

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

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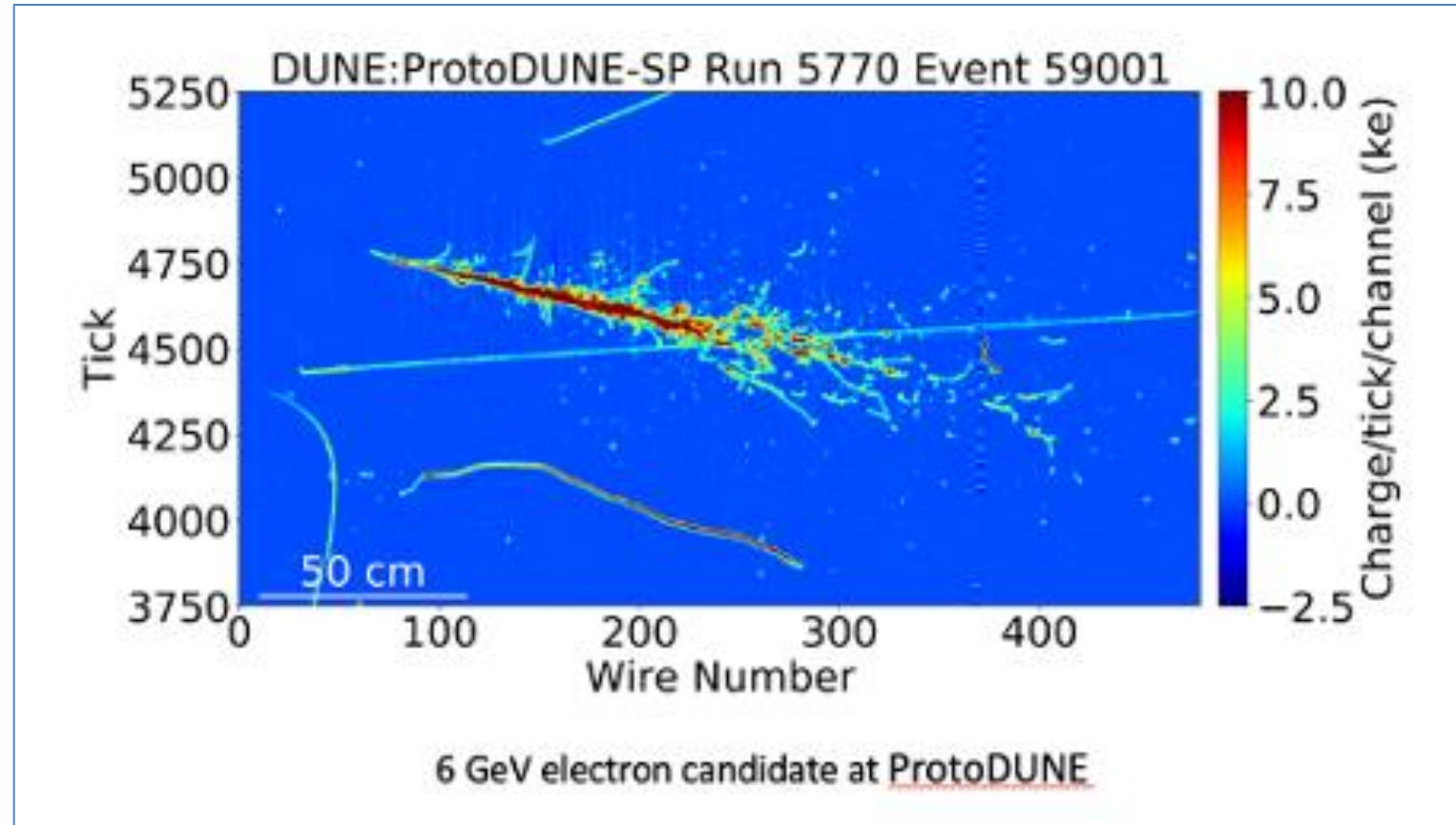
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Thanks To:

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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 2014 P5 report and 2013 European Particle Physics Strategy.

- **LBNF** – a highly capable neutrino science platform.

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

LBNF is a global platform analogous to LHC



- **DUNE** – a best-in-class neutrino experiment, designed, constructed, and operated by an international collaboration.

- U.S., along w/ multiple international funding agencies, contribute to Near and Far Detectors.

DUNE-US is analogous to US-CMS or US-ATLAS

- Fermilab serves as **host laboratory** for 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



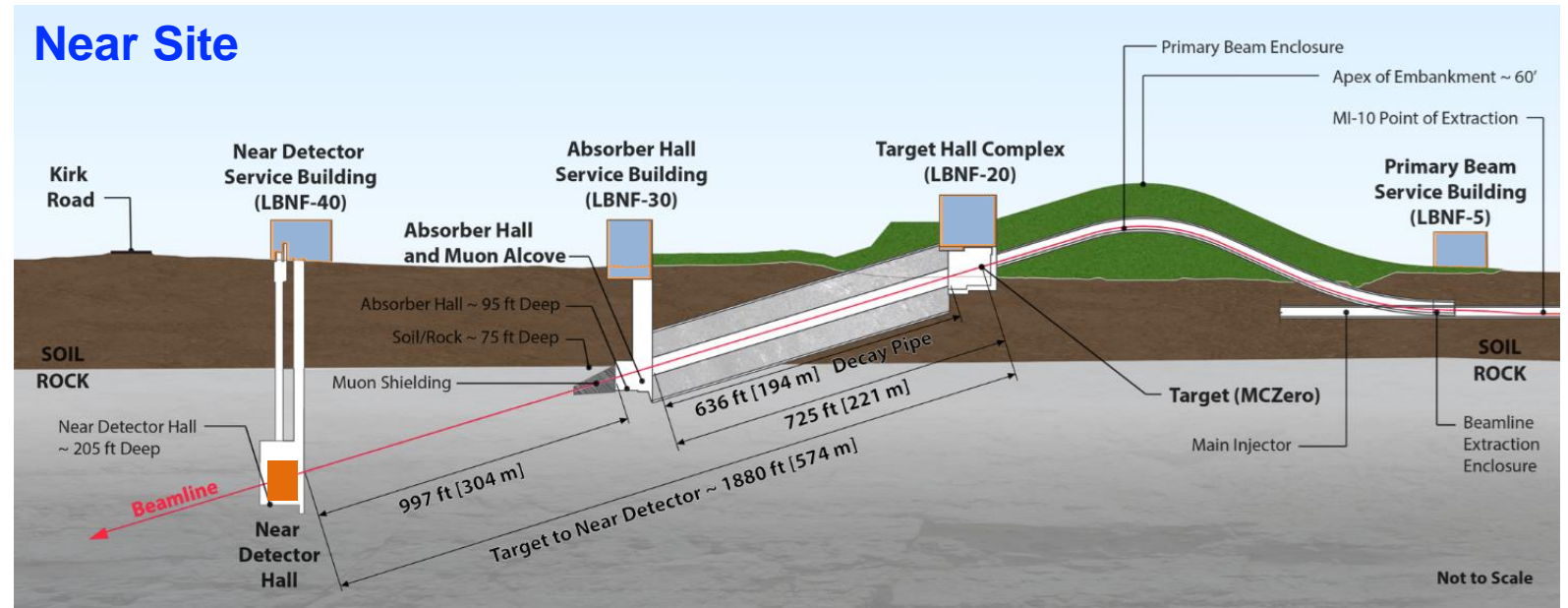
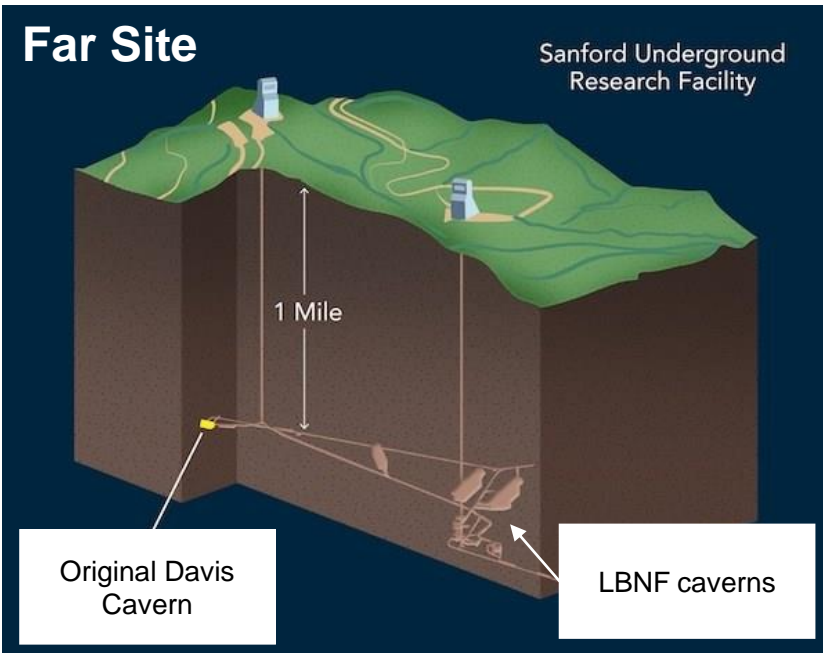
Proton decay

