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DESIGN STUDY OF NOVEL LIGHT GUIDE GEOMETRY FOR SCINTILLATION COUNTERS

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Two scintillating panels (S1 and S2) have been used as triggers in the high resolution spectrometers in Hall A of the Thomas Jefferson National Accelerator Facility. New panels are to be installed in place of S1 and S2 and it was proposed that the currently used 90° twisted light guides be replaced by a new adiabatic S-shape design (2 or 3 strips). Using CERN's Guide7, Monte Carlo simulations were performed on four different light guide geometries: rectangular, standard fishtail, 2-strip S-shape and 3-strip S-shape. It was found that the two S-shape designs gave roughly 2x improvement on collection efficiency and 1.2-1.4x improvement on time resolution over simple designs (rectangular and fishtail). The 3-strip S-shape guide (90 pico-second time resolution and a 30% collection efficiency) was recommended for replacement of the twisted shape; actual experimental comparisons are also advised.

Deux panneaux scintillants (S1 et S2) servent de déclencheurs des spectromètres à haute résolution de la salle A de l'accélérateur national Thomas Jefferson. De nouveaux panneaux seront installés pour remplacer les S1 et S2, et on a proposé de remplacer les guides de lumière courbés de 90o utilisés actuellement par un nouveau modèle adiabatique en S (à deux ou trois bandes). Des simulations de Monte Carlo fondées sur le guide 7 du CERN ont été effectuées pour quatre géométries différentes de guides de lumière : rectangulaire, standard en « queue de poisson », en S à deux bandes et en S à trois bandes. Les deux modèles en S doubleraient l'efficacité de collecte et ils permettraient une résolution temporelle de 1,2 à 1,4 fois supérieure à celle des modèles simples (rectangulaire et en « queue de poisson »). Le guide en S à trois bandes (une résolution temporelle de 9 picosecondes et une efficacité de collecte de 30 %) est recommandé pour le remplacement des guides courbés. Des comparaisons expérimentales sont également conseillées.

INTRODUCTION

Our understanding of the subatomic world relies a great deal on a detector's ability to identify properly an incoming particle. Properties such as momentum, energy and charge are used to distinguish among a vast array of particles (hadrons, leptons, mesons, etc.). In order to minimize background readings, triggers are used to allow the particle identification and tracking detectors (Cherenkov and Vertical Drift Chambers for instance) to be informed that a reaction has occurred and incoming particles will be received shortly.

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A particle should be minimally affected by a trigger detector it passes through by retaining the majority of its energy and being deflected only narrowly from its path. Fast and accurate timing (high time resolution) is also essential to avoid recording of misleading background radiation by the other detectors.

A timing scintillation detector consists of a large-area, flat plastic scintillation panel connected to a cylindrical photomultiplier tube (PMT) by means of a light guide. The panels are thin to minimize energy absorption and path deflection. The light guide offers a means of joining the very different cross-sectional areas of the scintillator (rectangular) and PMT (circular). In Hall A of the Thomas Jefferson National Accelerator Facility (Jefferson Lab), two identical scintillation panels (S1 and S2) serve as primary triggers and contain 90° twisted light guides (Alcorn et al. 2004).

The S1 layer is to be replaced by the S1m layer and it has been proposed that a new light guide design, S-shape, replace the currently used twisted design. In order to demonstrate that the S-shape design is a worthy replacement, Monte Carlo simulations were performed using CERN's Guide7 (http://blast02.lns.mit.edu/software/oddsNends/guide7/).

BACKGROUND - LIGHT GUIDES

When a particle passes through an inorganic scintillator, photons are emitted through molecular excitation (Leo 1987). These photons are transported through the transparent material of the scintillator and guide by means of total internal reflection. For reflection to occur, the angle of incidence relative to normal must be greater than or equal to the critical angle,

$$\theta_{cr} = \sin^{-1}\left(\frac{1}{n}\right),$$

where the outer material is assumed to be air with refractive index equal to one.

Collection efficiency and time resolution are used as main criteria for determining light guide efficiency, indicating a minimum change of the output from a scintillator by the transmission of photons through the guide. Collection efficiency is the number of photons collected at the PMT per number created in the scintillator. A high collection efficiency allows the observation of smaller signals amidst background noise and/or allows the use of thinner scintillators. High time resolution means small variation in the time a generated pulse takes to reach a specified observation threshold, and is needed for accurate triggering.

Simple vs. complex light guides

Simple light guides consist of straight sides and/or gradual tapering. They are cost-effective since they require only a short time to design and build. Rectangular and standard fishtail geometric shapes are commonly used simple guides.

Rectangular light guides are inefficient since the width of the scintillator is often much greater than the diameter of the PMT. Obstruction between adjacent detectors and PMTs should be minimized, so the guide is usually as wide as the PMT and not the scintillator which would lead to a loss of light at the connection between the scintillator and guide.

