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SDC
SOLENOIDAL DETECTOR NOTES

STRAW TUBE SUPERLAYER DESIGN CONCEPTS

May 20, 1991

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ABSTRACT

The purpose of this report is to review the procedures which have been proposed for the construction of straw tube superlayers and to evaluate them against various physics, mechanical and cost requirements. In the process of this evaluation, critical R&D issues have been identified which need to be resolved before a final decision on superlayer construction is made. A plan to reach this decision in a timely manner is proposed. The plan makes maximum use of ongoing FY 1991 R&D and focuses the effort for FY 1992 on the construction of a full-scale multi-superlayer or single superlayer prototype.

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1. INTRODUCTION

1.1. Physics Requirements for Outer Central Tracking

The tracking system plays a major role in exploratory physics, lepton and heavy quark identification, mass reconstruction, and in the formation of the trigger. We put emphasis on reliable pattern recognition capability, and in conjunction with the silicon inner tracking and the outer intermediate angle tracking, precise momentum and vertex resolution over pseudorapidity $|\eta| < 2.5$. At 1 TeV/c transverse momentum (p_T), the design goal for momentum resolution is $\sigma(p_T)/p_T < 25\%$ for $|\eta| < 1.5$. In order to achieve the design goal for momentum resolution, the spatial resolution must be $< 150\ \mu$m per wire. The intrinsic straw chamber resolution is $\sim 100\ \mu$m. Added to this are the errors due to alignment and electronics resolution on the drift time measurement. The alignment requirements are the following [A.Seiden, "Systematic Errors and Alignment", unnumbered memo, H. O. Ogren, "Straw and Module Placement", IUHEE 91-4 (1991)]:

$\Delta\phi < 35 - 50\ \mu$m

$\Delta r < 1$ mm

$\Delta z < 0.5$ mm.

The pattern recognition requirement is the reconstruction with high efficiency of all relatively high p_T (> 1 GeV/c) charged particle tracks for $|\eta| < 1.6$. The outer central tracking system must provide level 1 or 2 trigger information for tracks with $p_T >$ about 10 GeV/c. The amount of material in the tracking system must be minimised, since it will have several negative effects on the physics performance of the detector. Photons will convert, producing an increased trigger rate for high p_T electrons and interfering with identification of electrons from decays of interest. The extra charged particles will increase the tracking system occupancy, making pattern recognition more difficult. Charged particles will lose energy in the material, degrading the momentum measurement performance. However, there is significant material in front of the outer tracking system, about 8% of a radiation length at 90° incidence, due to the beam pipe and silicon tracking system.

1.2. Engineering Baseline Design

The engineering baseline design for the outer tracking system has been defined to provide a basis for mechanical engineering. This baseline has not been optimised for either engineering or physics concerns, but rather represents a "seroth" order layout used to define the engineering concepts needed for a complete outer tracker design regardless of which tracking technology is finally chosen. The baseline design is shown in Fig. 1.1, and the numerical data is given in Table 1.1 for the four outer superlayers, which are composed of straw tubes.

Table 1.1. Straw Section of Engineering Baseline Design.

Superlayer	Radius (m)	Number of Straws/Layer	Number of Layers/Superlayer	z_{min} (m)	z_{max} (m)	Stereo Angle (°)
3	1.21722	1912	6	0.03	3.550	-3
4	1.34963	2120	6	0.03	3.900	0
5	1.48205	2328	6	0.03	3.950	+3
6	1.61447	2536	9	0.03	3.950	0

Total number of straws (both ends): 121,968.

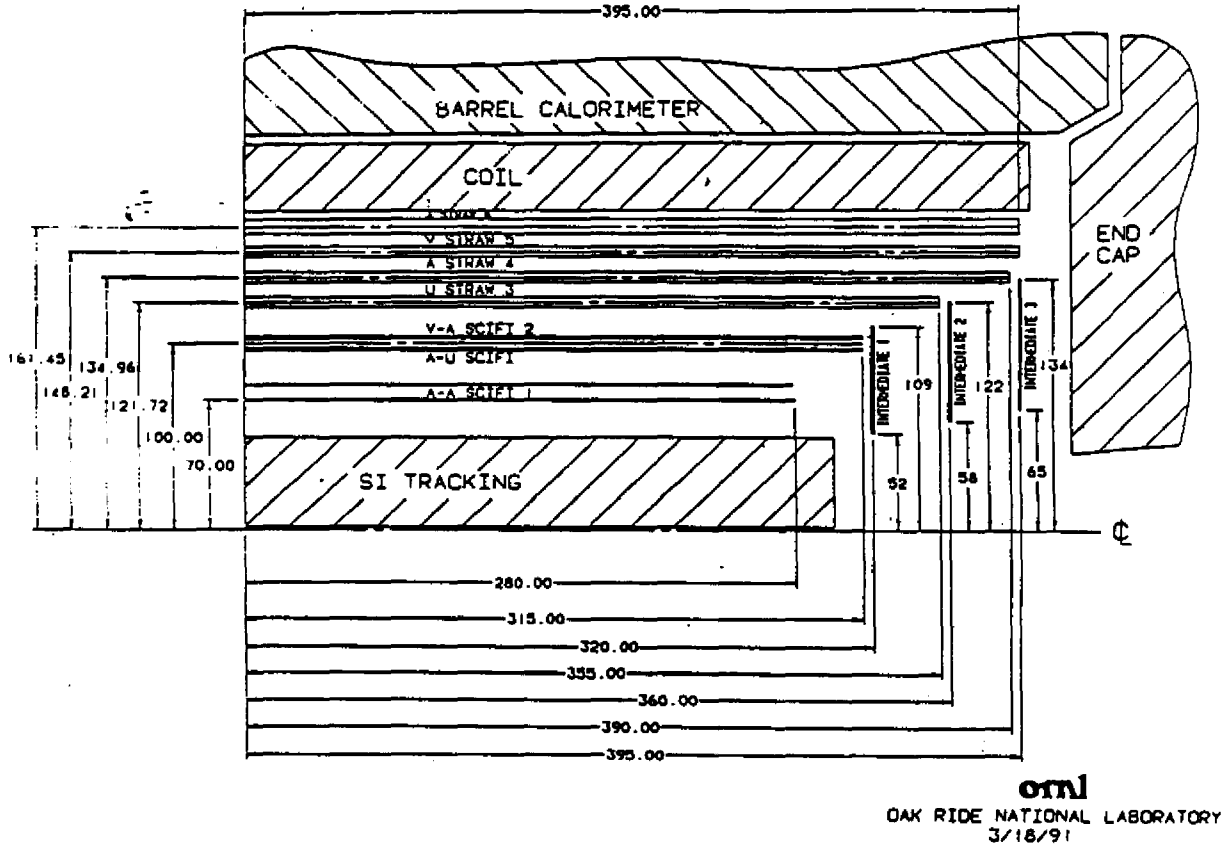

Fig. 1.1. A section through one quadrant of the tracking system of the baseline design

2. GENERAL DESCRIPTION OF STRAW TUBE SUPERLAYERS

2.1. Support Structure

The support structure for a straw tube superlayer will be a cylinder composed of a carbon-fiber epoxy material. The cylinder will span the full length of the superlayer (6 to 8 meters) and provide the primary precision support for the straw tubes, either directly or by means of thin rings attached to the cylinders. The cylinders will be supported only by means of end rings bonded to their ends. Calculations carried out at ORNL show that cylinders as thin as 0.3% X_0 can support the gravitational and wire tension loads of a straw tube superlayer.

2.2. Generic Superlayer Structure

All of the straw placement schemes discussed in this report involve the placement of straws in superlayers of six, eight, or nine (for the trigger superlayer) straws. Within each superlayer, the layers are staggered by the straw radius in order to resolve left-right ambiguities locally and allow hits from out-of-time bunch crossings to be rejected. Locally identifiable track segments can be obtained at the pattern recognition stage and for the trigger. Track segments in superlayers can be characterized as local straight line segments. Assuming that the track originates at the center of the tracking system, the slope of the line segment relative to the radial direction gives a measurement of the curvature, and therefore the transverse momentum, of the track. A tracking system design based on finding local track segments provides a powerful method for rejecting background from extra hits from any source (e.g., out-of-time bunch crossings, but this scheme was found to be useful in the Mark II central drift chamber at the SLC where the source of extra hits was synchrotron radiation). Local track segment finding also simplifies the pattern recognition, although sufficient redundancy within a superlayer and in the number of superlayers must be maintained to keep the efficiency high. The central tracking systems of many detectors have been designed to make use of local track segments – JADE, Mark III, Mark II (SLC upgrade), CDF, OPAL. A superlayer structure also simplifies the mechanical support. Single long straws are not self-supporting. However, several layers of straws held together in superlayers (probably at least six are needed) can form a rigid, mechanically stable structure. The mechanical support problem is then reduced to supporting the superlayers and aligning them spatially. There is also the possibility of supporting the wire tension within a subdivision of a superlayer. In the SDC detector, all of the elements of the tracking system – inner silicon system, outer central tracking, and probably also the outer intermediate angle tracking – are organised into superlayers, with each superlayer measuring the space coordinate and the local slope of the track segments. Track segments in each part of the tracking system will be linked to find tracks in the complete tracking system.

3. OPTIONS FOR THE CONSTRUCTION OF STRAW TUBE SUPERLAYERS

This section describes in some detail two proposed procedures for the construction of straw tube superlayers. Section 3.1 discusses a design based on the construction of straw tube modules which are self contained units providing support for wire tension, gas flow and electronics. Section 3.2 discusses an approach in which individual straw tube drift cells are pre-assembled and then transferred directly into superlayers on the support cylinders. This section describes the fabrication procedures, and Section 4 evaluates them based upon various physics and engineering criteria.

The basic 4 mm diameter straw tube is common to all superlayer construction methods. A brief description of this drift cell is given below.

The basic drift cell is constructed with a plastic based cylindrical cathode structure and a 25 μm diameter wire along the axis. Most of the straws that have been built are formed from an outer mylar wrap 12 μm thick and a 15 μm aluminised polycarbonate film inner layer. We have been using straws manufactured by Precision Paper Tubes, Wheeling, Illinois, and Stone Industrial, College Park, Maryland. The tubes are 4 mm in diameter with a 37 μm wall thickness. The standard aluminised coating is typically 1000 Å thick. The tubes have a DC resistance of 80 ohms/meter, the 25 μm wire has a 100 ohm/m resistance, and the characteristic impedance of the transmission line is 350 ohms. The weight of a straw is 0.5 grams/meter. Straws have also been made with an aluminised Kapton inner layer. These have the advantage that a thicker aluminum coating is possible (2000 Å). The resistance is about 24 ohms/meter, and the signal attenuation length is increased to about 7 meters. The straws are formed by winding a continuous 1 centimeter wide strip of aluminised plastic on a mandrel and then gluing the overlapping edges. This results in a rather uniform overall straw, but tension variations and gluing variations result in a diameter variation of about $\pm$ 25 μm and a deviation from circularity of about $\pm$ 50 μm. These variations can be important considerations when assembling a multistraw structure. The tubes are not naturally straight, with average bowing of 200 to 500 μm for a 50 cm length and 2-4 cm bowing at the 3-4 meter length. They also have very weak bowing resistance and will not support the wire tensional loads, even if glued in larger arrays. All methods proposed for using the straws for drift chambers must confront these properties of the straws. That is, the straws must be held straight in some manner, must be formed into regular arrays by some means, and the wire tension load must be transferred to some external support structure. Two options for accomplishing this are described below.

3.1. Straw Tube Modules (Units Providing Support for Wire Tension and Electronics)

3.1.1. Basic Module

The basic module design is shown in Fig. 3.1. Three important areas for development are the carbon composite shell, the endplate, and the attachment of the module to the superstructure. The outer shell holds the straws in position and maintains the alignment along the length of the module. Since the straws have

an internal wire support every 80 cm, they probably will be be forced into a rigid close packed array at this point and bonded before insertion into the shell. The unsupported 4 meter external shell does not have to be straight to 50 μm, since it is only between the 80 cm attachment points that it will be a free span. An independent alignment method will be used to attach the modules to the structure and provide the overall straightness. Also the trapesoidal cross section must be maintained between 80 cm support points by the shell. The endplate structure and the bonded straw positions maintain this shape at the support points.