- 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

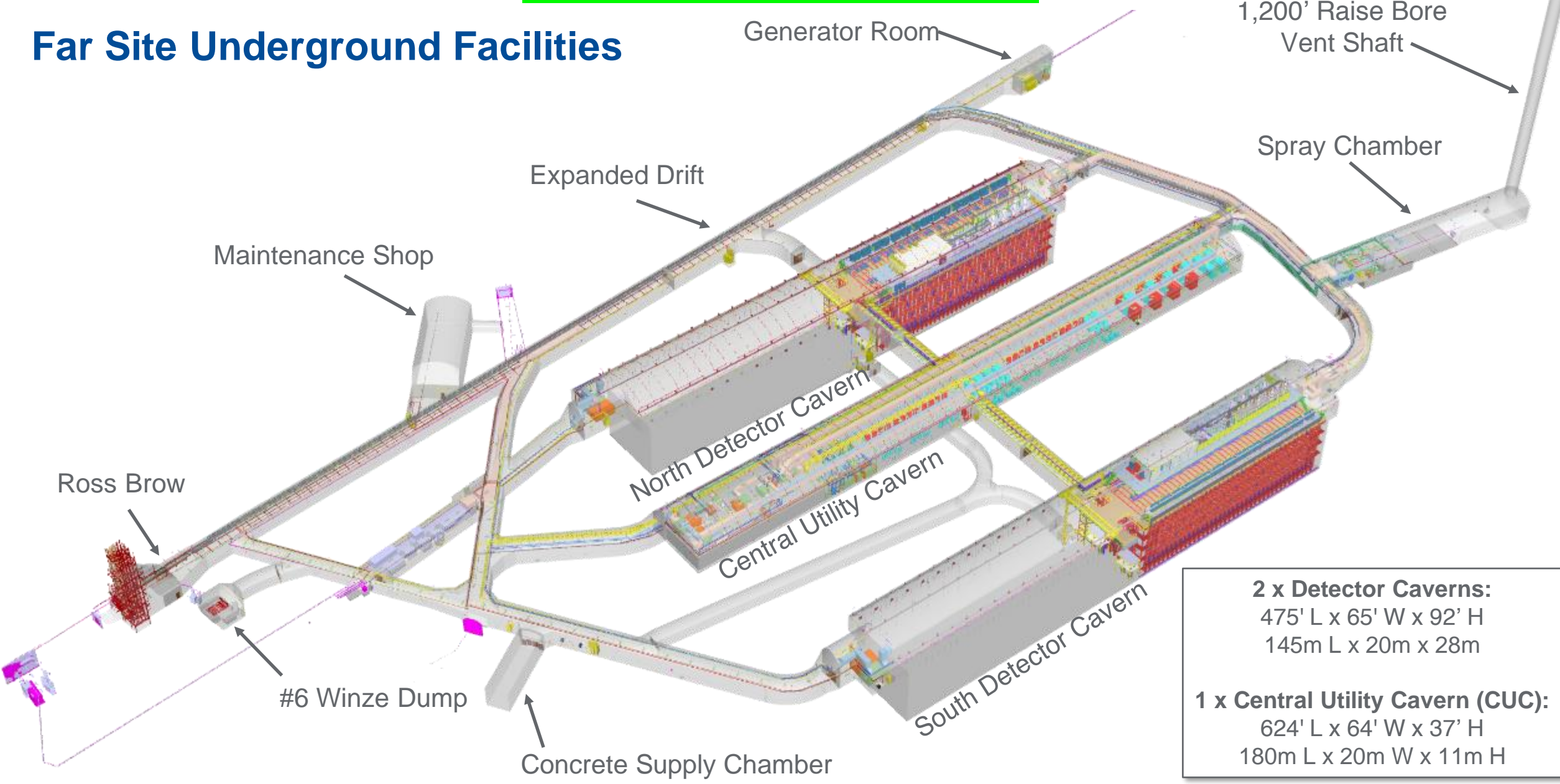


← South Dakota:

- 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

Excavation: completed in Feb-2024!

Far Site Underground Facilities



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

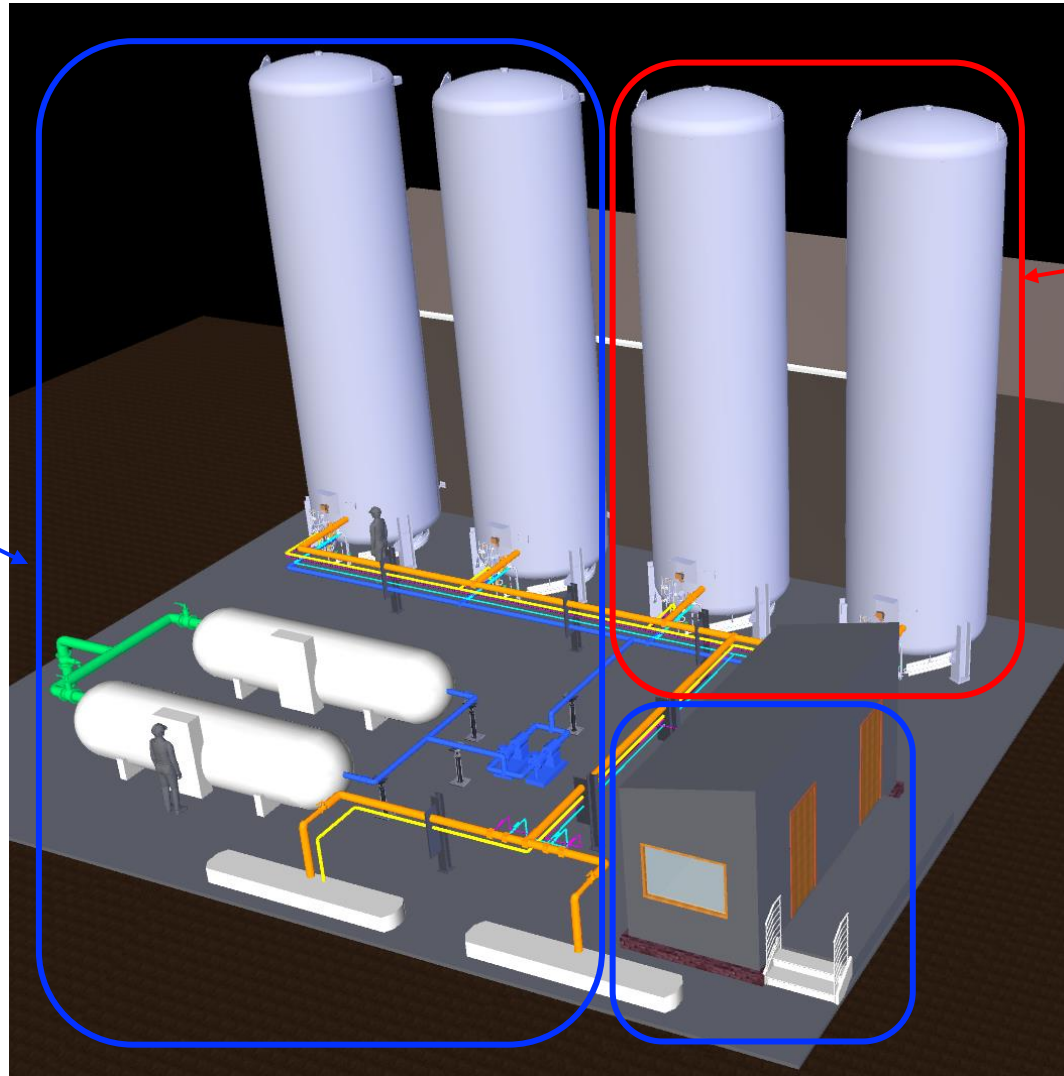
1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H



Far Site Cryo Scope

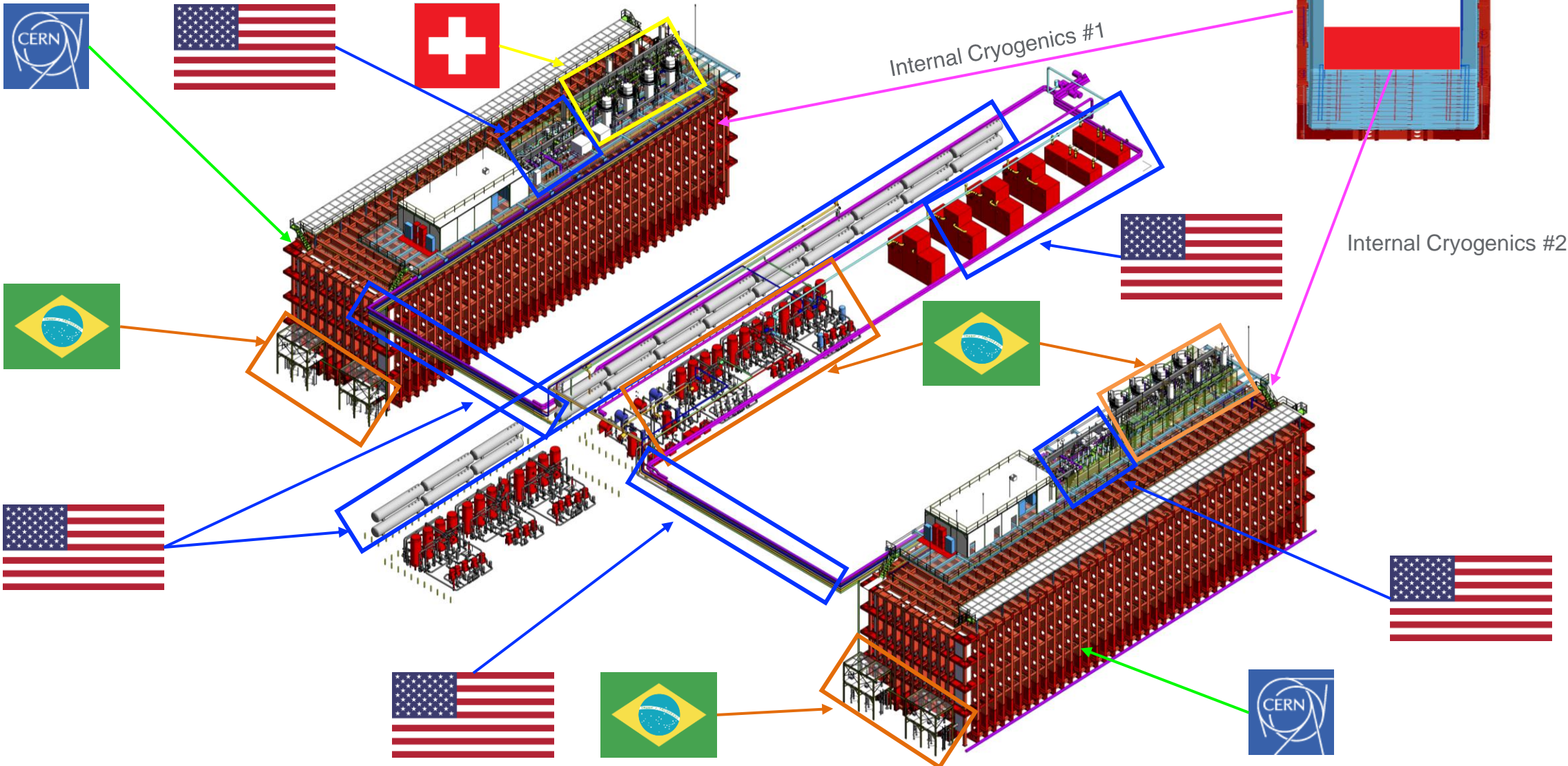
- **Cryogenics Infrastructure** to support first two detectors, each one holding 17.5 kTon total LAr mass. Design allows future expansion to final DUNE configuration of four detector modules.
- **Cryogenics Systems** includes engineering, procurement of materials, installation and testing of cryogenic systems for detector cryostats.
 - **Infrastructure** Cryogenics includes Argon Receiving facilities, Nitrogen System, Argon distribution, Cryostat Pressure control system, Miscellanea. **DOE** with **CERN** contribution for 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 modules (17.5 kTon each) w/ ability to conduct additional purchases for future modules. **DOE**.

