Building for Discovery: PIP-II, LBNF, and DUNE

Chris Mossey, Fermilab Deputy Director for LBNF/DUNE-US

04 December 2020

LBNF and PIP-II partners include:

- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST
- Brazil/FAPESP-UNICAMP
- Switzerland/SERI, and
- CERN

plus the DUNE international collaboration and consortia

Fermilab CERN Sanford Underground Research Facility U.S. DEPARTMENT OF ENERGY Office of Science

v4

Outline

- P5 Context
- PIP-II Update
- LBNF/DUNE Update
- COVID-19 Assessment
- Summary

The 2014 US Particle Physics Project Prioritization Panel (P5) endorsed a global particle physics program

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

- Build a world-class neutrino program
- Host it as a global project
- Upgrade Fermilab accelerator complex to provide >1 MW proton beam

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest priority large project in its timeframe.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

European Strategy Update

The US neutrino program is supported by the European Strategy

The 2014 US Particle Physics Project Prioritization Panel (P5) endorsed a global particle physics program

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

- Build a world-class neutrino program
- Host it as a global project
- Upgrade Fermilab accelerat

The 2020 Update of the European Particle Physics Strategy

Europe, and CERN through the Neutrino Platform .....should continue to collaborate with the United States and other international partners towards the successful implementation of the Long Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).

European Strategy Update

execute a highly capable Long-
ject plan and identified resources must
highest priority large project in its timeframe.

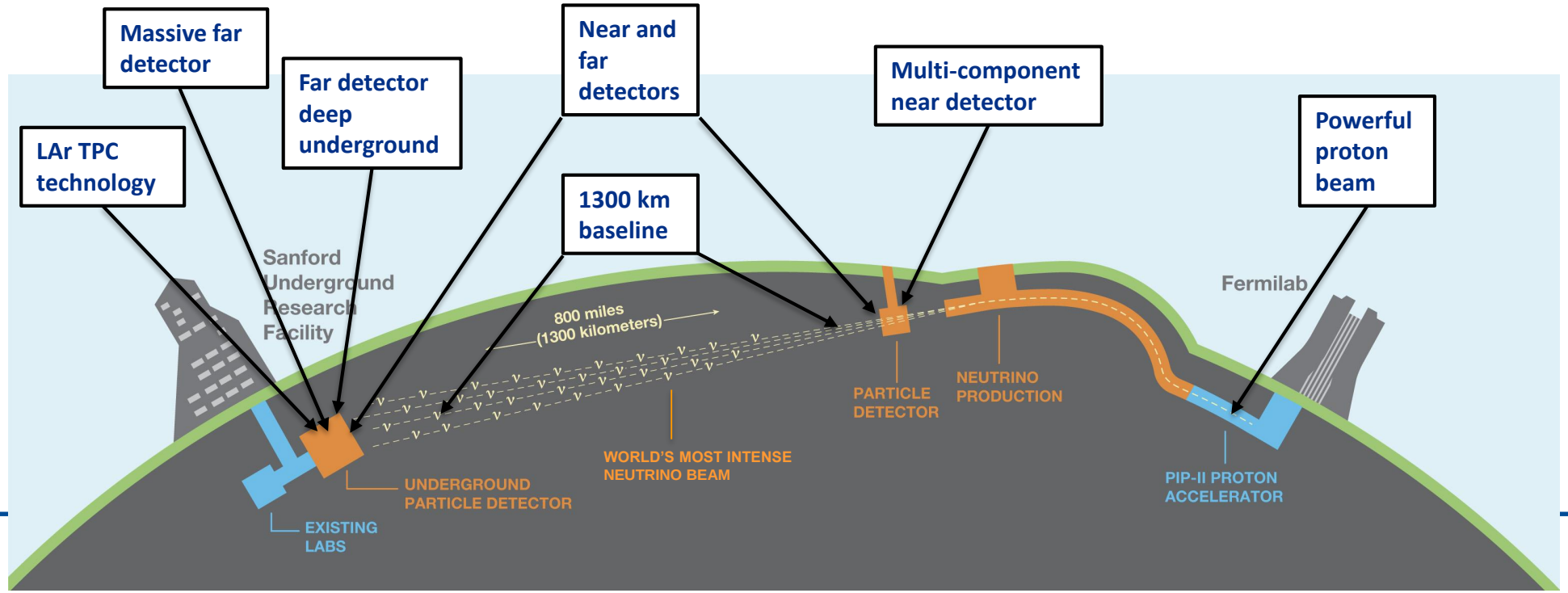
milab proton accelerator complex to produce higher intensity
ment Plan II (PIP-II) should proceed immediately, followed by construction,
>1 MW by the time of first operation of the new long-baseline neutrino facility.

European Strategy Update

The US neutrino program is supported by the European Strategy

PIP-II / LBNF / DUNE delivers…

- Powerful proton beams (**PIP-II**)
  - 1.2 MW upgradable to multi-MW in energy range of 60-120 GeV to enable world's most intense neutrino beam
- Dual-site detector facilities (**LBNF**)
  - Deep underground caverns (1.5 km) to support 4 x 17 kt liquid argon volume detectors
  - A long baseline (1300 km) neutrino beam, with wideband capability
- Deep Underground Neutrino Experiment (**DUNE**)
  - The next-generation neutrino experiment



LBNF/DUNE

Define: Two US Projects & One Global Experiment

Facilities

- PIP-II: a ‘DOE project’ with international contributions through partnerships
- LBNF: a ‘DOE project’ with international contributions through partnerships

Experiment

- DUNE: an ‘international project’ with contributions from DOE (“DUNE-US”) and international partners

Proton Improvement Plan – Phase II (PIP-II)

Bottom Line Up Front – PIP-II Status

- On site construction is underway
- Beam has been accelerated in the first two cryomodules
- International partner in-kind contributions - scope and schedule - have been finalized
- Performance baseline has been created and successfully presented in DOE reviews
- ESAAB presentation was held on 1 December; project is poised for baseline approval

CD-2 decision is imminent

PIP-II Mission

PIP-II will enable the world's most intense beam of neutrinos to the international LBNF/DUNE project, and a broad physics research program, powering new discoveries for decades to come.

PIP-II linac capabilities

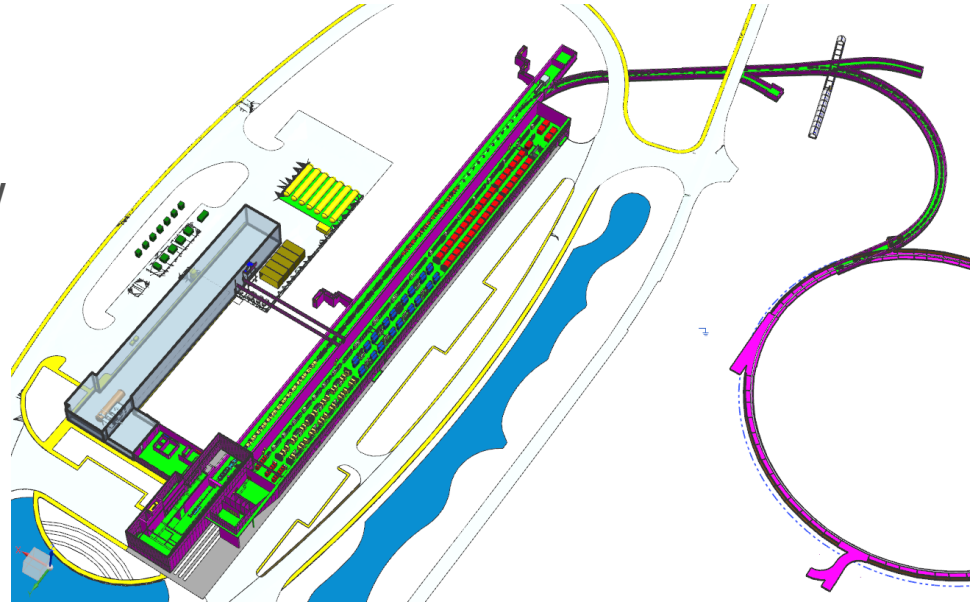
Beam Power

- 1.2 MW proton beam
- Upgradeable to multi-MW

Flexibility and multi-user capability

- Compatible w/ CW-operations
- Customized beams
- Multi-user delivery

Reliability



PIP-II Scope

800 MeV H− linac

- Warm Front End & SRF section

Linac-to-Booster transfer line

- 3-way beam split

Upgraded Booster

- 20 Hz, 800 MeV injection
- New injection area

Upgraded Recycler, Main Injector

- RF in both rings

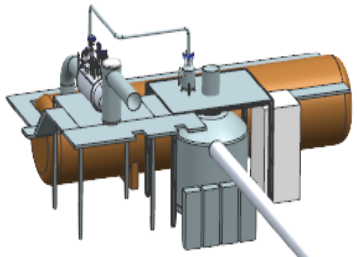
Conventional facilities, incl.

- Site preparation
- Cryoplant Building
- Linac Complex
- Booster Connection

The PIP-II scope enables the accelerator complex to reach 1.2 MW proton beam on LBNF target


Main Injector
Transfer Line
PIP-II
SRF Linac
Booster

PIP-II Superconducting RF CW Linac, 800 MeV Consists of Five Types of Cryomodules



Cryoplant

CDS

HWR
8 Cavities
162.5 MHz

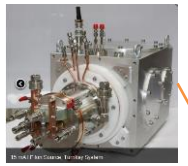
Single Spoke
SSR1 X 2
16 Cavities
325 MHz

Single Spoke
SSR2 X 7
35 Cavities
325 MHz

Elliptical
LB650 X 9
36 Cavities
650 MHz

Elliptical
HB650 X 4
24 Cavities
650 MHz

H- Ion source



RFQ

2.1 MeV

10 MeV

32 MeV

177 MeV

516 MeV

833 MeV

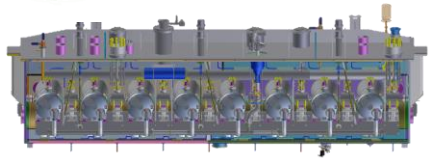
Superconducting

Room Temperature

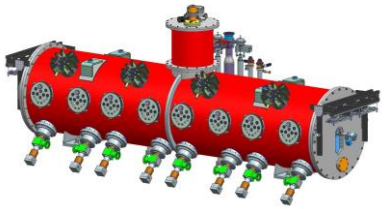
PIP-II Linac is technically complex, state of the art superconducting RF accelerator

PIP-II is the world's highest energy and power CW proton linac, and the U.S. first accelerator project to be built with major international contributions