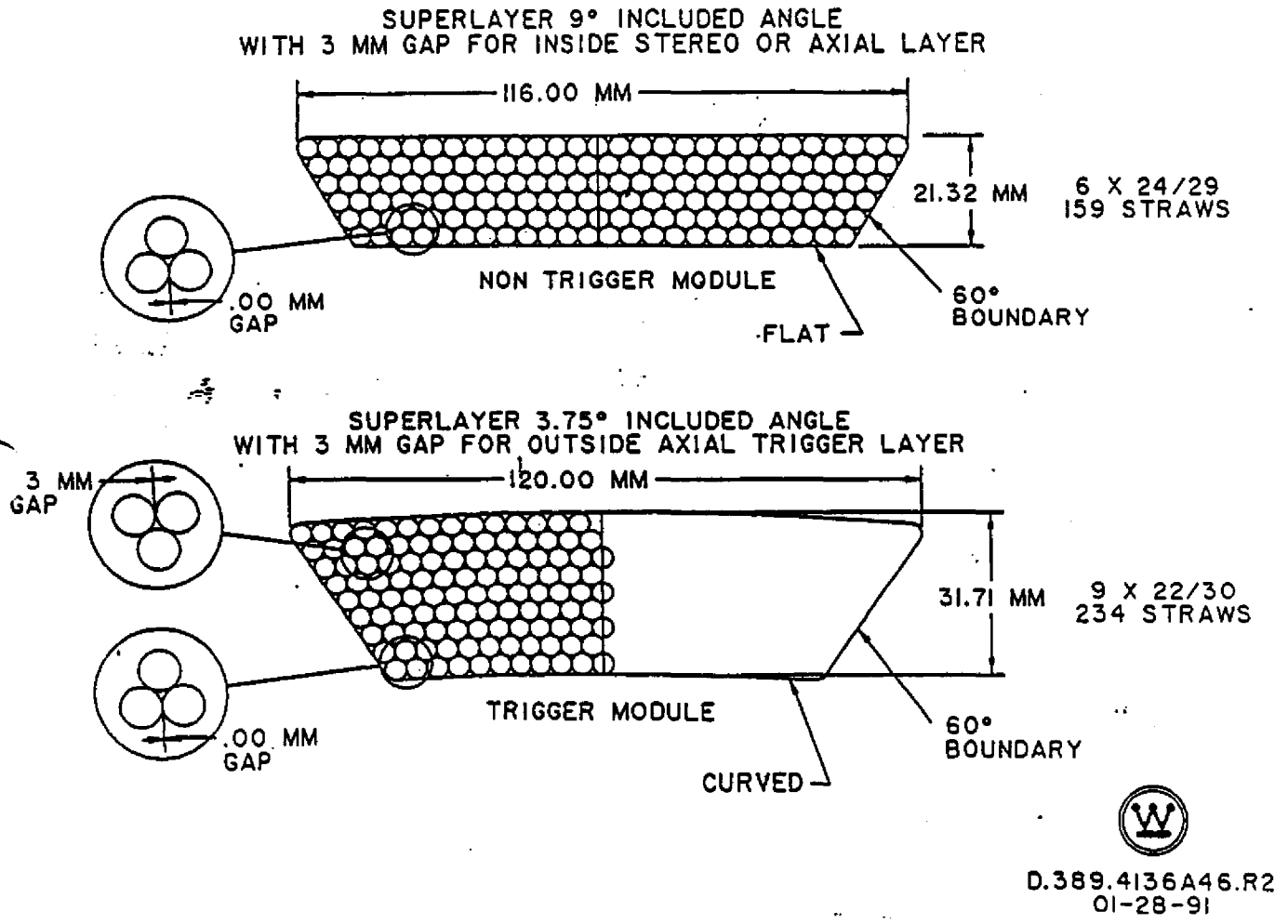

Fig. 3.1. Cross sections of two proposed module designs, one for layers 3,4 or 5, the other for layer 6.

Several carbon composite modules of 30 cm and 1 meter lengths have been constructed by Composite Horisons of Covina, California. The dimensions of these carbon shells are shown in Fig. 3.2. These were made with 4 layers of 2.5 mil prepreg carbon fiber tape (38 Million modulus). Measurements of these modules show that the intrinsic straightness over 80 to 100 centimeters can be held within the 50 μm accuracy limit.

Working with Composite Horizons, several tests of the expansion or contraction of the composite structure with respect to the room temperature mandrel (mold) size have been performed. By using the computer program, GENLAM, the final product size was accurately predicted. (See memo by R.Foster, May 6, 1991). In particular, it was confirmed that the expansion coefficient along the fiber direction is very slightly negative. This shows that we can produce a final shell to the required specifications.

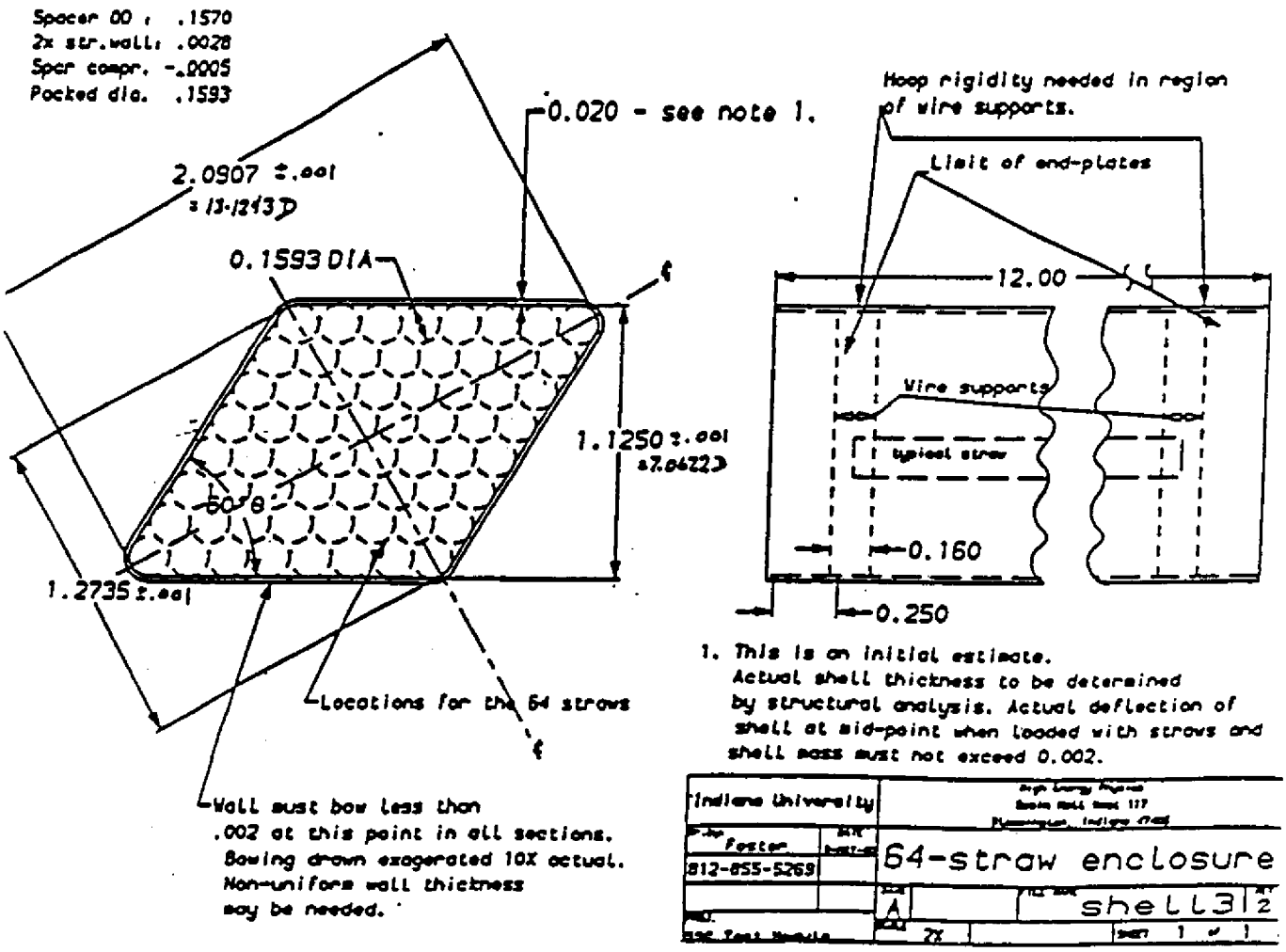

Fig. 3.2. Detail of the carbon shell for a 64 straw prototype.

The composite shell also takes the compressional load of the wire tension which is about 12 kg force for 240 straws. An analysis of the 240 straw module by Oak Ridge indicates that a 10 mil (250 μm) wall will support the tension. This is explained in a memo by J. Mayhall, Jan. 23, 1991. The molds for a 1 meter long module of this type are being fabricated, and it is expected that by June that shells will be available for loading with straws.

A total of four 30 cm long 64 straw modules have been built and tested using the 30 cm composite shells, and two additional modules of the same size are being produced. Groups at Indiana, Colorado, University of Michigan, KEK, and Pennsylvania are using them to understand multistraw tracking systems. An assembly view of this module is shown in Fig. 3.3. We have measured the straw positions at the end of the short module and found them to be within the specified ± 2 mil tolerance, as discussed in the memo by H. Ogren, April 29, 1991.

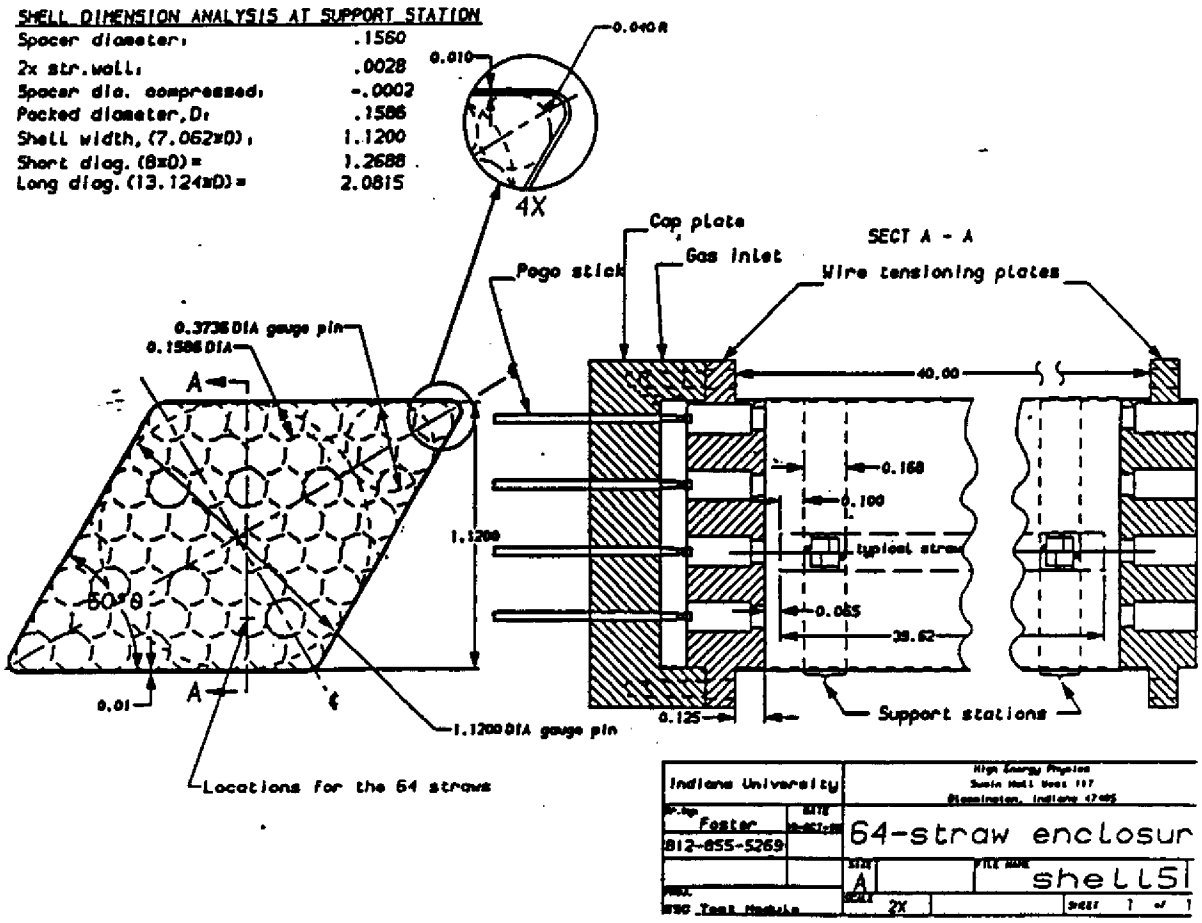

Fig. 3.3. Assembly drawing of the 64 straw prototype module.

A considerable amount of design and engineering work remain to be done on the 4 meter module. At the present time no fundamental difficulties with the concept are foreseen.

3.1.2. Endplate

Each module is capped with an endplate, as shown in Fig. 3.4. This endplate has multiple functions. It holds the signal wires and transfers the wire tension to the shell. It is also a gas manifold and provides

an electrical connection to the preamplifier for each signal wire. Prior to attaching the endplate during assembly, the straws and the wire supports will be premounted in the shell. The electrical connection to the inside metalized cathode at the ends of the module will be made by dip coating the ends of the straws with conducting epoxy. (An alternative spring contact cathode connector is also being studied.) The endplate will then be inserted into the shell but will not touch the ends of the straws. The straws can then be threaded with the signal wires, which are attached and tensioned with a solder connection to a clip in the endplate. (A solderless method of wire connection is being developed.) The endplate also acts as one side of a gas manifold. The drift chamber gas enters each straw through the same hole that holds the solder clip. The other side of the gas manifold is a plate that contains signal feedthroughs, which extend through the gas manifold and make contact with the solder clips. The printed circuit board for the electronics is attached to the feedthrough plate. This construction results in a very short end section on each module and a very low mass connection. The goal is not to allow the material in the endplate to exceed a few percent of a radiation length. The gas seal for the module is the two-piece endplate. This results in a simple leak tight unit and eliminates the necessity of forming a gas seal for each straw. The module shell itself becomes the gas barrier.

