Cryogenic Engineering at Fermilab

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Undergraduate Lecture Series

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Overview

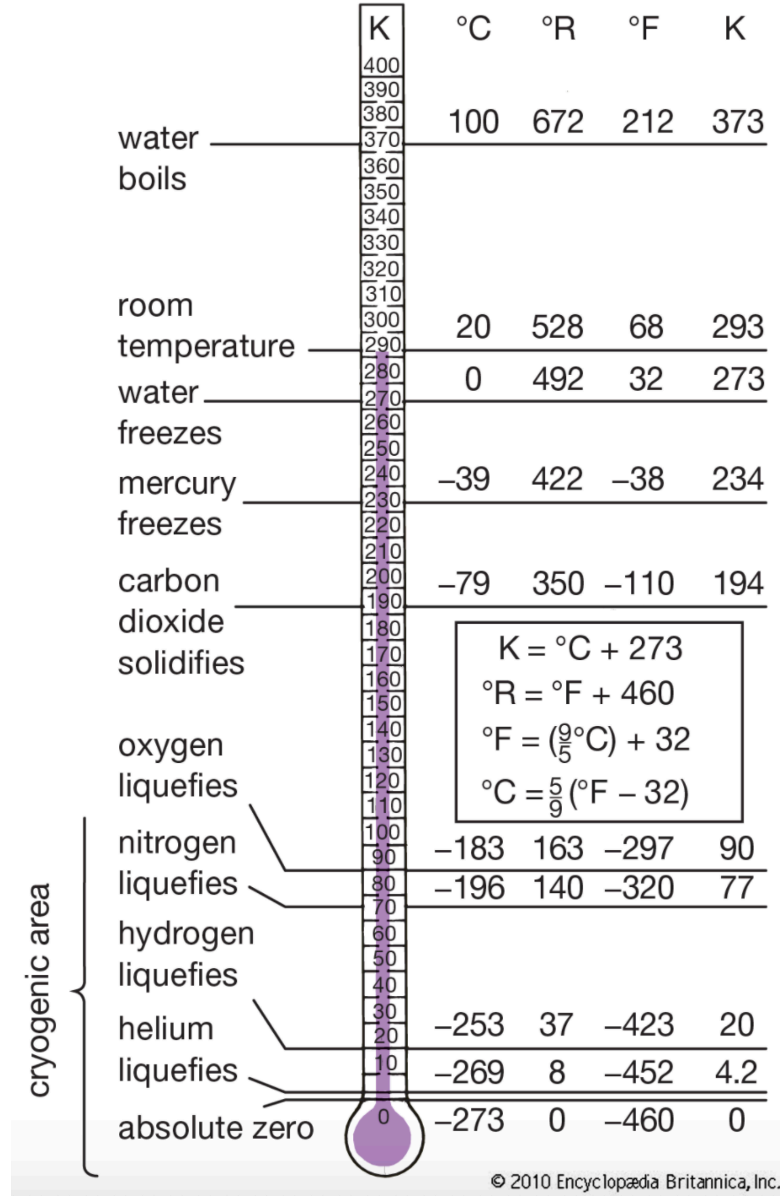
- About Me
- Basics of Cryogenics
- Cryogenic Engineers at Fermilab
- Projects
  - R&D Liquid Argon Projects
  - Short Baseline Neutrino Program
  - LBNF/DUNE
  - PIP-II
  - Muon G-2
  - Super Cryogenic Dark Matter Search

About Me

- B.S. in Mechanical Engineering
- M.S. in Mechanical Engineering (expected 2021)
- Started at Fermilab in 2017
- My Roles at Fermilab
  - Neutrino Division Technical Support Department, Cryo Group
  - Engineering support for liquid argon projects at PAB (Neutrino Division R&D facility)
  - Cryogenic piping and pressure vessel projects
  - Previous fSWE co-chair, current member
  - Recruiting efforts at national engineering conferences

Basics of Cryogenics

- Production and behavior of materials at very low temperatures
- Gases with boiling points below 150°C
- Typically use the Kelvin scale, which starts at absolute zero (0 K)



Basics of Cryogenics

Nitrogen (N_2)

- 78% of Air
- Boiling point: 77 K (–321°F)
- Freezing point: 63 K (–346°F)
- Non-toxic, odorless, colorless, inert, non-flammable

Argon (Ar)

- 0.93% of Air
- Boiling point: 87 K (–303°F)
- Freezing point: 84 K (–308°F)
- Non-toxic, odorless, colorless, inert, non-flammable

Basics of Cryogenics

- **Helium (He)**
- 0.0005% of Air
- Boiling point: 4.2 K (–452°F)
- Freezing point: 1 K (–458°F)
  - Must apply 2.5 MPa of pressure to form solid
- Non-toxic, odorless, colorless, inert, non-flammable
- Can reach temperatures as low as 2 mK using a dilution refrigerator

Storage and Transport

- Vacuum insulated containers (dewars)
  - No conduction or convection heat transfer through vacuum
  - Layers of reflective foil inside vacuum jacket reduces radiation heat transfer
- Foam insulated containers
  - Less expensive than vacuum insulated components
  - Not as effective
  - Take up more physical space
- Insulation reduces the rate at which cryogen boils off
- No dewar can provide perfect thermal insulation

