Proposal for continued ANL involvement in the Deep Underground Neutrino Experiment

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Argonne has a long history of leadership and success in the field of neutrino physics, from the operation of the ZGS to the establishment of a long-baseline neutrino physics program at Fermilab. More recently
ANL has contribute in myriad ways to the realization of DUNE, including: 1) Successful work in Cathode plane construction and integration for ProtoDUNE, 2) Successful work on photon detector readout system fabrication, installation, and operation, 3) Continued coordination of test-beam calibration and analysis, 4) Michel electron identification studies in ProtoDUNE, 5) A comprehensive nucleon decay mode study, 6) Experience with ND to FD extrapolations in NOvA, and 7) Stopping muon calibration efforts in MINOS and NOvA.

Argonne scientific interest totally matches the primary goal of DUNE, to measure the size of leptonic CP violation, with secondary goals of continuing the search for nucleon decay and observing neutrinos from a galactic supernova should one occur during the lifetime of DUNE. Crucial to all of these goals is a detailed understanding of the energy response of the DUNE Liquid Argon TPC. Our program through quality control and calibration will control and measure non-uniformity of the electric field. We will seek to exploit the possible complementarity of ionization and photons from PDS in improving the resolution of the energy measurement and minimizing the bias of the central value. A detailed analysis of Michel electrons in ProtoDUNE-SP is already underway with relevance to t entire physics program: neutrino oscillation, supernova neutrinos, and nucleon decay.

In the attached document, we present a summary of 1) the science opportunities of our continued involvement in DUNE, 2) plans for continued involvement in the high voltage system (HVS), 3) plans for continued involvement in the photon detector system (PDS), 4) A proposed laser calibration system, and 5) an opportunity for contributions to DUNE computing needs using high performance computing (HPC) resources at ANL. A timeline focusing on short-term involvement is included.

In its previous HEP projects, ANL has been able to find synergies throughout its large multi-purpose laboratory, such as engineering, computing and scientific resources, that contribute to the success of the U.S. High Energy Physics program. Just one example is our engineering studies on the NOvA plastic structures during a year during which most other work on NOvA came to a halt. Continued access to similar resources will be a valuable benefit for DUNE as it becomes the highest priority U.S. HEP project.

**ANL Contributions to DUNE Science**

**Opportunity:** The primary focus of the DUNE science program is to address the fundamental open questions in particle physics and astroparticle physics to determine if there is CP-violation in the lepton sector. The ANL science and research goal is to maximize the sensitivity to CP-violation with a combination of improved energy reconstruction and optimized event classification. Measurement of the CP-violation phase requires determination of the electron neutrino and antineutrino spectra, as measured from charged-current reactions with electrons or positrons in the final state. Our vision is to improve understanding of the neutrino spectrum by removing distortions from detector effects, through time projection chamber (TPC) laser calibration, and with a photon detector system (PDS) calibration/monitoring system, and through analysis which is central toward realizing this goal. Energy resolution effects smear the signal over all neutrino energies, washing out the oscillation features. We will explore the possibility of improving the accuracy of the energy scale by combining the measurements from the TPC with those from the PDS.

**ANL Contribution:** The ANL research program is focused on improving physics sensitivities using energy scale calibration and energy reconstruction that combines collected TPC charge with measured PDS light (with information on event timing and number of observed photons). The proposed technical contributions include 1) HVS (to provide efficient charge collection), 2) Laser Calibration (to reduce energy scale systematics from electric field non-uniformities), and 3) a PDS calibration system (to monitor the PDS stability in terms of gain, time-resolution, light collection efficiency, and linearity). The overall research focus builds upon ANL’s prior roles in successful construction, operation, and data analysis in ProtoDUNE-SP. In LAr, individual particle tracks ionize and some of the ions recombine with ionized electrons, producing prompt photons, whereas the non-recombined ions and electrons are collected by the TPC. Use of the light from recombination combined with collected charge has been shown to improve overall energy resolution in experiments like EXO, by more than 10%, with potentially larger impact in LAr DUNE. Our research program proposes to utilize calibration techniques that are being developed by ANL with ProtoDUNE data, such as Michel electrons, through-going muons and test beam particles to improve physics sensitivities. The computing will be used to optimize event classification to maximize the electron-neutrino electron efficiency. In particular, we propose to benchmark “baseline” CNN techniques, by utilizing expertise and capabilities in High-Performance Computing, against conventional data-flow/H-matrix algorithms.