The state-of-the-art PIP-II Superconducting RF Systems



5.9 m

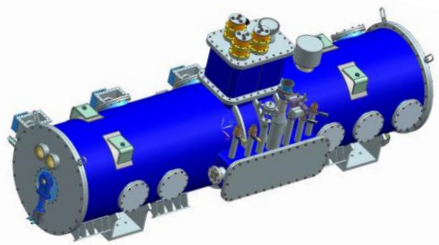


5.3 m

2023

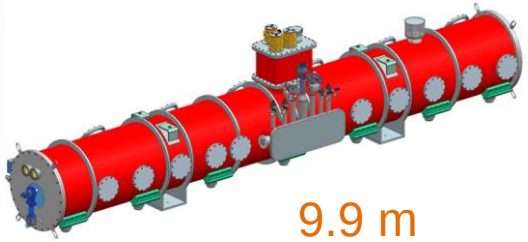
6.5 m

2023

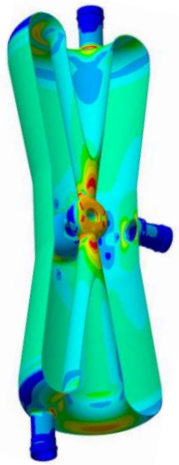


5.5 m

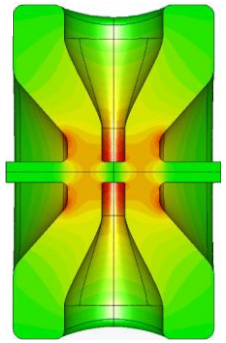
2021



9.9 m

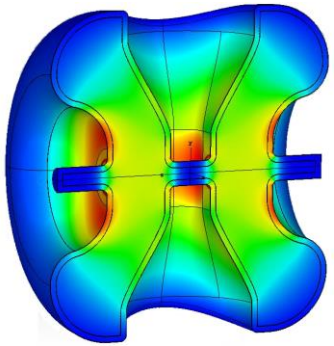


Half Wave Resonator
β=0.11 Q_0 =0.85x10^{10}

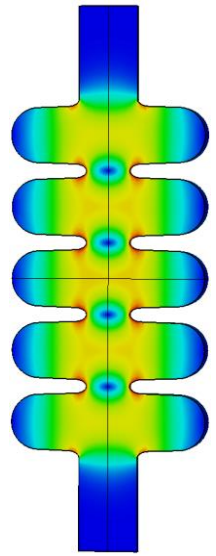


Single Spoke
SSR1
β=0.22 Q_0 =0.82x10^{10}

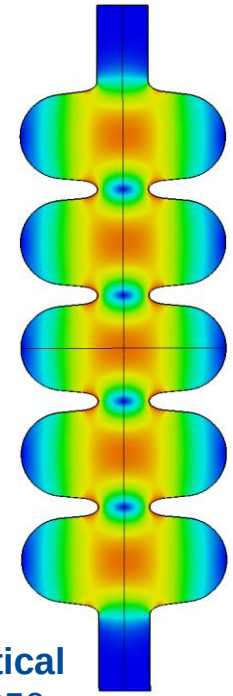
2022



Single Spoke
SSR2
β=0.47 Q_0 =0.82x10^{10}



Elliptical
LB650
β=0.61 *Q_0 =2.4x10^{10}

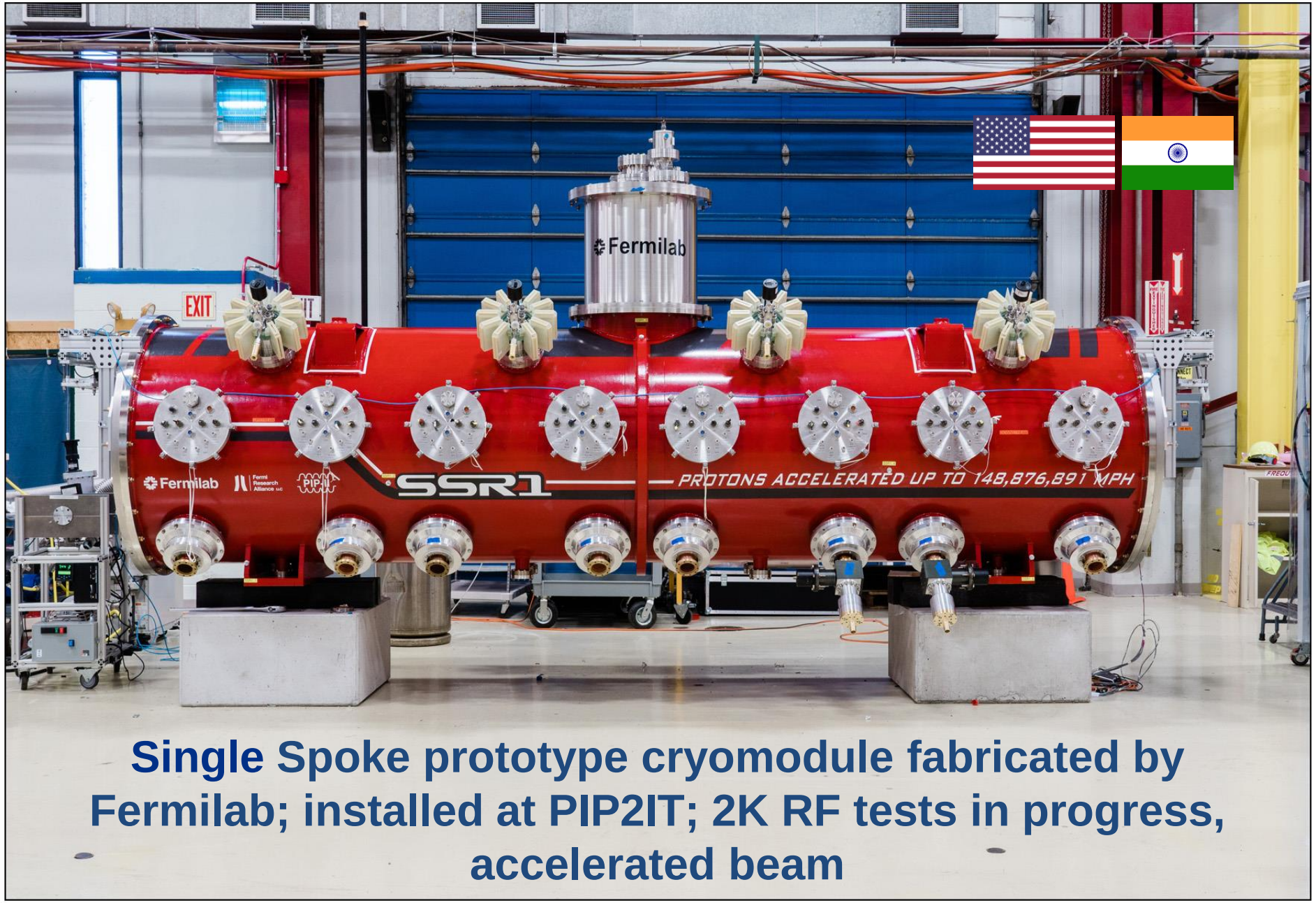


Elliptical
HB650
β=0.92 *Q_0 =3.3x10^{10}

✓ Performance validated ✓ Testing in progress Dates: component built

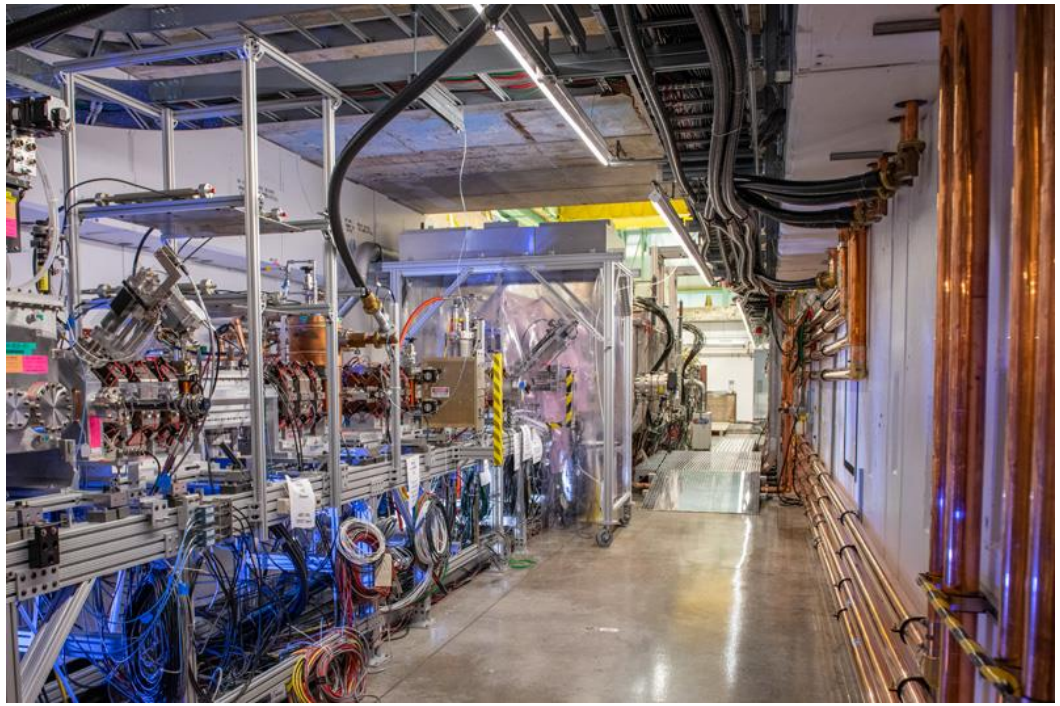
*unprecedented performance requirement

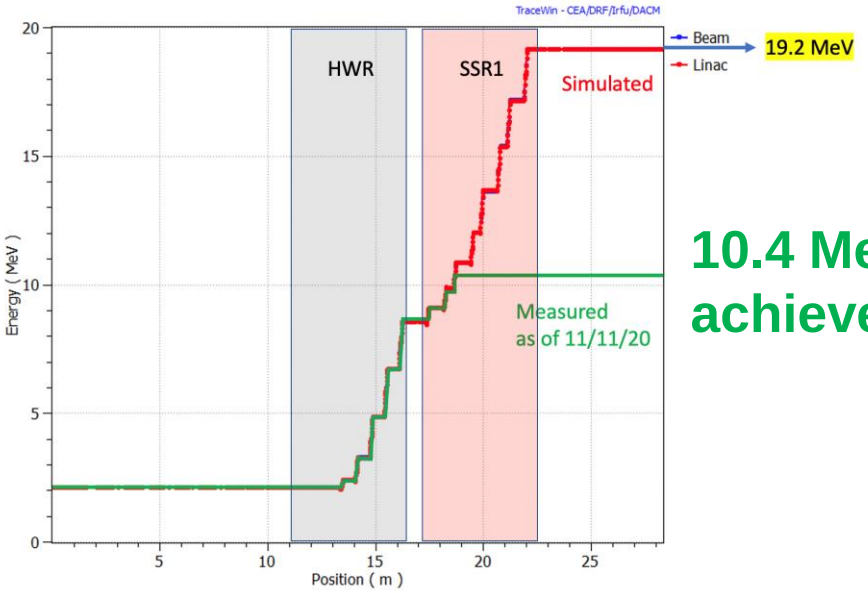
Half-Wave Resonator (HWR) Fabrication by



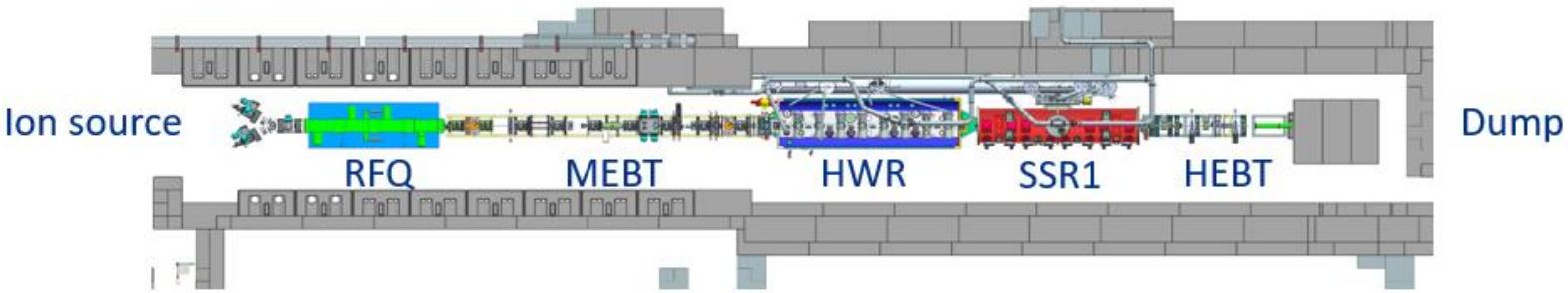
Single Spoke prototype cryomodule fabricated by Fermilab; installed at PIP2IT; 2K RF tests in progress, accelerated beam

First beam accelerated in PIP-II Cryomodules!





10.4 MeV achieved



Significant Milestone: SRF cryomodules and battery of accelerator systems demonstrate solid performance; design requirements are being validated; international partners' deliverables seamlessly integrated.

