Overview and Status of the Long-Baseline Neutrino Facility Far Detectors Cryogenics System

David Montanari
CEC-ICMC 23
09-13 July 2023
Thanks To:

• Mark Adamowski (Fermilab).
• Johan Bremer (CERN).
• John Campbell (Intelligas Consulting).
• Mike Delaney (Fermilab).
• Roza Doubnik (Fermilab).
• Jeremey Duncan (Fermilab).
• Jack Fowler (Duke University).
• Justin Freitag (Fermilab).

• Markus Graf (Fermilab).
• Matt Maciazka (Fermilab).
• Dawn Moore (Fermilab).
• Trevor Nichols (Fermilab).
• Adrien Parchet (Fermilab).
• Erik Voirin (Fermilab).
• Ian Young (Fermilab).
Outline

- Intro.
- Scope Overview.
- Infrastructure Cryogenics.
- Proximity Cryogenics.
- LAr Procurement.
- Summary.
The Long-baseline Neutrino Facility supporting the Deep Underground Neutrino Experiment

LBNF and DUNE were proposed in response to the 2014 P5 report and the 2013 European Particle Physics Strategy

- **LBNF** – a highly capable neutrino science platform
  - U.S. provides all conventional facility requirements to support an internationally led experiment
  - International partners provide key technology/in-kind contributions:
    - Cryostats – from CERN
    - Cryogenic Systems – supported by CERN/Brazil/Poland/Switzerland
    - Target/Beamline – key components from UK/CERN/Japan

- **DUNE** – a best-in-class neutrino experiment, designed, constructed, and operated by an international collaboration
  - The U.S., along with multiple international funding agencies, contribute to the near and far detectors

- Fermilab serves as host laboratory for the international collaboration

LBNF/DUNE represents a new model and global approach to physics in U.S.
Discovery Potential of DUNE

Neutrino CP violation
- The origin of matter in the universe

Supernova neutrinos
- Origins of neutron stars and black holes

Neutrino surprises
- New forces, particles, or laws of nature connected to neutrinos

Proton decay
- Unified origins of particles and forces
LBNF/DUNE: From Illinois (Near Site) to a mile underground in South Dakota (Far Site)

Illinois: ➔
- World’s most powerful and advanced neutrino beamline
- DUNE “near” detector

South Dakota:
- Surface and underground facilities
- Cryostats - Massive membrane cryostats to hold liquid argon
- Cryogenic systems (Nitrogen and Argon)
- DUNE “far” detectors – up to four liquid argon detector modules
Far Site Underground Facilities

Excavation: nearly 70% complete!

- Generator Room
- Vent Shaft
- Expanded Drift
- Maintenance Shop
- Ross Brow
- #6 Winze Dump
- Concrete Supply Chamber
- North Detector Cavern
- Central Utility Cavern
- South Detector Cavern
- Spray Chamber
- 1,200' Raise Bore

2 x Detector Caverns:
- 475' L x 65' W x 92' H
- 145m L x 20m x 28m

1 x Central Utility Cavern (CUC):
- 624' L x 64' W x 37' H
- 180m L x 20m W x 11m H
Max load: 6,123 kg.
Far Site Cryo Scope Graphics

Surface

Underground (4850L) = 1 mile deep

Argon Purification/Regeneration supporting full scope shown.

North Cavern (Detector #1 shown)

Central Utility Cavern (CUC)

South Cavern (Detector #2 shown)
Far Site Cryo Scope

• **Cryogenics Infrastructure** to support first two 17.5 kton total LAr mass detectors. Design allows future expansion to final DUNE configuration of four detector modules.

• **Cryogenics Systems** includes engineering, procurement of materials, installation and testing of cryogenic systems for detector cryostats.
  - **Infrastructure** Cryogenics includes Argon Receiving facilities, Nitrogen System, Argon distribution (pipes/valves), Cryostat Pressure control system, GN2 supply to cryostat insulation. **DOE** with **CERN** contribution Argon receiving.
  - **Proximity** Cryogenics includes reliquefaction and purification sub-systems, associated instrumentation and monitoring equipment. Deliverable is **In-Kind Contributions**. Installation is **DOE**.
  - **Internal** Cryogenics includes GAr/LAr distribution and cool down cryostat/detector. **In-Kind Contribution**.
  - Process **controls** includes readout modules, PLC architecture, HMI/SCADA, ODH, Integration. **DOE**.

