# BCAL **Segmentation Proposal**

D. Bennett[1], E. Chudakov[2], D. Lawrence[2], G.J. Lolos[3], P. Mattione[4], C.A. Meyer[4], Z. Papandreou[3], A. Semenov[3], I. Semenova[3], M.R. Shepherd[1], E.S. Smith[2], B. Zihlmann[2]

[1]*Department of Physics, Indiana University, Bloomington, IN 47405, USA*

[2]*Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA*

[3]*Department of Physics, University of Regina, Regina, SK S4S 0A2, Canada*

[4]*Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA*

---

**Executive Summary**

We request the restoration of an additional readout ring for the GlueX Barrel Calorimeter (BCAL), from the Project. This will require a subdivision of the inner most sum of three layers of silicon photomultipliers (SiPMs) into groups consisting of one and two layers, respectively, from the current summing of 3-3-4 to a new 1-2-3-4 scheme. The associated electronic channels cost is of the order of $370k. This subdivision is required to recover BCAL performance in terms of timing resolution, cluster identification (photon vs neutron), proton particle identification, invariant mass and likelihood analysis of exotic hybrids. Specifically, the additional ring will:

- Improve the impact time resolution at 1 GeV by approximately 20% and the position resolution from timing by about 30%.
- Improve the photon-neutron cluster suppression significantly as well as the neutron tagging ID.
- Improve the $\pi^+ \delta\beta$ resolution between pions and protons from the favoured exotic decays to the $b_1\pi$ channel by 18%.
- Benefit the calibration of the device significantly by permitting the calibration of a single SiPM that can be used in a boot-strapping method to calibrate the summed layers behind it.

## 1 Background

The BCAL will have 3840 SiPMs each coupled to its own lucite light guide. In 2009, during the BCAL Readout Review at Jefferson Lab, it was proposed to group the SiPMs into two towers of three for the inner layers and one tower of four for the outer ones, by performing an analog signal summation on a custom-designed board. This decision was taken mainly for budgetary reasons. A full performance impact study was not carried out at the time and the Calorimetry Working Group (CalWG) was not unanimous on that issue.

During the Calorimetry Review leading up to CD3, the issue of segmentation was brought up. One of the three reviewers expressed reservations over the summing, following the conclusion of the Review meetings. The Committee did not include these in their final report, but did highlight the following:

> *"3. It would be beneficial to develop a system for calibration and monitoring of the photosensor responses after they are installed on the detector. This is particularly important in the case of the SiPM summing option in which signals from multiple photosensors would be electronically added, with no provision for seeing the response of each one individually. A calibration procedure would be developed to certify the calibration at the single SiPM level. A possible solution would involve providing bias low voltage (LV) control for individual channels."*

So far, we have laid out the cabling for the LV, which is in (radial) layers and allows for individual SiPMs within each summed group to be turned on/off. This flexibility together with the LED-based monitoring system will provide checks on relative gain shifts of the SiPMs. A full calibration method will have to be developed, but clearly it will have to depend on the energy depositions in cells from photon showers. The outline of this procedure is presented briefly in Section 2, point 4.

Early in 2011, the CalWG begun exhaustive studies into the issue of segmentation and its impact, at four institutions. The issue is complex in that the segmentation in the light collection affects every measured variable. Our group decided that it would be nearly impossible to make a realistic comparison with any single piece of reconstruction code since these are often tuned to the specific geometry, i.e. we would not have confidence that differences were due to the segmentation and not the algorithm. It was for this reason that the more sophisticated KLOE algorithm and even the newer IU algorithm were set aside in preference to a straight-forward reconstruction algorithm limited to single photon events.

We have significantly advanced our understanding of the impact of various segmentation schemes on timing and energy resolution, and the conclusions are presented herein. Confidence on certain aspects of our procedure has been gained by validating our Monte Carlo simulations against our 2006 beam test data [1].