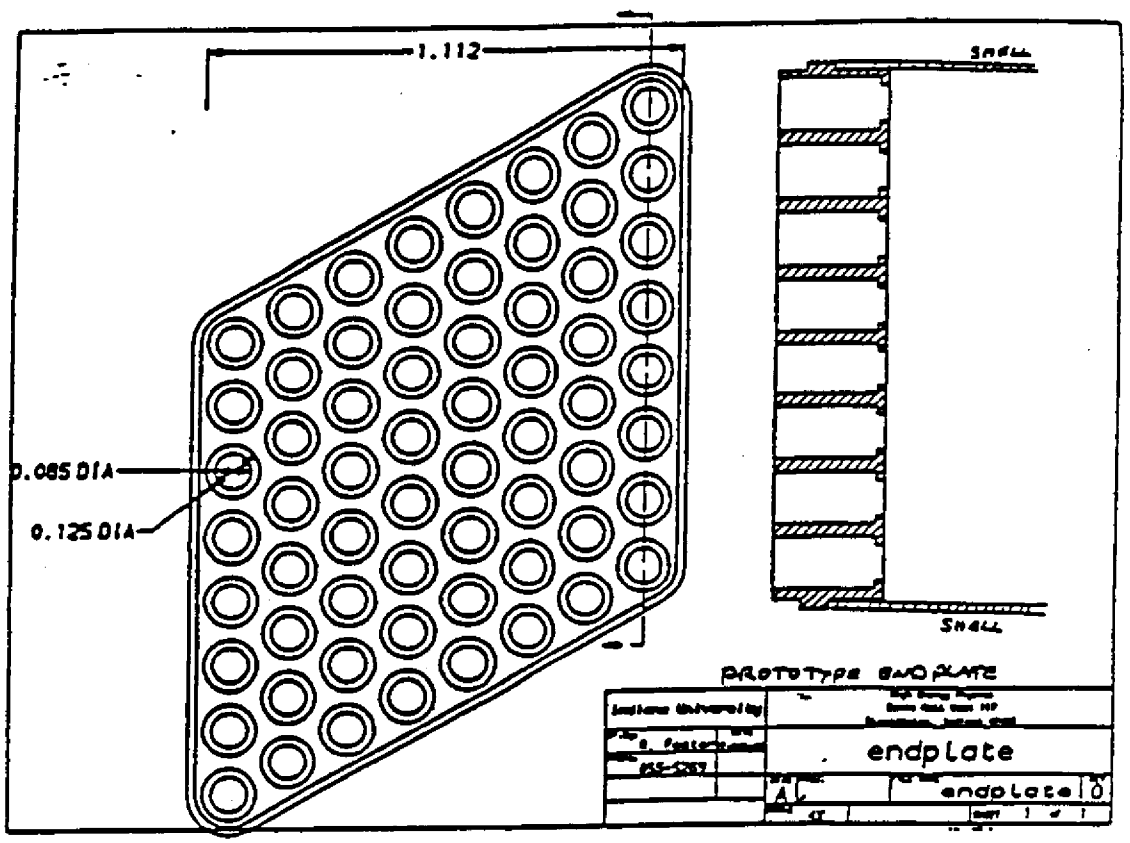

Fig. 3.4. Endplate design for the 64 straw prototype module.

A module together with the appropriate electronics becomes an independent operating drift chamber similar to a Sauli hexagonal chamber [R. Bouclier, *et al.*, Nucl. Instr. and Methods, A283, 509 (1989)]. It is anticipated that each module will be completely tested and measured before insertion into the tracking structure. This is an important step in the assembly. Each module can be mapped using X-rays to assure that placement tolerances are met with respect to the attachment fiducial points at each wire support position. The ultimate precision of the drift chamber is obtained by knowing the positions of the wires both at the ends of the modules and at the intermediate wire support points.

3.1.3. Module Attachment to the Support Structure

There are a number of methods that have been proposed for attaching the modules to the support structure.

a) Simple bonding to the support cylinder. This has the advantage of simplicity. It might require the construction of a module holder that maintains the module in alignment and rigidly positions it for bonding on the cylinder. There are a couple of disadvantages to this scheme. One is that it requires the cylinders and the modules to be assembled as a unit, so that each must be ready early in the construction sequence. There might be as many as eight such cylinders to construct, which would require careful coordination and might preclude construction of the modules at several sites. Another disadvantage is that it does not allow for easy repair if the module is damaged or needs replacement. It would require disassembling the entire structure to gain access to and replace the module. As an alternative in this scheme, the modules could be bonded to support rings spaced along the cylinder axis or directly to the cylinder. The gap between the cylinder and its required position could be filled with a thickness of bonding agent.

b) Bonding of support sleeves to the cylinder. The support sleeves are positioned on an alignment mandrel that positions them on the cylinder. The mandrel then is removed by slipping it axially out of the sleeves. The advantage of this method is that the final modules do not have to be bonded to the cylinder early in the assembly sequence. This is important both from scheduling considerations and for safety reasons, since it reduces the possibility of damage during construction. At a later stage in the assembly sequence, perhaps as late as the reassembly at SSCL, the tested modules could be installed, by sliding them in axially. At that time an alignment check would be made at several points on each module. This allows the option of bonding the modules in the sleeve at this point or designing an unlocking scheme that would allow the module to be removed at a later date. If the latter option were taken, it would be possible to replace a module quite easily during an extended shutdown, without disassembling the entire array of superlayers. There is one design under consideration that builds these sleeves as as integral part of the cylinder.

c) Attaching a module supporting device to the cylinder. This is more complicated than a sleeve. The module support device is bonded or mechanically attached to the cylinder using an alignment mandrel

as in the case of the sleeve. It has the advantages of the sleeve design, but could be made so that the module could be installed by directly clipping it in radially, rather than sliding it along its entire length. This has the advantage that radial obstructions in the internal support structure do not prevent a module from being removed and would in principle allow the interchange of a module at any time.

3.1.4. Stereo Modules

The axial modules and the stereo modules will be 4 meters long (half the length of the full tracking cylinder support). This makes the construction of the modules less cumbersome and keeps the occupancy low. It also reduces the module end displacement during rotation about the module center.

The stereo modules are rotated approximately 3° about their centers. This corresponds to a tangential shift of the end of each module by about 10 cm (the module width is about 12 cm). The radial shift of the end of the module from the reference circle due to this translation is 0.34 cm. In order to reduce interference of the corners of the modules, alternate modules would be radially shifted by about 0.5 cm as shown in Fig. 3.5 and 3.6. The final configuration gives complete coverage for all tracks.

The attachment of the stereo modules to the support cylinder can be done in any of the three schemes listed above.

3.1.5. Advantages of Modules

The straw modules are independent tracking units that can be assembled in parallel and completely pretested before insertion into the superlayer. They can be calibrated and tested with the final electronics. The modules are also repairable and replaceable as units. The envelope construction also simplifies the gas containment, which has safety advantages. The final alignment of the modules on the superlayers also is easier and less time consuming, since there will typically be only about 100 modules to place around the circumference of one superlayer at each end.

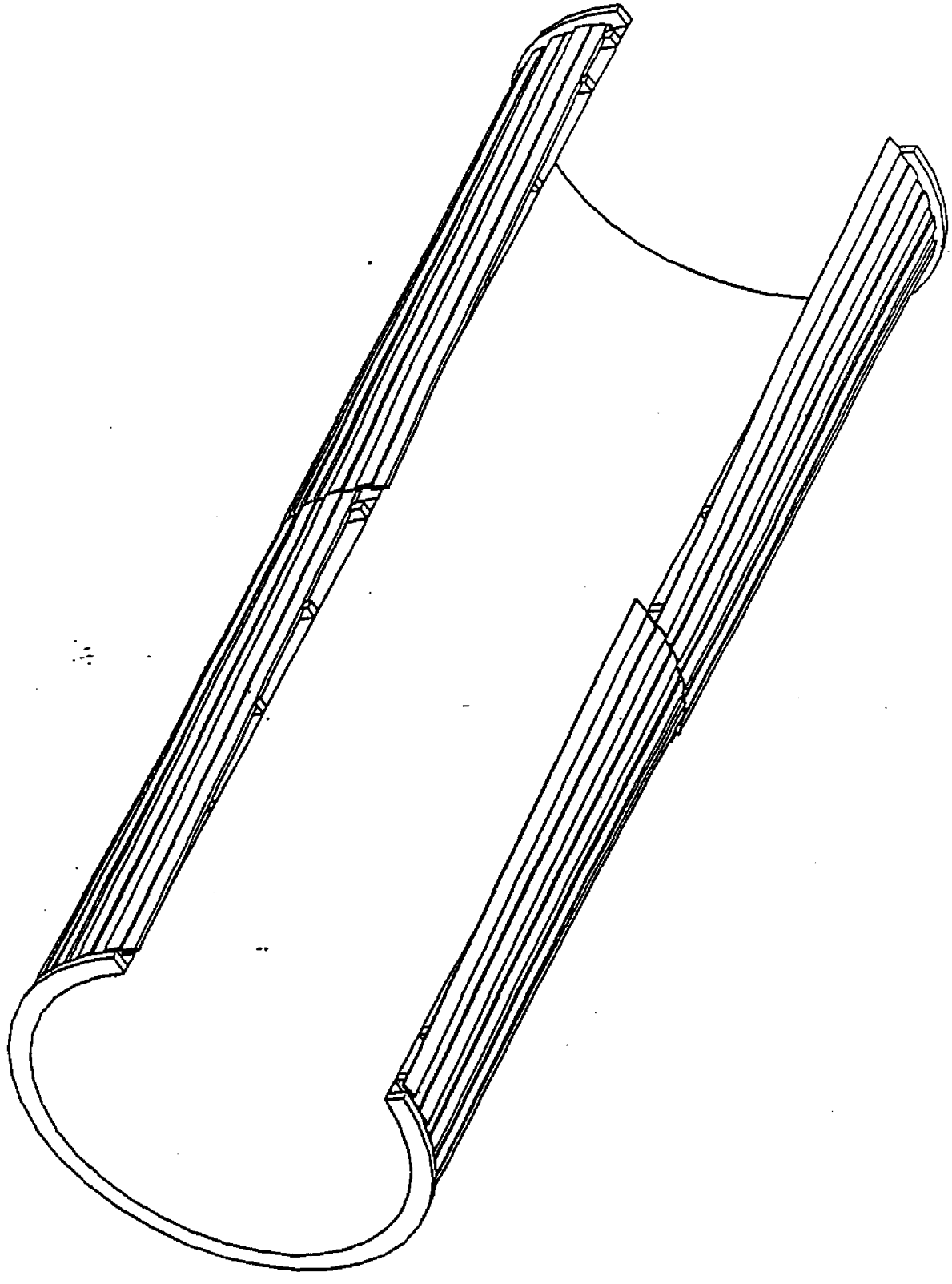

Fig. 3.5. A cut-away view of the stereo module superlayer.

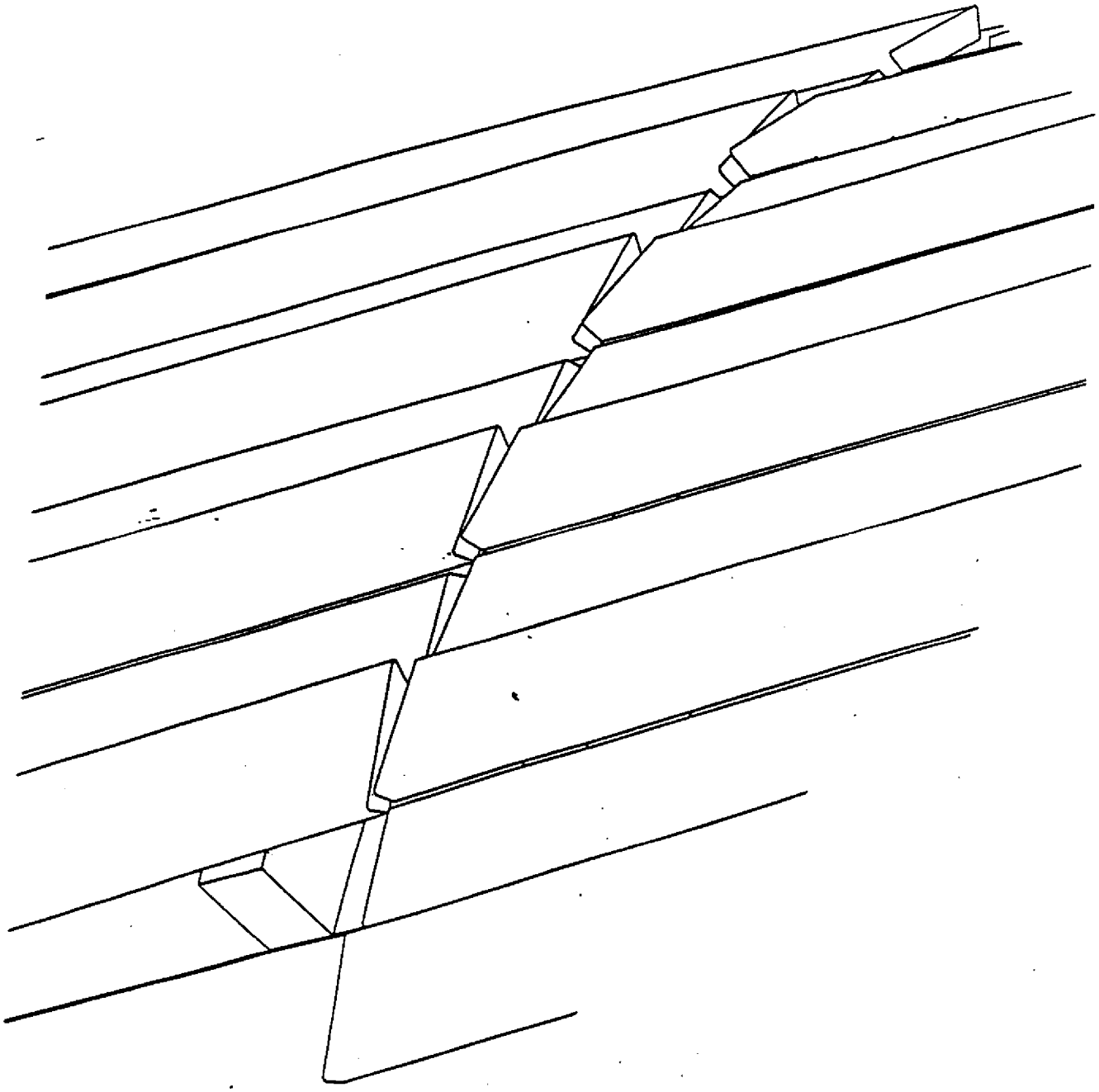

Fig. 3.6. A view at s=0 for the stereo superlayer showing the angles and radial displacements of the modules.

