Overview of the LBNF/DUNE Beamline

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NBI2017, Tokai-Mura, Japan

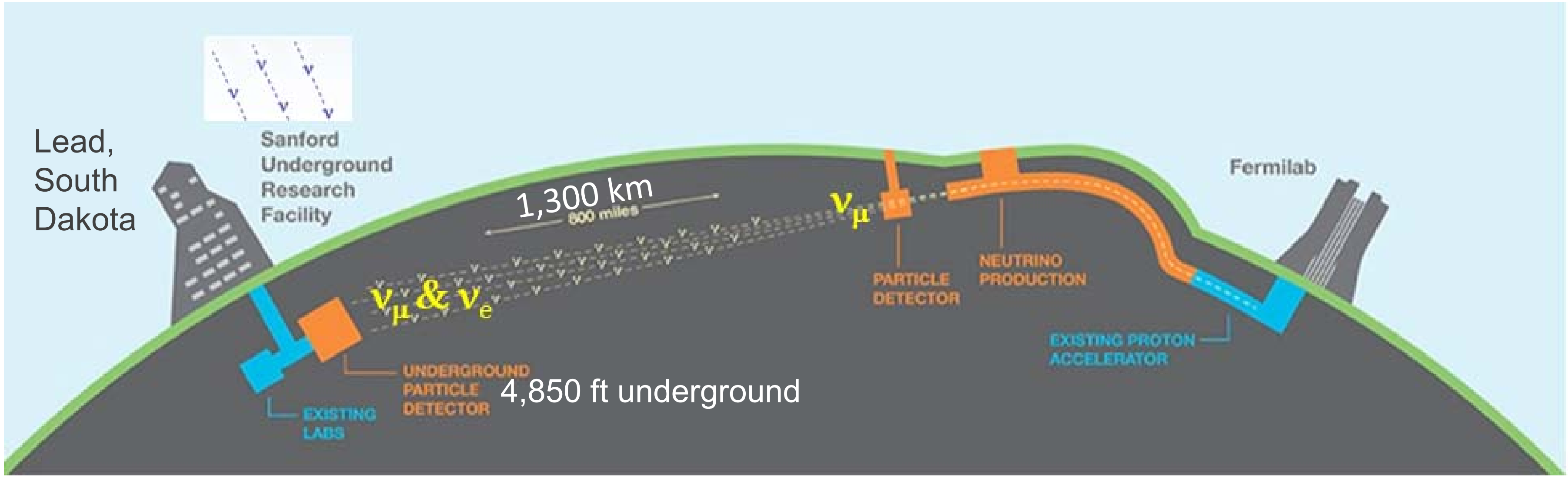
September 18, 2017

Outline

- LBNF/DUNE Scope and Milestones
- Beamline Scope
- Main Requirements & Assumptions
- Overview of the Beamline Reference Design
- Overview of the proposed Optimized Design
- Decision Process for the Optimized Beamline Design
- Summary

– For details on the design of Target Station Decay Pipe and Absorber, more in Salman Tariq's talk.
– For details on the Target and Horns design, more in Patrick Hurh's and Chris Densham's talks.
– For details on Neutrino Flux, more in Mary Bishai's talk

LBNF/DUNE Scope and Milestones



- CD-1R (Refresh) conceptual design approval in November, 2015.
- CD-3a approval in September, 2017 (Far Site pre-excavation and excavation – South Dakota).
- Our goal for beam to SURF is the 2026 timeframe.

LBNF/DUNE Scope and Milestones

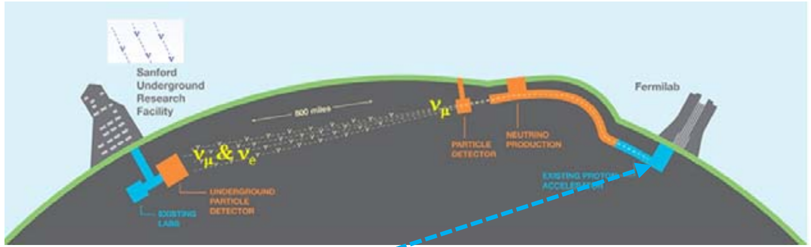
- Groundbreaking for the Far Site: July 21, 2017.

