Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

# The
# Long-Baseline Neutrino Facility

Jim Strait, LBNE Project Director

Open meeting for the scientific community to form LBNF

5 December 2014 (CERN)

12 December 2014 (Fermilab)

# Outline

- Overview of the Fermilab Neutrino Program
- Increasing proton beam power:  PIP and PIP-II
- The Facilities for a long-baseline experiment
  - The facilities team for LBNF
  - Neutrino Beamline
  - Sanford Underground Research Facility
  - Conventional Facilities at Fermilab and SURF
  - Cryogenic infrastructure
- Technically limited schedule
- Summary and Conclusions

# Accelerator-Based Neutrino Program at Fermilab

Fermilab hosts an active, diverse, international accelerator-based neutrino program

- Two neutrino beams in operation and a third under design
- A suite of experiments under development, taking data, or analyzing data
- Various R&D programs proposed or under way
- Supporting test beam program for detector development and calibration.

The program is driven by a number of themes:

- Long-baseline oscillations: $\nu_\mu$ disappearance and $\nu_e$ appearance
- Short-baseline oscillation: confirm or refute anomalies ... sterile neutrinos?
- Neutrino scattering experiments: measurements to support the oscillation programs; electro-weak and QCD/nuclear physics
- Detector development for the next generation of experiment

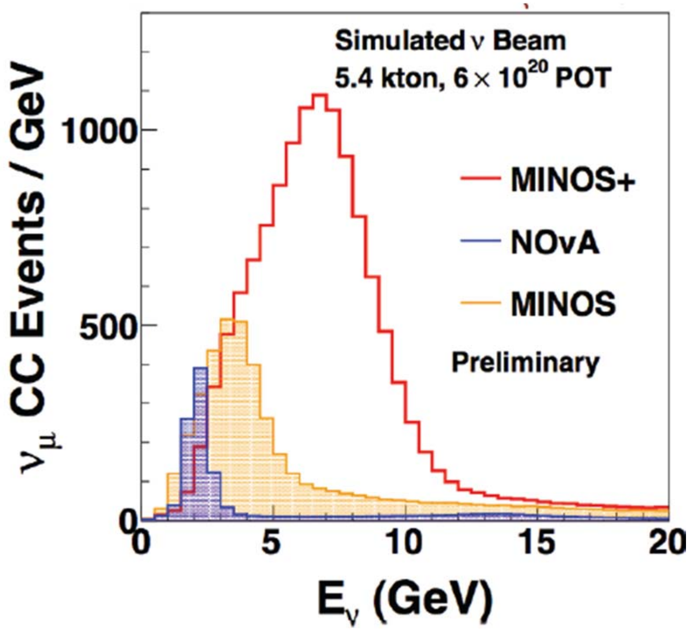
The Fermilab Neutrino Program Hosts Collaborators from across the globe:

Brazil, Canada, Chile, Czech Republic, Greece, India, Italy, Mexico, Peru, Poland, Russia, Switzerland, UK, US, ...

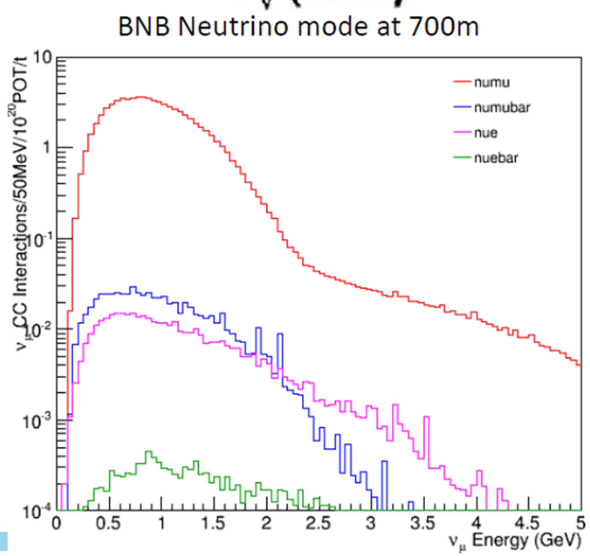
# Fermilab Accelerator Complex

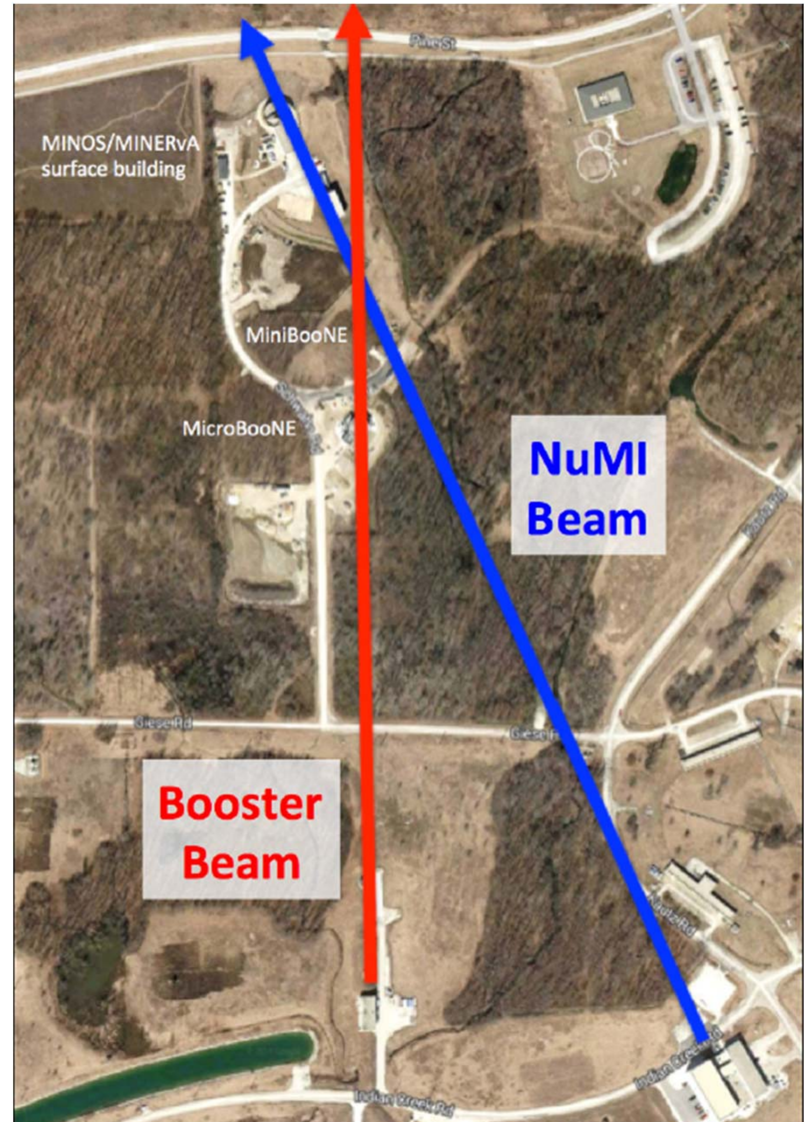
# NuMI and Booster Beams

NuMI:
- tunable
  1 GeV to
  >10 GeV
- Near hall
  at 1 km
- Far detectors
  735 – 810 km




BNB:
- Low energy
  0.1 – 1.5 GeV
- Focused on
  short-baseline
  oscillations and
  cross sections



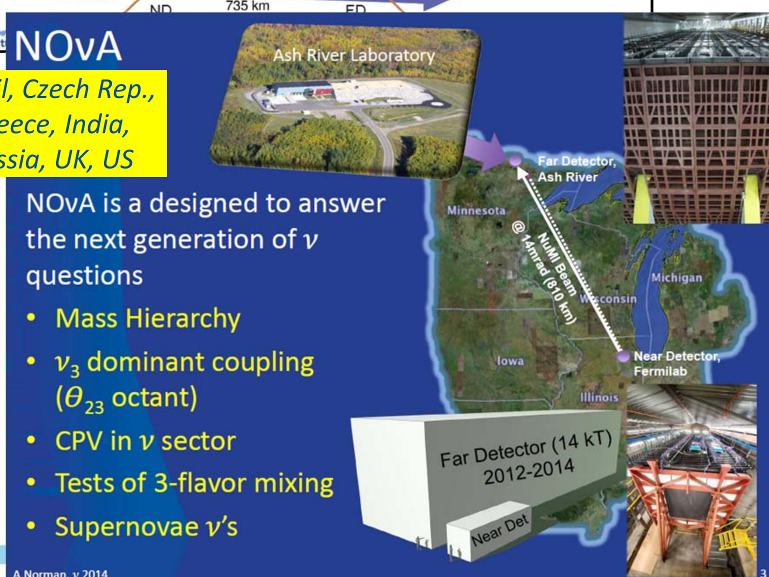



# Experiments in the NuMI Beam

## Long-baseline oscillation experiments

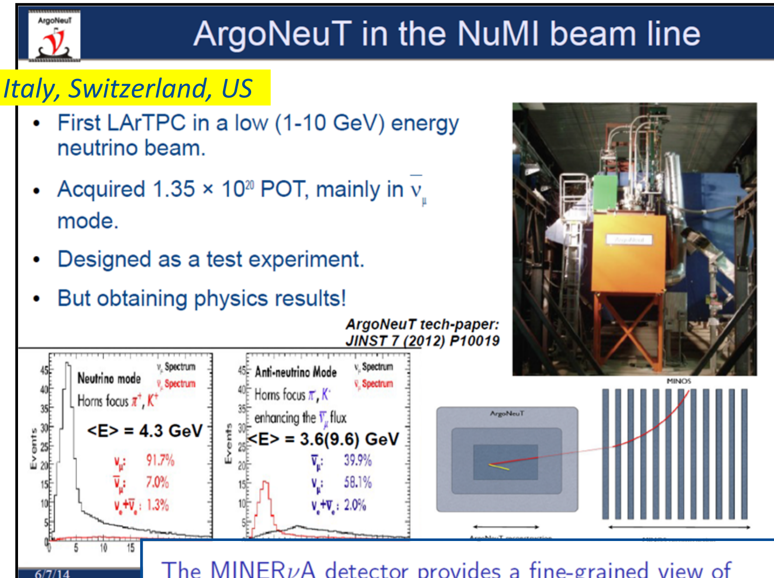
*Brazil, Greece, India, Poland, UK, US*

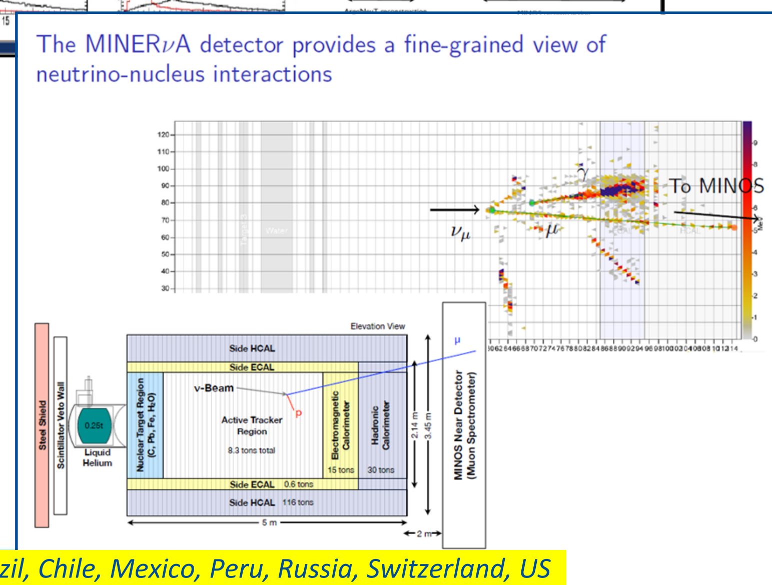

*Brazil, Czech Rep., Greece, India, Russia, UK, US*




## Neutrino scattering experiments

*Italy, Switzerland, US*

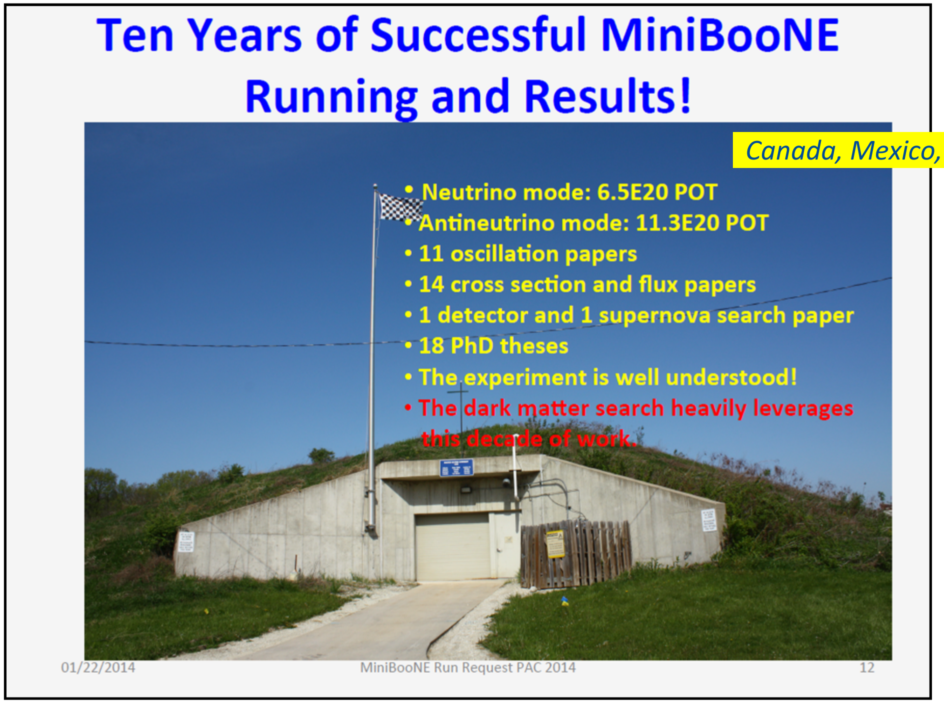



*Brazil, Chile, Mexico, Peru, Russia, Switzerland, US*

# Experiments in the Booster Neutrino Beam

## Testing short-baseline anomalies … sterile neutrinos?




*Canada, Mexico, UK, US*

MicroBooNE

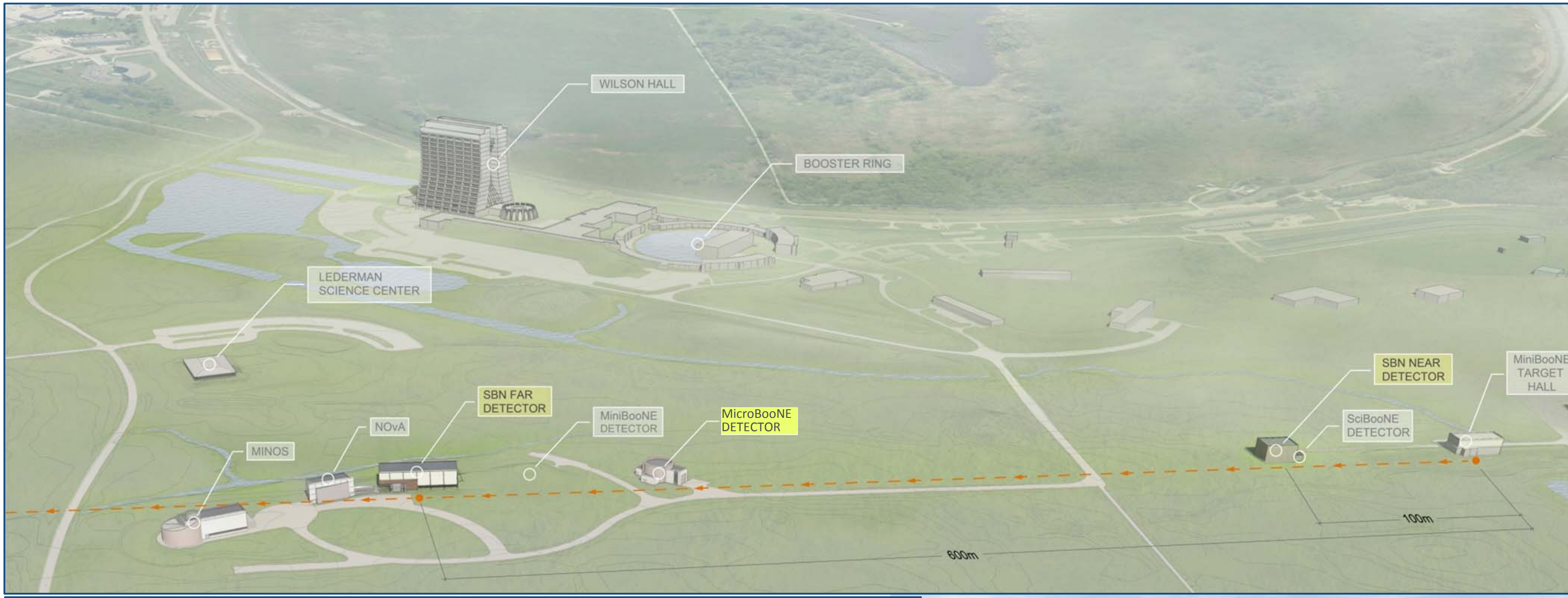
*Switzerland, UK, US*

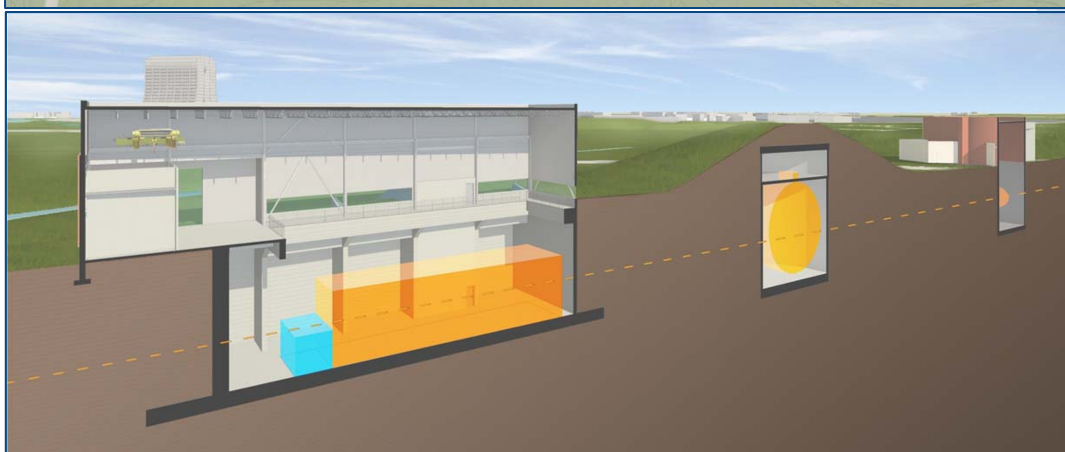
# Fermilab Short Baseline Neutrino (SBN) Program

