Project Summary

This document describes the completion plan for the IceCube MREFC project with a total of 86 strings. The completion plan includes a "DeepCore" sub-array of six new strings and the possibility of installing the strings planned for the final installation season in locations that optimize the high energy performance of the detector.

The DeepCore strings are instrumented with high quantum efficiency photomultipliers that are mostly positioned in the very clear ice below 2100 m. With seven of the neighboring conventional IceCube strings they will form the DeepCore detector with a neutrino energy threshold of $E_\nu \simeq 10$ GeV, to be compared with 100 GeV for IceCube. DeepCore will replace AMANDA as the low energy sub-array of IceCube. AMANDA will stop taking data in April 2009 and will be decommissioned. The cost of DeepCore will be funded by a \$4,126,587 award by Swedish, Belgian and German funding agencies and by some contingency funds of the MREFC IceCube project. This document describes the additional logistics requested to realize the replacement of the aging AMANDA sub-array of IceCube by superior instrumentation. This document also outlines our final endeavors, before the end of construction, to optimize the geometry of IceCube for optimal sensitivity to very high energy neutrinos.

Unlike AMANDA, DeepCore uses standard IceCube instrumentation and data handling and analysis tools. With a relatively modest one-time investment in logistics, the transition from AMANDA to DeepCore will for the foreseeable future significantly reduce fuel consumption, winterover operation and maintenance commitment, the personnel required for calibration in the austral summer season and the complexity of data analysis and simulation.

Importantly, DeepCore will also qualitatively expand the science scope of IceCube:

- DeepCore will provide enhanced sensitivity to solar WIMP annihilations, extending IceCube's reach to the experimentally and theoretically interesting WIMP mass range below 250 GeV.
- It will give improved acceptance for low energy atmospheric neutrinos at $E_\nu \simeq 10$ GeV, opening the energy window for atmospheric neutrino oscillation measurements, including ν_μ disappearance, ν_τ appearance and possibly the sign of the neutrino hierarchy.
- Taking advantage of the active vetoing capability provided by the surrounding IceCube array, DeepCore will also be able to explore the southern sky for possible transient neutrino sources such as AGN, GRBs, and the Galactic Center.

With DeepCore IceCube will extend into the neutrino energy range where Super-Kamiokande and several accelerator long-baseline experiments have revealed neutrino mass. DeepCore will probe the same physics with a statistics of atmospheric neutrino events of order 10,000 per year. In the next few years DeepCore will have a glimpse at physics that will only be accessible to the next generation of long-baseline experiments over a significantly longer timescale.

IceCube MREFC Project Completion Plan

1 Introduction

IceCube was designed to detect muons and electromagnetic showers initiated by neutrinos over a wide energy range. The string spacings were chosen in order to reliably detect and reconstruct muons above an energy threshold of 0.1 TeV, and to precisely calibrate the detector using flashing LEDs and atmospheric muons.

With the ongoing deployments, the optical properties of the South Pole ice have been measured with increased precision using various calibration devices. Our understanding of the response of the detector, especially in the deeper ice not instrumented by the strings of IceCube's predecessor, AMANDA, has improved significantly. The efficiency for separating neutrinos from background, *i.e.,* the effective neutrino area of IceCube, has increased by a factor 2–3, depending on the energy, over what was anticipated. The anticipated improvement in the precision of the reconstruction of the muon direction has already been achieved with the partially deployed detector and it has been confirmed by our observation of the cosmic-ray "shadow" of the moon.

Our plan for the final configuration of the detector consists of 86 strings and 160 IceTop tanks on the surface of the ice directly above the strings. The substantial investment made by the NSF and their partner funding agencies in constructing the IceCube facilities, a $275.3 million expenditure, will produce a detector that meets or exceeds original performance goals. Consistent with our original plan to adjust the detector geometry using data-driven new ideas, this proposal describes two extensions to IceCube that will improve its reach at the low and high ends of the neutrino energy spectrum. IceCube's "DeepCore" sub-array will lower IceCube's energy threshold by about an order of magnitude, while its High Energy Extension will improve its sensitivity at the highest energies by 30-40%. We will describe the designs and physics reach of both these extensions in the sections below.

This proposal does not request any new funding for these extensions. DeepCore hardware has been purchased using additional external funds from our non-US collaborators, and the dramatic improvements in fuel usage and drilling time per hole of the IceCube drilling system allow us to include the deployment and drilling costs of both extensions in the original MREFC budget.

At present Digital Optical Modules (DOMs) have been deployed on 59 strings and 120 surface tanks. The total number of installed DOMs is 3,780, 60 DOMs per string and 2 DOMs per surface tank. Close to 99% of the DOMs frozen into the ice are operating and the construction plan over the next two years is to install 18 additional strings in 2009/10 and the final 9 strings in 2010/11. The past and future of IceCube string deployments is shown in Table 1.

