Overview of the LBNE Beamline Design

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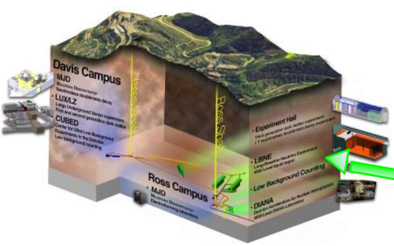


Outline

- LBNE Science Goals
- LBNE Project Scope
- LBNE Milestones
- Recent Beamline Scope Changes
- Beamline Design Overview
- Beamline R&D Plans
- Conclusions

LBNE Science Goals

LBNE is a comprehensive program to:

- Measure neutrino oscillations
  - Direct determination of CP violation in the leptonic sector
  - Measurement of the CP phase δ
  - Determination of the neutrino mass hierarchy
  - Determination of the θ_{23} octant and other precision measurements
  - Testing the 3-flavor mixing paradigm
  - Precision measurements of neutrino interactions with matter
  - Searching for new physics
- Study other fundamental physics enabled by a massive, underground detector
  - Search for nucleon decays
  - Measurement of neutrinos from core collapse supernovae
  - Measurements with atmospheric neutrinos

LBNE Collaboration

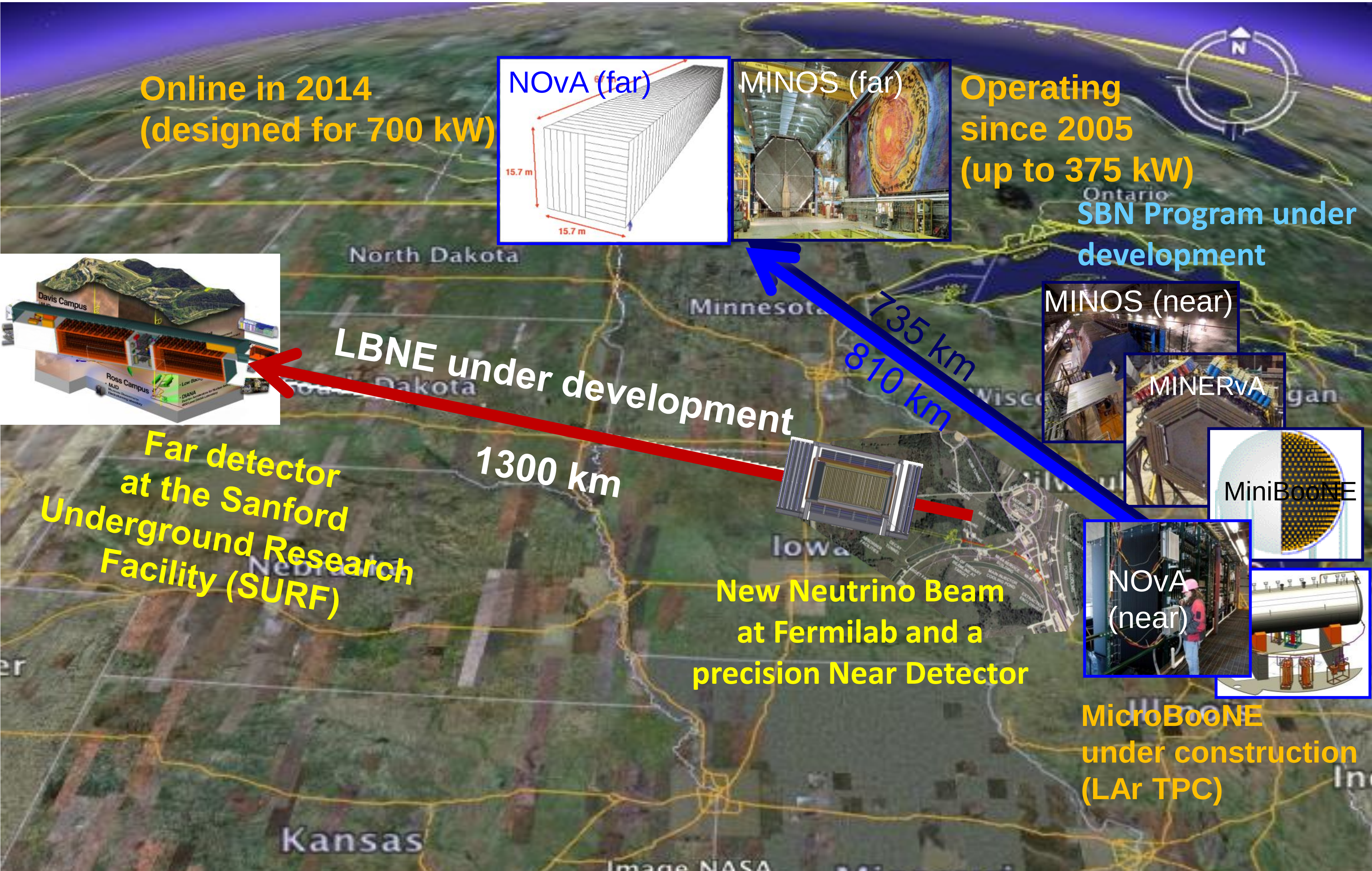
505 (379 US + 126 non-US) members,
88 (54 US + 34 non-US institutions), 8 countries

UFABC
Alabama
Argonne
Banaras
Boston
Brookhaven
Cambridge
Catania/INFN
CBPF
Charles U
Chicago
Cincinatti
Colorado
Colorado State
Columbia
Czech Technical U
Dakota State
Delhi
Davis
Drexel
Duke
Duluth
Fermilab
FZU
Goias
Gran Sasso
GSSI
HRI
Hawaii
Houston
IIT Guwati
Indiana
Iowa State
Irvine
Kansas State
Kavli/IPMU-Tokyo
Lancaster
Lawrence Berkeley NL
Livermore NL
Liverpool
London UCL
Los Alamos NL
Louisiana State
Manchester
Maryland

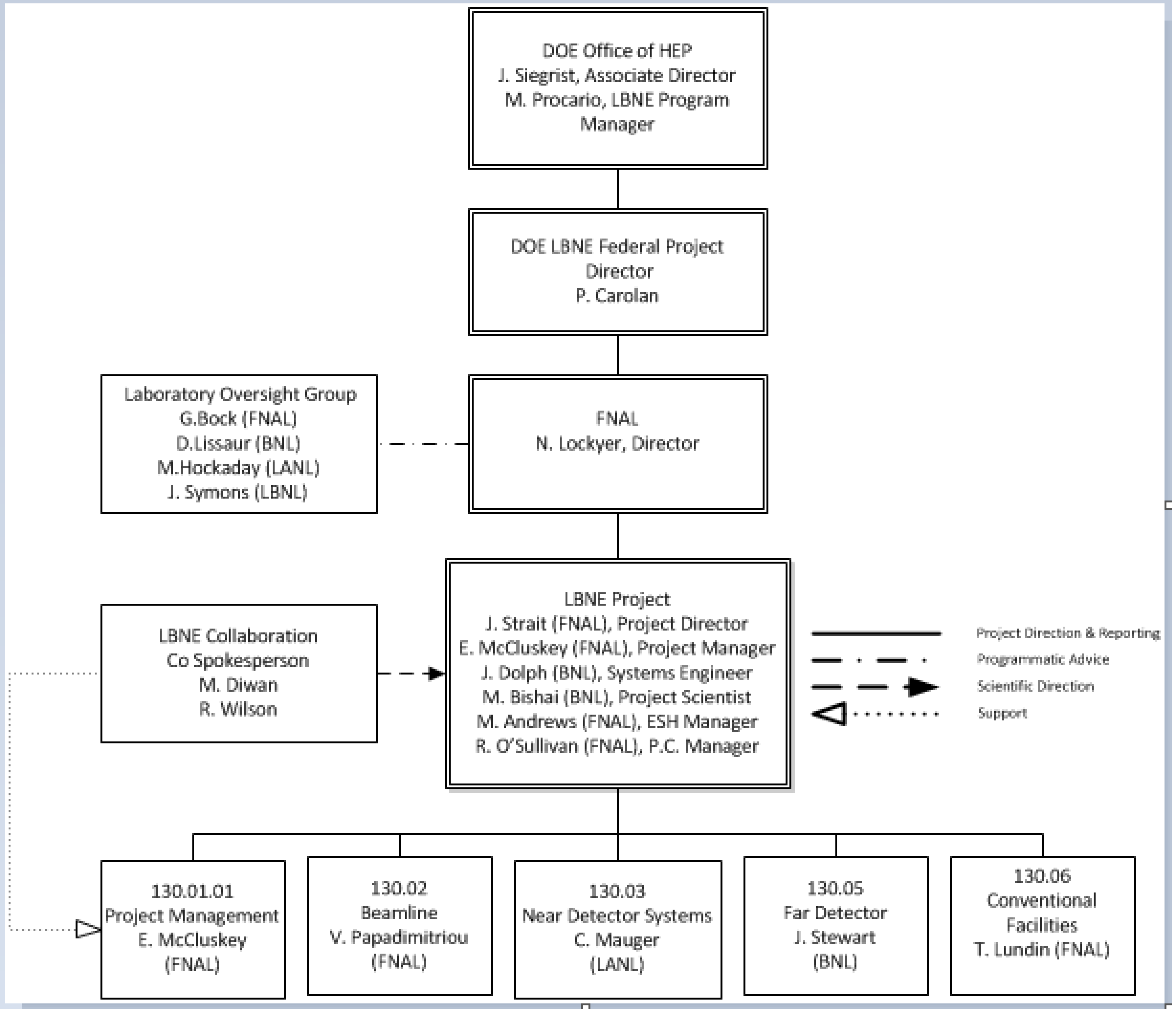
Michigan State
Milano
Milano/Bicocca
Minnesota
MIT
Napoli
NGA
New Mexico
Northwestern
Notre Dame
Oxford
Padova
Panjab
Pavia
Pennsylvania
Pittsburgh
Princeton
Rensselaer
Rochester
Rutherfod Lab
Sanford Lab
Sheffield
SLAC
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse
Tennessee
Texas, Arllington
Texas, Austin
Tufts
UCLA
UEFS
UNICAMP
UNIFAL
Virginia Tech
Warwick
Washington
William and Mary
Wisconsin
Yale
Yerevan

- Since December 2012:
  - Collaboration has increase in size by more 40%
  - Non-US fraction more than doubled

Neutrino Program at Fermilab



LBNE Project Organization



Evolving Scope of the LBNE Project

- LBNE is developing as an international partnership, with the goal of delivering an initial project consisting of:
  - A neutrino beamline, operating initially at 1.2 MW,
  - A highly-capable near detector system,
  - A ≥10 kt fiducial mass far detector underground at SURF
  - Conventional facilities including a cavern at the far site for a ≥ 35 kt fiducial mass far detector system.
  - The designs of the near and far detectors and of the beam will incorporate concepts from new partners.
- The planned project allows for future upgrades:
  - The beamline is designed to be upgradeable up to 2.3 MW proton beam power.
  - Future far detector module(s) can be installed in the underground cavern.

Importance of LBNE Science and moving forward

The LBNE science has been recognized to be top priority:

- Report of the Snowmass 2013 summer study
- European strategy for Particle Physics (update of 2013)
- P5 report, May 2014

> The Science Drivers:
> - Use the Higgs boson as a new tool for discovery
> - Pursue the physics associated with neutrino mass
> - Identify the new physics of dark matter
> - Understand cosmic acceleration: dark energy and inflation
> - Explore the unknown: new particles, interactions, and physical principles
>
> P5 Report, May 2014

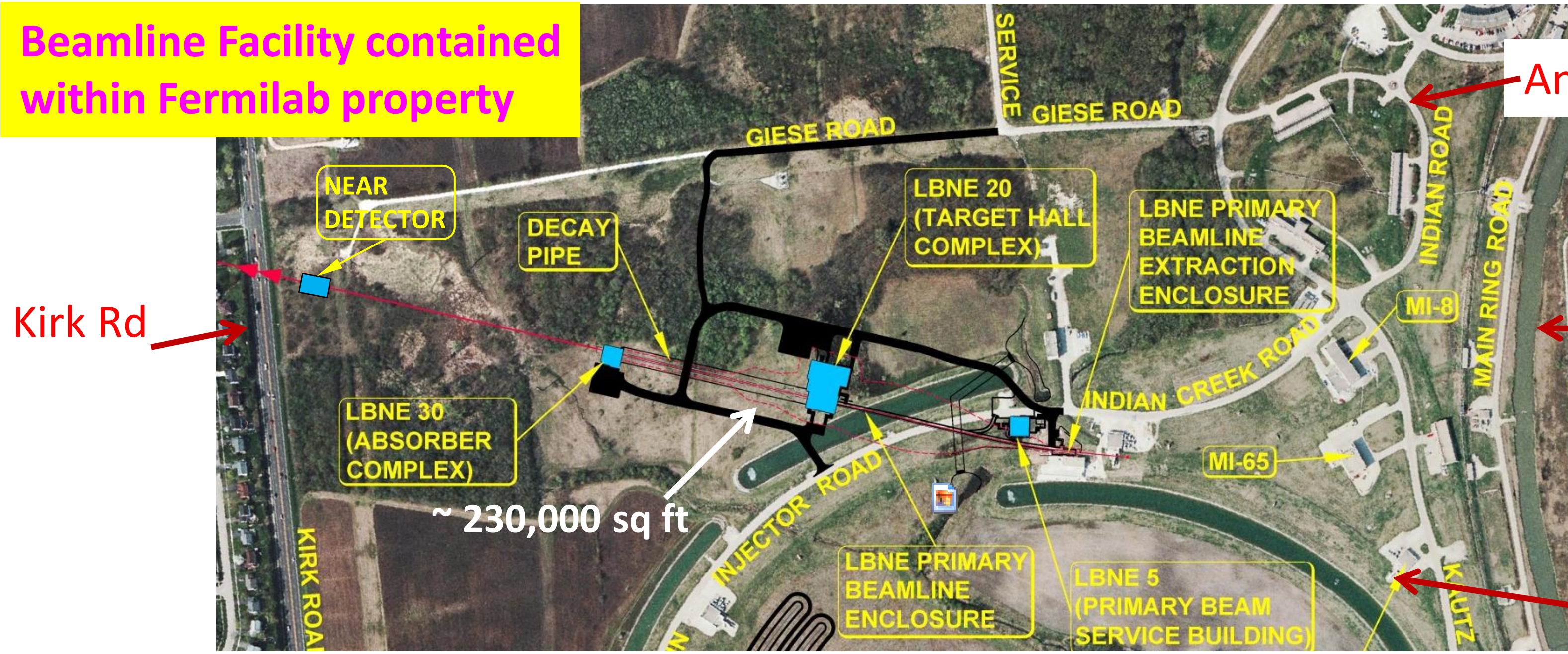
Direction to the LBNE Project by DOE and Fermilab Leadership on May 30, 2014:

- "As we work through what the process will be to internationalize, Fermilab and DOE management direction is that the project should keep working on what they are doing"

LBNE Milestones (in the current schedule)

- Critical Decision-0 (CD-0) approved, January 8, 2010.
- Successful Director's Review of the full-scope LBNE (26-30 Mar. 2012).
- Office of Science in DOE asking that LBNE is staged (19 Mar. 2012).
- A three month "Reconfiguration" process and recommendation for a phased LBNE (Aug. 6, 2012).
- Successful Director's Review of the Phase 1 LBNE Project (25-27 Sep. 2012).
- Successful DOE CD-1 Independent Project/Cost Reviews (Oct. /Nov., 2012).
- CD-1 approved, December 10, 2012.
- CD-3a expected in October 2015.
- CD-2 expected in January 2017 (baselining).
- CD-3b expected in October 2017.
- CD-4 Beamline ready for review, expected in Aug. 2023.
- CD-4 expected in May 2024.

LBNE Beamline Reference Design: MI-10 Extraction, Shallow Beam

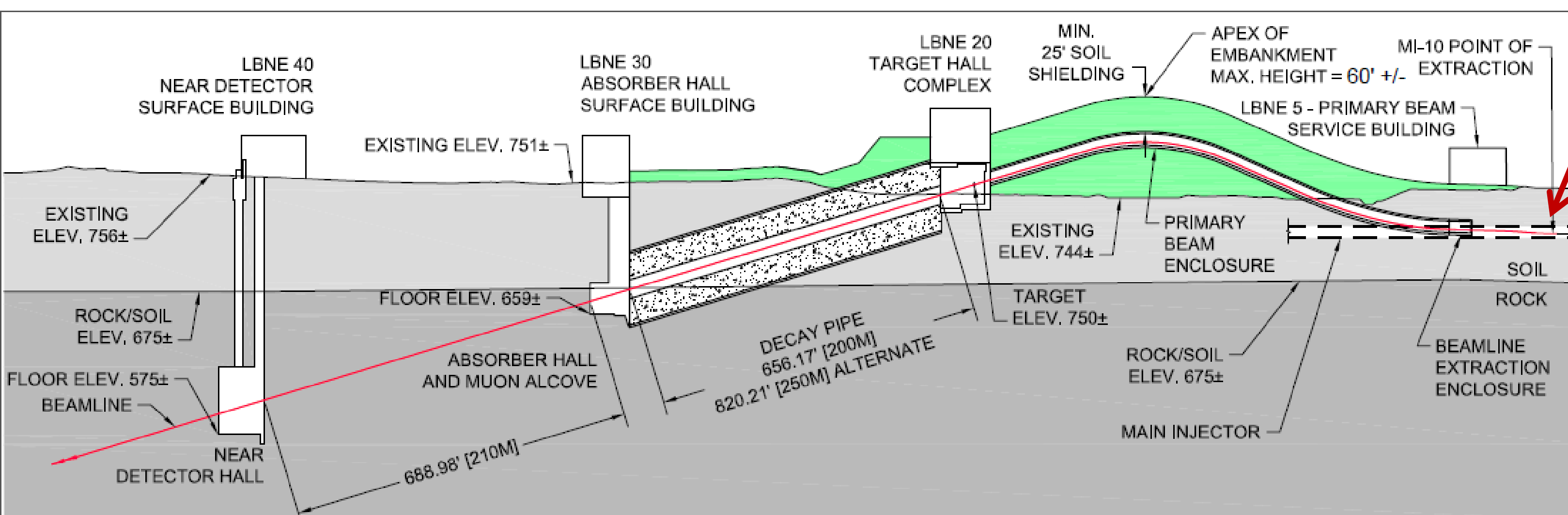


Antiproton Source

Kirk Rd

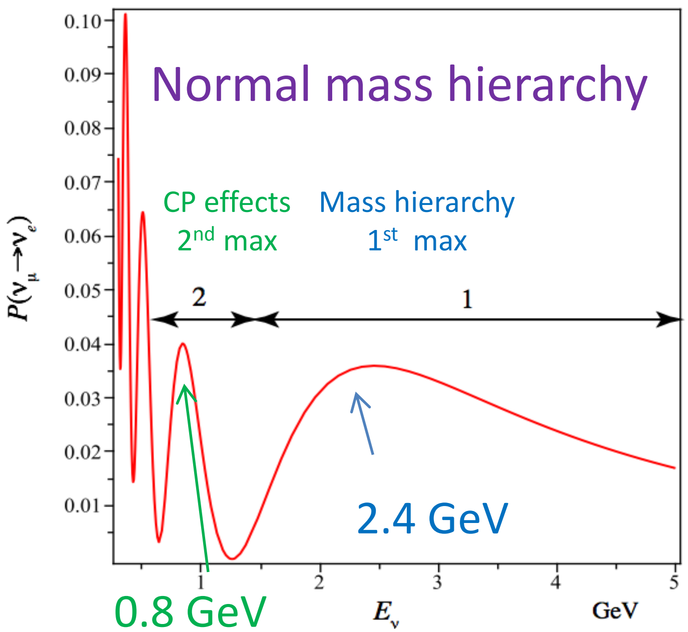
Tevatron

Main Injector



Beamline Requirements driven by the physics

- The driving physics considerations for the LBNE Beamline are the long-baseline neutrino oscillation analyses.
- Wide band, sign selected beam to cover the 1st and 2nd oscillation maxima. Optimizing for Eν in the range 0.5 – 5.0 GeV.
- The primary beam designed to transport high intensity protons in the energy range of 60-120 GeV to the LBNE target.