International and DOE Contributions – Surface



*Switzerland contribution is via CERN.

International and DOE Contributions – Underground



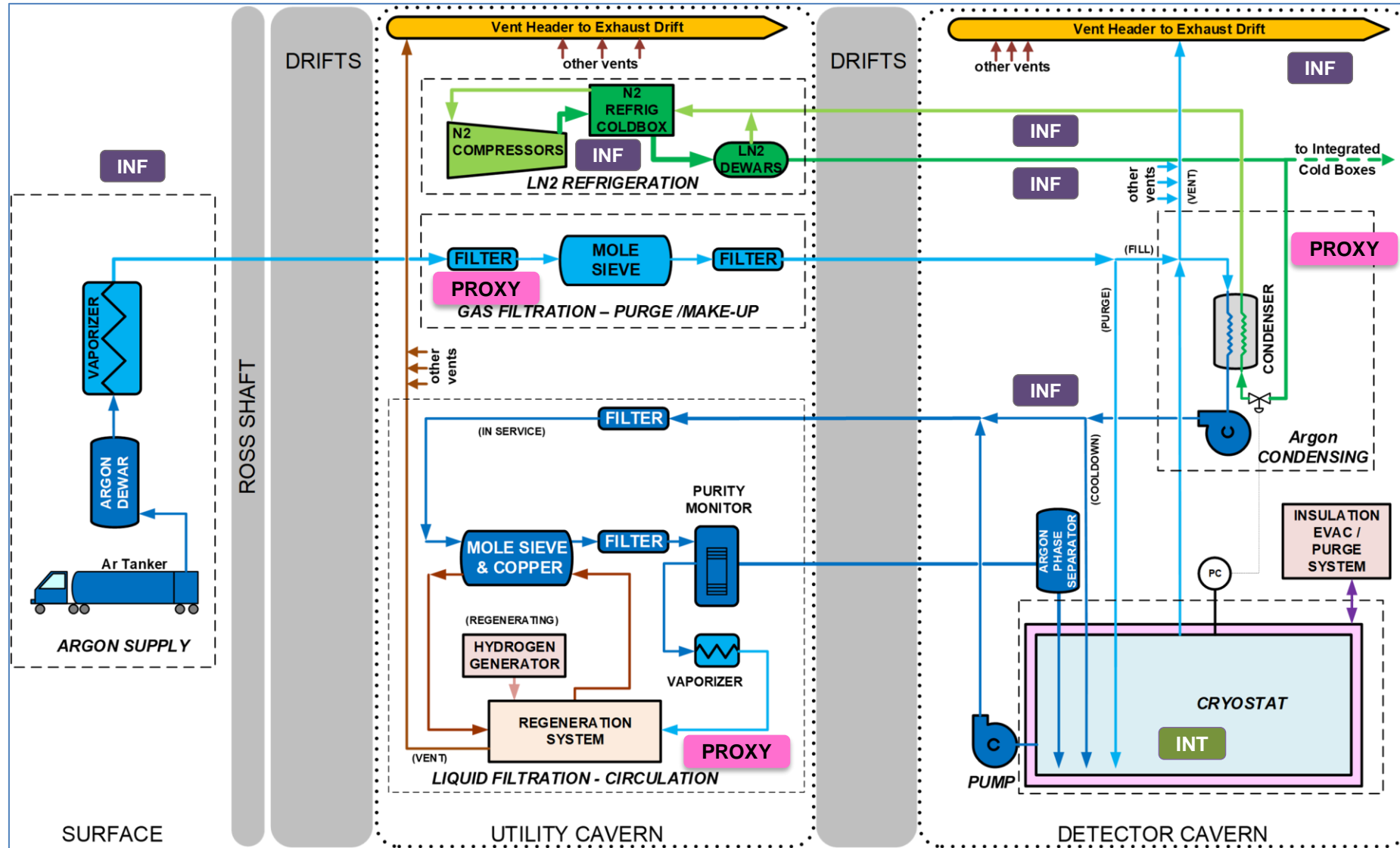
Modes of Operations

- 1) **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.
- 2) **GAr Circulation:** GAr is circulated in a closed loop and purified through GAr purification system. Reduces O₂ and H₂O to sub-ppm level.
- 3) **Cool-down:** LAr is sprayed at top cryostat until contents are around 90K (only for 2nd cryostat).
- 4) **Filling:** GAr is transferred from surface to be re-condensed underground. Once cryostat and detector are cold, LAr flows from condenser into each cryostat.
- 5) **Steady state operations:**
 - LAr is circulated from cryostats to be purified via external pumps (3 per cryostat, 2 initially in-service to achieve required purity levels of 100 ppt O₂ equivalent contamination, 1 available as spare).
 - Boil-off GAr is re-liquified in condensers outside of each cryostat and sent to LAr purification system before returning to vessel.
- 6) **Emptying:** Once experiment concludes and operations cease, cryostats are emptied, and Argon removed.

NO cryogenics/cryogenics in the shaft.

- Infrastructure
- Proximity
- Internal

Cryogenics Infrastructure Process Flow Diagram



Relevant Cryogenics Parameters

| Parameter | Value | Note |
|--|---|--|
| GAr Purge Flow rate | 1,123 m ³ /hr | From 1.2 m/hr |
| LAr filling flow rate | 0.8 / 0.5 kg/s | 1 st /2 nd Cryostats (w/ 3 LN2 refrigeration units) |
| LAr filling duration | 257 / 436 days | 1 st /2 nd Cryostats (w/ 3 LN2 refrigeration units) |
| Cryostat static heat leak | 48.7 kW | Each cryostat |
| Electronics heat load | 23.7 kW | Each cryostat |
| Total estimated heat load | 87.1 / 98.2 kW | Each cryostat (only) with 1/2 LAr pumps in operation |
| Condensers size (per cryostat) * | 3 x 100 kW = 300 kW | 3 LN2 units for cryostats 1 & 2, 4 th unit for 3 & 4 |
| Refrigeration capacity | 3 x 100 kW = 166 ton/day LN2 | Measured at condensers (> 99% uptime) |
| Maximum LAr circulation speed (assuming 5 days turnover) | 1.73 m ³ /min (40 kg/s) | 2 LAr pumps in operation (1 extra available as spare) |
| Nominal LAr circulation | 0.43 m ³ /min (10 kg/s) | Only 1 LAr pump in operation |
| Required LAr Purity | FD-1/HD: 100 ppt (~3.2 ms lifetime) FD-2/VD: 50 ppt (~6 ms lifetime) | O ₂ equivalent contamination (O ₂ , H ₂ O). ProtoDUNE achieved <10 ppt (30+ ms lifetime). |

* Condensers modularity may be different but need to match refrigeration modularity.

Infrastructure Cryogenics

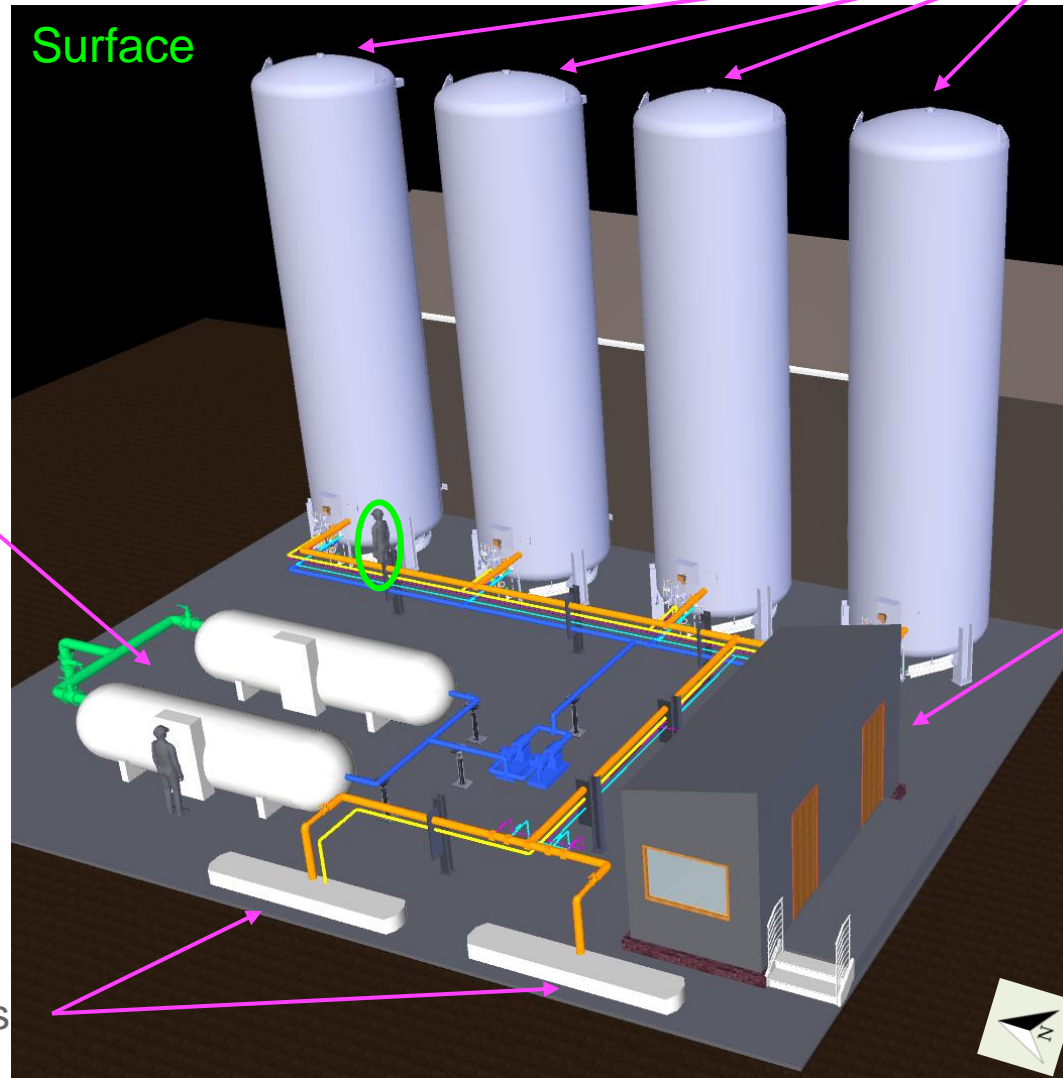
Argon Receiving Facilities

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

- Vaporizers
(2N redundancy)

