Production Geometry for the BCAL Modules

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Abstract

Geometry specifications for the GlueX Barrel Calorimeter modules and SiPM-based readout packaging are presented here. This information is being used in all our detector simulation packages, both stand-alone and full-description. Information from past reports has been collected herein and updated to reflect the final design dimensions and readout segmentation.

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[1] The information presented herein supersedes that in documents GlueX-doc-708, GlueX-doc-739 and GlueX-doc-922.

1 Calorimeter Module Dimensions

The electro-magnetic barrel calorimeter (BCAL) is a crucial detector subsystem of the GlueX detector, occupying the central polar region ($11^\circ < \theta < 126^\circ$) and is charged with detecting both neutral and charged particles from 40 MeV to 3.5 GeV.

BCAL consists of alternating layers of thin (0.5 mm) lead sheets and 1-mm-diameter SCSF-78MJ scintillating fibers (SciFi) manufactured by Kuraray [2]. The lead sheets are grooved after passing through a swaging machine and the fibers are bonded in the grooves using optical epoxy [3]. The resulting matrix has a *design* fiber pitch of 1.35 mm in the horizontal direction and 1.18 mm in the vertical. The BCAL is segmented into 48 modules and will contain nearly 750,000 fibres. The GlueX detector is shown in the top panel of Fig. 1, while the BCAL segmentation and views are shown in the bottom panel of the same figure.

The inner and outer radii of the BCAL are 64.3 cm and 90 cm, respectively. Each BCAL module will be built atop a $1\frac{1}{4}$ inch aluminum base plate and will be capped by an 8 mm aluminum top plate. These numbers result in a total radial dimension (thickness) of 26.175 cm (10.3") including the aluminum plates, and 22.2 cm for the PbSciFI matrix alone.

The BCAL radiation length thickness, at normal incidence, is $\sim 16X_0$ (with X_0=1.45 cm). This climbs to $\sim 67X_0$ at its maximum effective thickness, for photon angles near 15°, as arriving from the experimental target. The variation in radiation length as a function of incident angle and position as well as the photon distribution from a signature reaction are sketched in Fig. 2.

The volume ratio of lead:fibers:glue is 37 : 49 : 14 and the relevant chemical formulae are C_8H_9 for the scintillating fibers and $C_{60}H_{79}O_3N_2$ for the BC-600 two-component optical epoxy [1]. The matrix geometry has been measured using an optical microscope. The fibre pitch has been calculated from the number of layers and the total matrix thickness; it is updated in this document from the build statistics achieved during the construction of the first four production modules (Modules 01-04), as shown in Table 1. The cross-sectional matrix geometry is presented in Fig. 3.

The BCAL design dimensions are shown in Fig. 4, as specified in the signed drawings for the BCAL Construction Contract [2]. Each module is constructed in a "Mayan Pyramid" step fashion, having four steps of decreasing widths from bottom to top (13 cm, 12 cm, 11 cm and 10 cm). The number

[2] Kuraray America Inc., Houston, TX, USA (www.kuraray-am.com)
[3] St. Gobain Crystals & Detectors, Hiram, OH 44234, USA (www.bicron.com)