2 IceCube DeepCore

The IceCube DeepCore sub-array will replace the original AMANDA detector and provide the IceCube Neutrino Observatory [2] with sensitivity to neutrinos at energies over an order of magnitude lower than originally envisioned. Consisting of six new strings and seven neighboring standard IceCube strings, the sub-array will dramatically improve on AMANDA's capabilities through a combination of increased module density, higher quantum efficiency photomultiplier tubes (PMTs), deployment in the clearest ice at depths below 2100 m, and the use of the surrounding

Strings	04/05	05/06	06/07	07/08	08/09	09/10	10/11
Annual Baseline	*1*	*8*	*13*	*18*	*19*†	18†	9
Cumulative	*1*	*9*	*22*	*40*	*59*	77	86
†DeepCore Proposed					*1*	5	
†Cumulative					*1*	6	
IceTop Stations	04/05	05/06	06/07	07/08	08/09	09/10	10/11
Annual Baseline	*4*	*12*	*10*	*14*	*19*	15	6
Cumulative	*4*	*16*	*26*	*40*	*59*	74	80

Table 1: Actual and planned IceCube string deployments from 2004–2011. "Actual" numbers are in italics.

standard IceCube modules above and around DeepCore as a powerful active veto against the copious downward-going cosmic-ray muon background.

IceCube DeepCore will provide enhanced sensitivity to solar WIMP annihilations, extending IceCube's reach to the experimentally and theoretically interesting WIMP mass range below 250 GeV. It will give improved acceptance for low energy atmospheric neutrinos at $E_\nu \simeq 10$ GeV, opening a useful new window for atmospheric neutrino oscillation measurements, including ν_μ disappearance, ν_τ appearance and possibly the sign of the neutrino hierarchy. (At the energies relevant for ν_τ appearance, the ν_τ signature is a particle shower, indistinguishable from showers created in the interactions of other neutrino flavors such as ν_e.) Taking advantage of the active vetoing capability provided by the surrounding IceCube array, DeepCore will also be able to explore the southern sky for possible neutrino sources such as AGN, GRBs, and the Galactic Center. The increased pixel density of DeepCore will enable the reconstruction of more closely spaced cascades produced by an initial ν_τ interaction and the subsequent τ decay, extending the search for cosmological ν_τ to lower energies. Searches for exotica such as slow-moving monopoles and supersymmetric stau pair production will likewise benefit from DeepCore's extension of IceCube's capabilities.

The deployment of standard IceCube strings will proceed as planned and will not be adversely affected by the DeepCore string deployments. In fact, due to the extremely successful optimization of the IceCube drilling equipment and procedures, IceCube's total fuel usage is still well below the original MREFC request, even including the six additional strings. With the first DeepCore string already successfully deployed in the 08/09 season, the five additional strings are slated for deployment in the 09/10 season, along with over twice that number of standard IceCube strings. The compactness of the DeepCore array, the nearly identical string deployment procedure, and the straightforward and seamless integration of DeepCore modules into the existing IceCube readout data acquisition system, make the implementation of DeepCore essentially no different from the implementation of standard IceCube strings.

In Sec. 2.1 we describe aspects of the geometry and hardware that distinguish DeepCore from the standard array, and in Sec. 2.3 we describe the physics that this design will open up for us. In Sec. 4 we will provide an estimate of the small additional impact that DeepCore operation will have on IceCube's footprint at Pole and in the north in terms of power consumption, trigger handling, satellite bandwidth, standard production reconstruction processing, and simulation.

2.1 Design of IceCube DeepCore

The IceCube DeepCore detector will be deployed at the bottom center of IceCube, primarily below 2100 m depth, a region that confers several key advantages and makes it highly favorable for low energy neutrino detection and reconstruction. As estimated from *in situ* light sources [3] and ice core data [16, 18], the deep ice below 2100 m is on average 40%-50% clearer than the average ice above 2000 m. In the clearest region, around 2400 m depth, the absorption length reaches a maximum of about 230 m and the effective scattering length reaches 50 m. With less scattering and less absorption, the deep ice gives DeepCore improved efficiency for detecting and reconstructing the direction and energy of low energy events having scant light production. DeepCore will concentrate its digital optical modules (DOMs)[1] at these depths, with 50 DOMs on each string deployed below 2100 m depth and the remaining 10 DOMs deployed between roughly 1700-1800 m depth.

Extensive simulations were performed to optimize the geometry of DeepCore and to quantify the benefit of new high quantum efficiency PMTs offered by Hamamatsu [13]. These simulations studied several distinct geometrical configurations, varying inter-DOM and inter-string spacings and PMT efficiency, estimating the signal efficiency and background rejection of each configuration. The goal was to maximize sensitivity to neutrino signals in the 10–100 GeV energy range from a variety of possible signals while also demonstrating the feasibility of cosmic-ray background rejection factors of 10^6 or better. Note that a 10 GeV ν_μ charged current interaction will, on average, produce a 5 GeV μ, and that this muon will travel roughly 25 m. (A muon travels about 5 m/GeV).

As a result of these studies, IceCube DeepCore will use high quantum efficiency PMTs and a vertical DOM-to-DOM spacing of 7 m and a horizontal string-to-string spacing of 72 m (see Fig. 1; the uppermost 10 DOMs of DeepCore will have a 10 m vertical spacing). In contrast, IceCube spacings are 17 m and 125 m, respectively. The DeepCore DOM spatial density will thus be higher by about an order of magnitude than standard IceCube DOMs, making it more capable of detecting sufficient light from compact, low energy neutrino interactions to perform reliable reconstructions.

Figure 1 shows the chosen DeepCore layout that resulted from these MC studies. Figure 2 shows the relative improvement in effective area that DeepCore provides at low energies.

In its position at the bottom center of IceCube, DeepCore will be surrounded by 37 layers of DOMs above and 3 layers of strings in all horizontal directions. These surrounding DOMs will be used as an active veto against copious downward-going cosmic-ray muon background. As described in Sec. 2.2 below, early studies using relatively simple algorithms indicate that a background rejection level of better than 10^6, with high signal efficiency, can be attained.

