![Proceedings of Science logo]

Low-Mass Materials and Vertex Detector Systems

William E. Cooper*

Fermi National Accelerator Laboratory
P. O. Box 500
Batavia, Illinois, United States of America
E-mail: `cooper@fnal.gov`

Physics requirements set the material budget and the precision and stability necessary in low-mass vertex detector systems. Operational considerations, along with physics requirements, set the operating environment to be provided and determine the heat to be removed. Representative materials for fulfilling those requirements are described and properties of the materials are tabulated. A figure of merit is proposed to aid in material selection. Multi-layer structures are examined as a method to allow material to be used effectively, thereby reducing material contributions. Finally, comments are made on future directions to be considered in using present materials effectively and in developing new materials.

---

* Speaker

1. Introduction

Vertex detectors are the heart of modern particle detectors. They determine the precision with which particle trajectories can be traced to the ineraction point, can provide initial measurements of momentum, and link particle trajectories from the interaction point to the tracker region and outer elements of the detector. Achieving good performance and precision of trajectory reconstruction depends critcally on supporting sensors of the vertex detector stably, controlling material contributions to multiple scattering, and controlling the production of non-prompt paticles by limiting the amount of material. Vertex detector sensors, sensor support structures, readout structures including cabling and/or fibre optic circuitry for data transport and readout control, power delivery systems, cooling systems, and other vertex detector infrastructure all contribute to the material budget. The choice of materials and their geometry determines the effectiveness with which vertex detector goals can be met.

2. Low-mass design

The effective use of material in low-mass vertex detectors depends strongly on an understanding of physics objectives and sensor environmental and operational requirements. Requirements for a number of recent detectors can be found in design reports and letters of intent [1][2][3][4]. Physics objectives set acceptance and hermeticity requirements, the material budget, the precision with which hits and particle trajectories must be measured, magnetic field strength, and (along with accelerator characteristics) irradiation dose rates. In turn, these set the precision with which sensor positions must be known and maintained. Sensor requirements set environmental conditions, such as operating temperature, allowed humidity, cleanliness, and the extent to which light must be excluded. Power dissipation in sensors themselves, their readout, cabling and fibre optics receivers/drivers, power delivery circuitry (such as DC-DC converters, serial powering circuitry, and circuitry for ramping readout power) set a lower limit on heat to be removed. To that must be added heat which is transferred from outside the vertex detector region, for example, through external support connections and the beam pipe. Loads and moments associated with support and cooling connections between the vertex detector and outer detector elements must be accommodated. Since most vertex detectors are assembled at room temperature and in an environment of moderate humidity, geometric changes and stresses which may occur between assembly and operation must be understood and controlled.

Most current designs for silicon-based vertex detectors include five or six layers in a barrel – disk geometry, augmented by outer tracking in the central region and, sometimes to a lesser extent, in forward and backward regions. Multiple scattering limits the number of layers which contribute usefully to pointing resolution and places a premium on the spatial resolution of the innermost layers.

In the immediate vicinity of sensors, heat to be removed per unit area has a strong impact on which cooling methods will work well, the thermal conductivities needed in materials, and the amount of material required for heat removal. ILC and CLIC vertex detector designs have assumed that the accelerator beam structure would allow power to be ramped down between beam bunch trains, reducing average power and allowing heat removal by a combination of

natural and forced convection of dry gas. Sensors and their support structures are immersed in the gas flow paths. Distributing heat sources over the available sensor surfaces is an effective method of limiting power per unit surface area. The ILC estimated that 0.015 W/cm^2 could be removed with a sensor temperature of -10°C. CLIC groups assumed a power dissipation of 0.05 W/cm^2 and sensors operating at approximately room temperature. In both cases, heat is transferred either directly from sensor surfaces or through thin layers of material into the cooling gas, thereby limiting the need for materials with a high thermal conductivity.

The beam structure of designs for LHC and KEK experiments is incompatible with power ramping, which implies that liquid or 2-phase cooling is needed. Evaporative cooling with CO_2 is currently assumed. As a result, heat must be conducted from heat sources to the surfaces of cooling tubes before it is transferred into the coolant. Thermally conductive materials are essential for that heat conduction. Belle-II presently plans to augment CO_2 vertex detector and tracker cooling with dry gas cooling.