NEW ERA OF SRF PROTON ACCELERATION AT FERMILAB

Early Conventional Facilities Subproject Approved and Under Construction

Cryoplant Building Construction

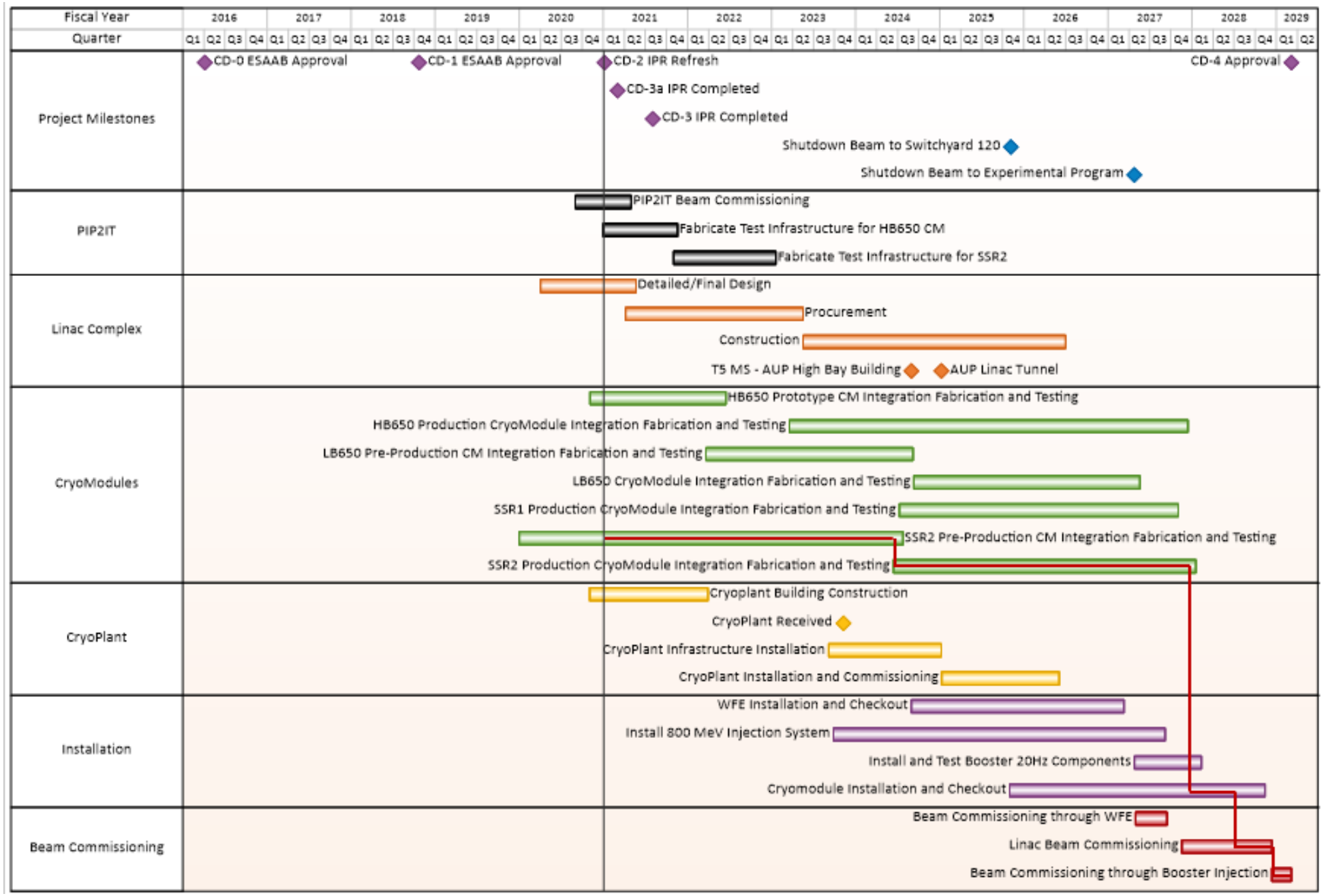
https://app.truelook.com/?u=fc1599677013#tl_live
https://app.truelook.com/?m=16002500832205565503647

PIP-II Site Status on Friday, 3 December 2020 @ 1:45 PM CDT

Conventional Facilities

- Cryoplant Building Construction underway
  - Notice to Proceed issued on 20 August 2020
- Linac Complex Design
  - 60% design review held in August
  - Final design started late September
  - Final design complete in Q2FY21
- Booster Connection
  - Current plan is to start design in FY22

PIP-II Summary Schedule



Schedule extended by 15 months compared to Jan IPR due to Covid-19 and funding profile

International Partnerships

PIP-II International Partners, Expertise and Capabilities

India, Department of Atomic Energy (DAE) (started 2009)
BARC, RRCAT, VECC; also IUAC

Substantial engineering / manufacturing experience; Superconducting magnets for LHC;
2 GeV synch light source

Italy, INFN (started 2016)

Internationally recognized leader in superconducting RF technologies
SRF cavity and cryomodule fabrication for XFEL; SRF cavities for ESS

UK, UKRI (started 2017)

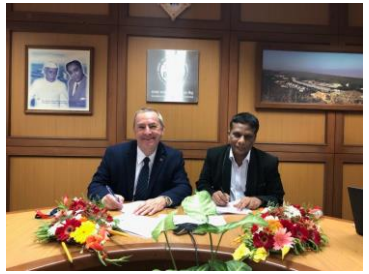
Substantial engineering and manufacturing experience; Construction, operation of synch light & neutron sources SRF cavity processing and testing for ESS

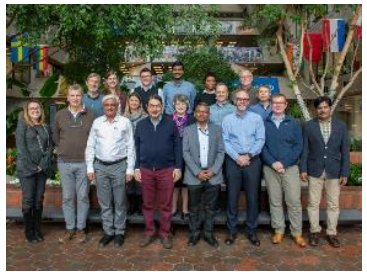
France, CEA, CNRS/IN2P3 (started 2017)

Internationally recognized leader in large-scale CM assembly
CM assembly for European XFEL and ESS; SSR2 cavities and couplers for ESS

Poland, WUST (started 2018)

Substantial engineering / manufacturing experience; CDS, LLRF, QC for XFEL, ESS





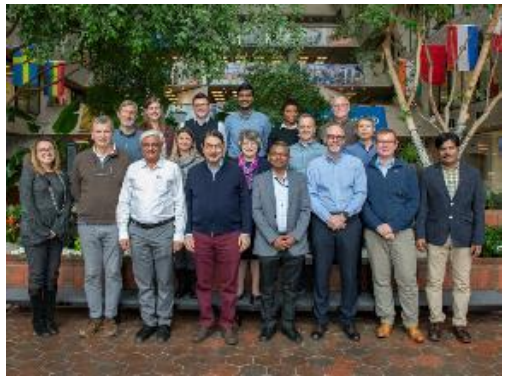
PIP-II International Partners contribute world-leading expertise, capabilities, and facilities

Strong engagement, commitment from International Partners

- ✓ PIP-II benefits from world-leading expertise, facilities, capabilities
- ✓ “Timing is perfect”

- ✓ UK Project Annex signed; Poland joined
- ✓ French Ministry decided on significant IKC to PIP-II. First time investing outside Europe

- ✓ Partner deliverables arriving, being tested and integrated, e.g. DAE amplifiers, INFN LB650 prototype cavity, DAE magnets

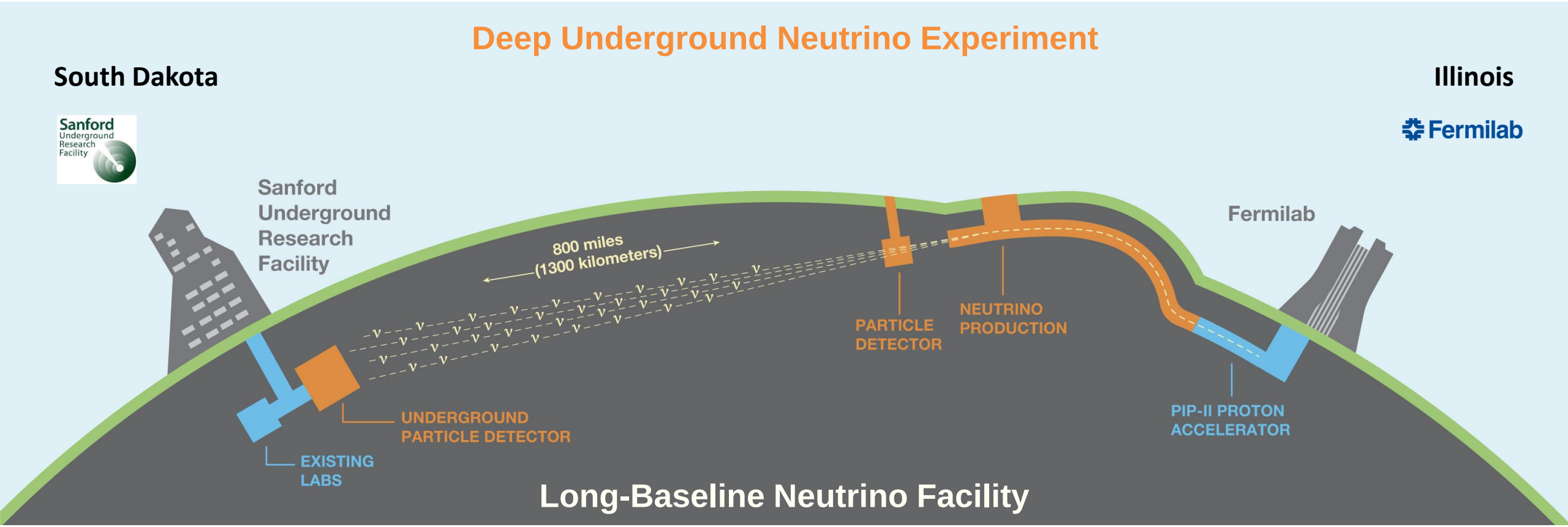


The Path to PIP-II baseline approval

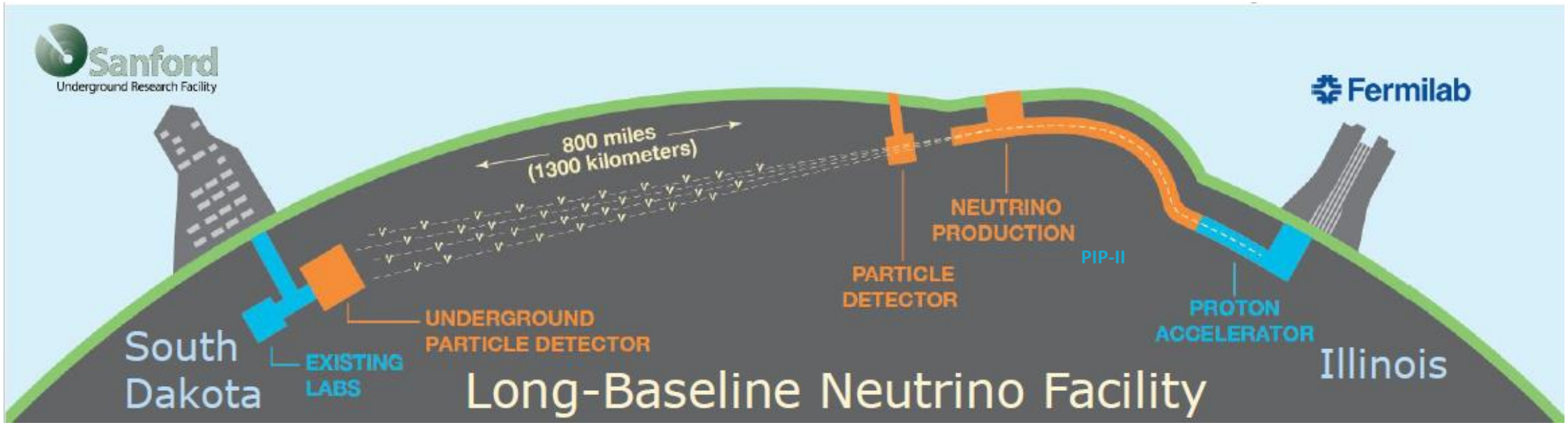
- ✓ Successful DOE CD-2/3a IPR review, Jan 2020
  - Few outstanding items to be resolved, incl.
    - ✓ French funding
    - ✓ Covid-19 impacts & risks
- ✓ Excellent DOE CD-2 Refresh Review, Oct 2020
  - Reviewers recognized that PIP-II is blazing a new trail in major accelerator projects in the US (international partners)
- ✓ ICE Review - Oct 2020
- ✓ PMRC – Nov 2020
- ✓ ESAAB – 1 December 2020
  - ✓ Strong team; experienced and aligned partners, ready to go
  - ✓ Technical design mature, validated, ready to baseline; First ~25 MeV built, beam commissioning ongoing
  - ✓ No gaps in international contributions

Long-Baseline Neutrino Facility (LBNF)

LBNF/DUNE Overview



LBNF will enable the United States to host the global high energy physics community to advance world class science into the fundamental nature of matter