2.2 Veto Performance

For neutrino energies in the 10–100 GeV range, backgrounds from cosmic-ray muons are particularly troublesome. It is easier for cosmic-rays to mimic lower energy neutrino interactions, and the cosmic-ray energy spectrum favors lower energies. Efficient removal of the cosmic-ray background is thus a fundamental requirememt for DeepCore. (Note that the IceTop surface detector provides some vetoing capability, but is only effective at higher energies and only covers a limited solid angle.)

Simulations have shown that DeepCore can use the surrounding IceCube modules as a highly effective, real-time, active veto against downward-going cosmic-ray muons. A robust veto algorithm

[1]Each DOM contains a PMT, and HV supply, digitization and communication electronics and remotely-controllable calibration light sources, all encased in a thick-walled glass pressure vessel.

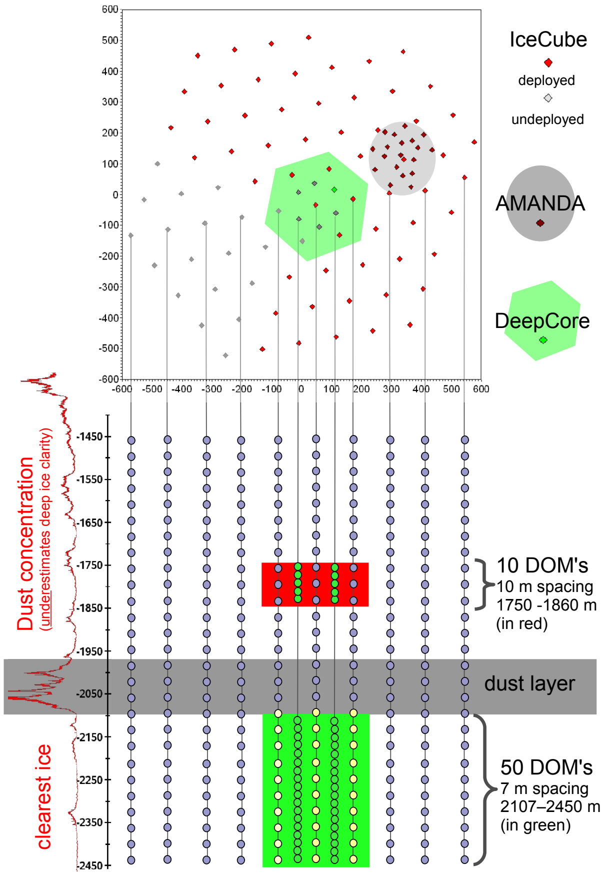


Figure 1: A schematic layout of IceCube DeepCore. The upper diagram shows a top view of the string positions in relation to existing AMANDA and current/future IceCube strings. The lower diagram shows the instrumented DeepCore region (highlighted in red and green) with the surrounding IceCube strings. On the left is a dust concentration curve which is related to the effective scattering length for Cherenkov photons in the ice.

has been developed to run online at the South Pole in order to reduce the satellite bandwidth requirements for operation of DeepCore while maintaining high signal efficiency. Further background rejection will be obtained using more sophisticated algorithms applied to the data after satellite transmission to the north.

Using light arrival times and amplitudes in DOMs in the DeepCore fiducial volume, the online algorithm first calculates their amplitude-weighted center of gravity (CoG) and average time. For each hit external to the DeepCore fiducial volume, it then calculates the velocity of a posited cosmic-ray muon traveling from that external hit to the CoG. Since the relative timing resolution of the DOMs is only a few ns (corresponding to less than 1 m travel distance at the speed of light), we are limited principally by the scattering of the Cherenkov photons in the ice. The velocity parameter is determined for all external DOMs in the event. If more than a certain number of external DOMs have a velocity that is compatible with c, the event is likely to have been produced by a cosmic-ray muon and is vetoed. Table 2 shows the signal and background efficiencies as a

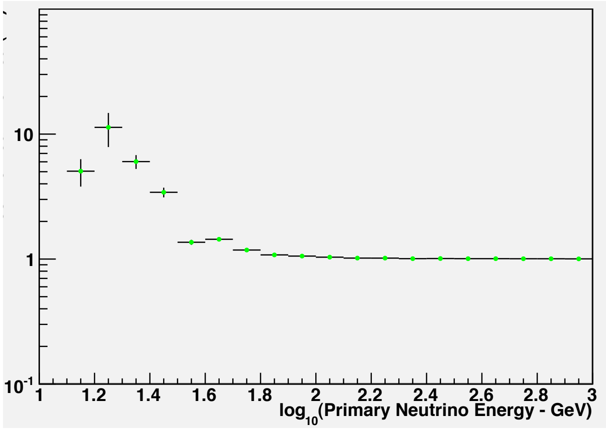


Figure 2: The relative effective areas of IceCube alone and IceCube with DeepCore, as a function of neutrino energy. There is a significant enhancement in the sensitivity to neutrinos at energies below roughly 30 GeV. Fully simulated atmospheric neutrino events satisfying a logical OR of an SMT4 trigger condition in DeepCore and SMT8 in IceCube were used.

function of the number of external DOMs compatible with c, at two different compatibility levels.