Requirements and assumptions

- We have been planning so far to start with a 700 kW beam (NuMI/NOvA at 120 GeV) and then be prepared to take significantly increased beam power (~2.3 MW) allowing for an upgradeability of the facility when more beam power becomes available.
- Fermilab is now planning to raise the beam power to 1.2 MW by the time LBNE starts operation.
  - We are currently assuming operation of the Beamline for the first 5 years at 1.2 MW and for 15 years at 2.3 MW.
- Stringent limits on radiological protection of environment, members of public and workers.
- The lifetime of the Beamline Facility including the shielding is assumed to be 30 years.

What is being designed for 2.3 MW

- Designed for 2.3 MW, to allow for an upgrade in a cost efficient manner:
  - Primary beamline
  - the radiological shielding of enclosures (primary beam enclosure, the target shield pile and target hall except from the roof of the target hall, the decay pipe shielding and the absorber hall) and size of enclosures
  - beam absorber
  - decay pipe cooling
  - remote handling
  - radioactive water system piping (in penetrations)

Recent scope changes/challenges

- Be ready for 1.2 MW at day one (changes required in many components of the neutrino beamline).
- Helium instead of air in the decay pipe to increase the neutrino flux and reduce the systematics (an upstream decay pipe window is required and more sophisticated air cooling).
- The helium in the decay pipe makes the design of the hadron absorber more challenging. We had to reduce temperatures and increase the safety factor even with air in the decay pipe.
- Understanding corrosion better for the decay pipe, target chase and absorber cooling lines.
  - Beamline corrosion working group
  - Corrosion consultant
  - Consulting with CERN and other HEP facilities

Proton Improvement Plan-II
Performance Goals

PIP-II doc: 1232
S. Holmes et al.

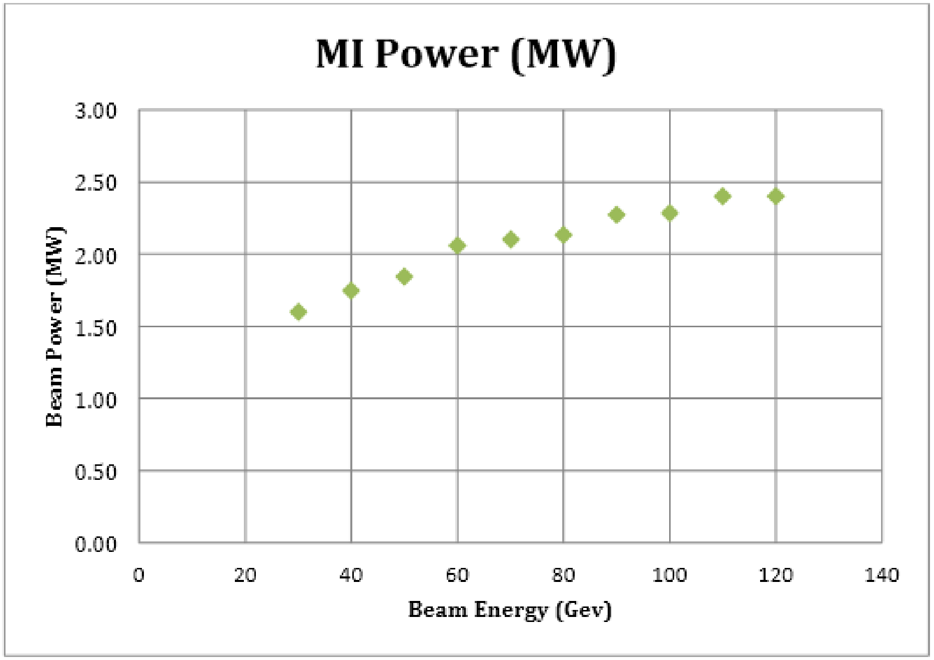
Performance Parameter	Requirement	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.6	msec
Linac Pulse Repetition Rate	15	Hz
Linac Upgrade Potential	CW	
Booster Protons per Pulse	6.4×10^{12}	
Booster Pulse Repetition Rate	15	Hz
Booster Beam Power @ 8 GeV	120	kW
8 GeV Beam Power to LBNE	80-120*	kW
Beam Power to 8 GeV Program	40-0*	kW
Main Injector Protons per Pulse	7.5×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.2	sec
Main Injector Cycle Time @ 60 GeV - 80 GeV	0.8	sec
LBNE Beam Power @ 60 GeV	0.9	MW
LBNE Beam Power @ 120 GeV	1.2	MW
LBNE Upgrade Potential @ 60-120 GeV	>2	MW

*First number refers to Main Injector operations at 120 GeV; second number to 60 GeV. The PIP-II configuration is capable of maintaining 1.2 MW down to 80 GeV.

Proton Improvement Plan-IV
Performance Goals

Energy (GeV)	Intensity (1e13)	Cycle Time (sec)	Power (MW)
120	15	1.2	2.4
110	15	1.1	2.4
100	15	1.05	2.29
90	15	0.95	2.13
80	15	0.9	2.13
70	15	0.8	2.1
60	15	0.7	2.06
50	15	0.65	1.85
40	15	0.55	1.75
30	15	0.45	1.6

P. Derwent, S. Holmes, I. Kourbanis, V. Lebedev

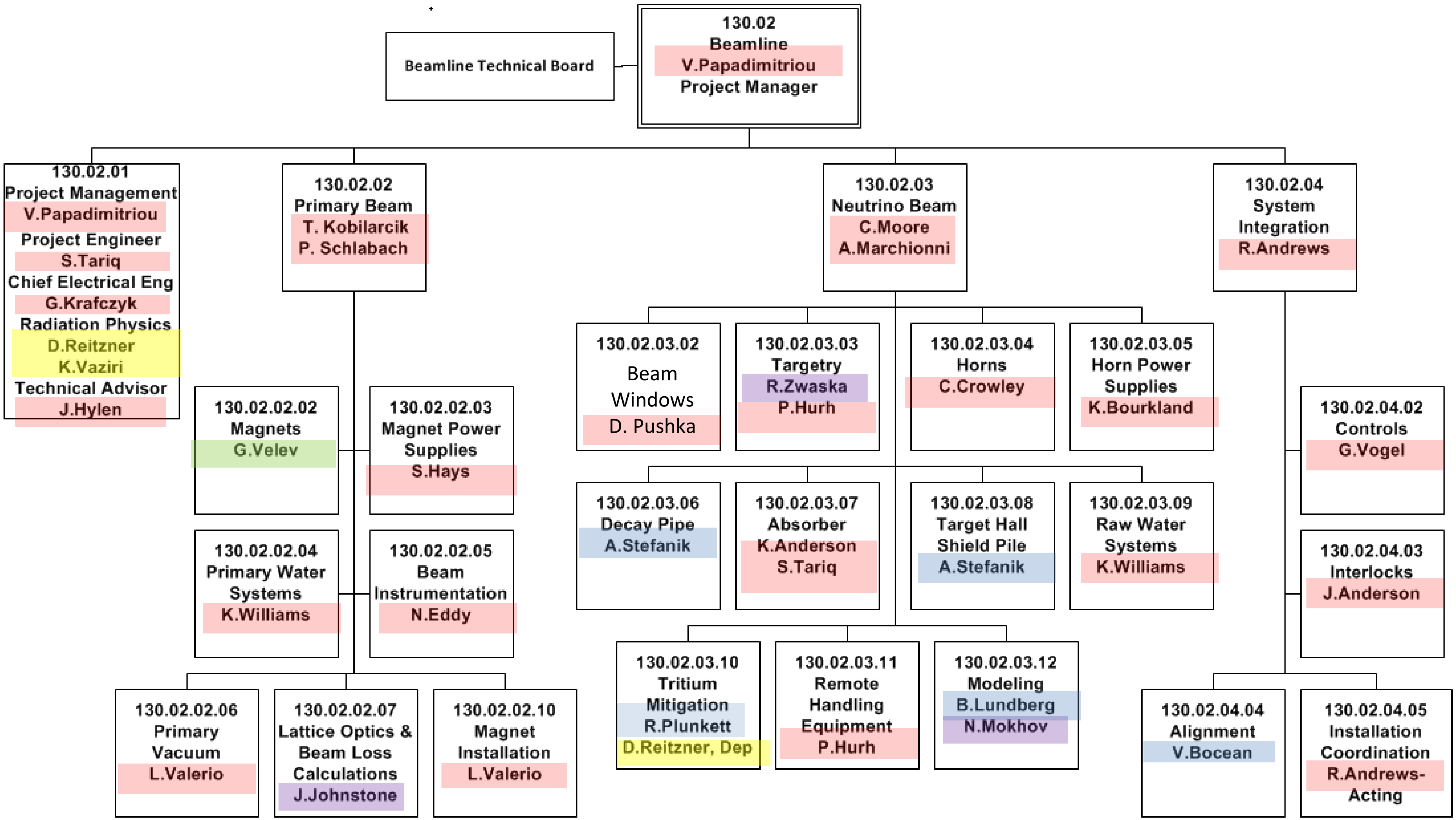


http://projectx-docdb.fnal.gov/cgibin/ShowDocument?docid=1295

http://projectx-docdb.fnal.gov/cgibin/ShowDocument?docid=1232

Beamline Organization

4 L3 Systems, 22 L4 Systems



Accel. Div. | Par. Phys. Div. | Tech. Div. | Accel. Phys. Cen. | ES&H Section

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- G. Velev
- G. Vogel
- K. Williams
- C. Worel
- B. Zwaska
- ………..
- E. McCluskey
- J. Strait

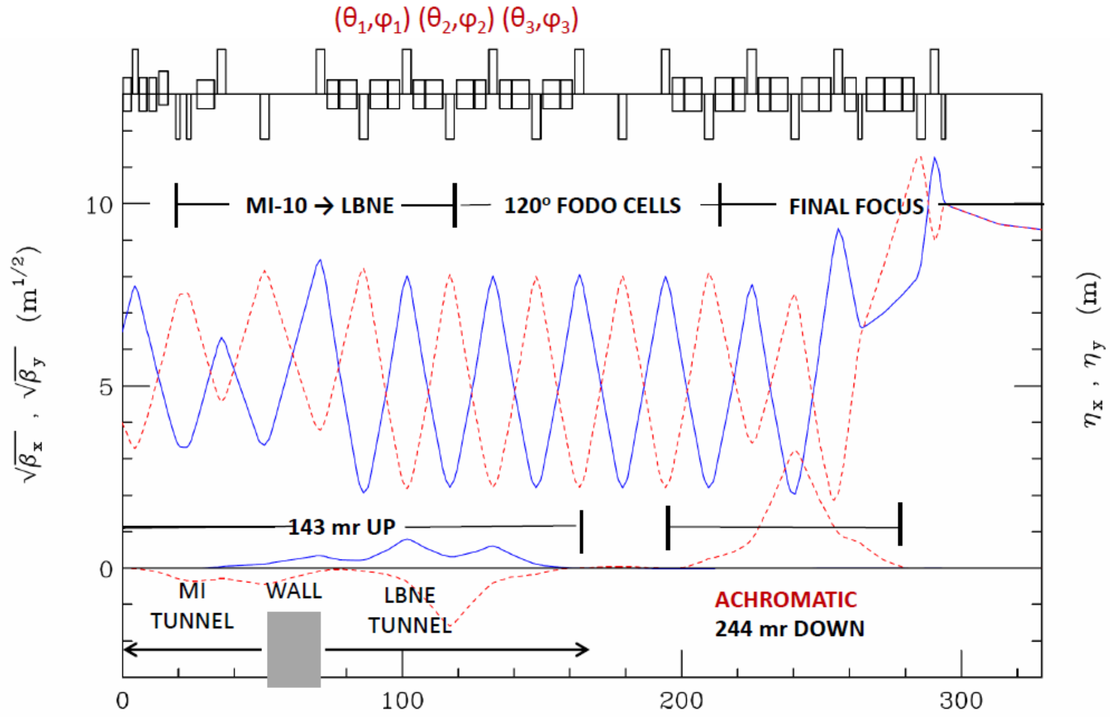
The Team is enhanced by a Technical Board and a Beam-simulation group and several other colleagues across Divisions, Sections and Centers

A Superb Team!!!
Many Thanks to ALL!!

Members of the Beamline Team during a New Year celebration in January 2014

Primary Beam and Lattice Functions

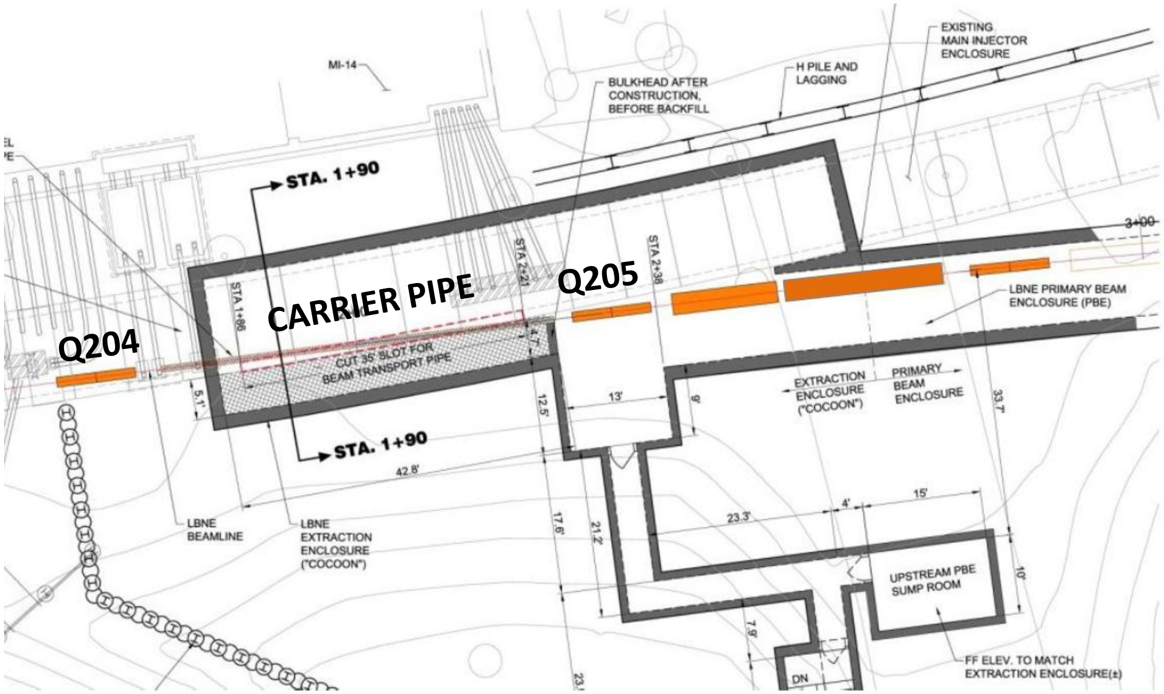
- The LBNE Primary Beam will transport protons of 60 - 120 GeV from the MI-10 extraction point of the Main Injector (MI) to the LBNE target to create a neutrino beam. The beam lattice points to 79 conventional magnets (25 dipoles, 21 quadrupoles, 23 correctors, 6 kickers, 3 Lambertsons and 1 C magnet).

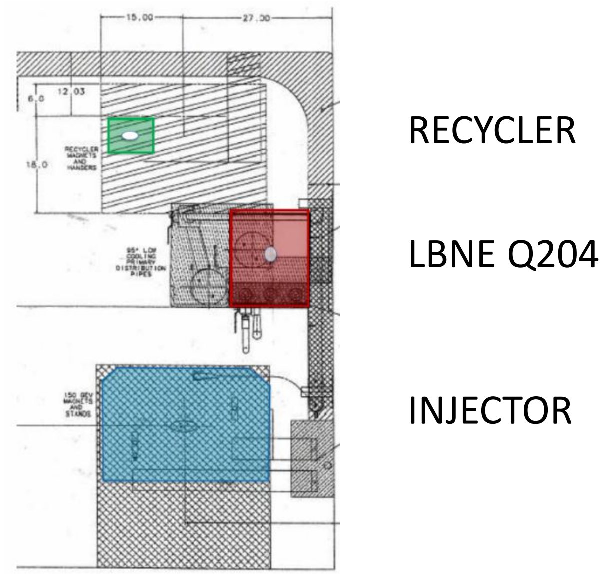


Horizontal (solid) and vertical (dashed) lattice functions of the LBNE transfer line

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 & $\Delta p_{99}/p = 11\text{x}10^{-4}$

MI-10 Tunnel → LBNE Enclosure Transfer



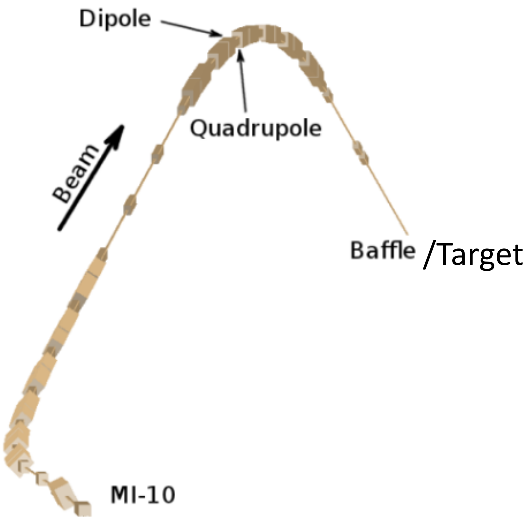


Transport from the existing MI tunnel enclosure into the new LBNE enclosure showing the carrier pipe connecting the MI-10 & LBNE enclosures (left), and separation of Q204 at the upstream end from the Main Injector & Recycler Rings (right).

Primary Beam

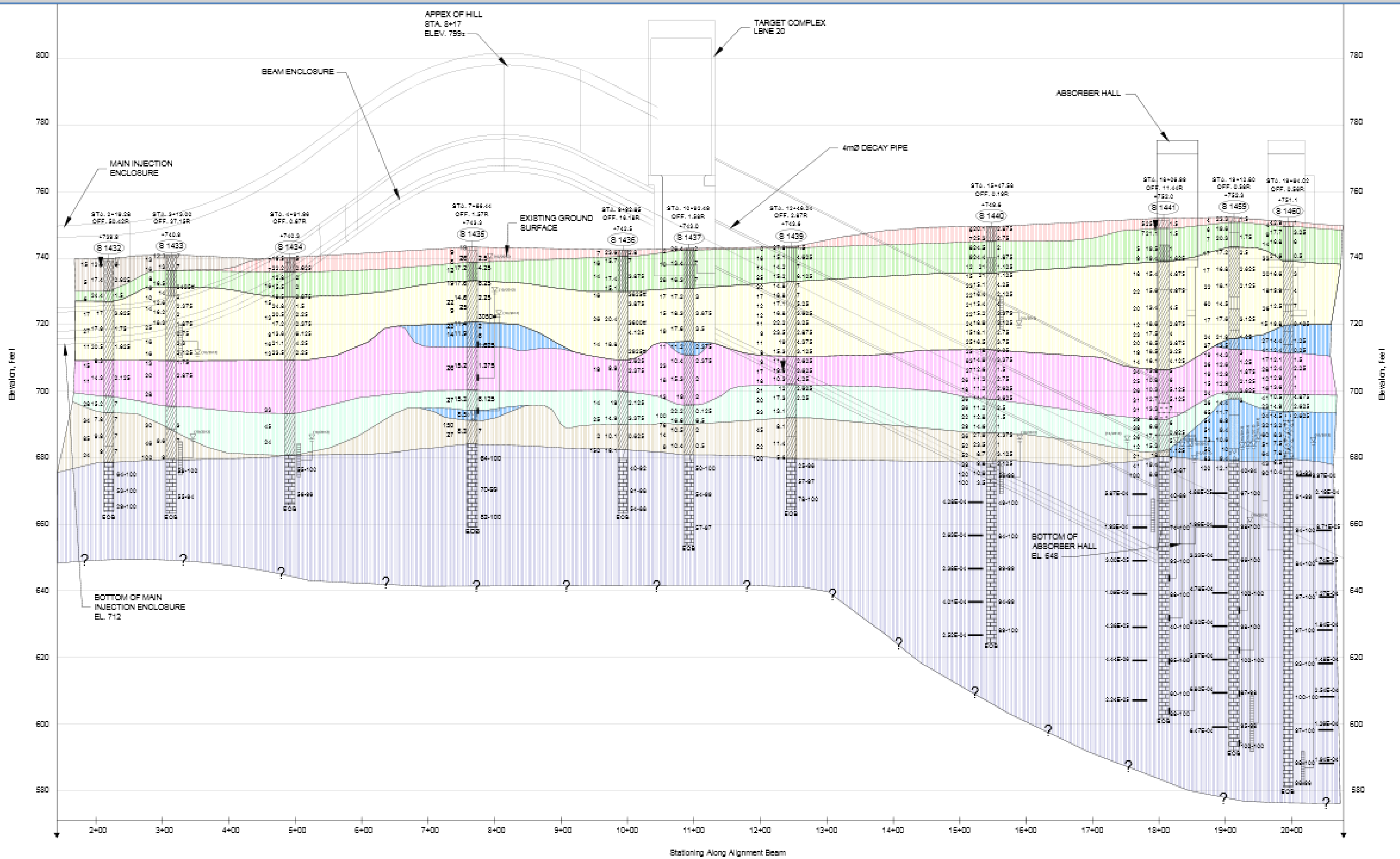
- Recent laser scanning of the MI-10 area and building of an accurate 3-D model.

