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**Pressurized Drift Tubes
Scintillating Fiber Hadron Calorimetry**

Final Report

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Abstract

Under this contract members of the MSU high energy physics group constructed a full-scale Pressurized Drift Tube Chamber intended for the GEM muon system at the SSC. We achieved a position resolution of $<90\ \mu$ over the full $5\ \text{m}^2$ area of the detector. This resolution satisfied the GEM resolution requirements of $<100\ \mu$ by a comfortable margin. Based on our SSC work we developed a new technique for creating wire supports in drift tubes with an overall placement accuracy of $<20\ \mu$. This technique requires only simple jiggling and can be duplicated and operated at low cost.

Also, we participated in the design and testing of a hadron calorimeter prototype for GEM. This work lead us to develop a semi-automatic welding machine to fuse together two plastic optical fibers. Copies of this machine are currently in use in the CDF endplug upgrade at Fermilab and additional copies are used widely in calorimeter and fiber-tracker construction.

I. Pressurized Drift Tubes (PI, C. Bromberg, 10% of effort)

A. Introduction

The GEM experiment at the SSC incorporated a 30 m long solenoid with a Barrel muon measurement system that filled the annular space 4 m - 9 m in radius and an endcap muon measurement system that filled the space 9 m inward from both ends of the solenoid.¹ The muon measurement system would have required the construction of 300-500 very large multi-planed precision wire chambers. We proposed and were funded by this contract and by the TNRLC to construct a prototype Pressurized Drift Tube Chamber (PDT) for GEM.

B. GEM PDT Prototype

The PDT prototype constructed at MSU was 4 m long, 1.3 m wide, consisting of four close-packed layers with each layer containing 32 tubes, each tube 3.8 cm in diameter. The design was documented in a series of GEM technical notes.² It was given a thorough review³ by an engineering evaluation team that validated the basic design. In less than 6-months we finalized the design, ordered the components and completed the construction of the PDT prototype. The chamber was delivered to the SSC in October of 1992.

C. Prototype Test Results

We made some early measurements with the prototype soon after its arrival at the SSC in the newly completed TTR test facility. Prior to a complete calibration of the PDT and the TTR we obtained results that indicated a local resolution of $\sim 80 \mu$ in the proportional mode at a pressure of 4bar. Measurements in the streamer mode also showed a resolution of 82μ averaged over the full length of the tubes.⁴ An independent analysis of our data by a group from Russia showed that we had been successful in achieving $< 20 \mu$ precision on the location of the wires. The Russians in a parallel effort constructed another PDT prototype that optimized chamber electronics. They obtained an even better resolution of $\sim 50 \mu$ in the proportional mode at 4bar after correcting for wire misalignments. If the PDT technology was chosen by the GEM experiment the two groups would have worked together to incorporate the best features of both designs.

It was fully acknowledged that our prototype had met the design goals of the experiment and the cost, including a separate trigger system, was about \$20M less

expensive than cathode strip chambers (CSC). The challenge of developing the CSC solution to muon tracking and triggering appealed to a majority of the steering committee and the CSC solution was chosen. All decisions, of course, were subsequently nullified by termination of the SSC.

D. Application of PDT Technology in LHC Experiments

At CERN the LHC experiment ATLAS, after a decision process similar to the one used in GEM, chose Pressurized Drift Tubes for the muon system.⁵ The name was changed to Monitored Drift Tubes (MDT) to indicate the emphasis on monitoring the distortions of the chambers to high precision with an in-plane alignment system. We and the rest of the faculty members in experimental HEP at MSU have joined the ATLAS collaboration. We continued the design process on pressurized chambers begun at the SSC, now with a focus on ATLAS.

The tubes in the MDT muon chambers for ATLAS can be over 6m long. When compared to GEM the effects of the sag of the wire at this greater length, the smaller diameter tubes, and the increased precision specified for these chambers require that in tubes with a length $>3\text{m}$ the wire must be supported at least once at the center of the tube. We had considered wire supports in the GEM chambers but found that the effects were just below the level of concern. Since wire supports would improve the resolution of these chambers we did investigate some design concepts for supports at that time.

Recently we documented (See Appendix 1 and 2) these concepts and expanded their relevance to the construction of the MDT chambers for ATLAS.⁶ One note described a general technique and several specific designs for creating wire supports in long drift tubes and in a second note we showed how to use these wire supports to construct multi-layers of tubes with $<20\mu$ precision on the wire placement.

We are encouraging both the US and European muon groups to investigate the use of this approach. Comparing the various construction procedures we find that significant cost savings and improved performance would result from using our proposed procedure.

II. Scintillating Fiber Hadron Calorimetry (PI, C. Bromberg, 10% of effort)

A. Introduction

Scintillating fiber calorimetry showed great promise as a technology for the large calorimeters that were to be part of the SSC experiments. Questions regarding its radiation hardness made its choice for the EM sections of the calorimeter too risky to pursue. Instead noble liquid calorimeters were chosen for the precision electromagnetic calorimetry in GEM. Plastic scintillator, however, could be used in the hadronic calorimeter where the radiation levels were much lower. We participated with other members of the Scintcal Collaboration in the design and the tests of a scintillating fiber hadronic calorimeter.

