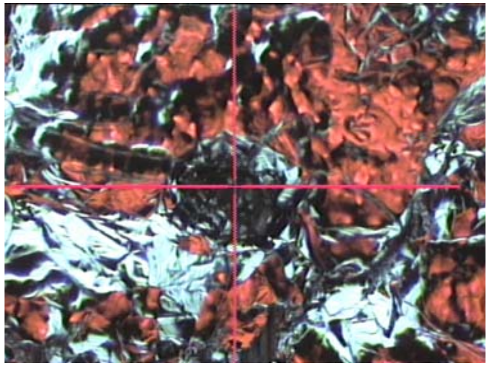
TPG encapsulated with
two plies of CFRP for the facing

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 flattened somewhat when CFRP was added.





This perforated hole was basically filled up completely with epoxy

Averaged Heat Load Density used in this FEA

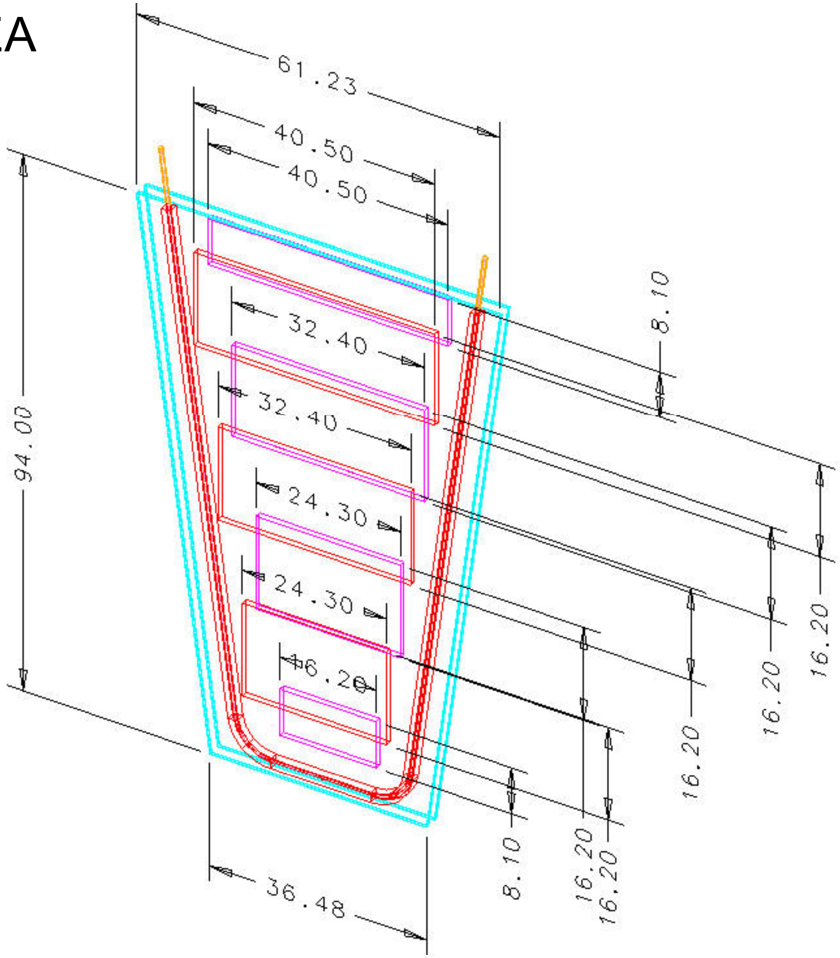
Sensor Dimensions

	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



The tentative basic structure – the blade, which consists of 2 substrates with cooling tubing in between.

Commercially Available ss 316L tubing

From Eagles Stainless Tube & Fabrication, Inc

SS 316L Yield strength = 2000 bars

OD, inches	t, inches	OD in mm	ID in mm	t, mm	Rad L due to 2 t	Pressure, bar due to yield	Pressure, bar with SF = 3
0.0645	0.009	1.6383	1.1811	0.2286	2.54%	558	186
0.0645	0.006	1.6383	1.3335	0.1524	1.69%	372	124
0.0645	0.004	1.6383	1.4351	0.1016	1.13%	248	83
0.0615	0.005	1.5621	1.3081	0.127	1.41%	325	108
0.0575	0.008	1.4605	1.0541	0.2032	2.26%	557	186
0.0575	0.005	1.4605	1.2065	0.127	1.41%	348	116
0.0575	0.003	1.4605	1.3081	0.0762	0.85%	209	70
0.0555	0.005	1.4097	1.1557	0.127	1.41%	360	120
0.0495	0.0085	1.2573	0.8255	0.2159	2.40%	687	229
0.0495	0.006	1.2573	0.9525	0.1524	1.69%	485	162
0.0495	0.004	1.2573	1.0541	0.1016	1.13%	323	108
0.0455	0.0065	1.1557	0.8255	0.1651	1.83%	571	190
0.0415	0.0075	1.0541	0.6731	0.1905	2.12%	723	241
0.0415	0.005	1.0541	0.8001	0.127	1.41%	482	161
0.0415	**0.0035**	**1.0541**	**0.8763**	**0.0889**	**0.99%**	**337**	**112**
0.0385	0.006	0.9779	0.6731	0.1524	1.69%	623	208
0.0355	0.006	0.9017	0.5969	0.1524	1.69%	676	225
0.0355	0.005	0.9017	0.6477	0.127	1.41%	563	188
0.0355	0.004	0.9017	0.6985	0.1016	1.13%	451	150
0.034	0.004	0.8636	0.6604	0.1016	1.13%	471	157
0.032	0.006	0.8128	0.508	0.1524	1.69%	750	250
0.032	0.005	0.8128	0.5588	0.127	1.41%	625	208
0.032	0.002	0.8128	0.7112	0.0508	0.56%	250	83
0.03	0.0035	0.762	0.5842	0.0889	0.99%	467	156
0.028	0.006	0.7112	0.4064	0.1524	1.69%	857	286
0.028	0.004	0.7112	0.508	0.1016	1.13%	571	190
0.028	0.0025	0.7112	0.5842	0.0635	0.71%	357	119

