Survey of Mechanical Options
for the BABAR Drift Chamber

K.T. McDonald

Princeton U.

March 25, 1996
The Goal

Deliver a low mass drift chamber (a box with 200,000 parts) for installation in BABAR by June 1998 ($7 \times 10^7$ s from now).

The Risk

Options are under consideration for several major technology choices that still involve R&D.

Long-term impact: might not meet schedule.

Short-term impact: the attendant uncertainty tends to block progress on other aspects of the project.
Major Mechanical Options

1. Endplate:
   - Flat or shaped?
   - Al or carbon fiber?

2. Inner Cylinder:
   - Load bearing or not?
   - Carbon-fiber/Al (or Be?) foil or Be/stainless-steel?

3. Joint (between endplates and cylinders):
   - no design
   - not testable until final assembly
   - final assembly not until after 6 months of stringing in baseline design

4. Assembly/Stringing:
   - Manual or semiautomatic?
   - String horizontally; assembly cylinders after, or
   - String vertically; assemble cylinders before?
Table 1. Survey of Large Cylindrical Drift Chambers

<table>
<thead>
<tr>
<th>Reference</th>
<th>JADE</th>
<th>Mark II</th>
<th>TASSO</th>
<th>CLEO</th>
<th>ARGUS</th>
<th>Benichou</th>
<th>VENUS</th>
<th>Mark III</th>
<th>OPAL</th>
<th>SLD</th>
<th>CLEO II</th>
<th>Mark II</th>
<th>CDF</th>
<th>KEDR</th>
<th>AMY</th>
<th>ZEUS</th>
<th>BES</th>
<th>KLOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber size</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_min (mm)</td>
<td>373</td>
<td>320</td>
<td>172</td>
<td>150</td>
<td>400</td>
<td>250</td>
<td>140</td>
<td>250</td>
<td>200</td>
<td>175</td>
<td>192</td>
<td>277</td>
<td>125</td>
<td>162</td>
<td>155</td>
<td>~200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_max (mm)</td>
<td>800</td>
<td>1509</td>
<td>950</td>
<td>859</td>
<td>1700</td>
<td>1260</td>
<td>1140</td>
<td>1850</td>
<td>1000</td>
<td>945</td>
<td>1519</td>
<td>1380</td>
<td>535</td>
<td>787</td>
<td>850</td>
<td>1150</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>L_max (mm)</td>
<td>3000</td>
<td>2692</td>
<td>3520</td>
<td>2000</td>
<td>4500</td>
<td>3000</td>
<td>2340</td>
<td>4000</td>
<td>1800</td>
<td>2150</td>
<td>2300</td>
<td>3214</td>
<td>100</td>
<td>1792</td>
<td>2030</td>
<td>2120</td>
<td>3300</td>
<td></td>
</tr>
<tr>
<td>Sense wires</td>
<td>1536</td>
<td>3204</td>
<td>5304</td>
<td>5940</td>
<td>12800</td>
<td>5120</td>
<td>12240</td>
<td>5832</td>
<td>6156</td>
<td>1512</td>
<td>9048</td>
<td>4608</td>
<td>2808</td>
<td>~12000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other wires</td>
<td>9612</td>
<td>7020</td>
<td>15912</td>
<td>24588</td>
<td>64400</td>
<td>21312</td>
<td>1584</td>
<td>?</td>
<td>32640</td>
<td>36240</td>
<td>?</td>
<td>30448</td>
<td>14520</td>
<td>27144</td>
<td>19584</td>
<td>16572</td>
<td>~36000</td>
<td></td>
</tr>
<tr>
<td>Total layers</td>
<td>48</td>
<td>16</td>
<td>15</td>
<td>6</td>
<td>15</td>
<td>17</td>
<td>6</td>
<td>17</td>
<td>20</td>
<td>15</td>
<td>12</td>
<td>25</td>
<td>15</td>
<td>30</td>
<td>20</td>
<td>~24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_min (mm)</td>
<td>414</td>
<td>367</td>
<td>213</td>
<td>180</td>
<td>286</td>
<td>175</td>
<td>238</td>
<td>199</td>
<td>246</td>
<td>309</td>
<td>155</td>
<td>182</td>
<td>195</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R_max (mm)</td>
<td>1448</td>
<td>1222</td>
<td>892</td>
<td>1213</td>
<td>961</td>
<td>901</td>
<td>1448</td>
<td>1320</td>
<td>1095</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometry</td>
<td>jet</td>
<td>square</td>
<td>square</td>
<td>square</td>
<td>hex</td>
<td>square</td>
<td>rect.</td>
<td>jet</td>
<td>jet</td>
<td>jet</td>
<td>jet</td>
<td>jet</td>
<td>jet</td>
<td>jet</td>
<td>jet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max drift (mm)</td>
<td>70</td>
<td>18</td>
<td>16</td>
<td>6</td>
<td>18</td>
<td>10</td>
<td>10</td>
<td>30</td>
<td>50</td>
<td>7</td>
<td>40</td>
<td>30</td>
<td>6</td>
<td>25</td>
<td>31</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. resolution (micron)</td>
<td>150</td>
<td>150</td>
<td>220</td>
<td>210</td>
<td>150</td>
<td>250</td>
<td>110</td>
<td>55</td>
<td>100</td>
<td>125</td>
<td>200</td>
<td>40</td>
<td>140</td>
<td>100</td>
<td>200</td>
<td>~100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dE/dx resolution (%)</td>
<td>10</td>
<td>5.6</td>
<td>15</td>
<td>3.5</td>
<td>7</td>
<td>7.1</td>
<td>7.2</td>
<td>6</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endplates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Rohacell</td>
<td>Al + H-C</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al + H-C</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Gl-F</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al or C-F</td>
<td></td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>76</td>
<td>35</td>
<td>30</td>
<td>5</td>
<td>21</td>
<td>76</td>
<td>28</td>
<td>5.1</td>
<td>31.8</td>
<td>50.8</td>
<td>50.8</td>
<td>21</td>
<td>30</td>
<td>20</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometry</td>
<td>flat + rib</td>
<td>flat + cone</td>
<td>flat</td>
<td>flat</td>
<td>cone</td>
<td>sphere</td>
<td>flat</td>
<td>cone</td>
<td>parabola</td>
<td>flat</td>
<td>flat</td>
<td>flat</td>
<td>flat</td>
<td>stepped</td>
<td>flat</td>
<td>flat</td>
<td>sphere</td>
<td></td>
</tr>
<tr>
<td>Wire load (tonnes)</td>
<td>1.2</td>
<td>2.3</td>
<td>3.1</td>
<td>33.7</td>
<td>6.8</td>
<td>14</td>
<td>13.3</td>
<td>6.8</td>
<td>20</td>
<td>25</td>
<td>3.4</td>
<td>4.5</td>
<td>5.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max deflection (mm)</td>
<td>8</td>
<td>3</td>
<td>0.6</td>
<td>0.5</td>
<td>7</td>
<td>7.9</td>
<td>1.4</td>
<td>3</td>
<td>1.8</td>
<td>~1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer cylinder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Al</td>
<td>Al</td>
<td>H-C</td>
<td>C-F</td>
<td>Al</td>
<td>Al</td>
<td>Al + H-C</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Gl-F</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>rods</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>25</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>12.7</td>
<td>6.4</td>
<td>5</td>
<td>posts</td>
<td>6</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner cylinder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Lexan</td>
<td>Gl-F</td>
<td>C-F</td>
<td>foil</td>
<td>C-F</td>
<td>paper</td>
<td>foil</td>
<td>Al + H-C</td>
<td>C-F</td>
<td>Be</td>
<td>C-F</td>
<td>C-F</td>
<td>Kevlar</td>
<td>Al + foam</td>
<td>C-F</td>
<td>foil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>3</td>
<td>5</td>
<td>3.3</td>
<td>1</td>
<td>1</td>
<td>0.75</td>
<td>2</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
<td>1.4 + 9</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load bearing</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stringing</td>
<td>horiz.</td>
<td>vert.</td>
<td>horiz.</td>
<td>vert.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prestressing</td>
<td>rods</td>
<td>rods</td>
<td>wires</td>
<td>external</td>
<td>rods</td>
<td>rods</td>
<td>rods</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C-F - carbon-fiber/epoxy, Gl-F = glass-fiber/epoxy, H-C = honeycomb

