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The design of stable, low-mass support and cooling structures

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Abstract

Designs of stable, low-mass support and cooling structures for intelligent trackers should take into account the additional power dissipation associated with local trigger generation, high speed communications, and power delivery, as well as the spatial distributions of heat sources. For many applications, a modular design can alleviate cooling and support issues and allow parallel fabrication at multiple locations. A proposed design for CMS phase 2 upgrade track trigger formation will be used to illustrate the extent to which design requirements are specific to intelligent tracking, ways in which those design requirements might be met, and implications for local tracker geometry, material selection, structural stability, and the material budget.

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The design of stable, low-mass support and cooling structures

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ABSTRACT: Designs of stable, low-mass support and cooling structures for intelligent trackers should take into account the additional power dissipation associated with local trigger generation, high speed communications, and power delivery, as well as the spatial distributions of heat sources. For many applications, a modular design can alleviate cooling and support issues and allow parallel fabrication at multiple locations. A proposed design for CMS phase 2 upgrade track trigger formation will be used to illustrate the extent to which design requirements are specific to intelligent tracking, ways in which those design requirements might be met, and implications for local tracker geometry, material selection, structural stability, and the material budget.

KEYWORDS: Overall mechanics design; Detector grounding; Detector design and construction technologies and materials; Detector cooling and thermo-stabilization; Particle tracking detectors.

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1. Introduction

The design of low-mass cooling and support structures for intelligent trackers should take into account sensor and tracker geometries, acceptable deflections, and locations and magnitudes of heat sources. Requirements are dependent upon details associated with the particular application. Accordingly, a snapshot of one of several evolving designs proposed for the CMS phase 2 upgrade is used to illustrate methods to address those requirements.

2. Overall geometry

The design which is described assumes an overall tracker length of approximately 2.8 m. The initial design assumed a maximum radius of 1.25 m. The overall R-Z geometry of that design is shown in Figure 1. We note that the outer radius of a more current design is 1.06 m.

Figure 1 R-Z geometry of the proposed tracker

Sensor modules are arrayed on “rods” in a 5-layer barrel geometry. Rods are supported from a full-length outer cylinder via carbon-fiber laminate disks. To limit rod deflections, the tracker is divided into left and right halves with separate rods, at slightly different radii, for each half. Rods overlap at $Z = 0$ to ensure that, for tracks originating within the interaction region and passing from one side of $Z = 0$ to the other, trigger information will be available at each end of the tracker. The shorter barrels extend coverage in forward and backward directions as coverage by the outermost barrel is lost.

3. R- ϕ arrangement of rods

An end view of the detector is shown in Figure 2. To ensure that sufficient material remains in the support disks while allowing rods to be inserted through openings in them, a minimum of 6 mm is required between structures of adjacent rods. For those limited portions of rods which overlap from one side of $Z = 0$ to the other, the clearance was reduced to 3 mm. In that region, the main issue is potential interference during the rod installation process. For the geometry chosen, a single transverse rod shape can be used for all five barrels.

Figure 2 R- ϕ geometry of the proposed tracker

4. Rod transverse geometry

The geometry of rod structures shown in Figure 3 was chosen to provide integrated cooling, minimize support material, and minimize deflections while ensuring that the azimuthal coverage of sensors in adjoining rods overlaps. The main structural element of a rod is a core consisting of a rectangular box beam of transverse dimensions approximately 40 mm x 40 mm and two flanges, each approximately 100 mm wide. The core runs the full length of the rod and provides surfaces on which sensor modules can be mounted and supports DC-DC converters and fibre-optic drivers. Flex-circuits / flex-cables make connections to each sensor module. Separate connections to left and right halves of each sensor module are presently assumed. The number of DC-DC converters and number of fibre-optic drivers per module remain to be determined. The latest locations proposed for them are shown; we have also considered locating DC-DC converters within the core box. In either case, advantage is taken of the thermal conductivity of carbon fibre laminate to limit temperature differences as heat flows to the cooling tubes.

The rod box and flanges are assumed to consist of laminate with six K13C2U carbon fibre plies. The resultant thickness is expected to be between 0.36 and 0.39 mm, dependent upon the cure pressure chosen. Six plies should represent approximately 0.16% X_0 . To limit the number of radiation lengths represented by sensor module structures, the number of plies in carbon fibre laminate stiffeners on each module surface has been reduced to three. Thermal bowing is reduced by symmetrising the resultant six plies about the central plane of a module.

Figure 3 End view of a rod

A spreadsheet calculation has been made of the longitudinal deflection of the longest rod. Results are shown in Figure 4. Simple support was assumed at two locations, one near the outer end of the rod and a second roughly 1/3 of the distance from the opposite end. The precise longitudinal location of the second support was adjusted to equalize deflection in the portion of the rod between supports and the portion which overhangs the support nearer $Z = 0$. No credit was taken for module stiffness. The maximum calculated deflection with a supported weight of 3.35 kg is approximately 97 μm ; of the total weight, the rod support structures contribute 1.30 kg. Rod box and flange dimensions are expected to be optimized so that transverse deflection is independent of rod azimuthal location. That would simplify rod installation and later knowledge of sensor transverse locations.

