Fermilab

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PIP-II and Future Neutrino Experiments

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8 January 2015

Cracow Epiphany Conference

Introduction

- The existing Fermilab neutrino program
- Increasing proton beam power:
  - PIP
  - PIP-II …
- The next long-baseline experiment (LBNE / LBNF / ELBNF)
  - Letter of Intent
  - Formation of Collaboration
  - Designs
- Short-baseline neutrino experiments

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

The program is driven by a number of themes:

- Long-baseline oscillations: ν_μ disappearance and ν_e appearance
- Short-baseline oscillation: confirm or refute anomalies / search for sterile neutrinos and other alternative models
- Neutrino scattering experiments: electro-weak and QCD/nuclear physics; measurements to support the oscillation programs
- Detector development for the next generation of experiment

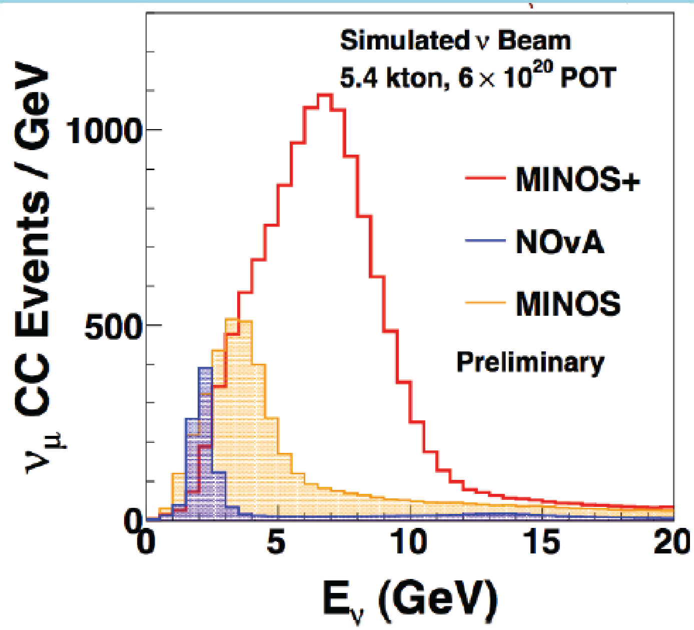
The Fermilab Neutrino Program Hosts Collaborators from across the globe:

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

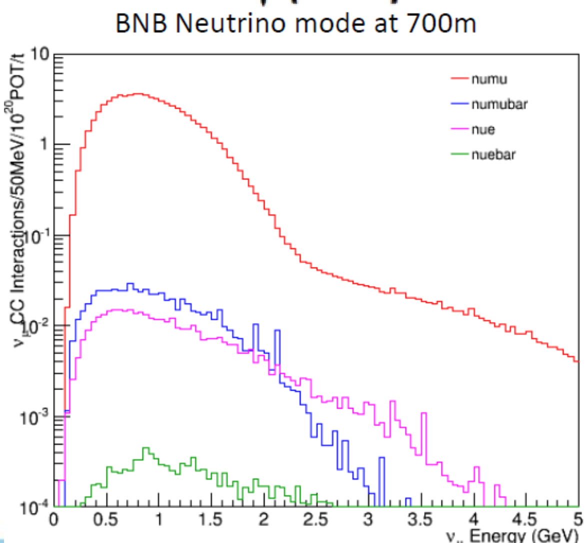
Fermilab Accelerator Complex

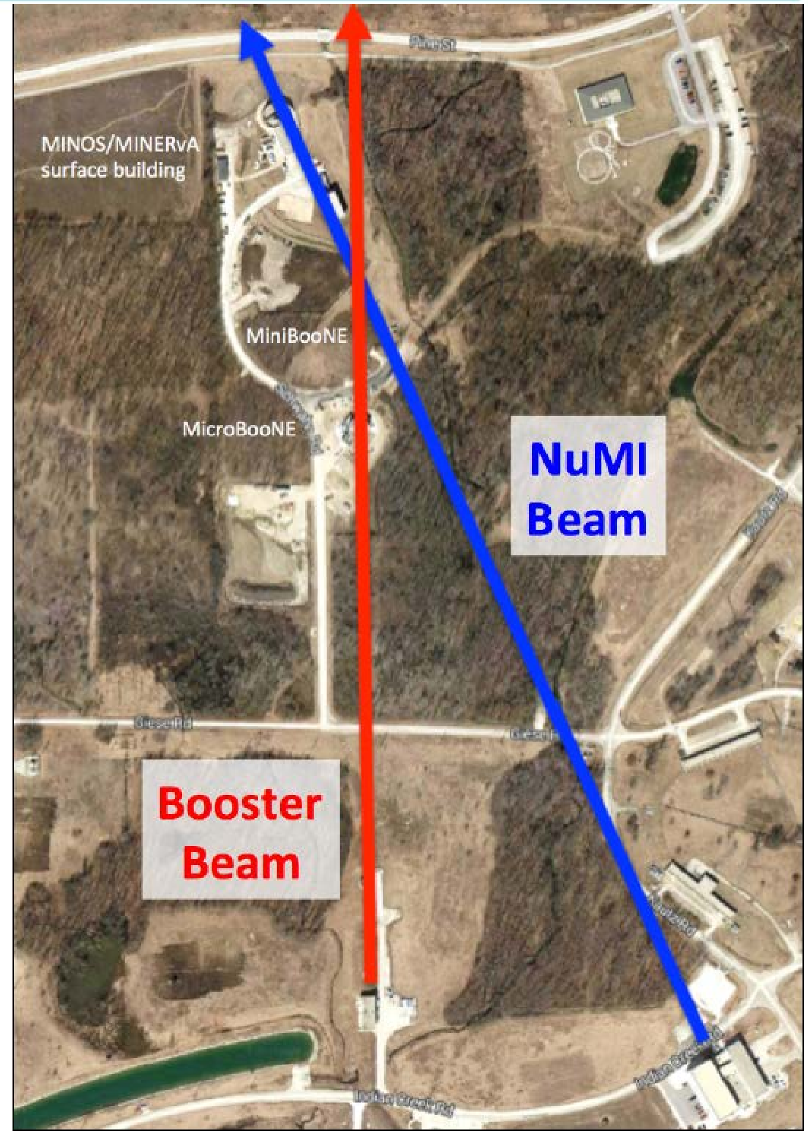
NuMI and Booster Beams

NuMI (350 – 700 kW):
- tunable 1 GeV to >10 GeV
- Near hall at 1 km
- Far detectors 735 – 810 km



BNB (10 – 30 kW):
- Low energy 0.1 – 1.5 GeV
- Focused on short-baseline oscillations and cross sections



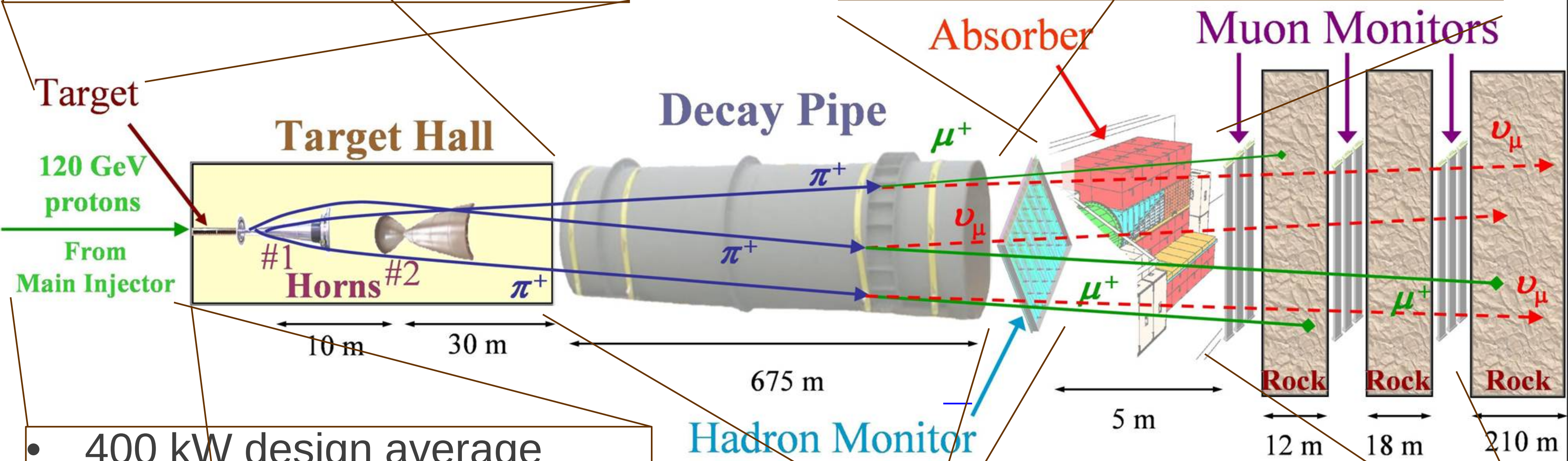


The NuMI Beam - "Neutrinos at the Main Injector"

- 2 interaction length, C target
- Produces π^+, K^+ mesons

- 2 m diameter
- Roughly decay length for 10 GeV π^+
- He-filled

- Absorbs ~ 40 % of beam power
- Allows high-energy muons to penetrate



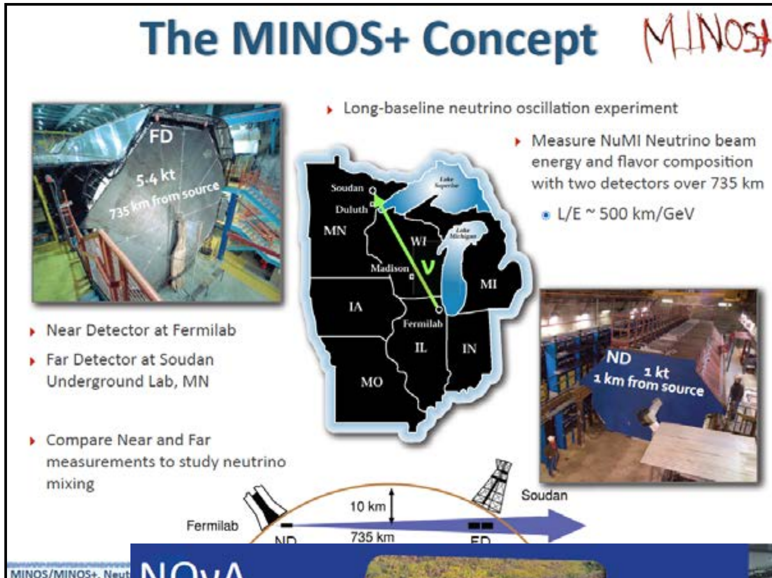
- 400 kW design average power
- 700 kW upgrade for NOvA
- $\sigma \sim 1$ mm

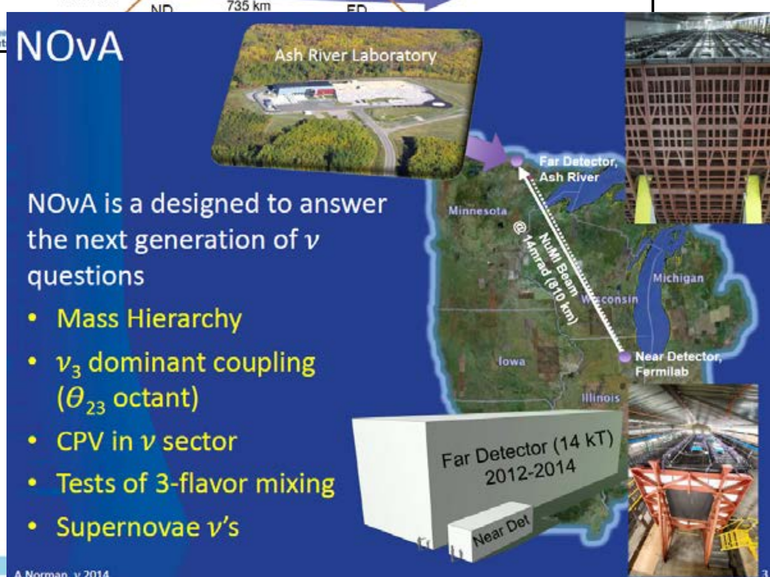
- Pulsed focusing horns
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focuses meson momentum band

