DEEP UNDERGROUND
NEUTRINO EXPERIMENT

A Conceptual Design for ND-GAr-Lite

DUNE ND-GAr Working Group

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Executive Summary

This document presents the conceptual design and performance of the ND-GAr-Lite detector, which is an alternative to the TMS Day-One near detector option that serves the critical task of muon momentum measurements for neutrino interactions in ND-LAr during the initial phases of DUNE. ND-GAr-Lite becomes possible if partial funding for ND-GAr is secured such that the magnet can be built. The central volume of the magnet would be instrumented with a minimal number of scintillator tracking plane stations ($\sim 5-6$), with their configuration optimized to achieve the muon momentum resolution needed for DUNE's early physics goals. The transition from this ND-GAr-Lite detector to the full ND-GAr detector provides a natural path to the full ND-GAr detector, which is required in order for DUNE to reach its full physics potential. The long-term cost of this option is less expensive than initially building TMS and eventually replacing it with ND-GAr, however the initial cost is higher. There is also an overall savings in scientific and technical effort if ND-GAr-Lite serves as the Day-One near detector. Two transition plans are presented: 1) from TMS to full ND-GAr (est. 6 months with no available muon spectrometry), and 2) from ND-GAr-Lite to full ND-GAr (est. 8 months with no available muon spectrometry). When both options are assumed to take place as a "single pass" (i.e., no attempt to take advantage of summer shutdowns, or to stage the installation to minimize no-spectrometry running), TMS does have a shorter transition period, however, if the ND-GAr-Lite transition were staged, the impact on ND-LAr data-taking could be minimized. In the first stage, the ND-GAr-Lite tracker stations would be temporarily removed to install the ECAL during a summer shutdown, then reinstalled to allow ECAL+tracker-station running during the next beam-on period. In the second stage, the tracker-stations would be removed and replaced by the HPgTPC. This staging would minimize and possibly eliminate no-spectrometry running, but the detailed plan is still in development; therefore, in this document, only the non-staged transition plans are presented.

ND-GAr-Lite performance is also presented. This detector achieves the necessary muon momentum resolution requirement (better than 4% resolution) for DUNE's early physics program. With a six-tracker-station configuration inside the ND-GAr-Lite magnet, the momentum resolution as a function of initial muon momentum in ND-LAr varies between 2% and 4% for muons created in neutrino interactions in the ND-LAr volume and tracked in ND-GAr-Lite. This six-station configuration has good efficiency for the phase space of muons exiting ND-LAr, losing primarily only large-angle muons ($> 50\,\mathrm{deg}$) that do not intersect the ND-GAr-Lite detector.

Finally, a preliminary cost and schedule for ND-GAr-Lite are presented. The schedule and costs of the scintillator tracker planes are based upon Mu2e's "as-built" experience and on vendor quotes for components. The total preliminary cost of the tracker is estimated to be just under $700k, not including management overhead, contingency, or escalation. Preliminary estimates for the SPY magnet cost and schedule were provided by ASG Superconductors, and a more detailed cost estimate is in progress, expected to be added to this document by mid-October. The cost envelope estimated by ASG, based upon their as-built MPD magnet for JINR, is between 15M€ to 18M€ for the solenoid. A cost estimate of $3M USD has been provided by our colleagues in India for the return yoke iron sourced in India.

Contents

1 Introduction and Motivation

The Deep Underground Neutrino Experiment (DUNE) aims to be a world-class, international particle physics experiment seeking to answer fundamental questions about the elusive neutrino. It will use a new high-intensity neutrino beam, that will be generated at the U.S. Department of Energy's Fermi National Accelerator Laboratory (Fermilab). The experiment will consist of a far detector (FD) located approximately 1.5 km underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, at a distance of 1300 km from Fermilab, and a near detector (ND) that will be located on the Fermilab site in Illinois. The FD will consist of a large, modular liquid-argon TPC (LArTPC) with a fiducial mass of roughly 40 kt. The ND will be located approximately 574 m from the neutrino source for the LBNF beam. The conceptual design for the DUNE near detector is described in detail in [1]. The ND will consist of several different components: a modular non-magnetized LArTPC (ND-LAr), a magnetized tracker containing a gaseous argon TPC (ND-GAr), and a large, magnetized beam monitor (SAND). SAND will remain fixed on the beam axis, while ND-LAr and ND-GAr will move transverse to the beam in order to collect data at various off-axis positions, providing different spectra by the PRISM concept.

ND-GAr consists of a high-pressure gaseous argon TPC (HPgTPC), surrounded by a calorimeter, both situated in a 0.5 T magnetic field generated by superconducting coils, and a muon system. The argon gas will be at a pressure of 10 atm to increase the rate of neutrino interactions. The design for the ND-GAr HPgTPC is based closely on the design of the ALICE TPC [2]. The drift region of the ALICE TPC has a diameter of roughly 5 m and a length of roughly 5 m. For ND-GAr, a high-pressure TPC of this size would have a fiducial mass of nearly 1 ton of argon and would contain approximately 1 million neutrino interactions on argon per year (defined as an exposure of 1.1×10^{21} protons on target) in the on-axis position. The calorimeter is inspired by the CALICE analog hadron calorimeter (AHCAL) [3]. The scintillating layers will consist of a mix of tiles and strips. A cutaway schematic of ND-GAr is shown in Fig. 1.

The complete ND-GAr detector is required in order for DUNE to reach its full physics potential, and is endorsed by the LBNC. While ideally the entire suite of near detectors would be ready for the start of DUNE operations, resource limitations may require a staged approach. DUNE's baseline plan for a Day-One detector replaces the ND-GAr magnetized gaseous TPC with a simpler Temporary Muon Spectrometer (TMS), built from steel and scintillator and containing a vertical magnetic field for sign-selection of neutrino vs. anti-neutrino events. The TMS is considered to be a well-costed and "safe" backup solution, based on established technology and drawing heavily on the MINOS detector design. As the name suggests, the Temporary Muon Spectrometer would eventually need to be replaced by ND-GAr.

ND-GAr-Lite, described in this document, is an alternative Day-One option that becomes possible if partial funding for ND-GAr is secured early enough. In that scenario, the ND-GAr magnet would be built and its central volume would be instrumented with a minimal configuration of scintillator tracking plane stations. The advantage of this approach is that it provides a natural staging toward the construction of the full ND-GAr detector. In the long-term, this option is less expensive in both cost and in effort than initially building TMS and eventually replacing it with ND-GAr. The disadvantage is a higher up-front cost.

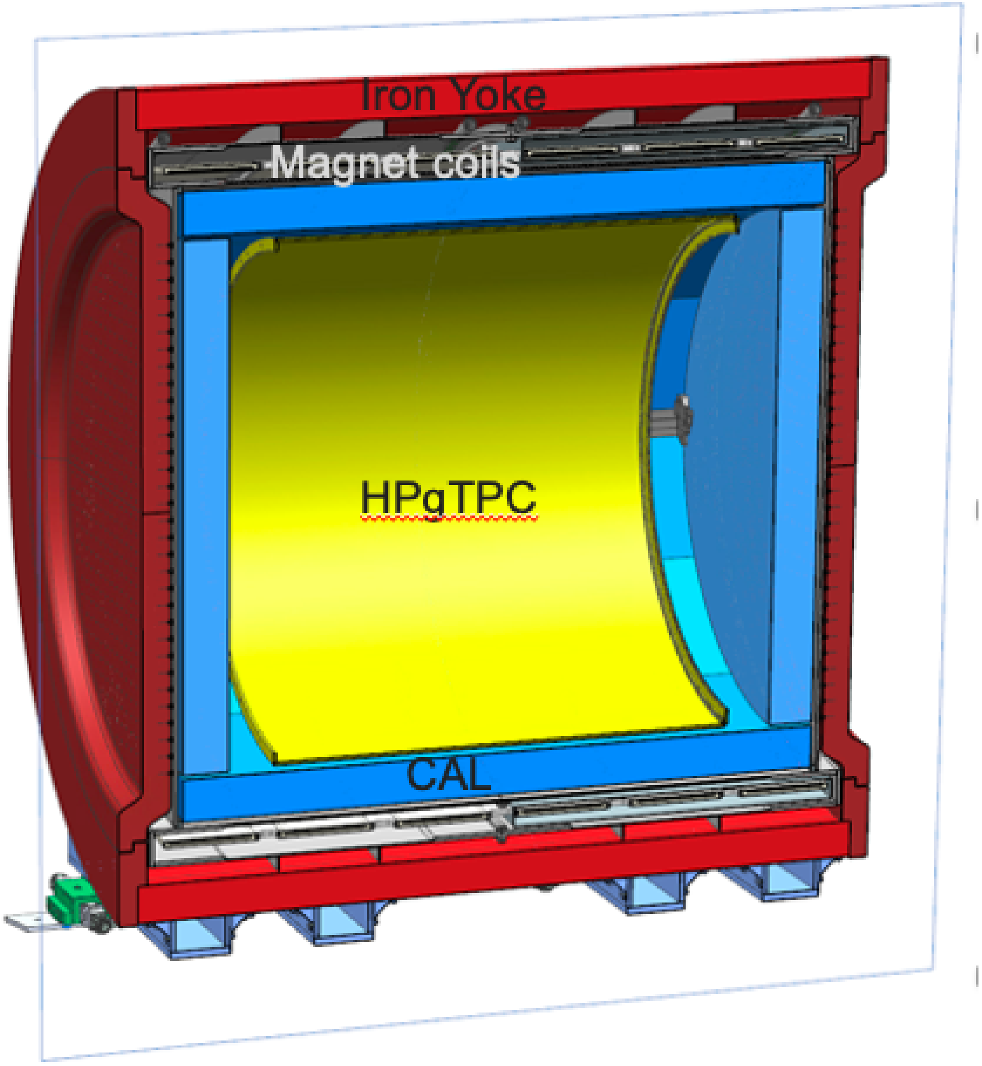


Figure 1: Cutaway view of the full ND-GAr detector system showing the HPgTPC, the calorimeter, the magnet, and the iron yoke. The detectors for the muon-tagging system are not shown.

2 Physics Motivation

The full physics program of DUNE is described in [4, 5, 6]. ND-GAr extends and enhances the capabilities of the near detector. It does this by providing a system that will measure the momentum and sign of charged particles exiting ND-LAr. For neutrino interactions taking place in the argon gas, it will extend charged particle measurement capabilities to lower energies than achievable in the far or near LArTPCs. It will also greatly extend the particle ID (PID) performance, particularly for proton-pion separation. These capabilities enable further constraints of systematic uncertainties for the long-baseline oscillation analysis. Since the target nucleus in the ND-GAr is the same as that in the near and far LArTPCs this information feeds directly into the interaction model constraints without complicating nuclear physics concerns.

Figure 2 shows the early running (left) and ultimate impact (right) of the ND-GAr detector on the long-baseline oscillation sensitivity to CP violation. As seen in the left panel, if Nature is kind enough to provide maximal CP violation, there is not much difference between the exposure required to achieve sensitivity with 3σ significance using TMS (labeled as "Day 1 ND") and ND-GAr (labeled as "Full ND"). Maximal CP violation is the most favorable case for DUNE's sensitivity, but a more realistic assessment of sensitivity is given by looking at the full range of possible values of δ_{CP} (or some fraction of that range of values). The right panel shows DUNE's expected sensitivity to 50% of all δ_{CP} values, for the same detector configurations. In this case, the experiment with TMS at the near site would require significantly more exposure to achieve 3σ significance than would be needed for the same significance level with the full ND-GAr detector. In addition, TMS may possibly never reach the 5σ significance level even with very long exposures. The full ND-GAr detector is ultimately needed to achieve DUNE's scientific goal for CP violation.

