13. PVC Modules

13.1 Overview

The fundamental building block for the NOνA Far and Near Detectors is the PVC module. A PVC module consists of a 32-cell PVC extrusion assembly, an end plate, and a fiber manifold. The 32 cells each contain a looped WLS fiber, described in Chapter 11, that is routed through the fiber manifold and terminates in an optical connector mounted on the fiber manifold. 14,136 such modules are required for the NOνA Far Detector.

13.2 Technical Design Criteria

The overall length of the completed modules, including the manifold, end plate and packing material must be less than 53 feet in order to fit on a truck for shipping. The PVC modules will ultimately be filled with liquid scintillator and must be leak free. The modules also hold wavelength shifting fiber that must be controlled so that its bend radius is not significantly less than the manufacturer's specifications. Each of the fiber ends must be precisely routed to one of the pixels on the APD photodetector.

13.3 NOνA Modules

NOνA modules consist of two 16 cell PVC extrusions described in Chapter 12 glued together to make a 32 cell extrusion assembly. A looped wavelength shifting fiber is then inserted down the length of each cell.

The module assembly is shown in Figure 13.1. The end of the extrusion assembly with the loop is sealed with a PVC end plate. At the other end of the extrusion assembly the two fiber ends per cell are routed through a PVC manifold to an optical connector. The manifold assembly is also sealed giving a module assembly that is a leak tight container for liquid scintillator.

13.3.1 32-Cell Extrusion Assembly

The 16 cell extrusions will be glued together to form 32-cell wide extrusion assemblies from which modules will be built. These extrusions will be measured and selected so that they match in thickness. Each extrusion assembly will be cut to the appropriate length and its ends abraded to increase the glue adhesion at the next stage of assembly. The process for these procedures will be described in section 13.4. The finished extrusion assemblies will be stored and shipped to the module assembly factory for just-in-time module construction.

13.3.2 End Plate and End Seals

The end plate is extruded from the same PVC as the 16 cell extrusions. It is formed such that it has a raised wall that covers the outside edge of the extrusion assembly, a channel through which liquid scintillator flows, and a ledge on each side of that channel on which the extrusion assembly sits. The end plate is glued across the end of the extrusion assembly, as shown in Figure 13.2. The length of the end plate is equal to the minimum width of the extrusion assembly. The side seals are glued such that they provide a leak tight seal at each side of the extrusion assembly. The side seals are designed to take up the tolerance of the width of the 32 cell extrusion assembly to assure a liquid seal with no part of the end closure extending beyond the end of the extrusion assembly. The center seal assures that there is a leak tight joint between the two 16 cell extrusions that comprise the extrusion assembly. Figure 13.3 shows a close-up view of the end plate and one side seal. Figure 13.4 shows how the side seals adjust the closure end assembly to take up the tolerance of the extrusion width dimension.

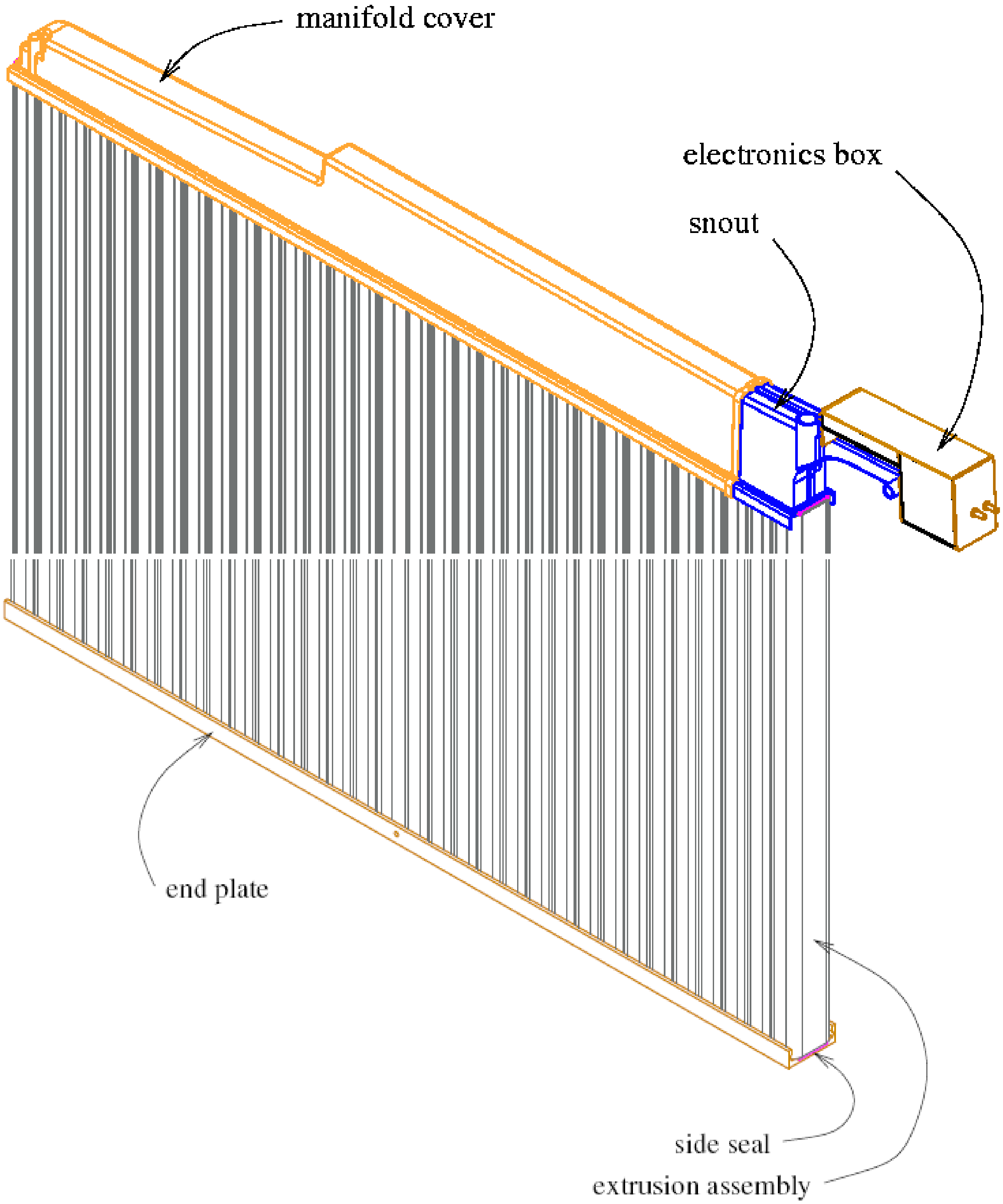

Fig. 13.1:   PVC module assembly showing the end plate at the bottom and the fiber manifold at the top. Both vertical and horizontal modules have the same configuration.

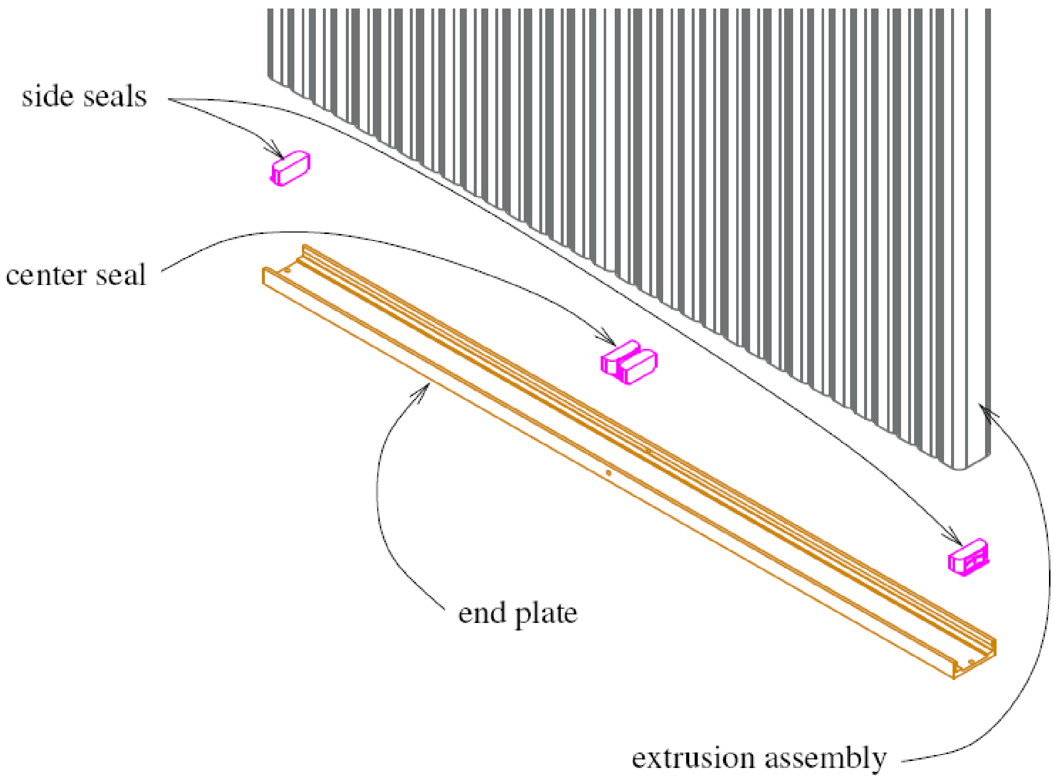

Fig. 13.2 Exploded view of the end plate as it attaches to the extrusion assembly.

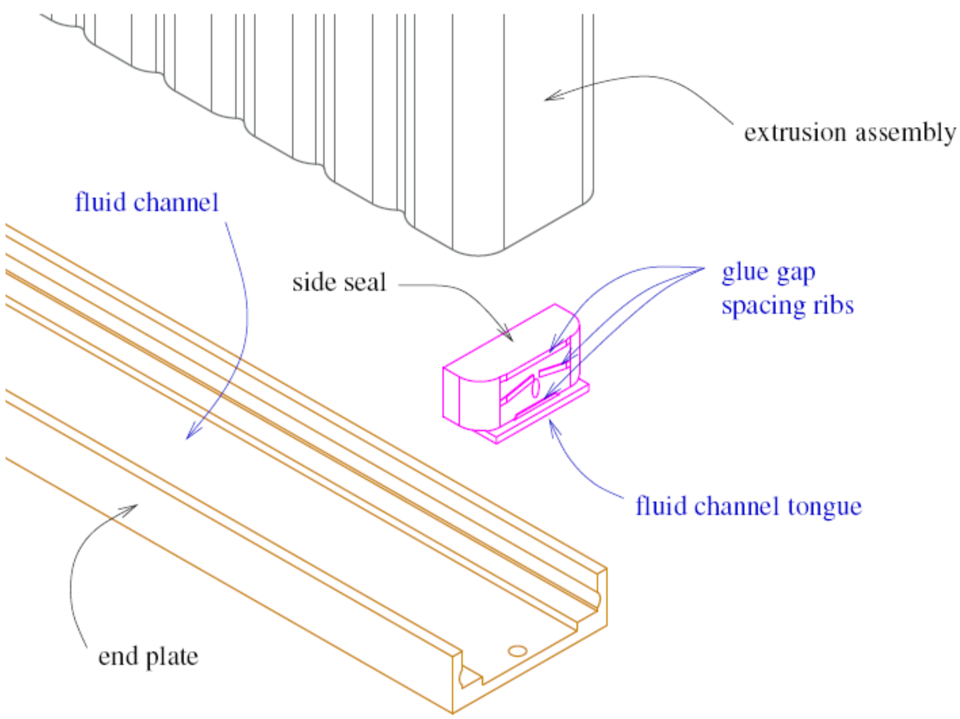

Fig. 13.3: Exploded view of a close-up an end plate assembly in the region of a side seal. The side seal enables sealing the last cell in an extrusion without extending the end plate past the edge of an extrusion assembly.

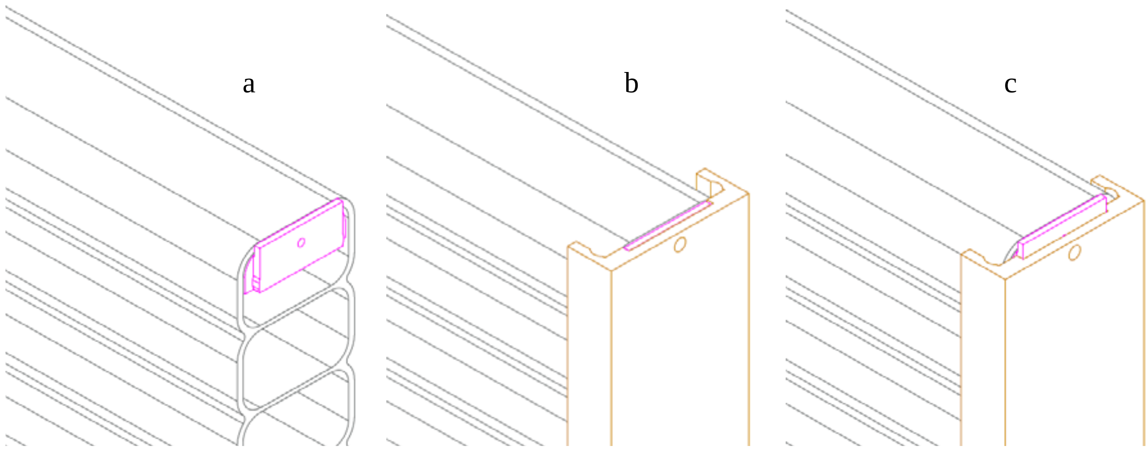

Fig. 13.4: Side seal function. (a) shows a side seal installed in the first or last cell of the extrusion assembly so that it is flush with the edge. (b) shows the relationship of the end plate, side seal, and extrusion assembly edge if the extrusion assembly is its minimum acceptable width. Here the side seal, the end plate, and the edge of the extrusion assembly are flush. (c) shows the relationship of the end plate, side seal, and extrusion assembly edge if the extrusion assembly is its maximum acceptable width. Here the side seal and the edge of the extrusion assembly are flush. Even though the end plate does not extend for the entire width of the extrusion assembly, the side seal still provides an ample seal surface with the end plate.

The side seals and center seal are injection molded parts made from PVC. Side seals and center seals are glued to the extrusion assembly and end plate using an epoxy glue that is chemically inert with liquid scintillator. Our tests show this glue fails in the cleavage peel mode at a pressure of about 380KPa (55 psi), about 3 times the maximum hydrostatic pressure at the bottom of the vertical modules. As an added safety factor, fiber glass webbing is glued around the edges of the module assembly using an extremely strong methacrylate adhesive around the edges of the module assembly which eliminates this cleavage peel failure of the side seal up to the strength of the PVC extrusion, about 830KPa (120 psi).

The procedure for attaching the end plate consists of four stages of gluing with two different types of glue, epoxy adhesive (3M2216), which has been shown to be chemically inert to liquid scintillator and methacrylate adhesive (e.g. Devcon Plastic Welder) which forms joints stronger than the PVC extrusion. The 3M2216 is used for any surfaces in contact with liquid scintillator. All surfaces to be glued with the chemically inert epoxy are abraded to increase glue strength. First the side seals (cells 1 and 32) and center seals (cells 17 and 18) are glued into the extrusion assembly as shown in Figure 13.2 using 3M2216. The structure of these injection molded parts, shown in Figure 13.3, assures that they are aligned with the extrusion cell and have the proper gap for maximum glue strength. This structure also assures that the glue injected into each part gives a reliable seal. The next step is to attach the end plate which is done after the end seal glue has cured and the wavelength shifting fibers are strung through each cell. A layer of glue (3M2216) between the end plate and the end of the extrusion assembly forms a butt joint that acts as a seal for the liquid scintillator. The end seals, already glued in place, align the end plate to the extrusion assembly. The structural adhesive (Devcon Plastic Welder) is then injected into the space between the outside of the extrusion assembly and the wall of the end plate. The placement of the two glues is shown in Figure 13.5. Finally a 10 cm long strip of fiberglass reinforcement netting is glued to each edge of the extrusion assembly at the end of the end plate to give additional strength against the possibility of cleavage peel at the side seals.

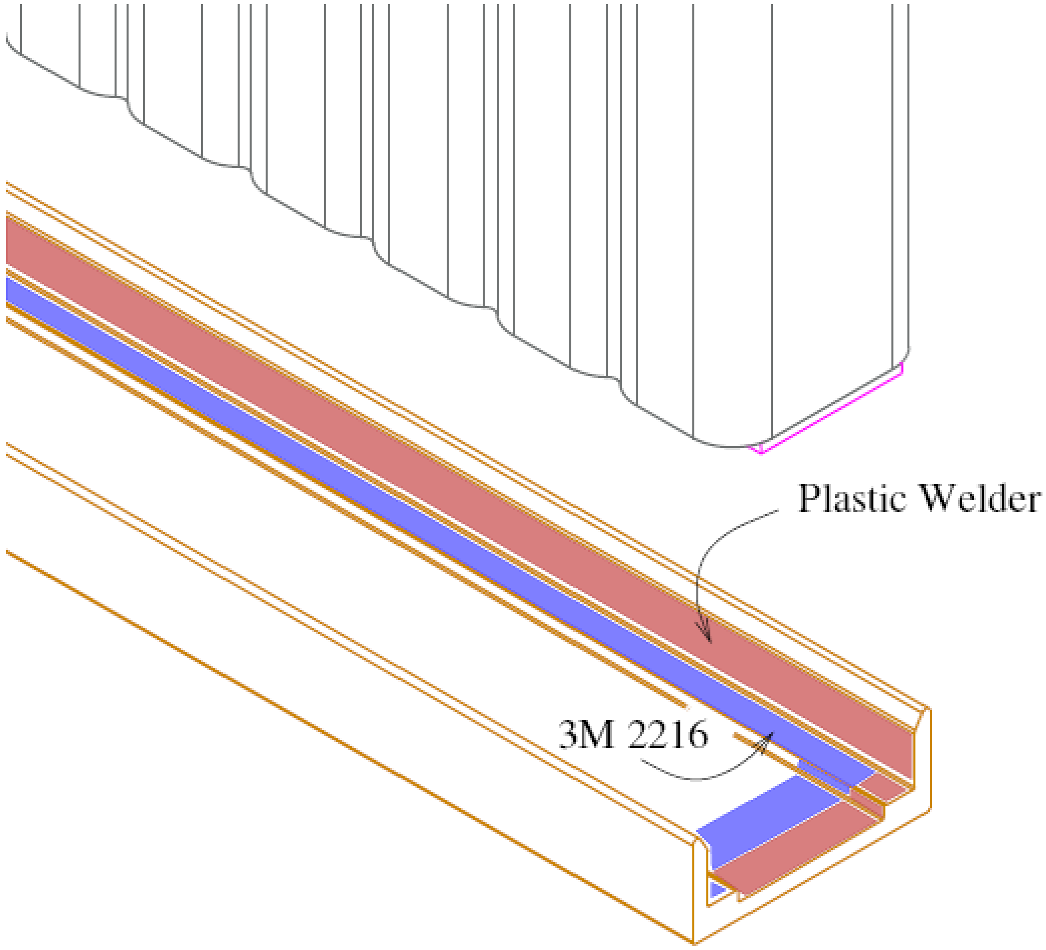

Fig. 13.5: End plate assembly showing the position of the two different glue joints.

13.3.3 Fiber Manifold

All parts of the fiber manifolds are made from black injection molded plastic. The manifold cover and snout are glued to the top of the PVC extrusion assembly in the same manner as the end plate described previously. The manifold has several functions: it must route the optical fibers in each of the manifold cells to an optical connector, it must protect the optical fibers from overbending, it must shield the optical fibers from cosmic ray events in the manifold, it must provide the interface for the APD electronics module, it must hermetically seal the back of the optical connector, and it must provide the liquid scintillator fill interface. Nearly identical fiber manifolds are used on both the vertical and horizontal modules. Two side-by-side vertical extrusion modules with their fiber manifolds are shown in Figure 13.6. The vertical extrusion manifolds have room for thermal expansion of the liquid scintillator. The horizontal extrusions have external overflow containers described in the detector installation section.

Figure 13.7 shows how the fibers are routed by the manifold to the optical connector. A manifold raceway assures that the bend radius of the fiber does not exceed the manufacture's specification. The raceway also optically isolates each fiber to reduce the occurrence of cosmic ray events through the scintillator in the manifolds. An exploded view of the parts of the manifold assembly is shown in Figure 13.8.

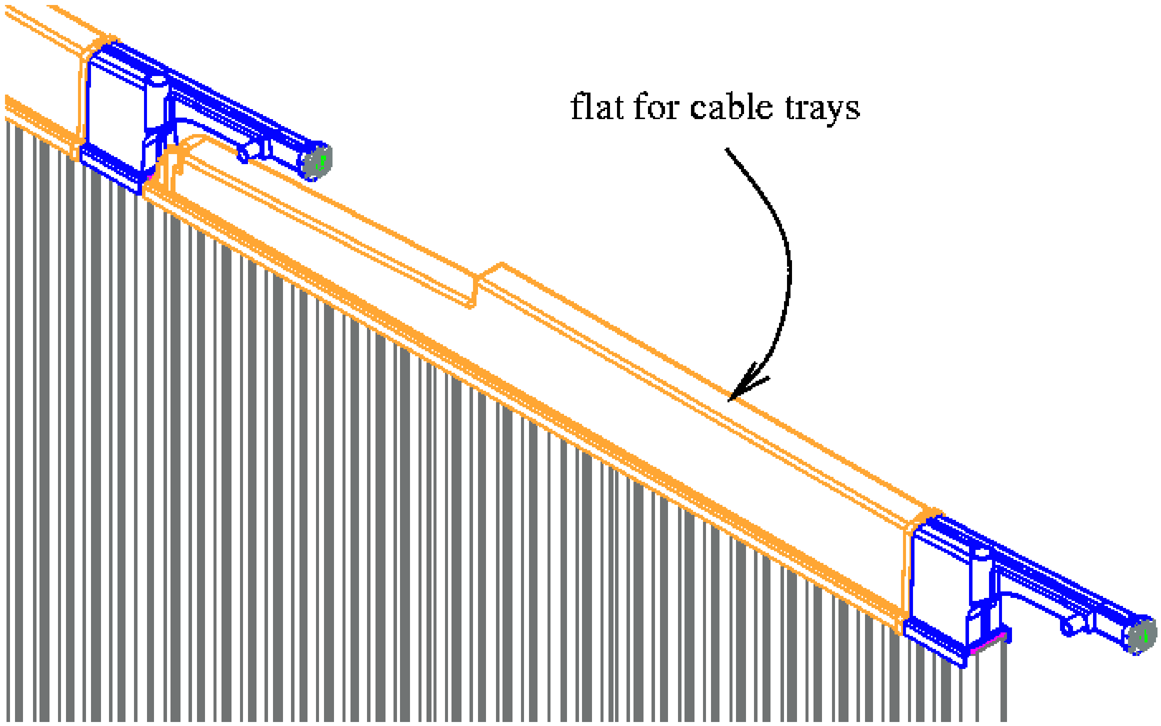

Fig. 13.6: Nesting of two adjacent manifolds. The top of the manifold cover will support cable trays for the electronics.