Figure 4 Rod deflection as a function of Z

5. Sensor grounding

Copper mesh co-cured with carbon fibre laminate has been used in L0 of the D0 silicon tracker to provide a common ground for sensors and their readout [1]. Co-curing is essential to ensure good electrical contact between the copper and carbon fibre. Copper thickness was $5\mu\text{m}$ with approximately 30% coverage by area. We considered a similar grounding method between sensor modules and readout within a rod. However, we also conjectured that carbon fibre laminate might provide sufficient electrical conductivity by itself. Test samples of carbon fibre laminate with transverse dimensions 102 mm x 229 mm and ply directions representative of those we expect to use in modules and rods were prepared and measured. Connections were made via 0.036 mm thick copper strips at each end of the laminate. The strips were located on opposite laminate surfaces and were co-cured with the laminate. The results are summarized in Table 1. Resistance ratios agree reasonably with expectations for the lay-ups of the laminates.

Table 1 End-to-end DC resistances of test samples

Lay-up with respect to the sample longitudinal direction (degrees)	Resistance (milli- Ω)
0, +75, -75, -75, +75, 0	71
0, +60, -60, -60, +60, 0	77
+90, +15, -15, -15, +15, +90	41

From these measurements, we would expect the end-to-end resistance for one of the longest rods to be approximately $0.20\ \Omega$ (not taking into account contributions from modules). Studies of reactance of the test samples as a function of frequency are in process. The good conductance of carbon fiber laminate may allow a reduction in the amount of copper-on-kapton mesh that would otherwise have been chosen for grounding. Studies of longer samples are planned to understand how frequently connections to the carbon fibre should be made.

6. Cooling

Evaporative CO_2 cooling is planned. Within a rod, cooling tubes (total length ~ 5.6 m for the longest rods) begin at the outer end of the rod and turn around near $Z = 0$. Separate cooling tubes are provided for the two layers of sensor modules. Cooling tube inside diameter has been tentatively chosen to be 1.8 mm. Wall thickness is presently taken to be 0.25 mm. We will need to demonstrate that cooling tubes of those dimensions can be fabricated reliably or make adjustments to the dimensions. Aluminium cooling tubes are presently favoured because they would represent approximately 1/5 the number of radiation lengths as stainless steel tubes of the same dimensions. On the other hand, aluminium is far more subject to corrosion, particularly when it is in contact with carbon, and is often more difficult to form without flaws. Either material should provide a sufficiently high pressure rating for evaporative CO_2 cooling.

To accommodate differential contraction between metal cooling tubes and carbon fibre, we plan to allow slippage by enclosing the cooling tubes in carbon fibre laminate sheathes. Sheathes would be epoxied to the inner surface of a rod box in a separate operation or co-cured with the laminate of the box. Sheathes could be made using the metal cooling tubes as mandrels.

With this arrangement, we expect to remove ~ 120 watts over the length of a tube. Decrease in temperature due to pressure drop with a flow rate of 1 g/s is expected to be $< 2.7^\circ\text{C}$.

Approximately 50% of the CO₂ should be evaporated with that flow rate. The flow rate was chosen to help ensure that the flow regime would be stable.

Sensor temperatures and temperature uniformity within a module have been studied via analytic approximation. The study was broken into two portions: temperature change from a cooling tube wall to the box flange to which sensor modules are attached and temperature change from the box flange to various locations within a sensor module. A significant temperature increase, $\sim 10.6^\circ\text{C}$, occurs between the cooling tube wall and the flange to which modules attach.

Figure 5 Temperature changes in the vicinity of a cooling tube (left) and transversely within a module (right). The module centerline is at 0 mm and the cooling tube is at 19 mm.

A similar calculation was made of the increase in temperature through the thickness of a sensor-interpose-sensor module. The temperature increase from the box beam flange to the sensor furthest from cooling is calculated to be 0.69°C . Of that total, 0.26°C occurs through the interposer (assumed to be 0.45 mm thick, have the conductivity silicon, and cover 20% of the available area). The remainder comes from layers of carbon fibre laminate, epoxy, kapton, silicon of the nearer sensor, readout chips, and bump bonds. The low total allows temperatures across the width of a module to be reasonably estimated by assuming all module layers contribute to transverse conduction in parallel. Temperature change near the cooling tube and variation across the width of a module are shown in Figure 5.

We conclude that temperatures within a module should vary less than $\pm 0.95^\circ\text{C}$. Sensor temperature should be dominated by conduction near the cooling tube and would average $\sim 12^\circ\text{C}$ above the temperature of the inner cooling tube wall. We expect to investigate modifications to the geometry in the immediate vicinity of the cooling tube to reduce that temperature.

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References

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