• **LAr procurement** for two 17.5 kton modules with ability to conduct additional purchases for future modules. **DOE**.
International and DOE Contributions – Surface
International and DOE Contributions – Underground

*Switzerland contribution is via CERN.
NO cryogens/cryogenics in the shaft.

Cryogenics Infrastructure Process Flow Diagram

- **INF**: Infrastructure
- **PROXY**: Proximity
- **INT**: Internal

Key Elements:
- **Argon Supply**
- **Ross Shaft**
- **Utility Cavern**
- **Detector Cavern**
- **Cryostat**
- **Argon Condensing**
- **Regeneration System**
- **Vaporizer**
- **Filter**
- **Mole Sieve & Copper**
- **Hydrogen Generator**
- **Vent Header to Exhaust Drift**
- **NO cryogens/cryogenics in the shaft.**
Modes of Operations

• **GAr Purge**: GAr slowly flows from bottom of cryostat at a rate sufficient to prevent back-diffusion of air, removing impurities from system. Reduces contaminants (O2, N2, H2O) to ppm level.

• **GAr Circulation**: GAr is circulated in a closed loop and purified through GAr purification system. Reduces O2 and H2O to sub-ppm level.

• **Cool-down**: LAr is sprayed at top cryostat until contents are around 90K.

• **Filling**: GAr is transferred from surface to be re-condensed underground. Once cryostat and detector are cold, LAr flows from condenser into each cryostat.

• **Steady state operations**:
  - LAr is circulated from cryostats to be purified via external pumps (four per cryostat, all initially in-service to achieve requisite purity levels of 100 ppt O2 equivalent contamination).
  - Boil-off GAr is re-liquified in condensers outside of each cryostat and sent to LAr purification system before returning to vessel.

• **Emptying**: Once experiment concludes and operations cease, cryostats are emptied, and Argon remove.
## Relevant Cryogenics Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAr Purge Flow rate</td>
<td>1,123 m³/hr</td>
<td>From 1.2 m/hr</td>
</tr>
<tr>
<td>LAr filling flow rate</td>
<td>0.8 / 0.5 kg/s</td>
<td>1st / 2nd Cryostats (w/ 3 LN2 refrigeration units)</td>
</tr>
<tr>
<td>LAr filling duration</td>
<td>257 / 436 days</td>
<td>1st / 2nd Cryostats (w/ 3 LN2 refrigeration units)</td>
</tr>
<tr>
<td>Cryostat static heat leak</td>
<td>48.7 kW</td>
<td>Each cryostat</td>
</tr>
<tr>
<td>Electronics heat load</td>
<td>23.7 kW</td>
<td>Each cryostat</td>
</tr>
<tr>
<td>Total estimated heat load</td>
<td>87.1 / 98.2 kW</td>
<td>Each cryostat (only) with 2/4 LAr pumps in operation</td>
</tr>
<tr>
<td>Condenser size (per cryostat) *</td>
<td>3 x 100 kW = 300 kW</td>
<td>3 LN2 units for cryostats 1 &amp; 2, 4th unit for 3 &amp; 4</td>
</tr>
<tr>
<td>Maximum LAr circulation speed (assuming 5 days turnover)</td>
<td>1.73 m³/min (40 kg/s)</td>
<td>All 4 LAr pumps in operation</td>
</tr>
<tr>
<td>Nominal LAr circulation</td>
<td>0.43 m³/min (10 kg/s)</td>
<td>Only 1 LAr pump in operation</td>
</tr>
<tr>
<td>Required LAr Purity</td>
<td>FD-1: <strong>100 ppt</strong> (~3.2 ms lifetime). FD-2: <strong>50 ppt</strong> (~6 ms lifetime)</td>
<td>O₂ equivalent contamination (O₂, H₂O). ProtoDUNE achieved &lt;10 ppt (30+ ms lifetime).</td>
</tr>
</tbody>
</table>

