Construction of the GlueX Barrel Calorimeter

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Abstract

The BCAL is a lead, scintillating fiber matrix designed as an electromagnetic calorimeter fo the GlueX experiment at Jefferson Lab. The construction details of the BCAL at the University of Regina are documented herein.

Keywords: Electromagnetic Calorimeter, Silicon Photo Multipliers, Scintillating Fibres
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1. Background

The SPARRO Group at the University of Regina joined the GlueX (then Hall D) Collaboration in 1999 and agreed to undertake the construction of the Barrel Calorimeter (BCAL) for GlueX. Research and development leading to the final design was carried out between 2000-2009, and this included the construction of several prototypes of increasing length. Among these, the first two full-scale prototypes, termed "Prototype 1" and "Prototype 2", were built at the Centre for Subatomic Physics (now Centre for Particle Physics) at the University of Alberta, by University of Regina students in 2004 and 2006, respectively.

In 2009 it was decided to establish the construction of all 48 modules at the University of Regina. The process started in the summer of 2009 with the construction of a third full-scale module, named "Construction Prototype", as a final proof of the construction methods and procedures. Construction of 48 production modules (plus a spare) was completed in December 2011. The BCAL was installed in the GlueX solenoid in late summer 2013 and has since been fully commissioned, is operational and its energy and timing calibration are in advanced stages.

2. Design Performance

The barrel calorimeter (BCAL) is positioned immediately inside the GlueX solenoid. This constrained the device's outer radius to be 90 *cm* while its inner radius was fixed at 65 *cm* to accommodate the CDC and FDC tracking packages within.

A principle goal of GlueX calorimetry is to detect and to measure photons from the decays of π^0's and η's which, in turn, can come from the decays of produced mesons or possibly from

☆This work was carried out as part of the GlueX Project at Jefferson Lab.
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excited baryons (N^* or Δ). The positions and energies of the photons must be determined to sufficient accuracy to allow for a complete kinematic reconstruction of the event. Detailed Monte Carlo studies [1, 2] indicated that the BCAL should be sensitive down to as close to 60 MeV as possible and up to a at least 2.5 GeV in energy, a measurements to date have confirmed these ranges. The device also provides timing information for charged particles and thus contributes to PID in the central region, in conjuction with the CDC. A further PID function for this device is to provide dE information.

The relevant parameters that determine the π^0 and η mass resolutions are the photon energy (E) and the polar and azimuthal position resolutions (σ_θ and σ_ϕ). The energy resolution (σ_E) depends on the number of photoelectrons (N_{pe}) collected by the photosensors. The photon position is determined by the readout segmentation in the azimuthal direction and the difference in arrival time (ΔT) of the scintillation light between the two ends of the barrel. The resolution in the time difference ($\sigma_{\Delta T}$), and therefore the polar angle resolution, also depend on the number of photoelectrons. In order to carry out its function, the BCAL needs to have close to 200 ps timing resolution [3, 4]. Other parameters of relevance for extracting physics are adequate segmentation to avoid multiple occupancy, good linearity and a sufficiently low-energy threshold for photon detection. The expected performance characteristics of the BCAL are given in Table 1 and details can be found in its history write-up [5] and the GlueX Technical Design Report [6].

Table 1: BCAL properties. Superscripts are the same as in Table 2. The resolutions are at $\theta = 90°$.

Property	Value	Ref.
Trapping efficiency^{c,d,e}	5.3% (min) 10.6% (max)	[7, 8, 9]
Attenuation length^b	(307±12) cm	[10]
Effective speed of light^b, c_{eff}	(16.2±0.4) cm/ns	[10]
Critical energy^e	11.02 MeV (8.36 MeV)	[11, 12]
Location of shower maximum^e	$5.0X_0$ ($5.3X_0$) at 1 GeV	[11, 12]
Thickness for 95% containment^e	$20.3X_0$ ($20.6X_0$) at 1 GeV	[11, 12]
Molière radius^e	17.7 g/cm^2 or 3.63 cm	[12]
Energy resolution^b, σ_E/E	$5.4\%/\sqrt{E} \oplus 2.3\%$	
Time difference res.^{b}, $\sigma_{\Delta T/2}$	70 ps/ $\sqrt{E}$	
z-position resolution^b, σ_z	1.1 cm/ $\sqrt{E}$ (weighted)	
Azimuthal angle resolution^f	~ 8.5 mrad	
Polar angle resolution^f	~ 8 mrad	

The energy resolution has been studied as a function of polar angle, at a dedicated beam-test run in Hall B Jefferson Lab, where a photon beam impinged on a prototype calorimeter module at small polar angles [13]. The extracted dependence is shown in Fig. 1.

