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CHerenkov detectors In mine PitS (CHIPS) R&D Proposal

P. Adamson[3], J.Austin[16], S. V. Cao[12], J. A. B. Coelho[13], G. S. Davies[4], J. J. Evans[6], P. Guzowski[6], A. Habig[8], A. Holin[5], J. Huang[12], R.Johnson[2], J. St John[2], A. Kreymer[3], M. Kordosky[14], K. Lang[12], M. L. Marshak[7], R. Mehdiyev[12], J. Meier[7], W. Miller[7], D. Naples[9], J. K. Nelson[14], R. J. Nichol[5], R. B. Patterson[1], V. Paolone[9], G. Pawloski[7], A. Perch[5], M. Pfützner[5], M. Proga[12], X. Qian[17], A. Radovic[5], M. C. Sanchez[4], S. Schreiner[7], S. Söldner-Rembold[6], A. Sousa[2], J. Thomas[5], P. Vahle[14], C. Wendt[15], L. H. Whitehead[5], and S. Wojcicki[10]

[1] *Lauritsen Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*
[2] *Department of Physics, University of Cincinnati, Cincinnati, OH 45221, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[4] *Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA*
[5] *Department of Physics and Astronomy, UCL, Gower Street, London WC1E 6BT, UK*
[6] *School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, UK*
[7] *University of Minnesota, Minneapolis, MN 55455, USA*
[8] *Department of Physics, University of Minnesota – Duluth, Duluth, MN 55812, USA*
[9] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA*
[10] *Department of Physics, Stanford University, Stanford, CA 94305, USA*
[11] *Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, UK*
[12] *Department of Physics, University of Texas at Austin, 1 University Station C1600, Austin, TX 78712, USA*
[13] *Physics Department, Tufts University, Medford, MA 02155, USA*
[14] *Department of Physics, College of William & Mary, Williamsburg, VA 23187, USA*
[15] *Physics Department, University of Wisconsin, Madison, WI 53706, USA*
[16] *Department of Physics, Large Lakes Observatory, University of Minnesota – Duluth, Duluth, MN 55812, USA*
[17] *Brookhaven National Laboratory, Upton, NY 11973, USA*

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A floating platform used in the fisheries industry

1 Executive Summary

This proposal outlines a path of development towards cost effective Mega-ton size neutrino detectors, via a series of smaller prototypes. The approach is to try to reduce all the infrastructure costs to a minimum by using a terrestrial body of water for mechanical support and overburden. Additional savings can be realized by using industrially available components wherever possible, optimizing photodetector coverage for GeV range accelerator neutrinos, and pushing for the development of cheaper photon detectors, already a major focus of a national R&D consortium.

The large detector mass that would be enabled by the successful outcome of this work supports the scientific goal already outlined in the Letter of Intent [2], to measure the CP violating phase angle, δ_{CP}, eventually to better than 25° in the NuMI beam. The gain in δ_{CP} reach that would be afforded to the LBNE program by utilizing 6 years of the NuMI neutrinos in CHIPS (as well as those already expected from NOνA and T2K) is very significant, and can ensure that a 10kt LAr detector will be sufficient to answer the outstanding questions to the precision presently desired by the community.

To measure CP violating effects, the sub-dominant appearance of electron neutrino events from the muon neutrino beam must be studied. The main challenge to this measurement is separating background neutral current events containing π^0 (two overlapping Cherenkov rings) from the signal electron neutrino charged current interactions (one Cherenkov ring). Water Cherenkov detectors have been demonstrated to work well for this purpose with efficiencies for positive identification of ν_e events of up to 80% . The final purity of the sample is a function of the neutrino beam spectrum and the resulting NC background rate.

Today, such a detector could be constructed for $1-2M/kt. This allows a total mass of 100kt to be considered, but not much more. The goal, over the coming decade, would be to reduce this cost by up to a factor 3, chiefly by reductions in photodetector costs. Pressure on that dominant photodetector cost will be applied from two sources in the coming years: from experiments that need large numbers of big tubes, potentially with high fidelity timing and position resolution, and from the competition between a number of different manufacturers in the US, Japan, and China. For example, Hamamatsu are already producing hybrid PMTs at 50% of the cost of the standard PMT design. The Daya Bay group is developing PMTs with MCPs instead of standard bases. The US based ETL company are developing 11" PMTs off the back of investment from the LBNE Water Cherenkov effort. The US consortium is developing large scale flat photon detectors which could revolutionize the landscape with their combination of fine position and timing resolution. The other major cost driver is the level of contingency necessary when estimating the costs. The prototyping planned here will actually *demonstrate* the real costs, thus potentially reducing the contingency normally required.

In the first year, resources are requested from DOE/FNAL to help build a 75 ton prototype of this novel detector concept. This detector concept is named CHIPS, for Cherenkov detectors In PitS and will be located in the Wentworth 2W flooded taconite pit near Gilbert, Minnesota. This location lies 7 mrad off the central axis of the NuMI neutrino beam from Fermilab. If the first year program of work is successful, and following a full technical review to take place in November 2014, the second year would involve deploying a much bigger, 10 kt structure, which would also be followed by a further review in November 2015. Assuming successful outcomes of both reviews, in the subsequent years the full 10kt volume would then be instrumented while

collecting physics data in parallel. The phases of the R&D are necessarily segmented into years because there is a clear deployment period, from April-October, while the lake is not iced over. There is no access to the submerged equipment outside of this period owing to the severe cold weather. Sometime between the end of year 3 and year 5 (depending on the amount of water that has been instrumented) CHIPS will start producing measurements of θ_{13}, θ_{23}, Δm^2_{23} and pushing limits on δ_{CP}.

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2 Introduction

Recent observations of a large mixing angle, θ_{13}, have refocussed the next generation long baseline experiments towards resolving the mass hierarchy and measuring δ_{CP}. While in principle aspects of these two measurements are similar, separating the two goals allows for a naturally phased program that has the potential to deliver significant physics results in both the short and long term. FNAL's new flagship LBNE project will deliver the best neutrino beam in the world for the study of neutrino oscillations once it comes online around 2023. Until then, following its intensity upgrade, the existing NuMI beam *is* the most powerful neutrino beam. That beam provides neutrinos to the NOνA experiment, which is in the optimal L/E position for oscillation measurements, and has a long enough baseline to be sensitive to matter effects. Indeed, the LBNE projections build upon the measurements that NOνA and T2K will take in the coming decade. The more of the NuMI neutrinos that can be measured in this time period, by increasing the detector mass in that beam, the more precise the eventual results from LBNE stand to be. NuMI is a unique facility that should be fully exploited as the LBNE beamline is built.

Degeneracies among the remaining unknown oscillation parameters mean that, unless nature has chosen extremely favorable values, NOνA will not be able to satisfactorily measure all the remaining unknowns with certainty because its detector mass is too small. Presently, there are no prospects for an improvement in this situation in the US until the first LBNE experiment, the 10kt LAr detector, is constructed and has taken data for several years. Current projections estimate the LBNE beam will be finished in 2023 and first results may appear 4-6 years later. This leaves a long drought of physics output from the Fermilab long-baseline neutrino program, after the initial excitement of the first NOνA data has died down and we are into the slow statistical sensitivity gains.

While one cannot achieve the ideal baseline to measure the mass hierarchy in the NuMI beam, studies performed by the e-numi group show that the NuMI beam provides the most sensitive conditions for measurement of δ_{CP} in the world today. A 100 kton water Cherenkov detector near the axis of the NuMI beam has the potential to measure δ_{CP} to better than 25° for all values of δ_{CP}. Figure 1(top) shows the resolution on δ_{CP} as function of δ_{CP} for 3+3 years of exposure for CHIPS in blue compared to that of the combination of NOνA and T2K (5+5y @ 6e20 p.o.t./y and 8.8e21p.o.t. respectively) in red. The first thing to notice is the complementarity of the two curves: CHIPS improves dramatically on the δ_{CP} resolution at the places where NOνA and T2K are at their worst. Finally, the green curve shows the resolution if all three experiments are combined, reaching a level of δ_{CP} of between 14-24°. This is a significant reach in δ_{CP} : in comparison a 10kt LAr detector in LBNE will have a similar reach of between 12-24° after 10 years of operation. Knowing δ_{CP} to 24° before starting the LBNE campaign will mean the eventual reach of LBNE is vastly improved.

The bottom plot in Figure 1 shows the band of δ_{CP} resolutions (minimum to maximum across all values of δ_{CP} in both hierarchies) against the off-axis angle of the detector. The choice of 7 mrad is within the best off-axis region for both ME and LE tunes in the NuMI beam.

