Monte Carlo Analysis of SciFi's in the HallD Barrel Calorimeter

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Abstract

Monte carlo simulations of the proposed design for the HallD barrel calorimeter (BCal) at Jefferson Lab have been performed using `Geant` and analyzed using Java Analysis Studio (`JAS`). Four different decay channels of the $\gamma p \to X$ reaction were studied in order to determine the (mean) energy deposited in the BCal as a function of the lead thickness for each final state particle. For each decay channel, five different geometries were tested with each geometry differentiated by the lead thickness in each module.

Monte carlo simulations were also carried out using the ray-tracing program `Guideit` in order to determine the light collection efficiency and photon time-of-flight (TOF) to the ends of 1 *mm* diameter, 4.5 *m* long single- and multi-clad scintillating fibers (SciFi). These were performed using an isotropic photon source placed at the center of fibers with geometric and optical properties similar to those manufactured by Kuraray and Pol.Hi.Tech.

Introduction

Current designs of the HallD barrel calorimeter (BCal) employ scintillating fibers (single- or multi-clad) embedded in a lead matrix, similar to that used in the KLOE[1] experiment. Specifically, the BCal design under investigation involves uniformly spaced 1 *mm* fibers sandwiched between specially grooved layers of lead. Alternating Pb/SciFi layers fill the 25 *cm* detector depth. Since the length of the HallD BCal is 4.5 *m*, fibers with long attenuation lengths such as Kuraray and Pol.Hi.Tech single- and multi-clad are under R&D at Sparro[2], with the former emerging as the front-runner for performance and cost considerations.

Although the range of lead thicknesses is conjectured to be 0.2 *mm* - 1.0 *mm*, a final decision has not been made on what thickness to use, and whether it should be constant or vary with radial depth.

What *is* known of the BCal design to date, however, is that it will consist of 54 modules each 4.5 *m* in length and 25 *cm* deep. The outer radius of the BCal is constrained to be 90 *cm* since it is located immediately inside the superconducting solenoid. In Fig. 1, ten segments are suggested giving a minimum of 108 independent azimuthal slices, each with 5 dual-ended readouts at varying depths. At the readout ends of the module, a PMT or HPMT (hybrid-PMT) will be connected for a total of 54x10x2 = 1080 PMT's.

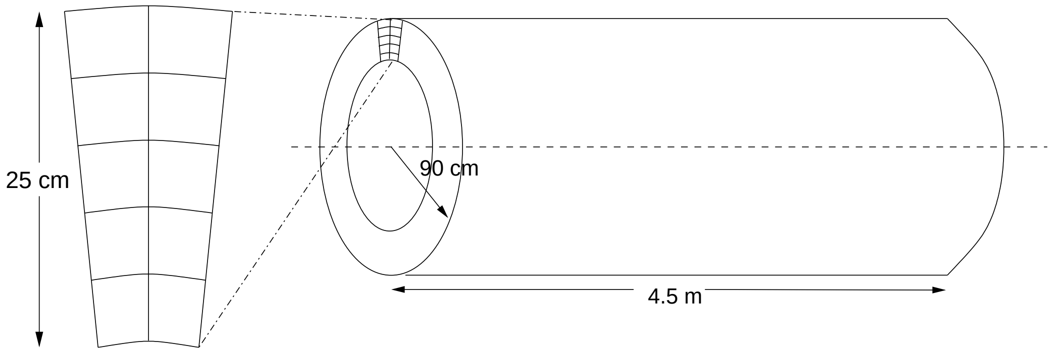
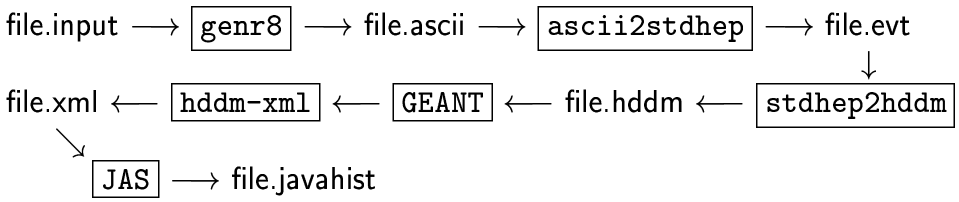


Figure 1: *Modular design of the barrel calorimeter made from layers of scintillating fibers sandwiched between layers of lead. Each of the 54 modules contains 10 segments connected to dual-ended PMT's.*

Energy Deposition Monte Carlos

Monte carlo studies using `Geant` have been performed in order to determine the mean energy deposited in the BCal for each final state particle as a function of detector depth. The goal is to determine the optimum thickness of lead to use in order to maximize the amount of energy deposited *in the* *fibers* (as opposed to the lead) while keeping the SciFi:Pb ratio as low as possible for cost reasons.

