1.6 Prototyping Plans

The prototyping plan for the ND LArTPC detector will address a specific set of technical targets between now and the initiation of detector production. Prototyping activities fall into two categories: component-level and integration-level prototyping. Component prototyping targets specific risks with the core ND-LAr technologies: charge readout, light readout, and such. It is primarily addressed via stand-alone small-scale tests, and the majority of these tests have been completed over the recent years of the ArgonCube R&D program, achieving Technological Readiness Level 4 (TRL-4). Integration prototyping addresses risks with interfaces, with TPC assembly processes and procedures, as well as some residual technical risks related to how these components come together and function coherently within the ND LArTPC design.

There are five stages to the integration prototyping plan: the SingleCube Demonstrator, the ArgonCube Module 0 Demonstrator, the ArgonCube 2x2 Demonstrator, the subsequent ND-LAr Full-scale Demonstrator, and the ND-LAr Module Row Prototype.

1. The **SingleCube Demonstrator** was a ∼30-liter fully-functional LArTPC designed to validate the integrated performance of the ND prototype charge and light readout elements in a field cage of similar mechanical design as the ND (TRL-5). This has been completed in 2020.

2. The **ArgonCube Module 0 Demonstrator** was a single 0.8-ton sub-scale LArTPC detector module that verified the technical readiness of the ND LArTPC module design (TRL-6) before the completion of the ND preliminary design phase. This has been completed in 2021.

3. The **ArgonCube 2x2 Demonstrator** is a detector composed of four sub-scale LArTPC modules (following the ArgonCube Module 0 design) to be operated in the NuMI neutrino beam in order to validate the neutrino signal reconstruction capabilities in advance of finalizing the ND-LAr design for the FDR (partial TRL-7, for detector performance). The prototype construction is well underway and final installation planned for the Fall of 2022.

4. The **ND-LAr Full-scale Demonstrator** is a production-scale LArTPC module that will provide an engineering validation of the full-scale component production, assembly, and testing processes (complete TRL-7) before the conclusion of detector design for the FDR.

5. The **ND-LAr Module Row Prototype** is an integration prototype consisting of five production-scale LArTPC modules integrated to a prototype segment of the ND-LAr Cryostat lid, with the goal of validating the ND-LAr production and installation processes in advance of the ND-LAr PRRs.

Fig. 1.73 shows each of these prototypes.

1.6.1 SingleCube Demonstrators

The SingleCube Demonstrator was a response to COVID-19 travel restrictions that prevented international partners from traveling to our primary prototyping site at the Univ. of Bern. The TPC has a drift length and mechanical interfaces identical to the 2x2 module, but is sized to

