Luminosity Pair Spectrometer Calorimeters: Materials Inspection and Test Plan

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Abstract

This document describes the in production and post production testing of luminosity pair spectrometer calorimeter module materials at the University of York. A description of the materials is included, along with a description of testing processes and required equipment. Handling and ESH concerns are also discussed. This document is a companion piece to "Luminosity Pair Spectrometer Calorimeters: Construction and Installation Plan", reading the companion document first is recommended.

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1. PAIR SPECTROMETER CALORIMETER TUNGSTEN AND SCINTLLATING FIBER PROPERTIES

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. 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. Properties and details of the scintillating fibers and tungsten are described in the sections below.

1.1. Scintillating Fiber Properties

A single module consists of 448 Saint Gobain (now Luxium) 0.47mm diameter BCF-12 [1] fibers. The fibers delivered and used are spares from the construction of the sPHENIX EM calorimeter [2]. These are supplied as 1.2m canes and are cut to 200mm segments. As such, a total of 16128m of fiber (13440 canes) is required for the construction of three calorimeter modules, not accounting for any wastage or spares. The key properties of the fibers are listed below.

- **Fiber handling:** Scintillating fibers are sensitive to incandescent or fluorescent indoor lighting (in particular, the UV component of such lights, which can damage them and affect their properties. Special procedures are required for handling, testing and storage.
- **Diameter:** The diameter mean value and variation is 0.47+/-0.01 mm, RMS < 0.02 mm. This will be measured using a digital caliper. One sample from each bag (see delivery method) will be retained for testing and measurement.
- **Emission Spectrum:** The fibers should emit light in the blue-violet wavelength range, peaking at 435 nm. This will be tested using a spectrophotometer.
- **Attenuation Length:** The attenuation length for blue light should be > 1.6m. The variation of light yield and attenuation length between bags should be less than 10%. Due to the short lengths of individual fiber required for the pair spectrometer calorimeter, <0.2m, this is not a concern.
- **Light Yield:** The average response to a 90Sr source shall be greater than 3.5 photoelectrons measured using a bialkali PMT or a SiPM at 200 cm from the source, with the opposite end of the fiber being blackened. The batch-to-batch or lot-to-lot variation of light yield and attenuation length should be less than 15%. As a practical matter, the light output will be determined in comparison to average light yield of a set of "standard reference fibers", identified during the First-Article testing, with an agreed upon light yield and attenuation length to which all subsequent production batches will be compared.
- **Scintillation Decay Time:** The decay time should be less than 3.2 ns. This property will not be tested, as it is a standard performance parameter of scintillating fibers.
- **Delivery Method:** The fibers will be delivered in 1.2m long canes. A total of 21.6 km has been delivered already, supplied in separate bags of 200 fiber canes per bag. Samples from each bag will be retained for testing and measurement purposes. As each cane will be cut into ~200mm segments, there is no particular need to measure each cane. Each individual cut segment will be measured.

1.2. Tungsten Powder Properties

Each module uses on the order of 1 kg of tungsten powder during construction. The key properties of the tungsten powder are listed below.

- **Powder handling:** Whilst not flammable due to the grain size utilized, special procedures must still be employed in the handling, testing, storage and use of the tungsten powder.
- **Density:** The density of the powder itself will not be tested. The overall density of the module, when it has been machined to the required dimensions and tolerances will be recorded. Instead, the grain size will be examined. The tap density of the powder is ~ $11 g/cm^3$.
- **Grain Size:** The tungsten powder used in production will be inspected using a Scanning Electron Microscope (SEM) scan to determine the approximate grain size of the powder. Grain sizes of 10-100μm are acceptable. As only a small sample can be scanned at a time, samples will be taken after a fixed amount of tungsten (25kg) has been used from the delivered sample.
- **Delivery Method:** 200kg of tungsten powder was delivered in a small plastic barrel. Small batches of no more than 5kg will be extracted for construction purposes.

2. PROCESSES AND PROCEDURES

This section will describe the processes and procedures that are required to evaluate each of the properties described the preceding section.

2.1. Scintillating Fibers – General Product Quality

2.1.1. In-Process Testing

The manufacturer must test and document its quality control of fiber production. Measurements of attenuation length and light output will be performed periodically on samples from each bag used in production. Both cut and uncut fibers will be tested. The manufacturer must specify the frequency and procedures used to test the scintillating fibers.