3 Requirements

These should be the same as TMS requirements (need to find document listing those).

4 ND-GAr-Lite Overview

A cutaway view of the full ND-GAr system is shown in Fig. 1. Details of the HPgTPC and calorimeter for the full ND-GAr are described in [1]. Here we present ND-GAr-Lite, a Day-One tracker option that uses the ND-GAr magnet system with a simplified tracker to achieve the early physics requirements for DUNE. In order to reach DUNE's full physics goals, this Day-One tracker would eventually be replaced by the HPgTPC and ECAL, bringing ND-GAr-Lite up to the full ND-GAr specification. The transition process from ND-GAr-Lite to full ND-GAr is described in Section 6. The transition from TMS to full ND-GAr is also presented. The ND-GAr-Lite path provides an overall savings in cost and in scientific and technical effort. If TMS is built, its cost is sunk (since it cannot be reused as part of ND-GAr), as are the many person-years of effort put in by a talented group of scientific and technical staff that could instead be directed to ND-GAr/ND-GAr-Lite. The loss of scientific effort and financial resources also have an impact on schedule, necessarily placing

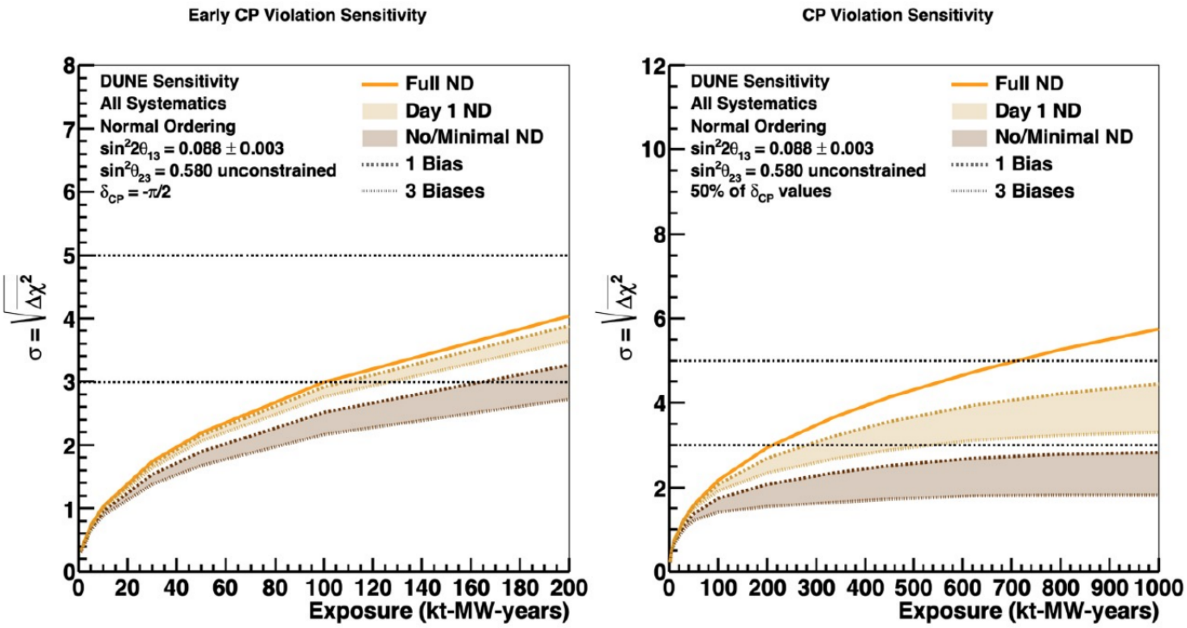


Figure 2: Impact of various near detector configurations on CP violation sensitivity, shown for maximal CP violation (left) and for 50% coverage of δ_{CP} space.

ND-GAr on a longer time scale than could be achieved if those resources were dedicated to ND-GAr-Lite and ND-GAr instead of TMS from the beginning.

4.1 Magnet and Pressure Vessel

The design of the magnet system has evolved over the past few years and no longer uses a separate pressure vessel as was described in Ref. [1]. The superconducting magnet uses a semi-continuous thin solenoid approach with 6 separate windings. The design is based on the decades-long evolution of internally wound, aluminum stabilized superconducting magnets. The required field in the warm bore is relatively low, 0.5T, therefore a single layer coil is sufficient to provide the needed current density even with a diameter of $\simeq 7$ m. The design parameters are conservative when compared to previously built magnets. The iron yoke must be asymmetric to guarantee a sufficiently low material budget between ND-LAr and ND-GAr. The magnet system design, a solenoid with partial return yoke known as SPY, makes its design rather unique.

A key feature of SPY is that the pressure containment for the 10 bar of Ar gas for the HPgTPC is now provided by the solenoid's vacuum vessel and "stayed" flat heads supported by the magnet system yoke. Figure 3 shows the exterior of the complete detector system. The partial iron return yoke for the magnet wraps around the sides, top, and bottom of the magnet, but has a window on its upstream beam face to minimize the amount of material between the ND-LAr and ND-GAr tracking regions as shown in this figure. The end flanges of the pressure vessel are "stayed" by the iron yoke end plates. Analysis of ND-GAr's pressurized system was performed to meet the requirement's of Fermilab's Environment, Safety, and Health Manual (FESHM), Chapter 5031.

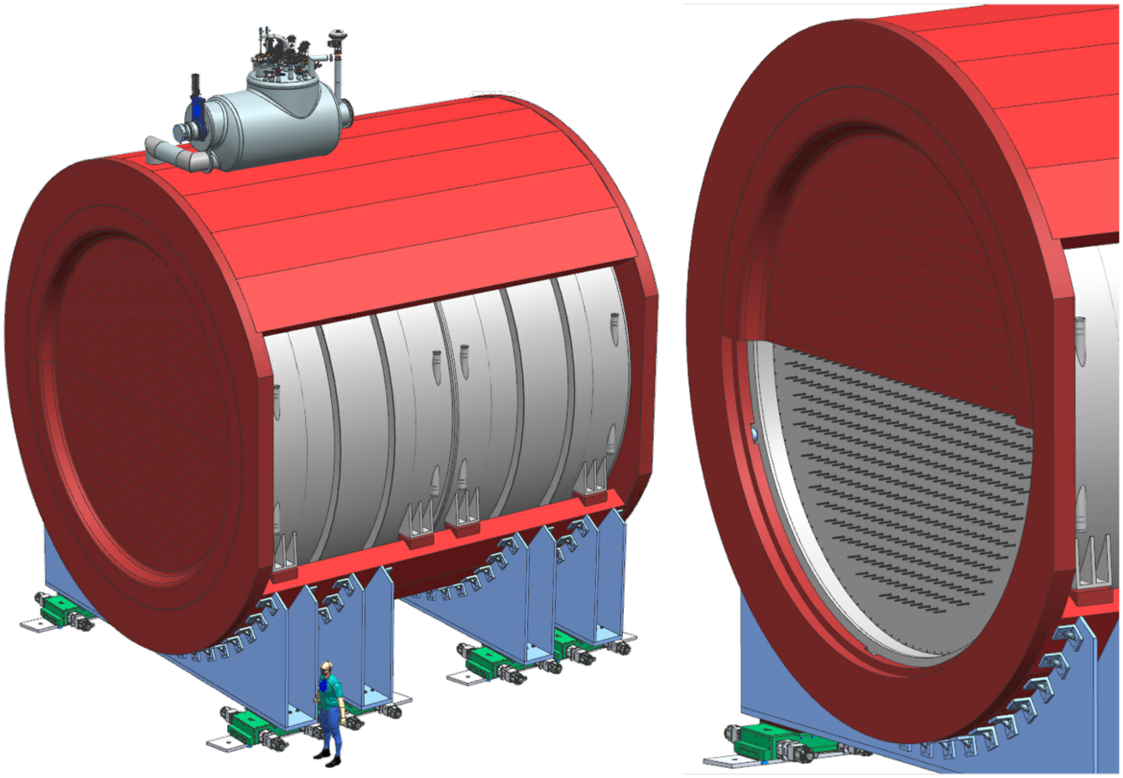


Figure 3: The left image shows exterior of the full system, with the magnet return yoke shown in red. The right image shows a cutaway view of one of the end plates, where some of the "stays" that support the load of the flat heads are visible.

More details about the magnet system will be presented in a dedicated magnet Conceptual Design Report, which is in preparation. Many of the features of the solenoid are based on the design of the solenoid for the MPD for the Nuclotron-based Ion Collider FAcility (NICA) at JINR [7].

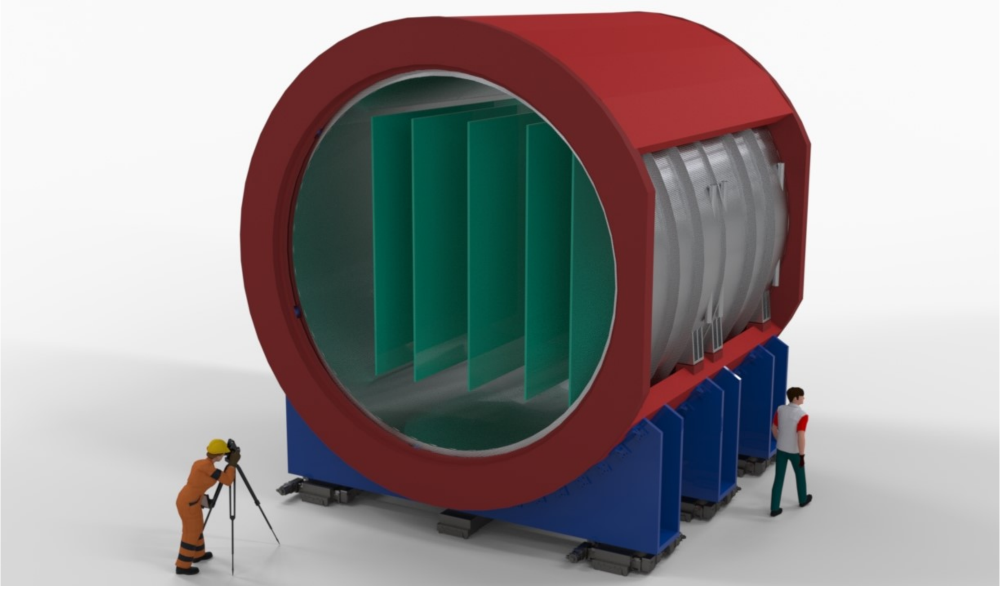


Figure 4: A rendering of ND-GAr-Lite is shown here. The return yoke end caps are removed to show the inner region.

4.2 Scintillator Tracker

The nominal design for the ND-GAr-Lite tracker consists of 5 tracking stations, as depicted in Fig. 4. Each tracking station is roughly 5.8 m wide and 5.1 m tall. Each station would be composed of an x-layer plane and a y-layer plane of scintillator bars. The scintillator bars are triangular shaped (shown in Fig. 5), approximately 2 cm tall and 4 cm along the base of the bar, giving 288 (256) channels per vertical-bar (horizontal-bar) layer. The basic detector module is called a quad counter, where the counter motherboard reads out the 4 SiPMs that detect the light from the 4 wavelength-shifting fibers. A schematic of the current design is shown in Fig. 6. Pre-production of the scintillator extrusions has now been completed and enough scintillator has been produced for a 4-plane 1 m^2 prototype and 3-plane 5 m long by 30 cm wide prototype. The 5 m long prototype will be tested in the Fermilab Test Beam Facility in the Fall of 2021. A photo of the extrusion is shown in Fig. 7.