- Contract awarded for LBNF preconstruction services: August 9, 2017. Kick-off meeting on August 29, 2017.

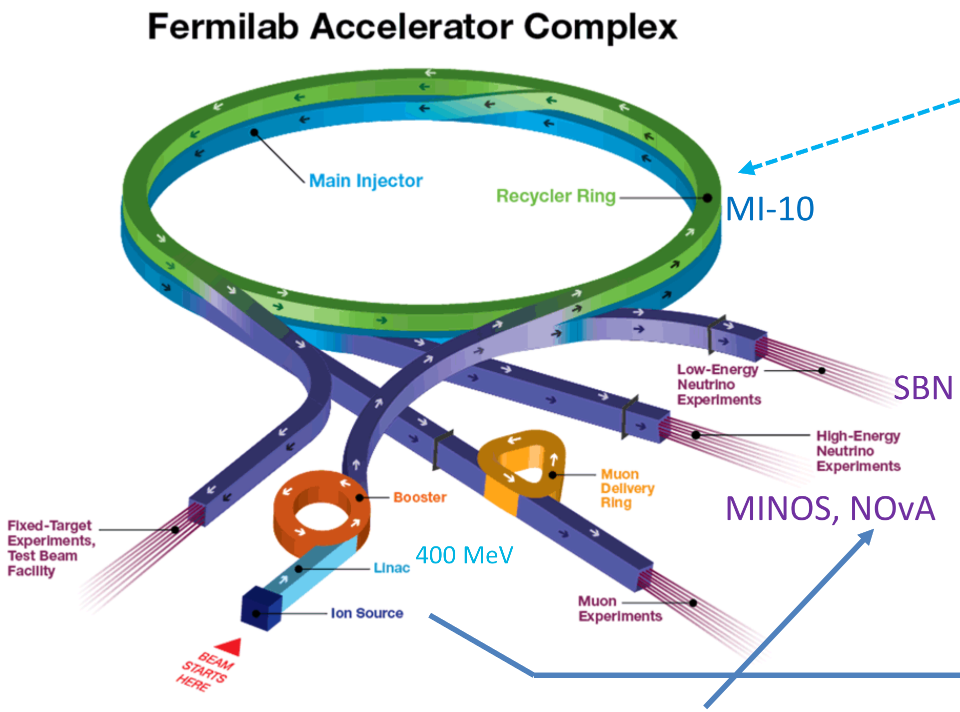
DUNE Collaboration meeting: August 2017

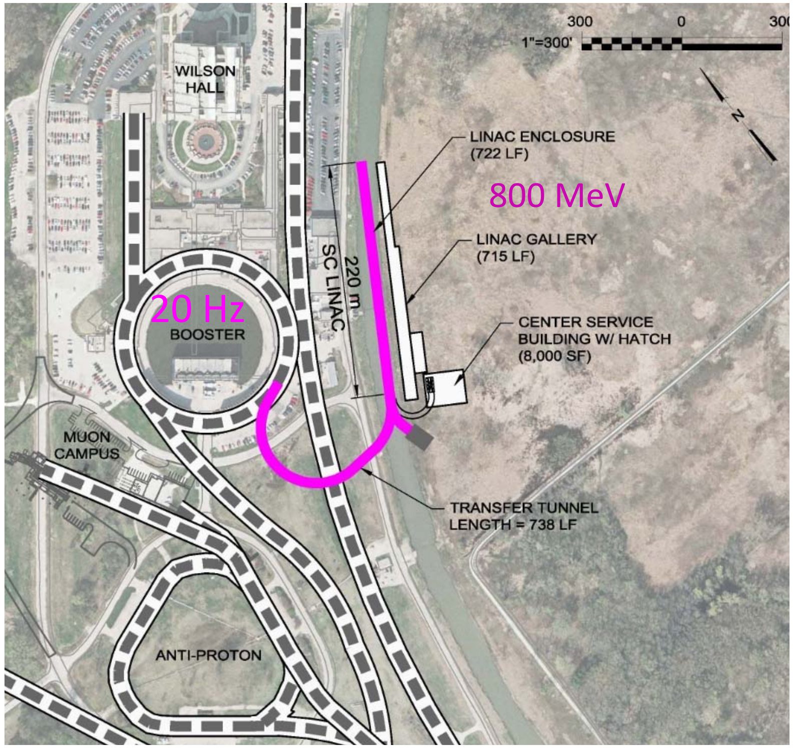
- Currently, 1087 DUNE collaborators from 176 Institutions and 30 Nations