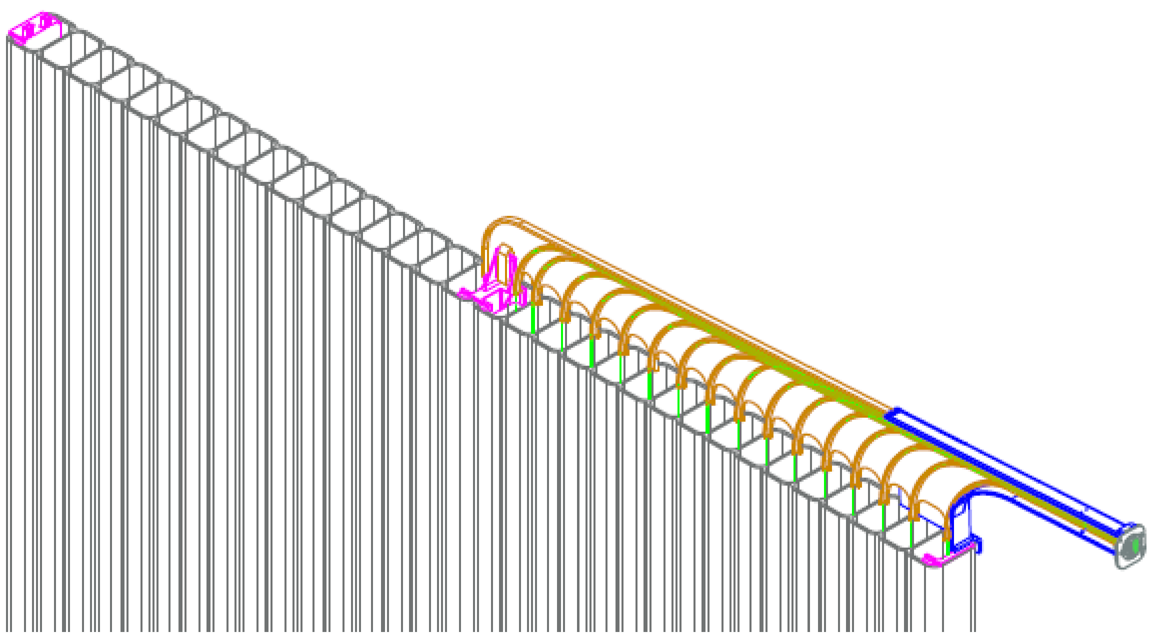

Fig. 13.7: Fiber routing to the optical connector for the first 16 cells. There are two fiber ends per cell routed to the optical connector.

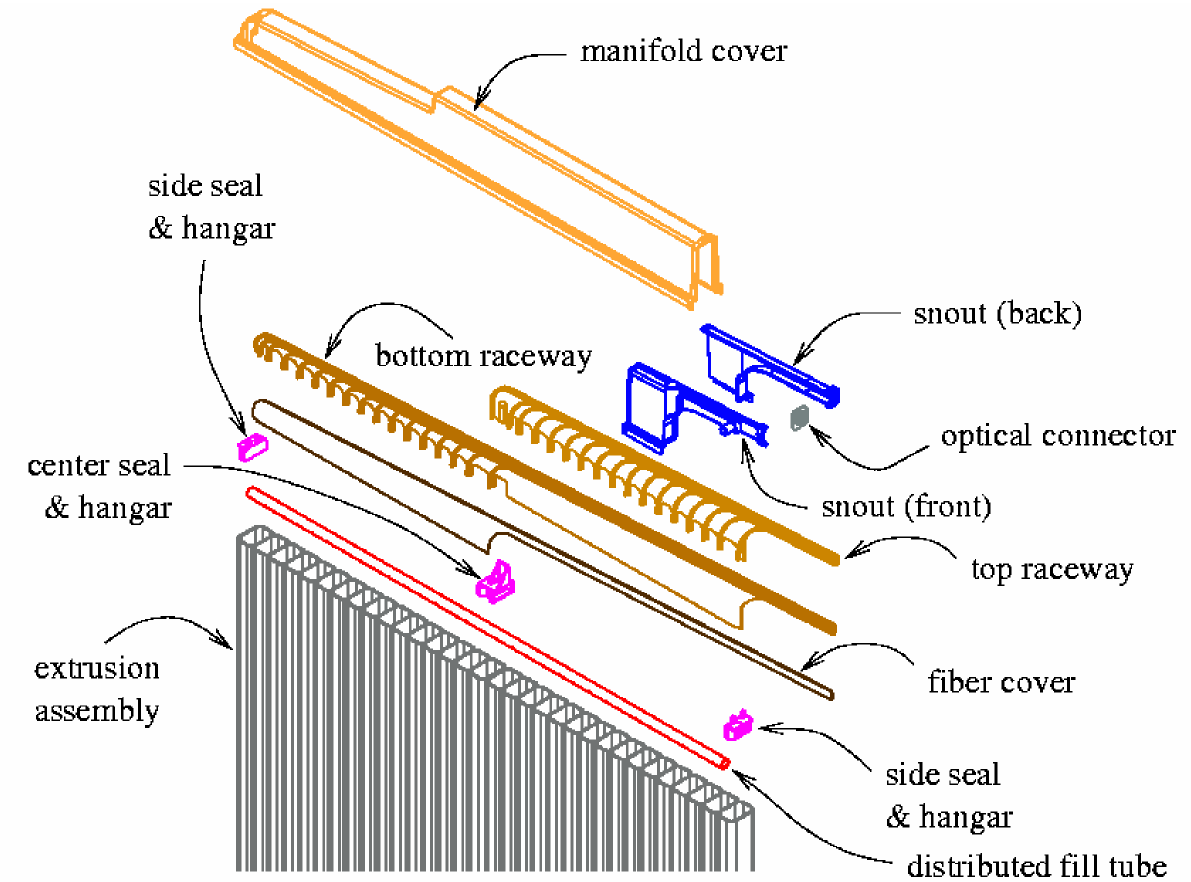

Fig. 13.8: Exploded view of manifold assembly.

The snout is the most complex part of the manifold assembly since it has to satisfy the most constraints. Physically the snout must fit over the manifold of the adjacent module to allow for close packing of the extrusions as shown in Figure 13.9. Since it defines the length of a module, it must be short enough so that the module will fit into a truck for shipping. It must also be sturdy enough to carry the APD photodetector and its associated electronics and cooling system. It routes the wavelength shifting fiber to the optical detector in a manner that facilitates efficient stringing. It also incorporates a seal between the cold optical connector and the liquid scintillator to prevent the possibility of pseudocumene vapor condensation on the fibers. The fiber routing and vapor seal are shown in Figure 13.10. Finally, the snout provides the fill and vent ports that allow the module to be filled with liquid scintillator and a tube to distribute the liquid scintillator flow down the sides of the cells as shown in Figure 13.11. The fill port is positioned above the first cell when the module is installed in the horizontal position so that the fill nozzle can be removed without draining oil from the extrusion. The fill port is also connected to an expansion tank for the horizontal modules. The vent port is 155 mm from the fill port on the horizontal modules and above the level of the first cell.

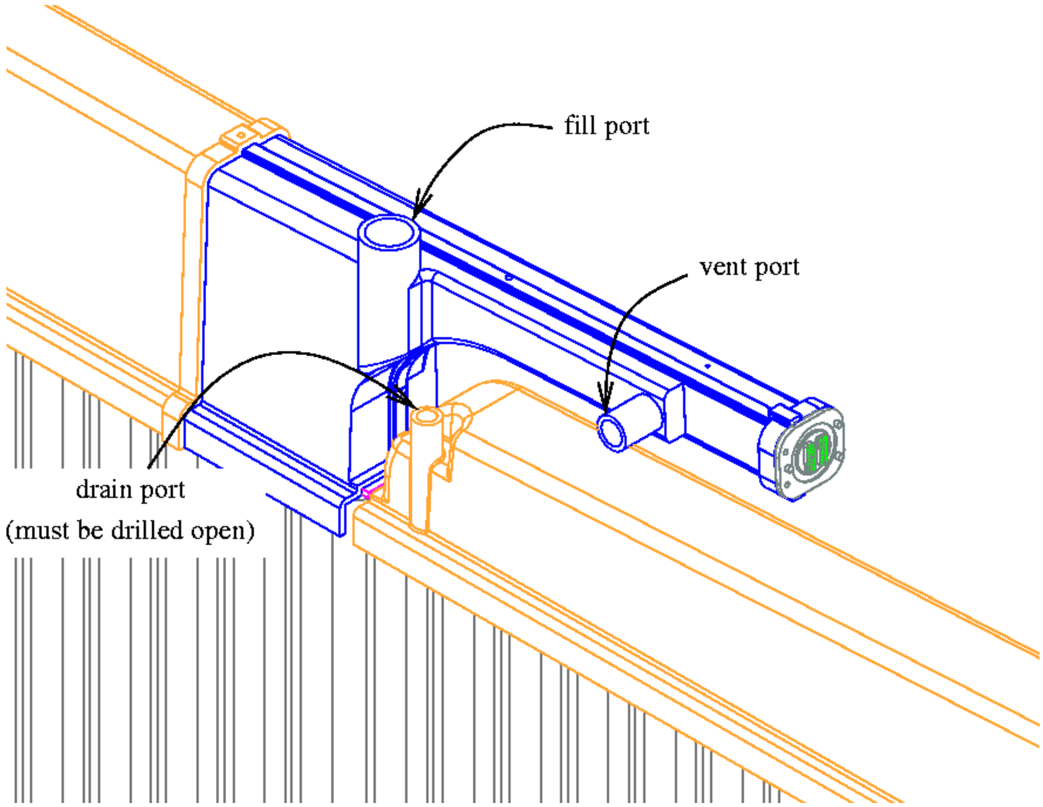

Fig. 13.9: The manifold snout fitting over the adjacent manifold. Also shown is the fill port on top of the snout and the vent port on the side.

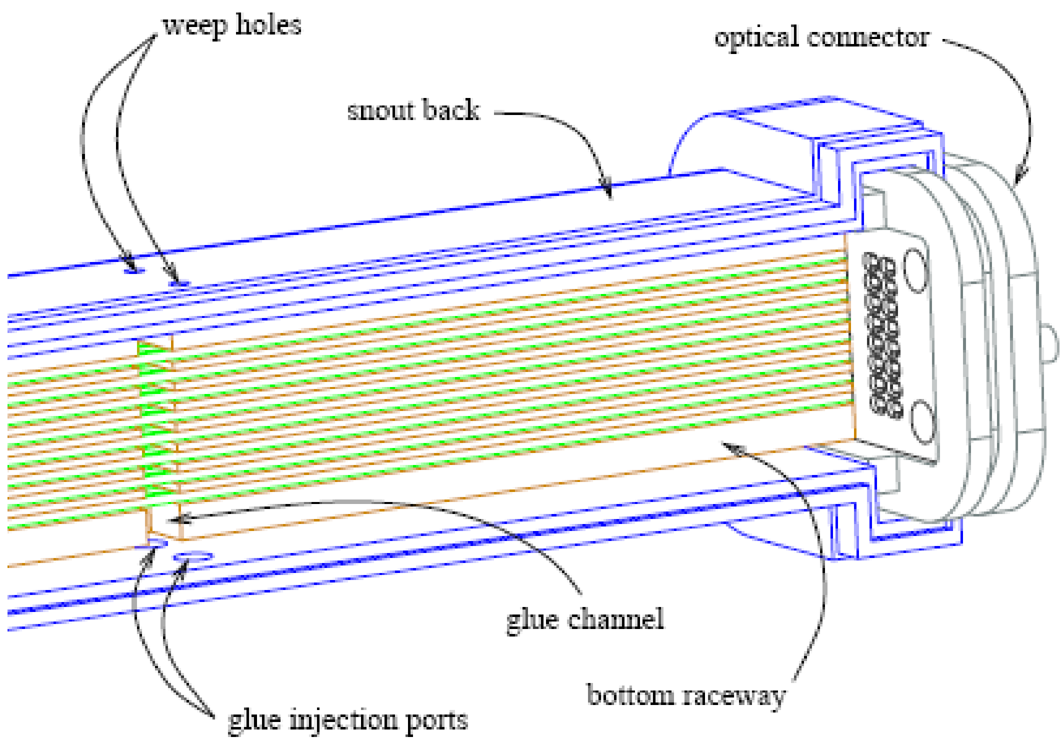

Fig. 13.10: Cutaway of the manifold snout showing the fiber routing to the optical connector and the vapor seal.

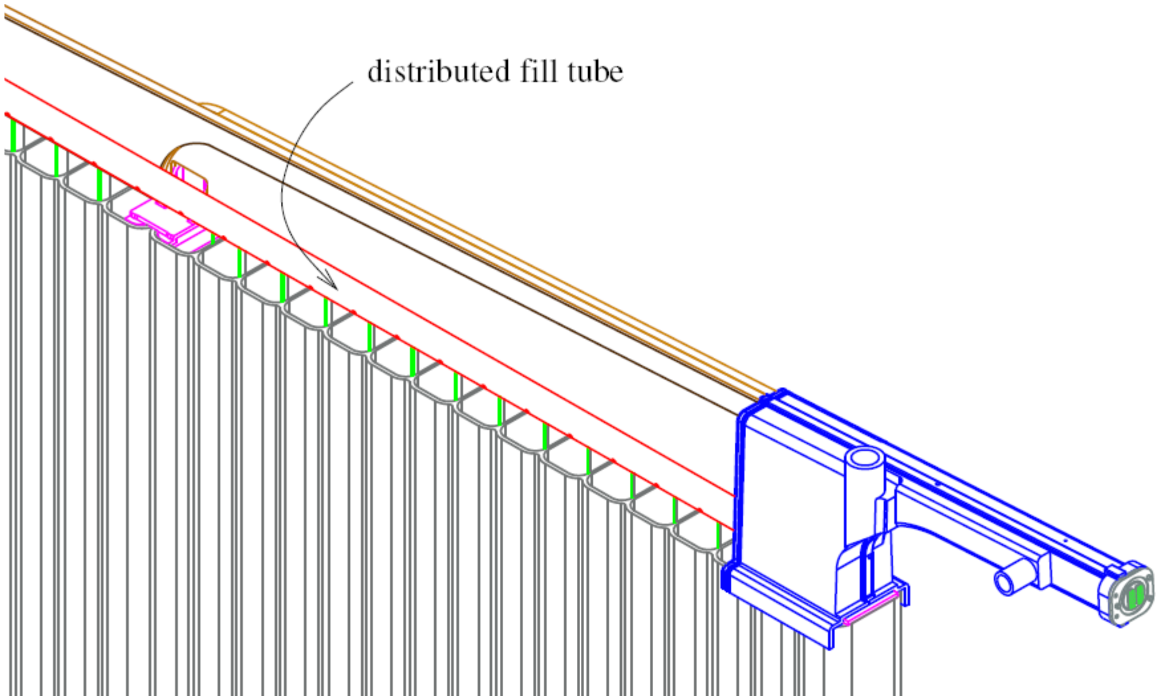

Figure 13.11: A cutaway of the manifold showing the snout with the fill and vent ports. The tube to distribute the liquid scintillator to the 32 cells of the extrusion assembly is also shown.

The manifold is glued to the extrusion assembly in much the same manner as the end plate assembly. However, its parts, shown in Figure 13.8, are assembled to facilitate threading of the fiber into the optical connector. Before any of the wavelength shifting fibers are strung through the cells, the side seals and center seal are glued into place, and the raceway closest to the snout is snapped into place. Then the side seals, center seal, back of the snout assembly, and optical connector are glued into place. The side and center seals are similar to those used for the end plate assembly except that they have features that support the fiber raceways. Figure 13.7 shows this part of the assembly with the first 16 fibers in place. A close-up of the snout at that stage is shown in Figure 13.12. A second raceway is then attached to the side seal and first raceway so that it covers the first raceway and the next 16 fibers are strung. After all the fibers have been strung through the cells and threaded through the raceways into the optical connector, the fiber cover, scintillator distribution tube, front of the snout, and manifold cover are glued into place. Figure 13.13 shows the glue joint between the snout and the manifold cover.

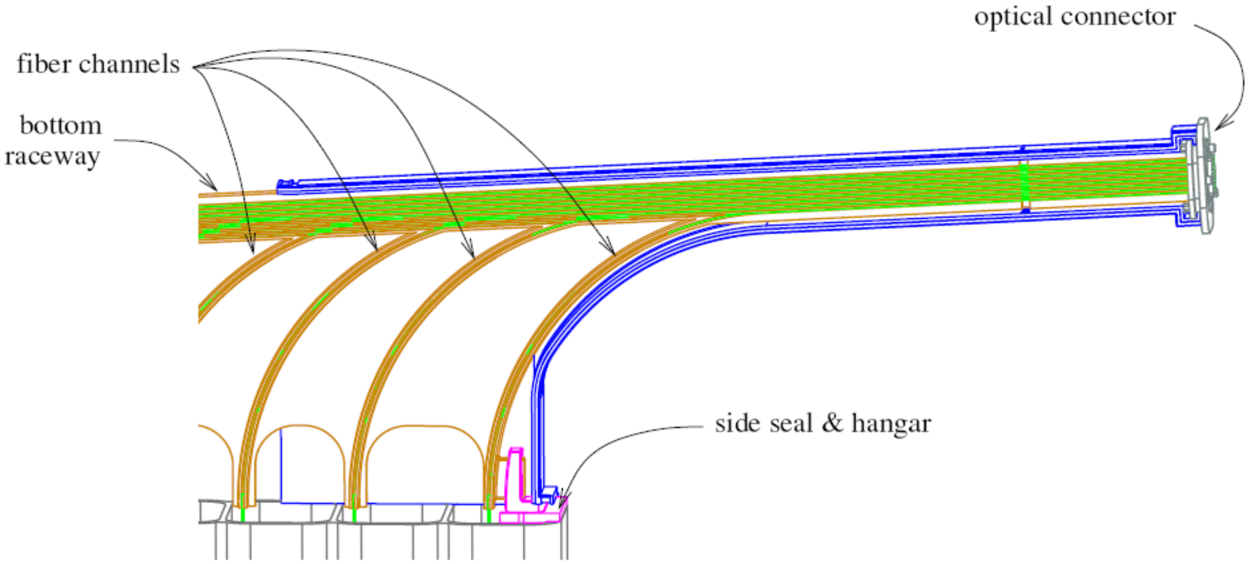

Fig. 13.12: Close-up showing the snout region assembly after stringing half of the wavelength shifting fibers.

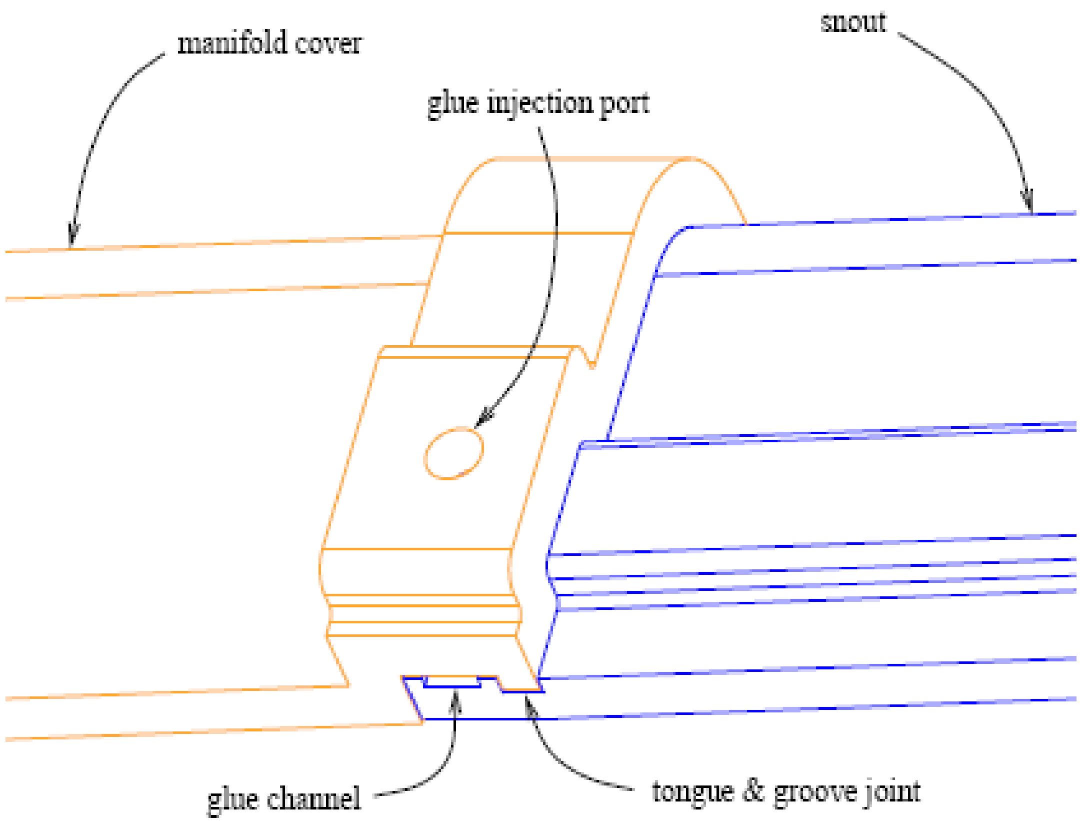

Fig. 13.13: Close-up of glue joint between the snout and the manifold cover. The manifold cover is slipped over the snout and then glue is injected into the tongue and groove joint.

13.3.4 Fiber Stringing

The fiber stringing machine is designed to insert fiber loops down the cells of the modules without damaging them. The machine consists of two major components: the fiber spooling apparatus, shown in Figure 13.14, and the far end vacuum adapter, shown in Figure 13.15. There are also fiber puller assemblies for each cell that are used to draw the fiber loops down the module, shown in Figure 13.16.

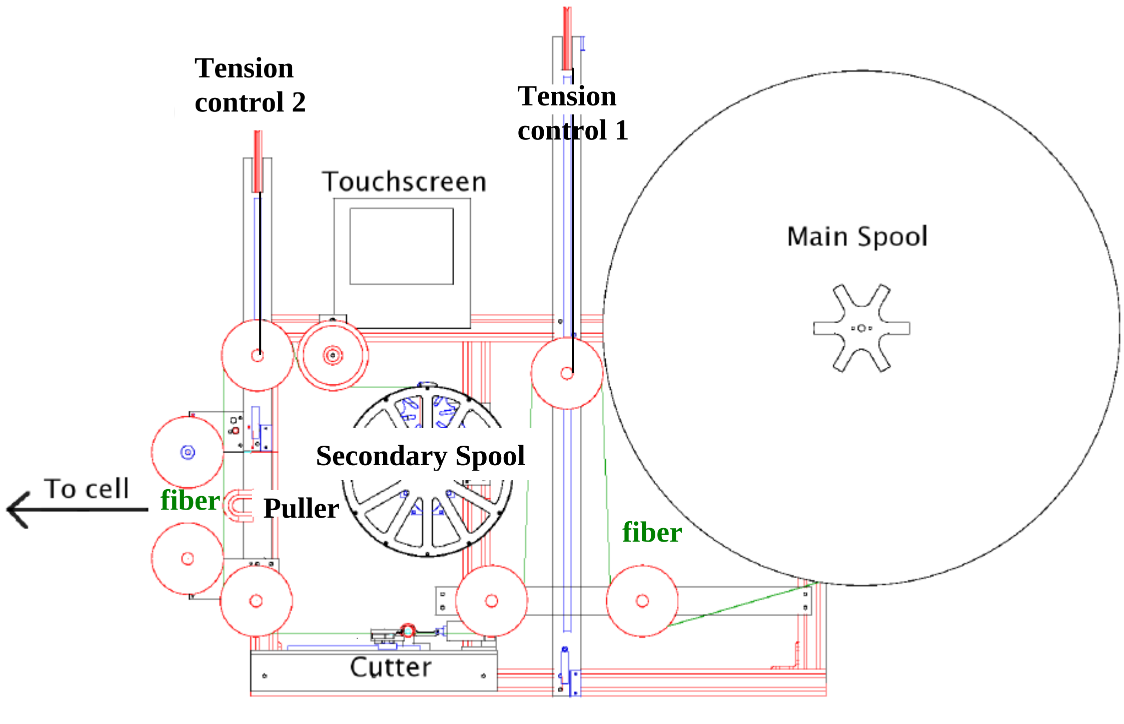

Fig. 13.14: Fiber spooling machine.