As seen in the table, we obtain high signal efficiency with excellent background rejection with this algorithm. With a background rejection of 10^3-10^4, the demands on the satellite transmission bandwidth are very small. Note that the algorithm presented here used just "hard local coincidence" hits and as such only considered DOMs whose neighbors also fired. This generically reduces the background from random noise but also degrades the background rejection of cosmic-ray muons that pass through the veto layers while only producing single, isolated hits in one or more DOMs.

2.3 Physics Potential of IceCube DeepCore

2.3.1 WIMPs

The advantage of DeepCore for low energy neutrinos is particulary evident in the case of the dark matter searches. The neutrinos from neutralino annihilations in the Sun or the Earth are expected to have energies ranging from a few tens of GeV into the TeV region, depending of course on the mass of the parent WIMPs. The muons created by these neutrinos in the detector would have energies averaging about $E_\nu/2$. The higher efficiency for low energy neutrinos in DeepCore translates into an IceCube effective volume for neutrinos from WIMP annihilations which is significantly larger than it would be without DeepCore.

The search for neutrinos from neutralino annihilation in the Sun has thus far been conducted when the Sun is below the horizon, to avoid atmospheric muon background. The possibility to reject atmospheric muons using the part of IceCube above DeepCore will make it possible to extend the search period to the full year by also including the time when the sun is above the horizon.

A simulation of the sensitivity of Icecube with DeepCore for neutrinos from neutralino annihilation in the Sun was carried out using a early prototype DeepCore design. This early design had 40 standard IceCube DOMs with a spacing of 10 m in the present DeepCore location. This is a less efficient configuration than the DeepCore design that we will be deploying, so the results presented

Velocity Range ($\frac{\text{m}}{\text{ns}}$)	Data Type	No. of DOMs in Velocity Range	
		0	**1**
0.25-0.40	Corsika	$\frac{460}{964063} = 4.8 \times 10^{-4}$	$\frac{632}{382935} = 1.7 \times 10^{-3}$
	ν_e Signal	$\frac{785}{861} = 91.2\%$	$\frac{840}{861} = 97.6\%$
	ν_μ Signal	$\frac{7582}{8496} = 89.2\%$	$\frac{8298}{8496} = 97.7\%$
0.25-0.45	Corsika	$\frac{735}{1501545} = 4.9 \times 10^{-4}$	$\frac{607}{1271845} = 4.8 \times 10^{-4}$
	ν_e Signal	$\frac{772}{861} = 89.7\%$	$\frac{795}{822} = 96.7\%$
	ν_μ Signal	$\frac{6761}{7704} = 87.8\%$	$\frac{6715}{7626} = 88.0\%$

Table 2: The signal and background efficiencies as a function of the number of external DOMs compatible with c, at two different levels of compatibility, for simulated ν_e, ν_μ and Corsika cosmic-ray simulated data.

here are conservative from that perspective.

Figure 3 shows the expected upper limits on the spin-dependent wimp-proton cross-section for IceCube alone and including DeepCore, for ten half years of exposure. Equilibrium between capture and annihilation rates in the Sun has been assumed. The atmospheric muon background has been reduced by a factor 10^6. The dashed line corresponds to 80 standard IceCube strings, and the solid line to IceCube including the six DeepCore strings with 40 DOMs and 10 m spacing on the string. It can be seen that the DeepCore will strongly improve the efficiency for low mass WIMP detection with IceCube. The final DeepCore with 60 Optical modules and higher quantum efficiency photomultipliers will improve this sensitivity even more. In addition, inclusion of data with the Sum above the horizon will increase the sensitivity for the ten-year period by almost 50% for the lowest neutralino masses.

2.3.2 Neutrino Oscillations

Sensitivity to neutrinos with energies as low as 10 GeV will enable IceCube's DeepCore to use atmospheric neutrinos to study ν_μ disappearance and possibly to detect ν_τ appearance. Depending on our detection efficiency for neutrinos in this low energy regime, how well we can control systematics, and the value of θ_{13} measured by other experiments, DeepCore may also be able to determine the sign of the neutrino hierarchy [15].

Analyses using standard IceCube strings to measure ν_μ disappearance are already underway and have produced encouraging results using data from IceCube's third year. During this time, only four of the 22 deployed strings were sufficiently surrounded by other strings to be viable for this analysis. We will be able to improve the neutrino oscillation analysis more than linearly as IceCube grows in size, due not only to an order of magnitude more data, but also to more effective background vetoing. However, IceCube DeepCore will give us access to considerably lower energies than IceCube alone–low enough to map out the oscillation minimum at $E_{\nu_\mu} = 28$ GeV in some detail. The angular resolution of muon tracks at these energies is fundamentally limited by the kinematics of the neutrino-nucleon interaction, and the muon track tends to be misaligned with the incoming neutrino. However, oscillations can be observed with very high significance

