QUALITY ASSURANCE PLAN FOR THE CONSTRUCTION OF THE BCAL

Version 3

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Abstract

The quality assurance plan for the construction of 48 production modules for the GlueX Barrel Calorimeter is laid out herein. Details are provided on procurement and inspection of materials, construction methodology and procedures, document control and quality records.

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Preamble

The methods of material preparation and matrix build up, which have been developed during the extensive R&D phase, resulted in good matrix uniformity for the first two full-scale Prototypes (1 & 2).

In early October 2009, a third, full-scale prototype was completed. This module, termed 'Construction Prototype', followed the 'Mayan Pyramid' design of the second full-scale prototype, although with four steps instead of the previous seven. Procedures were not followed throughout all phases of the Construction Prototype's build, primarily due to inadequate personnel training and supervision. Misalignment errors during construction were compounded and resulted in the produced matrix having regions of non-uniformity. As a result the construction procedures and quality control at all construction steps were completely overhauled. The new procedures were applied to the last 40 layers of this prototype producing a uniform matrix. Additionally, an important correction technique was developed and proven successful in the unlikely occurrence of that type of misalignment in the future.

In addition to updated and newly developed procedures, an instructional video is available to assist in the training of the students. Student labour for the first year of construction has been secured, in a manner allowing continuity with 5-6 students (already fully trained and experienced) staying on for this period, and only 1-2 new ones added to the crew each semester and who will undergo rigorous training.

1 Scope

The quality of a finished BCAL module is judged on two separate criteria.

1. First is the dimensional uniformity in meeting the stated objectives of all the geometric characteristics of the BCAL. To achieve this goal, quality control is required in all construction steps: lead processing, fibre handling, gluing, lay up of fibres and lead sheets and alignment checks.
2. Second is the optical quality of the BCAL, which reflects the quality control of the SciFi's, as well as the machining and polishing of the BCAL read-out ends. The controls on the SciFi quality will be the subject of a separate document and will only be touched upon briefly here.

The scope of this document is to detail the construction steps, and the procedures and checks in accepting/rejecting materials and/or matrix layers.

1.1 Key components to control and the methodology to be followed

1.1.1 Lead Sheets

The quality and condition of the lead (Pb) sheets are inspected upon receipt of a shipment from the vendor. One coil from each width is cut to length in order to verify the quoted number of cuts/pieces by the vendor. The first Pb sheet from each coil is checked for uniformity in thickness and width, with random measurements at various spots along the length and width using a micrometer caliper; the numbers are recorded. Deviations from contract specifications are handled in a manner detailed in Sections 4 and 6. A new brass gauge will be constructed to facilitate the thickness measurements of swaged sheets.

The straightness of each lead sheet is crucial for a straight build. The sheets must be roughly the same length after swaging (404±1) cm and have perfect or near perfect alignment of all grooves. The steps involved are detailed below.

Each sheet is cut to 396 cm length on a fibre-cutting mat along alignment markings, and is inspected for straightness along its entire length before and after the swaging operation. A) Curvature in the sheets either before or after swaging is corrected by taking advantage of the lead's plastic and pliable nature. When the curvature cannot be rectified the sheet is rejected. B) Occasionally, a sheet is damaged in passing through the swager. C) After swaging, a toothpick is run along a groove from one end to the other to visually verify that the sheet is perfect -- in other words that no groove ends somewhere along the length and appears on the other edge -- or is off by one groove. If it is off by two or more grooves the sheet is rejected. 'Perfect' and 'One-off' sheets are tagged as such and stored until needed in a build. The combined rejection fraction A)-C) has been kept at < 2%.

The upper left corner of each sheet (as seen in a top view after coming out of the swager) is clipped after swaging and all sheets are rolled right to left (top view).

1.1.2 Epoxy

Each epoxy shipment is inspected for the condition of resin cans and hardener bottles, and for the expiration date. The arrival dates, expiration dates and lot numbers are recorded.

The epoxy, the quantity used, and its viscosity, are also key components in the uniformity and integrity of the completed modules. The mixture of resin and hardener needs to satisfy short curing times (eight hours) while remaining fluid enough for long enough period of time (during layer building) so that excess epoxy will flow out the ends by the pressing/curing stage.