Preliminary Monte-Carlo studies give a position resolution with a core of approximately $\sim$0.8 mm and a tail of $\sim$2 mm (see Fig. 8). This study included the "as-built" dimensions of the scintillator extrusion, all physics processes, and an overall light-yield normalization based on the experience of Mu2e. The two side "bumps" seen in the distribution in Fig. 8 are from the build-up of the reflective coating in the lower two apexes, as can be seen in Fig. 7. This issue is understood and solvable; it will be addressed when production tooling is procured.

For the purposes of the prototyping and preliminary testing phase, we plan to use a copy of the Mu2e readout electronics (front-end to DAQ). For production, we have a number of options including the Mu2e architecture with minor modifications, or electronics similar to those now being designed for the TMS.

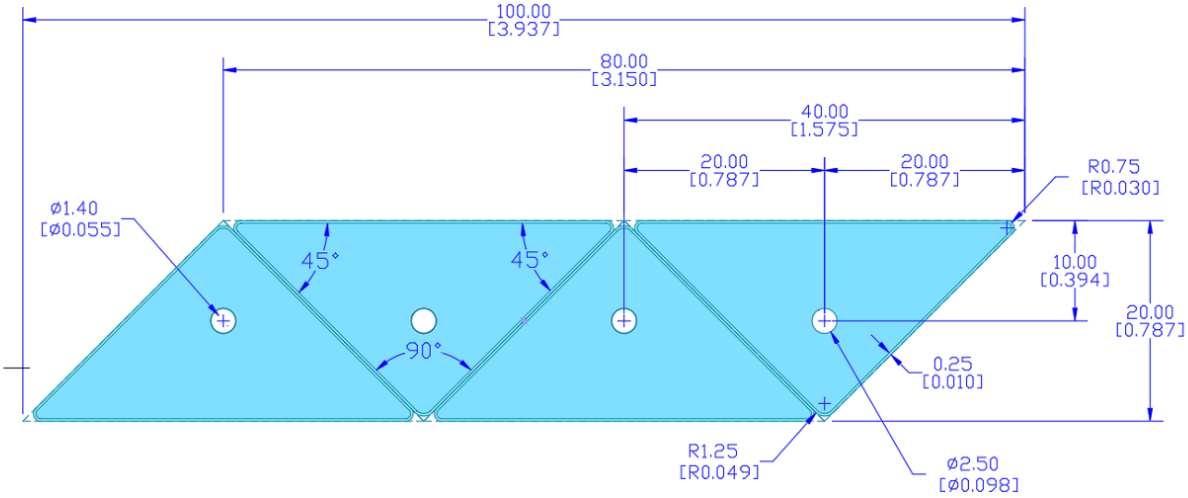


Figure 5: Dimensions of the triangular scintillator bars for the tracking planes with measurements given in millimeters [inches].

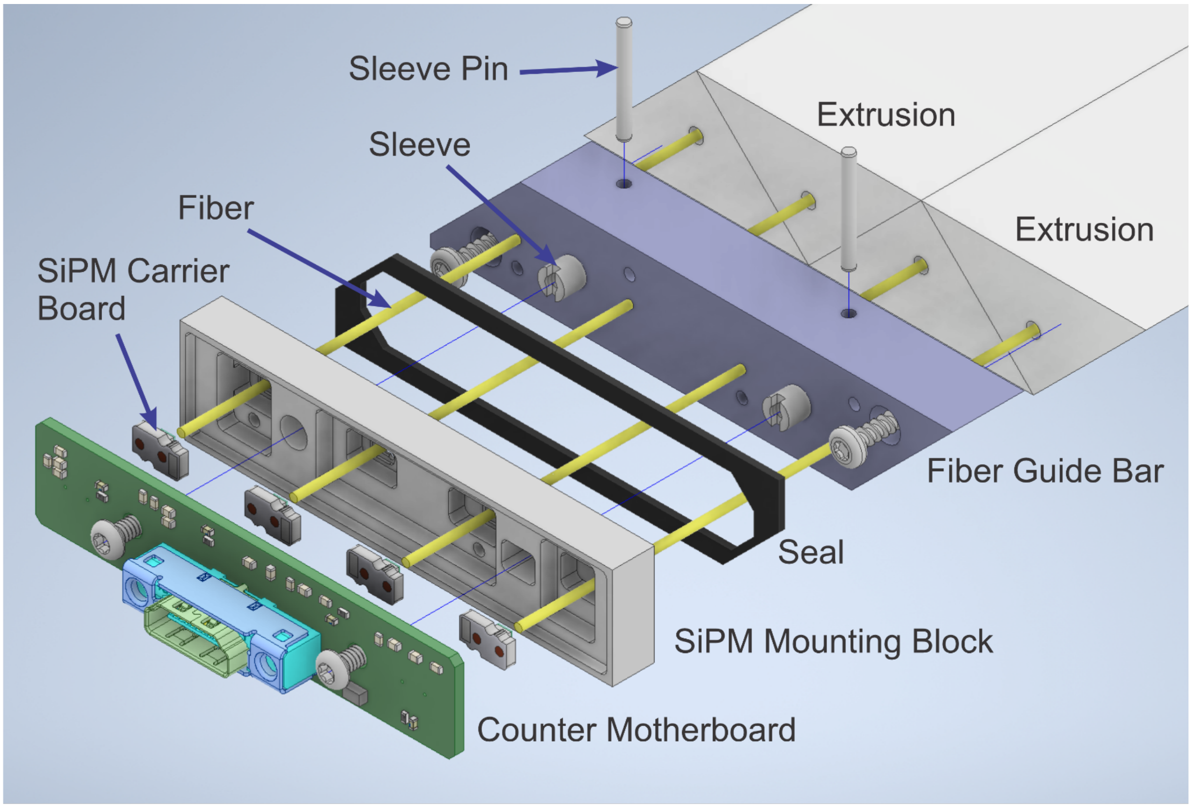


Figure 6: Schematic of quad-counter.

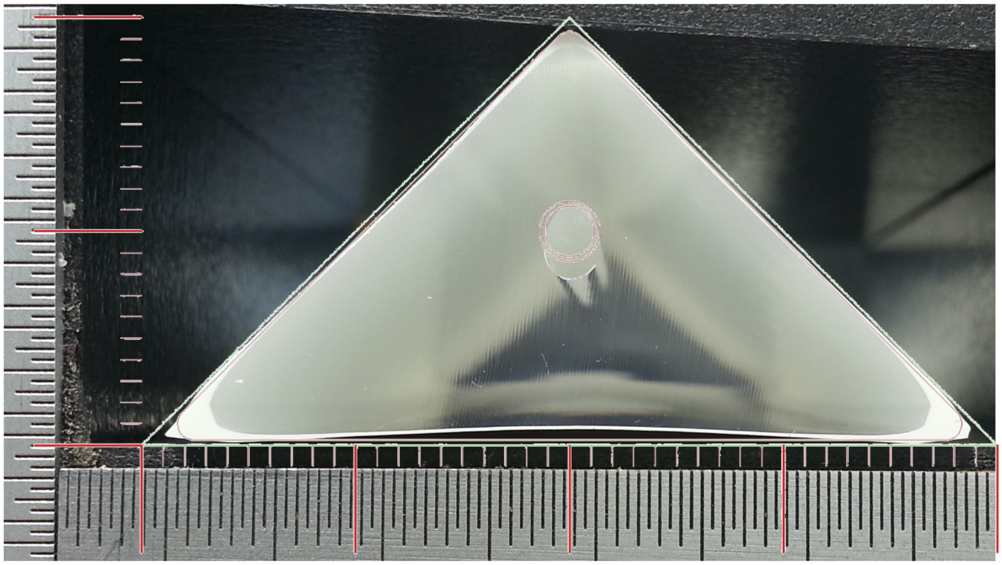


Figure 7: Photograph of one of the triangular extrusions produced in the prototype run.

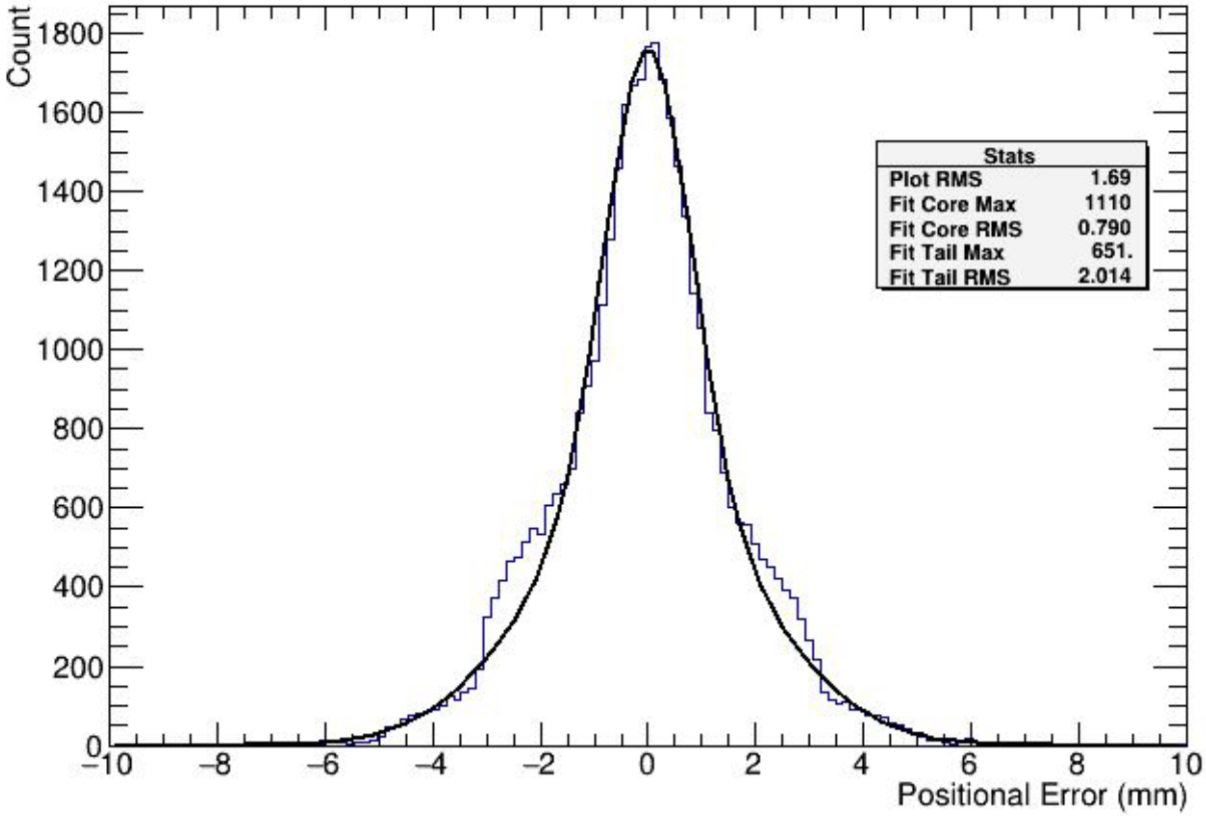


Figure 8: Monte Carlo results for the hit resolution of our scintillator. The MC includes the "as-built" geometry, all physics processes, and charge sharing.

4.3 Muon Tagger

ND-GAr will need an active layer, the Muon Tagger, outside the iron yoke that will detect particles that penetrate the iron. These data will be used in conjunction with the ECAL and HPgTPC to provide μ/π separation. The current design consists of a single layer outside the iron. The iron itself is not segmented in depth to allow for multiple measurements. For ND-GAr-Lite (or the TMS), μ/π is not currently a requirement (information comes from ND-LAr). However, the addition of the Muon Tagger in ND-GAr-Lite could still be useful. Current technologies under consideration include scintillator extrusions (which could be same as those used for the ND-GAr-Lite tracker), RPCs, or MicroMegas.