- Measure hadron & muon fluxes
- Arrays measure distributions

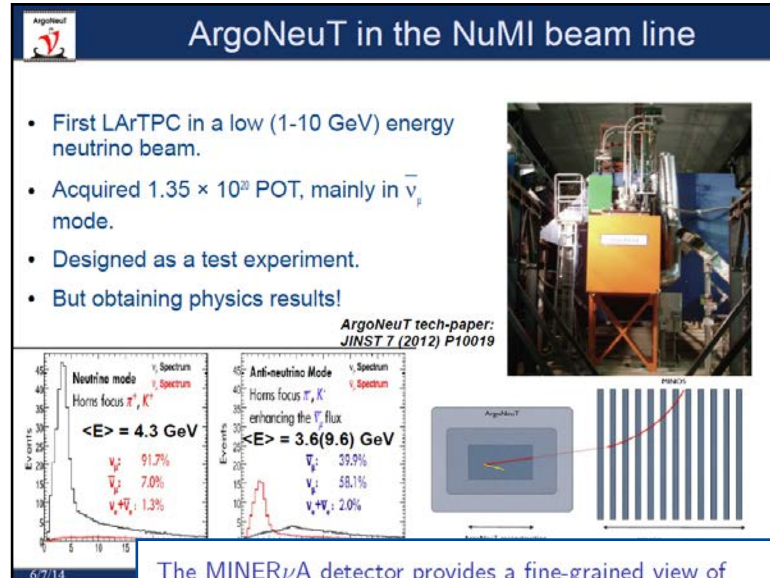
Experiments in the NuMI Beam

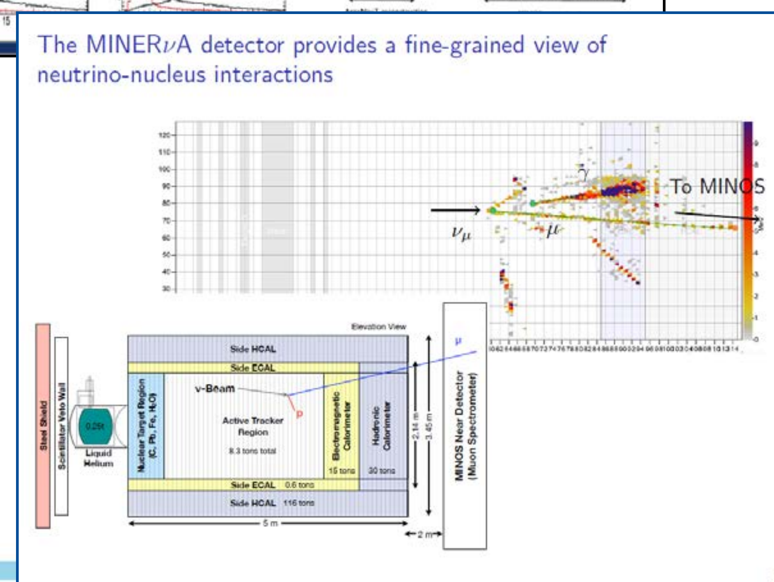
Long-baseline oscillation experiments





Neutrino scattering experiments





Experiments in the Booster Neutrino Beam

Scattering, testing alternative oscillations / sterile neutrinos

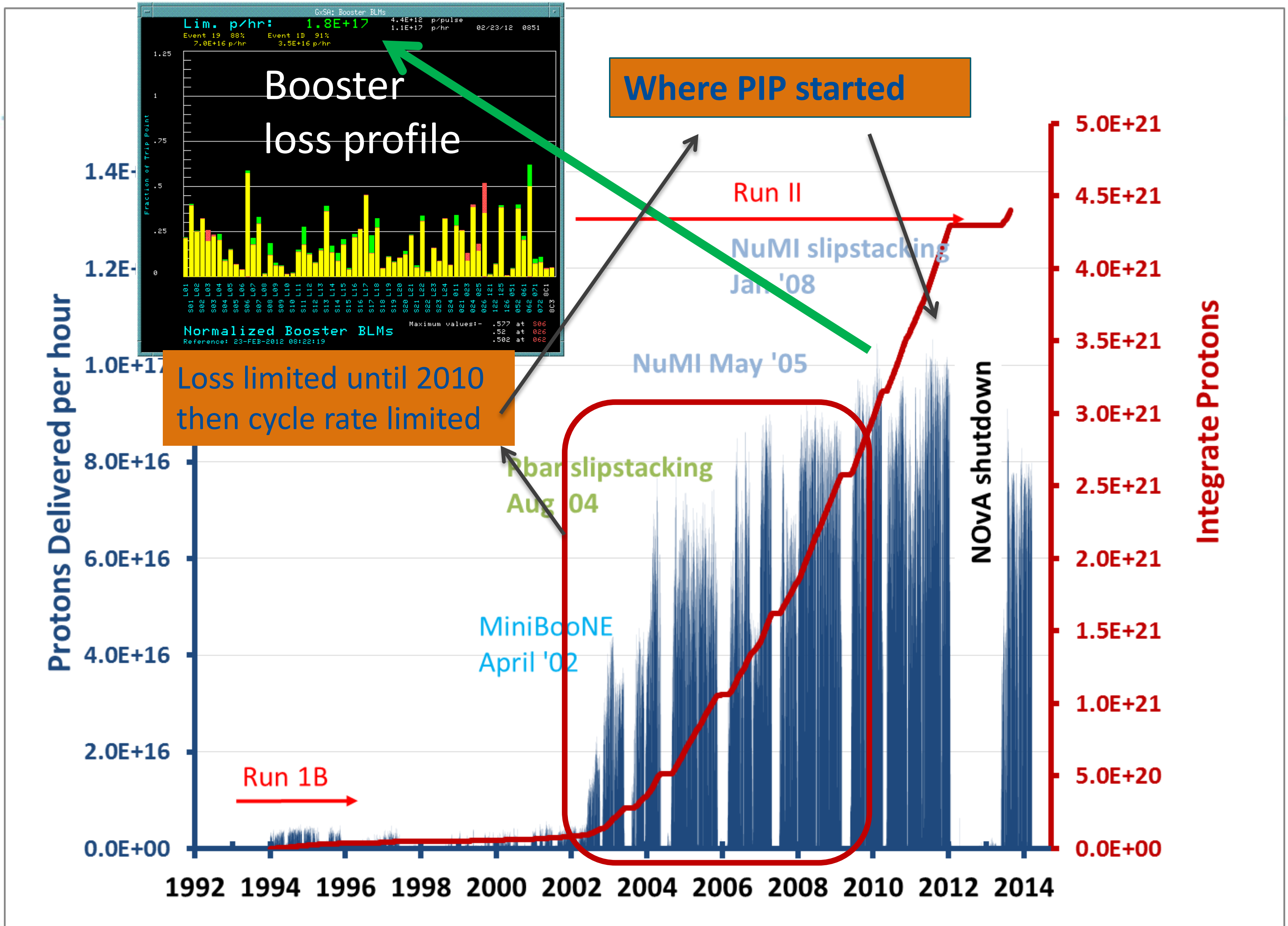
MicroBooNE

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.

PIP - Present Proton Production

- Linac produces 400 MeV H^-
  - Bunched at 200 MHz
  - 35 mA for up to 40 us at up to 15 Hz
- Booster produces 8 GeV protons (Booster neutrinos, muons, etc.)
  - Bunched at 53 MHz
  - Up to 5e12 (typically 4.3e12) in 1.5 us
  - Ramps at 15 Hz
    - Historically <<= 7 Hz with beam
- Main Injector produces 120 GeV protons (NuMI)
  - Bunched at 53 MHz
  - Up to 5e13 (typically 3.7e13) Operates as quickly as 1.33 s
  - With Recycler integration, designed for 700 kW
    - Has run at 400 kW


Lim. p/hr: 1.8E+17
Booster
loss profile
Normalized Booster BLMs
Where PIP started
Run II
NuMI slipstacking
Jan '08
NuMI May '05
Loss limited until 2010
then cycle rate limited
Pbar slipstacking
Aug '04
MiniBooNE
April '02
NOvA shutdown
Run 1B
Protons Delivered per hour
Integrate Protons
1.4E+17
1.2E+17
1.0E+17
8.0E+16
6.0E+16
4.0E+16
2.0E+16
0.0E+00
5.0E+21
4.5E+21
4.0E+21
3.5E+21
3.0E+21
2.5E+21
2.0E+21
1.5E+21
1.0E+21
5.0E+20
0.0E+00
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

Goals for the Proton Improvement Plan

- The ***Proton Improvement Plan*** should enable Linac/Booster operation capable of
  - Delivering 2.3E17 protons/hour (at 15 Hz)

  while

  - Maintaining Linac/Booster availability > 85%, and
  - Maintaining residual activation at acceptable levels

  and also ensuring a useful operating life of the linac through 2023, and Booster through 2030 or later

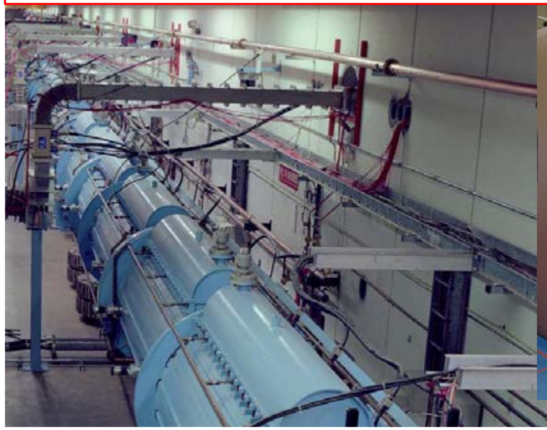
The scope of the ***Proton Improvement Plan*** includes

- Upgrading (or replacing) components to increase the Booster repetition rate
- Replacing components that have (or will have) poor reliability
- Replacing components that are (or will soon become) obsolete
- Studying beam dynamics to diagnose performance limitations
- Implementing operational changes to reduce beam loss

http://www-ad.fnal.gov/proton/PIP/PIP_index.html

Linac Overview

Designed for high intensity single shot proton injection



7835 Socket

7835

Linac	
Length (m)	200
Pulse Frequency	15 Hz
Kinetic Energy (MeV)	.750 - 4
Frequency (MHz)	201 & 804
Current (operational)	33 ma (Historical low)
Linac Lattice	LE ? HE - FODO
Nº of cavities	5 DTLs, 7 SC, 3 small

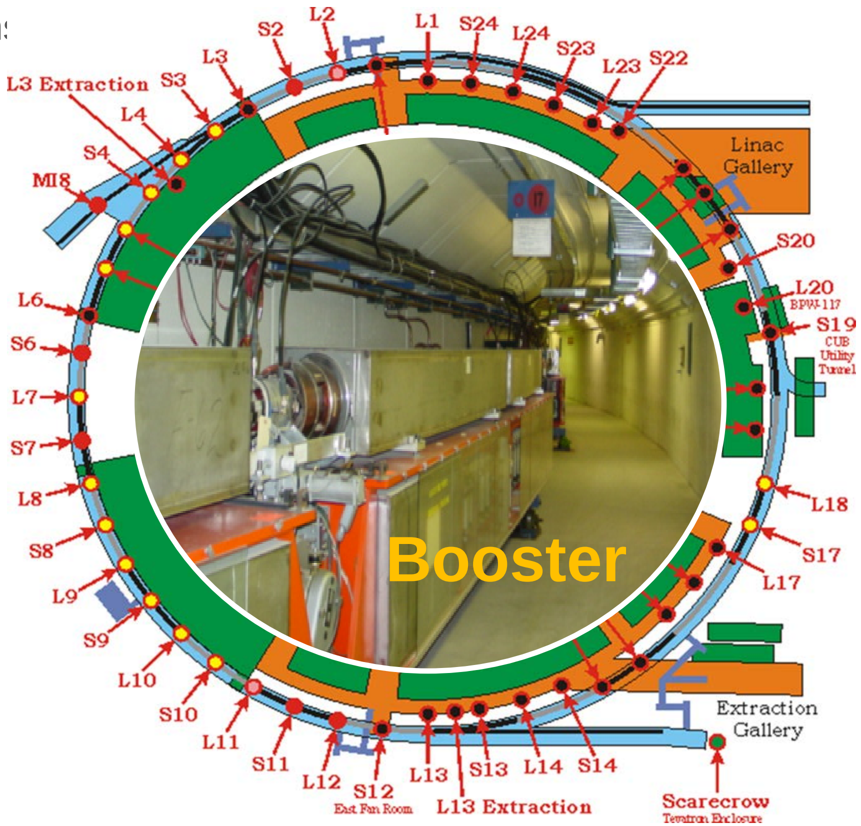
LE Linac		
Flat top	350	usec
Raise Fall time	75	usec
Average Axial Field	1.5	MV/m
Rep Rate	15	Hz
RF Peak Power	3.5	MW
Peak Current	35	mA
Beam width	20	usec
Power to the beam	787.50	KW
Average RF Power	19.16	KW
Peak Power	3.50	MW

