Design of the LBNF Neutrino Beamline

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US-Japan Workshop on Accelerators and Beam Equipment for High-Intensity Neutrino Beams

November 9, 2016

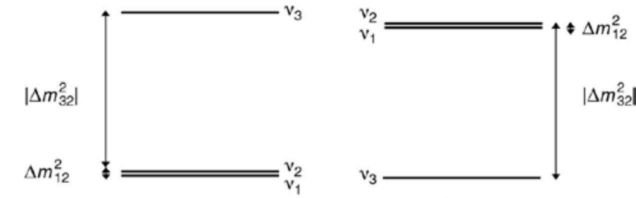
Outline

- LBNF/DUNE scientific goals
- LBNF Beamline Overview
- Recent engineering progress in various areas of the Beamline work
  - Progress on the optimization effort
    - Horns
    - Target
    - Impacted systems
  - Progress in other areas
    - Target chase atmosphere (air releases, inert gas)
    - Beam windows
- Schedule and milestones
- Conclusion

LBNF/DUNE Science Goals

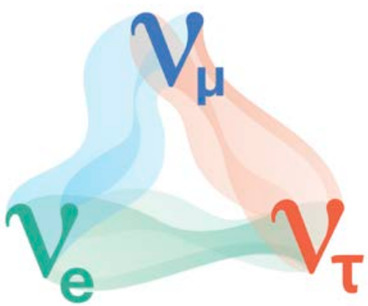
In a single experiment

LBNF/DUNE 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

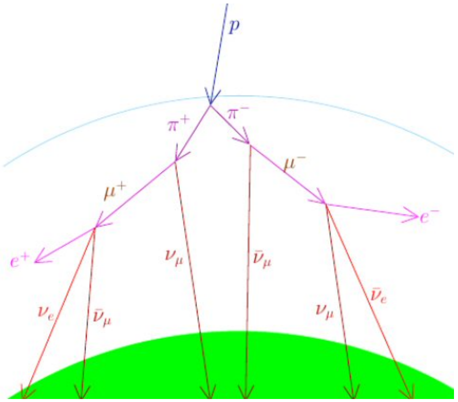
Start data taking ~ 2026



LBNF/DUNE Science Goals

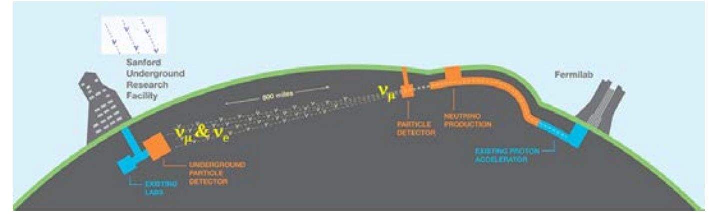
LBNF/DUNE is a comprehensive program to:

- Study other fundamental physics enabled by a massive, underground detector
  - Search for nucleon decays (reveal a relation between the stability of matter and the Grand Unification of forces?)
  - Measurement of neutrinos from galactic core collapse supernovae (peer inside newly-formed neutron stars and potentially witness the birth of a black hole?)
  - Measurements with atmospheric neutrinos

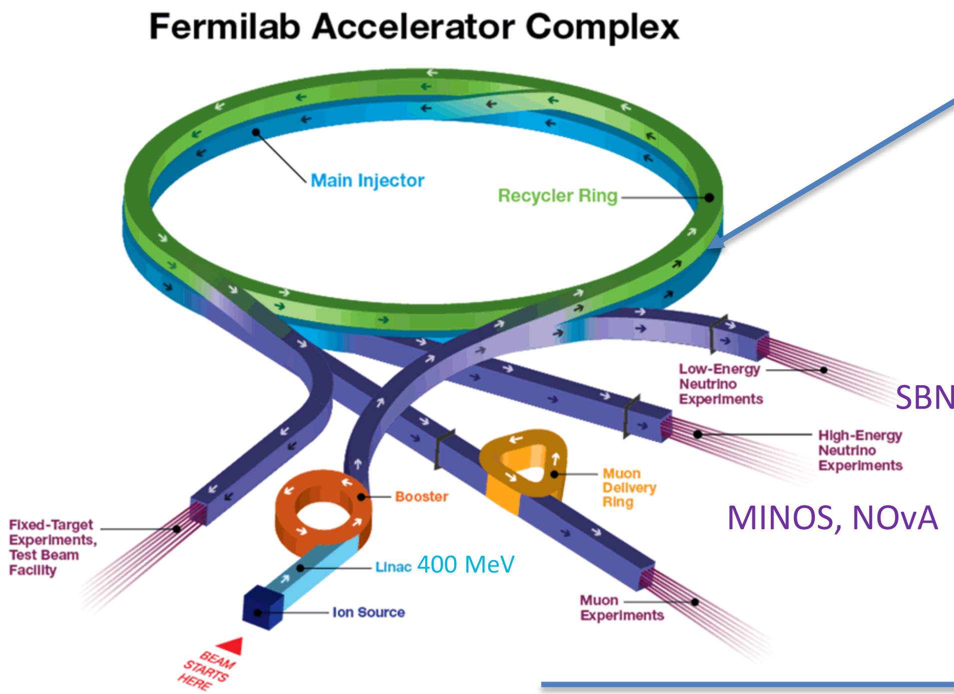


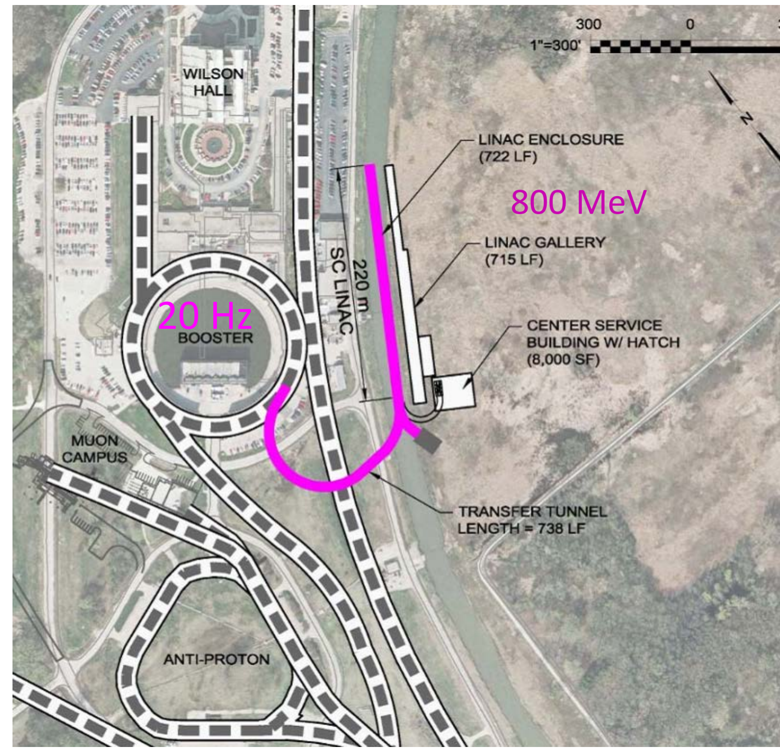
Start data taking ~ 2024

Fermilab Accelerator Complex



LBNF proton beam extracted from MI-10 straight section





701 kW on the NuMI/NOvA target in one supercycle on June 13, 2016!!

Proton Improvement Plan (PIP)

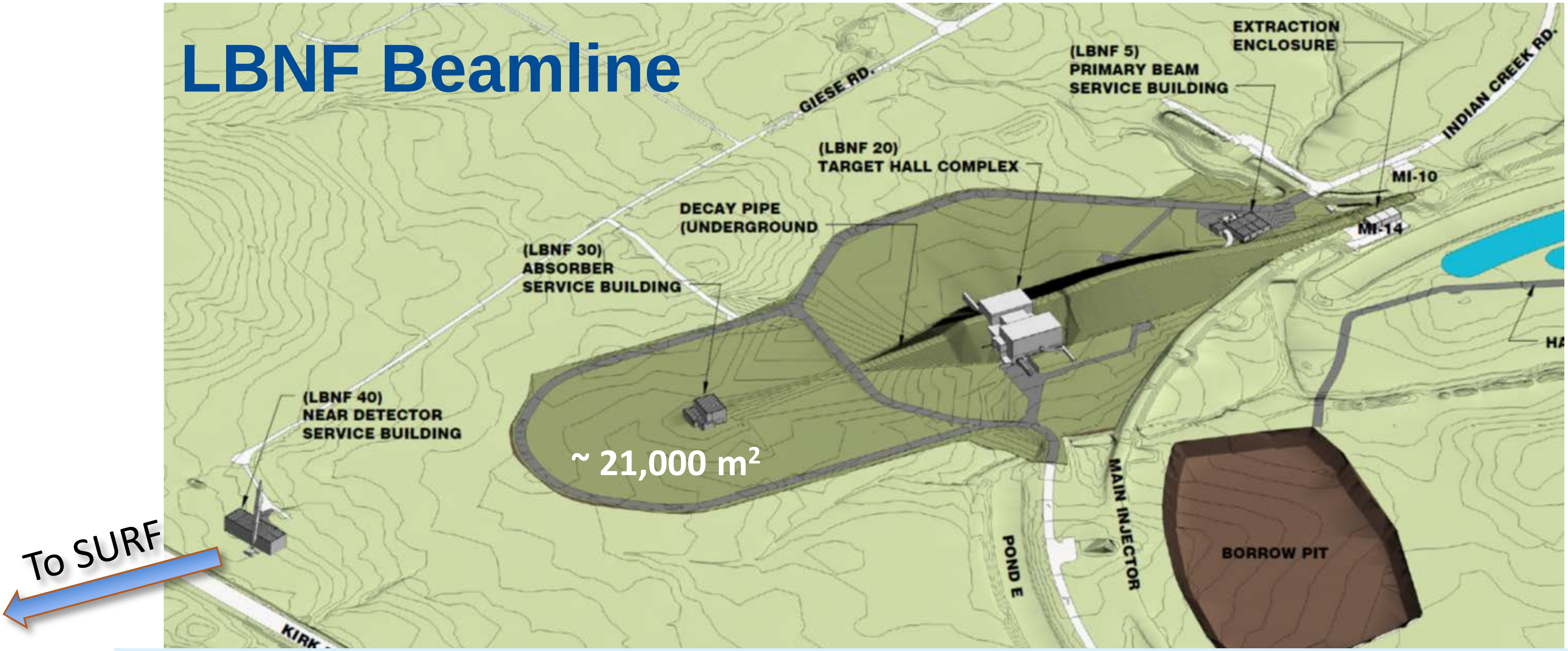
After Nov. 2016 expect to run at ~ 700 kW on a continuous basis