5 Physics Performance

The ND-GAr-Lite reconstruction requires hits in at least three unique tracking stations to form a track. The nominal design for ND-GAr-Lite uses five stations placed symmetrically about the center of the cylinder, shown in the upper panel of Fig. 9, however this geometry is not optimal for all muons to be reconstructed. Muons traveling at large angles or with low momentum may leave the detector before traversing at least three tracking stations. The efficiency for reconstructing lower momentum tracks can be improved by moving some tracking stations further upstream, as shown in the lower panel of Fig. 9, so that more of the muons will traverse three stations before exiting the detector. Additional ideas to improve reconstruction efficiency that have not yet been explored are: reducing the magnetic field, and improving the reconstruction algorithm to allow for multiple hits on the same tracking plane. However, as will be shown below, the configuration with more stations placed in the upstream part of the volume already results in sufficient muon performance to meet DUNE's early physics goals.

The tracker station optimization study was performed using a sample of 1.9×10^6 neutrino interactions generated in the liquid argon active volume using GENIE v2.12.10. Muon neutrino charged current events are selected to guarantee a muon, and the true neutrino vertex is required to be within the ND-LAr fiducial volume.

The distribution of muon momentum and angle with respect to the initial neutrino direction for muons that exit the downstream face of ND-LAr are shown in the upper two panels of Fig. 10. The upper panel shows the full momentum range, while the middle panel is zoomed in to momenta below 8 GeV. Since the width of the ND-GAr-Lite detector transverse to the neutrino beam direction does not extend much past that of ND-LAr, muons exiting ND-LAr at a high angle will not be captured by ND-GAr-Lite. The acceptance of ND-GAr-Lite is included by requiring that ND-LAr-exiting muons pass through an imaginary plane with the same dimensions as a nominal tracking plane and situated at the upstream side of the ND-GAr-Lite cryostat. The distribution of muons that pass this cut, effectively reaching ND-GAr-Lite, is shown in the bottom panel of Fig. 10. This last requirement primarily affects the angular distribution of muons, notably removing all muons with an angle of greater than $\sim$50 degrees.

The efficiency of a given tracking station arrangement was calculated by taking the ratio of muons that crossed at least three stations over the total distribution of muons that cross

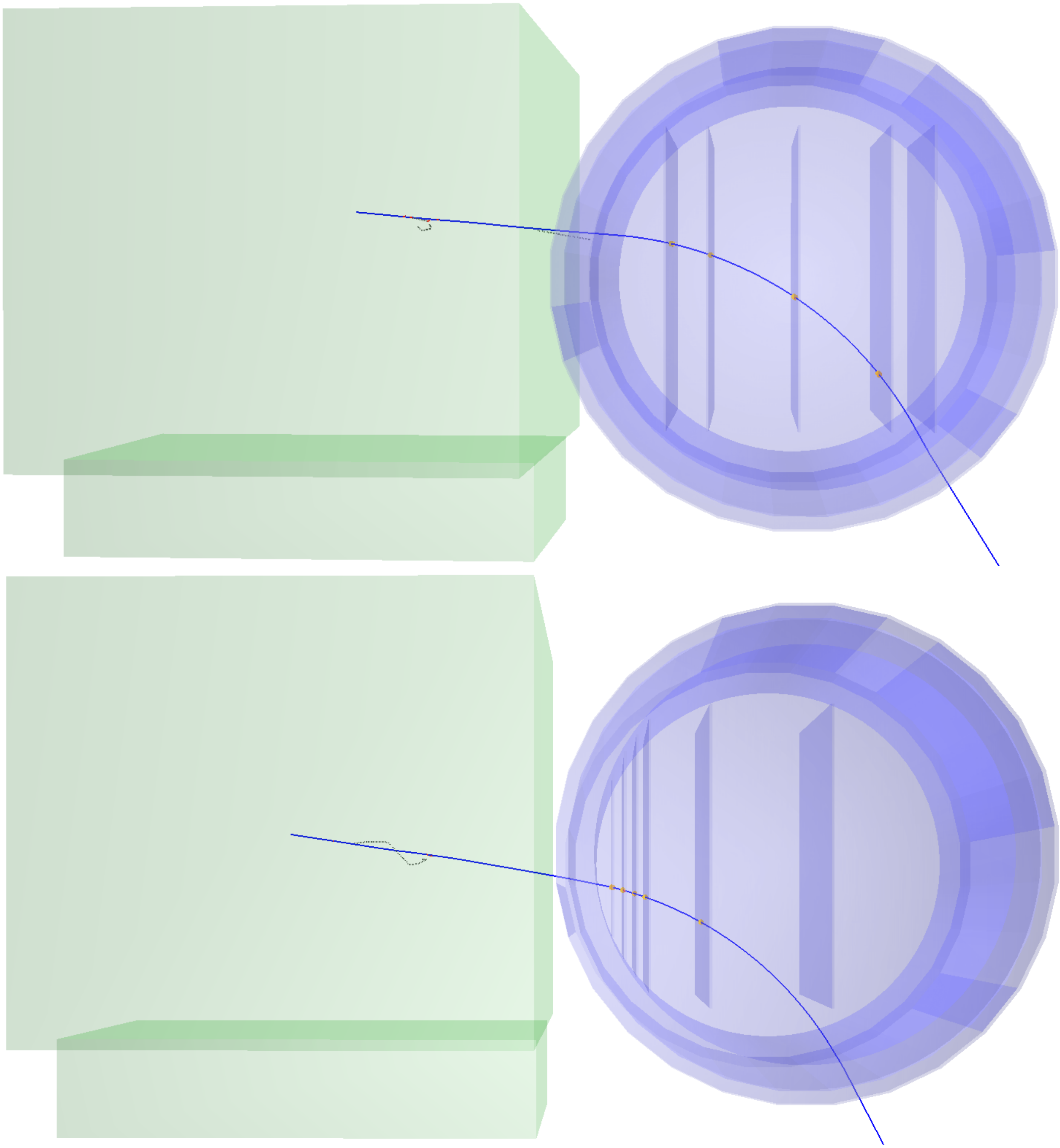


Figure 9: ND-GAr-Lite tracker station layout with the nominal five-station symmetric placement (upper image) and an optimized six-station placement (lower image). The transparent green box depicts ND-LAr with an exiting muon that enters ND-GAr-Lite.

the imaginary plane upstream of ND-GAr-Lite. The true trajectory and true particle ID were used to eliminate any ambiguity from the detector simulation, and the efficiency presented here does not account for reconstruction failures or misidentified tracks. The efficiency as a function of initial muon momentum and angle with respect to the neutrino for the nominal symmetric tracker station arrangement is shown in the upper panel of Fig. 11, with

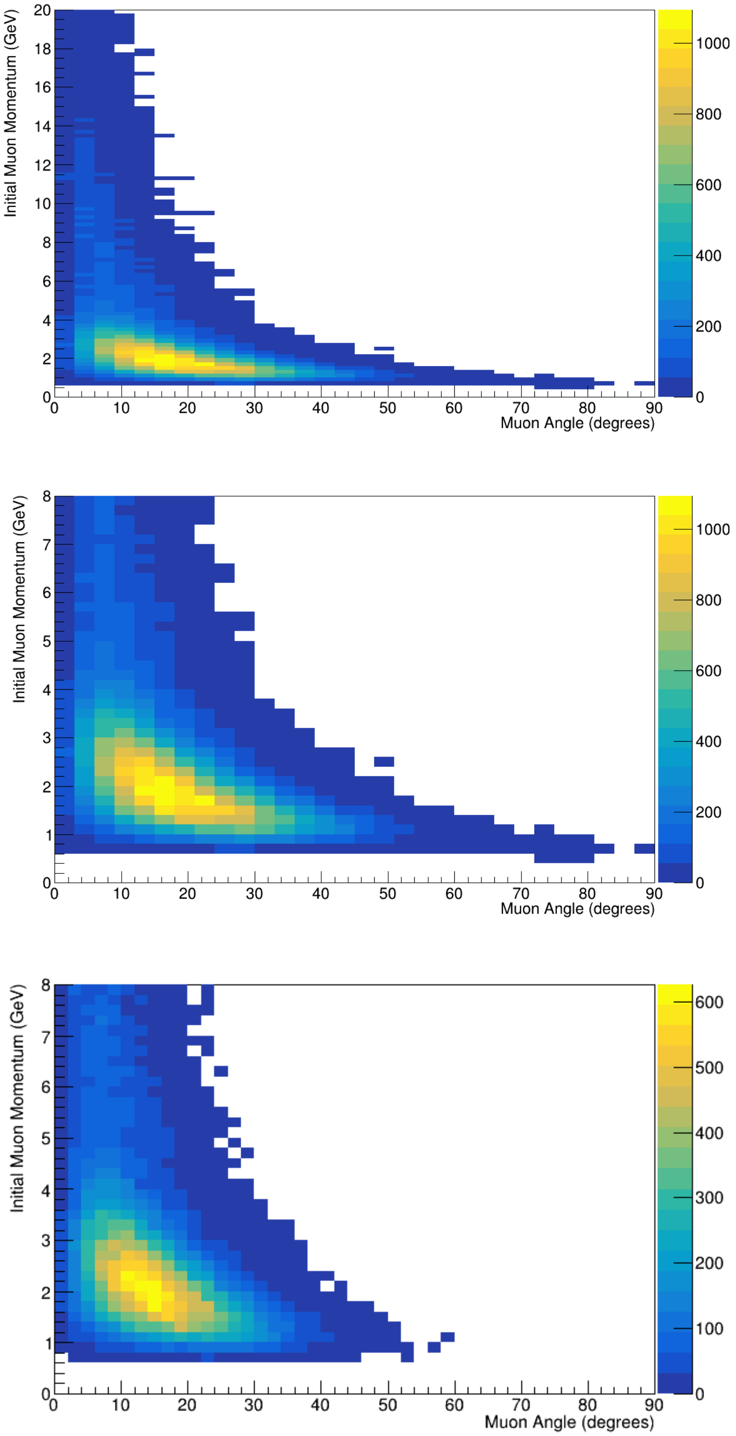


Figure 10: Distribution of muons that exit ND-LAr travelling downstream as a function of their initial momentum and angle with respect to the neutrino. The upper panel shows the full momentum and angular range. The middle panel is zoomed in to show momenta below 8 GeV. The bottom panel includes only the muons that cross an imaginary tracker-station-sized plane situated just upstream of the ND-GAr-Lite cryostat, showing that ND-GAr-Lite loses primarily large angle muons.

tracking stations located at the following positions in Z: (1266, 1336, 1486, 1636, 1706) cm in global world coordinates. The nominal arrangement has a lower momentum threshold of approximately 1 GeV/c, missing nearly all muons below that threshold, and performs poorly at angles greater than ~20 degrees.