High Energy Tunnel

High Energy Linac Gallery

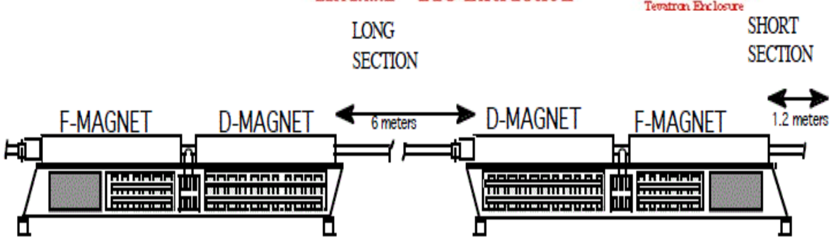
Booster Overview

- H$^-$ ions are stripped and multi-turn injected onto the Booster
- Protons are accelerated from 400 MeV to 8 GeV in 33 m
- Fast cycling synchrotron
  - Fast magnet ramping
  - Frequency of 15 Hz
- Single turn extraction

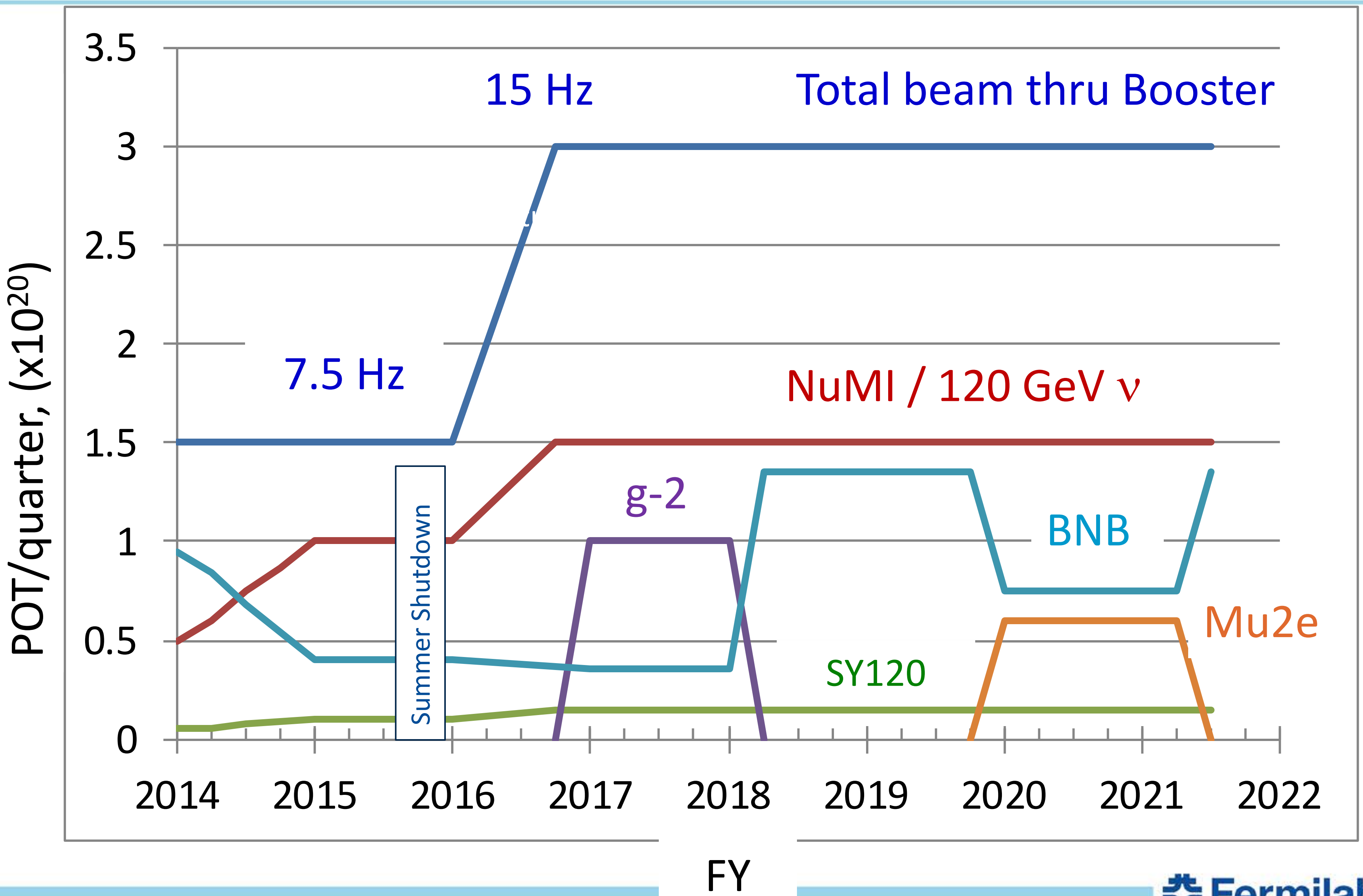


Booster	
Circumference (m)	474
Harmonic Number	84
Kinetic Energy (GeV)	0.4 - 8
Momentum (GeV/c)	0.954 - 8.9
Revolution period (μsec)	$\tau_{(inj)}$ 2.77 – $\tau_{(ext)}$ 1.57
Frequency (MHz)	37.9 - 52.8
Batch size	4.5 E12
Focussing period	FDooDFo (24 total)

Combined Function Magnets
No failures after initial phase…
but 8 spares have been refurbished as part of PIP…

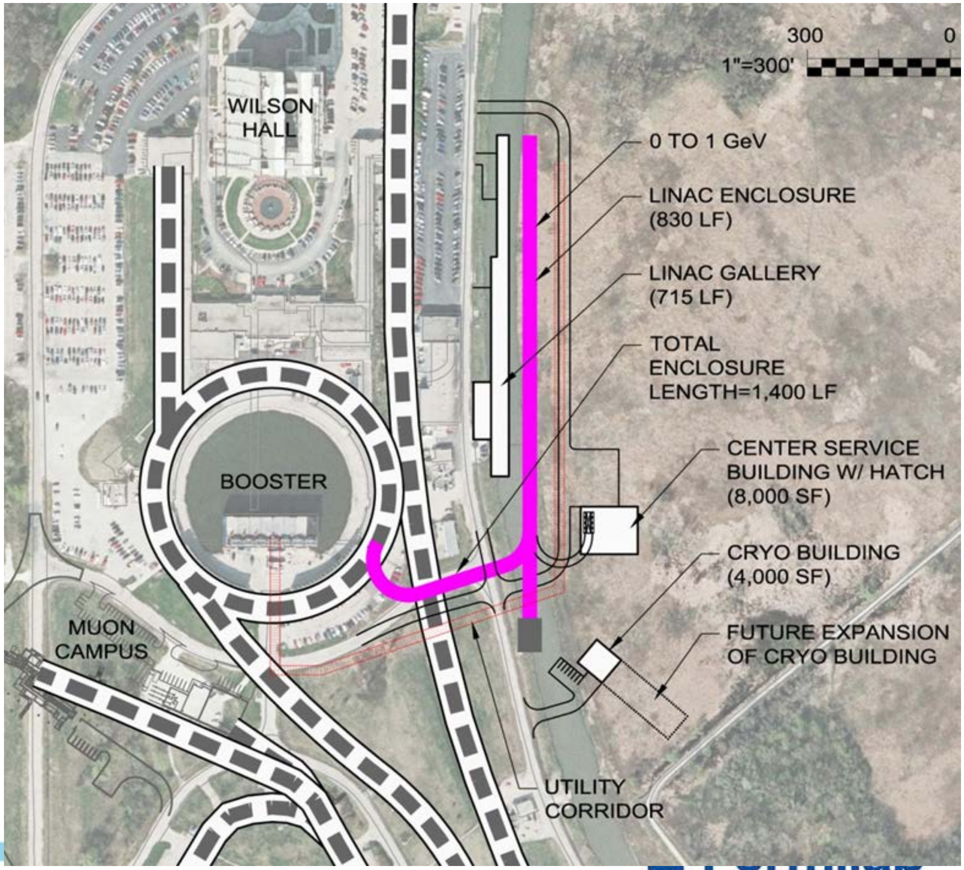


Proton Delivery Scenario with PIP
(Schematic – not accounting for long shutdowns)



Proton Improvement Plan II (PIP-II)

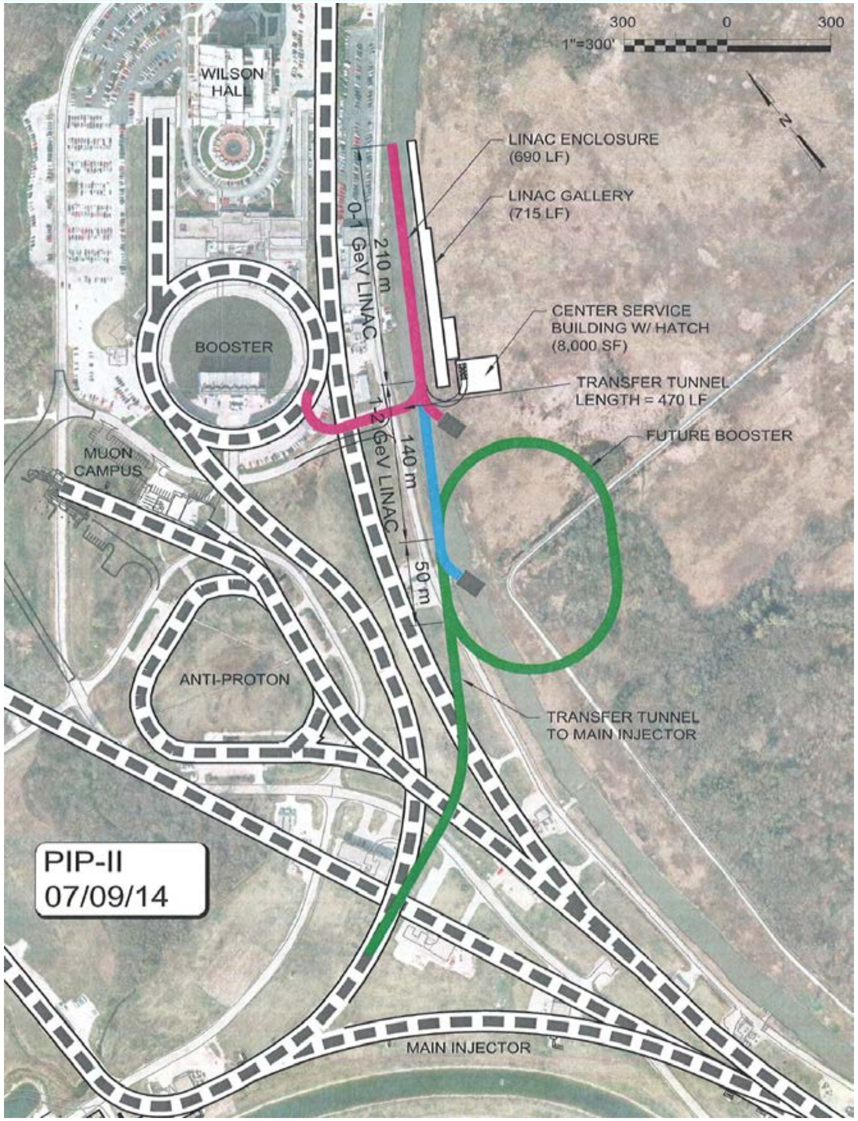
- Goal is to increase Main Injector beam power to 1.2 MW.
  - Replace the existing 400 MeV linac with a new 800 MeV superconducting linac => 50% increase in Booster intensity.
  - Shorten Main Injector cycle time 1.33 → 1.2 sec.
- Build this concurrently with LBNF => 1.2 MW to LBNF from t = 0.
- This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



