Water attenuation length measurement in JUNO

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Abstract

Water Cherenkov detectors play a fundamental role in neutrino physics and cosmic-ray research. The water attenuation length (WAL, also called water transparency) is the parameter serving as an indicator of water quality within the detector. This paper presents the design, implementation, and performance of a dedicated monitoring system developed to measure the WAL in situ in the water Cherenkov (Veto) detector of the Jiangmen Underground Neutrino Observatory (JUNO). The system incorporates five 20-inch PMTs with light guides, a stable LED light source and a calibration LED light source with optical fibers, and deployed at the bottom of the JUNO water pool in late 2024. The system provides the capability to continuously monitor water transparency throughout the water filling and commissioning phases in JUNO. Long-term monitoring data demonstrate a systematic improvement in water quality. The measured WAL increased from an initial value of 23 m at the beginning of filling operations to a stable value of 60 m during detector commissioning. With the ongoing operation of the water purification and recirculation system, the attenuation length has further improved, currently reaching about 75 m. The system operates stably, monitor detector performance and validating water circulation in JUNO water Cherenkov detector.

Full Text

Preamble

NUCLEAR SCIENCE AND TECHNIQUES , () Water attenuation length measurement in JUNO∗ Chuan-Shi Dong,1, 2 Ji-Lei Xu,1, † Hao-Qi Lu,1 Si-Bo Wang,1 Vit Vorobel,3 Tomas Tmej,3 Chang-Gen Yang,1, 2 Yong-Peng Zhang,1 Jun-You Chen,4, 1 Hong-Zhao Yu,2, 1 and Jun-Wei Zhang4, 1 1Institute of High Energy Physics, Beijing 100049, China. 2University of Chinese Academy of Sciences, Beijing 100049, China. 3Charles University, Faculty of Mathematics and

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Water Cherenkov detectors play a fundamental role in neutrino physics and cosmic-ray research. The water attenuation length (WAL, also called water transparency) is the parameter serving as an indicator of water quality within the detector. This paper presents the design, implementation, and performance of a dedicated monitoring system developed to measure the WAL in situ in the water Cherenkov (Veto) detector of the Jiangmen Under- ground Neutrino Observatory (JUNO). The system incorporates five 20-inch PMTs with light guides, a stable LED light source and a calibration LED light source with optical fibers, and deployed at the bottom of the JUNO water pool in late 2024. The system provides the capability to continuously monitor water transparency through- out the water filling and commissioning phases in JUNO. Long-term monitoring data demonstrate a systematic improvement in water quality. The measured WAL increased from an initial value of 23 m at the beginning of filling operations to a stable value of 60 m during detector commissioning. With the ongoing operation of the water purification and recirculation system, the attenuation length has further improved, currently reaching about 75 m. The system operates stably, monitor detector performance and validating water circulation in JUNO water Cherenkov detector.

Keywords: Water attenuation length; JUNO; Water Cherenkov

INTRODUCTION

they lack the capability for real-time, The water attenuation length (WAL) is a parameter to in- dicate the water transparency and quality in water Cherenkov detectors. Conventional WAL measurement methodologies have primarily relied on external sampling techniques, where water samples are analyzed in laboratory by a vertical tube, summarized in [1]. While these methods provide valuable reference data, situ monitoring of water quality dynamics within the oper- ational detector. Among existing large-scale experiments, the Super-Kamiokande (Super-K) collaboration has implemented a direct measurement approach employing an internal light source and CCD imaging system. By vertically translating the light source and measuring intensity variations, Super- K achieved a reported attenuation length of 97.9 ± 3.5 me- ters [2]. This method depended on mechanical positioning system introduce operational constraints and potential failure modes.

As another example of a typical water Cherenkov detec- tor, LHAASO-MD measures the WAL using a single pho- tomultiplier tube (PMT), multiple light source approach [3].