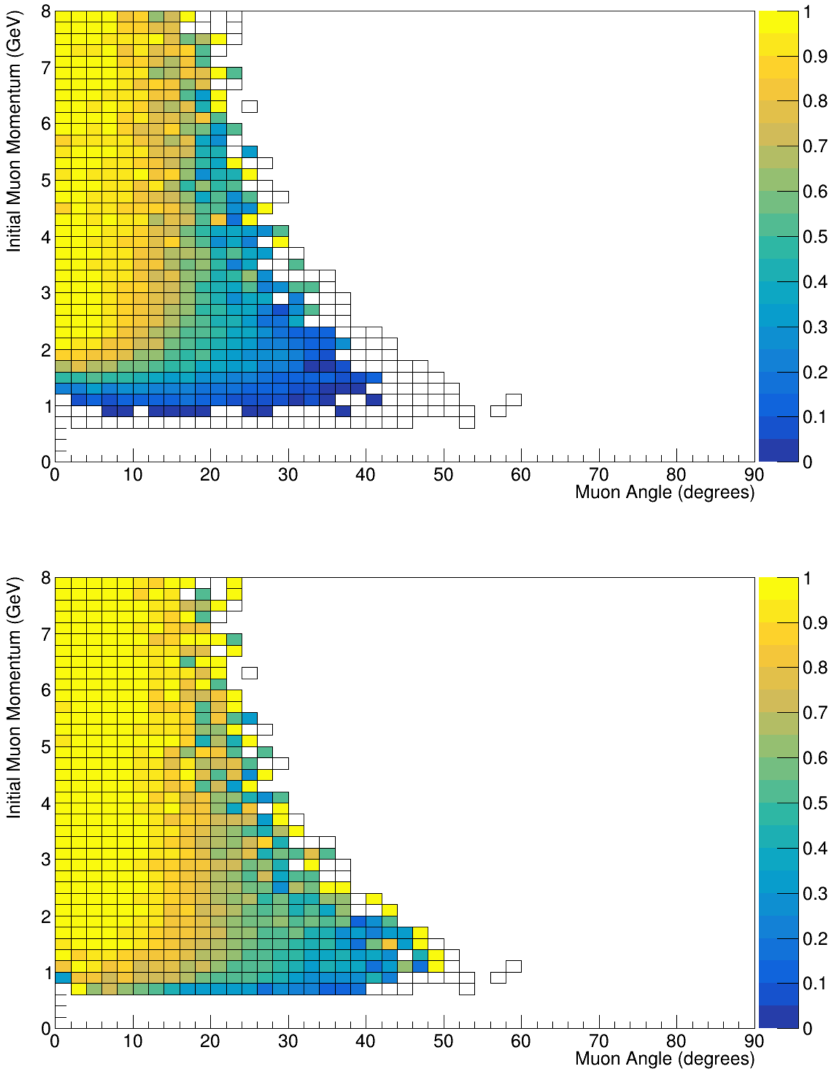


Figure 11: Efficiency of tracking muons in ND-GAr-Lite with the nominal symmetric tracking station arrangement (upper) and with the optimized six-station arrangement (lower). The box outline shows the region of muon phase space.

The current optimized tracking station arrangement uses six planes (using roughly the same total amount of scintillator) mostly placed in the upstream half of the ND-GAr cryostat. The nominal tracking plane size is 514 cm tall, however the inner radius of the cryostat is 336.25 cm. This places a constraint on how far upstream a tracking plane can be placed while maintaining nominal height, and therefore the plane height is reduced accordingly as planes are placed further upstream. The efficiency as a function of initial muon momentum and angle with respect to the neutrino for the nominal symmetric arrangement is shown in the lower panel of Fig. 11, with tracking stations located at the following positions in Z: (1181, 1201, 1221, 1241, 1341, 1541) cm in global world coordinates. The optimized tracking station arrangement extends the tracking capability to cover nearly all of the muon kinematic phase space, improves efficiency in nearly every bin, and lowers the threshold to track muons with initial ND-LAr momenta as low as 700 MeV/c. A muon produced in the LAr fiducial volume requires a minimum initial momentum of 800-900 MeV/c, on average, to escape the ND-LAr cryostat, as shown in Fig. 12. The linear relationship of initial muon momentum with location of the neutrino interaction ("Z vtx position") confirms that muons below approximately 700 MeV/c do not make it out of the ND-LAr cryostat, and therefore cannot be tracked by a downstream detector.

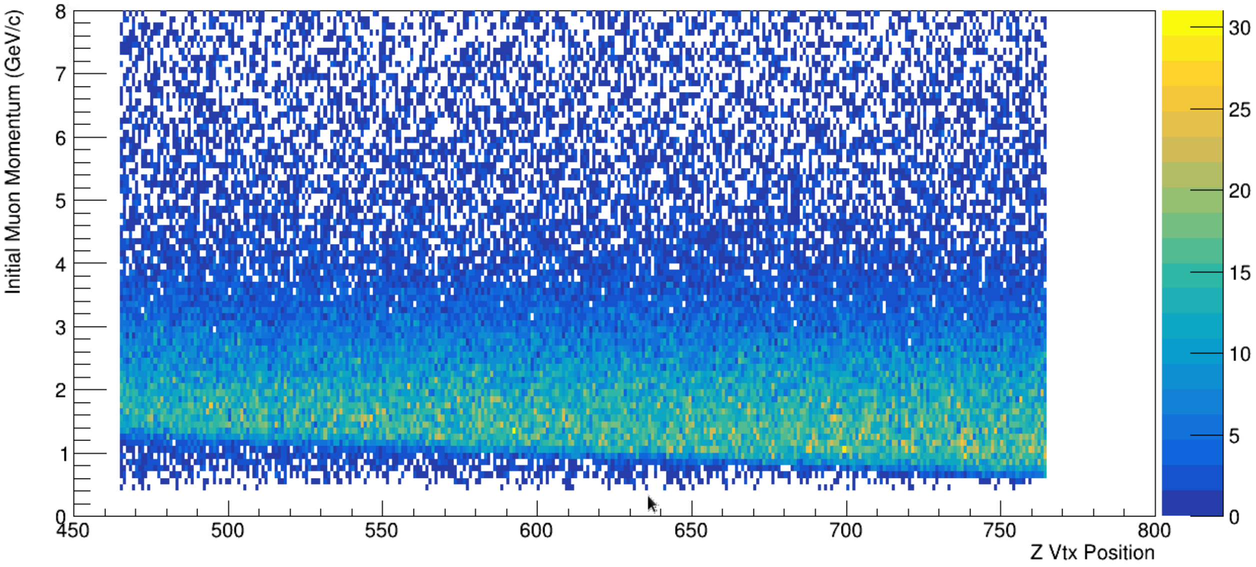


Figure 12: Initial momentum of muons that exit the downstream face of the ND-LAr cryostat. The horizontal axis "Z vertex position" indicates the location of the neutrino interaction along the neutrino beam direction, showing that muons below approximately 700 MeV/c will not exit ND-LAr.

The momentum resolution was studied for the optimized six-tracking-station arrangement using a muon gun that was parameterized to have a similar momentum and angle distribution as the GENIE generated events and which uses the same selection cuts as above. The initial muon momentum is calculated from the ND-LAr and ND-GAr-Lite reconstruction as well as any energy loss corrections for passive material in between the two detectors (for fully-contained muons only the ND-LAr measurement is needed). The ND-GAr-Lite reconstruction is based on a simple circle fit to the XY hits in each tracking station to measure the curvature of a track. The hit position uncertainty for the scintillator is simulated using a Gaussian distribution with $\sigma = 1$ mm for each direction in X and Y. The ND-LAr reconstruction is approximated using a momentum-by-range method, using the average energy loss in liquid argon, giving a resolution of about 3% or less. A basic energy loss correction is applied for the passive material between the active liquid argon in ND-LAr and the first tracking station in ND-GAr-Lite. The majority of the passive material is that of the cryostats of both ND-LAr and the ND-GAr-Lite magnet, with the primary materials being stainless steel and polyurethane insulation.

The momentum resolution and bias were determined by fitting a single Gaussian function to the fractional track residuals (defined in Eq. 1) as a function of the initial muon momentum.

$$\frac{\Delta p}{p} = \frac{p_{\text{reco}} - p_{\text{true}}}{p_{\text{true}}} \tag{1}$$

The results for the six-station arrangement where muons exited ND-LAr and were reconstructed in ND-GAr-Lite are shown in Fig. 13. Overall, the momentum resolution is below 4% for the majority of the momentum range and approaches a limit of about 2% as the momentum increases. The resolution is a bit worse below 1 GeV/c, with a maximum 6% resolution for the lowest energy muons that are reconstructed in ND-GAr-Lite. The momentum bias is relatively flat, between 1% and 2% for most of the momentum range, with a small apparent increase near 1 GeV/c. The low-momentum features in the bias and resolution plots are due to two main factors: the use of a fixed correction value for approximate energy lost in passive materials (which has a larger effect at lower momenta), and the simple ND-GAr-Lite reconstruction algorithm (which more often fits low-momentum tracks incorrectly due to their rapidly changing radius of curvature that is not well-approximated by a circle).

Figure 14 extends the result to lower momenta by also including muons that are contained within ND-LAr. For this combined sample of ND-LAr-contained and ND-LAr-exiting muons, the overall momentum resolution is still below 4% in all bins (right panel) along with a bias below 3% (left panel). The results shown here were obtained with an early stage of the ND-GAr-Lite reconstruction software along with approximations for the ND-LAr muon-range-based reconstruction and passive material energy loss corrections. Improvements in the resolution and particularly the bias are expected as the simulation and reconstruction are further developed. But the results shown here are already sufficient for DUNE's early physics goals.

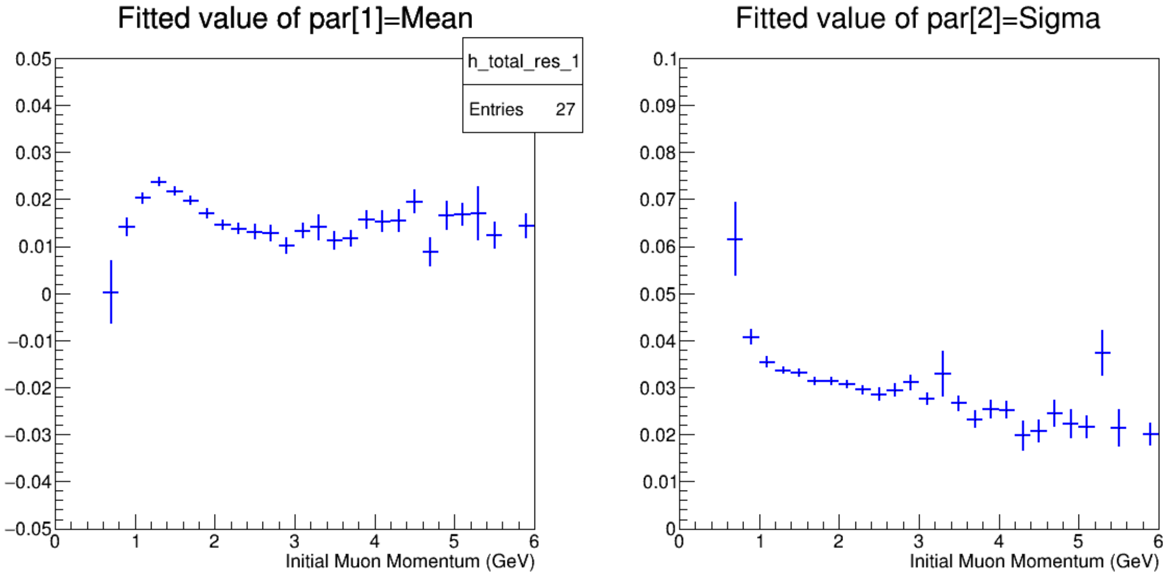


Figure 13: The fractional bias (left) and sigma (right) of the Gaussian fit for the momentum resolution as a function of the initial muon momentum for the six-station arrangement. This event sample only includes muons that exit ND-LAr and are reconstructed in ND-GAr-Lite.