3. Geometry and Parameters

In order to meet the above requirements, the BCAL design was based on scintillating fibers embedded in a lead matrix (PbSciFi), which results in a relatively high–resolution sampling

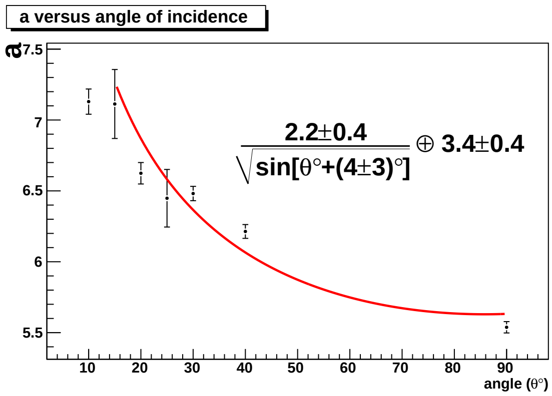

Figure 1: The statistical/stochastic parameter, a, of the energy resolution equation was determined to be ≈5.5% as shown in Table 1, at a polar angle of 90°. However, this term depends on the polar angle of incidence, and steadily decreases as the angle of incidence increases.

calorimeter. A zoomed-in view of the matrix is portrayed in Fig. 2. The ratio of the active scintillator to the passive high-Z material, as well as the diameter of the fibers, affects the energy and timing resolution, the radiation length, and the uniformity in the electromagnetic (EM) to hadronic response (the e/h ratio).

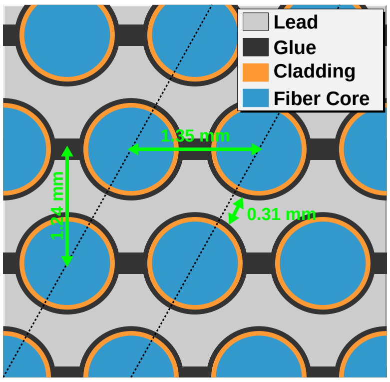

Figure 2: Close-up view of the BCAL matrix details for Prototype-1. The distance between layers of fibres (radial pitch) is 1.24 mm as opposed to the 1.22 mm of the production modules, while the azimuthal pitch is 1.35 mm.

Of direct relevance to the GlueX experiment is the calorimeter (EmCal) built for the KLOE experiment at DAΦNE [14, 15, 16], which also operated in a solenoidal magnetic field for more than a decade. The KLOE collaboration built a device with nearly triple the inner radius needed in GlueX and 4.3 m in length. The device utilized 1 mm diameter scintillating fibers, with a fiber to lead to glue ratio of 48 : 42 : 10. The BCAL design was based on that design, which, however, employed conventional PMT readout at each end that was possible due to the lower field and more favorable field gradient of KLOE compared to GlueX. The BCAL requires devices that are practically immune to magnetic fields; Silicon Photo–Multipliers (SIPM's) operate reliably in such conditions [17, 18, 19, 20, 21].

The BCAL design is depicted in Fig. 3. The barrel shape, polar angle acceptance, the 48 modules and the readout segmentation are clearly visible in the four panels. It should be noted that for budgetary reasons (electronics) the SiPMs are summed in a 1:2:3:4 configuration along the radial direction, as portrayed by the different colours in panel (d).