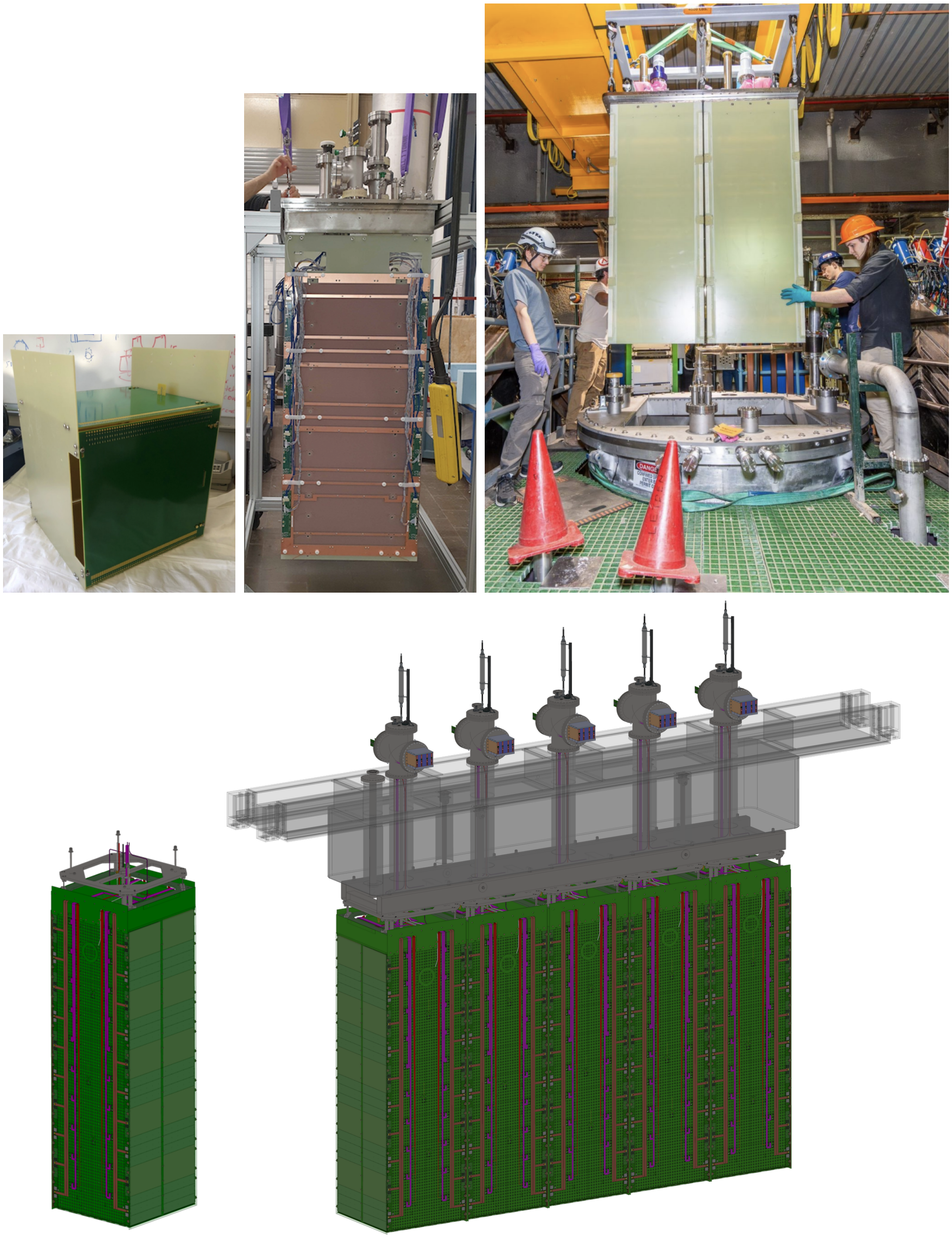

Figure 1.73: (Top, Left) The SingleCube LArTPC designed to test a single integrated large-format charge and light readout element. (Top, Center) The mechanical assembly of the first mid-scale TPC module (Module 0), including the cathode, field cage, and anode support panels. The module is a sub-scale prototype of the ND LArTPC module, at 70% drift length and 40% module height. (Top, Right) Installation of the four mid-scale TPC modules comprising the ArgonCube 2x2 Demonstrator. (Bottom, Left) The engineering model of the full-scale ND LArTPC module (1 m by 1 m footprint and 3.5 m height). (Bottom, Right) The Module Row Assembly, consisting of five full-scale modules integrated to a segment of the ND-LAr Cryostat lid.

support only one pixel readout tile and one light readout element (see Fig. 1.74). This facilitates an integrated test of the active detector elements in a smaller liquid argon cryogenic system in advance of their installation in the larger ArgonCube Module 0 Demonstrator. Instead of using a field cage based on high-resistivity polyamide film, it relies on a more conventional PCB-based field cage with discrete resistors, easily produced during the pandemic-induced curtailment of activities. Operation of a SingleCube TPC at Bern in Oct. 2020 provided the first integrated test of the ND LArTPC readout system, successfully imaging cosmic rays and operating stably over the planned week-long run. This test retired multiple risks associated with TPC component interfaces and performance targets such as system noise (<1000 e$^-$ ENC), LAr purity (>500 μs), as well as HV field strength (1 kV/cm) and stability (see Fig. 1.75). Five copies of the SingleCube TPC were built at LBNL and distributed to partner institutions for further system testing and refinement.