http://pip2.fnal.gov/

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

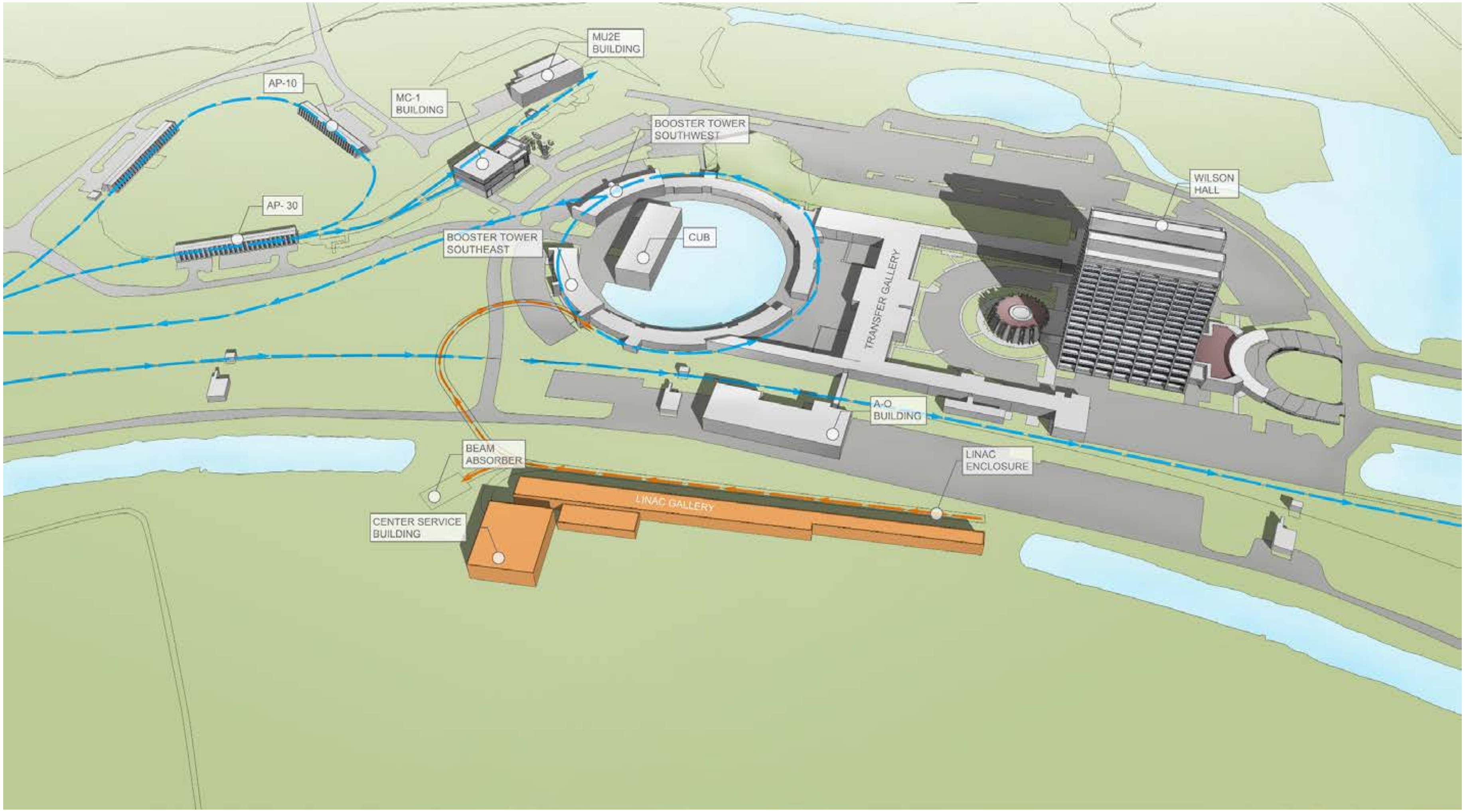


PIP-II Strategy

- Increase Booster/Recycler/Main Injector per pulse intensity by ~50%
  - Requires increasing the Booster injection energy to ~800 MeV
    - 30% reduction in space-charge tune shift w/ 50% increase in beam intensity
- Increase Booster repetition rate to 20 Hz
  - Maintain 1 MW in MI down to 60 GeV
  - Provide factor of 2.5 increase in power to 8 GeV program
  - Improve slip-stacking efficiency via larger orbit separation
- Modest modifications to Booster/Recycler/Main Injector
  - Accommodate higher intensities and higher Booster injection energy

⇒ ***Cost effective solution: 800 MeV superconducting pulsed linac, extendible to support >2 MW operations to LBNF and upgradable to continuous wave (CW) operations***
  - Builds on significant existing infrastructure
  - Capitalizes on major investment in superconducting RF technologies
  - Eliminates significant operational risks inherent in existing 400 MeV linac
    - Existing linac removed from service upon completion of PIP-II
  - Siting consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector

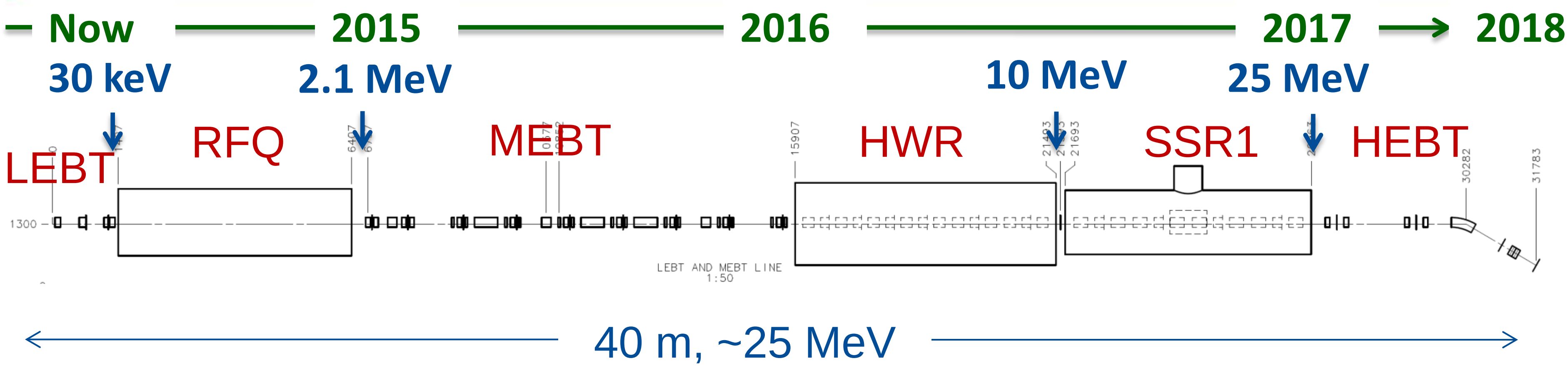
PIP-II Site Layout (provisional)



PIP/PIP-II Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.5	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	13	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Upgrade Potential (800 MeV)	NA	>100	kW
Booster Protons per Pulse	4.2×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
Beam Power to 8 GeV Program (max)	32	80	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.6×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	0.7	1.0-1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

PXIE (PIP-II Injector Experiment)



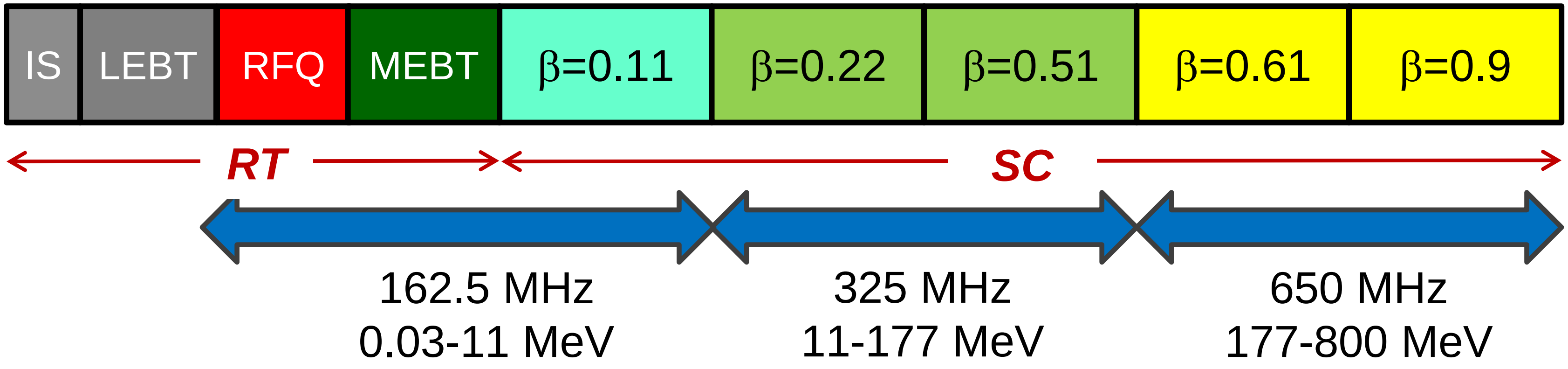
PXIE will address the address/measure the following:

- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Bunch extinction
- MEBT beam absorber
- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam, including resonance control and LFD compensation in pulsed operations
- Emittance preservation and beam halo formation through the front end

PXIE Ion source and LEBT are commissioned. RFQ in fabrication.

Collaborators
- ANL: HWR
- LBNL:LEBT, RFQ
- SNS: LEBT
- BARC: MEBT, SSR1

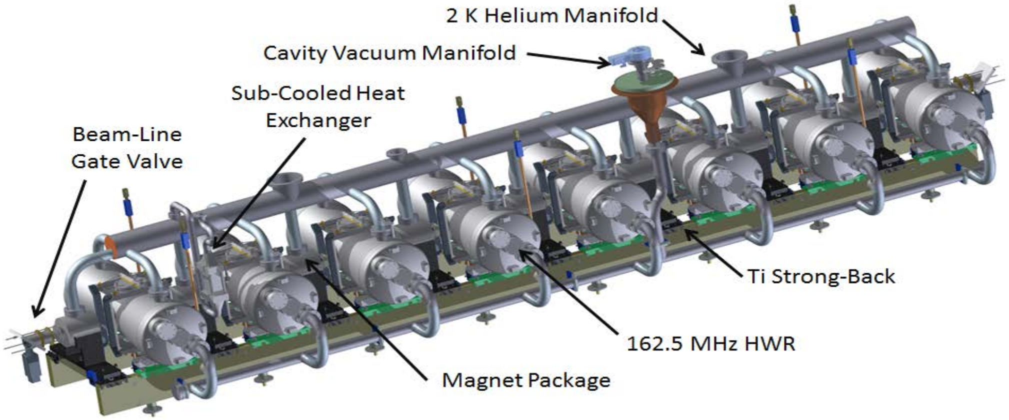
PIP-II Linac Technology Map



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	11-38	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.51)	325	38-177	35/21/7	SSR, solenoid
LB 650 (β_G=0.61)	650	177-480	30/20/5	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	480-800	24/10/4	5-cell elliptical, doublet