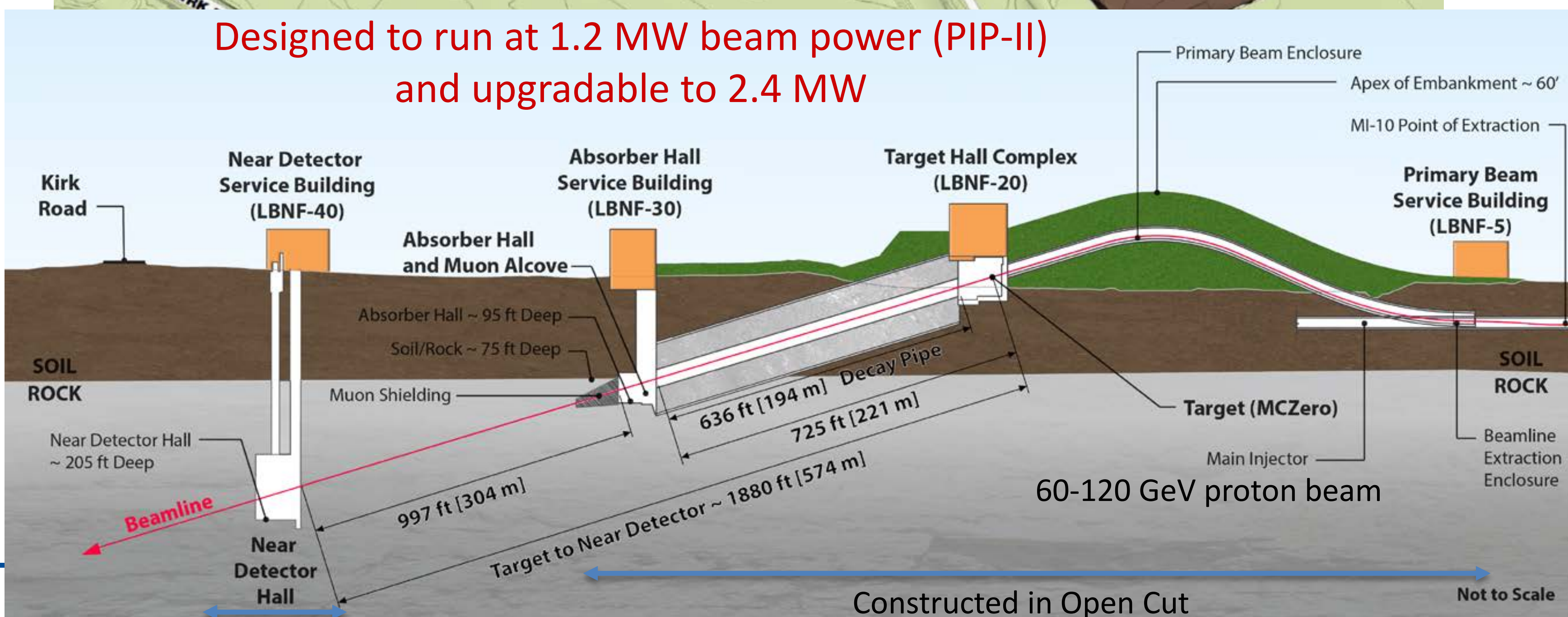
PIP-II ~ 2025

1.2 MW @ 120 GeV

100+ kW @ 800 MeV

LBNF Beamline

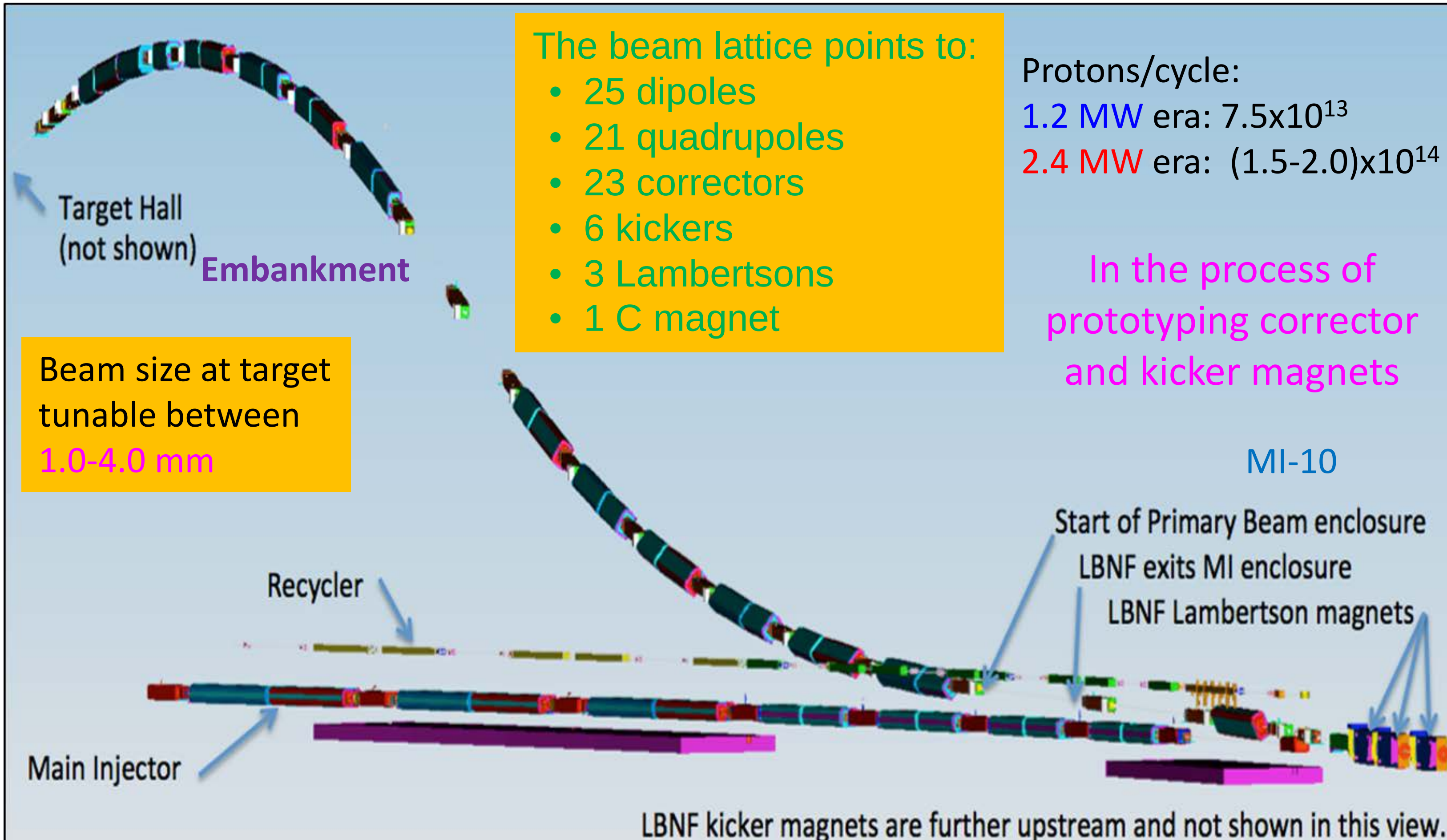




Tunneled excavation

Primary Beamline

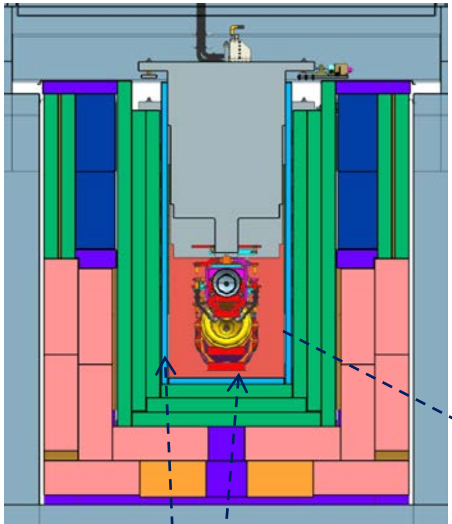
Primary beam designed to transport high intensity protons in the energy range of 60 - 120 GeV to the LBNF target, with repetition rate of 0.7-1.2 sec, and 10 μs pulse duration

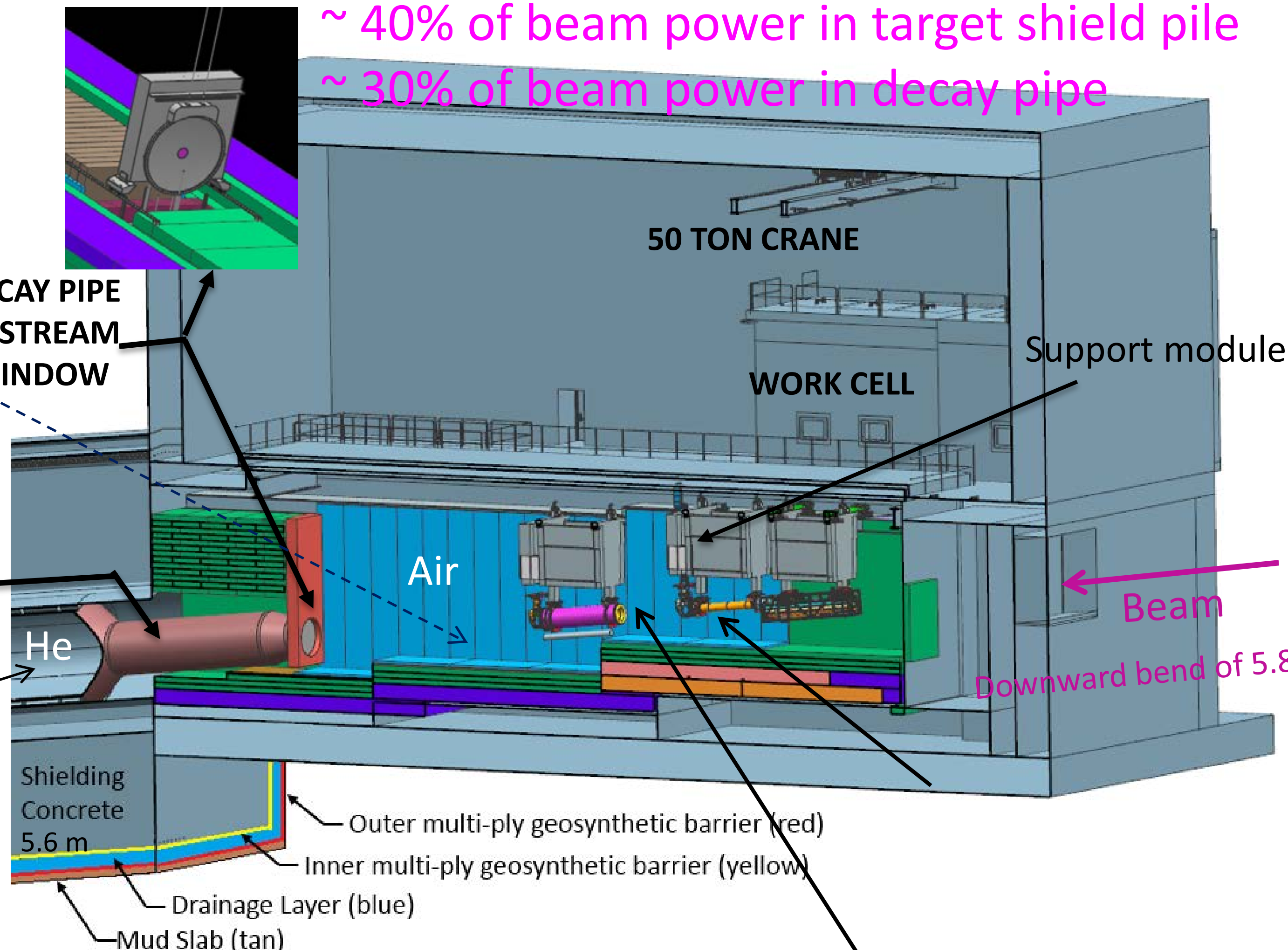


Target Hall and Decay Pipe Layout

~ 40% of beam power in target shield pile

~ 30% of beam power in decay pipe





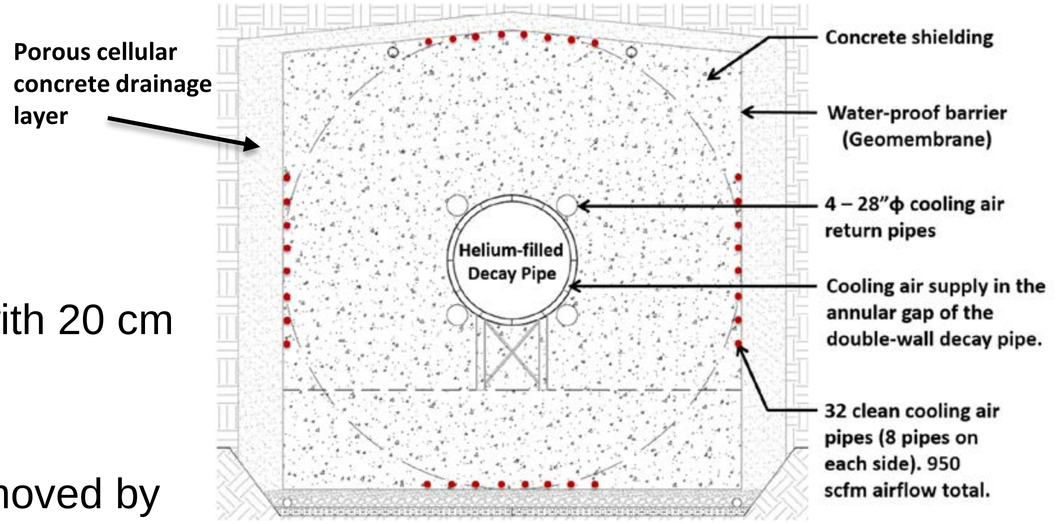
Decay Pipe: 194 m long, 4 m in diameter, double – wall carbon steel, helium filled, air-cooled.

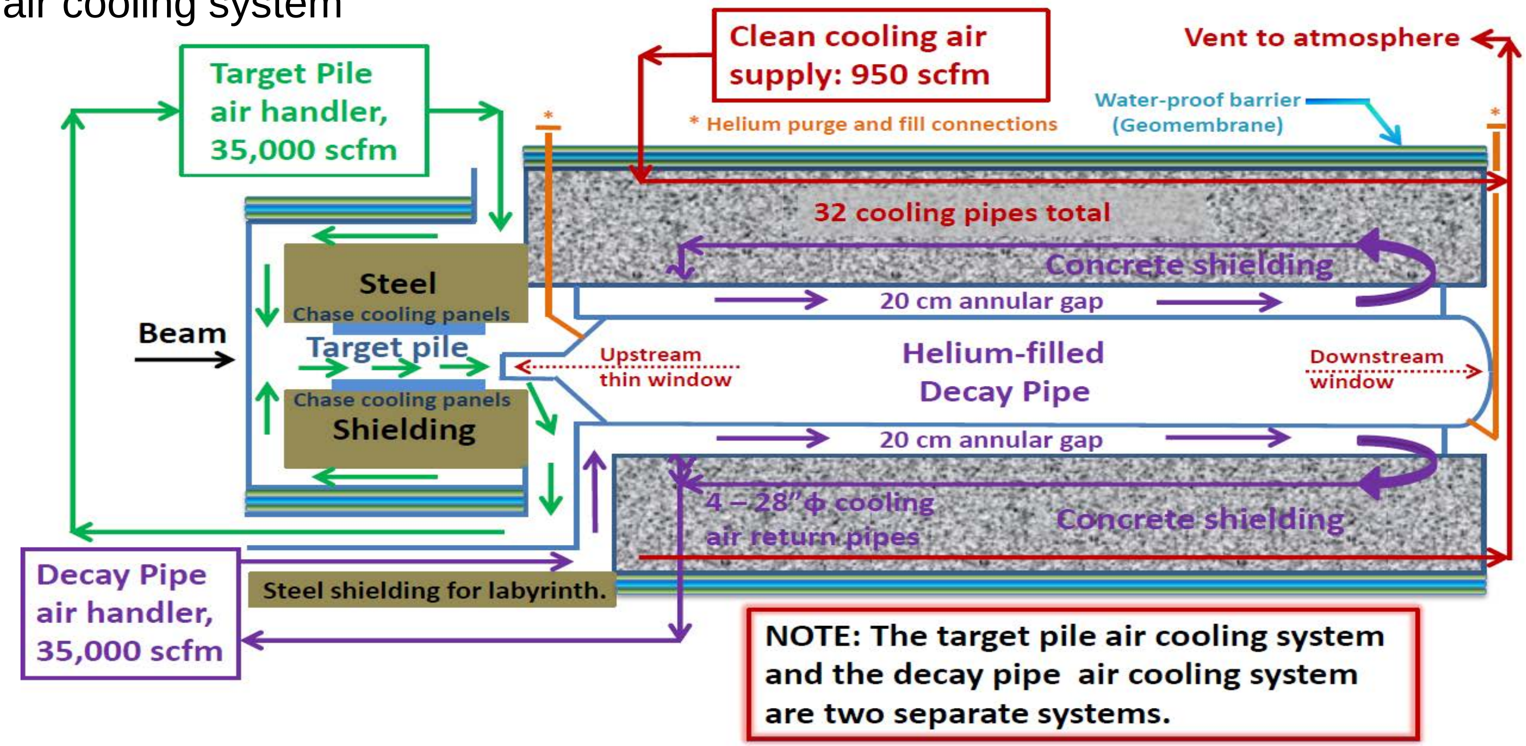
Main alternatives for Chase gas atmosphere: N_2 or He

Target Chase: 2.2 m/2.0 m wide, 34.3 m long air-filled and air & water-cooled (cooling panels). Sufficiently big to fit in alternative target/horns.