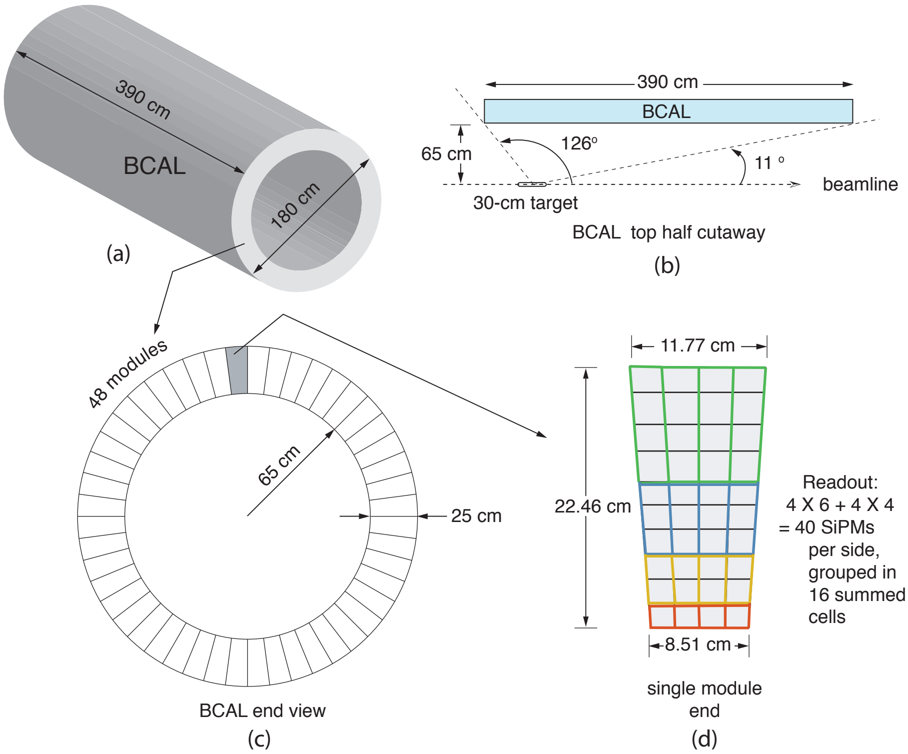

Figure 3: Sketch of Barrel Calorimeter readout. (a) BCAL schematic; (b) a BCAL module side view; (c) end view of the BCAL showing all 48 modules and (d) an end view of a single module showing readout segmentation in four rings (inner to outer) and 16 summed readout zones.

The design parameters for the BCAL are given in Table 2. These are grouped into the geometrical dimensions, fiber properties, and lead sheet dimensions, from which the bulk properties of the BCAL are determined, such as the effective mass (180) and atomic numbers (72), and density ($4.88 g/cm^3$). It should be noted that the number of radiation lengths reaches a peak value of $67 X_0$ at 14°.

4. Fiber Selection

Kuraray SCSF-78MJ fibers[1] were selected for the BCAL, as they have an attenuation length near 4 m. It is also important that the fibers yield the highest possible amount of light, as this

[1] Kuraray Plastic Scintillating Fibers (`kuraraypsf.jp/psf/sf.html`)

Table 2: BCAL parameters. Superscript: a - design parameters of the BCAL specified for the final detector; b - quantities that have been measured; c - specifications from the manufacturer; d - from literature; e - parameter calculated from known quantities; f = parameter estimated from simulations. The number of radiation lengths is at $\theta = 90°$.

Property	Value	Ref.
Total weight^a	25 metric tons	
Number of readout channels^a	3840 SiPMs	
Number of modules^a	48	
Module length^a	390 *cm*	
Module inner cord^a	8.51 *cm*	
Module outer cord^a	11.77 *cm*	
Module thickness^a	21.83 *cm*	
Module azimuthal bite^a	7.5°	
Number of fibres^b	736,800	
Radial fibre pitch^b	1.22 *mm*	
Azimuthal fibre pitch^b	1.35 mm	
Lead sheet thickness^c	0.5 *mm*	
Fibre diameter^c	1.0 *mm*	[7]
First cladding thickness^c	0.03 *mm*	[7]
Second cladding thickness^c	0.01 *mm*	[7]
Core fibre refractive index^c	1.60	[7]
First cladding refractive index^c	1.49	[7]
Second cladding refractive index^c	1.42	[7]
Volume ratios^b	37:49:14 (Pb:SF:Glue)	[24]
Effective mass number^e	179.9	[24]
Effective atomic number^e	71.4	[24]
Effective density^e	4.88 g/cm^3	[24]
Sampling fraction^f	0.125	[25]
Radiation length^e	7.06 g/cm^2 or 1.45 cm	[24]
Number of radiation lengths^e	$15.1X_0$ (total thickness)	[24]

feature impacts the energy and timing resolutions as well as the detection threshold. The attenuation length [22] and the number of photoelectrons [23], N_{pe}, have been reported previously. The quality assurance results confirmed that the fibres were of high quality and complied with GlueX specifications.