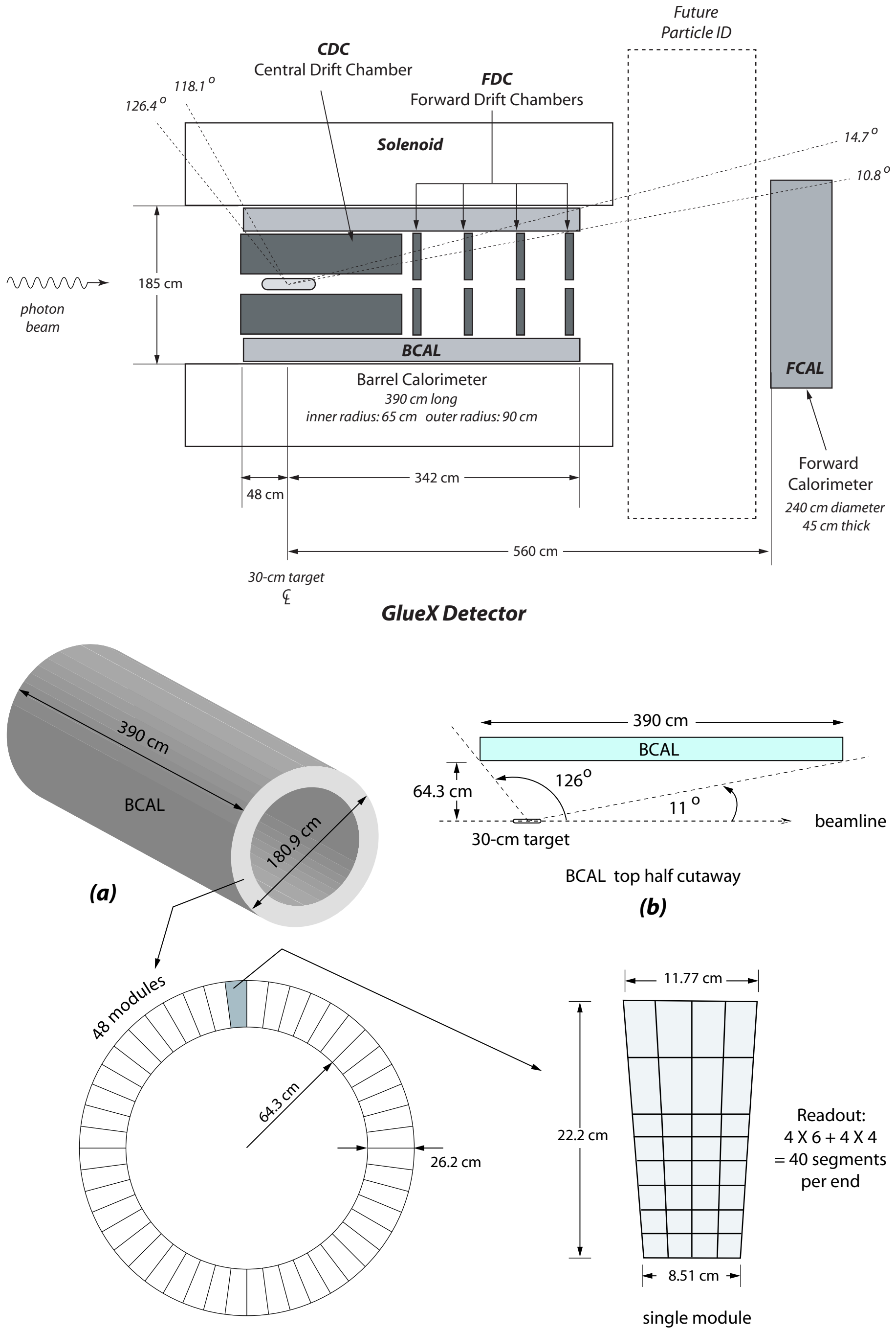

Fig. 1. *Top panel:* Schematic of the GlueX detector. The the dashed lines at angles (with respect to the beam direction) 10.8° through 126.4° represent the polar angule extent of the BCAL. *Bottom panel:* The BCAL module segmentation and perspective views. (a) BCAL schematic; (b) a BCAL module side view; (c) end view of the BCAL showing all 48 modules and (d) an end view of a module showing the proposed readout segmentation. (Courtesy of Alex Dzierba, modified to the updated outer segmentation.)