The tests of this calorimeter were done at BNL and results reported in a note prepared by the Boston group. Following these tests the GEM collaboration chose to put the break in the liquid calorimetry at 6 interaction lengths. This put much of the hadron calorimeter in the liquid and reduced the requirements on the scintillating calorimetry. The scintillating-tile/waveshifting-fiber technology was chosen for this "tail catcher" due to its low cost and proven capabilities.

Our group at MSU had considerable experience with "tile-fiber" calorimetry through our work in the CDF plug-upgrade project. We have developed many new techniques for handling the optical components needed to capture and transmit the light from the tile to the phototube. One of these is our invention under this grant of a semi-automatic welder for plastic optical fibers.

B. Semi-Automatic Fiber Splicer

We made considerable progress toward a semi-automatic machine in previous R&D (see DOE/ER/40587) that required only manual loading and could splice together two plastic optical fibers. We developed the machine and the welding technique further with funds from this grant. The ends of the fibers to be fused in our final design are first inserted into a thin sheath of polyolefin; the material used to make shrink tubing. The welding takes place in a glass tube that is split lengthwise into two half-tubes. This allows fibers to be easily loaded into and removed from the machine. The fibers are clamped between the half-tubes and pressed together pneumatically while heat is applied via an infrared radiator (projector bulb).

This improved design⁷ produces welds that are strong both in tension and in shear, and show a 92% transmission with only a 3% variation between welds as shown in Fig. 1. A full cycle that includes fiber preparation takes about 2 minutes (See Appendix 3).

The most common application of this machine is in tile-fiber calorimetry. This technology uses scintillating plates to generate light while imbedded wave-shifting fibers capture 8% of absorbed photons as wave-shifted photons. A clear fiber of the same diameter is welded to the wave-shifting fiber and used for light transmission to a phototube. Compared with a continuous waveshifting fiber, in clear fiber light can travel 8-10 times further to reach the phototube with same light loss. The welding also minimizes the cost and the physical size of the joint when compared to a coupling connector.

C. Applications in Experiments

Duplicates of our welding machine are currently in use at various sites. Three are used by the CDF collaboration in the plug calorimeter upgrade and one has been sent to CDF collaborators in Japan. Two more are used by the Research Department at Fermilab, and two RHIC groups are also using these machines.

Increasingly in HEP, the tile-fiber technology is being chosen for hadron calorimetry and so does the utility of our fiber splicer. The ATLAS experiment at CERN is investigating the use of welded fibers for its hadron calorimeter. We are currently working on design concepts of a fully automated machine that be will required for the >50,000 welds that are needed in this project.

III. Conclusion

Our wire supports for drift tubes and our welding machine for optical fiber applications are just two examples of the advances in detector technology made by during the SSC R&D period. While the SSC will never be built these advances will find many applications in HEP and elsewhere in the future.

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RESPONSIBILITIES ON THE CDF END PLUG UPGRADE:

- PRODUCTION OF THE OPTICAL FIBER/CONNECTOR ASSEMBLIES
- PRODUCTION OF THE OPTICAL READOUT CABLES
- PRODUCTION OF THE OPTICAL DECODER BOXES

FIBER/CONNECTOR ASSEMBLY LIGHT DISTRIBUTION

Figure 1. The MSU Semi-Automated Fiber Splicer as used in CDF.

A New Scheme for Construction of Long Drift Tubes with Wire Supports

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Abstract

A new technique is proposed for producing anode wire supports in long drift tubes. This technique could be particularly useful in the construction of the pressurized drift tubes used in ATLAS for the precision measurement of muons. In single tube production the technique can fix the position of the wire with respect to the outside of the tube to better than the required $10\ \mu$ accuracy. The technique can also simultaneously fix all of the wires in a chamber to the support points in a pattern identical to the ends.

Introduction

The anode wire in a long drift tube sags under gravity and is further displaced by the electrostatic forces on the wire segments that are not located at the center of the tube. Wire supports at regular intervals within the tube would reduce the effects of these distortions and allow tubes of any reasonable length and diameter to be constructed.

In ATLAS the tolerance on the wire placement within a tube is about $10\ \mu$ so that after stacking the tubes the wire placement is known to $20\ \mu$ (r.m.s.). To maintain this accuracy in the presence of electrostatic forces the distance from the inner wall of the tube to the wire must be known to better than $100\ \mu$ along its full length; a tolerance much less stringent than on the wire placement. To accomplish these requirements internal wire supports were proposed to reduce these deviations in the Monitored Drift Tube (MDT) chambers for ATLAS. Difficulties in perfecting this option led to the alternative, presented in the Technical Proposal¹, that allows the tubes to sag by the same amount as the wires thus reducing the number of supports needed to at least one in chambers with tube lengths greater than 3 m. We note, however, that about half the tubes in ATLAS will require at least one internal support.

In the baseline assembly procedure all tubes with an internal support require strict tolerances on the tube dimensions to reach the $10\ \mu$ wire placement accuracy. Also, the procedure requires a precise support that captures the anode wire to be inserted into the tube by a specialized machine. We present here a simple technique for creating anode wire supports in long drift tubes that is very different from the existing procedures but achieves the required placement accuracy and relieves some of the requirements on the tube manufacturing. Also, multiple supports can be realized with the same techniques allowing the use of smaller diameter tubes ($<3\ \text{cm}$) in even the longest ATLAS chambers should drift time and occupancy considerations require them.