This technique involves successively activating laser sources ∗ Many thanks for the Chinese Academy of Sciences, the National Key R&D Program of China. This work was supported by National Natural Science Foundation of China (Grant No. 12575210), the financial support from the Xie Jialin Foundation of

Institute of High Energy Physics (IHEP, No. E3546EU2); the European Structural and Investment Funds, the Min- istry of Education, Youth and Sports, and the Charles University Research Center in the Czech Republic. † Ji-Lei Xu, xujl@ihep.ac.cn at various distances to record the corresponding number of photoelectrons (PE) detected by the PMT. The attenuation length is subsequently derived from this data. The feasibil- ity of this method is highly dependent on the precise control and positioning accuracy of the light source.

The JUNO features a veto detector comprising a cylin- drical water pool with 43.5-meter diameter and height, in- strumented with 2,400 outward-facing 20-inch photomulti- plier tubes (PMTs) to detect Cherenkov radiation from cosmic muons. The water transparency influences the photon collection efficiency of these PMTs, consequently influences the detector' s cosmic veto efficiency. Therefore, the WAL is used to assess and monitor the water quality in JUNO veto de- tector. JUNO developed a novel in-situ measurement device and built a preliminary prototype in laboratory [4]. In contrast to mechanical translation systems, the JUNO design employs a fixed geometry utilizing waterproof 20-inch PMTs identical to those used in the main detector [5], coupled with calibrated light sources and 18-meter optical fibers. This configuration eliminates moving parts while maintaining measurement ca- pability for WAL exceeding 40 meters. The system' s design prioritizes operational reliability, cost-effectiveness, and real- time monitoring capability, providing immediate feedback on water quality variations during detector commissioning and operation. The JUNO' s first physics result already shown in [6], and the WAL measurement result and long term mon- itoring result has already shown in JUNO' s first detector performance paper [7].

This paper presents the comprehensive design, implemen- tation, and performance characterization of the JUNO WAL monitoring system. Section II and III detail the detector R&D, covering the measurement principle, system design, component testing, and final installation. Section IV presents Chuan-Shi Dong et al.

Nucl. Sci. Tech. , () measurement results obtained during JUNO' s commissioning phase.

II. THE WAL MEASUREMENT PRINCIPLE AND DESIGN

deviations from this power law. To minimize systematic un- certainties from stray light, PMT response variations, and differences among optical fibers, the water-to-air charge ra- tio was used for the final WAL fit, as given by the following equation:

A. The measurement principle

The principle of this measurement is based on a point-like light source emitting photons which are received by PMTs in the water at different distances from the source, as it was proposed in [1]. Photons are attenuated by water (following exponential law) and are lost due to the diminishing solid an- gle with distance (following inverse square law). Taking into account both effects, the PMT charge (Q) is expressed as:

0 Qac

(cid:18) (cid:19) (cid:18) = A exp (cid:19) Using this charge-ratio method eliminates the inverse- square law term (d−2), the PMT response term (qi), and the fiber transmission term (fi). What remains are a constant fac- tor A, which encapsulates four initial light intensity (Q0), and the WAL term.

Q(d)   d−2e−d/λ. B. Detector design Where d is the distance between PMT and light source and λ is the WAL.

Conventionally, the WAL is determined by fitting the pho- toelectron counts from PMTs placed at various distances from a light source. The relationship is described by the following equation: i = Qa i = Qw 0 d−2 i exp (cid:19) (cid:18) i and Qw In Eq. 2 and 3, the terms Qa i denote the number of photoelectrons detected by the i-th PMT in air and water, re- spectively. Q0 is the initial intensity of the point light source; di is the radial distance from the source to the PMT's photo- cathode; and qi is a coefficient representing the PMT's overall response, which includes its quantum and collection efficien- cies. To avoid the effect of light diffusion from point-like source and the water attenuation, the PMT charges are cali- brated using optical fiber in air and water, respectively. The calibration equations are expressed as: i = Qac 0 fiqa i = Qwc 0 fiqw The factor fi is the fiber constant that normalizes the in- tensity variations across different fibers, as detailed in Sec- tion III B.