3.2. Straw Tube Bundles or Single Straws (Support for Wire Tension and Electronics Provided by Support Cylinder End Rings)

3.2.1. General Concept and Prototype Performance

The goal of the straw tube bundle/single straw approach is to design a straw tube superlayer using simple, low risk engineering principles. By constructing and operating a 2.7 meter long prototype over the past 12 months, a technique for superlayer fabrication based on bonding individual straws to a stable base surface has been developed. This fabrication procedure provides the required precision and is simple to implement. Figure 3.7 shows data recorded from this prototype using cosmic rays, the details of which are described in SDC Note 90-00119. The SDC barrel tracker can be fabricated using the concepts developed in the construction of the 2.7 meter prototype.

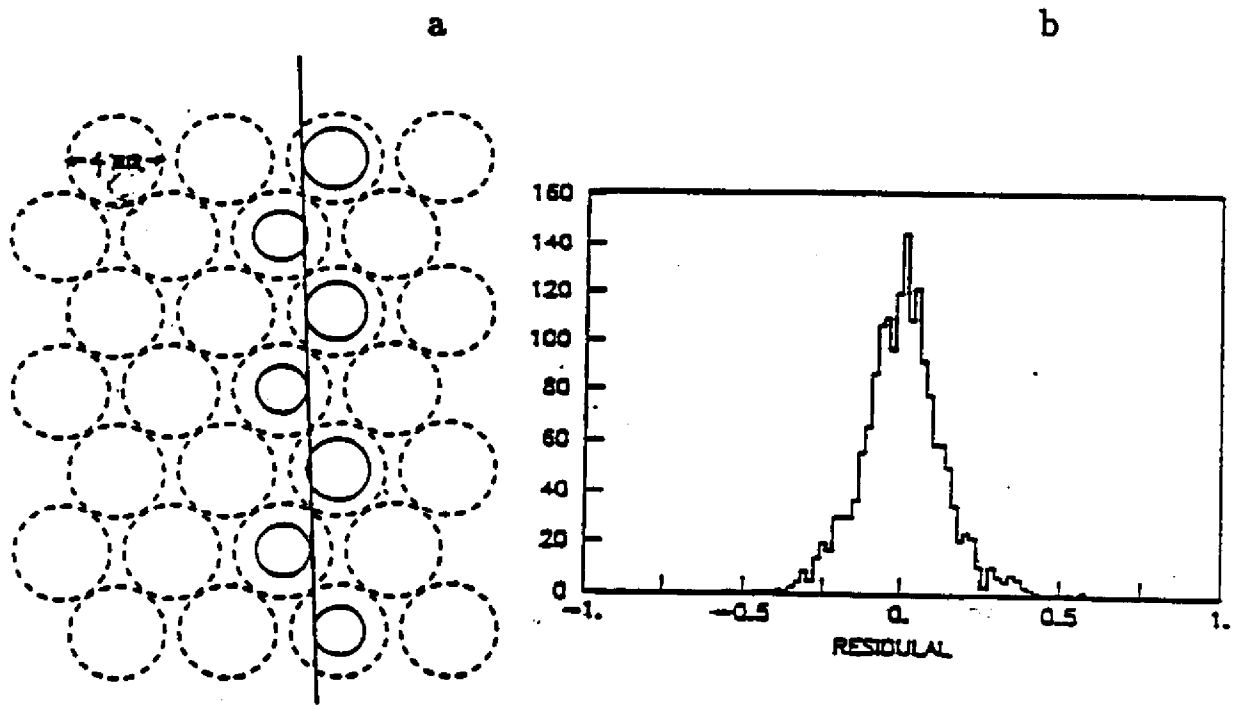

Fig. 3.7. Performance of a 2.7 m long superlayer constructed of individual straw tube drift cells. a) A triggered cosmic ray track traversing a superlayer. b) Distribution of the residuals in millimeters obtained using cosmic ray tracks. A standard deviation of 110 μm is calculated from a gaussian fit to the histogram.

Two straw tube superlayer designs are described in this document. In both, the tubes are placed onto a cylindrical support structure either individually or in groups. The primary structural difference between the

single straw concept and the modular approach is the method by which the wire tensile loads are transmitted to the base cylinder. The single straw approach transmits this load to the cylinder through rings on each end of the cylinder. Calculations done at ORNL (David Vandergriff) have shown that a carbon fiber cylinder with thickness less than 0.3% radiation length can support the wire tensile and gravitational loads of the straw superlayer. For this design, the straw tubes span the full 6 to 8 meter length of the cylinder with no support structure at $\eta = 0$. An intra-tube terminator, centered in the straw, divides it into two drift cells read out at each end. The terminator and sense wire supports allow gas to flow through the full length of the tube, and permit wire stringing after the cell is assembled.

3.2.2. Assembly of Pretested Drift Cells

Figures 3.8 and 3.9 illustrate the assembly and testing sequence for a single straw tube cell. Wire supports and end plugs are inserted into the straw tubes and the assembled unit placed on a temporary holding fixture (see steps 1 to 3 in Fig. 3.8). This fixture is mounted on a flat surface containing a jig which aligns the tubes using a series of "combs". This technique has been perfected using the operating 2.7 m prototype. Approximately 50 tubes would be mounted at a time. The sense wires are blown through the tubes using the feed mechanism shown in step 4 in Fig. 3.9. Experimental tests show that this procedure can be used to blow a wire through a tube 5 meters long with up to 6 wire supports. It is simple and reliable.

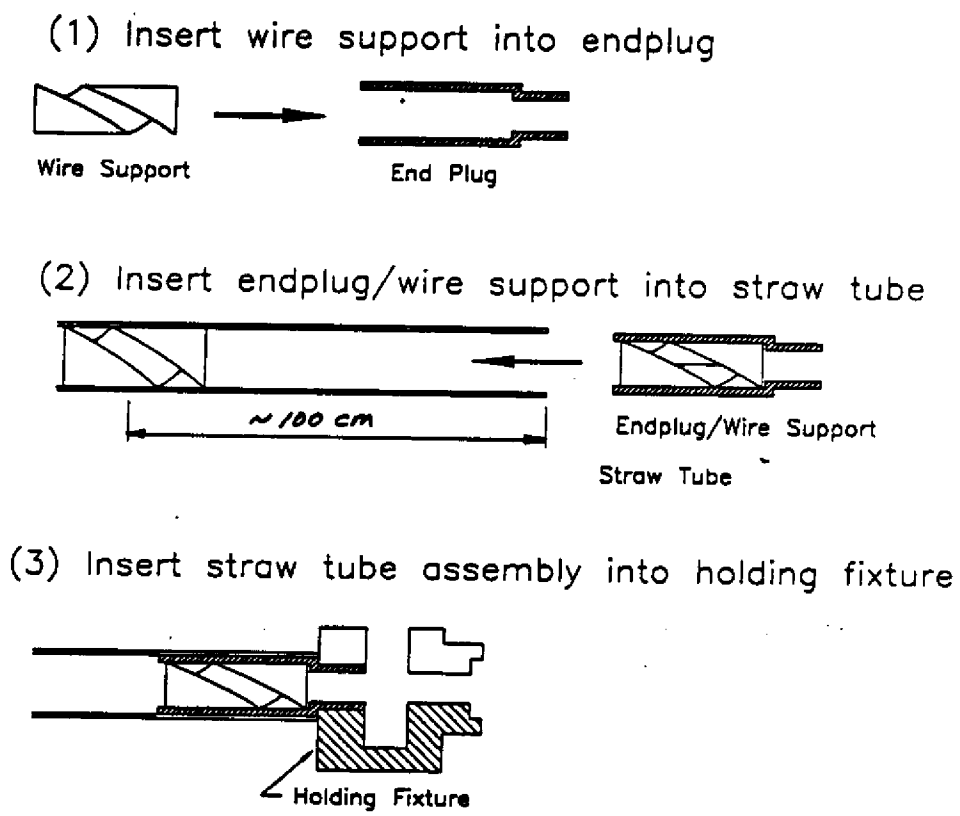

Fig. 3.8. Assembly sequence for a single straw cell: preparation of the tube and wire support.

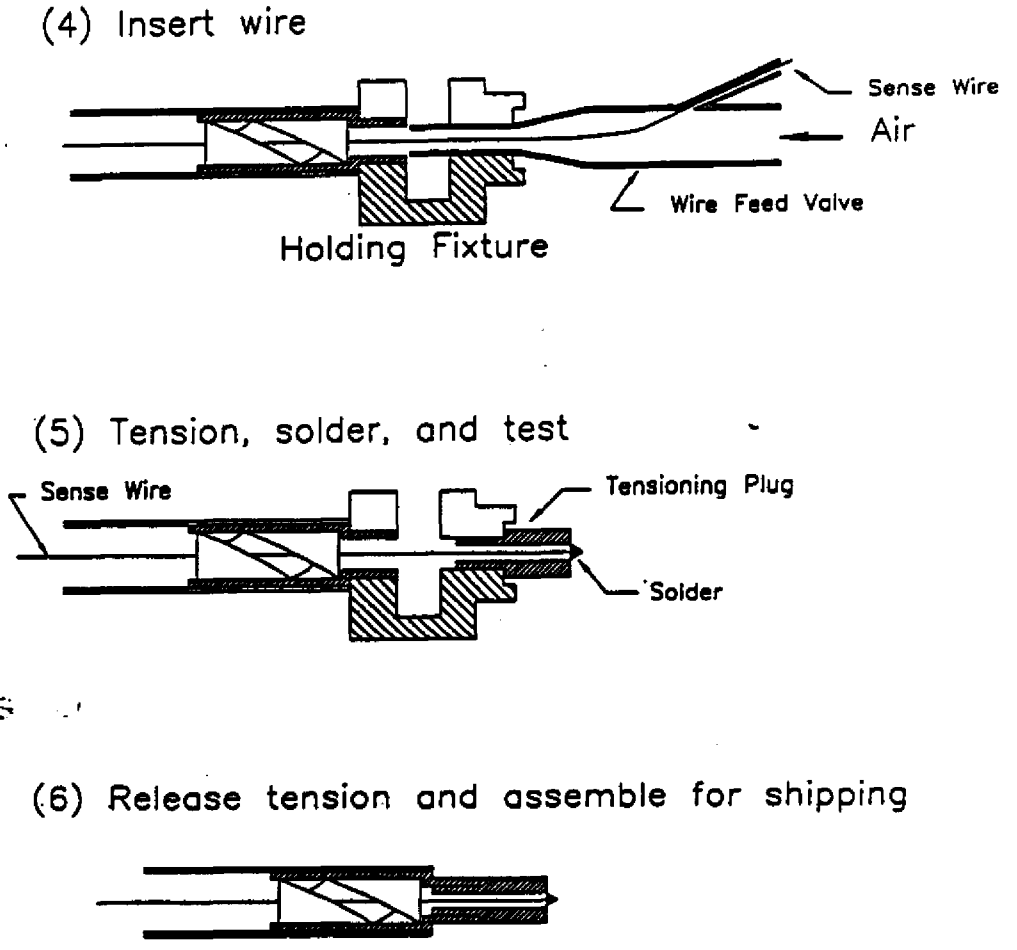

Fig. 3.9. Assembly sequence for a single straw cell: wire insertion and testing.