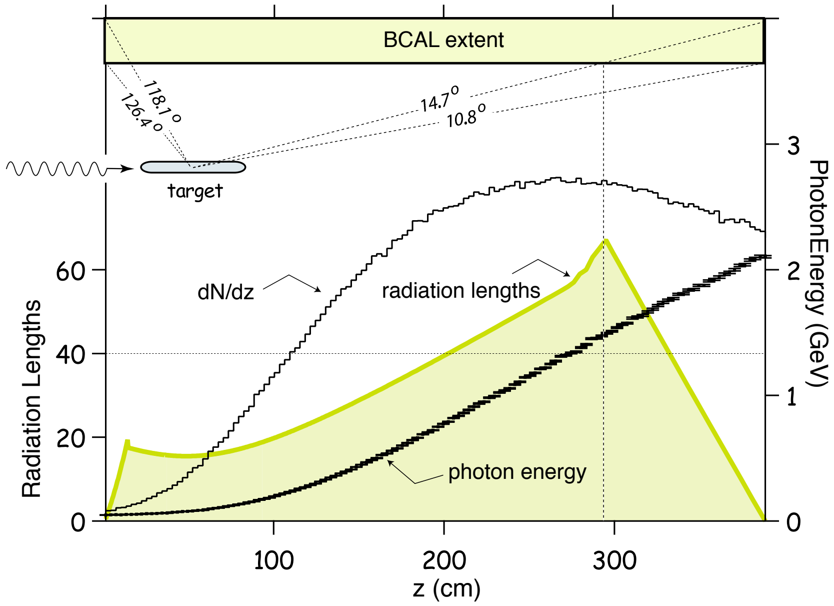

Fig. 2. The distribution of photons, their energy and integrated path length through the Pb/SciFi matrix as a function of position along the length of the BCAL for one of the GlueX signature reactions, $\gamma p \rightarrow \eta\pi^0 p \rightarrow 4\gamma p$, is shown. The target position and angular range subtended by the BCAL are also presented. (Courtesy of Alex Dzierba.)

Module Number	No. of Layers	No. of Fibres
01	187	15468
02	185	15414
03	184	15292
04	183	15253
Average	185	15357

Table 1
Build statistics from the construction of the first four BCAL modules.

of layers in each step is indicated on the drawing as is the fibre count. The design matrix height is 22.2 cm, as shown in Fig. 3, The average number of layers – following the construction of the first four production modules is 185, leading to an average vertical (radial) fibre pitch of 1.20 mm. These numbers are now final and are being used in the new round of Monte Carlo simulations to estimate the number of photoelectrons exiting the BCAL faces, following a photon hit [3].

The properties and features of the BCAL are summarized in Table 2. For other details the reader is directed to references [1] and [4].

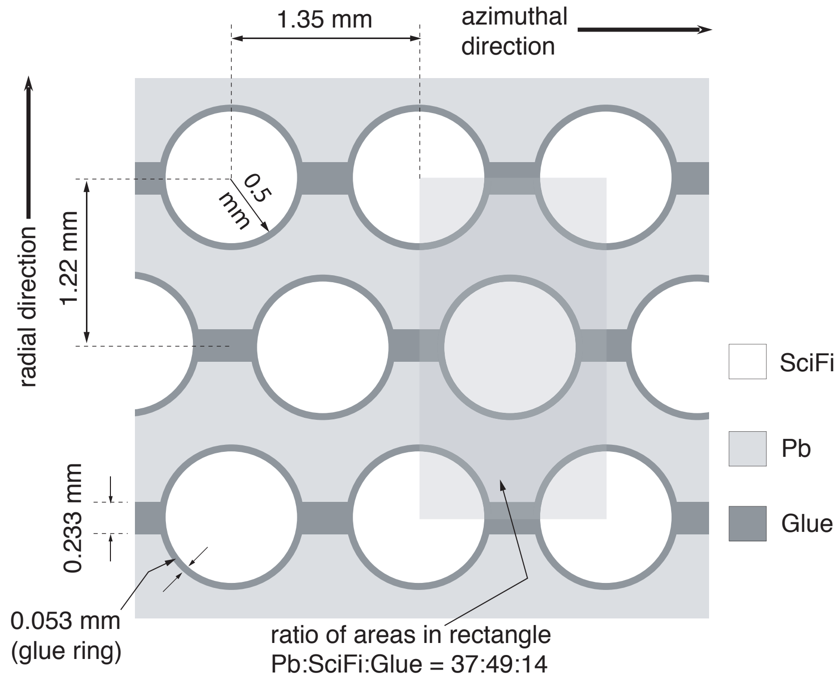

Fig. 3. A cross sectional area of the BCAL fibre matrix showing the placement of 1 mm diameter fibres in the azimuthal and radial directions. The dimensions of the azimuthal pitch, the glue box between the lead sheets and the glue ring around the fibres were determined from the prototype module using a measuring microscope. The radial pitch was calculated from the build statistics of the first four production modules. Particle tracks would appear to enter the matrix from the bottom. (Courtesy of Alex Dzierba, modified to the updated radial pitch.)