**Deliverables:** (1) Energy calorimetry using event tracks (TPC) and recombination photons (PDS), with the goal to measure the lepton energy deposition with a bias less than 1%. (2) Particle identification based on calorimetric and track reconstruction.

**Impact:** The Argonne group will strengthen the DUNE physics program with improved physics sensitivities through energy calibration and energy scale reconstruction, using beam particle and cosmic muon data from ProtoDUNE-I and ProtoDUNE-II. Argonne will apply our knowledge developed with the ProtoDUNE energy scale calibration to the DUNE analysis. The ANL group will enable improvements in particle identification through data processing with advanced HPC algorithms. ANL will collaborate with international and US collaborators within the Calibration, PDS, and Analysis/Reconstruction groups as a framework to lead to improved energy measurement and to help provide a more significant CP-violation result.

**Estimated effort**: Activities 1) - 2) will be staged, with a constant 1 FTE scientist and 1 FTE postdoc, starting in 2020 and continuing through DUNE Science phase. The scientist and postdoc science efforts are split with technical roles in HVS, PDS, Laser Calibration, and Computing areas.

**ANL Technical and Scientific Contributions for the DUNE High Voltage System (HVS)**

**Opportunity:** Building on our successful production, installation and operation of the Cathode Plane Assembly (CPA) for ProtoDUNE SP, Argonne will continue work on the DUNE HVS. The DUNE work performed at Argonne has been and will be a collaboration of the Experiments, Operation, and Facilities (EOF) Division and the HEP Division. In addition, the HVS work at Argonne will be conducted as part of a strong collaboration with the CERN and BNL HVS consortia leadership.

**Argonne Contributions:** Argonne proposes to continue to contribute to two engineering and construction projects.

Argonne will work closely with the HVS Consortia leadership to:

* Provide lead engineering support including stress analysis, model creation, and fabrication drawings of the HV system. (Guarino is the Lead Mechanical Engineer for the HVS)
* Coordinate production scheduling for the TPC HV components for the first 10-kt DUNE SP detector.
* Coordinate the shipping of TPC HV components from the factories to SURF.
* Lead the QA/QC planning and implementation for the entire HVS. This includes development of factory requirements, production procedures and QC checklists for multi-factory CPA/FC/EW manufacture
* Writing and editing of all CPA-related text in the DUNE TDR HV section
* Be a factory for CPA production, producing ~half of the 100 CPA Panels and the special end Panels needed for the first 10-kt DUNE SP TPC

Building on the engineering support provided to the protoDUNE DSS, Argonne will work closely with the DUNE Technical Coordination and the SURF Integration Project Office to:

* lead the engineering design of the Detector Support Structure (DSS)
* Perform all required analysis of the DSS
* Insure integration of the DSS with the cryostat and detector
* Oversee the fabrication of the DSS and delivery to SURF

**Estimated effort** ANL Personnel: Steve Magill – Project Physicist (HEP), Vic Guarino – Project Engineer (EOF Division), Ken Wood – Engineering Assistant (HEP), Frank Skrzecz – Engineering Assistant (HEP)

**ANL Technical and Scientific Contributions with Photon-Detection System (PDS)**

**Opportunity:** The ANL research program is focused on improving physics sensitivities using energy scale calibration and energy reconstruction that combines collected TPC charge with measured PDS light. An important aspect in understanding the detector response is the inclusion of timing and calorimetry information from the PDS. With the DUNE TDR requirements for increased PDS light yield, there is now an opportunity to explore whether the PDS can also be used to directly measure the energy calorimetrically, working as a cross-check to the energy measured by the TPC or improving the resolution when both measurements are used together. Achieving this goal puts stringent requirements on the calibration of PDS gain and its timing. The requirements for measurement and monitoring of the gain, time-resolution, the light collection efficiency and linearity are currently studied with collected ProtoDUNE data.

**Argonne Contributions:** Within the DUNE PDS Consortium, Zelimir Djurcic (ANL Scientist) is co-convener of the DUNE PDS Electronics and Calibration Working Group (WG) with a charge to optimize the PDS readout for DUNE and to enable international collaborators from Latin America to fabricate ~6,000 readout channels for the DUNE FD. The group has provided major input for the TDR chapters on PDS Readout, Calibration, and ProtoDUNE-SP. The ANL PDS focus on DUNE will be on the design and delivery of ~150 PDS Calibration and Monitoring channels for the 10-kt FD, including the optical, mechanical, and electronics components. ANL currently leads the PDS data analysis effort to fully characterize the ProtoDUNE-SP PDS and to transfer this expertise to the FD. Zelimir Djurcic is co-convener of DUNE’s ProtoDUNE Analysis and Operations WG. Aleena Rafique (ANL Postdoc) operated the PDS at CERN in the beam data-taking phase; she now leads the analysis of Michel electrons from stopping muons at ProtoDUNE-SP. The progress and results from the activities above have been presented at DUNE meetings, reviews (such as the recent 30% review), and at workshops. The short-term goal is to provide results on the ProtoDUNE-SP PDS performance needed to complete the TDR.