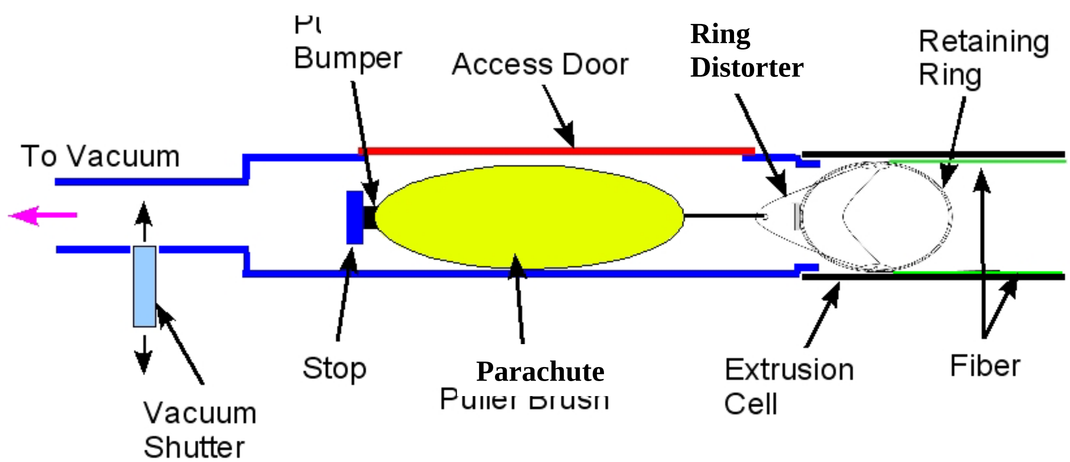

Fig. 13.15: The vacuum adapter showing the side view showing a single cell. The vacuum adapter (blue and red) is attached to the extrusion (black). The parachute hits the stop in the vacuum adapter. After all 32 cells are strung, the parachutes and distorters are removed through the access door located on top of the vacuum adapter.

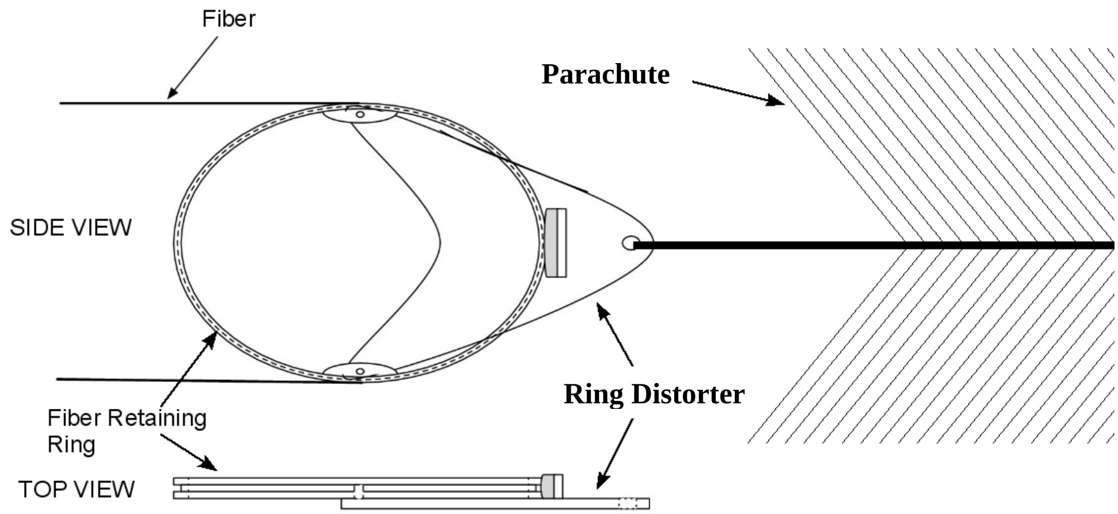

Fig. 13.16: Fiber puller assembly.

13.3.4.1 Fiber Stringing Operation

To begin the fiber stringing operation, the fiber spooler is positioned so that the operator initially aligns it to one side of the manifold end of the module. The vacuum adapter is attached to the other end of the extrusion. A microprocessor in the spooling machine controls the position of the machine and the length of the fiber depending on which cell is being strung. The machine controls the tension on the fiber while the vacuum rapidly draws it down the channel. When the fiber nears the end of its travel, the machine automatically cuts it to the proper length for that cell. The operation of this machine is described in more detail in the next section.

The vacuum adapter seals the edges of the extrusion assembly with a soft gasket so that all 32 cells have access to the vacuum. The adapter has a solenoid gate that isolates all cells except the one being strung from the vacuum. The gate is operated electronically from the microprocessor of the stringing machine.

Once the machine positions itself at the appropriate cell, the operator threads the fiber though the pulleys and clamps the end in the secondary spool. A button on the touch screen is pressed to begin spooling up half of the loop. After the spooling is complete, the operator attaches a fiber puller assembly, consisting of a fiber retaining ring, a retaining ring distorter, and a parachute. The fiber retaining ring is deformed into an oval when placed in the distorter to allow it to fit through the obstructions at the manifold ends of the cells. The configuration of this puller assembly is shown in Figure 13.16. The operator places the parachute in the cell and vacuum draws the assembly down to the far end of the extrusion. The spooler apparatus moves to the next cell and the vacuum adapter automatically switches the solenoid gate. After all thirty-two cells are strung, the vacuum adapter is removed and the fiber puller assemblies are removed from the retaining rings, leaving the rings in the cells. The retaining rings expand and fit tightly to prevent the fiber from creeping back up the cell during shipping.

13.3.4.2 Fiber Spooling Machine

The primary motivation of this design is the large number of repeated actions at both high speed and high accelerations during which the fiber must be maintained at a safe tension. This is accomplished with the semi-automatic machine described below.

The primary components of the stringing machine, some of which are shown in Figure 13.14, are as follows:

- Main spool: the 1 meter diameter fiber spool delivered by the fiber manufacturer. It is controlled by a servo motor.
- Secondary spool: the 1 m circumference metal spool that stores half of the cell's fiber in a helical groove. It is controlled by a servo motor.
- Tension control: The two tension control fiber loops operated such that, if the tension deviates from the desired value, the size of the loop changes. The size of each loop is determined by a wheel mounted to a track. The wheel is pulled upwards by a spring and is attached to a spring potentiometer to measure its position.
- Cutter encoder: an encoder on the wheel immediately before the cutter which senses how much fiber has passed this point.
- Puller: The fiber puller assembly that is sucked down the cell.
- PLC: Programmable Logic Controller, a specialized computer that controls the various electro-mechanical actuators and sensors including the two servo motors.
- Servo drive: electronics that controls the servo motors. It has preset speeds and acceleration profiles and receives signals from the PLC.
- Motor modes:
    - Tension mode: The PLC can read the position of the tension control wheels and control the speed of the corresponding spool to keep the tension at the desired value.
    - Position mode: The servo can direct a spool to turn a specified number of times and then stop.
    - Velocity mode: The servo can direct a spool to turn at a constant rate. This is used in two ways:
        - Jog: During setup, the operator can move either spool forwards or backwards at a fixed low speed. This is primarily when a new main spool is being started or for error recovery.
        - Secondary spool alignment: Returns the secondary spool to its home position after fiber release or when an error is detected.
    - Stopped: Keeps the motors stationary when the PLC is neither controlling the speed nor position of a spool.
- Touch screen: The touch screen is the operator interface to the PLC that allows commands to be issued and the machine status to be monitored. The possible controls are selected by the PLC depending on the state of the system.

At the beginning of a normal stringing cycle, the fiber already goes through Tension Controller 1 and is held clamped at the cutter as shown in Figure 13.17. The fiber is held in tension through the combined actions of the spring loaded tension controller and a servo motor on the main spool as shown in Figure 13.18. The tension is controlled through a closed loop feedback algorithm programmed within the PLC. This loop maintains the tension control wheel at a desired position (obtained through a displacement sensor) by controlling the velocity of the servo that drives the main fiber spool. The tension is maintained to prevent the fiber from uncoiling and is selected to be at a safe value for the fiber. The spooling machine is mounted to a slide that allows it to traverse perpendicular to the extrusion and line up with each cell. This slide includes a sensor so that the machine automatically determines the cell to be strung. Since the fiber length varies by cell because of the differing path length through the module manifold, the machine automatically spools the correct amount of fiber without operator intervention.

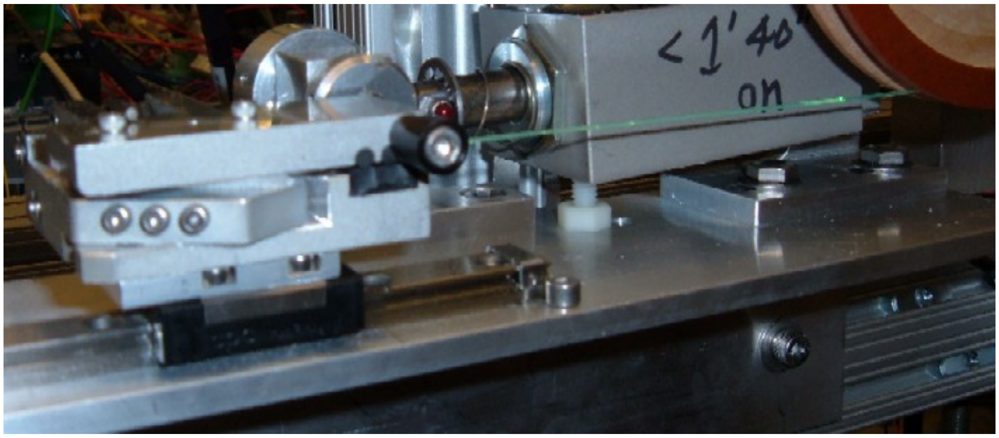

Fig. 13.17: Cutter/clamping mechanism

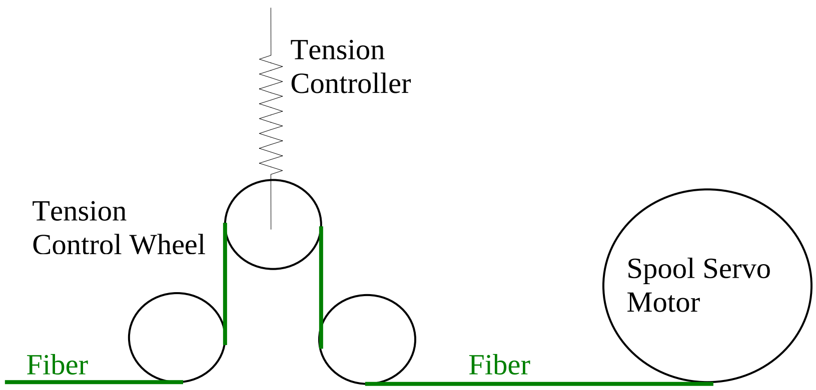

Fig. 13.18: Fiber tension control.

To begin, the operator releases the clamped fiber from the cutter and threads it through the guide rollers and Tension Controller 2 clamping it to the Secondary Spool. The operator then presses the touch screen and the secondary spool turns to accumulate the amount of fiber needed for the present cell. The secondary spool has a helical groove to keep the fiber separated and at a fixed diameter. A digital encoder attached to the shaft of the secondary spool ensures the correct amount of fiber is spooled. At this point, Tension Controller 2 is not activated and its tension control wheel is locked in place so that a precise length of fiber can be measured out.

Next, the operator attaches the fiber puller assembly to the fiber and activates Tension Controller 2, which also activates the vacuum. The two tension controllers are necessary because the fiber puller assembly fixes the fiber at its mid point creating two independent fibers that each require tension control during the stringing process. The operator then pulls the fiber puller assembly to the near end of the extrusion and the fiber is drawn down the length of the extrusion. During the travel down the extrusion, the fiber length is measured by an encoder attached to a guide roller located just before the cutter. This allows the fiber coming off the main spool to be automatically cut to the correct length on the fly. Safely cutting the fiber on the fly is accomplished by installing the cutter mechanism on a slide activated by a solenoid. At the cutting point, the solenoid fires so that the cutter and clamp move with the fiber for a short distance. Thus the cut occurs at a small relative velocity between the fiber and the cutter. The cutter/clamp mechanism also clamps the fiber so that the fiber is ready for the next cycle and still in tension. The second half of the fiber loop, having been premeasured in the spooling process, simply comes free of the secondary spool at the end of its travel using a Geneva mechanism to release that clamp.

During the entire stringing process, the PLC checks for various faults and takes automatic corrective actions. A more detailed version of the machine operation is found in Figure 13.19

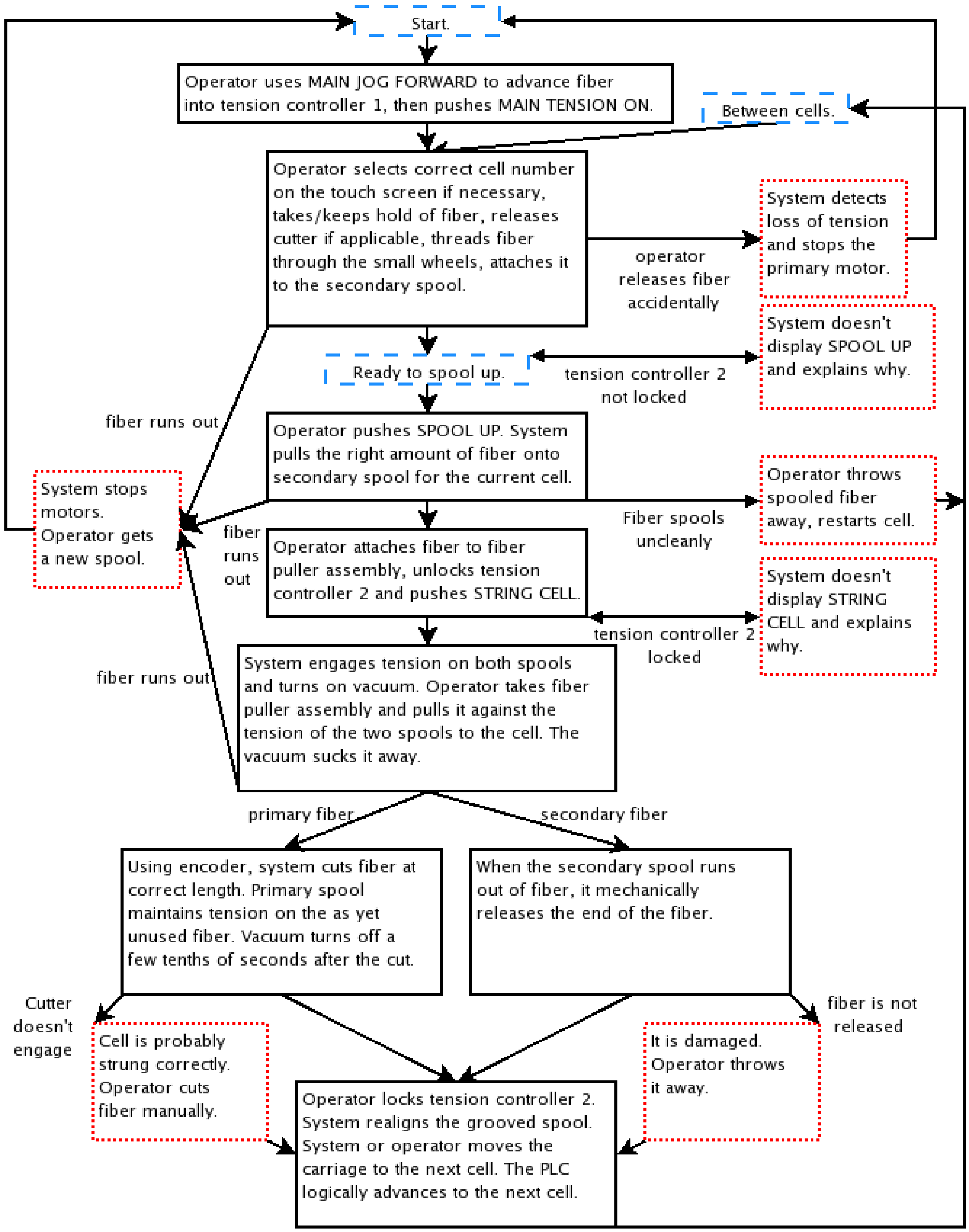

Figure 13.19: Flow chart of operation of the stringing machine. Solid black boxes are correct actions. Dashed blue boxes are system states. Dotted red boxes are error handling. Words in all caps are the names of buttons on the touch screen.

13.3.5 Optical Connector

The optical connector is an injection molded part made of Delrin that serves as the interface between the wavelength shifting fibers and the APD photodetector. It aligns the 64 fiber ends from the 32 module cells with the 32 pixels of the APD such that the fibers do not physically contact the APD surface. It must seal the face of the APD to prevent any condensation from the air and seal the manifold snout. The optical connector is mounted on the manifold module snout, shown in Figure 13.20, using a tongue and groove joint. This tongue-and-groove construction provides a rigid mechanical connection between the optical connector and the snout. In addition, it provides a light barrier and an environmental seal. Glue is inserted in the tongue-and-groove joint upon assembly.

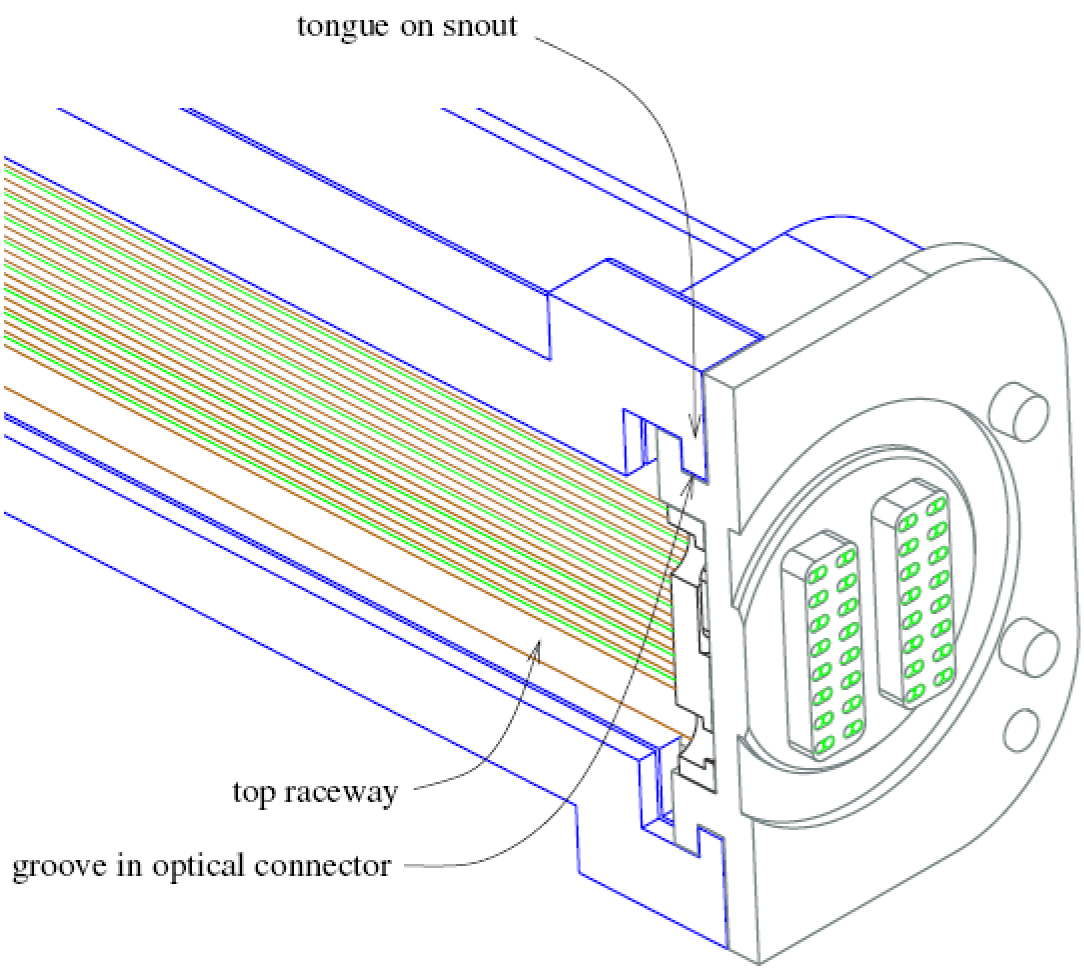

Fig. 13.20: Optical connector mounted on the manifold snout. Portions of the optical connector and the snout have been cut away to reveal the tongue-and-groove joint between the two components.

The optical connector has 32 oblong slots that each hold the two fiber ends from a single module cell. These slots are arranged in four rows of 8 to correspond to the APD pixel pattern. Each set of two rows is in one of the two raised bosses that fit through slots in the APD carrier board. Two dowel pins are used to provide precise $x-y$ alignment. In addition, the connector precisely controls the gap between the ends of the fibers and the face of the APD. This is accomplished by flycutting three spacer pins at the same time as the fiber bosses. All three spacer pins press against a reference surface in the electronics module to set the gap. This flycutting also provides an optical finish to the surface of the fiber ends. Figure 13.21 shows the face of the optical connector that is the interface to the APD. The optical connector seals the volume between the fiber bosses and the APD surface using a variant of an O-ring with an X-shaped cross-section called a quad ring. A quad ring groove contains the quad ring which is designed to allow flycutting the optical connector as many as four times, if necessary, to obtain the desired surface quality.