Cryogenic Safety

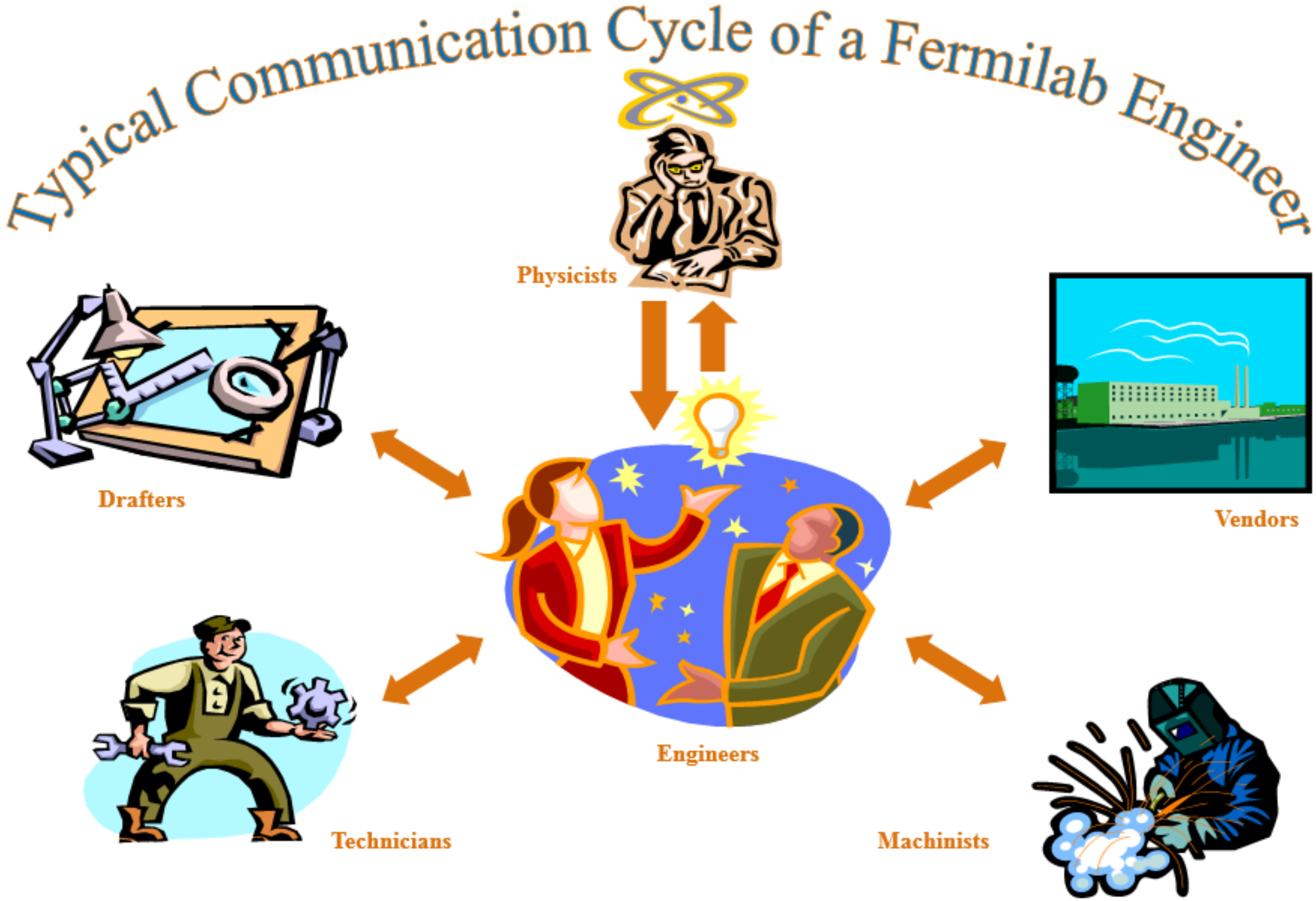
- Expansion ratios from cryogenic liquid to room temperature gas
  - Nitrogen: 1 to 696
  - Argon: 1 to 847
  - Helium: 1 to 757
- Cryogenic liquid contained in a sealed dewar
  - Heat from surroundings increases temperature of cryogen inside
  - Pressure inside dewar increases
  - Can lead to an explosion if there is no way to relieve excess pressure build-up
- Relief devices are used on all cryogenic dewars and piping to prevent over-pressure scenarios
- Set of ASME and FESHM codes for safe design and operation
- Release of gas from cryogenic vessels can displace oxygen in the air
- Specific PPE required when handling cryogenic liquids

Cryogenic Engineering at Fermilab

Cryogenic Engineering at Fermilab

- What do cryogenic engineers do?
  – Work on projects with unique and challenging requirements
  – Employ cutting edge technologies
  – Build, test, repair and upgrade the machines and systems that Fermilab scientists rely upon
  – Design systems to keep the Fermilab accelerator components thermally stable
  – Design, build, and operate systems for detectors that require massive amounts of liquid argon to detect neutrinos

Cryogenic Engineering at Fermilab



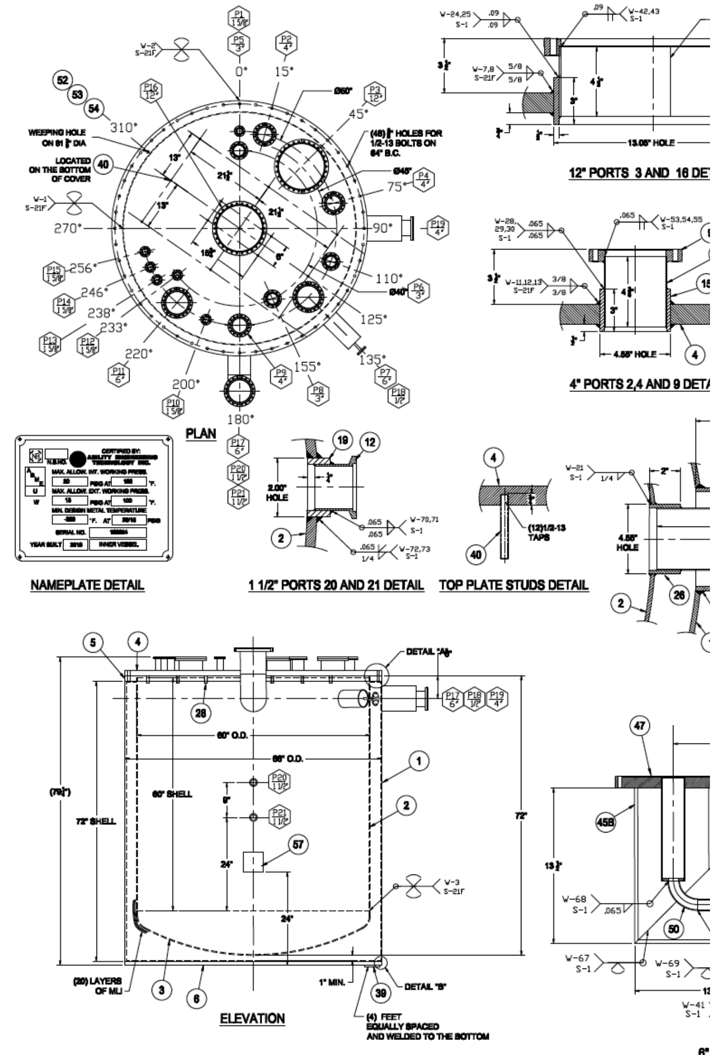
Courtesy of Mayling Wong-Squires

Liquid Argon R&D Projects

- Proton Assembly Building small scale projects
  - High purity liquid argon used for neutrino physics research
  - Set of filters removes oxygen and water from liquid argon
  - Liquid nitrogen used for condensing liquid argon in cryostats
  - Materials Test Stand (”Luke”)
    - Testing materials properties and outgassing rates in liquid argon
  - Iceberg
    - Testing electronic components for the DUNE project