Fermilab Accelerator Complex



LBNF proton beam to be extracted from MI-10 straight section





Since Jan. 2017 running between 650-700 kW on a continuous basis (peak power, 727 kW)

Result of NOvA Accelerator upgrades and the Proton Improvement Plan (PIP) for Linac/Booster

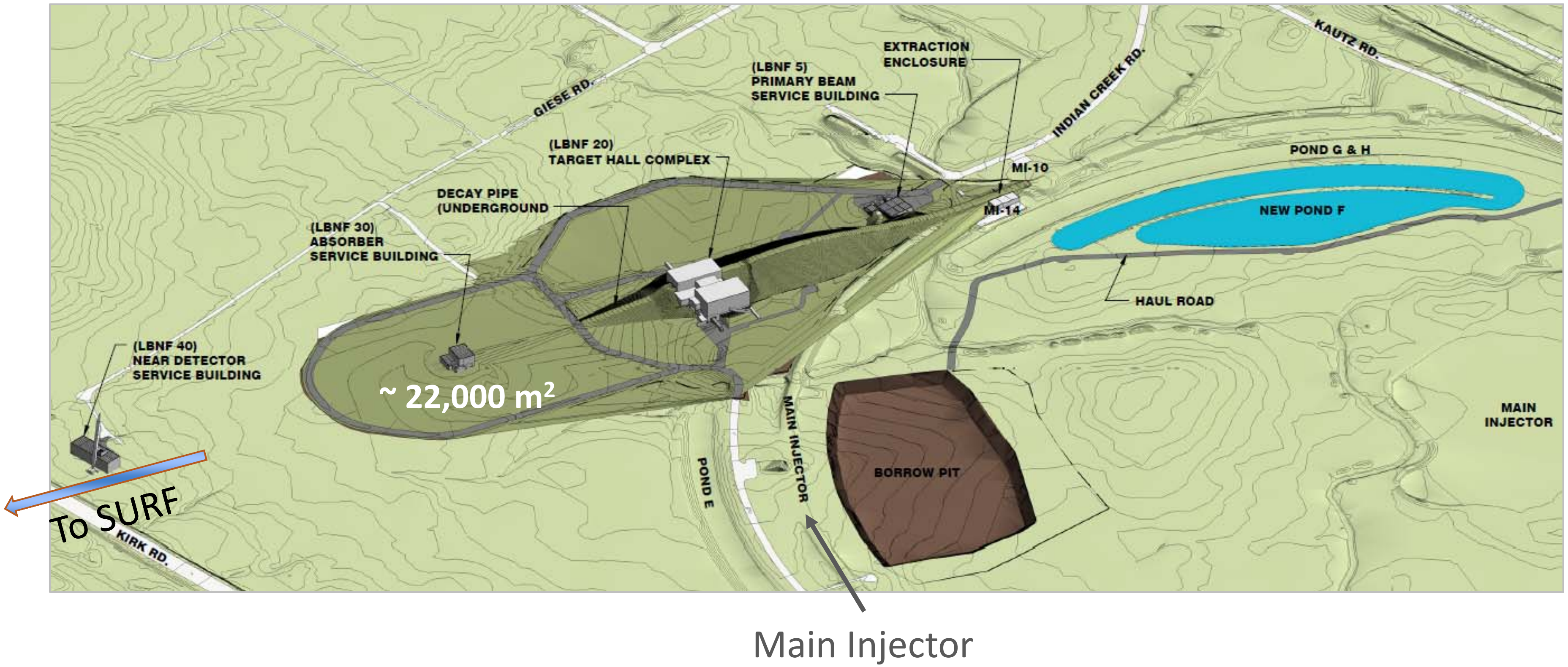
PIP-I+ plans

PIP-II (~2026)