⇒ Many variations of drift-chamber concept can be built.
Forward Endplate

Goal: low number of radiation lengths

maximum track length

Best solution (my opinion): Al toroidal cap with wire load supported at both inner and outer cylinders
– FEA analysis indicates could use only 2.5 mm Al:

Peak stress < 24 MPa = \(1/10\) ultimate strength,

Maximum deflection = 250 \(\mu\text{m}\).

Stress \(\propto\) 1/thickness.

Displacement \(\propto\) 1/thickness.

(See TNDC-96-25.)

– Similar to endplates built for SLD.

– Disadvantages:

  Time to hog out plate from block (use spun casting?).

  Any shaped endplate must have stiffening rings to
  suppress radial spread

\(\Rightarrow\) localized region with higher radiation lengths.
Von Mises Stress in Toroidal-Cap Endplate

Thickness = 2.5 mm Al
Radial and Axial Deflections of Toroidal-Cap Endplate

Thickness = 2.5 mm Al

Radial Deflection

Axial Deflection
Shaped Carbon-Fiber Endplates

(See TNDC-96-21 and -25.)

Cones and bicones can be made from flat sheets:

A 23.6° cone can be made if a 30° sector is cut out.
A layup of 11 (or 22, 33...) sheets would have 11 directions in which fibers are along cone generators, and would have fibers in 6 directions at any point.
FEA Analysis

If supported only at outer radius a bicone should be at least 8 mm thick, and a cone at least 12 mm thick.