Vaporizers: 2 x 500 kW

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



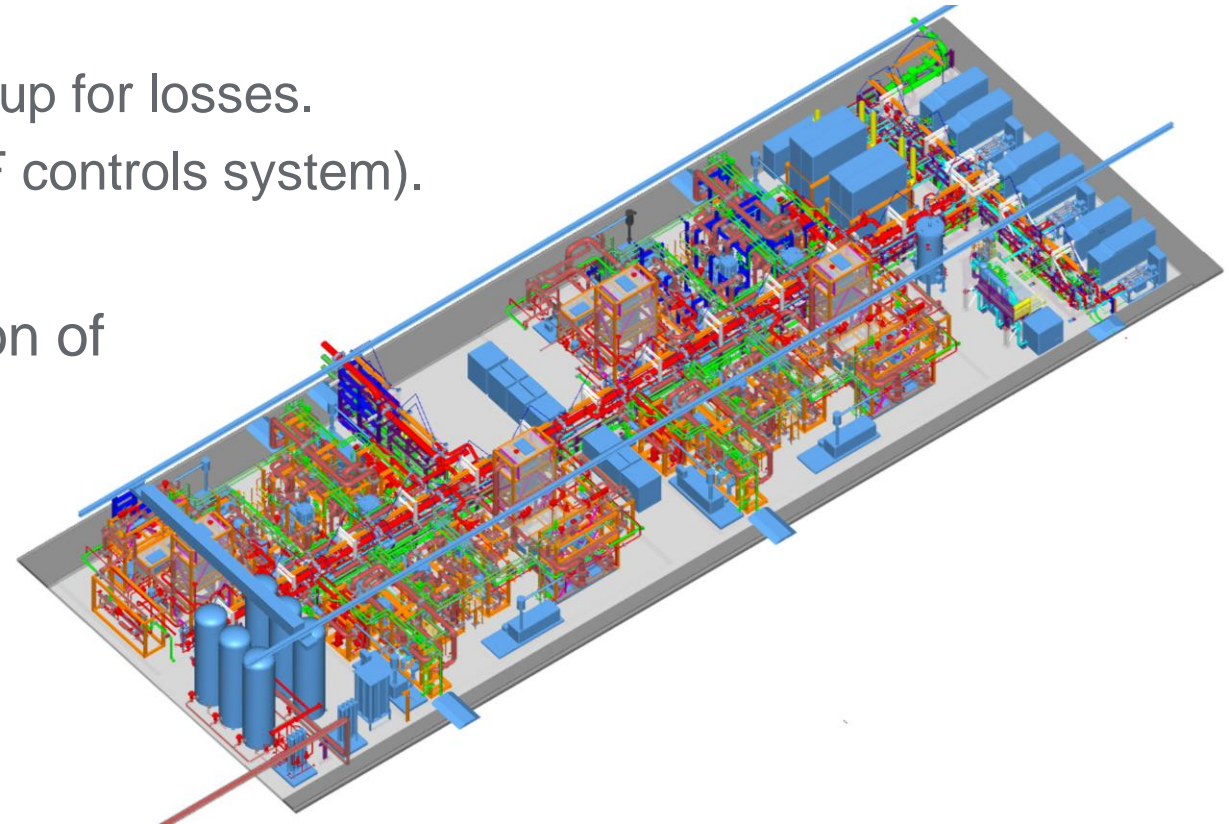
Argon Purity Shed
(Controls + Argon sampling
to verify impurities)

Space and utilities for
LAr Pumps (if needed)

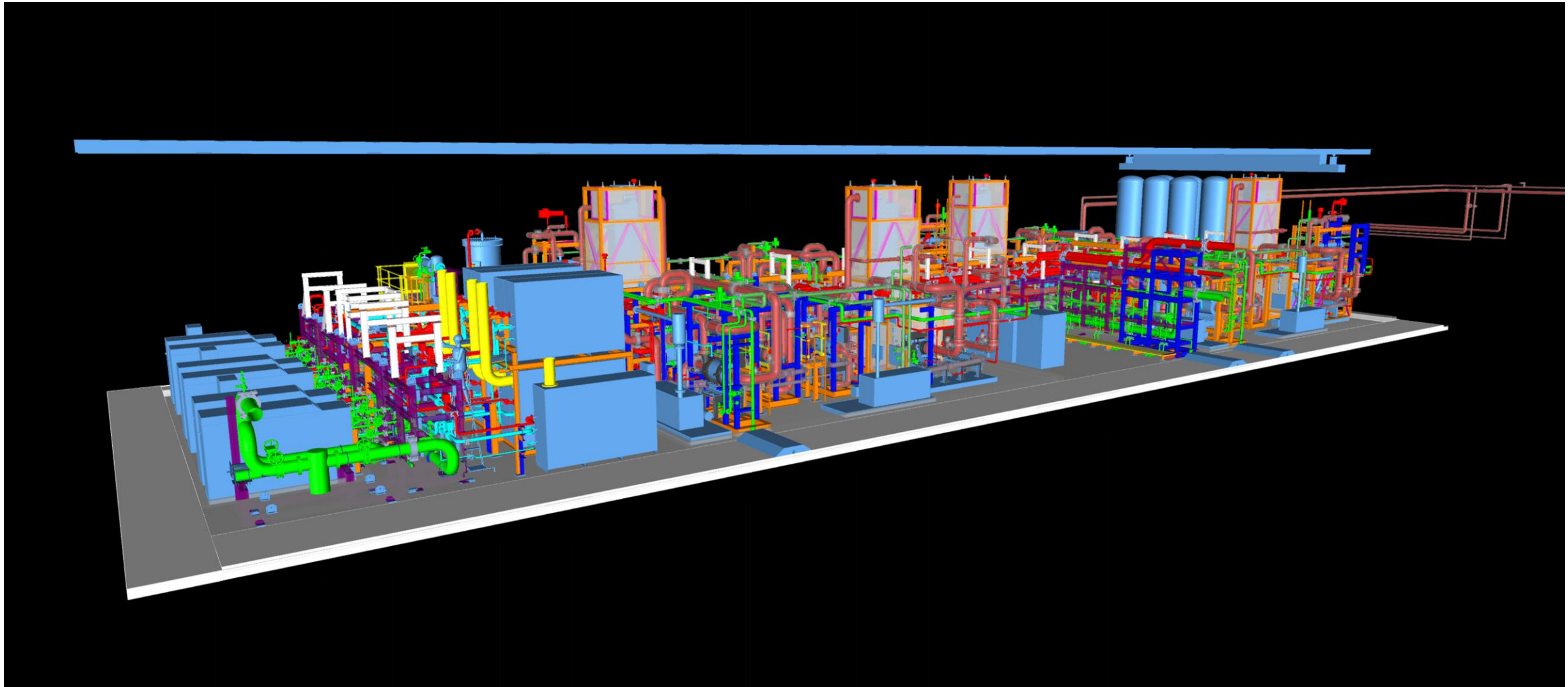
LAr Tankers Offloading stations

Nitrogen System

- **Consists of:**
 - Nitrogen Refrigeration System (4 x 100 kW units total). Modularity driven by ops.
 - LN2/GN2 Distribution.
 - LN2 storage.
 - GN2 generation to charge system and make up for losses.
 - Process Controls (to be integrated with LBNF controls system).
- Provides **refrigeration** (in 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.
- Under contract with **Air Products**.