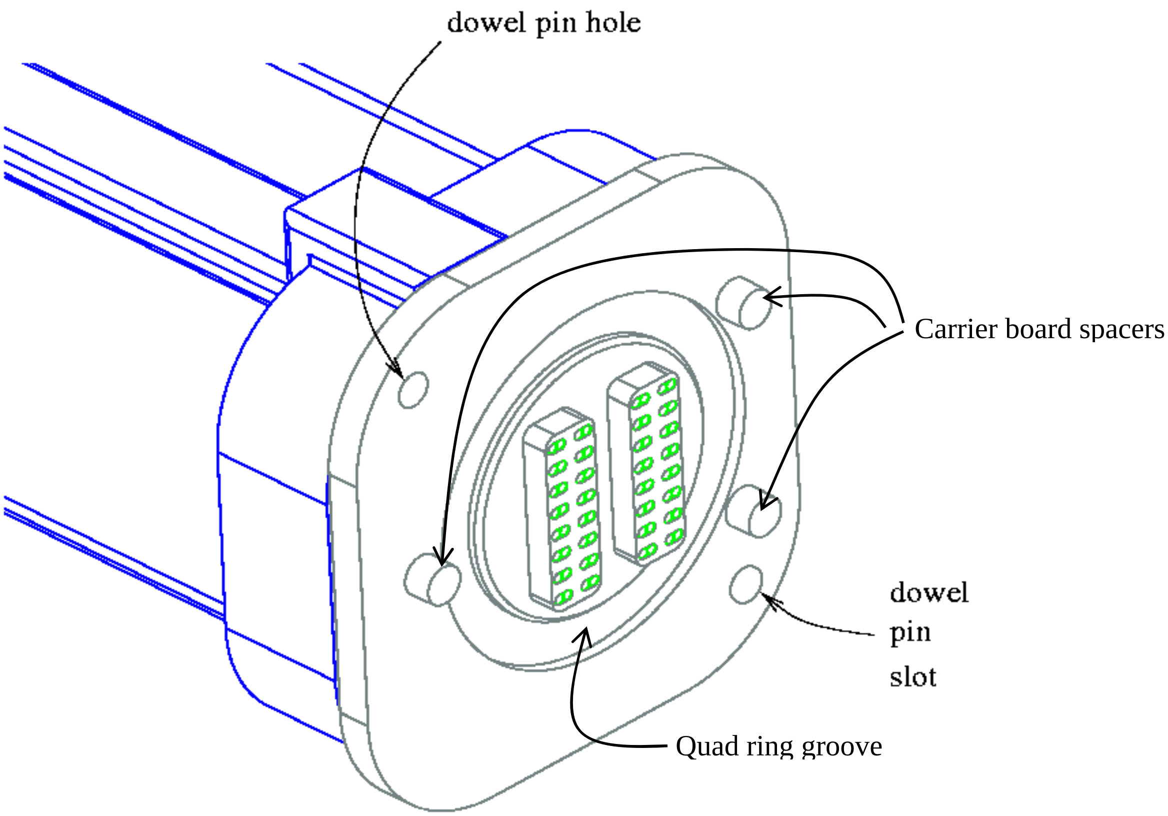

Fig. 13.21: The side of the optical connector that is the interface to the APD showing its alignment features.

The optical connector is constructed from two injection molded parts, shown in Figure 13.22. The two parts are ultrasonically welded together by the manufacturer of the parts. The two piece construction facilitates the potting of the fiber ends to provide a seal and to hold them rigidly for flycutting. As shown in Fig. 13.22, channels route glue to pockets which surround the fibers between the front and back parts. The channels are fed by glue injection ports on the back of the connector, Fig. 13.23. These ports are positioned above the fiber raceways when the modules are placed on the assembly table, so they remain accessible after fiber threading is completed.

Figure 13.24 shows a prototype connector after fiber threading has been completed and the potting glue has been injected. Note that the glue has surrounded every fiber at the point where they protrude from the connector. This figure also shows the same connector following fly cutting.

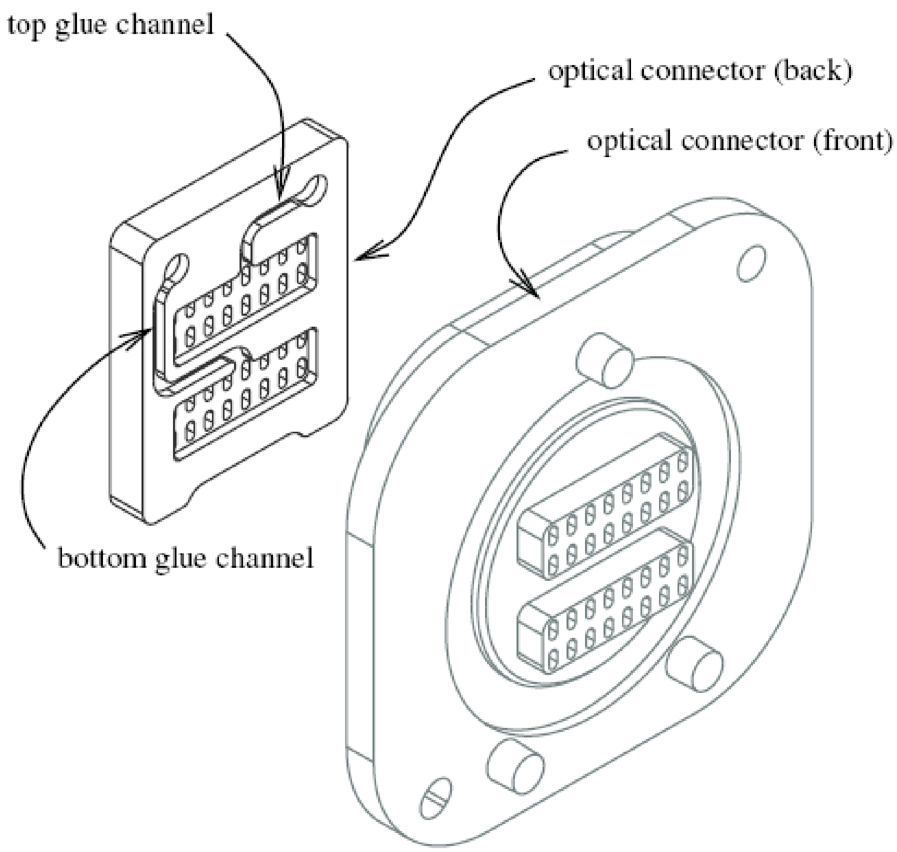

Fig. 13.22: Exploded view of an optical connector.

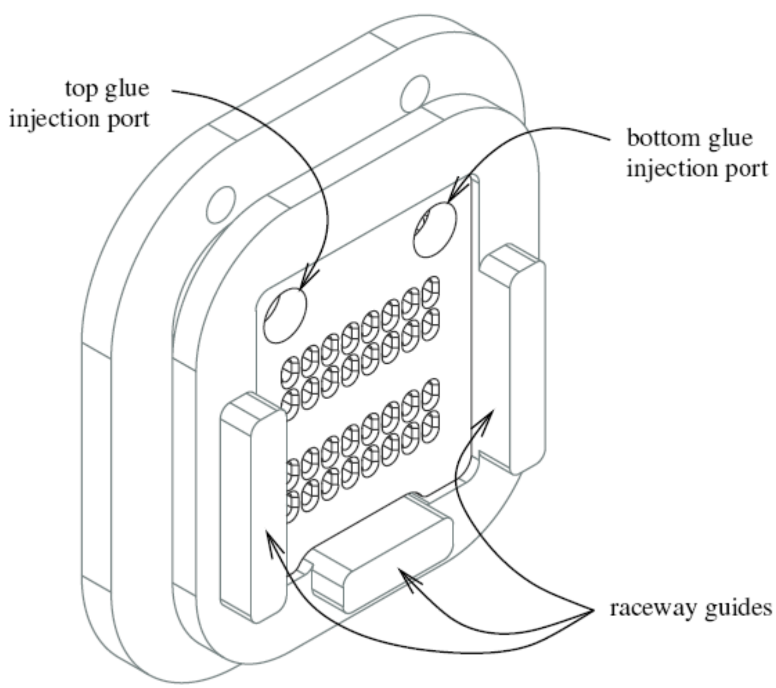

Fig. 13.23: Side of the optical connector that receives fibers in the snout.

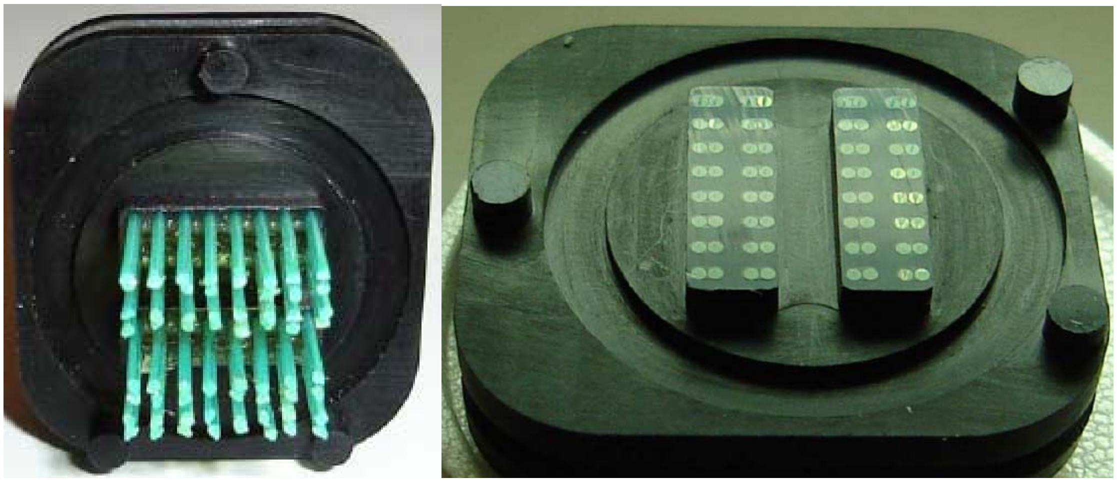

Fig. 13.24: A prototype optical connector with wavelength shifting fibers potted with glue both before and after fly cutting.

13.4 PVC Module Factories

13.4.1 Introduction

PVC modules will be assembled at two module factories, the extrusion assembly factory and the module assembly factory.

The extrusion assembly factory is motivated by a requirement that every individual PVC module used at Ash River be inspected and tested before becoming part of the unique, five-story high, 18 kiloton PVC structure. The 16 cell PVC extrusions arrive at the extrusion assembly factory located at Fermilab where they are inspected for quality, tested for structural properties, sorted by thickness so that the Ash River plane to plane adhesive layer will be consistently strong, and then glued together to make 32 cell module assemblies. Assemblies are trimmed to a precise length before shipping to the module assembly factory at the University of Minnesota. The extrusion assembly factory also functions as a buffer for the module production processes. Fermilab stores the extrusions it receives from the manufacturer and ships them to the module assembly factory as needed.

The module assembly factory is located at the University of Minnesota. There the wavelength shifting fibers are inserted, the module sealed and tested, and shipped to the far or near detector site as appropriate. The module assembly factory will produce 30 modules per day at production peak. The procedures for each of the factories are given below.

13.4.2 Extrusion Assembly Factory at Fermilab

The extrusion assembly factory receives the 16 cell extrusions and provides storage for them until they are needed. The raw extrusions will be unloaded from a truck and finished extrusion assemblies will be loaded to a truck using the same air caster system used at the extruder, Minnesota factory, and at the far detector. Stacks of raw extrusions and finished extrusion assemblies will also be moved within the factory using this air caster system. This factory tests each extrusion for compliance with mechanical and reflectivity specifications as well as internal cleanliness, assembles them into 32 cell extrusion assemblies, trims them to length, and abrades the ends. The extrusion assemblies are put in packages consisting of 2.5 planes which are shipped directly to the module assembly factory or stored until needed.

Although the detector installation must alternate a horizontal plane of extrusions with a vertical plane, the extrusion manufacturer produces many planes of horizontal extrusions before switching to vertical extrusions. The Fermilab factory and extrusion storage facility serves as a buffer to allow the module assembly factory at Minnesota to package two adjacent planes in a single shipment to the detector site. It also allows the installation to proceed at its maximum rate by matching the rate of the extrusion production with that of the assembly at the far detector site. The factory layout, based on the Fermilab Wideband Laboratory Building, is shown in Figure 13.25. A photograph of the building is shown in Figure 13.26. Additional storage is in other Fermilab buildings.

The assembly of two 16 cell extrusions into a 32 cell extrusion proceeds as follows and is shown by the sequence of arrows in Figure 13.25:

1. Unload a truck of 16 cell extrusions. An air caster system will be used to take the load off the truck and into the loading dock area;
2. Crane extrusion stacks to the floor of the Wideband Laboratory Building.
3. Use an air caster system to move the stack to the free standing crane area.
4. Remove packaging.
5. Use free standing crane to place extrusions in stacks sorted by thickness.
6. Inspect each extrusion for correct dimensional specifications, quality of extrusion webs, and shipping damage. Reject those that do not comply.
7. When 24 of the 16 cell extrusions of the same thickness exist, begin making 32 cell extrusion assemblies by using the free standing crane to lift 2 extrusions matched in thickness side by side onto a rolling table ;
8. Roll the table to the gluing area.
9. Crane the two extrusions from rolling table to one of three assembly tables.
10. Align one end of the extrusions;
11. The side of the table with one of the extrusions is hinged. It tilts down so that the edge of that extrusion is horizontal;
12. Apply a structural adhesive (e.g. Devcon Plastic Welder methacrylate adhesive) to the horizontal edge and rotate that side of the table so that the extrusions are again side by side.
13. Clamp the two extrusions together and allow the glue to cure (approximately 15 minutes);
14. Trim the ends of the assembly and save for structural analysis and reflectivity measurements;
15. Abrade ends of the assembly;
16. Scan the bar codes and enter assembly information into data base.
17. Stack extrusion assemblies into one stack until 30 (2.5 planes) are completed.
18. Package the stack for storage or shipping to module factory as needed.
19. Use dollies to roll empty pallet assembly to the overhead crane area and lift to loading dock.
20. Use air caster system to move completed stack to overhead crane area.
21. Lift stack to loading dock.
22. Put stack into truck going to storage or module assembly factory.

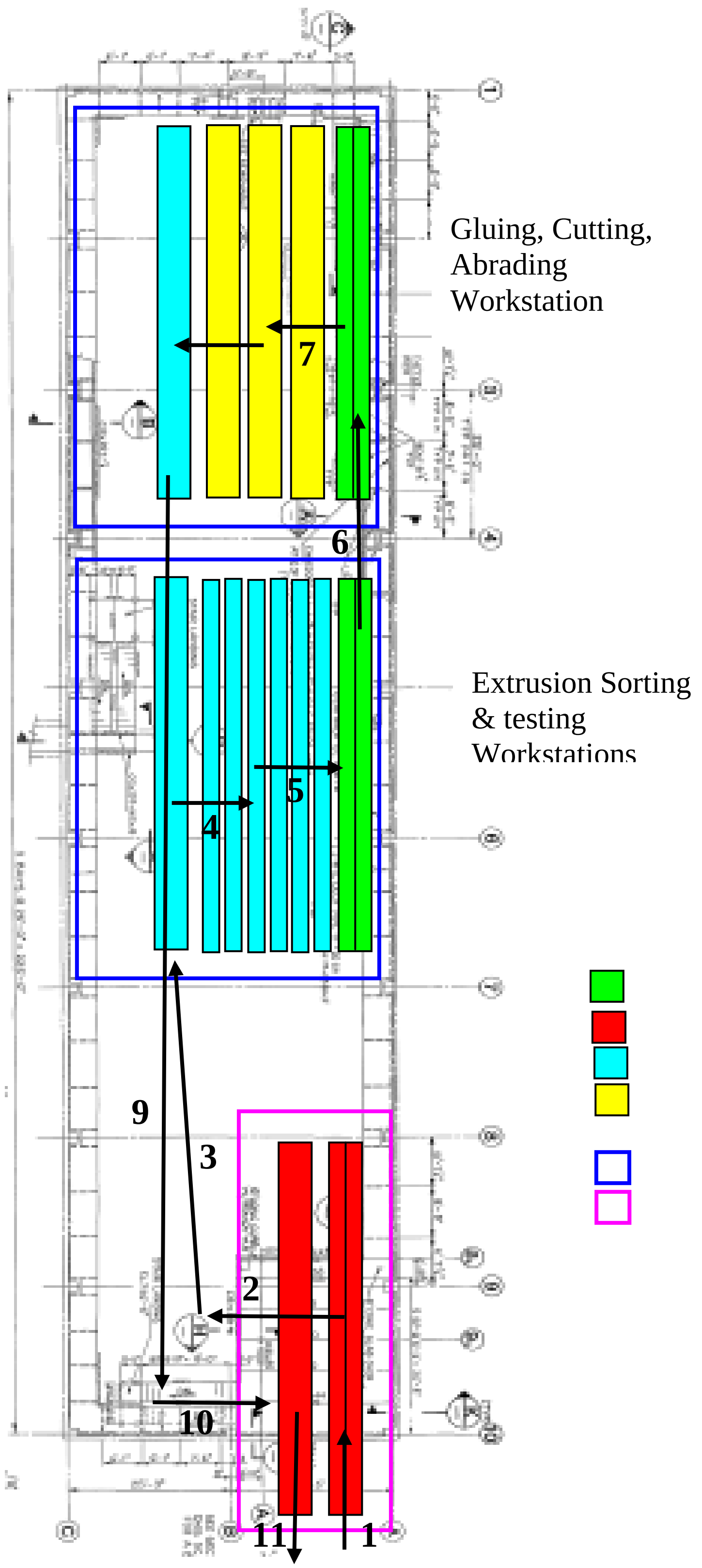

Fig. 13.25: Movement of extrusions through the extrusion assembly factory at the Fermilab Wideband Beam Laboratory. Increasing numbers show the flow of the extrusions.

Fig. 13.26: Photograph of Extrusion Assembly Factory at the Fermilab Wideband Laboratory. The red rolling door in the upper center of the picture is the location of the loading dock. The building has overhead crane coverage from two 15 ton cranes.

13.4.3 Quality Assurance of Extrusions at Extrusion Assembly Factory

The major components of a NOνA module will be tracked by entering their bar codes into a database using scanners. These data will allow the identification of unforeseen component or assembly procedure defects as the module is tested throughout its assembly. Such defective parts will then be removed from the inventory and defective procedures will be revised. This procedure begins at the extrusion manufacturer and the fiber test facility.

When each 16-cell extrusion arrives at the extrusion assembly factory it has been labeled and entered into the database at the extrusion manufacturer. The data for two 16-cell extrusions are linked when they are bonded into two 32-cell extrusion assemblies. Data from the glue batch are also added at this time.

Each extrusion arriving at the extrusion assembly factory will be visually inspected for damage that might have occurred during shipping. In addition the extrusion height, width, wall thickness, cell pitch, and web thickness will be measured to verify these are within tolerances and entered into the database. A visual inspection will also check the connection of each web to the body of the extrusion at the extrusion ends. Sections trimmed from extrusions will be tested for reflectivity and structural integrity to assure they meets specifications and the results from those tests will be entered into the database. To assure the structural integrity of the extrusions, a small sample from each extrusion run will be pressure tested to destruction. A small sample from between each 53 ft extrusion may also be pressure tested to destruction if a satisfactory technique for inspecting the full 53 feet of an extrusion cannot be developed.

13.4.4 Module Assembly Factory at Minnesota

The module assembly factory receives the extrusion assemblies, strings wavelength shifting fiber in each cell, threads the fiber through the manifold and into the optical connector, seals the cells and the optical connector, fly cuts the fibers in the optical connector, assures that the fibers are routed to the correct optical connector pixel and that no fibers are damaged, assures that the modules are leak tight, repackages the finished modules into a package of one vertical and one horizontal plane (24 per truck load), and ships the modules to the detector site for installation. Six such shipments will occur per week. Extrusions assemblies will be unloaded from a truck and finished modules will be loaded to a truck using the same air caster system used at the extruder, Fermilab factory, and at the far detector. Stacks of modules will also be moved within the factory using this air caster system. All glue joints that contact the liquid scintillator use a chemically inert epoxy adhesive (3M2216). When additional structural strength is needed, a methacrylate adhesive (e.g. Devcon Plastic Welder) is used. When both glues are used on a joint, the chemically inert adhesive is used in a butt joint as a gasket to seal the liquid scintillator from the structural adhesive. The factory layout, based on a currently available building, is shown in Figure 13.27. A scale model of the building and a photograph of the building is shown in Figure 13.28 and 13.29.

An overview of the assembly of a module is given below with the steps in logical, but not time order. The details are described later. Because of the time needed for the chemically inert epoxy to cure, the process to produce a module takes four calendar days. The throughput of the factory is 30 modules per day at its peak output.

1. Unload 32-cell extrusion assemblies from truck. An air caster system will be used to move the load off the truck and into one of the two receiving spaces in the factory. One crane bay will be used to receive and process vertical extrusions, the other for horizontal extrusions.
2. Inspect extrusion assemblies for possible shipping damage.
3. Use an overhead crane to lift extrusion assemblies from the stack of 30 modules to a gluing rack. Three inch spacers are placed between the modules to allow access for gluing of the module parts to the ends of the extrusion. Repeat to fill 4 gluing racks for a total of 30 extrusion assemblies.
4. The side and center seals for each end of the module are glued into place.
5. The fiber raceway assembly near the snout is attached to the center and side seals and manifold snout back half.
6. The manifold snout back half is glued in a butt joint to the extrusion assembly using a chemically inert epoxy adhesive. The optical connector has previously been glued into the snout half in a preassembly operation.
7. The glue is allowed to cure overnight.
8. Each of 30 extrusion assemblies that have already cured overnight is craned from a gluing stack onto a rolling table. The table is rolled to workstation part of the factory for fiber stringing, threading, and additional gluing.
9. The stringing machine is positioned at the first cell. Three stringing machines are used in parallel to process 10 modules each.
10. A shield tray is placed over the raceway to protect and support the fibers as they are strung.
11. A vacuum fitting covering all 32 cells is attached to the opposite end of the extrusion from the stringing machine.
12. Fibers are strung down the eight cells closest to the snout using the fiber stringing machine.
13. The first eight fibers are threaded through the raceway and snout while the next 8 cells are strung.
14. The last two steps are repeated for the remaining 24 fibers.
15. The vacuum fitting is removed.

16. The parachutes used to pull the fiber down the cells are removed.
17. The optical adapter is potted with chemically inert epoxy to seal the fibers in place.
18. The end plate is glued in a butt joint to the extrusion with the chemically inert glue.
19. The fibers in the snout are sealed with chemically inert epoxy by injecting glue into the snout sealing port.
20. The snout top half is glued in a butt joint to the extrusion using chemically inert epoxy.
21. The fill distribution tube is attached to the fill port on the snout.
22. The manifold cover is glued in a butt joint to the extrusion using chemically inert epoxy.
23. The joints in the manifold covers are injected with chemically inert epoxy adhesive.
24. All joints using the chemically inert epoxy are allowed to cure overnight
25. Structural adhesive is injected between the sides of the end plate and the extrusion for modules for which the butt joint has already cured overnight.
26. Fiberglass mesh is glued to the extrusion edge to reinforce the end plate side seals.
27. Edge stiffeners are glued to the bottom outside edge for the 2 outside vertical modules in a plane.
28. Structural adhesive is injected between the sides of the manifold cover and the extrusion on modules for which the joint has already cured overnight.
29. Structural adhesive is injected between the sides of the snout and the extrusion for which the joint has already cured overnight.
30. The structural adhesive is allowed to cure for 12 minutes.
31. The optical adapter is faced to a suitable finish using the fiber facing machine.
32. The module is checked for damaged fibers using the continuity tester.
33. The module is rolled under the crane bay at the testing area.
34. Shipping spacers are placed on top of the previous module and the module is craned onto the top of the shipping stack.
35. The module is tested for leaks using the leak tester. If leaks are found, the module is removed and repaired.
36. Read bar code for the module and enter progress into the database.
37. Modules are packed for shipping and loaded onto the truck using the loading air caster system.