In the Letter of Intent submitted to the Snowmass process [2], and to the FNAL PAC this coming January, we have described in detail the idea and physics reach of a 100kt CHIPS detector. It would be commissioned in the NuMI beam, in the flooded Wentworth 2W mine pit suspended from a floating dock on the surface. The pit is near Gilbert, northern Minnesota and belongs

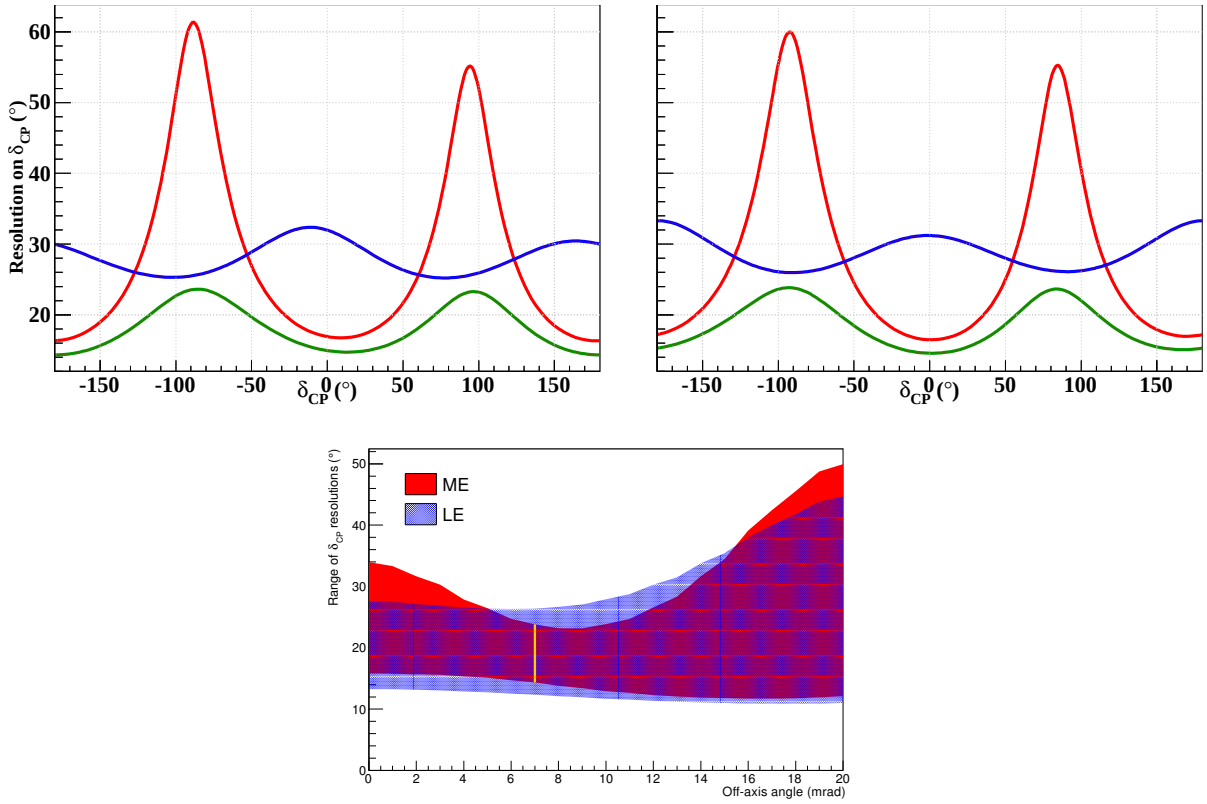

Figure 1: Top: Resolution on δ_{CP} achievable with CHIPS (3+3y blue) compared to the combination of NOνA*(5+5y) and T2K (8.8e21pot) (red) and then CHIPS,* NOνA *and T2K combined (green). Bottom: δ_{CP} resolution band for the 100kt CHIPS detector for off-axis angles from 0 to 20 mrad, for the ME and LE beams.*

to the Cliffs Natural Resources mining company. It would take data for a number of years, be complementary to NOνA in its focus on δ_{CP}, rather than the mass hierarchy, and improve the combined reach of NOνA and T2K very significantly. This would involve increasing the fiducial mass over multiple years, exploiting the experience to accelerate the expansion and therefore cutting contingency costs.

While CHIPS in the NuMI beamline will bridge the gap in physics results between the NOνA and LBNE eras, it can also enhance the physics reach of the LBNE project. The novel detector design being pursued requires very little investment in infrastructure. The bulk of the detector systems can be packed up and redeployed at another location in the LBNE beam line once that becomes operational. The second detector would be placed at a large off-axis angle (the Pactola Resevoir is at $\approx$ 20mr for example), where it would measure the second oscillation maximum, complementing the measurement of the planned on-axis detector. This would take advantage of the exceptionally good match between Cherenkov event reconstruction and neutrino energy, owing to the large quasi-elastic cross section at neutrino energies of about 1 GeV. The addition of the CHIPS data taken in the NuMI beam and then the redeployment of the CHIPS detector off-axis in the LBNE beam can improve the reach of such an LBNE detector to between 10-15 degrees, only a factor 2 worse than the neutrino factory predictions as shown in Figure 2.

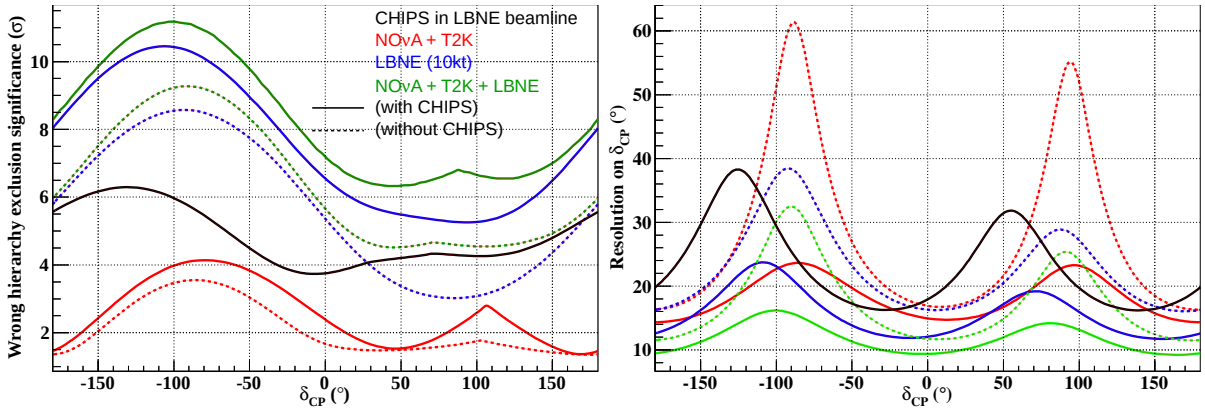

Figure 2: Mass Hierarchy and resolution on δ_{CP} achievable with CHIPS (3+3y blue) together with the 10kt LBNE detector. As you can see, the LBNE reach is already significantly improved by combining with data from NOνA *and T2K but with the CHIPS contribution from 6 years of NuMI running, in addition to re-deploying it off-axis in the LBNE beam, the reach in δ_{CP} of the LBNE program now appears on a similar footing to that of the neutrino factory, even with only a 10kt detector.*

Furthermore, this different detector technology is of interest to an orthogonal group physicists and so would likely not compete for human resources. In fact, it could be a way to increase the number of both US and European physicists committed to the broader LBNE program. In times of limited funds, any "off-program" development would have to be small in order to avoid running interference on the presently approved LBNE Liquid Argon detector project, but a small investment now could likely make a huge difference to the eventual outcome of the whole LBNE project.

3 CHIPS Conceptual Design

The CHIPS concept draws heavily on that put forward for the LBNE WC concept, but with less stringent criteria on the event energy threshold given that the main goal is to measure higher energy beam neutrino events. This allows the loosening of water purification and photodetector requirements essential for identifying very low energy events. All the details laid out in this proposal represent the first attempt to design the components of the CHIPS detector. The R&D program is chiefly meant to either prove the principle of the first solution or develop a working alternative.

3.1 Geometry

The detector shape is dominated by the need to position the detector as deep as possible under the water. Given that the pit has maximum depth of about 60m, the top of the detector must not be higher than about 40m below the surface of the pit to have a manageable cosmic dead time rate. This leads to a cylindrical geometry of 20m height with the radius as the only variable. Due to practical considerations deploying very large detectors, however, it is possible that an optimally sized module, combining relative ease of construction with economies of scale would

be the best solution, where the total mass would comprise three or four of these independent units. These sub-modules could share a main water purification plant or use unique ones. The breakdown of the cost versus volume and radius for fixed height are shown in Figure 3 which includes an infrastructure cost of $1M, $2M and $5M for the 10, 20 and 30kt CHIPS module with a photocathode coverage of 12%, and assuming that each PMT costs $3000, a conservative figure. There are clearly savings to be made with larger volumes. One goal of this R&D program is to identify the optimum module size for a total mass of 100kt of CHIPS detector(s).

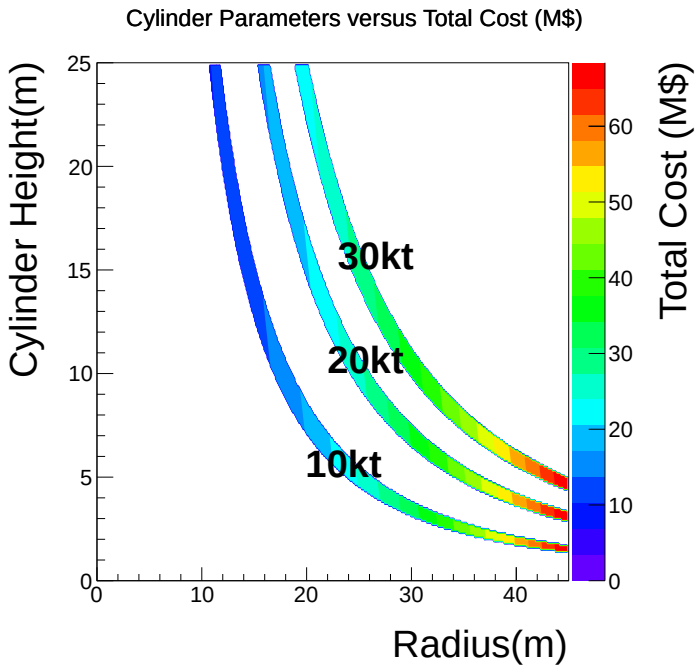

Figure 3: Various geometry parameters to compare costs. The z (color) axis shows the cost in $M, including a pedestal cost for the infrastructure of $1M, $2M and $5M for detectors of 10, 20, and 30kt. All plots assume $3000/PMT, and a 12% photocathode area coverage. The cylinder will be limited to 20m height due to water overburden considerations.