Ideally, the light intensity from a point-like source follows the inverse-square law, d−2. However, an ideal point source is not achievable in practice. Stray light, particularly from dif- fuse reflections of the Tyvek films in the veto system, causes Taking into account the spatial constraints at the bottom of the JUNO water pool, such as avoiding conflicts with the wa- ter inlet/outlet pipes and ensuring sufficient distance from the CD' s geomagnetic field coil, five sets of 20-inch PMTs were ultimately designed and installed along a 25-meter section of the pool floor, as illustrated in Fig. 1 [Figure 1: see original paper]. There also is a light source to measure WAL (W-LED), a calibration light source (C-LED) to calibrate PMTs, fibers, shutters, electronics and support structures. The PMTs and electronics are the same with JUNO micro-channel plate PMT [5] and electronics [8], and the waterproof technologies are also the same, which al- lows to perform long-term monitoring of the WAL. Five 20- inch PMTs are placed 5-meter intervals along the direction of the W-LED, with the farthest one located approximately 25 m away. As viewed from the W-LED, the five PMTs are arranged in a circular array, with the center of the circle ap- proximately aligned with the light source, as shown in Fig. 2 [Figure 2: see original paper].

This arrangement ensures that each PMT has an unobstructed view of the direct light from the source.

In the water pool of the JUNO, the walls are lined with the Tyvek reflective film to enhance the photon collection.

However, this has a unfavorable effect on the measurement of WAL. The reflected light interferes with the measurement of direct light, creating stray light effects, which has already been verified in laboratory prototype experiment [1, 4]. A cylindrical light guide was developed to shield against stray light. Fig. 3 [Figure 3: see original paper] illustrates a side cross-sectional view of a PMT and light guide. One 20-inch PMT was enclosed by a black high-density polyethylene (HDPE) tube with inner diameter 55 cm. A black HDPE tube with inner diameter 35 cm, length 1 m was mounted at the front of the PMT photocathode.

The backend of the PMT also was enclosed by HDPE. These tubes make a sleeve to block the un-direct photons propagat- ing from W-LED. In the 1 m tube, 5 shutters were mounted at the interval of about 20 cm also to block the stray light and only allow the direct light hit the photocathode. Each light guide of the 5 PMTs must strictly aligned toward the W-LED.

For easier installation, the inner diameter for each shutter is from 20 cm (the first shutter at the PMT side) to 27 cm (the WATER ATTENUATION LENGTH . . .

Nucl. Sci. Tech. , () Fig. 1. The design of the WAL measurement device at the bottom of the JUNO detector. outer side shutter) to make a horn shape with the flare angle 5 ∘ . Which means the light guide allowed to have an offset of $±$2.5 ∘ towards the W-LED during the installation. Due to the optical fiber' s divergence angle of approximately 25.4 ∘ , its support structure is mounted on the second shutter to ensure that the emitted light fully illuminates the PMT photocathode.

To prevent the black light guide affecting light collection of the JUNO veto detector, the entire light guide is wrapped in white Tyvek. Each PMT measurement unit is supported by stainless steel structure as shown in Fig. 2. The base of the structure is equipped with five adjustable foot bolts, allowing precise alignment of the PMT tube and light guide toward the W-LED. The weight of the PMT unit is more than 200 kg, which compensates the buoyancy of the PMT unit in water.

The LED source used in this system emits blue light pulses with a wavelength of 400 nm. To homogenize the output light, the LED source is inserted in a polyethylene (PE) cap- sule, creating a device known as a "diffuser" with diameter 32 mm. One diffuser (called W-LED) is housed in a black HDPE light shield, with only a 1 cm diameter circular out- put aperture at the end of the capsule, as shown in Fig. 4 Figure 4: see original paper.

This aperture acts as an isotropic point light source. Another diffuser (called C-LED) features a similar design but with a small hole and an adaptation for connection with an optical fiber as shown in Fig. 4(b). This is to ensure no light leak- age and allows only the light to be transmitted to the PMT exclusively through the optical fiber.

One quartz optical fiber was connected to the calibra- tion diffuser and then was splitted into 10 fibers (1-to-10 Y- splitter) to connect to 5 PMTs. Five of these fibers are con- nected to the PMTs for calibration, while the remaining five are kept as spares. Each optical fiber has a total length of 18 m. This uniform length ensures that all fibers can reach their respective PMTs and that photons arrive at each PMT simultaneously. The fibers of diameter 400 µm are protected with a jacket and stainless steel bellows [9]. Samples of the same fiber model underwent 0.75 MPa water pressure tests Fig. 2. Cross-section view of the five PMTs from the W-LED.