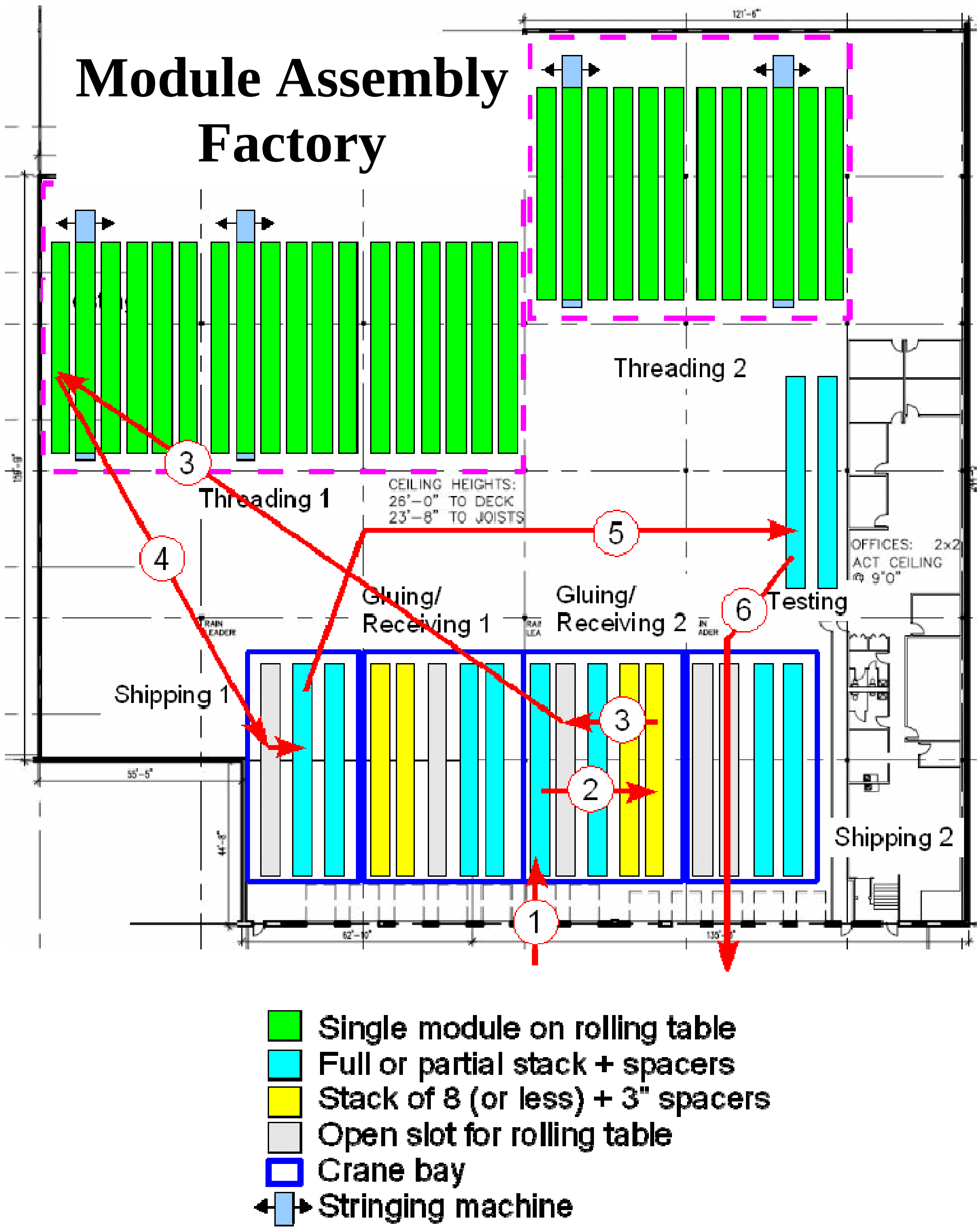

Fig. 13.27: Layout of the module assembly factory as it fits into a currently available space. The layout shows the two assembly areas outlined in blue and in pink. Moves of modules within the factory. 1) unloading from truck, 2) move to gluing platforms, 3) move to stringing/threading area, 4) move to shipping stacks, 5) move to testing area, 6) move to outgoing truck.

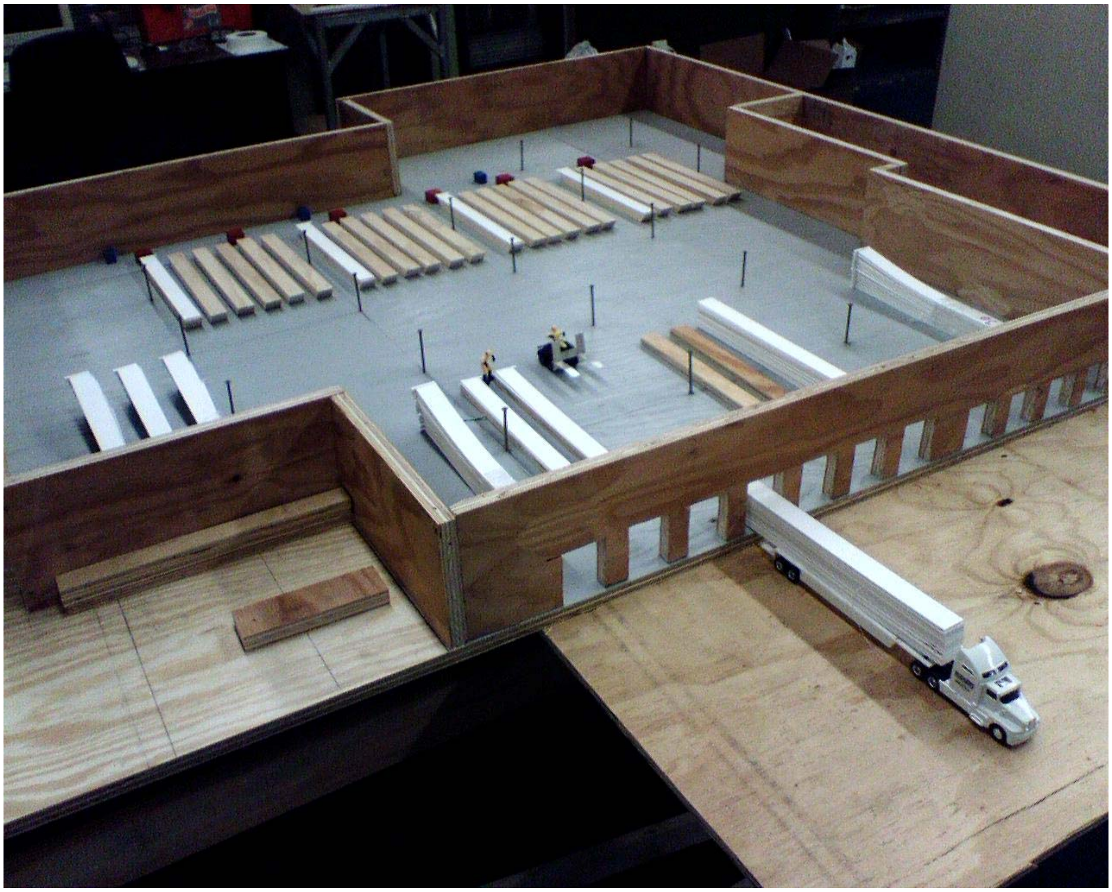

Fig. 13.28: A scale model of a typical factory space that is currently available. This model was used to develop some of the procedures in this document. The loading and unloading assembly area is near the loading docks as shown. The assembly area where individual modules are assembled is also shown. The long rectangles represent the modules.

Fig. 13.29: Picture of currently available warehouse space used as a template to design the module assembly layout. This space is typical of many such spaces near the University of Minnesota campus.

13.4.5 Quality Assurance at Module Factory

While producing modules, three crucial aspects of the detector will be continuously monitored: possible fiber damage, possible leaks, and glue quality. These quality assurance procedures are described in the next sections.

13.4.5.1 Quality Assurance of Fibers at Module Factory

The quality assurance procedures for the wavelength shifting fiber is designed to determine that the fiber was not damaged while in transit to the factory, to assure that the fiber was not damaged during module construction, check that all fibers were routed to the correct APD pixel, and to discover if any fiber damage occurred during shipping to the detector site.

Fiber arrives at the module assembly factory on 1 meter diameter spools (approximately 2 km of fiber on each spool). This fiber has already been tested to assure that it meets the required specifications and to check for shipping damage during shipping from the manufacturer. At the module assembly, a 10 meter sample from each spool will be tested for shipping damage. To do this, an attenuation measurement will be performed by looping the fiber around an aluminum cylinder with a machined groove (Figure 13.30). The fiber is illuminated at 20 locations in sequence by blue LED's. We obtain 20 amplitude measurements at .5 meter intervals along the 10 meter length. These data provide an attenuation measurement that will be compared to the previously measured performance of fiber from that spool.

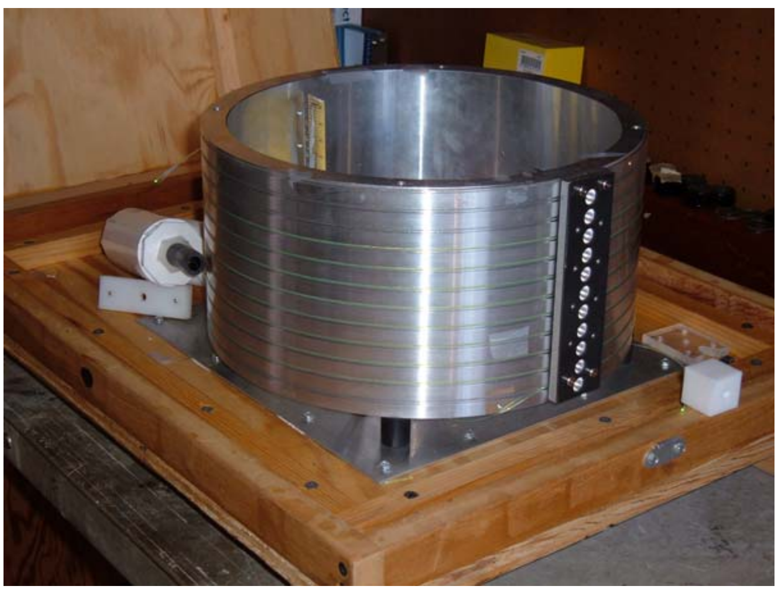

Fig. 13.30: Picture of light attenuation device.

The when fiber is strung through a cell, its spool is recorded by scanning its bar code. When the module is completed, each fiber is compared to that data to check for fiber damage. This procedure removes any lot-dependent variation in the post-fabrication attenuation checkout. This test is performed by injecting light from a blue LED into one end of the fiber loop through the optical connector and measuring the amplitude at the other end with a photo-diode. This will be a DC light amplitude measurement with the LED is illuminated for about 1 sec while a voltage measurement is performed on the photodiode circuit (Figure 13.31). The reproducibility of attenuation measurements on fiber is at the 3% level (Figure 13.32).

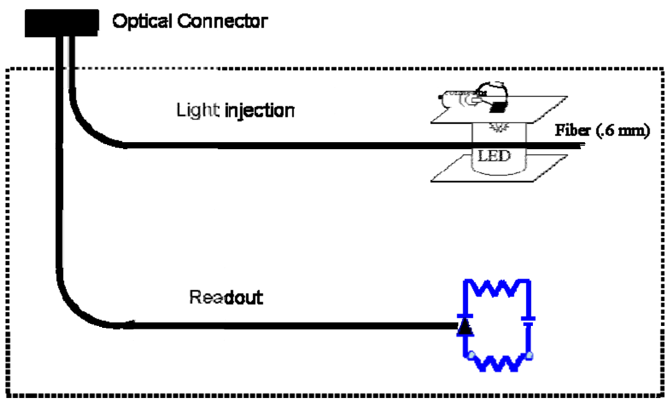

Fig. 13.31: Diagram of the light continuity machine showing integrating sphere for light injection (LED) and photodiode readout circuit (voltage measured across lower resistor indicates light output).

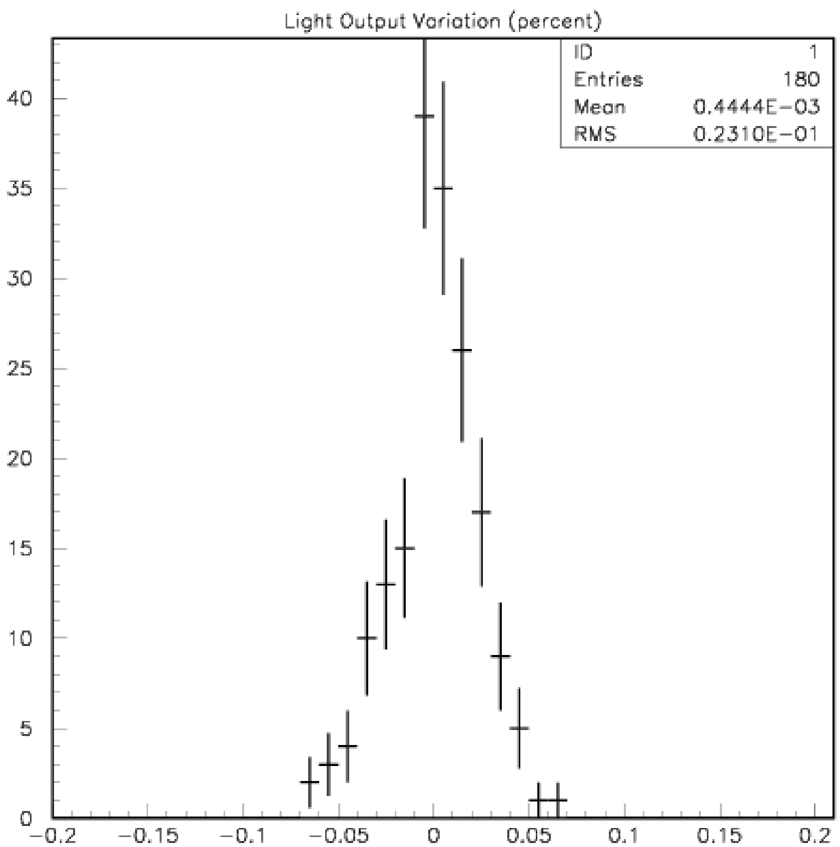

Fig. 13.32: Light output measurement variation on an undamaged fiber.

In order to simulate possible fiber damage, we have bent fiber beyond its recommended minimum bend radius and compared to pre-calibration data. Only a small (<1%) light loss was observed while the fiber was bent but recovered upon relaxation of the fiber. When the fiber is damaged by a kink, it shows a light loss that is large compared to the measurement accuracy (Figure 13.33) that does not recover even if the kink is straightened. There are irregularities (slight bulges in the fiber) intrinsic to the manufacturing process but their occurrence is low. The light loss associated with these is significantly less than damaged fiber.

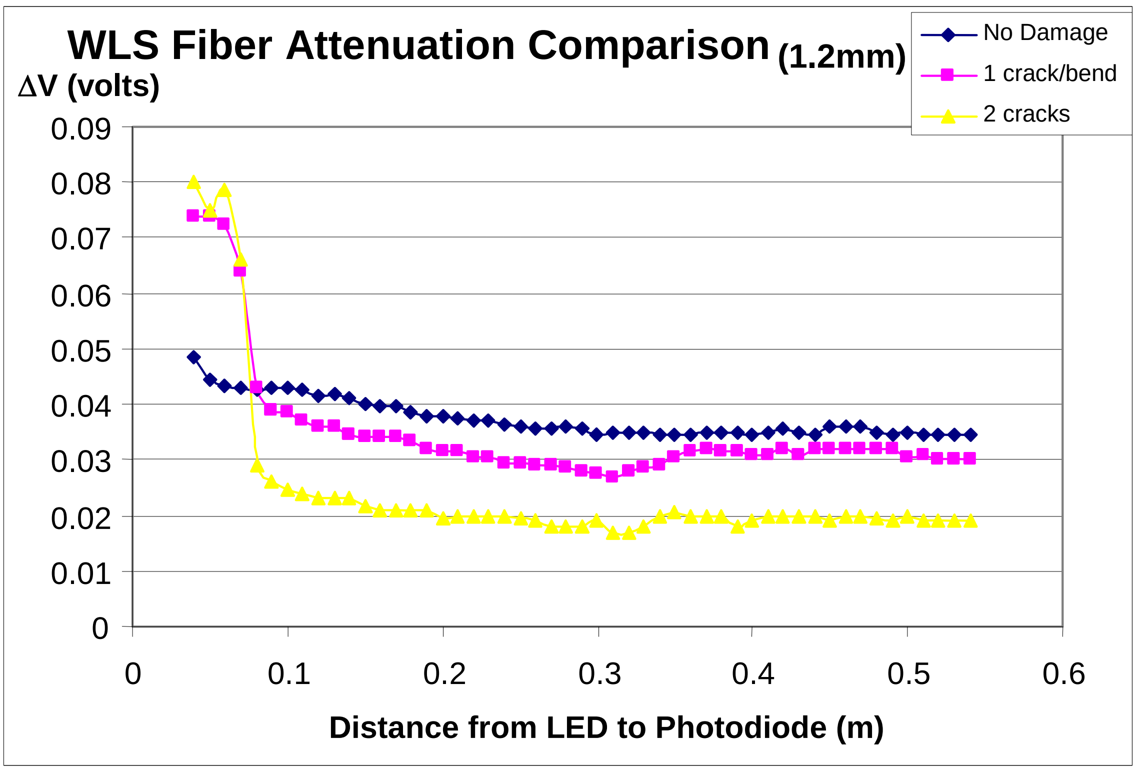

Fig. 13.33: Light out put as function of distance in fiber. Blue is for undamaged fiber, magenta is for fiber with one kink, and yellow is for fiber with two kinks.

Upon completion of the fiber continuity checkout, the data for each cell will be recorded in a database which can be used as the initial cell calibration. The fiber continuity test is repeated at the detector site with an identical device to check for damage in shipping.

13.4.5.2 Quality Assurance of Modules Against Leaks at Module Factory

Since the modules will hold the liquid scintillator without leaking, every assembled module will be tested to assure no leaks occur. This QA leak test will be performed when the module assembly is complete before it is shipped to the detector site and prior to installation at the detector site. Tests, given below, show that leaks that occur from assembly flaws are reasonably large and can be detected using a simple bubble bottle arrangement shown in Figure 13.34 which measures air flow through the modules pressurized to 20 psi, slightly above their operating pressure. Leaks below the level of sensitivity of this device have not been detected in our more sensitive florescent dye tests. This allows us to set an upper limit on the leak rate of the detector for modules that pass the QA procedure.

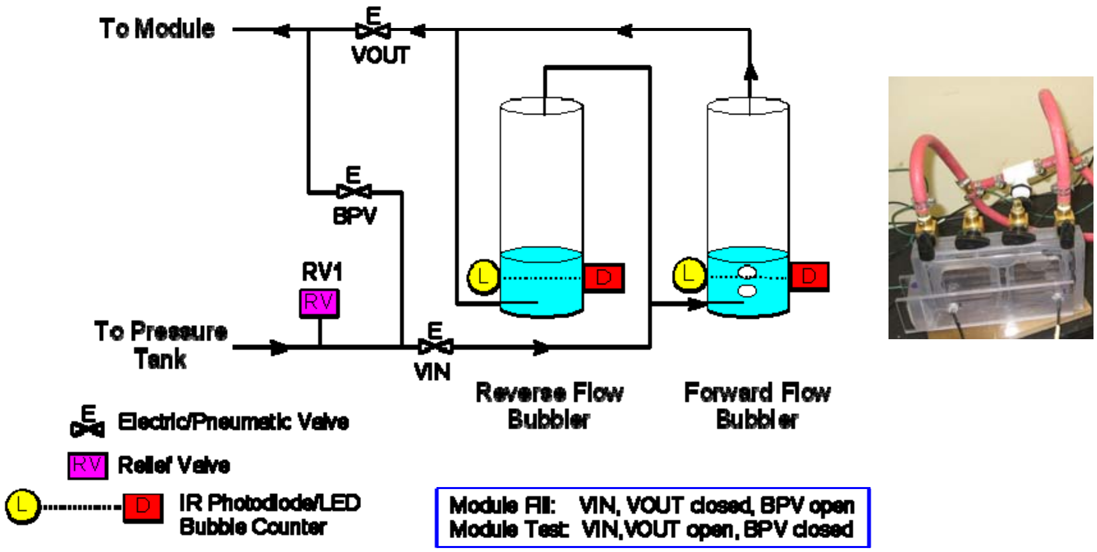

Fig. 13.34: A bubbling apparatus designed to check completed modules for leaks. Also shown is a picture of the bubble bottle.

The occurrence of a very small leak in a glue joint was investigated using short samples of the extrusion modules which were filled with water containing a fluorescent dye, a standard industry test to reveal very small leaks. These test modules were pressurized to 10 psi with compressed air. Their joints are examined periodically under ultraviolet light to look for evidence of the fluorescence as shown in Figure 13.35. Fluorescence down to an integrated leak volume from any single leak of 0.02 cubic centimeters of water can be detected by a trained observer as shown in Figure 13.36.