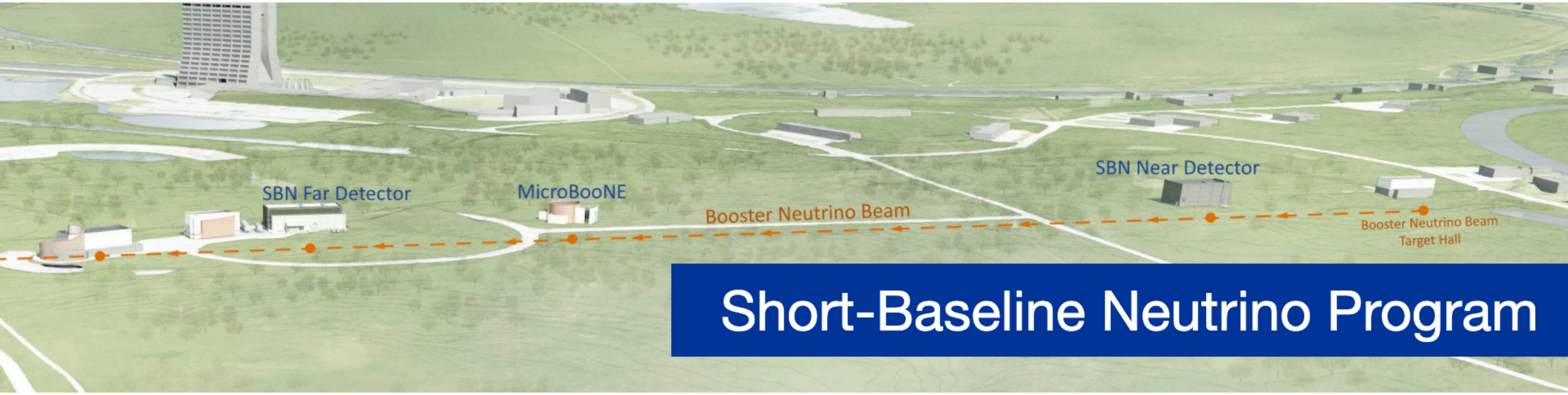
Liquid Argon R&D Projects

- Engineering the Iceberg Cryostat
  - Established the design parameters with physicists
  - Wrote the specification document
  - Worked with the fabrication company as the cryostat was being built
  - Designed associated liquid argon and liquid nitrogen piping for the project
  - Purchased all instruments and components for cryostat and piping
  - Sized relief devices based on over-pressure scenarios
  - Wrote in-depth engineering reports
  - Oversaw installation of piping and cryostat
  - Operate system and troubleshoot any issues that arise



Liquid Argon Neutrino Experiments

- Short Baseline Neutrino Program (SBN)
  - "The SBN Program will use its detectors to measure the energy spectrum and flavor of the neutrinos produced by the Fermilab Booster Neutrino Beam"
  - Consists of three experiments: MicroBooNe, SBN Near Detector, SBN Far Detector

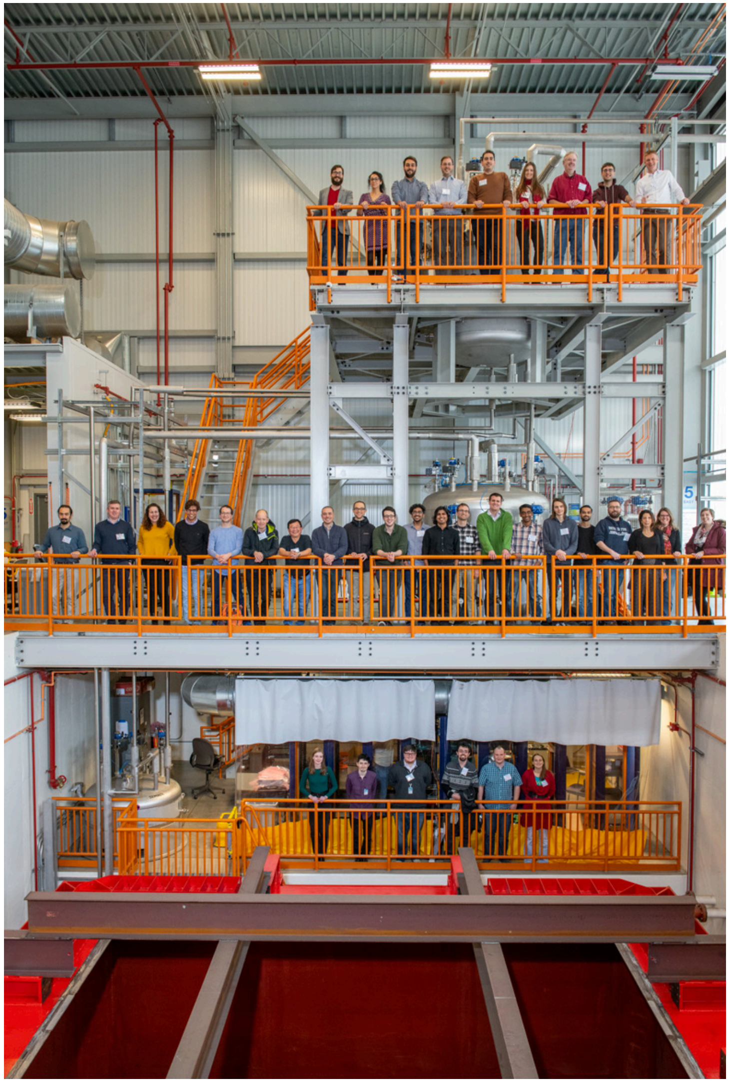


Liquid Argon Neutrino Experiments

- MicroBooNe
  - Operating and taking data since 2015
  - 80 tons of liquid argon

- SBN Far Detector
  - Began operations in May 2020
  - The ICARUS T600 detector is housed in two cryostats holding liquid argon time projection chamber modules and photodetectors
  - Largest of the SBN program detectors with 500 tons of liquid argon

- SBN Near Detector
  - 112 tons of liquid argon
  - Membrane cryostat housing a liquid argon time projection chamber
  - Currently in the design phase



MicroBooNe

MicroBooNe

SBN Far Detector

The second of two ICARUS detector modules is lowered into its place in the detector hall. Photo: Reidar Hahn

