Luminosity Pair Spectrometer Calorimeters: Fabrication and Assembly Plan

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Abstract

This document describes the construction of the luminosity pair spectrometer calorimeters module at the University of York. Production steps for the basic building blocks of the calorimeter, modules, are described. A subsequent preliminary installation plan for the stacking of the calorimeters at BNL is also included. ES&H concerns during construction and installation are also discussed.

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1. PAIR SPECTROMETER CALORIMETER INTRODUCTION

The luminosity pair spectrometer calorimeters are tungsten scintillating fiber calorimeters. These calorimeters consist of a matrix of scintillating fibers embedded within a tungsten powder and epoxy mix. Each calorimeter consists of twenty layers; each layer consists of three modules (i.e. 60 modules per calorimeter). A module is the basic building block of each calorimeter. A single module consists of 448 scintillating fibers embedded with tungsten powder and epoxy. These fibers are grouped into arrays of 16 for readout by a single Silicon Photomultiplier (SiPM). Figure 1 below shows each of these elements in turn.

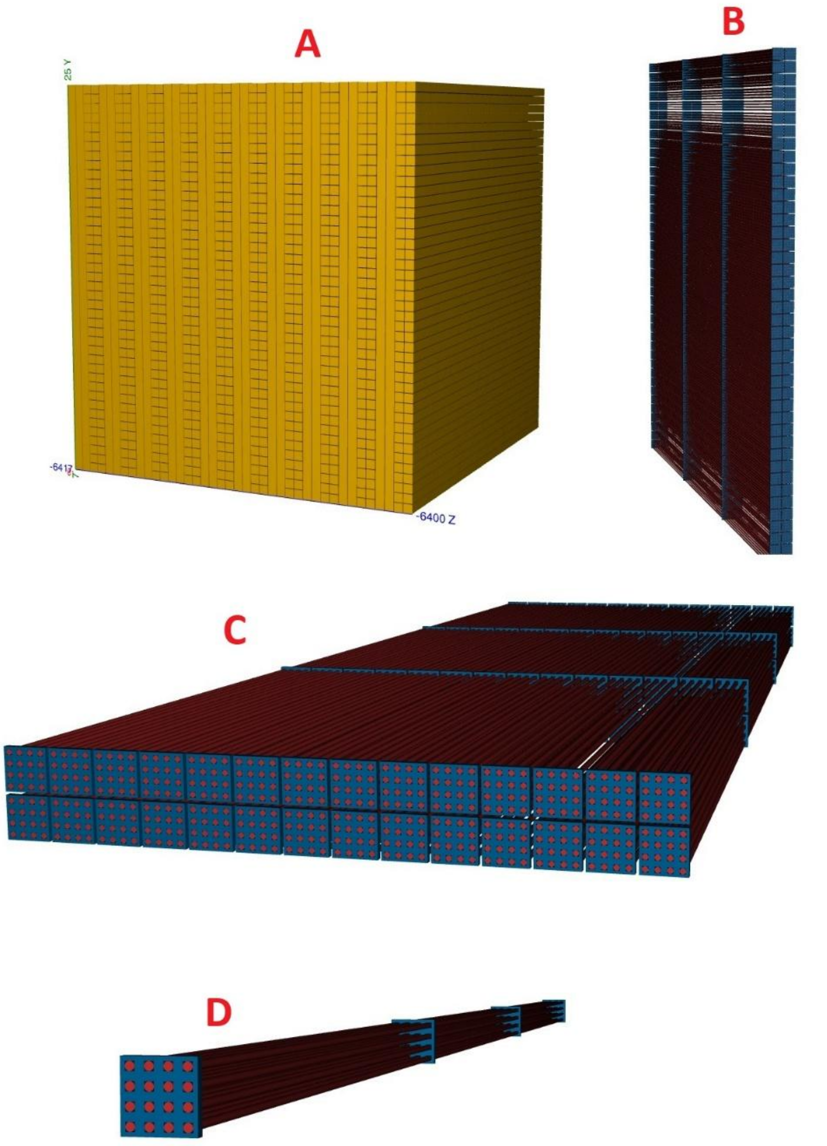

Figure 1. A Geant4 depiction of a pair spectrometer calorimeter, showcasing key components. A) A full calorimeter of 20 layers. B) A layer consisting of three stacked modules. C) A single module consisting of 448 fibers, arranged in 28 groups of 16. D) A single group of 16 fibers, this set of fibers would be read out by a single SiPM.

An individual module is 180 mm in length, 60 mm in width and 9 mm thick, roughly comparable in size to a large chocolate bar. Fibers run lengthways along each module. Fibers are grouped into sets of 16 for readout. The spacing of the fibers can be seen most straightforwardly from the design of the meshes that are used to hold them in place during construction as seen in Figure 2 below. These meshes were produced by Photofab [1] by chemically etching 0.25mm thick brass plates.

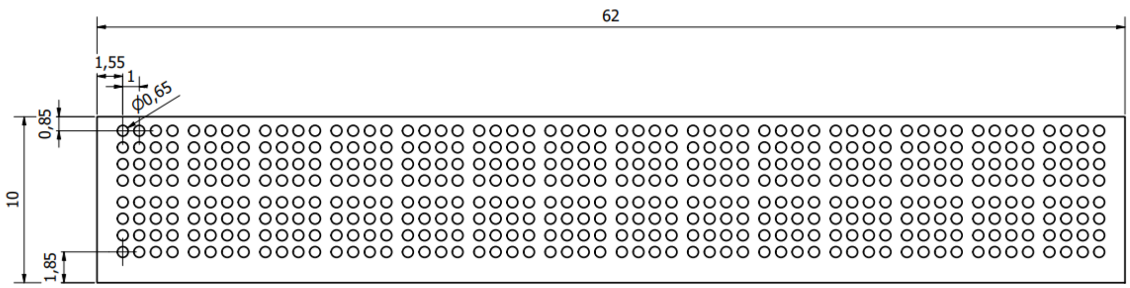

Figure 2. A CAD drawing of a fiber alignment mesh showcasing the fiber spacing and spacing between groups of 16 fibers. All dimensions are in mm.