## 2 Improvements due to the additional layer

Our extensive simulation work demonstrates the superiority of the 1-2-3-4 scheme on all parameters examined; not a single study showed that the 3-3-4 is better for any of these. Restoring the additional ring will:

(1) Improve the timing resolution significantly, as pictured in Figure 1. For the important angular coverage of $12° - 20°$, the improvement in the time average resolution ranges between 11-22% at 0.5 GeV and 19-21% at 1 GeV; for the time difference resolution it varies between 17-28% at 0.5 GeV and 25-34% at 1 GeV [2]. This translates directly into improved positional resolution and vertex reconstruction for neutral events and it also positively impacts cluster reconstruction in the forward region where we expect the strongest exotic population. This region is extremely important for exotics searches [3], as plotted in Figure 2.

(2) Special control samples of data can be selected using the 1-2-3-4 configuration where neutrons are rejected (or identified) with high confidence relative to photons. These can be extremely useful for tuning analyses of reactions with neutrons. Samples with little neutron contamination can be used to study backgrounds. Alternatively, reactions that contain neutrons in the final state are of interest and can be identified when high photon detection is not required. The probability method, employed here and shown in Figure 3, is based on correlations of energy depositions in the different readout layers, i.e. on the energy deposition profiles [4]. This technique powerfully compliments TOF separation in the most kinematically most populated, forward region. This will also positively impact any future GlueX program with nuclear targets.

(3) Improve the $\pi^+\delta\beta$ resolution between pions and protons, as graphed in Figure 4. We have studied the identification of pions and protons from the reaction $\gamma p \to \pi_1(1600)\, n \to b_1\pi^+ p$, with secondary decay products. We find that, on average, there is an 18% improvement in the $\pi^+\delta\beta$ resolution between pions and protons in the momentum region $1.15 - 1.85$ GeV/c, demonstrating improved particle identification capability in one of the key physics reactions.

(4) Benefit the calibration of the device significantly by having a single SiPM readout channel in the data stream. Performing the calibration in the

summed layers is non trivial. In general, the signal summing may make the energy resolution worse in comparison with the individual readout, if the responses of the sensors summed have not been equalized and the shower splitting between the cells involved fluctuates on a shower-to-shower basis. In particular, at small incident angles the shower is contained in only two layers (about 20 radiation lengths). The 1-2-3-4 summing scheme would allow the ideal individual calibration of these two layers, while the 3-3-4 scheme would not. At larger incident angles the response of the third layer can be measured.

Notes:

- Initial studies into using charged-particle tracks for calibrating the BCAL have been carried out [5]. Although this method is worthwhile pursuing further, it is inadequately accurate as a sole means of calibrating the calorimeter, due to the spread of the energy deposition as well as the production of hadronic showers, complicated further by the strong curvature of the tracks.
- The SiPM preamp and summing circuits are designed to have a dynamic range of greater than 1:400. The range of pulses expected in each readout channel result from photon showers generated from the threshold energy of 0.06 GeV to 2 GeV. The additional layer of SiPMs possibly relaxes the requirements on the performance of the electronics slightly, although, considering the uncertainties we conclude that going to the 1-2-3-4 scheme has a neutral effect on the electronics dynamic range.

## 3 Cost

The restored ring will require an additional 384 ADC and 384 TDC channels, with the commensurate increase in FADC and F1TDC modules, their crates, as well as low-bias power supplies and cables. The full budget estimate is shown in the Appendix.

- Note that the amount requested for the additional ring is roughly 5% of the total BCAL budget, and 0.5% of the Hall D cost. This should be placed in the context that the BCAL readout cost had been (somewhat unrealistically) estimated on an emerging technology (SiPMs) well in advance of any market knowledge.

## 4 The KLOE Experience

The BCAL has been designed and modelled after the KLOE EmCal at the DaΦne Facility at Frascati. The technology of spaghetti calorimetry was imported to GlueX from KLOE. Moreover, our reconstruction code is based on a translation of theirs from FORTRAN to C++.

Frascati is an $e^+e^-$ collider, which results in a symmetric polar angle distribution in their detector, as opposed to GlueX where we have a forward boost. The KLOE EmCal views photon showers with a maximum energy of 0.5 GeV, whereas the BCAL will view photons up to 3.5 GeV. Nevertheless, even in this favourable dynamic range situation, after years of physics analysis they concluded that their existing segmentation (4.4 x 4.4 $cm^2$ at double the diameter of the BCAL) was inadequate and they are working towards a segmentation upgrade having a factor of 16 improvement (four in the azimuthal and four in the radial direction), leading to a 1.1 x 1.1 $cm^2$ readout using small light guides and SiPMs [6].