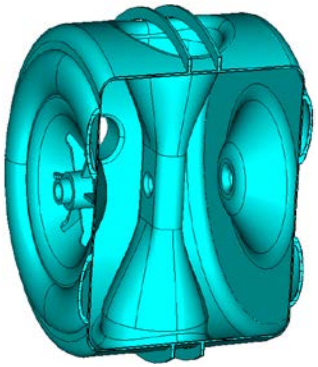
All components CW-capable

SRF R&D



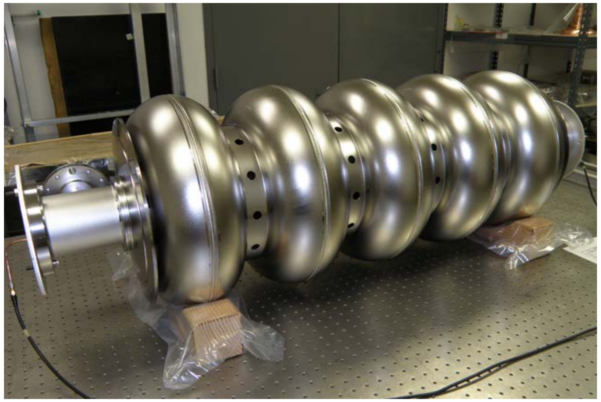
HWR

SSR1



SSR2

LB650



HB650

Possible Parameters for post-PIP-II Complex

Proton Source	**RCS**	**Linac**	
Particle Type	p	H-	GeV
Beam Kinetic Energy	8.0	8.0	GeV
Protons per Pulse	2.6×10^{13}	1.5×10^{14}	
Beam Pulse Length	0.0016	10	msec
Pulse Repetition Rate	20	20	Hz
Pulses to Recycler	6	NA	
Pulses to Main Injector	NA	1	
Beam Power at 8 GeV (Total)	660	3960	kW
Beam Power to Main Injector*	160/280	160/280	kW
Beam Power Available for 8 GeV Program*	500/380	3800/3680	kW
Main Injector			
Beam Kinetic Energy*	120/60	120/60	GeV
Main Injector Protons per Pulse	1.5×10^{14}	1.5×10^{14}	
Main Injector Cycle Time*	1.2/0.7	1.2/0.7	sec
LBNF Beam Power*	2.4/2.1	2.4/2.1	MW

*First number refers to 120 GeV MI operations; second to 60 GeV

PIP-II Collaboration

- Organized as a “national project with international participation”
  - Fermilab as lead laboratory
- Collaboration MOUs for the RD&D phase (through CD-2) :

National		IIFC
ANL	ORNL/SNS	BARC/Mumbai
BNL	PNNL	IUAC/Delhi
Cornell	UTenn	RRCAT/Indore
Fermilab	TJNAF	VECC/Kolkata
LBNL	SLAC	
MSU	ILC/ART	
NCSU		

- Ongoing contacts with CERN (SPL), RAL/FETS (UK), ESS (Sweden), RISP (Korea), China/ADS
- Annual Collaboration Meeting (June 3-4 at Fermilab)

  https://indico.fnal.gov/conferenceDisplay.py?confId=8365

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).

Beamline for a new Long-Baseline Neutrino Facility

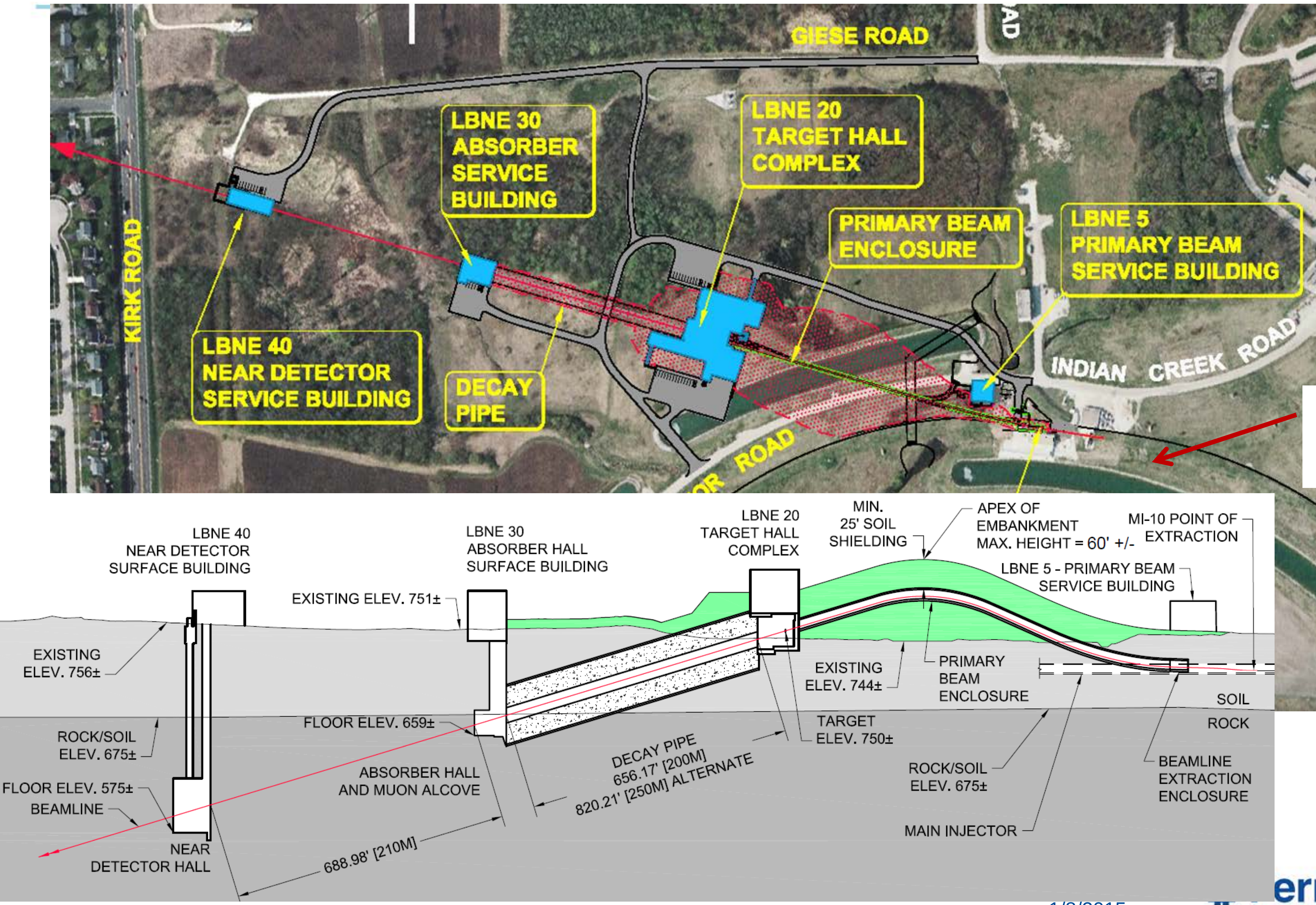
The facilities team has been working with the scientific community to develop facilities to support the experimental program.

- Has worked for many years with the LBNE Collaboration
- During the past year, have expanded to also work with the LAGUNA-LBNO Collaboration

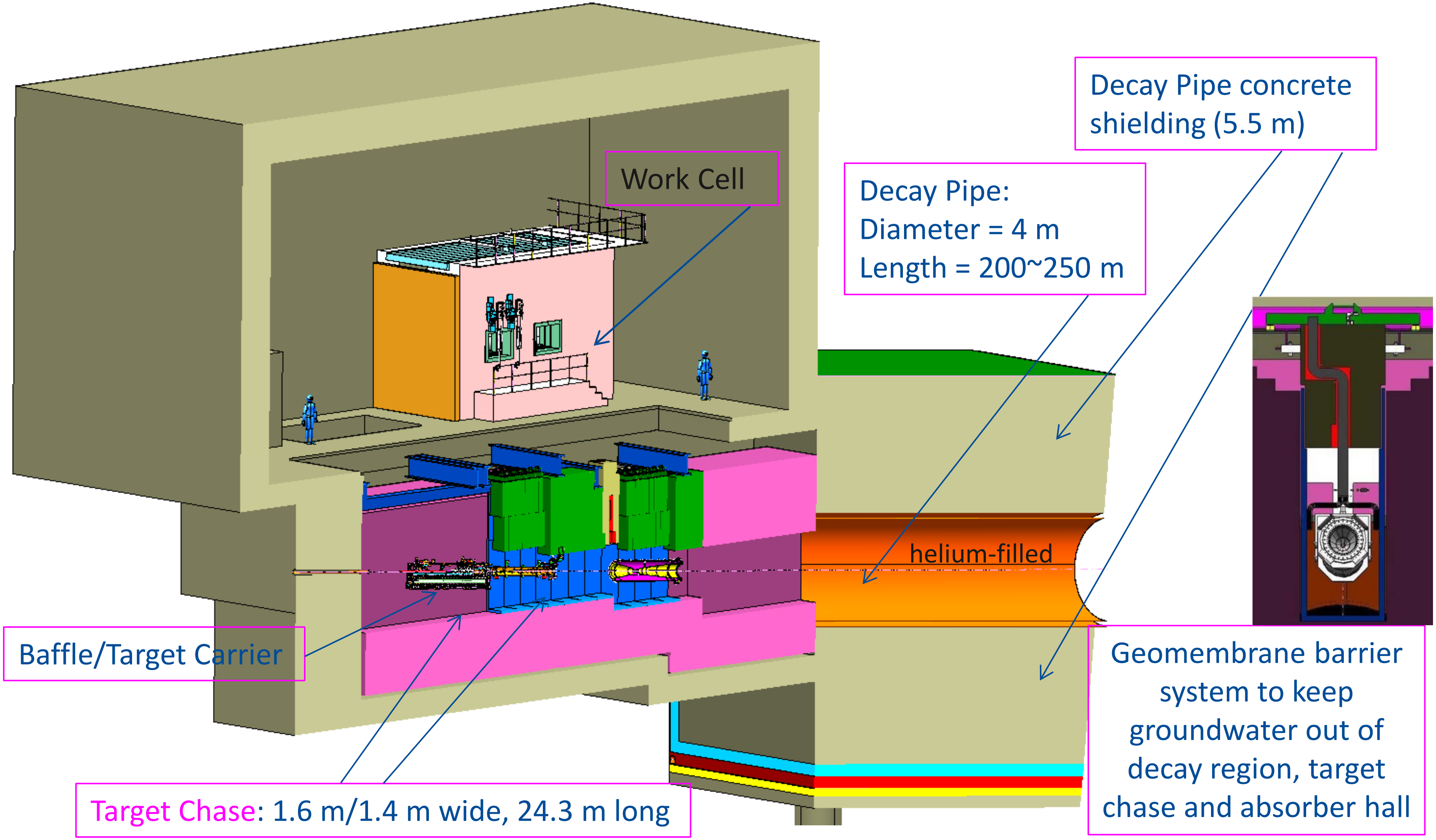
A design for a new neutrino beam at Fermilab has been under development in the context of the LBNE Project, it is the basis upon which the new collaboration will design their beam

