Pixel Detector Local Mechanical Supports with Integrated Cooling Based on Thermally Conducting Carbon Foam

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ABSTRACT: A design concept for local mechanical supports with integrated cooling for pixel detector upgrades at the SLHC is described. The design is based on using thermally conducting, low-density carbon foam. The fabrication of prototype structures is presented. The results from tests of thermal performance are given. Prospects for future developments are described briefly.

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1. Introduction

Silicon pixel detectors are expected to be used on a large scale for an upgraded tracking detector for the Super Large Hadron Collider (SLHC). The area of the SLHC pixel detector is anticipated to be larger by a factor of about three compared to the current ATLAS pixel detector. In addition, pixel layers are likely to be located both closer to the beam axis and at significantly larger radii than in the current detector. Barrels and disks will be required to cover the full pseudo-rapidity range $|\eta|<2.5$.

Pixel modules will be located on so-called local supports that integrate the mechanical support of the modules with cooling. We describe in this note a concept for the local supports based on using low-density, thermally conducting carbon foam as both a structural material and to conduct heat from the pixel modules to cooling tubes. The foam and other materials may be assembled to provide local supports for the innermost layers, large-area pixel elements at the outer barrel layers and forward/backward disks. Although the detailed design of the local supports may vary in the different regions, a common element in the proposed concept is to use low-density, thermally conducting carbon foam.

In the sections that follow, we briefly introduce the conceptual design possibilities using carbon foam. We then describe the fabrication of small prototypes and subsequent measurements of the thermal performance. These measurements are compared with finite-element calculations.

2. Concept Overview

The basic concept of using carbon foam as a structural and thermal material in a pixel local support is illustrated schematically in Figure 1. Pixel modules are mounted on one or both sides of the local support (barrel or disk sub-element). The carbon foam captured in part or in whole by facing material provides both stiffness to the structure and is the principal means by which heat is conducted from the pixel modules to the coolant tubes. The carbon foam may be used with different facing materials (carbon fiber, carbon-carbon or other materials) to obtain the required mechanical and thermal performance. Although two coolant tubes are shown in Figure 1, a single tube or a tube shared among modules is also an option. An important consequence of using thermally conducting foam is the ability to use round tubes that are more stable against pressure and to increase heat flow into the tube in comparison to flattened tubes used in the current pixel detector.

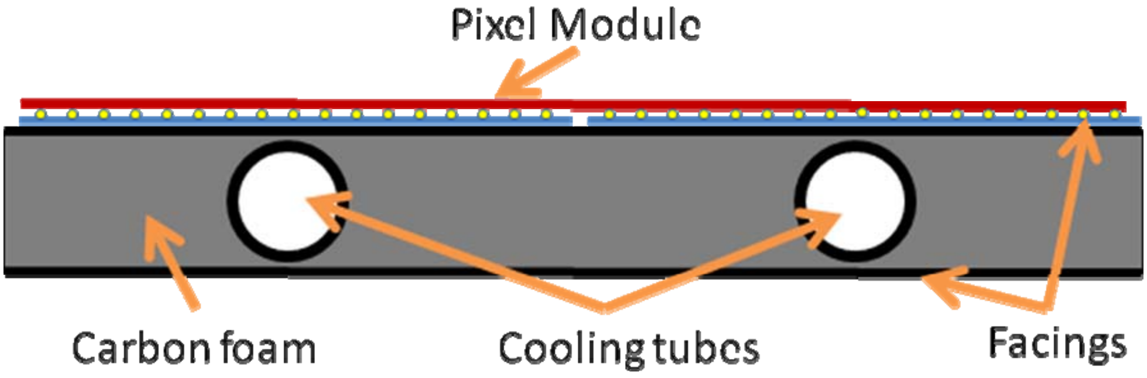

Figure 1 Concept for using thermally conducting carbon foam in local support structures.

Two types of carbon foam have been considered. Graphite foams from two vendors (POCO Graphite and Koppers) have been used to fabricate prototypes.[1] In addition, carbon foam based on enhancing the thermal conductivity of reticulated vitreous carbon (RVC) foam (Allcomp, Inc.) has also been used. [2] The principal challenge in the fabrication of the carbon foams is to maintain a reasonable thermal conductivity, K, and reduce the density,ρ, of the foam (and thereby the radiation length of the structure). The specific values of K and ρ used in the prototypes are given later.