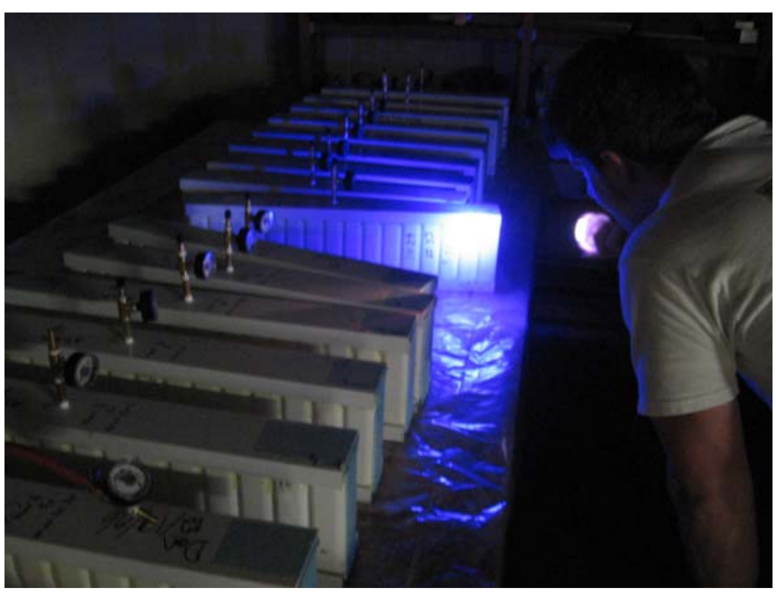

Fig. 13.35: Inspecting the test joints for the fluorescence that would indicate a leak

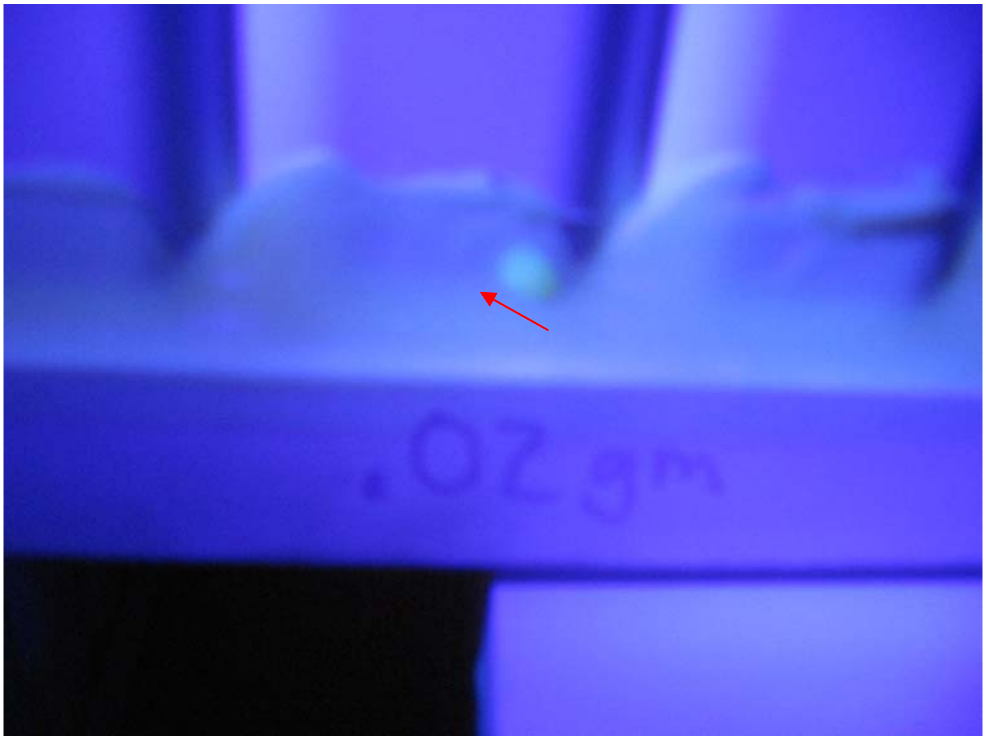

Fig. 13.36: The bright spot (indicated by the red arrow) shows 0.02 cc's of water (0.02 grams) with fluorescent dye placed at the glue joint of a test module. This is the smallest leak that can be consistently detected with this technique.

Thus far no leaks have been observed for 57 sixteen cell test modules for an average time of 90 days. Each of these 57 modules represent ½ the liquid seal length of a vertical module and ¼ that of a horizontal module which has both ends exposed to the liquid. Assuming that leaks flow at a constant rate, this gives a leak rate that is below 0.01 grams/ (1710 test modules each day). The detector has approximately 7500 vertical modules and 7500 horizontal modules. Assuming that the leak probability is proportional to the glue joint length, the maximum leak rate is 2.6×10^{-3} cc/vertical module/year and 0.5×10^{-2} cc/horizontal module/year. For the entire detector the leak rate has an upper limit of 0.1 liters/year, a negligible amount.

During the initial testing of glue joints for the test modules, 12 leaks were observed from a loss of pressure using a 1% accurate pressure gauge. Nine of the 12 leaks were very large with at least a 2 psi drop in 12 hours. The smallest leak found had a pressure loss of 2 psi in two days. All leaks were located using the standard soap bubble technique and repaired. The repaired modules were included in the sample of 57 in which no leaks have been observed using the fluorescent dye technique. This small sample of leaks gives information about the necessary precision of the leak QA procedure. A calibrated 6 micron hole in one of the test modules under the same conditions of 10 psi pressure gave a pressure drop of 0.5 psi in 22 hours or about 0.5 the rate of our smallest detected leak. Since the leak rate is proportional to the square of the hole diameter, this is equivalent to a 9 micron hole. Thus if our QA sensitivity can detect leaks below the 9 microns level, the probability of having any leak is small and an estimate of the upper limit for leaks is on the order of 0.2 liter/yr.

To determine the sensitivity of the bubble bottle technique, two 16 cell full length extrusions were tested. One had no leak and one was given a calibrated 6 micron leak. Figure 13.37 gives the integrated number of bubbles as a function of time for the module with no detectable leak. The time scale has an arbitrary zero but starts within a few minutes of it being pressurized to 20 psi. After about 2.5 hours, the bubble count essentially stopped. During this initial time the cells in the module are expanding under pressure causing the volume to change. The integrated bubble count in 7 hours after the initial few minute turn on was approximately 300 bubbles. By contrast, the module with the 6 micron leak, Figure 13.38, shows a bubble rate that is still increasing after 7 hours. The integrated bubble count 7 hours after the initial few minute turn on was approximately 500 bubbles. The bubble bottle QA method has sufficient precision to detect the types of leaks that occur from assembly flaws. The current plan has a QA leak test integrated over approximately 12 hours. Over this time scale both the atmospheric pressure and the factory temperature change sufficiently to cause fluctuations in the bubble count. Nevertheless the large qualitative difference in response between a module with a leak larger than 6 microns and one with no leaks remains.

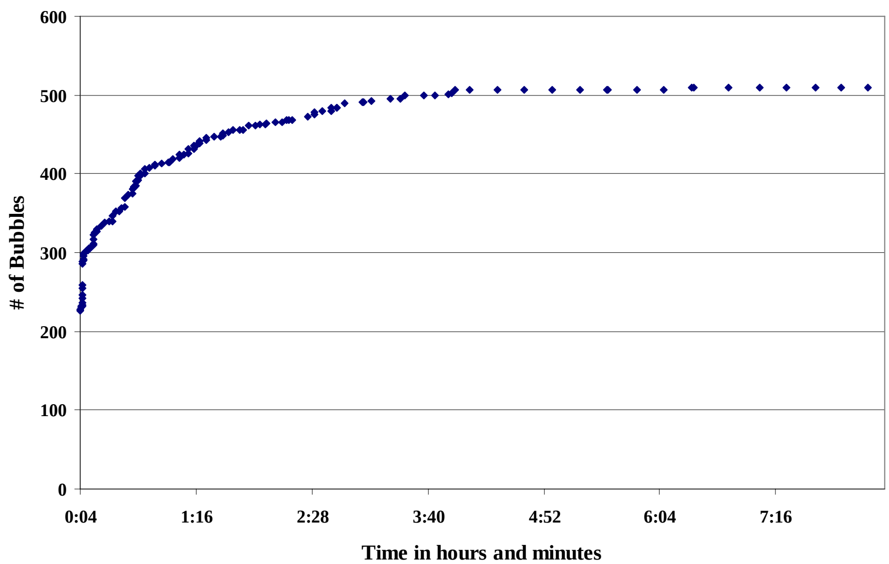

Fig. 13.37: Integrated number of bubbles as a function of time for a full length 16 cell module with no detectable leak.

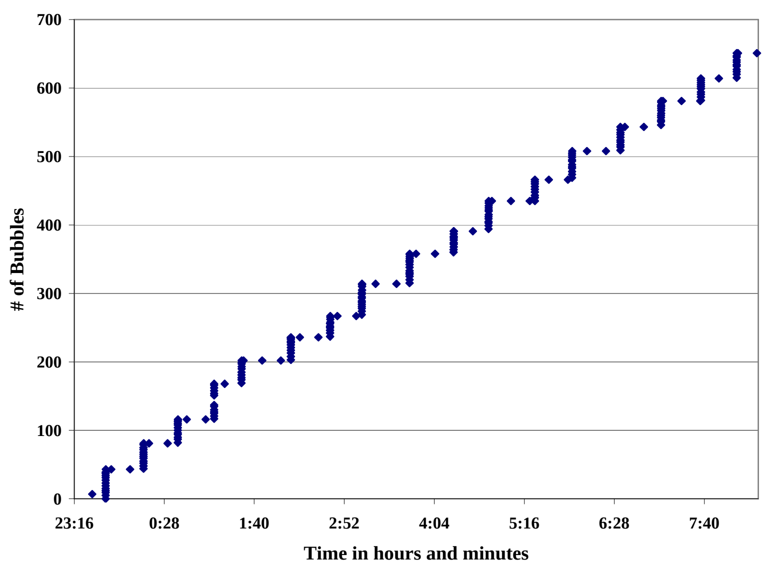

Fig. 13.38: Integrated number of bubbles as a function of time for a full length 16 cell module with a 6 micron calibrated leak.

13.4.5.3 Quality Assurance of Glue at Module Factory

During module construction, samples of the glue used in each joint will be saved. That glue will be examined after its fixture time has elapsed (15 minutes for the structural adhesive and 12 hours for the chemical inert epoxy) to assure that it has been mixed properly and has cured according to specifications. Each sample will also be tested after its full cure time has elapsed, 1 day for the structural adhesive and 7 days for the chemically inert epoxy. In addition each batch of glue (typically a 55 gallon drum) will be tested for its adhesive strength with the PVC used in the modules in tension, shear, and cleavage peel as shown in Figure 13.39. These tests will also allow each glue joint to fully cure before force is applied. These tests will be compared to the current results given in Figure 13.40.

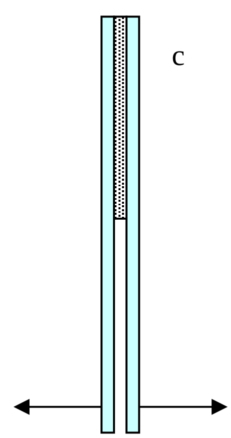

Figure 13.39: Configurations to test different components of stress on glue joints. PVC is light blue and glue is the black dotted volume. The arrows show the directions of the applied forces. (a) tests the glue joint in tension, (b) in shear, and (c) in cleavage peel.

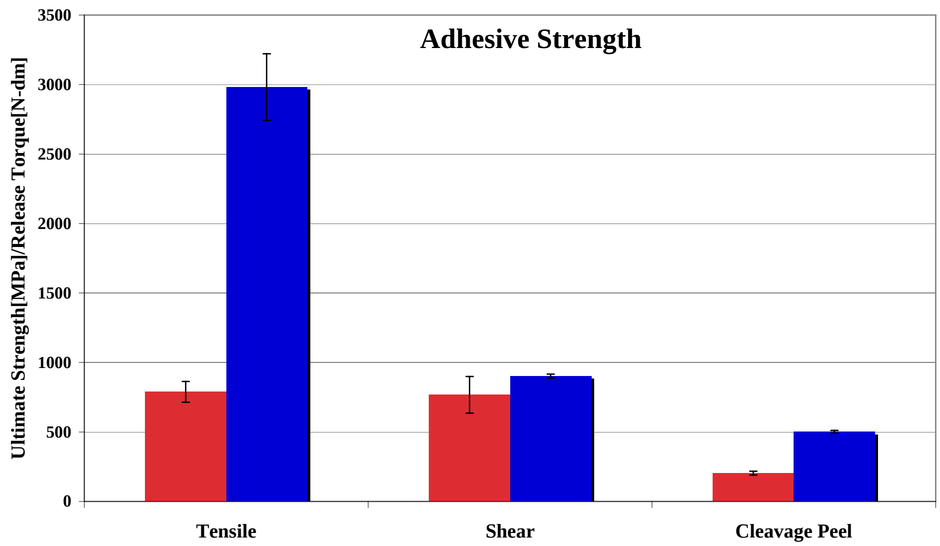

Fig. 13.40: The adhesive strength of 3M2216 gray (the chemically inert epoxy in red) and Devcon Plastic Welder (the structural adhesive in blue), the glues used in the construction of extrusion modules. The 3M2216 is tested with a roughened PVC surface. Tension and shear are given in Mega Pascal and cleavage peel is in Newton decimeters.

Prototype modules were pressure tested to destruction and the structural failures examined. Joints with 3M 2216 alone failed at 380 KPa or better. The maximum pressure in actual service is 130 MPa. Therefore, modules made with 3M 2216 alone would be expected to have a factor of safety of approximately 3. However all 3M 2216 joints will be reinforced with Plastic Welder. The failure of the 3M 2216 joints appeared to be due to cleavage peel at the side seals.

Joints prototyped with Plastic Welder were able to withstand pressures of 830 KPa, the maximum capacity of the available compressor, without failure. Figure 13.40 shows that the cleavage peel strength of Plastic Welder is approximately double that of 3M 2216. Since the actual modules utilize Plastic Welder as the structural adhesive, this gives a safety factor of approximately 6 for the glue joints. Joints made with a combination of the glues and tested to destruction did have the strength expected.

Due to tolerances in the extrusions, gaps may develop in adhesive joints at the end plate and manifold. The module parts are designed to produce gaps no lower than 0.5 mm, as adhesives strengths can for smaller gaps. The largest gaps may be on the order of 4 mm. Therefore, the strength of the module adhesives were tested for ranges of gaps from 0.5 mm to 4 mm. The results show that the adhesive strength provided by the combination of glues is adequate over the entire range of gaps expected in NOνA modules. In the worst case, the shear strength of 3M 2216 epoxy drops approximately linearly with gap thickness. Its strength at 4 mm thickness is approximately 50% of its strength at 0.5 mm thickness. Plastic Welder strength drops about 20% as the gap increases to 4 mm. As the factor of safety for the adhesives is approximately 6, the reduction in shear strength for larger gaps does not threaten module integrity. This range of gaps does not affect the tensile strength or the cleavage peel strength of the Plastic Welder.

Tests were also performed to determine the effect of the scintillator used in this detector on the glue joints. Specimens of the variety illustrated in Figure 13.39 were soaked scintillator and tested after 2 days, 7 days, 21 days, and 65 days. Glue thicknesses were 0.5 mm for shear and cleavage peel and 1 mm for tension. The temperature was elevated to 49° C during soaking to accelerated aging. For example, 65 days at 49° C approximates aging for 1-2 years at room temperature. For 3M2216, the glue strength appears not to be affected by the scinitillator. The specimens soaked in scintillator behave similarly to those soaked in plain mineral oil. For Plastic Welder, the results are similar for shear or tensile strength. However, there may be a small decrease in cleavage peel, which is currently not statistically significant at this time. It should be noted that the Plastic Welder isolated from the scintillator in the detector by the 3M2216. These lifetime tests are continuing.

13.4.6 Extrusion Assembly Factory Procedure and Rate

This factory receives extrusions as they are produced by the manufacturer and outputs extrusion assemblies at the rate needed to assemble the detectors. The maximum output rate of this factory is determined by the most time consuming task, the construction and packaging of the 32 cell extrusion assembly. The major assembly actions and their times are given below in rounded up person minutes per extrusion assembly:

Moving extrusions for gluing	33 minutes	(estimate)
Packaging, loading truck	21 minutes	(estimate)
Unloading truck to work area	19 minutes	(estimate)
Sorting extrusions by thickness	17 minutes	(estimate)
QA inspection	13 minutes	(estimate)
Roughening	12 minutes	(time and motion studies)
Gluing & trimming	11 minutes	(time and motion studies)

Based on time and motion studies, a single extrusion assembly will take approximately 60 minutes to complete the gluing and roughening operations.   This allows about 8 extrusion assemblies to be completed per shift for each assembly table using the procedure outlined in section 13.4.2. Four assembly tables will allow the extrusion assembly factory to match the output rate of the module assembly factory.

The module factory is organized around two major work areas shown in Figure 13.25. The numbers indicate the flow through the building. The both have free standing crane coverage to quickly move single extrusions and extrusion assemblies. The slower building overhead crane is used to move stacks of 30 extrusion assemblies or 60 extrusions to and from the loading area. In the sorting area, extrusions are sorted into four thickness classifications. Each 2 of the sixty 16 cell extrusions of the same thickness are then taken on an assembly table to the extrusion assembly area be glued together to make the thirty 32 cell extrusion assemblies of two and a half detector planes. These assemblies are then trimmed to a common length and abraded on their ends to prepare them for the module assembly factory. They are then packaged, taken out of the building and stored until needed by the module assembly factory.

An assembly table, shown in Figure 13.41, is 16 m long and 2 m wide. The width of the table top is divided in half so that it can swing from a horizontal to a vertical orientation. This allows the glue to be applied horizontally along the edge of one of the extrusions. Then the table top on which this extrusion is attached is swung up so that the 2 extrusions can be pushed together. The table has fittings to align the two extrusions and hold them in place. It also has clamps to push the extrusions together and hold them while the structural adhesive cures sufficiently. A structural adhesive dispenser and trimming saw are shared between two tables.

A detailed breakdown of the labor required to go from sixty 16 cell extrusions to thirty 32 cell extrusion assemblies in the factory is given in Tables 13.1 – 13.12

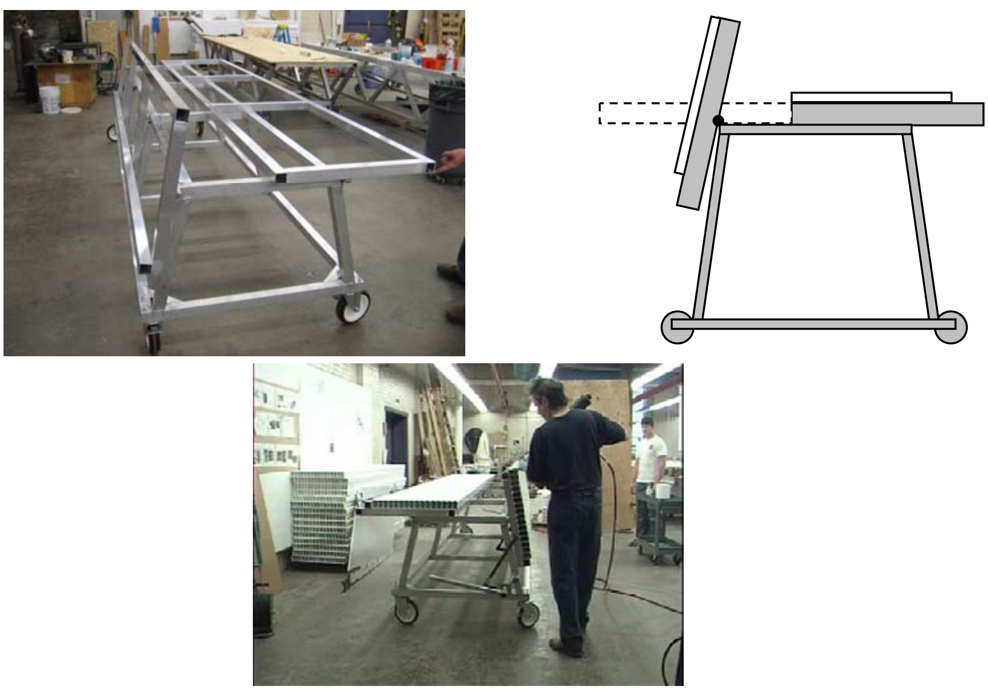

Fig. 13.41: Table used to combine two 16 cell extrusions into a 32 cell extrusion assembly. The 2 extrusions are shown in white on the drawing.

	Min/ Module	People	
Place dock plate	0.67	2	Estimate
Place air casters and connect tow device	0.33	3	Estimate
Float load_onto building loading dock platform	0.70	3	Estimate
Lower and remove air casters	0.37	3	Estimate
Total Time/ Module	**2.1**		
Total Labor/ Module	**5.5**		

Table 13.1: Unload the raw extrusions at the storage area.

	Min/ Module	Durat	People	
Place dock plate.	0.07	2	1	Estimate
Inspect and sweep truck bed	0.10	3	2	Estimate
Place overlay sheets on truck and over dock plate	0.17	5	2	Estimate
Scan stack bar code and enter in database	0.33	10	1	Estimate
Place air casters and connect tow device	0.33	10	2	Estimate
Float load to loading dock and onto truck	1.03	31	3	Estimate
Lower and remove air casters	0.37	11	3	Estimate
Update database to indicate load destination	0.03	1	1	Estimate
Drive to assembly building	0.50	15	1	Estimate
Total Time/ Module	**2.9**			
Total Labor/ Module	**6.3**			

Table 13.2: Load raw extrusions onto truck from storage facility to extrusion assembly building

	Min/ Module	People	
Place dock plate	0.67	2	Estimate
Place air casters and connect tow device	0.33	3	Estimate
Float load_onto building loading dock platform	0.70	3	Estimate
Lower and remove air casters	0.37	3	Estimate
Total Time/ Module	**2.1**		
Total Labor/ Module	**5.5**		

Table 13.3: Unload the raw extrusions at the assembly building.

Connect the crane rigging to the load	0.43	2	Estimate
Lift the load to clear platform wall	0.33	2	Estimate
Move load above landing area	0.33	2	Estimate
Lower load into pit	0.47	2	Estimate
Remove rigging from load	0.27	2	Estimate
Total Time/ Module	**1.8**		
Total Labor/ Module	**3.7**		

Table 13.4: Lower extrusions to ground floor

	Min/ Module	**People**	
Place air casters and connect tow device	0.33	3	Estimate
Float load to sorting area	0.47	3	Estimate
Lower load and remove air casters	0.37	3	Estimate
Remove protective packaging	0.67	1	Estimate
Total Time/ Module	**1.8**		
Total Labor/ Module	**4.2**		

Table 13.5: Move extrusion stack to sorting area

	Min/Module	**People**	
Scan the bar code on the top extrusion of the incoming stack	0.1	1	Estimate
Inspect extrusion obvious damage and enter in database	0.7	1	Estimate
Inspect webs for defects and enter in database	5	2	Estimate
Measure the thickness, width, length of the extrusion and enter in database	2.5	2	Estimate
Tag extrusion with a color to indicate thickness category	0.3	1	Estimate
Crane extrusion to proper thickness stack	7	2	Estimate
Remove empty shipping pallet when incoming stack is depleted	0.17	2	Estimate
Total Time/ Module	**15.8**		
Total Labor/ Module	**30.4**		

Table 13.6: Inspect, measure, and sort extrusions. The procedures for step 3 are not yet settled, so this step has more uncertainty than the others.

	Min/Module	People	
Roll empty table into sorting crane bay	3	2	Measured
Crane 2 extrusions from 1 sorted stack to the rolling table	7	2	Estimate
Roll table to assembly crane bay	3	2	Measured
Crane extrusions from the rolling table to gluing table	3.5	2	Estimate
Total Time/ Module	**16.5**		
Total Labor/Module	**33.0**		

Table 13.7: Transfer 2 extrusions to assembly area

	Min/Module	People	
Lower one side of gluing table	0.5	1	Measured
Apply structural adhesive to edge tilted extrusion	7	1	Measured
Raise the side of gluing table, latching it in the flat position	0.5	1	Measured
Clamp modules together	0.5	1	Measured
Allow glue to cure	15	0	
Total Time/ Module	**23.5**		
Total Labor/ Module	**8.5**		

Table 13.8: Glue two extrusions into a full-width extrusion assembly.

	Min/Module	People	
Trim one end of extrusion assembly to length	1.5	1	Measured
Roughen the last 1” of the outer surface	7	1	Measured
Roughen the insides of cells 1, 16, 17, and 32	5	1	Measured
Relax clamps	1	1	Measured
Crane to a stack of extrusions of the same thickness	4	2	Estimate
Total Time/ Module	**18.5**		
Total Labor/ Module	**22.5**		

Table 13.9: Cut extrusion assembly to length, roughen ends, and move to full plane stack.