The epoxy is mixed in a ratio of 100:28 by weight for the resin and hardener, respectively, in ordinary 6 oz. plastic drinking cups. The scale is calibrated daily using standard weights of 100g and 25g, and is zeroed after placing the plastic cup on it. The quantity of the epoxy used during construction can vary from operator to operator, however, the electro-pneumatic press -- that compresses the matrix during the epoxy curing phase -- successfully pushes excess epoxy out of the two ends of the module assuring uniform epoxy migration and coverage.

The epoxy remains fluid enough for 120-150 minutes; the time depends on temperature and humidity. The construction space is climate controlled and the stability has been such that computer recording of the temperature and humidity has not been necessary and only visual inspection and recording of the gauges are carried out during each build. Nevertheless, at the start of each construction shift, a small portion of epoxy from the first mixed batch is kept in a labeled plastic cup as a control reference of viscosity.

1.1.3 Leveling and Alignment

In the midst of building the Construction Prototype, Press #1 was partially disassembled and precisely re-leveled to 0.004” across its surface. Minor adjustments were made to level its table and an error in its construction was rectified. Recently, care was taken to level the newly built Press #2, achieving a table height variation of no more that 0.004” across its surface.

The relative position of the matrix with respect to the base Al plate is also a critical operation during the construction. The base plate defines the centerline of the module in the mounting frame and the absolute position of the matrix with respect to certain reference points on the plate define the precision with which the BCAL modules can be mounted and assembled to complete the cylinder. This information has been communicated to Ross Machine Shop (RMS), everything possible is being done to produce perfectly level Al base plates with no ‘crowning’ as well as a precisely machined 1 mm guide groove on the top of each of these plates. These numbers are recorded on the traveler documents by RMS and are rechecked at the UofR before construction begins.

Each lead sheet must be rolled onto the build in a precise manner, so that its grooves perfectly ‘lock’ into place, on top of the fibres from the layer below. Any misalignment in the fit is ‘felt’ during the lead rolling but is also checked using an alignment wire and groove runner.

1.2 Methodology for meeting specifications during construction

There are two issues that need to be addressed to assure dimensional uniformity of the finished modules and strict adhesion to dimensional tolerances.

- The most critical reference of matrix-base plate alignment is the centerline of the Al base plate.

A 1 mm wide and 0.5 mm deep groove engraved in the middle and along the base plate length will be used as the reference line. A 1 mm ∅ fibre is inserted and glued into the groove to act as the guideline for the first base swaged lead sheet. This method, coupled with the 'Mayan' alignment plates and alignment wire and runner system referred to below, assure a matrix build centered on the base plate's centerline groove. The fibre in the groove also acts as a restraining device preventing the base Pb sheet from "floating" on the viscous industrial epoxy during curing under pressure. The base Pb sheet is surveyed after epoxy curing to verify that it is straight, if it not it is removed and replaced.

- The construction of the matrix must be kept to tight controls in all dimensions of the completed portion of matrix.

The alignment of each lead sheet is checked using a 4-m-long piano wire, that at one end is attached to a ring that can slide down an alignment post, while the other end wraps around a second post and is tensioned using suspended weights. The posts are aligned to the centerline groove and the first post has a set screw to keep the ring in place and the wire just above the build. A high-density polyethylene 'runner', which has a comb-like bottom surface that fits in the lead sheet grooves and an optical sight (corrected for parallax) is run along the sheet, just under the wire. This takes 30 seconds, and any deviation from straightness is immediately apparent; in such cases the sheet is carefully removed and repositioned.

The height of the matrix from its Al base plate is measured after the curing phase of each build. This was done for the Construction prototype at 40 points, 20 along its front and 20 along its back edge, spaced about 20 cm apart, and from now on will be done at 16 points along the length. Deviations from uniformity have been observed in a front/back height difference; rotating the module by 180 degrees on the press table corrects this. The origin of this asymmetry in Press #1 still eludes us. When a module is built on Press #2 we will see if it is a design issue (affecting both presses) or a Press #1 assembly issue.