1.2 MW @ 120 GeV

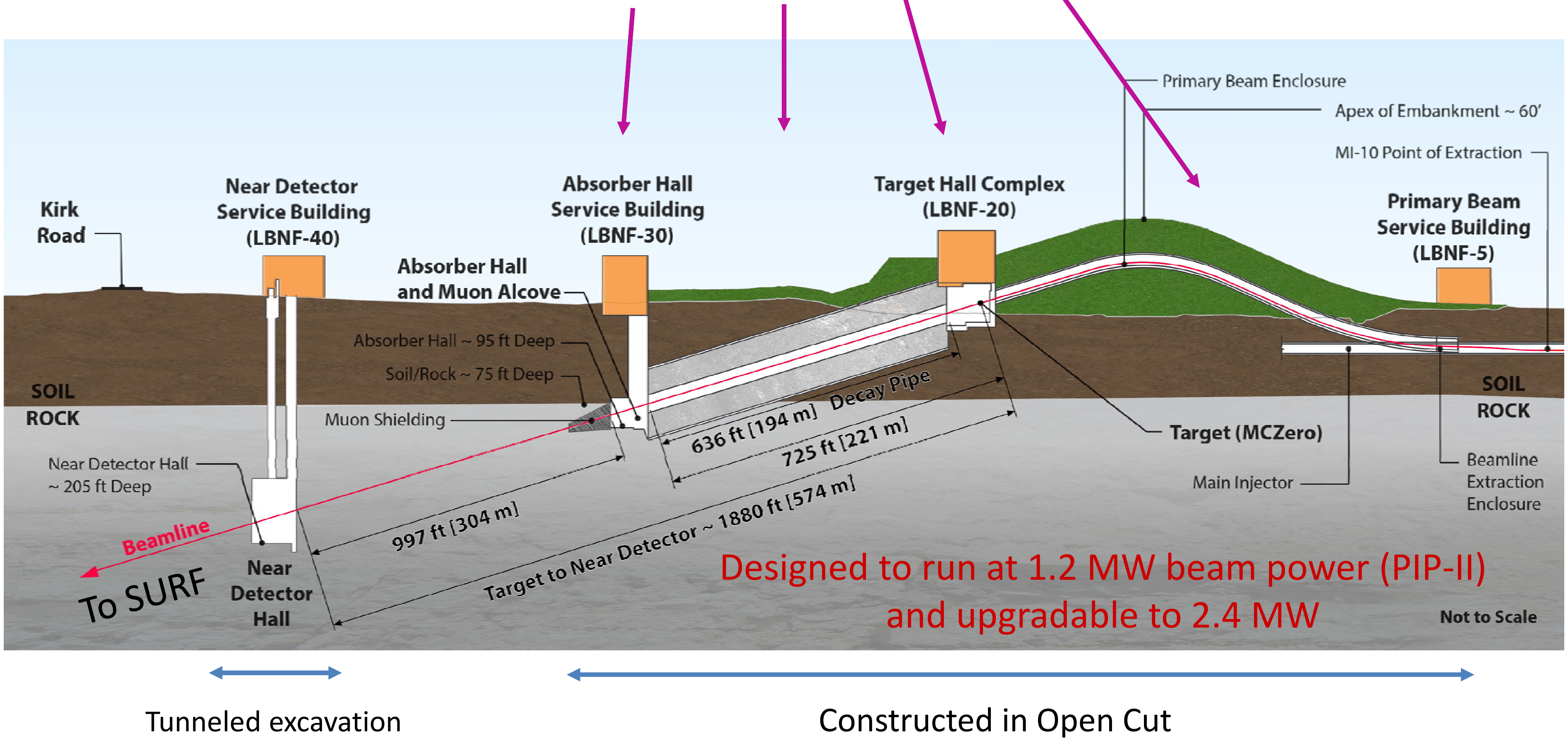
100+ kW @ 800 MeV

LBNF Conventional Facilities at Fermilab



Beamline for a new Long-Baseline Neutrino Facility

Scope for Beamline Technical Components



Beamline Scope

- Primary Beam (beam optics, magnets, magnet power supplies, LCW, vacuum, beam instrumentation).
- Neutrino Beam (primary beam window, baffle, target, focusing horns, support modules, instrumentation, horn power supply, target shield pile, decay pipe cooling and windows, hadron absorber, RAW, remote handling, storage of radioactive components, muon systems).
- Beamline System Integration (controls, interlocks, alignment, installation infrastructure and coordination).
- Beamline Modeling and Radiation Physics & Protection.
- Near Site Conventional Facilities.

Beamline Requirements & Assumptions

- The driving physics considerations for the LBNF Beamline are the long baseline neutrino oscillation analyses.
- Beam directed towards the Sanford Underground Research Facility (SURF) in Lead, South Dakota, 1300 km from Fermilab (5.8 degree vertical bend).
- The primary beam, single turn extracted from MI, is designed to transport high intensity protons in the energy range of 60-120 GeV to the LBNF target. (Pulse duration of 10 μs).
- A broad band, sign selected neutrino beam with its spectrum to cover the 1st (2.4 GeV) and 2nd (0.8 GeV) oscillation maxima => Covering 0.5 ~ 5.0 GeV
- All systems designed for 1.2 MW initial proton beam power (PIP-II, ~2026).
- Facility is upgradeable to 2.4 MW proton beam power (PIP-III / Booster replaced as well).

What is being designed for 2.4 MW

- Designed for 2.4 MW, since upgrading later would be prohibitively expensive and inconsistent with ALARA:
  - Size of enclosures (primary proton beamline, target chase, target hall, decay pipe, absorber hall)
  - Radiological shielding of enclosures (except from the roof of the target hall, that can be easily upgraded for 2.4 MW when needed)
