HIGH DENSITY SCINTILLATING FIBER TO WAVEGUIDE FIBER CONNECTORS

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ABSTRACT

In a scintillating fiber tracking system, one needs to connect a large number of scintillating fibers to a large number of waveguide fibers in a small amount of space around a cylinder. To date no existing connector design fully meets the needs of a tracking system. Some of the major considerations have been explored and a preliminary connector design has been produced. Although this preliminary design will most likely not be usable in a final tracking system, the major concerns and the important roles the connector plays in the design of a tracking system have been identified. This design has been tested for light transmission and evaluated for its advantages and disadvantages.

1. Introduction

A considerable amount of work has gone into designing a scintillating fiber tracking system such as the one which will be put into the DØ experiment at Fermi National Laboratory. In all of this work perhaps the most undefined part of the system to date is the design of the connectors that will be used to attach the large number of scintillating fibers to waveguide fibers. Today, no connector design exists that fully meets the needs of a scintillating fiber tracking system, and this problem must be addressed. This paper will discuss the needs that must be fulfilled by such a connector design. It will also describe a preliminary design produced at Purdue University, and it will present the shortcomings of this connector which should be addressed by future designs.

2. General Arrangement

Before discussing connector designs, one should understand the general arrangement of the fiber tracking system. Figure 1 shows the basic structure of the area of interest. Fiber ribbon modules are placed around a cylindrical substructure in four layers (two axial layers and two stereo layers), and each ribbon must be attached to a group of waveguide fibers via the connectors. The length of scintillating fiber from the edge of the tracking volume to the scintillating fiber connector is called the “hair length” of the ribbon. To minimize stress on the fibers, the scintillating fiber connectors must be constrained to the end of the substructure in the limited amount of space available. With this arrangement in mind, one can now begin to investigate the connector design to be used.
3. Connector Requirements

In general, the connector design must allow for all of the scintillating fibers to be connected to waveguide fibers within the small amount of space available at the end of the cylinder. There are a number of design parameters that must be met to achieve this goal. These considerations are listed here, along with an explanation of their importance.

1. The design needs to treat the ribbons on the cylinder as the basic construction elements rather than the individual fibers. Fibers are constrained into ribbon forms, and the connector should not stress the fibers by pulling them away from this ribbon form. In addition, the ribbons are constrained to specific location on the substructure, and the fibers in a ribbon should not be stressed by pulling them away from that location in order to meet with the connector. The connector should be designed to meet the needs of the fiber ribbons rather than stressing the fibers to meet the needs of the connector.

2. The design needs to be as compact as possible to allow all of the connectors to fit into the limited space of the tracking volume. This is not an easy task, because the entire cylinder will be covered with fibers, eight layers deep. Thus, many of the connectors will be constrained to a limited volume.

3. There must be a method for constraining the connectors in the space provided which minimizes "hair length" and does not stress the fibers. The "hair" is added scintillating fiber, and thus can be a source of random hits in the system. Also, long "hair" can get in the way when placing the ribbon on the cylinder. The method used for constraining the connectors to the cylinder can greatly effect the "hair length" of the ribbon. If the connector is constrained far from
the position of the ribbon, extra hair will be needed to add enough flexibility so that the fibers can be moved around to the connector location without putting excess stress on the fibers.

4. There must be a way to polish the connectors with the fibers in place. This basically involves providing a way to hold the connectors while they are polished. While this is not necessarily a difficult consideration to meet, it does bring up further questions as will be seen later in this paper.

5. The connector design should provide an intuitive and simple fiber mapping. The mapping indicates the way in which the fibers will be placed into the connector. With a good fiber mapping, the fibers will not have to cross over or twist around one another. Also, human hands will have to put the fibers into place, and a good mapping will make this job easier and lessen the chance for errors.

4. Preliminary Connector Design

The first connector produced at Purdue University attempted to meet the above design goals. Curved, stackable connectors were designed to connect 835 micron diameter scintillating fibers to 965 micron diameter waveguide fibers (stepping up in size to reduce light loss). The basic design of these connectors can be seen in

Figure 2: Purdue Connector Design

Because of the layout of the electronics used to detect the light from the waveguide fibers, two smaller sets of 128 waveguide fibers were matched to one
scintillating ribbon (containing 256 fibers). This design meets each of the above design goals in the following ways:

1. For treating the cylinder ribbons as the basic construction elements—
   • The design allows each ribbon to be connected through one complete connector rather than dividing one ribbon among more than one connector.
   • The design is curved to match the shape of the ribbons coming off the end of the cylinder, reducing the stress on the ribbon’s fibers.