In liquid and 2-phase cooling, coolants are normally enclosed in tubes in the vicinity of sensors to avoid the direct interaction of coolant with sensors and to control coolant pressure. Material represented by both the cooling tubes and coolant can be non-negligible. Cooling tubes are often chosen to be as small as practical consistent with coolant pressure drops and coolant pressure containment requirements. In that case, heat transfer in the vicinity of cooling tubes and from the exterior of cooling tubes into the coolant can lead to significant temperature differences. As with gas cooling, heat sources are often distributed and sensors and their support structures are often dimensioned to limit temperature differences parallel to the plane of the sensor surfaces.

3. Material properties

The effectiveness with which materials resist deflection, hence the effectiveness with which they provide stability, depends not only on material properties themselves but equally on the shape of each piece of material, the overall geometry in which material is deployed, and the way in which each piece of material is connected to other materials.

Representative properties of many commonly used materials are summarized in Table 1. Only materials compatible with use in the expected magnetic fields are included. The materials are sub-divided into three groups based upon their characteristics and application. For vertex detector applications, we seek materials with a low density (ρ), a large radiation length (X_0), a large elastic modulus (E), good thermal conductivity (k), an adequate tensile strength (T_U), and a coefficient of thermal expansion (CTE) which adequately matches that of silicon sensors. Poisson's ratio relates shear modulus to elastic modulus. Shear stress and delection matters most in structural components whose transverse dimensions and length are comparable and should be checked; they usually turn out to be negligible in most portions of vertex detector designs.

Table 1. Representative structural materials and typical properties

Material	ρ g/cm^3	X0 cm	X0 g/cm^2	k W/m-K	T_U MPa	E GPa	X0*sqrt(E/ρ) relative to Si	CTE ppm/deg C	Poisson's ratio
304 SS	8.03	1.71	13.7	16.3	505	200	0.12	17.3	0.29
Ti	4.54	3.56	16.16	21.9	434	116	0.26	11.4	0.32
PEEK 450g (unfilled)	1.23	10.42	12.812	0.24	100	3.7	0.26	50	0.4
Titanium Ti-6Al-4V	4.43	3.69	16.344	7.3	1000	113.8	0.27	8.6	0.342
Kapton 100 HN	1.42	28.58	40.58	0.12	231	2.5	0.54	20	0.34
Al 1100-H14	2.71	8.90	24.01	220	124	68.9	0.64	23.6	0.33
Al 6061-T6	2.7	8.90	24.01	152	310	68.9	0.64	23.6	0.33
G-10	1.7	19.41	33	0.288	517	18.6	0.92	9.9	0.12
(100) Si wafer, (100) direction	2.329	9.37	21.82	149	120	130	1.00	2.6	0.22
MetGraf 4-230 alum.-carbon	2.4	11.56	27.75	225	103	98.6	1.06	4	
AlN	3.25	7.55	24.53	140	197-270	330	1.09	4.5	0.24
(100) Si wafer, (110) direction	2.329	9.37	21.82	149	120	169	1.14	2.6	0.22
Si$_2$N$_4$ (Kyocera SN-240)	3.3	8.40	27.712	27	1020	300	1.14	2.8	0.28
SiC	3.21	8.00	25.68	150	250	450	1.35	2.77	0.21
Carbon-carbon	1.75	24.40	42.7	300	68	38	1.62	0.5-4	0.24
K13C2U quasi-isotropic laminate	1.71	30.70	52.5	95.3		137	3.92	-0.8	0.335
Boron fiber	2.61	20.18	52.68	27.4	3600	400	3.57	4.5	
ERG Duocel SiC 8% foam	0.257	100	25.68	5.28	2.76	2.76	4.68	2.2	0.22
Beryllium	1.848	35.28	65.19	151	345-517	303	6.45	11.4	0.037
K13C2U fiber	2.2	19.41	42.7	620	3800	900	5.61	-1.1	0.39
ERG Duocel 3% carbon foam	0.0525	813.333	42.7	0.033-0.050	0.17-0.34	0.102	16.20	2.2	