STRUCT/MARS simulations have shown that highest beam loss rate takes place in quadrupole magnet and two adjacent dipoles located right at the apex of beamline



- CF has initiated prel. design of NS facilities including placement of the pre-load embankment, structures to protect MI from movements, etc.
- Recent geotechnical investigations helped determine better the soil density and the amount of soil shielding needed on top of the embankment (24.5 ft). Review in March 2014 verified this amount of shielding.

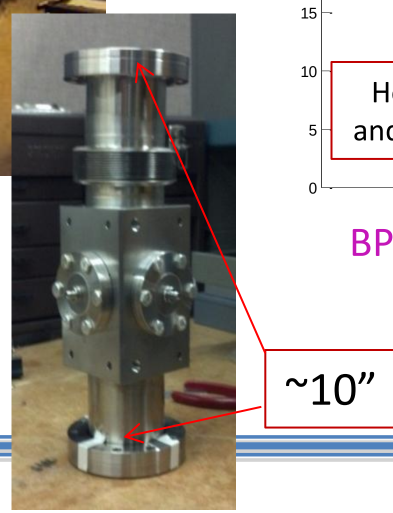
Core borings completed for the LBNE Beamline

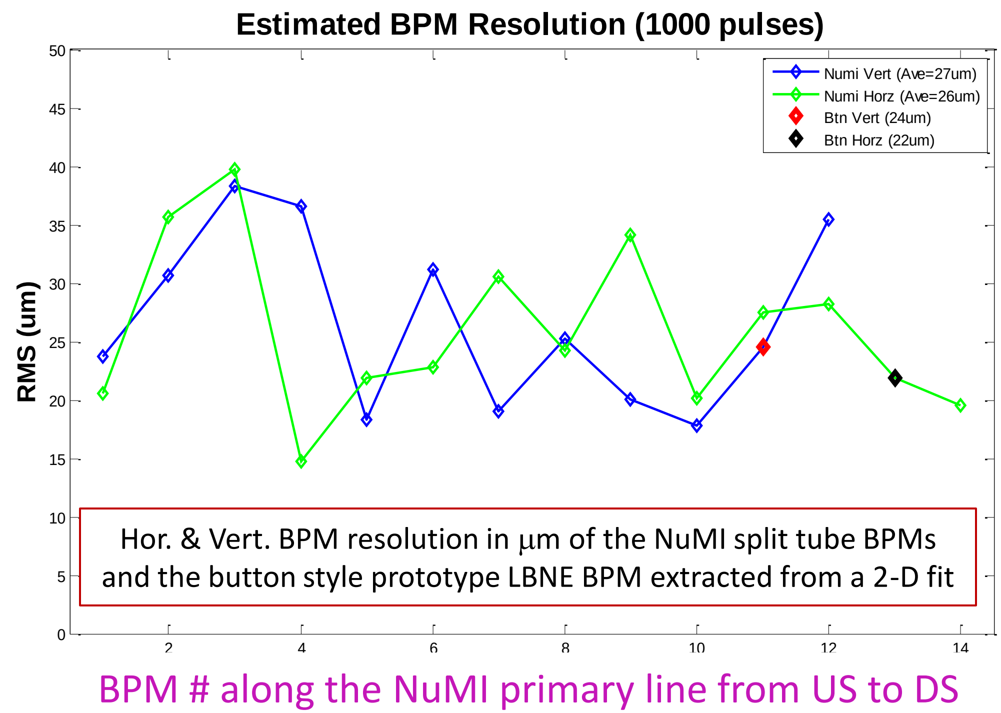


Primary Beam Instrumentation

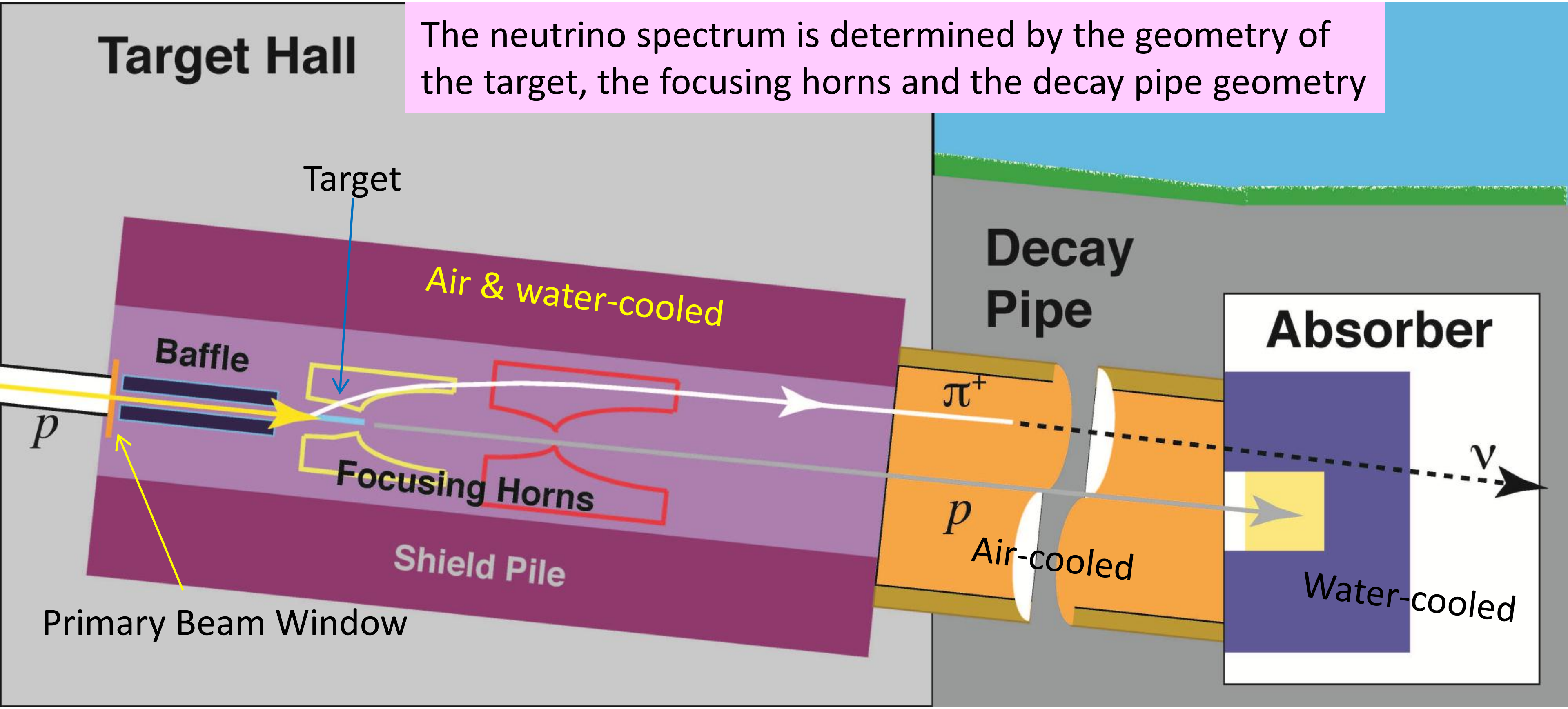
- Beam Position Monitors, Beam Loss Monitors, Beam Intensity Monitors, Beam Profile Monitors
- Prototype Beam Position Monitors (already operational in NuMI). Getting simultaneously x and y information.

Button BPM operational in NuMI





Major Components of the Neutrino Beam

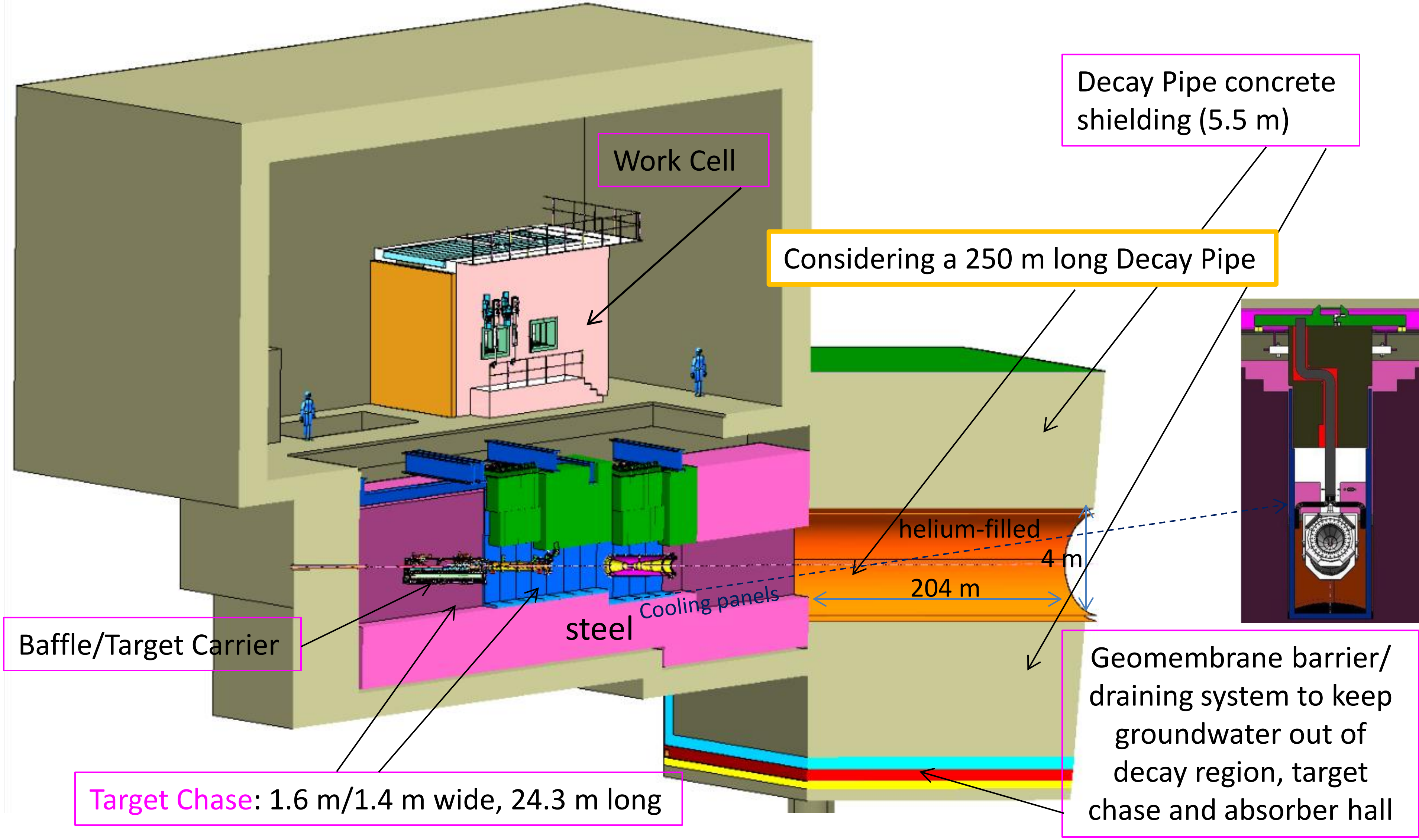


The neutrino spectrum is determined by the geometry of the target, the focusing horns and the decay pipe geometry

NuMI-like low energy target & NuMI design horns with some modifications for 1.2 MW operation

Tunable neutrino energy spectrum

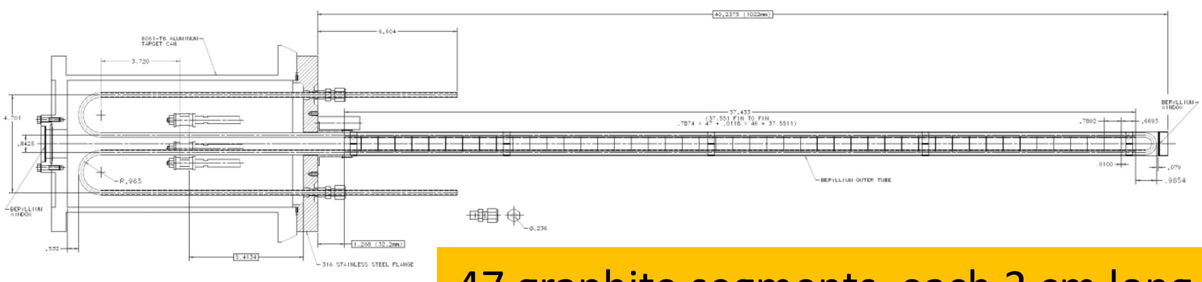
Target Hall/Decay Pipe Layout

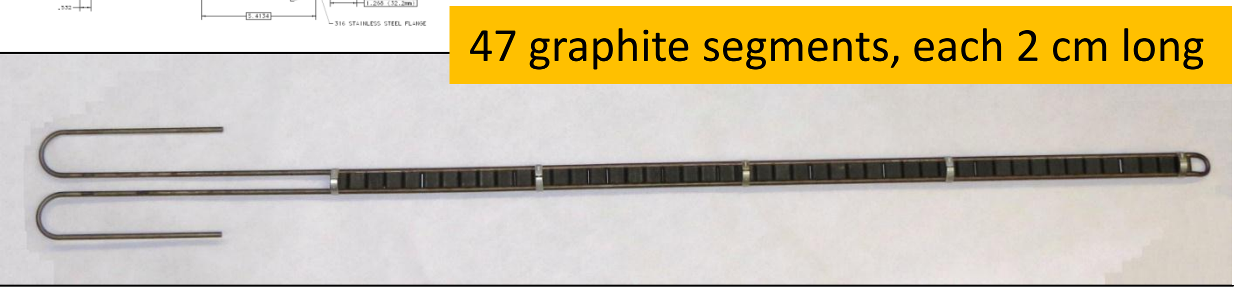


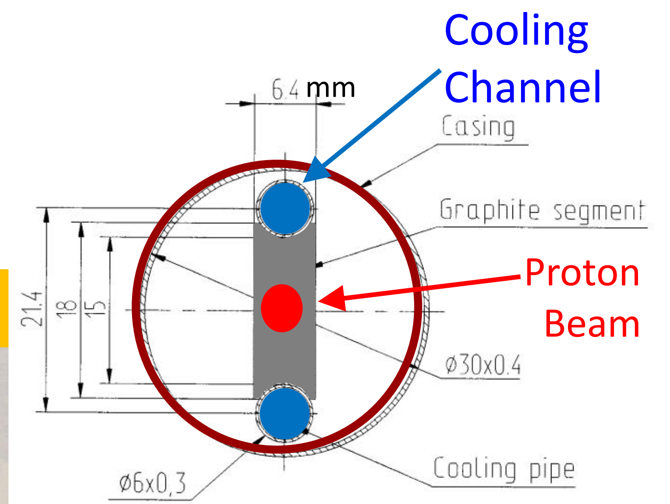
LBNE Target Design for 700 kW (CD1)

- Developed from the NuMI Low-Energy Target
  - Same overall geometry and material (POCO Graphite)
- Key change 1: Cooling lines made from continuous titanium tubing instead of stainless steel with welded junctions
- Key change 2: Outer containment can be made out of beryllium alloy instead of aluminum
  - Be generates less heat load and is stronger at higher temperatures
  - An all Be construction eliminates brazing joint to the DS Be window
  - Titanium alloys also being investigated

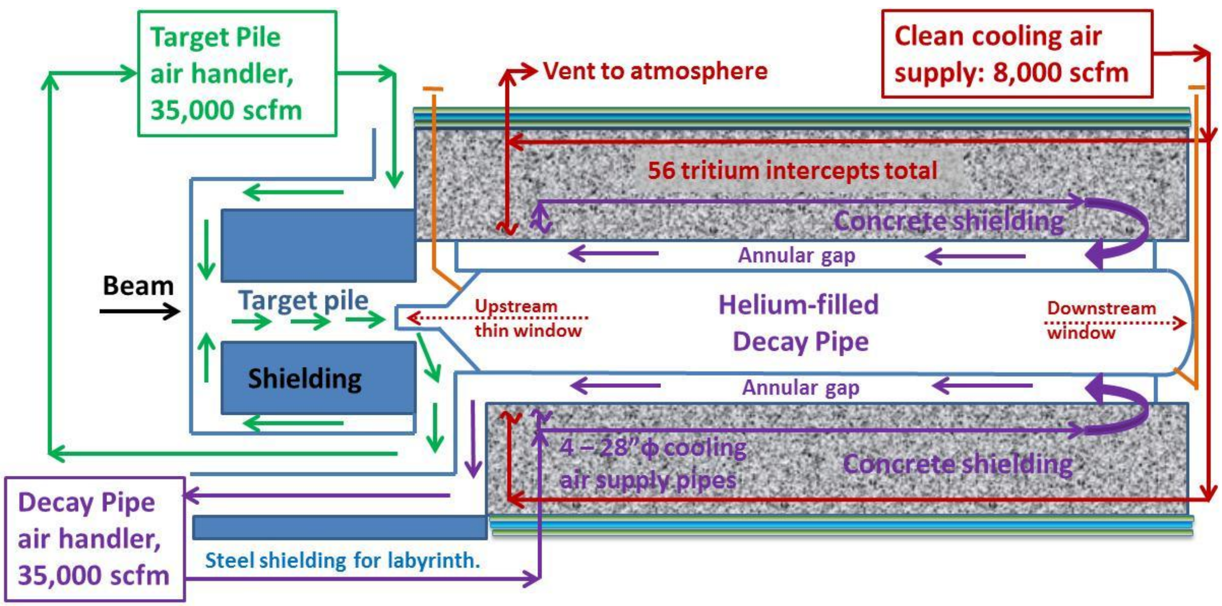
- Initial development of design started already for NuMI and it can be produced at Fermilab
- Expect to change target ~twice a year for 700 kW operation
  - Limited lifetime due to radiation damage of graphite
  - Annealing? (subject of RADIATE R&D)
- Option remains for Be as target material pending validation.
  - Radiation damage a factor of 10 less than graphite (subject of RADIATE R&D)

