Adiabatic Light Guide with S-shape Strips

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A light guide is an essential part of many scintillator counters and light collection systems. There is large interest in an adiabatic light guide which has high light transmission while converting the area of the light source to the shape of the photo-detector. We propose a variation of the adiabatic light guide which avoids a 90° twist of the strips, reduces the length of the light pipe, and significantly cuts the cost of production.

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A light guide for the scintillator counters has been the subject of many investigations since the 1950s, see Ref. [1] where the concept of the "adiabatic" transformation of the light guide cross section was evaluated. The light guide (LG) connects the scintillator counter and the photo detector (typically a vacuum PMT). The term "adiabatic" means that the cross section of the LG for propagating photons should be near constant and allow only slow deformation of the shape.

Designing an efficient LG for a wide, thin scintillator counter presents a challenge which was resolved by means of an adiabatic LG where the strips are slowly twisted by 90° [2–5], see Fig. 1. This was achieved by dividing the LG into several constant cross section strips and slowly twisting the plane of each strip. Near the PMT, when the number of remaining photons bouncing is small and the adiabatic concept is not essential, a conical section was used for further concentration of the light.

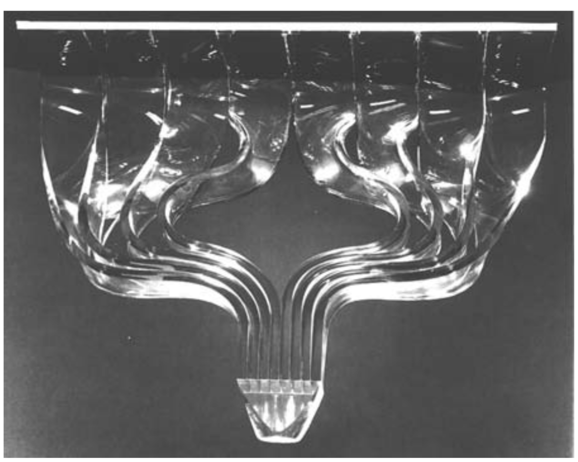

FIG. 1. Classical adiabatic light guide with twisted strips. Picture is taken from Ref. [2]). The PMT is attached to the LG through the conical section. The scintillator is attached to the top side of the LG.

The standard adiabatic LG [3] requires a 90° rotation of the strip, which is usually labor consuming and also leads to significant LG length, which adds to the spread of arrival time of photons at the photo-detector.

We propose here a cost effective, adiabatic LG in which the 90° twist is avoided. Instead of a strip twist, our LG has machined S-shaped strips and a modest out-of-plane bend. Production of these strips became possible due to modern machines such as laser cutting. A large number of such LGs were constructed at JLab and CMU, see Refs. [6, 7]. A three-strip example is shown in Fig. 2. This LG concept could also be useful in solar energy systems as it allows the transfer of the light collected in a large area to a compact photo detector (for example from a thin wave-length shifter to a silicon-based diode).

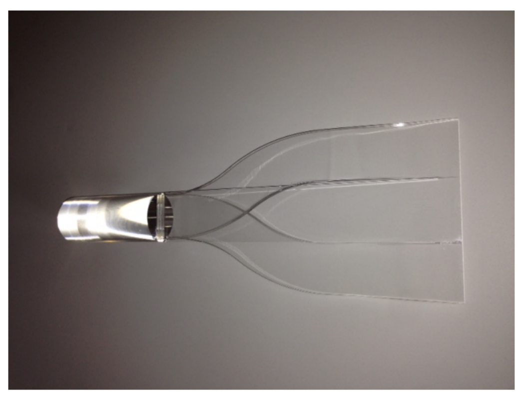

FIG. 2. The light guide made of two S-shaped strips and a straight central strip.

Monte Carlo simulations of our LG concept were previously performed using Guide-7 [8] and Geant4 [9]. In the current report we present new results of simulations made using Geant4, a Monte-Carlo based toolkit for simulating nuclear physics which is sourced in C++ [10]. Currently, generic Geant4 has all the components needed for the LG simulation. We have added a description of the custom parts of the code

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in an appendix to this paper for the convenience of the reader. Ref. [11] has the source codes of our MC.

I. PHOTON PROPAGATION IN THE LIGHT GUIDE

In the designing of the specific LG it is useful to get quantitative estimates of light propagation efficiency, so we included in this section a discussion of the LG basics for exactly such a reason. Fresnel's equations used in Geant4 provide a full description of the photon interaction with a smooth surface. Imperfections in the surface were not included in our MC.