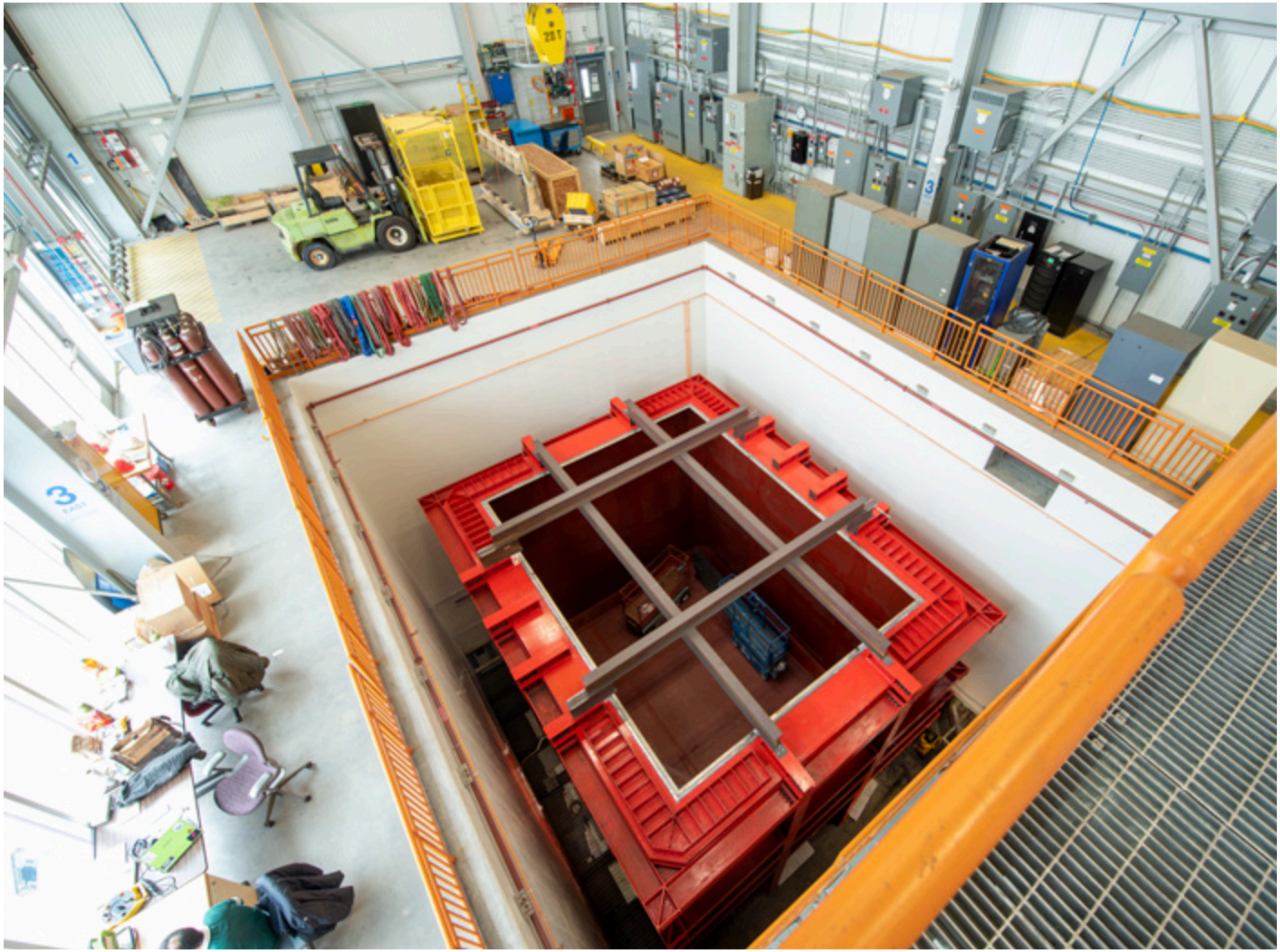
SBN Far Detector

View of the ICARUS detector inner TPC: on the left the cathode plane can be seen, while the wire planes and the PMT system are seen in the right

SBN Far Detector

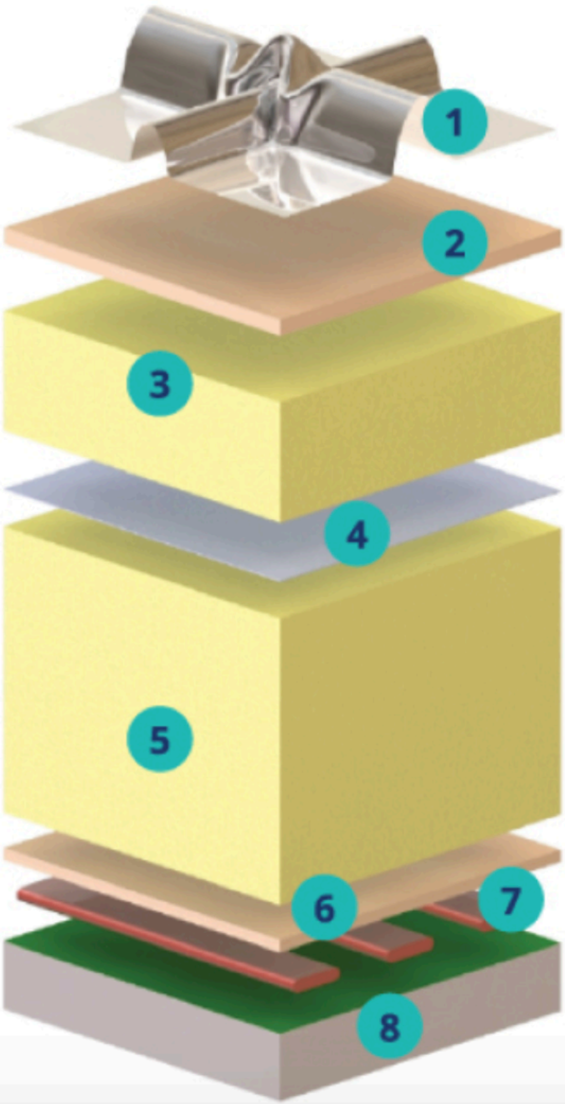
Fermilab

SBN Near Detector



SBN Near Detector

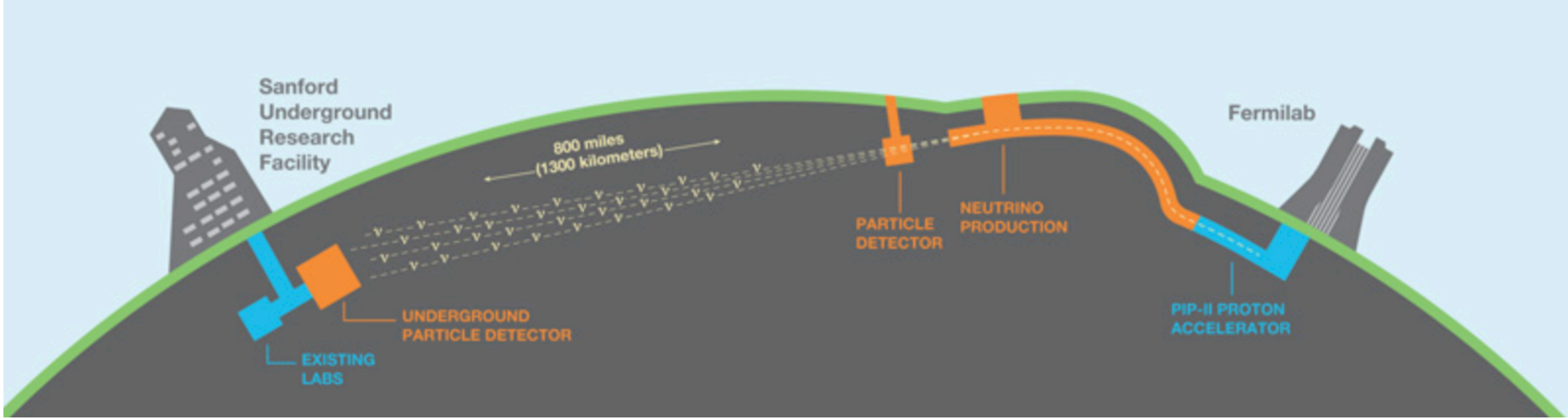
Membrane Cryostat Technology



1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Steel structure with moisture barrier