ss tubing used in this FEA

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

Thermal K of epoxy
(3M DP190 Gray) = 0.38 W/mK

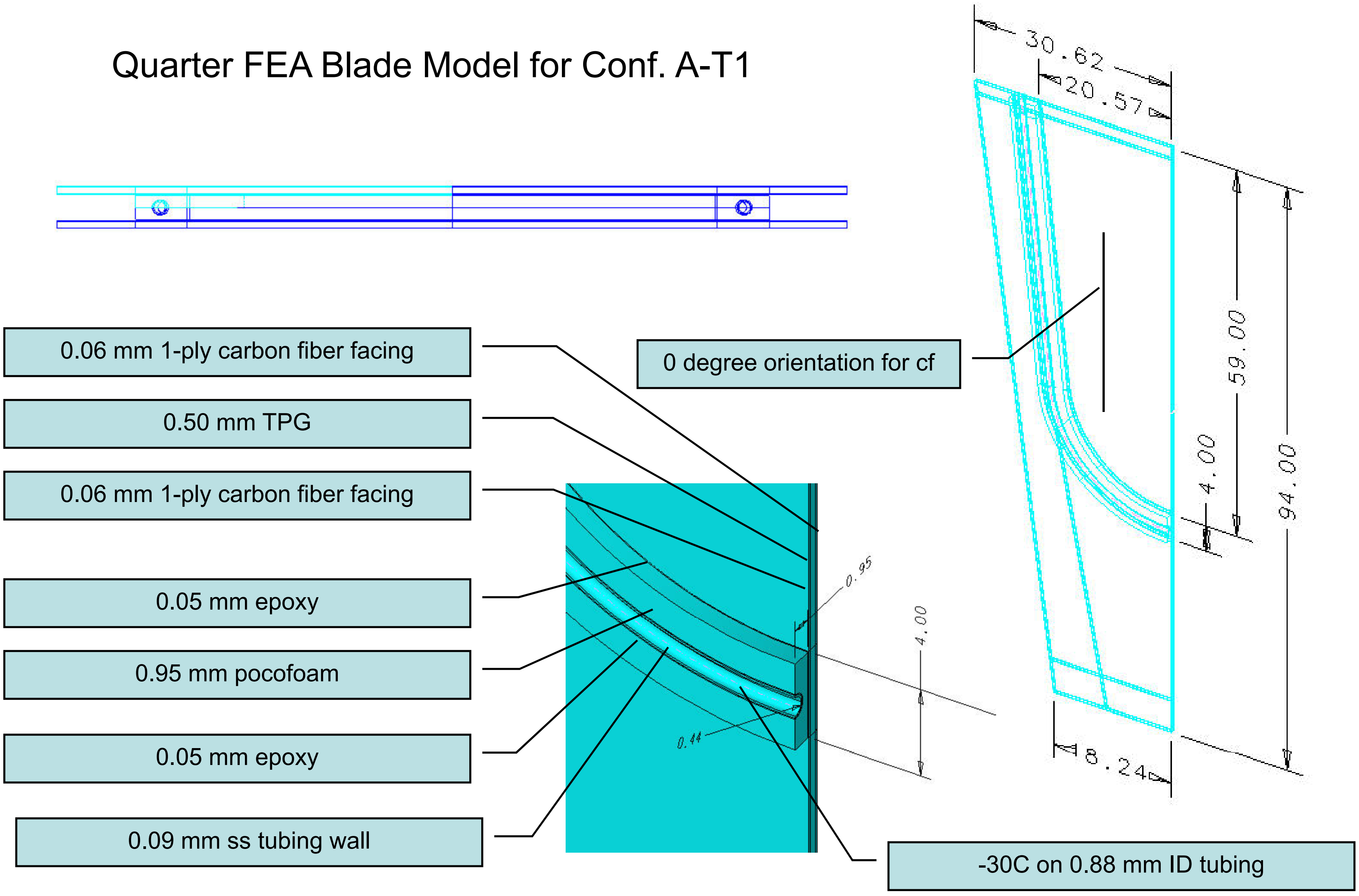
0/90 Carbon-Fiber Facing, In-Plane	= 63.3 W/mK
0/90 Carbon-Fiber Facing, Out-of-Plane	= 0.6 W/mK
0 Carbon-Fiber Facing, In-Plane	= 126 W/mK
0 Carbon-Fiber Facing, Out-of-Plane	= 0.6 W/mK
Carbon-carbon, In-Plane	= 225 W/mK
Carbon, Out-of-Plane	= 150 W/mK
Pocofoam, In-Plane	= 45 W/mK
Pocofoam, Out-of-Plane	= 135 W/mK