Three modules are stacked along their long edge to form a layer, 180 mm long by 180 mm wide and 9 mm thick. When 60 modules are combined into a calorimeter, the overall dimensions are 180 x 180 x 180 mm^3. However, note that these do not account for support structures and containers for the calorimeter modules. These are discussed later in the installation section.

In total, 180 modules will be needed to construct three full calorimeters (two for the pair spectrometer system and one as a "low luminosity" direct photon detector. The pair spectrometers will detect electron-positron pairs converted Bethe-Heitler (BH) photons from a thin foil placed between two magnets in the luminosity system. The low luminosity direct photon detector will detect direct BH photons, it will be utilized in the first few years of EIC running when expected BH photon multiplicities per bunch crossing are low.

These are sampling calorimeters, with the current design, the expected sampling fraction is ~2%. By reading out groups of 16 fibers corresponding to a rough 4.5 x 4.5 mm^2 area, a position resolution on the order of a few mm can be achieved. By rotating alternate layers, readout in both X and Y as well as Z (from layer number which is equivalent to depth) can be achieved. This will enable the 3D reconstruction of EM showers from incident particles.

2. MODULE PRODUCTION PROCESS

This section will describe the processes and procedures for the production of a single pair spectrometer calorimeter module.

2.1. Scintillating Fibers – Preparation

Before module production, scintillating fibers must be prepared. Prepared fibers are then arranged into the required matrix by aligning them through a series of brash meshes (as seen in Figure 2). These steps are detailed below.

2.1.1. Cutting

The Saint Gobain (now Luxium) 0.47mm diameter BCF-12 [2] fibers used in the calorimeter modules are supplied as 1200mm long canes. These are cut to 200 mm lengths. Canes are drawn from bags, each containing 200 canes, which are labelled and numbered, a record is kept of the bags used for the production of each module. A cane from each bag, as well as one cut sample, is retained for QA testing. Each cane is cut into short lengths by hand using a scalpel. It is advisable to pre-cut a large number of lengths prior to module production as each module requires 448 fibers.

2.1.2. End Melting

After cutting, one end of each fiber is gently melted using a heat source. This is to ensure that when populating the meshes in the next step, the fibers are kept in place at one end. Each individually cut fiber is melted by lightly touching them to a heat source, such as the one seen in Figure 3 below, to form a slightly wider `head` at one end. This process must be conducted in a fume cupboard with suitable ventilation and care must be taken as the fibers must be handled with gloves. The presence of a heat source increases the associated risk. Mitigation is detailed in the ES&H section. A large number of fibers should be pre-prepared in advance of the next step.

Figure 3. An example heat source used to melt fiber ends.

2.1.3. Mesh Filling

Once a suitable quantity (>500) of fibers is cut and melted, the next step can begin. This step involves populating a stack of four of the brass meshes of the type shown in Figure 2 with fibers. A specialized holder was created for this purpose which can be seen in Figure 4 below. This holder fixes two sets of four meshes in place. Prepared fibers can be dropped from above, un-melted end down, to populate the meshes. Typically, roughly 95% of the meshes can be populated by simply dropping the fibers down. However, due to static, some holes may not be populated. A visual inspection is required to ensure all 448 holes are populated with fibers. Once a stack of meshes is fully populated. It can be carefully removed from the dropper in preparation for the next step.

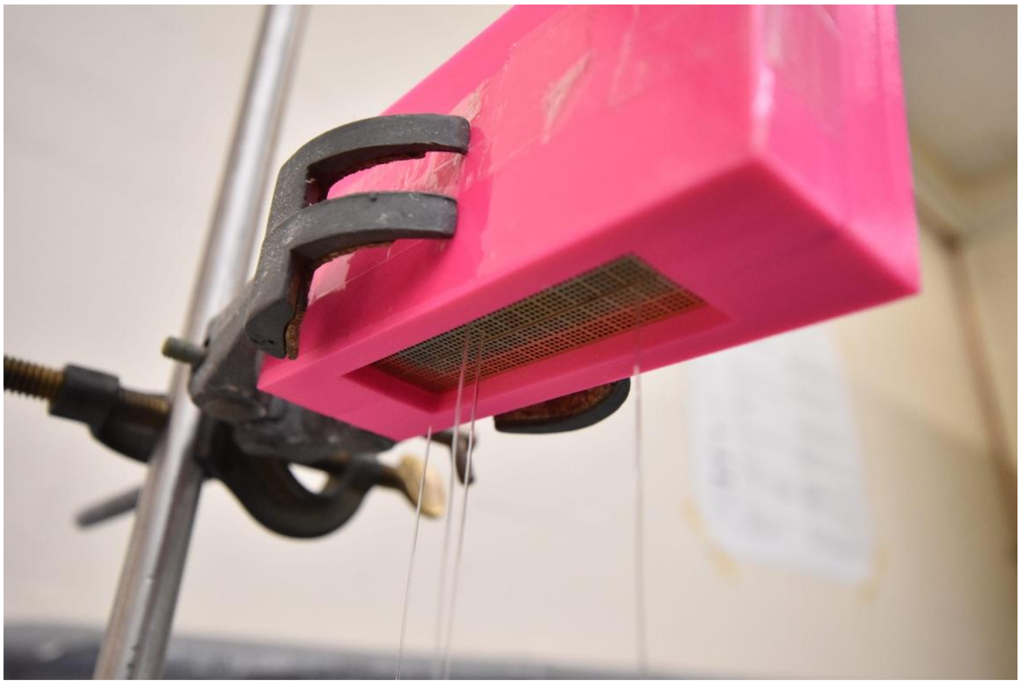

Figure 4. Two stacks of 4 meshes in a 3D printed holder to assist with the population of meshes with fibers.