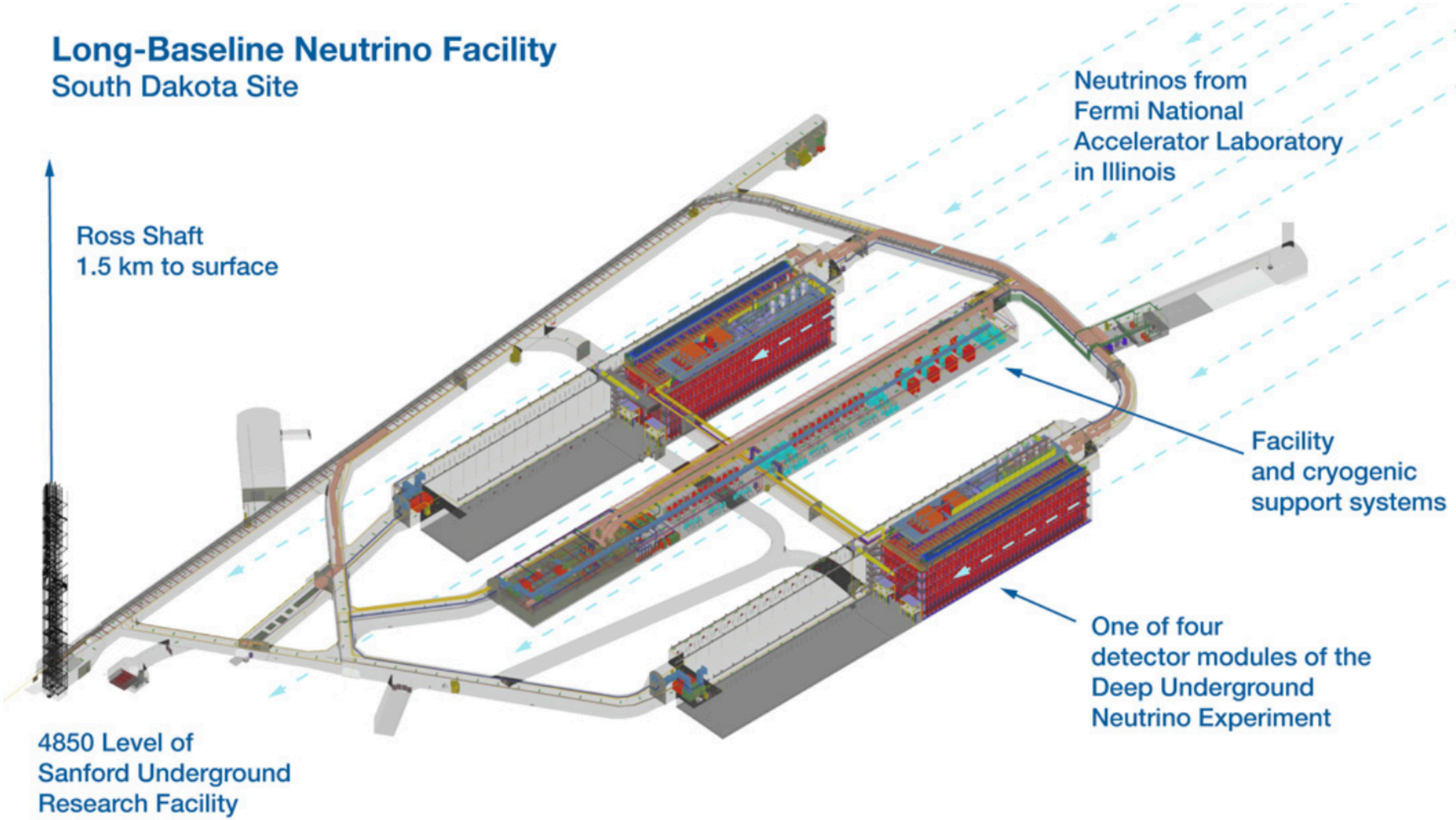
LBNF/DUNE

Long Baseline Neutrino Facility for the Deep Underground Neutrino Experiment

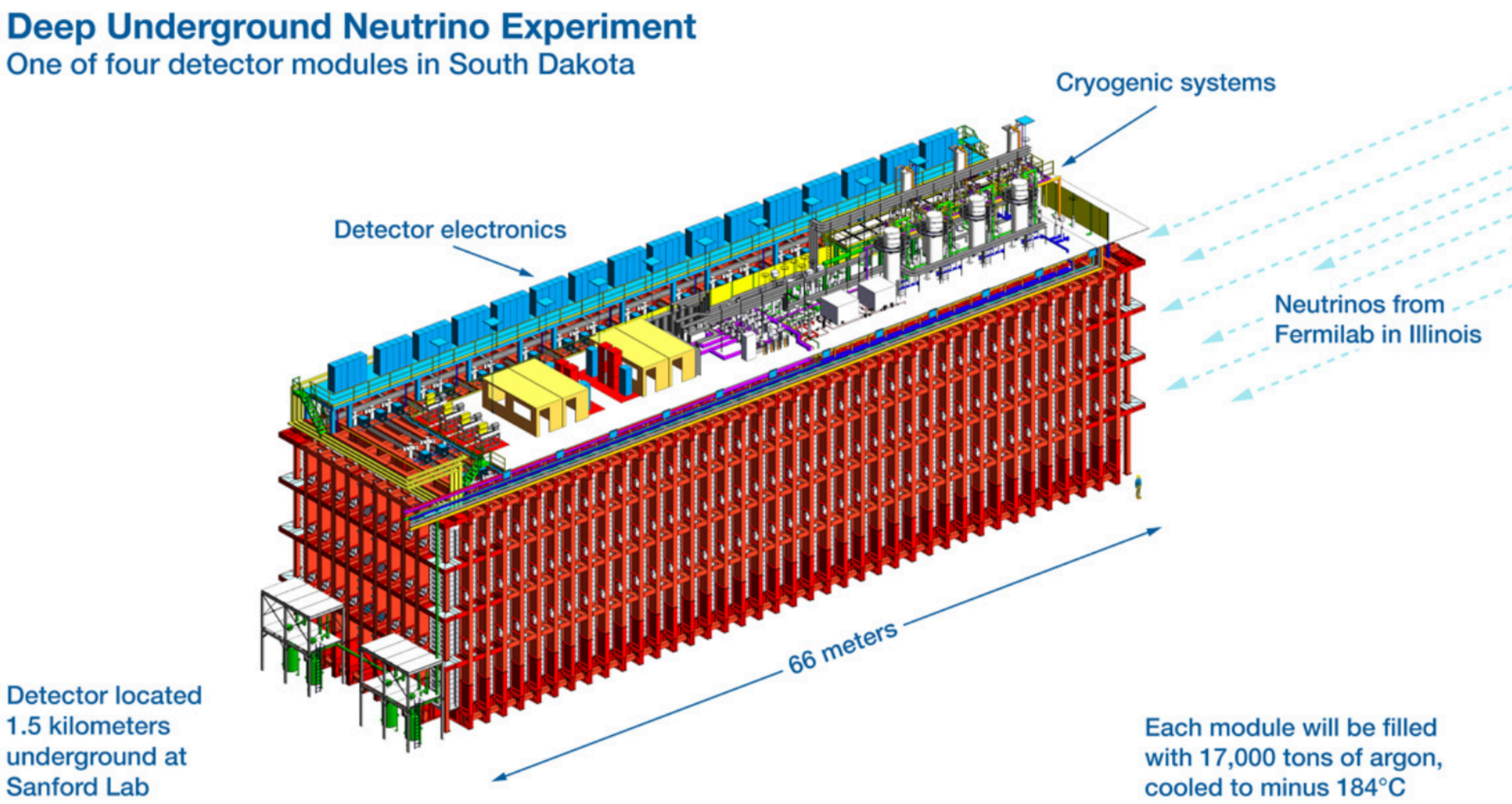


- Largest underground liquid argon experiment in the world
- Particles will be sent 800 miles from Fermilab to Sanford Underground Research Facility in South Dakota
- The detector in South Dakota will be installed 1 mile underground
- Experiment consists of 4 membrane cryostats, each as tall and wide as a four-story building and almost as long as a football field
- Filled with 70,000 tons of liquid argon
- 800,000 tons of rock will be excavated from Sanford Lab's underground caverns