5. Module Construction

Fourty eight BCAL modules were constructed, plus a spare. Each BCAL module consists of 185 layers of corrugated lead sheets, each of 0.5 mm thickness, sandwiching 184 layers of the selected 1-mm-diameter fibers bonded in 0.5 mm-deep grooves of the lead sheets using BC-600 optical epoxy[2]. This geometry, after machining to the trapezoidal shape, results in ~14,300 fibres per module. Each module's construction was organized into four steps of progressively decreasing width: 20 layers at 13 cm, 60 layers at 12 cm, 60 layers at 11 cm and 40 layers at 10 cm from the builds, the actual layer count was 20/63/63/39. This shape lends the nickname to the construction process of 'Mayan Pyramid' builds and is schematically depicted in Figure 4. Step-by-step construction procedures are detailed in reference [26].

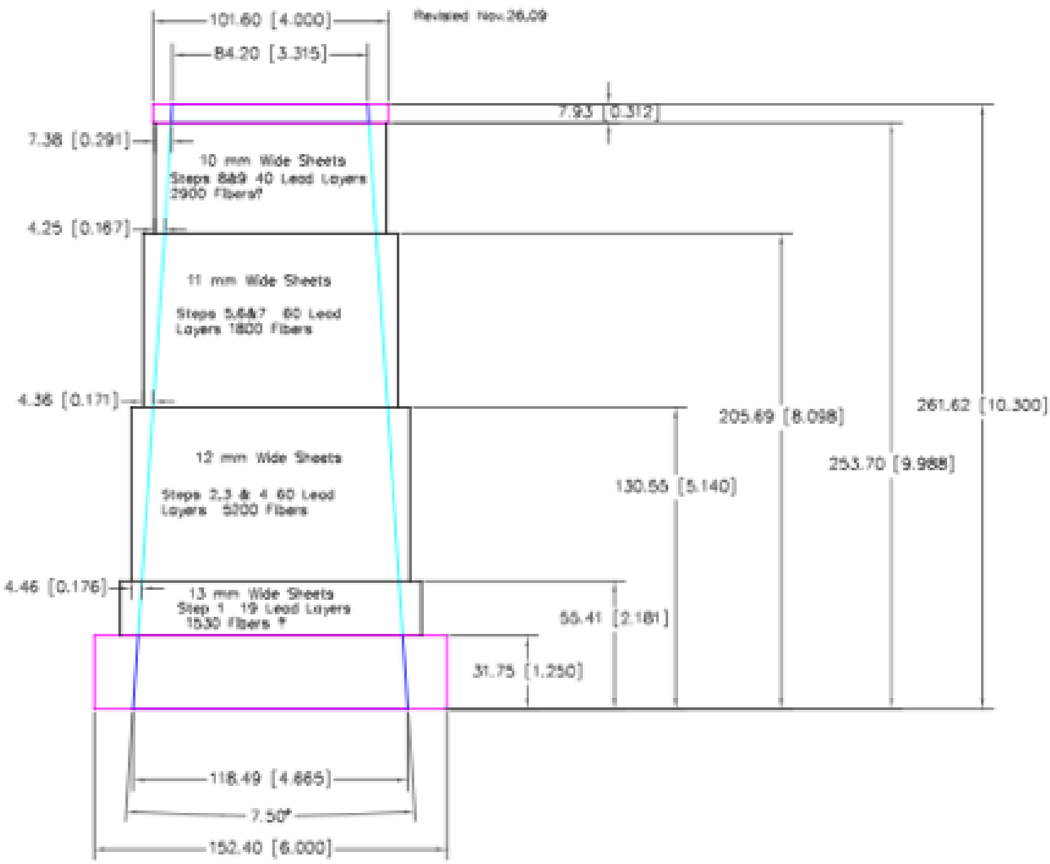

Figure 4: A cross sectional sketch of the BCAL in the construction stage is shown. Each module was built in the shape of a 'Mayan Pyramid' (black outline) in order to economize in the use of fibers; the pyramidal shape was machined into a trapezoidal one (cyan outline) at the end of the construction. (Color online)

The main instrumentation for the construction included two electro-pneumatic presses and a plastic deformation device ("swager") used to introduce grooves into the lead sheets. A standard overhead ventilation and filtration system was used and the lab was kept very clean to minimize

[2]St. Gobain Crystals & Detectors, Hiram, OH 44234, USA (www.bicron.com)

particulate matter that could descend on the gluing surfaces. The overhead fluorescent lights were covered with yellow UV-absorbing film (TA-81-XSR[3]) to protect the fibres from UV exposure, as detailed in [22].