Because the KLOE EmCal and GlueX BCAL detectors have similar design, the fact that KLOE determined that the EmCal readout segmentation needs a significant upgrade indicates that the BCAL would greatly benefit from one as well.

## 5 Margins/Contingency

We have taken decisions for the BCAL that will impact the physics extraction. Among these, SiPM summing was chosen (cost reasons) and an air gap was introduced (mechanical reasons) between the SiPMs and light guides, which will result in loss of light particularly significant at low energies. Also, we have no TDCs for the outer layers (cost reasons), which affects position resolution and cluster recognition. The study herein demonstrates that the addition of a ring will aid in recovering some of the lost performance.

## 6 Recommendation

We request the restoration of an additional readout ring for the BCAL. The associated electronic channels cost is of the order of $370k. This is requested to recover BCAL performance in terms of timing resolution, cluster identification (photon vs neutron), proton PID, invariant mass and likelihood analysis of exotic hybrids.

## References

[1] David Lawrence, "Matching BCAL M.C. Energy Resolution to 2006 Beam Test", GlueX-doc-1854 (2011).

[2] David Lawrence, "M.C. Studies of BCAL Readout Segmentation", GlueX-doc-1801 (2011).

[3] Alex. R. Dzierba, "Physics and Calorimeter Performance Metrics", GlueX-doc-985 (2008).

[4] A. Semenov and I. Semenova, "Photon-Neutron Separation with BCAL", GlueX-doc-1865 (2011).

[5] A. Semenov and I. Semenova, "Hadronic Calibration of BCAL", GlueX-doc-1344 (2009).

[6] P. Branchini, F. Ceradini, G. Corradi, B. Di Micco and A. Passeri, Journal of Physics: Conference Series 160 (2009) 012022.

# 7 Appendix

Graphs from the studies carried out supporting the above goals are shown below. The figure captions contain the requisite information.

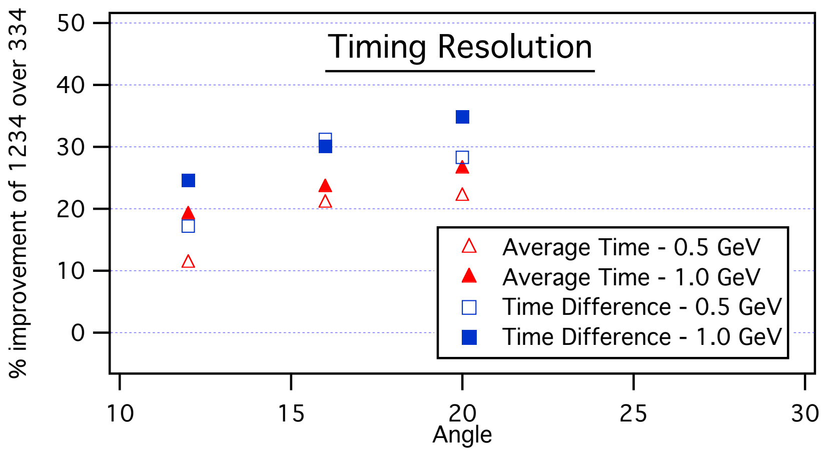


Fig. 1. This figure shows the percent improvement in the average time and time difference resolution of the BCAL in going from the 3-3-4 to the 1-2-3-4 segmentation [2]. The simulation at 90° shows that the two segmentations offer similar resolution; these points were not shown for ease of scaling the graph. As noted above, the region below 30° is vital for the investigation of exotics.