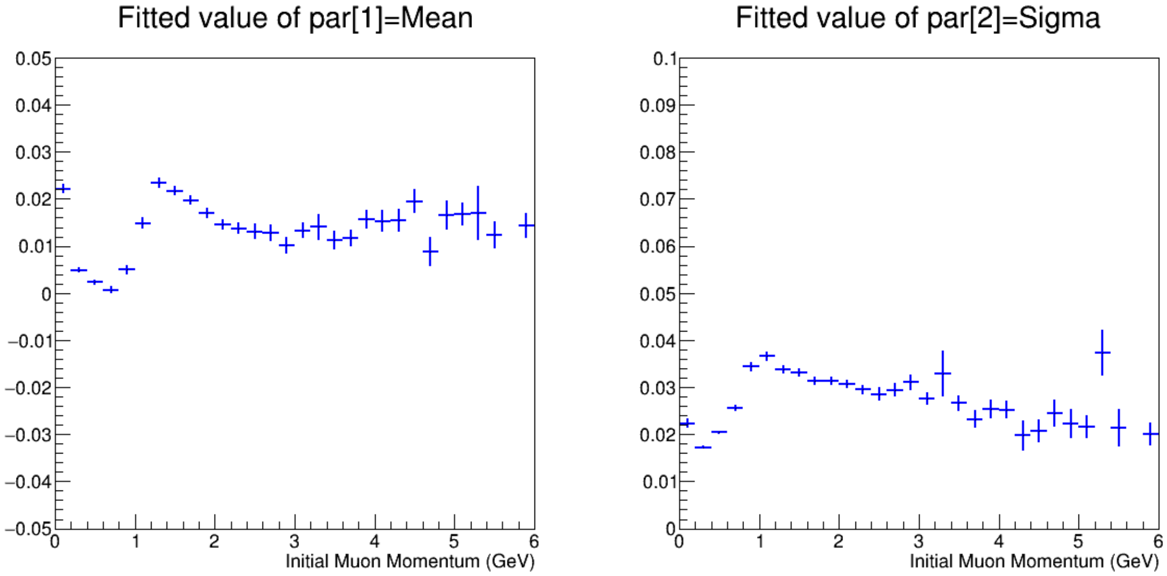


Figure 14: The fractional bias (left) and sigma (right) of the Gaussian fit for the momentum resolution as a function of the initial muon momentum for the six station arrangement. This event sample includes both muons that are fully-contained in ND-LAr and muons that exit ND-LAr and are reconstructed in ND-GAr-Lite.

6 Installation and Transition Plans

A preliminary installation plan for ND-GAr-Lite is presented, followed by the transition plans from TMS to ND-GAr or from ND-GAr-Lite to ND-GAr. Both transitions have the potential to be done at least partially during a 3-month summer shutdown, minimizing the amount of time that ND-LAr would operate without a functional muon spectrometer. In the case of ND-GAr-Lite, operation without a spectrometer can be nearly or entirely eliminated by staging the installation to occur during two consecutive summer shutdowns. In the first shutdown, the ECAL would be installed, and the scintillator tracker stations would be reconfigured inside. The experiment could run in this modified ND-GAr-Lite configuration for the next beam-on period, then during the subsequent shutdown the tracker stations would be removed and replaced by the HPgTPC. If the transition is scheduled to occur during a longer shutdown (1+ years), any of the transition scenarios mentioned above will fit within the shutdown period, eliminating all no-spectrometer data-taking.

In this document, we outline transition plans that are assumed to take place during what would otherwise be beam-on data-taking (i.e., not planned during a summer shutdown), thereby giving a pessimistic estimate of the amount of ND-LAr data that would be collected without muon spectrometry. These transition plans were developed with input from TMS experts (for removal of TMS) and from Mu2e magnet engineers (for durations and resources needed for ND-GAr magnet assembly and operational readiness review).

6.1 ND-GAr-Lite Installation

The majority of the ND-GAr-Lite installation process is dedicated to assembly and commissioning of the SPY magnet, which is described in detail in Ref. [?]. A brief overview is given below and summarized in Table 1.

The installation begins with placement of the Hilman rollers and cradles on the west rails in the ND Hall, followed by the lower half of the magnet return yoke steel. The magnet cryostat is then lowered down the shaft and into the hall. Special rigging is needed to rotate the cryostat into the correct orientation for the cradles. Once that is completed, the cryostat is lowered onto the lower yoke steel, secured, and aligned. The remaining steel for the barrel and end-ring yoke pieces are then installed. Next, the scintillator tracker modules are lowered into the hall and installed inside the volume defined by the inner diameter of the magnet cryostat. This process includes cable routing, connectivity tests, and an as-built survey of the tracker station locations. Once the tracker stations are in place and tested, the magnet yoke end-plates are installed.

Some of the magnet cryogenic system work will likely be able to take place in parallel with the magnet assembly, however, as a worst-case-scenario, is shown here in series with the other assembly work. The review documents for the operational readiness clearance are prepared also in parallel with previous tasks, but the review itself can only take place after the full assembly is completed.

Table 1: Preliminary installation plan for ND-GAr-Lite detector.

Task	**Duration (weeks)**	**Resources**	**Comments/Notes**
Install Hilmans and cradles on west rails	4	Riggers, Techs	
Install lower portion of steel yoke, align, secure with bolts	3	Riggers, Techs	
Stage rigging for craning-in cryostat, lowering into hall, removal of rigging	1-2	Riggers, Techs	Includes fixturing to rotate magnet after lowering into hall
Rig cryostat onto the lower yoke steel, secure, and align	4-8	Riggers, Techs	
Install remaining steel barrel yoke pieces	8	Riggers, Techs	
Stage scintillator tracker modules, lower into hall	1	Riggers, Techs	
Install scintillator tracker modules (including cable routing & connectivity tests)	2	Techs & uncosted sci	
Install rigging, install end yoke plates	4	Riggers, Techs	
Install magnet cryo system	8-16	Techs, Welder	Assumes all parts pre-staged and ready to go
Make system operational and pass ORC	16		Assumes review documentation prepared in parallel with previous tasks. Includes cryo, fringe field, gas system, ODH, high-pressure. Magnet cryo review estimate based on Mu2e DS.
Total downtime:			**51-64 wks. (13-16 mos.)**

6.2 ND-GAr-Lite to Full ND-GAr Transition

In planning the transition from ND-GAr-Lite to the full ND-GAr detector, we assume the starting point of a fully operational ND-GAr magnet instrumented with ND-GAr-Lite tracker plane stations described in previous sections.

In this scenario, the most straightforward transition to full ND-GAr would require removing the ND-GAr-Lite scintillator tracker stations in order to make way for ECAL and HPgTPC installation. The plan assumes that the ECAL modules (currently 12 barrel modules, and a number of endcap modules to be determined) are each assembled before lowering into the ND hall. The HPgTPC is similarly assumed to be built above ground, placed on a transport fixture shown in Fig. 15, and lowered into the hall. The remaining work to install the HPgTPC inside the magnet includes its insertion, and making all signal connections at their pressure vessel feedthroughs, as well as installing and aligning the laser calibration system. A significant fraction of the planned work is dedicated to operational readiness clearance reviews for the HPgTPC, including its gas and pressure systems, and the ECAL.

A high-level breakdown of the installation and commissioning tasks is shown in Table 2, assuming the full transition is done in a single pass.

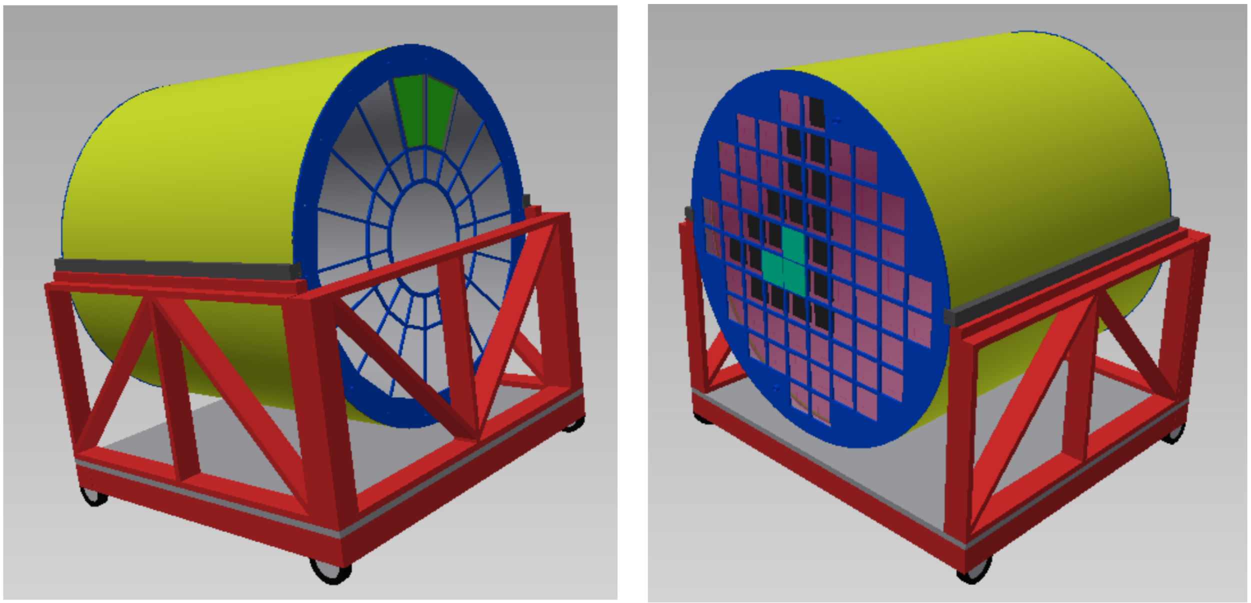


Figure 15: Concept of transport fixture for a fully-assembled HPgTPC, which will fit down a 38-foot diameter ND hall shaft.

6.3 TMS to Full ND-GAr

In planning the transition from TMS to the full ND-GAr detector, we assume that most of the work to assemble the magnet and install the detectors can be done while TMS is still operating.

A high-level breakdown of the installation and commissioning tasks is shown in Table 3. Task durations in parentheses are assumed to take place while TMS is still operating, and

Table 2: Transition from ND-GAr-Lite to full ND-GAr detector.

Task	**Duration (weeks)**	**Resources**	**Comments/Notes**
Remove end yoke plates	2	Riggers, Techs	
Remove ND-GAr-Lite tracker planes	1	Techs & uncosted sci labor	
Stage ECAL modules, lower into hall	1-2	Riggers, Techs	
Install ECAL (including cable routing & connectivity tests)	4	Riggers, techs, uncosted sci labor	
Crane HPgTPC (on transport fixture) into hall, stage for installation	1-2		
Install HPgTPC (including cable routing & connectivity tests)	8		
Install and align TPC laser system	2		
Install rigging, install end yoke plates	4		
Make system operational and pass ORC	8		Assumes review documentation was prepared in parallel with previous tasks. Magnet review not included, but does include reviews of gas system, ODH, high-pressure, etc.
Total downtime:			**31-33 wks. (~ 8 mos.)**

therefore do not contribute to beam operations without muon spectrometry; these tasks are not included in the "Total downtime" reported at the end of the table. As with the ND-GAr-Lite to ND-GAr transition, the ECAL modules and HPgTPC are assumed to be assembled before lowering into the ND Hall.

References

[1] **DUNE** Collaboration, A. Abed Abud *et al.*, "Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report," `arXiv:2103.13910 [physics.ins-det]`.

[2] **ALICE** Collaboration, G. Dellacasa *et al.*, "ALICE: Technical design report of the time projection chamber,".

[3] **CALICE** Collaboration, C. Adloff *et al.*, "Construction and Commissioning of the CALICE Analog Hadron Calorimeter Prototype," *JINST* **5** (2010) P05004, `arXiv:1003.2662 [physics.ins-det]`.