2.2. Production Mold Preparation

The next step in the production process is to prepare the production mold (see Appendix A for CAD drawings of the mold). The mold is primarily made of a non-stick plastic (White Delrin® Acetal Resin [3]), with one piece being stainless steel. It comprises of six pieces in total: the bottom, two side pieces, two end plates, and a top. Before production, the mold should be cleaned, gently scrubbing all surfaces of any residue by wiping with isopropyl alcohol and Kim wipes. Flat wooden sticks can be used for scraping if needed. Mesh slots should be cleaned using a toothpick. After this, silicon grease is applied to several edges to create a seal. Figure 5 shows the preparation of the joint between the bottom plate and one of the side pieces, a silicon grease is applied which seals the joint and prevents the epoxy used later from leaking out. After application of grease to these joints, all pieces except the top piece are screwed together. Also visible in Figure 5 are the grooves that the brass meshes will slot into.

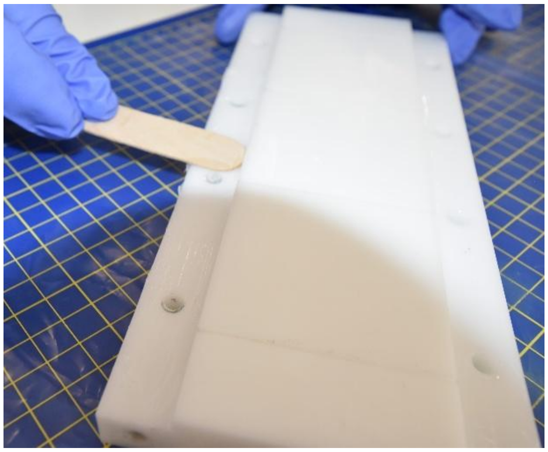

Figure 5. Silicon grease being applied to the joints in the mold.

After the joints are sealed and the five pieces, excluding the top piece, have been screwed together the mold is sprayed with PTFE spray, Figure 6, this helps ensure a clean removal of the finished calorimeter module from the mold at the end of the process. The mold is gentle tilted to spread the liquid PTFE across all surfaces that will come into contact with epoxy before being left to dry for several hours.

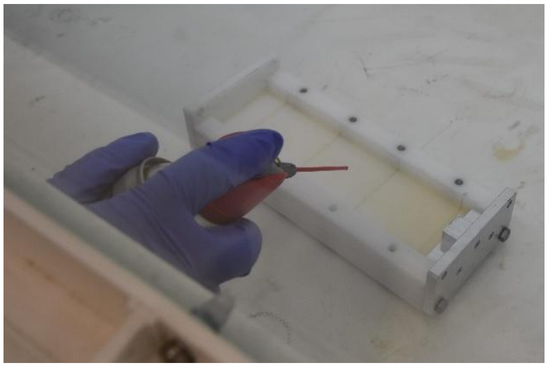

Figure 6. PTFE spray being applied to the inside surfaces of the mold.

2.3. Module Production

Once the mold is prepared and a stack of 4 meshes is filled with fibers, module production can begin in earnest.

2.3.1. Fiber Matrix Insertion

Inserting the matrix of fibers aligned inside the mesh stack is one of the most delicate parts of construction. The following steps are recommended to insert the fiber matrix into the mold.

a) Separate the stack of four meshes before insertion into the mold. At this stage, it is recommended to separate the meshes by a few cm each at most as in Figure 7. Be careful when separating the meshes not to pull any fibers out of the mesh stack. Gently apply some pressure flat across the melted ends of the fibers. An unused mesh is a good item to use for this purpose as it is the correct width.

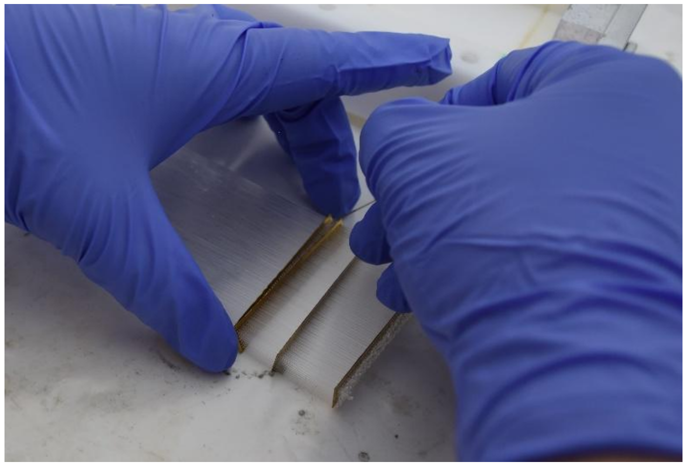

Figure 7. Separation of the brass meshes in preparation for insertion into the mold.

b) Mark the top of the mesh slots on the mold with a marker for visibility. Move it to a fume cupboard if it is not already there. Carefully move the mesh matrix to the mold. Insert the first mesh (with the melted fibers) into the fiber slot at the end of the mold which has a metal end piece. The mesh should be inserted such that the "lip" seen on the bottom edge of Figure 2 slots into the groove in the mold Carefully separate the other meshes further apart, approximately 5cm between each mesh. Apply gentle pressure to the melted ends of the fibers on the mesh that is inserted. Ensure that you do not catch any melted ends and pull them further out.

c) One by one, slot the other meshes into place, applying pressure to the melted end as you do so to ensure no fibers slide out. **Having 2 workers at this stage is highly recommended.** One should separate and insert the meshes whilst the other applies pressure to the melted fiber ends to ensure no fibers slide out.

d) Once the final mesh is slotted into place, gently tap the melted end to end to push all fibers towards the other end of the mold. Visually inspect the inserted mesh to ensure that no fibers have slipped out of any of the meshes. **If any fibers have slid out, remove the fiber in question and remove the meshes from the mold.** Recombine the meshes and refill the empty slot(s). Start over from step a). Figure 8 showcases a successfully inserted fiber matrix into the mold.

Figure 8. A fiber matrix successfully inserted into the mold. Note the green markings showing clearly the location of the mesh slots as mentioned in step b).