Peak displacements = 1.3 mm in bicone and 1.5 mm in cone.

Scale results of FEA analysis on following pages for Al by 10/thickness[mm] in case of carbon-fiber.
Von Mises Stress in Bi-cone Endplate

Thickness = 5mm Al

Stress (kg/m²) vs. Radius (m)
Radial and Axial Deflections of Bi-cone Endplate

Thickness = 5mm Al

Radial Deflection

Axial Deflection
Von Mises Stress in Cone Endplate

Thickness = 5mm Al
Radial and Axial Deflections of Cone Endplate

Thickness = 5mm Al

Radial Deflection

Axial Deflection
Flat Endplate – Supported at Outer Edge

(See TNDC-96-20 and -24.)

Analytic analyses available (Roark and Young).

Maximum stress $= 1/10$ ultimate stress $\Rightarrow$

$3.2$ cm Al, maximum displacement $= 3.3$ mm

$3.7$ mm carbon-fiber, maximum displacement $= 2.9$ mm.

Scaling laws for bending flat plates:

stress $\propto 1/\text{thickness}^2$

Displacement $\propto 1/(\text{modulus} \cdot \text{thickness}^3)$. 
3.2-cm-thick flat Al endplate, supported outer edge
Flat Endplate – Supported at Both Edges

Maximum stress = 1/10 ultimate stress ⇒

1.2 cm Al, maximum displacement = 2.2 mm

1.4 mm carbon-fiber, maximum displacement = 1.4 mm.
1.2-cm-thick flat Al endplate, supported both edges
Summary of Front Endplate Options

The thickness $t$ of the plates was chosen so the peak stress under 3500 kg wire load is 1/10 the ultimate stress.

The ordering below represents my personal preference.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Material</th>
<th>$t$ (cm)</th>
<th>$X_0$ (%)</th>
<th>Support</th>
<th>Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal</td>
<td>Al</td>
<td>0.25</td>
<td>2.8%</td>
<td>Both</td>
<td>0.25</td>
</tr>
<tr>
<td>Flat</td>
<td>Al</td>
<td>1.2</td>
<td>13.5%</td>
<td>Both</td>
<td>2.2</td>
</tr>
<tr>
<td>Flat</td>
<td>C-F</td>
<td>1.4</td>
<td>5.6%</td>
<td>Both</td>
<td>1.4</td>
</tr>
<tr>
<td>Flat</td>
<td>Al</td>
<td>3.2</td>
<td>36%</td>
<td>Outer</td>
<td>3.3</td>
</tr>
<tr>
<td>Flat</td>
<td>C-F</td>
<td>3.7</td>
<td>15%</td>
<td>Outer</td>
<td>2.9</td>
</tr>
<tr>
<td>Bicone</td>
<td>C-F</td>
<td>0.8</td>
<td>3.2%</td>
<td>Outer</td>
<td>1.3</td>
</tr>
<tr>
<td>Cone</td>
<td>C-F</td>
<td>1.2</td>
<td>4.8%</td>
<td>Outer</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Should the Inner Cylinder Be Load Bearing?

(See TNDC-96-20.)

If both inner and outer cylinders are load bearing the stresses in the endplates are reduced, permitting thinner endplates.

Thin cylindrical shells under axial load can fail by buckling:

\[
F_{\text{max}} = \frac{\pi^3 E t^{9/4} r^{1/4}}{6 l^{1/2} (1 - \nu^2)^{5/8}} \quad \text{(semi-empirical)}.
\]
Laboratory Test

Cylinder of radius 6” and length 36” from a sheet of G-10 ($E = 2.5 \times 10^6$ psi, $\nu = 0.3$) about 0.018” = 450 µm thick.

The calculated buckling force is then 425 pounds.

The G-10 tube buckled under 715-Lb load.

⇒ Semi-empirical formula gives a lower bound on the buckling force.
Summary of Load Bearing Cylinder Options

Thickness $t$ such that wire load $= 1/10$ the buckling load.

3/5 of the wire load should be carried by the inner cylinder, \textit{i.e.}, 1400 kg out of 3500 kg.

The length $l$ of the cylinders is taken as 3 m.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$</th>
<th>$r$</th>
<th>$t$</th>
<th>$X_0$</th>
<th>Compression $(\mu m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-F</td>
<td>140</td>
<td>24</td>
<td>1.5</td>
<td>0.6%</td>
<td>108</td>
</tr>
<tr>
<td>Be</td>
<td>300</td>
<td>24</td>
<td>1.1</td>
<td>0.3%</td>
<td>76</td>
</tr>
<tr>
<td>C-F</td>
<td>140</td>
<td>80</td>
<td>1.6</td>
<td>0.64%</td>
<td>14</td>
</tr>
</tbody>
</table>

Carbon-fiber cylinders would need an aluminum foil laminate to provide rf shielding. If this laminate is, say, 350 $\mu$m thick it would add an additional 0.4% radiation length.

\textit{Is a Be cylinder worth the trouble?}