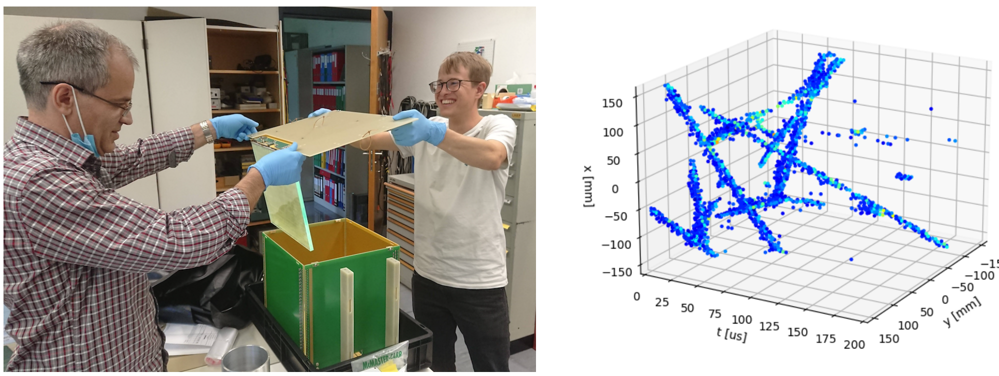

Figure 1.74: (Left) Installation of a LArPix tile and ArCLight panel assembly into the SingleCube TPC at the Univ. of Bern. (Right) An overlay of the raw data from 8 typical cosmic ray events collected during the first SingleCube operation in Oct. 2020.

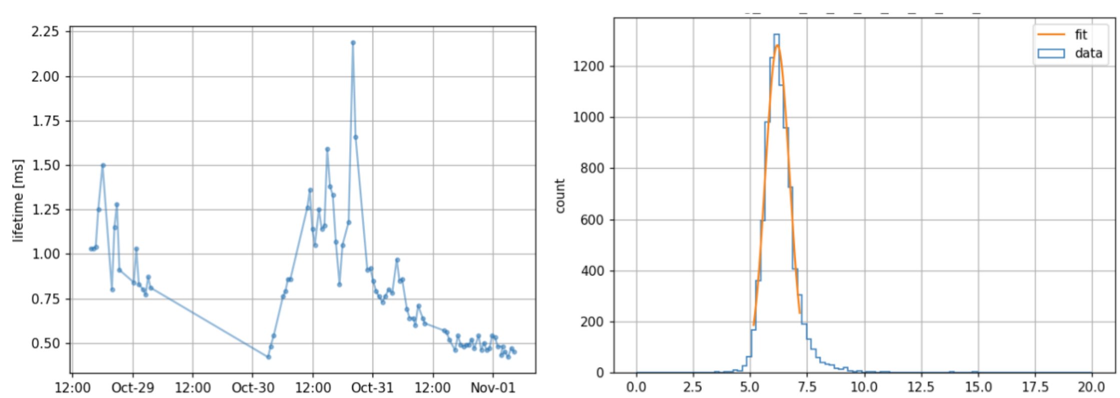

Figure 1.75: (Left) The electron lifetime measured using anode-cathode crossing cosmic ray muon tracks during the first operation of the SingleCube TPC (Right) The distribution of muon energy loss in LAr is consistent with that expected for cosmic ray muon tracks.