The avoidance of `stacked tolerances' is accomplished by laying the swaged sheets alternatively, so as to avoid height differentials between the front and read edge due to a small thickness variation from the swager and groove mismatch by incorrectly mating sheets below and above a given layer of fibres. Each lead sheet has the same corner clipped and rolled identically after swaging. Just before use in the build, each sheet is unrolled and rechecked for straightness and then rolled alternatively in a right-to-left and left-to right manner. The latter rolls are then rotated along a vertical axis by 180 degrees. Both types of sheets are dispensed always from the same end of the build, thus ensuring a close alignment on one side with a slightly varying alignment on the other due to small variations in the sheet length following swaging.

- The machining of each module along its long sides, and at the two ends, must conform to the signed drawings in the contract (D00000-01-07-1000 to D00000-01-07-2005). Specific potential problems have been identified and improvements have been incorporated in the projected process. To better understand the nature of the methodology below, we explain the experience learned from the three full-scale prototypes.

Prototype 1 was constructed as a rectangular piece for ease of construction. This method is forgiving in lateral layer building errors during construction, such as small deviations from right angles (tilting) along the long sides. Machining at the nominal 3.75° angle corrects irregularities that are more noticeable at the upper (narrower) layers. A significant portion of SciFi's is wasted in this method. Prototype 2 was constructed using a step-pyramid design, referred to as a `Mayan pyramid'. This method increases construction complexity and preparation time, however, the overall costs are significantly lower. The Construction Prototype was also build in the 'Mayan' fashion.

The construction of Prototype 2 brought into forefront the need for careful alignment of successive layers during construction as to save as many SciFi's as possible, while at the same time assuring that machining at the required angle does not result in final dimensions that are different (smaller) than designed. In fact, Prototype 2 resulted in a smaller module (narrower than planned) due to errors in alignment during construction.

A new technique was developed and applied for the first time for the Construction prototype, in order to align the 'Mayan' steps. Custom laminar, aluminum alignment plates (about 1 foot long) were built to ensure each 'Mayan' step is aligned with the centerline of the Al base plate, which guides a straight construction. Four sets of plates were made, each plate being 5cm, 5.5cm, 6cm and 6.5cm wide, so that each set totaled 10cm, 11cm, 12cm and 13cm in width when the plates were placed next to each other. The centerline between the adjacent edges of each set was plumb lined to the base plate that ensured alignment with the 1mm groove in the plate. Despite the misalignment errors in the building of the Construction Prototype, the machining cleaned up the sides to specifications and precise dimensions. This demonstrates that the alignment plate technique for each 'Mayan' step proved successful and will be employed towards the construction of the 48 production modules. Subsequently, the custom alignment posts, wire and runner were developed – as described above – and have been successfully employed so far towards the build of Module 1.

Custom Mayan step alignment plates as well the a post, wire and runner system will be utilized to assure that each successive step in the pyramid is built within height and location specifications and that each step will be built with enough tolerance in width to assure that machining of the sides at the* 3.75° *angle will result in a finished module within original specifications and machining tolerances.

1.3 Quality of machining to tolerances specified

Machining of each module will be done at RMS. The machining of the Al base (outer) and top (inner) plates includes the centerline groove and all the other reference and mounting fixtures designed into them. Each machined plate will be surveyed and the exact location of the mounting and alignment will be recorded in the traveler documents and will accompany the module that was constructed using these specific plates. Custom go/no-go gauges are being developed and will be tested on the Construction Module.

Machining of the module to specified length (390 cm) and final polishing of the read out ends has been performed successfully on all three full-scale prototypes and presents no challenges if the proper cutters are used. The length will be controlled to specified tolerances – with respect to a reference point in then middle of the outer Al plate – with the use of the CNC machine at RMS. The machining of the long sides of the modules to the angle tolerances specified will be done with reference to the centerline of the outer Al plate. The cutter head at the CNC lathe used at RMS is a tilting head and this is used to machine the modules to the specified taper. However, since this head cannot feed, it was decided to build jigs to `tilt' each module to 3.75° in order to machine the features on the sides of the aluminum base plates and the O-ring grooves. Following the experience from machining the Construction Prototype, it has been decided to dial-in the machining parameters from scratch for each module, rather than relying on a single setup and reproducibility after removing one module and bringing the next on the machine's table.