LBNF/DUNE


Long-Baseline Neutrino Facility
South Dakota Site
Neutrinos from
Fermi National
Accelerator Laboratory
in Illinois
Ross Shaft
1.5 km to surface
Facility
and cryogenic
support systems
One of four
detector modules of the
Deep Underground
Neutrino Experiment
4850 Level of
Sanford Underground
Research Facility

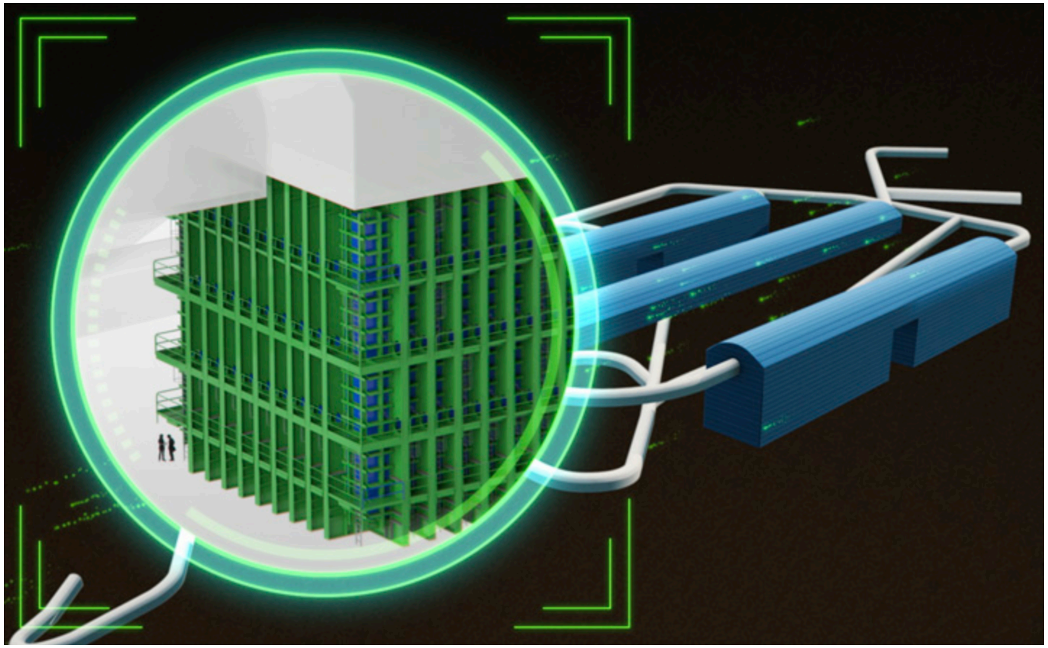
LBNF/DUNE



Deep Underground Neutrino Experiment
One of four detector modules in South Dakota
Cryogenic systems
Detector electronics
Neutrinos from Fermilab in Illinois
66 meters
Detector located 1.5 kilometers underground at Sanford Lab
Each module will be filled with 17,000 tons of argon, cooled to minus 184°C

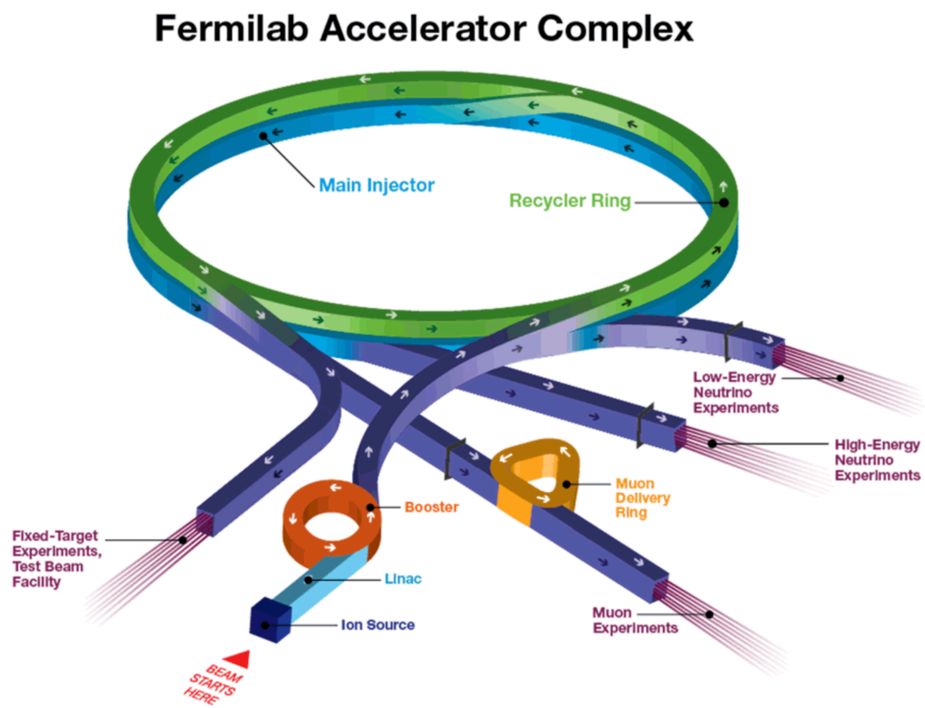
LBNF/DUNE

- The cryogenics system includes the pipes, pumps, filters and other equipment needed to chill, circulate and purify the liquid argon. The system will also circulate liquid nitrogen which will be used to keep the liquid argon cold
- During the initial filling period, LBNF plans for about five 18-ton deliveries by truck per day at the far detector. The argon will be piped from the surface as gas and recondensed to a liquid underground



