Measuring the Attenuation Length of Water in the CHIPS-M Water Cherenkov Detector

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Abstract

The water at the proposed site of the CHIPS water Cherenkov detector has been studied to measure its attenuation length for Cherenkov light as a function of filtering time. A scaled model of the CHIPS detector filled with water from the Wentworth 2W pit, proposed site of the CHIPS deployment, in conjunction with a 3.2 m vertical column filled with this water, was used to study the transmission of 405 nm laser light. Results consistent with attenuation lengths of up to 100 m were observed for this wavelength with filtration and UV sterilization alone.

Keywords: Water, Attenuation, Neutrino, Cherenkov, Detector, Filtration, Absorption

1. Introduction

The CHIPS (CHerenkov Detectors In PitS) R&D project will investigate the proof of principle for a novel and very inexpensive water Cherenkov

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4 detector [1]. Demonstration of a cost in the region of \$200-\$300 k per kilo-
5 ton (kt) is one of the goals of this program of research in order to realize
6 mega-ton scale detectors in the future within realistic financial constraints.
7 A prototype detector of between 3-5 kt of water is proposed for construction
8 7 milli-radians (mrad) off-axis in the NuMI neutrino beam, in a flooded mine
9 pit 708 km from the neutrino source at Fermilab. The prototype detector
10 will observe neutrinos via the detection of Cherenkov radiation produced by
11 their interactions in the water inside the detector.

12 A major part of the cost saving in the CHIPS concept is achieved by
13 enclosing the detector water volume in a very lightweight, water- and light-
14 tight containment vessel to be submerged in the Wentworth pit. The 60 m
15 depth provides an overburden of water to provide cosmic ray shielding at
16 the same time as physically supporting the detector volume. This avoids
17 the need to build a large structure or to excavate many kilotons of rock to
18 contain the target water. The Cherenkov light from neutrino interaction
19 remnants in the water will be collected by planes of 80 mm photomultiplier
20 tubes (PMTs) positioned on the inner downstream side of the detector. It is
21 therefore essential that the attenuation length of the Cherenkov light in the
22 water be long enough to ensure very little reduction from production point
23 to PMT. The pit once functioned as an open taconite mine and it is expected
24 that the water will contain substantial suspended particulates. These can be
25 removed by conventional filtering. The goal of this study was to understand
26 whether, after filtering the remaining dissolved solids in the water would
27 provide significant attenuation to the light. If this were to be case, further
28 treatment of the water such as reverse osmosis or de-ionisation would be
29 necessary, potentially leading to significant density differences between the
30 inner and outer water, as the purified pit water will be used as the inner
31 detector target mass. This could, in turn, lead to a significant increase in the
32 cost, not only of the water treatment system, but also of the outer structure
33 itself. The purification process and the method of the attenuation length
34 measurement are reported here.

35 The attenuation length of the water from the Wentworth pit, made using
36 a Secchi disk [2], is in the region of 2.5 ± 0.5 m. In order to achieve the 50-
37 100 m attenuation length required for a very large diameter detector [3], the
38 proposal is to fill the detector with pit water that has been passed through
39 a series of filters down to a Micron Rating of $0.2 \mu\text{m}$.

2. Experimental Setup

Pit water contained in a 50 (U.S.) gallon (189 litre) barrel is continuously passed through the cleaning system comprised of a UV sterilizer, a $1\text{ }\mu\text{m}$ carbon filter, and a $0.2\text{ }\mu\text{m}$ general purpose filter at a rate of 0.06 litres per minute (lpm) and circulated back into the barrel. The rate is set to simulate the rate of turnover in a large 30 m diameter CHIPS detector which will circulate 490 lpm for each 2 m high detector slice. Generally, about 7 turnovers are required in order to ensure that 99% of the water has actually passed through the filters [4]. This would lead to a full water exchange approximately every two weeks.

A vertically mounted cylindrical tube of 3.2 m length and 50.8 mm (2 inch) inner diameter schedule 80 PVC pipe was sealed with a transparent perspex plate at the bottom through which a single 6 mm water pipe was inserted. This setup was inspired by the measuring equipment at University of California, Irvine [5] and is shown in Figure 1.

The fully automated measuring apparatus was controlled by a BeagleBone Black (BBB) [6] single-board computer running Linux. The column was filled with the water from the barrel via a servo operated valve controlled by one of the BBB Pulse Width Modulation pins to direct the water away from the filters and into the tube. The schematic of the water system is shown in Figure 2. The fill pump was allowed to run until the column contained a total water height of 3 m, and was then stopped via a relay controlled by one of the BBB GPIO pins. A Thorlabs CPS405 collimated laser diode was mounted on a stage which allowed for adjustments in rotational and translational planes and was positioned to shine vertically upwards along the axis of the column. A lens with a focal length of 50 mm was inserted at the top of the column, 50 mm below a blue sensitive photo diode (1125-1009-ND 525NM) on axis at the top of the tube looking down at the laser.