Standard fishtail guides consist of gradual tapering in all directions from a rectangular shape to a circular one. Since an input flux of photons cannot be concentrated into a smaller cross-sectional area (Garwin 1952), light collection is low.

A complex adiabatic guide consists of gradual curves and bends. One example is the 90° twisted guide, as in the S1 and S2 layers, which consists of a flat panel cut into strips twisted at 90° so they all line up on the circular face of the PMT. This design usually requires more space as the twisting must be done very gradually in order to avoid sharp curves.

A new design: S-shape

Instead of twisting strips, the new design consists of strips that are bent upward or down and then cut into S-shapes that are curved inward toward the PMT. The small curvature of the S-shape ensures a greater collection. Two options are proposed for the S-shape design: 2-strip and 3-strip. The 3-strip design has an extra rectangular piece located between two of the S-shaped pieces.

MATERIALS AND METHODS

Guide7

Guide7, a Monte Carlo program written in FORTRAN developed by CERN (European Organization for Nuclear Research) to evaluate the properties of scintillation and Cherenkov detectors, was used throughout.

In Guide7, a particle detector's light producing mechanism as well as the geometry and transmission properties of the optical guiding system may be defined. For scintillating light production, photons are emitted isotropically from either a point or line source. The direction of emission is randomly chosen and the path of the photon is extrapolated until it encounters a boundary. At this point it either escapes or reflects, depending on the reflective properties at the surface. If the angle of incidence is greater than or equal to the critical angle with respect to normal, total reflection is assumed, otherwise it escapes. The process continues until the photon reaches the PMT window, escapes, or exceeds a predefined time limit.

Statistical fluctuations

The total time delay of each photon that Guide7 tracks to reach the PMT was entered into an analysis/histogramming program called PAW (PhysicsAnalysis Workstation) from CERN (http://wwwasd.web.cern.ch/wwwasd/paw/); the photons were then sorted into 5 pico-second (ps) bins, giving a distribution of photon propagation time inside the scintillator and guide (Fig

1 - top). In order to investigate the time resolution, statistical fluctuations due to scintillator time response, quantum efficiency and PMT jitter were applied. Scintillator rise and decay was modeled with a simple linear rise and exponential decay:

$$N(t) = \begin{cases} N_{\max}\dfrac{t}{\tau_1}, t \le \tau_1 \\ N_{\max} e^{-\frac{t-\tau_1}{\tau_2}}, \tau_1 < t \le \infty \end{cases}$$

Rise time τ_1= 0.9 nano-second (ns) and decay time τ_2 =2.1 ns were used. The PMT transit time jitter was modeled using a Gaussian distribution with mean of 2 ns and σ = 0.5 ns. The quantum efficiency of the PMT was assumed to be 20% (which is typical for the PMTs used in Hall A).

Photomultiplier pulse shape

According to Wright (http://www.electrontubes.com/info/papers.html), the output of a PMT may be represented as a current generator in parallel with a resistor and a capacitor where R and C are the intrinsic resistance and capacitance of the anode as well as any other components attached to the photomultiplier (anode load, cables). The voltage pulse (Figure 1 - bottom) due to an input current is given by:

$$V(t) = \sum_{t'=0}^{t'=t} N(t')Ve^{\frac{t'-t}{t}},$$

where N(t') is the number of electrons arriving at the anode at t' and V is the voltage drop across the anode. A decay constant (τ=RC) of 0.5 ns was used (Glister 2005).

Setup

Two simple light guides (rectangular and standard fishtail shapes) were compared with the two new designs (2-strip and 3-strip S-shapes). Only simple shapes such as planes and half-cylinders could be modeled using Guide7, which does not leave a way to accurately model the complicated geometry of the twisted light guide (an infinite number of half-cylinders would be needed).

For each guide, thirty separate points of photon emission were chosen in the scintillator. For each of these points, 300 runs were performed of Guide7. The threshold for each pulse to activate the discriminator was set at 5% of the maximum value of the first run with the variation among runs giving the time resolution.

The indices of refraction were set at 1.58 for the scintillator (Polystyrene), 1.49 for the light guide (acrylic), and 1.47 for the photocathode window (glass). A maximum of 10 000 emitted photons, 10 000 accepted photons,