5.1. Lead Handling

The lead[4] came in coils, cut to width by the vendor to accommodate the 'Mayan' construction process: 10-cm, 11-cm, 12-cm and 13-cm wide, and weighed 50-70 lbs each. Each coil yielded on average ten 398-cm-long cuts. Each lead coil was removed from its package in turn and an aluminum rode was inserted through the coils core and the rods ends were balanced on lead blocks at the in-feed edge of the swager table, thus creating a dispenser. Lead was dispensed from the bottom of the coil onto the swager table. First, a 30-cm long piece was cut from the beginning of each roll and was swaged to ensure uniformity of thickness across its area, measured using a standard brass gauge and micrometer. After swaging each sheet was layed flat, inspected and cleaned using ethanol and wipe-all lint free cloths. If there was excessive oxidation, a Brillo pad and ethanol were used to remove it. Small wrinkles or blemishes were rectified. Each sheet was inspected to ensure that it was perfectly straight and flat. Each cut was then rolled around a 15-cm-long, 3"-diameter section of PVC tubing and stored until needed in the swaging process.

5.2. Swaging

A plastic deformation machined, termed 'swager', was custom built, to produce 4-m-long lead sheets with 0.5 mm groves along its length, spaced 1 mm apart. It consisted of two motor-driven steel drums with adjustable speed settings that would rotate in a manner to draw in a lead sheet and extrude it from the opposite side with corrugated top and bottom surfaces. The machine was modelled after a similar device used in the construction of the KLOE electromagnetic calorimeter at Frascati [15]. A picture of the Regina unit is shown in Figure 5.

Each sheet was fed in at low speed and doused with ethanol while entering the swager to prevent sticking to the swager rollers. Once a 15-20 cm length was swaged and placed flat on the exit table, the motor speed would be increased. Teflon guides at the edge of the entrance and exit tables helped keep the sheet straight.

The in-feed person would gently feed the sheet into the swager being sure to keep it firmly against the guide using only a sideways force, while avoiding the creation of folds or wrinkles and pressing down on the sheet. The out-feed person would be ready to peel the sheet off the rollers if it become stuck and/or to ensure that it comes off the rollers and onto the out-feed table surface, before it could wrap around the swager's upper drum. If the sheet was stuck too firmly onto the top roller or catches the edge of the out-feed table and thus rips or bends, the swager would be turned off and the sheet is peeled off and any damage done would be assessed and repaired accordingly. Once the sheet was lying flat on the out-feed table the swager would be turned back on (if it had been turned off before) and the sheet is fed through continuously at a the speed dial at position 2 or 3, or at a speed that is easy for the out-feed person to handle. The out-feed person would gently keep the sheet flat on the out-feed table and be ready to stop the motor if any irregularity occurs.

[3] Window Film Systems, London, ON, Canada (www.windowfilmsystems.com)

[4] Vulcan Resources, a Division of Vulcan Global Manufacturing Solutions 1400 W. Pierce Street - Milwaukee, WI 53204