**Deliverables:** ANL will deliver the photon-detector calibration and monitoring system, consisting of electronics and optomechanical components, to operate over 20+ years.We will follow the technical steps as listed in PDS WBS: 1) Calibration/monitoring reviews. 2) Verification of the design through ProtoDUNE data collection and analysis. 3) Final selection and verification of materials for the flasher monitoring system. 4) Final pre-production prototype fabrication and testing. 7) Procurement and testing of the PDS monitoring/calibration electronics components. 8) Fiber cables and feedthrough Fabrication/Procurement. 9) QA/QC tests of the monitoring/calibration system (optical fibers, diffusers, LED drivers) for one 10-kt detector. 10) Monitoring/system production and delivery.

**Impact:** ANL will work with US and Latin American colleagues to contribute to the design, fabrication, and delivery of the PDS calibration/monitoring system components. We will further explore synergies with the proposed Laser Calibration System, and if the laser could be used in a joint TPC/PDS time calibration. The combined studies of charge and light-based energy reconstruction will improve the measurement of the neutrino spectra. Our involvement in the deployment of the PDS in ProtoDUNE-SP is key to success in updating the design and performing relevant analyses. Use of the scintillation light combined with collected charge has been shown to improve overall energy resolution in experiments like EXO by more than 10%, with a potentially larger impact in DUNE.

**Estimated effort**: We estimate that throughout the DUNE FD commissioning (2020-2025) we will require 0.75 FTE of physicist leading the PDS efforts together with 0.75 FTE postdoc, and 0.5 FTE engineer. We assume that this work is to be performed in collaboration with university groups who will assist in testing, QA/QC, integration, installation, and analysis efforts.

**ANL Technical and Scientific Contributions with Laser Calibration System**

**Opportunity:** A detailed understanding of the DUNE detector response is essential to achieve its physics goals. An important aspect in understanding its response is bias in the lepton energy scale. The draft DUNE Physics TDR (Section 4.4.1.1) indicates that a 1% bias in the lepton energy scale is significant for the sensitivity to CP-violation. To meet these requirements, the overall electric field distortion should be kept below 1%. With the electric field inhomogeneities in the DUNE detector expected to be up to 4%, a dedicated calibration laser system is required to provide an independent, fine-grained measurement of the E-field in space and time in order to reduce the E-field induced bias below1%. A UV-laser creates straight ionization tracks in LAr, and allows one to map the drift field along different paths in the TPC drift volume to evaluate space charge effects and detect other E-field non-uniformities. The energy and position reconstruction requirements for the physics measurements in DUNE translate into an E-field precision of <1%, an E-field measurement coverage of >75%, and an E-field measurement granularity in < (10 cm)3 voxels.

**Argonne Contributions:** The ANL group proposes to design, produce, and operate the laser calibration system that meets the requirements listed above. With our expertise and involvement in ProtoDUNE-SP, we propose to add optical feedthroughs at the top of the cryostat, install the beam transport system within the cryostat, and test a prototype of the laser system in the ProtoDUNE-SP phase II. Additional testing and final development of the full system for DUNE will follow and lead into fabrication and installation. The design of the laser system will be led by Dr. Zelimir Djurcic (a placeholder) in a close international collaboration with members of the recently formed DUNE Calibration Consortium. The ANL mechanical group is key for development of a successful system, due to their extensive experience in designing, prototyping, testing, fabrication, integration, and commissioning of large detector structures, including the areas of precision mechanics and motion control systems. ANL scientists and engineers have led and deployed calibration efforts in the Double Chooz experiment, and fabricated precise trolley systems with dimension/position tolerances of a few mm to precisely map B-fields. We have capabilities to fabricate beam steering and control systems with a positioning accuracy of the APA wire pitch (< 5 mm) over a 10-20 m distance to insert the laser beam unobstructed, through the field cage profiles. The ANL AWA team operates an NdYAG laser, which can be used during the prototyping phase, and they will provide operational expertise and safety instructions. ANL engineers lead the DUNE FD detector support structure (DSS) and will be indispensable in laser design and installation efforts.