Decay Pipe Layout

- 194 m long, 4 m inside diameter
- Helium filled
- Double-wall, carbon steel decay pipe, with 20 cm annular gap
- 5.6 m thick concrete shielding
- It collects ~30% of the beam power, removed by an air cooling system





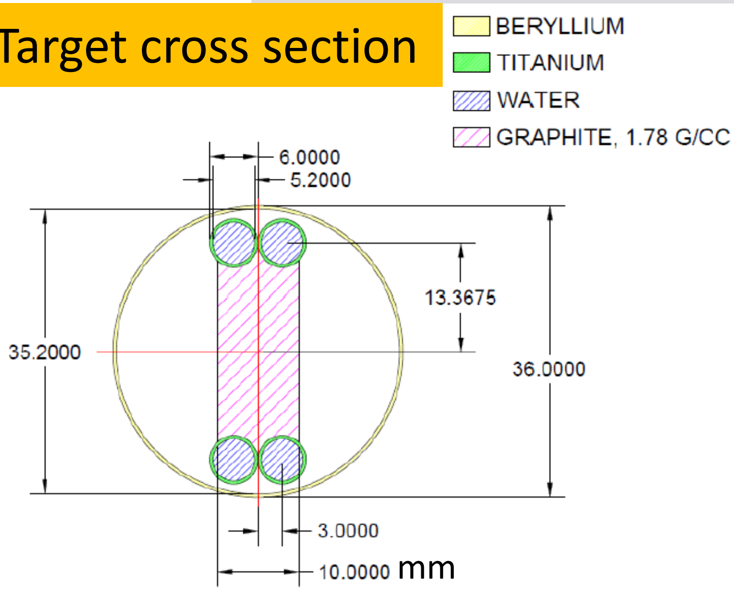
1.2 MW reference design target and horns

47 graphite target segments, each 2 cm long

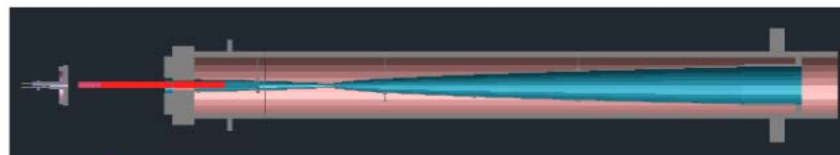
0.2 mm spacing in between
Two interaction lengths, 95 cm
First few fins have "wings", 26 mm disks

NuMI-like (low energy) with modest modifications target and (two) horns

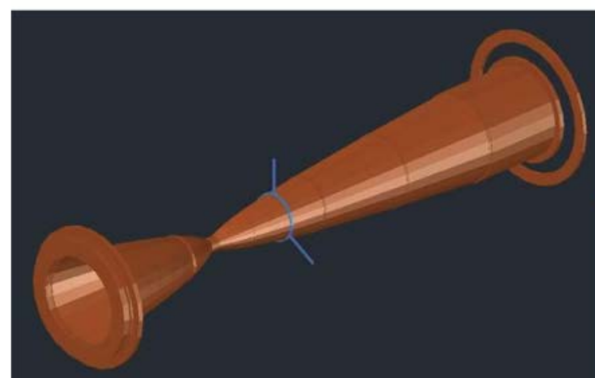
Target cross section



Operated at 230 kA for LBNF



Horn 1

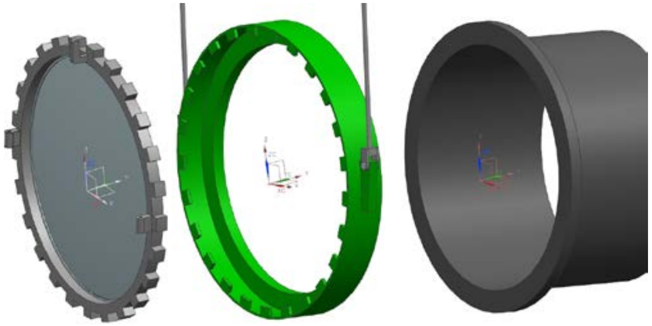


Horn 2 (Inner Conductor)

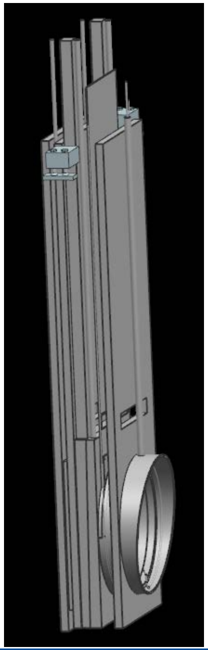
New Horn power supply needed - reduced pulse width of 0.8 ms.

Upsteam Beam Window Concepts

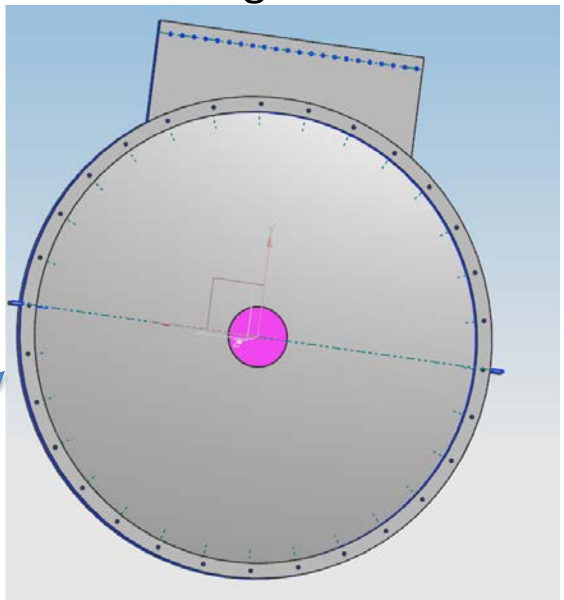
Autoclave with rotating ring



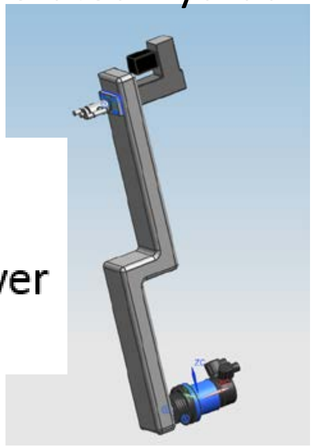
Pressured slabs

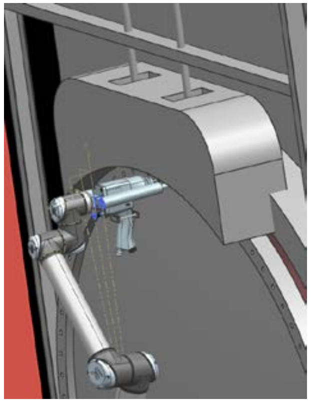


Bolted Flange Connection



Remotely operated Hydraulic Wrench





Consider Use of a flange with multiple bolts to apply load to the seal and restrain the force from the pressure over the window area.

Hadron Absorber

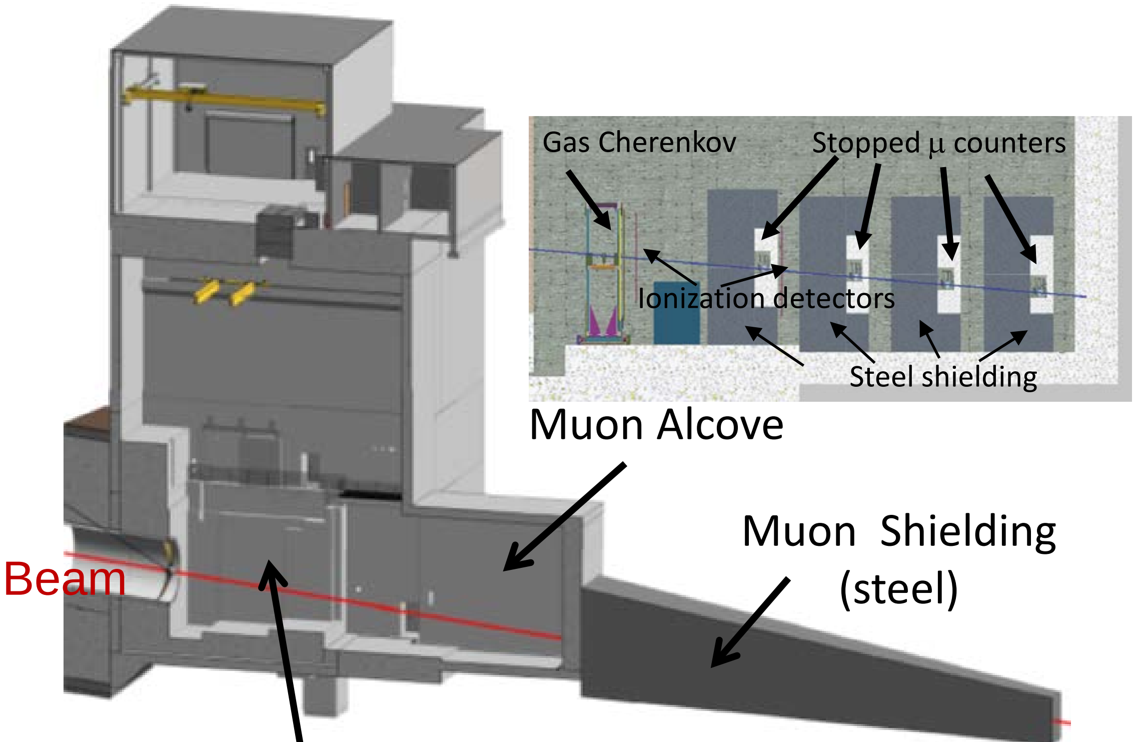
Absorber Hall and Service Building

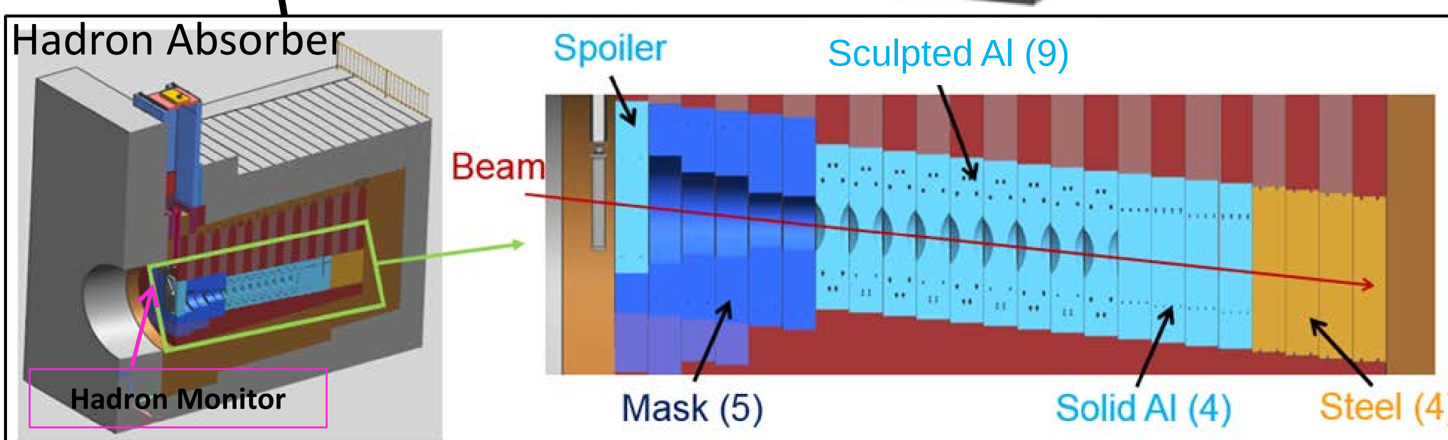
The Absorber is designed for 2.4 MW
~ 30% of beam power in Absorber: 515 kW
in central core 225 kW in steel shielding

Absorber Cooling

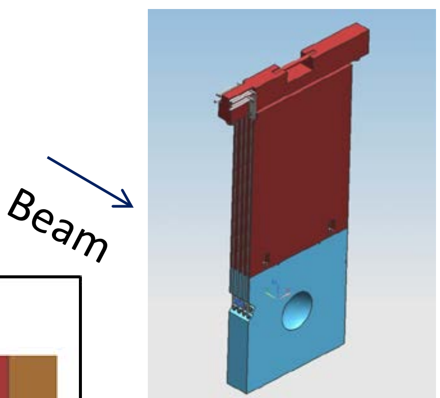
Core: water-cooled

Shielding: forced air-cooled





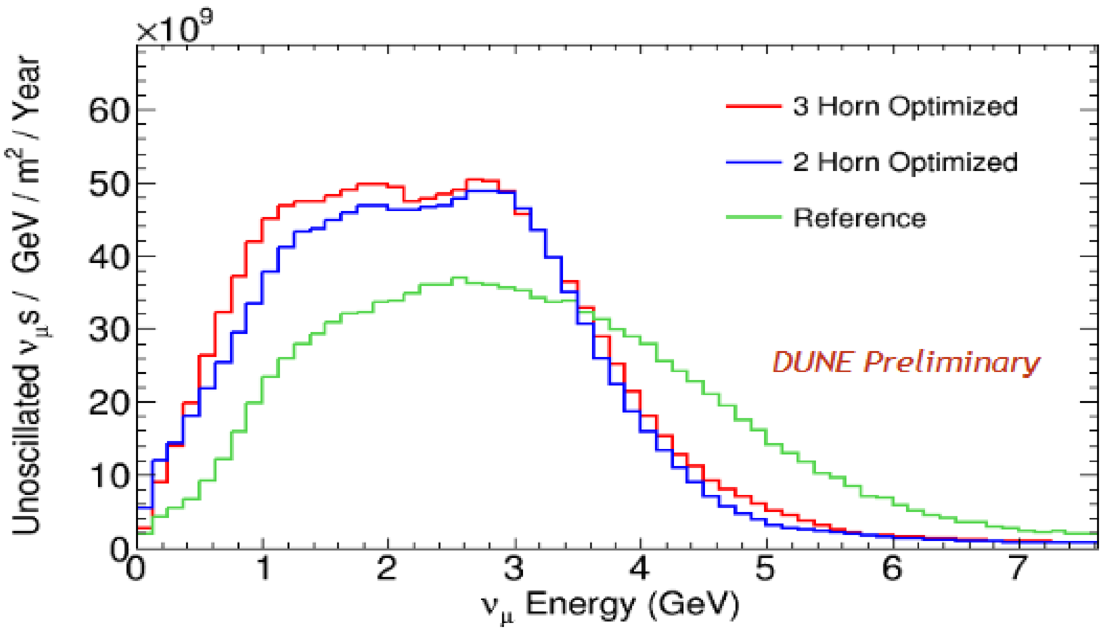
Core blocks replaceable (each 1 ft thick)



Flexible, modular design

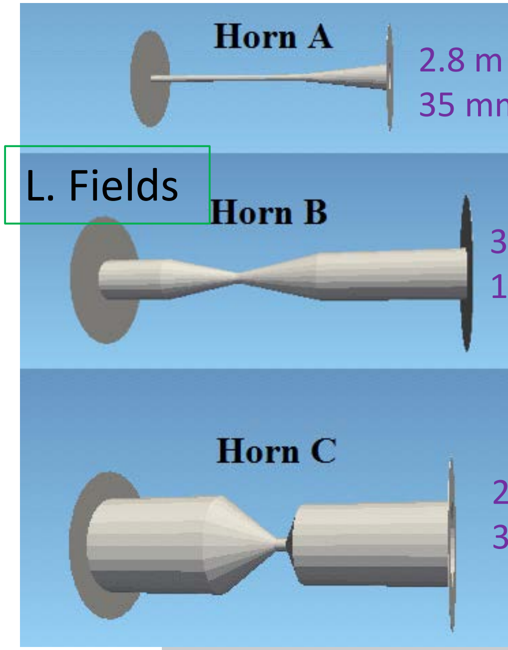
Optimizing target and horns

- Optimizing target and horns for better physics.
- Optimizing on the basis of sensitivity to CP violation.
- Encouragement by the CD-1 Refresh Review Committee to continue along these lines.
- The optimization leads to significantly more flux, a flatter spectrum in the energy range of interest and reduced high energy tail.