3. Prototype Fabrication

Small prototypes of a simple structure were fabricated to validate the design concept and for measurements of thermal performance using IR imaging. The principal components of one of the prototypes are illustrated in Figure 2 and Figure 3. The foam used in this prototype was obtained from Allcomp,Inc and had a density of 0.18 g/cc. The foam pieces were machined from a small block, including a groove for the aluminum cooling tube. The foam pieces were glued to thin, carbon-fiber facings using epoxy loaded with boron-nitride (30% by weight) to enhance the thermal conductivity.[1] Two materials were used for the facings: YSH-70 woven cloth 0.14-0.17 mm thick and a four-ply (90-0-0-90) laminate of K13D2U fiber 0.28-0.32 mm thick. The aluminum tube had an outer diameter of about 2.8 mm and an inner diameter of about 2.2 mm. The tube was bonded to the foam by a compliant thermal adhesive with a 0.1 mm bond line.[2] The width of the prototype was 24 mm and the length (of the facings) 213 mm.

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[1] The epoxy used was Hysol 9396.

[2] CGL-7018 from AI Technology.

Figure 2 Principal components of first foam prototype structure described in the text.

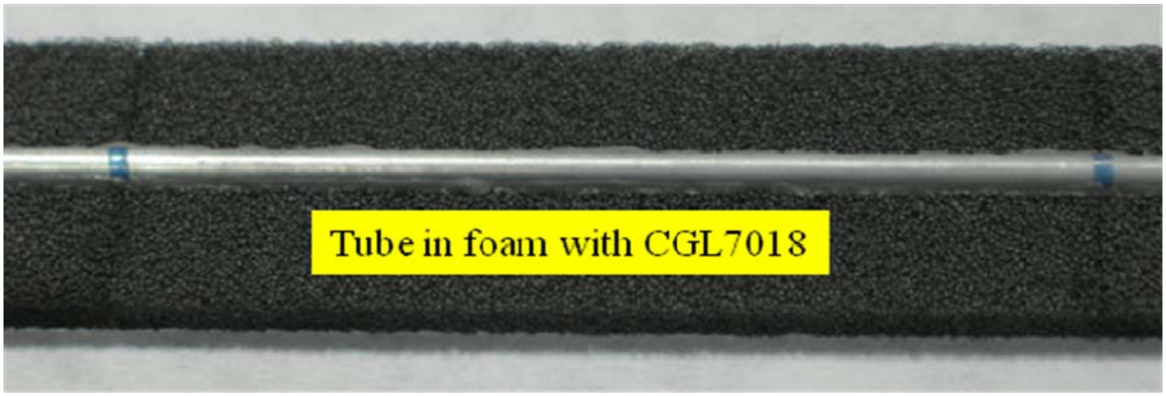

Figure 3 Close up of aluminum tube in foam described in the text. The blue bands are shims to establish a fixed bond line between the tube and the foam.

Three other prototypes were fabricated with different types of foam: POCO foam (ρ = 0.09 g/cc), Kfoam (ρ = 0.21 g/cc) another sample of Allcomp foam (ρ = 0.21 g/cc). The construction was identical to the first prototype except that the length was shorter (being about 7 cm rather than about 20 cm) and YSH-70 was used for both facings. A photograph of one of these smaller prototypes is shown in Figure 4.

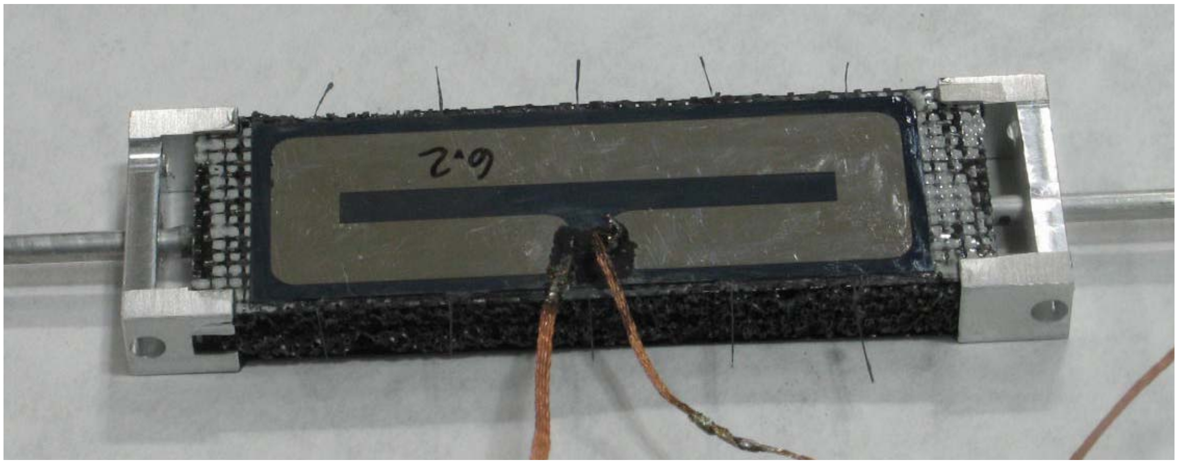

Figure 4 Small prototype (Kfoam) with platinum-on-silicon heater attached as described in the text.