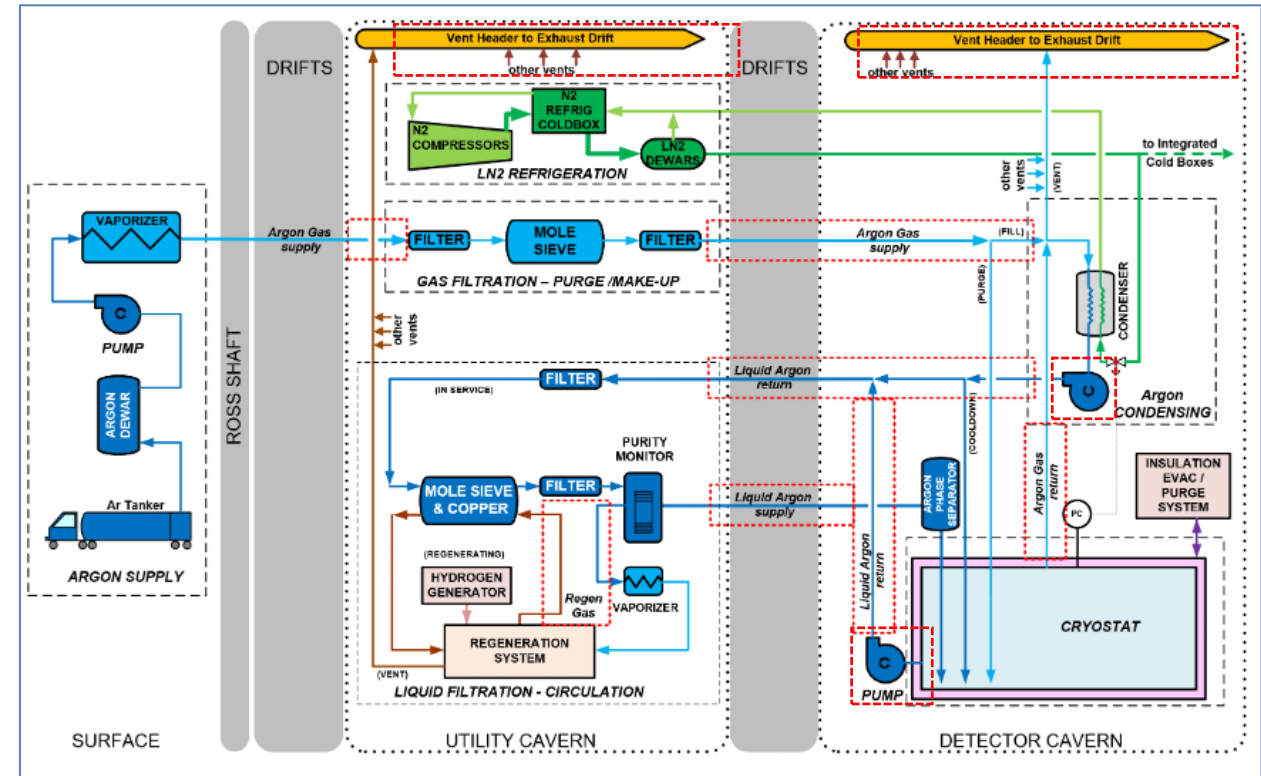


Nitrogen System view



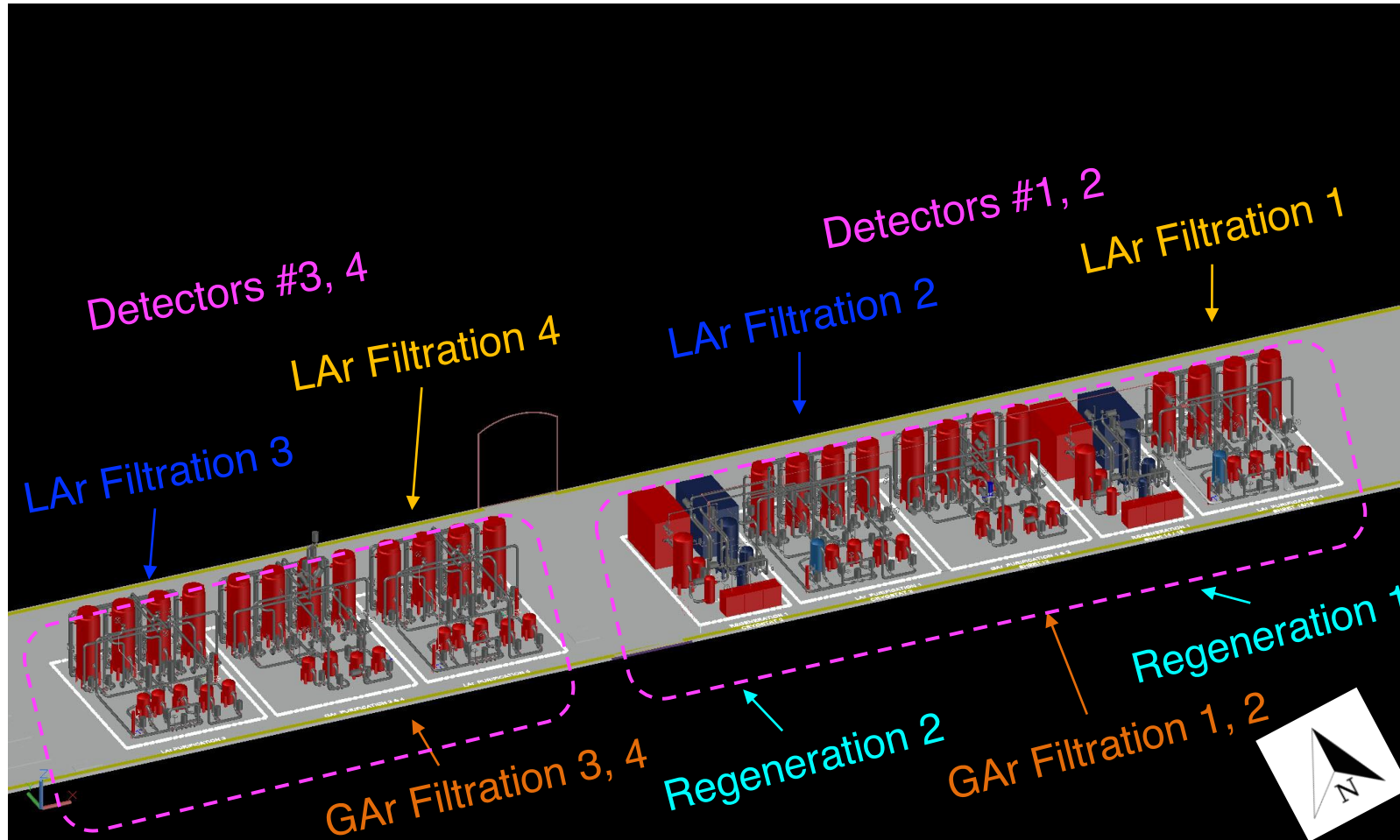
Argon Distribution

- Distributes **Argon** in liquid and gas phase.
- Connects items in separate Caverns (e.g., cryostat and argon purification).
- Connects equipment supplied by different parties in same cavern (e.g., Argon purification, regeneration).
- Also includes:
 - **LAr Pumps** and inline safety valves.
 - **Nitrogen** supply/return to/from Regeneration system.
 - CUC and North/South caverns **Vents**.
- Procured as Engineering/Manufacturing/Installation.
- **Challenges:**
 - Transportation and installation 1 mile underground.
 - Leak tightness.