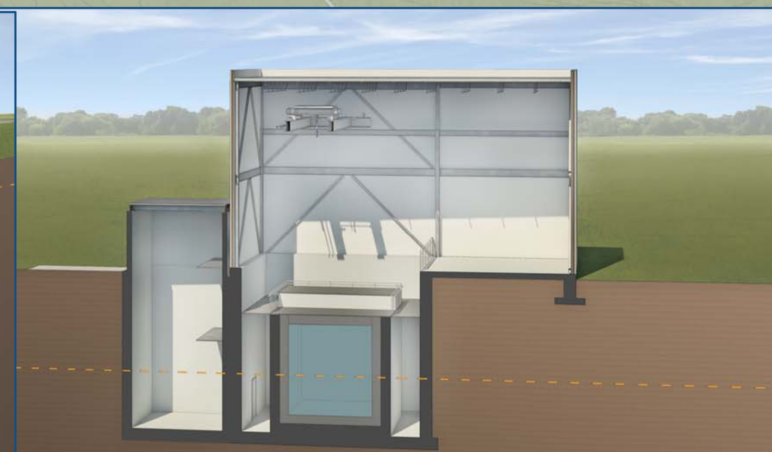
## Testing short-baseline anomalies … sterile neutrinos?

- Utilize successful Booster Neutrino Beamline (BNB) developed for MiniBooNE
- In 2015 next phase: MicroBooNE (approved for 6.6E20 P.O.T.)
- In 2018: Three LAr-TPC detectors:
  - Near: New detector using LBNE technology @ 110m from BNB target *Switzerland, UK, US*
  - Middle: MicroBooNE @ 470m *Switzerland, UK, US*
  - Far: refurbished ICARUS detector moved from Gran Sasso, Italy @ 600m *Italy, Poland, Russia, Switzerland, US*
- Motivations
  - Science: precise study of ν anomalies from the MiniBooNE and LSND experiments. Search for Sterile ν's
  - R&D: continued development of LAr-TPC technology for LBNF program
  - Build international partnerships for LBNF program

# SBN Program Layout





# SBN Program Development

- International partnership of the three collaborations developing joint proposal for submission to January 2015 PAC meeting
  - More than 40 institutions from 5 countries including 4 DOE labs and CER
  - Strong support from US DOE and NSF, INFN, and CERN. Additional support requests to CH NSF and UK STFC
- Very Fast timeline

  2014 – Proposal preparation initial design and logistics

  2014 – Civil construction start, near detector design, T600 refurbishing

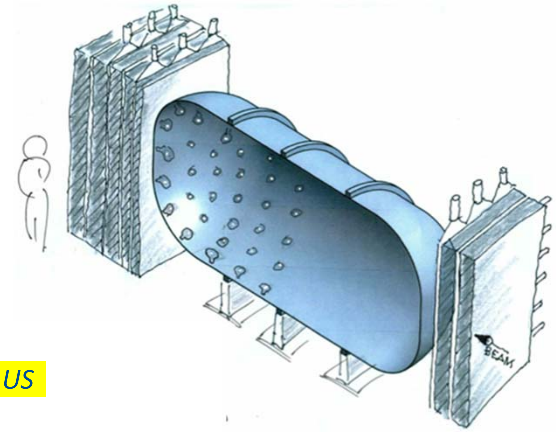
  2016 – Civil construction complete, near detector construction, T600 refurbishing

  2017 – Detector installation

  2018 – Beam operations with all three detectors
- Support expected from US DOE, US NSF, INFN and CERN.

# Additional Possible Experiments in the Booster Beam

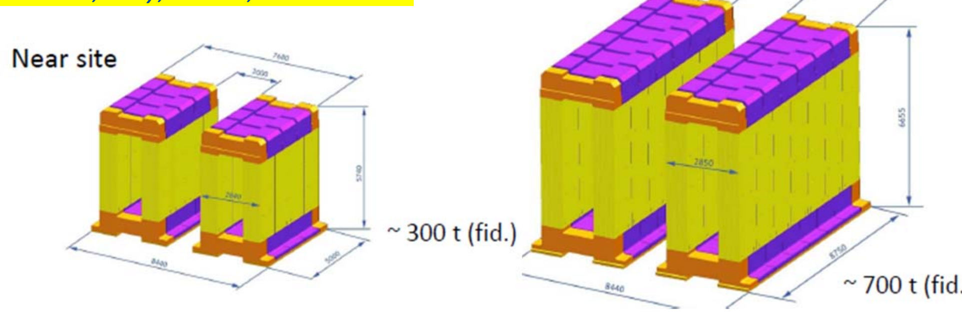
## Detector Development / Short-Baseline Anomalies / Supporting Measurements




*UK, US*

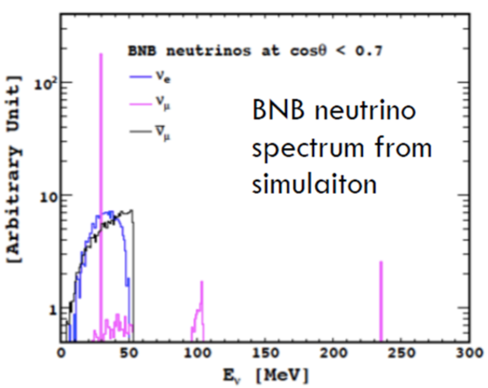
ANNIE: Measure ν-induced backgrounds relevant for large water detectors using an Optical Time Projection Chamber in BNB

*Croatia, Italy, Russia, Switzerland*



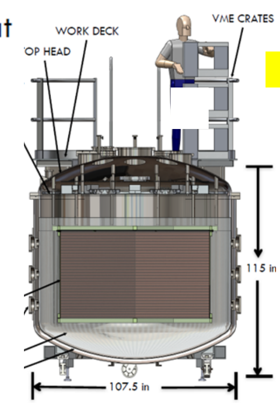

Short-baseline $\nu_\mu$-disappearance measurement in BNB (NESSiE)

CAPTAIN




space is available in and out of building at points A, B and C


*US*

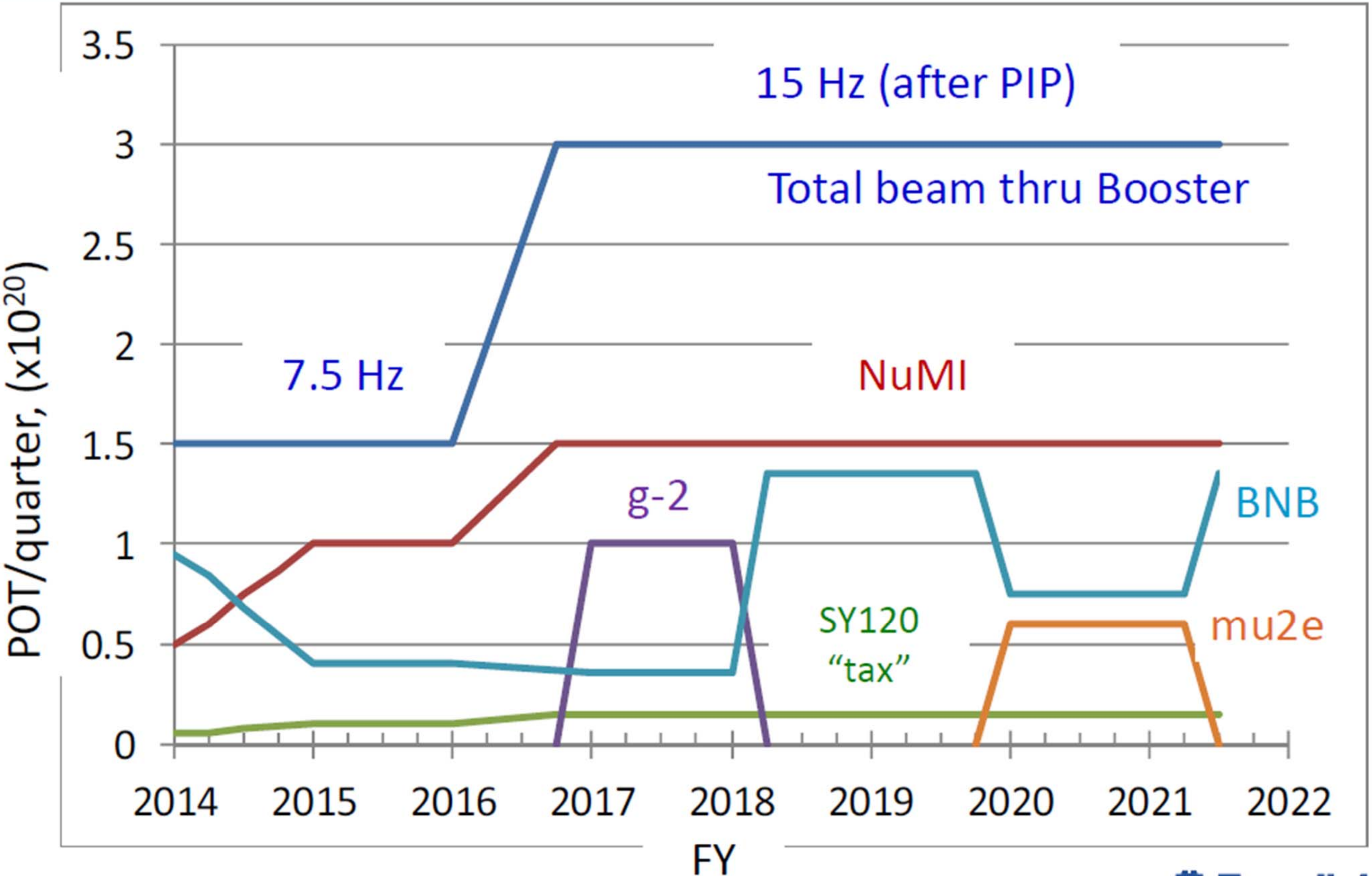



Calibrate LAr TPC response to low-energy neutrinos with stopped pion beam

# Increasing beam intensity

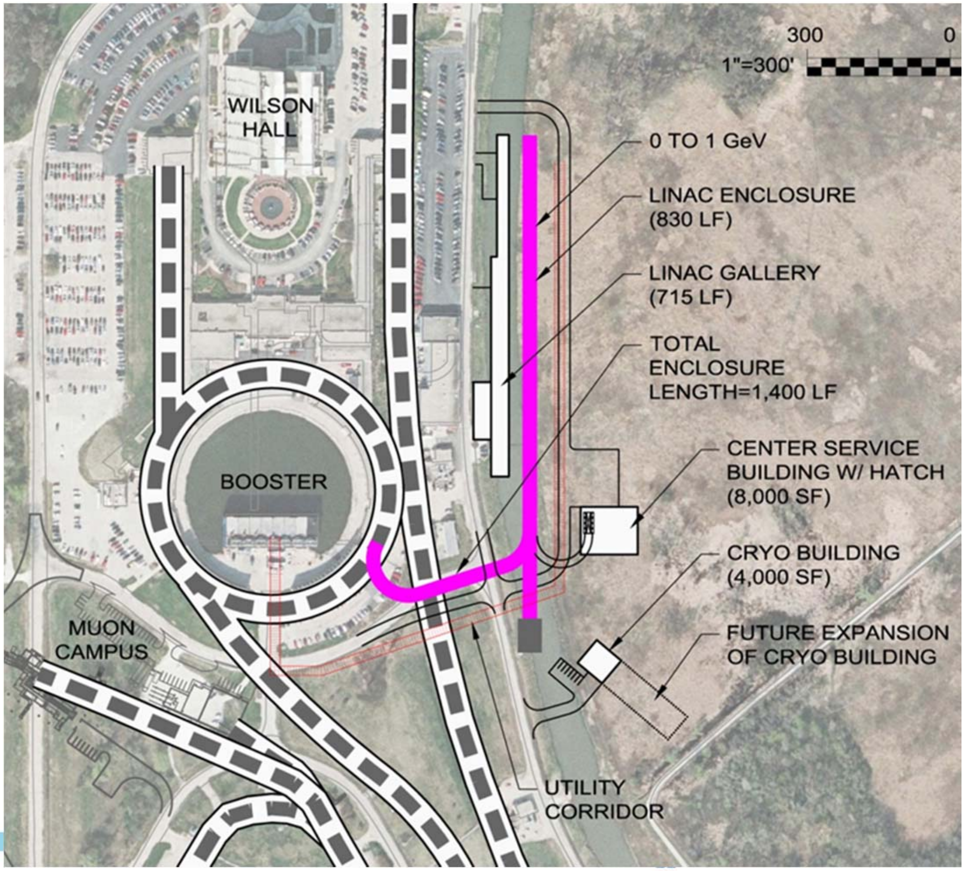
- Upgrades to the Main Injector and Recycler done as part of the NOvA construction will enable doubling the NuMI beam power to 700 kW
  - Convert Recycler to proton-stacking ring
  - Increase Main Injector ramp rate
  - ~10% increase in intensity per pulse
- Proton Improvement Plan (PIP) to increase proton flux from Booster to the Main Injector
  - Refurbish Booster RF system: 7.5 → 15 Hz beam operation
  - Upgrades to Linac and Booster for higher reliability
- Combined upgrades will deliver 700 kW to NOvA and increase the intensity of the Booster Neutrino Beam.