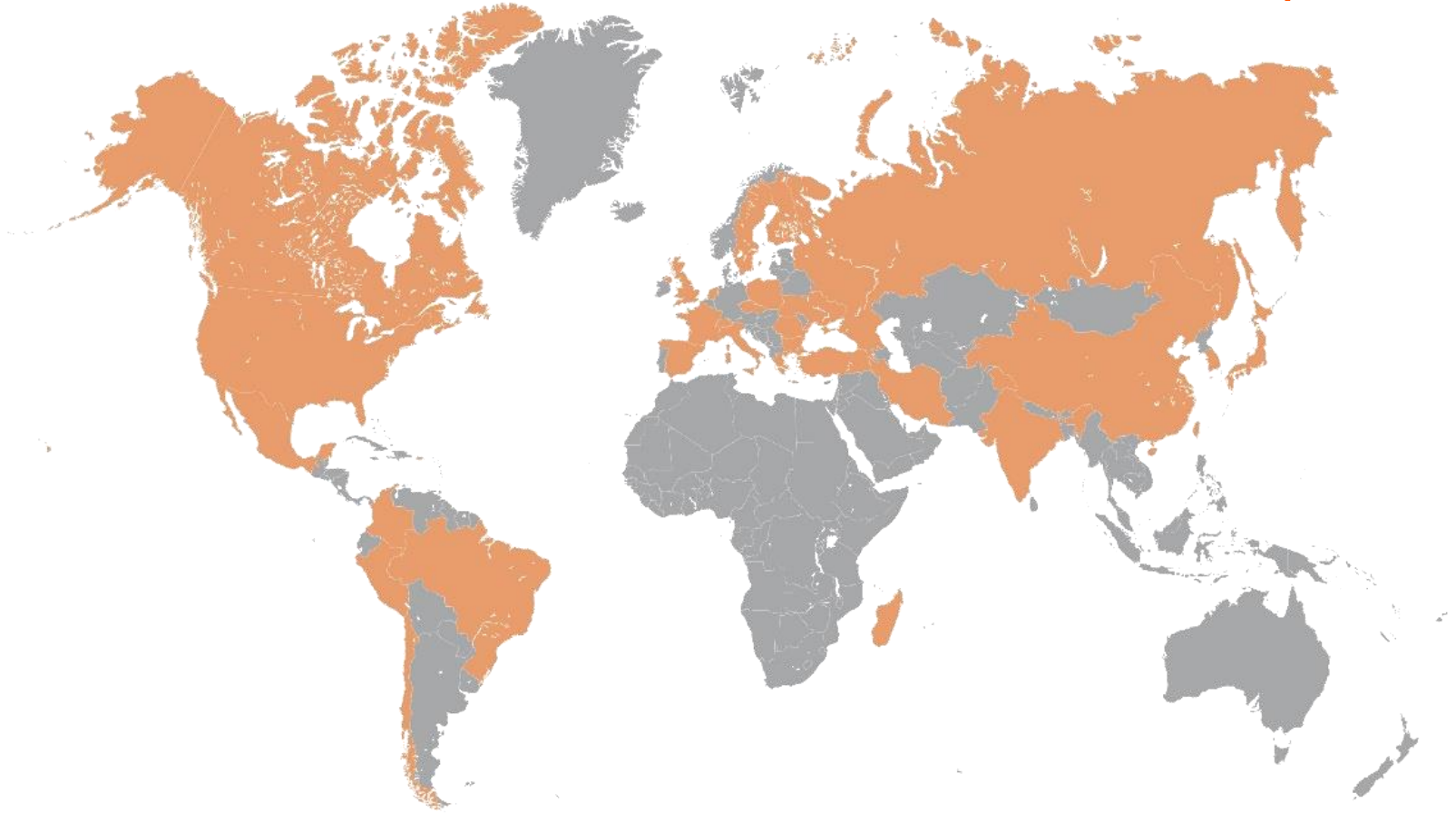
- **Long Baseline Neutrino Facility** – Platform to support the Deep Underground Neutrino Experiment (DUNE), provides:
  - Facilities at Fermilab, the "**Near Site**," to produce world's most intense neutrino beam and support the DUNE near detector
  - Facilities at the surface and 1.5 km underground at the Sanford Underground Research Facility (SURF), the "**Far Site**," to support the DUNE far detector modules
- **DUNE-US** – U.S. contribution to the international DUNE experiment.

LBNF + DUNE-US are one DOE O413.3B Project

DUNE experiment is managed by the DUNE Collaboration

> 50 % non-US

1229 collaborators from 201 institutions in 33 countries, including CERN



The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States

Bottom Line Up Front – LBNF/DUNE Status

Far Site

- All preparatory work to support cavern excavation phase of work in on track to complete by end of first quarter of 2021
- Contract to excavate underground caverns was awarded in October; work to start in Apr 2021
- 8m x 8m x 8m prototype (protoDUNE) for first far detector and cryostat has been successfully demonstrated at CERN; planning underway for “module 0” tests in 2021

Near Site

- Site preparation work for conventional facilities was completed in October 2020
- Beamline final design is at 60% complete and on track
- Final design for conventional facilities is at 30% complete; will be at 100% in Aug 2021
- Prototyping of LAr near detector is progressing successfully

- **Project is planning for DOE baseline review late 2021/early 2022**

With award of main excavation contract, significant cost uncertainty has been eliminated

LBNF/DUNE-US Strategy to Baseline

- HEP guidance:
  - DOE will continue to work to increase international participation in LBNF
  - Directed that all detector integration and installation costs be put on project
  - All needed scope must have a committed contributor or be on project by CD-2
- Project response in 2020 to fit with DOE funding guidance:
  - Added uncommitted beamline and cryo components to project scope – no gaps
  - Maintained plan to build full LBNF facility for Near Detector and up to four Far Detector modules
  - Completed extensive, end-to-end value engineering review
  - Moved DUNE-US contribution to international DUNE project to contingency:
    - Raised overall project contingency to ~40%
    - Created path to second detector by proposing to use contingency to support 2nd detector module assuming key international in-kind contributions (e.g., second cryostat for far detector)
  - Plan presented in July to DOE IPR review committee
- Feedback from review committee was desire to see two far detector modules in baseline scope
  - Active discussions underway between DOE and CERN/European funding agencies to commit to second detector components
  - Project is actively developing plan to support second far detector module in baseline

Updates – Far Site

Reliability Projects

Pre-Excavation including Early Excavation Work

Excavation/Buildings & Site Infrastructure (BSI) Work

ProtoDUNE

Cryostat/Cryogenic Systems

Reliability Projects

LBNF includes 9 “reliability” projects to refurbish or replace SURF infrastructure to support project construction and experiment operation.

Final Ross Rehabilitation – Final Shaft Guide Alignment

New Ross Shaft cage specially designed to support LBNF/DUNE

New drive units for Ore Hoists

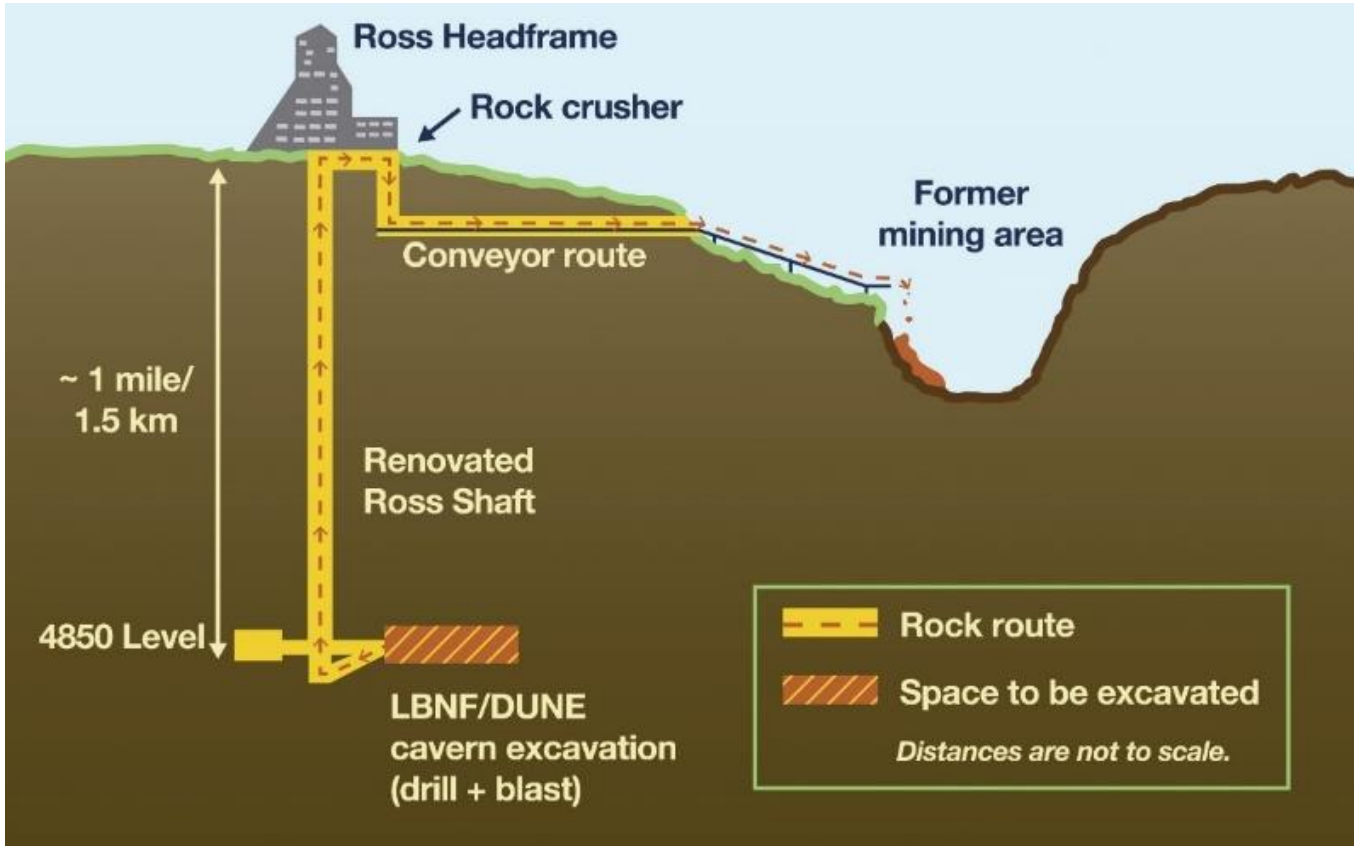
Replace hoist clutches and brakes

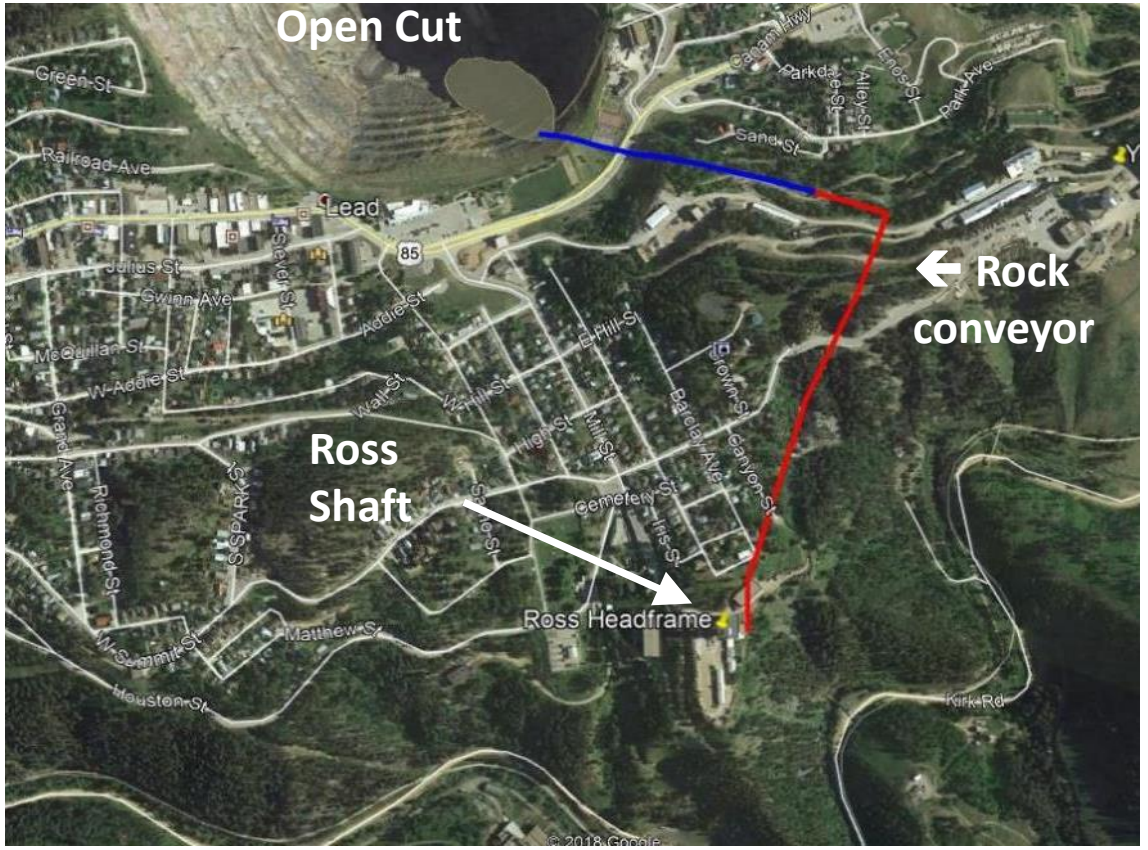
Replace hoist motors

All reliability projects on track to complete before the start of main cavern excavation work