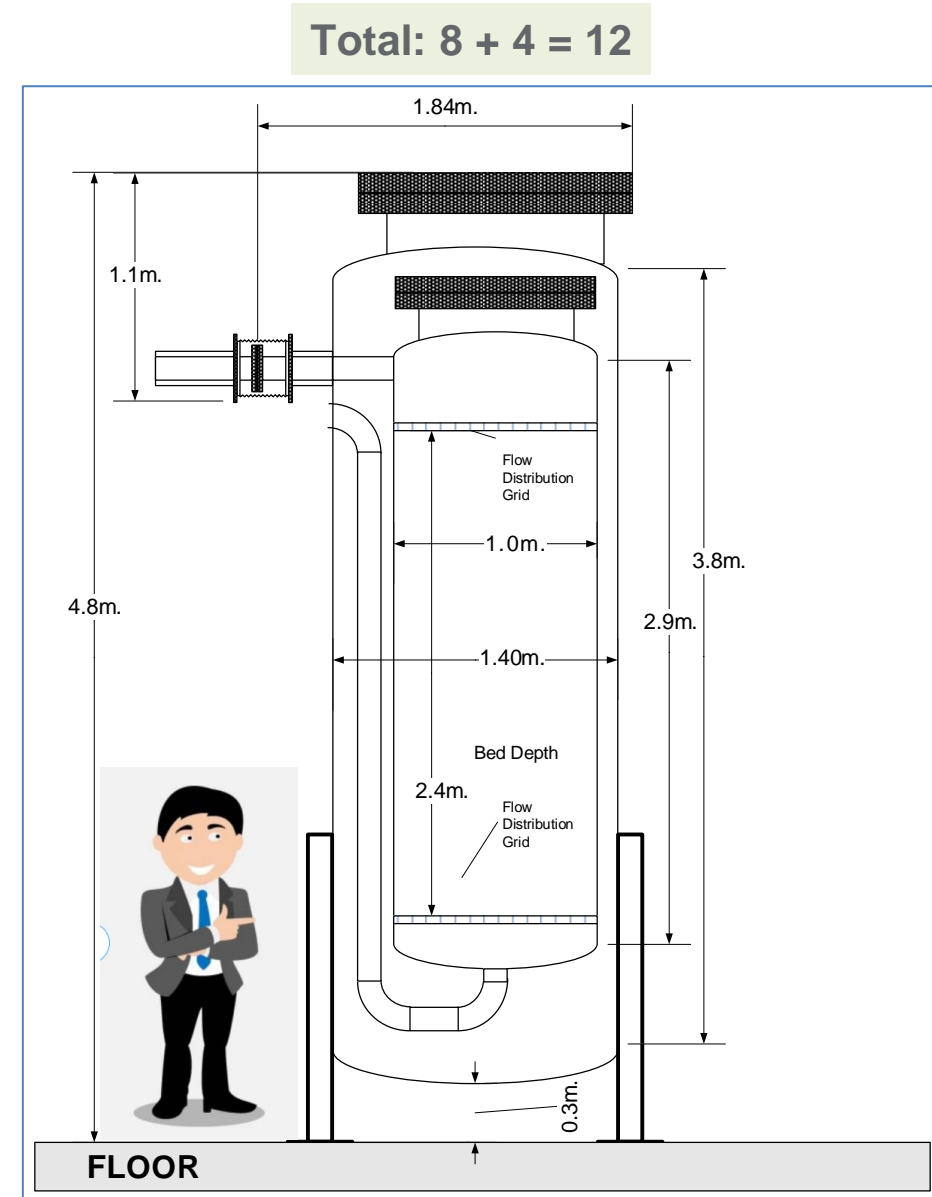
Proximity Cryogenics

Proximity Cryogenics in CUC



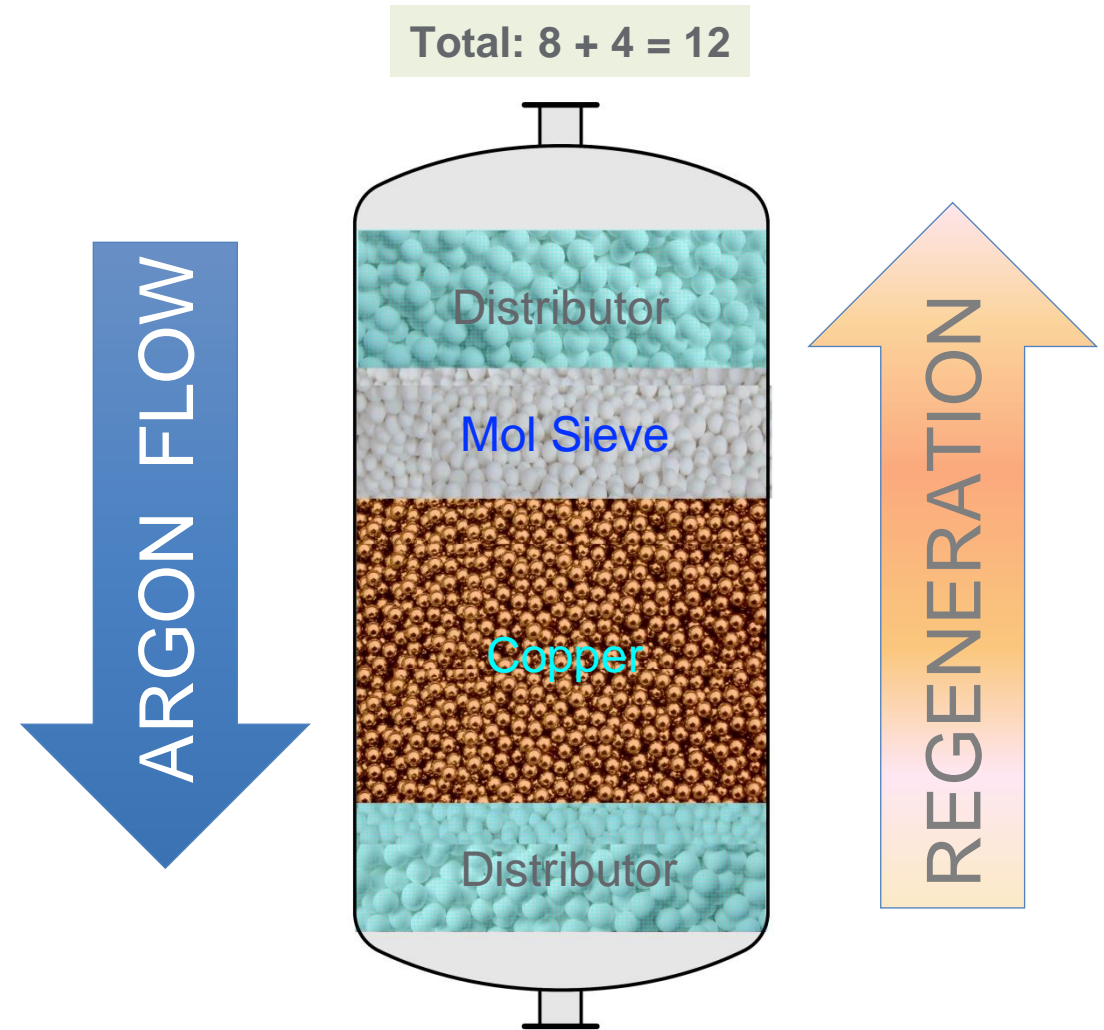
Proximity Cryogenics in CUC: Argon Filtration

- 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.



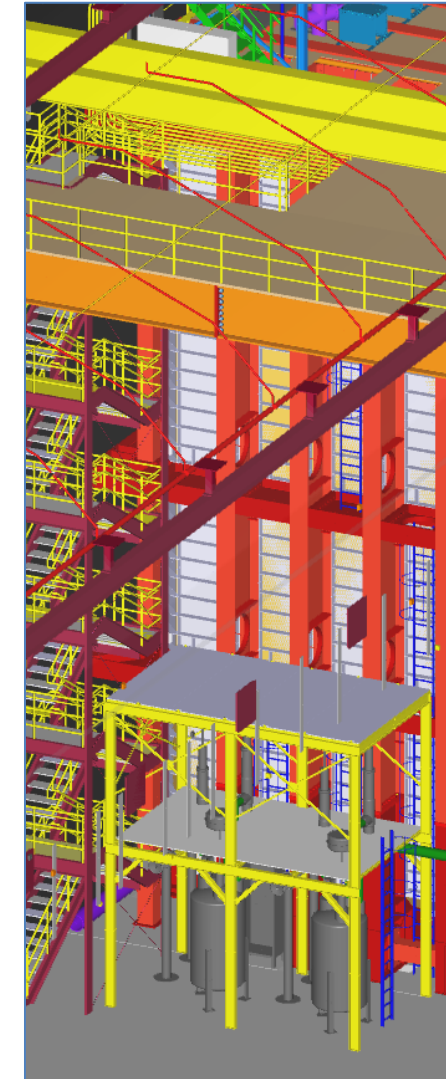
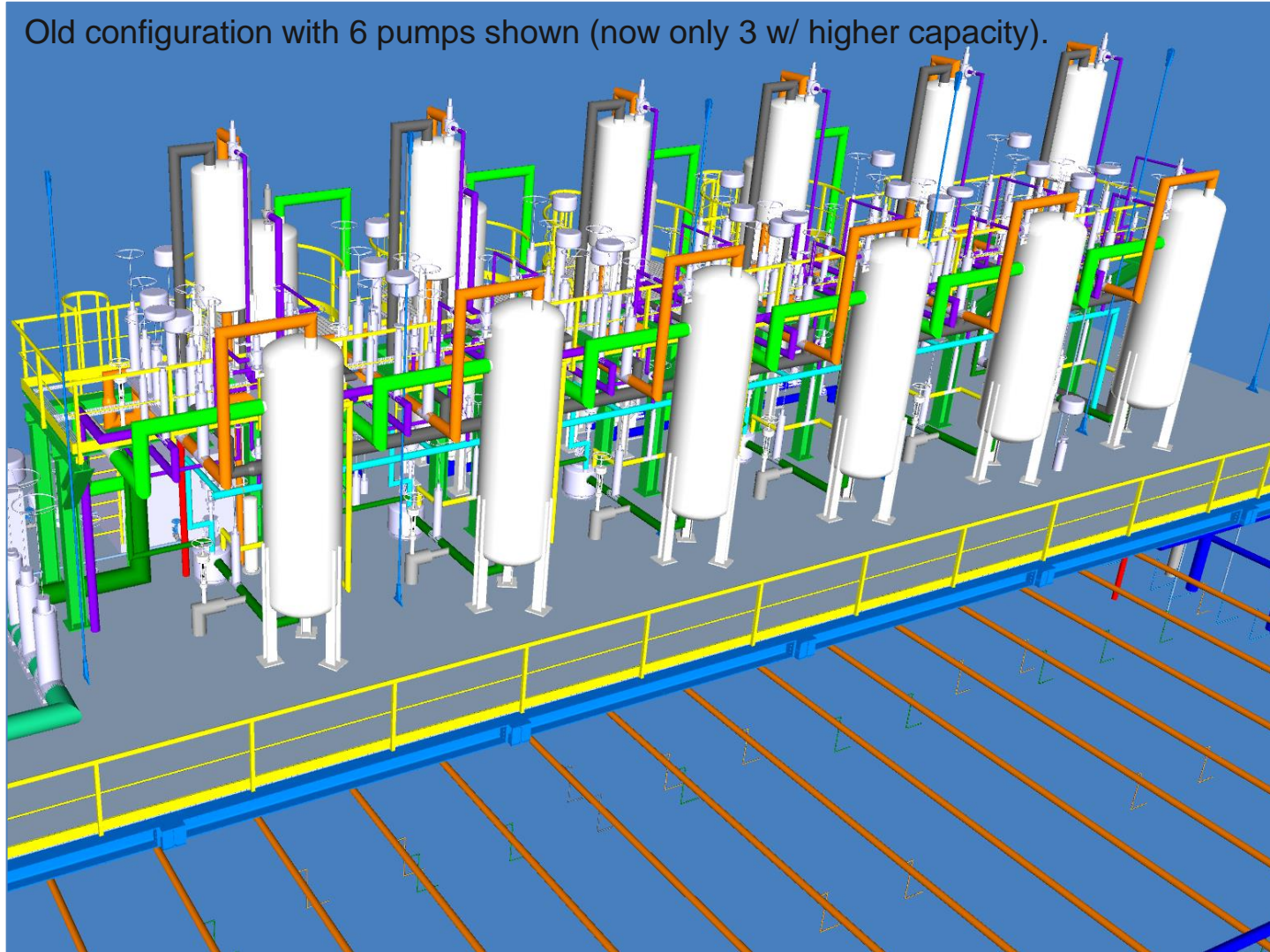
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Proximity Cryogenics in Detector Cavern: Argon Condensers System (South cavern) and LAr circulation (North cavern)

Old configuration with 6 pumps shown (now only 3 w/ higher capacity).



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)**.
- 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 mi (1,609 km) away!
 - Subcontract needs to be 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.

LBNF/DUNE by numbers

- **800,000 mTon** of rock excavated (x8 aircraft carriers!).
- **5,000 m³** of concrete (x13,000 washer/drier or x3,700 large refrigerators).
- 4 cryostats:
 - Each about **66 m x 19 m x 18 m** (217 ft x 62 ft x 59 ft).
 - Each filled with **12,600 m³** liquid Argon at **87K** (x5 Olympic swimming pools!).
 - Each containing a modular Detector.
- **9,000 meters** of pipes (~30,000 ft or 5.6 miles).
- **88** cryogenic vessels at **87K**:
 - 40 about 5 m high (16 ft).
 - 48 about 2-3 m high (7-9 ft).
- **24** LAr circulation **pumps**.

Summary

- Far Site Cryogenics builds upon successful LAr programs at Fermilab and CERN.
- Challenges related to location and logistics.
- Execute our plan to partner w/ industry and acquire systems.



Thank You!