# Proton delivery scenario (approximate)



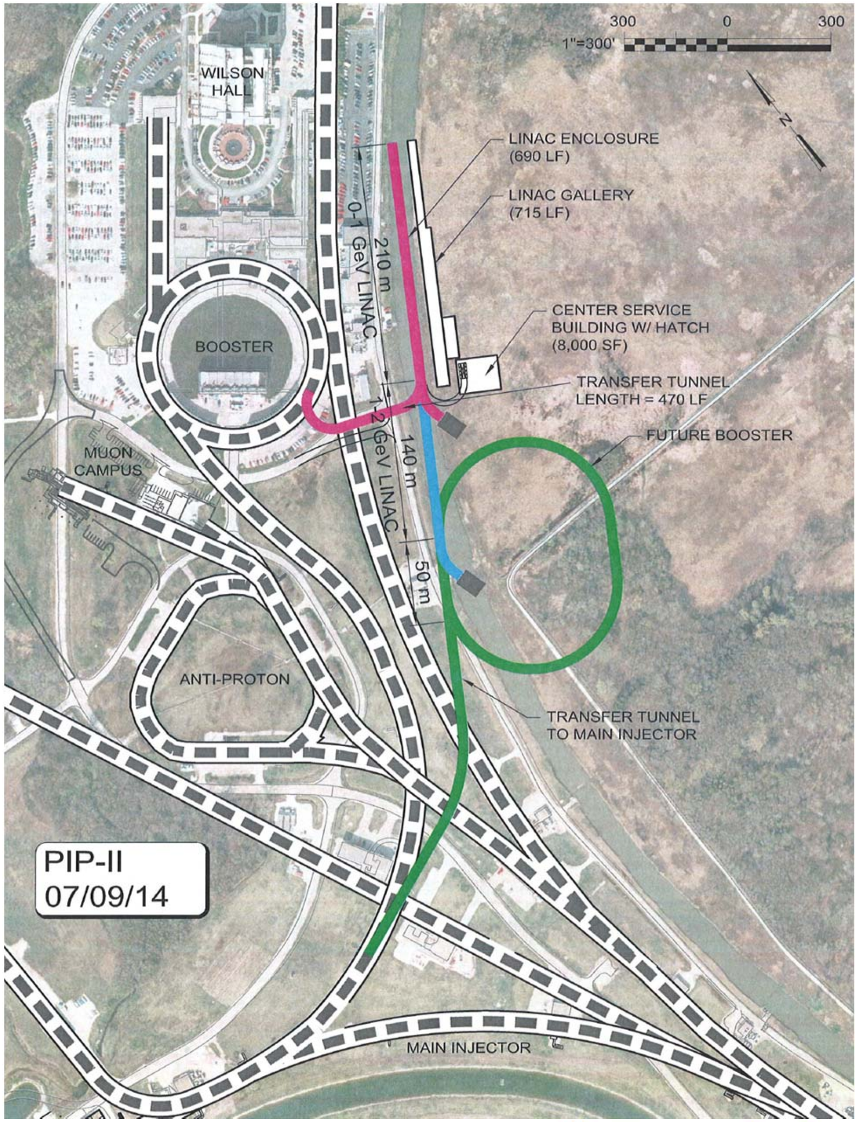
# Proton Improvement Plan II (PIP-II)

- Goal is to increase Main Injector beam power to 1.2 MW.
  - Replace the existing 400 MeV linac with a new 800 MeV superconducting linac => 50% increase in Booster intensity.
  - Shorten Main Injector cycle time 1.33 → 1.2 sec.
- Build this concurrently with LBNF => 1.2 MW to LBNF from t = 0.
- This plan is based on well-developed SRF technology.
- Developing an international partnership for its construction
- Strong support from DOE and P5



# Flexible Platform for the Future

- Future upgrade would provide
  > 2 MW to LBNF
- Flexibility for future experiments
  - 100's kW at 800 MeV
  - 100's kW at few GeV, depending on design of next upgrade
  - Example shown is for 2 GeV SRF linac + new Rapid Cycling Synchrotron



# Long-Baseline Neutrino Facility

Fermilab is prepared to host a Long-Baseline Neutrino Facility. Working with international partners it will provide the infrastructure required to carry out a world-leading long-baseline neutrino oscillation experimental program.

The facilities will include:

- A neutrino beam capable of operating at 1.2 MW and upgradeable to at least 2.4 MW
- Far site infrastructure to house a massive LAr TPC far detector 1300 km from Fermilab at the Sanford Underground Research Facility,
- Near site infrastructure to house the near detector
- Major technical infrastructure such as cryostats and cryogenic systems for LAr TPC detector(s).

# The LBNF Facilities Team

The work so far has been done mainly by the LBNE Project Team, already with significant international collaboration: *China, Finland, Japan, Switzerland, UK, US, …*

- Beamline: Fermilab with collaborations with UTA, RAL, RADIATE Collaboration, CERN, US-Japan Task Force, IHEP/Beijing, and others.
- Conventional Facilities: Fermilab, SURF and contractors; collaboration initiated with LAGUNA-LBNO team
- Cryostat and cryogenic systems: Fermilab; collaboration initiated with CERN and with LAGUNA-LBNO team.

The LBNF team will be built on this foundation, with expanded collaboration as this becomes a truly international program.

- Expanded roles for existing partners
- Augmented by additional partners

# The LBNF Facilities

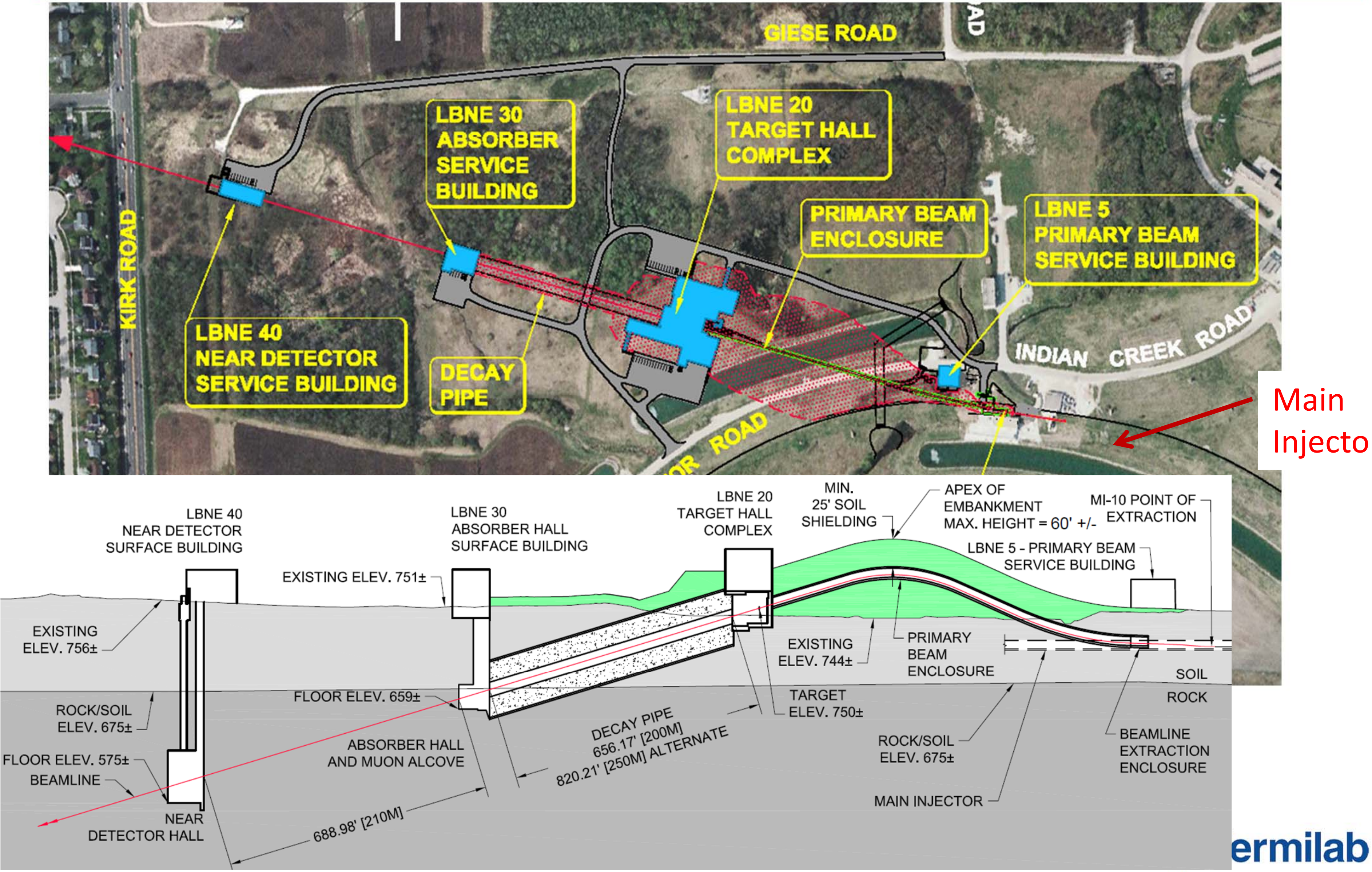
- The facilities team has been working with the scientific community to develop facilities to support the experimental program.
  - Has worked for many years with the LBNE Collaboration
    *Armenia, Brazil, Czech Rep., India, Italy, Japan, Russia, UK, US*
  - During the past year, have expanded to also work with the LAGUNA-LBNO Collaboration
    *Bulgaria, Finland, France, Germany, Greece, Italy, Japan, Poland, Romania, Russia, Spain, Switzerland, Turkey, UK*
- The LBNF facilities team will work with the new Collaboration, which will provide scientific and technical requirements for the LBNF experiment, to design and build the facilities that will enable a world-leading long-baseline program.
- The slides that follow summarize the current facility designs on which the new LBNF facility designs will build.

# Beamline for a new Long-Baseline Neutrino Facility

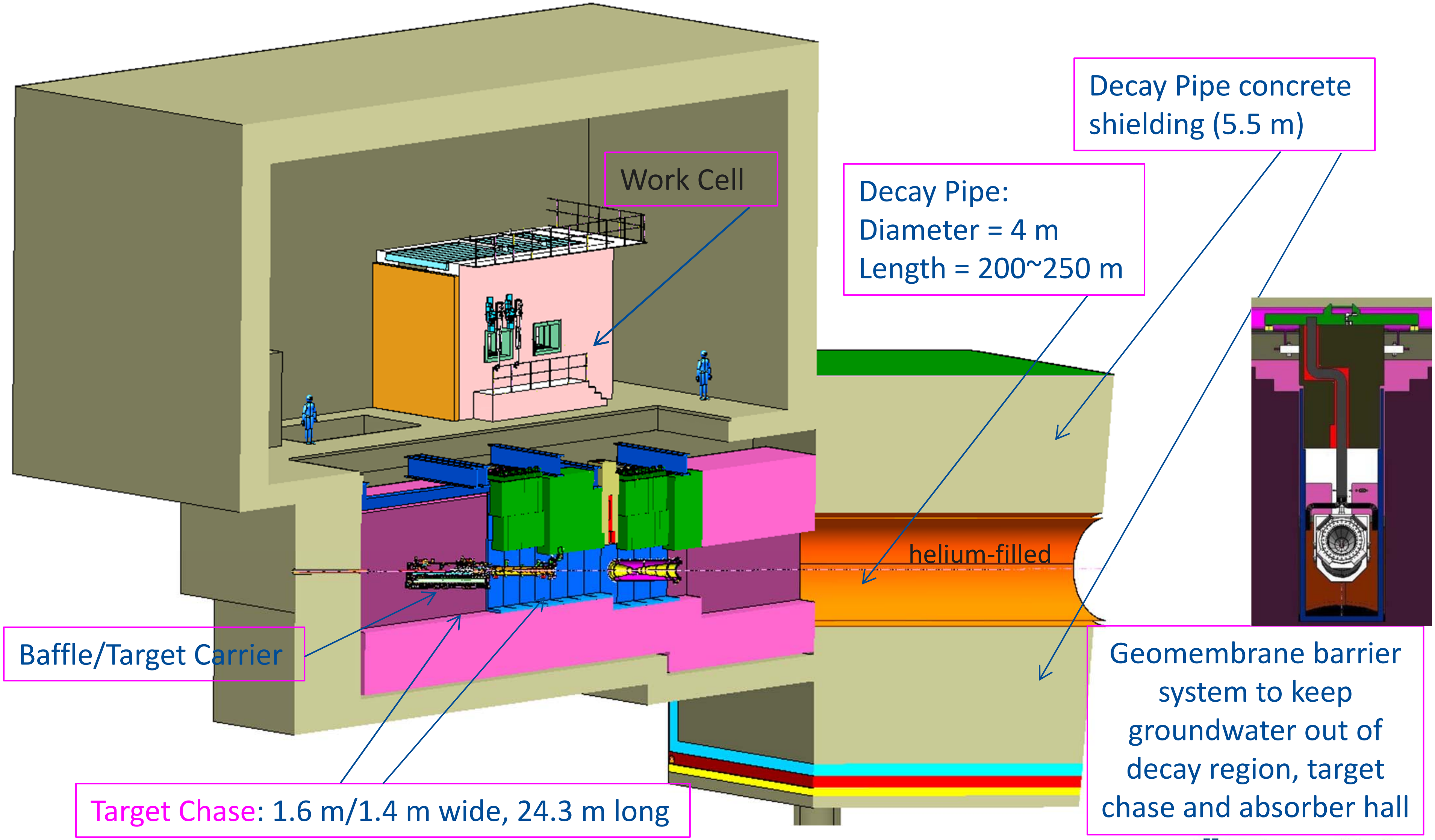
A design for a new neutrino beam at Fermilab is under development in the context of the LBNE Project, which will support the new Long-Baseline Neutrino Facility.

- Directed towards the Sanford Underground Research Facility (SURF) in Lead, South Dakota, 1300 km from Fermilab.
- Beam spectrum to cover 1$^{st}$ (2.4 GeV) and 2$^{nd}$ (0.8 GeV) oscillation maxima => Cover 0.5 ~ 5 GeV
- All systems designed for 1.2 MW initial proton beam power.
- Facility is upgradeable to ≥2.4 MW proton beam power.

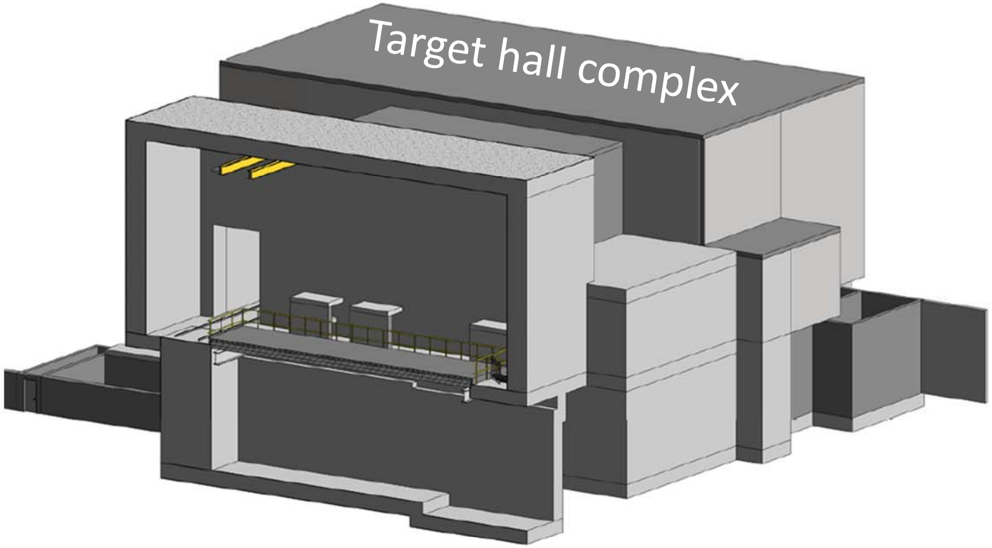
# Beamline for a new Long-Baseline Neutrino Facility