- 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



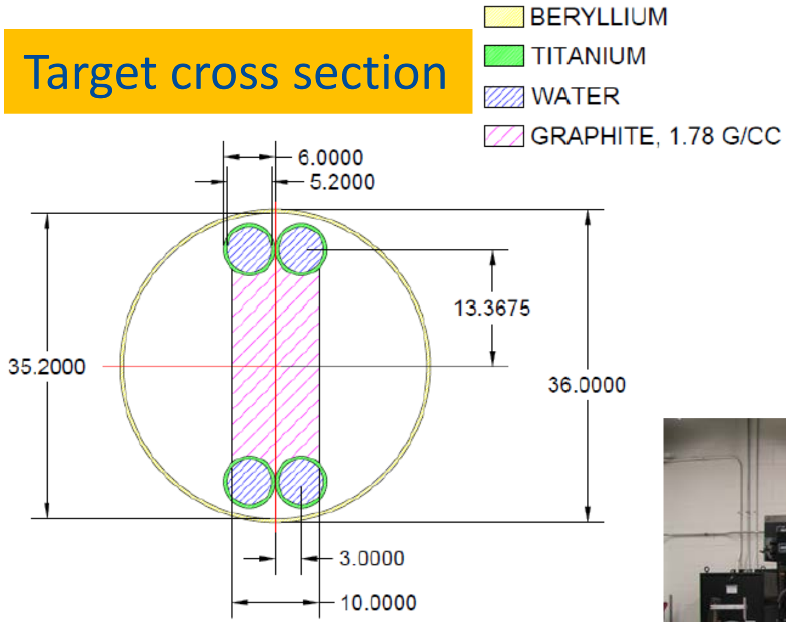
Target Hall and Decay Pipe Layout



Components inside the target chase

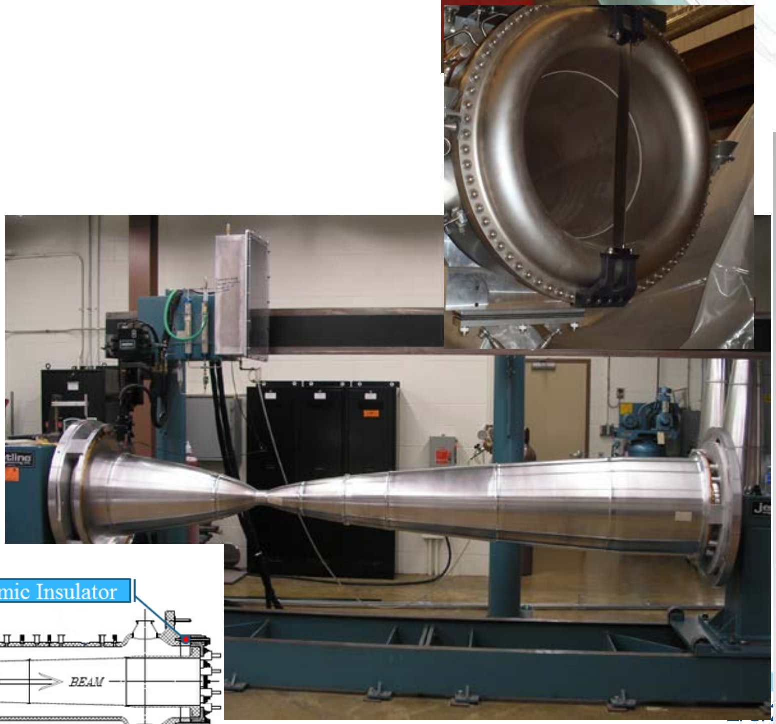
47 graphite target segments, each 2 cm long

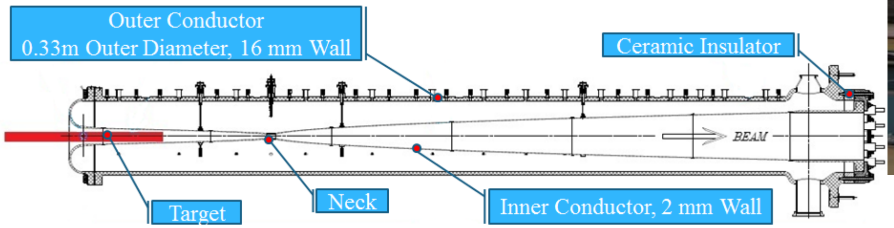
Target cross section



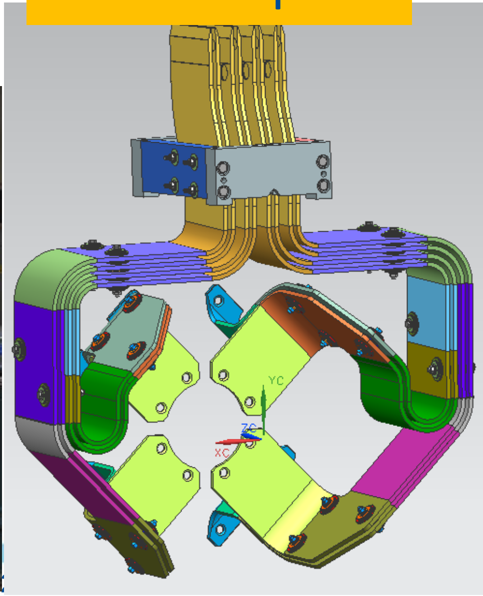
Baffle

Horn





Horn Stripline



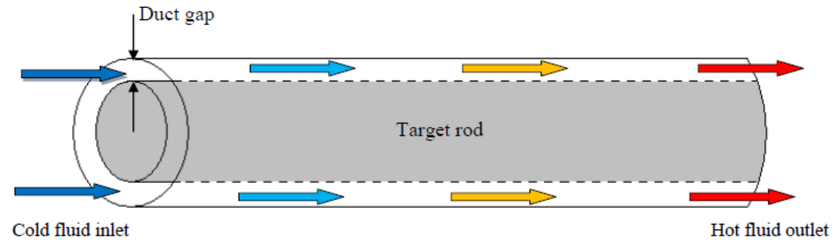
Novel Target Designs

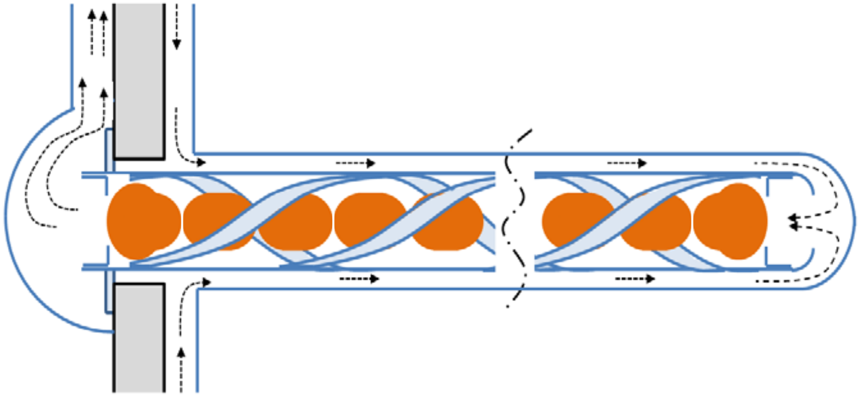
RaDIATE Collaboration

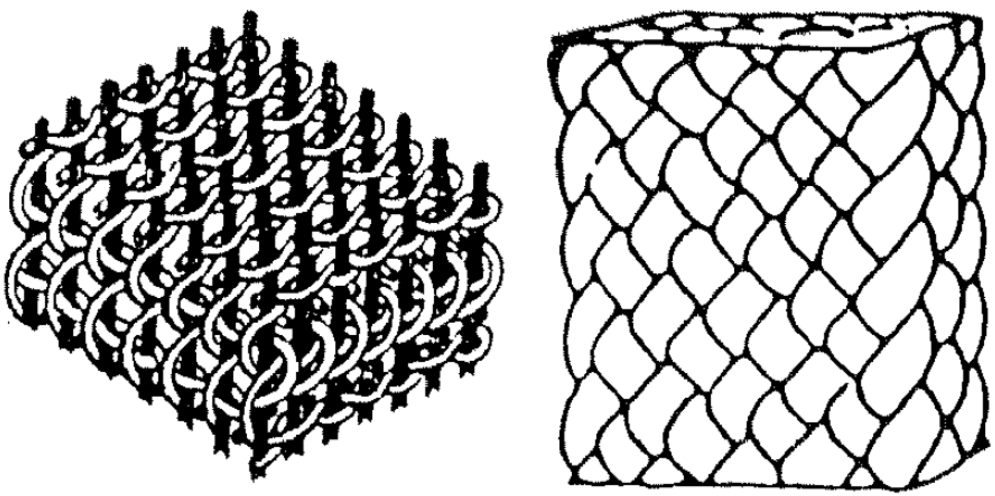
Radiation Damage In Accelerator Target Environments