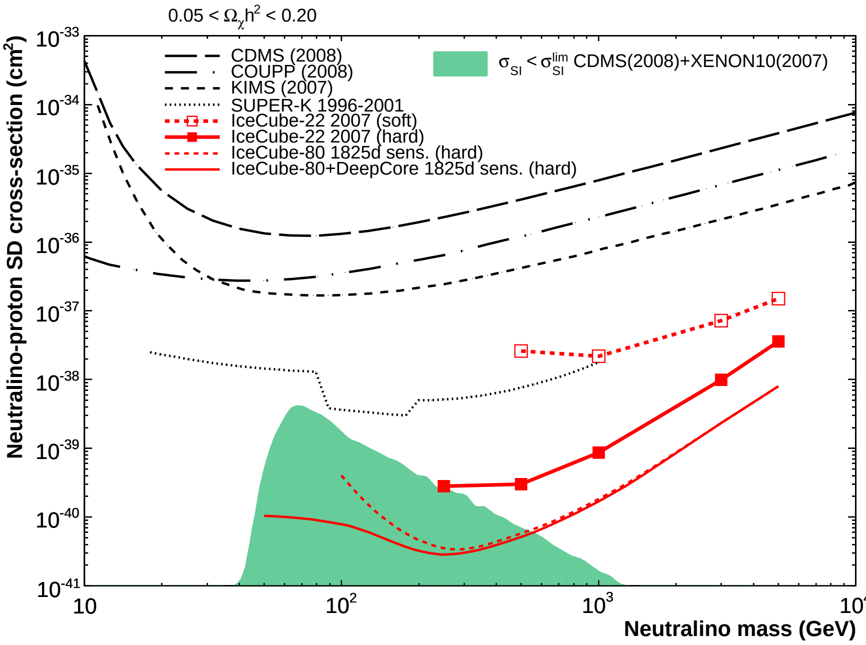


Figure 3: The expected sensitivities of IceCube, and IceCube with DeepCore, are shown alongside upper limits at 90% confidence level on the spin-dependent neutralino-proton cross-section $\sigma^{\rm SD}$ for soft ($b\bar{b}$) and hard (W^+W^-) annihilation channels, adjusted for systematic effects, as a function of neutralino mass. The upper limits use data taken by the 22-string IceCube detector in 2007 [1]. The shaded area represents MSSM models not disfavoured by direct searches [5, 6] based on $\sigma^{\rm SI}$. The limits from CDMS [5], COUPP [8], KIMS [14] and Super-K [11] are shown for comparison.

with an inclusive measurement over the range $-1.0 < \cos\theta < -0.6$, and incorporation of angular dependence will only improve the result. Figure 4 shows a simulation of this ν_μ disappearance measurement, indicating roughly a 20σ difference in the heights of the peak bin (with and without oscillations) with just one year of DeepCore data.

DeepCore will allow us to extract a sample of neutrino-induced cascades with sensitivity to ν_τ appearance from atmospheric $\nu_\mu \to \nu_\tau$ oscillations. Given the higher parent ν_μ flux and different decay kinematics of tau events relative to that of $\nu_{\rm e}$ CC and ν_x NC ($x = e, \mu, \tau$), we should be able to detect ν_τ both via the excess of cascade events and through the resulting spectral energy distortion, as shown in Fig. 5. This measurement would not only represent the largest sample of tau neutrinos ever collected (albeit inclusively), it may also be competitive with OPERA [10] in making the first appearance measurement of tau neutrinos due to oscillations, addressing the origin of this phenomenon at the Δm^2 characteristic of atmospheric neutrinos for the first time.

We will also pursue a more speculative analysis with DeepCore that has a potentially huge payoff. According to Ref. [15], we should be able to determine the sign of the neutrino hierarchy by exploiting asymmetries in matter oscillation effects and in detector response between neutrinos and antineutrinos for $10 < E_\nu < 30$ GeV, provided $\sin^2 2\theta_{13}$ is sufficiently large, and provided we can minimize background contamination and other systematic effects. This is a long-term analysis effort; the expected results from five years of DeepCore data are shown in Fig. 6, with a statistical

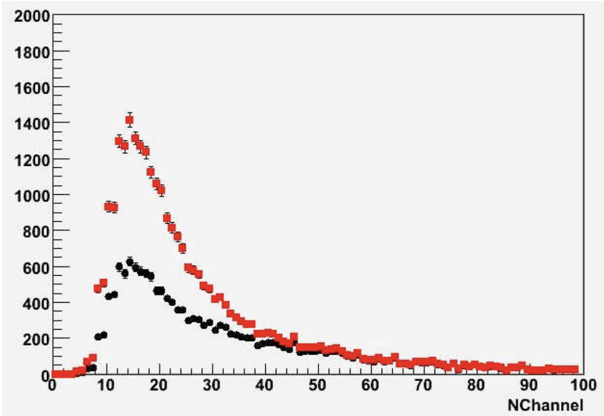


Figure 4: Simulated ν_μ disappearance with one year of DeepCore data. Circles (squares) show the number of upward-going ν_μ-induced muons observed for $\cos\theta < -0.6$, with (without) oscillations. Full three-flavor oscillations, the Preliminary Earth Model [12], and full detector simulation are used. Only statistical errors are shown, and events are selected based solely on their satisfaction of the trigger condition. No reconstruction was performed.

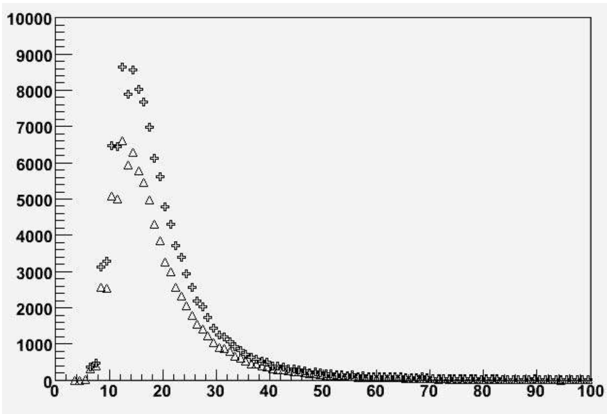


Figure 5: Simulated energy spectrum at trigger level for shower-like events in one year of DeepCore, with (triangles) and without (crosses) oscillations. The number of events is shown as a function of the energy deposited in the detector in GeV. The trigger is set to six or more DOMs in a 1μs time window, and to be conservative neutrinos have been forced to interact in the DeepCore fiducial volume. Showers are produced by ν_e (CC and NC), ν_μ (NC) and ν_τ (CC and NC) interactions. The obvious oscillation-induced excess and spectral distortion come from ν_τ appearance in atmospheric $\nu_\mu \to \nu_\tau$ oscillations.

separation between the normal and inverted hierarchies of approximately 7σ. We are currently performing a complete MC study to determine whether the systematic uncertainties associated with energy and direction measurement at such low energies are small enough for the analysis to succeed.