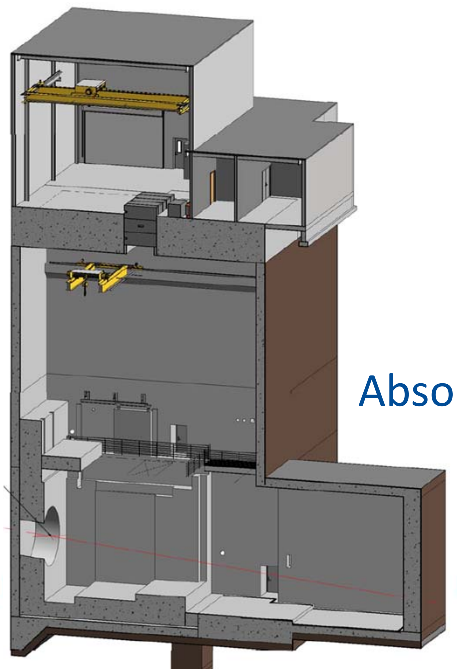


# Target Hall and Decay Pipe Layout



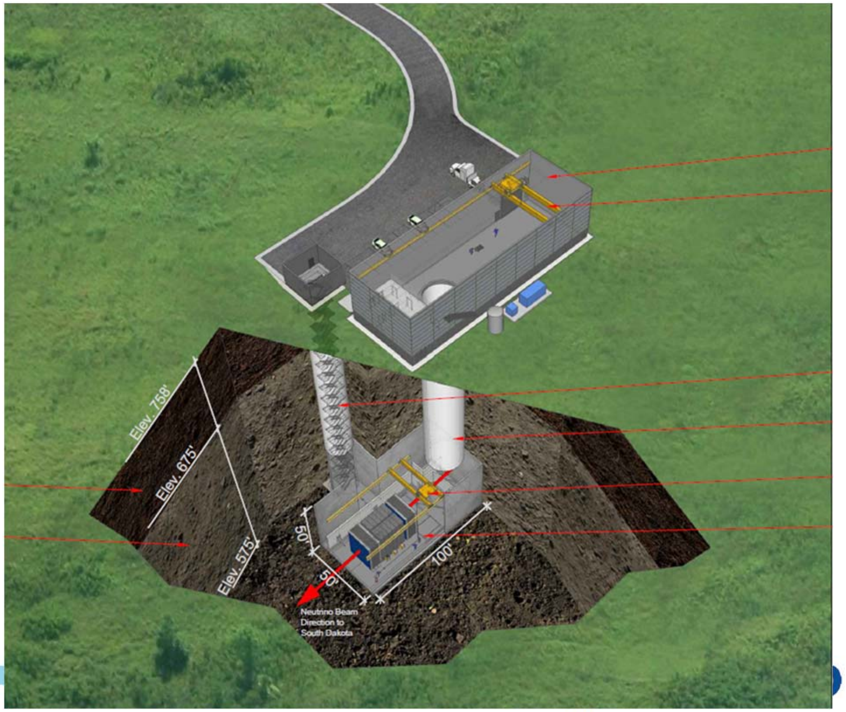
# Conventional Facilities Designs



Absorber hall

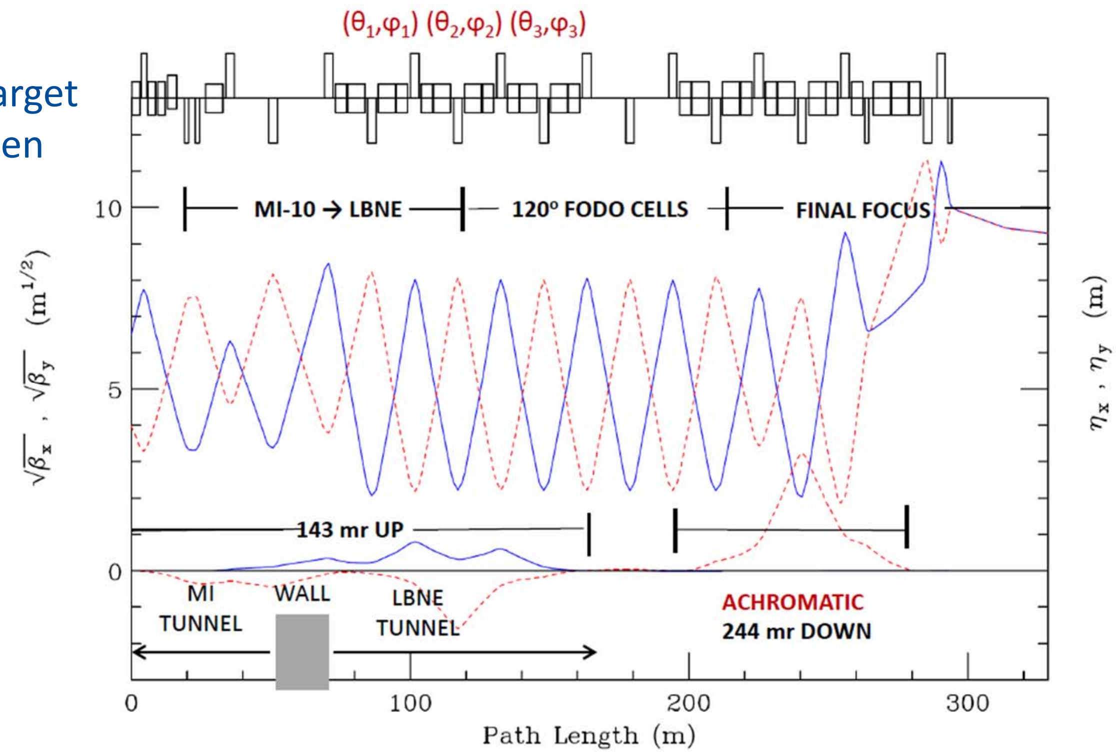
Near Detector Hall and Surface Building

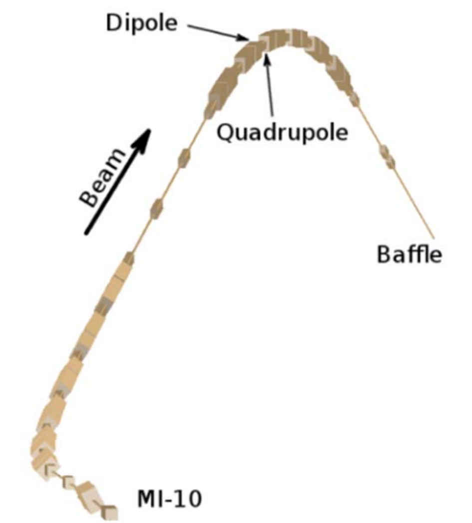


# Primary Beam and Lattice Functions

- The LBNF Primary Beam will transport 60 - 120 GeV protons from MI-10 to the LBNF target to create a neutrino beam. The beam lattice points to 79 conventional magnets (25 dipoles, 21 quadrupoles, 23 correctors, 6 kickers, 3 Lambertsons and 1 C magnet).

Beam size at target tunable between 1.0-4.0 mm




STRUCT/MARS simulations have shown that highest beam loss rate takes place right at the apex of beamline

Horizontal (solid) and vertical (dashed) lattice functions of the LBNF transfer line

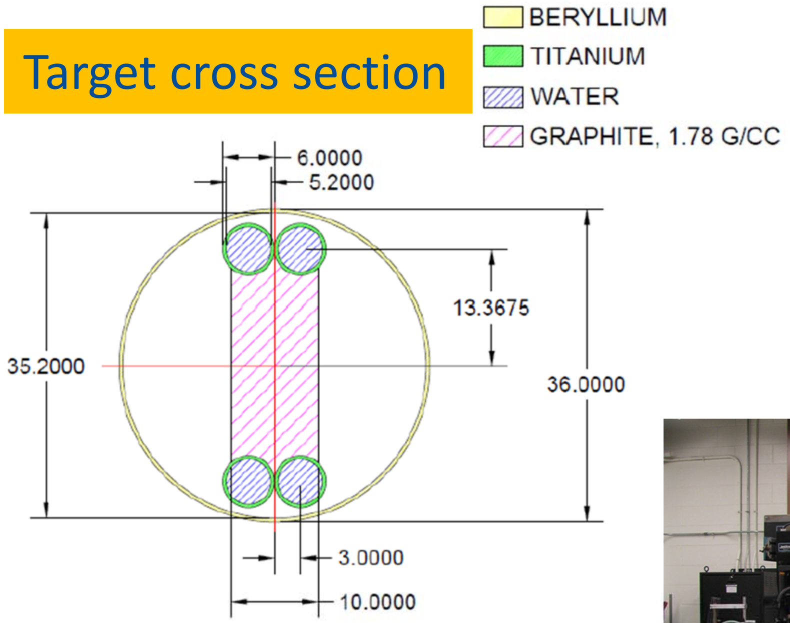
The final focus is tuned for $\sigma_x = \sigma_y = 1.50$ mm at 120 GeV/c with $\beta^* = 86.33$ m and nominal MI beam parameters $\varepsilon_{99} = 30\pi$ μm & $\Delta p_{99}/p = 11 \times 10^{-4}$

# Components inside the target chase

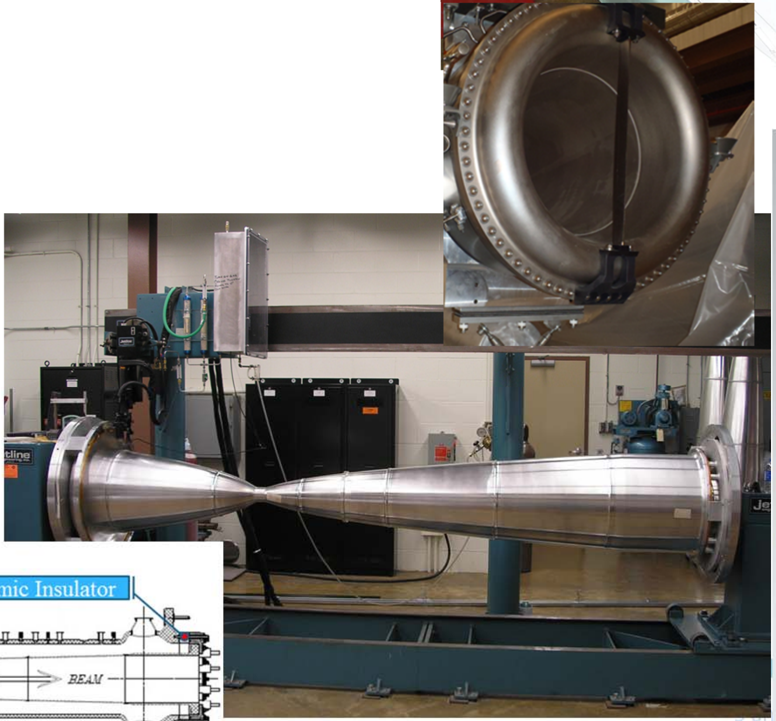
47 graphite target segments, each 2 cm long

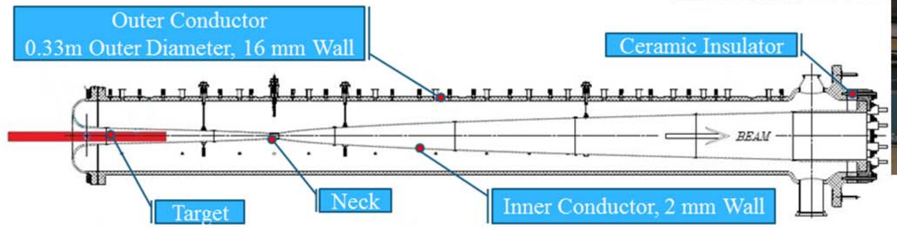
Baffle

Target cross section

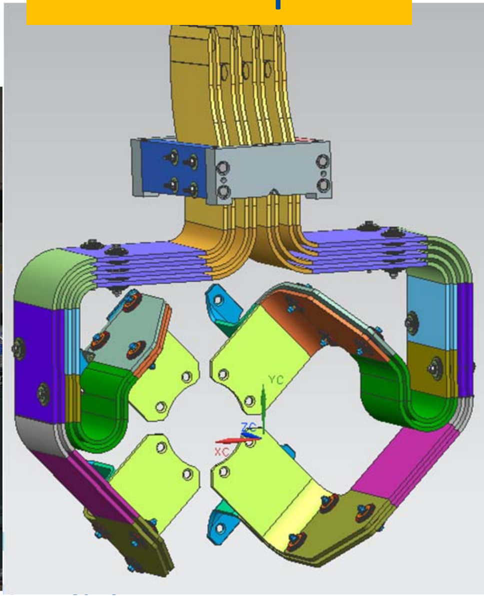



Horn

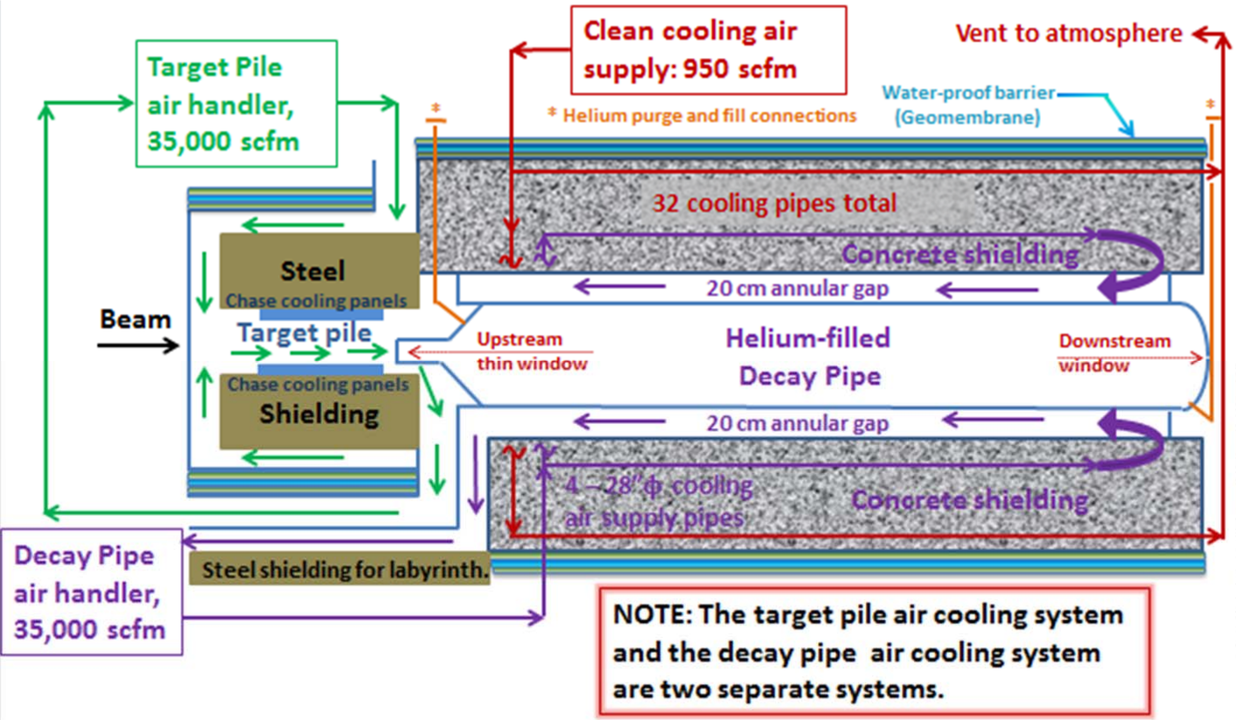


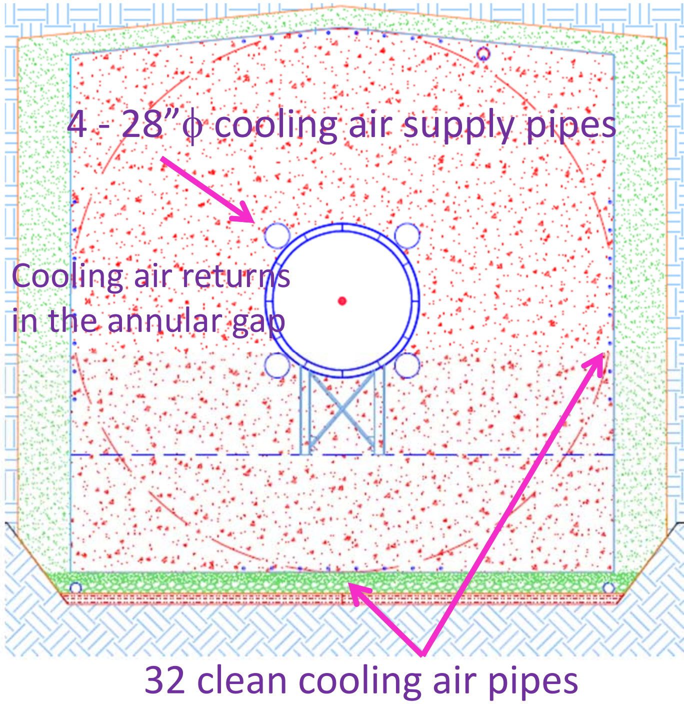



Horn Stripline

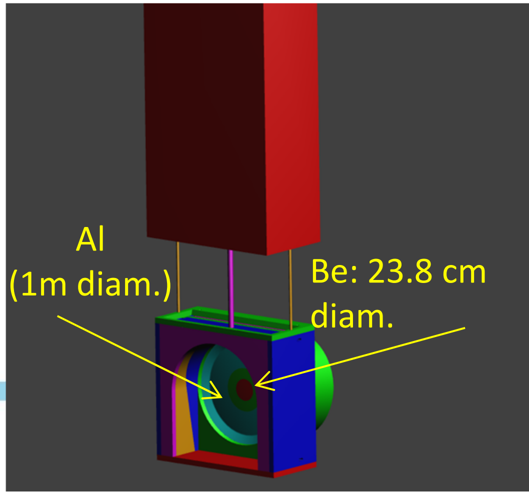


# Helium-filled/Air-cooled Decay Pipe




- Concentric Decay Pipe. Both pipes are ½" thick carbon steel
- Decay pipe cooling air supply flows in four, 28" diam. pipes and the annular gap is the return path
- The helium-filled decay pipe requires that a replaceable, thin, metallic window be added on the upstream end of the decay pipe

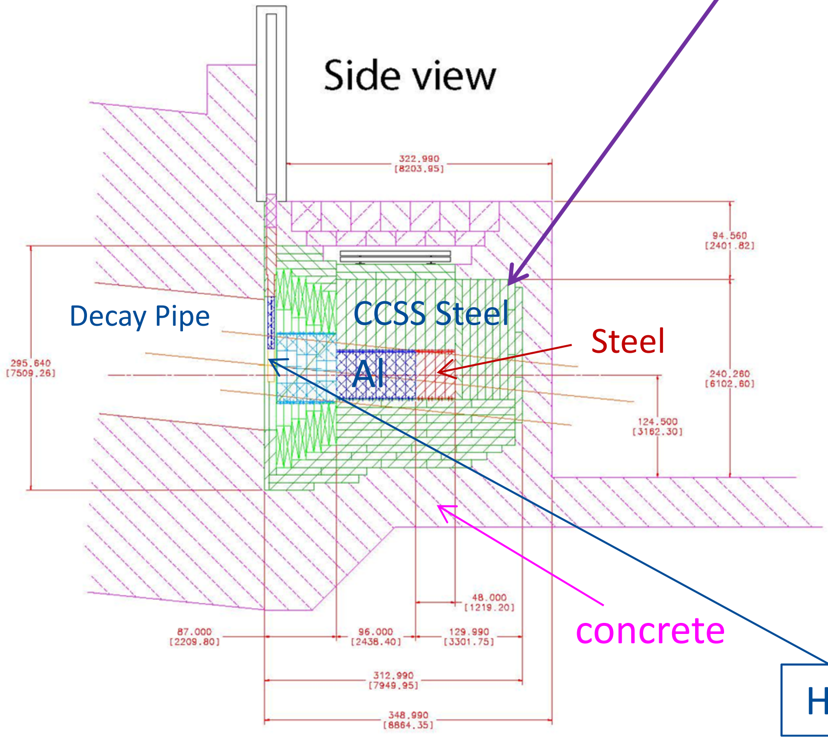


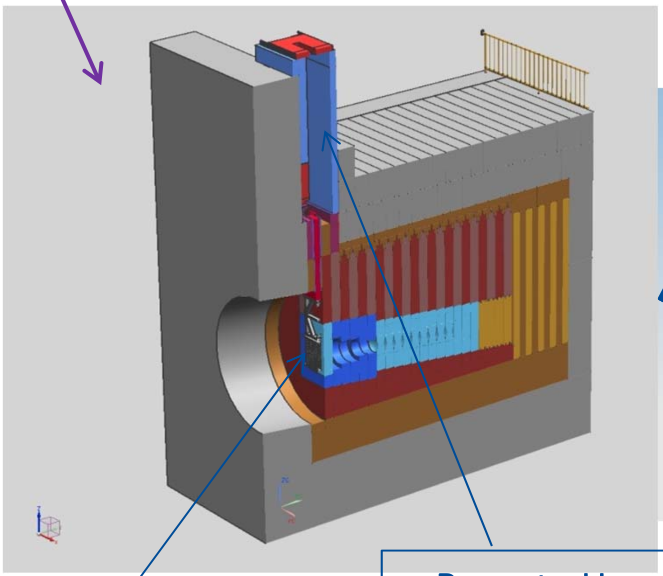
# Absorber Complex – Longitudinal Section

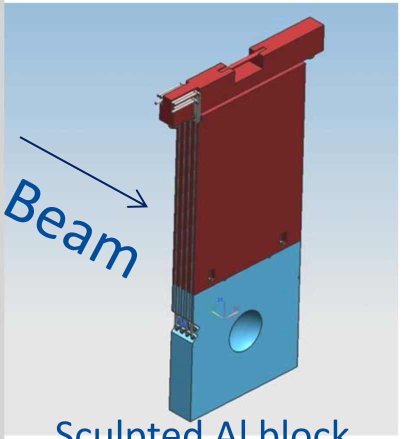
The Absorber is designed for 2.4 MW

A specially designed pile of aluminum, steel and concrete blocks, some of them water cooled which must contain the energy of the particles that exit the Decay Pipe.