The reflection does not change the absolute value of the photon speed relative to a normal to the surface. As a result, the photons emitted isotropically by the scintillator are divided into the initially trapped fraction (red) and instantly transmitted fraction (yellow) as shown in Fig. 3.

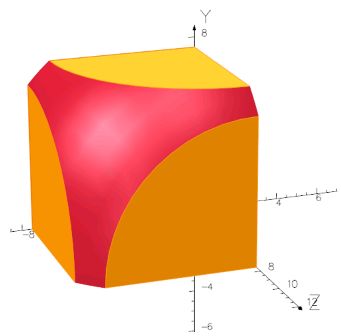

FIG. 3. Diagram illustrating the optical properties of the right angle block (1/8 of the phase space is shown).

The photons with an incident trajectory close to a normal to the surface or inclination angle $\theta \leq 41.1^{o}$) (for plastic scintillator n = 1.52) are able to escape - instantly transmitted (yellow cones in Fig. 3). When the photons originate in an inclination angle above 41.1^{o}, the photons are internally reflected inside the block until they reach the LG, (red area in Fig. 3).

For isotropic photon emission by the scintillator material the transmission fraction on one side of the scintillator equals $(1-\cos\theta)/2$ or 0.123 (out of 4π). With one PMT in the scintillator counter, the photons escape in five directions, each with a fraction of 0.123. The remaining fraction of 0.383 will go out to the LG after a number of reflections. The fraction of photons reaching the PMT was found from MC simulation.

Light transmission was investigated with several light guides. We used an isotropic emitter located in the middle of a straight section at the beginning of the LG and counted photons in the PMT attached to the end of the LG. The simulation that produced the results in the efficiency tables has $500,000$ initial photons. The LG design deals with deflection of the strip which is characterized by the ratio of the bend radius, r, to the thickness of the strip in the direction of the bend, t, and the bending angle, a/r, where a is the length of the curved area, see Fig. 4. The thickness of the strip, t, is 1 cm. The width of the straight sections, w, is 3 cm.

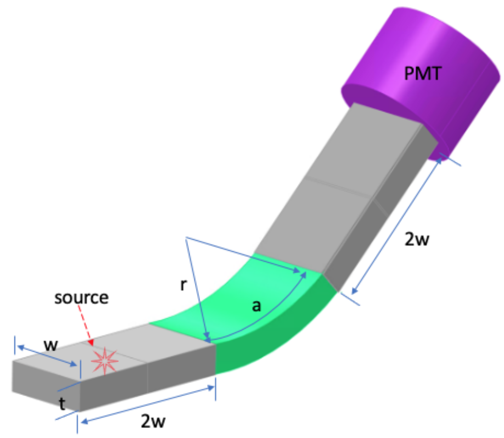

FIG. 4. The element of geometry of the classical bent strip. The curved section of the strip is shown in green. The photon source (shown as a red star) is located in the middle of the left straight section.

TABLE I. The results of MC simulation of the transmission probability through a light guide shown in Fig. 4 for the out-of-plane bending LG vs. the geometrical parameters r/t and a/r.

	r / t					
a / r	100	50	20	10	5	1
1.0	98.7	98.4	97.5	95.7	91.7	78.7
0.5	98.7	98.4	97.6	95.9	92.5	85.0
0.2	98.8	98.5	97.8	96.5	94.0	91.2
0.1	98.8	98.6	98.0	96.9	95.6	94.7

As one can see in Tab. I, the transmission is still high (92%) even for a sharp bend $r/t=5$ and a one radian bend angle, which is not obvious from the concept of an adiabatic LG.

A second set of simulation was made for an element of the proposed in-plane bend S-shape strips light guide, see Fig. 5.

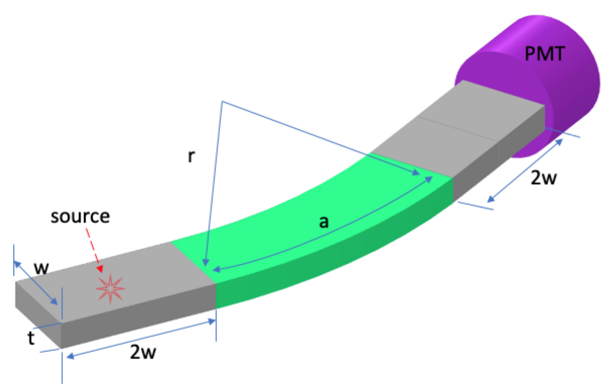

FIG. 5. The geometry of the s-shape in-plane bend strip. See also the caption for the Fig. 4.