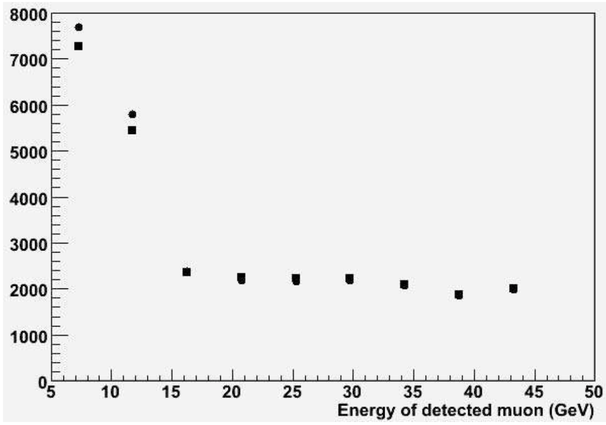


Figure 6: Predicted rate with 5 years of data for normal (squares) and inverted (circles) hierarchy, for ν_μ-induced muon tracks within 45^o of vertical that start within the DeepCore fiducial volume. Systematic errors are not yet estimated. Statistical errors are too small to be shown.

2.3.3 Southern Sky Point Source Searches

In the scenario in which TeV gamma rays emitted by galactic sources are of hadronic origin, neutrinos should be also emitted. Features such as cutoffs observed in gamma-ray spectra would be expected in neutrino spectra at around half the energy of that observed for the gamma-rays. Recently, the gamma-ray telescopes H.E.S.S., VERITAS and MAGIC have observed a population of galactic sources characterized by steep spectral index. Moreover, in several cases there is evidence of an exponential cutoff in the source spectrum at energies of 10 TeV or so, implying that sensitivity at low neutrino energies will be essential for observing these sources. The sources recently discovered are concentrated in the region of the inner Galaxy, most of them in the southern hemisphere, *i.e.,* outside the nominal field of view of IceCube. The southern sky is a prime target for observations by Mediterranean telescopes such as ANTARES [9].

AMANDA and IceCube searches for point sources have focused on the northern hemisphere, using the Earth to filter out atmospheric muons. With DeepCore we aim not only to lower the threshold of IceCube and increase sensitivity for soft-spectrum sources, but also to access the southern hemisphere using part of IceCube as an active muon veto. DeepCore will also have sensitivity to transient astrophysical sources in the southern hemisphere, such as Gamma-ray Bursts (GRBs) detected by the SWIFT and Fermi satellite observatories and the recently-discovered emitters of TeV gamma rays reported by the HESS experiment [4]. DeepCore's lower energy threshold will also give us sensitivity over 4π solid angle to the 5–10 GeV neutrinos predicted to be emitted if neutrons and protons in the GRB fireball decouple and then scatter inelastically [7].

Relative to the baseline IceCube design, DeepCore will offer a superior capability to identify the interaction vertex of downward-going ν_μ which interact inside the detector. Preliminary studies on the vertex reconstruction are encouraging and algorithms for energy estimation and track plus cascade reconstruction are under development as well. We are confident that we will be able with DeepCore to achieve an angular resolution similar or superior to that of AMANDA (2-3 degrees).

ANTARES and DeepCore both have an effective volume of about ten megatons for neutrinos in the energy range 100 GeV–1 TeV. For detecting potential southern sky point sources, ANTARES looks for upward-going events, while DeepCore looks for downward-going events. ANTARES will also detect neutrinos interacting outside its instrumented volume but will need to face the irreducible background from atmospheric neutrinos. However, a DeepCore downward-going analysis might profit from a suppression of atmospheric neutrinos, partially compensating the ANTARES advantage. In fact, during the design study of DeepCore, we have investigated the possibility to suppress downward atmospheric neutrinos by vetoing the muon which is produced by the same parent meson decaying in the atmosphere [17]. Even if the application in IceCube of this new idea is still under development, the possibility to suppress the atmospheric neutrinos could represent a major innovation in the field, testable with DeepCore only. Sensitivity to the southern sky including a full simulation of the veto of the atmospheric neutrinos is under development.

3 IceCube High Energy Extension

As mentioned earlier, our default deployment plan will deliver a detector that is superior to the original design. While this is a success, it is also important to contemplate the fact that the last two construction seasons represent our ultimate opportunity for optimizing the performance of the detector. We have therefore been studying the optimization of the final deployments.