* Condensers modularity may be different but need to match the refrigeration modularity.
Infrastructure Cryogenics
Argon Receiving Facilities

- **280 ton of LAr storage**
  (4 days at 70 ton/d)

- **Vaporizers**
  (2N redundancy)

  Vaporizers: 2 x 500 kW

  LAr Tankers Offloading stations

  Proposed LAr Storage: 4 x 50 m³
  (2 tanks from CERN)

  Argon Purity Shed
  (Controls + Argon sampling to verify impurities)

  Space and utilities for LAr Pumps (if needed)
Nitrogen System Scope

• Nitrogen Refrigeration System (4 x 100 kW units). Modularity driven by ops.
• LN2/GN2 Distribution.
• LN2 storage tanks.
• GN2 generation to charge system and makeup of losses.
• Process Controls (to be integrated with LBNF controls system).

• Provides refrigeration (in the form of evaporation of LN2) to detector cryostats:
  - Supports APA testing in cold boxes.
  - Condenses GAr during cool-down/fill.
  - Recondenses boiloff GAr during normal ops.
# Nitrogen System Requirements

<table>
<thead>
<tr>
<th>System Requirement</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Refrigeration Capacity (at Condensers)</td>
<td>$4 \times 100 \text{ kW} = 400 \text{ kW}$ \hspace{1cm} (221 ton/day LN2)</td>
</tr>
<tr>
<td>Availability / Uptime</td>
<td>$&gt; 99%$</td>
</tr>
<tr>
<td>LN2 backup storage (underground)</td>
<td>30 $\text{ m}^3$</td>
</tr>
<tr>
<td>Cooling Water (underground)</td>
<td>$&lt; 3,000 \text{ kW}$</td>
</tr>
<tr>
<td>Electric Power (underground)</td>
<td>$&lt; 3,000 \text{ kW}$</td>
</tr>
<tr>
<td>Main available footprint (including LN2 storage)</td>
<td>796 $\text{ m}^2$</td>
</tr>
<tr>
<td>Total footprint (underground) w/ additional space</td>
<td>894 $\text{ m}^2$</td>
</tr>
</tbody>
</table>

Equipment needs to fit within logistics constraints.
Nitrogen System Acquisition Strategy Executed; Phase 2 Subcontract Underway

- **Phase 1/pre-FEED**: Preliminary Engineering Study + Proposal for Phase 2. *Concluded*

  - Base: Engineering full system (supports 4 Detectors). *Awarded*
  - Option 1: Manufacturing/Installation/Commissioning first 3 units, full storage and distribution (supports *first 2 Detectors*). [DOE CD-3 Required before Award]
  - Option 2: Manufacturing/Installation/Commissioning 4th unit (supports *last 2 Detectors*).

- **Challenges**:
  - Logistics/installation.
  - Reliability.
## Appendix 1 – List of Performance Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Case</th>
<th>Type of Test</th>
<th>Duration (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Note1)</td>
<td>Storage Refill</td>
<td>Contractual Guarantee – minimum LIN storage refill rate</td>
<td>6 (Note 2)</td>
</tr>
<tr>
<td>2 (Note1)</td>
<td>Normal Operation / Liquefier Recycle mode</td>
<td>Contractual Guarantee – LIN Production rate</td>
<td>8</td>
</tr>
<tr>
<td>3 (Note3)</td>
<td>Normal Operation / Liquefier Recycle mode</td>
<td>Contractual Guarantee – LIN Production rate, all 3 liquefiers simultaneously</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Turndown</td>
<td>Operate liquefiers at 70% load</td>
<td>3</td>
</tr>
</tbody>
</table>

**Note 1:** Above tests 1 & 2 need to be completed for each of the 3 installed liquefiers

**Note 2:** A six-hour test would result in a LIN storage level change of more than 25% of capacity. This would be sufficient to have good accuracy in determining the LIN production rate by storage level rise. Note also that the guaranteed refill rate required is defined as 800 kg/hr but the expected refill rate capacity is >1,000 kg/h. By limiting the level rise during Test 1 to circa 25%, there would be sufficient storage capacity to allow Test 1 to be completed in sequence for the three liquefiers.