2 Light Guides

The complete information on the light guide plus Winston cones, termed *light collectors*, can be found in reference [**?**], including dimensions. Ten such light collectors have been manufactured by the TRIUMF machine shop out of a single pieces of acrylic material to these specifications (see Figure 5). This means that the rectangular, tapered and Winston cone segments are not separate. Several of these light collectors are being used in our current SiPM large-array cosmics tests. This design will be modified for the production devices, to include a trapezoidal shape at the collector's entrance, to precisely match the final sectoring of the calorimeter. Figure 7 provides an approximate view of the trapezoidal shapes, although these will be further modified as mentioned in the preceding section.

The dimensions of the light collectors are:

- The Phase-1 dimensions on the calorimeter side are 2×2 cm^2. These will be modified in the near future to the appropriate trapezoidal shape in order

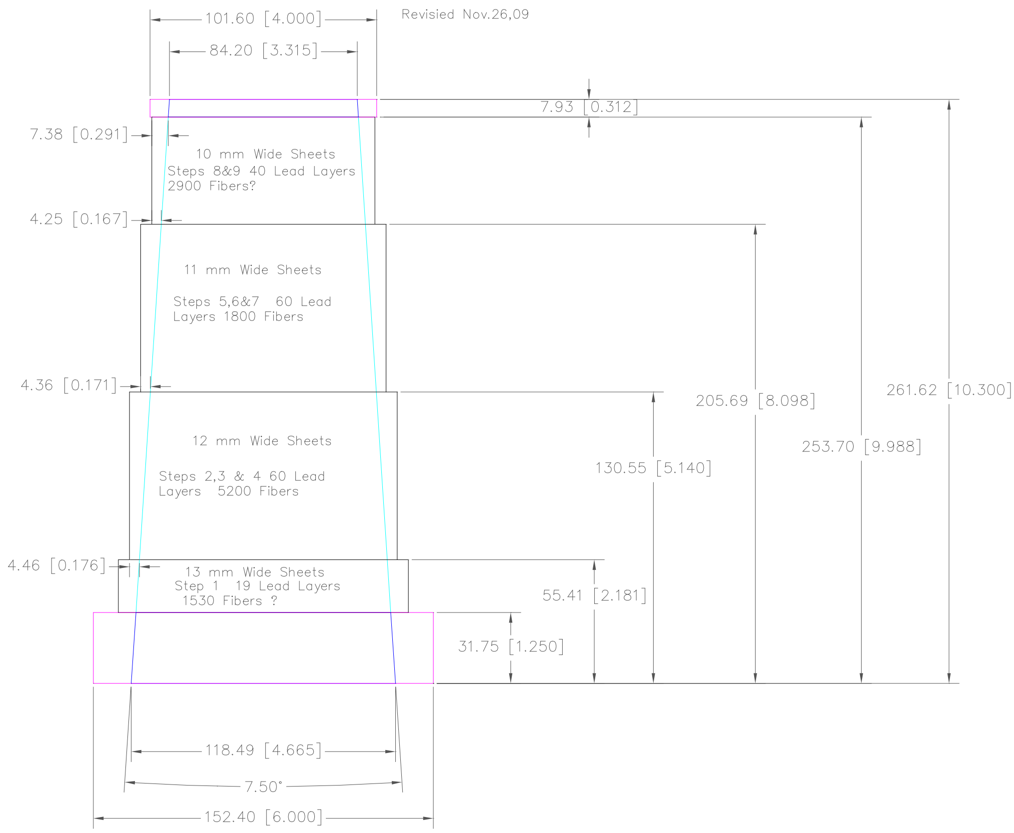

Fig. 4. The BCAL design dimensions are shown, including the base (outer) and top (inner) plates. The "Mayan" pyramid shape adopted during construction is shown in green, whereas the tapered blue lines display the final machined dimensions. *Note that this figure can be viewed and/or printed using Adobe products (Acrobat Reader, Acrobat Pro). It is not visible using the Mac OS X Preview application.*