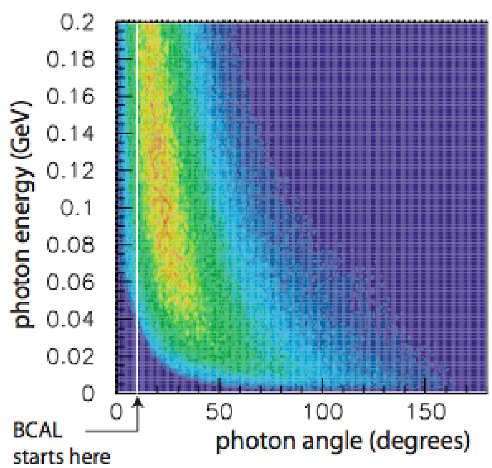


Fig. 2. This scatterplot [3] shows the energy versus angle for the lowest energy photon in the event for $\gamma p \to b_1 \pi^0 n$. The region below 30° is vital for the investigation of exotics, and here the energies of the photon span a great range. This scatterplot demonstrates the challenge for this lowest energy photon reconstruction: a large number of the low energy photons occur near the edge of the BCAL.

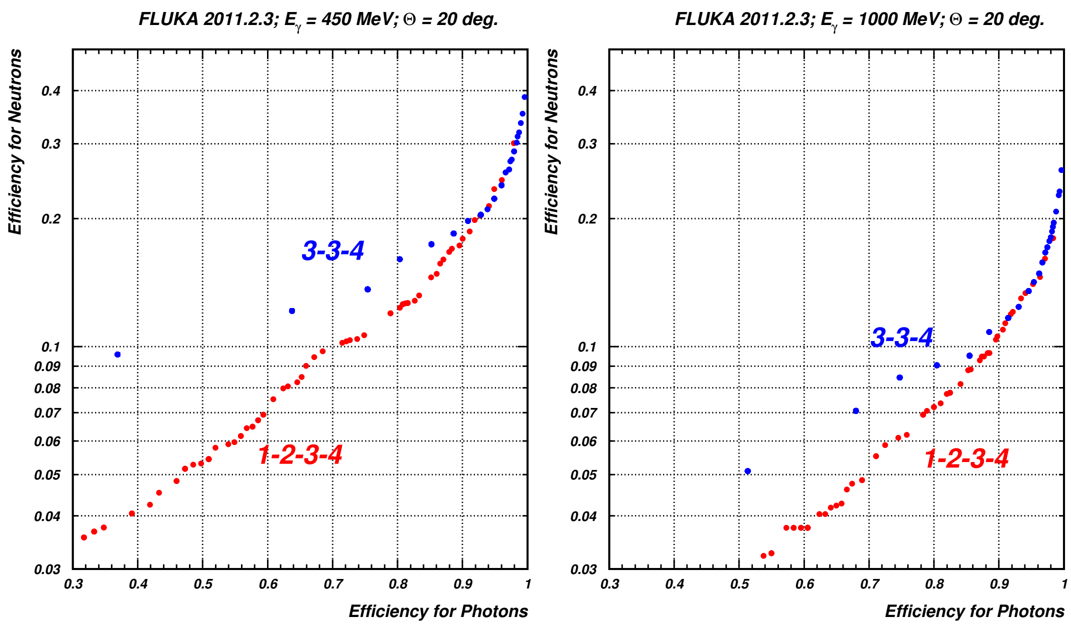


Fig. 3. These plots show the the suppression of neutrons for a fixed angle (20°). This was calculated from a probability hypothesis, which is based on mono-energetic photons and all neutrons that deposit the same energy in the entire module. Two energies were studied, 0.45 GeV and 1 GeV. Note that two segmentations are equivalent in the 90%-100% photon efficiency range, but diverge quickly below that. The gain in going to the 1-2-3-4 segmentation is evident in comparing the neutron efficiencies, for data subsets, e.g. in the 50-90% efficiency range. Such subsets are very useful in tuning the analysis code and establishing the confidence in exotic extraction.