Column 8 of the table provides a figure of merit for each material based upon the ability of the material to resist self-deflection in a simple structure. For a uniform strip of material of length L, thickness t, density ρ, and elastic modulus E, which is simply supported at its two ends, maximum bending deflection downward due to gravity acting normal to the strip surface is:

$$y = \frac{5 * \rho * L^4}{32 * E * t^2} \quad \text{or} \quad t = \sqrt{\frac{5 * \rho * L^4}{32 * E * y}}$$

Considering the parameters which specify material properties and converting "t" to the number of radiation lengths, we propose the material figure of merit (FOM) for resisting self-deflection listed in column 8 of Table 1 table (a larger FOM is better).

$$FOM = X0 * \sqrt{\frac{E}{\rho}}$$

If a figure of merit is greater than 1, a single strip of material of the same number of radiation lengths as represented by silicon will deflect less than silicon would by itself, and, ignoring thermal bowing, will reduce the silicon deflection. This characterization doesn't tell the full story, since it ignores the stiffness and weight contributions from sensors, their readout, and associated infrastructure, which support structure materials must address. It does, however, provide guidance on materials that should be considered and can be extended to other materials.

Materials have been subdivided into three groups in Table 1. The first group represents materials commonly used for structural applications, but not necessarily optimum for vertex detectors. Because of their relatively low FOM and relatively large CTE, their use in vertex detectors is usually limited to containment tubes for liquid or 2-phase cooling (when needed), to conductors for power delivery, and to insulating layers and stand-offs.

The second group represents standard materials for overall silicon support structures and sensor and readout substrates. Silicon itself is included in this group. Its thermal conductivity is good, its figure of merit is respectable, and its coefficient of thermal expansion should be nearly identical to that of sensors. The possible use of silicon as a structural element and the structural contributions from the silicon sensors should not be ignored. Indeed, the pixel sensors developed for Belle II [5] make direct structural use of sensor material as a primary structural element, thereby minimizing the need for additional material.

CTEs of other materials in group 2 are a better match to that of silicon with two exceptions: G-10 and K13C2U. The CTE of G-10 is relatively large, and G-10 can absorb moisture and other contaminants. Thin ceramic structures are often obtained from industry, which has considerable experience and cost-effective fabrication equipment associated with providing them to the electronics community. Brittleness and difficulties in controlling flatness and precise profiles can be issues. The FOMs of these materials are not as favorable as those of the last two materials in this group: carbon-carbon and K13C2U (as well as other types of carbon-fiber). As a result, these last two are of considerable importance in the design of structures which push the state of the art.

Carbon-carbon[1] is formed by pyrolytically transforming a blank of carbon fibre laminate into pure carbon, filling voids by heat treating in a carbon-forming gas (such as acetylene), performing repeated cycles of impregnation with carbon-carrying liquid, and performing a final heat treatment. Batch to batch variations require prototyping of each design. Generation of conductive contamination, difficulties in fabrication of thin materials, and the development of micro-cracks can be issues. Material properties depend strongly on the type of fiber in the laminate blank and on fabrication processes. The values listed in the table are for high modulus carbon fiber. Since fabrication starts with a blank of laminate, strength, modulus, and thermal conductivity can be direction dependent. The bottom line is that critical properties of the carbon-carbon from each source, and possibly batch, should be measured. Feature sizes, which can become apparent after machining, and pinholes in thin material may be additional considerations.

Carbon fiber is available from a limited number of suppliers.[2,3,4,5] K13C2U was listed in the table as a representative carbon fiber suitable for low-mass structures. It is normally obtained as pre-preg, that is, unidirectional fiber which has been impregnated with an epoxy or cyanate ester resin requiring an elevated temperature cure (120°C to 190°C). Multiple layers, or plies, of pre-preg are normally "layed-up" on a mandrel or within a mold at room temperature, then cured at elevated temperature to form a laminate. Laminate properties depend on the directions of the plies. Elastic modulus and thermal conductivity are normally higher in the plane of the laminate than perpendicular to the plane. A so-called quasi-isotropic laminate can be obtained by arranging plies at angles of $360^{\circ}/n$, where n is an integer greater than 2. In-plane properties of a quasi-isotropic laminate are independent of angle. K13C2U properties listed in

