Vertex Detector Mechanics

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Introduction

• The overall approach to mechanical support and cooling has been developed in conjunction with SiD.

• The support structures which have been studied rely heavily on the use of carbon fiber laminate (CF).
  – CF offers a high stiffness * radiation length product.
  – Operation near room temperature (> -10° C) has been assumed during design development.
    • Minimizes thermal distortion effects
  – Operation at lower temperature may be possible, but would require a more carefully engineered design.

• To control the number of radiation lengths, cooling with forced flow of dry gas has been assumed.
Representative Material Properties

- In general, we are interested in maximizing stiffness and minimizing the number of radiation lengths of a support structure.
- For beam-like deflection of a flat plate of fixed thickness, width, and length, deflection with gravity acting normal to the surface varies linearly with density and inversely with elastic modulus.
- We are also interested in controlling thermal distortions by minimizing differences in CTE.
- The table below suggests the choice of CF with portions removed.
- Behavior of a combined structure is more complicated.

<table>
<thead>
<tr>
<th>Material</th>
<th>Silicon</th>
<th>Beryllium</th>
<th>CF</th>
<th>¼ CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.33</td>
<td>1.848</td>
<td>1.56</td>
<td>0.39</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>131</td>
<td>290</td>
<td>228</td>
<td>57</td>
</tr>
<tr>
<td>Radiation length average (cm)</td>
<td>9.37</td>
<td>35.43</td>
<td>24</td>
<td>96</td>
</tr>
<tr>
<td>Relative deflection</td>
<td>1</td>
<td>0.36</td>
<td>0.38</td>
<td>0.38</td>
</tr>
<tr>
<td>Relative number of radiation lengths (average)</td>
<td>1</td>
<td>0.26</td>
<td>0.39</td>
<td>0.10</td>
</tr>
<tr>
<td>CTE (ppm/°C)</td>
<td>2.6</td>
<td>11.6</td>
<td>-0.6</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

CF modulus and CTE depend on the lay-up
MPI Ladder

• We were asked if we would look at deflections and make a thermal analysis of an MPI ladder. Thermal analysis remains to be done.
MPI Ladder

- Ladder was modeled as a window frame 3 mm wide on three edges and 1 mm wide on one long edge plus a thinner portion within frame.
  - Frame thickness = 0.3 mm
  - Thickness within frame = 0.05 mm
  - Overall length = 125 mm

FEA by C. H. Daly

Deflection = 82 µm

All silicon

Hand calculation gave 77 µm

$E_{\text{silicon}}$ was taken to be 110 GPa
MPI Ladder

- 0.25 mm of frame thickness was replaced by CF, leaving 0.05 mm silicon thickness over the full extent of the ladder.

FEA by C. H. Daly

Silicon + CF

Hand calculation gave 46 µm

$E_{CF}$ was taken to be 228 GPa

Deflection = 43 µm
SiD VXD Barrel End View

- 2 types of sensors
- A and B sub-layer geometry
- 6-fold symmetry
- To reduce mass, barrel layers are glued to form a unit.
- Up to 15 sensors per unit

Sensors:
IR_A = 14, 22, 35, 47.6, 60 mm
IR_D = 15.15, 23.13, 35.89, 48.41, 60.77 mm
Active widths: 9.1, 13.3 mm
Cut widths: 9.6, 13.8 mm
Beam pipe IR: 12 mm
Beam pipe OR: 12.4 mm
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Oblong boxes are openings in end rings and end membranes for cables, optical fibers, and air flow.

Splitting into two halves allows assembly about the beam pipe.

Possible clam-shell split line
SiD Sensor Assumptions

• VXD pixel size = 20 µm x 20 µm x 20 µm (or less) in the central pixel region
  – Provides good resolution and pattern recognition with five layers
  – Forward disks may have a coarser granularity

• Sensors are cooled by forced flow of dry gas.
  – Limits the number of radiation lengths

• To minimize Phi gaps between sensors, we assumed the following.
  – Sensor boundaries about active area are 0.25 mm wide.
  – Sensor thickness, including readout, is 0.15 mm.
  – The gap from the physical edge of one sensor to the surface of the next is 0.5 mm.
    • Of the 0.5 mm, we think 0.25 mm is needed. Portions of sensors could extend into the other 0.25 mm.

