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

**Opportunity:** A detailed understanding of the overall detector response is essential to achieve the DUNE physics goals. An important aspect in understanding the detector response is the bias of the lepton energy scale. The DUNE Physics TDR (Section 4.4.1.1) indicates that a 1% bias in the lepton energy scale is significant for the LBL sensitivity to CP-violation. To meet these requirements, the overall electric field distortion should be kept at 1% level. 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 precision 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 in the DUNE Far Detector (FD) TPC. 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 groups are a key for success due to their extensive experience in designing, prototyping, testing, fabrication, integration, commissioning of large detector structures, including areas of precise 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 few mm among other achievements. We have capabilities to fabricate beam steering and control systems with a positioning accuracy of <5 mm over a 10-20 mm distance to insert the laser beam unobstructed, trough the field cage profiles. In addition, the ANL AWA team already operates a NdYAG laser which can be used during the prototyping phase.

**Deliverables:** ANL will deliver a new laser calibration system for DUNE. The system will consist of a NdYAG laser installed above the cryostat. The system will include optics to reflect the laser beam into the cryostat, optical feed-throughs 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 laser tracks into the drift volume, either through field cage gaps and/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. ANL will review proposed the TDR baseline and alternate designs and will design a prototype the laser calibration system. We will present the design for reviews and build the system and deploy it in ProtoDUNE-SP-II. In parallel with our work on the Photon Detection System (PDS), we will also 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 as input to the physics analysis.

**Impact:** ANL will provide a laser system that allows measurement of the E-field in the DUNE TPC so that impact of the E Field on the energy scale calibration is less than 1%. ANL will enable participation of international collaborators to work on the laser calibration. The ANL laser calibration effort has synergy with Argonne’s photon-detector system calibration/monitoring. The combined studies of charge- and light-based energy reconstruction will improve the measurement of the CP violating phase. 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 0.60 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.