Mechanical model for optimized horns – 1st iteration

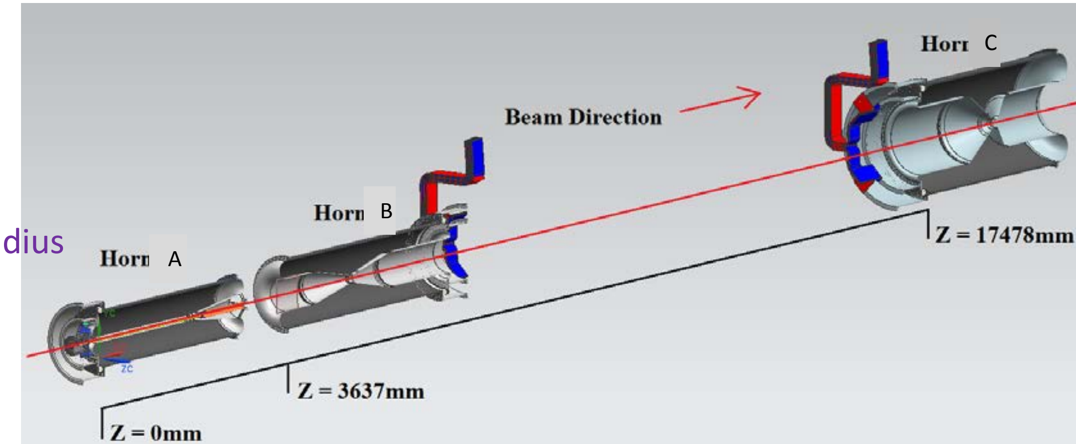
Optimizing target and horns for better physics



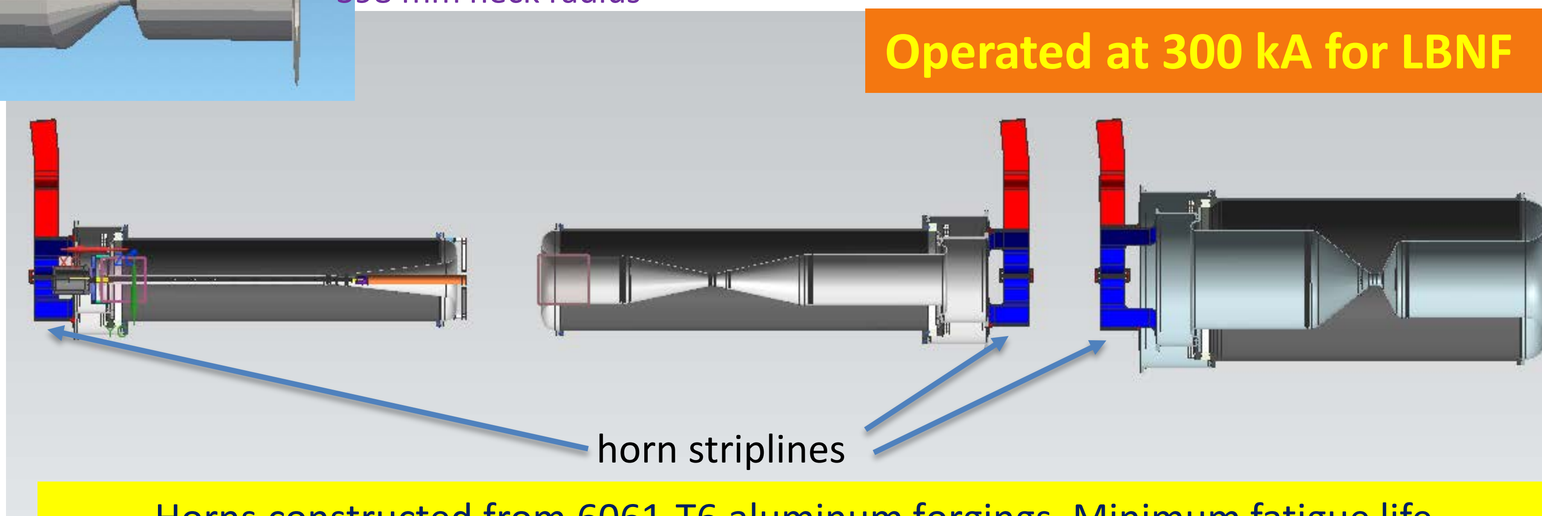
2.8 m long
35 mm neck radius

3.2 m long
191 mm neck radius

2.8 m long
398 mm neck radius

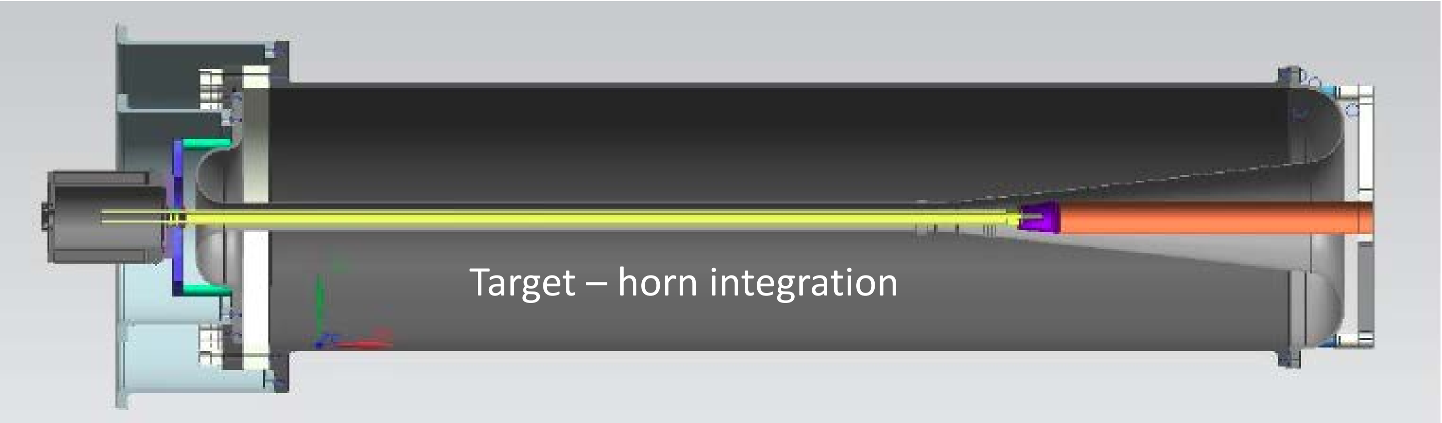


Operated at 300 kA for LBNF

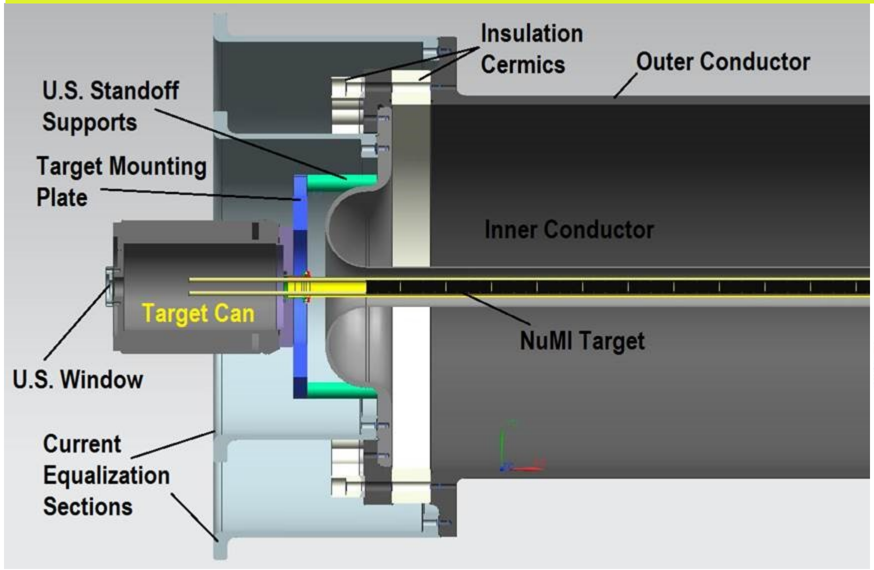


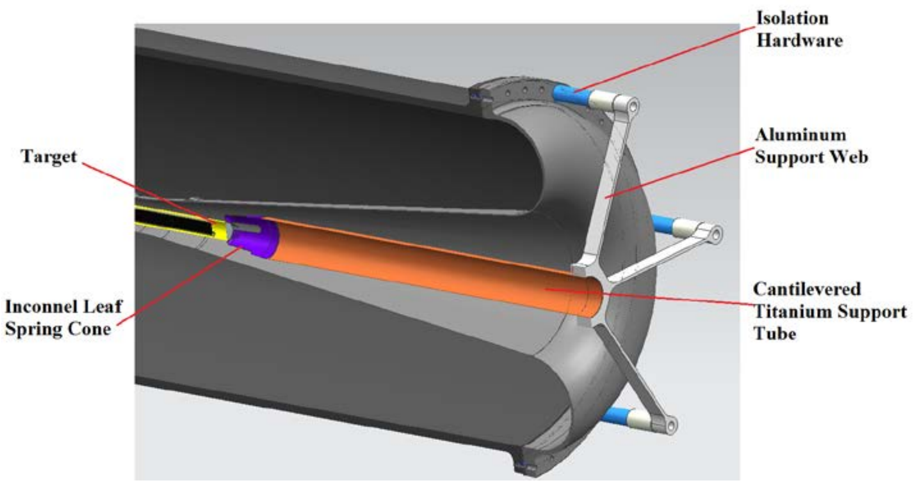
Horns constructed from 6061-T6 aluminum forgings. Minimum fatigue life requirements of 100 million pulses in the proton energy range from 60 – 120 GeV.

Mechanical model for optimized horn A and target integration – 1st iteration



2m long (4 interaction lengths) NuMI style target for first iteration of MARS simulations; cylindrical and spherical targets under R&D as well.

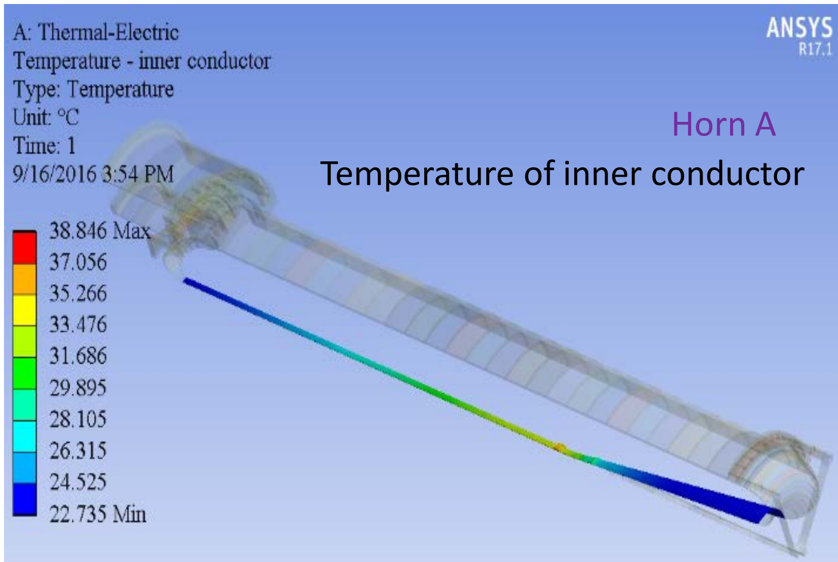




Finite Element Analysis for Horn A

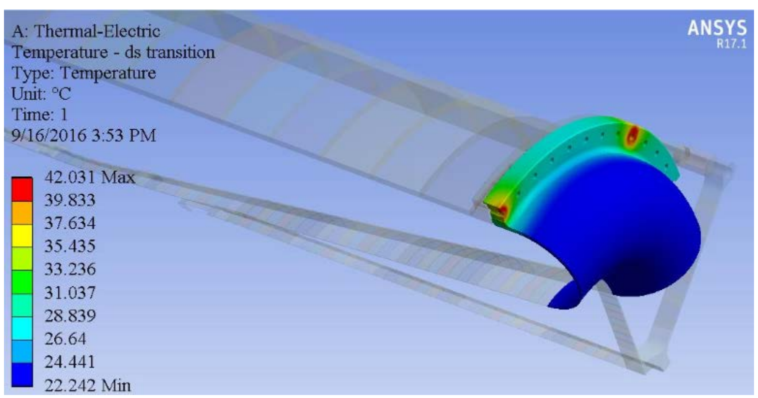
- First iteration thermal/stress FEA for optimized horn A.

