Mechanical Structure
of
The TOPAZ Barrel Drift Chamber

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Abstract

A Barrel Drift Chamber (BDC) is constructed for the TOPAZ experiment at TRISTAN, KEK. The BDC has a cylindrical shape with dimensions of 325.2 cm in inner diameter, 347.2 cm in outer diameter and 500 cm long. It consists of 1232 drift tubes made of conductive plastic cathodes, which are staggered in four layers. In this report, a design of the mechanical structure and construction procedures are described in detail.

1. Introduction

A Barrel Drift Chamber (BDC) has been constructed for charged-particle detection in the TOPAZ [1] detector. The TOPAZ is a general-purpose magnetic spectrometer at TRISTAN, a 30 GeV-30 GeV e⁺e⁻ collider built at KEK, National Laboratory for High Energy Physics, in Tsukuba.

The BDC is a cylindrical drift chamber placed on the outer surface of the superconducting solenoid and in front of the lead-glass calorimeter. The role of this detector is as follows;

(a) to measure track positions of charged particles accurately at the exit to the area with zero magnetic field,

(b) to determine positions of photons by measuring the electron-positron pairs converted in the solenoid magnet,

(c) to provide triggering signals for charged-particle tracks,

(d) to help pattern recognition in the Time Projection Chamber (TPC) by providing the two-dimensional track position at an early stage of the off-line analysis.

For these purposes, the BDC is requested to have a capability of measuring the two-dimensional position with spatial resolutions of better than 300 μm in the rθ plane and 10 mm in the Z direction, and with a detection efficiency larger than 95% for charged particle tracks.
Figure 1 shows an overall view of the BDC. The BDC has a cylindrical shape with dimensions of 325.2 cm in inner diameter, 347.1 cm in outer diameter and 500 cm long, and it is divided into 8 unit modules for easy fabrication. Each module consists of 156 drift tubes of 460 cm long staggered in four layers. A total number of drift tubes is 1232. Each drift tube is composed of a semi-rectangular cathode of conductive plastic and an anode wire of gold-plated molybdenum with 100 μm diameter.

The BDC is operated in a limited-streamer mode with a gas mixture of Ar(50%)/C₂H₆(50%) at an atmospheric pressure. Readout of the track position orthogonal to the anode wire is made by the drift time measurement and that along the anode wire is made by the cathode strip method.

In order to obtain good spatial resolutions of the BDC, requirements for the mechanical structure were carefully studied. In the design of the structure, following conditions are taken into account:

1) Anode wires should be positioned with an accuracy better than 200 μm in the TOPAZ detector.

2) A relative positioning accuracy of anode wires in a unit module should be better than 50 μm.

3) A tolerance for the deviation of distances between the anode wire and the wall of the conductive plastic tube should be less than ±1.0 mm in order to reduce the unbalance of the electrostatic force between them.

4) The maximum gravitational sag of the mechanical structure should be less than 1.5 mm.

Since the total weight of the BDC is limited to be less than 2,000 kg and the thickness available for the BDC is limited to be less than 20 cm, a very careful study was necessary to make a mechanical structure with such a large area which satisfies all the above requirements. In the succeeding sections of this paper, we report the design of the mechanical structure and the construction procedures in detail.

2. Design of the Mechanical Structure

The mechanical structure of the BDC module is shown in Fig.2. It has 156 drift tubes arranged in four layers, and three sheets of G-10 epoxy glass with printed copper strips are interleaved between the tubes. Every drift tube is fixed to the aluminum end-plates with screws for accurate positioning. All the drift tubes, the cathode sheets and the end-plates are glued together with epoxy resin.
Since the tensile strength of the plastic tube is not so large, the structure without surface panels is bent easily even with the gravitational force. To reinforce the structure, two panels of aluminum are glued on the inner and outer surfaces of the structure.

Before coming to this design, first, we estimated the amount of deformation of the structure due to the gravitational force with and without surface panels. Since the BDC has an arc-shaped structure and is supported only at both ends, the deformation occurs mainly along the longitudinal direction. The calculation was made for various panel materials and thicknesses under some geometrical assumptions.

Mechanical properties of the conductive plastic tube made of 'PAPIOSTAT' [2] are summarized in Table 1.