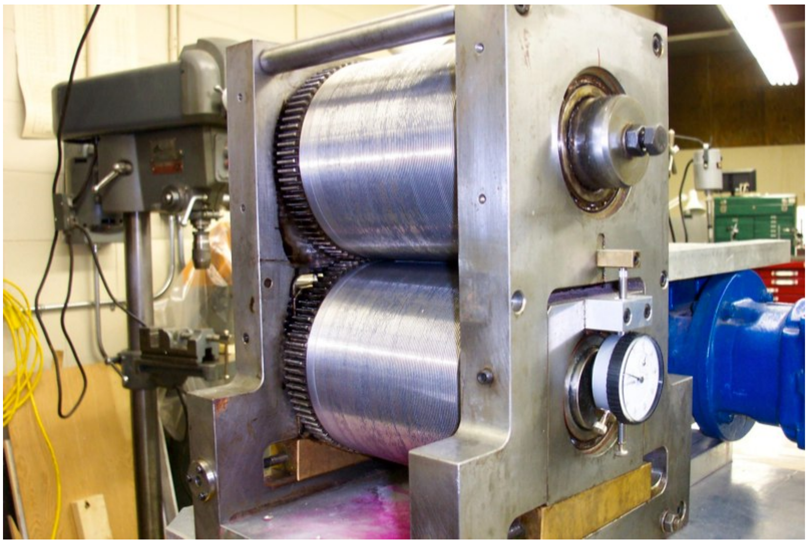

Figure 5: The swager machine is shown without its exit table, to allow a clear view of the steel drums and motor. The brass wedge at the bottom was used to adjust the spacing between to drums (measured by the gauge above it) so as to produce straight, corrugated sheets with the correct profile. (Color online)

When the sheet was completely swaged, one of its corners was clipped (using scissors) at a 45-degree angle so as to mark which edge came out of the guide side, as the swager tended to produce swaged sheets that were slightly thinner on the that side. The two outermost grooves were inspected to ensure that they ran continuously along the entire length of the sheet and did not disappear from one edge and appear on the opposite edge, an indication that the sheet did not come out perfectly parallel to the guide. The sheet would be acceptable for building if it was off by at most one groove and if it was not less than 404 cm long. The swaged sheet was then re-wrapped around the PVC tubing into a tight, compact roll until needed for the matrix construction. The sheets would be rolled it in one of two orientations: rolling from the end closer to the swagger (type 1) and rolling from the end away from the swagger (type 2). The different types were used in alternate layers of stacking during the construction process, to avoid tolerance stacking. All information was recorded in paper and electronic log books.

5.3. Module Construction

The lead-fiber matrix for each module was constructed on one of two identical electro-pneumatic presses. One of the presses is shown in Figure 6. Each press consisted of a 5-m-long steel tubing (colored blue in the photograph) having an aluminum plate on top, accurately machined to flatness. These were welded onto to a steel table frame which was bolted to the lab floor and levelled. The upper section of the presses consisted of frame through which 20 pistons with rams were fitted. The upper section was reclined and the pistons retracted when the matrix layers were being built. After usually 10 layers were laid, the upper section was brought to its vertical position and the rams deployed gradually in pairs from the middle to the outside, in order to press and squeeze out excess epoxy from the matrix ends. Ten aluminum arms would be folded down and be fastened to the press table using steel pins, to ensure that the pressure could not lift the upper section off the matrix. The pressure was applied continuously for approximately 20 hours, before the arms were loosened and the upper section and rams moved back to the reclined position to continue the layer stacking the next day. Details are provided below.

Figure 6: One of the electropneumatic presses is shown, with the aluminum connector arms and piston rams in the upright position. The press table is clearly seen as is the electronic control system in the lower left of the photograph. (Color online)

Aluminum base plates form the "spine" of each BCAL module. These were machined to have a length of 4.2 m and a thickness of $1\frac{3}{4}''$. To ensure that the base plates remained flat and horizontal, two 4" wide, 1" thick steel rails were bolted to the underside of the base plate, along its length and outer edges. All necessary features (a center-line, alignment groove to place the first guide fiber, bolt holes, slots, etc.) on the base plates were machined[5] prior to the matrix build. The features were checked before the build commenced, by measure the length of each bolt hole pocket with calibrated digital callipers, and the depth of each bolt hole pocket with calibrated digital depth gauge.

Sixteen, equally-spaced points were marked on each of the long edges of the base plate to be used as reference points in checking the accumulating matrix build height after each 20-hour press sequence was completed. The surface of the plate was abraded using 80 grit sand paper to improve epoxy bonding characteristics. The alignment groove was reworked, if necessary, using a dedicated tool. The base plate would be fixed into place using four corner brackets, mounted on the table, and pressed tight against the plates aluminum rails. Alignment was checked at every step. Two alignment posts were then set at the ends of the press. A piano wire could be threaded through both posts on adjustable, sliding (up and down) clamps. The wire was used throughout the build to ensure that the grooves of the matrix were being built parallel to the alignment groove on the base plate, but was removed during the build to allow the application of epoxy and the laying of fibers and lead sheets.