**Deliverables:** ANL will deliver a new laser calibration system for DUNE. The system will consist of an NdYAG laser installed above the cryostat. The system will include optics to reflect the laser beam into the cryostat, optical feedthroughs with a mounting structure for a steerable mirror, and precision motion control systems. In the design phase we will address the challenges that include the mechanical systems to aim its laser into the drift volume, either through field cage gaps or with laser periscopes that penetrate all the way through field cage sections. These solutions require precise mechanics for accurate beam positioning, and a cryogenic operation over the extended lifetime of 20+ years. We will present the design for review with comparisons to an alternate design, and build and deploy the system in ProtoDUNE-SP-II as prototype test for DUNE. In parallel with our work on the PDS, we will study the feasibility of laser operation with the proposed PDS system. Argonne will lead the development of laser calibration run plans for ProtoDUNE (and later for DUNE), operate the laser system, and analyze the data.

**Impact:** E-field measurement is a key limiting detector systematic to the CP-violation measurement. The ANL goal is to design a hardware laser system and software analysis which will realize energy scale uniformity better than 1% through the TPC, and to demonstrate this in ProtoDUNE-SP phase II. ANL will enable participation of international collaborators to work on the laser calibration. The ANL laser calibration effort has potential synergies with Argonne’s photon-detector system calibration/monitoring, and we will study the impact of the laser system on PDS operation and performance. The combined studies of charge- and light-based energy reconstruction will improve the measurement of the CP violating phase, by reducing systematics in the measured lepton energy scale. Our current involvement and deployment of the system in ProtoDUNE-SP is a key for our success in designing a system and performing relevant analyses. Therefore, the ANL group has proposed a well-rounded DUNE calibration program tied to energy reconstruction that motivates all three DUNE science drivers.

**Estimated effort**: We estimate that throughout the DUNE FD commissioning (2020-2025) we will require 0.75 FTE of physicist leading the laser system together with 0.75 FTE postdoc, and 0.5 FTE engineer. We assume that this work is to be performed in collaboration with university groups who will assist in testing, QA/QC, integration, installation, and analysis efforts.

**Argonne Technical and Scientific Contribution to DUNE computing**

**Opportunity:** The experiment, as already described in the draft TDR, will have very large computing and data handling needs, for real data as well as simulation needs that most likely will exceed the funding that OHEP will have available for computing for DUNE. One possible way to address this, and may be the only way, is to use computing resources that are available in DOE Office of Science High Performance Computing (HPC) centers supported by ASCR. Argonne is one of these centers and the HEP division at Argonne has used these resources successfully in the ATLAS experiment, where now large simulations, not possible anywhere else, are run on Argonne ALCF computing. The Computational Cosmology group at Argonne extensively uses the ALCF (as well as other HPC computing centers) at Argonne for their science and with that comes a deep expertise in using these novel and different computing architectures.

**Argonne Contributions:** The Argonne group proposes to be a gateway to enable access to HPC computing (currently existing as well as future Exascale resources) at Argonne by bringing together expertise from different divisions at Argonne to develop and provide frameworks and code that will enable DUNE simulation and analysis code to run on current and future HPC platforms at Argonne. In addition to HPC platforms there is also a large number of more conventional computing available at Argonne, if Argonne continues in DUNE. Within the ATLAS collaboration at the LHC, members of the HEP division together with colleagues from ALCF, paved the way for enabling the running of ATLAS simulations on ALCF. This resulted in some publications which would not have been possible without the use of HPC resources.

**Deliverables:** Although exact deliverables are not well defined currently, Argonne DUNE collaborators can play an essential, critical and coordinating role in defining the needs of the DUNE experiment and help bring HPC resources which will be needed to execute the science program of the collaboration.

**Impact:** The computing needs of the HEP program in the US, including LHC and DUNE, are much larger than the computing budget of DOE HEP. In order to do all the anticipated science with DUNE, new computing resources need to be identified. These resources exist in terms of current and future HPC ASCR machines, but they require additional resources to write the code that can be executed on these different and advanced computing architectures. Planning early to use these HPC resources, will allow faster and more precise results from DUNE.

**Estimated effort**: We estimate that initially 0.5 FTEs will be required for the first two years, then ramping up to at least 1 FTE.