We plan to machine 47 modules according to specifications - and install them in the BCAL frame - before machining the last "keystone" module. The latter will be machined to exact dimensions as a result of actual precision measurement of the remaining gap. Nevertheless, errors in construction can stack up and should be avoided at the assembly phase. RMS has been instructed to index and record the dimensions of each finished module at six points. This was done for the Construction Prototype and the data were provided to us. The same method will be used for the 48 production modules, each of which will be engraved with a serial number for identification purposes. This will allow the JLab crew to optimize placement of the modules in their cylindrical configuration.

2 Responsibilities

The construction of all 48 modules will take place at the UofR facilities. By construction, we mean the actual Pb/SciFi/Epoxy matrix build-up starting from pure lead strips, SciFi canes and epoxy as received from their respective vendors. The Pb sheets will be swaged at the UofR, while the Al plates will be machined at RMS prior to their use in matrix construction.

RMS will machine the modules, from their “build” state after construction to the specified final dimensions. The now completed modules will be inspected for dimensional and alignment specifications and for their optical properties. Digital photographs of their two read-out ends will be taken to document integrity of the fibres in the matrix and to map the location of any damaged fibres. In addition, uniform illumination of one end of the module using a photographic quality diffuser will be employed, and the transmitted light out the other end will be readout in a 2cm x 2cm grid pattern using a tapered Winston Cone coupled to a Hamamatsu calibrated photodiode that is, in turn, readout by a picoammeter. RMS has agreed to have these tests performed a their machine shop. This implies that each module that passes these quality assurance tests can be crated and shipped directly from RMS to JLab. This is a change from the initial plan as recorded in the Contract and a result of the new optical uniformity method developed since. This approach reduces module handling (loading and ulnloading on/off trucks) and risk of damage by not transporting the modules back to the UofR for optical testing.

The overall responsibility for the quality assurance and acceptance of the modules for shipment to JLab lies with the UofR group. Any quality problems identified by the UofR - and reported to JLab - will be resolved by consultation. Problems that can be rectified by either the UofR or by RMS will be corrected before shipment. If the problems or non-conformance to specifications cannot be easily corrected, the course of action to be taken will be determined by JLab. The decision will be either to accept the module(s) or incorporate them in the BCAL assembly, with corrective measures taken to either adjust the construction techniques/dimensions of subsequent modules, or to construct new module(s) to replace the defective one(s).

Deflection tests have shown that a finished module – suspended eight inches from each end – sags by no more than 2mm in the middle. This implies that the modules can be shipped without their double-spine bars. Fourty eight crates will be designed and constructed taking into account rigidity, stability (no tipping over) and loading/unloading. Finally, in order to protect the modules from exposure to light their machined ends will be covered with yellow UV-blocking fliter and a tedlar ‘hood’. The latter will be easy to remove and reinsert during inspections by Customs. Moreover, the long sides will be painted using a flat/mat black painted called ‘chalkboard paint’, following the trimming of fibres that stick out the sides as a result of machining.

3 Document Control

JLab has provided the final specifications and drawings. Once construction of the modules has started, significant changes in the design of these fixtures becomes either very difficult or costly or cannot be done at all without necessitating the construction of new modules. Smaller changes, if necessary, need to be agreed upon by UofR and JLab and implemented in amended drawings.

All components in the contract related to the modules are considered the responsibility of the UofR, excluding the assembly frame and Drift Chamber parts (shown in the drawings for reasons of completeness). Additions or modifications, that must be incorporated as the production commences, need to be mutually agreed to by JLab and the UofR and funded from supplemental sources.

For cost and time savings, the machining of all 48 inner and 48 outer plates is best done as a group. This will also assure better consistency because the set up of the machine will be done only once for each set of plates. Machining of these plates will take 50-70 working days to complete.

During the module construction, detailed documentation is kept that allows tracking of used (and discarded) materials, consumables, SciFi lot numbers and their location in the matrix and the environmental conditions during the various stages of each module construction. The documentation methods implemented during the building of the Construction prototype are:

1. Detailed fibre testing, lead swaging and matrix build is recorded in dedicated paper logbooks, one for fibre attenuation length tests, one for photoelectron measurements, and one for lead handling and matrix building. The recordings in the fibre logbooks will flow continuously from one logbook to the next, whereas each module will have its dedicated logbook for documenting its construction.
2. Work conducted is posted In a summary fashion in a password-protected electronic log (Elog) available via the web running on a UofR server.
3. Detailed fibre testing, lead processing and matrix build data is inserted into Excel sheets and are available off a separate password-protected web page.
4. Digital photographs are taken as additional documentation and made available on the above web sites.
5. RMS logs the final dimensions of each machined module and supplies them to the UofR in Excel, tracked by the module's serial number, and become part of the traveler documentation.