1.6.2 ArgonCube Module 0 Demonstrator

The ArgonCube Module 0 Demonstrator was a test of a single LArTPC module of the ND-LAr design, hosting 16 pixel tiles and 16 light readout elements, and was the first to use the resistive-film-based field cage and cathode. The TPC module had a footprint of 0.7 m by 0.7 m, and was roughly 1.4 m tall, as shown in the center panel of Fig. 1.73, with an active mass of roughly 0.8 tons of argon. With 70% of the width and 40% of the height of the ND-LAr module, the Module 0 demonstrator provided a realistic, albeit sub-scale, test of many aspects of the design. Fig. 1.76 shows the details of Module 0.

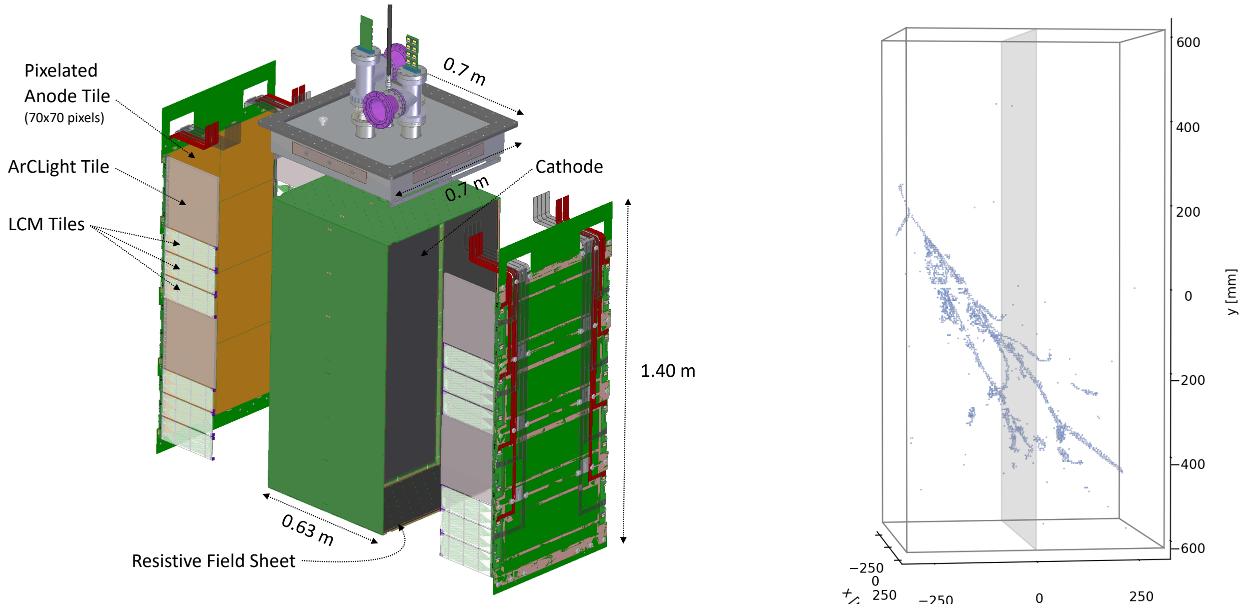

Figure 1.76: (Left) A schematic of the ArgonCube Module 0 Demonstrator (Right) Raw 3D data from a typical cosmic ray interaction in Module 0.

The Module 0 Demonstrator was operated twice fully-equipped: an initial run for 8 days in April 2021, and a subsequent run for 4 days in June 2021. An additional run in November 2020 served as test-bench for the High Voltage and field system. All of these runs were successful. They consisted of installation and operation of the module within the LAr cryogenic testing system at the Univ. of Bern. During these operations, more than 60 million cosmic ray interactions were detected and recorded.

The Module 0 Demonstrator retired many of the most prominent ND-LAr technical risks, achieving the following:

- validation of the component interfaces and subsystem scope boundaries,
- validation of the detector assembly process, including the component acceptance testing, custom fixturing, and assembly procedures,
- verification of the mechanical robustness (in liquid argon) of the modular LArTPC design, fabricated primarily of fiberglass laminate panels (G10),
- a stable and uniform TPC drift field of 1 kV/cm (a factor of two greater than the requirement),
- an stable and uniform electron lifetime of 2 ms (a factor of four greater than the requirement),
- a pixel charge readout noise of 900 e^{-} ENC, uncorrelated (just under the requirement),
- a module scintillation detection efficiency for signals of >50 MeV deposited energy, and
- stable operation, triggering, and data acquisition over more than one week.