Table 1. Mechanical properties of conductive plastic.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>2.2 - 2.7 kg/mm²</td>
</tr>
<tr>
<td>Elongation Percentage</td>
<td>5 - 10%</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>200 kg/mm²</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.16</td>
</tr>
</tbody>
</table>

A cross section of each drift tube has a trapezoidal shape, as is shown in Fig. 3. Horizontal widths are varied depending on the radius of each layer in order to reduce the gap between the neighbouring tubes.

It is rather difficult to calculate the mechanical strength of the BDC structure by an analytical method, because its arc-shaped structure is made of various materials such as aluminum panels, plastic tubes and G-10 panels with copper strips glued together.

In order to make a first-order estimation, we calculated the gravitational sag for the simple model as shown in Fig. 4, where arc-shaped structure is approximated by a flat plate panel. This plate is assumed to be supported at both ends in the longitudinal direction. Since the structure of the staggered drift tubes is still complex, we further assumed that the tubes are placed one over another. Figure 5 shows an equivalent model to calculate the gravitational sag of the plate. Since the plate is supported at both ends, a beam model can be used, where cross sections of the beams are shown in Figs. 5(b) and (c) for the cases without and with surface panels, respectively.

The maximum gravitational sag occurs at the center in the longitudinal direction of the beam and whose amount \( \delta \) is given by
\[ \delta = \frac{5}{384} \cdot \frac{WL^4}{EI} \]  \hspace{1cm} (1)

where \( E \) is the modulus of elasticity, \( I \) is the geometrical moment of inertia, \( L \) is the length of the beam and \( W \) is the weight of the unit length of the beam. For the beam with the cross section shown in Fig.5(b), \( I \) is expressed roughly as

\[ I \approx \frac{1}{12} (b_2^3h_2^3 - b_1^3h_1^3) + \frac{1}{4} b_1t_1h_2^2. \]  \hspace{1cm} (2)

For the beam made of composite materials as shown in Fig.5(c), the stiffness \( EI \) in the formula (1) can be substituted by the following form,

\[ EI = E_1I_1 + E_2I_2, \]  \hspace{1cm} (3)

where \( E_1I_1 \) is the stiffness of plastic tubes, and \( E_2I_2 \) is that of the surface panels. Equation 3 is correct when the shape of the cross section does not vary appreciably under the load. This is the case for the present model because the side walls of the plastic tubes connect upper and lower plates with the same strength and surface panels are also tightly glued to the plastic tubes. In Eq. (3), \( I_2 \) is given by

\[ I_2 = \frac{b_2^2}{12} [(h_2 + 2t_2)^3 - h_2^3] - \frac{1}{2} b_2t_2h_2^2. \]  \hspace{1cm} (4)

In the case that the surface panels are not used as shown in Fig.5(b), the maximum sag of the plate is calculated to be 5.6 cm, where \( E = 20,000 \text{ kg/cm}^2 \), \( L = 500 \text{ cm} \) and \( W = 7.8 \times 10^{-3} \text{ kg/cm} \) are assumed. It is clear that the plate structure without surface panels can not satisfy the requirements for the BDC.

In order to reduce the maximum sag, the mechanical structure can be improved in the following two points; (1) to increase \( E \) and \( I \) by adding the strong surface panels and (2) to increase the stiffness by taking the arc-shaped structure. We, first, study the effect of the panels glued on the inner and outer surfaces of the plastic tube plate. The effect of (2) is described in the next section.

Since the thickness of the BDC is limited from the available space, the geometrical moment of inertia, \( I \), can not be increased appreciably. Therefore, the only way to increase the stiffness is to use the material with a large tensile strength and with a low density.

We examined three candidates, namely a glass-fiber-reinforced plastic (GFRP), a carbon-fiber-reinforced plastic (CFRP) and an aluminum plate.
Mechanical properties of these materials are compared in Table 2.

Table 2. Mechanical properties of surface panel candidates.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Specific Gravity</th>
<th>Radiation Length (mm)</th>
<th>Tensile Strength (kg/m²)</th>
<th>Modulus of Elasticity (kg/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.7</td>
<td>89</td>
<td>7 ~ 28</td>
<td>7,000 ~ 7,400</td>
</tr>
<tr>
<td>GFRP</td>
<td>1.75</td>
<td>194</td>
<td>15 ~ 20</td>
<td>750 ~ 1,000</td>
</tr>
<tr>
<td>CFRP</td>
<td>1.5</td>
<td>188</td>
<td>45 ~ 60</td>
<td>5,500 ~ 6,000</td>
</tr>
</tbody>
</table>

It should be noted that the data for GFRP and CFRP depend largely on the fabrication procedure.