4. Thermal Performance

The thermal performance of the prototypes was evaluated using water cooling at about 20^{o}C and IR imaging. Heaters were attached to the facings with a thermally conducting compliant adhesive.[3] Two types of heaters were attached to the long prototype as shown in Figure 5. A platinum-on-silicon heater in the middle and two standard, copper-on-kapton heaters on either side to avoid end effects when imaging the central heater.

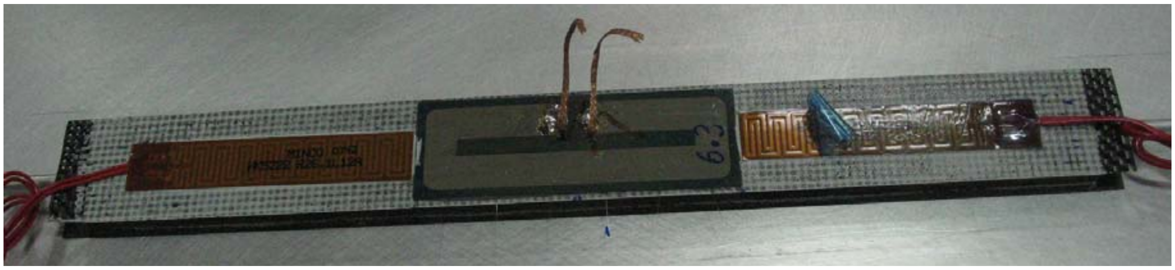

Figure 5 Heaters attached to the long prototype (YSH-70 side). The central heater is platinum-on-silicon. The heaters on either side are copper-kapton.

The thermal performance was measured by IR imaging with water coolant flowing at about 1 l/min as shown in Figure 6. IR images were used to estimate the temperature of the platinum-on-silicon heater.

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[3] SE4445 from Dow Corning.

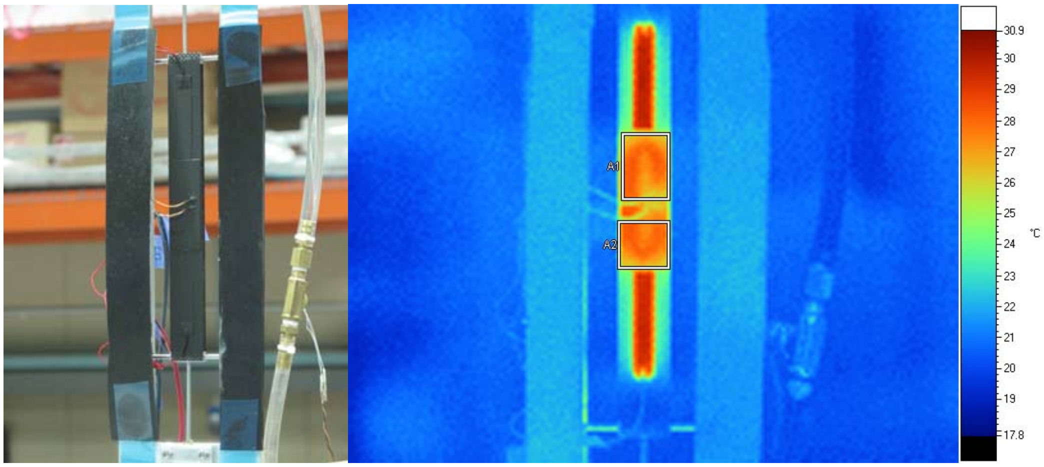

Figure 6 (Left) Setup for IR imaging and (Right) typical IR image.

The average difference in temperature (ΔT) for a given power/unit area on the heaters compared to the temperature with zero power is plotted in Figure 7 for single-side and double-side heating for the long prototype. There is a negligible difference between the two sides (different facing material and thickness not significant).