3.2 Mechanical Structure

Following several months of physics simulations and engineering discussions,the emerging concept is that CHIPS will comprise a mechanical truss frame surrounded by a light and watertight liner. The liner will be an opaque polymer membrane, like ones used in the geomembrane and roofing industry, and filled with purified water. The space frame will be made of hollow pipes, similar to those used in the roof structure in Figure 4(right), which can be filled with water or air to enable submersion or flotation.

Veto PMTs would point outwards to identify the cosmic ray muons entering the detector volume. All the PMTS would likely be contained inside watertight plastic housings with HV sent down to and signals sent up from the detector. The PMTs for LBNE have been designed to withstand 60m hydrostatic pressure, and so while the watertight housings are not completely necessary, for safety we think designing a generic watertight housing is important for the robustness of

the detector, especially given that these PMTs will have to be raised and lowered several times while the detector is being instrumented. This development will draw heavily on the KM3net and IceCube designs which have both already delivered a solution to this problem for different deployment scenarios. Common marina technology would be used to keep floating structures free of winter ice. The purification system for such a set up can be tailored for the level of water clarity needed. On the order of 6000 PMTs will be needed for the 10kt prototype (see Table 1). The baseline photodetectors could be similar to currently available 10"-12" PMTs [1, 8, 9] although it is hoped other possibilities become available over the course of the incremental construction.

Individual photodetector panels on the surface of the cylinder will be mounted on the space frame extending 1-2m perpendicular to the instrumented plane as shown in Figure 4; frame components will incorporate only enough mass to approximately cancel the buoyancy of the photodetectors, so that the assembly remains neutrally buoyant and spans the diameter without significant distortion. Molded acrylic watertight housings encompass the PMTs while providing a secure mounting system similar to that designed and tested for the LBNE WC option as shown in Figure 5 (in this case fixed to steel cables instead of support panels). Black molded plastic support panels with a layer of $Ti0_2$ on one side and a center hole for the PMT acrylic housing could be used for mounting on the space frame.

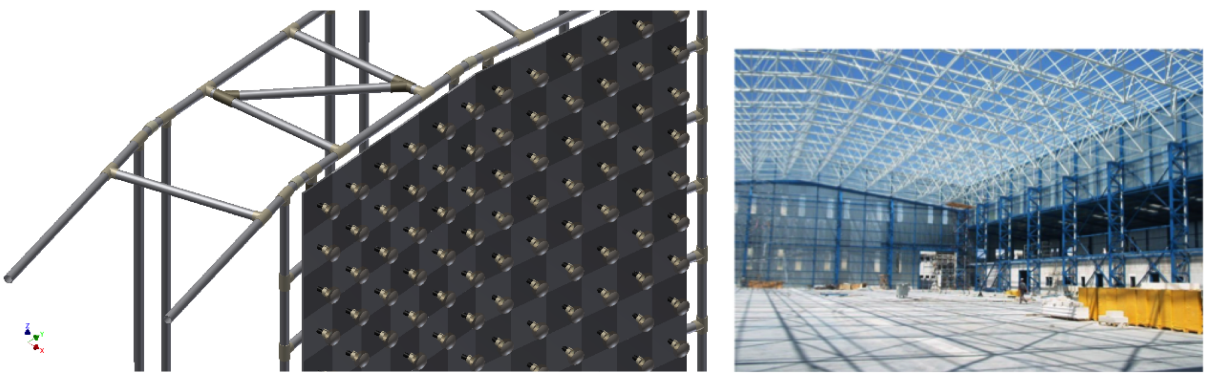

Figure 4: Panels supporting PMTs (left) and example of structure (right).

The minimum operation depth of 40m (and therefore the detector height of 20m) is set by the rate of cosmic ray muons, which rises to impractical levels at shallower depths. Even at 40m, the rate will be substantial and beam spills containing such background muons must be tagged for removal. Therefore a fraction of the photodetectors will be arranged inside a 2m-thick veto volume along the top and side of the cylinder, where they will reliably detect Cherenkov light from background muons. This veto volume also provides room for the support framework, and is separated from the active volume by the non-watertight light barrier made up of the individual PMT panels.

Outside the entire detector is the reinforced polymer membrane (liner) that blocks outside light and isolates the pure water inside from the pit water. Such a membrane material (*Hyperlon*) was selected for the proposed GRANDE experiment [3] and is one of many options used in the geomembrane and roofing materials industries for blocking water over large areas [4]. For CHIPS, the liner will be maintained in a cylindrical shape between several large stiff rings, connected to each other and moored in the lake using strong support cables. Such rings and mooring systems

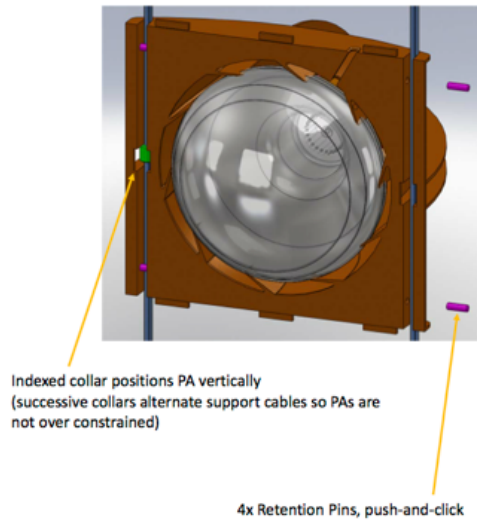

Figure 5: Acrylic water tight PMT housing [1]

are routinely used for construction of net cages in the aquaculture industry [5, 6], including deployments up to 64m diameter in open sea conditions [7]. See the schematic in Figure 6.

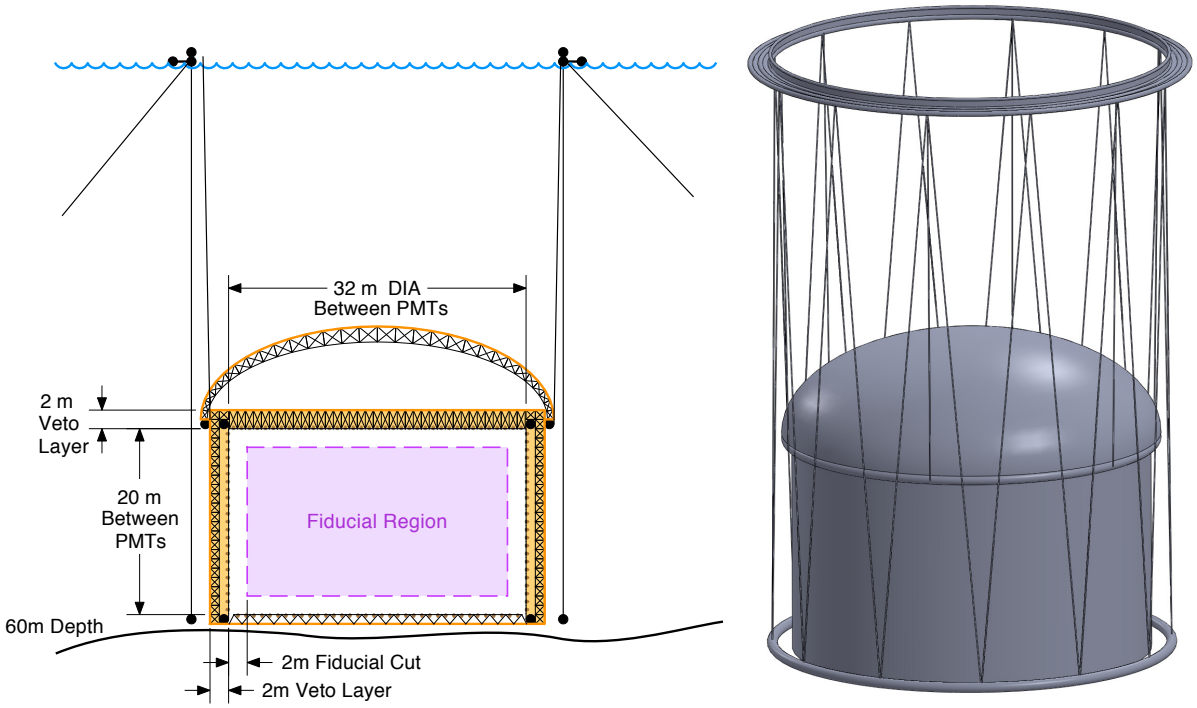

Figure 6: Full schematic showing CHIPS-10 prototype.

Because of forces acting on the liner surface, the design is expected to require additional support to relieve stresses in the liner and maintain its cylindrical shape. The main challenge is posed by differences in water density that may occur between the inside and outside of the liner volume. The corresponding forces have been estimated and can be well managed by the lightweight space

frame just inside the liner.

Each photodetector is served by a single electrical cable which is routed along the support framework and emerges in a bundle which likely goes directly to shore to limit the cable length. Connections to shore, for power and analogue signals, will be made with an umbilical of appropriate length. Additional connections to shore will be necessary for the flow of purified water. These connections can be sealed to suitable openings in the liner during deployment, and the corresponding umbilicals will then be routed to on-shore purification equipment.

3.3 Construction Procedure

Construction of each cylinder will begin with the large ring float and the protective structure above it, which are towed to the final location and moored. Within this enclosure, additional temporary floating docks will enable workers to assemble sections of the large bottom panel and to subsequently join them together.

Because of the raft support, plastic welding of liner strips or large prefabricated liner sections can be carried out above the water line and therefore can employ standard field techniques [4]. Around the growing perimeter of the base section, the liner will be wrapped upwards and sealed to the support ring (also assembled in place) which ultimately defines the bottom of the liner volume. Once complete, the raft pipes can be filled with water to eliminate their buoyancy, leaving the bottom panel temporarily in a floating configuration. The remaining vertical wall of the liner will then be built up around the perimeter in 1m increments, while filling the existing volume with enough purified water to maintain the top edge just above the water line where it is easily accessed by workers on the ring float.