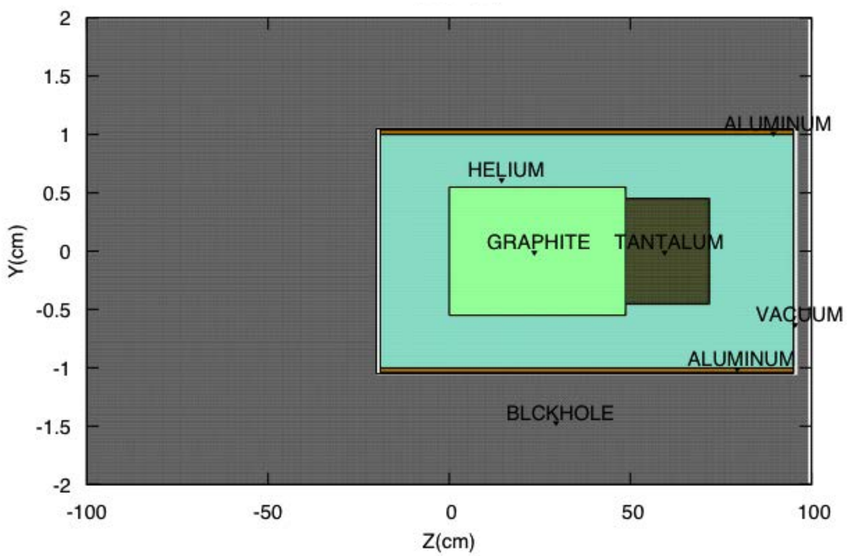
HiRadMat High-Radiation to Materials

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

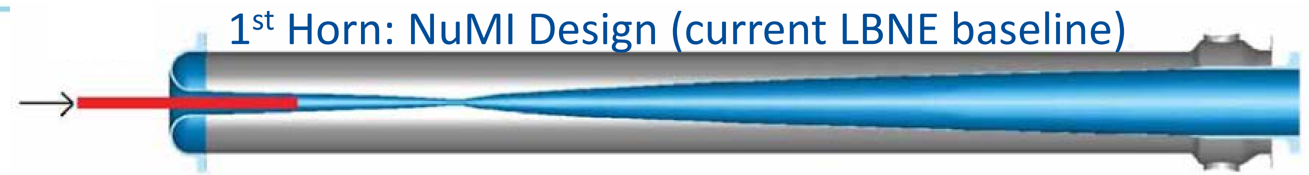


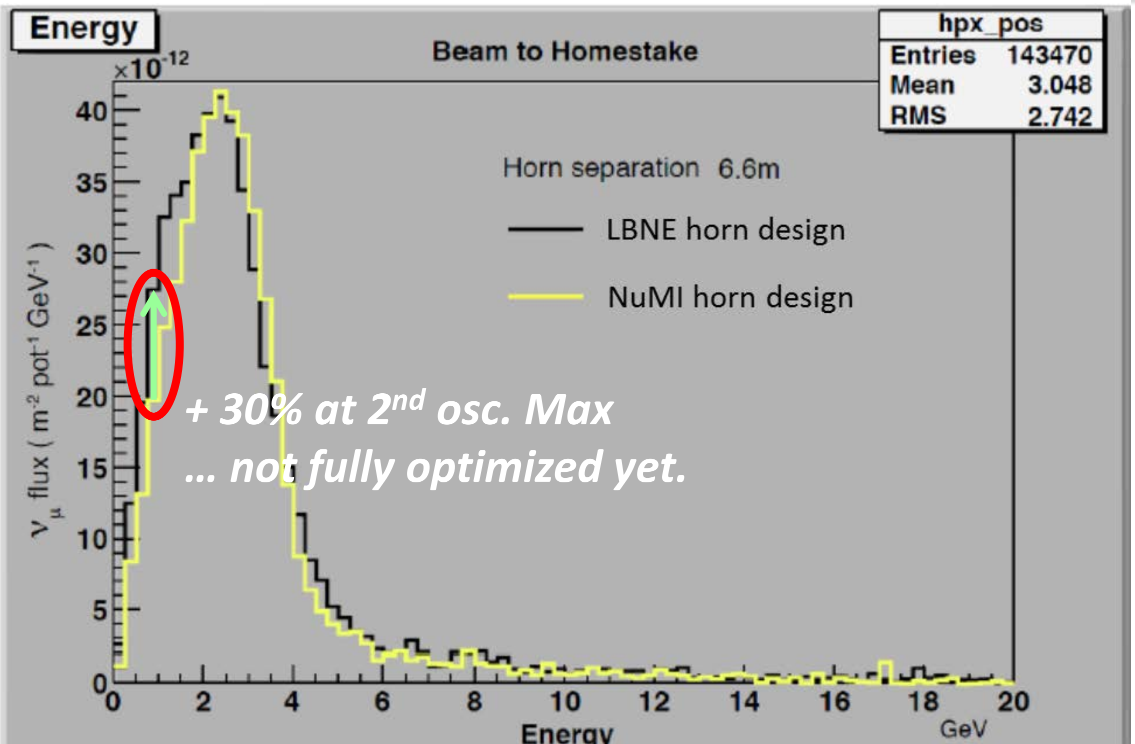






Improved Focusing for Second Oscillation Maximum





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

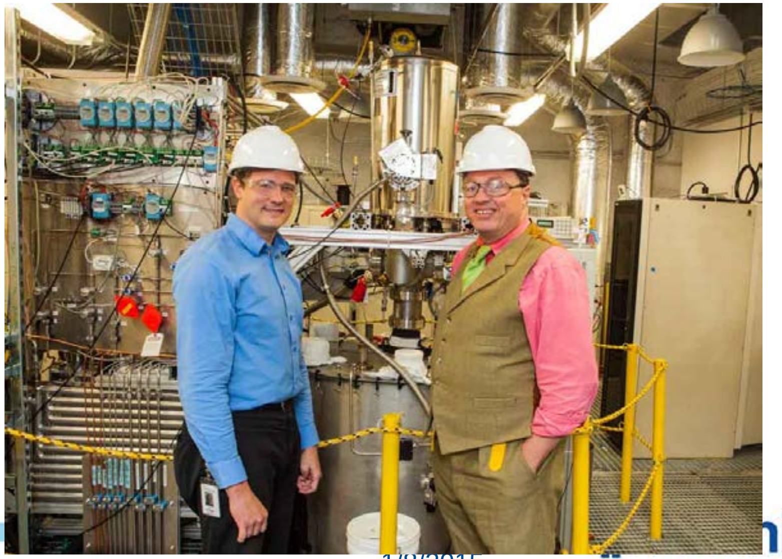
Sanford Underground Research Facility

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

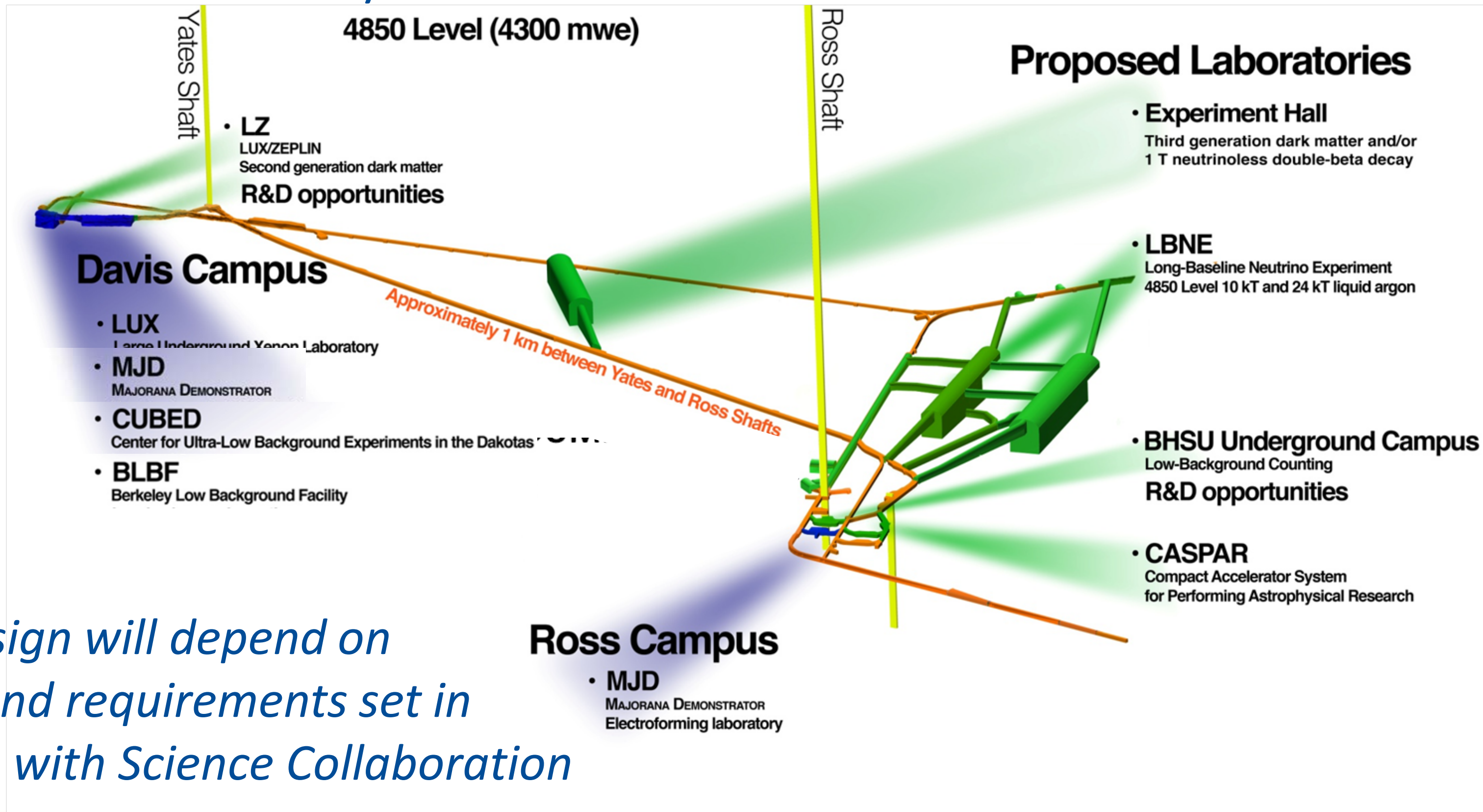
LUX (dark matter)



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*

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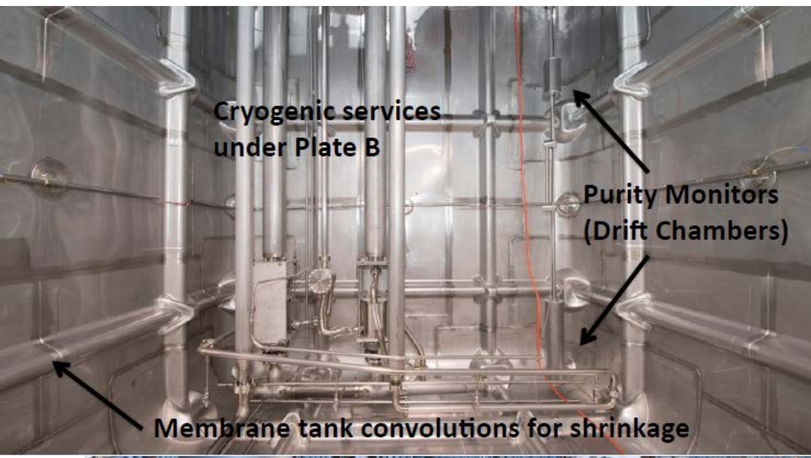
Cryostat Development

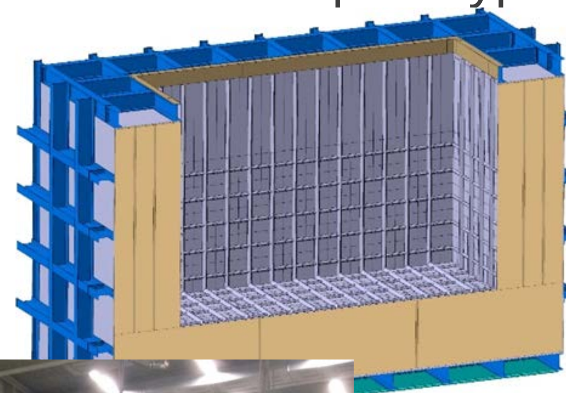
35 t membrane cryostat prototype operational at FNAL

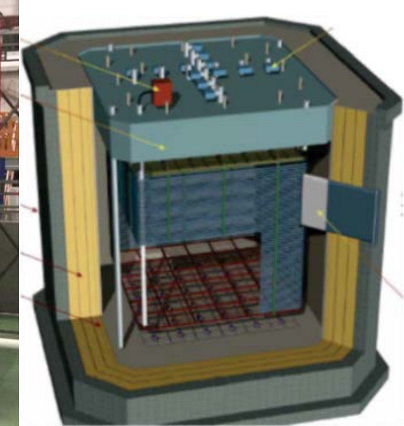
- Learn construction methods
- Purity tests
- Vessel for detector prototyping