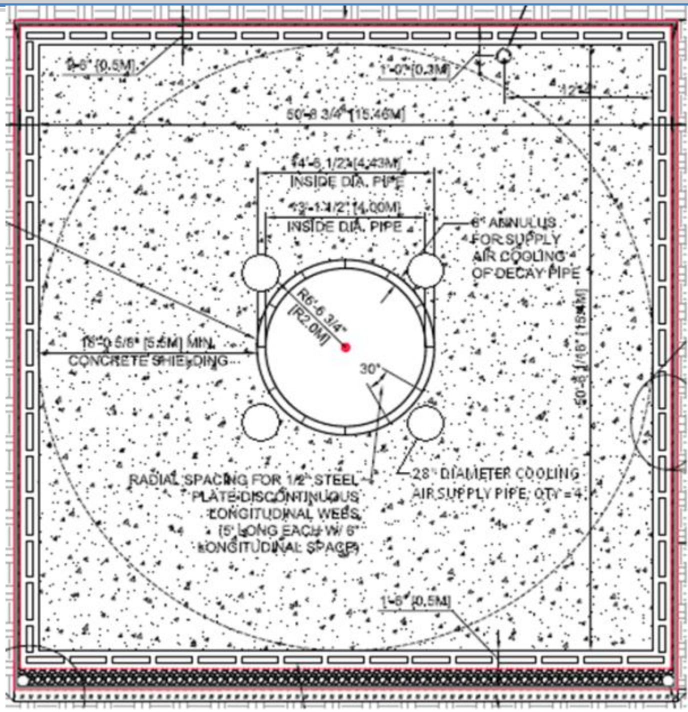




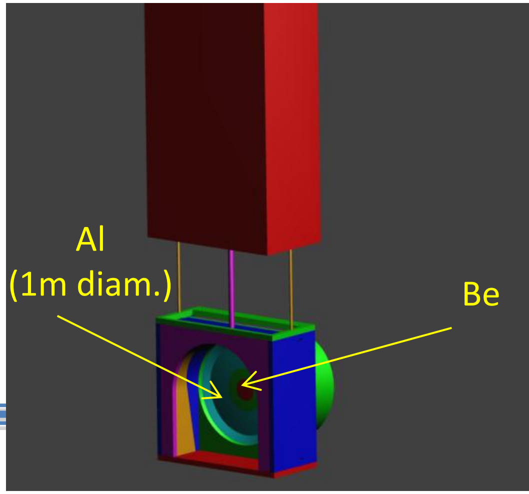


Helium-filled/Air-cooled Decay Pipe
(Helium increases the ν flux by ~10%)





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

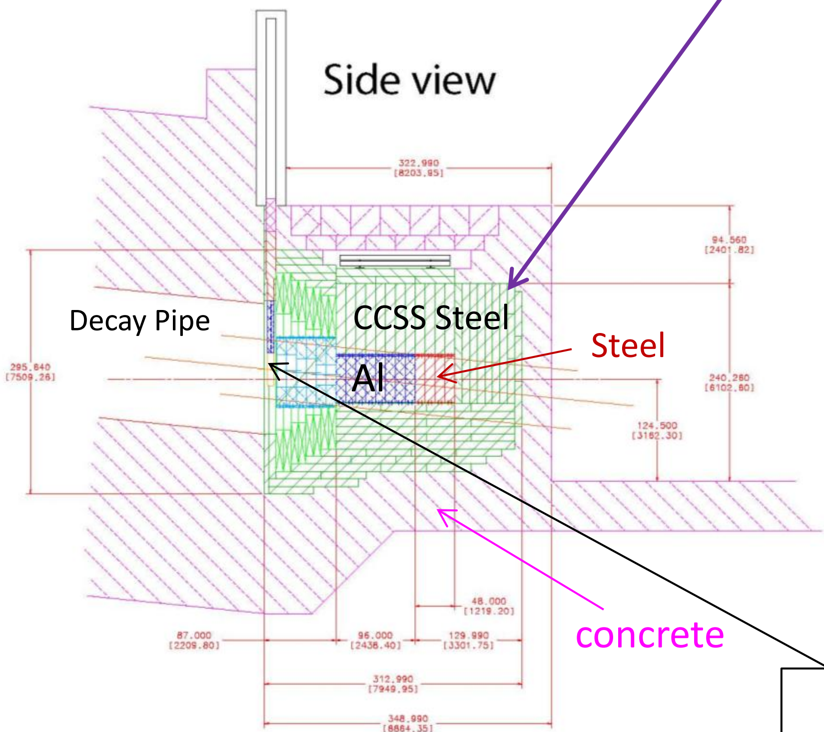


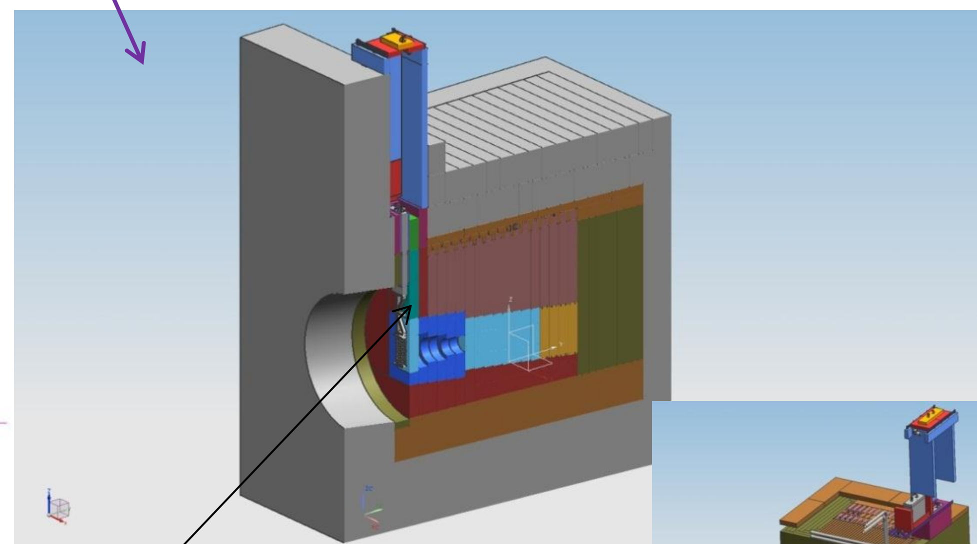
LBNE Absorber Complex – Longitudinal Section

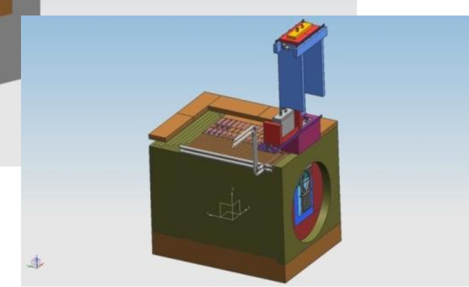
The Absorber is designed for 2.3 MW

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





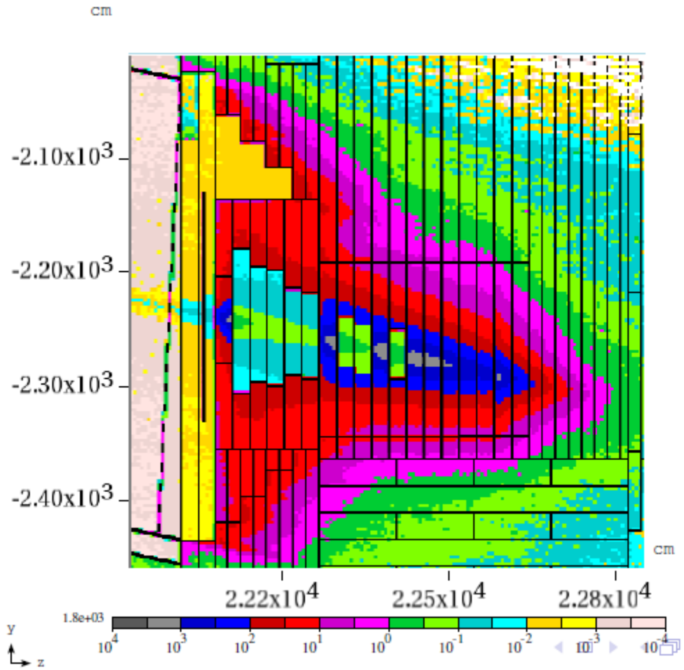


Hadron Monitor
(needs R&D)

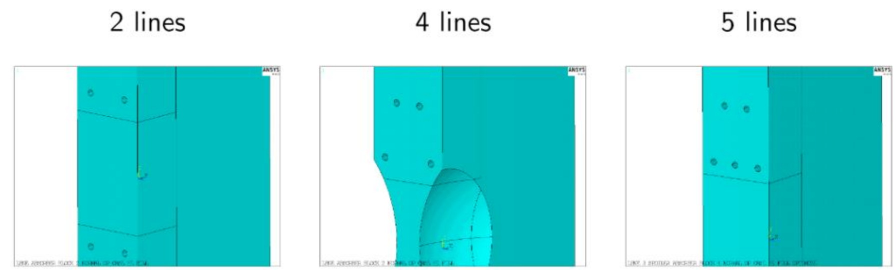
Absorber design

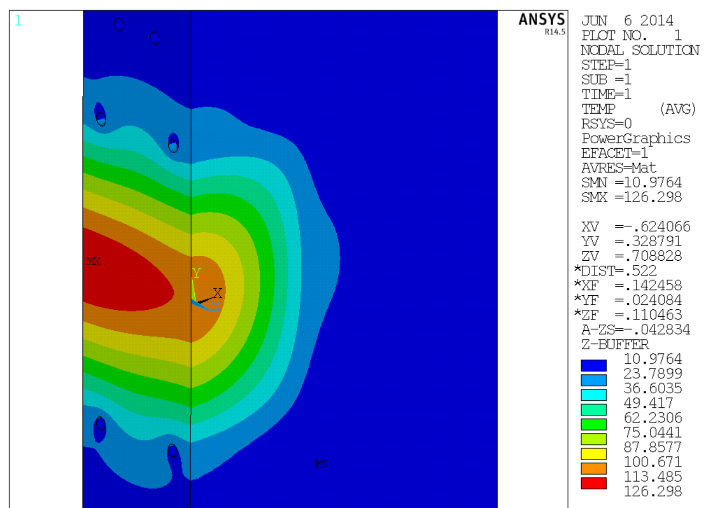
Al core temperatures reduced significantly since November 2013 (were about 170^{0}C)

Introducing one to three Al spoilers, thinner or sculpted blocks, different number & location of cooling lines, different water temperatures, different water flow rates,…