**Thermal, structural, mechanical engineering development in progress**






Sculpted Al block

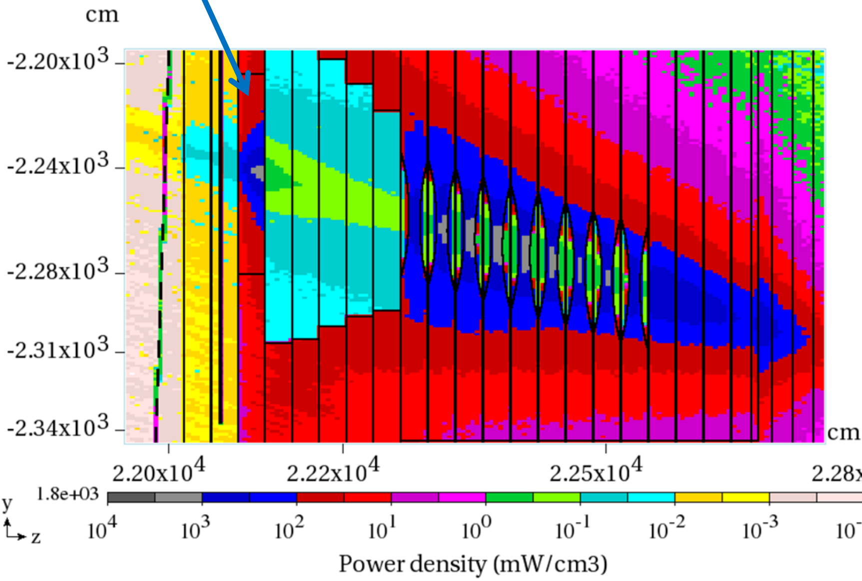
Hadron Monitor (HM)

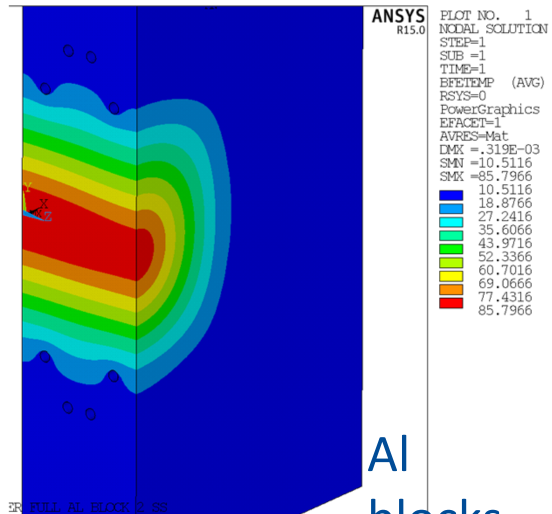
Remote Handling Facility for HM

# Absorber Design/MARS Simulations (2.4 MW)

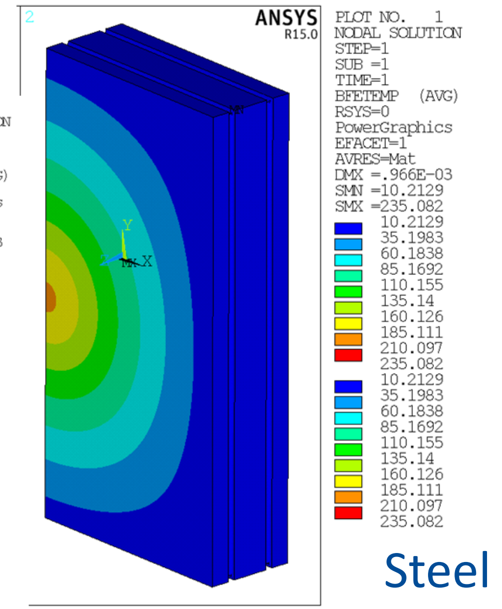
## 9 sculpted Al blocks and 4 solid Al blocks in the core

Al spoiler

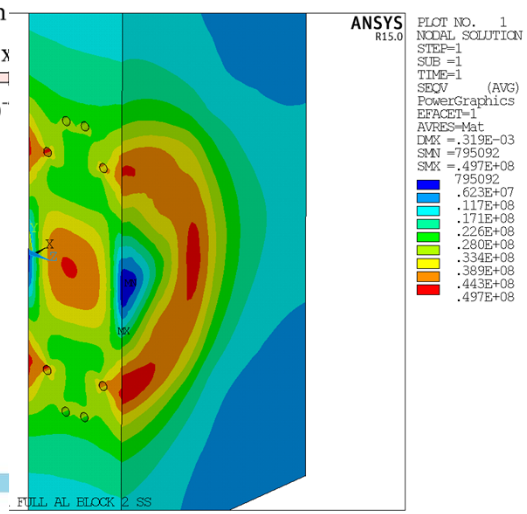


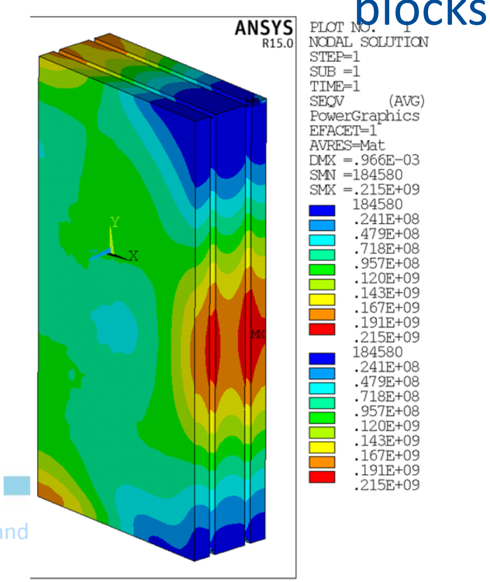




Al blocks



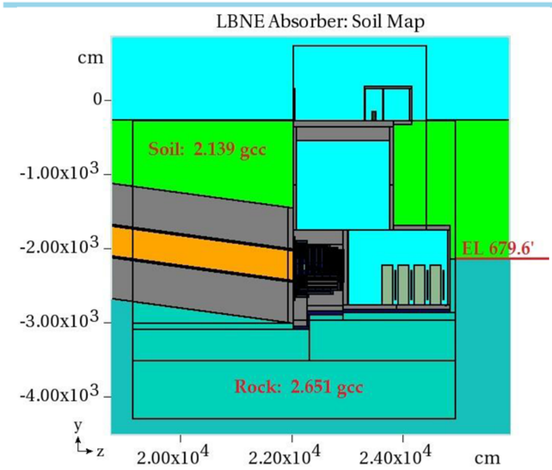

Steel blocks

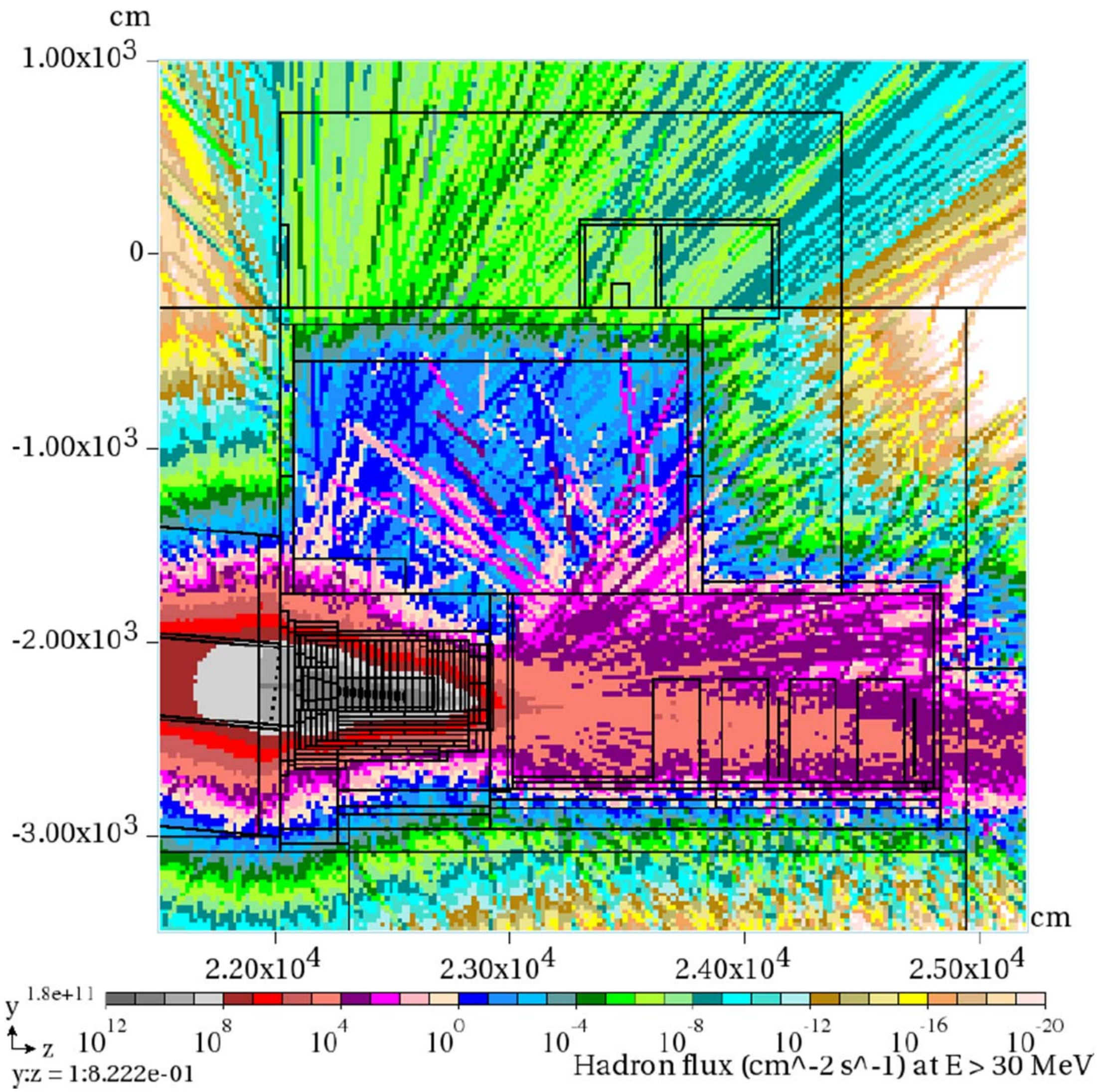



Max Temp Al: 86$^0$C
Max VM stress Al: 50 MPa at water line
Max Temp steel: 235$^0$C
Max VM stress Al: 215 MPa

# Hadron Flux ($cm^{-2}\ s^{-1}$) at E > 30 MeV (2.4 MW)





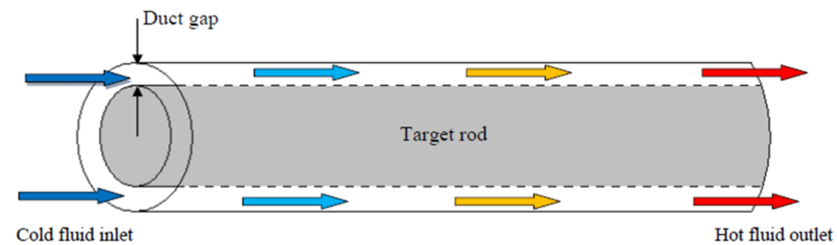

Fermilab

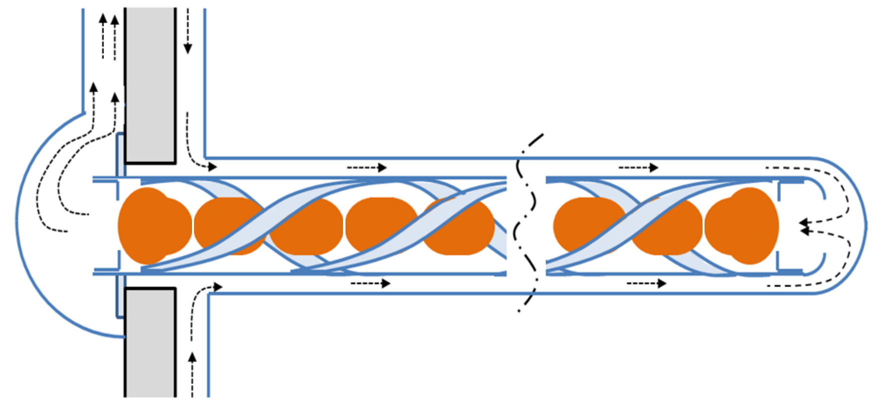
# Novel Target Designs

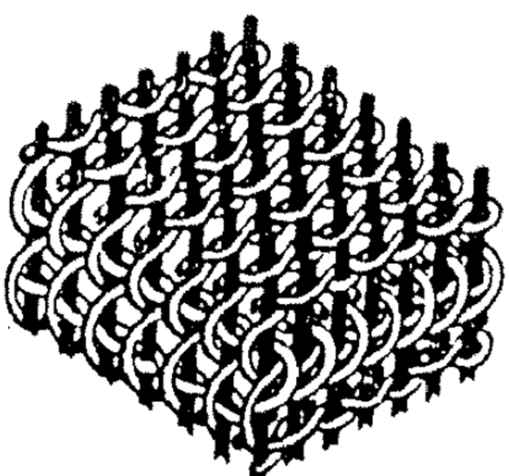
RaDIATE
Collaboration
Radiation Damage In Accelerator Target Environments

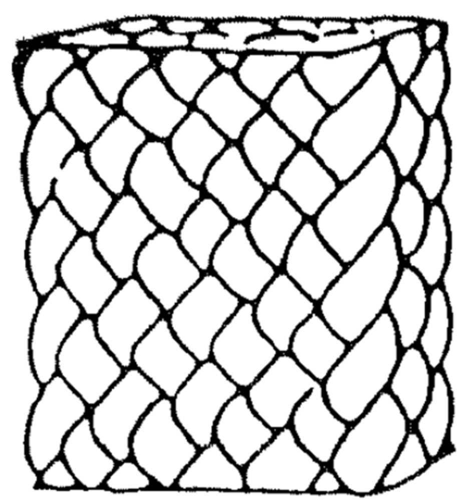
HiRadMat
High-Radiation to Materials

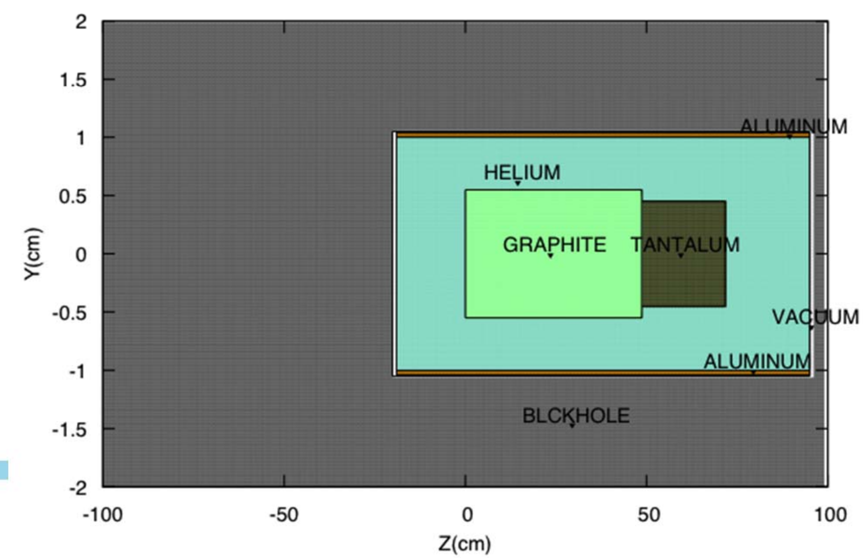
- High heat-flux coolants
  - Elimination of water
- Composite targets
- Segmentation
- Robust materials and assemblies