Supplemental Slides

Cavern Excavation



Cavern Excavation



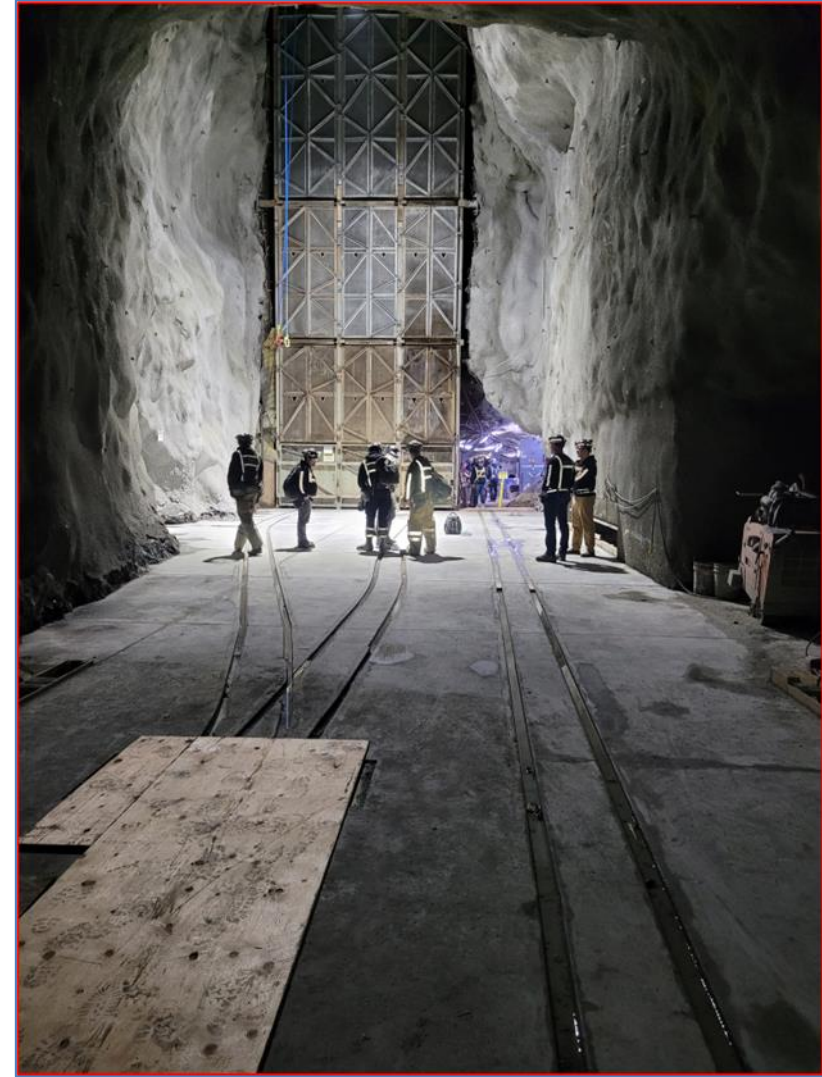
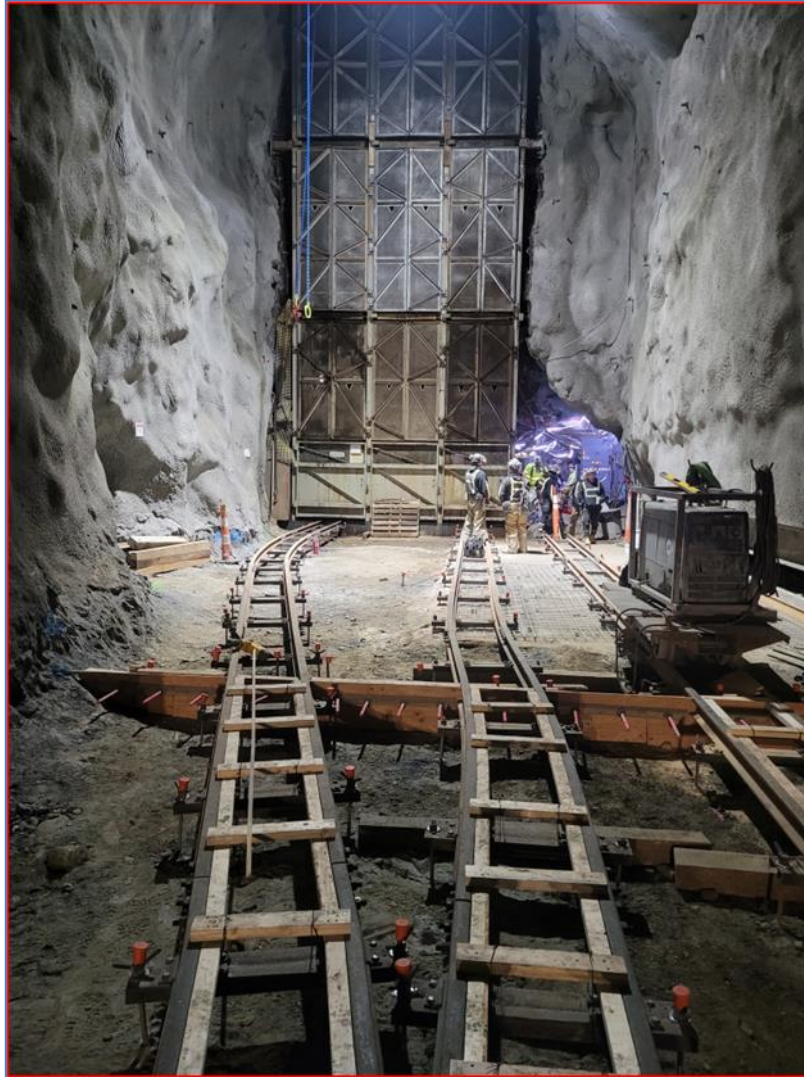
Cavern Excavation



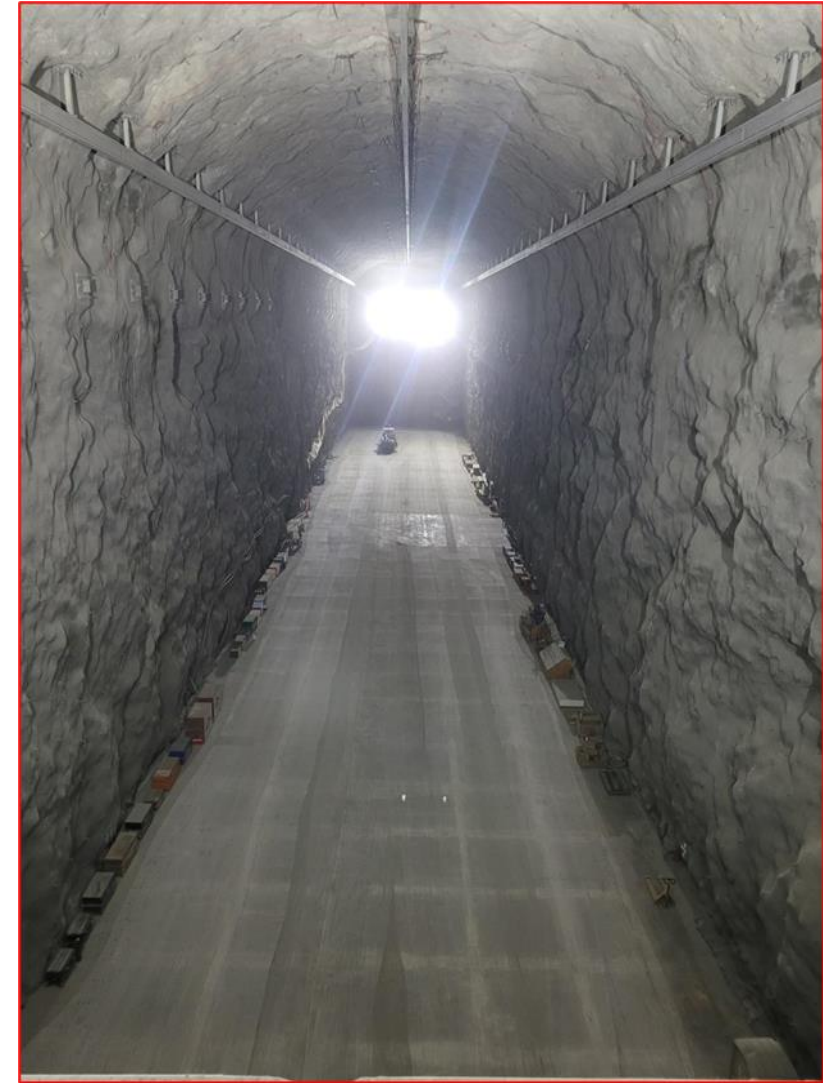
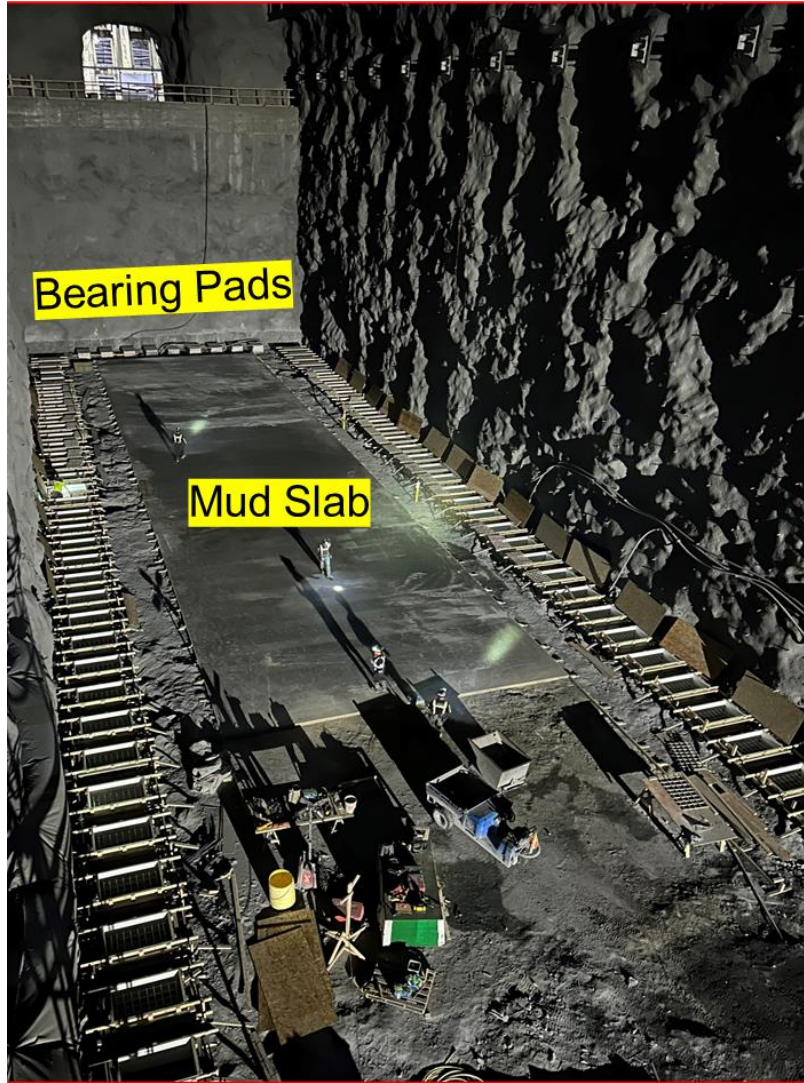
Excavation Status – North Cavern – Excavation Complete - Concrete Floor