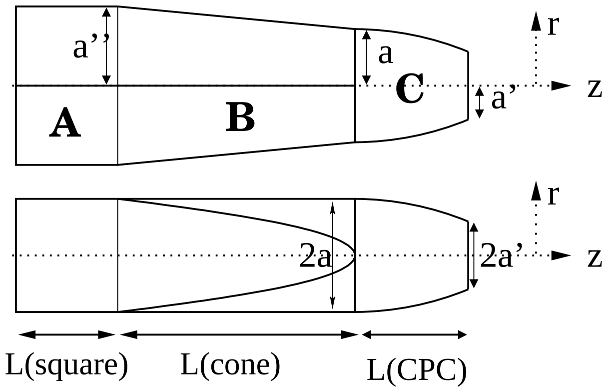

Fig. 5. A schematic drawing of the light collectors [9]. The total length (square plus cone plus CPC) is 10 cm.

to match the production sectoring.
- Length of 10 cm.
- Circular Winston Cone area of 1.26 cm^2. This matches the SM readout area.

3 Readout Segmentation

Based on the external BCAL Readout Review [5], strong justification exists for using a uniform (in area) readout for the BCAL since a non-uniform segmentation would adversely affect the floor term of the energy resolution. Nevertheless, practical considerations, namely the uneven energy deposition, which is high in the inner regions and low in the outer ones (see Figure 6), and the cost in terms of electronic channels, have led to a non-uniform solution.

The decision has been taken to use large-area, SiPM-based Sensor Modules (SMs) throughout the module. Two vendors are competing for that contract: SensL and Hamamatsu. Granularity and resolution requirements have lead to the following readout segmentation. More details on the electronics channel counts, units and cabling can be found in references [6] to [8].

- **Regions**
  - · Most of a particle's energy is deposited in the inner region, irrespective of the particle's energy or angle. As a result, finer segmentation is being employed for the inner 12 cm and coarser for the out 12.445 cm, in the radial direction.
  - · Inner Area: $\pi(79.475^2 - 67.475^2)$ cm^2 per side, or 1.11 m^2 total.
  - · Outer Area: $\pi(89.92^2 - 79.475^2)$ cm^2 per side, or 1.11 m^2 total.
- **Sensor Segmentation: 3840 readout sensors.**
  - · A 4×6 division (azimuthal $\times$ radial) of the inner 12 cm. This yields 24 readouts per module per side, or 2304 SM sensors for the inner layers.

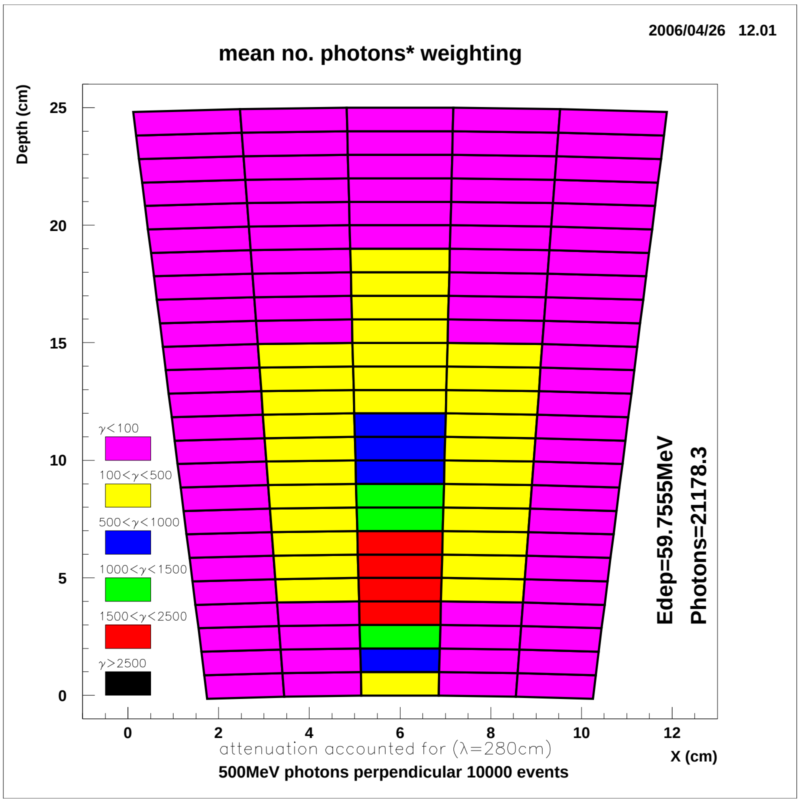

Fig. 6. Energy deposition profile for a 500 MeV photon incident at an angle of 90^o (perpendicularly). Each layer has a thickness of 1 cm. The first 12 layers are the inner ones and most of the energy is deposited there. At small incident polar angles ($\theta < 45°$), even if the photon is more energetic, the energy deposition is concentrated further inside the inner layers, and in fewer of them. This simulation does not include the Aluminum base plate. (Courtesy of Blake Leverington.)