II. STUDY OF THE LIGHT GUIDES

We evaluated spacial variation of the light collection for two versions of the LG for 15 and 25 cm wide scintillator plate of

TABLE II. The results of MC simulation of the transmission probability through a light guide shown in Fig. 5 for the in-plane bending LG vs. the geometrical parameters r/w and a/r.

	r / w					
a / r	100	50	20	10	5	1
1.0	98.5	98.2	98.0	97.1	95.6	81.2
0.5	98.6	98.4	98.1	97.2	95.9	85.2
0.2	98.5	98.2	98.0	97.5	96.4	91.5
0.1	98.5	98.4	97.9	97.5	97.2	94.8

25 cm length and 0.5 cm thickness for a 5 cm diameter PMT. The 3D picture for seven S-shape strip LG is shown in Fig. 6. Geant4 simulated tracks are shown in Fig. 7 and Fig. 8.

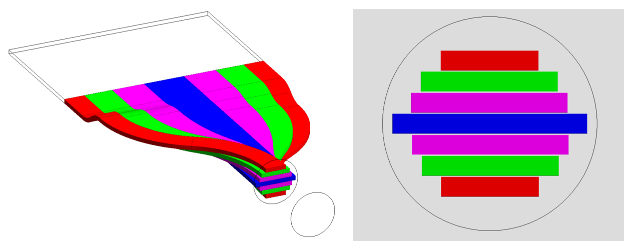

FIG. 6. The seven S-shape strip light guide design (left), made of three different S-shape strips and a straight central strip, and a direct view of the PMT (right). The r/t values for the out-of-plane bending strips in order from left to right (red to pink) are 6.7, 9.6, and 19.0 and the r/w values for the in-plane bending strips in order from left to right (red to pink) are 4.4, 3.8, and 5.7.

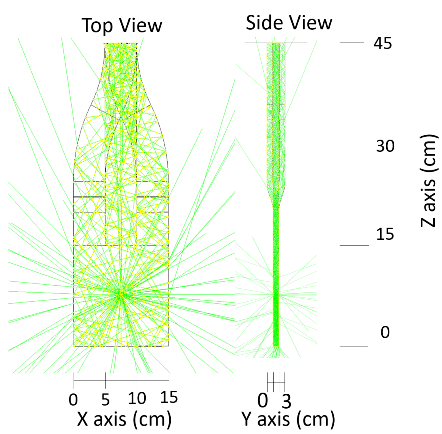

FIG. 7. Geant4 MC simulation of light propagation in the three S-shape strip design of light guide.

a. Efficiency and uniformity of photon collection. An investigation was done for the three S-shape strip LG. As it can be seen in Figs. 9 , 10 the light collection is close to 95% of the maximum possible with spacial variation on the level of 5%.

b. Photon time propagation in a light guide In this study, we used a scintillator with a thickness of 5 mm and dimensions 15 cm by 15 cm (see Fig. 7). The photon time propagation from the source to the PMT was found for isotropic emission and also for emission in the direction opposite to the LG. The photon arrival time for the first case is shown in Fig. 11 where there are two peaks, one at 2.5 and another at 3.9 ns. The first peak consists of a front portion: photons are going through the central strip of LG, and a delayed portion:

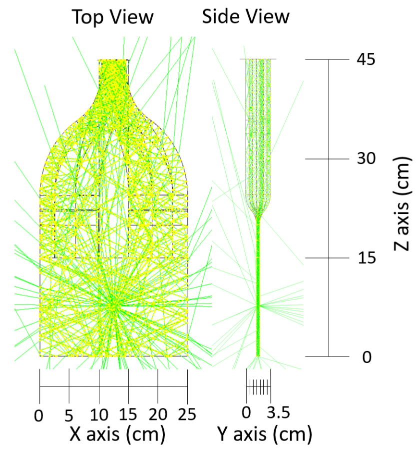

FIG. 8. Geant4 MC simulation of light propagation in the five-strip design of the S-shape light guide.

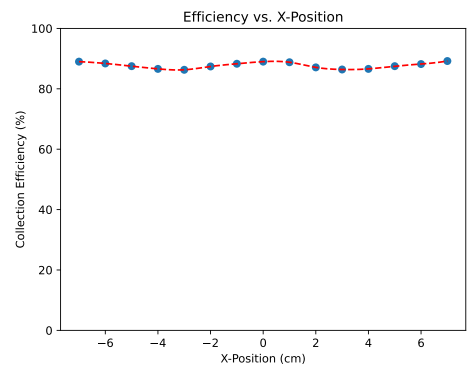

FIG. 9. Collection efficiency of light guide vs. position on x-axis of light source within scintillator.