[5]Ross Machine Shop, 40 Kress St., Regina, SK S4N 5Y3

The first build on a base plate would include epoxying a guide fiber into the plate's alignment groove using the optical epoxy. Once that set, the first 13-cm wide lead sheet was placed on the plate and uncoiled using the guide fiber, and checked with the piano wire to ensure that it would sit parallel to the alignment groove. Once this was met, the sheet was coiled back and removed from the base plate. Then, a grey-colored, two-compound industrial epoxy[6] was spread on the base plate using a hacksaw blade as a notch trowel and ensuring not to cover the guide fiber with any epoxy. The first lead coil was then placed on of the epoxy at the end of the base plate and lined up with the guide fiber. It was then uncoiled carefully, keeping it aligned with the groove fiber until completed uncoiled. This was rechecked with the piano wire.

Following this, two layers of optical fibers and two lead sheets were stacked on top of the first lead sheet. Optical epoxy (100:28 ratio of resin to hardener) was applied to the top surface of each lead sheet using paint brushes, ensuring no bristles remained behind. The epoxy shines naturally, allowing the easy location of particulate matter (dust specks, lint, bristles), which would be easily removed using a toothpick. A presorted fiber bundle (done on a copper-covered table, ground for static electricity) was laid on the epoxy starting at the middle of the module and gradually worked towards the end, ensuring that each groove contained a fiber. Each bundle was 2-3 fibers short in filling all grooves, and those last 2-3 fibers were individually placed in the outermost grooves for about 100 fibers for the 13-cm lead layer. The number of fibers in a bundle tracked with the 'Mayan' widths.

Each lead sheet would be pressed down in place using a Teflon roller, run down the length of the sheet from one end to the other. Each lead sheet was checked for alignment using the piano wire and a polyethylene "puck" (termed the "runner") with a cross hair drawn on its upper surface and machined grooves on its underside, which would allow it to slip into the lead sheet grooves and smoothly slide along the length of the lead sheet. The cross hair ran directly under the piano wire and was easy to inspect visually ensure that it did not deviate from the wire's direction, as can be seen in the zoomed photograph in Figure 7. After about 10 layers of fibers and lead had been erected, the build would be suspended for the day otherwise the epoxy would begin stiffening and its excess would become hard to expel during the pressing sequence. The "stiffness" of the epoxy was monitored by a sample placed right after its mixing into a clear plastic drinking cup and tested using a clear plastic spoon. A teflon sheet and a 1" aluminum plate would would be placed on top. The press rams would contact the aluminum plate and thus apply pressure to the build. After pressing for about 20 hours, the height of the matrix was checked (using a digital depth gauge) and recorded along the 2×16 reference points on the base plate to ensure an even build in terms of height off the table (i.e. thickness of the matrix).

After the last build of a module, the recordings would be added to the thickness of the base plate at each of the 32 locations, to calculate the final heght/thickness. The ends of the fibers would then be trimmed off using a pull saw as shown in the left panel of Figure 9. A machined 0.8 mm thick aluminum plate would be bonded to the top surface of each module using industrial epoxy, ensuring a flat surface within 1 mm along the entire top surface, which spanned 10×400 cm, to ensure that the CDC would fit inside. The 3 and 9 o' clock modules in the barrel configuration supported Thompson rails which allowed the tracking packages to slide inside the BCAL and into place during installation.

In summary, it would take approximately 18 days to produce a full module (185 layers), with this process occurring in parallel on two presses, one used in the morning and the other in the afternoon. This allowed the construction of 49 modules in about two years.

[6] Araldite 2011 epoxy, in a ratio of 5:4 (resin:hardner)

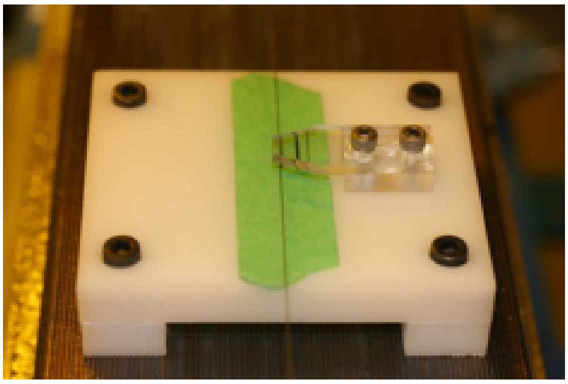

Figure 7: Piano wire runner used to ensure that the grooves in each lead sheet were absolutely parallel to the reference line and all other grooves underneath them. (Color online)