[4] **DUNE** Collaboration, R. Acciarri *et al.*, "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Conceptual Design Report, Volume 2: The Physics Program for DUNE at LBNF," `arXiv:1512.06148 [physics.ins-det]`.

[5] **DUNE** Collaboration, B. Abi *et al.*, "The DUNE Far Detector Interim Design Report Volume 1: Physics, Technology and Strategies," `arXiv:1807.10334 [physics.ins-det]`.

[6] **DUNE** Collaboration, B. Abi *et al.*, "Long-baseline neutrino oscillation physics potential of the DUNE experiment," *Eur. Phys. J. C* **80** no. 10, (2020) 978, `arXiv:2006.16043 [hep-ex]`.

[7] K. U. Abraamyan *et al.*, "The MPD detector at the NICA heavy-ion collider at JINR," *Nucl. Instrum. Meth. A* **628** (2011) 99–102.

Appendices

Table 3: Transition from TMS to full ND-GAr detector.

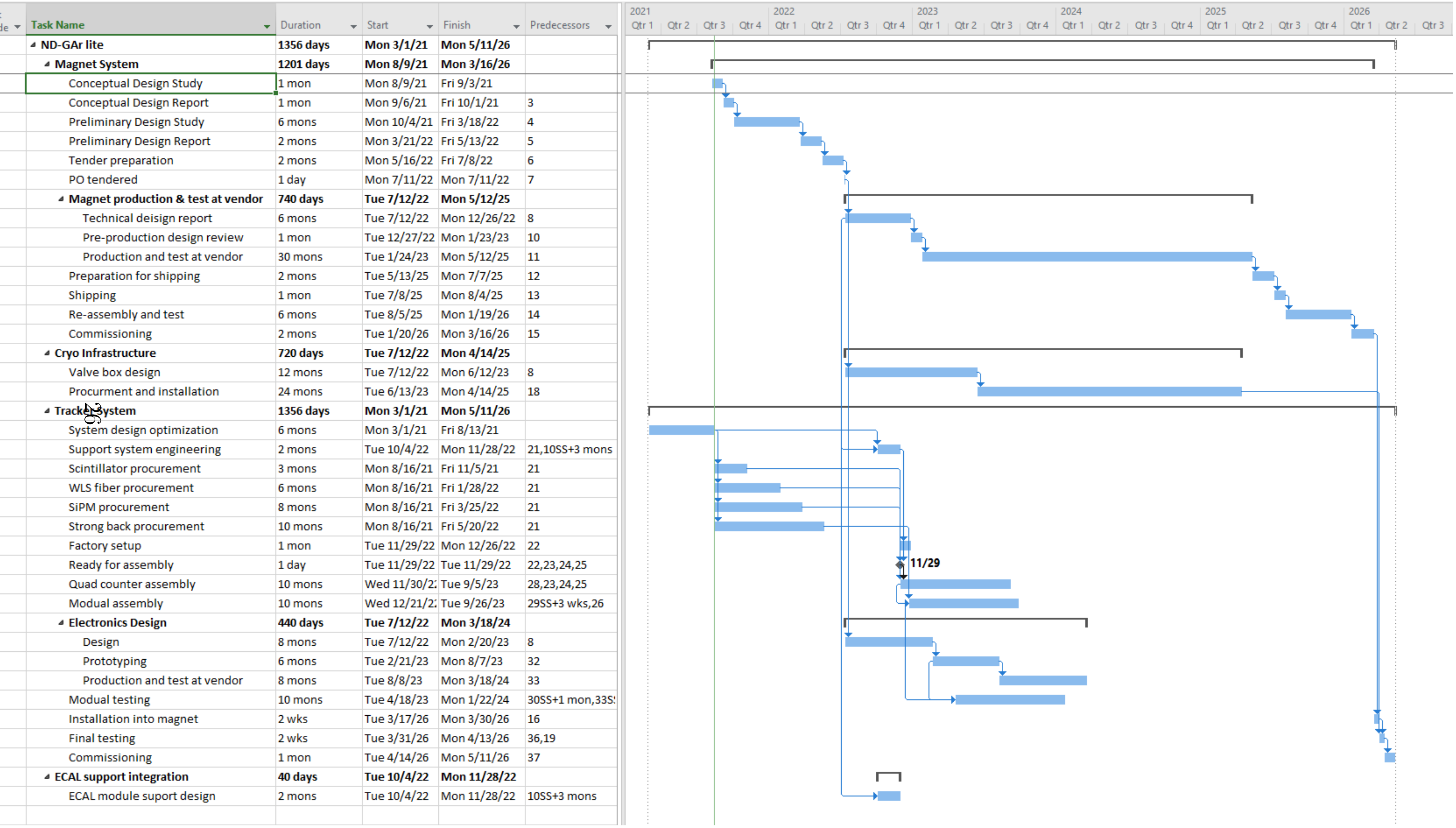
Task	**Duration (weeks)**	**Resources**	**Comments/Notes**
Install temp supports and cradles in staging area on west rails	(4)	Riggers, Techs	(TMS operating)
Install lower portion of steel yoke, align, secure with bolts	(3)	Riggers, Techs	
Stage rigging for craning-in cryostat, lowering into hall, removal of rigging	(1-2)	Riggers, Techs	Includes fixturing to rotate magnet after lowering into hall
Rig cryostat onto the lower yoke steel, secure, and align	(4-8)	Riggers, Techs	
Install remaining steel barrel yoke pieces	(8)	Riggers, Techs	
Stage ECAL modules, lower into hall	(1-2)	Riggers, Techs	
Install ECAL (including cable routing & connectivity tests)	(4)	Techs, uncosted sci	
Crane HPgTPC (on transport fixture) into hall, stage for installation	(1-2)	Riggers, Techs	
Install HPgTPC (including cable routing & connectivity tests)	(8)	Techs, uncosted sci	
Install and align laser system	(2)	Metrology	
Install rigging, install end yoke plates	(4)	Riggers, Techs	
Install magnet cryo system	(8-16)	Techs, Welder	Assumes all parts pre-staged and ready to go
Remove TMS (estimate from Tom L.)	3-6	Riggers, Techs	Current TMS design: must be in mid-off-axis position on west rails to remove 7 m magnet bus bars. Alternative TMS magnet design would reduce task duration.
Move Hilmans to ND-GAr, raise, remove temp supports. Move to south end of west rails.	2	Riggers, Techs	
Make system operational and pass ORC	16		Assumes review documentation prepared in parallel with previous tasks. Includes cryo, fringe field, gas system, ODH, high-pressure. Magnet cryo review estimate based on Mu2e DS.
Total downtime:			**21-24 wks. (5-6 mos.)**

A Cost and Schedule

A.1 SPY Magnet

We await a more detailed cost estimate from ASG Superconductors, which we expect to have in hand by the end of September 2021; we will update this appendix as soon as that information is available. ASG has provided a cost envelope of between 15M€ to 18M€ for the solenoid. A cost estimate of $3M USD has been provided by our colleagues in India for the return yoke iron sourced in India.

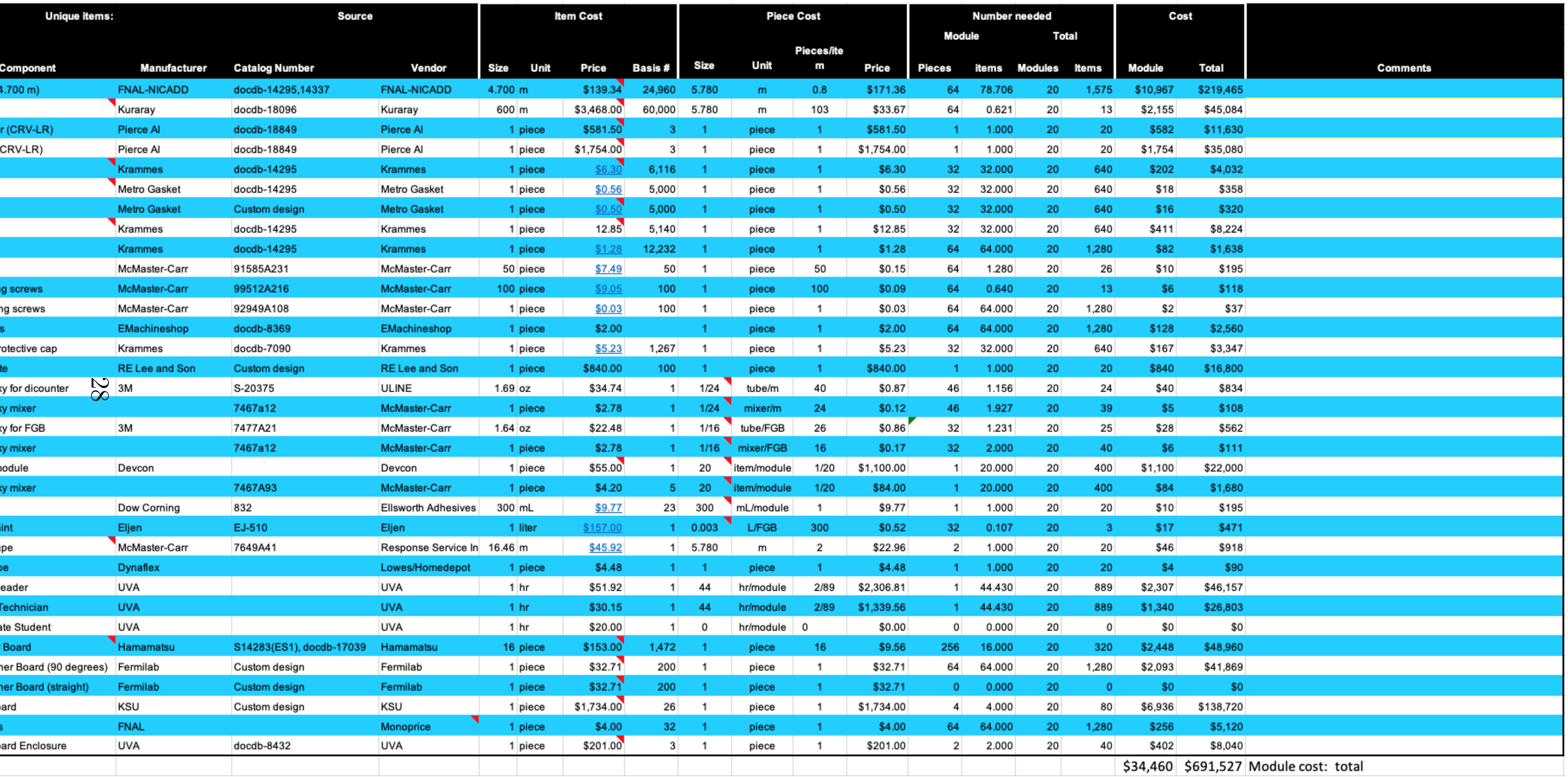
We have assembled preliminary schedule and data for SPY based on input from ASG Superconductors and on experience with previous magnet systems, shown in Fig. 16. Although this document represents the completion of the Conceptual Design Report task for the magnet system in the schedule, the rest of the dates in Fig. 16 should only be viewed in the context of durations, not actual start dates, since we do not know when a preliminary design study for the magnet system can be launched. and work will start on the scintillator tracker only after approval of ND-GAr-Lite.