Power density distribution



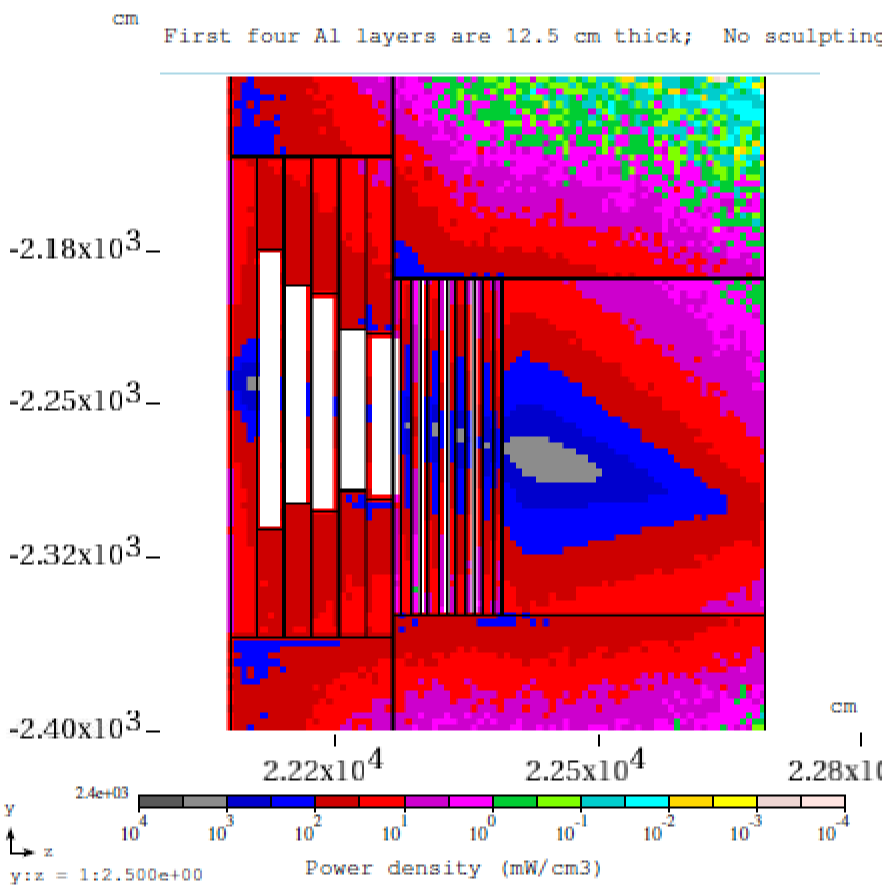


Block 4, 4 water lines(30cm/50cm), 3 spoilers, 20 gpm flow rate

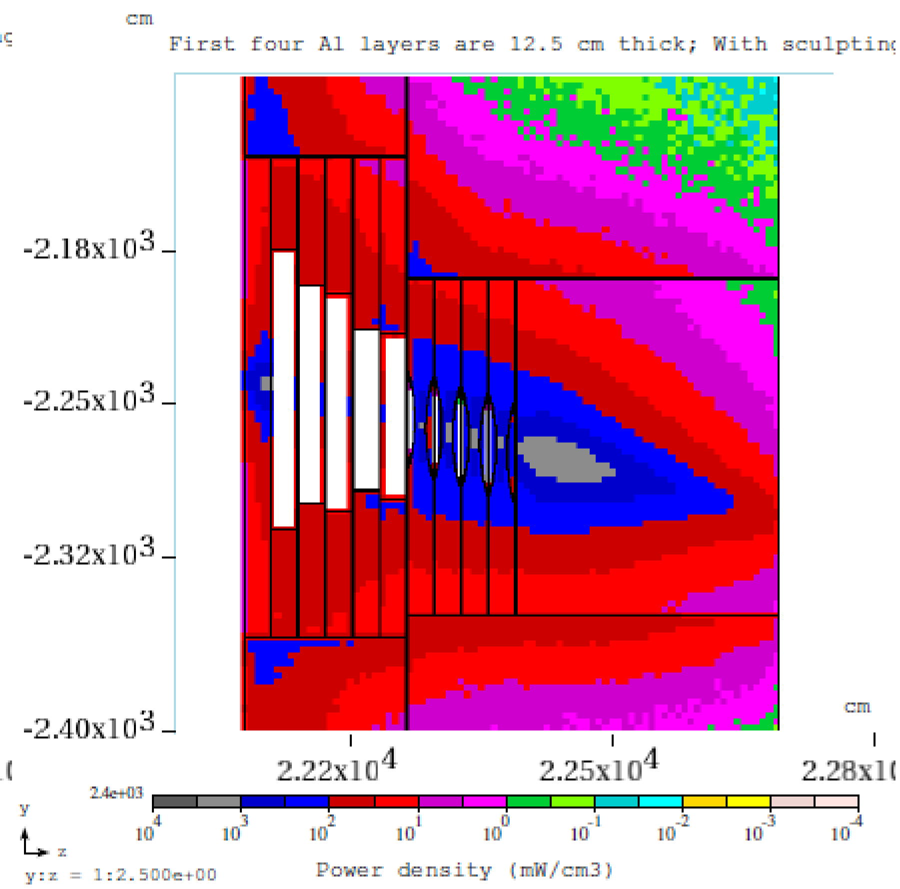
Max Temp 126^{0}C

Absorber Design/MARS Simulations

Thin Al blocks



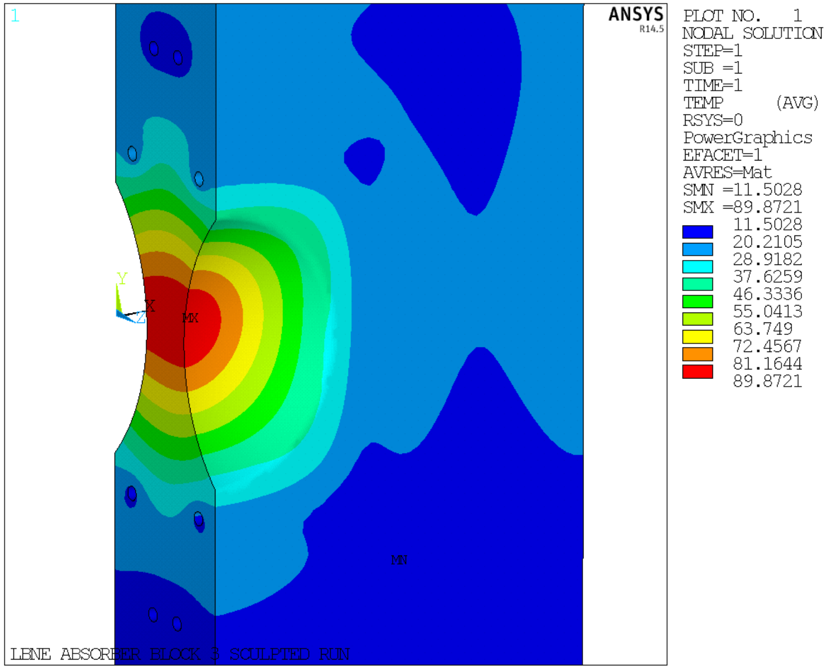
Sculpted Al blocks

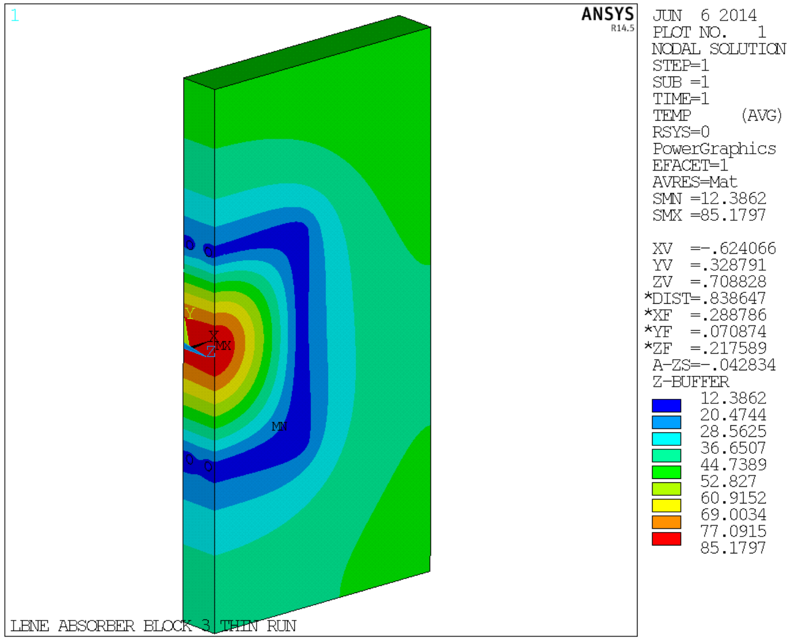


Absorber Design/MARS Simulations

Single Spoiler sculpted Al blocks

Single Spoiler thin (12.5 cm) Al blocks

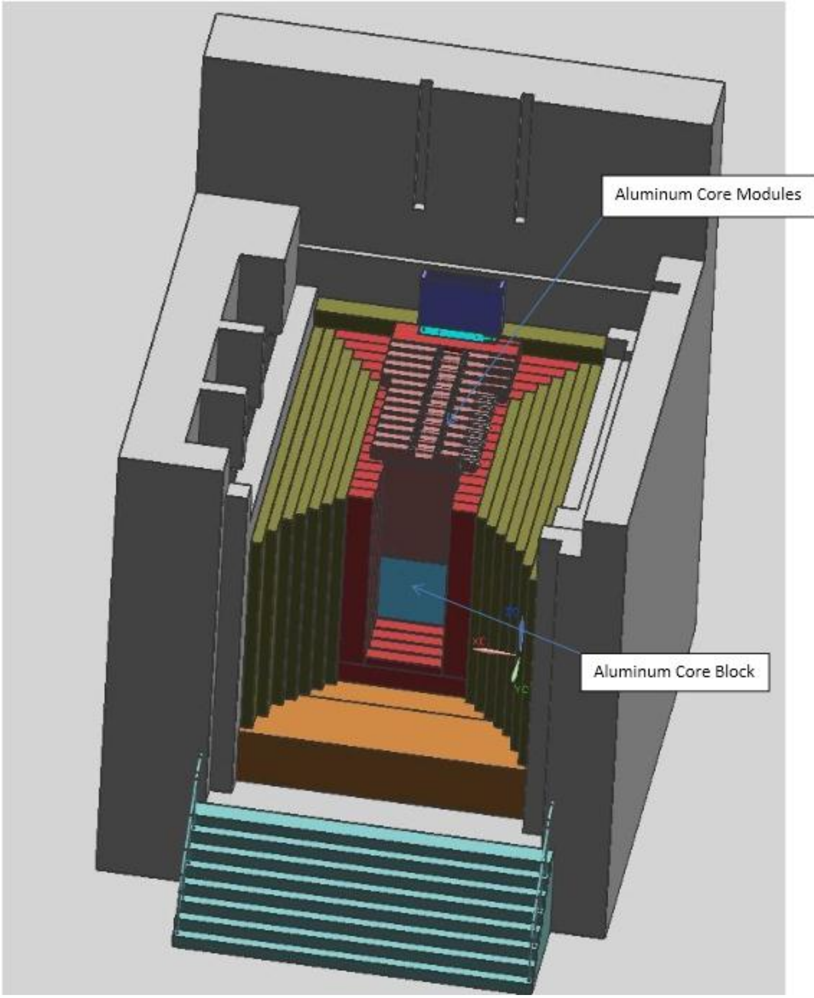


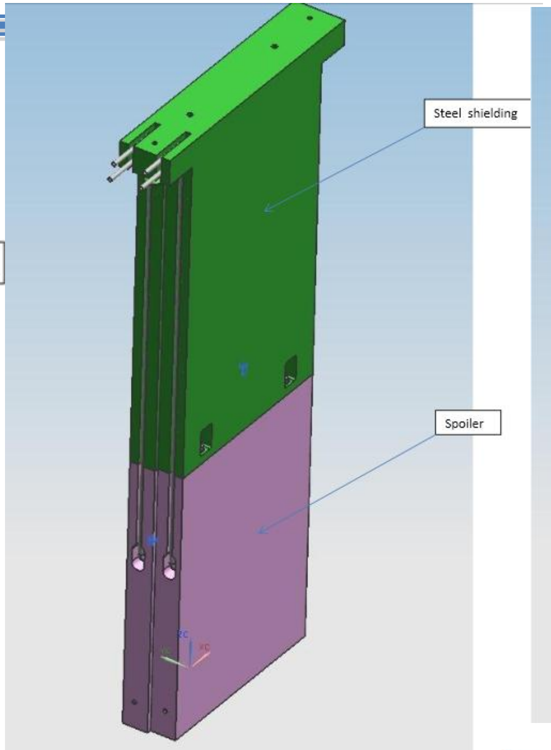


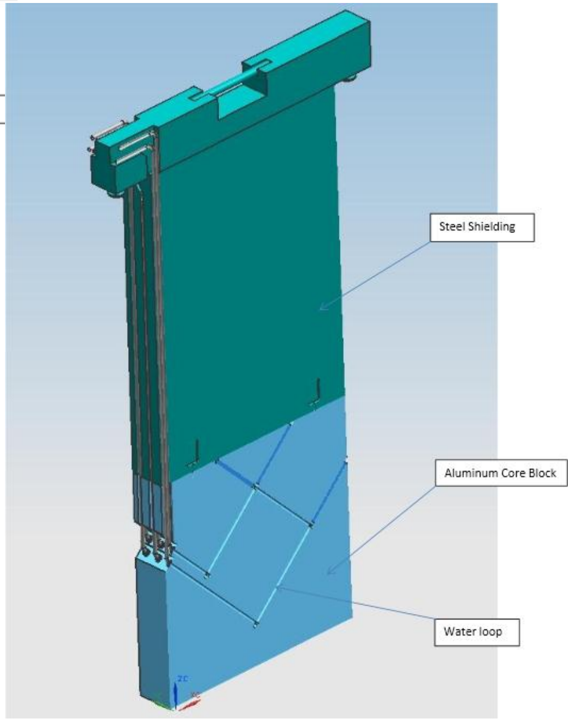
Max Temp 90^{0}C

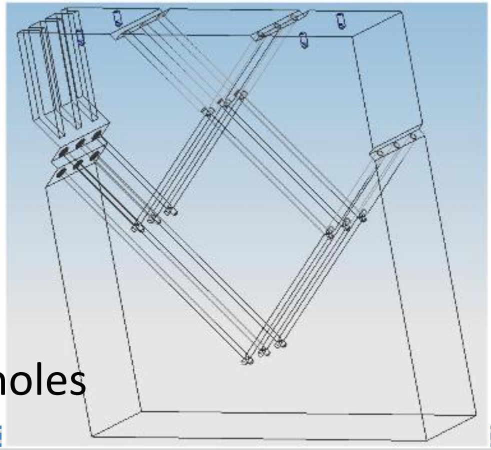
Max Temp 85^{0}C

Absorber Design







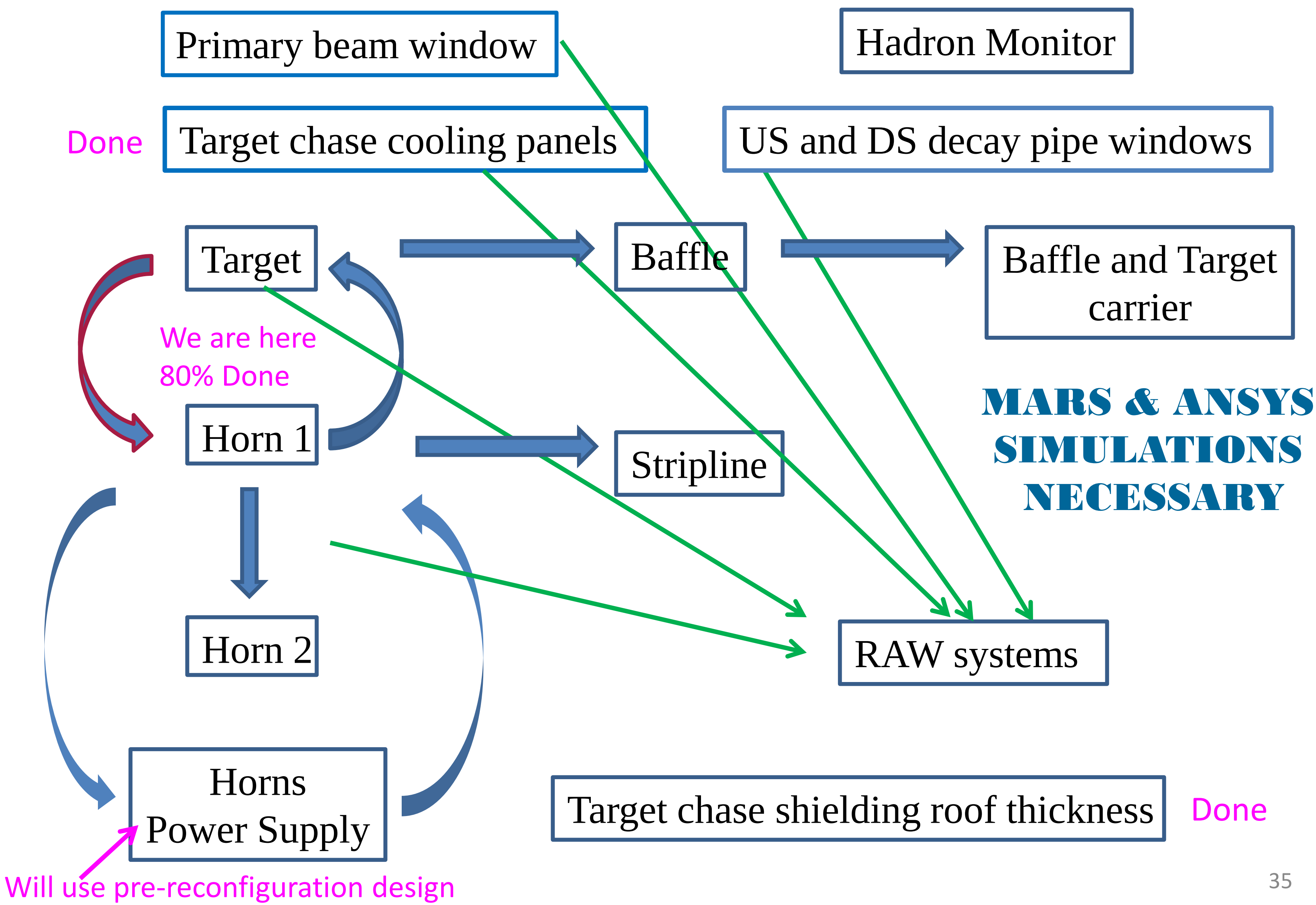


Aluminum core gun drilled holes

What will need to be re-evaluated or replaced at 1.2 MW
Increased collaboration opportunities

- Primary beam window
- Baffle and target, and their carrier
- Horns
- Horn power supply (we were using the NuMI one)
- Horn stripline
- Cooling panels for target chase
- Water cooling at the bottom of support modules for target/baffle and horns
- Upstream decay pipe window in the Helium filled decay pipe
- Raw systems (Target, Horns, Cooling Chase Panels, Absorber, Decay Pipe windows)
- Chillers for air handling and RAW Water systems
- Water evaporators
- Hadron Monitor
- Additional interlock system in the Absorber Hall (on top of thermocouples) to protect from primary beam accident
- Target chase shielding roof thickness
- Radioactive air releases

Sequence of work needed for designing for 1.2 MW



1.2 MW Target/Horn Considerations

- When LBNE was reconfigured in 2012, in order to save money we abandoned our LBNE optimized target and horn designs and opted for NuMI designs with small modifications. (e.g.we were able to verify the NuMI horns up to 230 kA instead of their 200 kA design value).

CD1

	LBNE Sept. 2012	LBNE March 2012
Beam Power	708 kW	708 kW
Horn 1 shape	Double Parabolic	Cylindrical/Parabolic
Horn current	200 kA	300 kA
Target	Modified MINOS (fins)	IHEP cylindrical
Target "Carrier"	NuMI-style baffle/ target carrier	New handler, target attaches to Horn 1

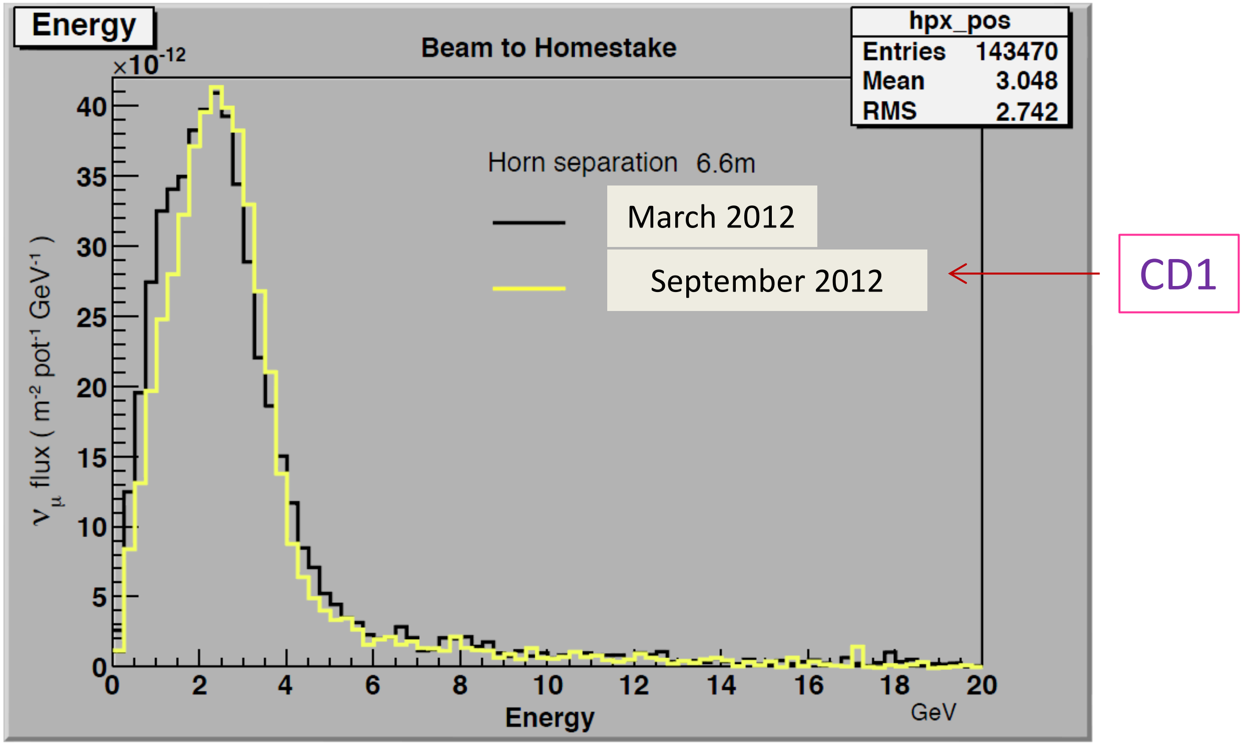
Tunable E_ν spectrum

LBNE CD1 – NuMI like horn 1

LBNE prereconfiguration horn 1

Target/Horn considerations

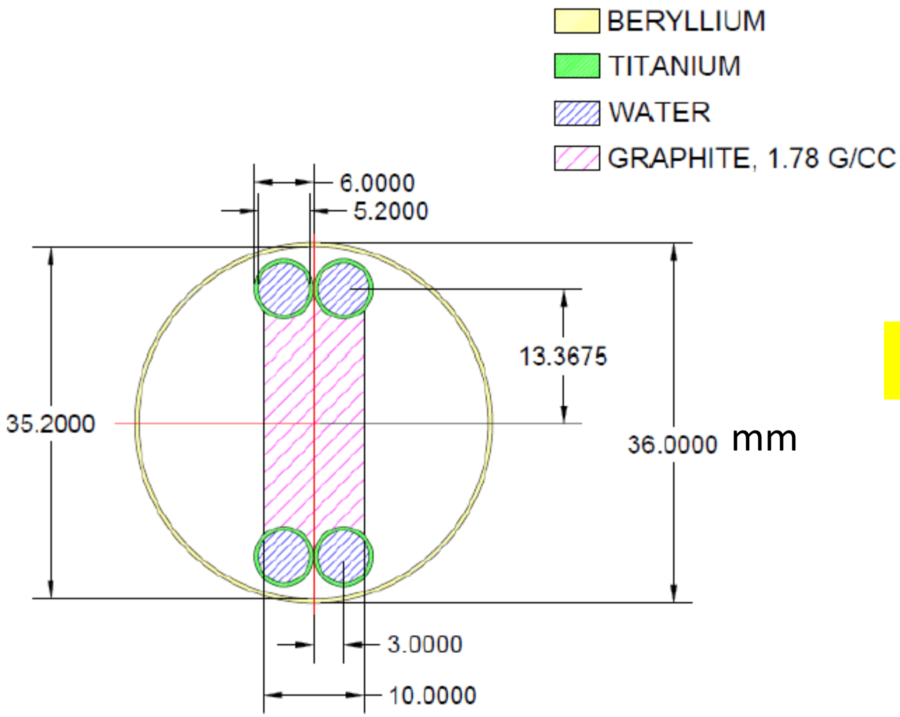
~ 25% less flux on the 2nd oscillation max.
~ 3% more flux on the 1st oscillation max.



1.2 MW Target/Horn Considerations

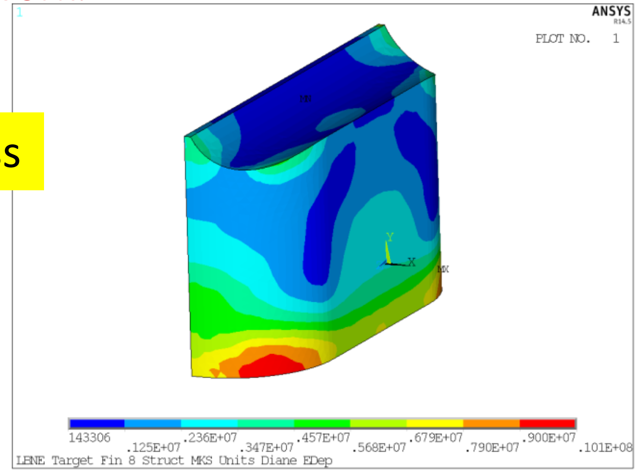
- Our current plan is to check if modest modifications to the CD-1 (NuMI-like) designs can get us to 1.2 MW, minimizing the redesign effort and the increase in cost.(Targets and horns are consumables).
- As a first attempt reduce stress by increasing beam spot size. Use NuMI target as a base but increase the fin width to 10mm and beam sigmas to 1.7mm.
- For the horns try to reduce the joule heating to make room for more beam heating (shorter pulse – cannot use the NuMI power supply).

Preliminary target design for 1.2 MW



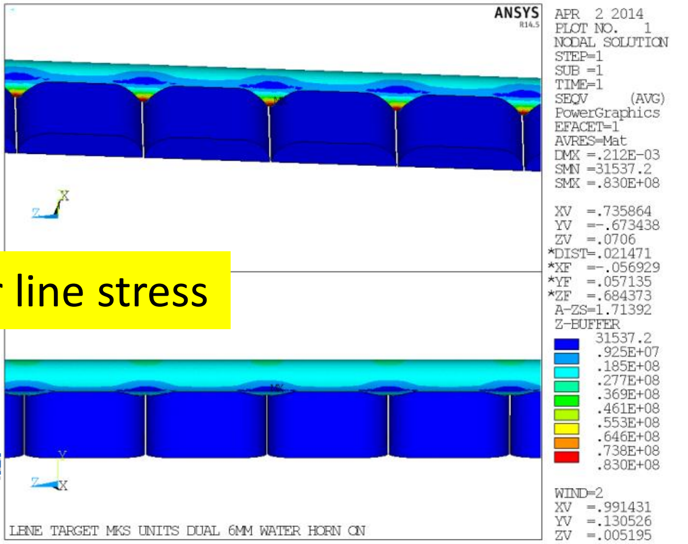
We are simulating this target design and the NuMI horns with MARS and GEANT. It will take a couple more iterations but we see no show stoppers for this design to work.