The materials used in the solution proposed here are not new. In the construction of open wire plane detectors, such as in a PWC, various techniques have been used to fix the anode wires in positions accurately determined by an external comb. This technique has already been proposed for fixing the wires at the ends of the MDT tubes². Any material like solder that makes a phase change from liquid to solid can be used for this purpose.

However, very careful soldering techniques are required to insure that the wire does not move during the rapid phase change from liquid to solid. Special solders must be also be used to avoid the amalgamation of the wire's gold plating into the solder that can allow the wire to loose tension. Glues also make this phase change, usually more slowly than solder, and can be relied upon to not affect the location of the wires. If a wire is disturbed during the application of the glue it returns to its original position by the action of the restoring forces on a wire under tension. If the restoring forces are large, as is the case near one of the combs, the wire moves rapidly through the glue, but more slowly if the restoring forces are small as is the case far from a comb. If the glue has a low viscosity the wire returns to its nominal position very quickly in most situations.

In long drift tubes fixing the wires at support points with glue (or other material with a phase change from liquid to solid) is made difficult by the inaccessible location of the supports. We have invented a number of techniques, a few described in a later section, that would allow the gluing of anode wires at support points inside of long drift tubes. Before we describe them, however, we discuss the capabilities that such techniques would enable.

Capabilities of Adaptive Wire Supports

Single Tube Construction

In the first application of adaptive wire supports we discuss the assembly of a single tube. The anode wire is threaded through a 1 mm diameter hole in the center of a thin disk-shaped wire support located at the midpoint of the tube. The disk (interference fit, spring loaded or crimped) is securely positioned in the tube and also serves to stiffen the tube's circular cross section. Since the hole diameter is large many techniques such as those that use a stiff leader can be used to thread the wire through the hole.

The anode wire is accurately located in the ends of the tube by a plug that positions the wire precisely at its center. The tube is rotated vertically to insure that the wire hangs straight and placed against a jig containing three small jig blocks located at the two ends and at the middle of the tube as shown in Fig. 1.

The jig blocks have a cutout whose shape depends on the specific multilayer assembly scheme chosen³. For semicircular cutouts (or fraction thereof) the diameter of the cutout matches the diameter of the plugs at the ends and the outside diameter of the tube at the middle. The centers of the jig block cutouts are positioned precisely along the jig centerline, therefore, they must also coincide with the wire. The wire, being free to move in the 1 mm hole, must pass through the center of the tube cross section at the support.

The glue is then injected into the support hole and allowed to cure. In this way the

Figure 1.
Jig for Gluing the Anode Wire into the Support

wire is fixed at the center of a circular cross section of the tube at the support location and the plugs at the two ends.

We have verified that the wire is not moved from its nominal position by the injection or curing of the glue. These tests used 6m long wires threaded through a small hole in a thin plate located at the midpoint of the wire. The wire was viewed in two transverse directions by microscopes located near the hole and monitored during the gluing process. We have observed no movements of the wire from its nominal position before gluing to the level of 2μ . Therefore, the uncertainty in the wire position relative to the outside of the tube will not be affected by the curing of the glue.

Once the glue has cured the tube can be removed from the jig and placed in any orientation. If the tube is realigned so that the center of the tube cross section at its midpoint lies on a line between the centers of the plugs then the wire support points must also lie on that line.

This procedure locates the wires to an outside reference to the required 10μ tolerance while allowing the tolerances on the tube wall thickness, eccentricity, and straightness, to be relaxed yet satisfy the 100μ requirement on the wire centering in the tube. Tubes with thin walls (250μ) produced to only rough tolerances can be used that would minimize the intrinsic inefficiency, radiation length fraction, and weight without sacrificing accuracy.

Multilayer Construction

There is a significant construction simplification that this technique enables if the glue insertion is delayed until the tubes have been bonded into the chamber package as shown in Fig. 2.

Figure 2. Drift tubes and gauge blocks bonded in a jig.

Aligning the tubes during this bonding at the tube ends (10μ) can be accomplished by several techniques that have already been developed but in this scheme the jigs *need only position the tubes between the plugs to the 100μ tolerance*. This tolerance can be easily achieved by constraining the tube package dimensions. Before the multilayer is removed from the jig three gauge blocks (reference flats) are bonded to the package at the center and two ends of the package. For convenience the gauge blocks can be aligned to lie in a plane parallel to the desired wire planes and separated from them by a known distance. A reference marker is fixed on the surface of each block so that the three markers lie on a straight line. The chamber is then rotated so that the wires are vertical, the reference flats are realigned and glue is inserted into each support hole and allowed to cure.

In the future, if the three gauge blocks are positioned to lie in the same plane and the reference markers lie on a straight line then the wire support points will also be aligned in the same way relative to the tube ends as when they were glued, i.e., straight and parallel

and absolutely located relative to the reference flats.