Fig. 3. Side cross-sectional view of one set of PMT, which include a 20-inch PMT, protective sleeve, shutters and optical fiber support structure.

PMT1PMT2PMT3PMT4PMT5W-LEDC-LEDStainless steel trussFiberOptical fiber support structureShutterPMTSleeve

Chuan-Shi Dong et al.

Nucl. Sci. Tech. , () III. THE DETECTOR COMPONENT TEST AND INSTALLATION Before the system installed onto the bottom of JUNO water pool, each component underwent a series of tests on the ground surface. These tests were designed to ensure proper functionality after deployment and to gather hardware data.

This data is essential for the error analysis and correction in the calculation of the WAL.

A. The LED performance test The measurement of the WAL requires the uniform emis- sion of the diffuser ball W-LED when photons pass through the 1 cm diameter aperture. The PMTs have about 85 cm ra- dial offset seeing from the W-LED, as shown in Fig. 2. The distance of the first PMT (PMT1) to W-LED is the shortest distance, about 5 meters, so the light emission angle is the largest, about 9.7 degrees. It is necessary to evaluate the uni- formity of the LED' s light emission within 10 degrees.

In a darkroom of the surface ground laboratory at JUNO, we horizontally positioned four PMTs on one side and mounted the W-LED on a rack on the opposite side with dis- tance about 7.5 m, as shown in Fig. 6 [Figure 6: see original paper]. All 4 PMTs pointed to the W-LED by adjusting the height of the bolts at the bottom of the stainless steel frames. After the alignment of each PMT was completed, the room was made light-tight. The W-LED provided light pulses with a width of approximately 15 ns.

The PMT waveforms were obtained by the data acquisition (DAQ) system of LPMT testing at JUNO onsite [10], and the charge of 4 PMTs was integrated.

Fig. 4. The two diffusers covered by black HDPE to served as (a) a point-like source for W-LED, and (b) a calibration source for C- LED, respectively. for 48 hours and underwent 8 cycles of water pressure in- crease and decrease during that time and showed no broken fiber. A fiber support bar is mounted on the second shutter, as shown in Fig. 5 [Figure 5: see original paper], and the

fiber can be screwed on the support bar. To assure that all the PMT units are identical, the light guide dimensions are all the same.

Fig. 5. Cross-section view of the five PMTs from the W-LED.

Fig. 6. The PMT unit and LED testing before installation. The four PMT assemblies aligned in the darkroom for preliminary tests.

To measure the light emission uniformity of the LED, po- sition of the LED source center was fixed and the source was rotated 2 degree horizontally at each step in the angle range from -10° to $+10^{\circ}$ for each PMT. The zero degree was de- fined as the LED light aperture is rightly towards the PMT.

WATER ATTENUATION LENGTH . . . Nucl. Sci. Tech. , () The PMT charges of 4 PMTs with different angles were plot- ted in Fig. 7 [Figure 7: see original paper]. Because different PMTs have different photon detection efficiency, the averaged charge of each PMT was normalized together for easier comparison. The plot indicates that within a range of $\pm 10^{\circ}$, the maximum variation in the collected signal is approximately $\pm 8.0\%$, and within a range of $\pm 3.0°$, the variation is in about $\pm 1.0\%$. This means that although the W-LED light intensity non-uniformity is smaller than 1% for the last 4 PMTs, the non-uniformity for the first PMT (PMT1 in Fig. 1) is about 8%. To eliminate this uncer- tainty, the water-air-ratio method introduced in section II A was deduced and used. Only the different light angle emitted from the W-LED induced by the different refractive index for air and water was considered, and the uncertainty is incorpo- rated into the error analysis in section IV A.

Fig. 7. The uniformity of the W-LED luminous intensity measured by 4 PMTs.