2.3.2. Tungsten Pour

After the fiber matrix is inserted into the mold the top piece of the mold should then be screwed into place. This prevents the meshes rising out of their grooves when tungsten is added. The top plate also divides the mold into three "sections" for easy pouring. The mold should be placed on a vibrating table within a fume cupboard during pouring. During pouring, work in a fume cupboard at all times, including the weighing of tungsten. Cover all work surfaces (including the surface of the vibrating table and the balance for weighing tungsten) in plastic sheeting to prevent the spread of any tungsten powder to the surrounding work area.

Once in place, the tungsten powder can then be added in stages. **For pouring purposes, roughly 1.5kg of tungsten powder should be available**. Weigh all quantities of tungsten before pouring using a balance accurate to 2 decimal places. A small beaker or cup should be used to weigh and pour tungsten. **After each step outlined below, apply gentle vibration from the vibrating table for one minute before proceeding to the next step.** Pour tungsten slowly, gently and evenly in each section in the stages below. Tungsten is added in small batches as follows:

a) Pour 20g into each section of the mold, 60g in total – 60g cumulative total

b) Pour 20g into each section of the mold, 60g in total – 120g cumulative total

c) Pour 60g into each section of the mold, 180g in total – 300g cumulative total

d) Pour 100g into each section of the mold, 300g in total – 600g cumulative total

e) Remove the top plate at this stage.

f) Pour 100g into each section of the mold, 300g in total – 900g cumulative total

g) Gently spread the surface of the tungsten to ensure it is level across the length of the module (between the meshes).

h) Pour 50g of tungsten in the gap between the mesh and the metal end plate. Pour a further 100g in the gap between the mesh at the other end and the resin end plate at the other end – 1150g cumulative total

i) Gently smooth the surface of the tungsten across the whole module as in step g).

Figure 9 demonstrates Step a) and Figure 10 shows the application of vibration between each stage. Figure 11 shows the mold filled with tungsten after step i).

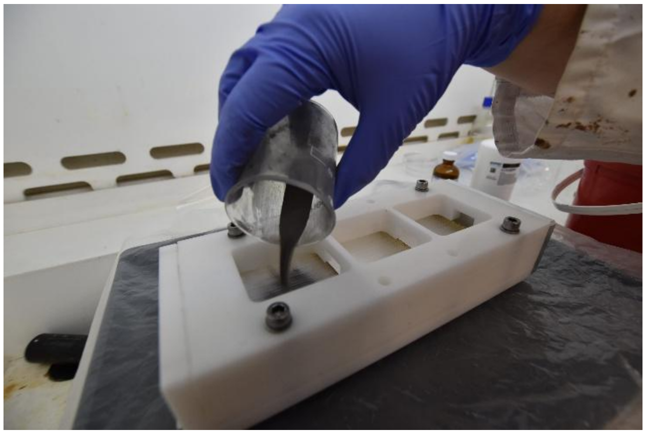

Figure 9. Pouring a small batch of tungsten in step a).

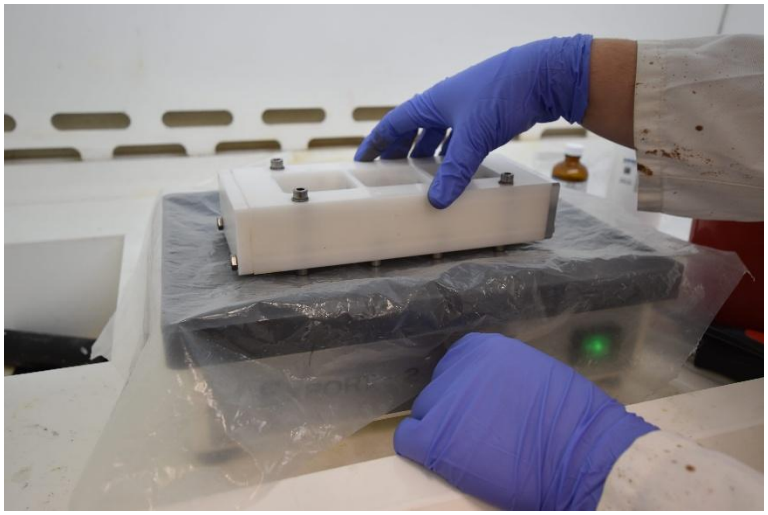

Figure 10. Application of vibration to the mold between filling steps.

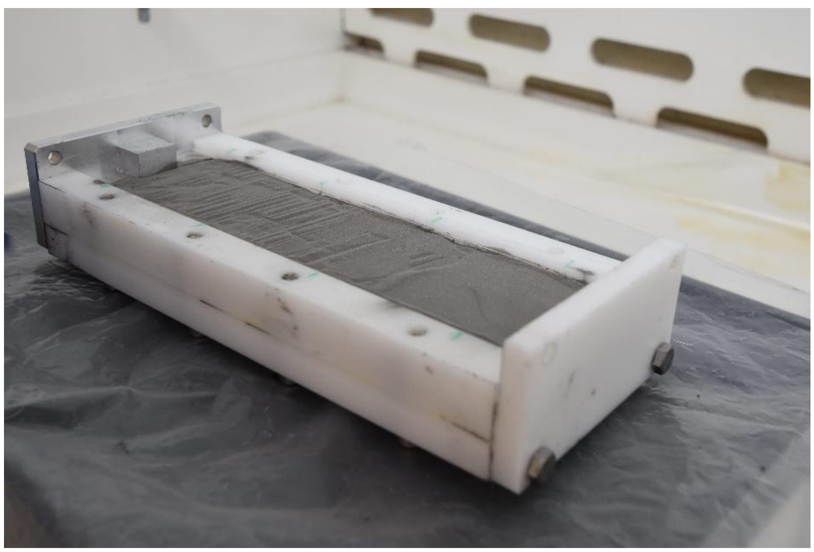

Figure 11. A filled mold after step i).

Once the mold is filled, it is ready for the next stage – epoxy pouring.