Analysis was done using `Java Analysis Studio (JAS)`, which primarily histograms the data from `Geant` and allows the user to visualize and manipulate the histograms in various ways. `JAS` uses xml files as input, which are created using the conversion utility `hddm-xml`. The whole simulation process is outlined in the following 'flowchart':



The BCal geometry is defined in the `Geant` input file BarrelEMcal_HDDS.xml which is then translated into Fortran using a translation code. To easier facilitate modifying this xml input file for different BCal geometries, a piece of C code was written which calculates the SciFi/Pb layer parameters and generates the xml code. This latter step was beneficial due to the way the geometry is defined, namely *many* alternating SciFi/Pb layers.

In order to facilitate a non-GUI interface to `JAS`, a batch analysis code (batchAnalysisMany.java) was written in Java which calls native `JAS` classes as well as HallD specific classes. In addition, batchAnalysisMany.java made calls to reaction-specific Java files (e.g., OmegaDeltaAnalysis.java) where the desired histograms are defined, although the only altered parameters are those needed to accommodate the number of final state particles[1].

The four decays channels simulated were:

$$\begin{aligned} \gamma\, p &\to \rho^0 + p && (1)\\ &\to \pi^+\pi^- + p \\ \gamma\, p &\to n + X \\ &\to n + \pi^-\,\pi^+\,\pi^+ && (2)\\ \gamma\, p &\to \omega\,\Delta^+ \\ &\to \pi^0\gamma + p\pi^0 && (3) \end{aligned}$$

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[1] If the number of final state particles is greater than 4, the array localParticleEnergy must be re-dimensioned in the HallD class files BarrelAnalysis.java and ForwardCalAnalysis.java.

$$\rightarrow \quad \gamma\gamma\gamma + p\gamma\gamma \tag{4}$$

The final state X in reaction (2) represents any resonance which eventually decays to three charged pions, while reaction (4) was included primarily as a self-consistency test to reaction (3) with all pions decaying to photons.

Five different lead-layer geometries were used:

- 0.2 *mm*, all 5 modules
- 0.5 *mm*, all 5 modules
- 1.0 *mm*, all 5 modules
- 0.2 *mm*, inside 2 modules; 0.5 *mm* outside 3 modules
- 0.5 *mm*, inside 2 modules; 0.2 *mm* outside 3 modules.

The fiber depth as defined for `Geant` is constant at 0.75 *mm*, representing the average path length through a 1.0 *mm* fiber that a particle effectively "sees" (due to the fiber's circular cross-section).

The reason for investigating the last two geometries is that most of the energy is most likely deposited in the first few modules if the ratio of SciFi to lead is larger. Therefore, perhaps less fibers are needed as the radial distance from the axis of symmetry of the solenoid increases, reducing the overall cost of the BCal.

Numerous shell scripts were written to submit the simulations in batch mode on the University of Regina's AlphaLinux cluster. Each SciFi/Pb layer was submitted using a different `Geant` random number seed, with 50,000 events simulated. One of the advantages of using `JAS` for the analysis portion of the simulations is that Java is a platform-independent language and is therefore easily portable to the Alpha's (although relatively inefficient since the newest version of `JAS` has only been ported to Compaq's Tru64 operating system).

Results of the different SciFi/Pb geometries for the various γp decay channels are shown in Figs. 2 - 5. The abscissa represents the mean energy deposited in the respective layer (SciFi or Pb) for the different final state particles identified in the legend, while the ordinate is the radial 'depth' of the detector represented here as the module number (0-4). Module identifications are clarified in Tab. 1. The lead-layer geometries are indicated on the right of each pair of plots.

Table 1: *HallD BCal module/depth definitions for the plotted results from* `Geant`.

Module #	Radial Depth Range from Center of Solenoid (cm)
0	65-70
1	70-75
2	75-80
3	80-85
4	85-90