Graphite fin stress



47 graphite segments, each 2 cm long

Water line stress



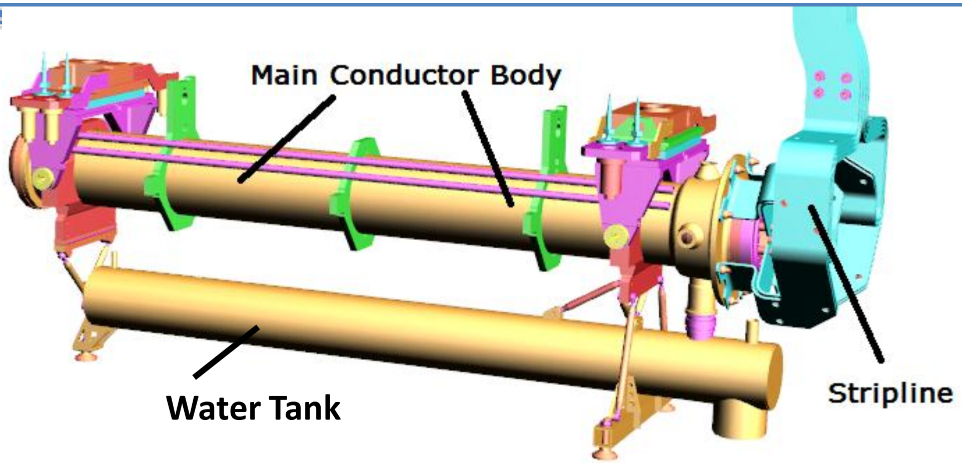
Preliminary target design for 1.2 MW

Target critical safety factors

Location	Material	Stress	Criteria	Safety Factor
Worst Case Fin	Graphite	10.5 MPa	UTS - 80MPa	7.6
Fin, Off-Center Pulse	Graphite	10.1 MPa	UTS - 80MPa	7.9
Water Line, Static	Ti grade 2	83 MPa	Fatigue - 270MPa @ 1e5 cycles, 150C	3.3
Water Line, Pulsed	Ti grade 2	M-126MPa, Alt- 32MPa	Goodman @ 90C (mean temp)	2.4
Can	Beryllium	25.9 MPa	Yield - 218 MPa @ 185C	8.4
Window	Beryllium	27.2 MPa	Yield - 218 MPa @ 185C	8.0

UK/RAL interested in collaborating on the target design (in addition to R&D)

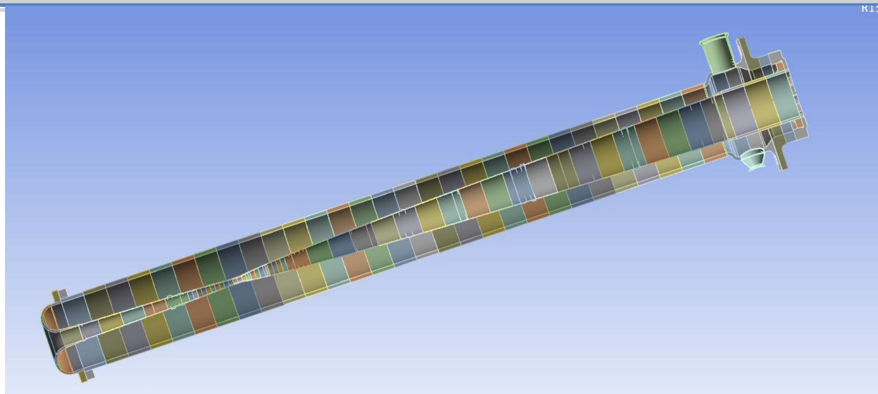
Horn Operation at 1.2MW

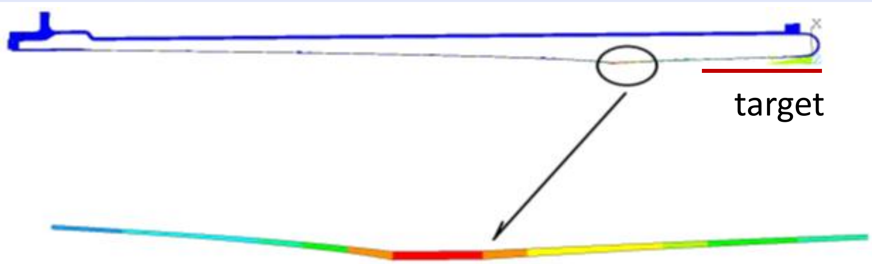


Parameters	700 kW	1.2 MW
Current Pulse Width	2.1ms	0.8ms
Cycle Time	1.33s	1.20s
Horn Current	230kA	230kA
Target Width	7.4mm	10mm
Protons Per Spill	4.9×10^{13}	7.5×10^{13}

- Beam heating and joule heating on horn 1 generate unacceptable power input into the horn inner conductor with the new target design and the NuMI horn power supply (2.1ms pulse width).
- Higher energy depositions from the target can be offset by reducing the current pulse width to 0.8ms (requires a new horn power supply).
- These changes allow the design current to remain at 230kA which is the upper current limit for a NuMI conductor design. We still need to analyze the horn stripline for 230 kA.
- Increasing the radius of horn 1 neck transitions and moving the upstream weld further upstream will bring the safety factors to comfortable levels.

Horn Current Analysis Results





Temperatures	700 kW	1.2 MW
Maximum	61 C	77.5 C
Minimum	37 C	44.5 C
ΔT C	24 C	32 C
Average (Steady State)	48 C	59.4 C

- Increase in temperature range contributes to an increase in stresses.
- These higher stresses affect the Safety Factor (S.F.) of the horn.

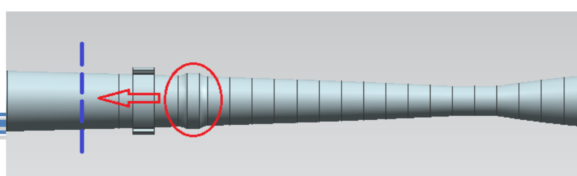
- Two common high stress areas are the Neck and U.S. Weld.
- There are fabrication steps and geometrical changes that can regain lost strength due to higher loading.

Increase radius at neck transition

Move further upstream

Stress Location	700 kW Safety Factor	1.2 MW Safety Factor
Neck	3.55	**2.78** → 4.4
Downstream Weld	6.74	4.94
Upstream Weld	3.20	**2.59** → 3.6
Upstream Transition	5.92	6.12

S. F. of 3 is a good goal

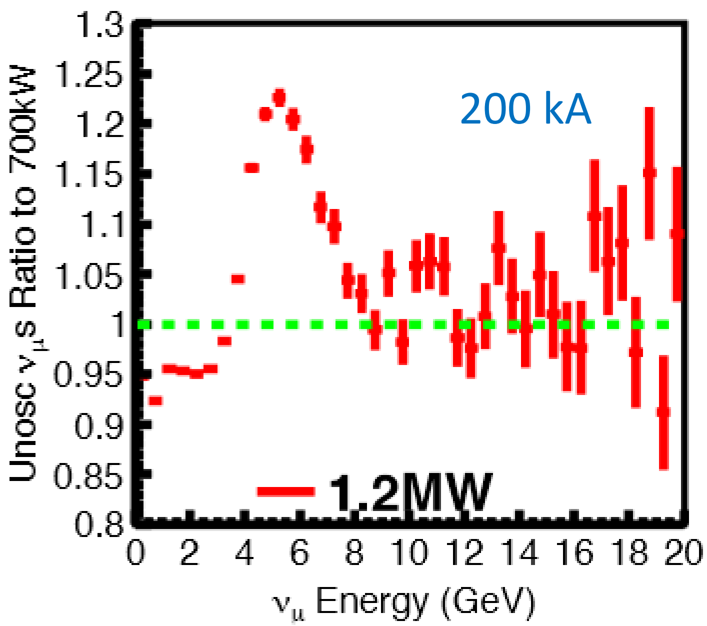


1.2 MW Target/Horn Considerations (Simulations)

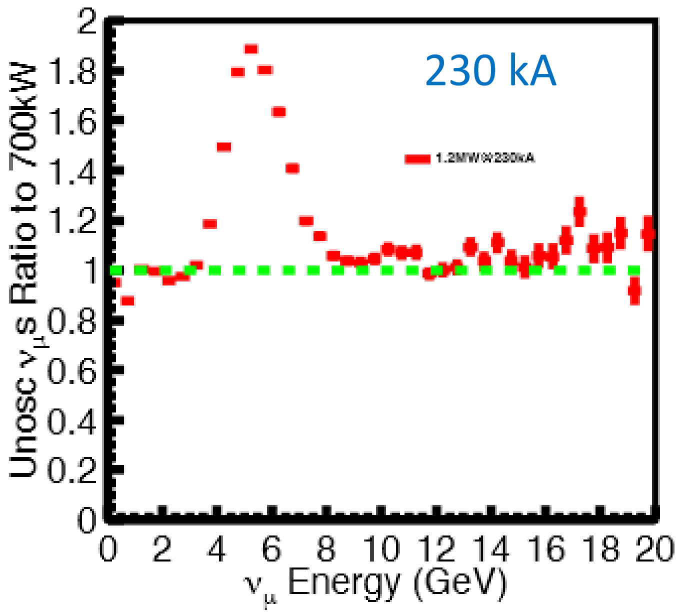
A lot of simulation effort needed

Energy Depositions, radiological:MARS

Physics oriented Beamline optimization: GEANT(MARS cross check)



Retrack target by 10 cm



Increasing the horn current from 200 kA to 230 kA almost cancels the reduction of flux due to retracted target

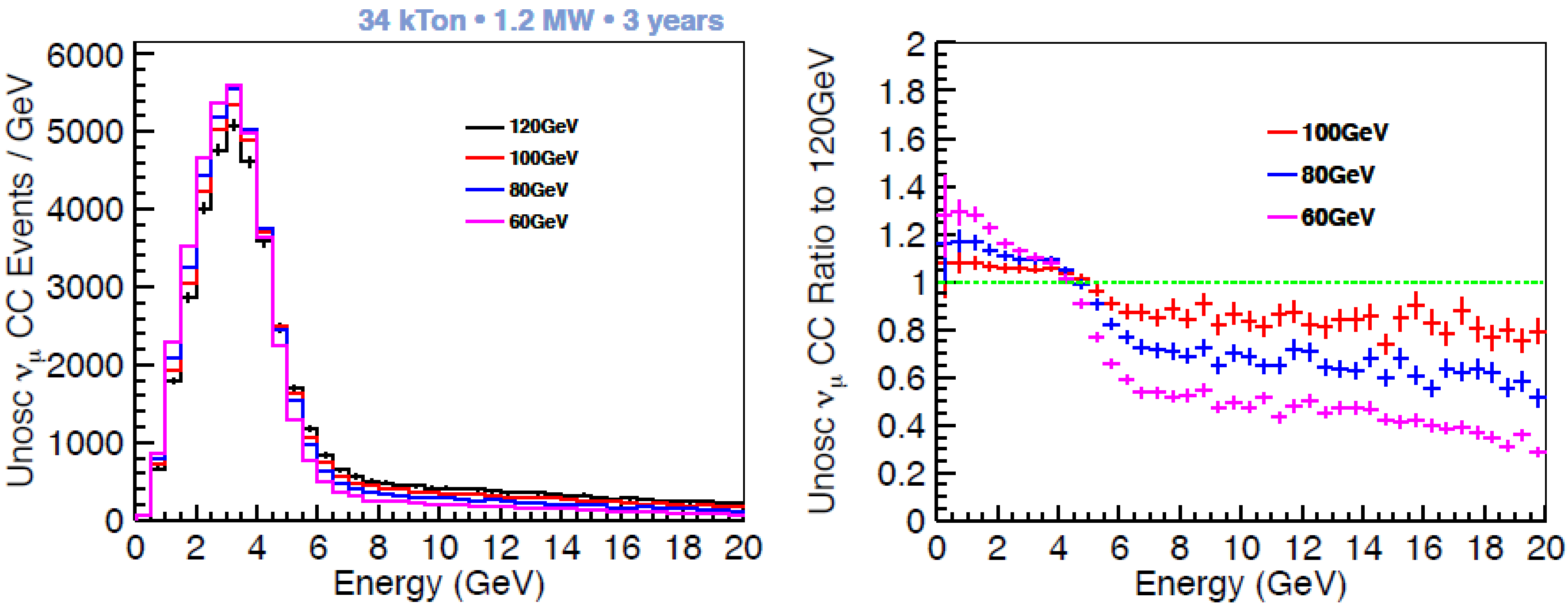
L. Fields

1.2 MW Target/Horn Considerations (Simulations)

A lot of simulation effort needed

Energy Depositions, radiological:MARS

Physics oriented Beamline optimization: GEANT(MARS cross check)



Retrack target by 10 cm

L. Fields

Considered design changes that increase the physics potential

Ratio of $\nu_\mu \rightarrow \nu_e$ CC appearance rates at the far detector

Change	0.5-2.0 GeV	2.0-5.0 GeV	Impact
DK pipe Air → He *	1.07	1.11	~$ 9 M
DK pipe length 200 m → 250 m (4m D)	1.04	1.12	~$ 30 M
DK pipe diameter 4 m → 6 m (200m L)	1.06	1.02	~ $17 M
Horn current 200 kA → 230 kA	1.00	1.12	small
Proton beam 120 → 80 GeV, 700 kW	1.14	1.05	Programmatic impact
Target graphite fins → Be fins Subject of R&D	1.03	1.02	Increase target lifetime
Total	1.39	1.52	

If both $55 M

- Simplifies the handling of systematics as well
- Recently approved

R&D needs (beyond engineering design)

- At 1.2 MW R&D will be needed on:
  - target (materials) – assuming minimal modifications will work
  - horns (2nd generation) – assuming minimal modifications will work

  (Optimization of 2nd generation target/horn configuration to increase flux at the 2nd oscillation max)
  - hadron monitor
- At 2.3 MW additional R&D will be needed on:
  - target (materials, shape, cooling,…)
  - horns
  - hadron monitor
  - primary beam window (only cooling aspects affected by 1.2 MW)
  - Possible impacts on Conventional Facilities

Current Target R&D the project is involved in and partially supports

- Be work: postdoc started in January 2014 at Oxford. Stage 1 literature study final report complete and delivered. Material characterization of unirradiated Be is starting. (RADIATE)
- Beryllium fin test: radiation damage studies that were proposed for ANU/NOvA (3 fins out of 50) were approved. Thermal contact test completed. Ready to install.
- Beryllium thermal shock testing at CERN's HiRadMat Facility expected in December 2014-February 2015. Oxford materials team integrated. Will use advanced microscopy to characterize material before and after beam test.
- Graphite: A new resistivity testing fixture designed and is being manufactured.(RADIATE)

High power target materials R&D

RaDIATE Collaboration

Fermilab
Pacific Northwest National Laboratory
University of Oxford
Science & Technology Facilities Council
Brookhaven National Laboratory

addresses radiation damage in several high power target candidate materials aiming to determine useful lifetimes (includes graphite and beryllium)

High Intensity Beam Single Pulse Test @ CERN's HiRadMat Facility

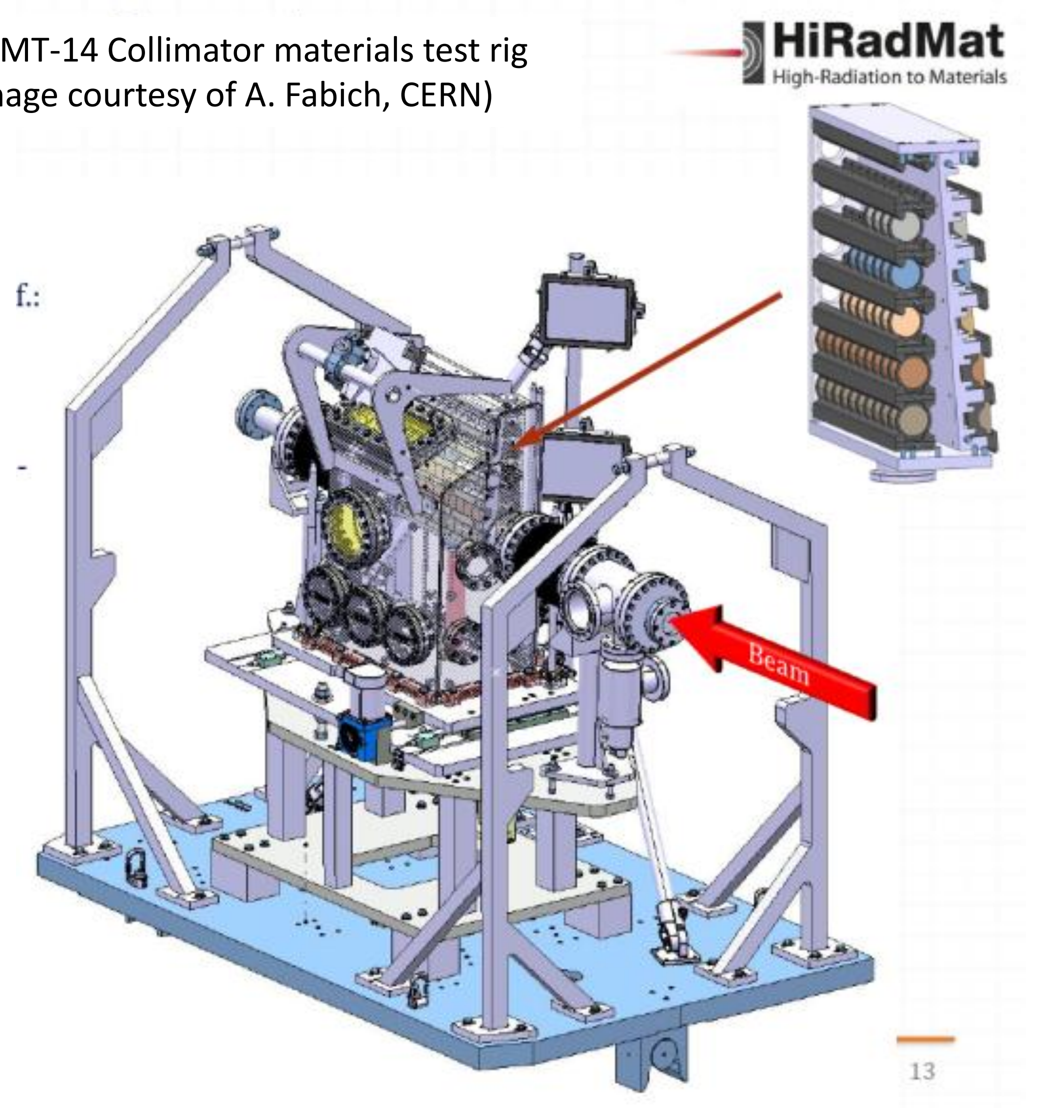
explore the onset of failure modes (crack initiation, fracture) of various beryllium grades/forms exposed to a high intensity, highly focused beam at the CERN SPS

High Intensity Beam Single Pulse Test at CERN's HiRadMat Facility

Planning to do single pulse beam tests on Be (and possibly other materials) for application to targets and beam windows

- Proton beam capabilities:
  - up to 4.9e13 ppp
  - 440 GeV
  - 0.1 mm – 2.0 mm sigma radius
- Test on Be windows/targets to detect:
  - Onset of plastic deformation (Diff. Image. Corl., strain gauge)
  - Fracture (DIC, leak detection, high speed camera)
  - Effect of mis-steered beam (DIC, strain gauge, leak detection)
  - Beam induced resonance (Strain gauge, LDV, High speed camera)
- May also use previously irradiated Be

HRMT-14 Collimator materials test rig (image courtesy of A. Fabich, CERN)

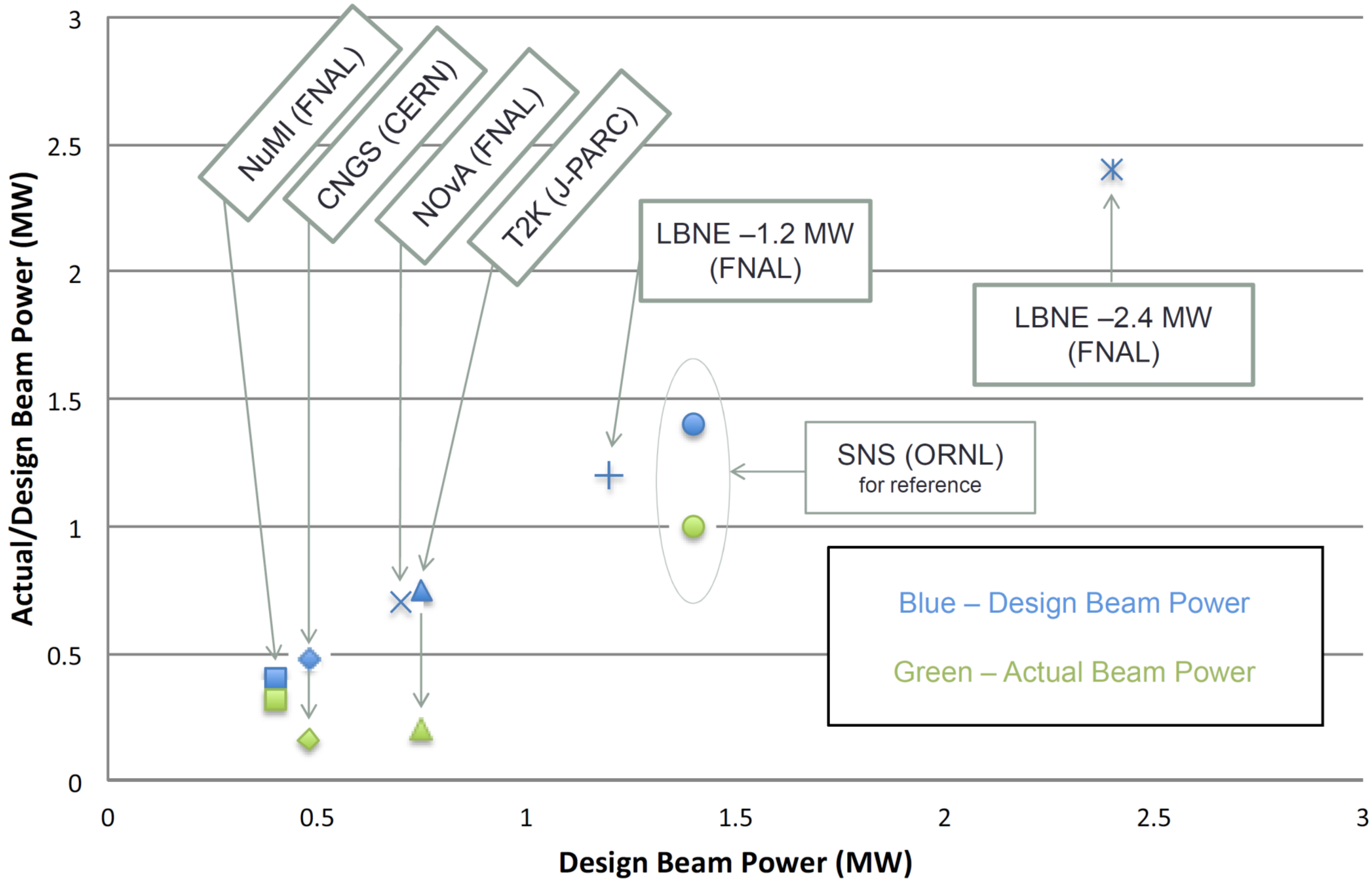


Conclusions

- Significant progress with preliminary design effort in many Beamline systems including systems that have to accommodate new scope.
- Lots of opportunities for collaboration on the design of specific Beamline components as well as on beam simulations and R&D efforts.
- We are excited and looking forward to design and build this Beamline working together with many of you and with all our international partners!!