2.1.2. Incoming Inspections or Acceptance Testing

All fibers were delivered in one shipment from BNL. As such, tests will be conducted upon usage of fibers in construction. For every five bags of fibers that are used, a sample of cut and uncut fibers from each bag will be tested. Before use in construction, fibers from each bag will be inspected visually for physical damage. If visual inspection is satisfactory, one full cane will be reserved for testing and the remaining canes will be cut to length. The attenuation length and light output relative to the standard reference fibers will be measured for the sample of canes and cut fibers from each of the five bags. Any bags failing contract specifications will be rejected.

2.1.3. Verification Testing

Verification testing is required to assure that it meets the minimal stated performance requirements. Randomly selected fibers from each bag will be tested, using the procedures specified in Section 3 and verified against manufacturer's test results on the key properties: light output, attenuation length, diameter, spectrum.

2.1.4. Failures and Non-Conformances

If more than 1% of the fibers from a given bag fail visual inspection or for one or more of the criteria in Section 1.1, the bag will be rejected. The outcome will be communicated to the manufacturer, and a joint decision will be taken whether the product shall be returned to the manufacturer.

2.2. Tungsten Powder – General Product Quality

200kg of powder was delivered in one small plastic barrel in a shipment from BNL. The manufacturer must test and document its quality control of the supplied powder. The manufacturer specified the average/typical grain size and the mesh sizing used to filter the powder. The density of the powder was also specified.

Tests were conducted upon delivery and will be conducted upon usage of tungsten in construction. The typical grain size was examined with an SEM scan upon receipt of the shipment. A series (at least 5) of SEM scans at sufficient magnification to examine multiple grains of the expected size. Grain sizes of 10-100µm are expected. The number of grains falling outside of the expected range in each scan was counted. If more than 3 grains outside of the expected range were counted in a given scan, this scan was marked as a failure. If more than 2 scans failed, the sample would be rejected. Such a failure could just be due to the sample taken, so a fresh sample would be scanned using the same procedure. A repeat failure for the second sample would result in the rejection of the supplied batch. Further measurements of grain size from the delivered barrel will be taken after every 25kg of tungsten is used.

2.2.1. Failures and Non-Conformances

As noted, if more than two series of SEM scans failed, the powder would be rejected. The outcome will be communicated to the manufacturer, and a joint decision will be taken whether the product shall be returned to the manufacturer.

3. EXPERIMENTAL/TEST SETUPS

This section will have an individual sub-section for each of the experiments/tests that will be performed. If the same experimental process will be used for multiple properties, it does not need to be repeated. Each experimental section should provide a detailed description of the method, resource requirements, conditions, and equipment.

3.1. Fiber Handling

3.1.1. General

a) Before placing a fiber on any surface (cutting mat, tray, box etc.), ensure the surface is clear of dust, debris, and smudges. Surfaces can be cleaned with isopropyl alcohol and Kim wipes. The fibers easily pick up dust and other motes of matter but are more difficult to clean. Take care to keep the fibers from touching the floor or other unclean surfaces during transportation or handling.

b) Wear clean nitrile gloves at all times when handling fibers.

c) When transporting uncut canes, keep them in their sealed bags when possible. Ensure that the length of the fibers does not trail on any dirty surfaces and that the fibers are not bent any tighter than a ~20cm radius of curvature.

d) Fibers can be damaged from exposure to UV radiation. Overhead incandescent or fluorescent lights emit UV. Ensure these are off when uncovered fibers are in the room. Ensure that fibers are stored in lightproof containers when not in use (e.g. shipping box, sealed plastic container wrapped in black film). Ensure that no external light enters the room when cutting or otherwise using fibers. During general handling, cutting, melting and module construction, only LED lighting (or lamps with UV film coverings) should be used.

3.1.2. Cutting

When cutting fibers, ensure that clean nitrile gloves are worn when handling fibers. Remove and cut fiber canes from only one bag at a time. Minimize exposure to UV light at all times. Cut the fiber canes on a clean cutting surface. Cut fibers should be placed in a clean plastic box covered in black cloth/lightproofing. The box should be labelled with the bag number for the fibers it contains. Only LED lighting (or lamps with UV film coverings) should be used. If any fibers remain in the bag after a cutting session, the bag should be placed back in the shipping container.