Pre-Excavation Construction

Work to construct the systems to transport ~800,000 tons of rock from underground excavation areas to “Open Cut”



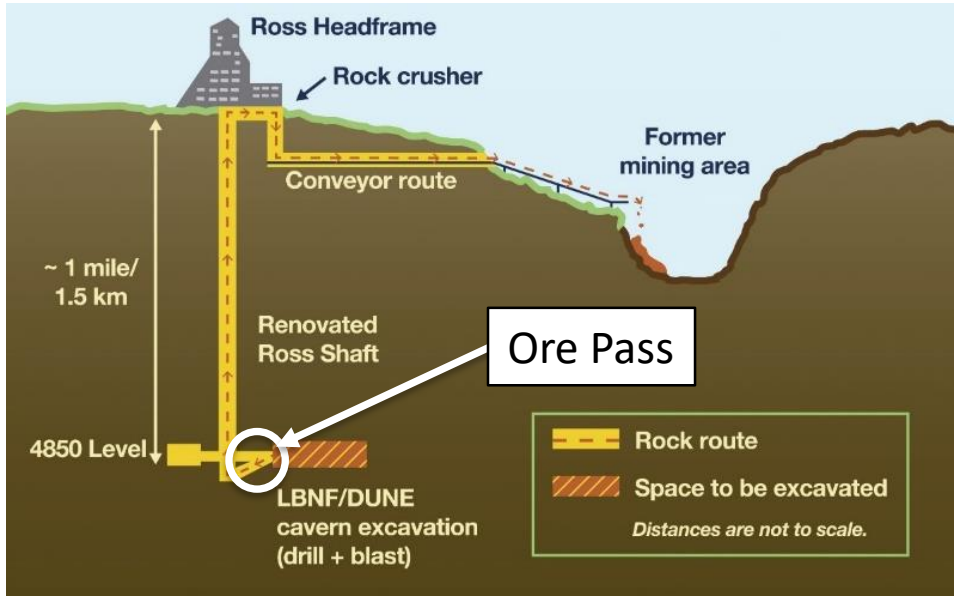


- Underground rock handling systems (ore passes, skip loading, temporary grizzly, rock spill collection system)
- Rock crushing system at Ross Headframe
- Installing 4200’ surface rock conveyor to open cut
- Ross headframe reinforcement
- Shaft utilities: fiber optic and power cables, water and gas piping
- Electrical service on the surface to the shaft
- Early excavation to facilitate ventilation

All pre-exc projects on track to complete before the start of main cavern excavation work

Pre-Excavation - Ore Pass

Temporary Grizzly



Ore pass after excavation

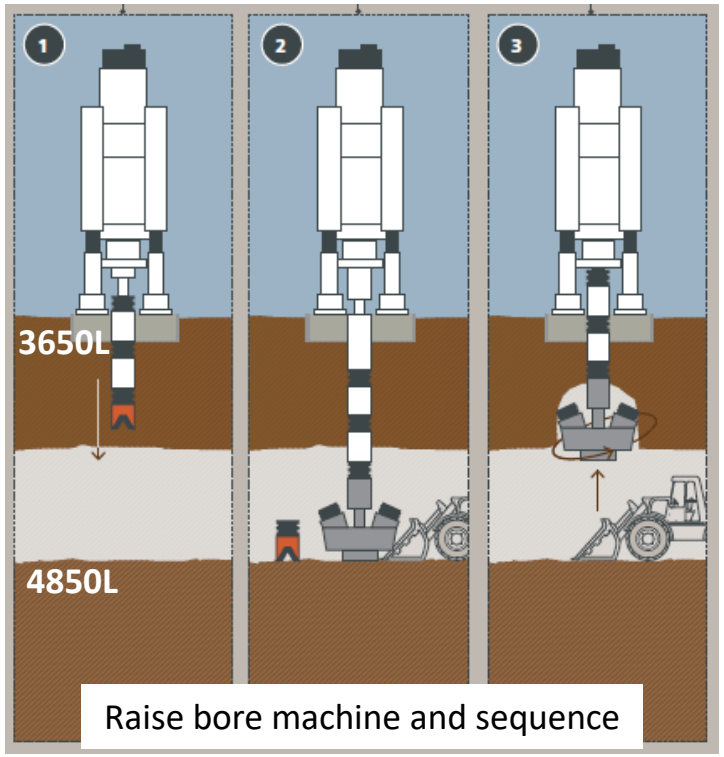
110’ of “muck” from flooding after mine closure in 2002 removed from Ore Pass to reopen path to move rock from underground to surface

Pre-Excavation – Raise Bore Cavern @ 3650L

- Early excavation work. Blasting at 3650L to create Raise Bore Chamber that will become top of new 1200' ventilation shaft down to the 4850L. Increased ventilation needed to support construction and operations.
  - First blast Jun 2020; last blast Oct 2020
  - Overall size: 50' Deep x 32' Wide x 23' High
  - Excavated rock removed: 34,400 FT^3; 3,000 tons

Installing ground support in Raise Bore Chamber

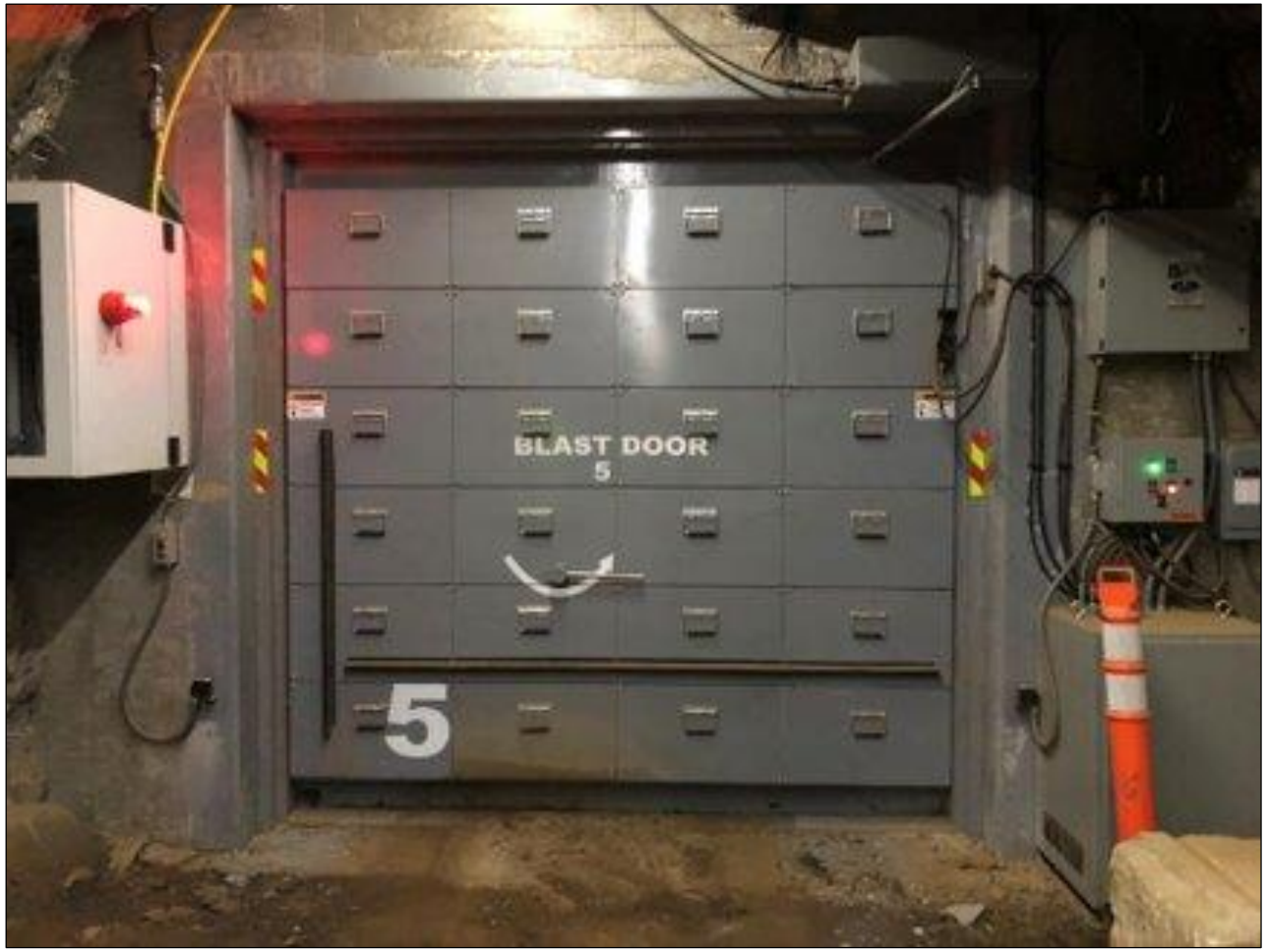
Concrete mud slab in place



Raise bore machine and sequence

Pre-Excavation - Blast doors – in place and operating at the 4850L

Blast Door 6 for north drift leading to Yates campus

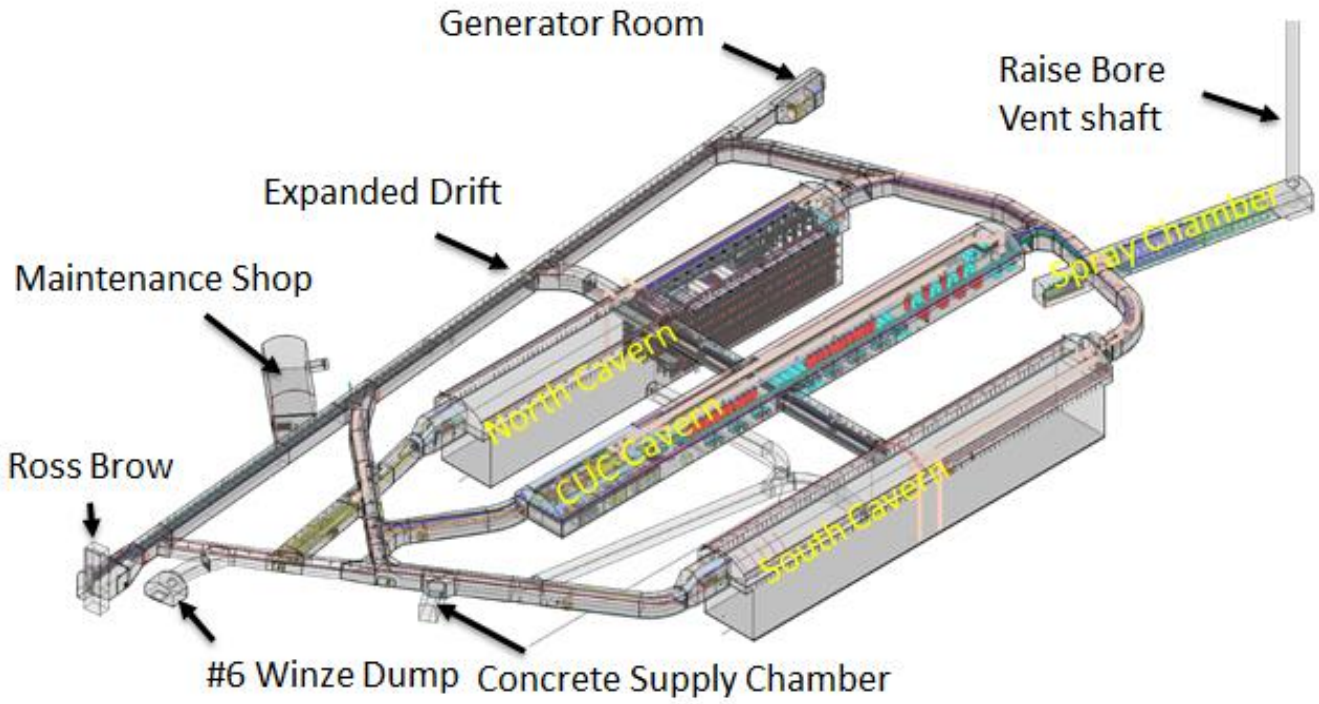


Blast Door 5 in closed position

Pre-Excavation - Construction of new Rock Conveyor almost completed

Main Excavation Work Status

- **Excavation Contract Awarded to Thyssen Mining Inc on 30 Oct 2020.**
- Initial authorization to mobilize issued to Thyssen on 3 Nov 2020
- All Far Site conventional facilities work, except BSI (post excavation utility systems), is now under firm-fixed price contract (> 75% of Far Site CF).
  - Remaining BSI contract work will be awarded in the 2023-2024 timeframe, when needed.