---

[1] I thank Stefan Gruenendahl for his comments on carbon-carbon.
[2] Mitsubishi Rayon Co., Ltd., http://www.mrc.co.jp/english/products/special/
[3] Toray, http://www.toray.com/globalnetwork/businesses/carbon/car_002.html
[4] TenCate, http://www.tencate.com/amer/aerospace-composites/composite-products/default.aspx
[5] Renegade Materials Corporation, http://www.renegadematerials.com/

Table 1 are those of a quasi-isotropic laminate. Enhanced properties in particular directions can be obtained by choosing a lay-up which isn't quasi-isotropic. This is often done to improve longitudinal properties of ladder or beam-like structures.

Because the elastic modulus and thermal conductivity of the resin is low compared to that of the carbon fiber, laminate properties depend on the resin fraction and are considerably lower than that of the raw carbon fiber. Resin content of the cured laminate depends on how much resin has been bled out during the cure, hence on the pressure that has been applied to the laminate during cure and the arrangement of "bleed material" to absorb resin. Typical resin content after cure is 50% by volume, though lower resin content can be obtained at higher cure pressures. Fracture of individual carbon fibers limits cure pressure to approximately seven atmospheres. Laminate with quite respectable properties can be obtained with a cure pressure as low as one atmosphere, which allows large area structures to be fabricated with a modest investment in equipment. An autoclave (oven that can be pressurized) or equivalent is normally used to cure at higher pressure.

The thickness of one pre-preg ply of K13C2U usually ranges between 60 and 65 µm before cure. After cure, the laminate thickness ranges from 50 to 62 µm per ply, depending on cure pressure and resin bleed-out.

The third group lists materials for specialized applications. These have the best FOMs. Currently available boron fiber has a minimum ply thickness of ~102 µm. It is available as fiber, as epoxy pre-preg, and as cyanate ester pre-pre. The elastic modulus of unidirectional fiber is more than a factor of 2 worse than that of K13C2U unidirectional fiber. However, where the increased ply thickness and lower elastic modulus are acceptable, boron pre-preg plies could be interleaved with K13C2U plies to obtain a laminate CTE which is close to that of silicon.

K13C2U fiber is listed in this group to indicate how much lower laminate properties are than the properties of the raw carbon fiber. The same considerations apply to laminates based upon boron and other fibers.

Because of its unique properties (low density, long radiation length, high elastic modulus, and good thermal and electrical conductivity), beryllium appears, at first glance, to be an ideal material for vertex detector structures. It is primarily available from a single supplier: Materion, Inc.[6] Its coefficient of thermal expansion is comparable to that of many other metals, but higher than that of silicon. To reduce material between the interaction point and the innermost sensor layers, beryllium is normally used for the central portions of beam pipe. Cylindrical pipe sections are formed by boring a billet (currently preferred unless the pipe diameter is too large) or by rolling sheet and providing a longitudinal braze joint (which adds material). Fabrication and yield issues currently limit the length of a cylinder to approximately 0.75 m, so a longer beam pipe is made by joining several shorter sections. Beryllium-beryllium joints and joints from beryllium to other metals, such as aluminum or stainless steel, can be made with an aluminum braze material, either by oven or electron beam brazing; electron beam brazing normally produces smaller and cleaner joints.

The main shortcomings of beryllium are that it is brittle, toxic, readily oxidizes in the presence of moisture and/or air, and the oxide can become airborne. As a result, environmental

---

[6] Materion, Inc., http://materion.com/Products/Beryllium.aspx

monitoring and other safety measures are necessary in facilities for machining and brazing beryllium; they may also be necessary in locations where beryllium products are used. For those reasons, its use is normally reserved for beam pipes where its unique properties are essential. Beryllium and beryllium oxide substrates and beryllium support and cooling structures were used in the CDF [6] and D0 [7] experiments. Beryllium surfaces were passivated to reduce oxidation, though the passivation coatings available at the time were not expected to be particularly durable. No deterioration of beryllium test samples exposed to D0 coolant flow (a deionized mixture of ~30% by volume ethylene glycol in water) was observed after ten years of operation. The use or avoidance of beryllium in vertex detectors should be a conscious decision based upon hazards, safety requirements, and performance.