Photodetector panels, used to fix the PMTs in place, are mounted to the exposed frame before filling. After completion of the walls, the top framework is built in from the perimeter, utilizing integral PVC pipe for temporary flotation. Finally all temporary flotation devices are filled with water and the finished detector is lowered into position via 40m long support cables. In principle, the assembly process can be stopped at any time, allowing a partially complete detector to be lowered and later retrieved for further work. Similarly, the structure will be raised up by pumping air into the pipes.

3.4 Lake Measurements

The pit water was measured in 2010-2012 to characterize the quality. The pH at the surface was measured to be 8.3±0.3 and dropped to 7.2 at 123ft depth. A full breakdown of the chemical components is reproduced in the appendix of the LoI [2]. More recently a campaign was undertaken to observe the weather in Wentworth 2W to verify that the calculations for the pressure differentials were based on correct assumptions. A small mooring was deployed to measure temperature and velocity characteristics of the pit. As little was known about the potential impact of the pit water on the wire rope and other hardware associated with the mooring, it was decided to do a limited duration deployment and recover the mooring before the onset of ice. This resulted in a month long deployment. The wire and associated hardware showed no corrosion at the end of this month, suggesting that longer duration deployments are likely safe, and our intent is to re-deploy next spring as soon as conditions allow.

The mooring consisted of six thermistors, a pressure sensor (to verify deployed depth), and two acoustic Doppler current meters (ADCPs), which measure currents by measuring small Doppler shifts of acoustic energy reflected off suspended particles in the water column. The instruments are either clamped to the mooring line (thermistors) or are in-line (ADCPs). An acoustic release was placed at the bottom of the mooring line, just above the anchor, in order to facilitate retrieval (the anchor is not recovered). In addition, a single conductivity-temperature-depth (CTD) probe was deployed, providing a profile of temperature and conductivity (from which dissolved solids concentration can be estimated) was made.

The profile data in Figure 7 (left) shows a well mixed, warm surface layer roughly 10m thick, with a strong thermocline between 10m and 20m, a mid-water column temperature minimum around 26m, and cool water below that depth. Data from the moored instruments immediately after deployment (green dots) is consistent with the profile data. The conductivity data (not shown) suggests that the increase in temperature with depth between 25m and the bottom is density compensated by an increase in dissolved solids. The moored temperature data (figure) suggests that there was significant cooling in the upper layer, as expected.

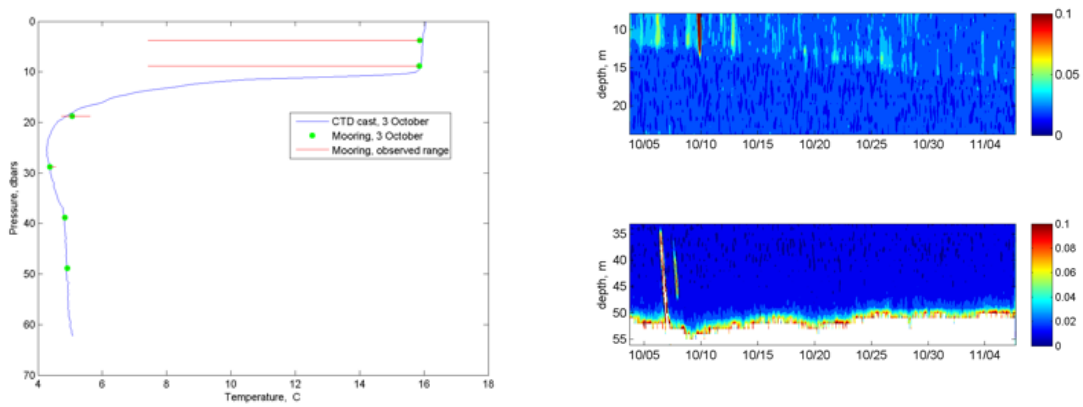

Figure 7: Left: temperature profile and corresonsding moored temperature measurements. Right: velocity magnitude profile time series, upper and lower ADCP

Velocity magnitude data in Figure 7 (right) shows frequent, small events in the upper layer with a single event around 10 October with velocities in excess of 0.25 ms-1. The upper layer can clearly be seen descending from 12m to roughly 17m over the course of the deployment. Aside from this single event, velocities in the upper layer rarely exceed 0.05m/s. The lower layer velocities are all less than 0.02m/s. A pair of unusual events on 7-8 October do not appear to be a geophysical signal. We are working with the instrument manufacturer to determine what might have caused this signal.

4 Simulations of optimal PMT configuration

The WCSim [10] program has been used to generate NuMI neutrino events in the CHIPS environment using GEANT4 [16]. WCSim was developed to study water Cherenkov (WC) detector options for the LBNE project. The overarching challenge of any WC detector when looking

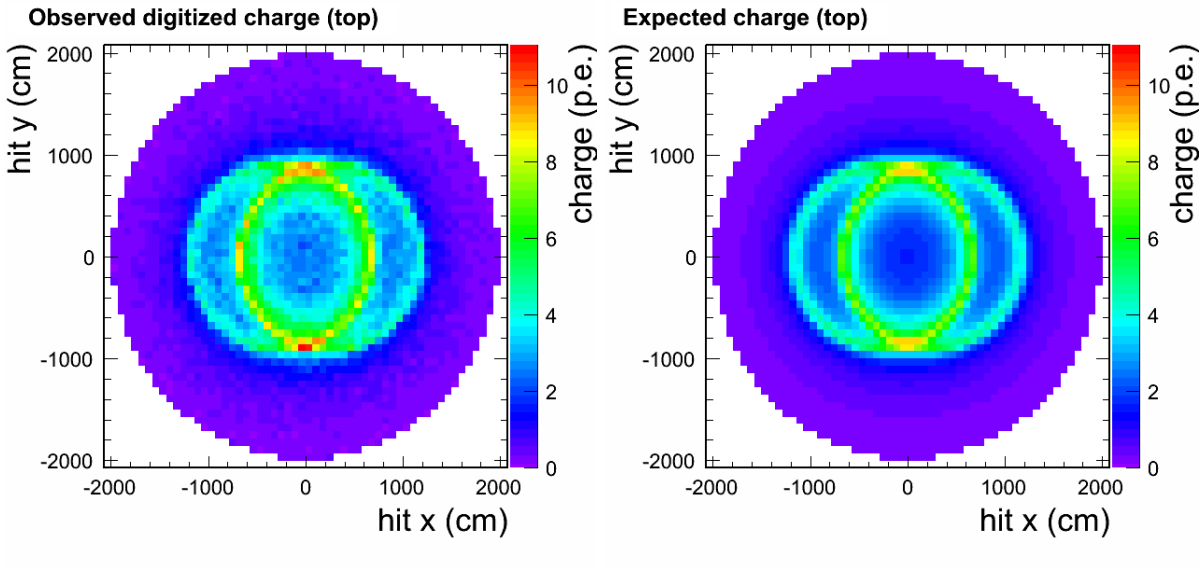

Figure 8: Event displays of the detector roof, for two electrons each of energy 500MeV traveling upwards from the centre of the detector with an angular separation of 0.27 *rad symmetric about the vertical axis. This corresponds to the decay of an upward-going* 1 *Gev* π^0 *into tracks of equal energy. Figure left shows the mean output when 100 events are simulated with WCSim, and Figure right shows the predicted most-likely charge distribution using the track fitter.*

for ν_e appearance is to be able to identify signal and background events with high efficiency. This needs not only reasonably sophisticated reconstruction software tools, but also a campaign of simulations comparing different geometries and detector coverage schemes to maximize the sensitivity to the signal coming from the direction of the beam.

4.1 Simulation

An initial CHIPS geometry has been added to WCSim describing a cylindrical detector of radius 20 m and height 20 m. It is instrumented with 10 % coverage using 10 inch high quantum efficiency PMTs. Figure 8 (left) shows an example charge distribution output by WCSim when two electron tracks are simulated, with the PMT response averaged over 100 events. A fuzzy ring is the typical signature of an electron in a WC detector, while a π^0 decaying to two photons will produce two such rings. An important feature of the event reconstruction will be the ability to distinguish a single ring from two overlapping ones.

4.2 Reconstruction

The event reconstruction is based on a method originally used for the MiniBooNE experiment [14] [13], modified to remove scintillation light. Given a set of initial track parameters, the algorithm predicts distributions for the charges and times of hits recorded by each PMT. The measured values are compared to these distributions to determine an overall likelihood, and the negative log-likelihood is minimised with respect to the track parameters to produce the reconstructed track objects.

The method is straightforward to apply to different types of particle, and can incorporate an arbitrary number of tracks. This allows the two photons from a neutral current π^0 decay to be distinguished from a single electron track. Using a similar method, the T2K experiment reports [18] that 69% of π^0 background events were removed from the ν_e sample when compared to the previous ring reconstruction method.

The charge component is calculated by considering the typical profile of Cherenkov light emitted by a particle of a given type and energy. The predicted photons are propagated to each PMT, accounting for the probability of absorption and scattering in the water, and for the solid angle, angular acceptance and quantum efficiency of the PMT. The predicted charge distribution using this method for two electron-like tracks, each of energy 500 MeV, travelling from the centre of the detector towards the roof, with an angular separation of 0.27 rad is shown in Figure 8 (right).

The time component is produced by parametrising distributions of PMT hit times using fits to Monte Carlo simulations. Fits to these parameters are then performed as a function of the track energy and the predicted mean charge at the PMT, allowing the time likelihood to be computed for each hit PMT. Work to automate this fitting process is in progress.

The two components are summed to produce an overall likelihood. A minimiser is in development, which will use Minuit [17] to determine the best-fit track parameters for the hypothesised particle species and number of tracks. Particle identification is performed by comparing the log-likelihood values for each configuration. In combination with WCSim, the completed fitter will enable detailed studies of the optimal PMT coverage and placement to be carried out.