The photodiode output was amplified using an operational amplifier circuit as shown in Figure 3. It was connected to the inputs of a trans-impedance amplifier, with feedback resistors of between 1 and $10\text{ M}\Omega$ depending on the required gain so that the photodiode was operated in short circuit mode and not reverse biased. There was a voltage offset such that the output rested at around 50 mV when the input current was zero. A clamping output buffer amplifier prevented the output from going above 1.8 V to avoid damage to the BBB input. The power source was a 9 V battery.

Once the column was full of water, the laser light was monitored in order

Figure 1: Left: schematic showing the key features of the water column (lengths in mm) and right: photograph of the setup in the laboratory showing the column (left), the filters(centre) and the barrel (forefront right).

Figure 2: Sketch showing the layout of the pipework for the water circulation and the attenuation length measurement. The water continuously circulates until a measurement is performed at which point the servo direction is changed such that the column is filled before turning off the fill pump.

77 to estimate the time it would take for the bubbles to rise and the water to
78 become stable after the turbulence caused by the fill pump. Figure 4 (left)
79 shows the photodiode ADC as a function of time. The fill can be seen to
80 occur where the ADC value falls to zero. A conservative period of 20 minutes
81 was taken to allow for recovery. This is the time period from the fill point to
82 the end of the x axis in the Figure. The light level can be seen to stabilize
83 after this time. The next step in the process is to pump out a given amount
84 of water. This also adds instantaneous vibration to the system, as shown in
85 Figure 4 (right) where the two peaks correspond to the drain pump turning
86 on and off and the recovery of the water clarity is seen in between. The BBB
87 DAQ script was programmed to wait for 20 minutes after filling and at each
88 measurement point.

89 The output from the photodiode circuit was digitized with one of the ADC
90 channels on the BBB and data recorded in ASCII files for analysis. A total
91 of 50 measurements was taken at each water height over a period of about
92 10 seconds. A quantity of water was then pumped out of the column and the
93 procedure of pausing and taking data was repeated. The attenuation length
94 was determined by measuring the intensity of light from the laser incident
95 on the photodiode as a function of the height of water in the column and

Figure 3: Amplifier circuit diagram (top) and fabricated board + photodiode (bottom)

Figure 4: The left plot shows the photodiode ADC as a function of time. The fill is occurring where the ADC value has fallen to zero and the turbulence renders the water completely opaque. The right plot shows a time range after the fill is complete. When the drain pump turns on and off, the pipe shakes and this vibration causes turbulence in the water for a short time as evidenced by the peaks.

then performing an exponential fit to the graph. The error on the water height steps was less than 1 cm; the fill time and emptying time were very repeatable. The number of steps could be varied by changing the amount of time the drain pump ran between data taking steps.

The water was circulated continuously through the filtration system in between taking regular attenuation length measurement runs. Improvements in the attenuation length were tracked as a function of time and therefore the effectiveness of the filtration and UV systems could be investigated.

3. Data Analysis

The intensity of the light at the top sensor is given by

$$I = I_0 e^{-x/\lambda} \quad (1)$$

where I_0 is the light intensity with no water in the column, λ is the attenuation length and x is the water height. The data are fit to extract the attenuation length.

The accuracy of the measurement is limited by the length of the column, the stability of the laser and the photodiode, the stability of the ambient temperature, the vibrational stability of the environment, the stability of the

112 BBB ADC and the amplifier circuit noise. There is therefore a limit to the
 113 maximum attenuation length measurement achievable.

114 The attenuation length in the 100kt detector is required to be at least
 115 30 m at 405nm, as determined by reconstruction studies done on simulated
 116 neutrino interactions [3] but a longer attenuation length translates into more
 117 light at the PMTs and therefore better reconstruction of the interaction.
 118 Clearly, the longer the column, the more sensitive the measurement can be
 119 as it will increase the difference between the light levels when empty and full.