2.3.3. Epoxy Mixing and Pouring

To bind the tungsten powder together and solidify the module, an epoxy is used. Epotek 301 [4], a two-part clear, room temperature curing epoxy is used for this purpose. This two-part epoxy must be mixed in a 4:1 ratio by weight between the two parts (A and B). A balance accurate to at least 2 decimal places should be utilized in the following. Weigh and mix the epoxy into small glass beakers. The epoxy is mixed and poured in 25ml batches as follows:

a) Weigh out 20g of Part A. Gently stir for two minutes using a glass rod – reverse stirring direction one minute into this process such that it is stirred for one minute in each direction (clockwise and anti-clockwise).

b) In a separate beaker/glass, weigh out 5g of Part B. Due to the viscosity of Part B, using a small pipette for “pouring” this epoxy out for weighing is recommended.

c) Pour the part B into the Part A beaker. Gently stir the mixture together for four minutes using a glass rod – reverse stirring direction two minutes into this process such that the mixture is stirred for two minutes in each direction (clockwise and anti-clockwise). After stirring, visually check that the mixture is homogenized and no “strands” are visible in the mixture. If they are, stir for a further minute in each direction.

d) Apply gentle vibration from the vibrating table to the mold. Gently pour the epoxy mixture over the tungsten in the mold, ensuring that you cover the module as evenly as possible. Figure 12 shows the pouring process in action.

e) After pouring, apply further vibration for ~1 minute.

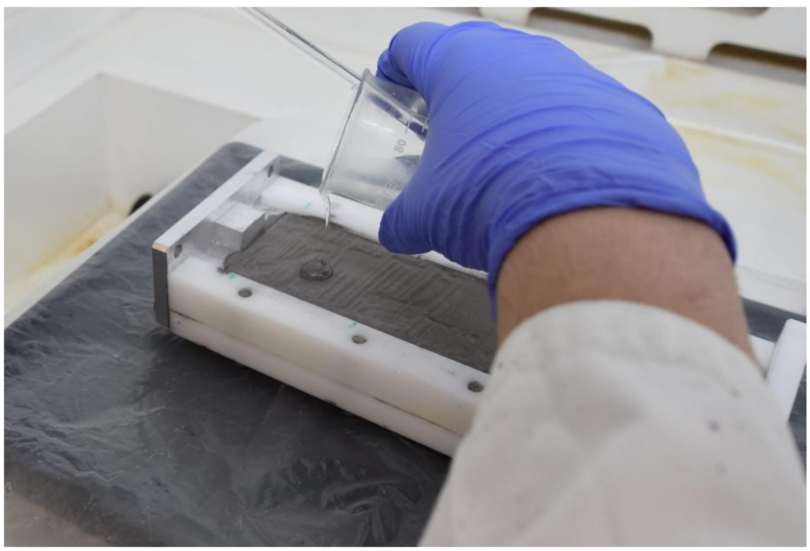

Figure 12. Pouring a batch of epoxy over the mold.

Repeat this process such that 50g of epoxy (two batches) of epoxy has been poured over the mold. **When mixing the second batch, ensure that beakers are not re-used for different Parts.** E.g. do not re-use a Part B beaker to weigh Part A. **Preferably, use a clean set of beakers for each mixed batch.** After two batches have been poured, wrap the mold loosely in foil. Place it in a vacuum chamber that can go down to ~1 Pa as seen in Figure 13. Bring the chamber down to this level and allow the module to rest for several minutes. After degassing, the top of the module should look slightly dry as in Figure 14.

Figure 13. Mold loosely wrapped in foil placed in a vacuum chamber.

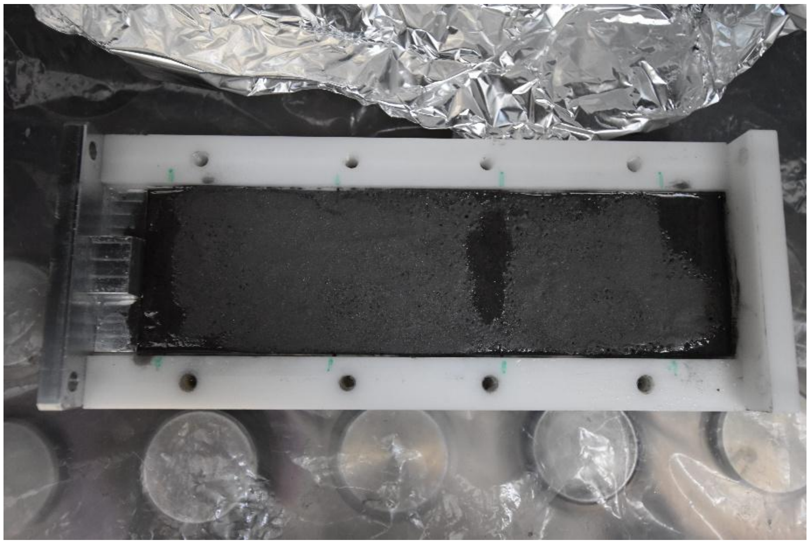

Figure 14. Partially dry top surface of the mold after removal from the vacuum chamber.

After the module is removed from the vacuum chamber, place it back in the fume cupboard and mix up a third and final batch of epoxy using steps a)-e) above. After pouring the final batch, repeat the vacuum chamber process. Following the second de-gassing round, a layer of epoxy should remain on top of the mold as seen in Figure 15. The mold is now ready for the final stage.

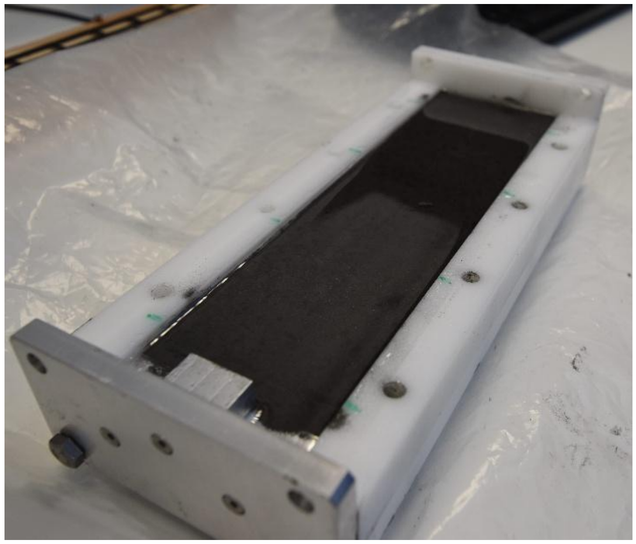

Figure 15. Mold after the final epoxy pour and second de-gassing.