• To eliminate the need for barrel sensor-sensor longitudinal overlap, we assumed 125 mm long sensors (6” technology).

• We assumed that sensors are flat as fabricated and do not need to be flattened by support structures.
SiD Sensor Assumptions

• To allow low-mass support with dry air cooling, we assumed a sensor operating temperature > -10° C.
  – Reduces thermal expansion issues with carbon fiber support structures
  – Reduces thermal insulation requirements
• For an initial cooling study, we assumed that average power dissipation of central pixel sensors = 131 µW/mm² and that power is uniformly distributed over a sensor.
  – Given present technologies, that implies power is ramped.
  – It allows reasonable sensor temperatures with laminar air flow.
    • Laminar flow minimizes the likelihood of flow-induced vibration.
  – In the forward disks, where pixels may be a factor of 4 larger in area, we assumed 33 µW/mm².
• We would expect to modify sensor assumptions to match sensor developments.
Barrel Layers

- Sensors are supported from and glued to a carbon fiber (CF) shell.
- Each barrel layer includes a CF end ring, which controls out-of-round distortions.
- Openings provide cable, optical fiber, and dry gas passages.
- Other openings to reduce mass and adjust gas flow would be added.
- End membranes connect one layer to the next to form a half-barrel.
- To control material, the use of fasteners has been limited.
  - Three fasteners per end ring
Finite Element Analysis (FEA)

- An initial model was developed by Colin Daly (University of Washington) to represent the barrel 1 carbon fiber (CF) support structure, sensors, and epoxy which holds sensors in place.
- All sensors are on the outer surface of the carbon fiber (CF).
- A & B layers have been placed leaving 0.54 mm from the edge of an A-layer sensor to the surface of a B-layer sensor.
- All barrel 1 sensors are shown 9.6 mm wide (9.1 mm active).
- B-layer sensors overhang CF ~3.3 mm.
SiD Half Barrel (Innermost Barrel)

- 3 layers of K13C pre-preg (had been 4 layers)
- Composite thickness = 0.195 mm
- 0/90/0 degree lay-up
- CF strut width = 2 mm
- Sensor width for this barrel = 9.6 mm (could change)
- 0.1 mm silicon
- 0.05 mm epoxy
- End rings included
SiD Half Barrel (Innermost Barrel)

- Deflection with gravity acting vertically = 1.6 \(\mu\)m
- Demonstrates the benefits of a support structure with larger transverse dimensions
- Innermost barrel tests beam-like deflections
- Next to outermost barrel will test out-of-round deflections (not done yet)
SiD Half Barrel (Innermost Barrel)

- Deflection with gravity acting horizontally = 0.5 µm
- Suggests a split at equator works better
  - A surprise to some of us
- The good results suggest that uncontrolled loading from cables and fibers at the ends may not be so much of a problem.
SiD VXD Elevation View

- 5-layer pixel barrel: $Z = \pm 62.5 \text{ mm}; 14 \text{ mm} < R < 61 \text{ mm}$
- 4 pixel disks per end: $Z = \pm 72, \pm 92, \pm 123, \pm 172 \text{ mm}; R < 71 \text{ mm}$
- 3 forward disks per end: $Z = \pm 208, \pm 542, \pm 833 \text{ mm}; R < 166 \text{ mm}$
  - Could be pixels or pairs of micro-strips
- Coverage extends to $\cos(\theta) = \pm 0.99$. 
SiD VXD Elevation View

- Outer split cylinders couple to the beam tube at \( Z = \pm 214 \) and \( \pm 882 \) mm, are supported by the beam tube, and stiffen it.
- High modulus CF has been assumed for most support structures.
  - Typical thickness, 0.26 mm, assumes 4 layers of pre-preg.
  - In many places, average thickness can be substantially reduced by cutting holes.
- CF membranes support the barrel and disks.
Beam Pipe Deflections

• For these calculations, an all-beryllium beam pipe was assumed.
  – Wall thickness of 0.25 mm was assumed in the central, straight portion.
• The radius of conical portions was assumed to increase with \( dR/dZ = 17/351 \).
  – Wall thickness in the conical portions was chosen to correspond to collapse at slightly over 2 Bar external pressure.
• An inner detector mass of 500 g was assumed to be simply supported from the beam pipe at \( Z = \pm 900 \text{ mm} \).