5 Electronics and PMT read out

The design of a generic on-PMT electronics system will be developed for testing in year 2 of this proposal. The need for this step forward is two fold: the HV cables are expensive and heavy given the length from the bottom of the pit to the shore (≈120m); the forward look to faster photon detectors will necessitate on-board digitization and zero suppression to allow manageable data rates. The deployment of different (newer, cheaper, faster) PMTs throughout the CHIPS program can be aided by this approach. Much of this work has already been carried out for other applications. In particular, KM3net have developed a multi-channel ASIC applicable to their specific configuration of using several 3" tubes in the same glass housing (something our simulation program will study). The addition of an optically powered CW HV unit is now standard technology for reducing the need for long coax cables and instead utilizing just one twisted pair cable per PMT for both power and signal in parallel. While this has some time to be developed and integrated with existing designs, it is expected that this will provide a much cheaper and easier solution for the very large volume detectors foreseen. Furthermore, because this functionality has already been developed for other applications a long development time is not foreseen to be necessary.

	PMTs@12%	PMTs@10%	veto PMTS	FV (H x R)	liner (H x R)
CHIPS-10	7793(10”)/5571(12”)	6500(10”)/4642(12”)	460	16mx14m	22mx18m
CHIPS-25	16624(10”)/11960(12”)	13854(10”)/9967(12”)	626	16mx23m	22mx27m

Table 1: components required for the CHIPS-10 prototype and for the nominal CHIPS-25. The numbers for both 10% and 12% PMT coverage are shown.

6 Calibration System

Figure 9 outlines a detector calibration system, based on a system successfully deployed previously [11], that can meet the requirements of CHIPS-10. While the system is labeled “calibration” for simplicity, it fills a range of commissioning, calibration, and monitoring goals. In steady operation, the system provides measurements of PMT time offsets, time resolutions, and charge slew; PMT gains and charge response; average wall reflectivity *in situ*; and water attenuation length. During detector installation and commissioning, the system allows for testing of PMTs as they are deployed and for real-time monitoring of the purification plant’s efficacy.

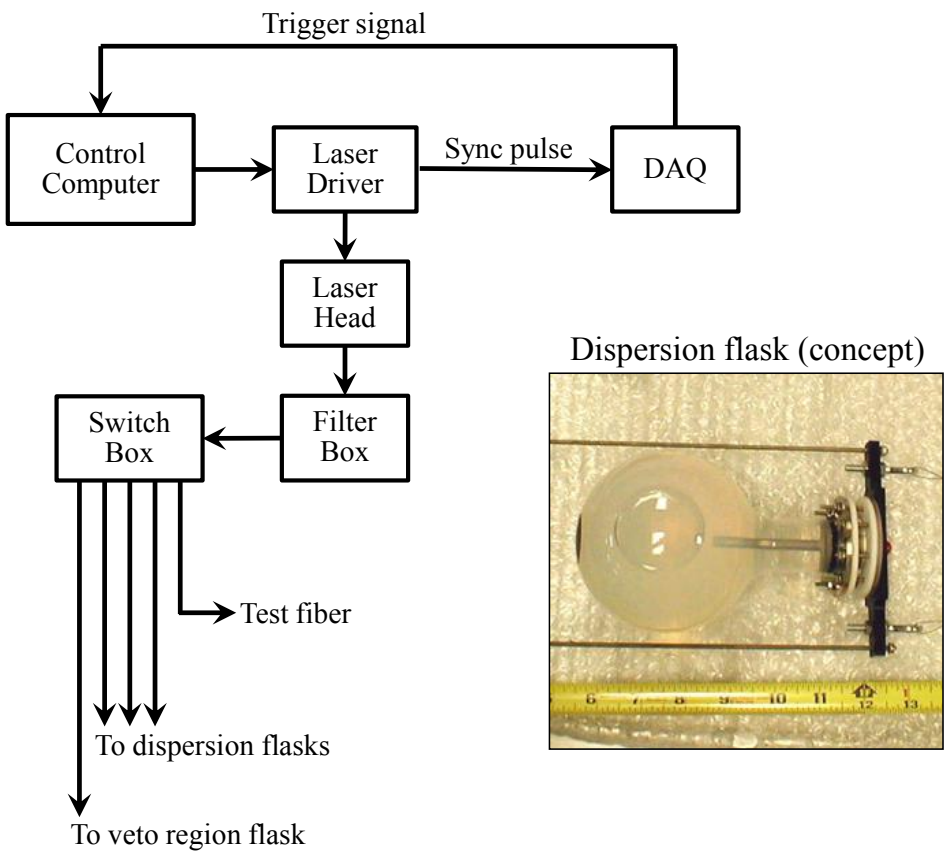

Figure 9: A sketch of the laser system described in the text. (Inset) An example light dispersion flask.

As outlined in the figure, a computer-contolled laser driver (*e.g.*, PicoQuant PDL 800-B) is coupled to a diode laser head (*e.g.*, PicoQuant LDH series) to provide <100 ps FWHM laser pulses. The laser head is swappable to allow a choice of wavelengths, and the laser driver allows both externally and internally triggered operation. The laser driver provides a NIM synchronization pulse that will feed into the DAQ system to allow for precision time offset and time resolution measurements of the PMTs.

The laser head output is directed into a fiber switch box that allows the system to drive multiple calibration locations. One output fiber remains "free" for testing and diagnostics. Three or four fibers lead to light dispersion flasks suspending throughout the volume of the detector. These fibers penetrate the containment vessel via sealed feedthroughs. A final fiber leads to a light dispersion flask (or bare fiber) located in the veto region. The veto region does not require full calibration infrastucture, and this optional veto fiber serves as a cross check of our cosmic-ray-based understanding of veto PMT behavior. A concept of the light dispersion flasks is shown in Figure 9, where a four-inch round flask is filled with LUDOX colloidal silica and fitted with an optical connector.

For CHIPS-M, a minimal system is sufficient to demonstrate the concept and to achieve the limited needs of this part of the program: triggered laser control, one laser head, and a single fiber or flask. More generally, the system can grow as CHIPS R&D evolves, with additional fiber channels and control features being introduced without loss of prior investment. One example of possible long-term expansion is indicated in the figure, where the laser output is optionally fed through a filter box to allow for precision intensity ratios when studying PMT saturation effects and other high-charge behavior. (This filter box would be omitted in the early stages.)

7 R&D Program

There are three deliverables within the overall CHIPS R&D program. These are:

1. the practical prototyping and verification of the CHIPS-M, a 75t model detector;
2. the full engineering design for the CHIPS-10, the 10kt prototype detector, its subsequent construction and its associated physics measurements;
3. the full engineering design for CHIPS-25 ("25" here refers to an educated guess of what the optimal module size will eventually be and is not prescriptive)

7.1 Year 0: October 2013 - December 2013 (Preliminary Activity)

Funding Source : (University cash($50k) and in-kind contributions)

There are a number of distinct issues which will be addressed in the coming months and will likely continue through until next spring.

1. Design of the 5mx3m radius CHIPS-M model cylindrical light tight liner and structure
2. Design of layout for cabling to shore
3. Design of prototype DAQ system
4. Design of layout for filtration pipe to shore

5. Measurement of under water currents and temperatures (already accomplished).

The measurements made by the LLO at Duluth in October 2013 have provided us with data showing that the Wentworth lake has a typical temperature gradient and that the pressure gradients produced with the typical bad weather which was experienced during the period were not unduly large and well within the calculations used for the straw man design of the liner structure.

7.2 Year 1: January 2014 - December 2014

Funding Source : University cash ($100k) and in-kind contributions; DOE and STFC seed-corn funds ($200k), NSF grants

The goals of the first year's R&D will be to verify that a light tight, water tight structure can withstand the pressure differentials caused by density differences in the water due to chemical and temperature gradients outside (compared to the purified water inside); that the water purification feeds and signal cables can be routed and defended against the ice during the winter; that the PMT signals are sufficient to see Cherenkov radiation from cosmic rays with the DAQ system and that the materials to be used in the water are not negatively affected by the alkalinity of the pit water. In summary, all parts of the construction process will be tested with full depth deployment of this model cylinder in the first year.

1. Procurement of containers, liner, cables, pipes, floating dock, purification plant
2. Procurement of DAQ GPS infrastructure and integration in IceCube system
3. Deployment and commissioning of 5mx3m prototype
4. Commissioning of IceCube DAQ system to monitor spills
5. Optimization of PMT arrangement and size via full simulation and reconstruction
6. Winter

A significant fraction of this first full year's program (and funding) will focus on the design for the 10kt prototype, being informed by the above small prototype testing and verification.