2.3.4. Curing

The final construction stage is to place the mold into a low temperature oven at 50°C for 2 hours. The mold should be rotated in the oven after 1 hour to ensure an even distribution of heat across the module. **Do not cure at higher temperatures as this risks damaging the fibers in the mold**. After two hours, remove the module from the oven and allow it to cool for 30-60 minutes.

2.3.5. Module Removal from Mold and Machining

Once the mold cools, the finished module can be removed from the mold. Unscrew all parts of the mold. Start by removing the end pieces, gently flex these back. Due to the application of PTFE earlier, they should cleanly separate without the application of much force. Next, remove the two side plates. Again, apply gentle lateral pressure and these should separate cleanly. Finally, remove the module from the base. Gently pull the module upwards, it should separate. If it has stuck at any point, try to gently lever the module upwards using a flat, blunt instrument (e.g. a flat metal spatula). **Only apply force from the ends, not the center of the module.** Once the module is separated, clean the mold as in Section 2.2 and begin the process again. An example of a finished module after removal from the mold can be seen in Figure 16.

At this point, modules can be machined down to the exact dimensions (180mm x 60 mm x 9mm) required. Tolerances of +/-0.1mm are required which cannot be achieved without machining. Machining of completed modules is carried out by the University of York mechanical workshop.

Figure 16. Top view of a finished module after removal from the mold.

3. PRELIMINARY INSTALLATION PLAN

This section details the preliminary installation plan of calorimeters at BNL for final in-situ detector construction. Prior to stacking the modules, all modules (180 for three calorimeters, plus any spares) will be shipped to BNL. Each module will be shipped in its own individual lightproof container (see below). For shipping purposes, containers will only be loosely sealed (1 screw in each corner) to enable easier inspection on arrival and by customs authorities if needed. Lightguides will be glued on place on the end of each module prior to sealing. Prior to shipping, SiPM readout boards will also be glued into place. When shipping the modules, a bespoke foam cutout will be used to house each module and readout board securely and safely in a larger crate. See the "Luminosity Pair Spectrometer Calorimeters: Materials Inspection and Test Plan" document, Section 3.7, for further details on shipping considerations.

3.1. Support Stand Assembly

Prior to assembly an inventory will be taken of all of the necessary 80/20 support pieces and accessories as identified by the drawing package to ensure that they are present. Lifting mechanics will be tested to ensure they are operational prior to installation. The pieces will then be cut and assembled as directed on construction drawings. Once assembled, all sliding parts will be inspected to verify the shelves and forward-most detector plane is able to be moved and locked in position. The shelving will be tested with dummy 70 kg loads, approximately the weight of a full calorimeter, to ensure they remain stable and hold the load. The lifting mechanics will be tested with the loads in places. Once this is confirmed, the test loads will be removed and the tunnel will be moved to the tunnel for integration. The stand will be anchored to the floor in the designated location. Following this, the calorimeters can be stacked in place as described in the next section and the tracker planes installed.

3.2. Calorimeter Stacking

Upon arrival and following inspection, all modules will be sealed into an individual lightproof container. The design of this container is being finalized, but it is expected to be similar to that shown in Figure 17 below. These containers will need to be stacked to form each calorimeter. A frame which utilizes small slots/rails for each container to slide into will be used. This frame is still being designed, but the slots will look similar to those shown in Figure 18 below.

Figure 17. View of a module within a lightproof container with the top taken off. Notice the gap on the right between the module and box edge, this is to leave space for the lightguide. Preliminary design, subject to finalization.

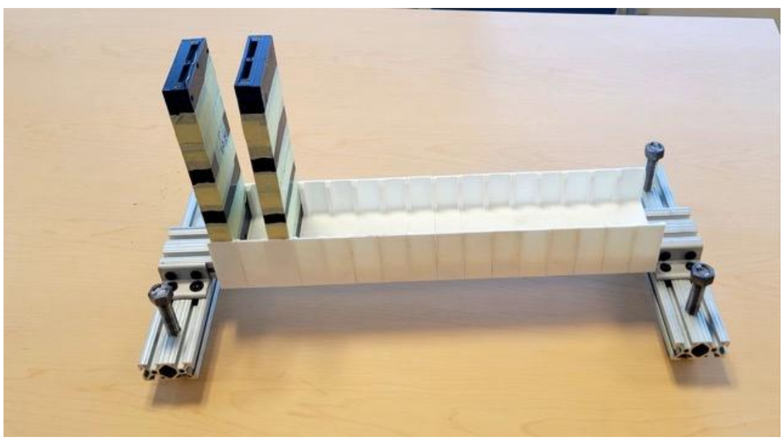

Figure 18. Current stand prototype showing two modules stacked for vertical readout. Slots in the support frame to hold modules are expected to be similar.

Modules will be stacked in layers, with each layer alternating in orientation. The first layer is orientated in the X direction (fibers horizontal to the support stand) to enable positional readout in the Y direction (vertical). The second layer is orientated in the Y direction (fibers vertical to the support stand), enabling X position readout, and so on. All X layers should be orientated with the readout end facing the same direction. Similarly, all Y layers should be orientated with the readout end facing the same direction. For the top pair spectrometer calorimeter, Y readout will be from the top of the calorimeter. For the bottom pair spectrometer calorimeter, Y readout will be from the bottom of the calorimeter. The low luminosity direct photon detector should have Y readout from the top of the calorimeter. The X readout direction should be consistent for each calorimeter and will depend upon eventual space constraints in the lumi area.