The maximum sags are calculated for the cases that the plastic tubes are sandwiched by these materials of 2 mm thick. Results are shown in Table 3.

Table 3. Maximum sag for the plane plate sandwiched by the 2 mm thick surface panels

<table>
<thead>
<tr>
<th>Panel Material</th>
<th>Aluminum</th>
<th>GFRP</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Sag (mm)</td>
<td>3.2</td>
<td>16</td>
<td>3.9</td>
</tr>
</tbody>
</table>

From this estimation, and from the commercial availability, the cost and the easiness in forming the arc-shaped structure, we determined to use the aluminum plate for the surface panels.

3. Three-Dimensional Structural Analysis

The distortion of the BDC module due to the gravitational force was calculated by the finite element method. The program code for structure analysis used in the present study is called ISAS (Integrated Structure Analysis program) [3]. The calculation was done with HITAC M200 at the Computer Center of The University of Tokyo. The structure model of the BDC module is shown in Fig. 6. Since the structure is symmetric in the longitudinal direction, we analyzed only a half of the structure in order to reduce the computing time.
In this calculation the BDC structure is approximated by an ensemble of plates made of aluminum and plastic. As input data, 980 plate elements and 605 nodal points are used.

In the calculation, the following conditions are assumed:

1) The tensile strength of the adhesive layer such as a layer between the aluminum panel and plastic tubes, and a layer between two plastic tubes is larger than that of the plastic tube itself. Therefore glued layers do not peel off before plastic tubes are broken.

2) The force applied to the structure is assumed to be only due to the gravitational one.
   In the BDC structure, the anode wire is strung with the tension of 320 g, and the total load applied between two end-plates is 50 kg. Because of the honeycomb-type structure, this load acts mainly as a compression force in the longitudinal direction. Compared to the tensile strength of the material, this load is negligibly small.

3) The structure is supported only at both ends.

4) Side covers made of aluminum plates are ignored.

5) The thicknesses of end plates, the inner surface panel and the outer surface panel are 15 mm, 2 mm and 2mm, respectively.

6) The wall thickness of the plastic tube is 1.2 mm.

7) It is assumed that the side walls of the plastic tubes are arranged in a straight line, as shown in Fig.6.

Results of the calculation for the displacements are shown in Figs. 7-9 and Fig. 11.

Figure 7 shows displacements of the outer aluminum plate in the X direction as a function of the Z position, where (a), (b) and (c) correspond to results at three azimuthal angles \( \psi = 0^\circ, 9^\circ \) and \( 18^\circ \).

Figure 8 shows displacements of the outer surface in the Y direction as a function of the azimuthal angle \( \psi \), where (a), (b) and (c) correspond to results at three Z-positions, \( Z = 0 \), \( Z = 125 \) cm and \( Z = 250 \) cm. Figure 9 shows displacements of the outer surface in the Z direction, where (a) shows the \( Z \) dependence at \( \psi = 0^\circ \) and (b) shows the \( \psi \)-dependence at \( \psi = 0^\circ \). From this calculation, it is found that the maximum sag was 1.2 mm at the center in the Z direction. Displacements in X and Y directions are less than 0.5 mm.

In the TOPAZ detector BDC modules are mounted on the cryostat as shown in Fig. 10, so that the direction of the
gravitational force is different for each module. We calculated the displacement for each module position.

Figure 11 shows results for modules at sector positions No.1, No.0 and No.6 indicated in Fig. 10. The maximum sag is around 1.0 mm for the modules placed at positions No.1, No.2, No.5 and No.6

4. Fabrication of the Main Components

4-1 Conductive plastic tubes

Conductive plastic tubes of 4.6 m long was fabricated by an extrusion method. Plastic material is polystyrene mixed with carbon grains. Resistivity of the tube was controlled by the amount of carbon. Measured resistivity was around 50 kΩ/sq. The size of the cross section and wall thicknesses of the tube were carefully controlled with an accuracy better than 100 μm.

4-2 Aluminum end-plates

End-plates placed at both ends of the BDC hold the anode wires with high precision. Accuracies of the position and diameter of the holes drilled on the 15 mm thick endplates is a key factor for an accurate positioning of anode wires. A numerically-controlled machine was used for drilling holes under the constant temperature of 22°C. Accuracies of hole positions were measured and the results are shown in Fig. 12, where histograms for the difference between designed coordinate of holes and measured ones are represented. These results indicate that the accuracy of hole positions is better than ± 30 μm.