3.1.3. Melting

When melting fiber ends, clean nitrile gloves should be worn when handling fibers. **Due to the use of gloves in combination with high temperatures, caution is advised**. Take regular breaks when melting fibers to ensure concentration is retained. Melt the cut end of a fiber where possible. Keep fibers from a given bag together when storing and handling. Once a fiber end is melted, place the fibers in a clean plastic box covered in black cloth/lightproofing. The box should be labelled with the bag number for the fibers it contains. Only LED lighting (or lamps with UV film coverings) should be used.

3.1.4. Module Production

During fiber handling for module production, clean nitrile gloves should be worn when handling fibers. Only LED lighting (or lamps with UV film coverings) should be used when populating fiber meshes or when inserting the meshes and fibers into a production mold.

3.2. Fiber Diameter

Clean powder free nitrile gloves should be worn when handling fibers and measures previously described to minimize UV light exposure should be used. Diameter should be tested every five full bags of fiber canes that are used.

a) Take the five retained fiber canes, one from each bag, alongside the retained cut fiber from each bag (10 total).

b) Using a micrometer calorimeter, gently measure and record the diameter of each fiber at five evenly spaced points along the length of the fiber (~ every 22cm for a cane, every 4cm for the cut fiber). A rough estimate by eye should be sufficient.

Use the flat part of the caliper to avoid scratching/slicing of the outer layer of the fiber and take care not to apply too much force during measurements. This may accidentally crush the fiber.

3.3. Fiber Emission Spectrum and Fiber Light Output Tests

An equivalent procedure to the BIC Fiber Inspection procedure [3] will be utilized to test each of these elements. As all fibers are in hand, this will be done per set of 5 fiber bags used as outlined in other sections

3.4. Tungsten Powder Handling

During the handling of tungsten powder for the tests outlined below, clean powder free nitrile gloves and lab coats should be worn at all times. For SEM testing, a small sample of tungsten (~10g) should be drawn from the main container into a small glass beaker.

3.5. Tungsten Powder SEM Scan

A small sample of tungsten powder was stuck onto a carbon disk for insertion into an SEM. A JEOL JXA-8800 was used for this purpose at York. The sample was inserted and scanned at roughly 180x magnification as seen in Figure 1 below. Grain sizes were measured and counted based upon similar images using the procedure outlined above in Section 2.2.

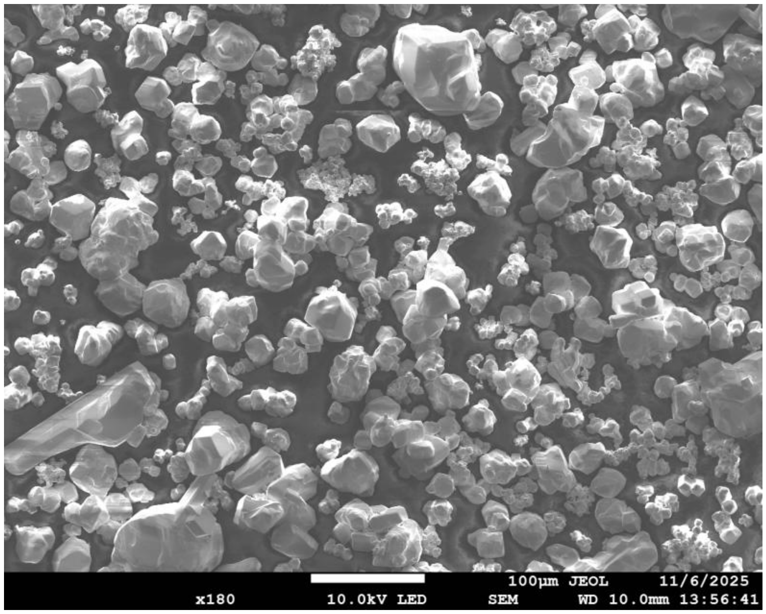

Figure 1. A typical tungsten powder sample SEM scan.

3.6. Module Machining

After machining, module dimensions will be checked for consistency. Expected dimensions are 180 mm x 60mm x 9 mm. Each dimension will be measured using vernier calipers. Dimensions should match to within +/- 0.1 mm. Modules will also be weighed using a balance with a precision of at least 2 decimal places. An average module weight will be determined once a suitable number have been machined. All modules should be within +/- 1% of this average weight.