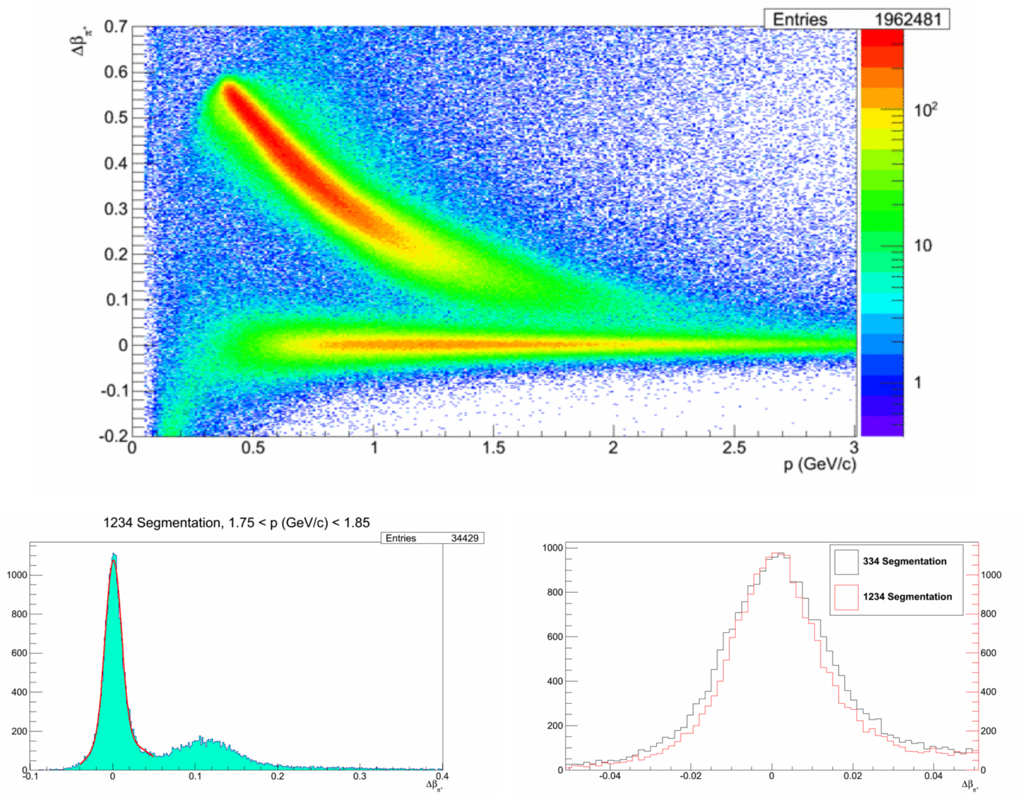


Fig. 4. We have studied the identification of pions and protons from the reaction $\gamma p \to \pi_1(1600)\, n \to b_1 \pi^+ p$, with secondary decay products. The particle identification for protons and pions is shown for the 1-2-3-4 segmentation in the top panel; the 3-3-4 segmentation looks qualitatively similar. Projected slices in momentum from both plots were taken and fitted, as shown in the left panel of the bottom row. A comparison of these fits is shown in the bottom-right plot, demonstrating that the $\pi^+ \delta\beta$ resolution improves by about 18% in the momentum region where the bands of the protons and positive pions begin to merge. In the simulation it was assumed that the charged-particle timing resolution improvement for the 1-2-3-4 segmentation is identical to that of photon clusters. No background events were included.

| Item | Quantity | Unit Cost ($) | Extended Cost ($) |
|---|---|---|---|
| Sum/preamp board mods | 96 | | 0* |
| Internam cabling (FADCs) | 384 | 4 | 1,536 |
| Internal cabling (TDCs) | 384 | 4 | 1,536 |
| Low Voltage | 48 | 250 | 12,000 |
| Bias Voltage | 48 | 250 | 12,000 |
| LEMO connectors | 768 | 10 | 7,680 |
| LEMO cables (external) | 768 | 50 | 38,400 |
| Discriminator boards | 24 | 1,600 | 38,400 |
| Disc to TDC cables | 24 | 20 | 480 |
| TDC boards | 12 | 3,424 | 41,088 |
| FADC boards | 24 | 4,500 | 108,000 |
| VSX crates | 3 | 12,000 | 36,000 |
| VME-64 crates | 2 | 8,000 | 16,000 |
| Crate CPUs | 5 | 4,000 | 20,000 |
| Crate trigger processor | 3 | 5,000 | 15,000 |
| Trigger Interface | 5 | 3,000 | 15,000 |
| Signal distribution | 3 | 2,500 | 7,500 |
| TOTAL | | | 370,620 |
| *Small, incremental cost at present | | | |

Table 1
This table shows the cost to instrument the innermost ring of the BCAL.