These procedures can be extended to accommodate any number of support points along the length of the tube, any number of tube layers and, if desired, a support structure with or without an alignment system⁴ installed. A single support in 4m long tubes and two supports in 6m long tubes would result in a 2m long free span of wire in each chamber.

If the entire assembly must take place in only the horizontal orientation (e.g., for space reasons) then before the glue has cured the tube package (or a single tube) must be displaced at the support point relative to the ends by an amount equal to the wire sag.

Adaptive Support Techniques

As mentioned in the Introduction we have thought of many techniques for insertion of the glue into the hole or other phase changing procedures consistent with the assembly steps discussed in the previous section. We will describe here a few of the more promising techniques.

One technique accomplishes the remote injection of glue into the 1 mm hole using a support shown in Fig. 3. Prior to insertion in the tube the 1 μ l glue reservoir (cavity) in the support is filled with a glue and the wall of the 1 mm hole is painted with an activator that will start the curing process once the glue is injected into the hole. The glue reservoir is connected to the 1 mm hole and to a larger 10 μ l gas reservoir by narrow channels (tubes); surface tension preventing the glue from running out of its reservoir. If the pressure in the tube is reduced to 0.9 bar the gas will expand in its reservoir by about 10%, pushing the glue out of its reservoir through the narrow channel and into the 1 mm hole. The glue is then allowed to fully cure before the tube is re-pressurized.

Figure 3. Wire Support with Glue Injector

Since atmospheric pressure is not constant a gas diffusion path into the gas reservoir is also provided that allows a slow gas leakage through its walls insuring that only a rapid decrease in the pressure will cause the glue to be injected into the hole. Methods that use over-pressure are also possible but may require a mechanical linkage to force the glue out of its reservoir. We plan on producing some simple prototypes to determine the proper glue and activator, channel and reservoir sizes/shapes to use. Our first tests of this procedure will use Acrylic glues and activators. These glues set in a few minutes once activated.

Another more intrusive technique requires a small hole to be made in the tube at the location of the support. This would allow glue to be injected into a channel in the support that leads to the 1 mm hole. A plug would then be glued into the hole to reseal the tube or it can be sealed with glue alone. This procedure would be appropriate for single tubes or for tube multilayers if the setup of the glue occurs after the layers are stacked for bonding.

The glue could be placed in the 1mm hole just prior to insertion if the glue does not set up quickly. In this technique the wire is threaded through another hole in the support disk and is tensioned there. A small slit connects this hole with the central 1mm hole allowing the wire to be moved into the glue when the tube is placed in the alignment jig.

Conclusions

We have presented techniques that will allow a wire to be precisely fixed inside of a tube by gluing the wire to its support. There are many variations on this theme and other techniques may exist, however, we are confident that the ones presented here can be made to work reliably. The delayed gluing scheme presented here offers great flexibility in the assembly procedures. Given the advantages that these techniques would have over existing methods of long drift tube construction we recommend that their development be investigated fully.

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An Assembly Procedure for Drift Tube Chambers with Anode Wire Supports

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Abstract

An assembly procedure is described for the pressurized drift tube chambers being developed for ATLAS. The procedure achieves a high precision placement ($<20 \mu$ RMS) of the anode wires and achieves the required moderate precision ($\sim 100 \mu$ RMS) on the placement of the thin-wall tubes relative to the wires. A reusable template accurately places the anode wires at the tube ends. A new method for creating wire supports in long drift tubes transfers this placement to the supports.

Introduction

The assembly of a precision drift-tube chamber is made difficult by the need to control the sag of the anode wire in long pressurized tubes. The sag of the wires can be minimized by supporting the wire at regular intervals within the tube allowing tubes of any reasonable length and diameter to be constructed. In the monitored drift tube chambers (MDT) for ATLAS the tubes are aluminum, 3 cm in diameter. The longest tubes approach 6m in length and will require at least one wire support. A procedure is being developed where the wire, end plugs and supports are inserted as a unit into these tubes by a robot¹. The completed tubes are then stacked into multilayers (3 or 4 tube layers each), one multilayer on the top and one on the bottom of a mechanical support structure that also serves as an assembly jig and contains an internal alignment system. We have been investigating alternative methods for tube production and for module assembly that is simple, uses equipment that is easy to maintain, and can be exported easily to many sites.

In a recent ATLAS note² we described a new method for creating anode wire supports in long drift tubes using an adaptive support technique. Initially, the anode wire in an adaptive support is free to move within a small hole (1 mm) in the support but at a later time the wire is permanently fixed in the hole and to the support by injecting glue into the hole. We have verified that the injection and curing of the glue does not disturb the initial position of the wire within the 1 mm hole. One option for glue injection requires penetrating the tube wall with a needle. Another option is to pre-load the support with a small amount of glue before it is inserted into the tube. We have designed a support with a reservoir for a stable glue. Glue injection and curing is triggered by lowering the pressure within the tube; a simple method unique to chambers designed for pressurized operation. In this way the precise positioning of the wire relative to an external reference at the both ends of the tube can be translated to the internal adaptive supports.