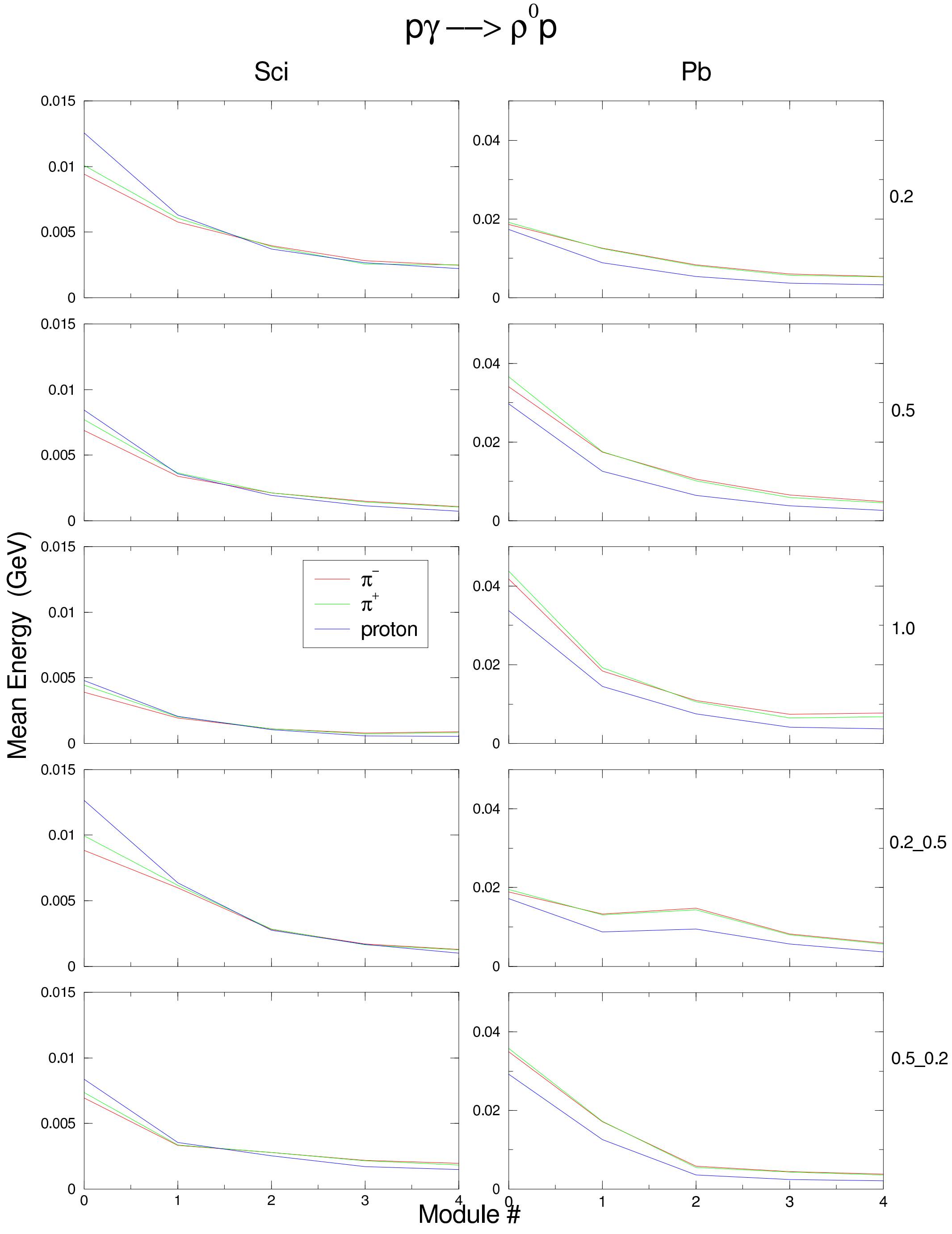


Figure 2: *HallD* `Geant` *BCal Results.*

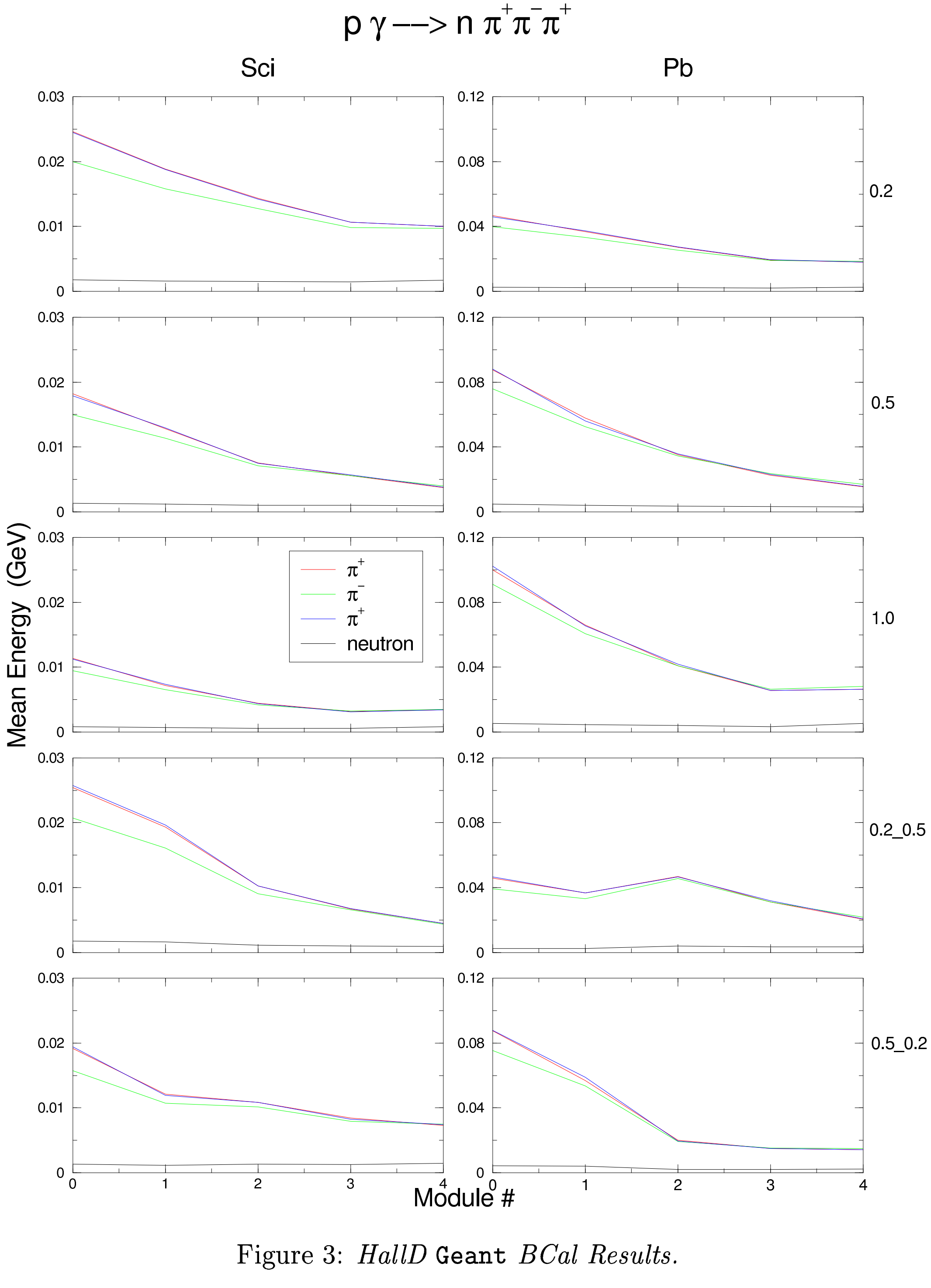


Figure 3: *HallD* `Geant` *BCal Results.*

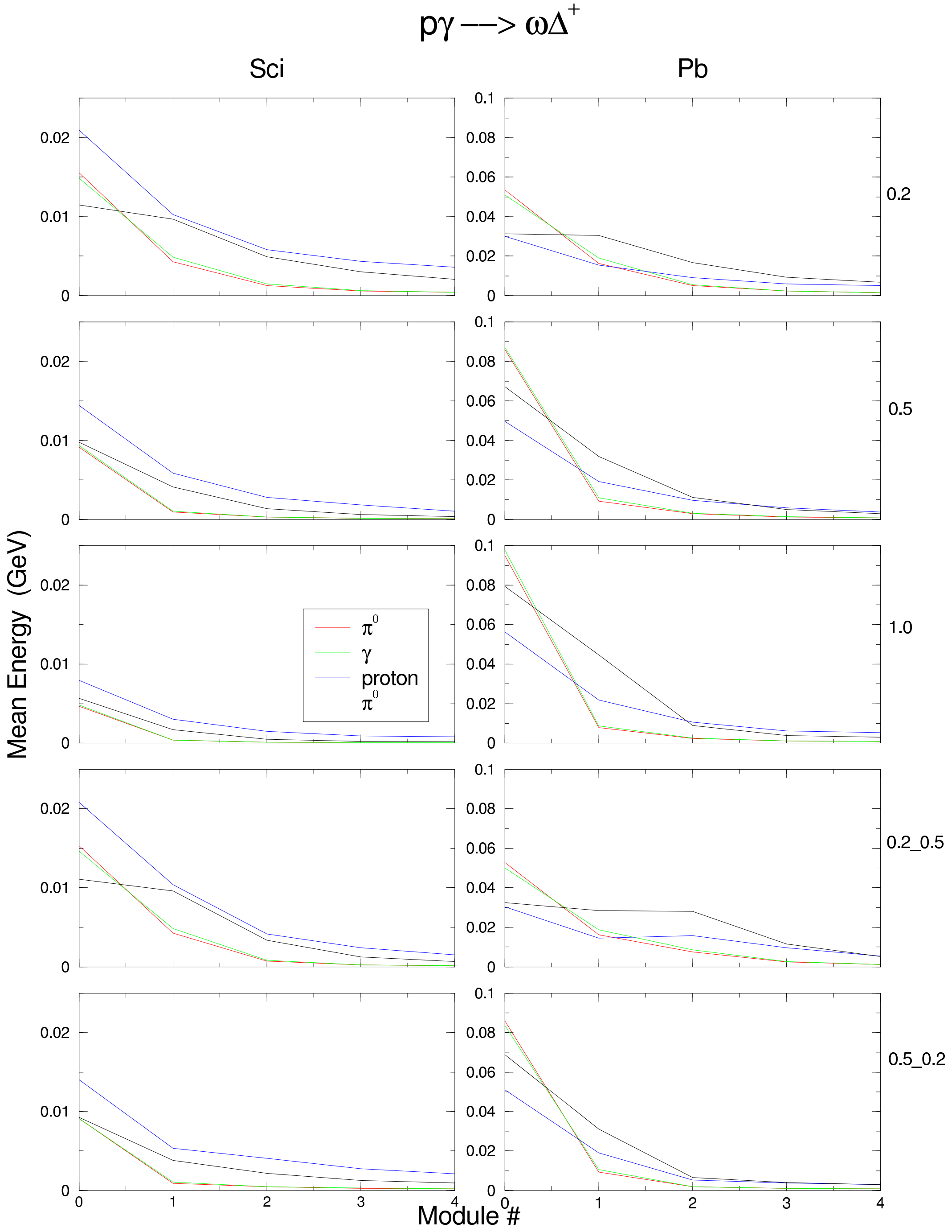


Figure 4: *HallD* `Geant` *BCal Results.*

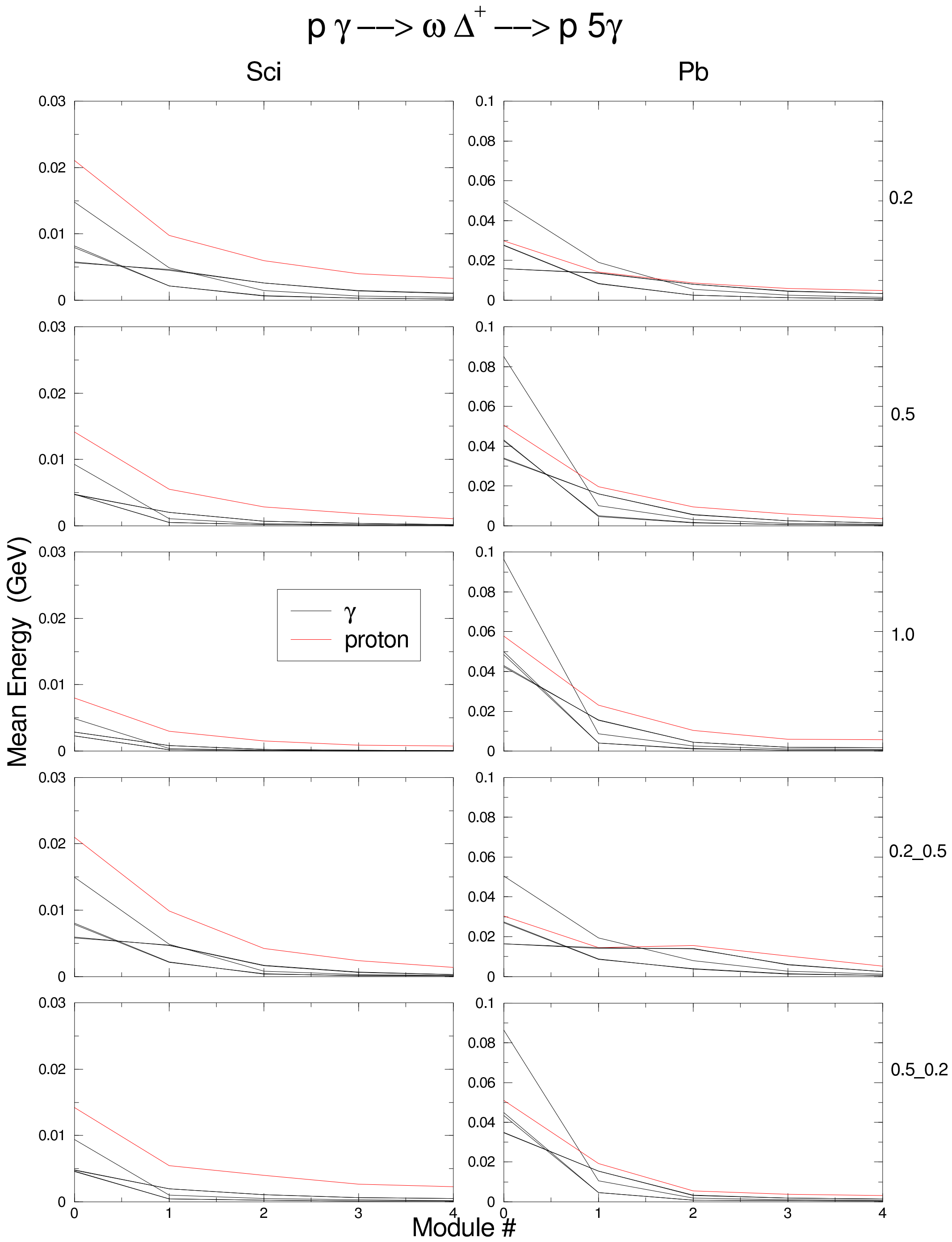


Figure 5: *HallD* `Geant` *BCal Results.*

SciFi Light Yields: `Guideit`

R&D of different types and manufacturers of scintillating fibers (single- or multi-clad, Kuraray or Pol.Hi.Tech respectively) is currently under way at the University of Regina[2]. Although a final decision has not been made (to date) on which fiber is the most suitable, there exist fiber properties which tend to be loosely manufacturer-independent. These include the core and cladding indices of refraction, and the fiber geometry. In general, each layer of cladding tends to represent approximately 3% (0.03 *mm*) of the total 1.0 *mm* diameter of the fiber. The core index of refraction is typically n_{core}=1.6, while the first layer of cladding has n_{clad1}=1.49 for single-clad fiber and the second layer has n_{clad2}=1.42. Thus, using monte carlo techniques, one can model a 'generic' fiber in order to determine the light collection yield (efficiency) of an arbitrary photon source within the fiber.

One such ray-tracing program is `Guideit` by Daniel Simon. By constructing a detector of a user-defined number of 2-d surfaces (cylinders, circles, planes, etc.), one can model the fate of photons interacting with the surfaces according to the laws of geometric optics.

It is desirable to know what fraction of photons from hypothetical SciFi events reach the end of the 4.5 *m* fibers, to which will be connected a PMT within the HallD BCal. For our purposes, a compound surface must be constructed within `Guideit` which represents each of the two fiber types. To obtain a first-order approximation of the light yield at the ends of the fibers, a isotropic photon 'source' was located at the geometric center. In addition to basic statistics such as the number of photons passing through a given surface, `Guideit` also allows histogramming of a limited set of variables which are output in `PAW`'s `hbook` format. Therefore, the time-of-flight (TOF) of the photons to the end of the fibers was also investigated in order to determine the rise times necessary for the detection and readout electronics.

Single-Clad Fibers

Figure 6 shows the surface definitions in `Guideit` representing a single-clad scintillating fiber. All units are in *cm*, with the isotropic photon source located at the midpoint (225 *cm*) of the 450 *cm* fiber length, on the Cartesian z-axis. The origin is at the center of the upstream end of the fiber. A total of five