The final material listed is ERG Duocel SiC foam. It is readily available with a density 8% that of solid SiC. Although it has been advertised as available with a 3% density, efforts by UK researchers to obtain samples with this lower density were unsuccessful. Its CTE is a good match to that of silicon. Its low elastic modulus requires a thickness of 1.5 to 2 mm to provide good support of thin (0.02 to 0.05 µm) sensors. Studies by the LCFI group showed that a 1.5 mm thick layer of 8% foam gave excellent preservation of the flatness of 25 µm thick sensors during a temperature decrease of more than 50°C.

Plastic, carbon, and ceramic foams are available from many vendors.[7,8,9,10,11,12] Except for SiC foam, they haven't been listed in the table, primarily because their use tends to be application specific and their properties and cell structures vary with vendor. All are candidates for the foam material of the multi-layer structures described in the next section. Plastic foams usually have low mass and low thermal conductivity. Many carbon and ceramic foams offer low density, a favorable radiation length, and good thermal conductivity. They can also be beneficial in augmenting thermal conductivity in the immediate vicinity of cooling tubes.

Thermal pyrolytic graphite (TPG, PG, or PGS)[13] has such high in-plane thermal conductivity (700-1750 W/m-K) that it is an almost universal cure when augmentation of heat transfer is necessary in structures with transverse dimensions comparable to those of silicon sensors. It is available from Panasonic, with or without an acrylic adhesive coating, in several thicknesses between 25 µm to 100 µm. It is also available with different dimensions from other suppliers[14-15]. Independent measurements of in-plane and out-of-plane thermal conductivity were reported several years ago [8]. Results for out-of-plane conductivity were significantly lower than those reported by producers.

Adhesives can be particularly important in connecting structural elements together into a full structure. Some of the more important issues are cure time, cure temperature, bond strength and possible deterioration of strength with time, creep, compliance (to mitigate the effects of

---

[7] Airex, http://www.corematerials.3acomposites.com/54.html

[8] Evonik Industries, http://www.rohacell.com/product/rohacell/en/Pages/default.aspx

[9] Allcomp Inc., http://www.allcomp.net/

[10] Koppers, http://www.kfoam.com/img/KFOAMProductBrochure.pdf

[11] PocoGraphite, http://www.poco.com

[12] Ultramet, http://www.ultramet.com/refractoryopencells.html

[13] Panasonic, Inc. http://www.panasonic.com/industrial/electronic-components/protection/pyrolytic-graphite-sheet.aspx

[14] MinTEQ, http://www.minteq.com/our-products/minteq-pyrogenics-group/pyroid-ht-pyrolytic-graphite/

[15] Momentive, http://www.momentive.com/Products/Main.aspx?id=22860

materials with CTE differences), radiation hardness, joint thickness, ease of application, chemical activity and contamination (particularly for adhesives in contact with sensors), resistance to solvents and coolants, and re-workability (important in applications where sensors must be removable without damage).

4. Multi-layer structures

Multi-layer (or composite) structures are often used for sensor support within barrels and disks. The primary advantage of a multi-layer structure is that the (moment of inertia) x (elastic modulus) product, which resists bending, can be increased without a commensurate increase in material. In the simplest case, two layers of structural material are separated by a low-mass foam spacer, as shown in Figure 1. As the figure suggests, widths and thicknesses of the various layers need not match one another. Material dimensions are normally chosen to control sensor flatness under changes in environmental conditions and to maintain sensor flatness while achieving the desired structural stiffness. When allowed by required sensor locations, sensors can be placed on the two surfaces of a central core to minimize the effects of environmental changes.
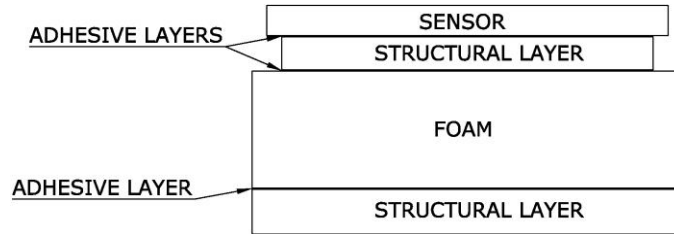

Figure 1. End view of a composite ladder

Many standard texts and reference books, such as [9] and [10], address bending of composite structures made of a single material. A few equations follow which address composite structures of the type we normally encounter, that is, structures which incorporate several materials.

