Design optimization of JUNO-TAO plastic scintillator with WLS-fiber and SiPM readout

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Date: 2023-07-14T00:00:00+00:00

Abstract

Plastic scintillator (PS) embedding wavelength shifting (WLS) fiber is widely used in high energy particle physics, as muon taggers, and also in medical physics and other applications. In this work, a simulation package is built to evaluate the effects of the diameter and the layout of the optical fiber on the light yield with different configurations. The optimal optical configuration was designed based on the simulation and then validated with two PS prototypes under certain experimental conditions. In the study, the top veto tracker (TVT) of the JUNO#2; TAO experiment, comprised of 4 layers of 160 strips of PS was designed and evaluated. When a muon tagging efficiency of a PS strip is higher than 99%, the threshold is evaluated. The efficiency of 3-layer out of 4-layer of TVT will be higher than 99% even with the tagging efficiency of a single strip as low as 97% using a threshold of 10 p.e. assuming 40% SiPM PDE.

Full Text

Design Optimization of Plastic Scintillators with WLS-Fibers and SiPM Readouts in the Top Veto Tracker of the JUNO-TAO Experiment

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Supported by School of Physics in Sun Yat-sen University, China.

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Abstract

Plastic scintillator (PS) embedded with wavelength-shifting (WLS) fiber is widely used in high-energy particle physics as muon taggers, as well as in medical physics and other applications. In this work, a simulation package was built to evaluate the effects of optical fiber diameter and layout on light yield across different configurations. The optimal optical configuration was designed based on simulation results and subsequently validated with two PS prototypes under experimental conditions. The study designed and evaluated the top veto tracker (TVT) for the JUNO-TAO experiment, comprising 4 layers of 160 PS strips. When a PS strip achieves muon tagging efficiency higher than 99%, the threshold is evaluated. The efficiency for 3 out of 4 TVT layers remains above 99% even when the single-strip tagging efficiency is as low as 97% using a 10 p.e. threshold, assuming 40% SiPM photon detection efficiency (PDE).

Keywords: Plastic scintillator, WLS-fiber, Light yield, Optical transmission performance, Muon tagging efficiency, JUNO-TAO

Introduction

Collisions between primary cosmic rays and Earth' s atmosphere produce large numbers of muons, with average kinetic energies of several GeV at sea level. Due to their high energy, large mass, minimal deceleration and deflection in electromagnetic fields, and small bremsstrahlung effects in matter, muons possess strong penetrating power.

A muon veto detector subsystem with high tagging efficiency is crucial for reducing backgrounds induced by cosmic-ray muons in experiments with limited overburden near the surface, where muon flux is typically four to seven orders of magnitude higher than in deep underground laboratories such as Jinping, Gran Sasso, and Canfranc. Neutrino experiments, dark matter searches, and neutrinoless double-beta decay experiments require muon veto systems with tagging efficiencies exceeding 99%. Plastic scintillator detectors offer advantages of easy machining, flexible structural design, and efficient, stable performance. PS detectors with WLS fibers and optical photodetectors (multi-anode PMTs or SiPMs) have been employed in OPERA, MINOS, LHAASO, and numerous other experiments, with additional applications in geological imaging, reactor monitoring, and other fields.

The Taishan Antineutrino Observatory (TAO or JUNO-TAO) is a satellite experiment of the Jiangmen Underground Neutrino Observatory (JUNO). TAO' s primary purpose is to provide a precise neutrino energy reference spectrum for JUNO and benchmark measurements for nuclear databases. The TAO detector system consists of a central detector (CD), outer shielding, and a veto system. The CD will be positioned approximately 30 m from a reactor core at the Taishan Nuclear Power Plant, containing 2.8 tons of gadolinium-doped liquid scintillator in a spherical acrylic vessel. With only 4 m of concrete vertical overburden, TAO’ s major backgrounds are muon spallation products and accidental coincidences from natural radioactivity, requiring the top veto tracker (TVT) to tag muons with >99% efficiency.

This paper compares Geant4-based simulation with prototype measurements in Section II, validates light yield consistency for through-going muons, and further examines WLS fiber diameter and layout for enhanced light yield in Section III. An optimized PS strip design with WLS-fiber and SiPM readout is proposed for the JUNO-TAO TVT system, providing high light yield and muon tagging efficiency while serving as a reference for PS detector design. Experimental validation confirms the optimal design’ s reliability. Section IV demonstrates the expected TAO TVT performance with the proposed design, and Section V provides a summary.