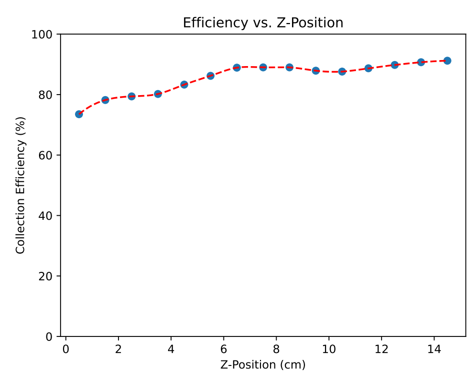

FIG. 10. Collection efficiency of the light guide vs. position on z-axis of light source within the scintillator.

photons are going via a few reflections before entering the LG.

Fig. 13 confirms that emission in the direction opposite to the LG is the origin of the second peak in time of arrival.

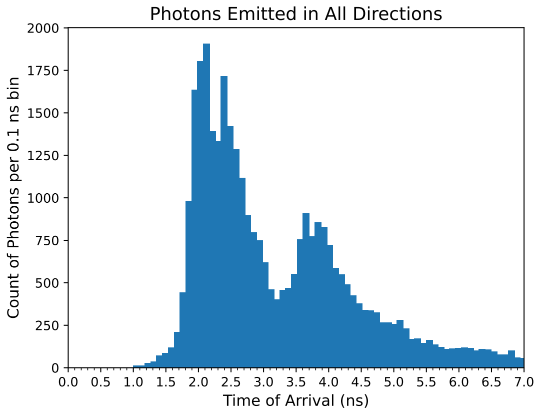

FIG. 11. Photon arrival time at PMT for the photons emitted isotropically.

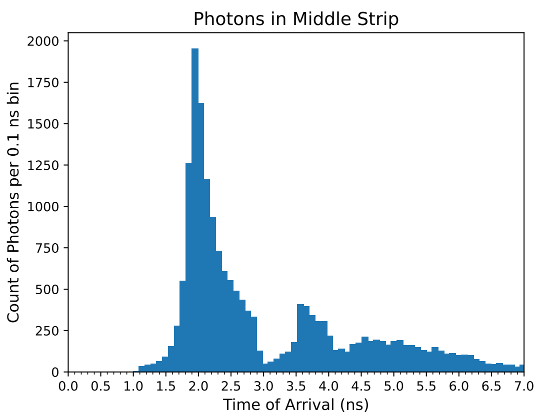

FIG. 12. Photon arrival time at PMT for the photons that travel through the center strip.

III. CONSTRUCTION METHODS

At JLab, for construction of the LG we used the 10 mm thickness S-shape strips produced by Eljen Technology [12]. An oven was used to do bending of the strips out-of-plane using a jig. Finally, a holder was used for machining the strip ends, see Fig. 14.

At CMU, the 5 mm thick S-shape strips were cut from a sheet of plexiglass by using a commercial laser cutter. The laser-cut edges were then flame polished using a hydrogen-oxigen torch. Tests showed that this resulted in superior light transmission when compared to acetylene-based flame polishing. A custom bending fixture was made to heat and bend the strips. Totally, about 300 LGs were constructed for the HCAL-J detector [7], see Fig. 15.

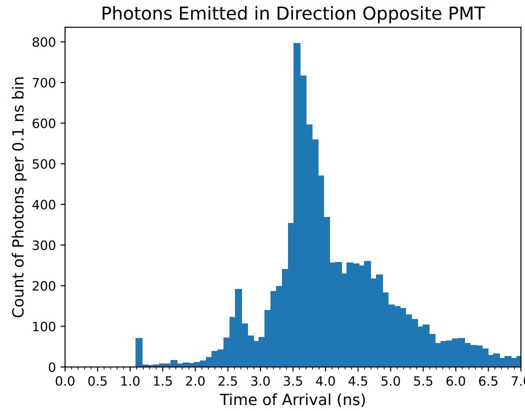

FIG. 13. Photon arrival time at PMT for the photons emitted in the direction opposite to the LG.