It set the basis for continuing to the production and integration of all four modules for the 2x2 program. Initially, four additional modules were planned, but given the good performance of Module-0, only three additional modules were built.

One additional module, called Module X, was built to test an alternative field cage design based on spray-on resistive epoxy, instead of resistive kapton film. This alternative design was easier to manufacture and relied on more cost-effective materials. Module X was operated in October 2023. While the design achieved the targeted field strength, the resulting field did not meet requirements for uniformity over the LArTPC volume.

1.6.3 ArgonCube 2x2 Demonstrator

The ArgonCube 2x2 Demonstrator consists the ArgonCube Module 0 LArTPC along with three copies (Modules 1, 2, and 3) arranged in a 2x2 grid within a shared high-purity LAr bath. As with Module 0, these other LArTPC modules were assembled and tested in high-purity LAr at the Univ. of Bern, and then shipped fully-assembled to FNAL. The team at Bern also provided the cryostat and cryogenics system components in support of this prototype. Fig. 1.77 shows some of this infrastructure.

Figure 1.77: (Left) The cryostat for testing individual LArTPC modules for the 2x2 Demonstrator (Center) The cryostat for the ArgonCube 2x2 Demonstrator (Right) The 2x2 cryostat and cryogenics system at the Univ. of Bern.

The demonstrator TPC modules were installed in the Neutrinos from the Main Injector (NuMI) neutrino beam in October 2023, in the former location of the MINOS Near Detector. Fig. 1.78 shows the LArTPC module installation. A start of operations is planned for early 2024. Data from operation of the 2x2 in this neutrino flux will enable a number of physics and technology studies. The primary goal is to achieve the requirements on neutrino event reconstruction with the modular ND-LAr design and extract physics observables. The NuMI neutrino beam provides a flux of neutrinos which covers the energy range of the LBNF beam. It is an excellent benchmark to demonstrate that complex final states can be reconstructed and matched to a downstream tracker. As the latter several planes of MINERvA will be used, in a very similar setup as will be implemented in the DUNE ND with ND-LAr and TMS. Specifically, the 2x2 program will allow for the:

1. Evaluation of the relative performance of multiple LArTPC modules operating within a

common high-purity LAr bath.

2. LArTPC module performance in response to beam neutrino interactions.
3. Evaluation of the signal reconstruction fidelity in a high-intensity environment.
4. Evaluation of the impact of dead volumes using signals which span multiple LArTPC modules.
5. Test of component longevity or drift of system performance over a O(1) yr duration of operation.
6. Validation of detector interfaces with DUNE DAQ, Slow Controls, and Computing.
7. Identification of any LArTPC design aspects that may adversely impact future ND-LAr operations.