**Note 3:** Stable operating of the controls system will be demonstrated; each liquefier will be turned on/off with any combination of the other systems in operation and unaffected.

Tests 1, 2, 4 repeated for 4th unit as well. Testing parameters may be adjusted based on utilization of units #1-3.
Argon Distribution

- Distributes Argon in liquid and gas phase.
- Connects items in two separate Caverns (e.g., cryostat and argon purification).
- Connects equipment supplied by different parties in same cavern (e.g., Argon purification and regeneration).
- Includes Nitrogen supply/return to/from Regeneration system.
- Includes CUC and North/South caverns Vents.
- Procured as Engineering/Manufacturing/Installation

**Challenges:**
- Transportation and installation 1 mile underground.
- Leak tightness.
Proximity Cryogenics
Proximity Cryogenics in CUC
Proximity Cryogenics in CUC: Argon Filtration

- **LAr Filtration:**
  - 4 LAr Filter/cryostat (8 total).
  - Filled with Mol Sieve and Copper to adsorb Water and Oxygen respectively.

- **GAr Filtration:**
  - 4 GAr Filter/pair of cryostats (4 total).
  - Filled with Mol Sieve and Copper to adsorb Water and Oxygen respectively.

- **Mechanical filters for dust/etc.**
- **Automated regeneration using hot Ar/H2 mix (500 K).**

- **Challenges:**
  - Size!
  - Logistics: transportation and installation 1 mile underground.
Proximity Cryogenics in CUC: Argon Filtration

- **LAr Filtration:**
  - 4 LAr Filter/cryostat (8 total).
  - Filled with Mol Sieve and Copper to adsorb Water and Oxygen respectively.

- **GAr Filtration:**
  - 4 GAr Filter/pair of cryostats (4 total).
  - Filled with Mol Sieve and Copper to adsorb Water and Oxygen respectively.

- Mechanical filters for dust/etc.
- Automated regeneration using hot Ar/H2 mix (500 K).

**Challenges:**
- Size!
- Logistics: transportation and installation 1 mile underground.
Proximity Cryogenics in Detector Cavern: Argon Condensers System (FD-2) and LAr circulation (FD-1 shown)
LAr Procurement

- Working with experienced consultant and industry to develop strategy for LAr procurement and maintain cost up-to-date since 2015 (multiple RFIs and LAr industry day at site).

- Planning IDIQ subcontract to purchase all LAr required at Far Site: 4 x 18,600 ton (= 74,400 ton).
  - 1st cryostat.
  - 2nd (and 3rd, 4th).

- Max delivery rate: 70 ton/day for 10 mo (1st Cryostat).

- Standard grade: < 5 ppm O₂, < 10 ppm N₂ and H₂O. On average, deliveries to Fermilab are sub-ppm.

- Notable Challenges:
  - Production on average 1,000 m (1,609 km) away!
  - Subcontract in place 18-24 mo ahead of start of deliveries.
  - Tight supply-demand situation: demand within 2-3% of Maximum Deliverable Volume.
  - Demand expected to increase 3-4%/y with about same amount of nameplate capacity increase.
  - Industry forecasts 5 years out. Deliveries expected to start in 2028.
Summary

• Very exciting project!
• Industry scale cryogenics supports DUNE Far Detectors.
• Builds upon successful LAr programs at Fermilab and CERN.
• Challenges related to location and logistics.
• Executing our plan to acquire systems.
Thank You!
North Detector Cavern – West End

Drilling holes for blast charges for bench C (left) and removing muck (right) in North Detector Cavern (4850-33)
North Detector Cavern

North Cavern (4850-33) adjusting ventilation

North Cavern (4850-15) midpoint connection drift
Central Utility Cavern

Blow piping east end of central utility cavern (4850-36)