Maximum current: 300 kA
Current pulse width: 0.8 ms

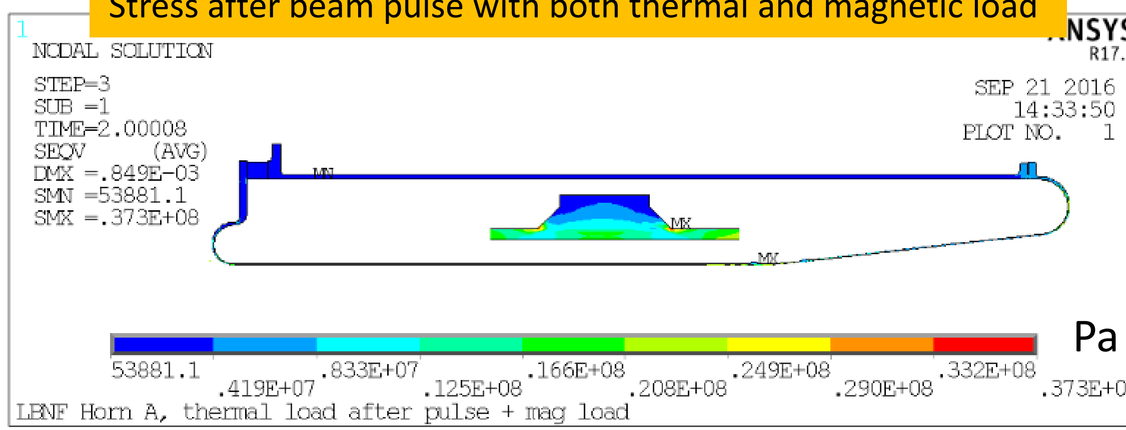


Preliminary FEA for Horn A shows:

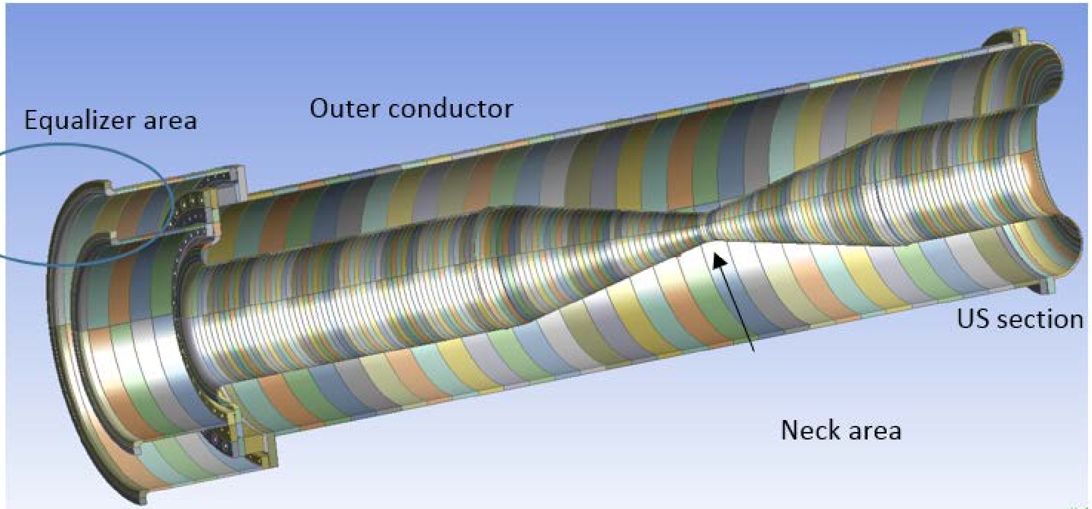
- Acceptable inner and outer conductor temperatures and stresses.
- Support of target at DS end too hot (> 1,000^{0}C); needs redesign.
- Tentative design philosophy is to extend target containment tube till end of Horn A and support through helium-cooled titanium tubes.



Stress after beam pulse with both thermal and magnetic load



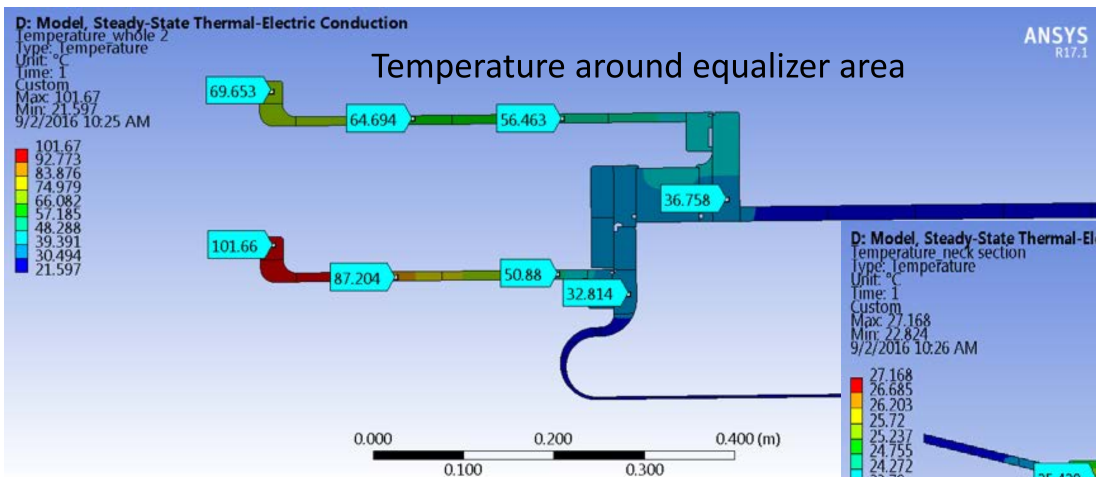
Finite Element Analysis for Horn B

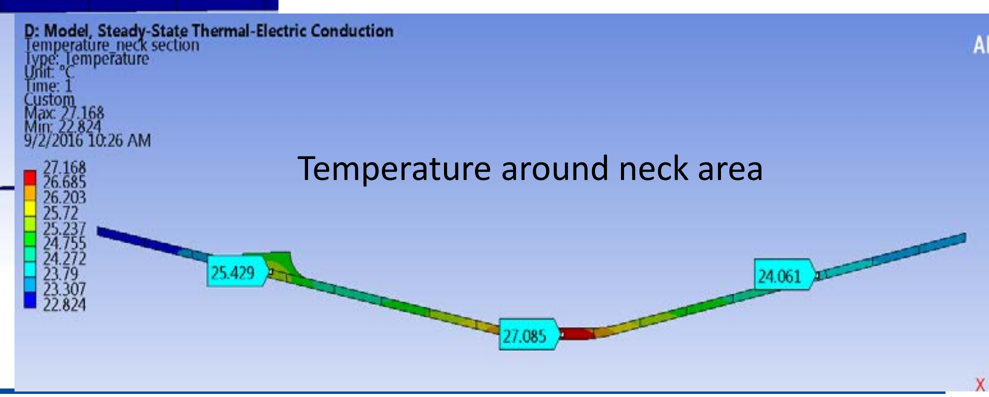


Maximum current: 300 kA
Current pulse width: 0.8 ms

Preliminary FEA for Horn B shows:

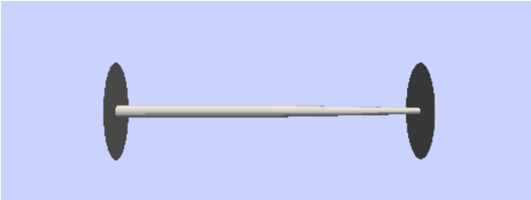
- Acceptable conductor temps
- Inner conductor neck wall can be thinned out (from 4 mm to 3 mm)
- Hot equalization sections. Must be modified. We know how to address.

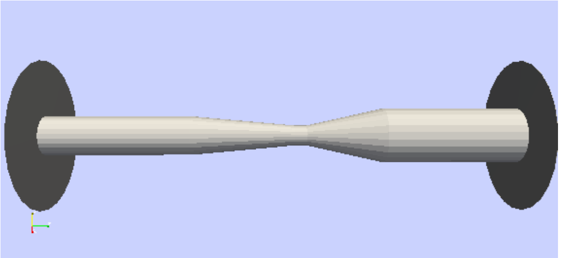


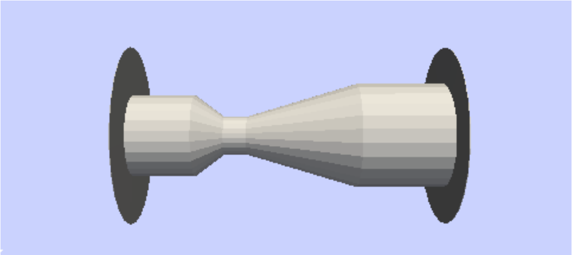


Cylindrical Horn A / integrated target

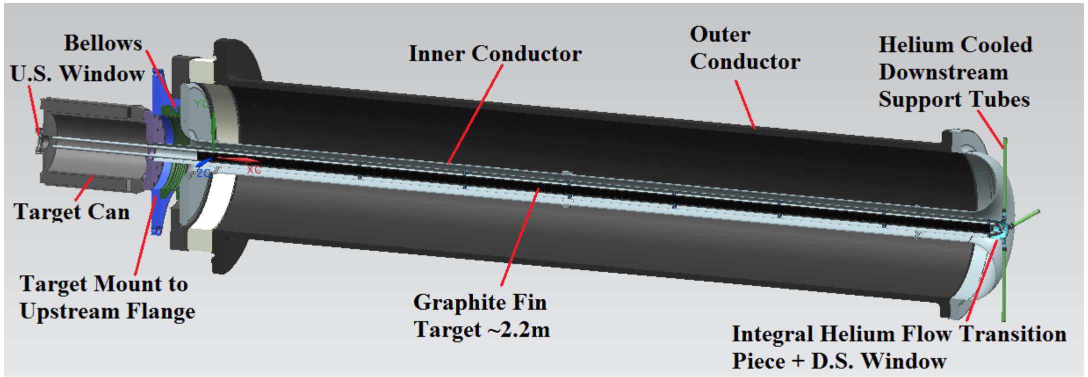
- Shorter cylindrical horn A (2.2m), longer (3.9 m) horn B
- Shorter, cylindrical horn A easier to build; easier to support and cool target that way

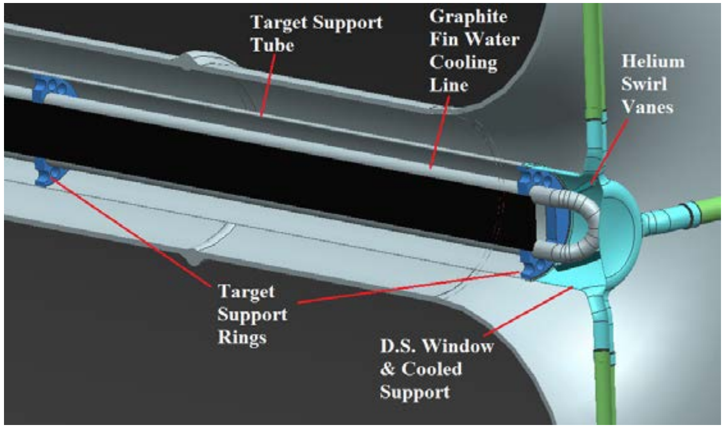






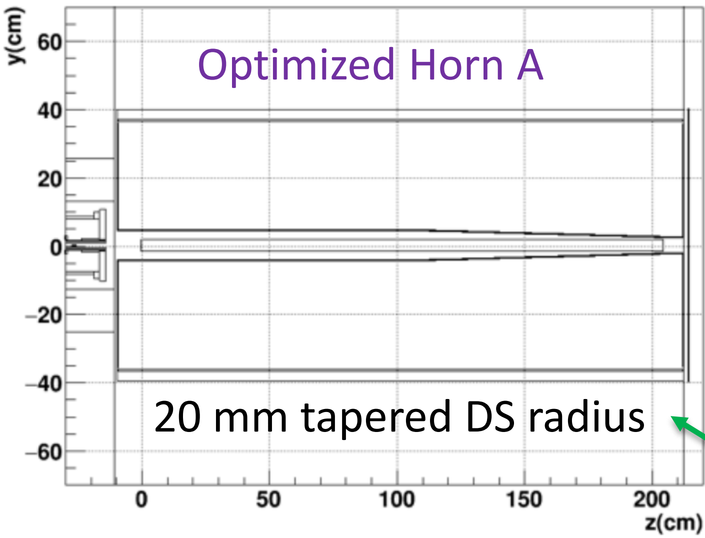
- Target fins cooled by two water tubes; horn inner conductor cooled by water spray and air flow
- Helium exhaust tubes act as support for D.S. end of target
- Horn A and target to be exchanged as one unit



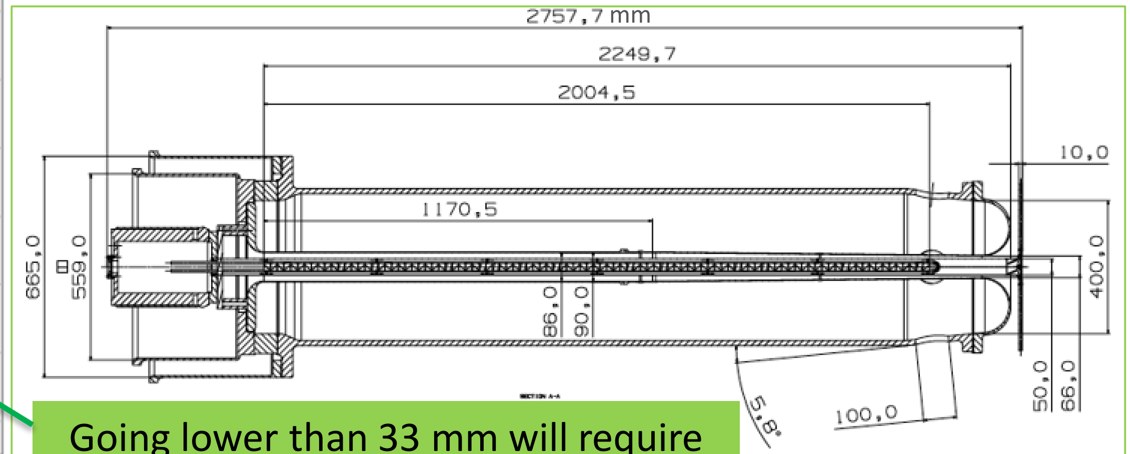


Tapered Horn A

- On September 22, 2016 we decided to move forward with a “tapered” Horn A because it provided improved neutrino flux and CP sensitivity.