  - A 4×4 division of the outer 10 cm. This yields 16 readouts per module per side, or 1536 sensors for the outer layers.
- **Energy Information: 1152 FADC-250 channels.**
  - A 4×2 division (azimuthal $\times$ radial) of the inner 12 cm. This yields 8 ADC channels per module per side, or 768 ADC channels for the inner layers.
  - A 2×2 division of the outer 10 cm, with each division being readout by four SMs. This yields 4 ADC channels per module per side, or 384 ADC channels for the outer layers.
  - The FADC channels will be grouped in 72 16-channel 12-bit VSX units [6].
- **Timing information: 768 F1 TDC channels.**
  - A 4×2 division (azimuthal $\times$ radial) of the inner 12 cm. This yields 8 TDC channels per module per side, or 768 TDC channels channels for the inner layers, grouped in 24 32-channel 60 ps VSX units [6].
  - It was decided not to deploy TDC readout channels for the outer layers.

The ideal dimensions of the readout cells for one side of a single module the reader are drawn in Figure 7. In that figure, the readout is divided into inner (each 2.00 cm thick and shaded green) and outer (each 5.13 cm thick and shaded yellow) cells. The 1 inch Aluminum base plate is shown at the bottom, but will be replaced by a $1\frac{1}{4}$ inch. At the top, the division into equal azimuthal bites is visible, with the module subtending a 7.5^o bite and each sector in ϕ subtending 1.875^o. The numbers of 64.3 cm and 90 cm at the right of the figure refer to the inner and outer radius of the module in units of cm, and each of the horizontal dimensions refers to the line segment immediately below it with the only exception being the number of 5.0468 cm that refers to the segment above it (top trapezium side for the first outer layer). The final dimensions will most likely deviate somewhat from these, in order to accommodate the tight packing of light guides and sensors, as well as cost in customizing the light guides in as few shapes as possible[16]. A schematic of the proposed layout is shown in Figure 8.