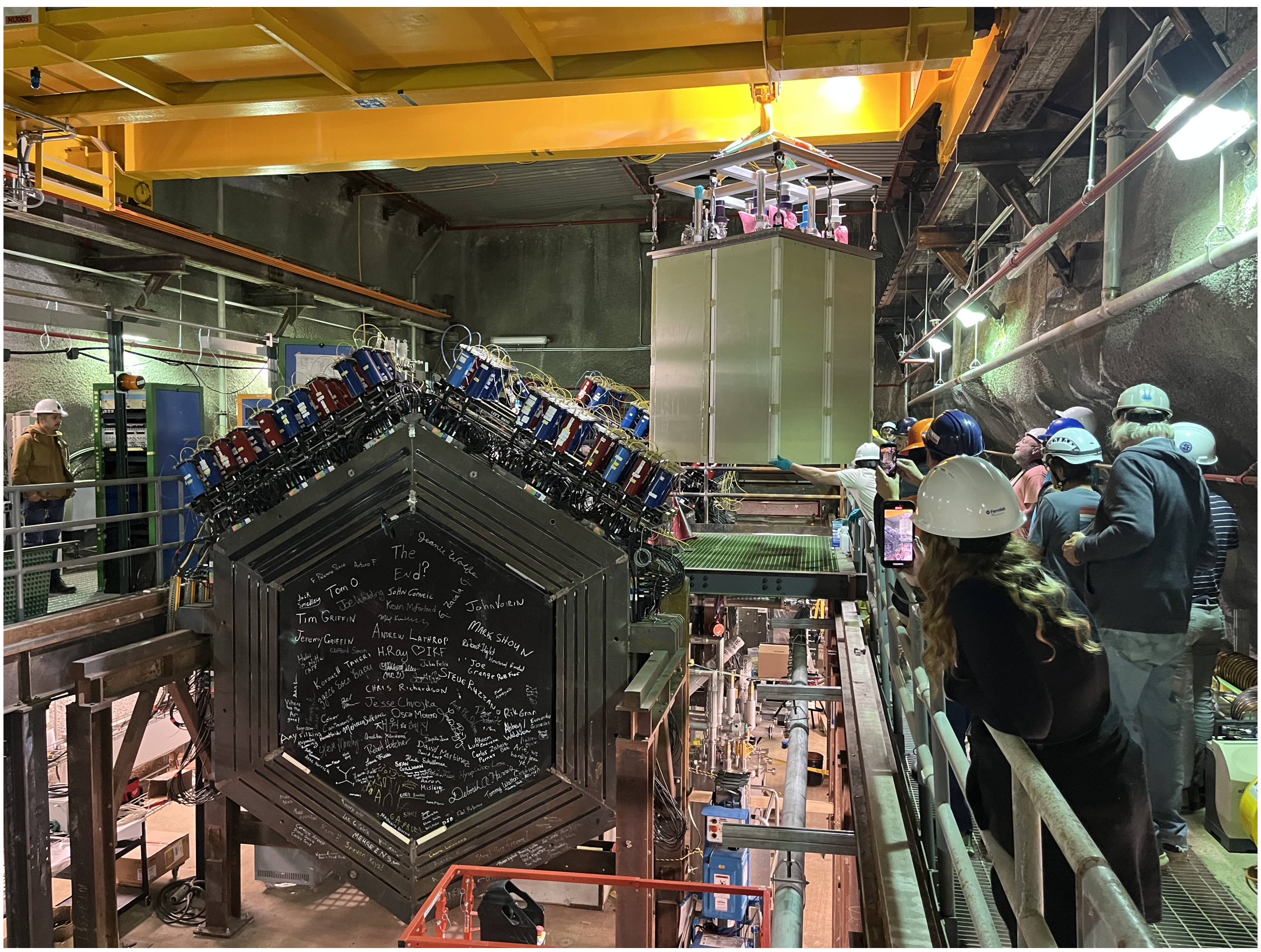

Figure 1.78: A photograph of the installation of the four LArTPC modules into the 2x2 Demonstrator cryostat in the former location of the MINOS Near Detector.

1.6.4 ND-LAr Full-scale Demonstrator

The ND-LAr Full-scale Demonstrator is an engineering demonstrator for the ND LArTPC module design. Two phases of FSD operation are foreseen: an initial phase between the completion of the detector preliminary design and the final design, and a second phase between the completion of the final design and the start of ND production.

In the first phase we will construct and operate one full-scale LArTPC module according to the ND design. It will be operated in a 1.5-m-diameter and 4-m-tall cylindrical cryostat capable of hosting this one module, and is serviced by a O(10 ton) high-purity LAr cryogenics system.