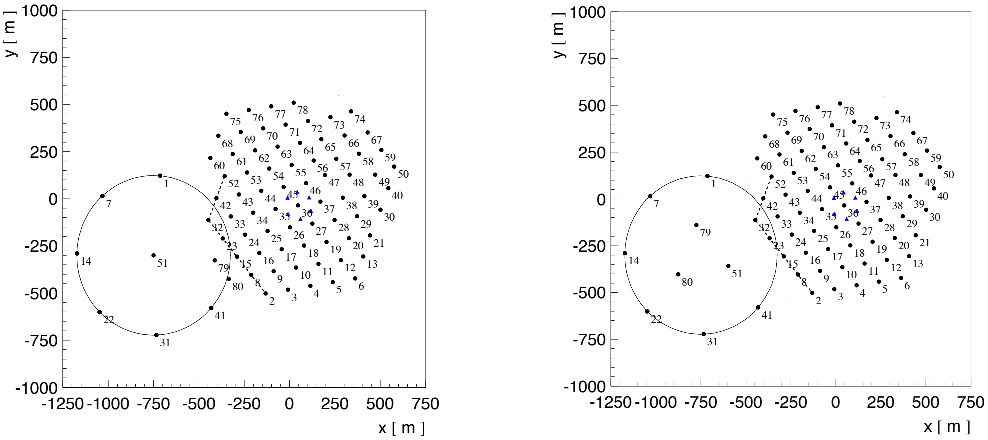
Clearly, with the instrumentation cycle essentially completed, the only adjustable parameter is the location of the strings relative to the 59 already deployed. Their location is constrained by the location of the drill camp and the reach of the drill. Optimization of the final geometry of IceCube will also take into account relevant results obtained with the 40 and 59 string configurations. While we emphasize that this effort is ongoing and subject to change, it is clearly focused on improving the effective area of IceCube at high energies.

The targeted improvements would be complementary to those achieved with the DeepCore array at lower energies. The science goals of the ongoing optimization are clear and focus on the highest energy sources of cosmic neutrinos. AMANDA has reached a limit on the flux of gamma ray bursts (GRBs) that is at the level of the flux predicted by conventional fireball phenomenology supplemented with the hypothesis that GRB are the sources of the highest energy cosmic rays.

With this assumption, the central GRB engines necessarily accelerate protons as well as electrons. The decay of pions produced by protons interacting with synchrotron photons yields neutrinos in the PeV energy range. Their flux is calculable and the result is that IceCube has the possibility to confirm that GRBs are the sources of the cosmic rays after the observation of 200 bursts in coincidence with detections of the Swift and Fermi satellites. Should no discovery be made, the results will still be relevant to the ongoing efforts to identify the sources of the highest energy cosmic rays. In general, improvement of the reach of IceCube in the PeV energy range will increase the instrument's sensitivity to any high energy neutrino flux that extends into that range, e.g. to some models of cosmic ray production in active galaxies. We also know from ongoing simulations of the completed detector that for E^{-2} spectra, the statistical significance of point source analyses is dominated by events above 100 TeV. In Fig. 3 we present the results of studies that optimize the performance of IceCube in the PeV and EeV energy range without significant impact on other science.

While the work is still underway, at this point we anticipate the following improvements in sensitivity:

- Performance increase for the proposed geometry in the range energies 10 TeV–3 PeV is 30%,



(a) (b)

Figure 7: The two High Energy Extension geometries under consideration. The geometry in the left diagram gives slightly better performance for the highest energy neutrino-induced muons that come in at nearly horizontal angles. The geometry in the right diagram is best for highest and intermediate energy (0.1–10 PeV) muons.

- 25% at 1 PeV
- 30% at 10 PeV

These numbers are likely better for the more uniform geometry, especially for the intermediate energies.

Even higher performance increases, between 73% and 80%, are obtained for older geometries using a specialized ultra high energy simulation. This result directly impacts the possibility of observing GZK events produced when high energy cosmic rays interact with the microwave background. The effective area of IceTop is increased by a factor 2.2.

It is possible to contemplate further extensions using this technique after the completion of the MREFC project, for instance with another 24 strings as shown in Fig. 8. These would target the increase of the IceCube's effective area by a factor of two over a wide range of (high) energies for a cost that we estimate at $25M.

4 Resource and Support Requirements

4.1 IceCube DeepCore

4.1.1 Funding Requirements

The total cost estimate for the DeepCore is $5,168,883. This estimate is very mature and is based on the actual costs of procurement and labor for the existing 59 in-ice strings. The breakdown of costs falls into four main categories as shown in Table 4.1.1.

DOM production costs include all hardware and labor required to fabricate, integrate, test, and ship 360 high quantum efficiency DOMs for deployment on the six high-density DeepCore

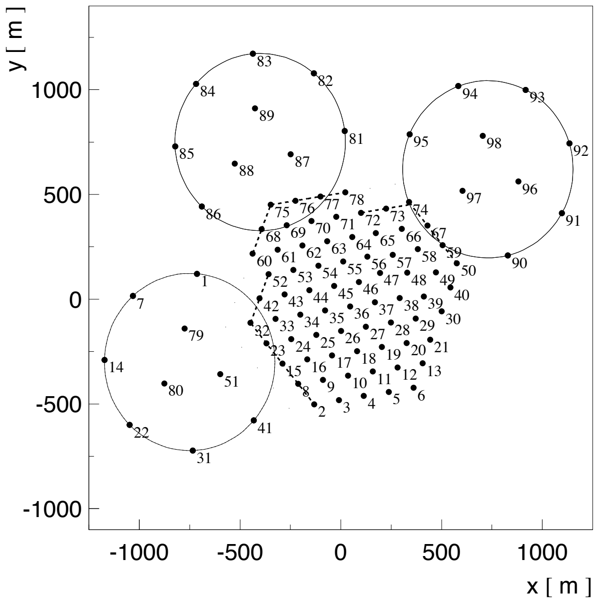


Figure 8: The high energy extension planned for the 2010/2011 deployment season is depicted by the left-most circle and inner triangle of strings, with string numbers less than 80. Possible subsequent high energy extensions, which would each add as much effective area for high energy neutrinos as the first extension, are shown above and to the right of the IceCube array.