4-3 Surface panels

Material of aluminum surface panels is A5052-H34. Bending of the rectangular flat plate of 500 x 132 cm² into an arc-shaped panel was done by a pressing method. Accuracy of the bending radius was carefully controlled. After the pressing, the uniformity of the radius of the panel was measured on an arc-shaped construction table, whose radius was machined with an accuracy better than 100 μm. The bent panel was placed on the construction table without any extra stress except the self-weight, and the gap between the panel and the surface of the construction table was measured. We required that this gap was less than 2 mm all over the panel, and when it was larger than 2 mm, the panel was re-pressed. After pressed two or three times, all panels had passed the examination.

5. Assembling of the BDC

5-1 Principle of the positioning of the plastic tubes and
Since the accurate positioning of the anode wire is necessary to get the designed position resolution, we adopted a method illustrated in Fig. 13. The end-plates hold plastic feed-throughs for the anode wire positioning. At both ends of the drift tube, aluminum end caps which have holes at the center were glued to the tube. In order to align the positions of the end plate hole and the drift tube, both holes were aligned accurately on the same axis by inserting the construction pin. With these pins inserted, plastic tubes were glued together. After epoxy adhesive was cured, these pins were pulled out from the end plates.

5-2 Test of the assembling procedure

In order to establish the assembling procedure of the BDC structure, we constructed the test module with the sizes of 1/3 in length and 1/4 in width. Forty drift tubes were staggered in four layers. All parts of the chamber were the same as those used in the real module. In this model test, emphasis was placed on the study of the glueing process. A special construction table was prepared and various jigs kept the relative positions of drift tubes accurately. During the curing process of epoxy adhesive, which is about 12 hours, the uniform pressure was applied to the glued layers by the evacuation method.

After various trials, jigs and methods in the glueing process were improved, and finally, the model which satisfied the requirement was constructed. Performances of the test module were measured with the electron beam from the INS synchrotron. The positional resolution of 200 m and the track detection efficiency of 97% were achieved [4].

5-3 Assembling of the module

Each BDC module was assembled on the arc-shaped construction table shown in Fig. 14. Aluminum surface panels, plastic tubes and copper-printed G-10 cathode sheets are glued together with epoxy resin adhesive. Assembling procedures and jigs for glueing were established based on the prototype experience.

Detailed descriptions of the assembling procedures are listed in the following:

1) To set the inner surface panel on the construction table.

2) To set the end-plates at both ends of the inner surface panel. They are fixed by bolts to the construction table.

3) To set side bars which keep the position accuracy of drift tubes during the curing process of adhesive. (Side bars are covered by the anti-adhesive solvent.)
4) To smear the top surface of the panel with epoxy adhesive by use of spatulas.

5) To smear three surfaces of each drift tube, a lower surface and both side surfaces with epoxy adhesive.

6) To glue end-caps to both ends of the plastic tube.

7) To arrange these tubes on the inner surface panel.

8) To align the holes of the plate and that of the end-cap on the same axis by inserting the construction pin.

9) To fix the end-caps to the end-plate by screws.

10) To set the cathode sheet, whose inner surface is smeared with epoxy adhesive, over the drift tubes.

11) At this stage, arrangement of the first layer is finished. The next step is to cover whole surfaces of the structure with the vinyl sheet. To evacuate the space between the construction table and the vinyl sheet down to the pressure of 0.7 atm. Then the uniform pressure of 0.3 kg/cm² is applied on the structure during the curing process of adhesive for 12 hours.

12) Assembling processes of the second, the third and the fourth layer is the same as that of the first layer.

13) Finally, to glue the outer surface plate on the top of the fourth layer, and to fix it to the end plates with screws.

6. Measurements of the Gravitational Sag

The size of the gravitational sag of the completed module was measured on the construction table with the use of an R-gauge as shown in Fig. 14.

Procedures of the measurement are as follows:

1) First, the distance from the construction table to the top surface of the plate was measured with the depth gauge. A number of measured points are 30, 5 steps in the azimuthal angle and 6 steps along the Z direction.

2) Next, the module was supported by the spacers of 7 mm thick at four corners, and the distance was measured by the same way as described in 1).