2 x Detector caverns:
475’ x 65’ x 92’

1 x Central utility cavern:
624’ x 64’ x 37’

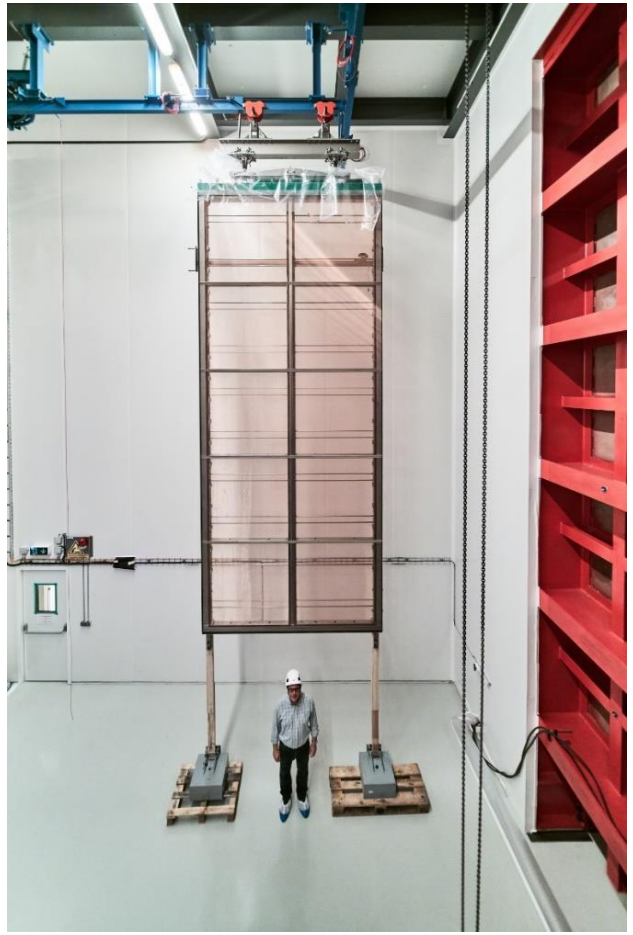
Award of the main Cavern Excavation Contract is a major project milestone

ProtoDUNE detectors at CERN

- 1/20th scale Prototype of the full-size detectors to be installed at 4850L at Sanford Lab have been constructed and tested
- Each prototype holds 770 tons of liquid argon vs. 17,700 tons that each full-size detector module will hold.
- Single Phase (SP) “horizontal drift” APA technology proven; CERN Neutrino Platform now preparing for final “Module 0” test starting this summer. Also, developing a “vertical drift” technology as potential option for second detector module.

SP APA protoDUNE module at CERN before construction of clean room

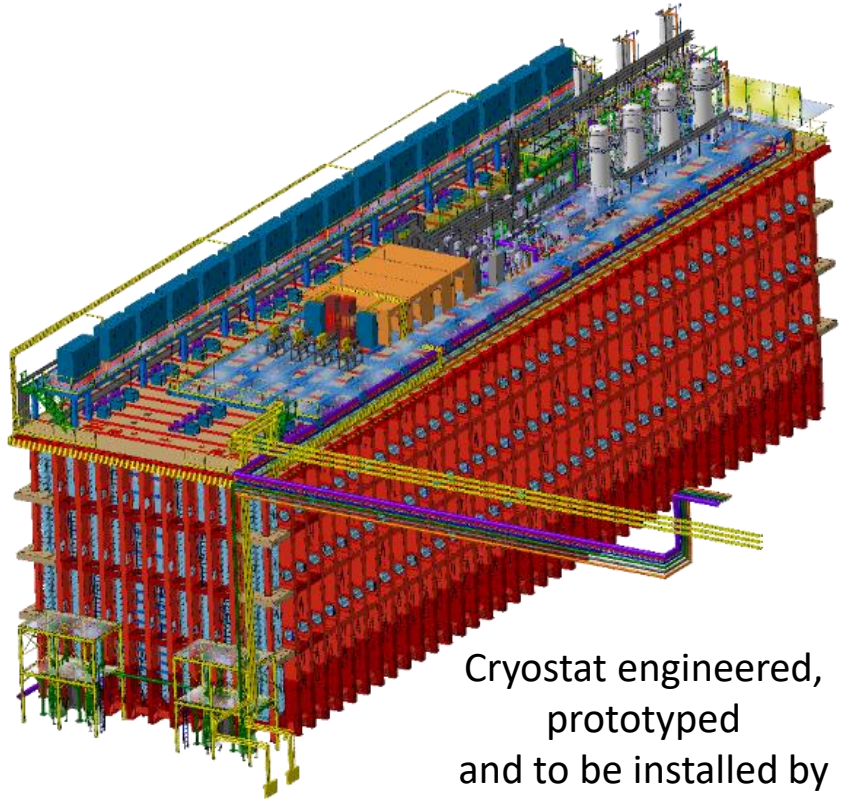
First protoDUNE paper published yesterday, see Fermilab News and IOPScience - JINST



Anode Plane Array

Far Site Cryostat/Cryogenics Systems

- Cryostat:
  - Using membrane technology proven in LNG transport ships.
  - 8m x 8m x 8m prototype demonstrated by CERN
  - Warm structure final design completed in Nov 2018.
  - Membrane design completed in Apr 2019.
- Nitrogen System
  - To be procured via contract for engineer/manufacture/ install/commission system.
  - Acquisition Plan approved by DOE in Oct-2020.
  - Planning for contract award in 2022.
- Argon Cryogenic Systems
  - Brazil/UNICAMP to provide purification and recirculation systems
  - Poland/WUST to provide internal cryogenics systems
  - Switzerland/SERI to provide condensing system



Cryostat engineered, prototyped and to be installed by CERN

	Length (mm)	Width (mm)	Height (mm)
Membrane (internal)	62,000	15,100	14,000
SS plate (internal)	63,600	16,700	15,600
Steel structure (external)	65,836	18,936	17,836

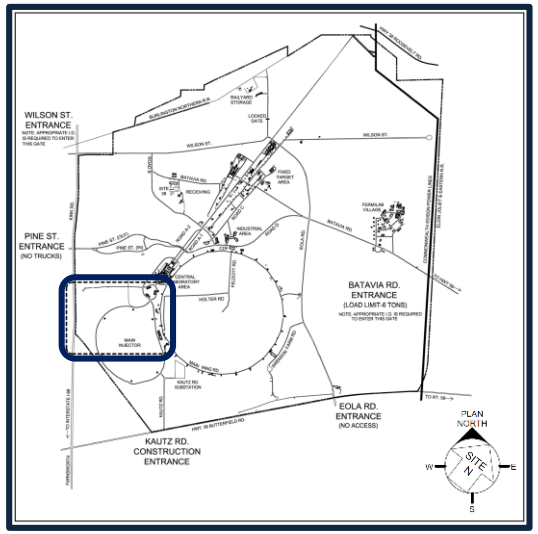
Updates – Near Site

Conventional Facilities Update

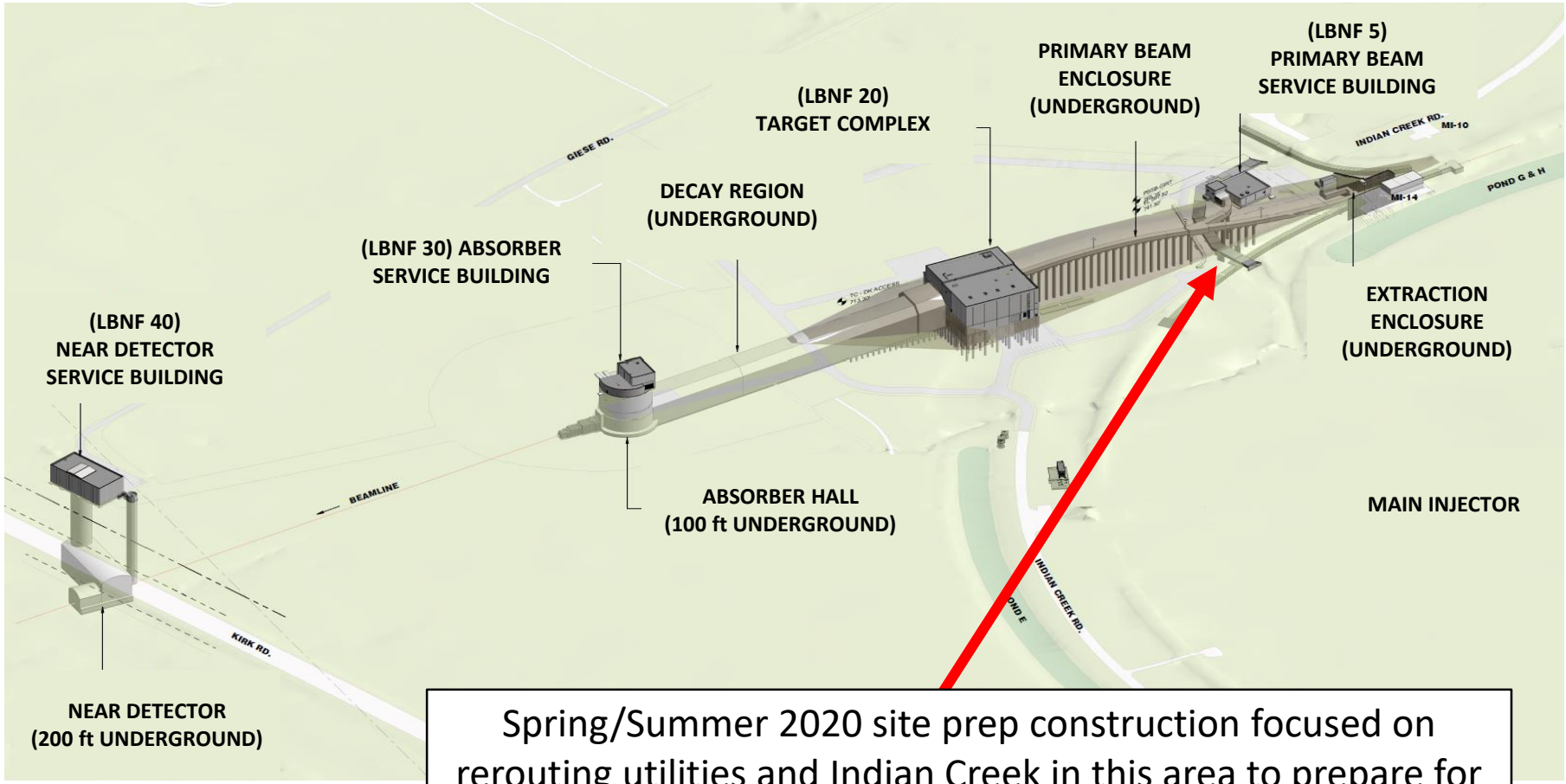
Near Detector Complex

Beamline

LBNF Near Site Conventional Facilities – at Fermilab



LBNF project area located in SW corner of Fermilab site near Kirk Rd



Spring/Summer 2020 site prep construction focused on rerouting utilities and Indian Creek in this area to prepare for the main LBNF construction planned to begin Fall 2023

NSCF Site Preparation Work

- Prepared site for LBNF Beamline facilities. Rerouted Indian Creek, relocated utilities, replaced Fermilab cooling pond with cooling tower.
- Work completed 22 October 2020

Rerouting Indian Creek with a new 450+ foot long culvert system with fish channel