This note describes a multilayer assembly procedure where the tubes are pre-wired and closed with end plugs but glue injection into the support holes is delayed until the tubes are bonded into a nearly rigid package. Adaptive supports are pre-loaded into the tubes and anode wires are soldered into precise wire guides that press-fit into the end plugs of each tube. The guide, commercially produced, contains an orifice that is precisely centered in the guide with a diameter only a few microns larger than the diameter of the anode wire. Once the wire is tensioned and secured the tubes can be tested for gas and high voltage leaks and stored until multilayer construction begins.

A surveyed flat surface serves as a reference plane and as a stacking jig for a multilayer. The pre-tested tubes are stacked to the required precision in bonding fixtures attached to the jig. Two reusable templates adjust the ends of the tubes by moving the wire

guides slightly (a few 10's of microns) to center the wires in the holes of the template to high precision ($<20\text{ }\mu$). The templates are fixed to the jig and constrain the wires to be in their proper grid positions in two dimensions at the ends of the tubes relative to the jig reference plane.

If the jig plane is oriented vertically the wires do not sag relative to it. If the jig is oriented horizontally the wires sag by known amount. In either case the tubes can follow the wires to required moderate precision ($100\text{ }\mu$ RMS). The jig reference plane is used to obtain high precision ($<20\mu$) in the placement of fiducials on the surface of the package at the ends and at the support points at a precisely determined and fixed distance from the wires. Once the epoxy sets the multilayer becomes a nearly rigid package, the templates can be removed from the jig and the gas connections made to the tubes.

While still secured in the jig the pressure within the tubes is lowered slightly triggering the injection of the glue into the support holes. In this way all of the wires are simultaneously fixed at the internal supports in a pattern that is identical to the wire pattern at the ends relative to the fiducials. The fiducials are, therefore, a permanent external reference for the internal location of the wires. We do not rely on the accuracy of the tube walls, tube surfaces, extreme cleanliness or precision tube stacking to position the wires prior to bonding. We rely only on the accuracy of the jig and the stability of the adhesives to maintain the wire positions relative to the fiducials. This relieves most tolerances on the tube dimensions and on the tube straightness to levels normally supplied by industry for very thin-wall tubes and enables a simple assembly procedure. A more complete description of the components needed in the assembly procedure is presented in the following sections.

Wire Placement at the Tube Ends

A design study for an end plug and wire guide is shown in Fig. 1. The accurate placement of the wires at the ends is accomplished without using the aluminum tube wall or the surface of the end plugs as these surfaces may be too soft or variable to achieve the desired precision. We use, instead, a commercially produced wire guide containing a precision orifice concentric to a few microns with the outside of the guide. The diameter of the orifice is also controlled to a few microns and is slightly larger than the diameter of the anode wire. An anode wire threaded through the orifice can be accurately located at the center of the guide to better than a $10\text{ }\mu$ accuracy. We have found that threading $50\text{ }\mu$ wires through a $50+\text{ }\mu$ orifice in an artificial jewel is easy if a tapered channel is included in the design of the wire guide as shown in Fig. 1.

The wire guide fits partially into the end plugs but not to the depth of the orifice. The outer surface of the guide is spherical and centered on the location of the precision orifice. When this surface is used to position the guide the design avoids any angular projection error in the position of the wire orifice.

The wire supports, pre-loaded with a glue cartridge and threaded with a leader wire, are inserted into the tube.[§] The end plugs are passed over the ends of the leader wire and are then crimped into the tube ends.[‡] An anode wire is attached to the leader and pulled through one end plug, the 1 mm hole in each support down the length of the tube and through the other end plug. The leader is then detached and each end of the anode wire is threaded through the orifice in the wire guides. The wire guides can then be press fit into the end plugs, the anode wire tensioned and finally soldered (or crimped) into the guides.

[§] The leader wire is steel (piano wire) and can pass easily down the tube and yet its diameter is smaller than the 1 mm diameter hole in the supports. The wire is rolled on a drum when outside the tube.

[‡] The diameter of the tube at the end plug is crimped down by about $50\text{ }\mu$ under the nominal tube diameter to prevent the formation of any shear stresses at the end of the tube later during stacking.

Figure 1. Tube end showing End Plug and Precision Wire Guide

A port in the wire guide is provided to inject a small amount of glue to the wire making a good gas seal and a second mechanical hold on the tension. The tube can now be tested for gas leaks and mechanical problems such as a loss of wire tension. Electrical properties can also be tested but without the anode wire glued to the supports.

The pre-tested tubes are stacked in a bonding jig using components similar to those shown in Fig. 2. During bonding the reusable combs shown in Fig. 2a position the tubes on the bottom and top layers of a multilayer to the required $100\ \mu$ accuracy (a factor of five less precision than is needed for the wires) with a $50\ \mu$ clearance to allow for some adjustment of the tube ends. If the tubes are horizontal the comb heights above the jig reference plane will compensate for the sag of the wires by letting the tubes bend by a similar amount to a $100\ \mu$ accuracy. If the tubes are vertical in the jig then all the comb heights will be the same because the wires do not sag in this orientation. There are as many combs as are necessary, perhaps one per meter, to achieve the $100\ \mu$ tube placement accuracy over the full length of the tubes. The middle layers are constrained to the same accuracy by the upper and lower layers in a close packed arrangement and by the side braces that constrain the tube package to its nominal width as shown in Fig. 2a.