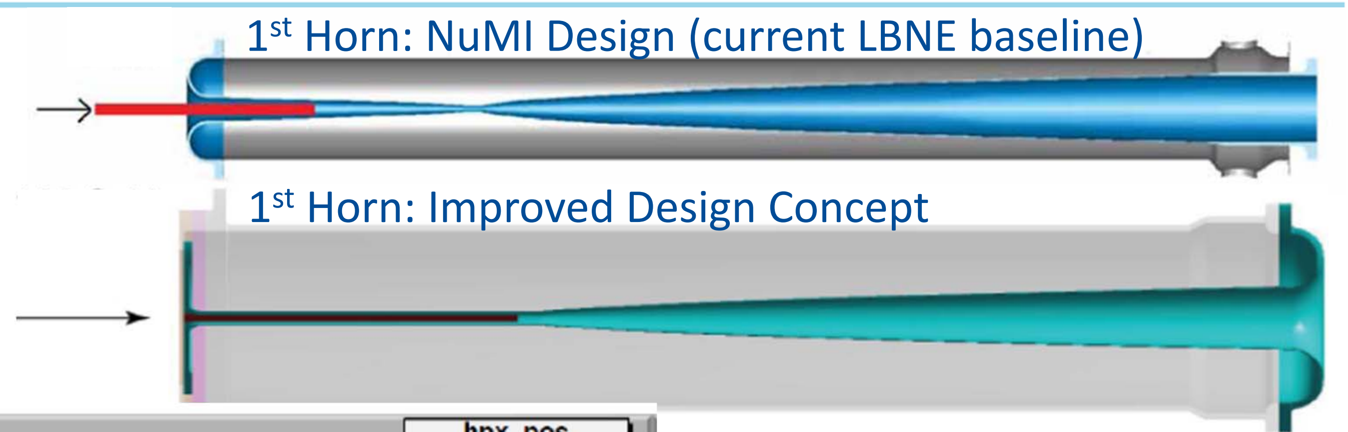



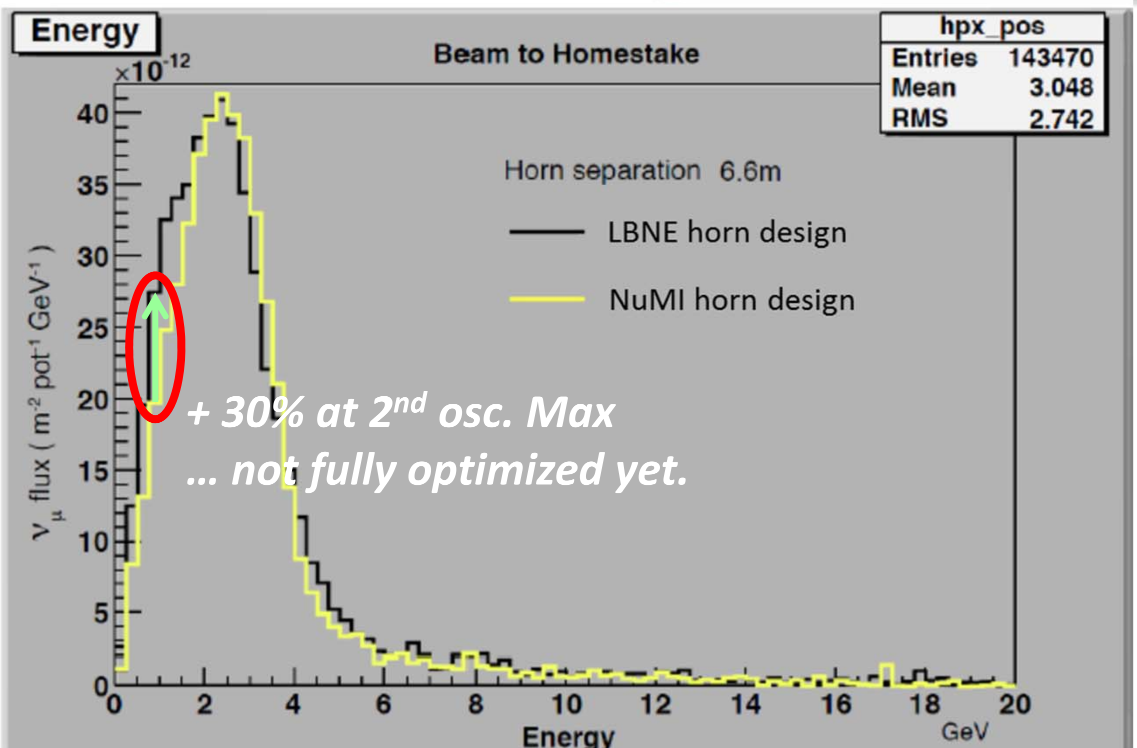






# Improved Focusing for Second Oscillation Maximum



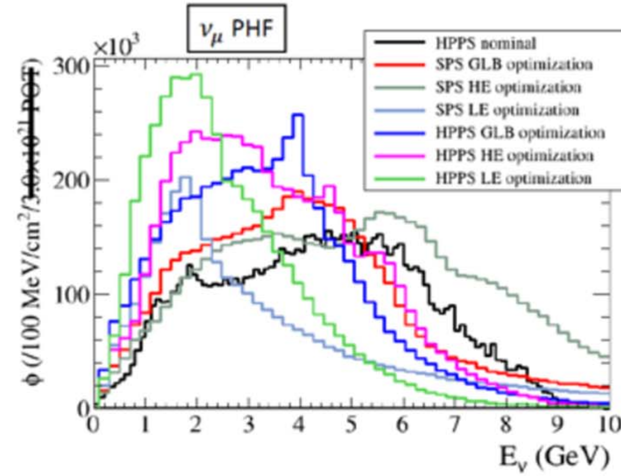

Significant improvements are possible and needed, which collaborators could bring into the design of the LBNF beam design.



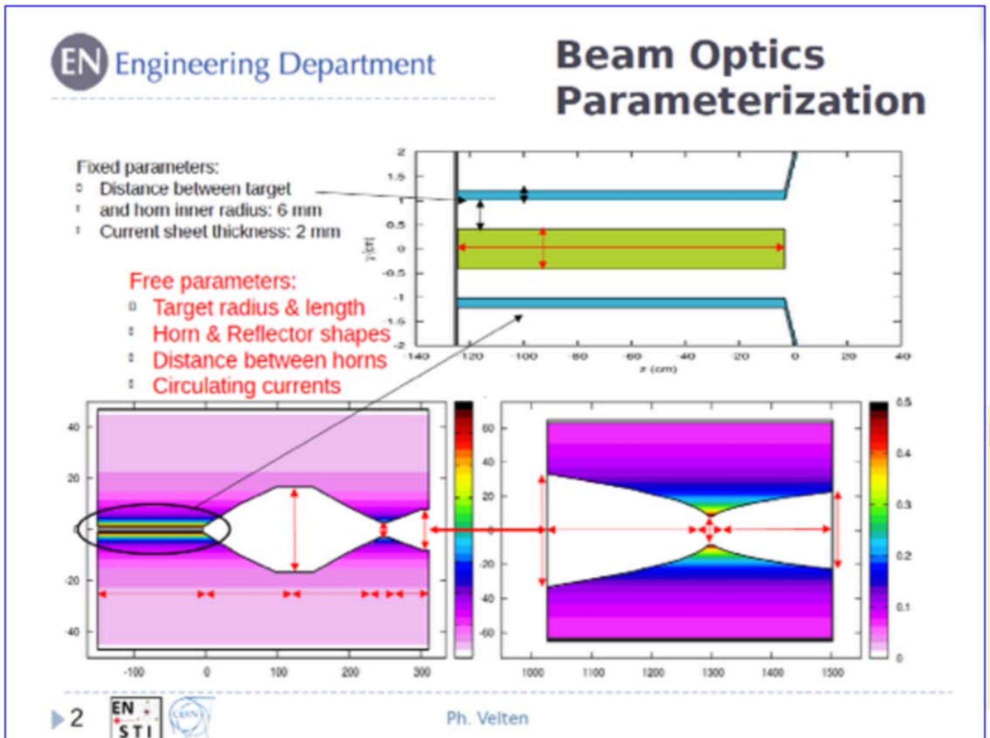
Fermilab

# CN2PY ν-beam optimisation

- Beam target and focusing system optimization using Genetic Algorithm
  - Multi-variable analysis of horn/reflector parameters
  - Optimization:
    - **use GLOBES** to maximize the $\delta_{CP}$ sensitivity at the FD
    - **HE-optimization**: maximum yield of ν-s in the range [1-10]GeV
    - **LE-optimization**: maximum yield of ν-s in the range [1-2] GeV



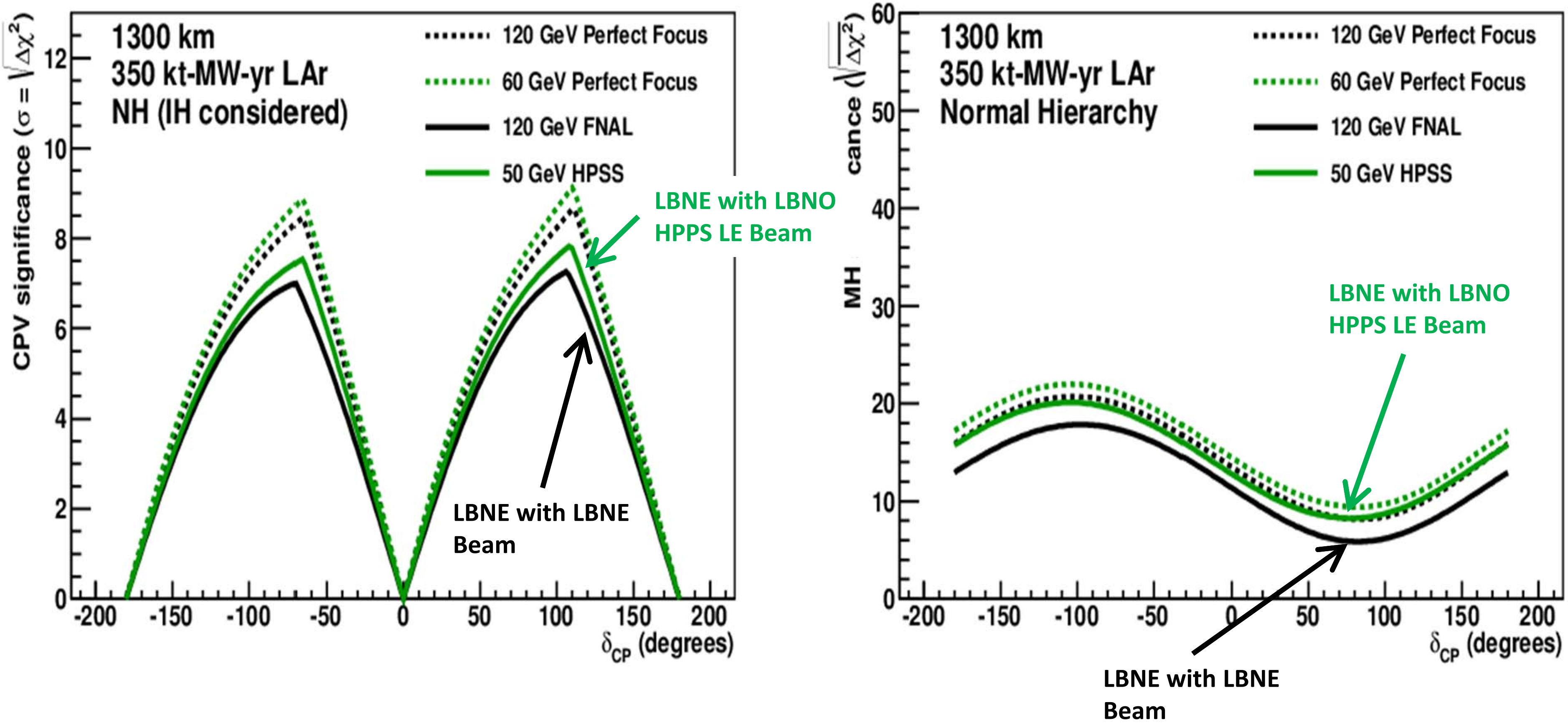

POT normalization for SPS: 3.75E+20
POT normalization for HPPS: 3.0E+21




- New optimization for CDR, using additional engineering constraints:
  - $R_{min}$ horn ~27mm
  - Same relative position horn/reflector for 400/50 GeV beams
  - Target length <1.3 m

I. Efthymiopoulos - CERN 03-Nov-2014 16

# Apply LBNO-design low-energy beam (HPPS LE) to LBNE



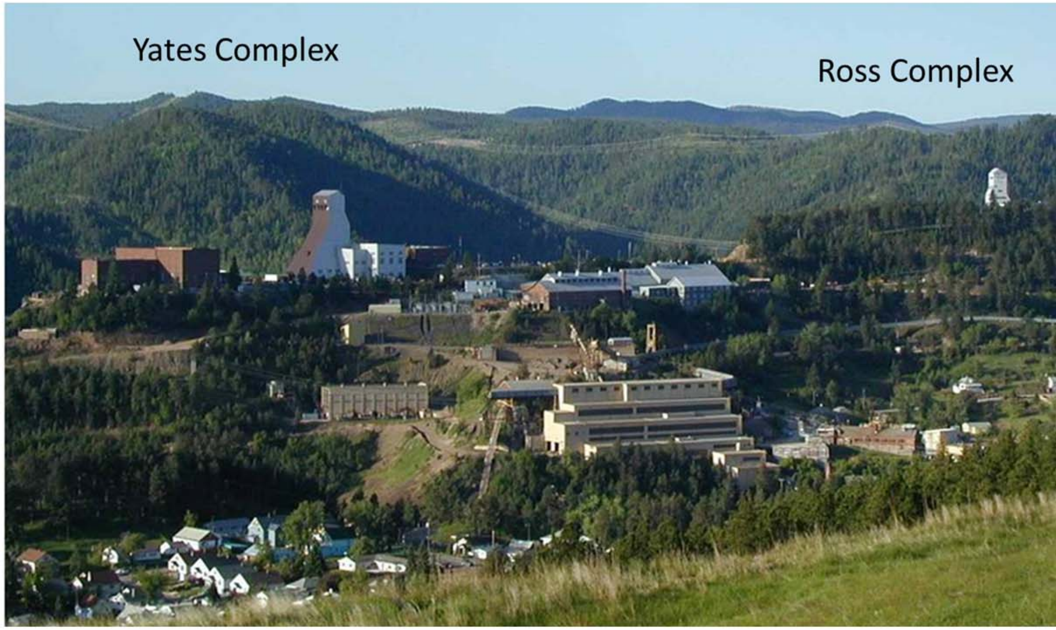

- Application of HPPS LE beam spectrum to LBNF baseline
  - modestly improves CP violation reach
  - improves minimum $\Delta\chi^2$ by ~x2 for MH

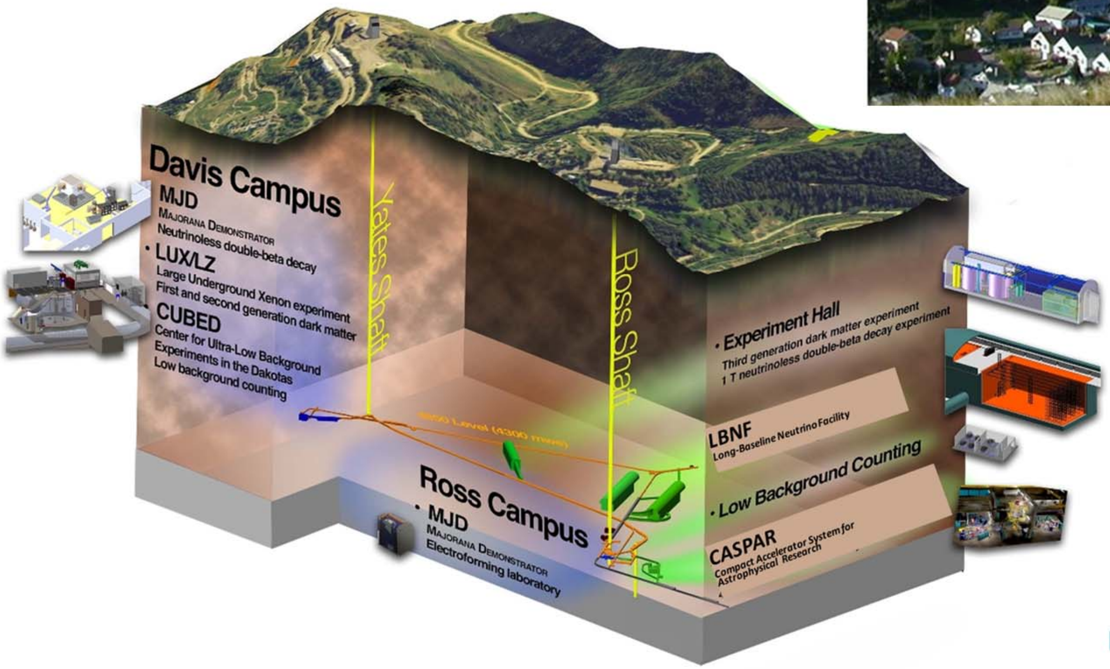
# Sanford Underground Research Facility

Experimental facility operated by the State of South Dakota.