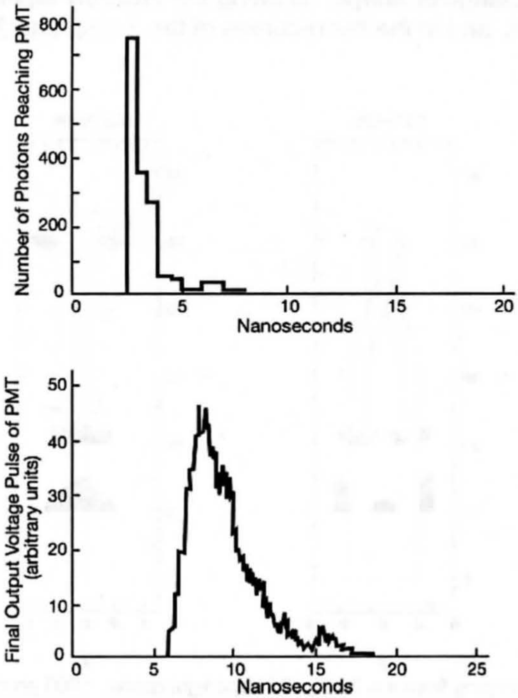

Fig 1 Distribution of photon propagation times in scintillator and light guide and final output pulse of PMT

100 second (s) running time and 30 ns photon time delay were defined. Attenuation length was defined as infinity. All detectors were modeled with a 6 cm long acrylic cylinder attaching the 5 cm diameter PMT to the light guide. Scintillator dimensions of 1 x 10 x 20 cm and guide length of 28.5 cm were used.

Verification of Guide7

Two tests were performed to verify that the guides could be accurately modeled using Guide7. The first test was experimental and compared the angle and position of laser light escape with that of photon escape in Guide7 for varying angles and positions of entrance into a single S-shape strip. Excellent agreement within the limits of experimental uncertainty was found between Monte Carlo simulations and experimental results for the angle of emission.

The other test consisted of plotting photons rejected by Guide7 along with the dimensions of the scintillator and guide to ensure photons were escaping from the predicted locations. After applying a few corrections (found with the aid of this analysis), the photons were recorded as escaping where expected: at the connection point between the scintillator and guide for the rectangular shape, all along the inwardly tapering edges for the fishtail shape, and in the bend/curves of the 2-strip and 3-strip shaped guides (Fig 2).

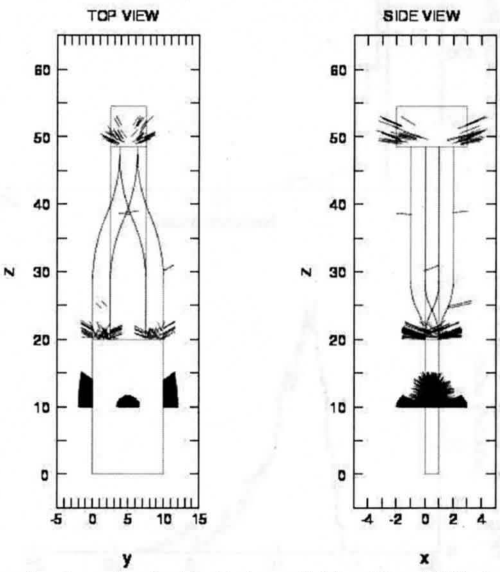

Fig 2 Photons escaping from the 3-strip S-shape light guide. 1000 photons were emitted from centre of scintillator in positive z-direction; all dimensions in cm

RESULTS

Guide7 simulations gave an average collection of 16.37% for fishtail, 18.47% for rectangular, 30.01% for 2-strip and 31.20% for 3-strip shapes. Statistical analysis applied to Guide7 results gave average time resolutions of 0.11 ns for the fishtail, 0.13 ns for rectangular, 0.10 ns for 2-strip and 0.09 ns for 3-strip shapes.

Assuming a minimum ionizing particle depositing 2 MeV/cm and a mean energy of 100 eV/photon, 20 000 primary photons will be created in the scintillator. With a 20% quantum efficiency in the PMT, roughly 1200 photoelectrons will be generated by the PMT for the S-shape guides (compared to roughly 600 in standard fishtail and rectangular shapes). The S-shape guide therefore produces a much stronger signal that can be more easily discerned from background.

It was found that the 6 cm long cylinder at the end of all the guides decreased collection. By removing the cylinder, but keeping the same overall length, the 2-strip and 3-strip S-shape collection improved by roughly 7%.

Gorenstein and Luckey (1963) state that a twisted guide has twice the collection value of a standard fishtail shaped guide one of the same dimensions (0.6 x 41 x 46 cm scintillator, 46 cm long guide and 5 cm diameter PMT), although they state a 12.5% collection for the fishtail shaped guide which could not be reproduced using Guide7 (we found only 3.5% collection i.e. a more reasonable value for such a large inward taper).

CONCLUSIONS

Based on Guide7's Monte Carlo simulation results, we would recommend that an adiabatic light guide design is a better choice than a simple one. Furthermore, a 3-strip S-shape design offers slightly higher collection efficiency and time resolution than does a 2-strip S-shaped guide for an initial thickness and width of 1 cm and 10 cm respectively and a 28.5 cm total length. A cylindrical connection between the guide and the PMT is not recommended because of the drop in collection efficiency.

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