Configurations Analyzed in this FEA

- Two cooling layouts.
  - Conf. A >> U-shape
  - Conf. B >> Lateral X2

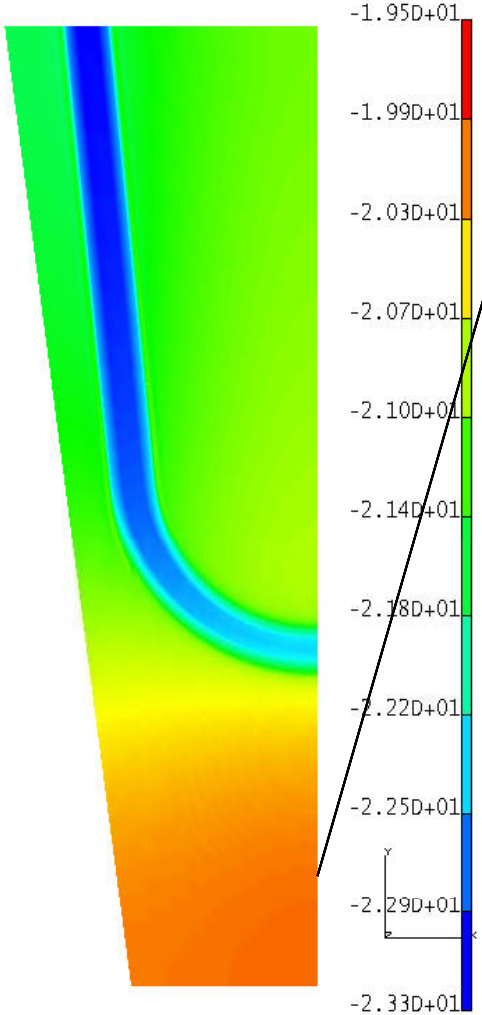
- Two different sets of layer thickness
  (same overall substrate thickness at 0.62 mm)
  - T1 >> 0.06 mm 1-ply cf + 0.50 mm TPG + 0.06 mm 1-ply cf
    - (total rad L % = 0.025% + 0.205% + 0.025% = 0.255% of X0)
  - T2 >> 0.12 mm 2-ply cf + 0.38 mm TPG + 0.12 mm 2-ply cf
    - (total rad L % = 0.049% + 0.157% + 0.049% = 0.255% of X0)

Quarter FEA Blade Model for Conf. A-T1

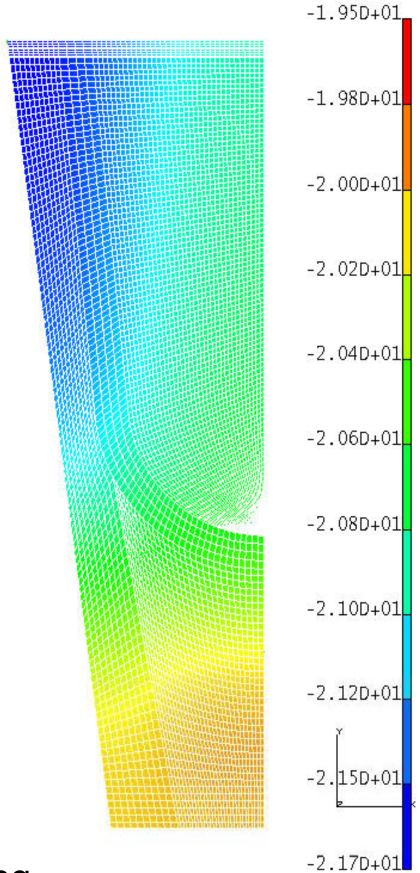


Conf. A-T1: 0.06 cf + 0.50TPG + 0.06 cf Substrate

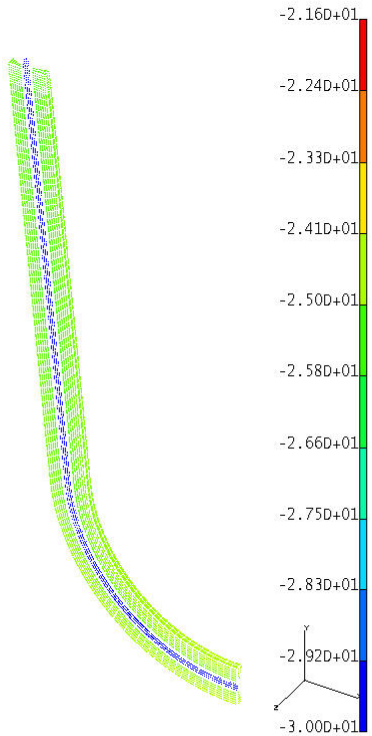
200% heat load (0.318 W/cm^2)
4.44 W on this half substrate