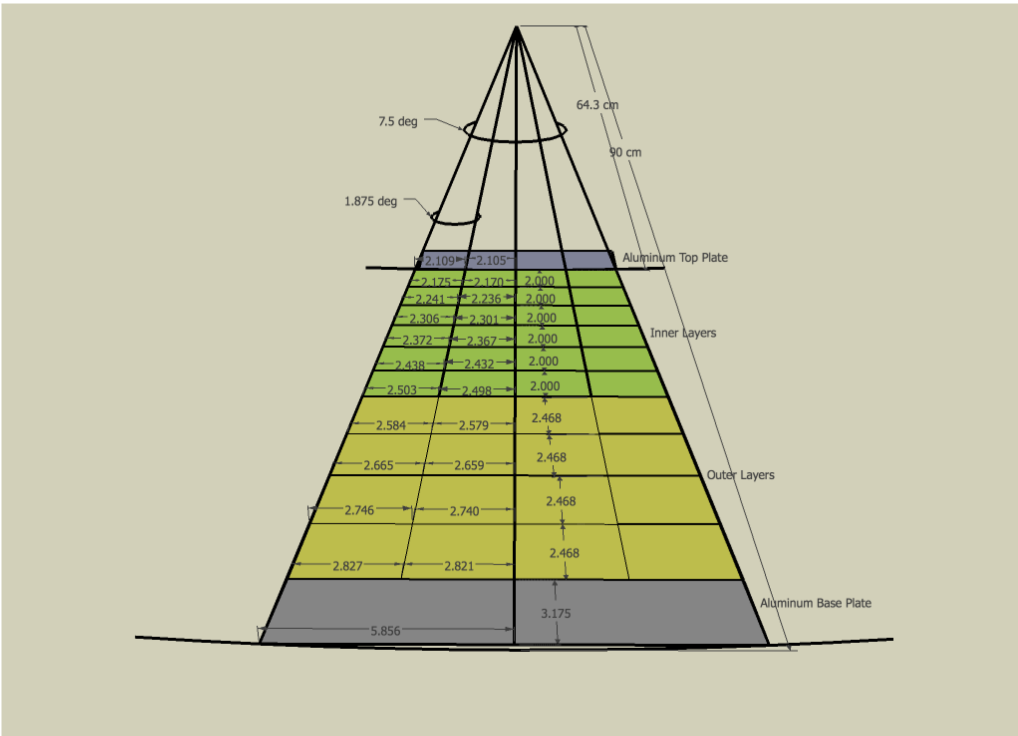

Fig. 7. Ideal dimensions of the BCAL readout cells, for one side of one module. Note that the six inner layers each have a thickness of exactly 2 cm, whereas their trapezium sides vary, increasing from a bit over 2.1 cm to over 2.5 cm; each sector would be read out by its own SM. The two outer layers have a thickness of 5.137 cm each, and would contain four SMs each. Only the left inner cells (with respect to the central ϕ ray) are labeled for reasons of clarity. The right side is mirror-symmetric. For more details the reader is directed to the text.