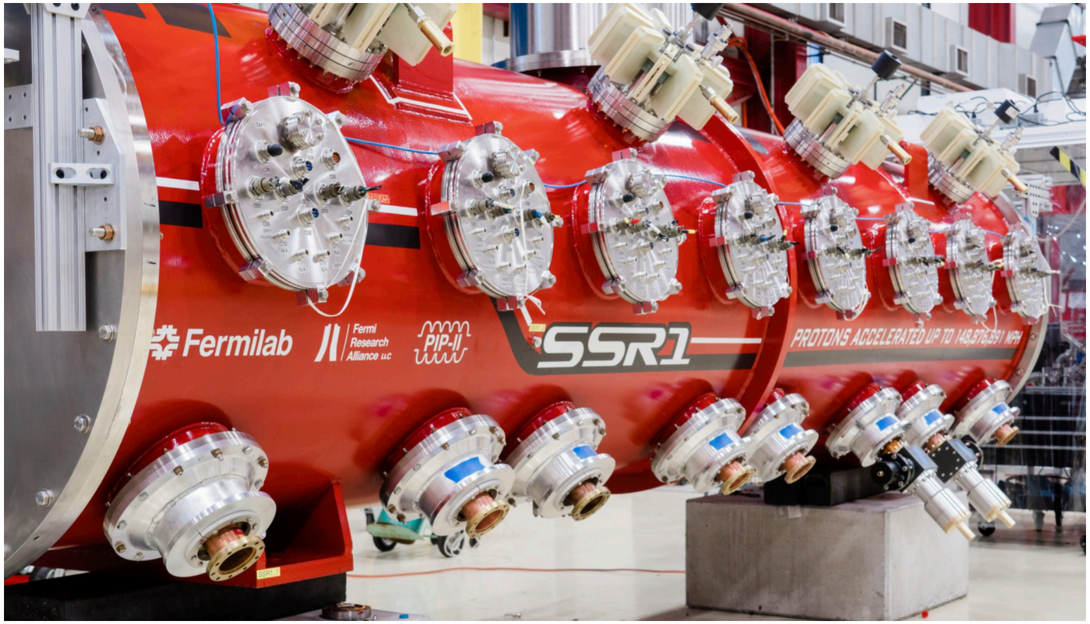
PIP-II

- Proton Improvement Plan II – upgrades to the Fermilab accelerator complex
- The world's most intense neutrino beam
- Superconducting radio-frequency (SRF) cavities make it possible to accelerate intense proton beams to higher energies in relatively short distances
- SRF cavities, made of niobium, generate electric fields that propel the particle beam forward
- Several of these cavities are held inside a vessel called a cryomodule



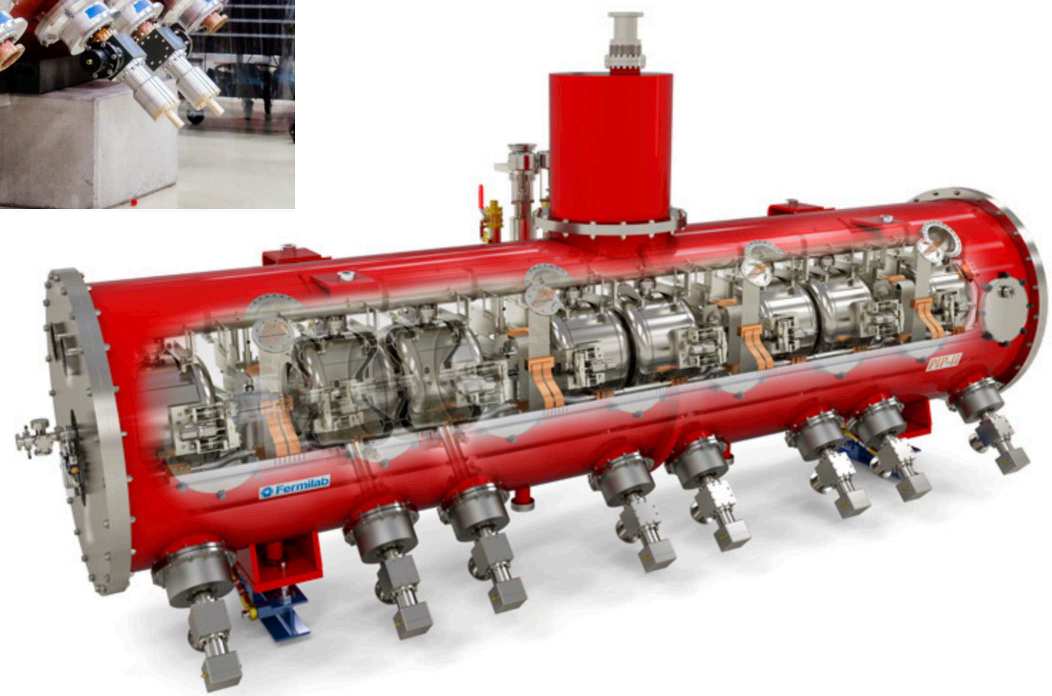
Fermilab

PIP-II



The cryomodule is filled with liquid helium and keeps the SFR cavities at a few Kelvin

This extreme cold temperature is key to their operation and efficiency

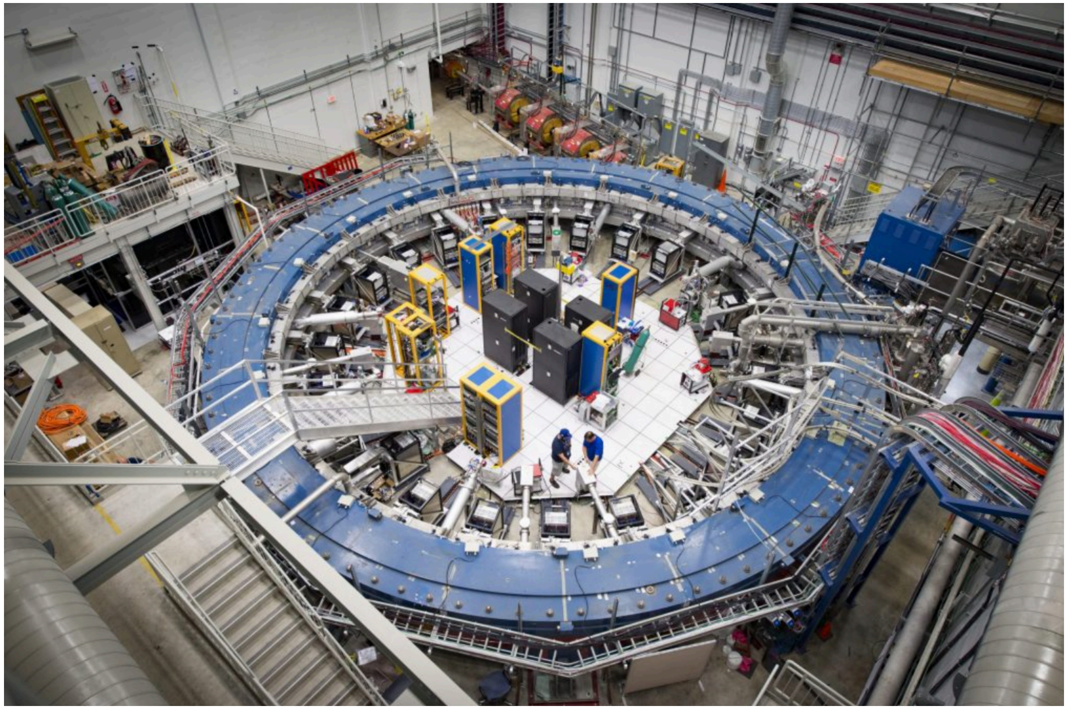


Muon G-2

- 50-foot diameter superconducting electromagnet
- In 2013, the magnet was moved from Long Island to Fermilab in one piece
- The move took 35 days and traveled 3,200 miles over land and sea
- Muons orbit around the storage ring at nearly the speed of light
- Muons are continually decaying into neutrinos and positrons
- The neutrinos fly away undetected, but the positrons are measured