Task Name	Duration	Start	Finish	Predecessors
ND-GAr lite	**1356 days**	**Mon 3/1/21**	**Mon 5/11/26**	
Magnet System	**1201 days**	**Mon 8/9/21**	**Mon 3/16/26**	
Conceptual Design Study	1 mon	Mon 8/9/21	Fri 9/3/21	
Conceptual Design Report	1 mon	Mon 9/6/21	Fri 10/1/21	3
Preliminary Design Study	6 mons	Mon 10/4/21	Fri 3/18/22	4
Preliminary Design Report	2 mons	Mon 3/21/22	Fri 5/13/22	5
Tender preparation	2 mons	Mon 5/16/22	Fri 7/8/22	6
PO tendered	1 day	Mon 7/11/22	Mon 7/11/22	7
Magnet production & test at vendor	**740 days**	**Tue 7/12/22**	**Mon 5/12/25**	
Technical deisign report	6 mons	Tue 7/12/22	Mon 12/26/22	8
Pre-production design review	1 mon	Tue 12/27/22	Mon 1/23/23	10
Production and test at vendor	30 mons	Tue 1/24/23	Mon 5/12/25	11
Preparation for shipping	2 mons	Tue 5/13/25	Mon 7/7/25	12
Shipping	1 mon	Tue 7/8/25	Mon 8/4/25	13
Re-assembly and test	6 mons	Tue 8/5/25	Mon 1/19/26	14
Commissioning	2 mons	Tue 1/20/26	Mon 3/16/26	15
Cryo Infrastructure	**720 days**	**Tue 7/12/22**	**Mon 4/14/25**	
Valve box design	12 mons	Tue 7/12/22	Mon 6/12/23	8
Procurment and installation	24 mons	Tue 6/13/23	Mon 4/14/25	18
Tracker System	**1356 days**	**Mon 3/1/21**	**Mon 5/11/26**	
System design optimization	6 mons	Mon 3/1/21	Fri 8/13/21	
Support system engineering	2 mons	Tue 10/4/22	Mon 11/28/22	21,10SS+3 mons
Scintillator procurement	3 mons	Mon 8/16/21	Fri 11/5/21	21
WLS fiber procurement	6 mons	Mon 8/16/21	Fri 1/28/22	21
SiPM procurement	8 mons	Mon 8/16/21	Fri 3/25/22	21
Strong back procurement	10 mons	Mon 8/16/21	Fri 5/20/22	21
Factory setup	1 mon	Tue 11/29/22	Mon 12/26/22	22
Ready for assembly	1 day	Tue 11/29/22	Tue 11/29/22	22,23,24,25
Quad counter assembly	10 mons	Wed 11/30/2	Tue 9/5/23	28,23,24,25
Modual assembly	10 mons	Wed 12/21/2	Tue 9/26/23	29SS+3 wks,26
Electronics Design	**440 days**	**Tue 7/12/22**	**Mon 3/18/24**	
Design	8 mons	Tue 7/12/22	Mon 2/20/23	8
Prototyping	6 mons	Tue 2/21/23	Mon 8/7/23	32
Production and test at vendor	8 mons	Tue 8/8/23	Mon 3/18/24	33
Modual testing	10 mons	Tue 4/18/23	Mon 1/22/24	30SS+1 mon,33S
Installation into magnet	2 wks	Tue 3/17/26	Mon 3/30/26	16
Final testing	2 wks	Tue 3/31/26	Mon 4/13/26	36,19
Commissioning	1 mon	Tue 4/14/26	Mon 5/11/26	37
ECAL support integration	**40 days**	**Tue 10/4/22**	**Mon 11/28/22**	
ECAL module suport design	2 mons	Tue 10/4/22	Mon 11/28/22	10SS+3 mons

A.2 Scintillator tracker

The schedule for the tracker is based on the experience from the Mu2e experiment, design of new electronics and recent prototyping work. We have costed the scintillator tracker for ND-GAr-Lite based on 300 m^2 of active detector area and the design discussed in Section 4. The component costs are based on vendor quotes, the labor is based on Mu2e "as-built" experience and uses university labor rates. The electronics costs are based on the Mu2e electronics. With a new design, we expect these costs to be reduced. No management overhead, contingency or escalation is included.



Unique items:	Source			Item Cost				Piece Cost				Number needed				Cost		
												Module		Total				
Component	Manufacturer	Catalog Number	Vendor	Size	Unit	Price	Basis #	Size	Unit	Pieces/item	Price	Pieces	items	Modules	Items	Module	Total	Comments
.700 m)	FNAL-NICADD	docdb-14295,14337	FNAL-NICADD	4.700	m	$139.34	24,960	5.780	m	0.8	$171.36	64	78.706	20	1,575	$10,967	$219,465	
	Kuraray	docdb-18096	Kuraray	600	m	$3,468.00	60,000	5.780	m	103	$33.67	64	0.621	20	13	$2,155	$45,084	
r (CRV-LR)	Pierce Al	docdb-18849	Pierce Al	1	piece	$581.50	3	1	piece	1	$581.50	1	1.000	20	20	$582	$11,630	
CRV-LR)	Pierce Al	docdb-18849	Pierce Al	1	piece	$1,754.00	3	1	piece	1	$1,754.00	1	1.000	20	20	$1,754	$35,080	
	Krammes	docdb-14295	Krammes	1	piece	$6.30	6,116	1	piece	1	$6.30	32	32.000	20	640	$202	$4,032	
	Metro Gasket	docdb-14295	Metro Gasket	1	piece	$0.56	5,000	1	piece	1	$0.56	32	32.000	20	640	$18	$358	
	Metro Gasket	Custom design	Metro Gasket	1	piece	$0.50	5,000	1	piece	1	$0.50	32	32.000	20	640	$16	$320	
	Krammes	docdb-14295	Krammes	1	piece	12.85	5,140	1	piece	1	$12.85	32	32.000	20	640	$411	$8,224	
	Krammes	docdb-14295	Krammes	1	piece	$1.28	12,232	1	piece	1	$1.28	64	64.000	20	1,280	$82	$1,638	
	McMaster-Carr	91585A231	McMaster-Carr	50	piece	$7.49	50	1	piece	50	$0.15	64	1.280	20	26	$10	$195	
g screws	McMaster-Carr	99512A216	McMaster-Carr	100	piece	$9.05	100	1	piece	100	$0.09	64	0.640	20	13	$6	$118	
ng screws	McMaster-Carr	92949A108	McMaster-Carr	1	piece	$0.03	100	1	piece	1	$0.03	64	64.000	20	1,280	$2	$37	
s	EMachineshop	docdb-8369	EMachineshop	1	piece	$2.00		1	piece	1	$2.00	64	64.000	20	1,280	$128	$2,560	
rotective cap	Krammes	docdb-7090	Krammes	1	piece	$5.23	1,267	1	piece	1	$5.23	32	32.000	20	640	$167	$3,347	
te	RE Lee and Son	Custom design	RE Lee and Son	1	piece	$840.00	100	1	piece	1	$840.00	1	1.000	20	20	$840	$16,800	
xy for dicounter	3M	S-20375	ULINE	1.69	oz	$34.74	1	1/24	tube/m	40	$0.87	46	1.156	20	24	$40	$834	
xy mixer		7467a12	McMaster-Carr	1	piece	$2.78	1	1/24	mixer/m	24	$0.12	46	1.927	20	39	$5	$108	
xy for FGB	3M	7477A21	McMaster-Carr	1.64	oz	$22.48	1	1/16	tube/FGB	26	$0.86	32	1.231	20	25	$28	$562	
xy mixer		7467a12	McMaster-Carr	1	piece	$2.78	1	1/16	mixer/FGB	16	$0.17	32	2.000	20	40	$6	$111	
nodule	Devcon		Devcon	1	piece	$55.00	1	20	item/module	1/20	$1,100.00	1	20.000	20	400	$1,100	$22,000	
xy mixer		7467A93	McMaster-Carr	1	piece	$4.20	5	20	item/module	1/20	$84.00	1	20.000	20	400	$84	$1,680	
	Dow Corning	832	Ellsworth Adhesives	300	mL	$9.77	23	300	mL/module	1	$9.77	1	1.000	20	20	$10	$195	
int	Eljen	EJ-510	Eljen	1	liter	$157.00	1	0.003	L/FGB	300	$0.52	32	0.107	20	3	$17	$471	
pe	McMaster-Carr	7649A41	Response Service In	16.46	m	$45.92	1	5.780	m	2	$22.96	2	1.000	20	20	$46	$918	
pe	Dynaflex		Lowes/Homedepot	1	piece	$4.48	1	1	piece	1	$4.48	1	1.000	20	20	$4	$90	
eader	UVA		UVA	1	hr	$51.92	1	44	hr/module	2/89	$2,306.81	1	44.430	20	889	$2,307	$46,157	
Technician	UVA		UVA	1	hr	$30.15	1	44	hr/module	2/89	$1,339.56	1	44.430	20	889	$1,340	$26,803	
ate Student	UVA		UVA	1	hr	$20.00	1	0	hr/module	0	$0.00	0	0.000	20	0	$0	$0	
Board	Hamamatsu	S14283(ES1), docdb-17039	Hamamatsu	16	piece	$153.00	1,472	1	piece	16	$9.56	256	16.000	20	320	$2,448	$48,960	
ner Board (90 degrees)	Fermilab	Custom design	Fermilab	1	piece	$32.71	200	1	piece	1	$32.71	64	64.000	20	1,280	$2,093	$41,869	
ner Board (straight)	Fermilab	Custom design	Fermilab	1	piece	$32.71	200	1	piece	1	$32.71	0	0.000	20	0	$0	$0	
oard	KSU	Custom design	KSU	1	piece	$1,734.00	26	1	piece	1	$1,734.00	4	4.000	20	80	$6,936	$138,720	
s	FNAL		Monoprice	1	piece	$4.00	32	1	piece	1	$4.00	64	64.000	20	1,280	$256	$5,120	
oard Enclosure	UVA	docdb-8432	UVA	1	piece	$201.00	3	1	piece	1	$201.00	2	2.000	20	40	$402	$8,040	
																$34,460	$691,527	Module cost: total

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

22 June 2021

Dear Alan and Alfons:

LBNC and other review committees have recognized the importance of ND-GAr and its measurement program in fulfilling DUNE's goal of definitive measurements of CP violation in neutrino oscillations. However, the resources to realize the full detector in the initial phase of DUNE remain unrealized, which has led to a temporary muon spectrometer (TMS) placed in the baseline configuration to serve the critical task of muon momentum measurements for neutrino interactions in ND-LAr during the initial phases of the experiment. While the LBNC has endorsed this approach, the current TMS concept does not provide elements that would be used in ND-GAr. It is recognized that a path which initially places components that would eventually become part of ND-GAr would be preferable. This has led to the ND-GAr-Lite concept, in which the role of TMS is fulfilled by installing a muon tracking system within the ND-GAr magnet which could be realized with reduced resources relative to the full ND-GAr concept. The magnet could eventually house a high-pressure gas argon TPC, calorimeter, and other components that comprise the "full" ND-GAr detector.

We would like to charge the ND-GAr proto-consortium to produce a conceptual design report for ND-GAr-Lite that contains:

- A conceptual design for ND-GAr-Lite describing the detector elements and its performance, conforming to the known constraints from other DUNE ND subsystems and related infrastructure.
- A transition plan, accounting for technical development and the expected and necessary resource availability, that would lead to the full ND-GAr detector. The plan should lay an explicit timeline for key developments that accounts for the physics needs of DUNE and its expected operational cycle in terms of beam exposure, potential shutdowns, and the logistics necessary to deliver and install/replace components.

The documentation is essential for planning and as a reference for a number of audiences and stakeholders, including the DUNE collaboration and relevant funding agencies. We suggest that you appoint an editorial team to oversee the writing of this report. We request that an initial complete draft of the document be completed by 15 September for distribution within the DUNE management.

Faithfully,

Regina Rameika

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Fermi National Accelerator Laboratory
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