All five documentation systems have been employed successfully for the Construction Prototype.

4 Procurements

The Al plates were custom ordered because they are not of standard thickness and length. The uniformity in thickness, which is the most critical aspect of quality, will be checked with appropriate gauges and recorded. If necessary, the plates will be machined to achieve the required. Before used, each sheet will be cleaned by the Construction Manager is the UofR machine shop using a water and soap solution that renders its surface ready for maximum adhesion.

The Pb sheets delivered by the vendor at the specified length and widths will be visually inspected for straight cut and will be spot-checked for thickness using a special micrometer for flat sheets. If the thickness is within contract specifications as measured using a micrometer caliper, they will be swaged, as this is the ultimate test of both uniformity and purity. If the swaged sheets result in higher than normal rejection due to curvature (an indication of either thickness or hardness variations, more detailed checks will be performed to determine chemical composition and thickness consistency. If the tests indicate variance from specifications, the lot will be rejected and shipped back to the vendor. So far, all Vulcan Resources Inc. lead supplied and tested by us show excellent condition and quality and conformance to contract specifications.

There are separate documents that list the quality assurance protocols for the SciFi's and inspection and testing protocols. Briefly, a random selection of a certain fraction of fibre canes from each pre-form will be tested for attenuation length using a calibrated photo-diode. The same fibres will be additionally tested using a collimated ^{90}Sr electron-emitting source and readout by a calibrated PMT to determine the number of photoelectrons determined. The spectral response of fibres will also examined using a spectro-photometer, and their outer diameter will be checked. If the fibres meet or exceed the specifications, as laid out in the contract with the vendor, that lot from the same pre-form will be used for matrix construction. All canes will be subsequently inspected for length and visual imperfections during fibre sorting. If the number of rejected canes exceeds 1% of the lot, the lot will be rejected and returned to the vendor with a record of the canes that failed minimum length and/or visual inspection.

The epoxy used will be ordered in batches because it has a finite shelf life. The same is true for the industrial epoxy used to glue the base Pb sheet to the base Al plate. The consistency and viscosity of the epoxies, as well as their setting and curing times is known to us from experience and any abnormalities will result in rejecting the batch; e.g. mixed epoxy is not clear after thorough mixing, excess bubbling, too runny or two viscous immediately after mixing.

5 Quality Records

5.1 Inspection Records

All materials (SciFi's, Pb, Al plates) will be recorded according to lot number, shipment number or any other identifying method used by the vendor and the dates the testing took place. The Quality Assurance and Acceptance Record (QAAR) – also referred to as ***'traveler documentation'*** – that will accompany each module shipped to JLab will contain the results of the testing as listed in Section 4, above. The QAAR will also contain the running log of each module construction with the labour man-hours employed; the materials used for each thickness completed that day/shift. In addition, at the start of a new operation of layer construction, the dimensions of the matrix will be recorded as to height, uniformity and alignment of layers completed.

Each module will be surveyed after matrix construction is completed and all dimensions will be logged in the QAAR before the module is shipped to RMS. At the latter, a record will be kept of the settings on the module and cutter head and the results of the first measurements after the initial passes of the cutter along the long sides. Any corrections made will be also recorded in the log. Finally, the finished module will be surveyed for conformity to specifications in angles cut, length and alignment. Integrity of the matrix itself will be tested and recorded with digital photography and photodiode readings using light sources with diffusers that will clearly show non-uniformities in transmission and any dead fibres.

A copy of the QAAR and the total labour and materials used for the construction of each particular module will accompany each module. In addition, all documentation will be accessible electronically, as detailed in Section 4.

5.2 Calibration

The instrumentation that will be used to check and record dimensions is mechanical and requires no recalibration of maintenance. Micrometers and calipers will be used for the Pb sheet testing and the matrix measurements while under construction. The final measurements after machining at RMS will be made using the readout of the CNC lathe that will be calibrated and inspected according to the standards of the industry.