Current experiments:

- LUX (dark matter)
- Majorana ($0\nu\beta\beta$)
- Several smaller experiments




Future home of:

- LZ (G2 dark matter experiment)
- CASPAR (Compact Accelerator System for Astrophysical Research)
- LBNF

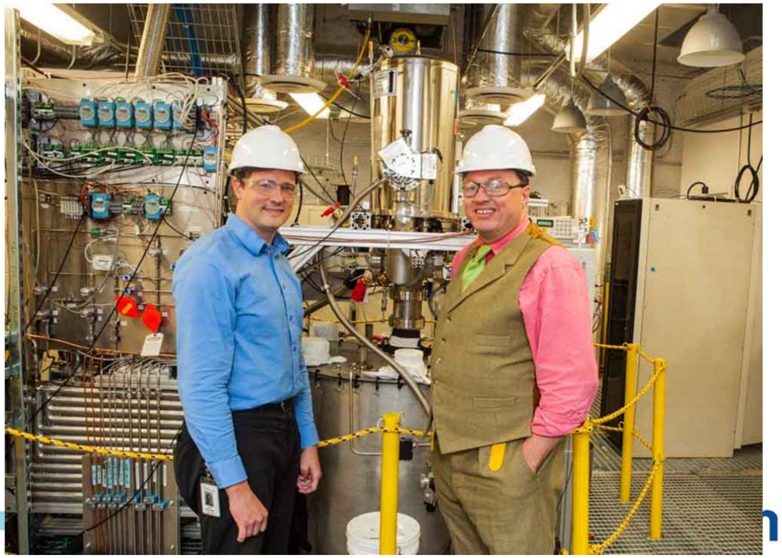
# Sanford Underground Research Facility

Entrance to Davis Campus


Majorana Demonstrator ($0\nu\beta\beta$)


- Experimental Facilities at 4300 mwe
- Two vertical access shafts for safety
- Shaft refurbishment in process and has reached the 2000 foot level
- Total investment in underground infrastructure is >$100M
- Facility donated to the State of South Dakota for science in perpetuity

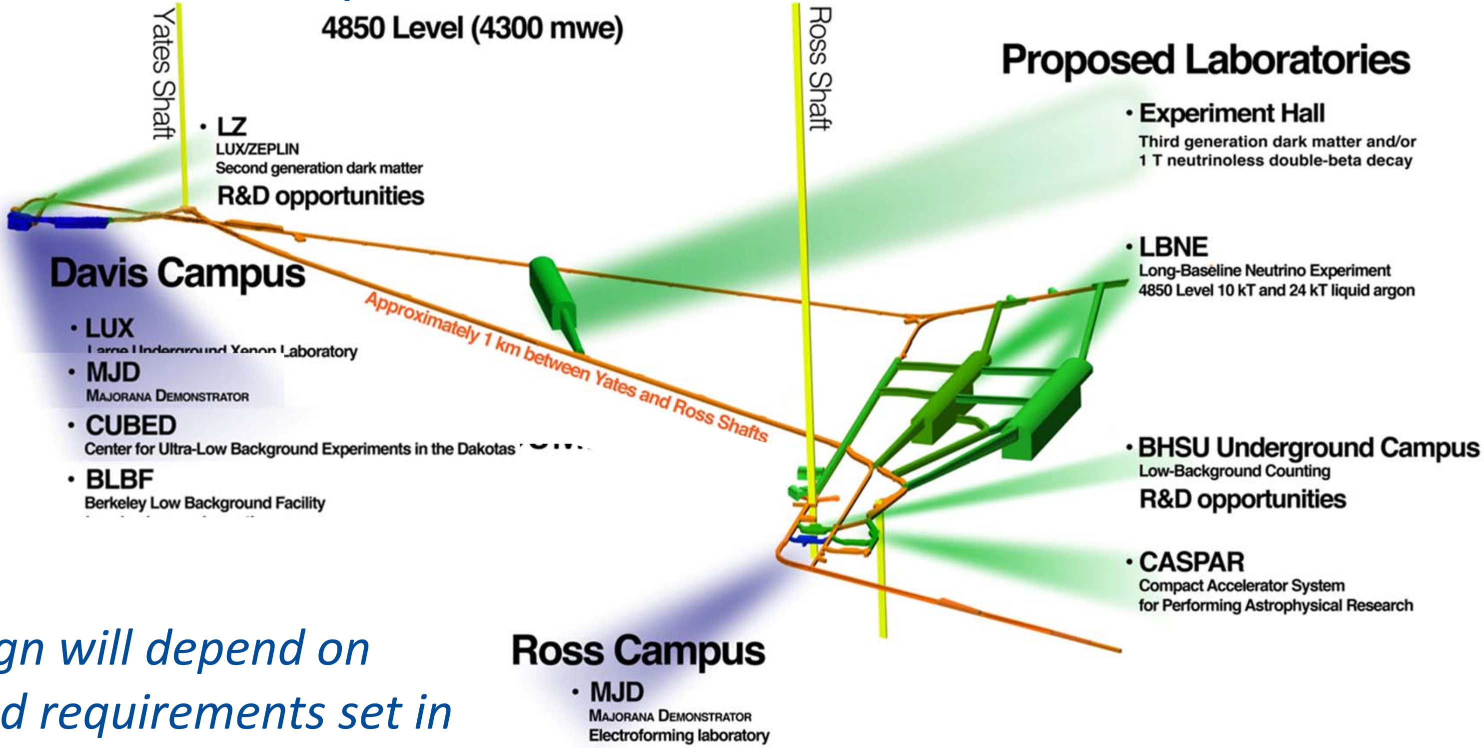
LUX (dark matter)



# Planned Location of LBNF Cavern(s)

Current reference* design:

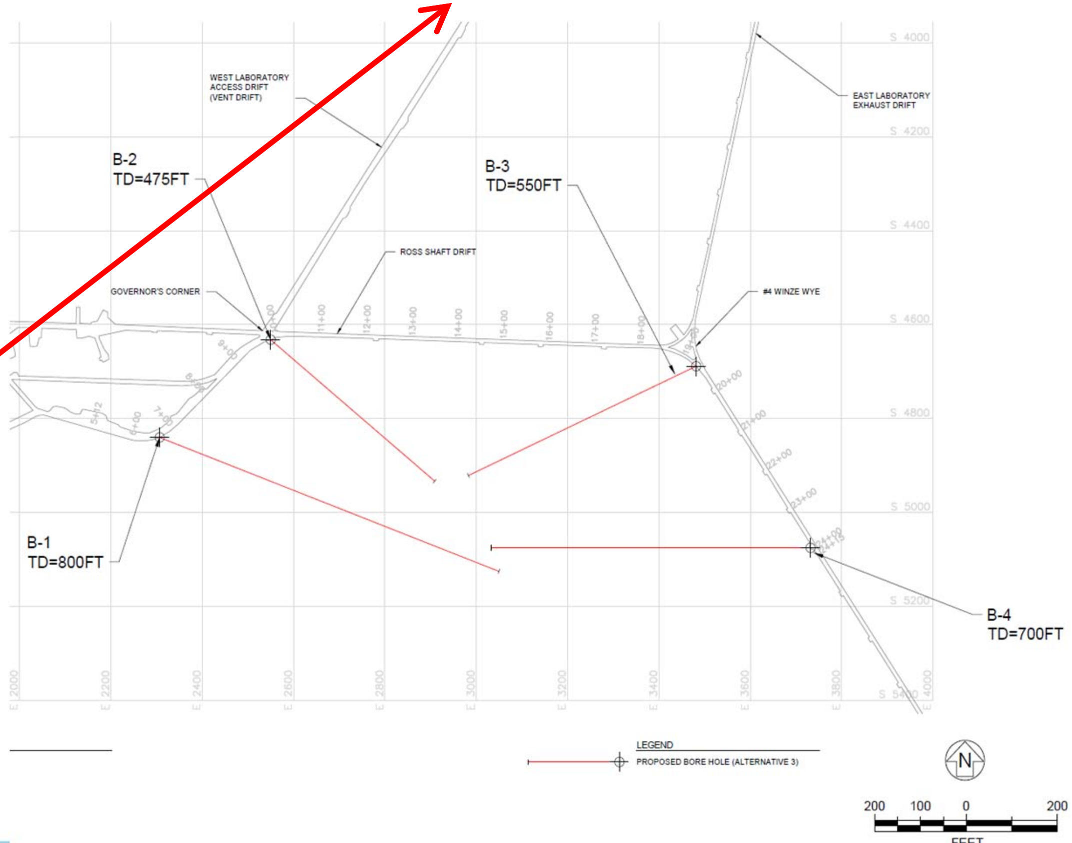
- Rectangular caverns for rock-supported cryostats
- 2 caverns: 10 kt + 24 kt fiducial mass sizes
- 10 kt cavern fully outfitted and detector-ready
- 24 kt cavern excavated only




* *Actual design will depend on strategy and requirements set in discussion with Science Collaboration*

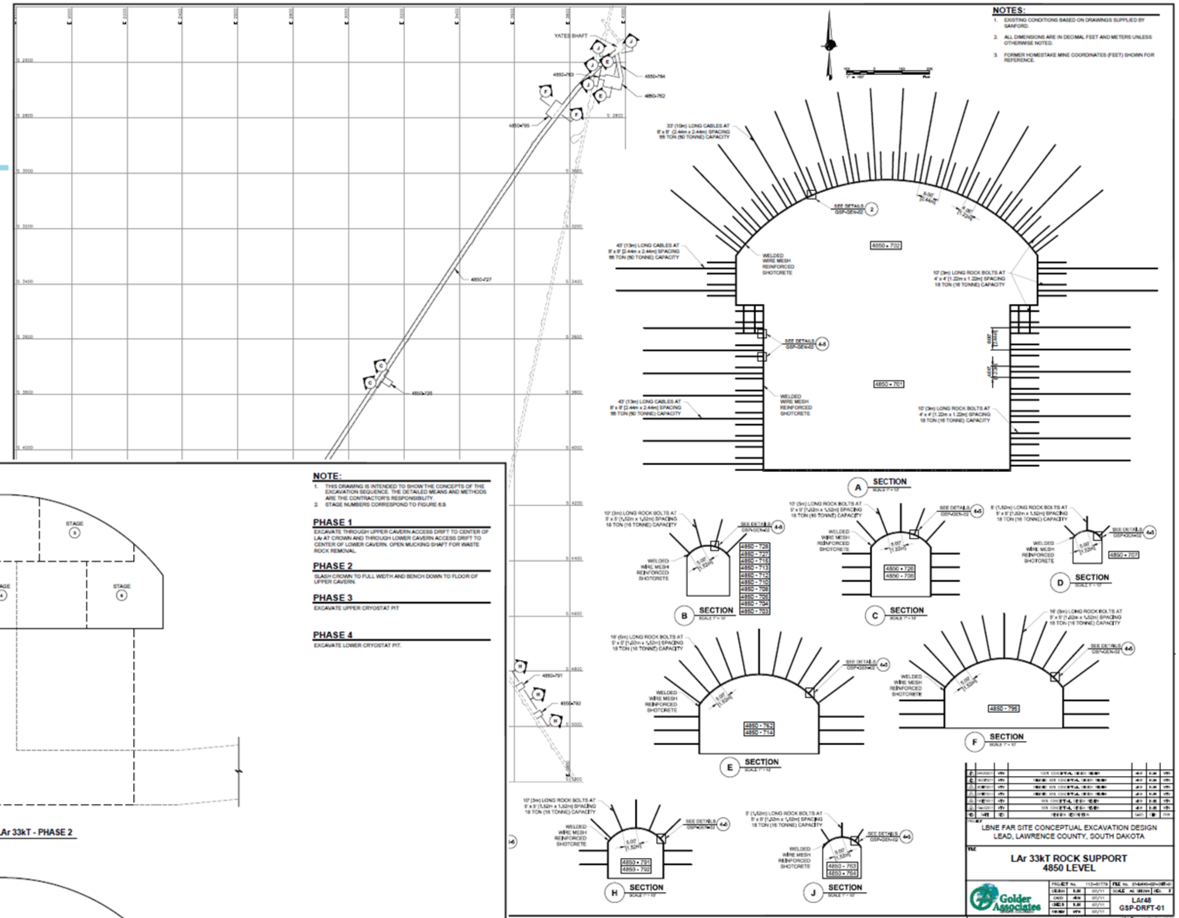
# Geotechnical Investigation Program

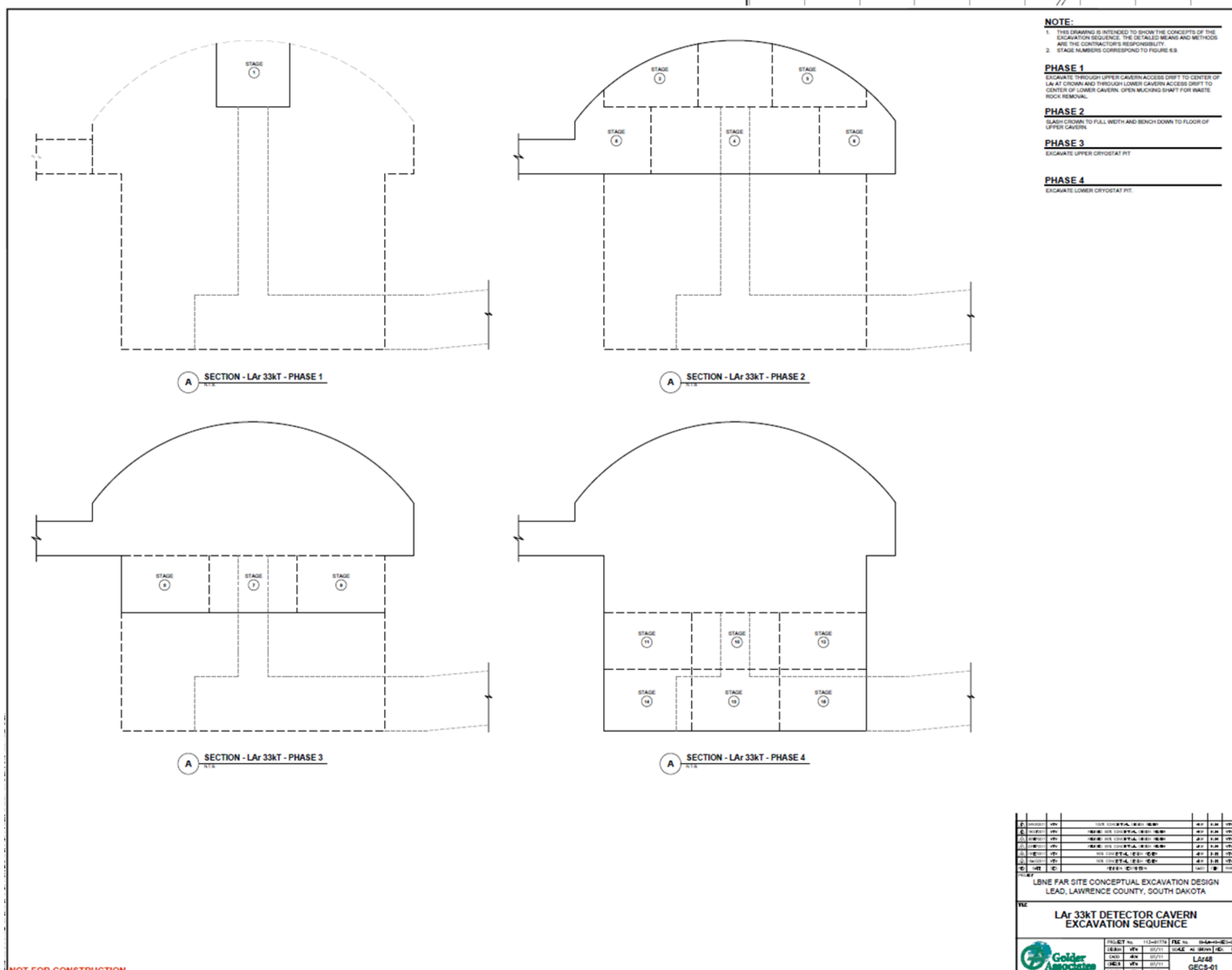
A geotechnical exploration program at the 4850L has been completed to explore the rock mass south of the south access drift.  Analysis of geotechnical data is on-going to determine maximum span and preferred cavern geometry.