B. The fiber non-uniformity test The characteristics of PMTs, such as PMT gain and de- tection efficiency, may change with the time, and need to be calibrated at each time of data taking. Light from the cali- bration LED travels entirely within the optical fibers and is emitted directly at the front of each PMT' s photocathode.

This method eliminates influence of the water during the cal- ibration process. To reduce the PMT calibration uncertainty, these 10 fiber non-uniformity need to be tested.

In the calibration, the C-LED and one PMT were fixed, and only test these 10 fibers one by one in short time. The mon- itor PMT showed the C-LED light intensity is stable during the calibration. To reduce the test uncertainty, each fiber was measured by 4 different PMTs, see Fig. 8 [Figure 8: see original paper]. The light intensity can be expressed by PMT charge. The charges measured by the four PMTs were normalized to the value obtained from fiber 1. This procedure yields the relative charge of each sub- sequent fiber with respect to fiber 1, with the maximum ob- served deviation remaining within 2%. The mean value of the 4 time measurements as the final intensity value for each fiber and the value difference is the fiber non-uniformity. Finally, 5 of them were selected as the optical measurement fibers, while the other 5 are kept as spare fibers.

Fig. 8. The light intensity going through each fiber measured by

4 PMTs. The bottom panel displays the relative difference mea-

sured by the 4 PMTs, with the data normalized to the value from the fiber 1.

C. The WAL device installation Before filling water into the water pool, five PMTs with their light guides were installed at the bottom of the water pool, as shown in Fig. 9 [Figure 9: see original paper]. The optical fibers and cables were routed underneath a steel grid frame which is used to support the tyvek film. while the electronics boxes were mounted on the side of the PMT support structure, as shown in Fig. 9(a).

To make all the PMTs position at the right place and direc- tion, a handheld laser measuring instrument was applied at the W-LED place and a target was made and positioned in the PMT light guide. The laser light must hit the marker on the target and go through the small hole in front of the tar- get by adjusting the bolts at the bottom of the structure. This could make sure the PMT light guide rightly towards to laser source. After alignment, the laser source was replaced with W-LED. Fig. 9(b) shows the overview of the WAL measure- ment device after installation, seeing from the W-LED to 5 PMTs. The PMT photocathodes in the light guide can be clearly seen from W-LED position.

IV. WATER ATTENUATION LENGTH MEASUREMENT AND MONITORING A. Data process and uncertainty analysis The underwater LED source used in W-LED and in C-LED contains a circuit providing light pulses of about 15 ns width, 5 ns rise time. LED wavelength is 400 nm. Intensity of the light pulses it adjustable via applied power supply voltage de- livered from an electronics module above water. The module delivers also trigger signals to the LED source with frequency 1,000 Hz.

The width of each waveform is 1 µs, about 1 ns per point.

The first 100 ns are used as the waveform baseline. A peak- finding algorithm was applied within the next 800 ns win- dow. The charge was integrated from 40 ns before the max- imum of signal peak to 80 ns after the peak. For each time of measurement, both W-LED and C-LED will flash at least Chuan-Shi Dong et al.

Nucl. Sci. Tech. , () Fig. 9. The WAL measurement device installed at the bottom of the water pool. (a) The view of one PMT after installation. (b) The overview of the WAL device after installation seeing from the W-LED position. 2 minutes to obtain more than 120 thousand waveforms. The integrated PMT charges (Q) are filled in the histogram, as shown in Fig. 10 [Figure 10: see original paper]. The mean charge is extracted by fitting the charge spectrum with a Gaussian-convoluted Poisson distri- bution. The mean value (µ) is about (46.3 ± 0.1) PEs, which means the fitting error is within 0.5%. ble once the water pool was filled. The prerequisite Qa data was obtained on December 15, 2024, during a light-tightness test conducted before the water filling process began.

The uncertainties based on charge measurements in water and air in Eq. (6) are considered here.The fiber calibration coefficient in water is denoted as cw Similarly, the fiber calibration coefficient in air is denoted as ca i = 1/Qac i . According to the formula for propagation of uncertainty, the relative error of Vi in Eq. (6) can be expressed (cid:115)(cid:18) σcw (cid:19)2 (cid:19)2 (cid:18) σQw (cid:19)2 (cid:18) σca (cid:18) σQa (cid:19)2 The statistic uncertainty in each term of the calibration (cw i) and charge collection (Qw i) in Eq. (8) is below i or Qa or ca 0.5%.