DOM Production	$2,549,847
Cables	$1,286,157
DAQ	$132,879
Drilling & Installation	$1,200,000
Total Cost	$5,168,883

Table 3: Breakdown of costs for IceCube DeepCore.

strings. Cable costs include cable production at Ericsson, breakout installation at Seacon, testing, inspection, and shipping. Data Acquisition costs include DOM hub and DOR card fabrication, test, and integration. Drilling and string installation costs include drill fuel, drilling and installation team labor, and South Pole footprint.

The $1.2M estimate for drilling and installation does not include the non-recurring cost of drill season startup or shutdown. Drilling fuel costs are based on the cost of fuel delivered to Pole. The assumption for this estimate is $11.73 per gallon delivered. The target drilling fuel estimate per hole is now 5200 gallons. This equates to $366K in drill fuel cost for the six high-density strings. At present we routinely deploy strings using less than 4,700 gallons. We therefore anticipate that the fuel for deploying the six additional strings will be covered by the savings made by progress in fuel efficiency for recent deployments.

Sweden	Stockholm	$2,800,000
Belgium	VUB	$300,000
	ULB	$209,907
	Mons	$105,080
Germany	Wuppertal	$136,500
	Mainz	$165,540
	Humboldt	$34,560
	Aachen	$225,000
	Heidelberg	$150,000
Total		$4,126,587

Table 4: The contributions by non-US collaborators to IceCube DeepCore.

4.1.2 Funding Commitments

The non-US IceCube collaborators have committed funding for the cost of all materials, equipment, and labor required to produce the six high-density strings. The estimate above shows this cost is $3,968,883. The commitments made by funding agencies in Sweden, Belgium, and Germany amount to $4,126,587. These commitments have been realized as cash transfer to UW or direct purchase of hardware for the high-density strings.

The contributions by non-US institutions are shown in Table 4.1.2.

4.1.3 Support Requirements

It is important to state upfront that DeepCore has been developed as a replacement for AMANDA. AMANDA operations will be terminated on April 30, 2009. Not only is DeepCore a more attractive instrument from the scientific point of view, it has the advantage of using IceCube technologies and data acquisition and analysis tools. This is in contrast to the AMANDA detector, which has to be operated using outdated electronics, whose calibration is cumbersome and time consuming and whose data handling and analysis requires the maintenance of additional specialized software tools. In a typical season AMANDA requires 15 man-weeks at the Pole for maintenance and calibration. Operation requires 20 kW of power. In all respects replacement of AMANDA by DeepCore represents a significant saving of resources. Additional support for the six high density strings will be required to transport cargo to Pole, power for string operations, increased bandwidth to support higher data rates, and very modest increased maintenance resources.

Flights: Each string will require approximately 2.3 LC-130 flights to Pole. LC-130 capacity is 26,000 lbs per flight. The weight of each string breaks down as follows:

Fuel per hole is assumed to be the current target of 5,200 gallons. Actual fuel consumed is likely to be less than the targeted amount and will fall within the originally planned fuel budget that assumed 7,200 gallons per hole.

Drill fuel for the high density strings is likely to fall within the planned amount for the remaining 21 strings. Table 6 shows details of the drilling fuel plan, predicted actual use, and the amount needed for the high density strings. The plan number of 6,000 gallons (reduced from the 2004

Cables	19,400
DOMs	3,040
SJB	400
Drill fuel	31,200
Total	54,040 lbs

Table 5: Breakdown of weight components for each DeepCore string.

Planned fuel use 21 strings	126,000	gallons
Predicted actual use 21 strings	90,300	
Difference	35,700	
Estimate for 6 high density strings	25,800	
Additional savings	9,900	

Table 6: The drilling fuel plan for the remaining 21 strings comprising IceCube and DeepCore.

baseline amount of 7,200) is from the RPSC APP. The predicted actual use is based on 08/09 actual drilling fuel consumed per hole.

Power: Each DeepCore string will require 400 Watts of power for a total of 2.4 kW.

Data: IceCube DeepCore is expected to have an exclusive trigger rate of about 15 Hz assuming a simple majority trigger of three DeepCore DOMs in a time window of 1 μs. As discussed in Subsec. 2.2, Monte Carlo studies have shown that applying a simple online veto algorithm can reduce the DeepCore data rate (dominated by cosmic-ray muons) by over a factor of 1000 while keeping 95% of the signal from low energy neutrinos. The required additional satellite bandwidth for DeepCore thereby amounts to 0.5 GB/day, only about 1% of the total IceCube satellite bandwidth usage.

Maintenance: The high-density strings will require the same level of maintenance as any other IceCube string. This would include routine minor changes to firmware, power supplies, or DOR cards. Winterovers already in the IceCube M&O plan would perform most of these tasks at essentially no additional cost to the project or NSF. Not having to operate AMANDA will significantly reduce training and on-site duties of the winterovers. Again, we repeat that the additional resources required by DeepCore are, in all aspects, more than offset by the termination of AMANDA data taking.

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