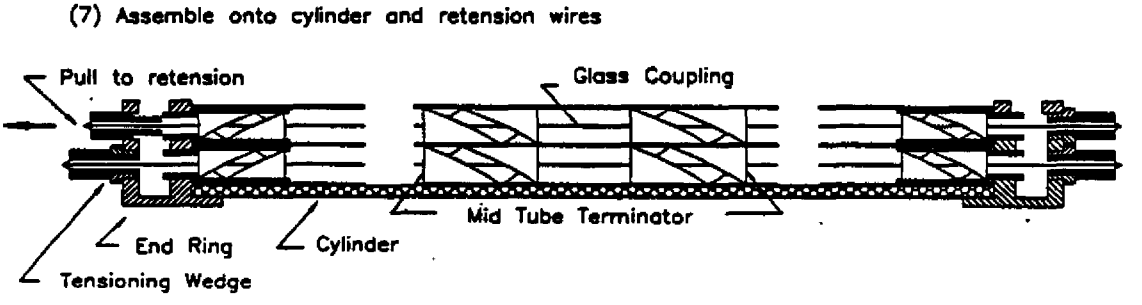

Fig. 3.10. Assembly of tested straw tube drift cell onto the support cylinder.

Next, the wire is tensioned and secured in a clamping plug. The drift cell can now be fully tested (gas, high voltage and readout with a radioactive source). After these tests, the wire tensioning plug is released and slips into a recess in the tube end plug (step 6 in Fig. 3.9). The wire elasticity is sufficient to hold the tensioning plug in the tube. These pretested drift cells are now ready for mounting on the support cylinder. Completed straw tube cells on the support cylinder are shown in Fig. 3.10.

The details of wire support construction are discussed in Section 4.1.5. A solution for the fabrication of a mid-tube terminator and insulating wire break is presented in Section 4.1.8.

3.2.3. Superlayer Assembly Concept

Assembly of the straw tube tracking system into superlayers is accomplished by placing individual straws on a support structure. The first construction step is to assemble each straw tube drift cell as described above. The straw assemblies consist of wire supports, mid-termination, end plugs and a sense wire. The tested and certified straw drift cell is ready for further assembly into superlayers.

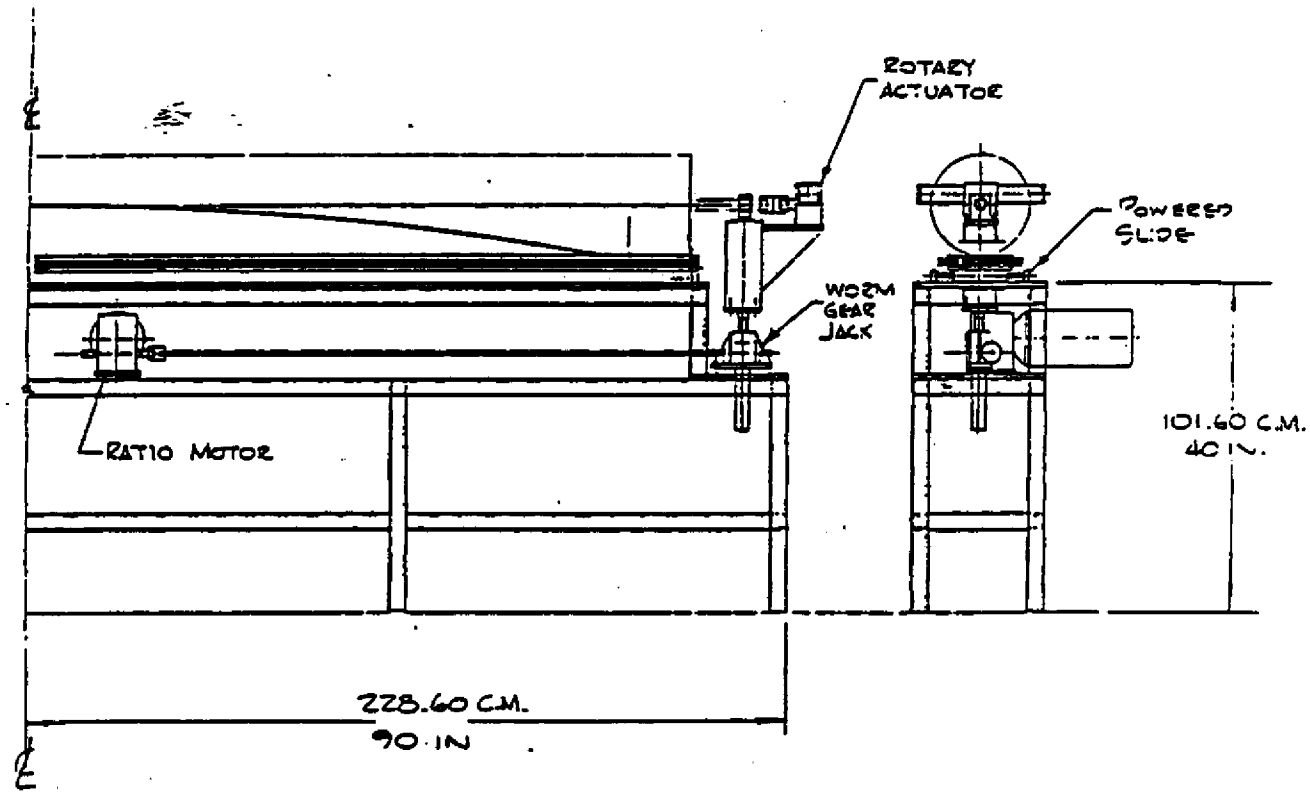

Fig. 3.11. Prototype straw tube placement machine.

The certified straw tubes are packaged and shipped to final assembly sites. They are assembled onto the support cylinder individually or in groups. The single straw concept is preferred at this time, but both concepts are being evaluated. An automatic straw laying device is being developed to apply individual

straws to the support cylinder (Fig. 3.11). The FY 1991 R&D effort places high priority on automation of the straw laying procedure. This will verify that precision and speed requirements have been met. A superlayer is completed by laying a full complement of straws onto the cylinder (Fig. 3.12). The sense wires are re-tensioned by pulling the wire clamp into position in the end plate. The wire tension is transferred to the support cylinder through the endplates. Each endplate consists of two plates separated by a few millimeters, with the space between the two plates serving as a manifold to provide gas to groups of tubes (Fig. 3.13).

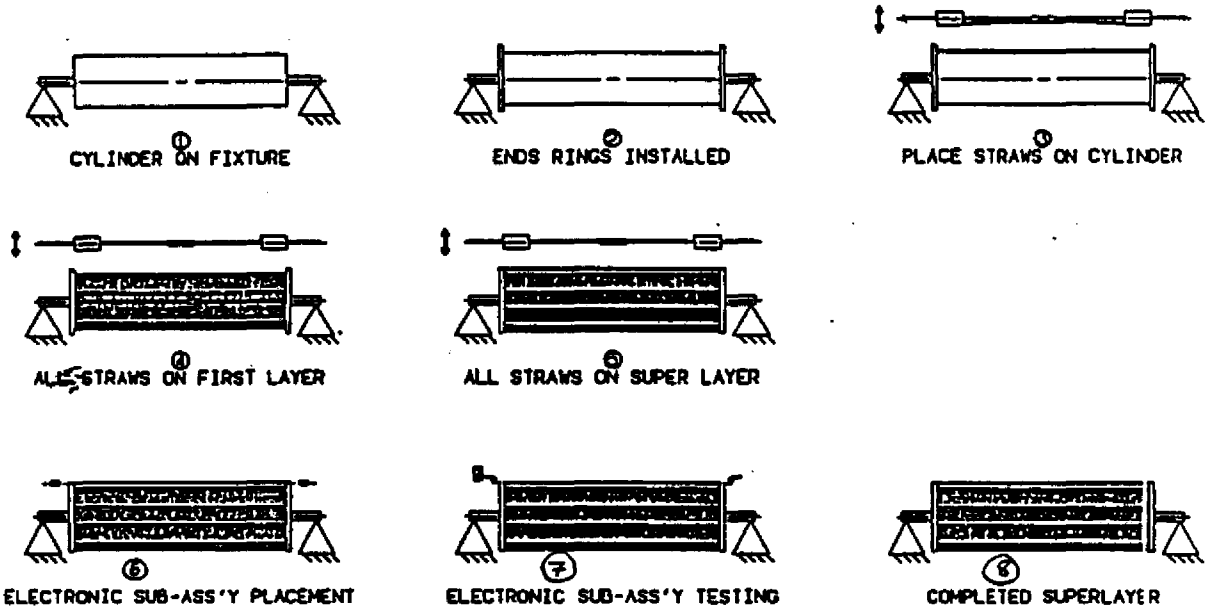

Fig. 3.12. Placement of straw tubes onto support cylinder.

The straw tube is aligned relative to the support cylinder by a placement fixture. The tubes are glued at about 30 cm intervals, which locates them with respect to a fixed reference point on the cylinder. The position of the wires at the wire support locations will be mapped using a Sr-90 or X-ray source after construction. At final assembly of the tracking superlayers into the full tracking detector, the fiducial reference marks on the cylinder are aligned with respect to each other. This provides corelation of the entire central tracking components.

The assembly goal is to automate the straw laying and alignment procedure so that a single straw is placed on the stable-base cylinder in 5 to 10 minutes. This rate allows 50K to 100K straw drift cells to be mounted per year at each assembly site. This final step would be performed at only two sites due to the relative sophistication of the environmental control and placement tooling required for the assembly.

3.2.4. Stereo Straw Tube Superlayers

Straw tubes can be formed into hermetic, simple geometry in axial superlayers. For stereo layers the straw tube geometry can be no longer uniform or hermetic and a tracking solution using scintillating fibers, which can be wound in a low pitch spiral on the surface of a cylinder, is more desirable. However, a solution using the straw tube construction described in this section is also possible. This requires replacing the simple cylindrical support structure with a hyperbolic support surface. The straws would be laid with small angle stereo using the same fabrication technique described above for the axial straw layers.

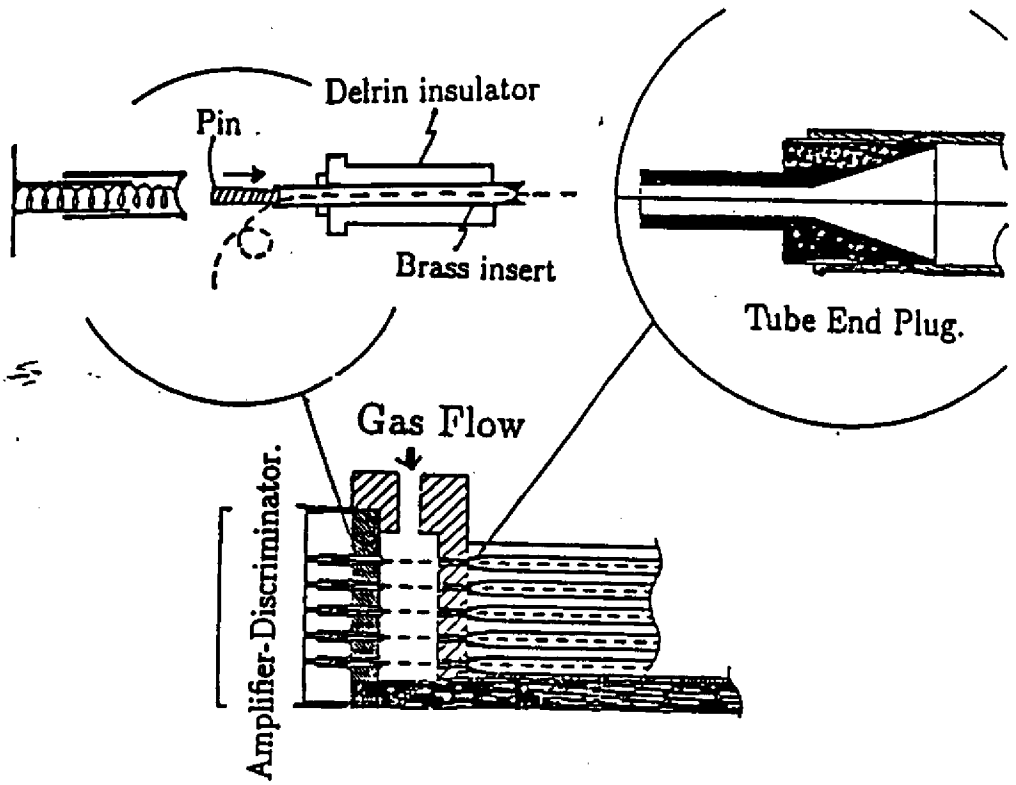

Fig. 3.13. End ring detail showing an assembled superlayer.

3.2.5. Conclusions for the Single Straw Approach

The advantages of this procedure for straw tube superlayer construction stem from the utilization of low risk and simple engineering. The resulting detector has very low mass construction and results in an isotropic and hermetic superlayer construction, advantageous for triggering and track reconstruction. By pretesting the individual straw tube drift cells at many sites, the advantages of mass production can be realized. To insure quality control of the final superlayers, only a few sites (probably two) would be used for the environmentally controlled straw tube placement and alignment. This fabrication procedure will allow the complete assembly of approximately two cylindrical superlayers per year at each assembly site.