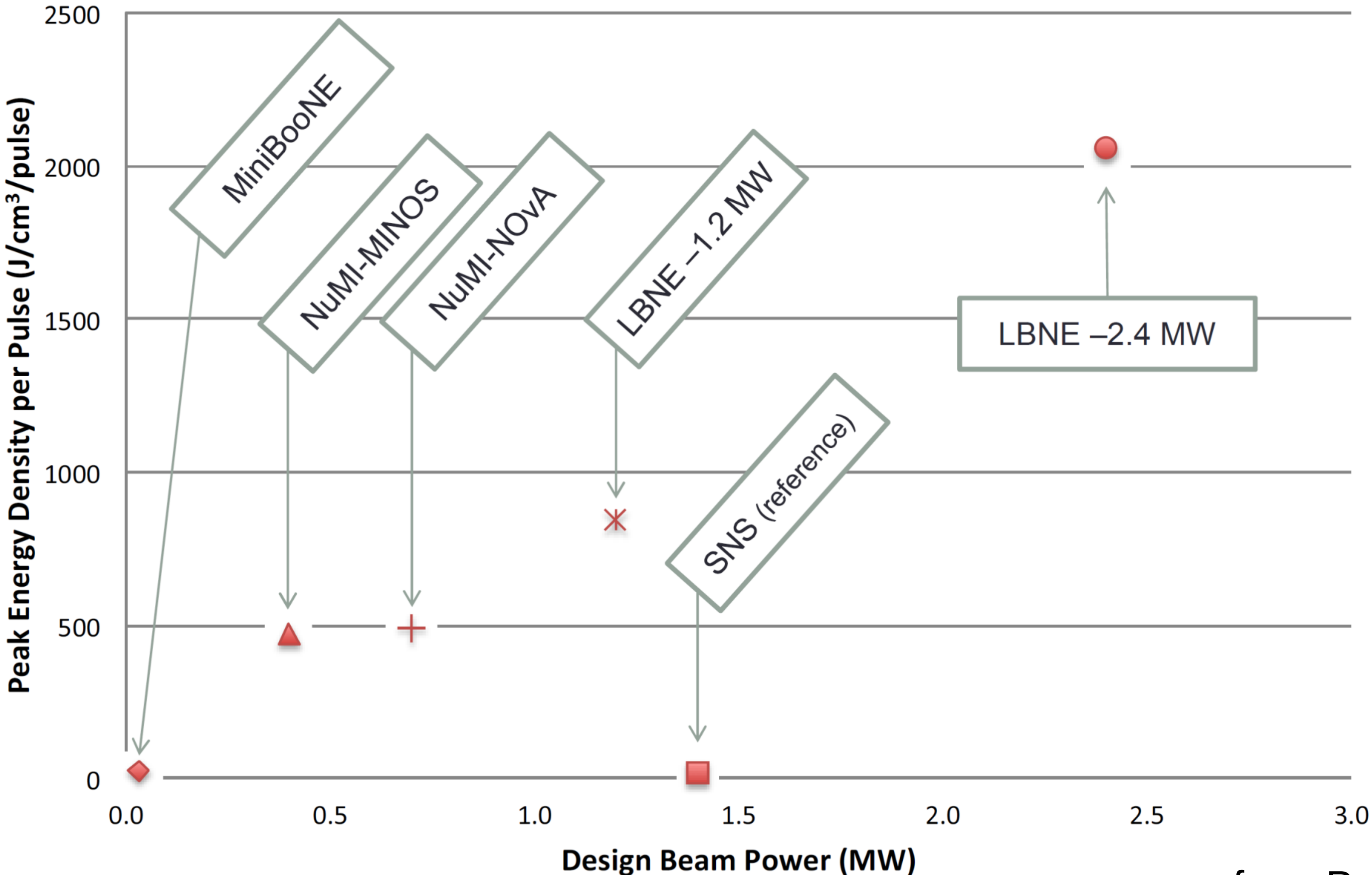
BACKUP

Neutrino Target Facility Comparison



from P. Hurh

Thermal Shock in FNAL Neutrino Program



from P. Hurh

Pre-reconfiguration design of the target system with double layer cooling (Accord with IHEP/Protvino)

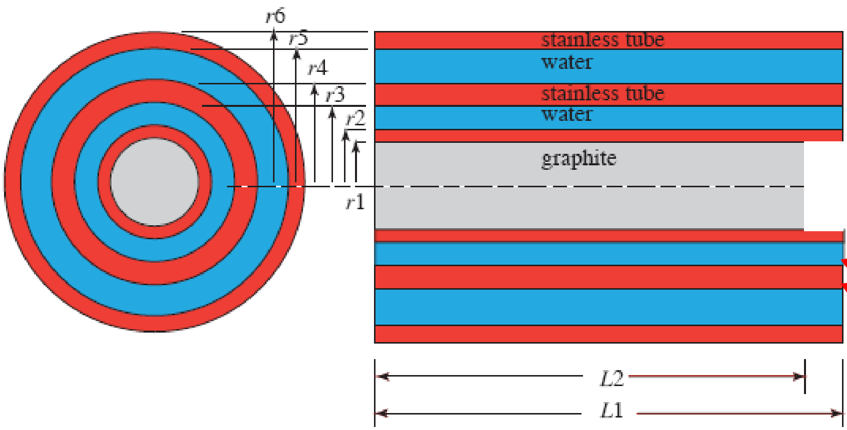


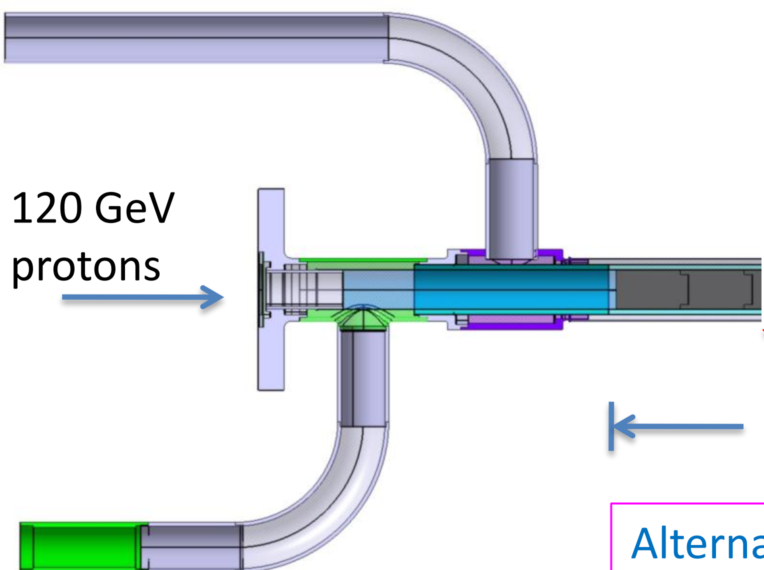
Figure 1. Target Assembly

Final report: LBNE Doc 2423, Sept. 2012

Target material: POCO ZXF-50 graphite

Radial thickness (mm)	
IHEP design	
7.65	graphite
0.3	stainless
1.7	water
0.3	stainless
2.2	water
0.3	stainless
12.45	**Total**

120 GeV protons



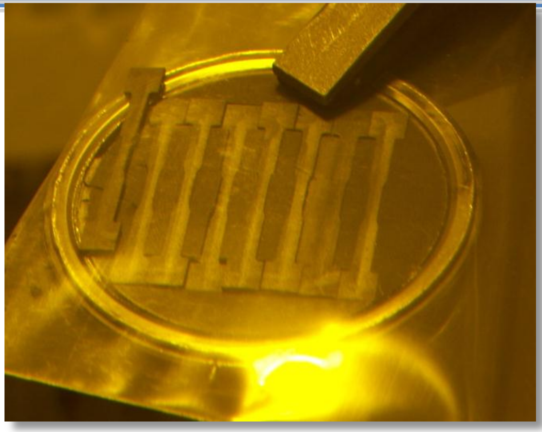
95cm

A row of 15.3 mm diameter and 25 mm length graphite segments separated by 0.2 mm gaps.

Alternatives: Other graphites, C-C composite, HBN, Be, etc.

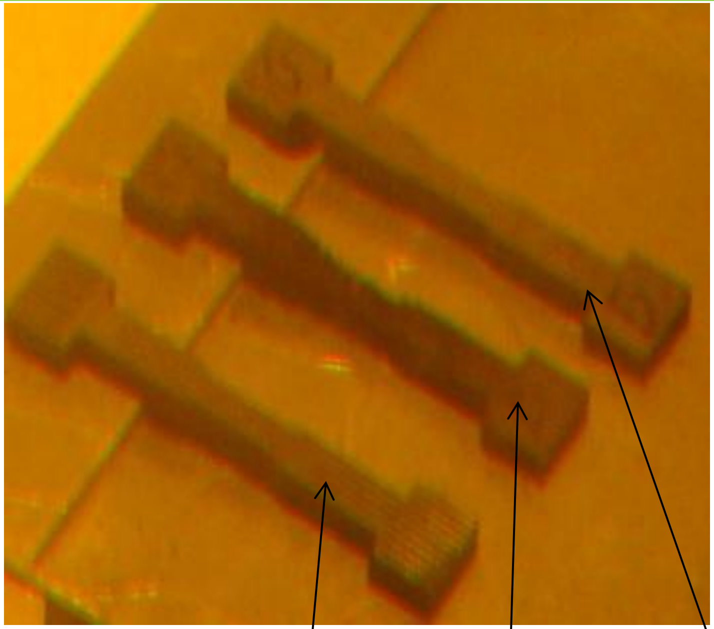
Target Samples from BLIP test

Irradiation damage in water-cooled 3D carbon composite LBNE candidate target samples irradiated at BLIP.



- Peak integrated flux about 5.9e20 proton/cm^2
- Average over 1 sigma area about 4.6e20 proton/cm^2
- ~ 150 tensile samples tested

The HBN samples lost a lot of mass (30-50)% and were very weak and brittle



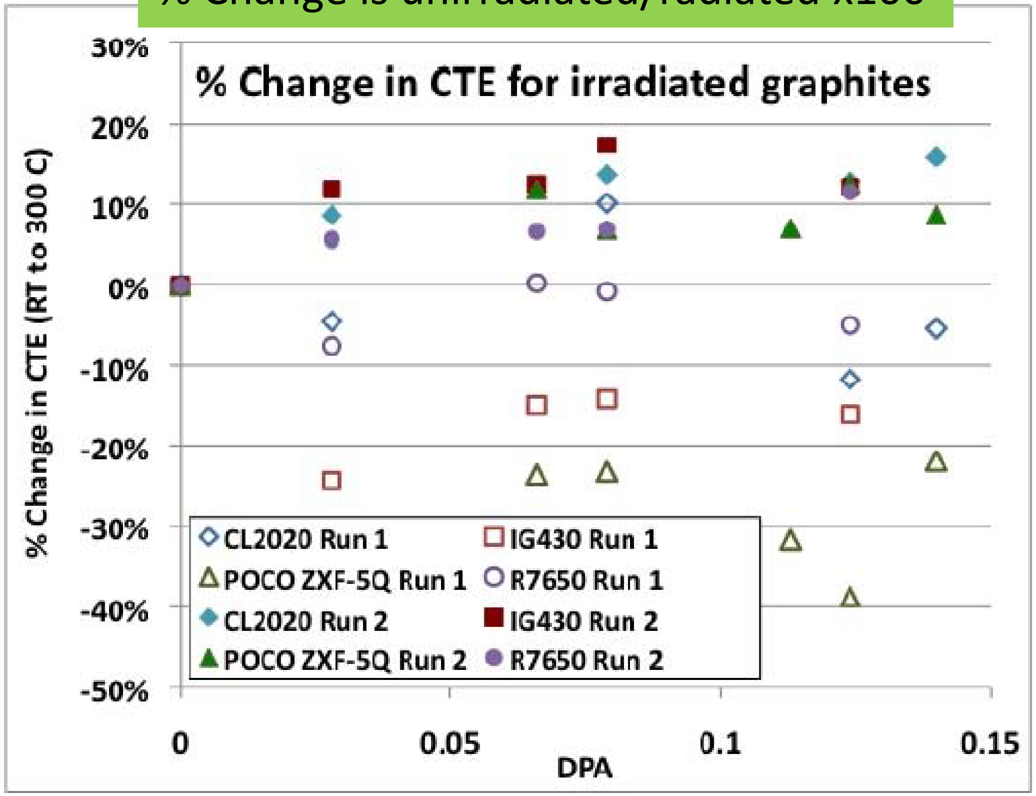
Argon environment

Un-irradiated

Water-cooled

BLIP test results and recommendations
(an example of some of results below – tensile properties also explored)

% Change is unirradiated/radiated x100

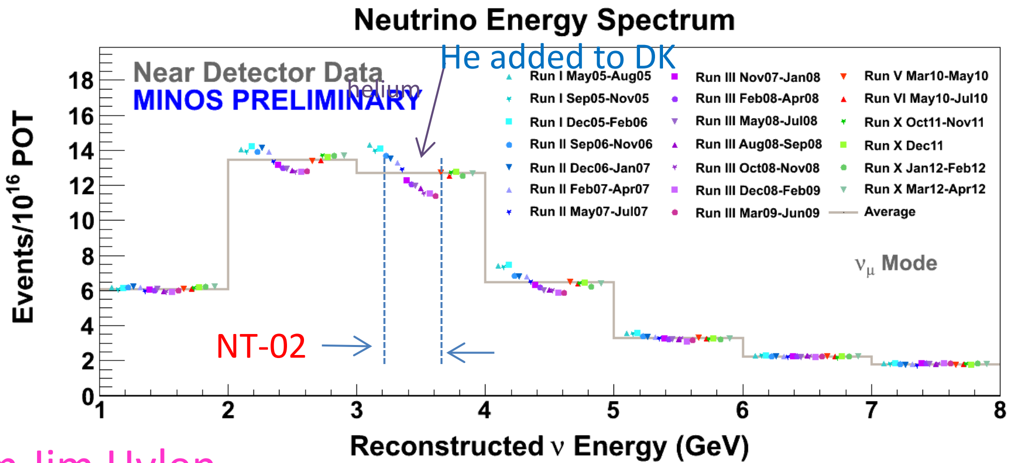


Comparison of change in coefficient of thermal expansion (20-300°C) for graphite samples during two consecutive thermal cycles after irradiation. Open symbols: first cycle; Filled symbols: second cycle

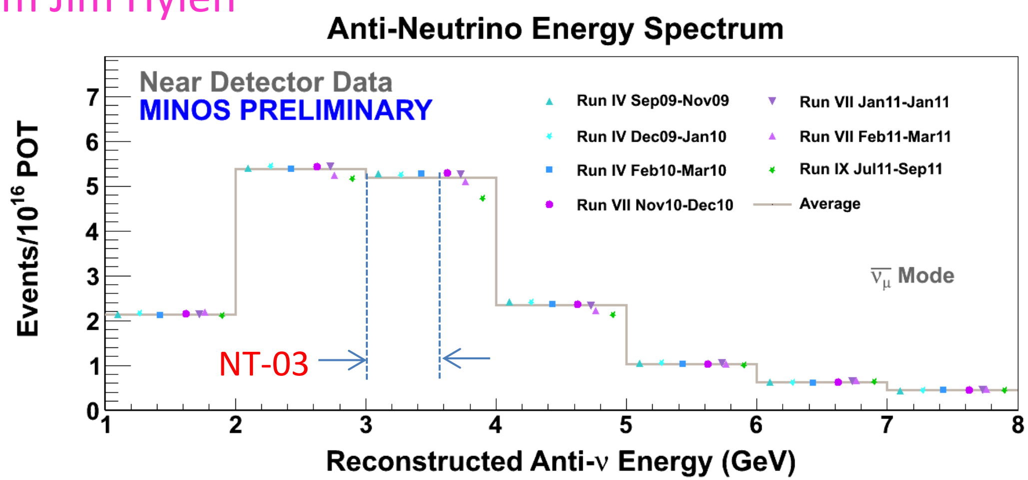
R7650 graphite shows the smallest negative change in CTE before annealing but all graphites exhibit a 10% higher CTE after annealing

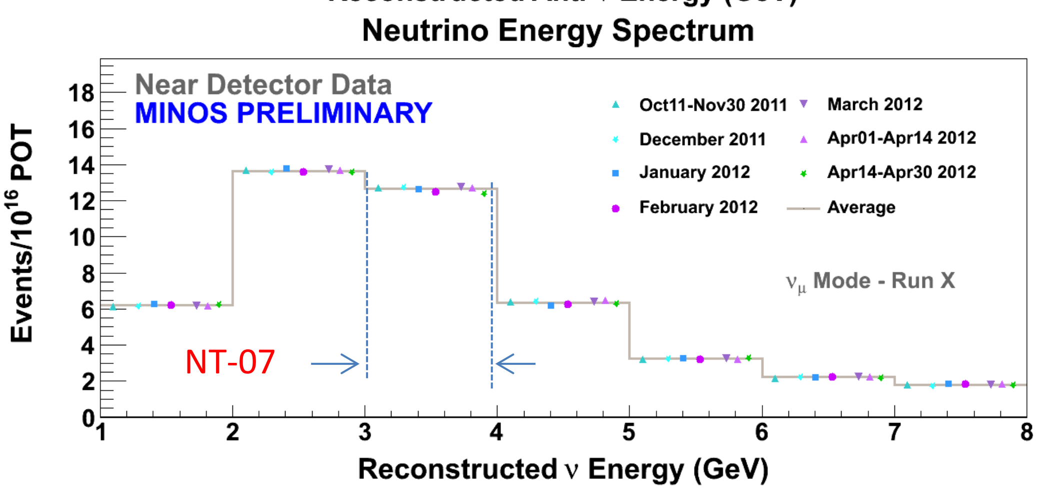
In February 2013 the final report (LBNE doc 5724) was completed . The studies confirmed that out of the seven materials tested, the LBNE default target material (POCO ZXF-5Q graphite) is the best choice on the basis of strength and coefficient of expansion after irradiation. Also promising was the Toyo Tanso IG-430 graphite used in the second T2K target. A Carbon-Carbon composite material (3D weave) was partially tested and looks promising as well.