Inner detector weight contributes ~ 0.008 mm.

Maximum stress ~ 20 MPa
Beam Pipe Deflections

- A basic assumption has been that the beam pipe would be guided, not just simply supported, at its ends.
- If one insists that the beam pipe be simply supported, then the outer support cylinder for the vertex detector could be extended to ±1.85 m.
- Connect to beam pipe at ±1.85 m and ±0.90 m (not optimized).
  - Deflections of outer cylinder are not taken into account.
Dry air was assumed to enter the barrel at a temperature of -15°C. We assumed no heat transfer from the beam pipe to the innermost layer, that is, the beam pipe would have thermal intercepts. A total power dissipation of 20 watts was assumed for the barrel. Based upon the results, that seems reasonable.

Cooling performance as a function of Reynold’s number

<table>
<thead>
<tr>
<th>Reynold’s number</th>
<th>Total barrel flow (g/s)</th>
<th>Ave. ΔT air (°C)</th>
<th>Max sensor T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>9.0</td>
<td>2.21</td>
<td>-2.44</td>
</tr>
<tr>
<td>1200</td>
<td>13.5</td>
<td>1.47</td>
<td>-4.61</td>
</tr>
<tr>
<td>1800</td>
<td>20.2</td>
<td>0.98</td>
<td>-6.36</td>
</tr>
</tbody>
</table>

Results as a function of layer are shown on the transparencies which follow.
VXD Barrel Cooling

Average Sensor Temperature for 20 Watts, -15 C Air Supply

Sensor temperature (degrees C)

Layer

N_Re 1800
N_Re 1200
N_Re 800
VXD Barrel Cooling

End-to-end Temperature Difference for 20 Watts, -15 C Air Supply

Sensor temperature difference (degrees C)

Layer

N_Re 1800
N_Re 1200
N_Re 800
Disk Cooling and Manifolding

• Sensors of the four disks per end closest to the barrel were assumed to have the same power dissipation per unit area as barrel sensors, 131 µW/mm². For eight disks (both ends) power dissipation would be 17 watts.

• Two options were considered for the three outermost disks per end.
  – Pixels twice the size in each transverse dimension as those of the barrels, so ¼ the power per unit area. Total power dissipation (both ends) = 13 watts.
  – Pairs of silicon micro-strips. Total power dissipation (both ends) = 7 watts.
  – We assumed the larger of the two values, 13 watts.

• To size manifolding to deliver and distribute air, we assumed power dissipation of the barrel and all disks would total 50 watts.

• One obvious possibility is to distribute air via the outer support cylinder. For a 15 mm wall separation, nearly the full circumference is needed to maintain laminar flow. (The Reynold’s number in portions seeing full flow = 1900). We assumed air entered support cylinder passages at a temperature of -20° C.
Summary

• A design based largely upon carbon fiber support structures has been developed.
  – That design is intended to be suitable for sensor operation at > -10° C.
• Feasibility of the design depends upon sensor developments.
  – We expect to follow developments and to take them into account.
• An initial FEA model has been developed for barrel sensor structures.
  – Gravitational deflections for 125 mm barrel sensors are small.
  – Deflection of a ladder with simple support at its ends is noticeably larger.
• We have begun to re-examine beam pipe deflections and the outer vertex detector support cylinder.
  – Changes could result.
• An initial study suggests that approximately 20 watts can be removed from the barrel, and 50 watts from the entire vertex detector, by air cooling with laminar flow.
• The number of radiation lengths represented by VXD structures has been reduced considerably (earlier talk at this workshop).