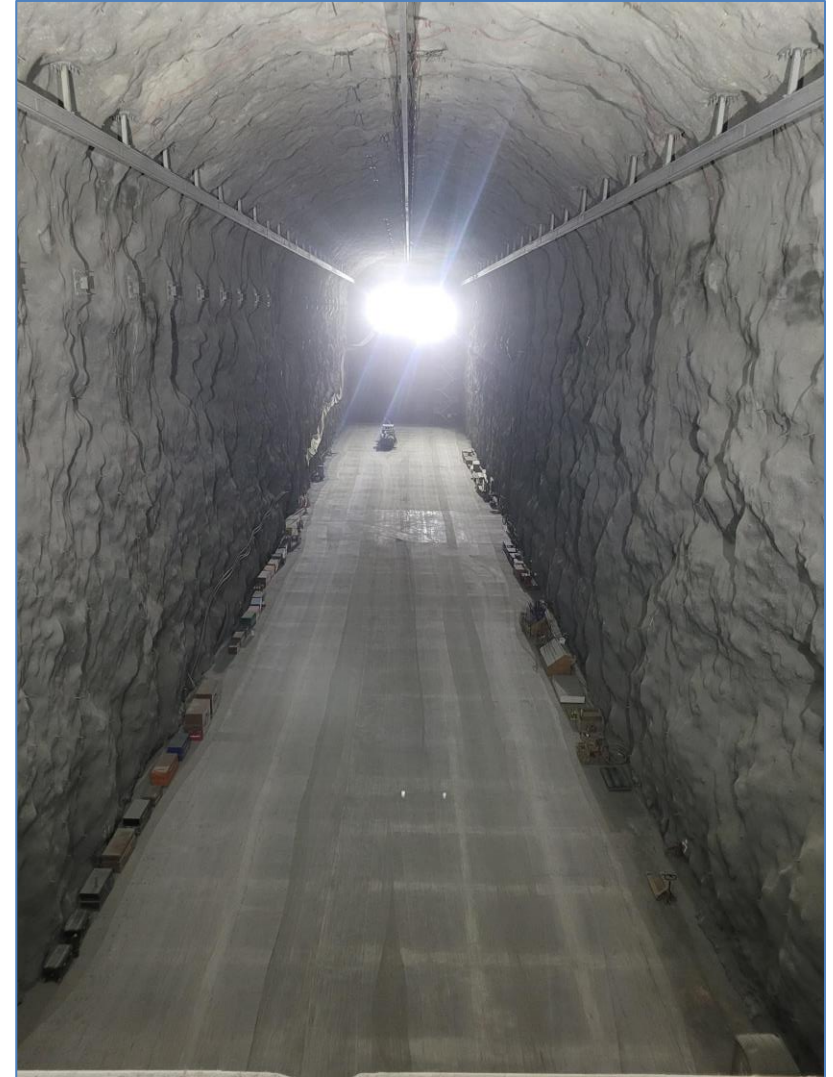
Ross Brow



North Cavern Concrete



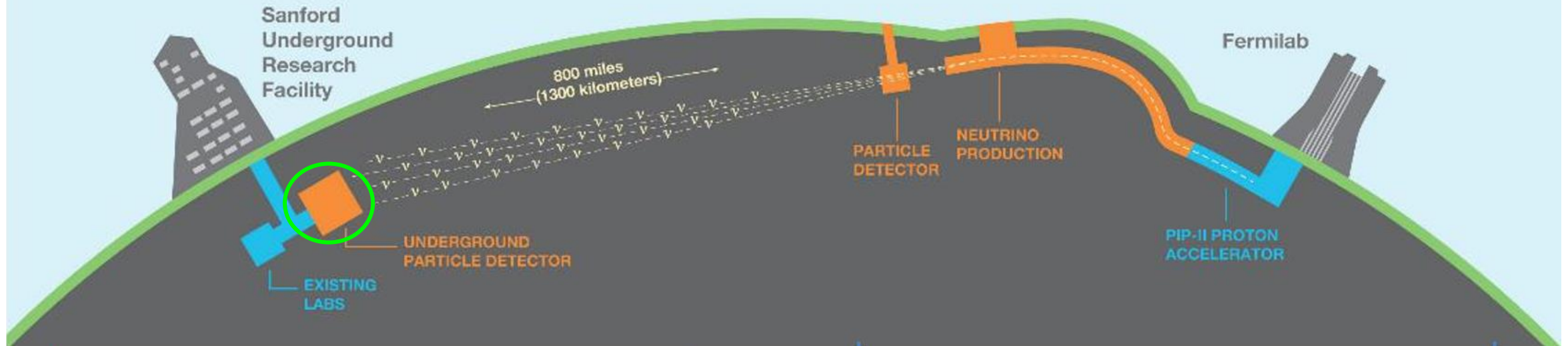
South Cavern Concrete



DOE Project Scope - Delivered at Two Sites through Five Subprojects

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

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



Three subprojects

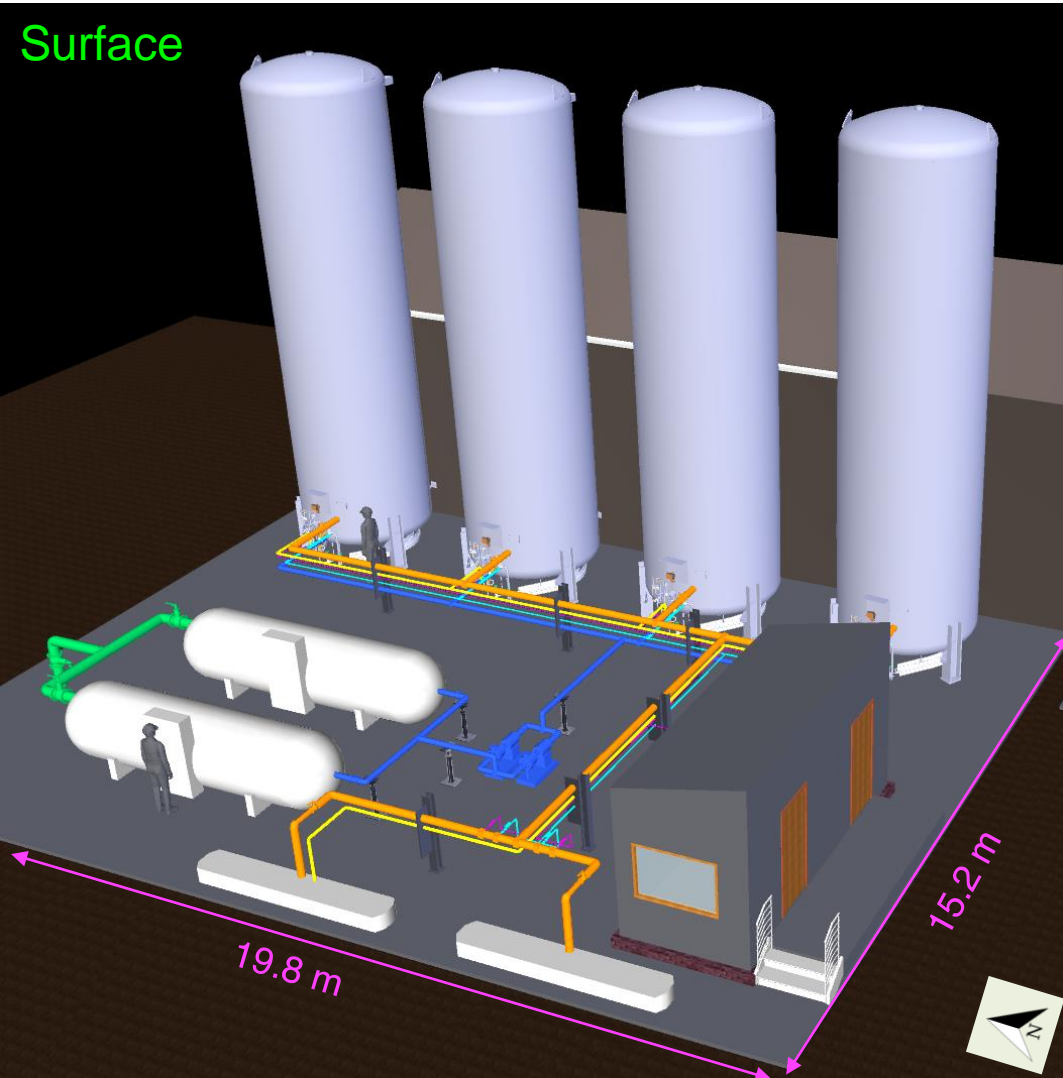
Two subprojects

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

- **NSCF+B** – Near Site Conventional Facilities + Beamline
- **ND** – Near Detectors

Far Site Cryo Scope Graphics

Surface



Underground (4850L) = 1 mile deep

Argon Purification/Regeneration supporting full scope shown.