Central Utility Cavern corner trench drain (4850-36)
# FDC.04 Summary Schedule

| Category               | FY 23 Q1 | FY 23 Q2 | FY 23 Q3 | FY 23 Q4 | FY 24 Q1 | FY 24 Q2 | FY 24 Q3 | FY 24 Q4 | FY 25 Q1 | FY 25 Q2 | FY 25 Q3 | FY 25 Q4 | FY 26 Q1 | FY 26 Q2 | FY 26 Q3 | FY 26 Q4 | FY 27 Q1 | FY 27 Q2 | FY 27 Q3 | FY 27 Q4 | FY 28 Q1 | FY 28 Q2 | FY 28 Q3 | FY 28 Q4 | FY 29 Q1 | FY 29 Q2 | FY 29 Q3 | FY 29 Q4 | FY 30 Q1 | FY 30 Q2 | FY 30 Q3 | FY 30 Q4 | FY 31 Q1 |
|------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| **FDC Milestones**     |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| FDC SP - CDZ/3 ESAAB Approval | ✔️        |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Authorization for use and possession of underground areas (AUP) |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Completion of commissioning of Nitrogen System |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Completion of FS Cryogenic Infrastructure Threshold KPPs |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Completion of FS Cryogenic Infrastructure Objective KPPs |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| **Engineering**        | Nitrogen System |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| In-Kind Contributions  |          | ✔️        |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Argon Receiving        |          |          | ✔️        |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Argon Distribution and Vents |          |          |          | ✔️        |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| **Manufacturing**      | Nitrogen System |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| In-Kind Contributions  |          |          | ✔️        |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Argon Receiving        |          |          |          | ✔️        |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Argon Distribution and Vents |          |          |          |          | ✔️        |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| **Installation & Testing** | Nitrogen System |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Argon Condensers System / Purification / Regeneration #1 |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Argon Receiving        |          |          |          |          |          | ✔️        |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Argon Condensers System / Purification / Regeneration #2 |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Main LAr Pumps #1      |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Main LAr Pumps #2      |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| **Cool-down and filling** | Purge/cool-down #1 |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Filling #1             |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Purge/cool-down #2     |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
| Filling #2             |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |

**Legend:**
- Milestone
- Nitrogen System
- IKC
- Argon Receiving
- Argon Distribution
- Filling
- Purge/cool-down
DOE Project Scope - Delivered at Two Sites through Five Subprojects

Far Site – SURF in Lead, SD
Facility/Infrastructure and Far Detectors

- FSCF-EXC – Far Site Excavation
- FSCF-BSI – Far Site Building & Site Infrastructure
- FDC – Far Detectors and Cryogenic Infrastructure

Near Site – FNAL in Batavia, IL
Facility/Infrastructure, Neutrino Beamline, and Near Detectors

- NSCF+B – Near Site Conventional Facilities + Beamline
- ND – Near Detectors
Far Site Cryo – Cryogenics Systems Scope

- LBNF Cryogenics system supports first two Detectors situated within cryostats filled with 17.5 kton LAr. Design upgradable to support 4 total detector modules, each filled with 17.5 kton LAr.

- **Infrastructure Cryogenics (INF):**
  - Receive Argon.
  - Transport Argon to cavern.
  - Provide refrigeration via Nitrogen System (refrigeration, storage, distribution).
  - Distribute Argon (LAr/GAr) as needed.
  - GAr boil-off and pressure control system.
  - Installation of In-Kind Contributions.
  - GN2 supply to cryostat insulation.

- **Process controls.**
  - Integration of all items and development of infrastructure (PLC, HMI/SCADA, ODH).

- **Proximity Cryogenics (PROX):**
  - Circulate and purify LAr.
  - Achieve and maintain LAr purity (< 100 ppt Oxygen equivalent).
  - Recondense boil off GAr and purify GAr (boil off and purge).

- **Internal Cryogenics (INT):**
  - Distribute GAr/LAr within the cryostat for purge, cool down, fill. Part of Far Site Integration.