120 As an illustration, two examples are investigated. Taking the empty light
 121 level to be 3600 ADC counts in order to use most of the dynamic range
 122 of the 12 bit ADC, an attenuation length of 106 m would correspond to a
 123 drop in intensity to 3500 ADC counts (3%) over a 3 m long length of water
 124 when the column was full. Similarly, an attenuation length of 52 m would
 125 correspond to a drop in intensity of 6% and the light level would measure 3400
 126 ADC counts when full. Each attenuation length measurement involves $N \approx 10$
 127 separate measurements of the light level between full and empty which leads
 128 to an expectation of the uncertainty on the gradient to be the error on a single
 129 point divided by $\sqrt{N}$. With very long attenuation lengths (>50 m) a linear
 130 approximation works for the purposes of this illustration. Figure 5 shows the
 131 possible range of uncertainty produced by the pipe length limitation on the
 132 true attenuation length of 52 m and 106 m as a function of the single point
 133 error. The red lines show the lower limit and the blue lines show the upper
 134 limit. This provides a sanity check that a measurement of 100 m is safely
 135 far from the limitation of the 3 m column if the combined systematic error
 136 per point is kept at below about 30 ADC counts. Each contribution to the
 137 systematic error was measured as described below.

138 *3.1. Systematic Errors*

139 The contributions from the various sources of systematics were measured.
 140 As shown in Figure 6 the BBB ADC was measured to give a purely random
 141 jitter with a standard deviation of 1.1 ADC counts by measuring one of the
 142 BBB ADC channels connected to a simple voltage divider circuit. The laser
 143 specification gives a stability of the laser output power of 1% over a 1 minute
 144 period and 2% over an 8 hour period. The attenuation length measurement
 145 run time is between one and two hours, so a systematic of 1.5% for the overall
 146 stability during this time period might be expected.

147 The photodiode and laser stability are measured together by monitoring
 148 the ADC output as a function of time for a full water column. In addition

Figure 5: An illustration of the effect of the single point uncertainty on the measurement of the attenuation length, assuming a true attenuation length of 52 m and 106 m. In the case of a 16 ADC count error on each point (as measured in Section 3.3), shown by the vertical line, the attenuation length could be mis-measured by up to 2.5 m and up to 12 m respectively

149 ambient vibrations which affect the full water column are folded in to this
 150 measurement. Figure 7 shows the dependence of the photodiode output with
 151 temperature over a period of a few hours. The temperature was found to
 152 have the largest impact on the system stability of all the systematics.

153 3.2. Cleaning Rate Measurement

154 Once the water was being passed through the filtration system, samples
 155 were taken regularly from the barrel to observe how the attenuation length
 156 increased with time. The temperature was continuously monitored through-
 157 out this procedure and used to estimate the errors on the data points for each
 158 attenuation length measurement. Initial measurements of the unfiltered pit
 159 water can be seen in Figure 8 (top left), where the attenuation length was
 160 measured to be 1.6 ± 0.05 m. The result is in reasonable agreement with the
 161 measurement with the Secchi disk for white light. Other results can be seen
 162 after 12 days (top right) and after 25 days(bottom).

163 Figure 9 shows the outcome of the measurements over a four month
 164 period. Larger errors are associated with measurements during the colder
 165 months when the laboratory heater cycles produced large temperature re-
 166 lated variations in the ADC output. The temperature was the dominant sys-
 167 tematic delivering an uncertainty over the course of each attenuation length

Figure 6: Top: BBB ADC channel reading from a voltage divider as a function of time. Bottom: the projection of the time evolution showing a standard deviation of 1.1 ADC counts.

Figure 7: Top: Photodiode ADC as a function of temperature for a full water column taken over a period of a few hours. A linear fit shows a change of about 38 ADC counts per °C. Continuous temperature monitoring was used to estimate the size of the errors on the data points for a given attenuation length measurement run.

168 measurement of sometimes up to 38 ADC counts per point for a change be-
 169 tween single point measurements of 1°C. However, it can be seen that the
 170 filtration system is effective with a clearly increasing trend in attenuation
 171 length up to values of 50-60 m, and referring back to Figure 5 within the
 172 accuracy of the measurement system. This suggests a relatively simple fil-
 173 tration system will be adequate for a detector size of 30 m diameter. It can
 174 also be seen that a circulation time of about 3-4 months should provide an
 175 attenuation length of 50 m.

176 3.3. System Improvements

177 Once the time constant of the water cleaning had been determined, steps
 178 were taken to make the setup more stable to improve the accuracy of the
 179 measurements at longer attenuation length and to ascertain whether further
 180 cleaning would be possible. This was done by insulating the electronics and
 181 laser from temperature changes, increasing the water recirculation speed to
 182 clean the water much faster, and working in April when the temperature was
 183 warm enough to avoid the heater cycles. It is possible that an additional

Figure 8: Plot showing water attenuation measurement for raw pit water (top left); after filtering for 12 days (top right) and after filtering for 25 days (bottom)

Figure 9: Plot showing how attenuation length improved with time while the water was continuously circulated through the filtration system.