NSCF: Backfilling Main Injector Cooling Pond and Installing New Cooling Tower

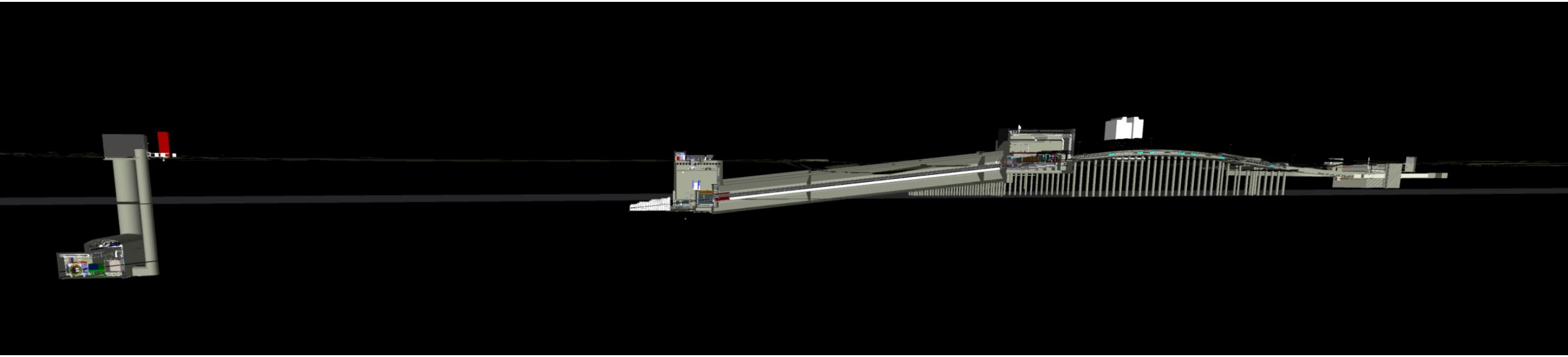
Filling in “Pond F” to create site for LBNF Facilities; replacing cooling capacity with new cooling tower – now completed

NSCF: Rerouting Power Distribution

Utilities relocation to support LBNF Facilities – now completed

Near Site Conventional Facilities Design Status

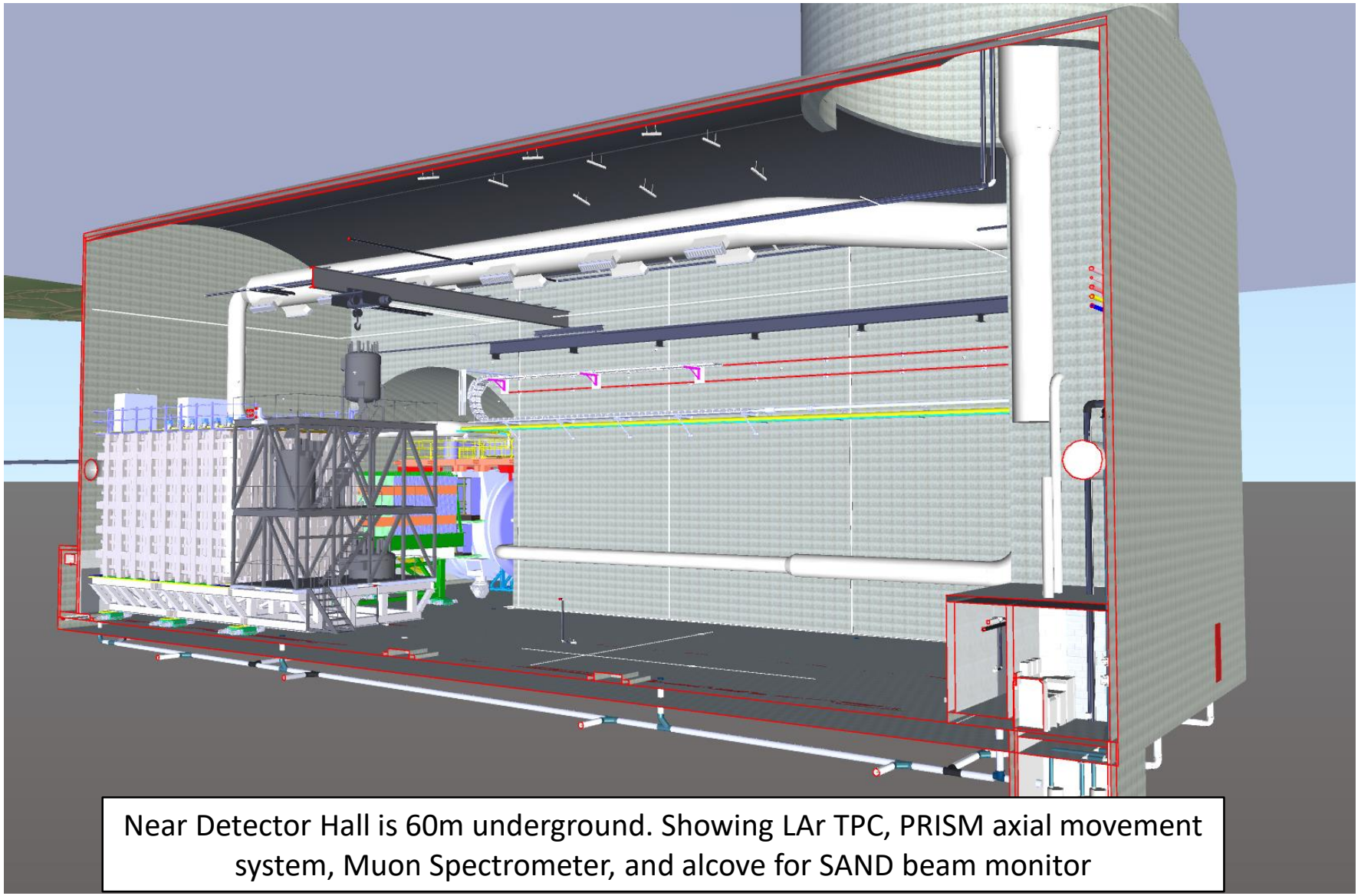
- Final Design has reached 30% maturity
- Next major deliverable will be 60% Final Design, on schedule for delivery in Feb 2021.
- 100% Final Design to be completed August 2021
  - Will be well positioned if stimulus funding bill is enacted and funds are available



Near Detector Complex

- LBNF facilities will support DUNE near detector with ability to move LAr TPC and Muon Spectrometer axially up to 30m.

- LAr TPC to use ArgonCube modules (up to 35).



Near Detector Hall is 60m underground. Showing LAr TPC, PRISM axial movement system, Muon Spectrometer, and alcove for SAND beam monitor

ArgonCube Module 0 LAr TPC: HV Test

First module of the ArgonCube 2x2 Demonstrator:

- Prototype for the Near Detector LArTPC Module
- 70% drift, 70% anode width of ND module
- 50% height of ND module
- TPC hosts 16 pixel tiles, 16 light modules

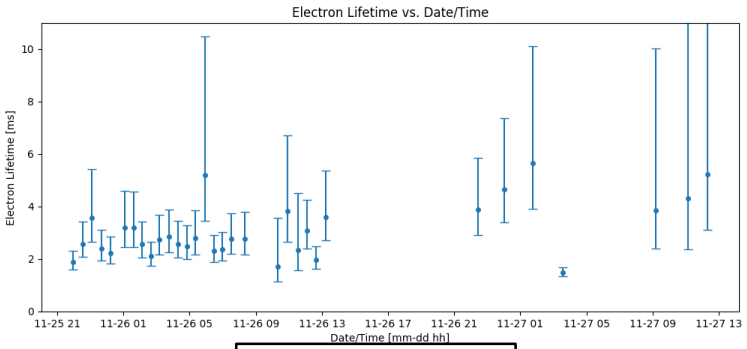
HV Test:

- First large-scale tests of:
  - Resistive sheet field cage
  - LAr flow & purity for ND TPC design
- Only 1 pixel tile, 1 ArCLight, 1 LCM module installed

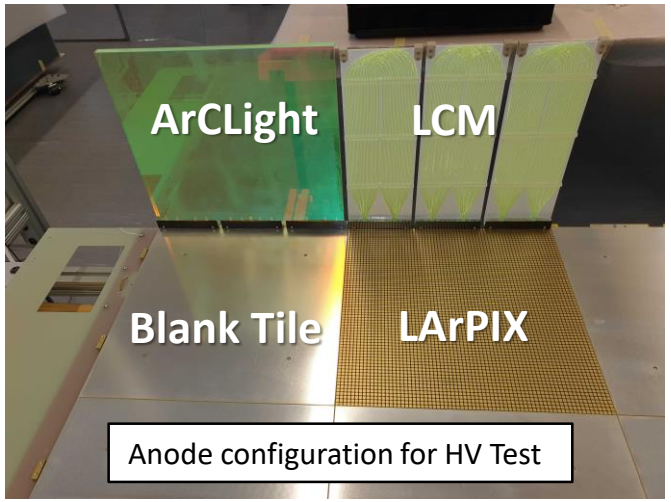
Progress:

- Operated in single module cryostat @ Bern *25 Nov 2020*
- **Stable HV:** at fields up to 1 kV/cm
- **High Purity:** Electron lifetime >2 ms

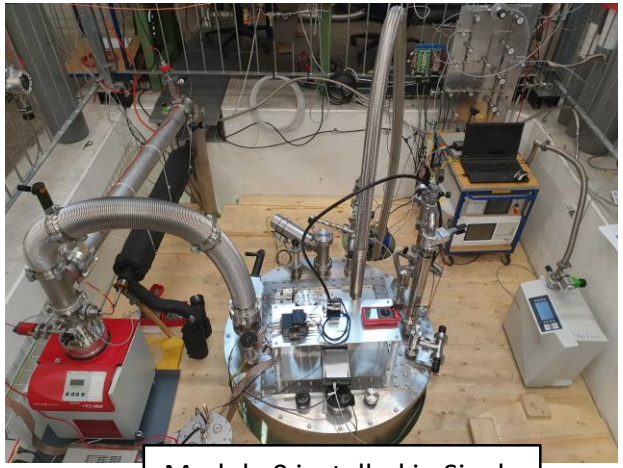
Ready to proceed to fully-instrumented Module 0 test



e- lifetime > 2 ms



Anode configuration for HV Test



Module 0 installed in Single Module Cryogenics System

Anodes installed to Field Cage

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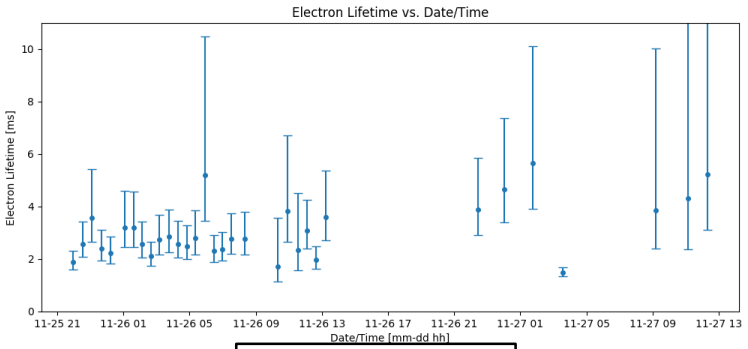
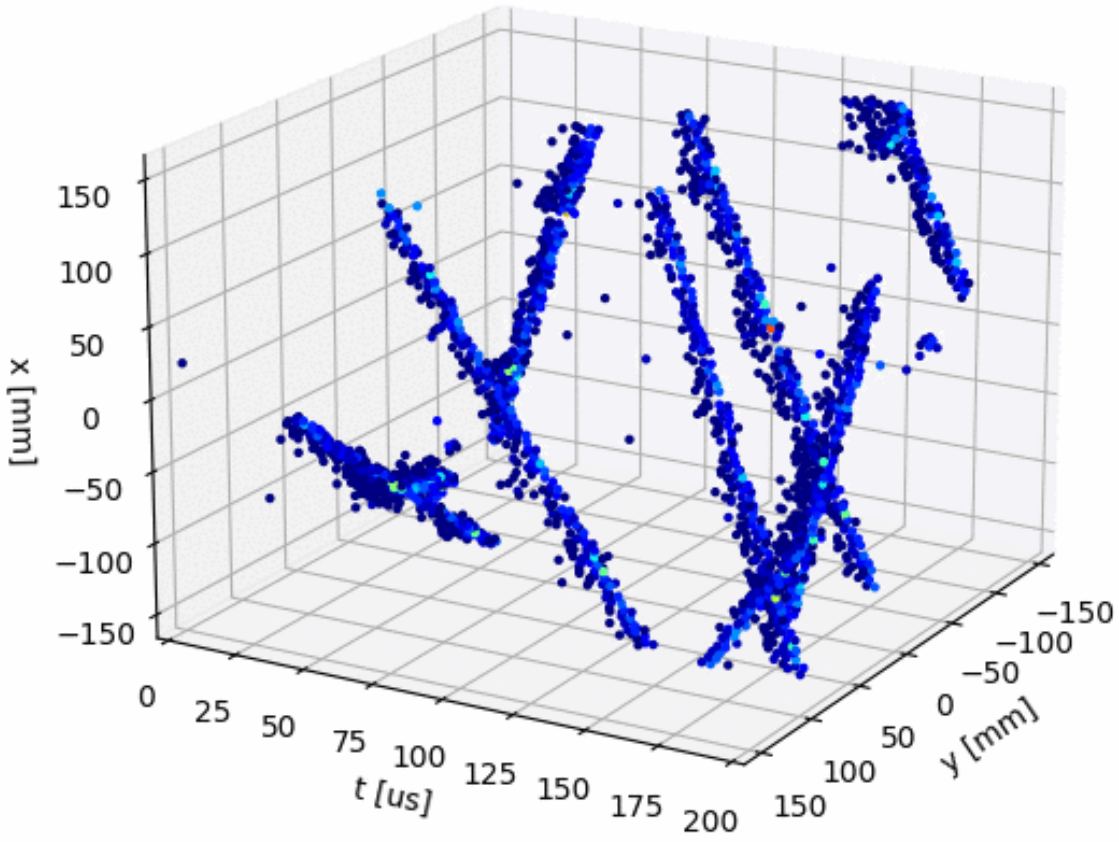