ZXF5Q Graphite core degradation



From Jim Hylen





NT-02

10% - 15% ν decrease

over 6.1e20 POT

radiation damage ? (~ 1 DPA)

or oxidation, or ... ?

plan to autopsy next year

NT-03

No indication of degradation

over 1.8e20 POT

(anti-nu 9/29/2009 - 3/22/2010)

NT-07

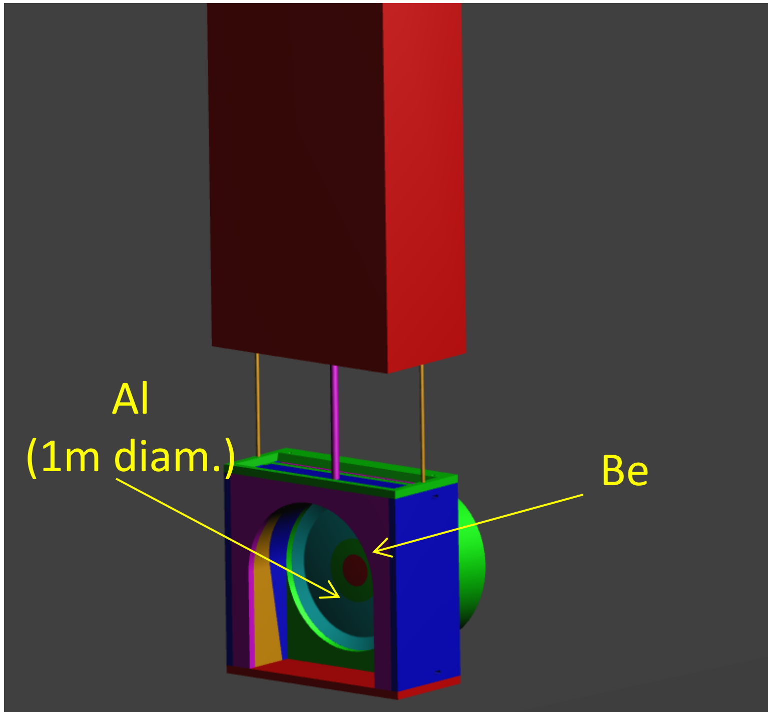
No indication of degradation

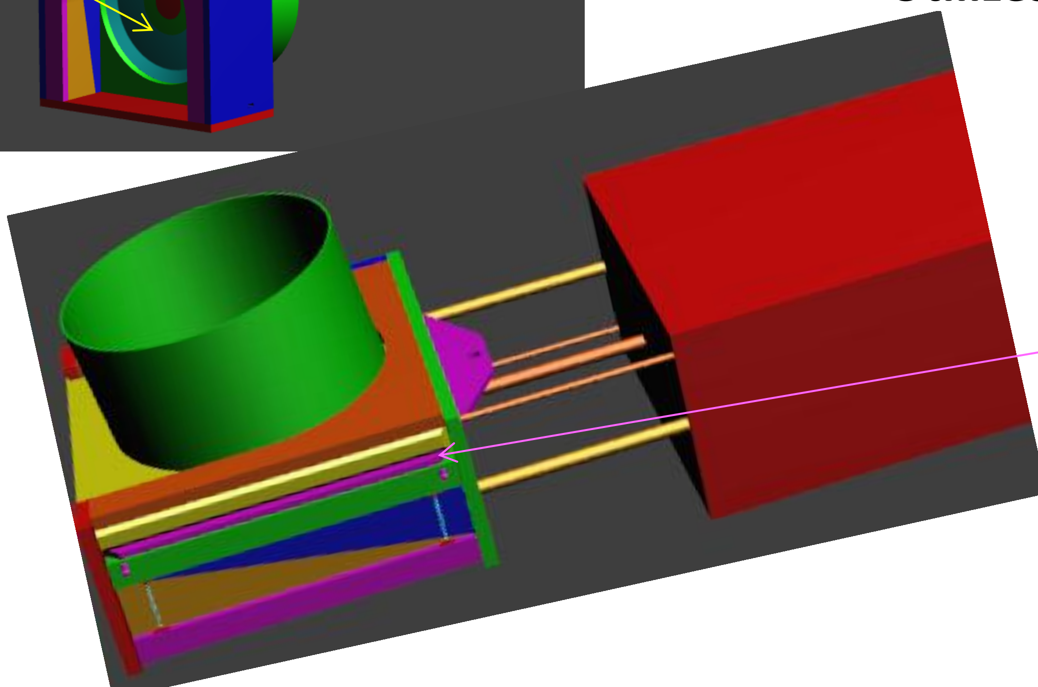
over 2.6e20 POT

Why does later graphite appear more robust ?

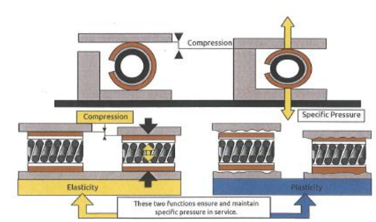
Current Concept for Replaceable Decay Pipe Window

- Shows functional details only - screw drive actuator will be incorporated in top plate and driven with module-thru rods
- Water cooling plates not shown
- Most hardware anodized aluminum
- Utilizes Helicoflex Seal

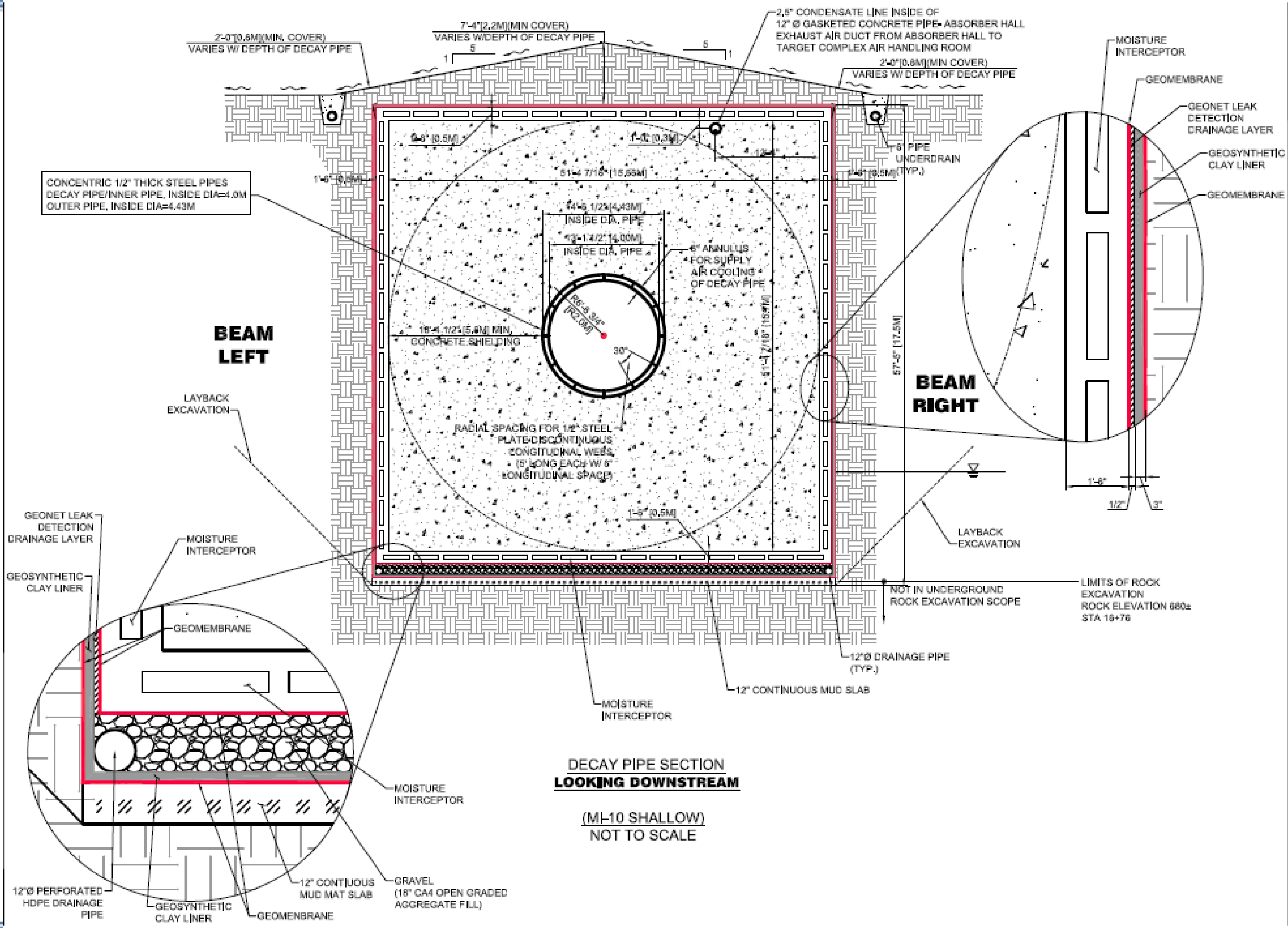




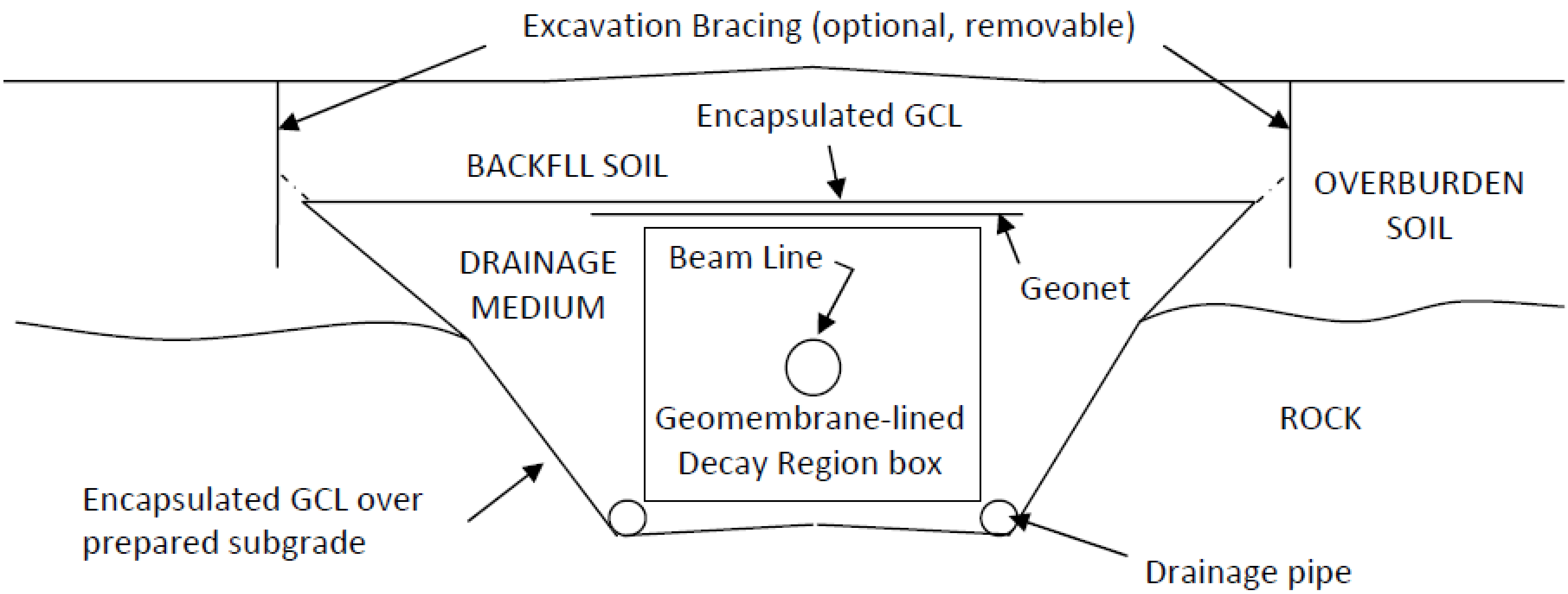
The sealing principle of the HELICOFLEX® family of seals is based upon the plastic deformation of a jacket of greater ductility than the flange materials. This occurs between the sealing face of a flange and an elastic core composed of a close-wound helical spring. The spring is selected to have a specific compression resistance. During compression, the resulting specific pressure forces the jacket to yield and fill the flange imperfections while ensuring positive contact with the flange sealing faces. Each coil of the helical spring acts independently and allows the seal to conform to surface irregularities on the flange surface. This combination of elasticity and plasticity makes the HELICOFLEX® seal the best overall performing seal in the industry.



Decay Pipe Cross Section – Reference Design



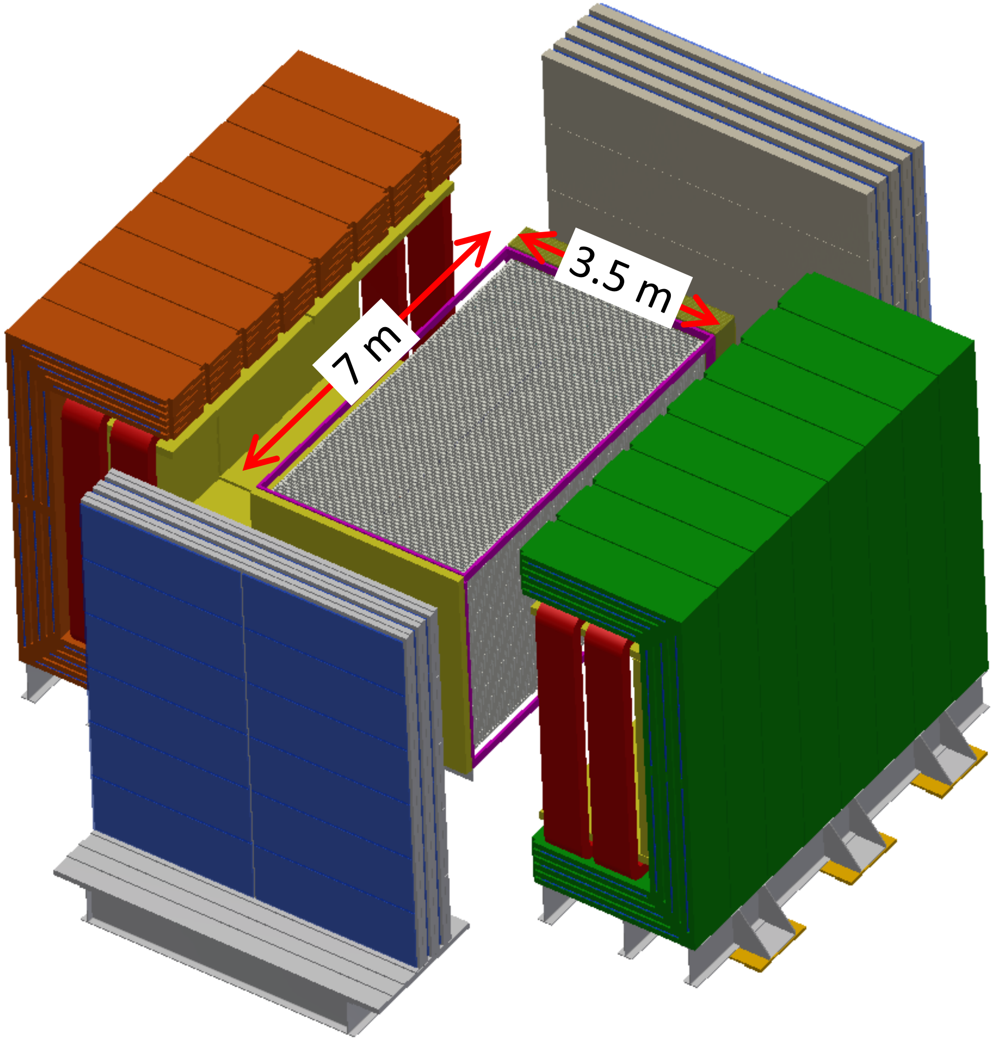
Alternate Design - Edward Kavazanjian, Consulting Engineer LBNE docdb # 4419



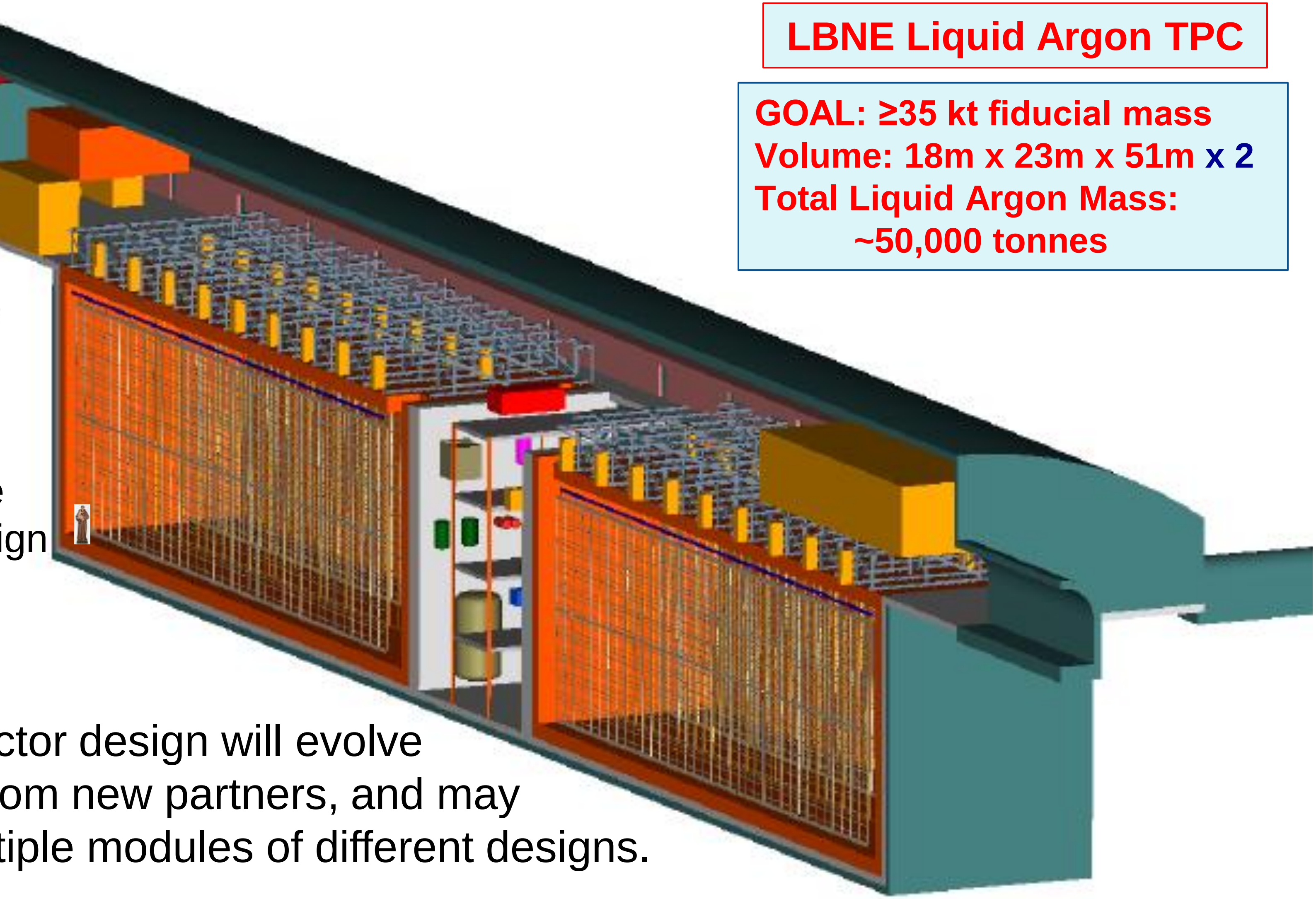
- Outer barrier layer constructed with industry standard methods
- Independent inner and outer barrier layers
- Minimizes potential for through-going defect
- **We look towards combining features from both the Reference and Alternate designs.**

Near Neutrino Detector

- Proposed by collaborators from the Indian institutions
- High precision straw-tube tracker with embedded high-pressure argon gas targets
- 4π electromagnetic calorimeter and muon identification systems
- Large-aperture dipole magnet

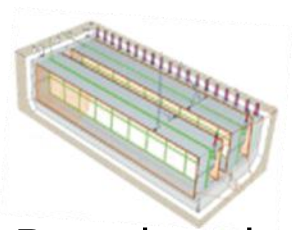


Far Detector



LBNE Liquid Argon TPC

GOAL: ≥35 kt fiducial mass
Volume: 18m x 23m x 51m x 2
Total Liquid Argon Mass:
~50,000 tonnes



Based on the ICARUS design

Actual detector design will evolve with input from new partners, and may involve multiple modules of different designs.