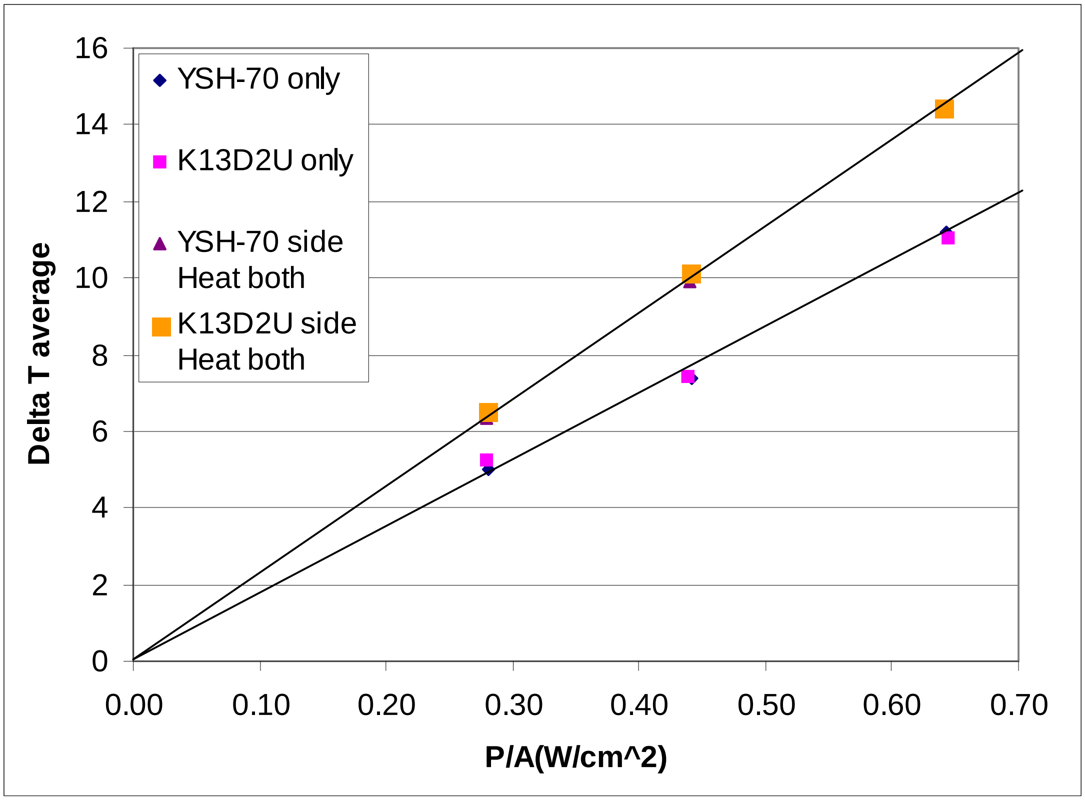

Figure 7 Average ΔT vs heater power (W)/area (cm^2) for single-side and double-side heating for the long prototype described in the text.

Similar measurements were made on the other prototypes but in these cases with a heater only on one side. All results for single-side heating are summarized in Table 1. The ΔT in this table is calculated by averaging the temperature over the surface of the heater. The values for the thermal conductivity, K, were obtained from the foam vendors apart from the x-y value for Koppers foam that we infer. The value of K for Allcomp 1 is based on a single measurement in one direction of one sample. The range of K values for Allcomp 2 come from a single sample (a cube) measured in each of the three directions. Clearly more data on the thermal conductivity are required.

Foam	**ρ(g/cc)**	**K(W/m-K)**	**ΔT_{ave}/W**
Allcomp 1	0.18	~ 6	~ 1.2
Allcomp 2	0.21	7 - 10	~ 1.0
POCO	0.09	~ 17(z) ~ 6(x-y)	~ 1.3
Koppers	0.21	~ 30(z) ~ 10-15(x-y)(est)	~ 1.0

Table 1 Summary of the average ΔT/W for single-side heating for the four prototypes with the properties shown.

5. Comparison with Finite Element Calculations

A finite element model of the long prototype (Allcomp 1 foam) was constructed to compare with the measurements. The materials properties used in this model are given in Table 2. The tube inner wall temperature was taken as 20.25°C based on the water flow rate and bulk temperature of 20°C.

Item	**Dimension**	**K (W/mK)**
Silicon heater	0.28 mm thick	148
Heater adhesive(SE4445)	0.1 mm thick	0.6
YSH-70	0.14 mm thick	0.6 transverse
YSH-70 adhesive	0.05 mm thick	1.55
Foam		6-30 varied
Tube adhesive(CGL-7018)	0.1 mm thick	1??
Aluminum tube	2.8 mm OD, 2.19 mm ID	180
K13D2U adhesive	0.05 mm thick	1.55

K13D2U	0.28 mm thick	1.0 transverse

Table 2 Materials dimensions and properties used in the finite element model described in the test.