Mechanical Design layout of Horn A



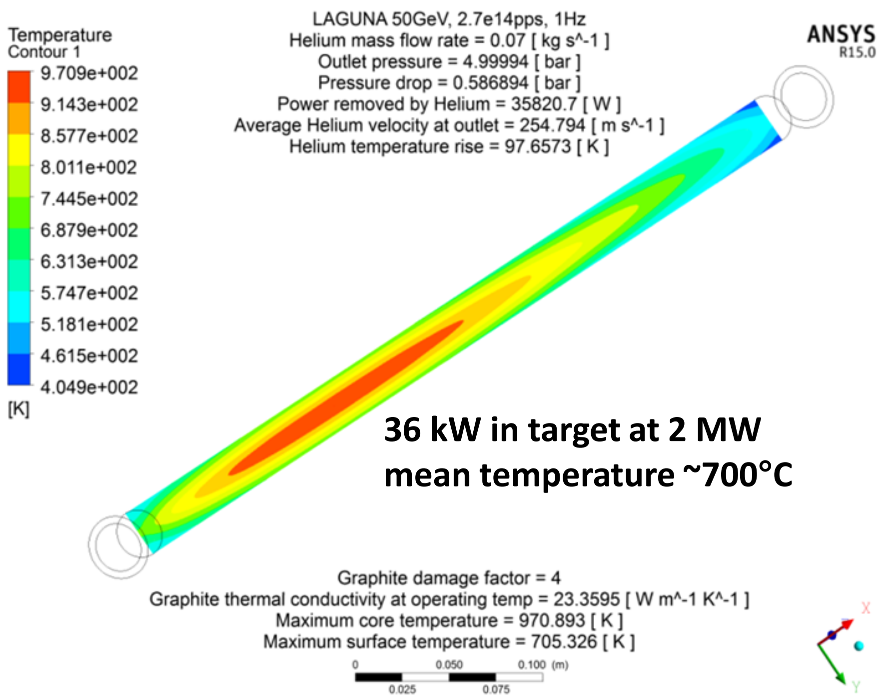
Going lower than 33 mm will require thickening of inner conductor

- Working on mechanical designs of horns B and C and on implementing all horns in 2nd MARS iteration
- FEA will follow
- NuMI-style target, 2 m long for now
- Collaboration with RAL on target conceptual design and mounting to horn
- A mounting design that allows for a separately replaceable target is desirable

Target developments

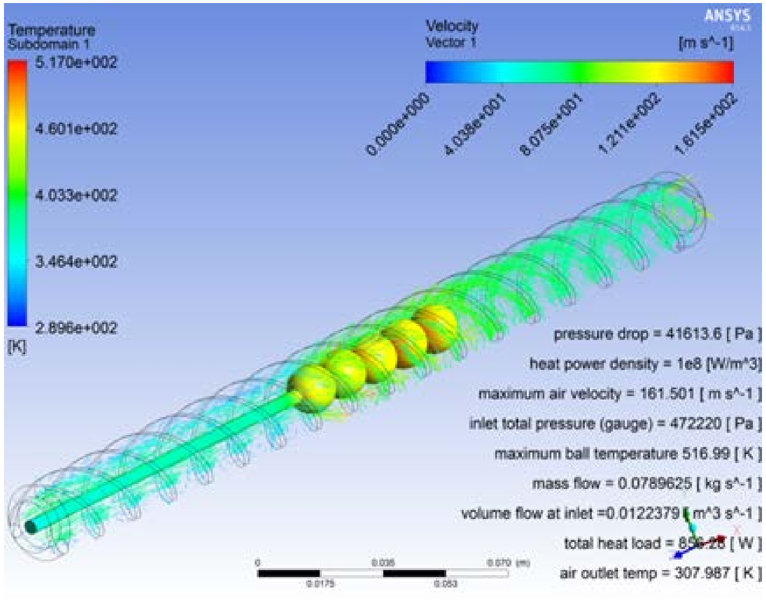
Can we build a target lasting over a year?

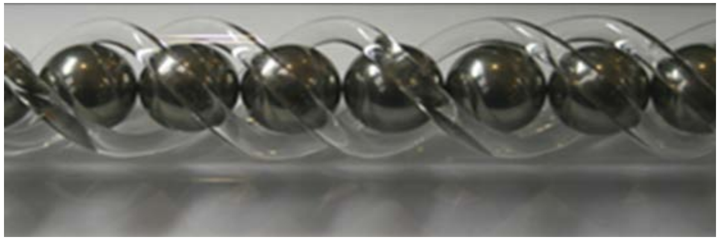
Helium-cooled graphite rod



36 kW in target at 2 MW
mean temperature ~700°C

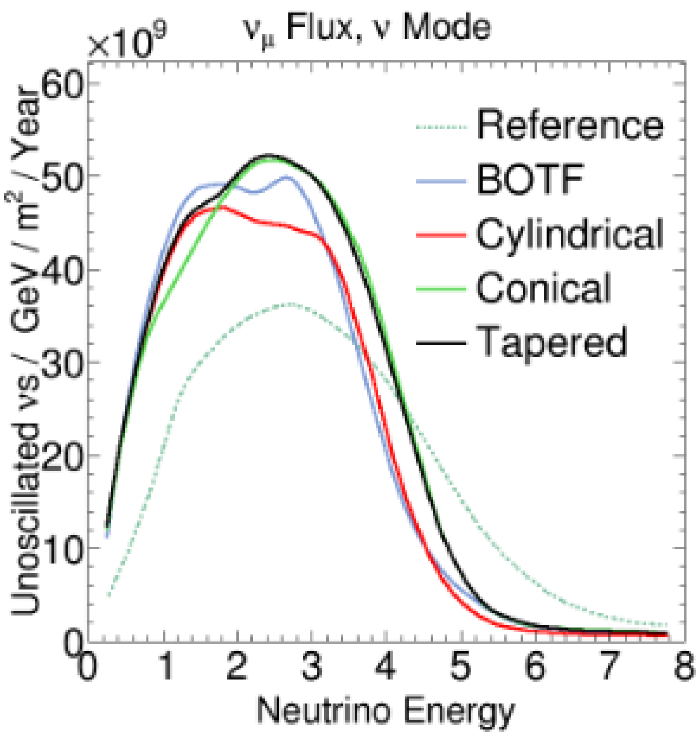
Helium-cooled spherical array target
Be or graphite

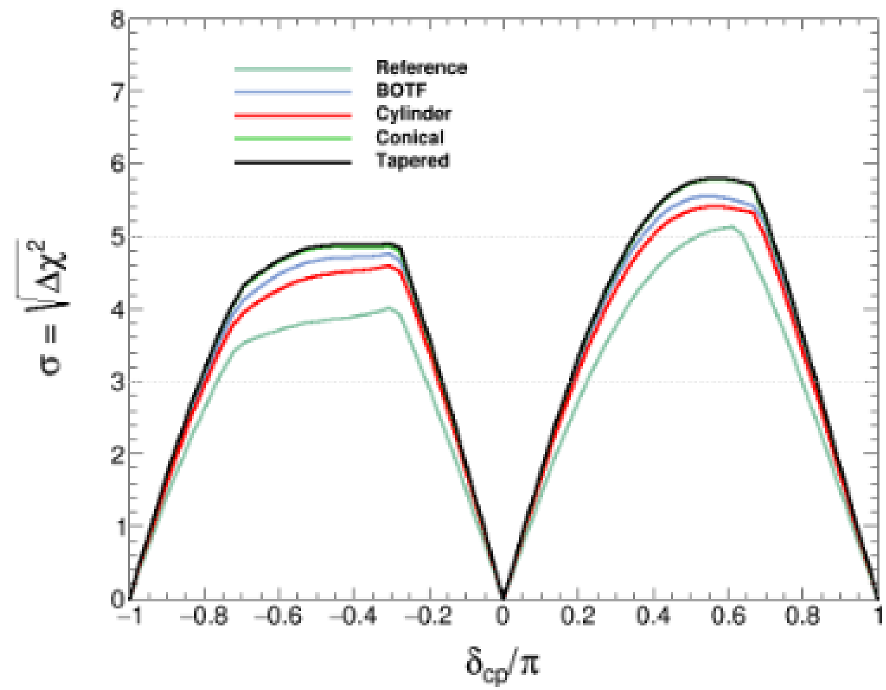




Optimizing target and horns

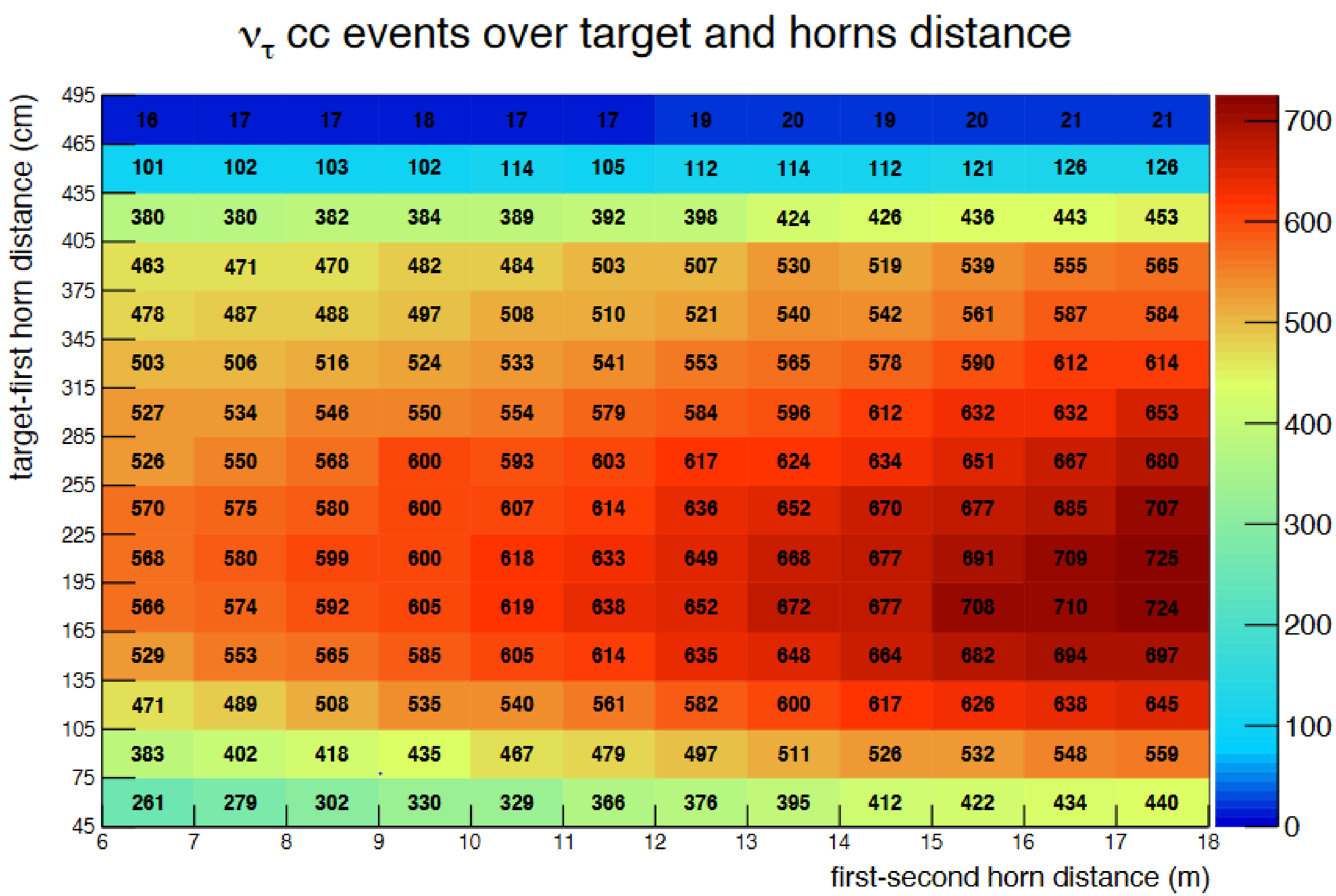
- Optimizing target and horns for better physics.
- Optimizing on the basis of sensitivity to CP violation.





Tau appearance optimization

- Studies indicate that more than 700 events per year is possible.
- Using NuMI like target and horns



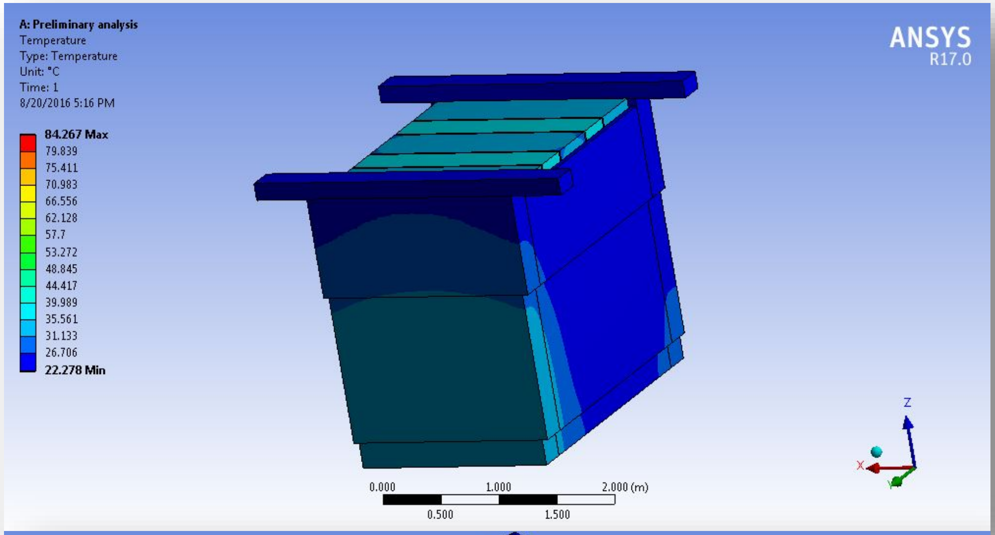
Impacts on other systems

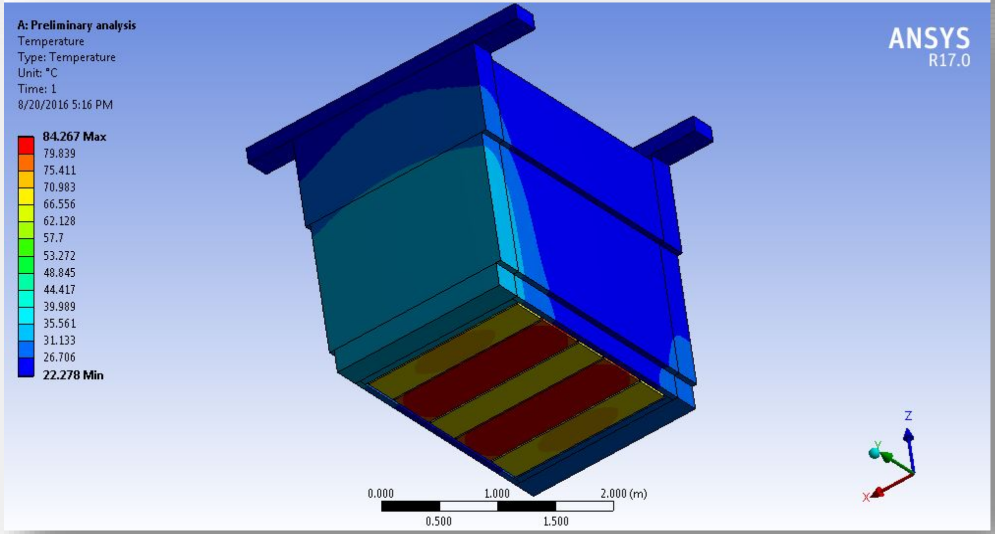
Re-assess:

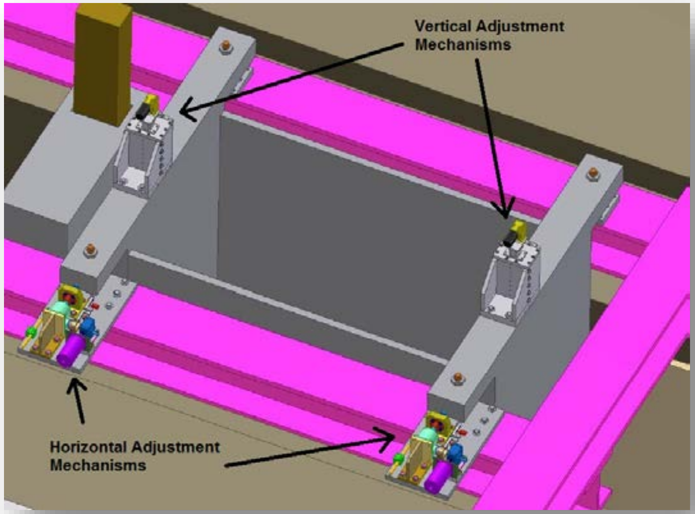
- Horn support modules
- Horn power supply
- Target shielding/cooling
- Decay pipe shielding/cooling
- Decay pipe upstream window and snout
- Remote handling (casks, morgue capacity analysis, work-cell,..)
- Hadron absorber
- Muon shielding in the end of the hadron absorber
- Conventional Facilities

Horn Support Modules preliminary FEA

- Life-of-facility components, adjustable and serviceable by remote control
- Modules analyzed at beam energies 60-120 GeV
- Max temperature found was ~ 84 ^{0}C for Horn A which is well within limits for mainframe



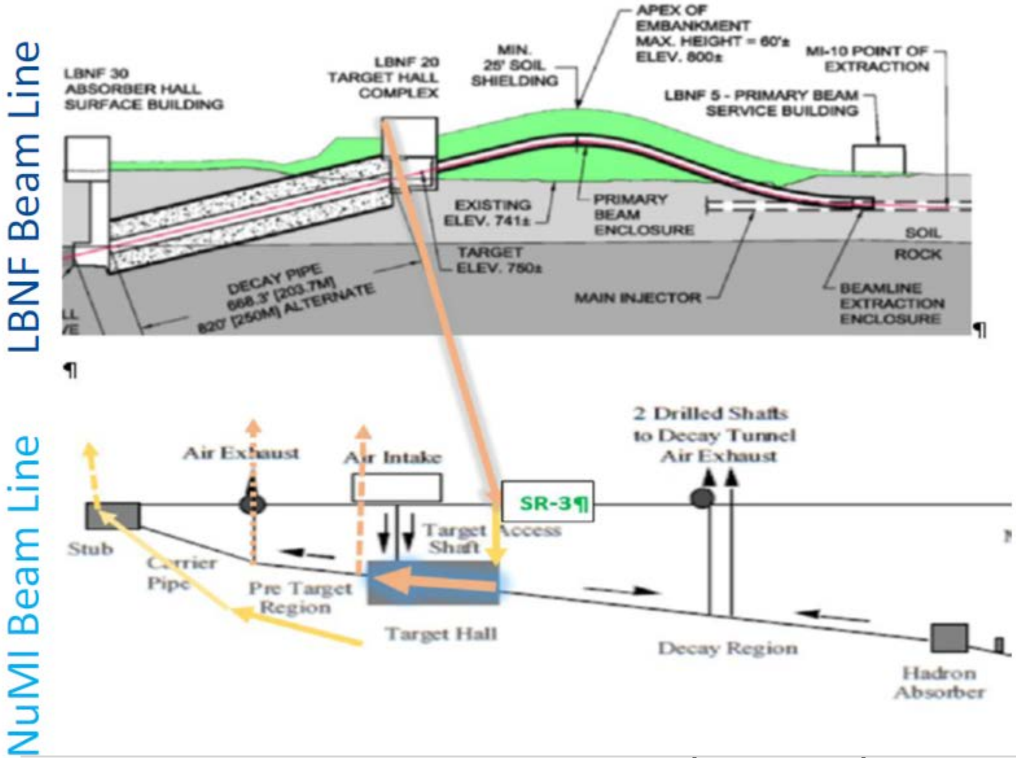




Gas in the target chase

- Issues to be further understood with the reference design that has air in the target chase:
  - Repeating air-releases calculations with bigger chase, shorter decay pipe (Preliminary results just became available from three independent analyses)
  - Corrosion (work in progress; on the basis of NuMI measurements, 20-60 ppm of Ozone expected in LBNF at 2.4 MW operation with only minimal amounts of nitric acid generation.
- Developing alternative design with Nitrogen in the target chase (CDR follow-up)

Air in the target chase – Activated Air emissions



LBNF goal < 30 μrem
(100 μrem Lab budget)

Ar^{41} in test sample at NuMI is a factor of a few lower than calculations but too close to the limit

Decay Volume used	$T_{transit}$ (min)	Rrelease (Ci/yr)	Ar-41 fraction	MEOI (%)
out of LBNF (TH)	0	1526	34.7%	670
LBNF (PT)	33	754	57.1%	331
pipe (LBNF to NuMI)	3	1419	36.6%	623
pipe + NuMI (TH)	56	520	71.5%	228
pipe + NuMI (PT)	28	827	53.6%	363
pipe + NuMI (TH+PT)	81	381	83.4%	167
pipe + NuMI (TH+PT+Carrier pipe)	137	232	95.9%	102

Maximally Exposed Offsite Individual

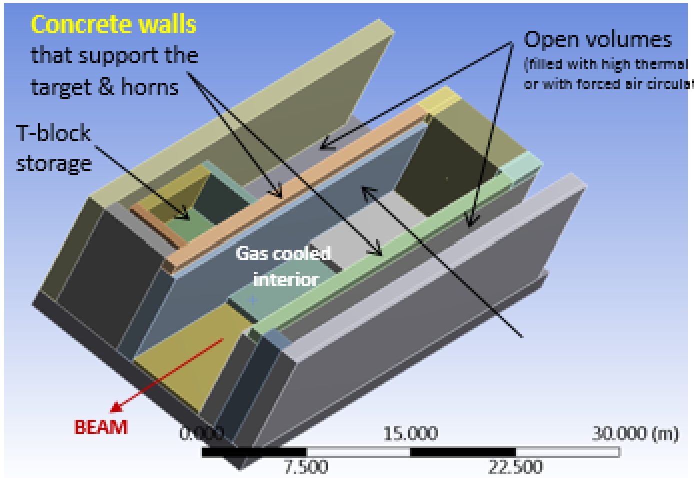
If we use inert gas in target chase do we still need NuMI for cooldown?

Nitrogen in the target chase

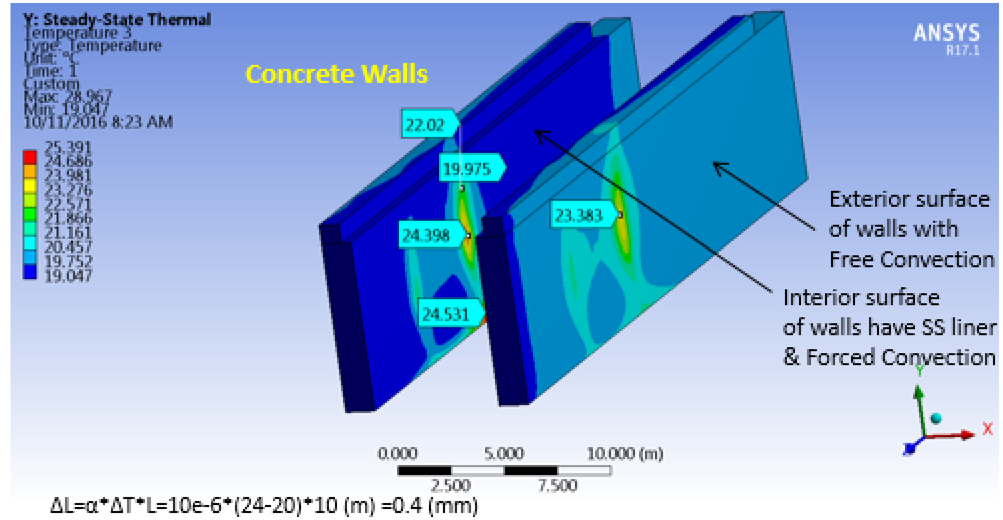
- Requires robust leak-tight seals at all openings and feedthroughs, plus leak tight seal at decay pipe & and window interfaces.
- Need minimal leak rate ~6 cfm or about 2 orders magnitude less than that for air – due to ODH and nitrogen cost considerations.
- Requires containment vessel (not accessible for repair) within concrete tub that might affect thermal stability of the concrete which is currently directly cooled with air flow (alignment considerations).
- Hatch covers need to be removable including the supporting crossmembers (modular design) since we don't know the exact position, dimensions, etc. of all components and need to accommodate different component. configurations in future. Sealing at the seams and cross-beam interfaces is especially challenging.
- Requires a nitrogen fill and monitoring system plus ODH considerations.
- System will need to operate at positive pressure to prevent air/oxygen coming in and accommodate barometric pressure changes due to weather.

Inert gas in the target chase – Do we need to cool the concrete?

Target Chase concrete structure as modeled in ANSYS

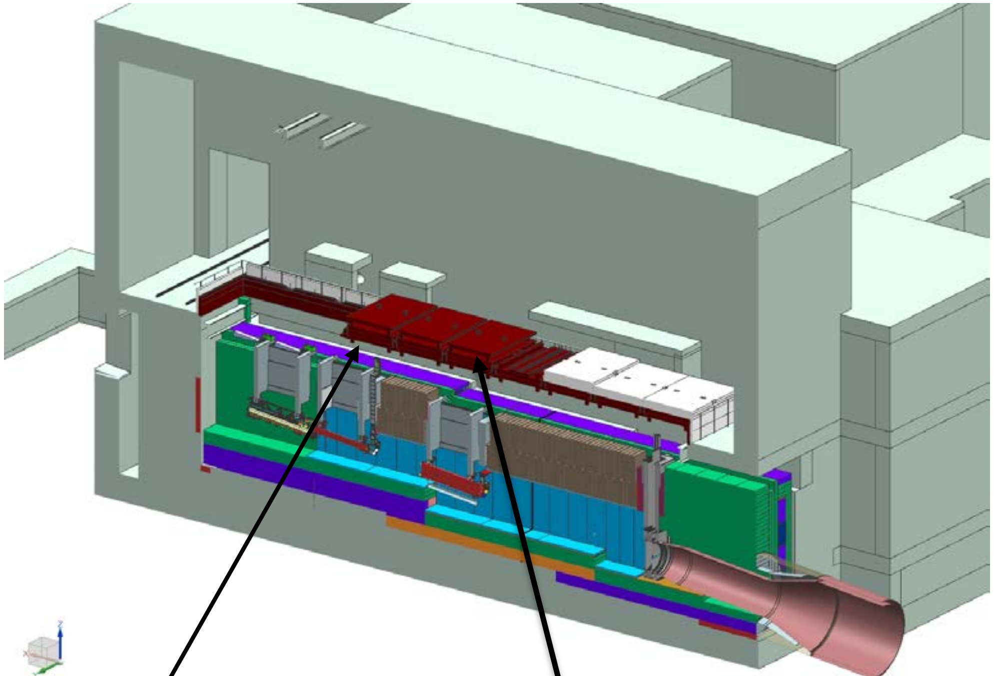


FEA thermal results for the interior Concrete walls

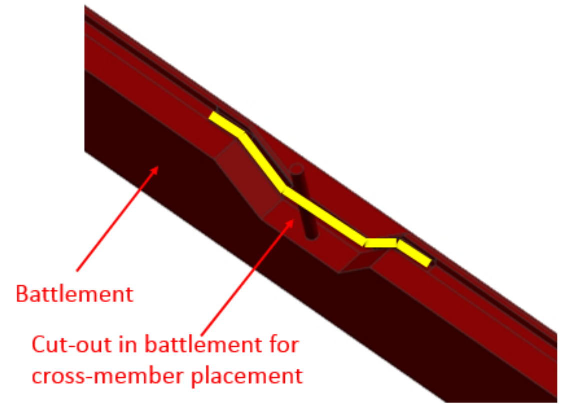


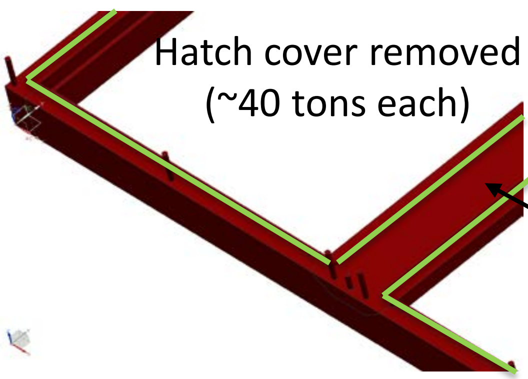
- The **concrete walls** support the chase components (target and horns) and therefore need to see a minimal thermal variation (ΔT ≤ 4°C) in order to maintain component alignment.
- The interior of the concrete walls have a stainless steel liner (for gas containment) and a small air gap is assumed between the liner and concrete wall. The surfaces of the liner are actively cooled by the gas.
- By applying a free-convection boundary condition at the outer wall surfaces, an acceptable temperature rise is achieved, with a maximum vertical wall displacement of 4mm (alignment tolerance is ~ 8mm).
- Investigating forced air circulation.