The key technical targets of this prototype are:

1. Exercise the final-design component production and QC testing procedures at $\sim$3% of the scale of the ND-LAr production.
2. Identify potential QA/QC issues and use them to refine the QA/QC program in advance of component production.
3. Establish and exercise the module assembly processes for the full-sized ND LArTPC modules, including: assembly rigs and lifting fixtures, documented assembly procedures, hazard analyses and safety reviews, etc.
4. Establish the testing program to be used at the Module Assembly and Test Facility (i.e. the ND LArTPC assembly line).
5. Prototype key interfaces to the ND-LAr cryogenics system, with a focus on thermal management and purity.
6. Demonstrate that the full-scale LArTPC design continues to meet the key technical specifications described in the preceding section on Module 0 technical targets (e.g. cryo-mechanical stability, HV, LAr purity, charge readout noise, and scintillation efficiency).

A second round of FSD operation is planned to occur approximately six months after the first test. This second run will provide an opportunity to implement any revisions arising from the first run or from the ND-LAr final design review recommendations.

1.6.5 ND-LAr Module Row Prototype

The ND-LAr Module Row Prototype is an engineering prototype for the ND LArTPC production and integration process, to be performed jointly with the ND-LAr Cryostat development team. It consists of the production and testing of 5 ND-LAr TPC modules, and their subsequent integration with a single prototype lid segment from the ND-LAr cryostat, as shown in Fig. 1.80.

The key technical targets of this prototype are:

1. Exercise the final-design component production and QC testing procedures at $\sim$15% of the

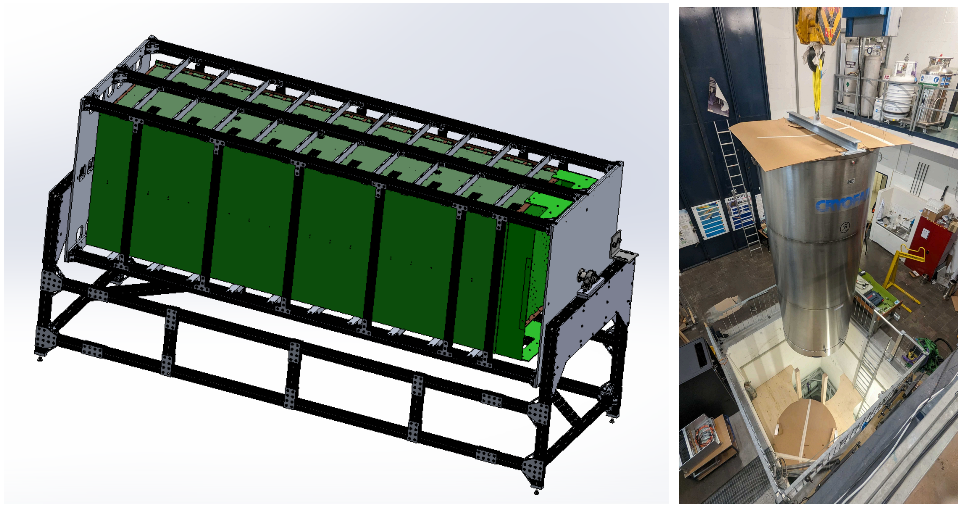

Figure 1.79: (Left) A rendering of the ND-LAr TPC Module assembly fixture, designed to facilitate assembly of the modules in a horizontal orientation (Right) A photograph of the installation of one of the two FSD 1.5-m-diameter and 4-m-tall cryostats in the laboratory space at the Univ. of Bern, taken in Dec. 2023.

scale of the ND-LAr production. Validate time and resource estimates in advance of full production.