For each calorimeter, modules should be stacked into layers sequentially until 20 layers are complete. Care should be taken with the weight of the modules as each module is ~1kg in weight despite being relatively small. See ES&H information in Section 4.2.

3.3. Electronic/Readout Connections

Once all modules are stacked into the support frame, readout boards can be connected to each module. Power and readout connections can then be connected and routed to DAQs for each calorimeter. Exact readout and power connections are still TBC. Cables should be routed cleanly and clearly marked to avoid confusion.

4. ENVIRONMENT, SAFETY & HEALTH CONSIDERATIONS

Environment, Safety and Health (ES&H) considerations during construction and installation are detailed below. Any other local restrictions or rules not detailed below should be adhered to at all times. E.g. Jefferson Lab or Brookhaven National Lab general work place risk assessments and procedures.

4.1. Construction

During construction, recommendations on risk assessments should be adhered to at all times. All workers should read, understand and sign the relevant work and laboratory risk assessments. Mitigating safety measures outlined on Safety Datasheets for relevant materials should be undertaken. In general mitigations include:

- Wearing clean powder free nitrile gloves whilst handling fibers.
- Wearing clean powder free nitrile gloves and lab coats whilst handling or using epoxy or tungsten powder or any other chemicals (silicone grease, PTFE spray)
- Safety glasses should be worn when working with any chemicals, particularly when mixing epoxy.
- Keeping all work surfaces clean.
- Disposing of all waste in designated “Offensive Waste” bins, including plastic sheeting laid down whilst producing modules. Safety Datasheets should be consulted in full before the disposal of any chemicals.
- Handling epoxy and tungsten powder in a fume hood at all times.
- Only melting fibers with sufficient mechanical ventilation, e.g. within a fume hood.
- Taking care when handling molds/modules that have been in the low temperature oven for any length of time.

When melting fibers, this should only be done in a fume cupboard/hood with suitable mechanical ventilation. Care must be taken when melting fibers as gloves must be worn which presents an elevated risk due to the presence of a heating element. Workers should work for no more than 10 minutes at a time when melting fibers, taking a short break (2-5 minutes) every 10 minutes to ensure full concentration. No worker should continuously melt fiber ends for more than 2 hours at a time including breaks.

4.2. Installation Considerations

Due to the heavy nature of the calorimeter modules and the elevation of the support stand, steel toe capped shoes should be worn during installation to prevent foot injuries should any modules be dropped. Due to the nature of the support structure and payload, there is a concern for the stand being very top-heavy and the center of gravity is much higher. During installation, measures will be taken to ensure the mounting to the deck and support frame is suitable for the top-heavy payload and stand. Clean powder free nitrile gloves should be worn when handling modules outside of containers. When connecting or installing electronics, systems should be powered down. A full risk assessment will be prepared in advance of installation. All workers will be required to read, understand and sign this risk assessment before commencing work.

5. REFERENCES

[1] – Photofab, Chemical Etching Company, https://www.photofab.co.uk/
[2] – Saint-Gobain Crystals, Plastic Scintillating Fibers Product Sheet (2107-21), https://luxiumsolutions.com/sites/default/files/2021-11/Fiber-Product-Sheet.pdf
[3] – McMaster-Carr, White Delrin® Acetal Resin Sheet, https://www.mcmaster.com/8573K21/
[4] – Epotek 301 2-part Epoxy, Meridian Adhesives, https://meridianadhesives.com/products/epo-tek-301/