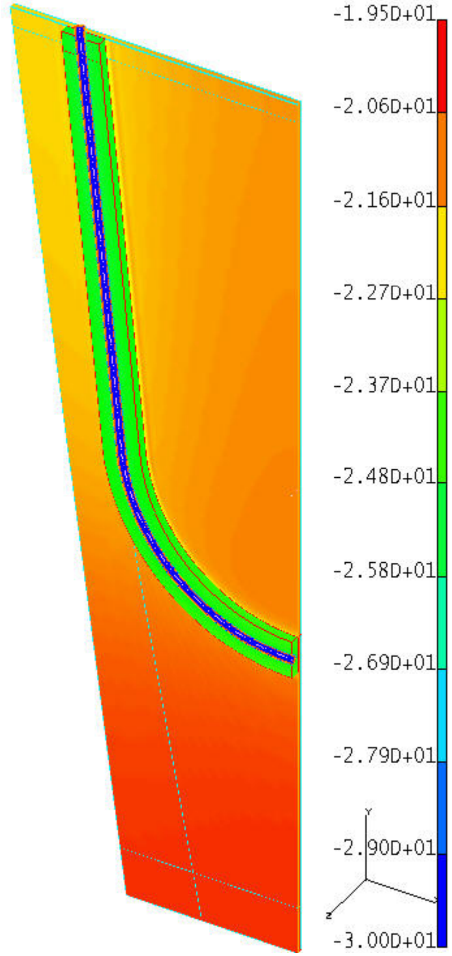


-19.5C



ΔT = 8.4 C
from tube to epoxy



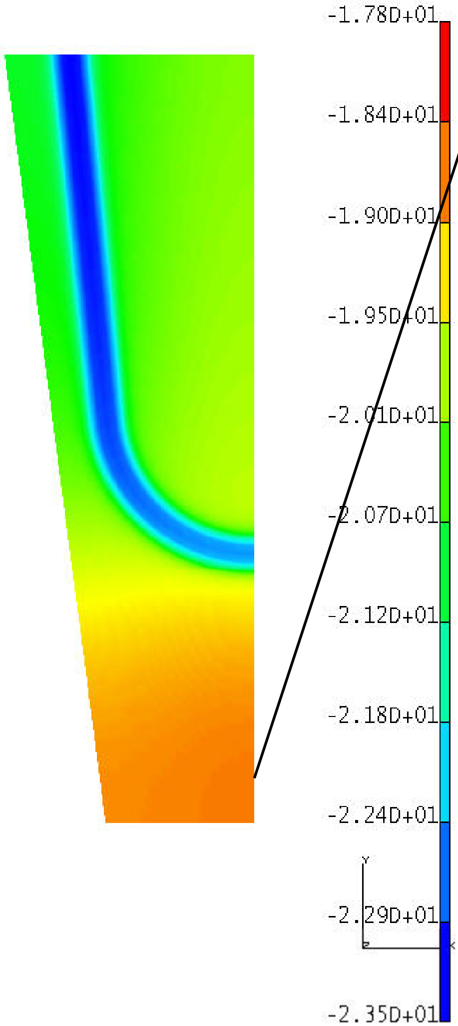


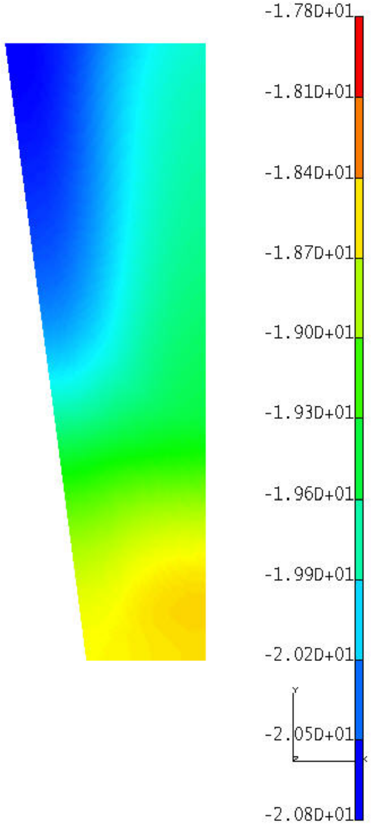
ΔT = 3.8 C across substrate
ΔT = 2.2 C across cf top facing

Overall ΔT = 10.5 C

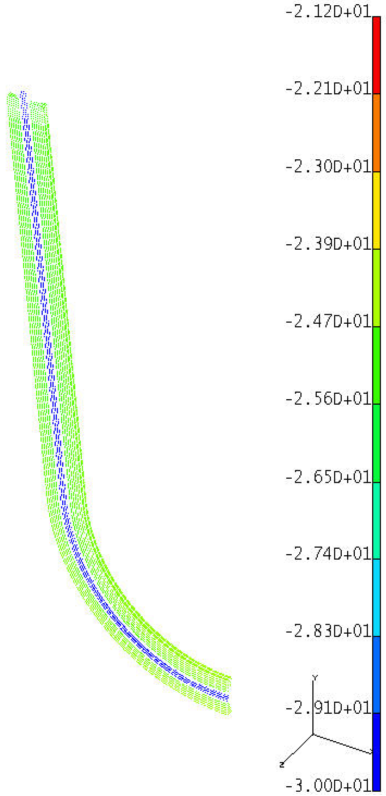
Conf. A-T2: 0.12 cf + 0.38TPG + 0.12 cf Substrate

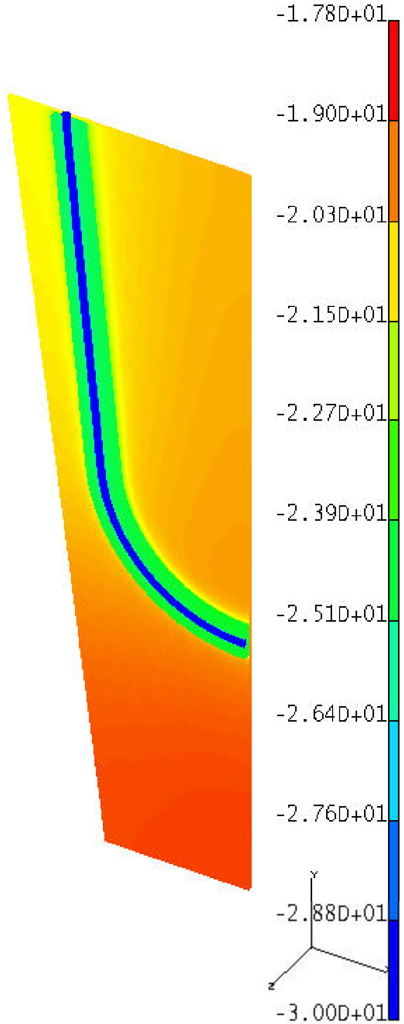
200% heat load (0.318 W/cm^2)
4.44 W on this half substrate