Fig. 10. An example of PMT5 charge distribution triggered by W- LED and fitted by the Gaussian-convoluted Poisson. The fitted av- erage charge is about 46.3 PEs.

Each PMT’s water-to-air charge ratio can be calculated out (Vi), and then WAL (λ) can be fitted by Eq. (6). This method effectively minimizes systematic errors from stray light, lead- ing to a more accurate determination of the WAL. While the PMT response is sensitive to the geomagnetic field [11], this effect is canceled out in our relative measurement, which is normalized via fiber calibration.

Long-term, real-time measurements of Qw became possi- For the second and fourth terms in Eq. (8), two additional systematic uncertainties are considered:

1. Uncertainty from non-uniformity, introduced by the

change in the LED’ s angular emission profile between water and air;

2. Uncertainty associated with the PMT’ s non-linear re-

sponse. The uncertainty in item 1 is estimated from the 3.0 ◦ maxi- mum deflection of the light’ s emission angle, which is caused by refraction between the water and air media. This yields an uncertainty of $±$1.0%, as determined in Sec. III A.

WATER ATTENUATION LENGTH . . . Nucl. Sci. Tech. , () The measure- ment by W-LED trigger in water and air, which corresponding to the second and fourth terms of Eq. (8), given that the PMT charge in our measurement does not exceed 600 PEs and 1200 PEs for the PMT1. The PMT non-linearity should be considered, which was measured in the LPMT mass production (Fig. 31 [Figure 31: see original paper] in [5]), but only the mea- surement data points for the nonlinearity versus the PE num- ber. To simplify the application and account for nonlinearity corrections, a logarithmic polynomial function was used to fit the measurement data. The fitted non-linearity function (η) was obtained as $\eta = -2.1\ \ln2(\text{Qmeas}) + 21.3\ \ln(\text{Qmeas}) - 55.1$, Given that the measured data fluctuated within a band, the fitted nonlinearity yielded uncertainties of 0.44% at 600 PEs and 1.32% at 1200 PEs, respectively.

In addition, an absolute uncertainty of 0.02 m is assigned to the distance di to account for the measurement precision and potential minor displacements of the bottom device, which causes about the system uncertainty smaller than 0.1%.

Table 1 . Summary of the systematic and statistic uncertainties of Vi.

Source of uncertainty Value Uncertainty of the collected charge (Qi) $< 0.5\%$ Uncertainty of the fiber calibration (ci) $< 0.5\%$ Uncertainty of diffuser non-uniformity Non-linearity uncertainty at 600 PEs Non-linearity uncertainty at 1,200 PEs PMT position uncertainty Total uncertainty of Vi 0.44% 1.32% The uncertainty budget for the WAL measurement is sum- marized in Table 1. It is evident that the dominant contribu- tions arise from the PMT non-linearity and the light source non-uniformity. The total uncertainty of charge ratio is about 2%, which will be used in the WAL fitting.

B. WAL measurement results and monitoring The WAL measurement system was commissioned in Jan- uary, 2025. The first measurement, conducted on January 10th, determined the WAL to be 22.8 ± 1.0 m, as shown in Fig. 11 Figure 11: see original paper. The 5 points are charge ratio from 5 PMTs, the WAL (λ) is fitted by Eq. (6). Fig. 11(b) shows the WAL reached about 75 m in October.

The long-term evolution of the WAL since January 2025 is presented in Fig. 12 [Figure 12: see original paper]. During the water filling stage before February, the WAL is about 23 m. After the full filled the water, the water purification system started. The WAL was quickly increased and reached about 60 m, and stabilized at this value during the commissioning time from February to August. In August, the top of water pool was sealed with ni- trogen, then the WAL increased, and reached about 75 m [7].