APPENDIX A – CAD DRAWINGS

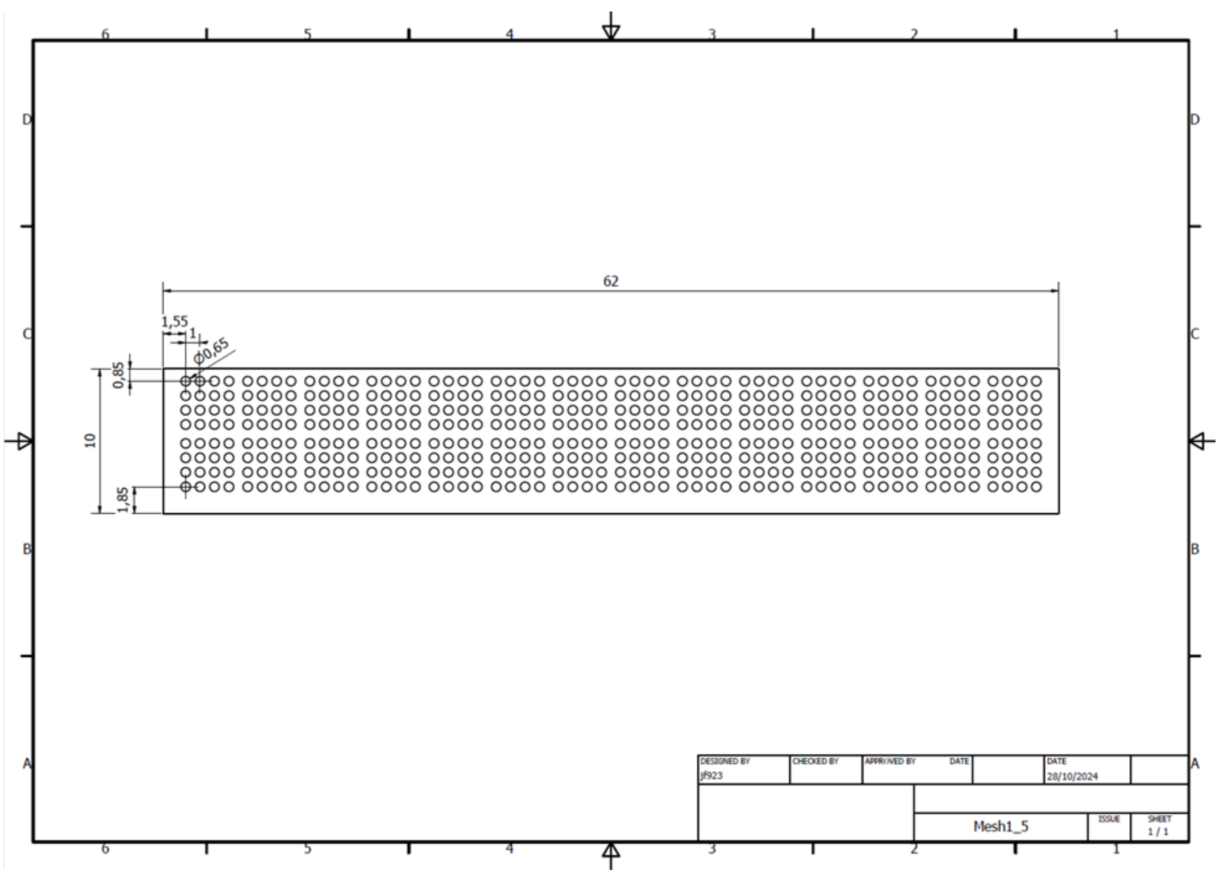

Figure 19. CAD Drawing of the brass mesh that holds fibers in place during module construction.

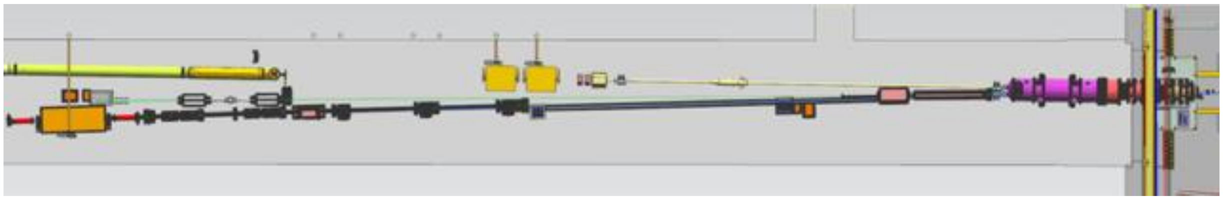

Figure 20. Preliminary CAD rendering of the Far-Backwards region of ePIC. The Lumi detectors can be seen on the far left of the diagram, between the two beamlines.

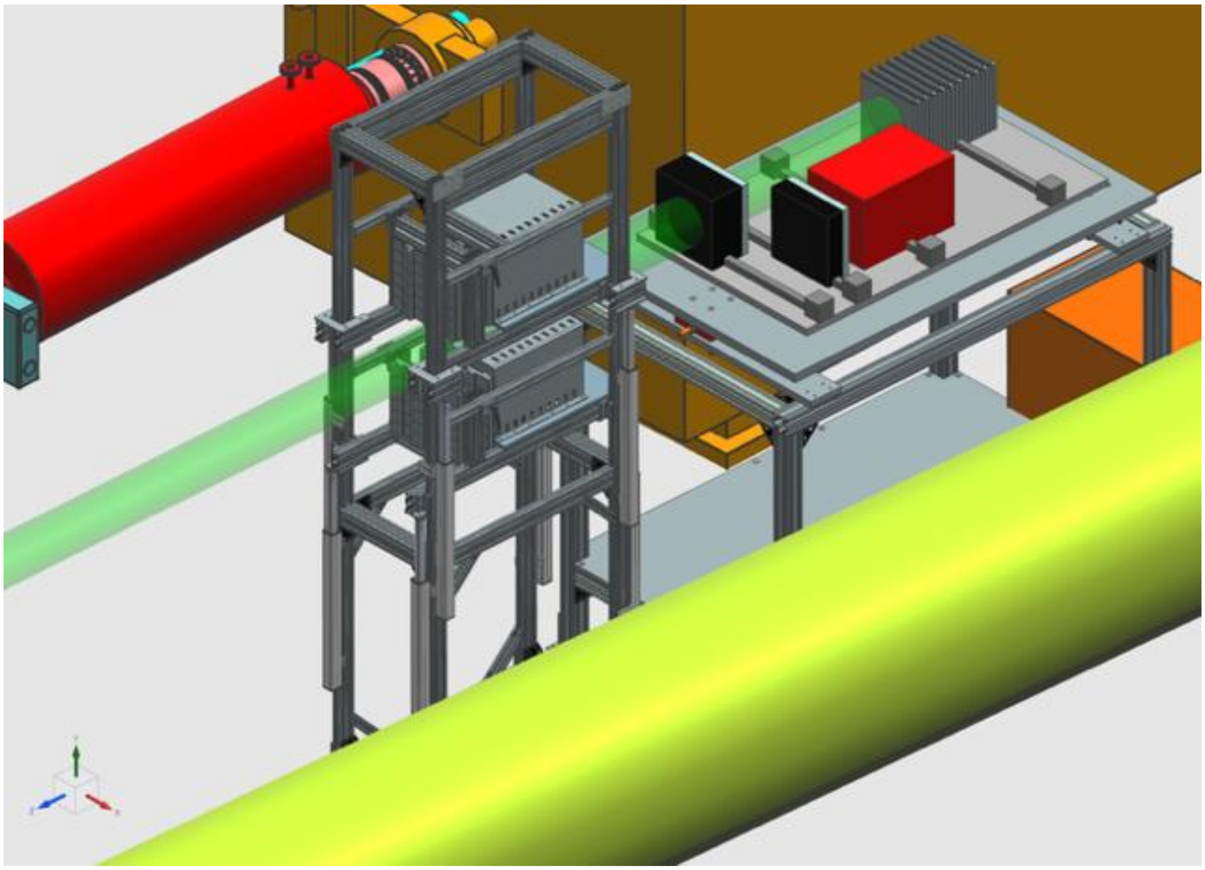

Figure 21. Preliminary CAD rendering of the luminosity system. The front stand shows the two pair spectrometers in situ. The table behind this holds the Direct Photon Detector and shows the movable SR filter that will be in place. The BH photon beam is illustrated in green.