4. EVALUATION OF DIFFERENT APPROACHES

4.1. Engineering and Manufacturing Feasibility

In the outer tracking system, we can divide the feasibility into two different areas. One is the feasibility of producing straw elements, whether they are single cells or modules. The other is the feasibility of placing elements on a support cylinder to make a superlayer. The superlayers are combined to form the tracking system. There are many overlap areas of the two approaches we have discussed so far. The design of the cylinder and structure to support them is one. Another common area is the components used to complete a single straw cell, such as a wire support.

In the following subsection, we will discuss not only the common areas but also the differences between the two approaches and their consequences.

For a feasibility study of constructing the outer tracking system, there have been several prototype systems built. One is based on a modular concept, and the other is based on a single straw concept.

The construction of four 64 straw modules each 30 cm long has been completed. The experience in dealing with these multistraw systems has given us an understanding of the engineering feasibility of extending the design to 4 meters. We are using them to study alignment, resolution, electronics prototypes and interfaces to them. We have designed and built three different molds for forming the composites and worked closely with Composite Horisons and ORNL in understanding the final shells. The design of a composite mold for a trapesoidal module 1 meter in length has been completed. The construction of this mold is now in its final phase, and the first trapesoidal shell should be finished by the end of May, 1991. The design for a full-length, 4 meter trapesoidal mold should be started in June, 1991.

For a prototype employing a single straw placing concept, a 2.7 meter long 64 channel chamber was constructed in September, 1990, on a flat surface (which simulates the support structure). The chamber has been operating since then. Using the prototype, studies such as resolution as a function of high voltage and gas mixture, attenuation length, and performance of different electronics have been performed. A test to simulate the SSC rate is being set up using several high radiation sources (Sr^{90}). Electronic responses, space charge, and resolution are some of the tests to be conducted.

4.1.1. Support Cylinder

Straw elements, whether they are modules or single straws, are held in place by support cylinders. Studies carried out at ORNL and WSTC show that the support cylinder can be constructed with the desired thickness and the tolerance we want and at reasonable cost. The cylinder is made of carbon fiber composite. The construction is 1 cm of Rohacell foam sandwiched between two 10-mil layers of carbon fiber composite. Calculation shows that an 8 meter cylinder with a radius of 1.5 meter deflects less than 10 microns at the middle when end rings are attached. Extensive cost estimates were done by ORNL and WSTC, and Table 4.1 shows the summary of the cost estimates for manufacturing the cylinders. Smaller size cylinders

are routinely constructed, and no great difficulties are expected. We have already proposed to construct a smaller size (about 4 meters in length and 0.75 meter in radius) cylinder in FY 1992.

TOTAL COST ($K)

CYLINDRICITY REQUIREMENT (IN.)

CYL. O.D. (FT)	.001	.002	.005	.010	.020
4.4	660	330	182	173	145
5.2	1870	390	315	205	170
6.6	2375	1190	400	258	216
7.8	2810	1405	585	450	255
9.2	3310	1655	1380	635	442
10.5	3780	1890	1575	722	590

MACHINING REQUIRED

EXPENSIVE

AFFORDABLE

R&D REQUIRED

Table 4.1. Cost of large cylinders of several diameters and for several grades of precision.

4.1.2. Placement Tooling

The next important issue is to develop a technique to place straw elements accurately and reasonably quickly onto the support cylinder. This requires an indexing mechanism and placing equipment. Like the base cylinder, tooling is required for both approaches although the details may be a little different. The design of the tooling is in progress.

4.1.3. Supporting Structure

There have been some conceptual designs from ORNL and WSTC on how to support the several superlayers once they are constructed and how the outer tracker will be supported. Although there is a great deal of detailed work required, no really difficult problems have been identified.

4.1.4. Straws

The basic drift cell is constructed with a plastic based cylindrical cathode structure and a 25 μm diameter

wire along the axis, as described in Section 3. Most of the straws that have been built up to now are formed from an outer mylar wrap 12 μm thick and a 15 μm aluminized polycarbonate film inner layer. We have been using straws manufactured by Precision Paper Tubes, Wheeling, Illinois, and Stone Industrial, College Park, Maryland. The tubes are 4 mm in diameter with a 37 μm wall thickness. Straws up to 3 meters have been constructed. The manufacturers have indicated that longer lengths are possible. A more detailed discussion will be required if lengths up to 8 meters are required. We also need to negotiate cost and schedule for manufacturing runs of very large numbers of straws.

4.1.5. Wire Supports

Due to electrostatic instability, a wire support is required about every 80 cm. Several designs for wire supports have been carried through to fabrication. Over 2400 pieces of the "double V" design (Fig. 4.1) have been produced by RTI plastics. Other companies are now bidding on the project in order to establish costs for large scale manufacture.

Another design is the "Twister," which has a spiral hole inside a plastic cylinder as shown in Fig. 4.2. The wire supports are made by first extruding a long solid plastic rod of the appropriate diameter. The rod then is passed through a special fixture for machining out a spiral groove along the length of the rod. As the rod exits the fixture, 1 cm long sections are sliced off the rod. Strict quality control will be used to ensure the depth of the spiral groove and the diameter of the rod are within tolerance. This method for mass producing wire supports has been shown to be reliable and easy to implement at very low cost.

4.1.6. Shell

For a modular concept, an external carbon composite shell holds the straws in alignment and supports the wire tension. For the engineering baseline design, for example, at least 672 composite shells would be fabricated. The number of modules would be disposed as follows:

a) Trigger layer #6 would have 192 modules. There would be two types of molds required, one for the in-facing and one for the out-facing modules.
b) Stereo layer #5 – 176 identical modules
c) Axial layer #4 – 160 identical modules as in layer #5
d) Stereo layer #3 – 144 identical modules as in layer #5.

Thus three different types of modules would be required. The module design and manufacture would represent the most significant aspect of the engineering work in this approach. As part of the preparation of the 1 meter long mold design, we have compared the mold and part sizes for a 8 × 8 inch test panel of a six layer panel using Hercules UHMS3501-6 prepreg tape with a 38 million modulus. The report (R. Foster, April, 1991) is included, and the results agree well with a simple calculation using the GENLAM program. The tests on the the 1 meter module will help us understand the problems in increasing the length to 4

meters. Design of a full-scale module shell will begin about June, 1991, and the first prototype should be available in Fall, 1991.

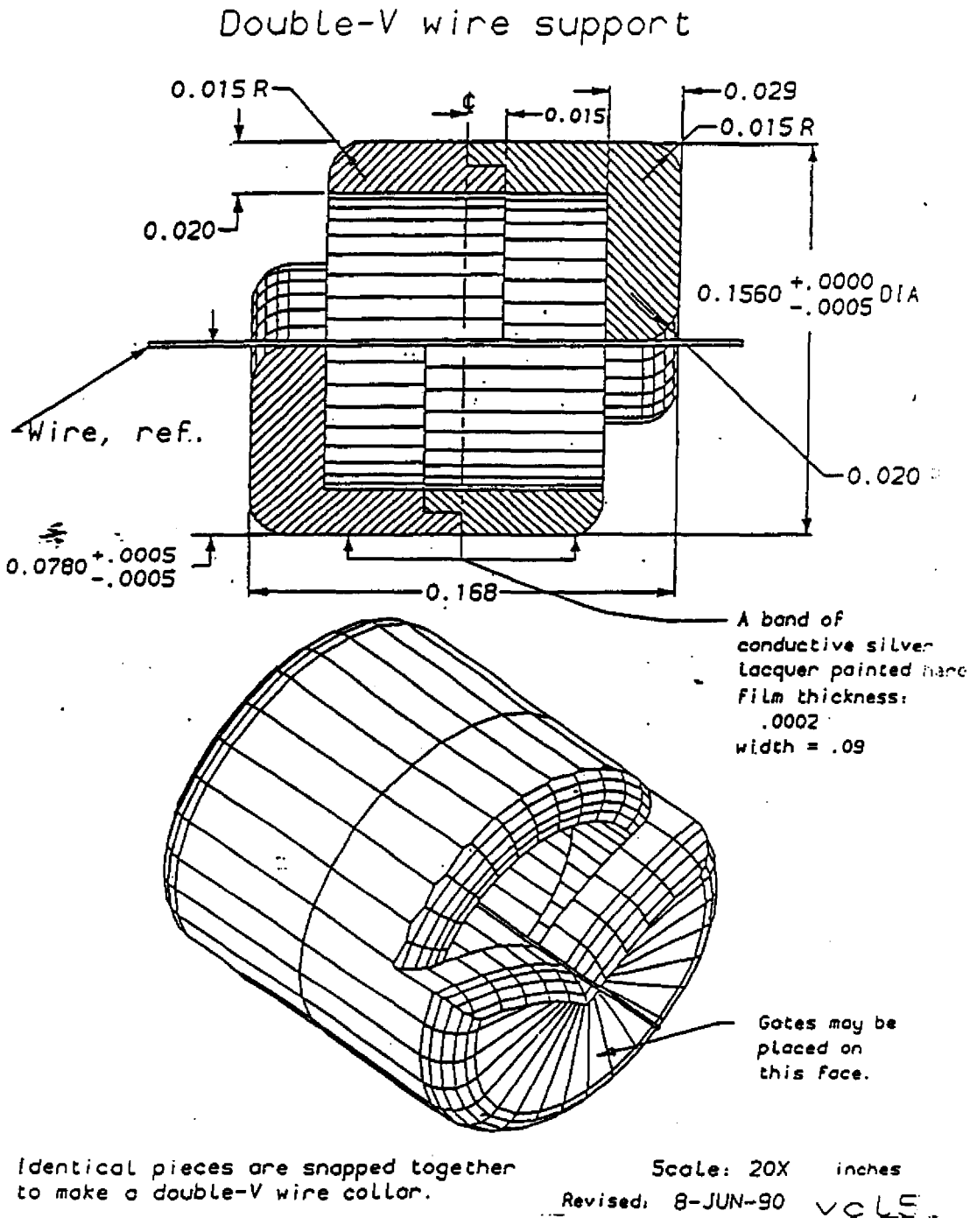

Fig. 4.1. Drawing of the "double-vee" wire support.

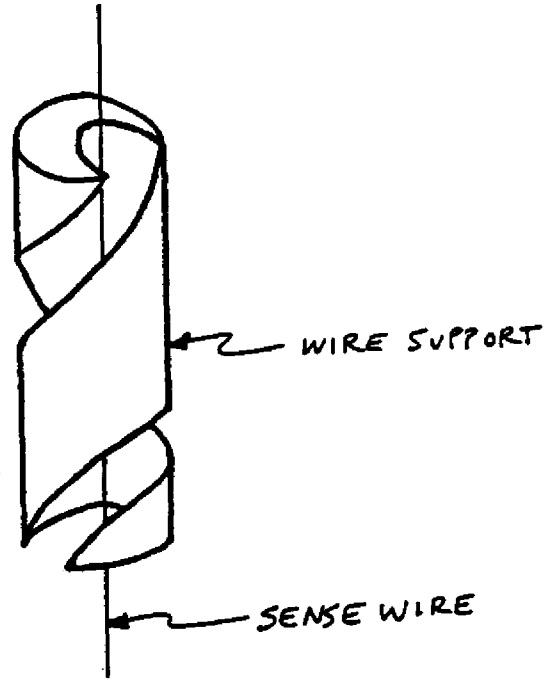

Fig. 4.2. Conceptual drawing of the "twister" wire support.

4.1.7. Endplates

The endplate designs are different for the different approaches. For the modular concept, an endplate which fits into the end of the module is required. For the single straw concept, the straw tube termination plate and gas manifold is part of the end ring used to support the cylinder.

For small size endplates, manufacturing has been carried out for the 64 straw modules using numerically controlled milling techniques. For the straw tracking system of the engineering baseline design, about 2500 pieces are required and would probably be done in a similar manner, although molding techniques are being examined.

For a large continuous endplate, the plates would be made of carbon composite material. The holes on the plates would be drilled after the endplates are mounted on the base cylinder using a precision indexing mechanism. There are two plates on each end of the cylinder, one of which is the end ring for the support cylinder.

4.1.8. The Mid-tube Termination and the Wire Coupling

One way to reduce the material at the middle of the straw tube tracker is to terminate the sense wires inside the tubes, as shown in Fig. 3.10. The termination permits gas flow. For this scheme there are two requirements. One is the terminator itself, and the other is the wire coupling through an insulator at the middle.

The manufacturing of the mid-tube termination will employ many of same techniques used in manufacturing the wire supports. First, a long composite rod with an inner core of conductive plastic with the proper resistivity with a coating of dielectric skin will be made. The rod is then passed through a fixture identical to the one used for the wire supports. A spiraled groove (with a depth slightly less than cut in the wire supports) will be machined out of the rod. As the rod exits the fixture, 1 cm slices are cut. Strict quality control will be used to ensure the electrical properties of the composite rod meet specifications.

A mechanically continuous wire with an electrically insulating coupling will be manufactured using a borosilicate hard glass to couple to the ends of 25 μm gold plated tungsten wire. The ends of the wire are inserted into a small glass tube which is held in a carbon base fixture. The fixture is heated enough to allow the fusing of the wire ends to the glass. This method allows current automation techniques used for handling small diameter wire to be employed to mass produce the wire couples. The glass coupling provides good mechanical strength and good electrical insulation with very little mass and at a very small cost. This technique has already been demonstrated satisfactorily.