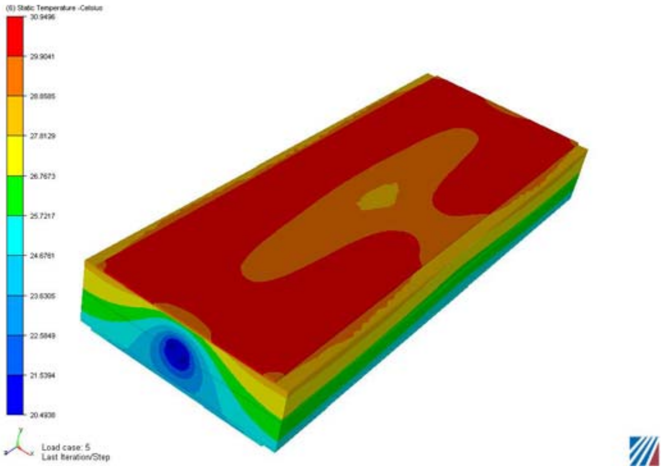

Figure 8 Example output from the finite element model described in the text.

A representative picture of the output of the model is shown in Figure 8. The values of the foam thermal conductivity were varied and the peak ΔT calculated for single-side and double-side heating. The results are summarized in Table 3. The results for single-sided heating are calculated for the YSH-70 side, although there is very little difference between the two sides. The power assumed is about 0.63 W/cm^2 (about 8.3 W for the heater).

	Sandwich Foam Thermal Conductivity-W/mK / Peak Differential Degrees C			
Heater	**6(z, x, y)**	**10(z, x, y)**	**17(z)/6(x, y)**	**30(z)/10(?x, y)**
Double	**15.25**	**11.76**	**11.95**	**9.87**
Single	**10.61**	**8.26**	**7.98**	**6.70**

Table 3 Predicted ΔT for different foam thermal conductivities for single-side and double-side heating.

The best agreement with the data (Figure 7) is for a foam thermal conductivity of about 6 W/mK, in agreement with the direct measurement of the foam K. However, it should be noted that there are uncertainties in the properties and dimensions (of the adhesives in particular) and so the extraction of a foam K from this analysis is uncertain.

A sensitivity analysis, the average temperature drop across each “layer” in the finite element model is shown in Table 4 for heating on both sides. The largest temperature difference occurs in the foam.

		Temperature differentials	
Silicon surface	**35.49**	**YSH50 Side**	
77	**35.379**	**0.111**	**silicon**
8	**34.309**	**1.07**	**SE4445 Adhesive**
1	**33.073**	**1.236**	**YSH70 Facing**
76	**32.891**	**0.182**	**YSH70 Facing Adhesive**
33	**23.303**	**9.588**	**Foam Delta**
78	**20.893**	**2.41**	**Al tube adhesive**
34	**20.831**	**0.062**	**Al tube**
coolant	**20.25**	**0.581**	**Convective film**
45	**20.84**	**0.59**	**Convective film**
48	**20.894**	**0.054**	**Al tube**
82	**23.381**	**2.487**	**Al tube adhesive**
37	**32.872**	**9.491**	**Foam Delta**
79	**33.054**	**0.182**	**K13D2U adhesive**
50	**34.562**	**1.508**	**K13D2U facing**
69	**35.631**	**1.069**	**SE4445 Adhesive**
Silicon Surface	**35.725**	**0.094**	**silicon**
		K13D2U side	

Table 4 Surface temperature and temperature differentials from the finite element model for the different elements of the model for double-side heating; foam thermal conductivity of 6W/mK.

6. Conclusions

The concept of using thermally conducting, carbon foam as a structural material and to conduct heat to cooling tubes for possible structures for an upgraded pixel detector has been demonstrated. The mechanical and thermal properties (K) of the foam may be chosen, within acceptable limits, to achieve a range of mechanical and thermal properties. The foam can be machined into complex shapes and can be potentially used for large-area stave (barrel region) and disk-section (forward/backward region) structures, as well as for stave-like or monolithic (half-barrel structures for the innermost layers of an upgraded pixel detector.

Acknowledgments

The assistance of W. Shih (Allcomp, Inc), T. Golubic (Koppers) and L. Weichmann (POCO Graphite) in providing information and foam samples is gratefully acknowledged.

References

[1] A general description of graphite foams may be found at http://www.ms.ornl.gov/researchgroups/cmt/foam/foams.htm and specific information on POCO foam

may be found at http://www.poco.com/tabid/67/Default.aspx and for Koppers foam at http://www.kfoam.com/mainsite/about.htm

[2] http://www.allcomp.net/