A 50 Ton Scale Water Cherenkov Test Platform in a Charged Particle Test Beam

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Abstract: Water Cherenkov and water-based particle detector technologies are used to realize multi-kiloton scale experiments such as the currently operating Super-Kamiokande experiment [1], the planned Hyper-Kamiokande experiment [2] and the proposed THEIA detector [3] and ESSnuSB detectors [4]. These experiments are operated, planned or proposed to study a broad range of physics including neutrino oscillations, nucleon decay, dark matter and neutrinoless double beta decay. The neutrino oscillation programs of Hyper-K and ESSnuSB will also include kiloton scale near or intermediate detectors used to study neutrino production and interactions in the absence of neutrino oscillations, such as the Hyper-K Intermediate Water Cherenkov Detector (IWCD) [5]. Realization of these physics programs will require new detector technologies and percent-level calibration of detector responses and models of physics processes within the detector. The Water Cherenkov Test Experiment (WCTE) [6] is a proposed 50 ton water Cherenkov experiment to be operated in an East Area charged particle test beam at CERN starting from 2022 or 2023. The experiment may be used to study the performance and detector response for detector technologies including multi-PMTs, LAPPDs and dichroicon, Gadolinium (Gd) loading and water-based liquid scintillator (WbLS) [7], and the effectiveness of various calibration techniques.

Water Cherenkov Test Experiment: The water tank for the WCTE will be $\sim$ 4 m tall and have a diameter of $\sim$ 4 m, allowing for the study of particle propagation over a few meter distance and for containment of neutrons. A photosensor support frame inside the tank will allow for the mounting of photon detectors over the fuller inner surface. The experiment will be operated with charged particle fluxes of $\pi^{\pm}$, p^{+}, $e^{\pm}$ and $\mu^{\pm}$ incident momenta ranging from $\sim$ 200 MeV/c to $\sim$ 1200 MeV/c. It is proposed to operate the experiment in the T9 secondary beam line at the CERN PS. Low momentum muon and electron particle fluxes will be provided directly from the secondary beam, while low momentum hadrons will be produced with a tertiary production target. Particle momenta will be measured with a compact spectrometer using a Halbach array permanent magnet with a dipole field and silicon strip or wire chamber tracking layers. Particle identification will be carried out with a time-of-flight (TOF) detector and aerogel Cherenkov threshold detector. The TOF detector will be segmented in order to identify kinks when pions decay to muons before entering the detector.

The detector tank, photosensor support frame, basic water system, spectrometer and beam particle identification detectors are valuable infrastructure that can be used for the testing of water Cherenkov and WbLS technologies. The initial phase of the WCTE operation is in large part driven by the Hyper-K and IWCD requirements to test multi-PMT photosensors and calibration techniques and make measurements of neutron production with Gd loading. Beyond the initial phase, there is interest to use this infrastructure for the study new photon detectors, such as dichroicons, and WbLS. The operation of additional phases would likely take place in the 2023-2025 time frame.

Gd Loading in WCTE: The addition of $\mathrm{Gd_2(SO_4)_3}$ to a water Cherenkov detector allows for high efficiency of neutron detection through the neutron capture on the Gd nucleus and subsequent deexcitation of the nucleus. The improved neutron detection efficiency enhances the detection of inverse beta decays, provides a statistical handle for the identification of charged current quasielastic antineutrino scatters and may be used to identify atmospheric neutrinos that are backgrounds for proton decay searches. The application of Gd to water Cherenkov detectors had been established by the EGADs experiment and loading of Gd into the Super-K detector has begun in 2020 [8]. The ANNIE experiment [9] aims to measure neutron production from neutrino interactions in the Fermilab Booster neutrino beam. Applications of neutron tagging in neutrino-nucleus scattering may be affected by uncertainties in the modeling of secondary neutron production in the scattering of hadrons produced in the neutrino interaction or captures of muons on nuclei. The WCTE provides a platform to measure this secondary neutron production with well characterized hadron and muon fluxes.

WbLS in WCTE: The proposed THEIA [10] experiment achieves a broad physics program through the application of water-based liquid scintillator (WbLS) [7] to detect low energy processes using scintillation light and high energy processes with directional information using Cherenkov light. As a neutrino detection technology, WbLS combines the advantages of a water Cherenkov detector with the capability to identify and make calorimetric energy reconstruction of below threshold particles that are invisible in a Cherenkov detector. After operation in pure water and Gd loading phases, the WCTE may be used as a test platform for WbLS. In this capacity it can be used to study the performance of the WbLS circulation and purification system, to study new photon detectors suited to operation in a WbLS detector, and to make measurements of scintillation and Cherenkov light production particle fluxes of different types and energies.

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Novel Photon Detectors in WCTE: The multi-PMT photosensor concept places many small PMTs pressure tolerant, water-tight vessel along with high voltage circuits and front-end readout electronics. This provides improved spatial, timing and directional granularity compared to large 50 cm or 20 cm diameter PMTs. The concept was originally developed for KM3NeT [11] and IceCube [12], detectors that deploy strings of photosensors throughout the detector volume. The Hyper-K collaboration has adapted the concept for detectors where the photosensors are placed at the outer boundary of the detector. The WCTE will be the first opportunity to study the multi-PMT in this type of configuration. The Hyper-K experiment also requires improved timing resolution and lower noise in multi-PMTs compared to KM3NeT and IceCube, and the achievement of the required performance in these areas will be studied for large-scale deployment in the WCTE.

The discrimination between Cherenkov and scintillation photons in a WbLS detector can be achieved through multiple approaches, including time separation and wavelength separation. Separation by wavelength may be achieved by so-called Dichroicon photosensors that use dichroic filters to separate long wavelength Cherenkov photons from short wavelength scintillation photons [13]. Separation of Cherenkov and scintillation light may also be achieved in the timing distributions of prompt Cherenkov light and delayed scintillation light. To achieve this separation high timing and spatial resolution photon detection is necessary to precisely measure photon arrival times and to determine the production vertex to make photon time-of-flight corrections. Large area picosecond photodetectors (LAPPDs) with ~ 50 ps timing resolution are a promising technology for this application [14]. A phase WCTE operation with WbLS loading will provide a platform to test these or other advanced photodetector technologies with well understood particle fluxes.

Fully Integrated Test Platform and Calibration: Many of the challenges faced in water Cherenkov detectors are only fully realized when the various detector systems are operated in a fully assembled detector and understanding of the detector response through calibration measurements is attempted. In addition to the R&D of individual technologies, it is invaluable to be able to test new technologies in a full detector with well understood particle fluxes. The WCTE is expected to provide this type of platform for the experiments and R&D efforts described in this LOI and for any new efforts that may be undertaken in the coming years.

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