	Min/ Module	People	
Identify bar codes with plane and enter in database	0.10	1	Measured
Place air casters and connect tow device	0.33	3	Estimate
Float load to pit shipping area	0.53	3	Estimate
Lower and remove air casters	0.37	3	Estimate
Package the plane	1.00	1	Estimate
Total Time/ Module	**2.3**		
Total Labor/ Module	**4.8**		

Table 13.10: Move completed stack to overhead crane area.

	Min/ Module	People	
Connect the crane rigging	0.43	2	Estimate
Lift to loading dock	0.47	2	Estimate
Move above loading dock platform	0.33	2	Estimate
Lower onto platform	0.33	2	Estimate
Remove rigging	0.27	2	Estimate
Total Time/ Module	**1.8**		
Total Labor/ Module	**3.7**		

Table 13.11: Lift stack to the loading dock.

	Min/ Module	People	
Place dock plate.	0.07	1	Estimate
Inspect and sweep truck bed	0.10	2	Estimate
Place overlay sheets on truck and over dock plate	0.17	2	Estimate
Scan stack bar code and enter in database	0.33	1	Estimate
Place air casters and connect tow device	0.33	2	Estimate
Float load to loading dock and onto truck	1.03	3	Estimate
Lower and remove air casters	0.37	3	Estimate
Update database to indicate load destination	0.03	3	Estimate
Total Time/ Module	**2.4**		
Total Labor/ Module	**5.9**		

Table 13.12: Load completed extrusion assemblies for shipment.

13.4.7 Module Assembly Factory Procedure and Rate

This factory receives extrusion assemblies from the Fermilab factory as they are needed to match the rate of detector assembly. To assure smooth operations, the factory will be able to store up to 1 month of extrusion assemblies or finished modules as a buffer against shipping disruptions. The receiving, inspection, and storage tasks for the extrusion assemblies are asynchronous from the module assembly, packaging, and shipping to the detector sites. The output rate of this factory is matched to the peak detector installation rate of about 30 modules per day which results in six truckloads per week to the far detector site.

The module production process is primarily determined by the most time consuming processes in the assembly, the stringing of the fiber down each of the 32 cells, and the threading of the fiber through the manifold into the optical connector. Our time and motion studies have indicated that these two processes take about 75 minutes. Each module will take 3.9 person hours to assemble. This estimate is based on time and motion measurements for actions that make up 68% of the time. The major assembly actions and their times are given below in rounded up person minutes:

Gluing operations	75 minutes (79% time and motion measurement)
Stringing fibers	45 minutes (74% time and motion measurement)
Moving modules	45 minutes (36% time and motion measurement)
Threading fibers	30 minutes (time and motion measurement)
Flycutting	15 minutes (time and motion measurement)
Packaging and loading truck	10 minutes = 240 minutes/24 modules (estimate)
QA fiber mapping	6 minutes (time and motion measurement)
Unloading truck	6 minutes = 144 minutes/30 modules (estimate)
QA leak testing	1 minute (30% time and motion measurement)

The module factory is organized around 2 assembly areas as shown in Figure 13.27. The shipping and receiving area has crane coverage and is near a loading dock with at least 4 bays. In addition to receiving extrusion assemblies at the beginning of the process and shipping the finished modules at the end of the process, this area is used to distribute the extrusion assemblies to gluing racks and then to individual work tables at the beginning of the assembly process. It also combines the finished modules into stacks for testing and packaging at the end. The second area consists of rolling worktables of individual modules for stringing the fiber down the cells, threading the fiber through the manifolds, gluing the manifolds and end plates to the extrusions, and creating an optical surface on the fibers in the optical connector.

The factory will function for approximately 12 hours/day for 5 days/week and produce 30 modules/day. There is a great deal of flexibility in this schedule which is well suited to the student labor we will employ.

A given module takes 4 days to emerge fully assembled, tested, and packaged in a stack of 24 modules ready for shipping to the detector site. This allows for two overnight times in the assembly where the chemically inert epoxy is allowed sufficient time to cure and an overnight leak test. The following sections will follow a set of 30 modules through these four days through the factory.

13.4.7.1 Module Factory Flow Day 1

The flow of modules through the factory on their first day is illustrated by Figure 13.27 arrow 1 & 2. A typically day would have one stack of 30 raw extrusion assemblies left over from the previous day and one stack of 30 delivered that day. The rectangles are the length of an assembled module. The areas outlined in blue have crane coverage.

Fifteen extrusion assembles are removed from each stack of 30. They are lifted one by one by the crane and put into gluing racks which each hold 8 extrusion assemblies using a free standing crane such as shown in Figure 13.42. A gluing rack is shown in Figure 13.43. The side and center seals are glued into cells 1, 32, 16, and 17 on both ends of the extrusion. The bottom fiber raceway and the lower part of the manifold snout are also glued to the manifold end of the extrusion. These operations are shown in detail in Figures 13.44 – 13.46. This glue is the chemically inert epoxy. These extrusions then sit overnight for the glue to cure.

Only 13.2 person hours are needed to processes the modules on their first day. This will take only 3.2 hours of actual time so the time of delivery of the 30 modules during the day is not crucial. A detailed breakdown of the labor required for these 30 modules on their first day in the factory is given in Tables 13.13 – 13.16.

	Min/Module	People	
Glue optical adapter into the manifold snout lower half.	3	1	Estimate
Glue cures overnight	0	0	
Total time/module	**3.0**		
Total Labor/module	**3.0**		

Table 13.12: Manifold preassembly labor. This can be done anytime before the parts are needed.

	Min/Module	People	
Move air caster halves into truck & connect to pallets	0.5	3	Estimate
Float load on aircasters	0.3	3	Estimate
Pull load off truck into receiving area	0.7	3	Estimate
Lower load off aircasters	0.2	3	Estimate
Total Time/ Module	**1.7**		
Total Labor/ Module	**5.1**		

Table 13.13: Labor to unload the extrusion subassemblies from the truck. Time for the operation is estimated to be 48 minutes for 3 people to unload 24 extrusion assemblies.

	Min/Module	People	
Move 30 modules from stacks onto 4 gluing platforms.	4	2	Estimate
Total Time/ Module	**4**		
Total Labor/ Module	**8.0**		

Table 13.14: Labor to distribute the extrusions from the incoming stacks to the gluing platforms. The total time for this procedure is 96 minutes.

	Min/Module	People	
Place side seals & center seals in cells.	11	1	Measured
Snap the lower fiber raceway into the center & side seals.	1	1	Measured
Inject glue into the seals to make a leak-tight joint	2	1	Measured
Clean up runoff glue	1	1	Measured
Glue the manifold snout lower half to the extrusion	4	1	Measured
Glue cures overnight.	0	0	
Total Time/ Module	**19.0**		
Total Labor/ Module	**19.0**		

Table 13.15: Assembly steps for the side & center seals, the lower fiber raceway, and snout lower half.

Fig. 13.42: Commercial free-standing overhead crane system for module handling.

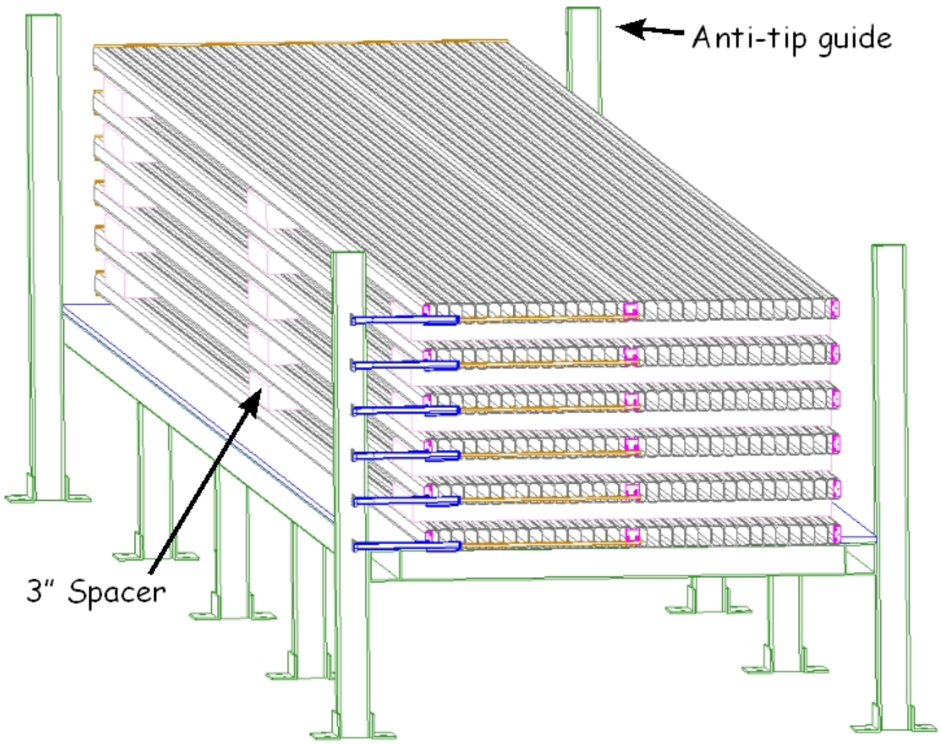

Fig. 13.43: Gluing rack for 8 modules. The center and side seals are glued into each end as is the lower fiber raceway and the lower half of the manifold snout assembly.

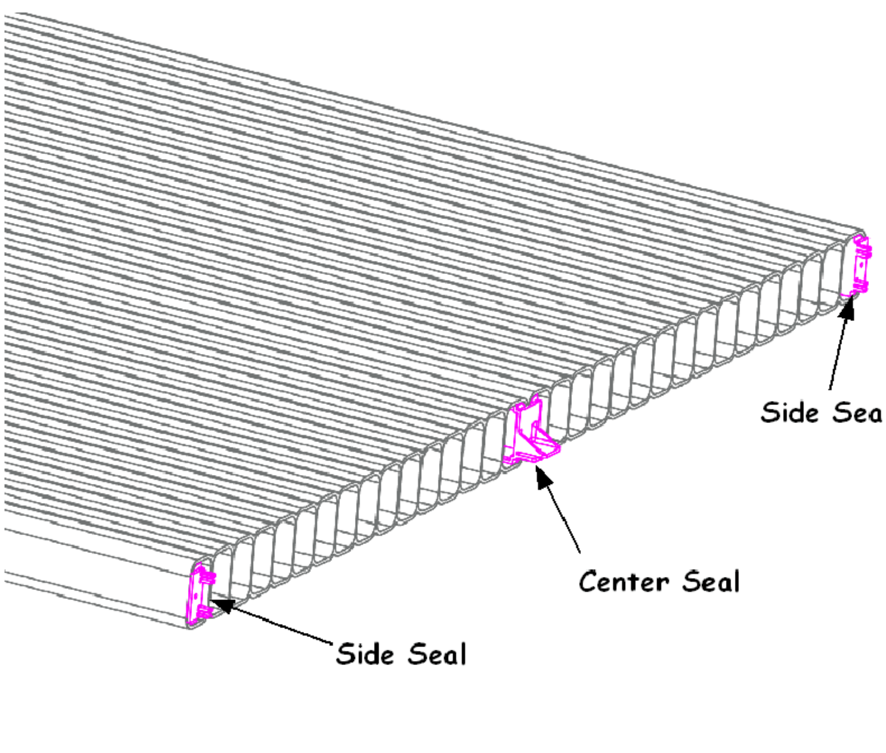

Fig. 13.44.: Assembly of side and center seals in the extrusion.

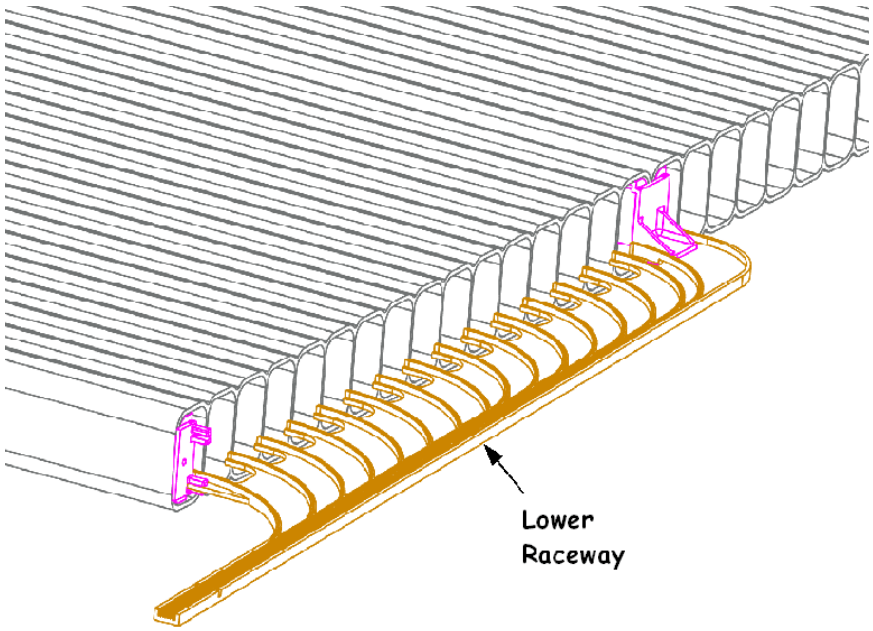

Fig. 13.45: Attachment of the lower fiber raceway to the module. This part snaps onto the center and side seals and references the center of the extrusion assembly through its connection to the center seal.

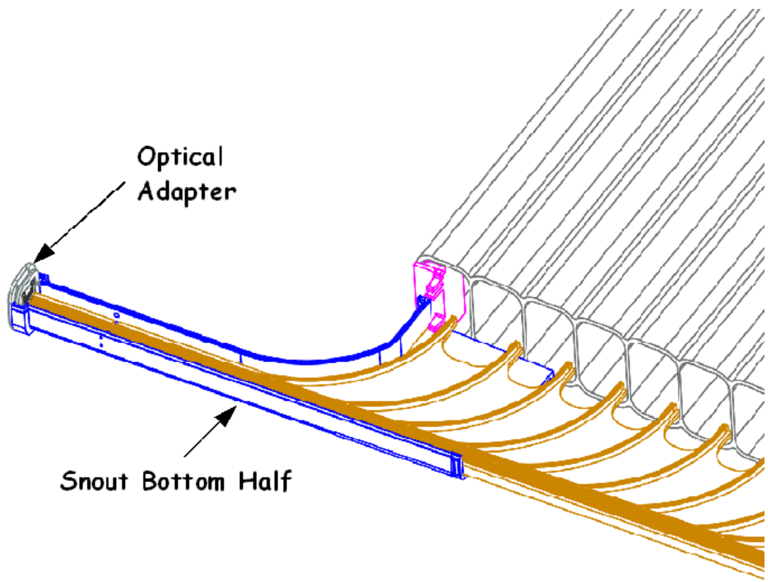

Fig. 13.46: Placement of the snout lower half on the module. The lower fiber raceway locates this part relative to the center of the extrusion assembly. The optical adapter has been preassembled on the snout lower half.

13.4.7.2 Module Factory Flow Day 2

The flow of modules through the factory on their second day is illustrated by Figure 13.27 arrow 3. The 30 extrusions that have cured on the 4 gluing racks overnight are now each craned on to a rolling table and that table is rolled to the worktable area. These modules replace those which are in their 3rd day of assembly and have been brought back to the crane coverage area for assembly into shipping stacks of 24 modules as shown in Figure 13.27 by arrow 4.

In the worktable area, the modules will have fibers strung into each cell, the fibers threaded through the manifold into the optical connector, the fibers glued into the optical connector, and the end plate and manifold glued into place. Three separate crews string and thread the modules using three stringing machines. The fiber stringing proceeds in groups of 8 cells. Once 8 cells are strung by one person, a second person threads these fibers through the raceway and into the optical connector. Meanwhile the first person strings the next 8 cells. A third person on each crew detached the vacuum adapter and fiber puller assembly and glues the end plate and manifold parts. These operations are shown in detail in Figures 13.47 – 13.57. The optical connector has been described in section 13.3.4. The glue used during this day is the chemically inert epoxy. These extrusions then sit overnight for the glue to cure.

As in day 1, most of the assembly is done by human hands. However, stringing the looped fiber rapidly down an extrusion cell without putting undue stress on the fiber requires a semi-automated machine described previously in section 13.3.4. A semi-automated glue dispenser assures the correct epoxy mixing and flow rate. A detailed breakdown of the labor required for these 30 modules on their second day in the factory is given in Tables 13.17 – 13.212.

	Min/Module	People	
Roll work table into crane bay from shipping bay.	3	2	Measured
Crane module from gluing platform to work table.	4	2	Estimate
Roll work table to stringing and threading station	3	2	Measured
Total Time/ Module	**10.0**		
Total Labor/ Module	**20.0**		

Table 13.17: Distribute the extrusions from the gluing platforms to the work tables.

	Min/Modul	People	
Position stringing machine at extrusion.	2	1	Estimate
Place shield tray over raceway of first eight cells	0.25	1	Estimate
Attach vacuum connector to other end of the extrusion	1	1	Estimate
Mount new spool of fiber on stringing machine if necessary	2	1	Estimate
String fiber for 1 cell: enter cell number, thread correct fiber length onto doubling wheel, attach retaining ring and parachute to fiber, pull parachute to cell, activate vacuum, cut fiber to correct length when strung.	1	1	Measured
String fiber for next 7 cells.	7	1	Measured
String fiber for next 3 sets of 8 cells	24	1	Measured
Remove vacuum fitting and parachutes for the module	6	1	Estimate
Total Time/Module	**43.3**		
Total Labor/ Module	**43.3**		

Table 13.18.: String fibers through the module cells.

	Minutes/Module	People	
Thread 32 fibers through manifold into optical connector in groups of 8.	30	1	Measured
Total Time/Module	**30.0**		
Total Labor/ Module	**30.0**		

Table 13.19: Thread fibers through fiber raceway and manifold snout into the optical connector.

	Min/Module	People	
Glue end plate to the extrusion with butt joint	11	1	Measured
Glue upper half of snout to extrusion, butt joint	2	1	Measured
Attach fill distribution tube.	3	1	Estimate
Glue mannifold cover to extrusion, butt joint	11	1	Measured
Inject manifold cover/snout joint with glue	4	1	Estimate
Glue cures overnight	0	0	
Total Time/Module	**31.0**		
Total Labor/Module	**31.0**		

Table 13.20: Glue end plate and manifold parts with chemically inert epoxy.

	Min/Module	People	
Pot fibers into optical adapter	2	1	Estimate
Inject glue into snout fiber seal	2	1	Estimate
Glue cures over night	0	0	
Total Time/ Module	**4.0**		
Total Labor/ Module	**4.0**		

Table 13.21: Pot fibers in the optical connector with chemically inert epoxy.

Fig. 13.47: Rolling a worktable with an extrusion assembly.

Fig. 13.48: Stringing machine operator preparing a fiber.

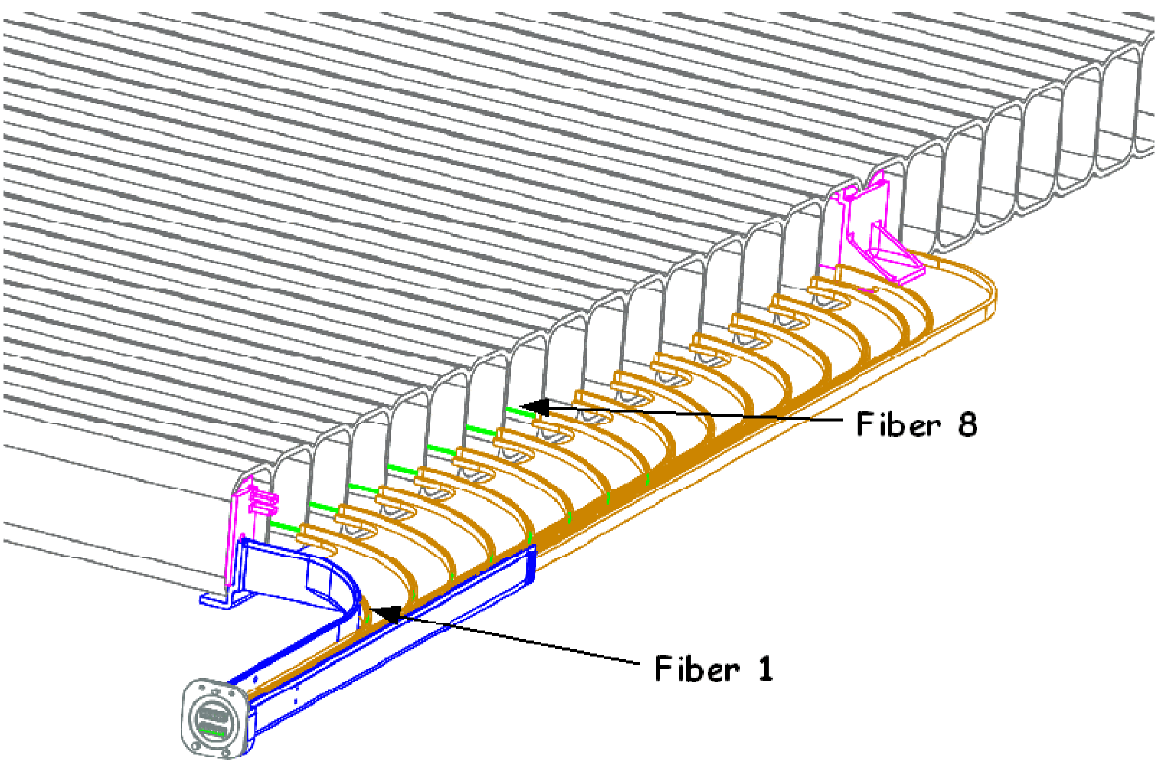

Fig. 11.49: Fibers 1-8 are strung down the cells and threaded through the lower raceway and snout.

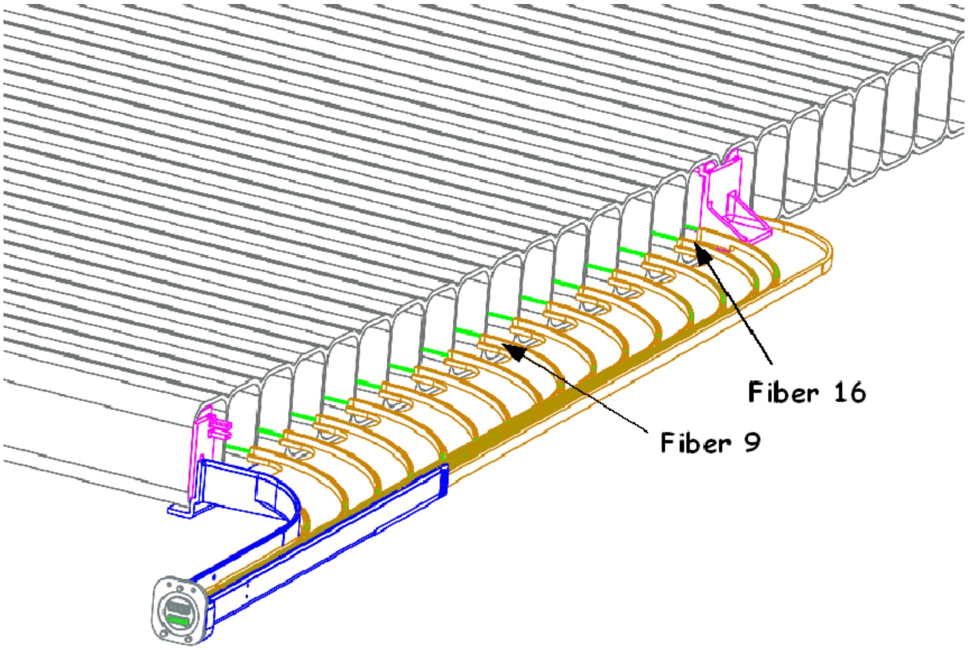

Fig. 13.50: Fibers 9 -16 are strung down the cells and threaded through the raceway and snout.