II. Prototype of PS Strip with WLS-Fiber and Simulation

Muons deposit energy when passing through materials via muon ionization energy loss. The average energy loss per unit distance (mass thickness) is described by the Bethe-Bloch formula (1) [3, 50]:

$$= Kz2Z2mec2\beta2\gamma2Wmax) - \beta2-$$

where K is a constant, z is the incident muon charge unit, me and c are electron mass and light speed, Z and A are the atomic and mass numbers of the material, Wmax is the maximum transferable kinetic energy to an electron, I is the mean excitation energy, β is the particle velocity relative to light speed, γ is the Lorentz factor, and δ is the density effect correction factor—all constant for a given material.

For thin media with Z < 20, such as PS strips, muons traverse nearly straight paths. A portion of the deposited energy converts to light in the PS strip, which is extracted by WLS-fibers. SiPMs coupled to the fibers provide an effective, robust, and rapid method for photon detection and signal conversion.

A PS prototype with WLS-fiber readout was designed and fabricated (Figure 1 [Figure 1: see original paper]), designated as Option 1. It measures 2 m (length) × 0.1 m (width) × 0.02 m (thickness) with four 1 mm diameter optical fibers. The pink lines represent equally spaced WLS fibers inserted into the PS surface, with 1.9 m straight sections arranged symmetrically in both dimensions. Two fibers are grouped for coupling to optical sensors, reducing sensor count—four SiPMs per group (red circles) or two PMTs per PS end. The PS is wrapped in reflective aluminum foil except at fiber exit points. Further details are available in Ref. [51].

The prototype was tested with cosmic-ray muons using the setup shown in Figure 2 [Figure 2: see original paper]. Muons are selected by two small scintillator monitors at different positions, triggering PS strip signal recording. Nine equally spaced points along the strip were measured relative to the PS center. The PS strip was fabricated by Beijing Hoton Nuclear Technology Co. Ltd [53] using BCF92 WLS fiber [54, 55].

A Geant4-based Monte Carlo simulation [47, 49, 52] was developed using manufacturer parameters for PS, reflective film, and WLS-fiber [55, 56]. The simulation comprises three components: (1) detector geometry with PS and fiber optics, (2) physical processes including ionization, bremsstrahlung, multiple scattering, pair production, Compton scattering, photoelectric effect, scintillation, Cherenkov light, wavelength shifting, Rayleigh scattering, bulk absorption, and boundary processes, and (3) data extraction with PS and PMT/SiPM as sensitive detectors. A parameter interface allows setting material properties including PS attenuation length, scintillation yield (photons per MeV deposited energy), and reflective film reflectivity. Parameter scanning yields simulation responses such as light yield (photoelectrons, p.e., accounting for PDE/QE) along the PS longitudinal direction. ^{2} analysis against experimental data produced the optimal parameters in Table 1 , used consistently in subsequent optimization.

Figure 3(a) [Figure 3: see original paper] compares measured and simulated light yield at different positions, showing good agreement within errors for PMT sensors. Light yield should be symmetric about the PS center, but differing PMT quantum efficiencies produce asymmetry. SiPM light yield exceeds PMT yield. Given compactness, robustness, and higher yield, SiPMs are proposed for TVT. Figure 3(b) shows energy spectrum comparison at the PS center, with good agreement except for isolated points. Since individual PMT/SiPM devices have varying QE/PDE, subsequent studies use uniform QE/PDE values to focus on optical rather than electronic effects.

III. Optimization of PS Strip Layout

Building on experimental-simulation agreement, we studied PS strip configurations, including WLS-fiber diameter and arrangement, for light yield and tagging efficiency optimization.

A. Light Yield: nPhotons × PDE

Figure 4 [Figure 4: see original paper] shows light yield versus fiber diameter for two PS configurations with equal fiber counts. Each point represents light yield for muons hitting the PS center. The magenta point shows the Option 1 PMT prototype measurement. Red lines simulate 100 mm wide PS with ~20 mm fiber spacing; blue lines simulate 200 mm width with ~40 mm spacing. Most photons are collected via WLS-fibers, though some PS scintillation photons reach SiPMs directly (bottom straight lines), contributing a fiber-diameter-independent component. The trend indicates that larger fiber diameter and smaller spacing increase light yield. A 1.5 mm fiber diameter is recommended based on performance and cost.