2. For compactness—
   • The amount of material used to boarder the fiber hole area has been minimized. Some amount of material is obviously needed (for dowel pin holes, screws for clamping, and structural integrity), but that material has been reduced as much as is mechanically safe.
   • The hole to hole spacing for the fiber holes has been minimized. This reduces the amount of space taken up by the connector along the circumference of the cylinder.

3. For constraining the connectors—
   • The curved design of the connector allows for stacking the connectors and adhering one to the other.
   • This design allows one to slide one connector across the top of the lower connector so as to meet the offset of the stereo ribbons. Figure 3 shows how one might arrange four connectors to match to the ribbons on the cylinder. This means that each connector is placed right in front of the ribbon location, which reduces the stress on the fibers as well as the “hair length” of the ribbon.

4. For polishing—
   • Notches placed on the top and bottom of the connector provides a way to constrain the connector for polishing once the fibers are in place.

5. For a simple and intuitive mapping—
   • The connectors provide a staggered hole design to match the staggered arrangement of the fibers. This design makes it obvious which fiber goes where. Also, each fiber follows a simple path to its hole, never having to cross over or twist around other fibers.

5. Material Considerations

In the discussion thus far, we have addressed how the connector should be shaped to meet certain mechanical goals. Once these goals have been met, there
are still a number of questions as to how well the connector pieces fit together to achieve good optical transmission:

• Of what material should the connectors be made?
  
  - A plastic is generally desired, but it must provide certain properties. It must hold its shape rigidly despite any changes in environment or stresses it might undergo. If the connector is to be milled, then the plastic must allow for precise milling. Finally, if the plastic is too hard, problems can occur during polishing. The polishing device can force small chips of the plastic into the faces of the fibers.

• What type of mechanical production should be used?
  
  - Bit milling with the use of computer numerical controlled milling machines (CNC's) is a traditional way to produce precision parts; however, there is still some question as to how well hole to hole spacing can be precisely reproduced over the many connectors that will be made.
  
  - Laser milling is a more recent innovation which is being explored. Test samples produced at Oak Ridge National Laboratory showed that hole to hole spacing can be controlled with high precision. However, the tests also showed that work still needs to be done to better control the shape and size of the holes that are produced.
  
  - Injection molding is ideal for giving the highly reproducible precision pieces needed for the connectors. However, the cost of producing these pieces will be much greater than production using one of the above techniques unless the volume produced is very high (perhaps higher than would be produced for the DØ detector).
• How should the connector pieces be made to align properly?
  - Dowel pins whose locations are precisely placed in the piece during production are probably the best devices available for precision alignment. These dowel pins obviously have to be put into place after the connector has been stuffed and polished.

• How should the connector pieces be clamped together?
  - Screws can be used for the clamping, but one must be concerned with how many screws are needed and where they should be placed to allow for the best connection.
  - Spring-loaded clamps may allow for a quick and easy way to clamp the connector pieces together. If they are designed correctly, they may provide thorough clamping all along the connector face.

For the connector parts produced at Purdue, Delrin plastic was used. This plastic has some of the needed properties (though greater rigidity would be preferable), and it had been used in producing other fiber connectors with relatively good results. The production of the pieces was accomplished with bit milling using a CNC machine at Purdue’s Central Machine Shop. Each side of the connector contains two dowel pins for precision alignment. The dowel pin holes can be seen in Figure 2. For clamping, a total of eight screws (four screws on each side) were evenly spaced throughout the connector. These too can be seen in figure 2.

The first connector sets were produced and a light yield test was performed to evaluate the optical connections made throughout one half of the connector. Ten scintillating fibers were equally spaced throughout one half of a scintillating fiber connector, and ten waveguide fibers were equally spaced throughout one waveguide fiber connector. The two sides were then polished and clamped together, and an experiment was performed to calculate the percentage of light transmitted through the junction. The following describes how that experiment was conducted.

A point (x) along one of the scintillating fibers is exposed to an ultraviolet light source which stimulates the scintillator to emit light. Some intensity of that light makes it to the end of the scintillating fiber that is in the connector. We call this intensity $I_0$. In the ideal case, the connector would be 100% efficient, and the full intensity of that light would be passed into the waveguide fiber. This light would then be attenuated through the waveguide fiber, and the light received at the output end of the waveguide would be

$$I_{ideal} = I_0 e^{(-L/L_0)}, \quad (1)$$

(where $L_0$ is the attenuation length of the waveguide fiber, and $L$ is the length of the waveguide fiber).