1. Finalize design of CHIPS-10 internal structure and liner using lessons learned
2. Preliminary design of universal PMT covers and fixtures
3. Preliminary design of universal on-PMT electronics
4. Development of CHIPS-10 DAQ read out
5. Development of CHIPS-10 Calibration Scheme
6. Produce Conceptual Design for CHIPS-10

7.3 Year 2: January 2015 - December 2015

Funding Source : DOE/NSF/STFC ($1M)) This stage has a large focus on procurement. It will be the first year when a significant number of components and materials will be procured. The goals are as follows:

1. Procure fraction of purification plant
2. Procure 10kt liner and structure
3. Procure full size floating fish cage
4. Procure 5-10 prototype on-PMT electronics and HV cards
5. Procure 5-10 PMTs + prototype acrylic housings
6. Raise old structure and inspect liner, structure and PMTs
7. Deploy full size liner, structure, purification plant
8. Deploy PMTs
9. Commission prototype DAQ system and monitor beam spills
10. Monitor attenuation length with LED system

7.4 Year 3: January 2016 - December 2016

Funding Source : DOE/NSF/STFC/ERC?($2M)

1. Consider new ideas available for light detection
2. Procure 500 on-PMT electronics and HV cards
3. Procurement of first 500 PMTs (baseline design) + acrylic housings
4. Procurement of second tranche of purification system
5. Raise structure and inspect liner, structure and PMTs
6. Deployment of 500 PMTs,
7. Deployment of second tranche of purification plant
8. Commission readout and monitor beam spills
9. Reconstruction development and signal identification (handful of events expected)
10. Development of calibration system

7.5 Year 4: January 2017 - December 2017

Funding Source :DOE/NSF/STFC,ERC?($2-3M)

1. Consider new ideas available for light detection
2. Procure $2.0M PMT equivalent units (baseline 850 tubes or cheaper equivalent) + acrylic housings
3. Procure commensurate number of on-PMT electronics and HV cards
4. Procure third tranche of purification system
5. Raise structure and inspect liner and structure
6. Deploy next 850 baseline PMT equivalent units
7. Add second section of purification plant
8. Commission readout and monitor beam spills
9. Reconstruction development and signal identification (2 handfuls of events expected with full bottom face instrumented)
10. Perform calibration
11. Produce CHIPS-25 Technical Design Report and Proposal

7.6 Year 5: January 2018 - December 2019

Funding Source:DOE/NSF/STFC,ERC? ($3M)

1. Consider new ideas available for light detection
2. Procure $3.0M PMT equivalent units (baseline 1300 tubes or cheaper equivalent)+acrylic housings
3. Procure commensurate number of on-PMT electronics and HV cards
4. Raise structure and inspect liner, structure and PMTs
5. Deploy next 1300 baseline PMT equivalent units and second section of purification plant
6. Commission readout and monitor beam spills
7. Reconstruction development and signal identification (50 events per year signal expected)
8. Calibration

It would be expected that a number of technical publications will be produced during the first three years of the R&D program: the final CHIPS design; the Calibration system; Characterization of the different PMTs used in the detector.

8 Work Breakdown Structure: brief description of elements

Both CHIPS-M and CHIPS-10 will follow the same Work Breakdown Structure. A brief description of the top level WBS elements is given here. The Gantt chart for the project in two phases (CHIPS-M and CHIPS-10) is depicted in Figures 10 and 11.

8.1 Infrastructure at Wentworth

We will deliver shipping containers to the shore of the Wentworth Pit at the closest shore point to the deepest position at the east end of the lake. These will be transportable and temporary, although more of them will likely house the bigger volume of electronics as time goes on. We do not envisage investing in a permanent building at the lake shore. One container will house the DAQ electronics while one will house the purification plant.

8.2 Land-Water Interface

The land-water interface is a very crucial part of the program. Providing a robust and safe interface for the electronic cables and purification plant pipes which must withstand very cold winter temperatures (as cold as the Poles) as well as rather warm temperatures in the summer (unlike the Poles). This umbilical unit has to be especially designed and also cared for to ensure around the year delivery of data. We will purchase a length of floating dock from which to deploy our containment structure which will reach from the shore into the water to avoid the need for boats.

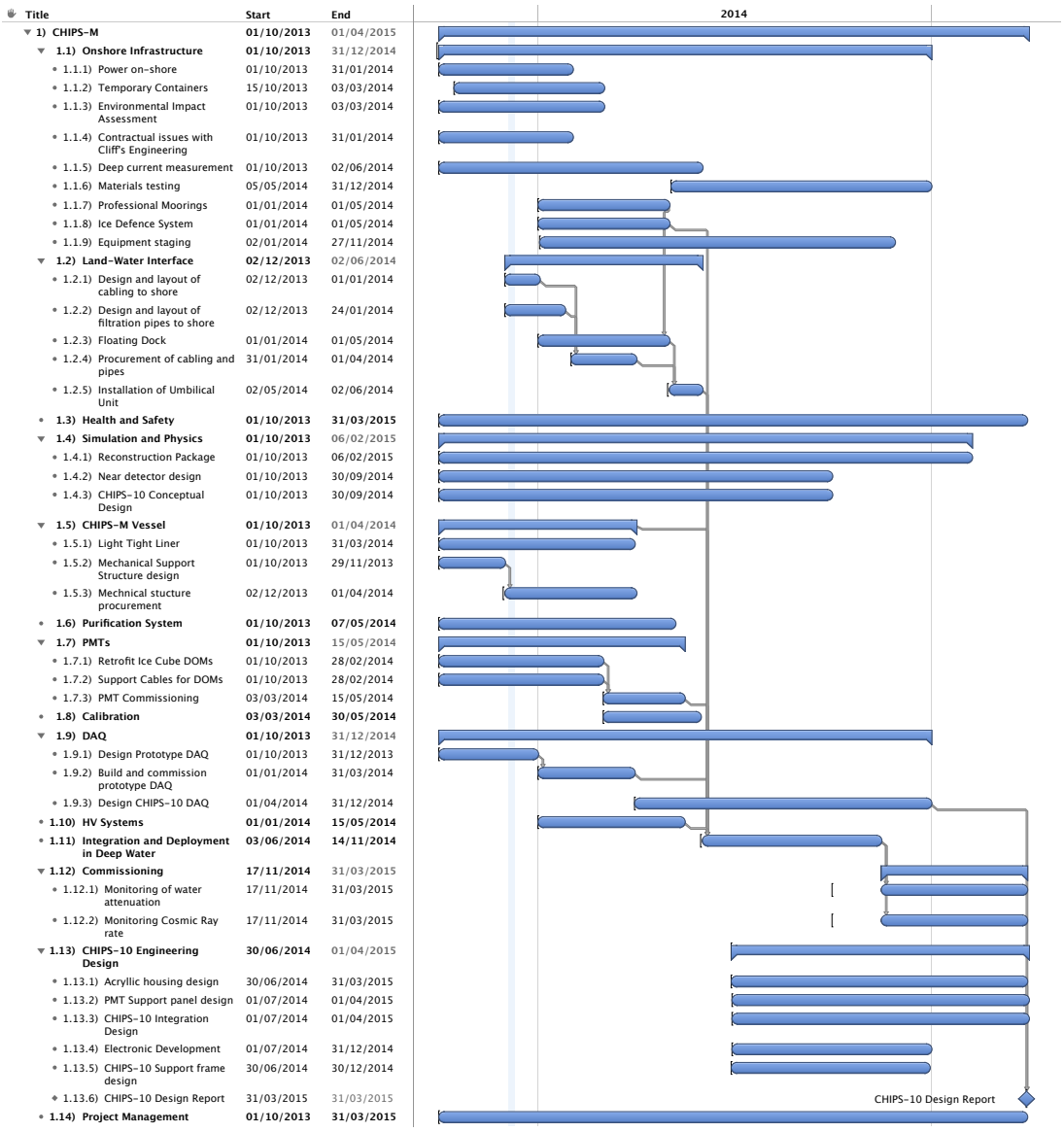

Figure 10: : Gantt depiction of CHIPS-M sub-project

8.3 Health and Safety

This issue is obviously of paramount importance. While the floating docks are designed for people to walk on, a clear set of rules and training must be devised for all individuals planning on taking place in the deployment and commissioning of the CHIPS detectors. Also issues associated with HV and water would need to be properly dictated. The University of Minnesota at Duluth will take responsibility for safety. Their existing experience with both mines and lakes makes them the obvious choice for this activity.