The location of the so-called "neutral axis" of this type of structure can be determined from the equation:

$$y\_neutral = \Sigma(y_i * E_i * A_i)/\Sigma(E_i * A_i)$$

where y_i, E_i, and A_i are the centroidal location, elastic modulus, and area of the ith material, respectively. Once the location of the neutral axis has been determined, then the E*I product can be calculated about the neutral axis:

$$E * I = \Sigma(E_i * I_i) + \Sigma(E_i * A_i * (Y_i)^2)$$

with Y_i measured from the neutral axis of the combined structure. I_i is the moment of inertia of the ith material about its own neutral axis. Values of I_i for most shapes can be found in structural design tables. For a rectangular shape (applicable to the sketch):

$$I_i = \frac{1}{12} * b_i * (d_i)^3$$

where b_i is the width and d_i is the height of the ith material.

Placing structural material further from the neutral axis benefits the E*I product, thereby reducing the material necessary to obtain a given E*I product. This is the primary benefit of a

multi-layer structure. The ladders being developed by the PLUME collaboration [10] illustrate a multi-layer ladder concept with a central core between two sensor – flex cable layers.

5. Future directions

Most materials employed in low-mass vertex detectors have been available for a decade or more. Improvements in material fabrication techniques have led to a gradual, but steady, improvement in the properties of current materials. Learning to use materials well may be just as important as developing new materials. On the other hand, we all welcome new materials with significantly improved properties on which we can draw. Many material developments are the result of a cooperative effort among universities, industry, and major physics research facilities and address needs from outside the high energy physics commuunity. Those cooperative efforts should be encouraged.

Power dissipated in sensors, readout, cabling, data and control communications, and power delivery circuitry plays a key role in determining how much heat must be removed. Advances in reducing power dissipation in each of these areas would be extremely beneficial to reducing material contributions, would benefit the computer, electronics, and medical communities, and may turn out to be driven by them. We should do our part to participate in and encourage a cooperative effort.

References

[1] ILC Collaboration, *ILC Technical Design Report Volume 4 –Detectors (2013),* http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

[2] ILD Concept Group, International large Detector DBD, http://ific.uv.es/~fuster/DBD-Chapters/Chapter%204%20ILD.pdf (2012)

[3] CLIC Collaboration, *Physics and Detectors at CLIC: CLIC Conceptual Design Report,* arXiv:1202.5940 (2012)

[4] Belle II Collaboration, arXiv:1011.0352, *Belle II Technical Design Report,* arXiv:1011.0352 (2010)

[5] L. Andricek et al., *Ultra-thin fully depleted DEPFET active pixel sensors,* TIPP 2011, http://indico.cern.ch/getFile.py/access?contribId=75&sessionId=22&resId=0&materialId=slides &confId=102998

[6] The CDF II Collaboration, *The CDF Detector Technical Design Report,* Fermilab-Pub-96/390-E (1997)

[7] S. N. Ahmed et al., *TheD0 Silicon Microstrip Tracker*, arXiv: 1005.0801 (2010)

[8] C. A. Heusch et al., *Direct measurements of the thermal conductivity of various pyrolytic graphite samples (PG, TPG) used as thermal dissipation agents in detector applications,* Nucl. Instr. Meth. A 480 (2002) 463-469

[9] E. Oberg,, *Machinery's Handbook 29th edition,* Industrial Press (2012)

PoS(Vertex 2013)036

[10] W. Young et al., *Roark's Formulas for Stress and Strain, 8th edition,* McGraw Hill (2011)

[11] A. Nomerotski et al., *PLUME collaboration: Ultra-light ladders for linear collider vertex detector,* Nucl. Instr. Meth. A650 (2011) 208-212