The testing of the SciFi's, on the other hand, requires the use of spectro-photometer, photomultipliers, photodiodes and their accompanying computerized readout units. The former will be tested periodically against sources of known wavelength (calibration LED's and/or UV laser) and a reference SciFi (gold standard) for both spectral shape and number of photoelectrons generated and detected by the photo-sensors.

5.3 Personnel Qualification

The UofR group within GlueX/Hall-D (The SPARRO group) has two faculty members (Lolos and Papandreou) who have been involved in the construction of all BCAL module prototypes so far and who have been trained by the physicists and technicians who built KLOE. In addition, there are two graduate students still with the group that have been members of the student labour that built Prototypes 1 and 2 and have helped develop the techniques for SciFi testing using the spectra-photometer and conventional as well as SiPM photo-sensors. A large number of GlueX reports, a training video, and two, refereed journal publications serve as a measure of the group's expertise in module construction and quality assurance and testing methodology. These four individuals trained the initial complement of student and technical personnel that will carry on the construction and evaluation.

Mr. Dan Kolybaba, a UofR machinist for over 30 years, has been hired as the BCAL construction manager. He is an experienced instrument maker and has been involved in the project from its original project definition studies and over several BCAL prototypes. He designed and built the earlier (smaller) press-frames and designed the currently used full-scale press-frame and also designed and built the swaging machine. He is an excellent person to check tolerances, oversee the construction and correct any problems early on and to interact with the personnel and engineers at RMS. Finally, he oversaw every detail of the Construction Prototype's build and personally rolled all lead sheets following the discovery of the misalignment described above. Mr. Kolybaba and the two faculty members will train and oversee the students on all construction tasks, from now on. Mr. Kolybaba is also in charge of shipping and receiving.

Dr. Semenov is a Research Scientist in the Regina group. He and Dr. Papandreou train the students in fibre testing and QA by overseeing the results of measurements and determining whether retesting is required by a standard set of protocols. This monitoring will be done at the beginning of each morning, following the over night data analysis.

The technicians and engineers at RMS have long experience in large and demanding projects and are certified to all safety and operational requirements necessary for the machining of the modules to the tolerances and specifications laid out. They machined the long sides of Module 2 and the two read-out ends of a 2 m-long module that now resides at JLab, and, recently, the Construction Prototype during which no issues of concern were observed.

6 Non-Conforming Items

There are potential sources of non-conformity, the optical and the mechanical. Any non-conformity will be reported to JLab and solutions will be sought by consultation.

- Optical non-conformity can come from vendor-supplied SciFi's and such will invariably manifest itself on the SciFi quality assurance and performance testing. In such an event, the results of the testing will be communicated to JLab and the vendor (Kuraray). The UofR group will make recommendations based on the measurements and the expertise of the group. The decision of whether the non-conformity will not adversely affect the performance of the BCAL and the SciFi's can be used or that non-conformity cannot be tolerated by the specifications of BCAL performance rests with JLab. In the latter case, the SciFi's will be rejected and returned to the vendor. Testing of the first article fibres and those from the first five production fibres, totaling almost 200,000 fibres, have been communicated to JLab and jointly to Kuraray. So far, the fibers meet specifications for each batch/lot, shipment and cumulatively.

- Dimensional non-conformity of the lead sheets in thickness, width and length of coils.

- Dimensional non-conformity of machined aluminum plates and final machining of module.

- Mechanical non-conformity is one that results in either deviation from dimensional tolerances or de-lamination. The former was encountered during the build of the Construction Prototype and lessons were learned on how to avoid it or correct it in the unlikely recurrence; procedures have been revamped as a result. If the module does not align precisely with the centerline groove, there can be a displacement towards one of the long sides; this can be corrected by machining to smaller width with the correct angle. This will necessitate the construction of another module with larger width to compensate, a process that does not involve any major adjustments in the construction process. De-lamination is a catastrophic failure of epoxy related nature and the module must be rejected and replaced. In order to protect against de-lamination during the positioning of the modules, thin Al foil (tape) that has glue on one side and can be wrapped around the modules can be used, a technique employed by KLOE. JLab and the UofR will take such a decision jointly should circumstances dictate.