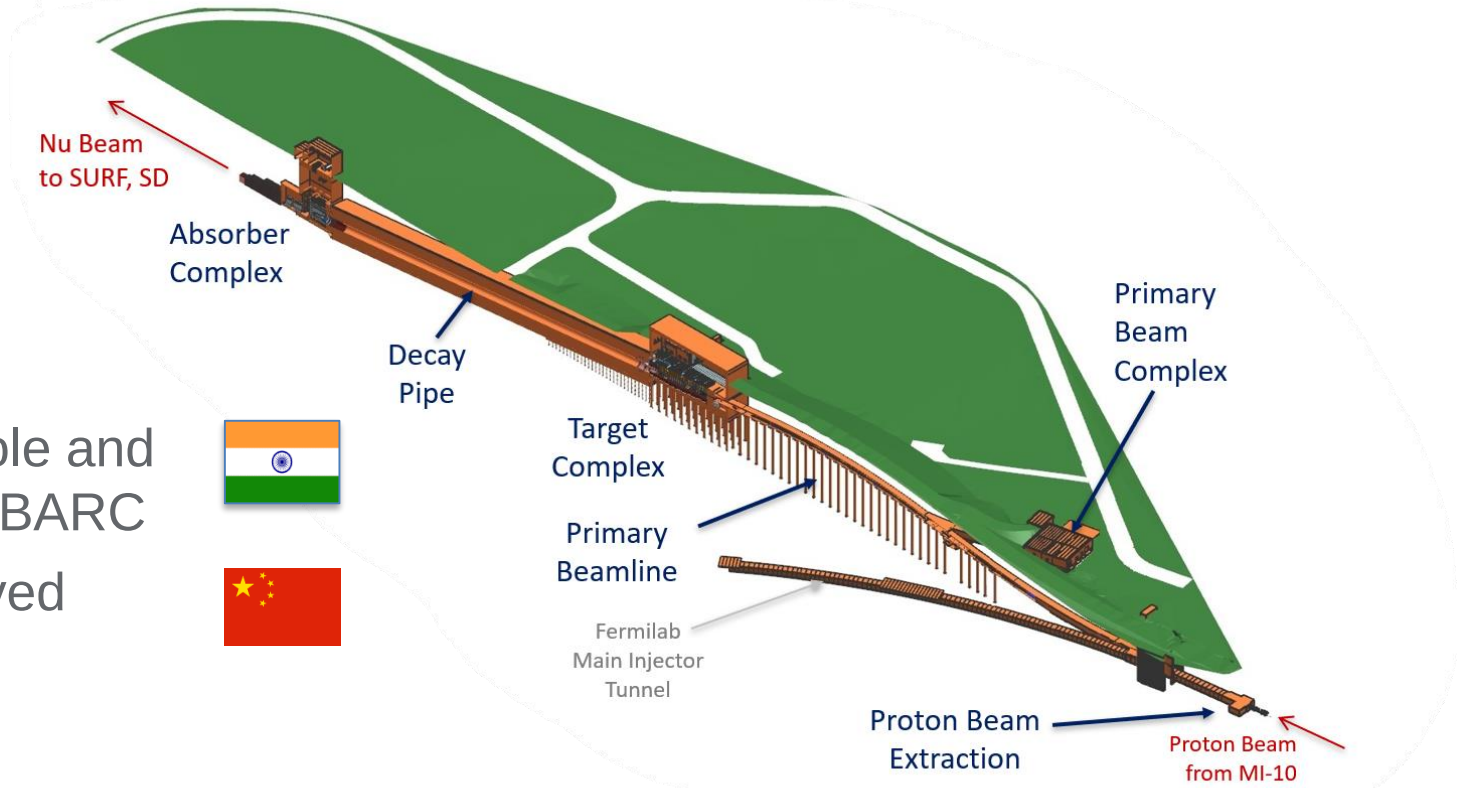
e- lifetime > 2 ms

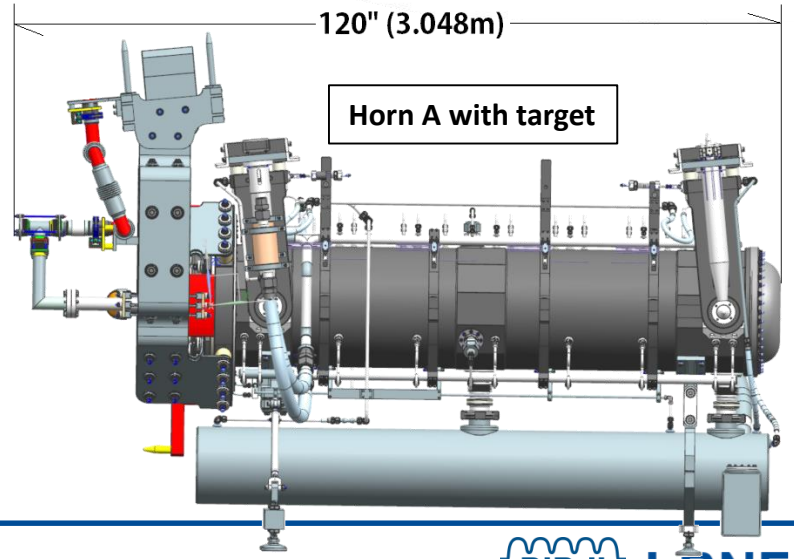


Overlay of 8 typical cosmic rays images from Module 0 HV test

Beamline

- Final design at 60% overall
- Primary beamline
  - Main proton beamline magnets (dipole and quadrupole) to be provided by India/BARC
  - Corrector magnets have been received from China/IHEP
- Neutrino beamline
  - Target, baffle, and associated systems from UK/RAL
  - Stripline feedthrough and Hatch Cover prototypes from Japan/KEK-JPARC





Project Schedule

- Final schedule is dependent upon CD-2/baseline funding profile
- Far Site:
  - Excavation of main caverns start April 2021
  - Start of cryostat installation in 2024
- Near Site:
  - Neutrino beam line completion planned immediately following PIP-II commissioning

LBNF/DUNE looking ahead to 2021 – Review Plan to CD-2

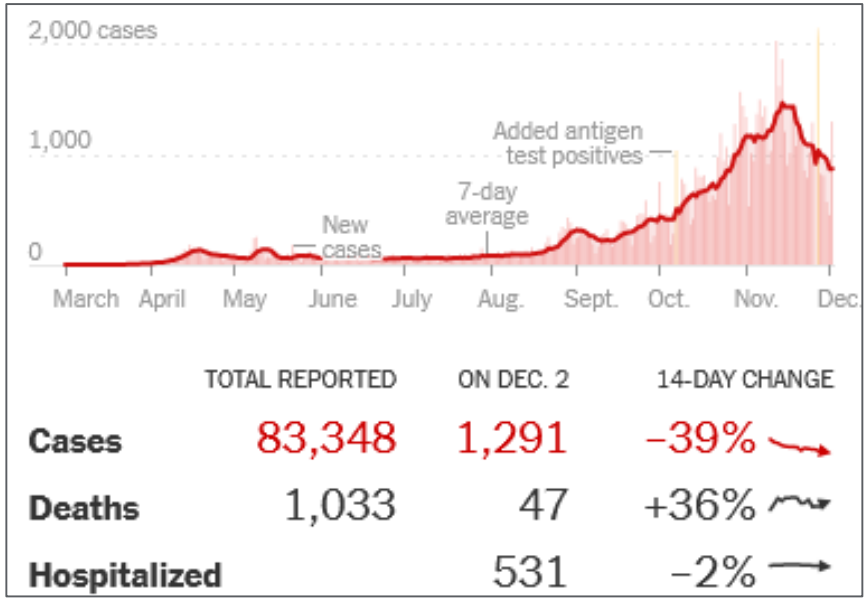
- Schedule:
  - DOE Progress IPR: January 6-7 and 11-13, 2021
  - DOE Progress IPR: June/July 2021
  - Director's CD-2/CD-3B Review: September 2021
  - DOE CD-2/CD-3B IPR: December 2021

- Project CD-2/3B must be approved by summer 2022 to continue excavation beyond limit authorized under CD-3A

COVID Discussion

COVID-19 Impacts on PIP-II and LBNF/DUNE-US

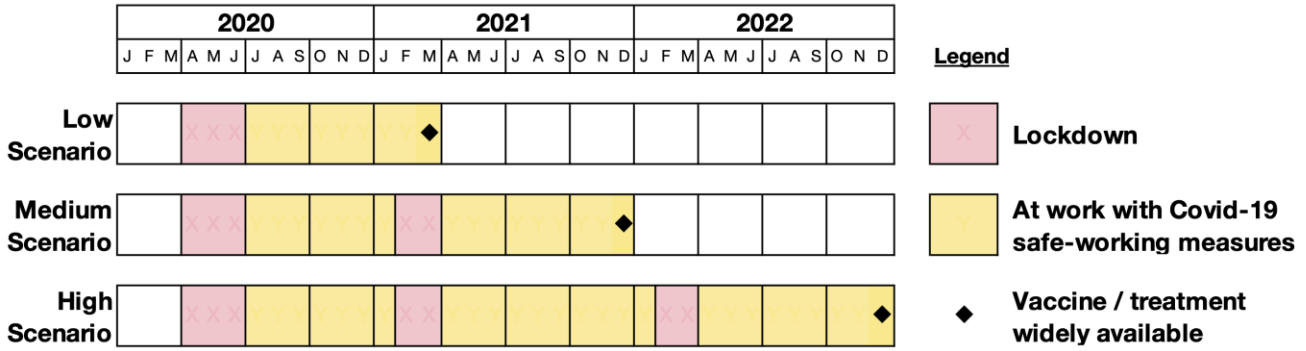
- PIP-II: Impact on international partners varied resulting in overall 15 months delay to schedule
- LBNF/DUNE: although prototyping and work at partner laboratories has been impacted, nature of current project work (dominated by civil construction and design work) has limited extent of impact.
  - Exception at Far Site:
    - SURF closed for ~6 weeks, from late March to early May, due to COVID-19, delaying completion of pre-excavation work.
    - South Dakota has developed into a national hotspot since late August.
    - Since then there have been some minor COVID related delays that have not impacted critical path.
    - Generally, project has been able to mitigate impact of COVID positives through tracing/quarantine protocols implemented in partnership with SDSTA and KAJV (construction contractor).



South Dakota COVID 7-day case average

Fermilab Project Approach Assessing Risk of COVID-19

- Fermilab Chief Project Officer framework to assess risk of COVID-19 impacts used for both PIP-II and LBNF/DUNE-US.
- General approach assumes three timeline scenarios for when a vaccine is available and lockdown risk mitigates.
  - Scenarios include schedule inefficiencies across different activities (e.g., management, computer-based, at national lab, university, vendor, partner, civil construction)
- Implementation:
  - Near-term schedule inefficiencies (6 months) in FY21 have been planned into the projects
  - Longer-term schedule inefficiencies are combined with COVID-specific risk assessments to develop cost/schedule risk impacts to projects in low/med/high scenarios.



► **PIP-II and LBNF/DUNE-US plans include "Medium" scenario with some margin.**

Summary

- LBNF will provide a world-class platform for the global high energy physics community and the international DUNE experiment powered by the highly capable PIP-II accelerator.
- PIP-II is first US international accelerator project.
- International partnerships are essential for the success of the PIP-II and LBNF projects.
- Highly engaged, proactive project teams and international partners continued strong technical progress despite pandemic challenges.
- PIP-II is ready to baseline
- LBNF/DUNE-US has eliminated significant cost and schedule risk with the award of the main cavern excavation contract and will be ready to baseline by the end of 2021 timeframe.

We greatly appreciate the HEP community commitment to complete the P5 vision and enduring strong support from the community, DOE/SC, and our International Partners!

Thank you. Questions?

Thank you to Lia Merminga, PIP-II Project Director and the PIP-II project team for materials and support