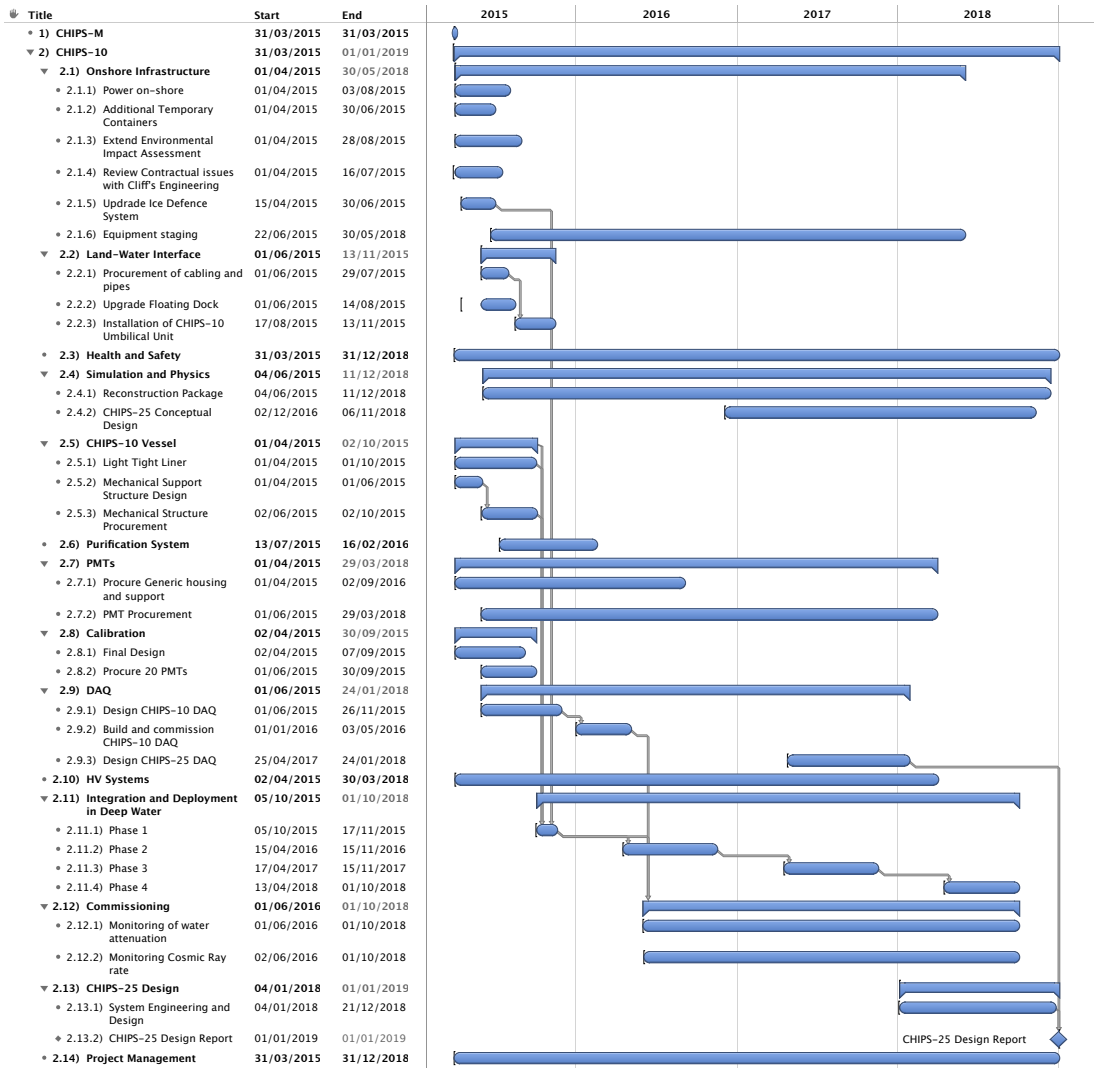

Figure 11: : Gantt depiction of CHIPS-10 project

8.4 Simulation of PMT layout and physics reach

The WCSim [10] program has been used to generate NuMI neutrino events in the CHIPS environment. The overarching challenge of any WC detector when looking for ν_e appearance is to be able to identify signal and background events with high efficiency. This needs not only reasonably sophisticated reconstruction software tools, but also a campaign of simulations comparing different geometries and detector coverage schemes to maximize the sensitivity to the signal coming from the direction of the beam.

8.5 Prototype Detector Structure (5mx3m CHIPS-M, CHIPS-10)

This WBS element represents the prototype structure as a whole, encompassing the mechanical structures the floating supports, and the liners for both prototypes.

8.6 Purification System

The first (small) stage of the larger purification system will be deployed for the CHIPS-M prototype. It will then grow as resources are available into a system able to purify the entire 10kt of CHIPS-10.

8.7 PMTs

We intend to borrow a number of PMTs, from our Ice Cube colleagues. Initially between 5-10 tubes will be deployed for CHIPS-M. The following year a small number of "baseline" tubes will be procured and deployed. The third year shows the step up to several hundreds of PMTs procured and deployed. Support panels will be constructed to hold the PMTs and simultaneously isolate the inner volume from the outer veto region.

8.8 Calibration

The calibration system is initially used as a ubiquitous tool for all types of commissioning tests. It can be used to check that PMTs are working, it can be used to measure the attenuation length of the water and measure the efficacy of the purification system.

8.9 DAQ

For the first prototype system, we have agreed with IceCube to borrow an existing single PC based system capable of reading out five digital optical modules (DOM). The final CHIPS DAQ system will draw heavily on the idea of the IceCube approach, and gaining experience with this system will provide very useful information for the final DAQ design which will be happening somewhat in parallel.

Some alterations to the IceCube DAQ software are necessary to enable GPS spill time tagging so that any PMT activity associated with the NuMI beam spill time can be identified. The final system will feature a DOM-lite design with a front-end board providing high-voltage generation and hosting a digitiser chip and FPGA for triggering and readout. The digital signals from the optical modules will be transferred to a MicroTCA crate [12] on the surface either via twisted-pair or optical fibre, depending on the cost and availability of suitable connectors and cables that can withstand the high pressure environment in the lake.

8.10 HV system

The initial HV system will be provided by the on-board CW supply and so only a low voltage (60-120V) supply and dedicated cables will need to be provided for the first test. The final system will be similar and will be clarified during year 2 and possibly 3 of this R&D program.

8.11 Integration and Deployment in deep water

All the components must be brought together at the pit and installed under controlled conditions. This has to be very carefully planned and executed under the command of a project engineer. This role will likely be fulfilled by Alec Habig (Duluth) in conjunction with Jerry Meier from the Soudan Mine Crew.

8.12 Commissioning

Cosmic rates and light attenuation will both be monitored throughout the first winter. The data will be used to benchmark MC. The second year will hopefully have prototype on-tube electronics and HV.

8.13 System Engineering and Design

For both the CHIPS-10 and CHIPS-25 designs, full engineering concepts must be worked through to make sure all specifications have been defined and that all the pieces fit together. For CHIPS-M, this will be chiefly aided by being able to stage the structure in smaller pieces in the MINOS surface building. The engineering and design effort encompasses the development of the cost effective on-PMT digitizers and power supplies for a more cost effective approach for very large numbers of PMTs as well as the mechanical structures.

8.14 Governance and Project Management

The funders group will have final say in how resources are spent in the first year or two when resources are expected to be very tight. This will comprise all individuals who have contributed resources from their institutions or grants. Once full R&D funding has been secured from the various funding agencies, this job would be taken over by the Collaboration Board.

The collaboration structure will be set up by the Collaboration Board. The Collaboration Board would have representation from all collaborating institutes and would likely morph out of the Funders group over time.

The lines of responsibility are particularly important given that the experiment will be remote from any DOE laboratory or University site. The University of Minnesota will take on this responsibility and legal issues must be hashed out during the first year of this R&D project.

A preliminary request has been initiated to Cliffs Natural Resources mining company for a 10 year lease on the pit and its immediate surroundings. A short term agreement, until the end of

2013 has already been put in place to enable the water current measurements to be carried out before the end of the year.

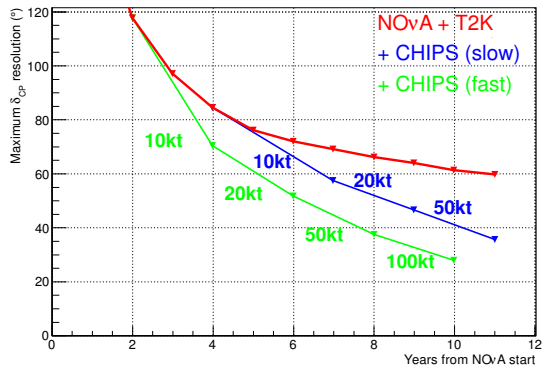

Figure 12:

9 Potential physics reach of CHIPS 10kt prototype and beyond

Following the completion of CHIPS-10, (and in the time leading up to its completion) data will be taken in the NuMI beam. It is hoped that after the successful demonstration of the CHIPS-10 to identify ν_e events, and the corresponding milestone of being able to build such a detector for the target cost of substantially less than the present \$1-2M/kt, we would proceed with the construction of the first full size ($\tilde{2}$5kt FV) CHIPS-25 detector. Depending on funds available, this could be deployed over one year and be ready to expand the available mass for measuring δ_{CP} up to 35kt, possibly by 2019.

Figure 12 shows how adding a phased-CHIPS detector in the NuMI beam line improves the δ_{CP} resolution over the default configuration of NOνA and T2K only. Two approaches are shown; the fast track approach of building a 10 kt detector two years after NOνA and increasing this to 20, 50 and 100 kt every subsequent two years. The other is a slower-track approach, which is the one outlined in this R&D proposal (blue line), where 10 kt is produced five years after the NOνA turn on, and increased to 20 and 50 kt after seven and nine years respectively. It should be noted, however, that it is possible the completion of CHIPS-10 will be totally limited by funding after the first two years. A faster funding profile could lead to the physics capability shown by the green line.

10 Funding Strategy and Costs

One very important issue for the success of the R&D program is the ability to get started on the work immediately. To this end, we have convened a "funders group", a number of universities who are willing to make a small contribution of cash, effort or both, to get the program started. These funds will be made available immediately with the hope that there would be some matching funds available from FNAL/DOE/STFC in due course and are at the level of about \$110k for the first year. A contribution to the deployment via travel funds has recently been made available by the Royal Society and STFC at the level of \$40k. A decision on full R&D funding from STFC is expected in June 2014. We are requesting that DOE/FNAL

contribute at the level of $200k, starting in January 2014 through the end of the calendar year.

Should this required level of funding be made available in 2014, we are confident that the first stage of the program can be completed.

Table 2 shows the costs for the first year of activity. Table 3 shows the costs for CHIPS-10 in the second year. Table 4 shows the costs for CHIPS-10 in the third year. Table 5 shows the expected expenditures for each of the five years of the R&D project. Table 6 shows the in kind contributions in the first year from the university groups.