For JUNO-TAO TVT, a 20 cm PS strip width is recommended based on fabrication, electronics, and cost considerations. Multiple layout options were evaluated (Figure 5 [Figure 5: see original paper]), all 2 m long and 20 mm thick. Options 2-4 use 200 mm width with eight fibers at similar spacing, while Option 1 uses 100 mm width. Option 2 doubles Option 1' s front fiber arrangement. Option 3 distributes four fibers on each PS face. Options 3-1 and 4 use different arrangements—Option 3-1 is more uniform than Option 2 but not staggered like Option 4. Fiber straight lengths are 1.9 m for Options 1-3 and 1.5 m for Options 3-1 and 4. Table 2 summarizes configurations.

Performance differences were evaluated via simulation in three comparative studies: Option 2 vs. 3 examines fiber placement dependence; Option 2 vs. 3-1 examines uniformity effects; and Option 2 vs. 4 examines layout dependence.

To isolate angular effects, vertically incident muons were simulated first. Figure 6(a) [Figure 6: see original paper] shows SiPM photon counts (nPhotons) for Options 1-4, where light yield = nPhotons × PDE. The black, red, and green lines (Options 1, 2, and 3) show overlapping Option 2 and 3 distributions, indicating minimal front/back placement effects. Option 2' s average nPhotons is nearly double Option 1' s. Option 4 exceeds all previous options, demonstrating significant layout impact. All distributions have equal entries, so peak heights reflect distribution widths.

A second simulation used realistic muon energy and angular distributions [57, 58]. Figure 6(b) shows results for Options 2, 3-1, and 4, with Option 4 achieving the highest average photon count, followed by Option 3-1 and Option 2.

From formula (1), deposited energy is proportional to muon track length. In the realistic simulation, oblique incidence produces track lengths shorter or longer than the 20 mm PS thickness. Figure 6(b) shows higher nPhotons than Figure 6(a), with averages nearly doubled and small-amplitude signals appearing. Figure 7 [Figure 7: see original paper] shows two-dimensional distributions of total photons versus track length for the three options, with highest event density at 20 mm (vertical incidence). The normalized photons per unit length show Option 4 averaging 11.23 photons/mm, nearly double Option 2' s 6.09. This confirms Option 4 as most effective for equal energy deposition.

B. Transmission Performance

Option 2 and Option 4 show distinct light yields despite similar fiber counts and dimensions. To understand fiber arrangement effects, an optical survey evaluated photon reflection times before WLS-fiber absorption. Survey points (Figure 8 [Figure 8: see original paper]) cover PS center and edges, with 15,000 isotropic photons generated per point to simulate muon excitation.

More reflections before fiber entry reduce SiPM detection probability, while more photons entering the fiber increase detection probability. An R-value quantifies this trade-off: total photons entering the fiber divided by average reflections before entry.

Figure 9 [Figure 9: see original paper] shows R-value distributions for Options 2 and 4. The upper left panel (center width position) shows Option 4 exceeding Option 2 along the entire length. The lower left panel (edge width) shows similar values except at length edges where Option 2 surpasses Option 4. The upper right panel (center length) shows trade-offs along the width, while the lower right panel (length edge) shows Option 4 exceeding Option 2 within 30 mm of the width center.

Results indicate that sparse fiber regions sharply reduce photon entry while increasing reflections, whereas dense fiber regions dramatically increase photon entry while decreasing reflections. Globally, Option 4' s R-value exceeds 200, while Option 2 remains below 200. Integrating R-values over the entire PS region shows Option 4' s transmission performance is 2.21 times better than Option 2' s, explaining its superior photon collection. However, Option 4' s larger R-value distribution range indicates worse optical export uniformity due to its uneven fiber layout.

In summary, higher fiber density in the PS central region yields higher effective light output. For maximum light yield, placing more fibers in the PS middle is advantageous.

C. Muon Tagging Efficiency and Inefficiency

Assuming 30% SiPM PDE, the sum of four SiPM outputs at both ends was analyzed for tagging efficiency. Figure 10 [Figure 10: see original paper] shows two-dimensional light yield distributions at both ends for Options 2, 3-1, and 4. Option 4 exhibits the strongest, most divergent range. A muon is detected when both ends exceed threshold simultaneously. Tagging efficiency is defined as N_{tag}/N_{all}, where N_{all} is the total muon event count and N_{tag} is the detected count (environmental background excluded).