In the actual case, however, only some percentage ($T$) of the intensity ($I_0$) will be transmitted to the waveguide. This percentage will then be attenuated through
the waveguide fiber, and the light received at the output of the actual waveguide will be:

\[ I_{\text{actual}} = I_0 T e^{-L/L_0}. \]  

(2)

Each of the scintillating fibers was stimulated at various points along its length. For each of those stimulation points, \( I_{\text{actual}} \) and \( I_0 \) were measured. We could then calculate the light transmission (T) from the above equations:

\[ T = \frac{I_{\text{actual}}}{I_0} = I_{\text{actual}} / I_0 e^{-L/L_0}. \]  

(3)

The average percentage of light transmission was calculated for each of the 10 fibers. The results of this test are plotted in Figure 4. The average light transmission over all of the fibers was about 81%.

![Figure 4: Light transmission of prototype connector. At points where good clamping was achieved, the light transmission was 85-90%.

The results of this light yield test to be performed on these connectors show some obvious conclusions. The first conclusion is that the technique used to hold the connectors during polishing needs to be improved. The grooves placed in the connectors are very useful, but the stand used to hold the connectors allowed for excessive vibration during polishing.

The second and more obvious conclusion which is drawn from the data in Figure 4 is that a better technique for clamping the two sides of the connector together is needed. The light transmission is obviously better (approaching 90%
transmission) at the points where the screw clamps are placed while it decreases (down to 75%) where the clamping force is less. A “quick fix” to this problem is to introduce another set of screws for each side of the connector; however, the problem might be better addressed by incorporating easier to use spring-loaded clamps which would place clamping force throughout the face of the connector.

6. Problems With Connector Design

In addition to the above conclusions drawn from the light yield test, producing this connector has provided much insight into the problems involved with designing a workable connector. Below is a list of the major problems involved with each of the initial considerations.

1. With treating the cylinder ribbons as the basic construction elements—

   - In essence, this design still connects one fiber to another, which facilitates the need to handle individual fibers while stuffing the connectors, separates and spreads out the ribbon, and detracts somewhat from the ribbon as the basic construction element.

2. With compactness—

   - Much of the length of the connector comes from the material between each of the 256 fiber holes, even though hole spacing is minimal. The fact that some material is needed between the holes of a fiber to fiber connector means that such a connector must be considerably larger than the ribbon width itself.

3. With constraining the connectors—

   - The space taken up by the connector makes it very difficult to fit enough connectors for all of the ribbons into the space provided. This problem can be slightly mitigated by reading out some channels at each end of the cylinder. One procedure considered is to add a ring at the end of the cylinder which provides a large enough circumference for all of the connectors. The fibers would then come from the cylinder ribbons up to the larger ring and into the connectors on the ring. However, the connectors produced at Purdue are around 1.5 times as long as the ribbon width, requiring a ring with a radius about 1.5 times the radius of the ribbon support cylinder. This extra space must be taken up by the fiber “hair” which goes from the cylinder ribbon to the connector, and this is quite undesirable.

   - To further indicate the problem of constraining all of the needed connectors in the space provided, Figure 5 shows a configuration considered for accomplishing the task. Apart from the difficulty involved in constraining the connectors in this way, the ribbon fibers would have to be “twisted”
away from the orientation they have as they come off the cylinder. This would produce stresses on the fibers, constraining them far away from their positions they would naturally take.

Figure 5: Two setups for accommodating multiple connectors. On left is a strategy for incorporating connectors for all the fibers in 4 doublets placed around the entire circumference of the cylinder. On right, a strategy to incorporate connectors for only half of the fibers. The other half are connected to waveguides at the opposite end of the cylinder.

- Because of its design, this connector allows one to limit the “hair length” significantly. Having a connector on the ribbon with the desired shorter hair length may cause a problem during mounting. Because of this, one would like to consider the possibility of stuffing and polishing the connectors after mounting the ribbons. At Fermilab, attempts are being made to provide for this possibility.

4. With a simple and intuitive mapping—

- This connector provides the simplest mapping imaginable for a fiber to fiber connector; however, it still requires that all of the fibers in the tracker be individually stuffed into place. Improvements can be made with stuffing techniques if a ribbon to ribbon connector design is considered in the future.
7. Conclusion

The connector design is an essential component of a scintillating fiber tracking system. Since completing this study, the number of factors to consider in producing a connector design have continued to rise. The connector must not interfere with the structure used to support the tracking system. There will be a preferred modularity for the trigger system, and the connector must provide for that modularity. This leads to a consideration of the sizes of the cylinders to be used, as well as the spacing to be used between each fiber on a cylinder. The connector is the point at which all of these considerations come together, and its design must be carefully woven into the design of the system as a whole.

The importance of the connector design has been grossly underestimated in the past. This work is only a step in recognizing its importance. Although the final connector design may evolve significantly from the design presented here, the major issues have been identified and a structure for future development has been provided.