184 speed up in the water clarity with recycle rate was due to there being no
 185 chance for any bacteria to survive such short circulation times, although this
 186 is conjecture.

187 Figure 10 (top) shows the photodiode ADC for a full water column in
 188 the improved set up as a function of time. The lower histogram shows the
 189 projection with a standard deviation of 15.7 ADC counts. This measurement
 190 incorporates all of the systematic uncertainties and results in an overall un-
 191 certainty of 0.5%. While this is smaller than the specification for the laser
 192 stability, the measured systematic error of 16 ADC counts is nevertheless
 193 applied to each data point in the subsequent attenuation length fit proce-
 194 dure. This is well below the target of 30 ADC counts described above for
 195 attenuation lengths above 50 m.

196 3.4. Final Results

197 Figure 11 shows three attenuation length measurements taken at inter-
 198 vals of 0, 1.5 and 12 hours of water circulation with attenuation lengths
 199 of $\lambda=1.68\pm0.02$ m, 22.4 ± 1.2 m and 139 ± 42 m respectively. This increase in
 200 speed of water cleaning is just due to the increased circulation rate of the
 201 water through the filters and sterilizer.

Figure 10: Top: ADC + photodiode stability after system improvements. Bottom: the projection of the ADC values showing an RMS of 15.6 ADC counts.

202 4. Simulation

203 A dedicated simulation program was developed to cross check and dis-
 204 entangle any contributions to the attenuation length measurement from the
 205 optical setup. The simulated photon's trajectory was traced according to the
 206 rules of geometrical optics and could be absorbed in the water with a prob-
 207 ability depending on the water absorption length. A photon was considered
 208 as detected if it reached the photodetector. The simulation made use of the
 209 ROOT [7] software framework but all the code describing the photon trans-
 210 portation and interaction processes was developed independently. All the
 211 optical elements, including the focussing lens in front of the photodiode, and

Figure 11: Plot showing attenuation length measurements for three different levels of water clarity, at the start (dot-dash), after 1.5 hours(solid) and after 12 hours(dashed). The y axes have been normalised for comparison to take out longer term drift as described.

the material boundaries present in the experimental setup were considered in the photon ray-tracing; the laser beam width and divergence were modelled according to the Thorlabs data sheet [8]. The geometrical parameters for the laser (direction, starting position) and the photodiode (position, size) could all be individually varied. The water level and its attenuation length could also be varied. The beam divergence is very small, and measurements made with the above setup were unable to detect any light more than 5mm away from the laser center. Therefore it was deemed unnecessary to simulate any scattered light from the inside of the tube as our measurements showed it would not be possible to detect such a low light level.

Given a random starting position and direction each photon was propagated through every material boundary, where Snell's Law was applied, up to the photodetector plane. The focussing lens was modelled by applying refraction at the spherical surfaces.

The simulated data points and the fit to them showed there were no

Figure 12: Left: light intensity measured by the photodiode expressed in ADC counts, as a function of the water level for experimental data (dots) and simulation (squares). The attenuation length (λ) extracted from a fit (solid line) to the data points is $\lambda = 1.51 \pm 0.01$ m. Also shown is the simulation with an input value of $\lambda = 1.5$ m whose corresponding fit (dashed line) gives $\lambda = 1.49 \pm 0.01$ m. Statistical errors only are used. Right: a longer attenuation length of $\lambda = 20.8 \pm 0.2$ m for the data and the input to the simulation of $\lambda = 21$ m shows the corresponding fit of $\lambda = 20.8 \pm 0.5$ m.

unexpected systematics associated with the optical geometry: for example the refractive index changes from air to perspex, to water, to air, to glass and to lens did not produce any effect which could be mistaken for a change in attenuation length. The simulation results are summarised in Figure 12 where it is shown that the relative attenuation length fits are both in good agreement with the results from the experimental data and demonstrate no unaccounted for systematic effects for both short and medium attenuation length.

5. Conclusions

The attenuation length of the water from the Wentworth Pit 2W, site of the CHIPS experiment, has been measured during filtration. The UV sterilization and simple filtering method was found to be capable of delivering in the region of 100 m attention length at a wavelength of 405 nm. This is completely adequate for a 30 m diameter CHIPS detector as shown by detailed simulation and reconstruction studies. Without the need for the exclusion of dissolved solids, the operational complexity and cost of the water treatment

243 system is minimised. Furthermore, the density difference between inside and
244 outside the detector is small leading to reduced requirements on the mechan-
245 ical strength of the lightweight structure and associated cost implications.

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