Figure 11 [Figure 11: see original paper] shows efficiency versus threshold for the three options at 20%, 30%, and 40% PDE (black, blue, red). At 20% PDE and 10 p.e. threshold, Option 4 exceeds 90% efficiency while Options 2 and 3-1 fall below 90%. With increasing threshold, Option 2' s efficiency drops fastest, followed by Option 3-1, while Option 4 decreases slowest.

Figure 12 [Figure 12: see original paper] shows thresholds required for 99% tagging efficiency. At 40% PDE, Option 2' s threshold cannot exceed 1.5 p.e., Option 3-1' s cannot exceed 2.4 p.e., but Option 4 can use a 3 p.e. threshold, significantly reducing SiPM dark noise contributions. Thus, Option 4 is superior in both light yield and tagging efficiency and is selected as the optimal configuration. Table 3 summarizes single PS strip thresholds and efficiencies at 40% PDE.

An Option 4 prototype was built with identical PS, fiber, and film parameters but different backend SiPM PDE. Two K-series MicroK-40035-TSV SiPMs [59] were used with a LeCroy HDO4104A oscilloscope for data acquisition. Figure 13 [Figure 13: see original paper] compares experimental and simulated energy spectra at the PS center, analyzing signals >3 p.e. to avoid dark noise and background. Below 12 p.e., simulation matches experiment well. The most probable signal amplitude is ~8 p.e., implying ~32 p.e. for the final TAO configuration with four SiPMs per end. Discrepancies at 15-25 p.e. and >25 p.e. arise from imperfect SiPM-PS coupling and muon monitor module width differences affecting hit location. Nevertheless, Option 4' s light yield substantially exceeds the pre-optimized Option 1, validating the optimization approach.

Inefficiency studies simulated muon track length distributions in PS strips. Figure 14 [Figure 14: see original paper] shows the fraction of events exceeding track length thresholds. The three configurations exhibit similar trends within 1% difference. The 99% event fraction corresponds to a 3 mm threshold, indicating 1% of muons have track lengths <3 mm. With 20 mm PS thickness, these edge events involve large zenith angles grazing the PS edge. In a staggered multi-layer module, such edge events produce longer tracks in adjacent layers, enabling detection. Thus, single-layer module tagging efficiency exceeds single-strip efficiency.

IV. Performance of JUNO-TAO TVT

Based on these results, the JUNO-TAO top veto tracker (TVT) was designed as a 4-layer PS system (Figure 15(a) [Figure 15: see original paper]). The side view shows layer seams overlapping to eliminate dead space, with 2 cm gaps between layers. The top view shows four layers covering the spherical central detector' s projection to optimize cost and coverage.

Figure 15(b) shows multi-layer versus single-strip tagging efficiency. Black (any 1 of 4 layers) and red (any 2 of 4) lines nearly coincide with single-strip efficiency due to small interlayer gaps. Blue (all 4 layers tagged) shows efficiency reduction due to layer dead space. Green (any 3 of 4 layers) demonstrates that even with single-strip efficiency as low as 97% (10 p.e. threshold at 40% PDE, Table 3), the 3-of-4 layer efficiency remains >99%.

Background simulations (^{238}U, ^{232}Th, ^{40}K chains) show rates of 1280 ± 40 Hz for any 2-of-4 layers and <10 Hz for any 3-of-4 layers exceeding a 3 p.e. threshold. Therefore, requiring 3-of-4 layer coincidence effectively tags muons while rejecting background.

V. Summary

Numerous PS-WLS-fiber configurations were evaluated via simulation, examining fiber diameter, layout, and transmission performance effects. Based on light yield and muon tagging efficiency, the optimal WLS-fiber PS configuration was identified under given constraints. Bench tests of Options 1 and 4 measured a most probable summed signal of ~32 p.e. at one end for the optimized Option 4—four times Option 1’ s yield—validating the simulation package.

Inefficiency mechanisms were studied, leading to the JUNO-TAO TVT design. Simulation conclusions are: at 40% SiPM PDE, single PS strips achieve 99% tagging efficiency at a 3 p.e. threshold in AND mode (both ends required), with background rates <10 Hz (nearly zero) for any 3-of-4 layer coincidence. At 10 p.e. threshold (97% single-strip efficiency), the 3-of-4 layer TVT efficiency remains >99%.

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