Muon G-2

Starting the experiment in 2015: “Bringing the ring down to its operating temperature of minus 450 degrees Fahrenheit required cooling it with a helium refrigeration system and liquid nitrogen for more than two weeks. This was not an easy task since the magnet shrank by at least an inch as it cooled down. This could have damaged the delicate coils inside if it was not done slowly.” – Symmetry Magazine

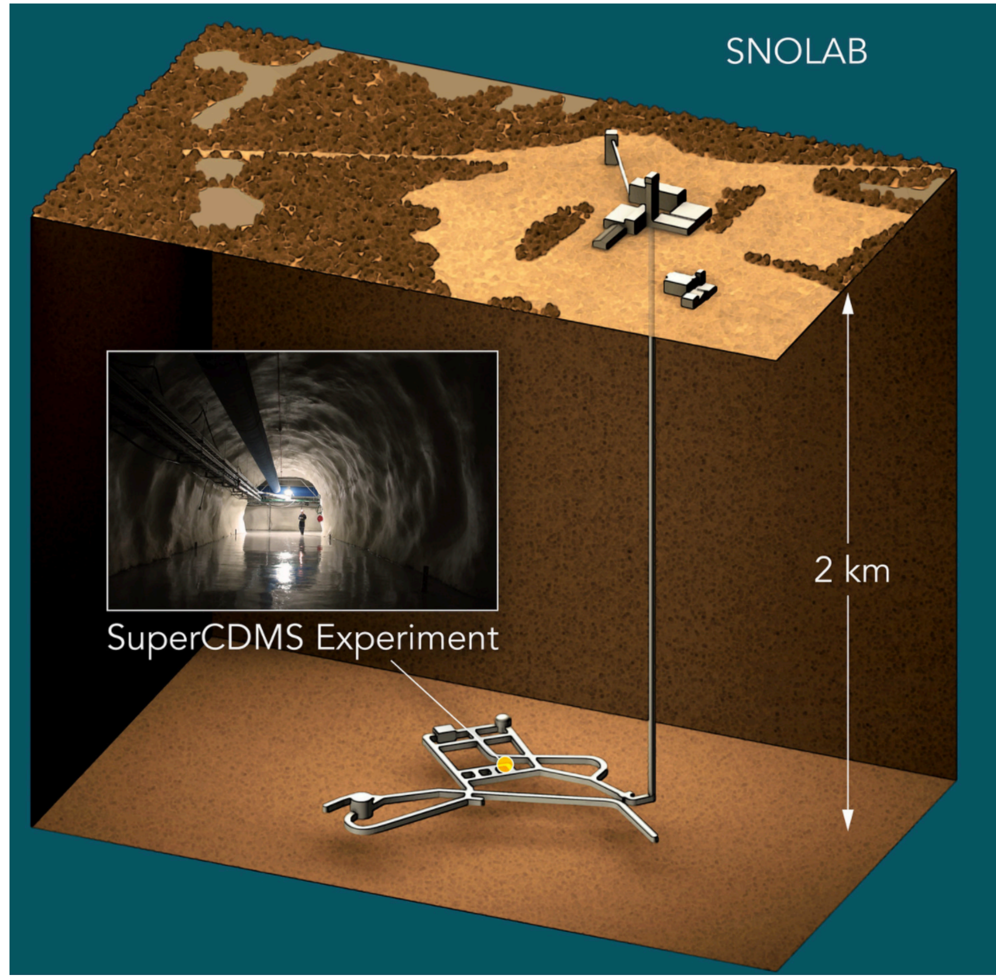


Super Cryogenic Dark Matter Search Experiment

- The SuperCDMS collaboration is searching for dark matter particles with masses smaller than ten times the mass of the proton
- Will be located underground at SNOLAB in Canada
- This location will provide shielding from high energy cosmic ray particles and from radioactive decay byproducts
- In October 2019, SuperCDMS scientists cooled their dilution refrigerator down to 5.3 millikelvin, the lowest temperature ever achieved at Fermilab

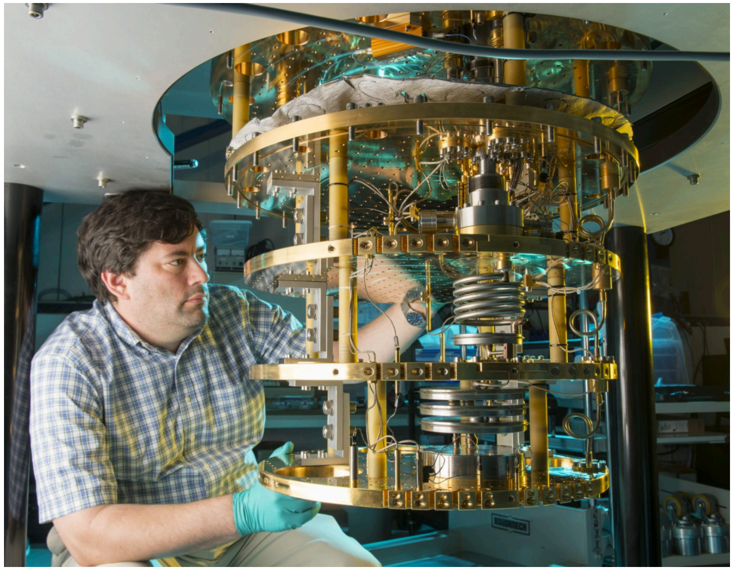
Super Cryogenic Dark Matter Search Experiment

"The colder the crystals in the dark matter detectors, the easier it will be to spot vibrations caused by dark matter particles. It's kind of like stepping outside during a Chicago winter with only a lightweight jacket. Just as people are more likely to notice you shivering if it's 20 below rather than above freezing, so too are dark matter detectors more likely to spot a dark matter particle at lower temperatures."



Super Cryogenic Dark Matter Search Experiment

- Dilution Refrigerator
  - Helium-3 and helium-4 are isotopes of helium
  - At high temperatures, they stay mixed and at low temperatures, they separate
  - SuperCDMS dilution fridge contains both isotopes
  - When mixed, a spontaneous quantum mechanical phase change occurs
  - Helium-3 “evaporates” into the helium-4 by pulling heat from a nearby energy source (the fridge itself)
  - This phase change cools the fridge and the detectors detectors



“Because there are so few people doing this kind of work, we couldn’t turn to the literature to see how a particular material will perform”

– Matt Hollister, Fermilab scientist

Thank you for your time!

Any questions?