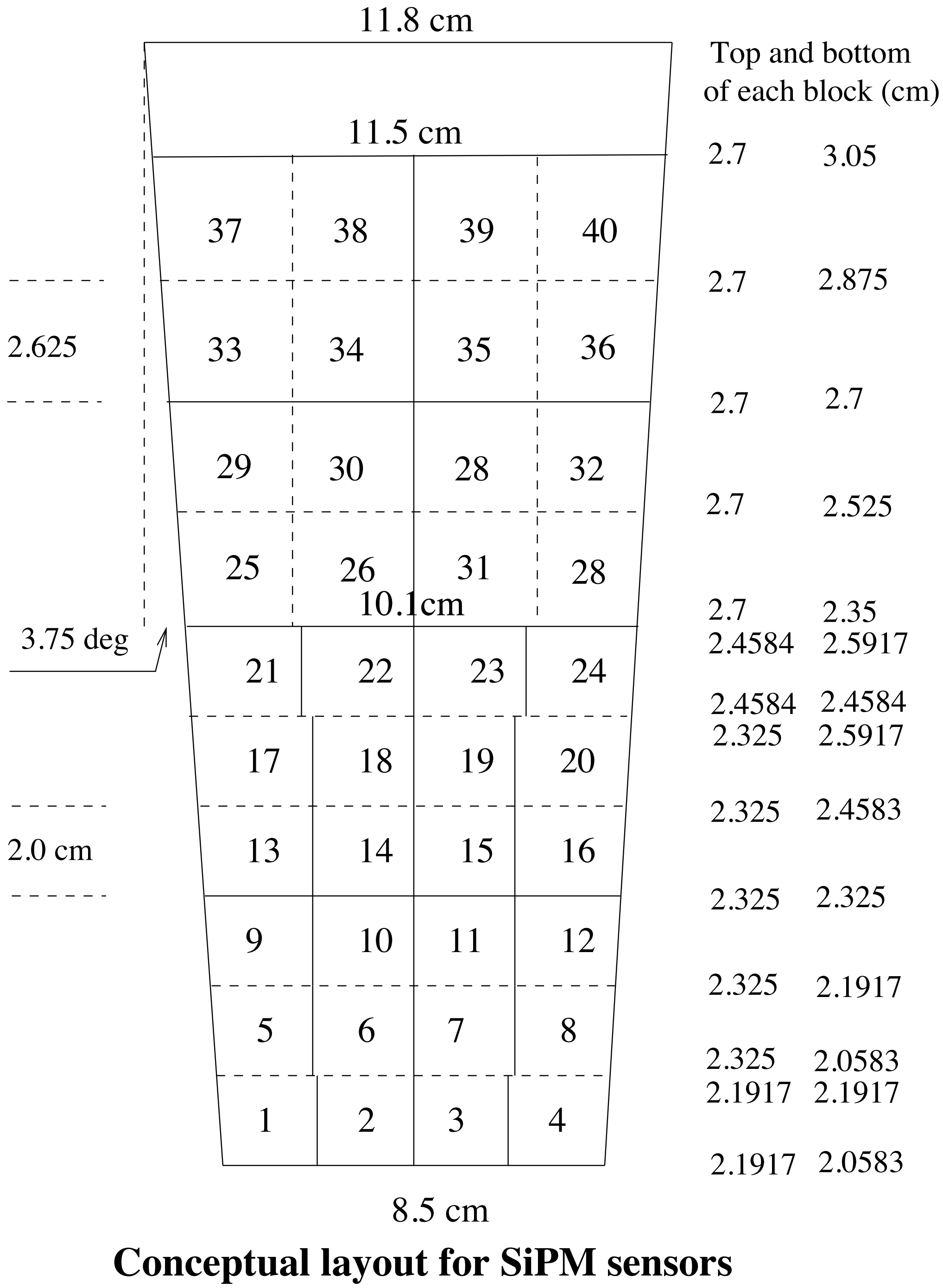

Fig. 8. Proposed layout of the area on the BCAL face corresponding to the 40 SiPM sensors. The dimensions of the bases of each block are given for reference. This scheme results in a total of 9 different guides for the outer region and 11 different guides for the inner region, for a total of 20 different light guides (8 have a mirror image and 4 are rectangular). The vertical height of all outer guides is 2.625 cm and the vertical height of the inner guides is 2.0 cm. The proposed summing groups for SiPMs are enclosed by solid lines. (Courtesy of Elton Smith.)

4 Summary

Updates to crucial BCAL dimensions and configurations were presented herein, superseding the information in documents [17] to [19].

The *non-uniform* readout option for the BCAL comprised of 2304 inner layer segments and 1536 outer layer ones for a total count of 3840, and this should be used in the stand-alone GEANT3 and FLUKA simulation packages as well as in the complete detector package HDGEANT. For the stand-alone package, the number of layers should be 185 and the fibre pitch should be 1.20 mm, leading to a total 22.2 cm height for the matrix build. To examine issues connected to the ADC dynamic range, the proposed grouping of SMs in towers needs to be taken into account, as described in Section 3, and this was done in reference [3].

Property	Value	Ref.
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]	22.2 cm	
Module azimuthal bite[a]	7.5°	
Radial fibre pitch[b]	1.20 mm	
Azimuthal fibre pitch[b]	1.35 mm	
Lead sheet thickness[c]	0.5 mm	
Fibre diameter[c]	1.0 mm	[10]
First cladding thickness[c]	0.03 mm	[10]
Second cladding thickness[c]	0.01 mm	[10]
Core fibre refractive index[c]	1.60	[10]
First cladding refractive index[c]	1.49	[10]
Second cladding refractive index[c]	1.42	[10]
Trapping efficiency[c,d,e]	5.3% (min) 10.6% (max)	[10,11,4]
Attenuation length[b]	(307±12) cm	[12]
Effective speed of light[b], $c_{\rm eff}$	(16.2±0.4) cm/ns	[12]
Volume ratios[b]	37:49:14 (Pb:SF:Glue)	[1]
Effective mass number[e]	179.9	[1]
Effective atomic number[e]	71.4	[1]
Effective density[e]	4.88 g/cm^3	[1]
Sampling fraction[f]	0.125	[13]
Radiation length[e]	7.06 g/cm^2 or 1.45 cm	[1]
Number of radiation lengths[e]	$15.5X_0$ (total thickness)	[1]
Critical energy[e]	11.02 MeV (8.36 MeV)	[14,15]
Location of shower maximum[e]	$5.0X_0$ ($5.3X_0$) at 1 GeV	[14,15]
Thickness for 95% containment[e]	$20.3X_0$ ($20.6X_0$) at 1 GeV	[14,15]
Molière radius[e]	17.7 g/cm^2 or 3.63 cm	[15]
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]	$\sim$ 8.5 mrad	
Polar angle resolution[f]	$\sim$ 8 mrad	

Table 2
BCAL properties. 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 as well as the resolutions in the table are all at $\theta = 90°$ incidence.

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