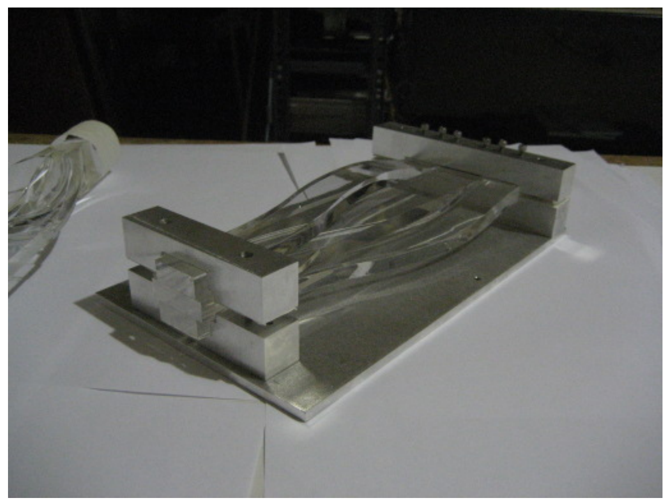

FIG. 14. The holder with a light guide used at JLab for LG construction.

IV. SUMMARY

The results have shown that the new S-shaped, three-strip light-guide configuration has very good light collection efficiency. Furthermore, the smaller bending angle has allowed for the possibility of a shorter light guide, and an associated reduced jitter in the photon time propagation, and therefore has led to a better overall time resolution for scintillation counters using the smaller-bend light guide. Additionally, the proposed light guide is a cost-effective option for a light guide because it requires much less manpower to construct. This concept of a light guide could be useful in solar energy systems as it allows transfer of the light collected in a large area to a compact photo-detector.

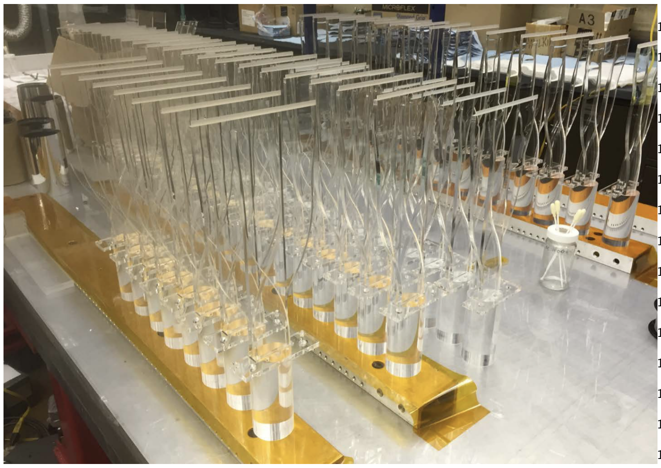

FIG. 15. Adiabatic LGs made at CMU.

V. APPENDIX A: THE GEANT4 BASED CODE

The code (can be found in Ref. [11]) is a modified version of the "OpNovice2" example provided by CERN, with the only modifications being in the ActionInitialization.cc, DetectorConstruction.cc, EvenAction.cc (added), HistoManager.cc, PrimaryGeneratorAction.cc, Run.cc, RunAction.cc, SteppingAction.cc, and their corresponding header files. In ActionInitialization.cc, the event action was added. In DetectorConstruction.cc, the physical/logical volumes for all the pieces are constructed and placed accordingly, the materials were given their respective refractive indexes (scintillator n=1.52, plexiglass n=1.50, and air n=1.0), and the optical surfaces were defined. In EventAction.cc, there is a counter variable created to count the photons that reach the phototube. In HistoManager.cc, there are several histograms added to illustrate results from the simulations, such as time of arrival or initial polar/azimuthal angles of the photons. In PrimaryGeneratorAction.cc, extra code was added to emit photons with random azimuthal and polar angles, thus giving them a random direction in three dimensions. In Run.cc, extra code was added to title the axes of the added histograms. In RunAction.cc, code was added to retrieve the values of the counters that count the photons that reach various volumes and also print those results. In SteppingAction.cc, there is an "if" statement that checks to see if the photon is in the volume of the phototube, and if it is, one is added to a counter, the time of arrival is stored in a histogram and the track of the photon is stopped. The counter then gets stored and the final value is sent to the run action where it is printed. The stepping action also retrieves the initial polar/azimuthal angles where they are then stored in the histograms in the cases of transmission/reflection. For each of the files modified, code was added to their corresponding header files to initialize variables or to return values from one source file to another. Aside from the modifications described above, everything else from the "OpNovice2" example provided by CERN is the same.

VI. ACKNOWLEDGMENTS

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