Nitrogen in the target chase – Hatch Cover Assembly



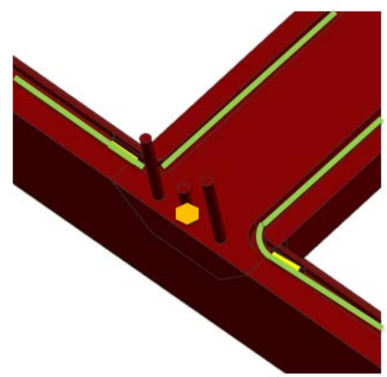
10 Hatch Covers (some stacked for target replacement)





Hatch cover removed (~40 tons each)

Hatch Cover Seams with supporting cross beams underneath



LBNF/DUNE Milestones

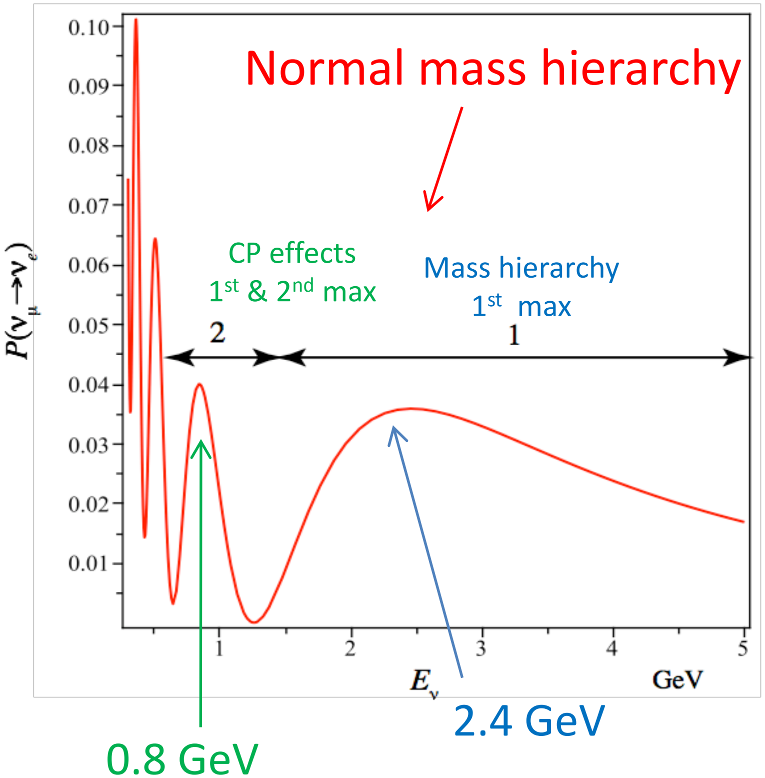
- Critical Decision-0 (CD-0) approved, January 8, 2010.
- CD-1 Refresh approved, November 5, 2015 (Conceptual Design)
- CD-3a approved, September 1, 2016 (far-site pre-excavation and excavation)
- Complete Sanford Laboratory reliability projects in FY2018
- CD-2 for the entire project expected in December 2019 (baselining)
- Complete first cryostat and cryo systems construction to enable detector installation to begin in 2021
- Commission first 10 kTon far detector in **2024**
- Add a second 10 kTon far detector and the near detector by **2026**
- Produce neutrino beam in **2026**

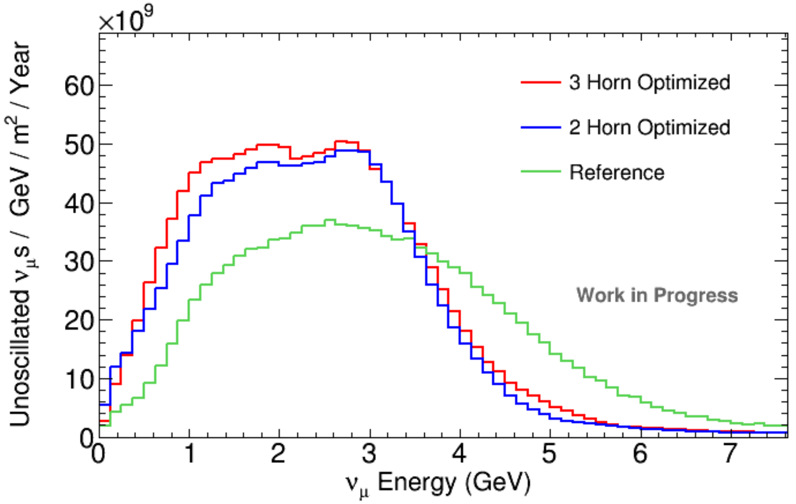
Conclusion

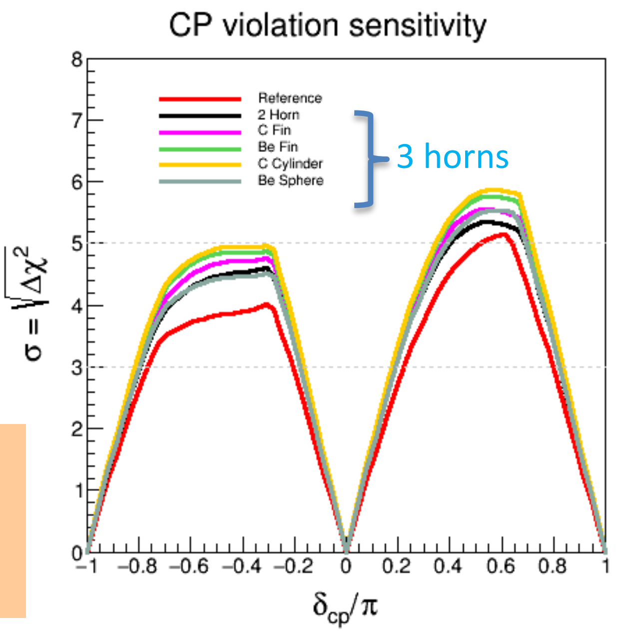
- Reference conceptual design for the LBNF Beamline already available and approved by DOE.
- Considerable effort and satisfactory progress on beam optimization and design improvement areas.
- Need to take decisions on alternative/optimized options by October 2017 so that we can start the next phase of the design with the new fiscal year.

Backup

Beamline Requirements and LBNF/DUNE neutrino beam spectra





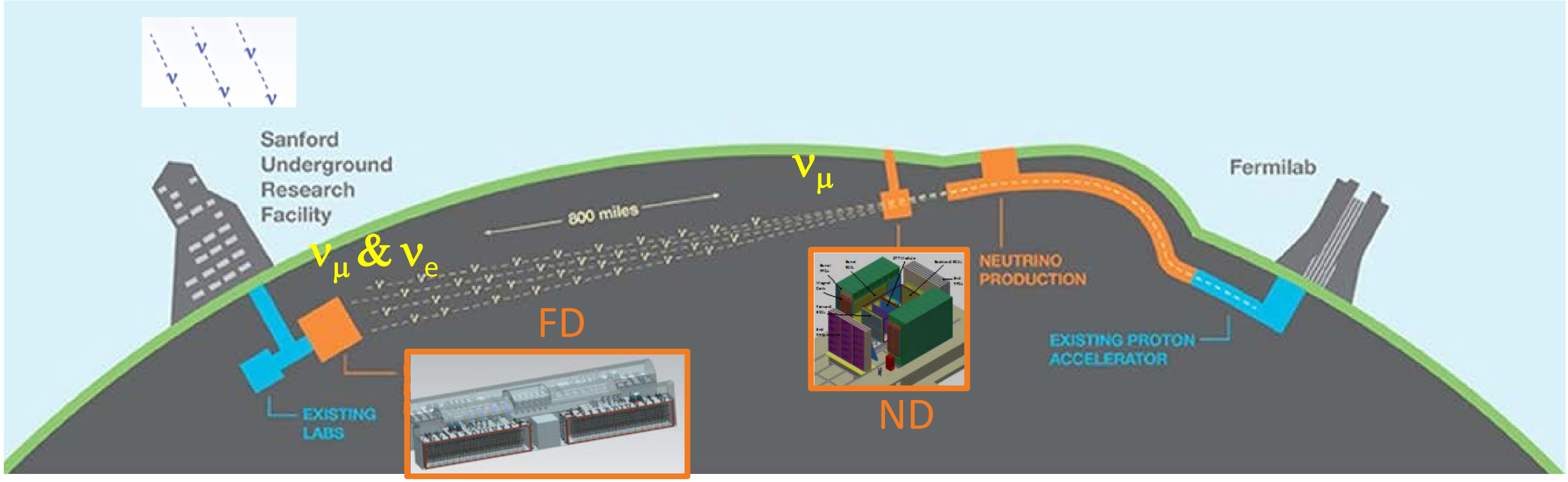


- Need a wide band beam to cover the 1st and 2nd oscillation maxima

3.5 yr ν_μ + 3.5 yr $\bar{\nu}_\mu$
40 kt detector,
PIP-II beam power(1.03-1.2 MW)

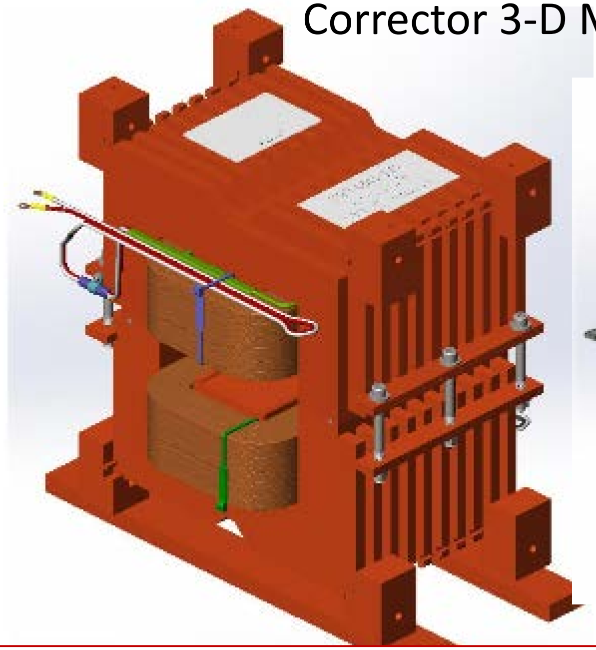
Facility and Experiment

- **LBNF**:
  - Near site: Fermilab, Batavia, IL – facilities and infrastructure to:
    - create a broad band, sign selected neutrino beam
    - host the near DUNE detector
  - Far site: Sanford Underground Research Facility, Lead, SD – facilities to support the far DUNE detectors (4850 L)
- **DUNE**:
  - Near site detector and Far site detectors

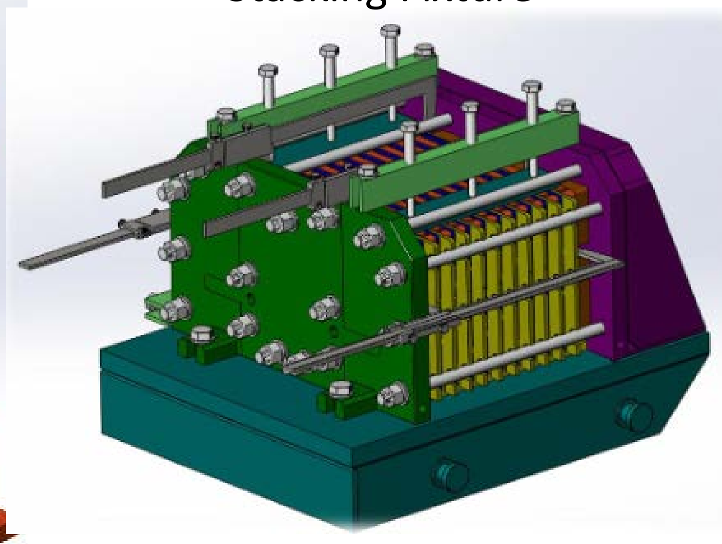


Corrector Magnet prototyping progress – IHEP/China

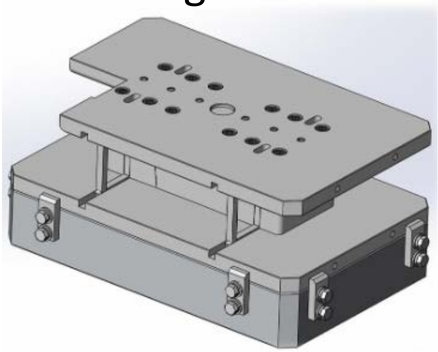
Corrector 3-D Model



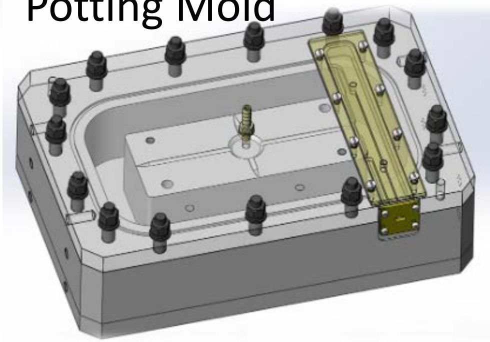
Stacking Fixture



Winding Former



Potting Mold

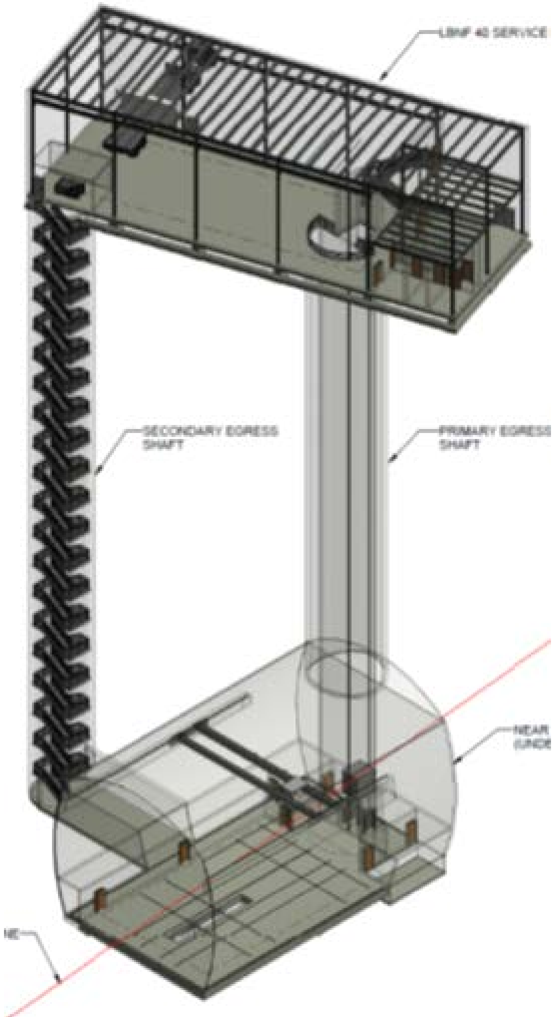


Maximum Magnet (Core) Length	17.25 (12) in
Maximum cross-section	24x24 in^2

- Fermilab design, double-checked by IHEP colleagues. Large aperture, air-cooled, relatively high field, large good field region, sufficiently flexible design.
- IHEP finished with final drawings and technical files of tooling needed and began fabrication of tooling early October, 2016 (punching die, stacking fixture, winding former and potting mold).
- Fittings of coil and room temperature cure epoxy from Fermilab.
- Prototype complete – February 2017.
- SOW in review stage, covering additional 24 production corrector magnets.

Near Detector Hall and Detector

Near Neutrino Detector Hall and LBNF 40 Service Building



~205 ft deep

Three types of Near Detector considered:

- Fine-Grained Tracker (reference)
- High-Pressure Gaseous Argon TPC
- Lar-TPC