ΔT = 8.8 C
from tube to epoxy

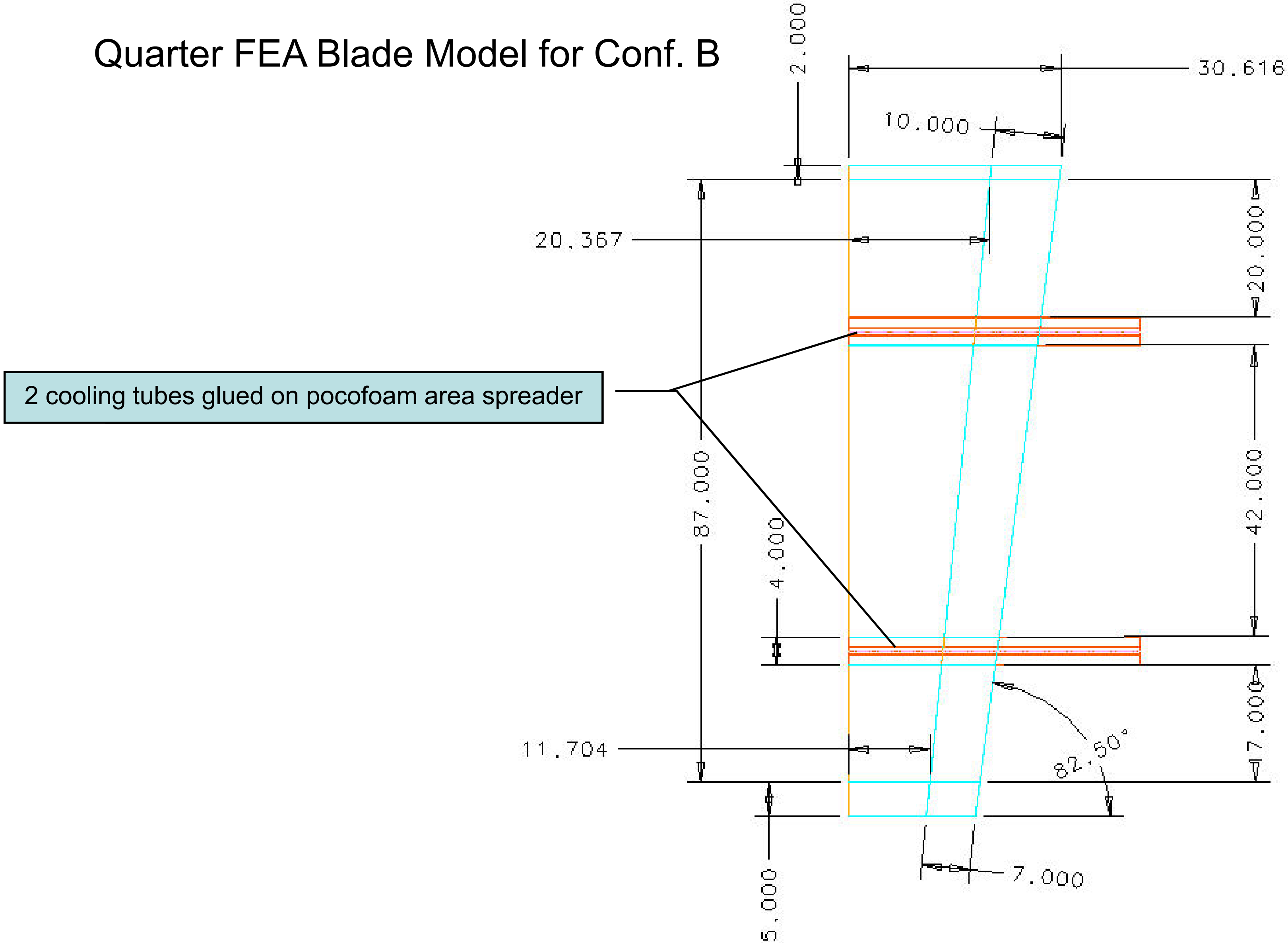




ΔT = 5.1 C across substrate
ΔT = 3 C across cf top facing

Overall ΔT = 12.2 C

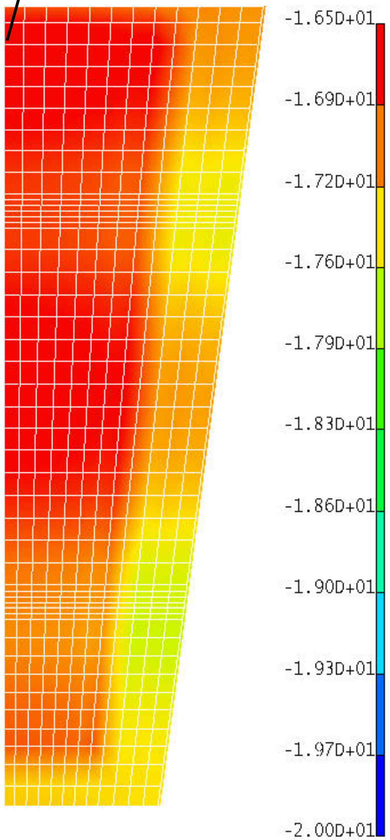
Quarter FEA Blade Model for Conf. B

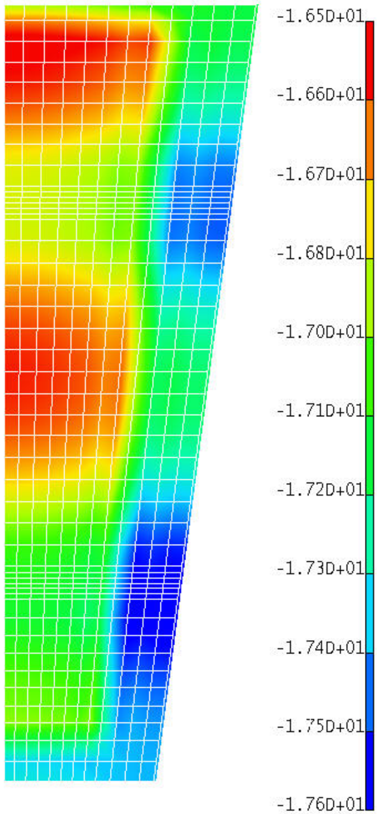


Conf. B-T1: 0.06 cf + 0.50TPG + 0.06 cf Substrate

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

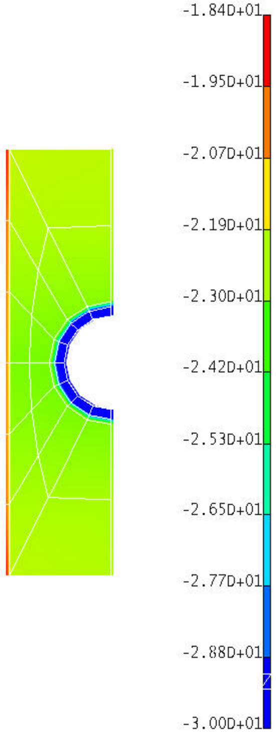