4.1.9. Straw Tube End Plugs

The end plugs are necessary for the single straw concept. The end plugs for the straw tubes serve three purposes:

1. They provide a path to ground for the straw tube.
2. They provide an access for gas into and out of the straw tube.
3. They provide for wire support at the extreme ends of the straw tube.

The end plug will be a stepped (in outside diameter) hollow cylinder 2 cm long made by injected molded conductive plastic. The inner surface of the end plug will be coated with an insulator or have an insulating ceramic sleeve around which the conductive plastic is molded. A small diameter wire support will then be inserted in the large diameter end of the end plug (see Fig. 3.8).

4.2. Ease of Assembly, Alignment and Servicing

The basic assembly of the straw tracking system consists of 4 steps. The first is quality control of individual straws. The second is to prepare them for placement on the support cylinder either individually or by assembling them into multistraw elements. At this stage the basic straw tube elements will undergo testing and quality evaluation. The third is placing and aligning the elements on the cylinder. The last is the overall test of the superlayer including electronics.

4.2.1. Ease of Assembly

Depending on the approach, the individual straw test steps will be a little different. For one approach (for example, the single straw approach), the testing will be extensive since it is somewhat difficult to replace tubes once they are placed on the support cylinder. For another approach (for example, the modular approach), the testing may not have to be as extensive since the testing will be performed after a module is constructed.

Here are some scenarios showing how to assemble the outer tracker using different concepts.

For the single straw concept, the following steps are required. After the straw tubes are inspected by eye and the necessary components, such as the wire support and end plugs, are placed inside the tubes, the tubes are placed in a jig shown in Fig. 3.9. We expect to mount about 50 cells at one time. The jig is placed on a optical table or an equally flat surface. The sense wire is strung and tensioned.

The wire is inserted using the special Y shaped valve, shown in Fig. 3.9. As air passes through the primary branch of the valve, the wire is pulled along and follows the path of the air flow through the wire supports and out the other end. This technique has been reliable for quickly inserting wires into horizontally oriented 5 m straws with 6 wire supports. This technique can be easily adapted for automation. The length of wire inserted into the straw could be measured by a low friction tracking wheel that rotates as the wire is passed over the wheel.

After the sense wire is strung, gas will be introduced into the tube for gas leak, high voltage and source test. After selecting good cells, the tension in the wire is relieved by taking out the feedthrough from the second plate and inserting it into the end plug (Fig. 3.9). These tubes are then ready to be placed on the cylinder. These pretest steps can be done in several locations independent of support cylinder preparation. The 8 meter long assembled single straw cells can then be transported to the site for placing them on the cylinders.

After they are placed on the cylinder, the wire is retensioned by simply moving the feedthrough to the second plate (Fig. 3.10). Of course, if any wire breaks at this point, it can be replaced easily. The gas sealing is not done tube by tube. It is accomplished by pouring a thin layer of low viscosity silicon glue on the endplates. The glue will flow around the end plug (or feedthrough). This technique was used in earlier chambers that we constructed and found very effective.

In the modular approach the individual straws would pass an initial quality check and then have wire supports bonded at locations separated by 80 cm. Groups of 240 straws would be held in a jig clamped and bonded at the wire support positions to lock in an accurate close packed structure, as shown in Fig. 4.3. These units would then be placed in the carbon shells and bonded. After making the electrical connection to the straw cathodes, the endplates would be added and the wires would be strung. At this point the entire module could be tested and calibrated.

In the baseline design, a total of about 700 modules would be produced. It is anticipated that the

assembly could be done at several different sites over a two year period. As a separate assembly step the modules would be attached to the superlayer support and aligned as shown in Fig. 3.5. In one of the assembly scenarios this final step could be done at the SSCL.

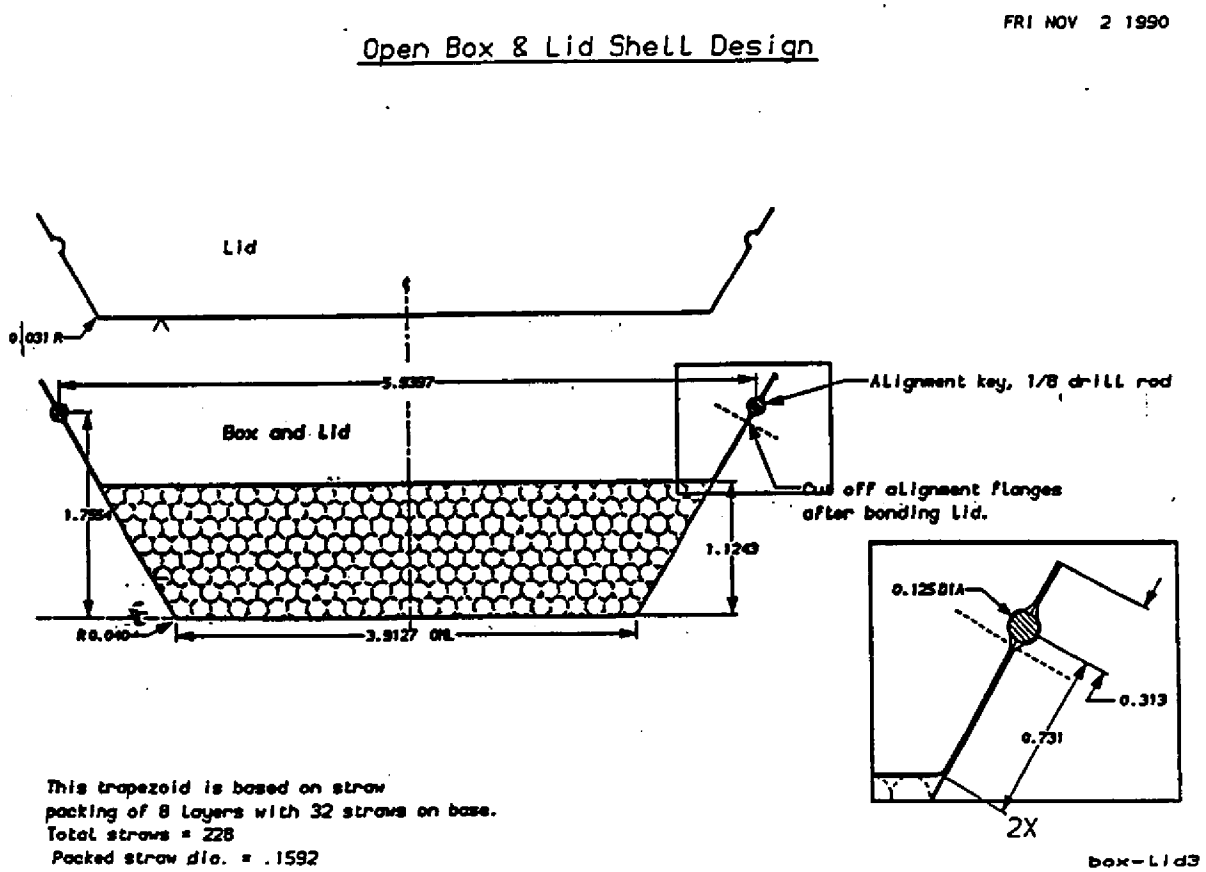

Fig. 4.3. Diagram of the box and lid modular design.

4.2.2. Alignment

For the modular concept, alignment takes place in three steps. They are the alignment of straw tubes with respect to the shell, the alignment of shell with respect to base cylinder, and the alignment of cylinders with respect to each other. In the first step, the wire position will be checkeded using X-ray sources once they are strung. This step can be carried out on the modules in parallel. The alignment of shells to cylinder requires a placement tooling as discussed earlier. A low mass structural support between the module and cylinder is necessary for both axial and stereo modules. This final alignment step should be much less time consuming than in the single straw concept.

For the individual straw concept, only two steps are required for detector alignment. First, once the tubes are mounted on the cylinder, the position of wires will be surveyed using a Sr^{90} source and slits. This procedure has been used in prototype tests and found to be effective. The second step, alignment of

superlayers with respect to each other, is the same as for the modular approach.

4.2.3. Servicing

Although a wire chamber is quite reliable once it is made operational and stable, some kind of servicing will be still required. For electronics and gas leaks, the proposed designs are equally effective since gas supply and electronics are modular. If a situation where a section of tubes has to be removed occurs, it is very likely the repair would be done during a long shut down where the chamber has to be moved out to an open area. However it may be possible to carry out this repair without removing the entire superlayer, depending on the design of the module support. One design requires removal, replacement, and realigning the bad module. In the other design it is necessary to remove the bad section of tubes, and then restack the straws. This procedure has been developed. The superlayer cylinder must be removed for this operation.

4.2.4. Stereo Superlayers

Modules can be held in place on the support cylinder by attaching them to the support rings. This approach can also be used for the stereo modules. In order to keep the transverse shift of the ends of the modules small, each 4 meter module is rotated about its center by about 3°. The difference in radial positions (resulting from this rotation) along the length of the stereo module is made up by the low mass attachment fixture at each ring. The interference between the corners of the modules at each end is eliminated by displacing alternate modules by a small (0.5 cm) radial offset. This displacement is also taken up by the attachment fixture. The resulting stereo superlayer, as shown in Figs. 3.5 and 3.6, is quite similar in appearance to the axial superlayer. Track coverage for the stereo layer over the whole length is complete.

For the single straw tube approach, a stereo superlayer is to be constructed on a tapered cylinder which has a smaller radius at the center compared to the ends. A detailed cost estimation of this type of cylinder has not been done.

4.3. Long Term Structural Integrity

4.3.1. Radiation Resistance

All of the straw tube components are radiation resistant. Carbon fiber, mylar and tungsten wire are very radiation resistant. The straws have also been tested and present no problems. The effects of anode and cathode aging due to high currents are also well studied and documented. The mixtures of CF_4 with a hydrocarbon (such as Isobutane) are well studied. Nevertheless, the radiation resistance of all final components must be established by testing.

4.3.2. Thermal Effects

Because of the large amount of heat generated by the electronics and nearby cryogenics and the requirements on alignment and stability, very good environmental control is necessary for the whole tracking

system. However, it is expected that there will be some temperature variation during construction and operation.

The support cylinder made of carbon has virtually zero thermal expansion coefficient. The 8 meter long mylar changes about 2mm in length under a temperature change of 5° C. Since the tubes are glued on the cylinder, there will be some small stress on the glue joint. In the modular option, the straws would expand lengthwise in the module, but not touch the endplates.

4.3.3. Long Term Structural Integrity

All material creeps, especially plastics. Because of this, in all designs, it is important that the tubes are not under stress. The material which takes up the most of the stress in the outer tracking is the carbon fiber. Since carbon fiber is excellent against creep, no problem is anticipated because of creep. Mylar has low moisture absorption. Immersed in water for 1 week at 25° C, it absorbs 0.3% of its weight. Moreover, the difference in the thermal expansion coefficient changes by about 5–10% when the relative humidity changes by 10%. The behavior of the carbon fiber cylinder of the shell may be more complex due to moisture absorption than that of the mylar because it involves fibers in different angles and glues. A careful study has to be done.

4.4. Interface with Electronics and Cooling

A module is a stand-alone drift chamber with its own gas, high voltage, and electronics. The basic interfacing is via the endplate structure. Several designs have been proposed.

In the individual or bundled straw design, although the endplate is one continuous plate, the electronics and gas supply are provided for every 200–300 channels such that a bad electronic card can be removed and replaced and the gas supply turned off to a set of tubes so a leak can be isolated. Because the endplate provides a good support for mounting electronics and providing gas, one does not have to worry about the misalignment while working on the ends. The cooling gas lines run around the endplate providing the cooling for electronics. Again the endplate provides a good support for the cooling gas lines.

4.5. Material in the Particle Path

The basic straw material represents a total thickness of $\pi \times$ wall thickness for each straw. For a six layer system this is 697 μm of mylar. We take into account the internal wire supports by increasing this by 10% giving a total of 0.32% of a radiation length for each straw layer.

In the modular version the carbon shell thickness will be 250 μm. The entire shell will then have an equivalent thickness of about 600 μm per superlayer or about 0.24 percent of a radiation length at 90° incidence. The support cylinder will have about 0.24% of a radiation at 90° (Table 4.2). There may also be a small amount of extra material in the support structure for attaching modules on the cylinder. The endplates can be quite thin. The endplates for the prototype 64 straw module have an effective thickness

of less than about 0.5 cm of plastic. This would contribute a thickness of about 2% of a radiation length normal to the ends. To this must be added the printed circuit board, electronics, cooling, cabling, and cylinder support struts. Figure 4.4 shows the effect of these items. Figure 4.5 shows the material for the whole tracking system in the baseline design.

tracker component	radiation length(%) at 90 degrees	sum with modules shell	sum without modules shell
Silicon system + beam pipe	8.0	8.0	8.0
fiber system+ supports	5.0	13.0	13.0
support cylinder	0.29		
module shell (10 mil wall)	0.24		
straws and supports	0.32		
support cylinder	0.29		
module shell (10 mil wall)	0.24		
straws and supports	0.32		
support cylinder	0.29		
module shell (10 mil wall)	0.24		
straws and supports	0.32	15.6	14.8
support cylinder	0.29		
module shell (10 mil wall)	0.24		
straws and supports	0.48		

Table 4.2. The material budget for both the single straw and modular approach near 90°.