In parallel, the water resistivity, another parameter of wa- ter quality, measured by JUNO water circulation system was Fig. 11. The WAL measurements and fitted at (a) the first measure- ment before the water circulation, and (b) one measurement in mid- October in JUNO stable data taking stage. also plotted in Fig. 12. During the commissioning time, sometimes the water circulation was stopped, then the wa- ter resistivity decreased quickly, which corresponds to the dropped points from February to August. After nitrogen sealed, the water resistivity increased, and the WAL also in- creased, which means the water quality became better and better.

V. CONCLUSION This paper has presented the design, implementation, and operational performance of a novel in-situ WAL monitoring system developed for JUNO. The system represents enabling real-time, continuous monitoring of water transparency di- rectly within the operational detector. Based on a fixed-geometry design utilizing JUNO’ s standard 20-inch PMTs and calibrated light sources transmitted through optical fibers, the device eliminates mechanical moving parts while main- 510152025Distance (m)0.50.60.70.80.91Charge ratio / ndf 2c 10.31 / 3Prob 0.01614A 0.04731-1.575 l 0.9599-22.8 / ndf 2c 10.31 / 3Prob 0.01614A 0.04731-1.575 l 0.9599-22.8 510152025Distance (m)0.3Charge ratio / ndf 2c 3.529 / 3Prob 0.317A 0.006199-0.4046 l 5.407-75.58 / ndf 2c 3.529 / 3Prob 0.317A 0.006199-0.4046 l 5.407-75.58

Chuan-Shi Dong et al.

Nucl. Sci. Tech. , () Fig. 12. Long-term monitoring of the water attenuation length and water resistivity. Taken from [7]. taining measurement capability for WAL exceeding 40 m.

The system’ s performance has been validated during JUNO’ s commissioning phase. Following the activation of the water circulation system, monitoring data revealed a rapid improvement in water quality, with the WAL increasing to approximately 60 m. A further enhancement to 75 m was achieved after the detector was sealed under a nitrogen atmo- sphere in August, demonstrating excellent agreement with de- sign specifications. These results confirm the system’ s capa- bility to provide accurate, real-time feedback on water quality dynamics during operational phases.

The successful implementation of this monitoring method- ology offers several advantages: reliability through simplified mechanical design, cost-effectiveness compared to complex positioning systems, and immediate re- sponse to water quality variations. The design principles and technical solutions presented here provide a valuable refer- ence for future large-scale water Cherenkov experiments. operational [1] L. Wang, J.L. Xu, S.X. Lu et al., Novel design for 100 meter-scale water attenuation length measurement and monitoring, JINST 19 (2024) P05051. [2] The Super-Kamiokande Collaboration, S. Fukuda et al., The Super-Kamiokande detector, Nucl. Instrum. Meth. A 501 (2003) 418-462. [3] C. Li et al., An apparatus to measure water optical attenuation length for LHAASO-MD, Nucl. Instrum. Meth. A 958 (2020) [4] J. Chen, J. Xu, Y. Huang et al., Study of a Compact Device for Water Attenuation Length Measurements, 2025 JINST 20 P12031. [5] JUNO Collaboration, A. Abusleme et al., Mass testing and characterization of 20-inch PMTs for JUNO, Eur. Phys. J. C 82 (2022) 1168. [6] JUNO Collaboration, Angel Abusleme et al., First mea- JUNO, neutrino surement arXiv:2511.14593v1 [hep-ex] 18 Nov 2025. oscillations reactor [7] JUNO Collaboration, Angel Abusleme et al., Initial perfor- mance results of the JUNO detector, Chin. Phys. C in press. [8] A. Coppi et al., Mass testing of the JUNO experiment 20-inch PMT readout electronics, Nucl. Instrum. Meth. A 1052 (2023) [9] Y-shape fiber with SMA 905 in Xin-rui fiber company: https://www.xi-ri.com/productinfo/693943.html. [10] Zhaoyuan Peng et al., A test system for the JUNO 20-inch PMTs prior to installation, 2025 JINST 20 P06039. [11] G. Zhang, et al., The study of active geomagnetic shielding coils system for JUNO, 2021 JINST 16 T10004.