- **LAr procurement** for two 17.5 kton modules with ability to conduct additional purchases for future modules.
# Scope Assignment

<table>
<thead>
<tr>
<th>Item</th>
<th>FD-1</th>
<th>FD-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat (Part of FS Integration)</td>
<td>CERN</td>
<td>CERN</td>
</tr>
<tr>
<td>Cryogenics Systems Integration</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>Nitrogen System (Refrigeration + LN2 Storage + distribution) –</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>Engineering / Manufacturing / Installation / Commissioning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argon Receiving Facilities (surface)</td>
<td>DOE + CERN</td>
<td>DOE + CERN</td>
</tr>
<tr>
<td>Argon condensers system – Engineering / Manufacturing</td>
<td>Switzerland*</td>
<td>Brazil</td>
</tr>
<tr>
<td>Argon distribution</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>Argon purification and regeneration – Engineering / Manufacturing</td>
<td>Brazil</td>
<td>Brazil</td>
</tr>
<tr>
<td>LAr circulation – Engineering / Manufacturing</td>
<td>Brazil</td>
<td>Brazil</td>
</tr>
<tr>
<td>GAr boil-off and pressure control</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>Process Controls</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>Internal Cryogenics – Engineering / Manufacturing (Part of FS Integration)</td>
<td>Poland</td>
<td>Poland</td>
</tr>
<tr>
<td>Installation of In-Kind Contributions (IKC)</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>Collect safety docs and obtain safety approval</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>Purge and cool down</td>
<td>DOE</td>
<td>DOE</td>
</tr>
<tr>
<td>LAr procurement and LAr fill (**only LAr for FD-2, not labor)</td>
<td>DOE</td>
<td>DOE**</td>
</tr>
</tbody>
</table>

*All committed contributions.*

*Switzerland contribution is via CERN.*
International and DOE Contributions – Surface
All committed contributions.

*Switzerland contribution is via CERN.

International and DOE Contributions – Underground

Internal Cryogenics #1

Internal Cryogenics #2
## Overview Cryogenics Installation

### General [supports FD-1 and FD-2]
- Installation activities spread out to reduce peak underground occupancy.
- Cryogenics supporting Integrated cold boxes not included here.
- 1 resource/partner overseeing installation of supplied equipment.
- Assumed 1 FRA oversight per area: CUC Nitrogen, CUC Argon, Detector Cavern, Surface.

### Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Qtr.</td>
<td>Jan 2</td>
<td>Feb 2</td>
<td>Mar 2</td>
<td>Apr 2</td>
<td>May 2</td>
<td>Jun 2</td>
</tr>
<tr>
<td>2nd Qtr.</td>
<td>Jul 2</td>
<td>Aug 2</td>
<td>Sep 2</td>
<td>Oct 2</td>
<td>Nov 2</td>
<td>Dec 2</td>
</tr>
<tr>
<td>3rd Qtr.</td>
<td>Jan 3</td>
<td>Feb 3</td>
<td>Mar 3</td>
<td>Apr 3</td>
<td>May 3</td>
<td>Jun 3</td>
</tr>
<tr>
<td>4th Qtr.</td>
<td>Jul 3</td>
<td>Aug 3</td>
<td>Sep 3</td>
<td>Oct 3</td>
<td>Nov 3</td>
<td>Dec 3</td>
</tr>
</tbody>
</table>

**Notes:**
- Installation activities spread out to reduce peak underground occupancy.
- Cryogenics supporting Integrated cold boxes not included here.
- 1 resource/partner overseeing installation of supplied equipment.
- Assumed 1 FRA oversight per area: CUC Nitrogen, CUC Argon, Detector Cavern, Surface.
LAr Procurement Status

• Discussing **Acquisition Plan** with DOE FSO.
  - Uses most up to date industry info and LAr supply report from consultant.

• Industry moving towards **rail for LAr transport**.
  - Very advantageous for LBNF.

• BNSF runs 3 times/week to Upton, WY from Houston, TX and Chicago, IL (likely clusters supplying LAr for LBNF).

• **Long haul**: railcars from Houston and/or Chicago (100 ton/car).
  - Will reduce uncertainty over 1,000+ m journey on road.

• **Transfill** at Tiger Transfer in Upton, WY.
  - Very impressive operation. Affordable.

• **Short haul**: tanker trucks from Upton, WY to Lead, SD (20 ton/truck).
  - Easier to handle and coordinate. Local driving only. No need of team drivers.