Figure 2. Jig Components: a) Precision Template, b) Tube Combs, c) Gauge Bar

A thin coating of structural epoxy is spread on each tube as it is added to the stack so that the crevice between each tube of the layer and the contact points with neighboring layers are coated with epoxy. Epoxied to the top and bottom of the tube package between the combs are thin flat sheets of fiberglass or aluminum. These stabilize the tube package with respect to pressure and provide a flat surface on which to mount the reference fiducials.

The jig has two reusable templates with holes as shown in Fig 2b that match the diameter of the spherical surface on the wire guides. Each template has been made from a master template thus insuring an identical pattern of wires for all chambers. After the tubes are stacked in the jig and before the epoxy has set the templates are placed over the wire guides moving the tubes slightly ($\sim 50 \mu$) to align the guides with the template holes. Fixtures to the jig place the two templates, wire guides and, therefore, the ends of the anode wires to the required $<20 \mu$ precision in two dimensions in an absolute coordinate system with respect to the jig reference plane and remain there as the tubes are bonded into a nearly rigid package.

At this time gauge bars with fiducial pins permanently fixed to them as shown in Fig 2c are bonded to the top of the package at each end and at intervals corresponding to the support locations. The fiducials are placed to a $<20 \mu$ accuracy with respect to and at a fixed distance from the wires in two dimensions as can be determined by spacers attached to the jig; epoxy fills a small gap between the gauge bars and the tube package. If the jig is horizontal the height of the gauge bars relative to the jig reference plane can compensate for the well known sag of the wires (and tubes). If the jig is oriented with the wires and tubes running vertically then no compensation is necessary as the wires must be straight and parallel to the reference plane. In this way the tubes are fixed with their centerlines located on the wires to a 100μ accuracy, as specified.

After the structural epoxy cures the multilayer becomes a nearly rigid structure. With the tube package still in the jig the templates can be removed and the gas manifold attached to each tube. If the pressure is then lowered slightly in the tubes it will trigger the injection of the pre-loaded glue into the 1 mm hole in each support. In this way the wires

are fixed in their current locations in the supports. These locations are on a precise grid determined by the templates to $<20\ \mu$ accuracy with respect to the fiducials, as specified.

After the support glue fully cures the combs can be removed allowing the bonded multilayer packages to be released from the jig and transported to a site where they will be mounted on the alignment/support structures. Mounting points are located at the ends of the multilayers and at intervals corresponding to the location of the internal supports. Small adjustments can be made at the mounts to realign the fiducials of both multilayers as they were in the bonding jig and the nominal alignment system parameters recorded. The mounts can now be permanently fixed in their current positions and the alignment system will monitor the distortions of the chamber package from this initial state. The fiducials, however, will always remain as a visible and permanent reference to the wires; a safety feature that should be present in all assembly procedures.

The Adaptive Supports

The remote injection of glue into the 1 mm hole in the supports is accomplished using a support as shown in Fig. 3. Prior to insertion in the tube a polyethylene cartridge containing a small amount of glue is loaded into the support in a slot shaped for the cartridge. The cartridge has two reservoirs, one for gas ($\sim 20\ \mu\text{l}$) and one for the glue ($\sim 3\ \mu\text{l}$), connected by a narrow tube.

Figure 3. Wire Support with Glue Injector

The glue reservoir has a nozzle directed into the 1 mm hole. Surface tension prevents the glue from running out of its reservoir prematurely. The wall of the 1 mm hole opposite the cartridge is painted with an activator that will start the curing process once the glue is injected into the hole. If the pressure in the tube is reduced to 0.9 bar the gas will expand in its reservoir by about 10%, pushing some glue ($\sim 2 \mu\text{l}$) out of its reservoir through the nozzle into the 1 mm hole. The glue is allowed to fully cure before the tubes are re-pressurized.

We have produced some simple prototypes of this glue injection system. In cartridges similar to the one shown in Fig. 3, tested with water, a lowering of the pressure indeed pushes the fluid into the 1 mm hole. Our first tests of this procedure with glue will use acrylic glues and activators. These glues are reasonably stable but will set in a few minutes once activated.

Conclusions

We have discussed assembly procedures for the ATLAS MDT chambers using adaptive wire supports. These procedures can accommodate any number of supports along the length of the tube and any number of tube layers and do not rely on the walls of the aluminum tubes to position the wires to the specified accuracy.

The assembly places fiducials on the tube package that are visible and remain as a permanent reference to the wires. This will allow chamber (multilayer) construction to be asynchronous with the development and construction of the support structure, alignment components, mounting hardware and perhaps other components of the MDT system. Given the long lead time needed to assemble the large number of multilayers required for ATLAS this independence should remove many of the possible bottlenecks in the construction schedule.

We hope to produce a number of supports and glue cartridges, test some of them ourselves, but also provide a significant number to others who are interested in making tests of these construction procedures.

Footnotes and References

1. ATLAS Technical Proposal, CERN/LHCC/94-43, LHCC/P2, 15 December 1994.
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A SEMI-AUTOMATED SPLICER FOR PLASTIC OPTICAL FIBERS

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ABSTRACT

A semi-automated splicing machine has been built capable of splicing plastic optical fibers of various diameter. The heat source used to fuse the fibers is a 250 W projector lamp. This differs from other splicing apparatuses which use wire coils with a current flowing through them. A complete description of the splicing machine is given along with results on the quality of the splices. The splicing machine is currently being used to splice fibers for the CDF Hadron End Plug Upgrade. A description of a UV scanner that is used to test splice quality in production is also presented.