2. Establish and exercise the Module Assembly and Testing Facility. Verify the throughput of this production facility and revise for efficiency in advance of full production.
3. Validate the assembled TPC module handling and transport procedures.
4. Prototype the fixturing and procedures for integration of the TPC modules to the cryostat lid segment. Validate time and resource estimates in advance of ND-LAr installation.
5. Validate the interfaces to the ND-LAr Cryostat lid segment, ND-LAr cryogenics, and system electrical grounding. Exercise the mechanical support and cable routing procedures.
6. Validate the assembled module row lifting and transport procedures, and clearances for installation into the cryostat. Prototype and test lifting fixtures.
7. Validate personnel and equipment safety controls for detector integration and installation.
8. Prototype the Module Row check-out procedure, to be used during detector integration and installation.
9. Establish and exercise the detector metrology and alignment procedures.

The ND-LAr Cryostat and ND Installation and Integration teams have additional goals for this joint prototype, beyond the ND-LAr-specific goals provided here. Given that each module will be cryogenic tested during actual detector production, we do not plan to perform cryogenic testing of the assembled row (which would require significant additional expense not commensurate with the residual risk). The modules produced for this prototype may also be used to exercise this single-module cryogenic testing program, if the MATF cryofacility is ready at that time. While we currently assume that these initial modules will only serve as prototypes, the whole modules or some subset of their parts may be promoted to spares for the full ND-LAr detector if appropriate.

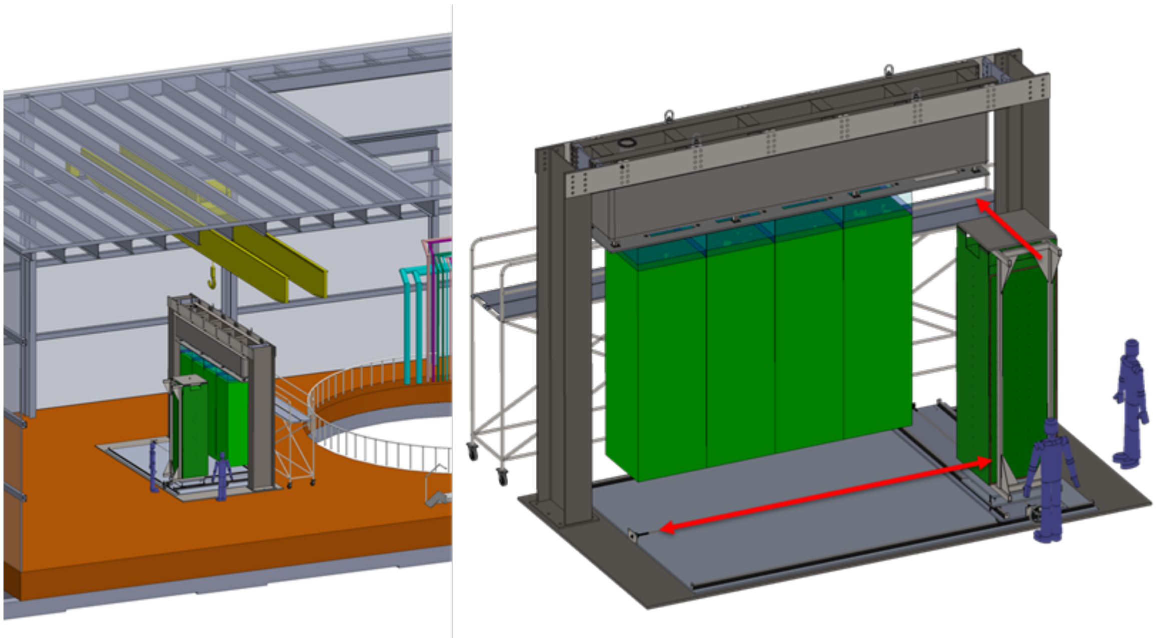

Figure 1.80: (Left) An preliminary engineering rendering of the ND-LAr row assembly process in the Near Site surface building. (Right) A rendering of five ndlar) TPC modules being integrated to a cryostat lid segment using the planned row assembly fixture. A mobile base on tracks allow translation of a module in two dimensions for alignment and installation, and a catwalk provides access to mechanical attachment points and for cable routing.