  - Primary Beamline components
  - The water cooled target chase cooling panels
  - The decay pipe and its cooling and the decay pipe downstream window
  - beam absorber
  - remote handling equipment
  - radioactive water system piping
  - horn support structures are designed to last for the lifetime of the Facility

Beamline Requirements and Assumptions

- Currently assuming 20 year operation of the Beamline: first 5 years at 1.2 MW and for another 15 years at 2.4 MW.
- The Beamline Facility is assumed to be able to operate for a 30 year span. Design life of Target & Absorber Hall Complexes and of Decay Pipe is 50 years; design life of water barrier system around them is 80 years.
- Uptime (including the uptime of accelerator complex): aiming to at least 55%.
- Stringent limits on radiological protection of environment, members of public and workers.
- We provide a 6-cell storage morgue with sufficient space for 2 years of LBNF running at 1.2 MW and assume that Fermilab will provide any additional storage needed for radioactive components - C-0 Remote Handling Facility.

Actively implementing lessons learned from NuMI/MINOS, NuMI/NOvA, T2K and other Neutrino Facilities.

LBNF Beam Operating Parameters

Summary of key Beamline design parameters for $\leq$1.2 MW and $\leq$2.4 MW operation

Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase			
Proton Beam Energy (GeV):			
60	1.5E+14	0.7	2.06
80	1.5E+14	0.9	2.14
120	1.5E+14	1.2	2.40

$(1.1 – 1.9)\times 10^{21}$ POT/yr

Pulse duration: 10 μs
Beam size at target: tunable 1.0-4.0 mm

Protons on target

- The goal for accumulating 120 GeV protons at the neutrino target with beam power of 1.2 MW is 1.1×10^{21} protons-on-target (POT) per year. This assumes 7.5×10^{13} protons per MI cycle of 1.2 sec. The total LBNF efficiency used in the POT calculation is 0.56 (0.57) and includes the total expected efficiency and up-time of the accelerator complex as well as the expected up-time of the LBNF Beamline.