1. Introduction

Recent designs for collider detector upgrades as well as designs for detectors at the LHC and, until recently, the SSC have made substantial use of fiber technology. The CDF End Plug Upgrade¹ projects consists of $\approx 50,000$ channels. The SDC detector for the SSC would have had $\approx 250,000$ channels. A typical readout scheme is to have the wavelength shifting fiber (WLS) spliced to a clear (undoped) fiber of the same diameter. The WLS fiber end is then embedded in the scintillating tile while the other end is either connected to a cable or routed directly to a photomultiplier tube (see Fig. 1).

In order to splice such a large number of fibers, a splicing machine has been designed with the following criteria:

- Transmission across the splice must be larger than 90%.
- The variation on the transmission must be less than 3%.
- The splicing machine should be made as operator independent as possible.
- The capability to splice fibers of arbitrary length without damaging the fibers.

In the following sections we will present a description of the splicing machine, its operation and maintenance as well as the quality of the splices. We'll end with a description of a UV light scanner used to monitor the splicing quality during production of fibers for the CDF End Plug Hadron Upgrade. We will also present some initial results from production fibers.

FIGURE 1. - Image of a partially assembled CDF Hadron End plug Megatile showing the routing of fibers from connector to scintillator.

2. The Splicing Machine

2.1 Overview

The splicing machine is shown Figs. 2 and 3. The central section of the machine includes the 250 W projector lamp and half tubes used to constrain the fibers during heating. The use of half tubes instead of whole tubes was motivated by the desire to splice any length of fiber without the need to pull one fiber through a whole tube to remove it. This is more efficient and less likely to damage the fibers. Figure 4 shows a pair of cassettes. A whole tube is placed beneath each half tube to provide support during splicing.

FIGURE 2. - View of the entire splicing machine.

FIGURE 3. - Close-up of the central region showing the lamp and half tube cassettes.

FIGURE 4. - Half tubes loaded into a pair of cassettes. Notice the whole tubes beneath the half tubes used for additional support.

Each cassette is attached to an upper or lower cross bar that also contains chucks for holding the fibers in position. The bottom chucks have small holes drilled into them through which a slight suction is created by a small vacuum pump to aid in positioning the fibers prior to splicing. The upper and lower chuck are initially separated by about 1 inch.

The inside reflector of the projector lamp was coated with 1300 Å gold coating on top of a 500 Å chrome coating to maximize reflection in the infrared. The lamp is focused on the center of the half tubes. A vertical heat shield made of tungsten is mounted on the top chuck in front of the half tubes. A 1/4 inch wide notch is cut in the center of the shield to constrain the heating to the center of the half tubes where the fibers meet. The lamp is

mounted on an x-y-z mount to help focus the lamp; normally this is needed only when the lamp is changed.

2.2 Fiber Preparation

In order to obtain consistent splices, the ends of the fibers are prepared using the single fiber polisher shown in Fig. 5. The fiber ends prepared in this manner have a very uniform flat surface. This tends to reduce the sigma in the light transmission through the splice by about 1%.

FIGURE 5. - Single fiber diamond polisher used to polish the ends of fibers prior to splicing. The polisher was designed at FNAL.

Immediately prior to splicing, the fibers are inserted into a partially shrunk piece of shrink tubing approximately 1 inch long. The shrink tubing is preshrunk using a gauge pin of the same diameter as the fibers being spliced. This adds a highly desirable degree of strain relief to the spliced joint.

2.3 Operation

After the fibers have been positioned in the bottom fiber chucks, the splicing procedure is initiated by pressing both start buttons simultaneously. During the splicing process the top chuck is lowered to meet the bottom chuck, constraining the fibers in between. At this point the half tubes join to completely enclose the fibers. The top and bottom chucks are held together with approximately 100 psi of pressure controlled by the vertical pressure regulator located on the left side of the splicing machine. The left hand fiber chucks are attached to the top and bottom cross bars with a horizontal slide track. During the splice the fibers are constantly pushed together to obtain a good splice. The left most pressure regulator controls pressure delivered to the slide tracks to maintain horizontal pressure between the fiber ends during the splice.

2.4 Maintenance

The splicing machine requires a minimum degree of maintenance in order to maintain top performance. The half tubes are cleaned on a daily basis using alcohol. Once a week the cassettes are removed and the insides scraped with a gauge pin to remove any build up of material caused by the heating of the tubes.

FIGURE 6. - Results of the transmission across one splice.

results plotted in Fig. 6b. The increase in σ is caused by the added fiber-to-fiber variations. In either case the net transmission is 91%.

2.5 Radiation and Strength Testing

A sample of fibers was sent to the University of Tsukuba for radiation testing. Table 1 shows the transmission, tensile strength and radius at which the splice breaks as a function of radiation dose. The splices do not exhibit any dependence on radiation doses up to 2 Mrad.