surface are needed to define the fiber: 3 cylinders + 2 circles (ends). Two cylinders representing the core-clad interface are necessary due to the

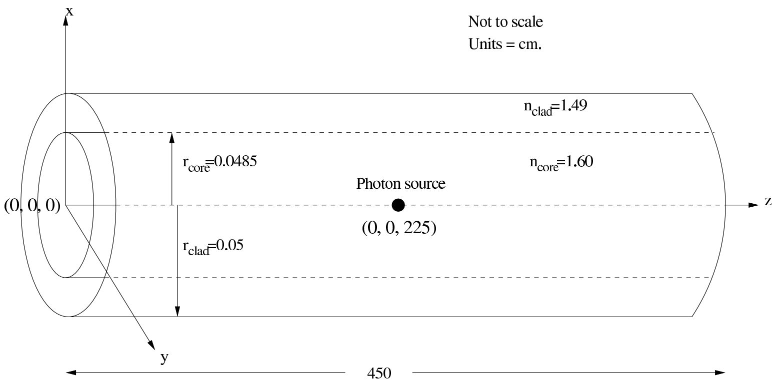


Figure 6: *Schematic of the* `Guideit` *input parameters for a single-clad fiber.*

way surfaces are defined within `Guideit`, in that photons must be able to pass back and forth across this interface. Every surface must be defined as a certain type of *gate*:

1. **Top gate**: allows photons to pass to the next sequence and histograms are booked; else photon is terminated
2. **Bottom gate**: allows photons to pass to the previous sequence and histograms are booked; else photon is terminated
3. **None gate**: photons pass through gate and are terminated, no histograms are booked
4. **Gate**: photons pass through and are terminated, histograms are booked,

and *realm* (photons incident from the INSIDE or OUTSIDE).