WBS	item	materials cost	effort cost	in kind	total
1.1	**Onshore Infrastructure**	**21k**		UMn	**21k**
1.1.1	On-shore power		in kind	UMn	
1.1.2	Shipping Containers	6k	in kind	UMn	6k
1.1.3	Environmental Impact		in kind	UMn	
1.1.4	Cliff's Engineering		in kind	UMn	
1.1.6	Materials Testing		in kind	UMnD	
1.1.7	Professional Moorings	10k	inclusive		10k
1.1.8	Ice Defense System	5k	in kind	UMnD	5k
1.1.9	Equipment Staging		in kind	UMn	
1.2	**Land Water Interface**	**15k**		UMn	**15k**
1.2.1	10xHV/signal cables(1.3km)	5k	in kind	W&M	5k
1.2.2	Purification pipes (200m)	5k	in kind	UCL	5k
1.2.3	Floating Dock	5k	in kind	UMnD	5k
1.3	**Health and Safety**		15k	UMn	**15k**
1.4	**Software**			UCL,UM,ISU	
1.5	**CHIPS-M Vessel**	**35k**	**30k**		**70k**
1.5.1	liner	10k	in kind	UW	10k
1.5.2	support frame design	15k	15k	UW,UC	30k
1.5.3	support frame procurement	15k	15k	UW,UC	30k
1.6	**Purification System**	**25k**	in kind	UMn	**25k**
1.7	**PMTs**	**3k**		UM,UT	**3k**
1.7.1	Borrow Ice Cube DOMs		in kind	UW	
1.8	**Calibration**	**10k**	in kind	CIT,ISU	**10k**
1.9	**DAQ system**	**5k**	in kind	UK	**5k**
1.10	**HV System**	**5k**	in kind	W&M	**5k**
1.10.1	Twisted Pair Cables	5k	in kind	W&M	5k
1.11	**Integration and Deployment**		**60k**	All groups	**60k**
1.12	**Commissioning**		**20k**	All groups	**20k**
1.13	**CHIPS-10 Engineering Design**	**5k**	**105k**		**110k**
1.13.1	Acryllic housing design		20k	UW,UT	20k
1.13.2	PMT support panel design		20k	UC	20k
1.13.3	CHIPS-10 Integration design		20k	W&M	20k
1.13.4	Electronics development	5k	20k	UPitt	25k
1.13.6	CHIPS-10 support frame design		25k	UW	25k
1.13.6	CHIPS-10 Technical Design Report				
1.14	**Project Management**		**20k**	Consultant	**20k**

Table 2: : Cost breakdown of first year activities (CY 2014): $379k Total. Given the likely funding profile, full funding will likely not be available until May or June of 2014. In that case, the WBS 1.13 could be started after May as this does not need to reach the prototype phase until after the winter of 2014.

WBS	item	materials	effort	in kind	total
2.1	**Onshore Infrastructure**	**132k**	**50k**	UMn	**287k**
2.1.1	On-shore power		10k	UMn	10k
2.1.2	Shipping Containers	12k	5k	UMn	17k
2.1.3	Environmental Impact		20k	UMn	20k
2.1.4	Cliff's Engineering	100k		UMn	100k
2.1.6	Professional Moorings	15k	inclusive		15k
2.1.8	Ice Defense System	10k	5k	UMnD	15k
2.1.9	Equipment Staging		10k	UMn	10k
2.2	**Land Water Interface**	**10k**	**5k**	UMn	**15k**
2.2.1	10xHV/signal cables(1.3km)	5k	in kind	W&M	5k
2.2.2	Purification pipes (200m)	5k	5k	UCL,UMn	10k
2.2.3	Floating Dock	20k	5k	UMnD	25k
2.3	**Health and Safety**		15k	UMn	**5k**
2.4	**Software**			UCL,UM,ISU	
2.5	**CHIPS-10 Vessel**	**300k**	**70k**		**370k**
2.5.1	liner	200k	15k	UW	215k
2.5.2	support frame	100k	30k	UW,UC	130k
2.5.2.1	support final design		25k	UW	25k
2.6	**Purification System**	**40k**	**5k**	UCL	**45k**
2.7	**PMTs**	**55k**	**20k**	UW,UT	**76k**
2.7.1	Procure 10 PMTs	20k	in kind	UT	20k
2.7.2	10 Acrylic Housings	10k	in kind	UT	10k
2.7.3	10 Support Panels	10k	in kind	UC,UW,UT	10k
2.7.4	PMT commissioning		in kind	UT	
2.8	**Calibration**	**10k**	in kind	CIT,ISU	**10k**
2.9	**DAQ system/Electronics**	**22k**	**20k**	UK	**42k**
2.9.1	DAQ crate	5k	in kind	UK	5k
2.9.2	On PMT Prototype	5k	in kind	UPitt	5k
2.9.3	GPS hardware	10k	in kind	UM	10k
2.9.4	DAQ system design	2k	20k	UK	22k
2.10	**HV System**	**5k**	in kind	W&M	**5k**
2.11	**Integration and Deployment**		**60k**	All groups	**60k**
2.12	**Commissioning**		**200k**	All groups	**200k**
2.13	**CHIPS-25 Engineering Design**		**20k**		**20k**
2.13.3	CHIPS-25 Integration Design		20k	UMn,UW	20k
2.14	**Project Management**		**100k**	TBD	**100k**

Table 3: : Cost breakdown for CHIPS-10 in the second year (CY 2015) : $1179k Total

2.1	**Onshore Infrastructure**	**112k**	**25**	UMn	**127k**
2.1.1	On-shore power		10k	UMn	10k
2.1.2	Shipping Containers	12k	5k	UMn	17k
2.1.4	Cliff's Engineering	100k		UMn	100k
2.1.9	Equipment Staging		10k	UMn	10k
2.2	**Land Water Interface**	**60k**	**5k**	UMn	**65k**
2.2.1	HV/signal cables(13km)	50k		W&M	50k
2.2.2	Purification pipes (400m)	10k	5k	UCL	15k
2.3	**Health and Safety**		**15k**	UMn	**15k**
2.4	**Software**			UCL,UM,ISU	
2.5	**CHIPS-10 Prototype**				complete
2.6	**Purification System**	**200k**	in kind	XXX	**200k**
2.7	**PMTs**	**480k**		UT	**480k**
2.7.1	Procure 200 PMTs	400k	in kind	UT	400k
2.7.1	200 Acrylic Housings	40k	in kind	UT,TBD	40k
2.7.2	200 Support Panels	40k		UC,UT	40k
2.7.3	PMT commissioning		in kind	UT	
2.8	**Calibration**	**30k**		CIT,ISU	**30k**
2.9	**DAQ system**	**35k**		UK	**35k**
2.9.1	DAQ crate	5k	in kind	UK	**5k**
2.9.2	5 Off shelf digitizers (15)	30k	in kind	UK	**30k**
2.10	**HV System**	**25k**	in kind	W&M	**25k**
2.11	**Integration and Deployment**		**60k**	All groups	**60k**
2.12	**Commissioning**		**200k**	All groups	**200k**
2.13	**CHIPS-25 Engineering Design**		**50k**		**50k**
2.13.1	CHIPS-25 Integration Design		30k	XXX	30k
2.13.2	CHIPS-25 Liner Design		10k	UM,W&M	10k
2.13.3	CHIPS-25 Support Frame Design		10k	UM,W&M	10k
2.14	**Project Management**		100k	XXX	100k

Table 4: : Cost breakdown for CHIPS-10 in the third year (CY 2016) : $2.35M Total

WBS	Total	FY1	FY2	FY3	FY4	FY5
X.1. Onshore Infrastructure	**592k**	26k	212k	127k	127k	100k
X.2. Land Water Interface	**390k**	10k	15k	65k	100k	200k
X.3. Health & Safety	**75k**	15k	15k	15k	15k	15k
X.5. Prototypes	**410k**	40k	370k			
X.6. Purification System	**870k**	25k	45k	400k	400k	
X.7. PMTs	**6961k**	3k	78k	480k	1600k	4800k
X.8. Calibration	**110k**	10k	10k	30k	30k	30k
X.9. DAQ	**817k**	20k	42k	35k	180k	540k
X.10. HV system	**185k**	5k	5k	25k	75k	75k
X.11. Deployment	**460k**	60k	100k	100k	100k	100k
X.12. Commissioning	**420k**	20k	100k	100k	100k	100k
X.13. CHIPS-10,25 Design	**115k**	95k	20k			
X.14. Project Management	**450k**	50k	100k	100k	100k	100k
TOTAL	**11855k**	**379k**	**1112k**	**1477k**	**2827k**	**6060k**

Table 5: : Cost Summary Table

Funder	Cash($k)	(FTE)	Individuals	Contribution	Potential Bids ($k)
UCL	35	1.1	(2S+1P+3A)	DAQ/Management/Simulation	
Manchester	10	0.5	(1P+2A)	DAQ/Simulation	
U.Minn	30	0.7	(1T+1P+2A)	Staging/Project Engineer	
UW Madison		0.2	(1RP)	5 IceCube DOMs and DAQ(loan)	
UT Austin	3	0.8	(2S+1E+1A)	PMT Engineering/Machine Shop	
U.Pitt	5	0.3	(1S+1P+2A)	Electronics Development/Design	
CalTech	20	0.3	(1A)	Calibration/Technical Effort	
Tufts		0.3	(1P)		
Cincinati	5	0.2	(1P+2A)	Machine Shop	50(EAGER?)
W&M	5	0.2	(3U+1P+3A)	design/machine shop/HV	50(EAGER?)
Duluth		0.2	(1U+1C+1A)	Water Study, Management	50(INSPIRE?)
Iowa State		0.5	(1P+1A)	Calibration/ND Design	
STFC/RS (UK)	40			Deployment/Management	
total	153	5.3	39 (19 A)		150

Table 6: : University Contribution in kind for year 1: S=grad student, P=postdoc, T=technician, A=academic, U=undergrad, E=engineer, RP=research professor

11 Summary

Although ambitious, this R&D proposal documents a path from today to a 10kt prototype CHIPS detector over the next 3-5 years. The most crucial first step has been partially funded by the university groups, the Royal Society and STFC, and the remaining funds are requested from DOE/FNAL to enable the program to be carried out through end of 2014. This totals about $200k and will cover the period through the first technical review. A new bid for funds will then be prepared for end of 2014, hoping for a successful first phase of tests on the CHIPS-M module and corresponding successful technical review.

Lastly, achieving a recognized project status at FNAL will enable us to apply for other large sources of money (such as ERC for example) in order to aid in the major construction of the 10kt prototype in the coming 3-5 years.

The overarching idea, to develop inexpensive, yet very large, neutrino detectors is a priority for our field. A complementary detector, on axis in NuMI, off axis in the LBNE beam will bring significant gains in the race towards the measurement of δ_{CP}.

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