17 m^3 membrane cryostat prototype under construction at CERN

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

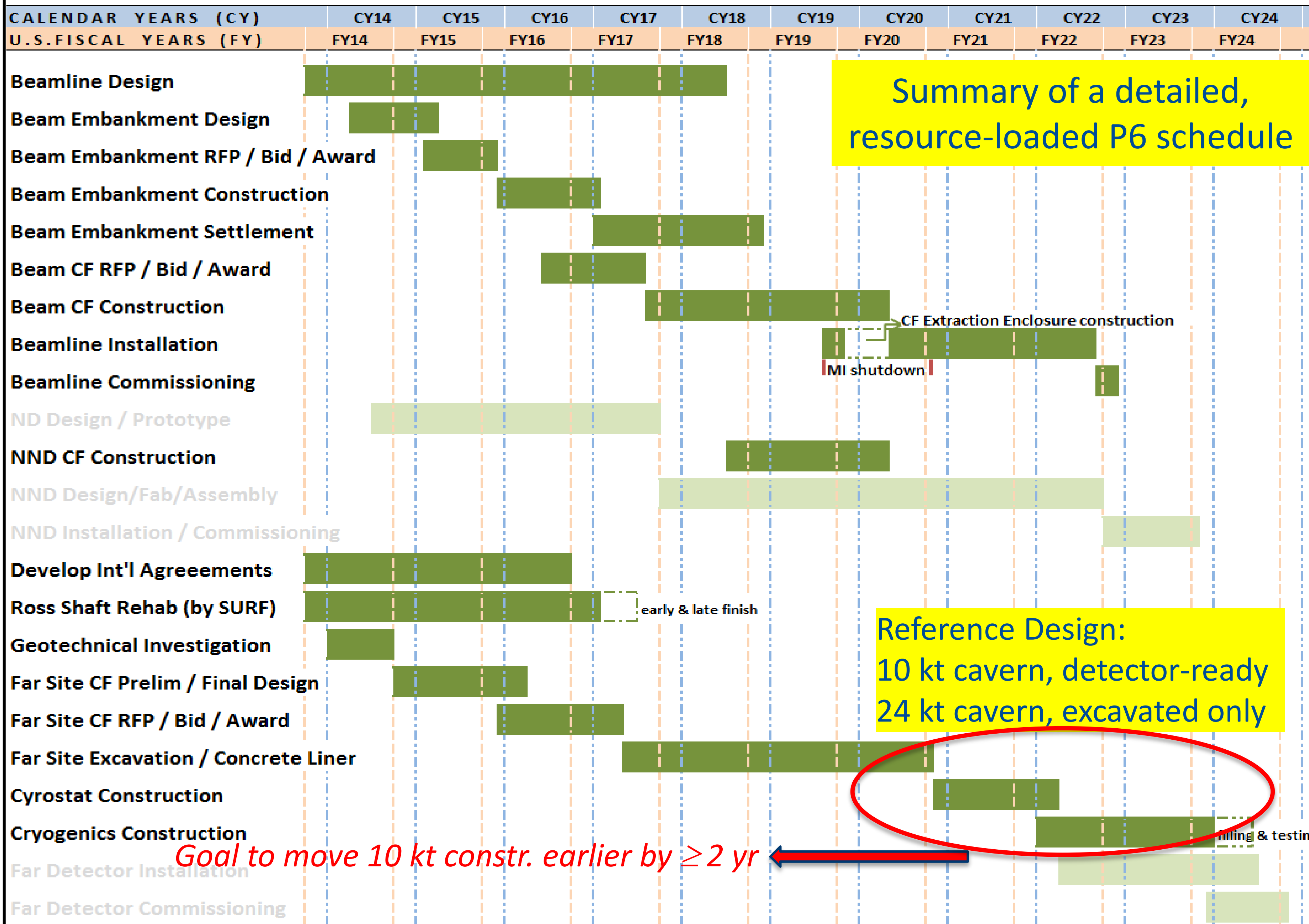






Potential Technically-Limited Schedule for International LBNF

19 Sep 2014



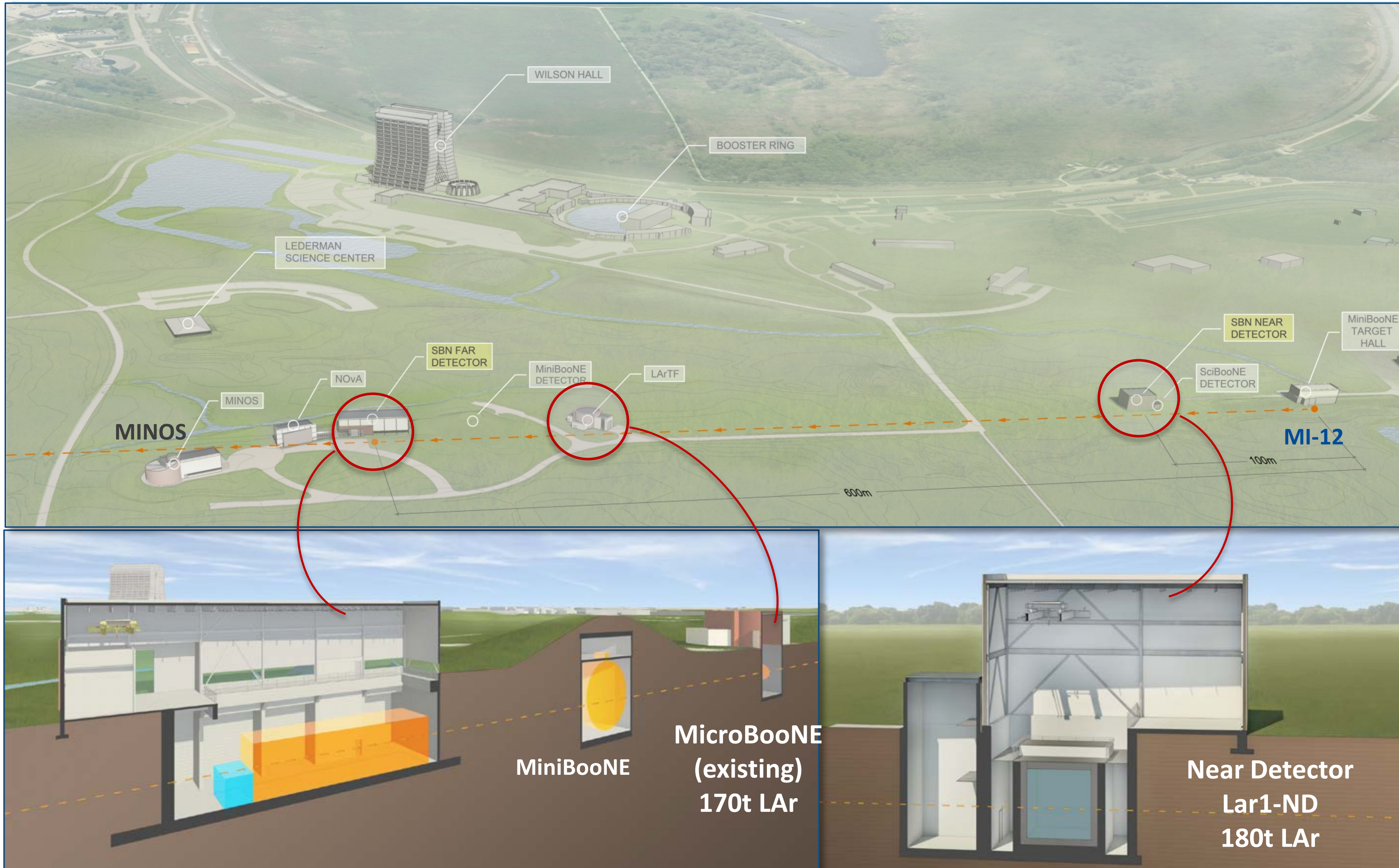
LBNF Process

- International approach building off European Strategy and US P5 Report
  - CERN Medium-Term Plan (MTP), 2014
    - Includes a neutrino platform to assist with program in US or Japan
    - https://cds.cern.ch/record/1711111/?ln=en
  - P5 long-range plan for US HEP
    - Includes strong support for the physics of a long-baseline neutrino experiment, and support for an international experiment in the US (LBNF)
- Form a new international collaboration (LBNF or ELBNF)
  - Form an interim International Board (iIEB), representative of worldwide community
    - First meeting at Fermilab September 23-24
  - LOI drafted under IIEB and commented/signed by community
    - https://indico.fnal.gov/conferenceDisplay.py?confId=9090
    - Sergio Bertolucci will present LOI to Fermilab PAC next week
  - ELBNF Proto-collaboration meeting Jan. 22-23
    - https://indico.fnal.gov/conferenceDisplay.py?confId=9209
- Conceptual Design Report (CDR) to PAC summer 2015

Fermilab Short Baseline Neutrino (SBN) Program

- Utilize successful Booster Neutrino Beamline (BNB) developed for MiniBooNE
- In 2015 next phase - MicroBooNE (approved for 6.6E20 P.O.T.)
- Starting in 2018- Three LAr-TPC detectors:
  - Near: New detector using LBNF technology @ 110m from BNB target
  - Middle: MicroBooNE @ 470m
  - Far: refurbished ICARUS detector moved from Gran Sasso, Italy @ 600m
- Motivations
  - Science:
    - Precise study of ν anomalies from the MiniBooNE and LSND experiments. Search for Sterile ν's
    - Very large neutrino samples in near detector for cross-section studies with LAr
    - Sample of higher energy neutrinos from NUMI off-axis beam in far detector
  - R&D: continued development of LAr-TPC technology for LBNF program
  - Build international partnerships for LBNF program (CERN, Italy, Switzerland, UK)

SBN Program Layout



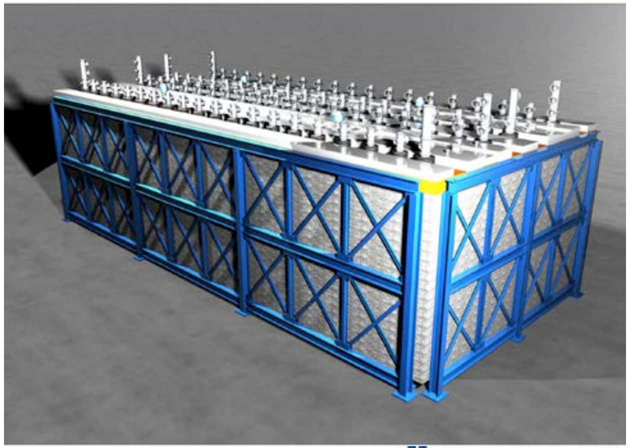
Far Detector: ICARUS T600

- T600 detector consists of two 300t cryostat modules
- Successful operation at Gran Sasso in CNGS beam
  - Achieved electron lifetime >15ms
- Move from Gran Sasso (LNGS) to CERN
  - Modules arrived in Nov. & Dec.
- Refurbish at CERN: new cryostats, new electronics, upgraded light detection

First TPC ready to leave LNGS

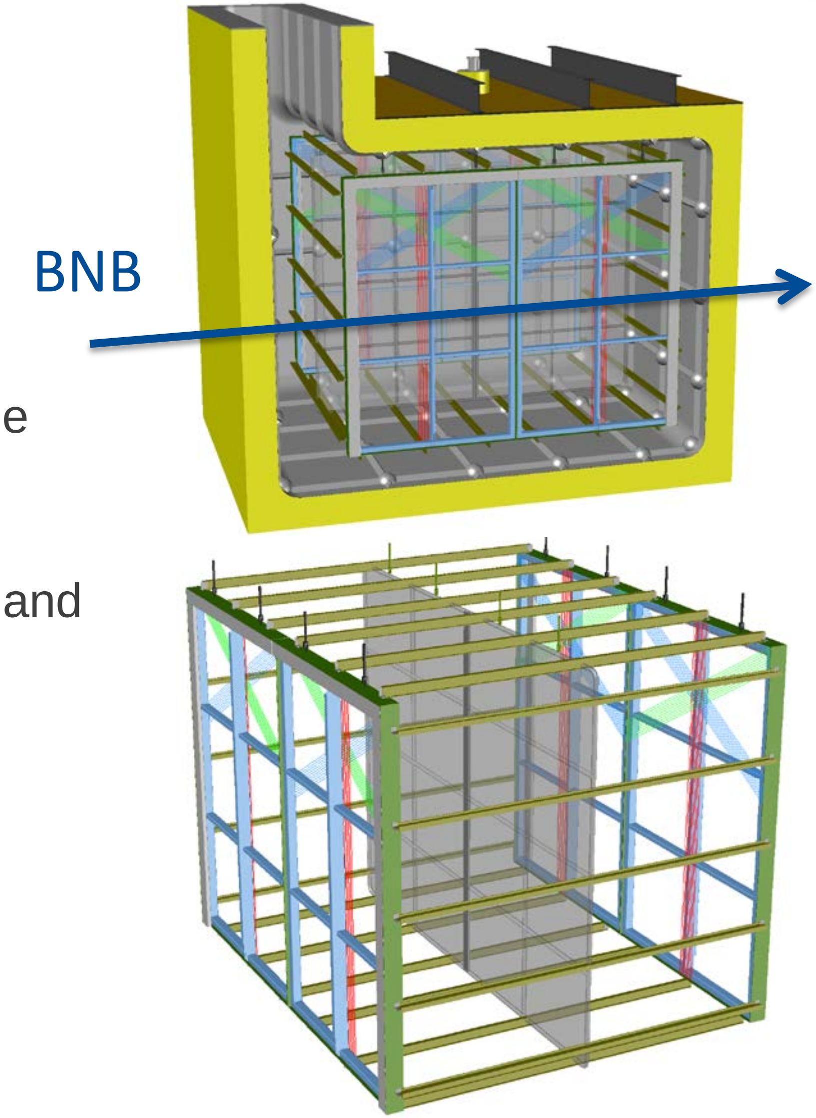
First ICARUS TPC Loading into Container at LNGS

3D Model of new ICARUS Cryostats



Near detector: LAr1-ND

- New LAr TPC detector based on and testing LBNF technology
  - Build on MicroBooNE and LBNF 35 ton experience
  - Test LBNF components in neutrino beam
  - Explore design alternatives
- Cryostat: membrane technology and minimize surfaces in LAr gas ullage
- TPC: LBNF style preassembled cathode and anode planes but with cathode in the middle and no wire wrap on the anode planes
- Electronics: LBNF cold electronics including processing FPGA in cold
- Light detection: starting point is LBNF style acrylic bars with SiPM readout.



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 CERN
  - Large overlap between LAr1-ND and MicroBooNE collaborations
- Very Fast timeline

  2014 – Proposal preparation initial design and logistics

  2015 – 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 from US DOE and NSF, INFN, CERN, and UKSTFC. Additional support requests to CH NSF and US NSF

Review

- Fermilab is performing neutrino experiments with two beamlines:
  - BNB: MicroBooNE (formerly MiniBooNE, SciBooNE)
  - NuMI: MINOS+, MINERvA, NOvA (formerly ArgoNeuT)
- Projects are in place to increase proton power:
  - PIP to 700 kW + BNB + Muons
  - PIP-II to 1.2 MW, eventually 2+ MW
- The next long-baseline experiment (LBNE / LBNF / ELBNF)
  - International letter of Intent presented to Fermilab PAC Jan. 15
  - First Proto-Collaboration meeting Jan. 22-23
  - Designs exist at some level, international effort to advance
- Short-baseline neutrino (SBN) experiments being planned
  - Build off of ICARUS and other LAr work

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PIP-II and Future Neutrino Experiments

Robert Zwaska

8 January 2015

Cracow Epiphany Conference