Therefore, one cylinder of the core-clad interface is a top gate and INSIDE realm, while the other is a bottom gate and OUTSIDE realm. A detailed geometry specification follows:

Surface 1: Core-Clad

Surface Type	Cylinder
Sequence Number	1
Center Coordinates	(0,0,0)
Radius	0.0485
Vector to Other End	(0,0,450)

Internal Index	1.60
External Index	1.49
Surface Detail	None
Attenuation Length	280
Surface Roughness	0.9999
Realm	Inside
Gate Type	Top

Surface 2: Clad-Air

Surface Type	Cylinder
Sequence Number	2
Center Coordinates	(0,0,0)
Radius	0.05
Vector to Other End	(0,0,450)
Internal Index	1.49
External Index	1.00
Surface Detail	None
Attenuation Length	280
Surface Roughness	0.999
Realm	Inside
Gate Type	None

Surface 3: Core-Clad

Surface Type	Cylinder
Sequence Number	2
Center Coordinates	(0,0,0)
Radius	0.0485
Vector to Other End	(0,0,450)
Internal Index	1.49
External Index	1.60
Surface Detail	None
Attenuation Length	280
Surface Roughness	0.9999
Realm	Outside
Gate Type	Bottom

Surface 4: Upstream End

Surface Type	Circular
Sequence Number	2

Center Coordinates	(0,0,0)
Radius	0.05
Normal Unit Vector	(0,0,-1)
Internal Index	1.60
External Index	1.60
Surface Detail	None
Attenuation Length	280
Surface Roughness	0 (Perfectly absorbing)
Realm	Inside
Gate Type	Gate

Surface 5: Downstream End

Surface Type	Circular
Sequence Number	2
Center Coordinates	(0,0,450)
Radius	0.05
Normal Unit Vector	(0,0,1)
Internal Index	1.60
External Index	1.60
Surface Detail	None
Attenuation Length	280
Surface Roughness	0 (Perfectly absorbing)
Realm	Inside
Gate Type	Gate

Source

Theta Min	0.0
Theta Max	180.0
Phi Min.	0.0
Phi Max	360.0
Starting Position	(0,0,225)

Options

# of Sources	1
Photons per Source	10000
# of Sequences	2
# of Surfaces	5
Speed of light	3E+10
Bulk Attenuation	YES

Diagonal Tracking	NO
Reflectivity	YES
Statistical Output	YES
Angular Distribution	NO

Multi-Clad Fibers

Multi-clad scintillating fibers have also been modeled to ascertain the light collection improvement over single-clad fibers. Again, each layer of cladding represents 3% of the total fiber diameter, with the outer cladding having a index of refraction of 1.42 as shown in Fig. 7. The `Guideit` input file is similar to that for the single-clad fiber, with the addition of the extra layer of cladding. All geometric input parameters are also shown in Fig. 7.

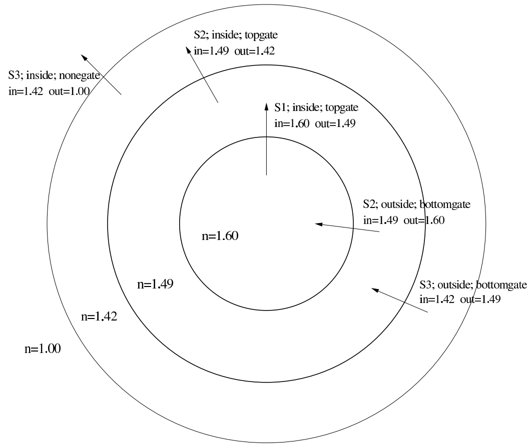
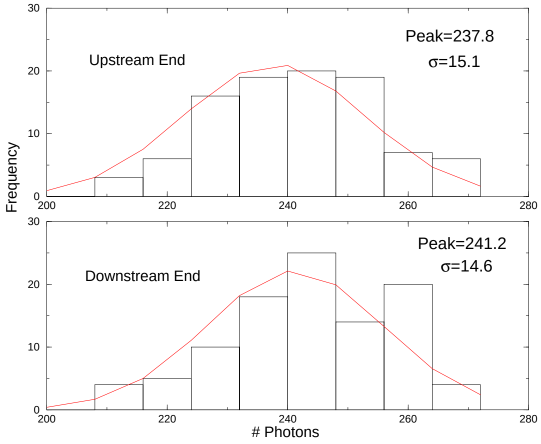


Figure 7: *Schematic of the* `Guideit` *input parameters for a multi-clad fiber.*

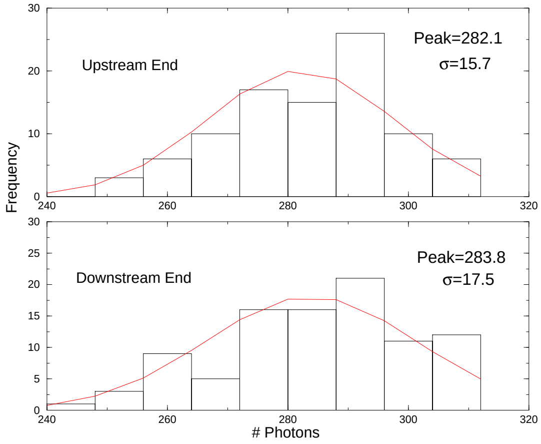
Results

Light Collection Efficiency

For each fiber type, 100 runs of `Guideit` were performed each with a different random number seed. One photon source with 10,000 isotropically distributed photons was simulated at the center of each fiber. The number of photons reaching either the upstream or downstream end of the fiber were counted, histogrammed, and fit with a Gaussian in order to determine the light collection yield with error. Histograms with statistical results are shown in Fig. 8(a) and Fig. 8(b), with approximately 2.4% of the photons reaching the ends of the single-clad fiber where they will interact with the PMT's. The multi-clad results however, show an approximate light collection efficiency of only 2.8%, about a 20% improvement over single-clad. This is contrary to the empirically expected improvement of 50%-70% of multi-clad over single-clad. No explanation can be given at this time, althoug there is possibly a problem in how the multi-clad geometry is defined.