2.5 Results

The transmission across the splice is calculated using the following procedure: we first splice a 1m length of Y11 to a 1 meter length of clear. The free end of the clear fiber is mounted to a photodiode while the free end of the Y11 is held fixed. A UV source then scans the length of the Y11. During the scan the output from the photodiode is recorded along with the position of the UV light. The fiber is then removed and cut approximately at the halfway point of the Y11. The two pieces of Y11 are then spliced together and the fiber rescanned. The ratio of the two scans is then taken and the transmission determined by taking the ratio of the horizontal lines to either side of the splice. This procedure removes any ambiguity that exists when fitting exponentials (single versus double exponential etc.) to the curve before and after splicing.

One hundred spliced fibers were scanned to measure the transmission. The first 20 fibers were scanned both before and after the Y11-to-Y11 splice. Figure 6a shows the transmission results for these first 20 fibers. Taking the average of the before scans for these fibers and using that as the before scan for all 100 fibers gives the

	TRANSMISSION		TENSILE STRENGTH		BENDING RADIUS AT BREAK	
			(kg)		(mm)	
RAD DOSE	SAMPLE 1	SAMPLE 2	SAMPLE 1	SAMPLE 2	SAMPLE 1	SAMPLE 2
CONTROL	90%	88%	3	2.9	11.5	-
0.3 MRAD	92%	88%	2.4	2.8	9.5	9
0.5 MRAD	90%	91%	3.2	3.3	11.5	14
1 MRAD	87%	91%	2	3.2	9	14
2 MRAD	89%	92%	2.5	3	8.5	9

TABLE 1 - Results of radiation test done at the University of Tsukuba.

FIGURE 7. - Linear UV scanner used to measure the transmission of the fibers after gluing into the connectors.

2.6 Fiber Dependence

Although the splice quality is not dependent on the fiber diameter there are certain fiber characteristics which affect the transmission through the splice. The first characteristic is the type of cladding on the fiber - multicladd or standard clad. In preparing the fibers for splicing any damage inflicted to the cladding is reflected in a larger variation of the light transmission. Standard clad fiber are more sensitive to cladding damage during polishing. The other characteristic is a property of the fiber core. Kuraray International produces two versions of each fiber type. These are distinguish as S-TYPE and NON S-TYPE. The major difference between these two types of fibers is the way in which S-TYPE fiber is

allowed to cool after manufacturing; the process making the fiber more flexible. We have found that using our method of splicing the transmission through the splice in S-TYPE fibers is about 10% lower than splices in NON S-TYPE fibers.

3. Connector/Fiber Assembly Scanner

3.1 Overview

Figure 7 shows the UV scanner assembly used to test the spliced fibers after they have been glued into connectors. The box at the top of the picture contains photodiodes which are read out via PC. A set of normalization fibers are glued into one connector and routed to the photodiodes. These connectors remain in place to remove any variation from scan to scan. The connector/fiber assembly (pigtail) under test is plugged into the connector end of the normalization fibers. A box containing a UV lamp scans the length of the pigtail.

FIGURE 8 - Output of a scan from the linear scanner. The data has been normalized using the normalization fibers.

The scan begins at the normalization fibers and stops at the end of the pigtail. The data from the normalization fibers are used to remove any variation in response of the photodiode, photodiode/fiber coupling or light output from day to day. The light output at a fixed distance from the fiber end for each fiber is compared to the light output detected at the normalization fiber to determine the relative transmission of that fiber.

The stability of the scanner is monitored to insure there is no time dependence in the measurement of the transmission. A sample of light output from 150 points for each of 10 Y11 fibers were compared with a previous measurement of the same fibers from 3 months prior. The sigma of the distribution of the comparison between scans is $\approx 2\%$.

FIGURE 9 - Distribution of the variation of the light transmission for fibers produced during production for the CDF Hadron End Plug Upgrade.

during production. The variation includes contributions from the following sources: fiber-to-fiber variations, splice variations, variations in light output caused by mirroring one end of the Y11 fiber, and connector variations. The total sigma is $\approx 3.5\%$.

4. Conclusions

A splicing machine has been designed and built which has the capability of splicing large numbers of fibers with uniform results. The machine is in almost constant use during the production of fibers for the CDF Endplug Upgrade Project. In addition, a scanner has been designed and built to monitor fiber production. The scanner can monitor splice transmission as well as checking that the proper lengths of fiber have been assembled.

REFERENCES

1. G. Apollinari, P. de Barbaro and M. Mishina, *CDF END PLUG CALORIMETER UPGRADE PROJECT*, to be published in the proceedings of the IV International Conference on High Energy Physics, La Biodola, Elba, Sept. 19-25, 1993.

3.2 Results

The output of a scan after normalization is shown in Fig. 8. The lines are different lengths due to the various lengths of Y11 fiber employed in the calorimeter. The flat line at the top of the graph is a direct monitor of the UV lamp to insure that the lamp remains stable during the time of the scan. If the lamp output varies between scans the variation will be removed by use of the normalization fibers. The scan of the pigtail also checks the lengths of each Y11 fiber to ensure that the pigtail has been properly assembled prior to installation in the Megatile.

Figure 9 shows the relative variation for over 1300 fibers so far assembled