Proton source: 0.85
MI eff. in PIP-II era: 0.93
Scheduled accel. shutdowns: 0.84

Eff. of accelerator complex: 0.65

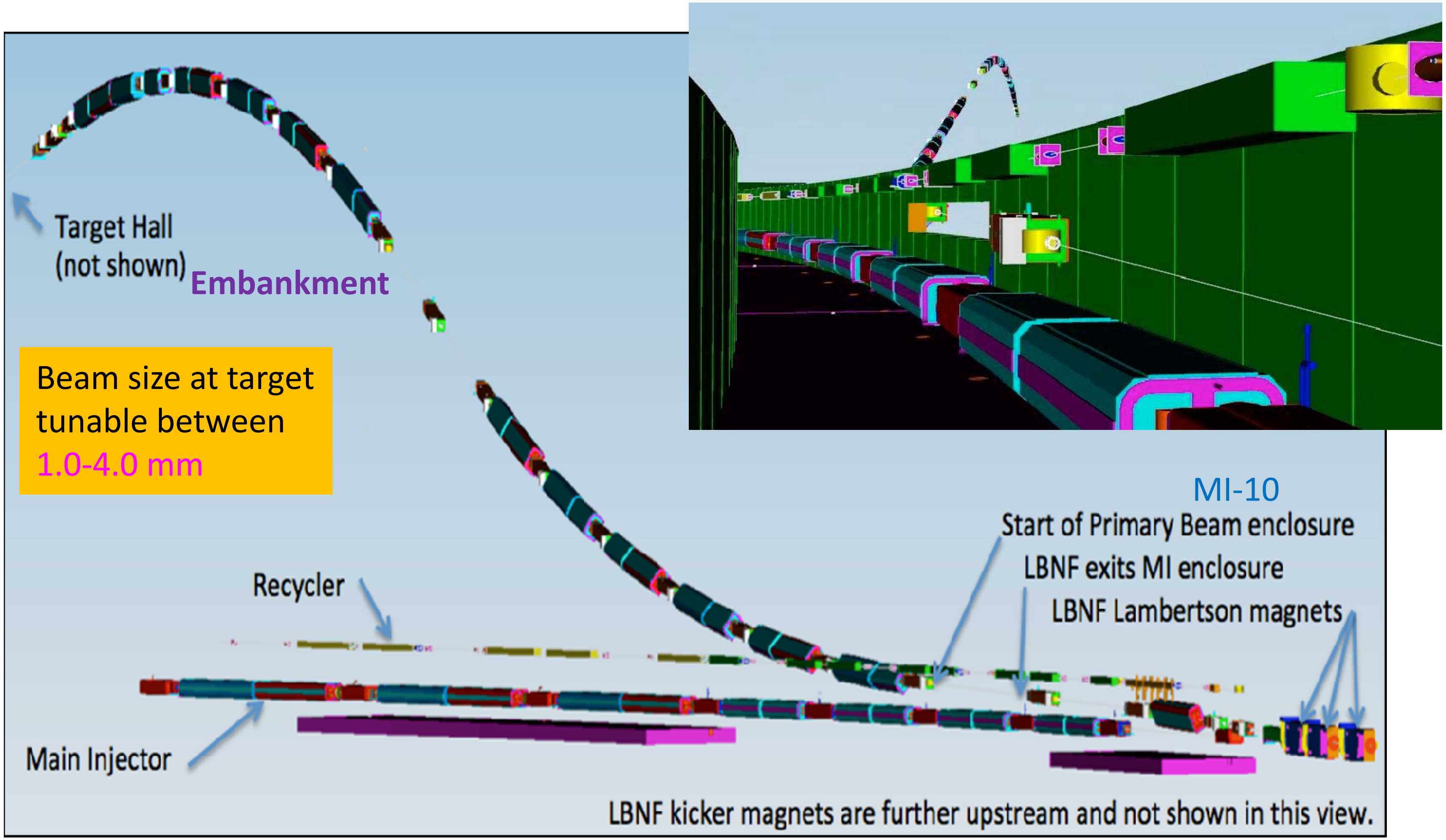
Maintain Beamline (NuMI data): 0.98
Horn + target replac.: 0.91 (0.93 in opt. design assuming one horn and one target repl./year)
Programmatic: 0.95