For the design where tension is taken up by the stable cylinder rather than by the shell, the amount of material at 90° is less than the modular design by about 30%, which is about 0.3% of a radiation length. The thickness of the support cylinder is about the same for all designs because compression load is not the determining factor of the thickness of the cylinder.

The material in the region of the endplates may be slightly higher when the compression load of the wire tension is transferred through the endplates to the base cylinder. However, since a base cylinder requires an end ring for its support, and the end ring will be one of two plates, the increment of the material would be small compared to the modular design. The present design scheme calls for continuous straw tubes without a breakage at $\eta = 0.0$. The sense wires are terminated at the middle. This design provides the minimum material near and at $\eta = 0.0$.

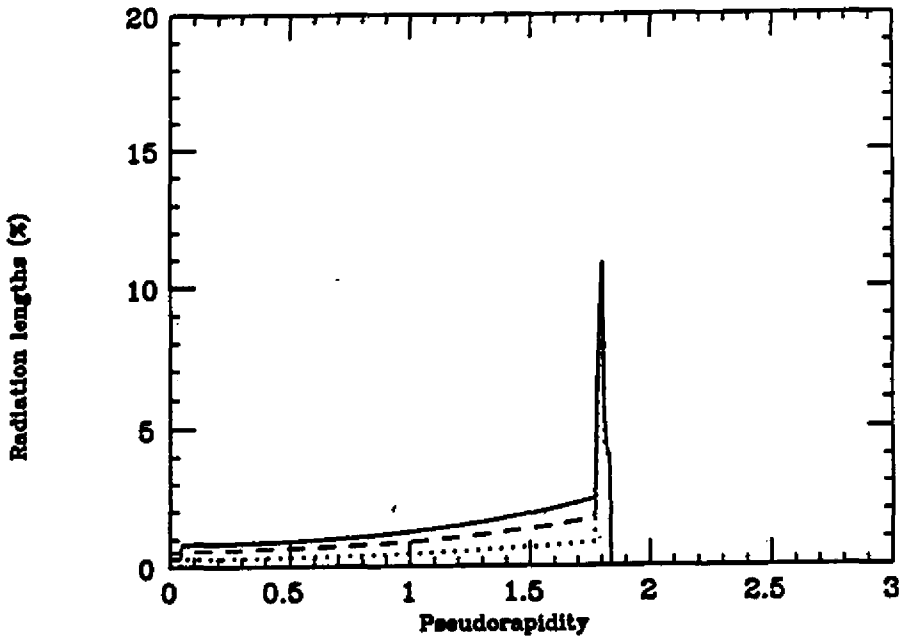

Fig. 4.4. The amount of material in radiation lengths as a function of η due to the straw tracking system. Dotted line: straws and electronics; dashed line: adds the support structure; solid line: adds the shells.

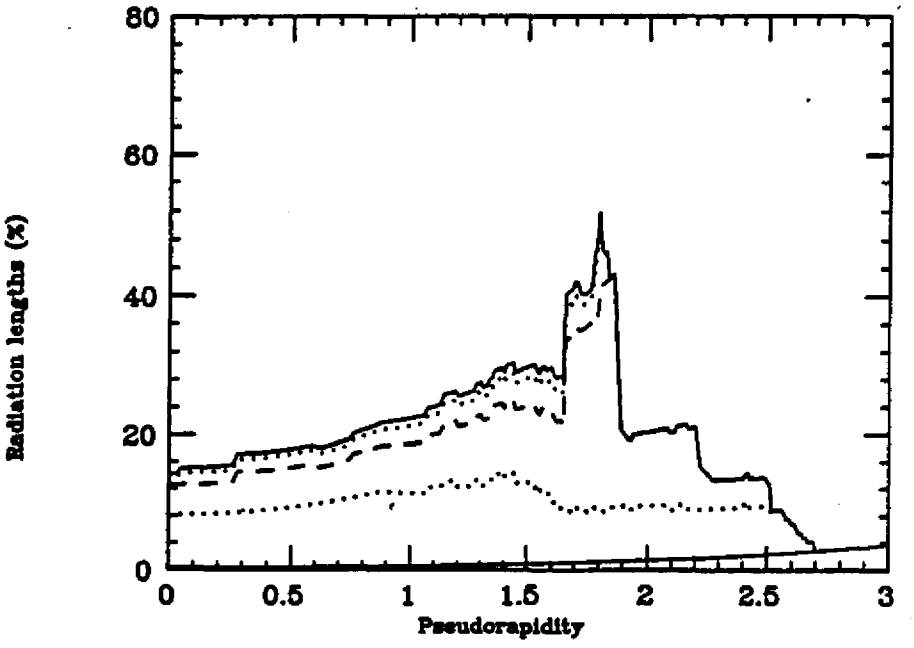

Fig. 4.5. The total amount of material as a function of η from the beam through the tracking system. Solid line near horizontal axis: beam pipe; next higher dotted line: adds the silicon system; dashed line: adds the scintillating fiber system; dotted line adds the straw system with no shells; solid line: adds the shells in the modular approach.

4.6. Triggering Considerations

Both approaches use superlayer structures, so the differences are really in detail. Triggering on straws in both the KEK 3/4 coincidence and synchronizers makes use of the drift time difference for radially aligned wires. The curvature determined from local track segments, assuming the tracks pass through the origin, is used to make a cut in transverse momentum. Modules for axial superlayers need to be curved to follow the circumference of a cylinder in order to keep the wires radial. Since the stereo superlayers in the module approach cannot have wires which are exactly aligned radially, we plan to use only axial superlayers in the trigger. Perhaps the stereo superlayers could be used with a looser curvature cut, and in coincidence with an axial superlayer trigger. If stereo straws could be placed in superlayers directly on a precise hyperbolic cylinder, the wires would be radially aligned and could be used in the trigger in the same way as for axial superlayers, but it is not clear that this warrants the mechanical complexity of such a design. Computer simulations of the trigger are under way and will provide information as to the number of superlayers needed. If one or two axial superlayers are sufficient, the nonradial stereo wires will not cause a problem. Because of cost, we do not expect to implement the trigger for all superlayers in any case.

Another possible problem for the trigger with the module approach is the trigger connection across module boundaries. This can be accomplished without inefficiency, in principle, since the modules overlap. The wiring and logic, however, will be more complicated with modules.

An advantage for the module approach is that the trigger electronics can be an integral part of the front end electronics and mounted directly on the module. The front end electronics, including the trigger, can then be tested for each module separately as part of a parallel construction and testing procedure.

4.7. Pattern Recognition Considerations

The pattern recognition approach for all schemes, since they involve superlayer structures, is to find track segments locally in superlayers and then link them. The segments from all parts of the tracking system, the silicon inner tracker, the outer central tracker, and the outer intermediate angle tracker, are linked to reconstruct complete charged particle tracks. Pattern recognition for the trigger is discussed in the previous section.

As for the trigger, a module approach will involve complications due to module boundaries and nonradial wires. These complications would not be present in the scheme with superlayers of wires placed on precise cylinders. However, the problems of pattern recognition in crossing boundaries have been solved before for jet cell chambers, such as the Mark II and CDF central drift chambers. As long as module boundaries do not line up radially, a track which crosses a boundary in one superlayer will be found without complication in a neighboring superlayer. As long as there is sufficient redundancy in the tracking system, module boundaries should not be a problem. The algorithm could also be written so that track segments crossing boundaries would be found in the first pass. The geometry of nonradial wires can be calculated in software. The first pass of the pattern recognition should be able to find track segments without correction (this should be

investigated in the computer simulation). For axial superlayers the effect is small since the displacement is radial and so has little effect on the curvature determination. Track segments will probably be found first in the axial superlayers and then linked to those in the stereo superlayers. Stereo superlayers are somewhat more complicated since the radial displacement is coupled to the determination of the coordinate along the wire.

5. CONCLUSIONS AND RECOMMENDATIONS

The support structure for the straw tube superlayers has evolved to a design which can accommodate all the straw tube superlayer options discussed in this report (see Section 2.1). The main remaining issue to be resolved deals with the detailed procedure to be used to construct the superlayers. The institutions working on this problem (Colorado, Duke, Indiana, ORNL and WSTC) have formed an integrated straw tube group which will pursue a coordinated R&D program leading to the best, most cost effective solution. The program we have developed will insure that a straw tube tracker is available for the turn on of SDC. Section 5.1 describes the straw tube placement concept and Section 5.2 presents the R&D work required to arrive at the detailed solution.

5.1. Proposed Straw Tube Placement Concept

The procedure for fabrication of a superlayer has three main steps.

STEP ONE: Assembly and quality control of individual straw tube cells. This step is common to all approaches we are considering for the construction of superlayers. The straws could have wire supports inserted and wires strung, high voltage, and gas flow, and be completely tested for gas leaks and with a radioactive source, or simply be visually inspected. After this quality control, the drift cells would be passed on to assembly stage two or three.

STEP TWO: Fabrication of multi-straw tube elements. The drift cells would next be assembled into multi-straw elements. These elements could be self contained (e.g., see the modular description in Section 3.1) or an intermediate fabrication stage which would be used to transfer the multi-straw elements directly to the support cylinder. In either case, the multi-straw element would be subjected to testing and quality control before passing to the next assembly stage. Note that steps one and two can be performed at multiple assembly sites.

STEP THREE: Placement of straw tube elements onto support cylinders. At this stage in the assembly process the pretested straw tube elements would be placed on the support cylinders, aligned and attached. A final check of wire placement and quality control of the superlayer section would be performed. This step is in common to each of the options being considered.

Step one is necessary for all methods of straw tube superlayer construction and will be pursued as a cooperative effort. Step three, the placement of straw tube elements onto support cylinders, is required for all methods of superlayer construction, but will differ in detail if the elements are single straws, straw tube bundles, or self-contained modules. For the single straw approach, step three is most time critical. Step two is most time critical for the modular approach.

This R&D program will lead to a single design of a superlayer or sector in time for the construction of a 2000 tube prototype by the end of 1992. This prototype will be used to establish in detail the superlayer

construction procedure and will demonstrate the measurement precision attainable. This plan requires a decision on the straw placement technique by about October, 1991. In order to make this decision, we have established minimum R&D milestones that must be met for a given superlayer fabrication procedure if it is to remain as an alternative. The general FY 1991 R&D plan with the milestone requirements is presented in Section 5.2.

5.2. Critical R&D Milestones for Straw Tubes

The R&D program needed to determine the best straw tube superlayer structure is described in this section. The critical issues in the design will be alignment tolerance, the assembly techniques needed to achieve it, and the resulting cost. The R&D will be directed towards these issues.

The R&D program is outlined below.

1. Single cell Q. C. and testing
   - Wire supports
   - Terminators
   - Cathode integrity
   - Wire insertion and holding
   - Gas seal
   - Electrical connections
   - Straw handling techniques
2. Prototype multistraw element
   - Support shell engineering
   - Assembly sequence
   - Relative straw/wire alignment
   - Q. C. testing and acceptance
3. Front end and triggering electronics
   - Testing and evaluation of prototypes, interface boards
   - Cooling, utilities
4. Placement of straw tube elements on support cylinders
   - Support cylinder
   - End ring design
     - Structural
     - Wire, gas connections
   - Element placement tooling
     - Handling
     - Bonding

- Alignment

5. Cost and schedule

The critical milestones leading to a decision are:

	Milestone	Date
MODULES		
	Construction and evaluation of a 1 meter module. Evaluation items:	
	alignment	
	precision	
	temperature/humidity	
	gas tightness	
	cost	
	assembly procedure	10/91
	Design of 4 meter carbon fiber shell	7/91
	Fabrication of 4 meter shell	11/91
	Evaluation of 4 meter module	
	Evaluation items as above.	1/92
	Detailed conceptual design of modular superlayers (axial and stereo)	10/91
SINGLE STRAW		
	Construction and testing of 6 meter drift cells, to evaluate:	
	wire support	
	stringing two piece wire	
	mid-tube terminator	
	gas tightness	10/91
	Detailed conceptual design of superlayers (axial and stereo)	10/91
	Development of detailed schedule for superlayer construction	10/91

Prototype 3 meter straw tube placement device; straw placement studies	10/91
Begin construction of 3 meter superlayer with endplates	1/92
Conceptual design of 8 meter straw tube placement tool and fabrication of 8 meter straw	3/92

Critical dates:

1 Oct 91 - Internal design review: Straw placement decision

1 Jan 92 - Internal design review: Just before beginning construction of multi-superlayer prototype.

6. COST AND SCHEDULE

There has been a detailed schedule and cost estimate of the central tracking system for the LoI. This work was done by Westinghouse Science and Technology Center and Oak Ridge National Laboratory. The modular tracking system was chosen for the cost estimate for the LoI, but it had an alternate support assembly, so we expect that there will be some differences in both costs and schedule between the present design and that of the LoI. The LoI estimate of the cost for the central outer tracking system was $50.0M, of which $20.8M were electronics costs. We will try to have more up-to-date costs and schedules for the designs discussed in this document by the time of the engineering review.