The bottom surface of the top plate was abraded using an orbital sander with 80 grit sandpaper as done with the base plate. A dam was built around the perimeter of the top lead sheet, using two strips of yellow sealant tape, to hold the industrial epoxy needed to afix the top aluminum plate, without any of the measured epoxy running off the edges as portrayed in the left panel of Figure 8) . For a few modules, when the 32 points indicated build height off by 2-3 mm, strips of dry wall tape were used as layer along the low spots, to result in a sturdier construction under the top aluminum plate, as opposed to simply filling the low spots with more industrial epoxy. After the top plate was placed and aligned, it was pressed down and held in place using 16 angled brackets which were bolded to pre-machined threaded holes on the top surface of the top plate and then bolded to vertical arms connected to the press table. Adjustable fixed stops were located at each end to ensure that the top plate was aligned with the base plate as shown in the right panel of Figure 8).

Figure 8: The white-tape dam built to hold the industrial epoxy for the top plate is shown on the left panel. The fixed stops which held the top plate motionless while the epoxy was curing, are shown on the right panel. (Color online)

5.4. Module Machining

The modules were shipped in pairs to Ross Machine Shop where they were machined to their final dimensions, subject to tolerance specfications. The modules' ends (faces) were also polished. A photograph of cutter used, is presented in Figure 9.

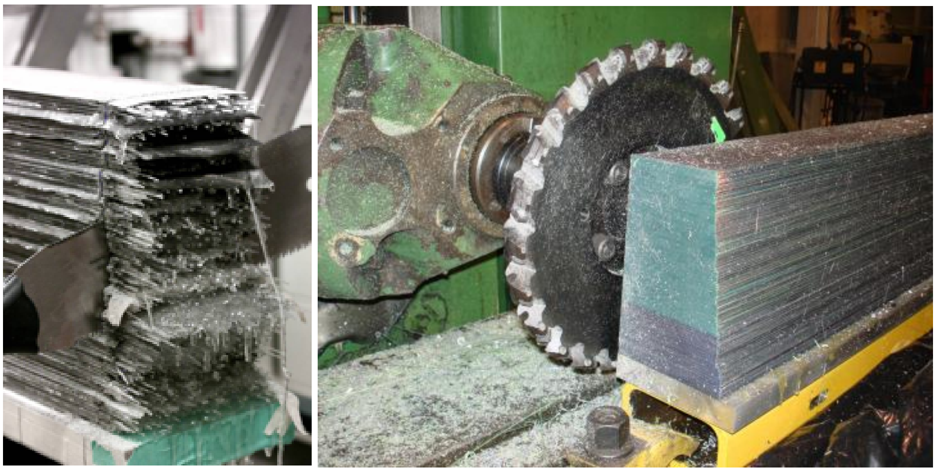

Figure 9: *Left panel:* A photograph of the end of a module after the completion of its build, showing the sawing of the excess length. *Right panel:* This photograph shows the machining of a prototype BCAL module. The cutter is clearly visible. Each set of four cutter blades was followed by a fifth, “wiper” blade, which removed excess lead so as to avoid scarring the lead-fiber surface. (Color online)

6. Delivery to Jefferson Lab

Each module was packed in custom designed crates. Four crates at a time were shipped to Jefferson Lab, using a dedicated truck with temperature control. The modules were kept at 15°C during their travel, to ensure that extreme temperatures between Regina winters (as low as −30°C in January, for example) and corresponding temperatures at Newport News (as much as 20°C in January would not stress the modules and cause delamination. The precautions were perhaps overly conservative, as we tested a prototype module by leaving it in −30°C overnight at our loading dock and them module survived with no damage.

7. Summary

The BCAL is a lead, scintillating fiber matrix designed as an electromagnetic calorimeter fo the GlueX experiment at Jefferson Lab. This detector was researched, designed and built at the University of Regina with machining carried out by Ross Machine Shop in town.

The BCAL achieved tolerances was within specifications, allowing a close-packed assembly of the modules into a barrel shape. The detector has been installed, commissioned and calibrated with cosmic rays, as well as charged and neutral particles from photon beam data running..

8. Acknowledgments

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