(a) *Single-clad*

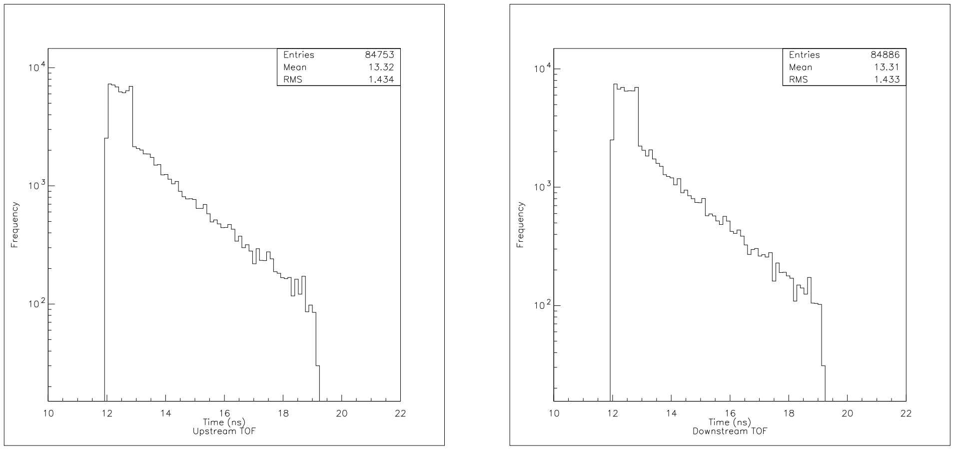


(b) *Multi-clad*

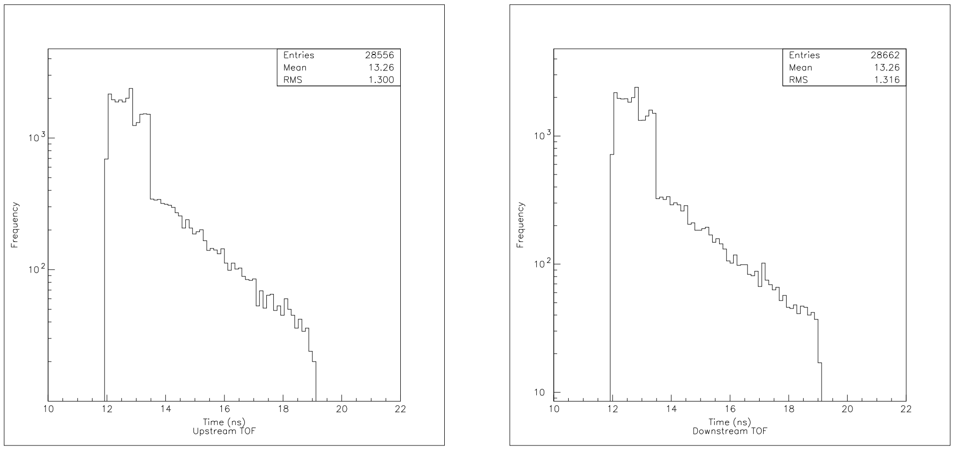
Figure 8: `Guideit` *results for the number of photons (out of 10000) collected at the ends of 4.5 m fibers. Isotropic photon source at center.*

Time of Flight

Photon time of flight (TOF) results for single- and multi-clad fibers are shown in the histograms of Fig. 9(a) - Fig. 9(d) respectively. The mean TOF for 4.5 m single-clad fibers was found to be 13.31 ns, and 13.26 ns for multi-clad fibers.



(a) *Single-clad: Upstream* (b) *Single-clad: Downstream*



(c) *Multi-clad: Upstream* (d) *Multi-clad: Downstream*

Figure 9: *Photon time of flight histograms. Isotropic source at center of 4.5 m fiber.*

References

[1] A. Antonelli et al., Nuclear Instruments and Methods in Physics Research A **354** (1995) 352; M. Adinolfi et al., Nuclear Instruments and Methods in Physics Research A, submitted.

[2] S. Vidakovic, “Tests of Scintillating Fibers for the Hall D Barrel Calorimeter”, SPARRO Group Internal Report, August 2001