Prototype detection unit for the CHIPS experiment

Maciej M. Pfützner¹
Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom
E-mail: maciej.pfutzner.12@ucl.ac.uk

Abstract. CHIPS (CHerenkov detectors In mine PitS) is an R&D project aiming to develop novel cost-effective neutrino detectors, focused on measuring the CP-violating neutrino mixing phase \(\delta_{\text{CP}}\). A single detector module, containing an enclosed volume of purified water, would be submerged in an existing lake, located in a neutrino beam. A staged approach is proposed with first detectors deployed in a flooded mine pit in Northern Minnesota, 7 mrad off-axis from the existing NuMI beam. A small proof-of-principle model (CHIPS-M) has already been tested and the first stage of a fully functional 10kt module (CHIPS-10) is planned for 2018. One of the instruments submerged on board of CHIPS-M in autumn 2015 was a prototype detection unit, constructed at Nikhef. The unit contains hardware borrowed from the KM3NeT experiment, including 16 3 inch photomultiplier tubes and readout electronics. In addition to testing the mechanical design and data acquisition, the detector was used to record a large sample of cosmic ray muon events. The collected data is valuable for characterising the cosmic muon background and validating a Monte Carlo simulation used to optimise future designs. This paper introduces the CHIPS project, describes the design of the prototype unit, and presents the results of a preliminary data analysis.

1. CHIPS project

CHIPS [1] is an R&D project with two main goals. The physics goal is to accelerate the global search for CP violation in the neutrino sector and the measurement of \(\delta_{\text{CP}}\) by studying long-baseline \(\nu_e\) appearance. The development goal is to significantly decrease the cost of water Cherenkov detectors for neutrino beams, reaching $300k per kt of fiducial mass (currently ca. $1M/kt). The core idea is to use modules submerged in existing lakes or flooded pits, with the water providing structural support and shielding from cosmic rays. The reduced civil engineering effort compared to placing the detector underground will be the main source of cost savings. A single module will consist of a lightweight cylindrical structure, wrapped in a light- and watertight liner, sealing in a volume of pure water, treated with a minimal filtering system. An internal wall will separate the detector into an inner and outer volume for active muon veto. Photomultiplier tubes (PMTs) placed along the walls and organised into planes with common readout hubs will detect Cherenkov light produced by charged particles created in neutrino interactions. The PMT layout and photocathode coverage will be optimised for beam events with the help of a detailed Monte Carlo simulation. The R&D cost can also be driven down by reusing existing hardware solutions, e.g. the readout systems from the KM3NeT experiment.

¹ On behalf of the CHIPS collaboration
First detector modules will be submerged in the Wentworth Pit 2W—a 60 m deep flooded mine pit in northern Minnesota. It is located in the NuMI beam, 7 mrad off-axis, 708 km away from the target. The detectors are designed to be modular, allowing them to be expanded after initial deployment or moved to a different location. One such considered site is a reservoir in the future LBNF beam, located at a baseline of 1250 km, 20 mrad off-axis.

CHIPS-M, a small-scale model, has already been tested at the Wentworth Pit, submerged in 2014 and again in 2015. With a $3.3 \times 3.3$ m octagonal truss and a geomembrane liner, it served as a technology testbed for prototype instruments, the water purification system and detector integration. The next step will be CHIPS-10, a fully functional detector with 10 kt fiducial mass, measuring 30 m in diameter and 20 m in height. The deployment of its first stage, consisting of top and bottom caps and a single vertical slice, is planned for 2018.

The GLoBES simulation package [2, 3] is employed to study CHIPS physics reach. The detector properties are based on the performance of Super-Kamiokande. NuFIT 2014 global fit results [4] are used as the true values of the oscillation parameters. Figure 1 displays the sensitivity of a 100 kt CHIPS and 10 kt DUNE for an example scenario where CHIPS runs for 4 years in the NuMI beam and is moved to the LBNF beam as it starts operation for further 6 years. The studies show the possibility of significant acceleration of physics results with relatively modest funding.

![Figure 1. Physics sensitivities for 10 kt DUNE running for 3 years in neutrino mode and 3 years in antineutrino mode (3 + 3 years, red lines), a 100 kt CHIPS detector running for 2 + 2 years in the NuMI beam and 3 + 3 years in the LBNF beam (20 mrad off-axis, green lines), and their combination (blue lines). Left: $1\sigma$ resolution of the $\delta_{CP}$ measurement as a function of the true value of $\delta_{CP}$. Right: Exclusion significance of CP violation. Normal hierarchy is assumed.](image)

2. Prototype detection unit
A prototype plane was designed and constructed at Nikhef in the Netherlands. It contains the hardware from a single KM3NeT Digital Optical Module, including 16 3 inch Hamamatsu PMTs and full readout electronics, enclosed in a robust pressure vessel made of inexpensive PVC piping (Fig. 2). Clear acrylic domes glued to PVC act as windows for the PMTs. An aluminium cylinder houses the central readout boards, with feedthroughs for power supply cables and an optic fibre for communication and data acquisition. The unit was deployed on board of CHIPS-M on the 30th of September 2015. It started data taking almost immediately, however issues with an external wiring hub limited the recorded data to approximately two days. CHIPS-M was successfully recovered a month later.

During data taking, the time and pulse-length (time-over-threshold) of every PMT hit is sent to shore and stored on disk. The individual PMT rates, settling at 1 kHz to 2 kHz after one day
of running, are dominated by dark current, but events caused by cosmic muons can be identified using hit coincidences. A simple event-forming algorithm selects all hits within a 30 ns window and not more than 5 ns apart. Time calibration of the PMTs is performed with events from special runs, during which a flashing LED was illuminating the detector.

A Monte Carlo (MC) prediction is compared to the observed data. The simulation software, based on Geant4 [5], is used to optimise the design of future CHIPS modules and to guide reconstruction development. The CHIPS-M MC model is tiled with clones of the prototype plane, imitating a fully-instrumented detector. With one of the copies treated as the original plane, this setup makes it possible to correct for geometrical acceptance.

Figure 3 shows the rates of events with different number of coincident hits. The data is compared to MC predictions with different water attenuation properties, consistent with an independent measurement indicating roughly 3 m total light attenuation (at 405 nm wavelength). The total rate of recorded events with at least three hits is approximately 60 Hz.

An MC-based acceptance correction allows to estimate the total rate of cosmic ray muons passing through CHIPS-M. Taking into account the imperfect agreement of data and MC gives a conservative value of $\leq 140$ Hz. An analytical correction based on the size and depth difference, yields a predicted rate of $\leq 17$ kHz in CHIPS-10. This is equivalent to an average of 0.17 events in the 10 μs NuMI beam spill. With a typical duration of a cosmic event in CHIPS-10 of 220 ns it corresponds to a dead time of 0.4 %. These results are important for veto design considerations and a more detailed analysis is ongoing.

The next version of the plane to be used in CHIPS-10 is being designed based on experience with development and testing of the prototype. In addition, ways of increasing light collection, such as adding Winston cones or removing the need for acrylic domes, are being tested.

References
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