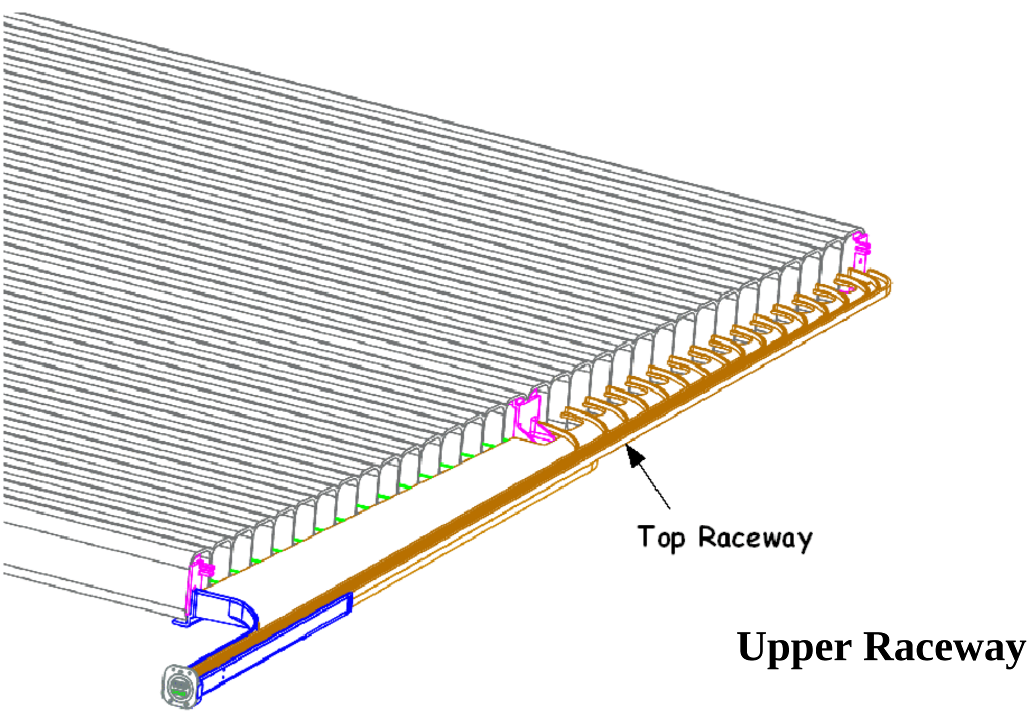

Fig. 13.51: The upper raceway is snapped in place over fibers 1-16 covering the lower raceway.

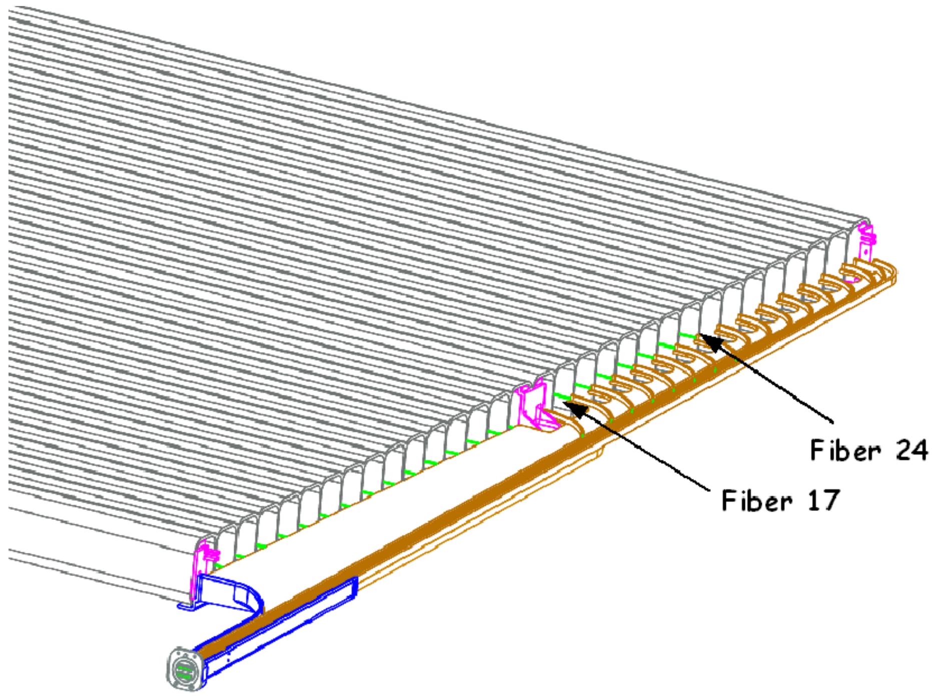

Fig. 13.52: Fibers 17-24 are strung down the cells and threaded through the upper raceway and snout.

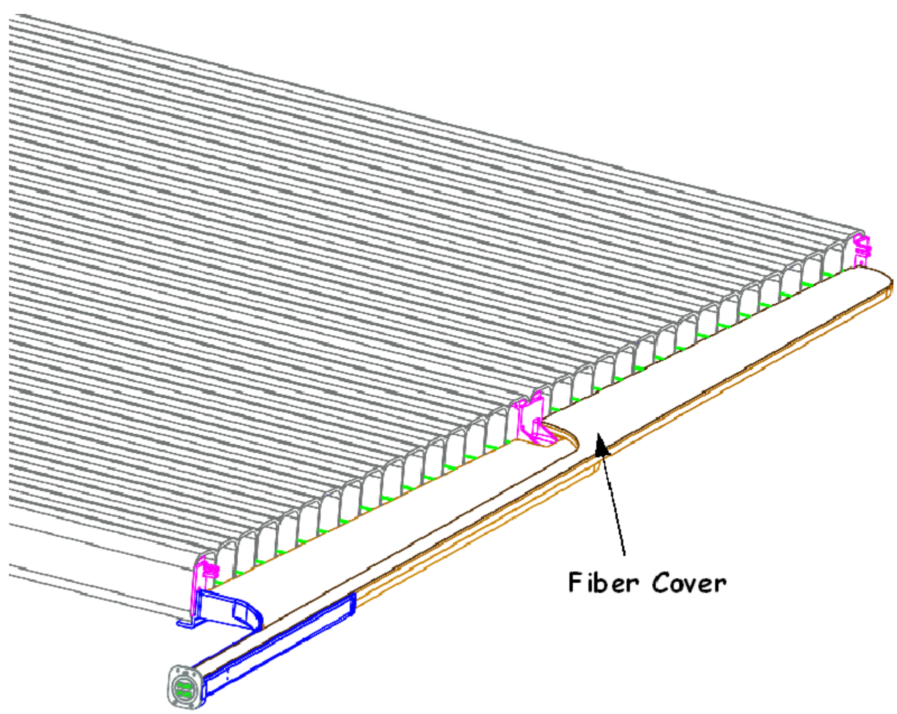

Fig. 13.52: Fiber cover is snapped in place over fibers 17-32 after the last 8 are strung.

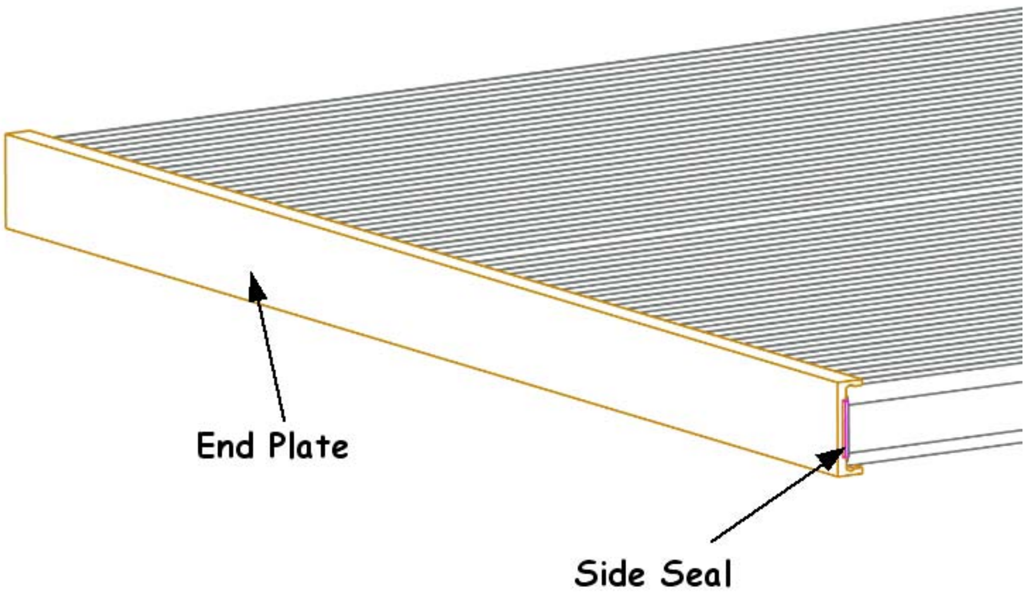

Fig. 13.54. End plate is glued to the extrusion.

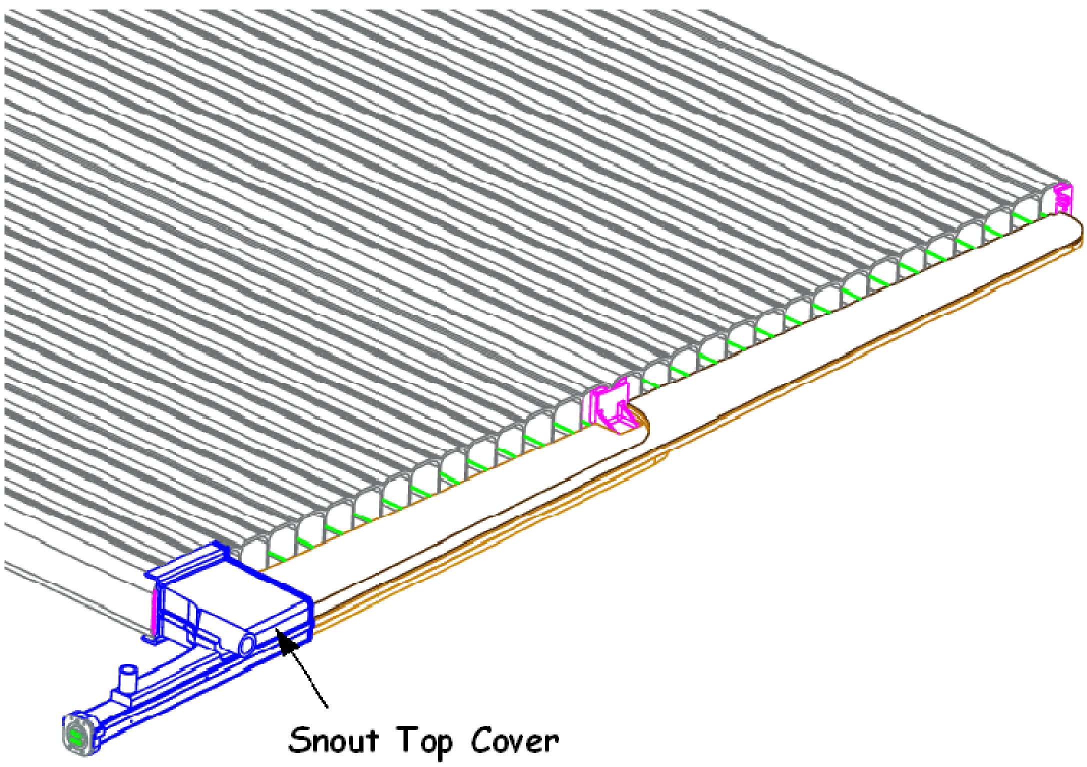

Fig. 13.55.: Glue snout top cover to the module.

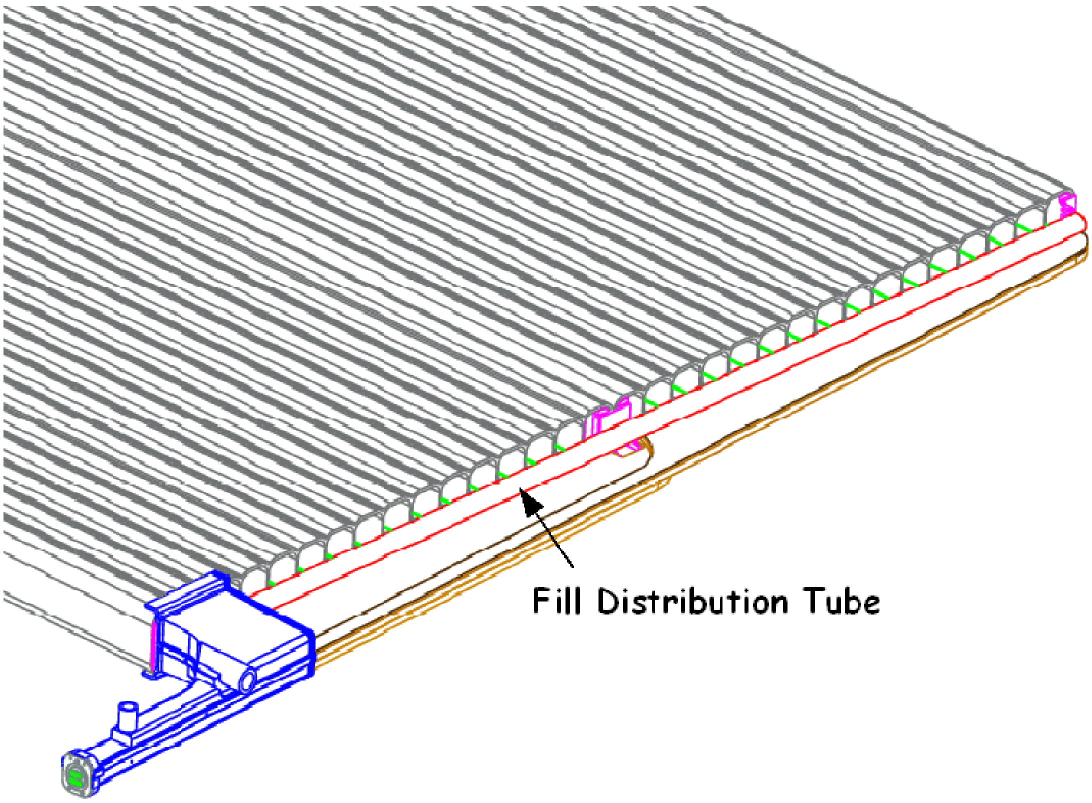

Fig. 13.56: Attach the fill distribution tube to the module.

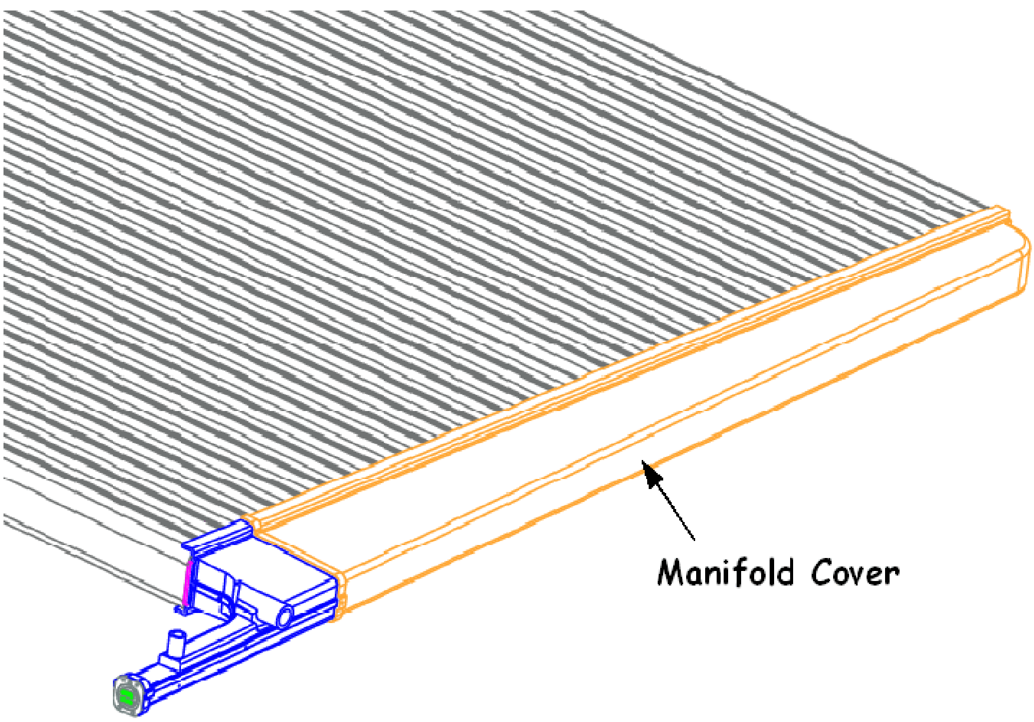

Fig. 13.57.: Glue manifold cover to the extrusion and snout.

13.4.7.3 Module Factory Flow Day 3

The flow of modules through the factory on their third day is illustrated by Figure 13.27 arrow 4 & 5 The 30 extrusions have cured on their individual worktables overnight. Now all of the external parts of the glue joints of both the manifold and the end plate are reinforced with structural adhesive. As soon as the structural adhesive has cured enough for handling, the optical connectors are flycut and the fibers are tested for optical transmission. Any module with a damaged fiber will cause the module to be rejected, a situation we expect to occur very infrequently. Rejected modules are replaced with good ones from storage. Following this testing, the modules are rolled to the crane area and assembled into a shipping stack of 24 modules. When the day's stack is completed, it is moved, using the air caster system, to the leak testing area where 24 hours of leak testing begins.

A detailed breakdown of the labor required for these 30 modules on their third day in the factory is given in Tables 13.22 – 13.27. Flycutting is shown in Figure 13.58.

	Min/Module	**People**	
Glue end plate and add fiberglass mesh reinforcement	6.5	1	Measured
Glue mannifold cover to extrusion	6.5	1	Measured
Glue manifold cover/snout joint	3	1	Measured
Glue edge stiffeners (2 edges/vertical plane)	0.33	1	Estimate
Structural adhesive cures	12	0	
Total Time/Module	**28.3**		
Total Labor/Module	**16.3**		

Table 13. 22: Add structural glue to strengthen joints. Edge stiffeners or only glued on 2 edges every 24 modules (vertical planes only).

	Min/Module	**People**	
Trim fiber ends with a hot wire cutter	0.5	1	Measured
Align fiber facing machine and attach the snout	5	1	Measured
Flycut optical connector	10	1	Measured
Total Time/ Module	**15.5**		
Total Labor/ Module	**15.5**		

Table 13.23: Flycut the optical connector.

	Min/Module	People	
Connect fiber tester to optical connector and scan bar code	5	1	Measured
Start the fiber test program	0.5	1	Measured
Fiber tester program runs	0.2	1	Measured
Total Time/Module	**5.7**		
Total Labor/Module	**5.7**		

Table 13.24: Test for fiber damage.

	Min/Module	People	
Roll module work table to crane bay.	3	2	Measured
Crane each module from its work table to the shipping stack	5	2	Estimate
Total Time/ Module	**8.0**		
Total Labor/ Module	**16.0**		

Table 13.25: Transfer of the modules to the shipping stack. The total time for this procedure is 192 minutes.

	Min/Module	People	
Connect air casters and towing device to stack	0.4	3	Estimate
Float load to leak testing area	0.6	3	Estimate
Lower load off casters and remove them	0.5	3	Estimate
Total Time/ Module	**1.5**		
Total Labor/ Module	**4.5**		

Table 13.26: Use air casters to move shipping stack to leak testing area. This operation takes 36 minutes.

	Min/Module	People	
Leak tester is connected to all modules in the stack and scan each bar code	0.5	1	Estimate
Place safety shield around the module stack	0.2	1	Estimate
Presurize modules to 20 PSI and begin test.	0.3	1	Measured
Run automated leak test overnight		0	
Total Time/Module	**1.0**		
Total Labor/Module	**1.0**		

Table 13.27: Leak test. The total time for this procedure is 24 minutes

Fig. 13.58. Flycutting an optical connector.

13.4.7.4 Module Factory Flow Day 4

The flow of modules through the factory on their fourth day is illustrated by Figure 13.27 arrow 6. When the 12 hours of leak testing is completed, the results are checked to make sure there are no leaks. This procedure is given in section 13.4.6. In the rare instance that a leak is found, the module with the leak is removed from the stack and replaced with a good one from storage. A stack of 24 modules is then packaged for shipping and loaded on a truck.

A detailed breakdown of the labor required for these 30 modules on their fourth day in the factory, assuming no leaks are found, is given in Tables 13.28 and 13.29.

	Min/Module	People	
Leak tester is disconnected from all modules in the stack and scan each bar code	0.2	1	Estimate
Remove safety shield from around the module stack	0.2	1	Estimate
Examine results and make database entries	0.2	1	Estimate
Total Time/Module	**0.6**		
Total Labor/Module	**0.6**		

Table 13.28: Leak test. The total time for this procedure is 36 minutes.

	Min/Module	People	
Apply protective packaging around the snouts and plastic wrap over the modules	1.25	1	Estimate
Place dock plate	0.08	2	Estimate
Inspect and sweep truck bed	0.13	1	Estimate
Place overlay sheet on truck bed	0.20	2	Estimate
Place air casters and connect tow device	0.42	3	Estimate
Float load with air casters	0.04	3	Estimate
Push load on to truck	1.25	3	Estimate
Lower load off air casters	0.04	3	Estimate
Remove air casters	0.42	3	Estimate
Total Time/ Module	**3.8**		
Total Labor/ Module	**8.4**		

Table 13.29: Packaging and loading of completed modules. The total time for these steps is 91 minutes.

13.5 Changes in the Module and Factory Designs Since the CDR

The primary change since the CDR is to change the factory model. In the CDR there were 3 factories that all did the same assembly tasks. There are now 2 factories each with different functions. This is motivated by using a 16 cell extrusion as the basis of the detector and gluing two such extrusions together to form the basis for a 32 cell detector module. Now one factory receives the 16 cell extrusions and produces the 32 cell extrusion assembly. This factory also serves to match the production of the extrusion manufacturer to the other factory, which produces finished detector modules.

Other minor changes involve improvements in the engineering of the parts that make up the modules. These changes are motivated by the cost improvements gained by injection molding and the impact of time and motion studies on the design.

13.6 Work Remaining to Complete the Module and Factory Designs

Production of the integration prototype and purchase of a floor mounted crane for time and motion studies may cause some factory procedure and module design modifications to optimize the cost.

Testing of modules under severe stress and further aging continues to determine if any modification is needed to either handling or gluing procedures.

Value engineering on both the module design and the factory procedures continues to discover ways to reduce cost.