-16.5C

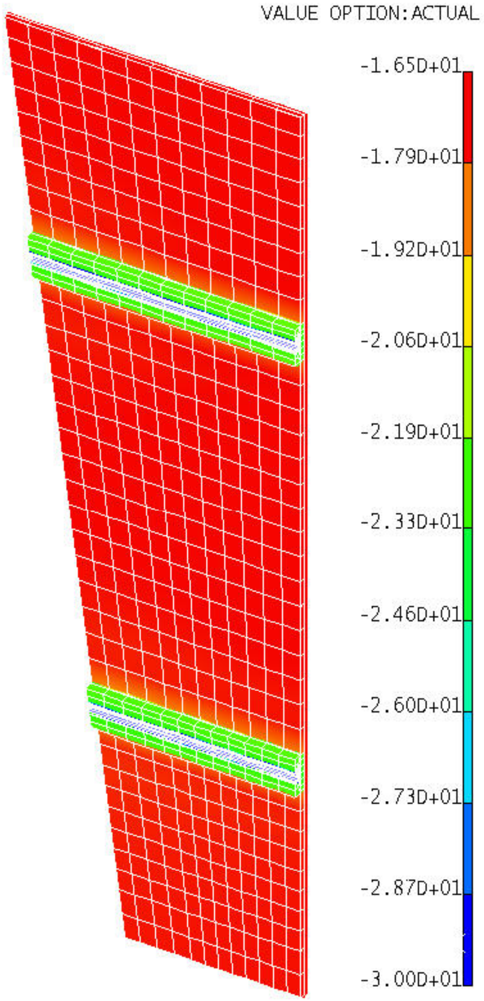




ΔT = 3.5 C across substrate
ΔT = 1.1 C across cf top facing

ΔT = 11.6 C
from tube to epoxy

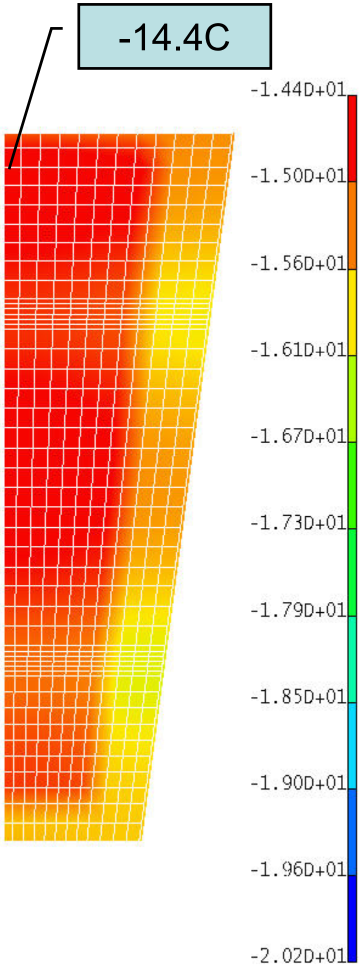


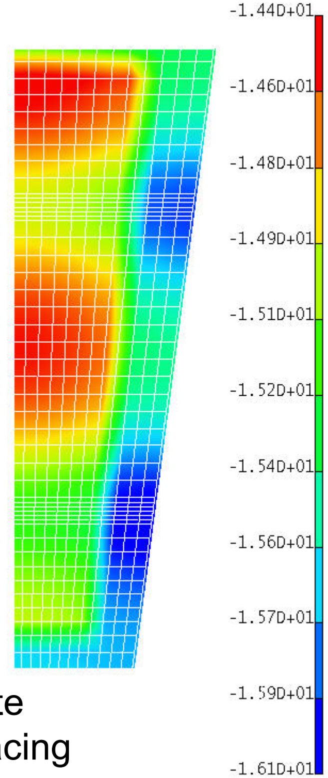


Overall ΔT = 13.5 C

Conf. B-T2: 0.12 cf + 0.38TPG + 0.12 cf Substrate

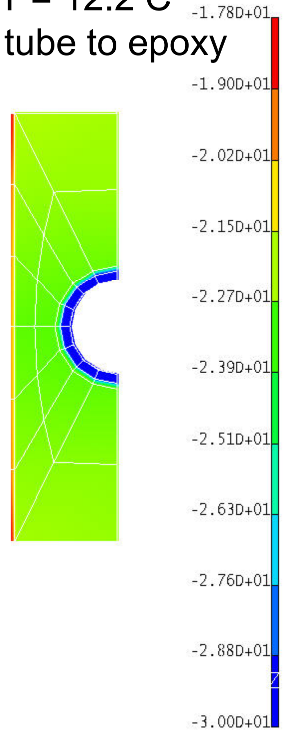
200% heat load (0.318 W/cm^2)
4.44 W on this half substrate