3.7. Module Inspection Before and After Shipment

Each module will be shipped in its own individual lightproof container. 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. All modules will be placed in their individual lightproof containers for shipping. Each container will be numbered. During shipment, containers will only be loosely sealed (1 screw in each corner) to enable easier inspection on arrival and by customs authorities if needed. The modules will be visually inspected before and after shipment. Any visible defects on modules, e.g. cracks or marks on the epoxy, visible fibers or loose lightguides will be recorded. Modules will be shipped in wooden crates containing a bespoke high-density foam insert, this foam will be precut with grooves to hold each individual module. Depending upon size, multiple such crates and foam inserts may be needed.

Upon receipt of the shipment, all modules will be visually inspected again for damage, cross-checking against pre-shipment records. Any modules which have sustained additional damage will be separated and tested individually. Their performance against a set of undamaged referenced modules (at least 10, chosen at random) will be evaluated. Should they deviate significantly from the reference modules (e.g. >1% density/weight variations or >5% light yield difference), they will not be used in the installation. They will be retained as spares unless there are extremely significant differences, to be decided on a case-by-case basis. Any modules with extremely visible damage, e.g. chipped pieces from module, crack splitting the module or clearly damage fibers, will be discarded. Some may be retained for testing purposes at the discretion of the testing and installation team.

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. Scintillating Fibers

Fibers should be handled using clean powder free nitrile gloves at all times. Any damaged, spare or waste fibers (e.g. excess from cutting) should be disposed of in an “Offensive Waste” bin or similar. Due to the small nature of the fibers, dropping small pieces may occur. Lab spaces should periodically be swept to find dropped fibers. A UV flashlight can be utilized for this purpose as fibers should be more readily apparent under UV light (as they have been dropped, they are already considered damage/waste so there is not concern from UV exposure). In all other circumstances, fibers should be handled with overhead lights switched off (and blinds/curtains closed) to avoid UV light exposure. LED lighting should be used instead.

4.2. Tungsten Powder

When handling tungsten powder, clean lab coats and powder free nitrile gloves should be worn at all times. No more than 5kg of tungsten should be removed from the main storage barrel at a time. When pouring or handling tungsten, this should be conducted within a fume cupboard/hood. Working surfaces should be covered by disposable plastic sheeting to avoid the spread of tungsten powder/dust. After working, dispose of the plastic sheeting in an “Offensive Waste” bin or similar.

5. RECORDS AND DOCUMENTATION

This section details all of the documentation that will be generated and exchanged during the manufacturing lifecycle. In all likelihood there will be many transient documents that are created that will not be collected or maintained as part of the project. This transient documentation need only be listed if it is pertinent to a specific experiment or test.

5.1. Manufacturer/Producer Records

For every item that is manufactured, the manufacturer will be responsible for maintaining records (travelers) of all raw material that are used in the fabrication process, and document the processes and procedures that were used for production. The resultant documentation will be compiled into a report and will be provided to the project as part of the deliverable, which will be reviewed, validated, and then placed in the central data repository.

Due to the re-use of spare materials from sPHENIX construction, documents for the tungsten powder and scintillating fibers should already be available.

5.2. Deliverable Documentation and Records

This includes test results, tables of measurements, parameter lists or other records that must be provided to the project. All testing and inspection data that is collected as part of the validation, verification and testing plan will be provided to the project as part of the final report.

List all deliverable documentation here

- Storage and handling procedures.
- Manufacturer's measurement procedures, fiber end treatment, including "reference fibers" performance, fiber drawing and lot/batch labelling method.
- Shipment schedule and packing lists.
- Existing testing documentation of sPHENIX EMCAL construction materials.

6. REFERENCES

[1] – Saint-Gobain Crystals, Plastic Scintillating Fibers Product Sheet (2107-21), https://luxiumsolutions.com/sites/default/files/2021-11/Fiber-Product-Sheet.pdf

[2] – *Design and beam Test Results for the 2-D Projective sPHENIX Electromagnetic Calorimeter Prototype*, C.A. Aidala et al., IEEE Transactions on Nuclear Science (Volume: 68, Issue: 2, February 2021), https://doi.org/10.1109/TNS.2020.3034643

[3] – *Scintillating Fiber Inspection and Test Plan*, S. Joosten and Z. Papandreou, https://eic.jlab.org/Documents/DET/Quality/ITP/ECAL/BIC%20Fiber%20Inspection%20and%20Test%20Plan.pdf