Then the size of the sag was calculated as the differences of the two values measured with and without spacers. Figure 15 shows the results of the measurements. Accuracy of the
measurement is better than ±0.2 mm, where the error is due to the inaccuracy of the R-gauge and due to the nonuniformity of the construction table. The maximum sag of 1.5 mm agrees approximately with the results of the calculation. (Note that the length of the model for the calculation was 5.0 m and the length of the real module was 4.5 m.)

7. Installation

All modules were assembled at the Ishioka Work of Aiga Electric Co. Ltd., Ishioka, Ibaragi Prefecture. They were transported to INS for the performance test with cosmic rays. After finished the test, they were transported to Tsukuba Experimental Hall, and successfully installed into the TOPAZ detector.

Figure 16 is a picture showing the installation of the BDC. The BDC was slid into rails attached on the surface of the magnet cryostat. The one end of the BDC was fixed to the cryostat wall, but the other end was kept free for sliding in the longitudinal direction. With this method, the extra stress due to the difference of the expansion rate could be avoided.

The position accuracy for setting the BDC relative to the cryostat wall was around 1 mm, and the displacement of each module was measured with the accuracy of about 200 μm.

8. Conclusion

We have constructed the barrel drift chamber of the TOPAZ detector. In order to get the designed position resolution, we studied the mechanical structure and the construction procedure carefully. The size of the maximum gravitational sag of the BDC module was measured to be less than 1.5 mm, which are in the designed value, and the agreement between the calculation and the measurement is fairly good. A slight difference may be due to the crudeness of the approximation for mechanical properties of composite materials.
Acknowledgements

The authors are indebted to the members of the TOPAZ collaboration for their cooperation in various stages of this work. They are also grateful to the crew of the engineering center of Lawrence Berkeley Laboratory, University of California, for their advices in designing the mechanical structure. The structural analysis of the BDC was carried out at the Computer Center of The University of Tokyo.

The fabrication of mechanical components was done by Toshiba Corp., and the assembling of the BDC modules was made by Aiga Electric Co. Ltd.

They express their thanks to Mrs. M. Tsukada and Miss. H. Fukushima for their help in making the manuscript.
References


3. ISAS, Integrated Structure Analysis Program. Hitachi Co. Ltd.

Figure Captions

Fig. 1. TOPAZ Barrel Drift Chamber.

Fig. 2. Mechanical structure of the barrel drift chamber module.

Fig. 3. Cross section of the drift tube. Dimensions are given in mm.

Fig. 4. Plane-plate model for the structural analysis. Dimensions are given in mm.

Fig. 5. Simplified plane-plate model for the structural analysis, where plastic tubes are piled up on the same row. (a) shows the beam supported at both ends, and (b) and (c) show cross sections of the beam without and with surface panels.

Fig. 6 The model of the BDC module for the structural analysis by use of the finite element method.

Fig. 7 Vertical (X) displacements along the Z axis at three different azimuthal angles.

Fig. 8 Horizontal (Y) displacements as a function of the azimuthal angle at three different Z-positions.

Fig. 9 Longitudinal (Z) displacements of the outer surface as a function of (a) the azimuthal angle Ψ at Z=0 and (b) the Z position at Ψ=0.

Fig. 10 Arrangement of BDC modules in the TOPAZ detector.

Fig. 11 Vertical displacement due to the gravitational sag for modules placed at three different positions. (a),(b) and (c) correspond to the modules No.1, No.0 and No.6 in Fig.10.

Fig. 12 Position accuracies of holes drilled on the end plate. (a) shows the horizontal and vertical coordinates. (b) and (c) show histograms of differences between designed positions and measured ones of holes.

Fig. 13 Positioning of the drift tube. Holes on the end plate and on the endcap are arranged on the same axis by inserting the construction pin.

Fig. 14 Schematic view of the construction table for assembling the BDC module and for measuring the gravitational displacement.

Fig. 15 Vertical displacements at three azimuthal angles. Points o and x show the data at positive and negative
azimuthal angles. Solid lines are only for eye-guide.

Fig. 16  Installation of the BDC into the TOPAZ detector.
Fig. 5
1. Al plate element
2. Side wall element
3. Horizontal wall element
4. End plate element
Fig. 7
Fig. 8
Fig. 9
View from the non-chimney side

Fig. 10
Fig. 11
Fig. 12
Fig. 13

- End plate
- Plastic tube
- Screw
- End cap
- Construction pin
Fig. 14

Depth Gauge

R - Gauge

Barrel Drift Chamber

Construction Table
Fig. 15