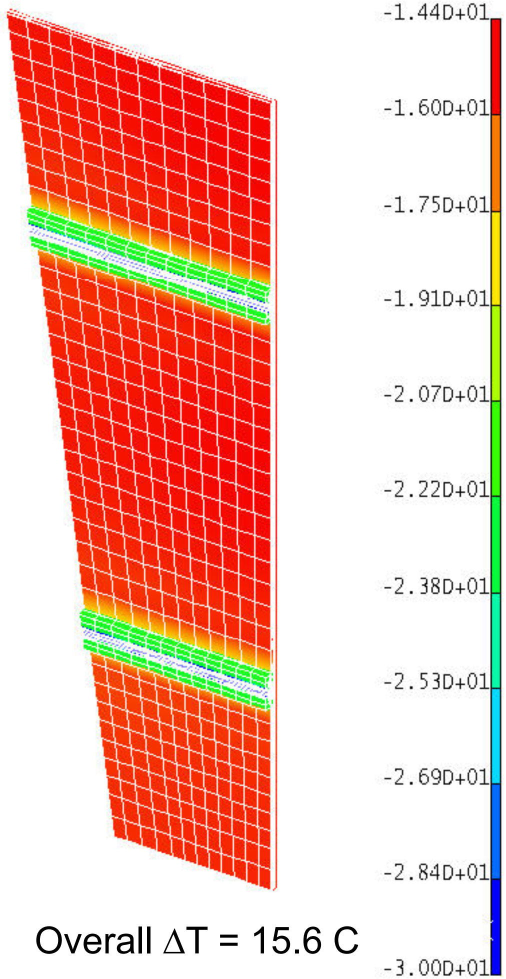




ΔT = 5.8 C across substrate
ΔT = 1.7 C across cf top facing

ΔT = 12.2 C
from tube to epoxy





Overall ΔT = 15.6 C

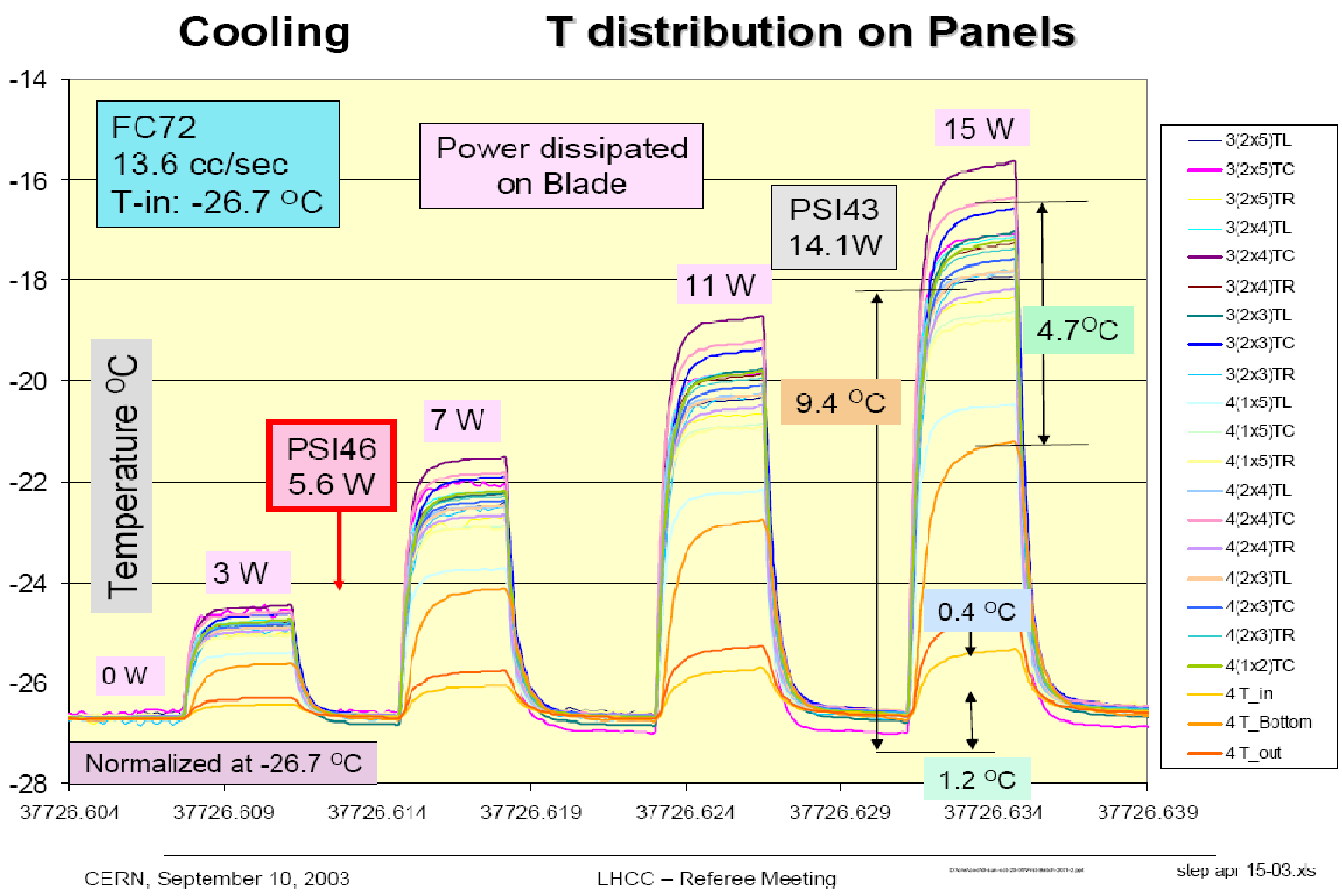
Summary of Results

<< All substrates are with overall thickness 0.62 mm and under 200% heat load >>

Configuration	ΔT, tubing	ΔT, tube epoxy	ΔT, foam	ΔT, subs epoxy	ΔT, substrate	ΔT, overall
A-T1	0.2	5.2	1.3	3.7	3.8	10.5
A-T2	0.2	5.2	1.3	4.2	5.1	12.2
B-T1	0.3	7	1	4.5	3.5	13.5
B-T2	0.3	7	1.1	5.1	5.8	15.6
A - berylium					13.9	19.4