Area near Yates shaft extensively studied for WCD option.

# Excavation and Ground Support Plans



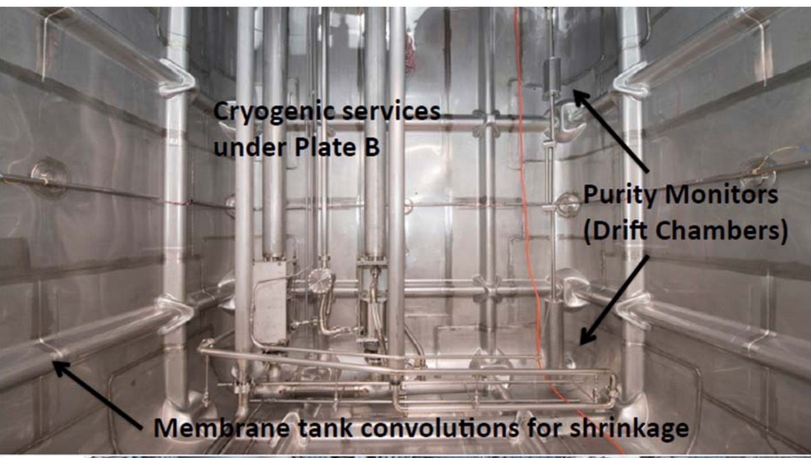
# Cryostat Development

35 t membrane cryostat prototype operational at FNAL

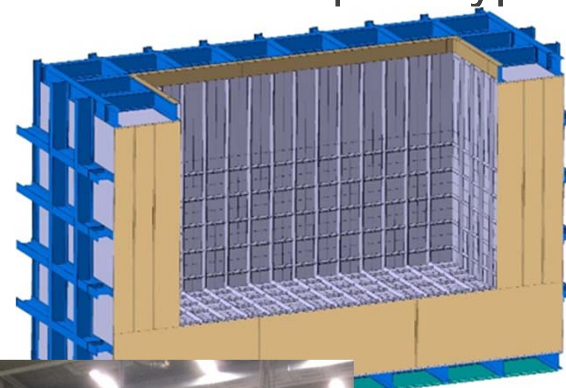
- Learn construction methods
- Purity tests
- Vessel for detector prototyping

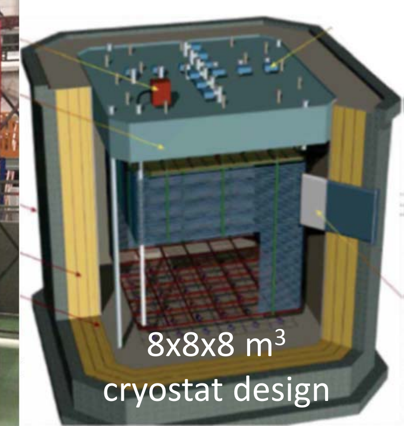
17 $m^3$ membrane cryostat prototype under construction at CERN

- Learn construction methods
- Purity tests
- Vessel for detector prototyping



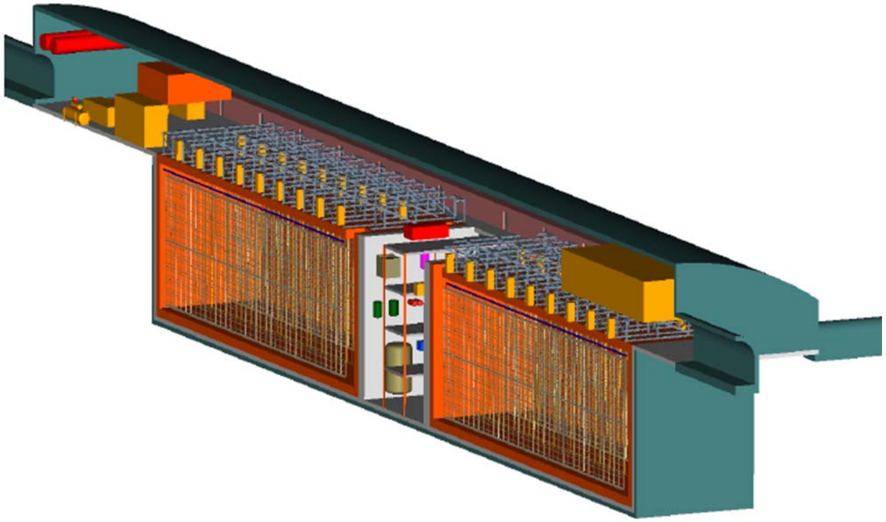






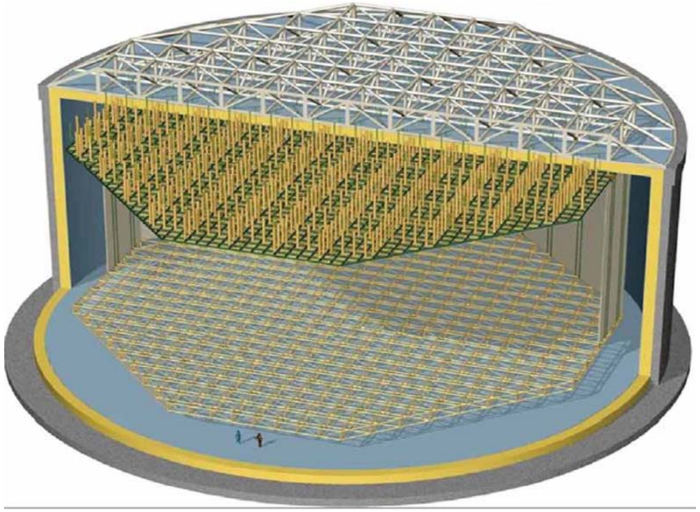
# Rectangular vs. Cylindrical Cryostat

LBNE Design:
Rectangular, rock-supported cryostat



- Current reference design
- Rectangular geometry makes maximum use of excavated volume
- Rectangular geometry requires rock support

LBNO Design:
Cylindrical, free-standing cryostat

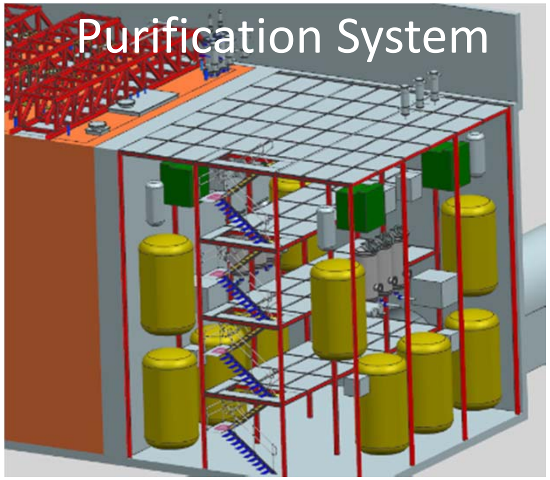


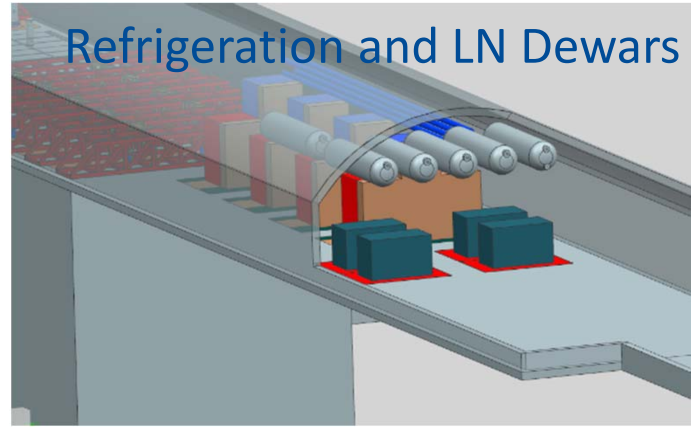
3D Tank & Detector Model Screen Shot (courtesy ETH Zürich)

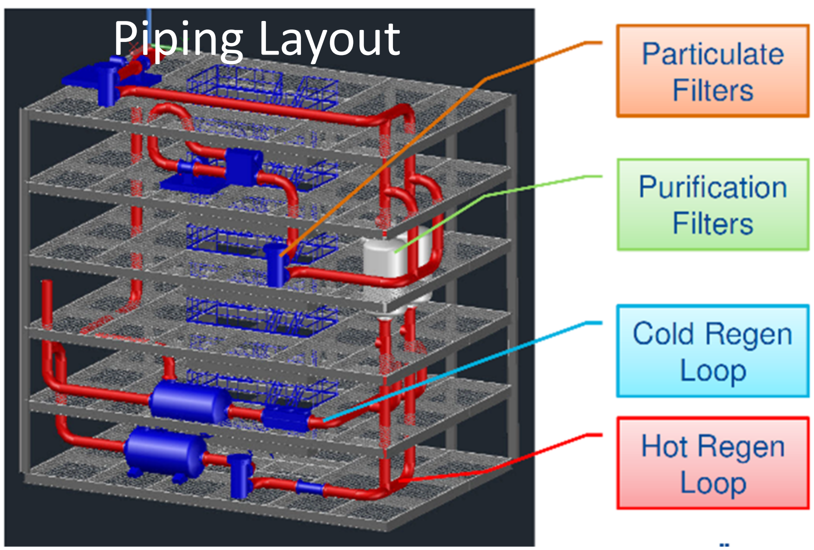
- Follows industry standard design and construction methods
- Requires larger span cavern, similar to LBNE WCD design

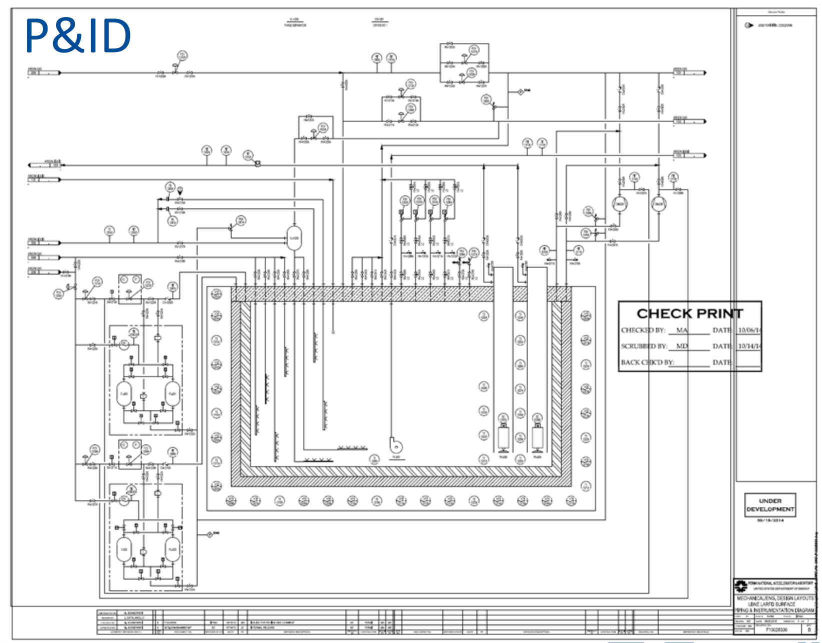
Joint LBNE – LBNO – FNAL – CERN evaluation launched

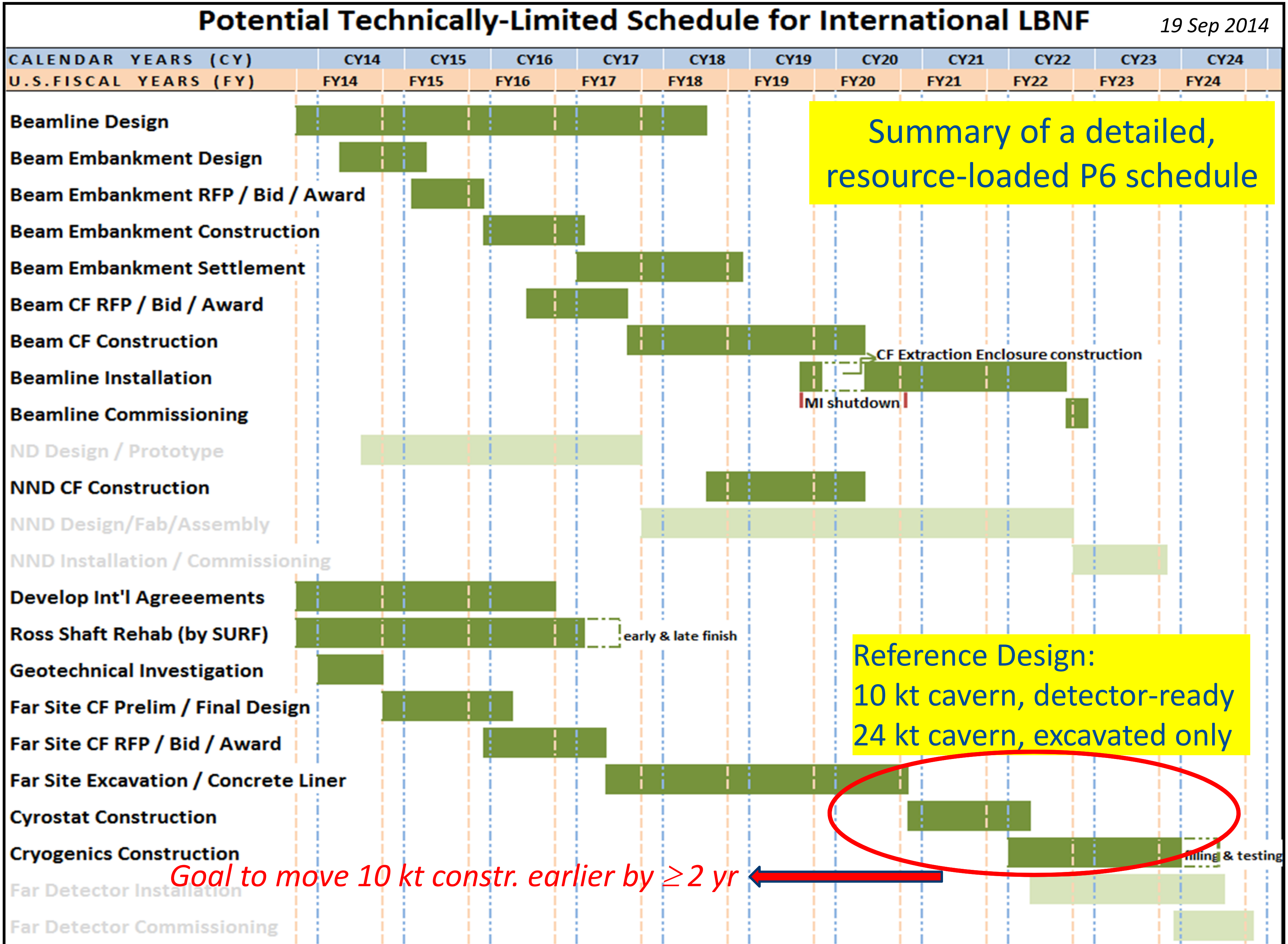
# Cryogenic System Design




Potential Technically-Limited Schedule for International LBNF
19 Sep 2014
CALENDAR YEARS (CY)
CY14
CY15
CY16
CY17
CY18
CY19
CY20
CY21
CY22
CY23
CY24
U.S.FISCAL YEARS (FY)
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
FY23
FY24
Beamline Design
Beam Embankment Design
Beam Embankment RFP / Bid / Award
Beam Embankment Construction
Beam Embankment Settlement
Beam CF RFP / Bid / Award
Beam CF Construction
Beamline Installation
Beamline Commissioning
ND Design / Prototype
NND CF Construction
NND Design/Fab/Assembly
NND Installation / Commissioning
Develop Int'l Agreeements
Ross Shaft Rehab (by SURF)
Geotechnical Investigation
Far Site CF Prelim / Final Design
Far Site CF RFP / Bid / Award
Far Site Excavation / Concrete Liner
Cyrostat Construction
Cryogenics Construction
Far Detector Installation
Far Detector Commissioning
Summary of a detailed, resource-loaded P6 schedule
CF Extraction Enclosure construction
MI shutdown
early & late finish
Reference Design:
10 kt cavern, detector-ready
24 kt cavern, excavated only
filling & testing
Goal to move 10 kt constr. earlier by ≥ 2 yr

# Summary and Conclusions

- Fermilab hosts an active, diverse, international accelerator-based neutrino program.
- Fermilab has a record of delivering high-intensity proton beams with high reliability and long running time for neutrino physics.
- On-going upgrades will increase the Main Injector beam power to 700 kW over the next ~2 years.
- PIP-II will further increase the beam power to 1.2 MW and provide a platform for future beam power >2 MW.
- Fermilab is prepared to host LBNF and work with international and U.S. partners to provide:
  - A high-intensity, broad-band neutrino beam
  - Conventional facilities for the LBNF detectors at SURF and Fermilab
  - Major technical infrastructure for the LBNF detectors