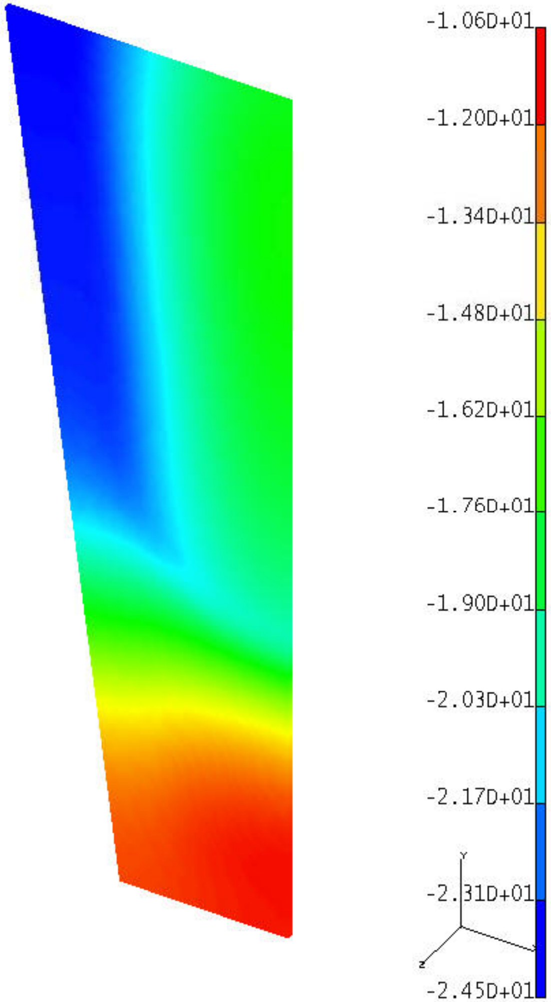
Configuration A-T1 performed the best with least temperature drop.

For Comparison

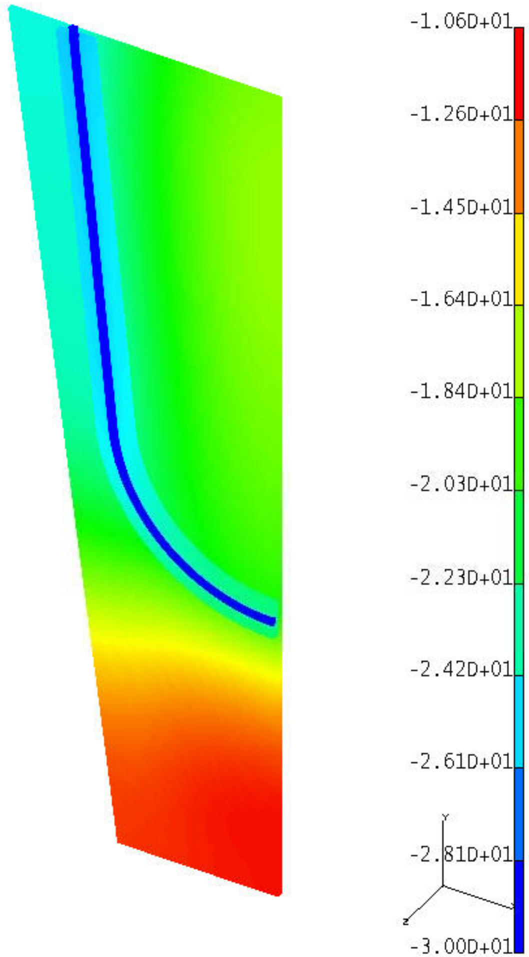


Conf. A: 0.62 mm thick Berylium Substrate

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



ΔT = 13.9 C across substrate



Overall ΔT = 19.4 C

Conclusions on this FEA with 200% Heat Load

- The temperature drops across the substrate were small.
- The temperature drops across the tubing and pocofoam were small.
- The major temperature drops occurred across the epoxy layers.
- The temperature drops of the thicker TPG with 1-ply cf facings configuration (-T1) were slightly better than the thinner one (-T2) by about 2 degrees C.
- In some previous FEA work,
  - The direct gluing of the small tubing to the TPG would result in a huge temperature drop. (~15 C more). An area spreader made of pocofoam or CC might be preferred.
  - The thermal performances of the pocofoam and CC were found about the same.
- For the cooling layout of configuration A, the major temperature drops across the substrate should be even smaller if the tip of the U-shape cooling tube is pushed deeper towards the beam axis. (It may not be preferred as it means more mass of material in region closer to the beam.)

Proposed Conceptual Design

- TPG will be used for the core of the substrate.
- The major function of the carbon fiber facing is to provide the encapsulation. This can be simply made by adding one ply of carbon fiber reinforced plastics (CFRP). So 1 ply K139-EX1515 CFRP will be used unless extra rigidity is needed.
- Pocofoam is much less expensive than CC and much easier to make. Pocofoam will be tried first.
- The U-shape cooling line profile will be used. The tip of the U channel may be arranged 10~20 mm closer to the beam axis if acceptable.