Uptime essentially the same in Reference and Optimized Designs

Overview of the Reference and Optimized Design

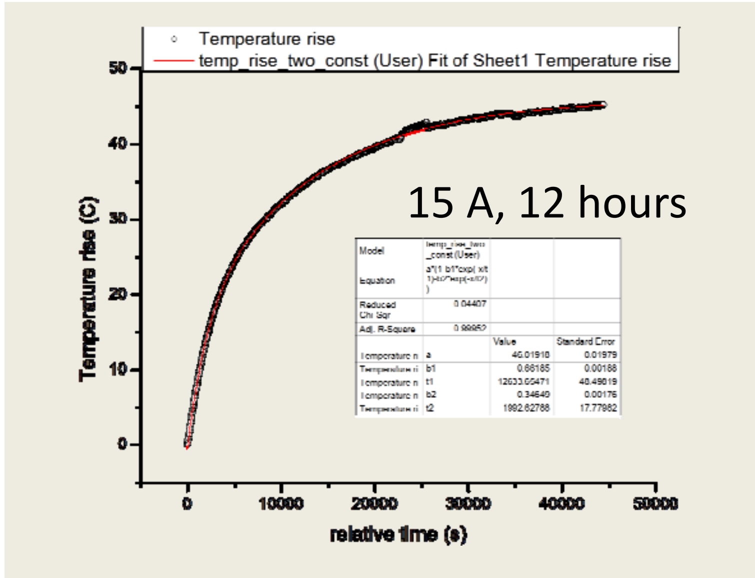
Primary Beamline

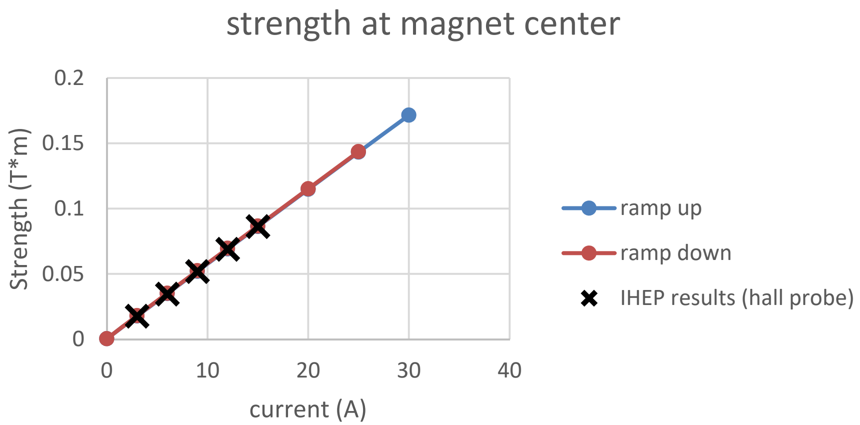
Beam optics point to 79 conventional magnets: 25 dipoles, 21 quadrupoles, 23 correctors, 6 kickers, 3 Lambertsons, 1 C Magnet

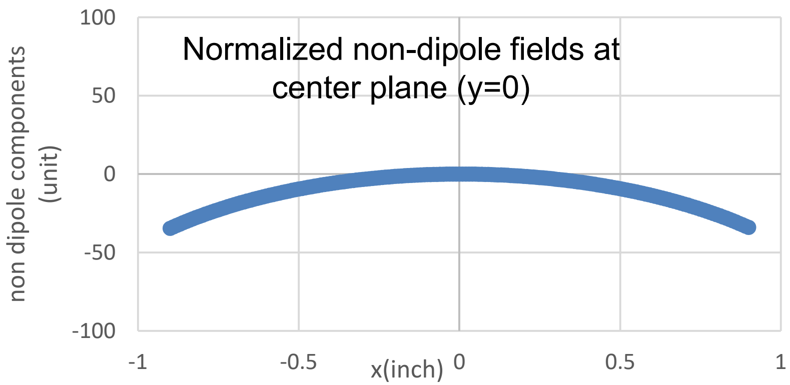


LBNF prototype corrector magnet testing

- Corrector magnet prototype (assembled at IHEP/China) is being currently tested at Fermilab - thermal studies and magnetic measurements.

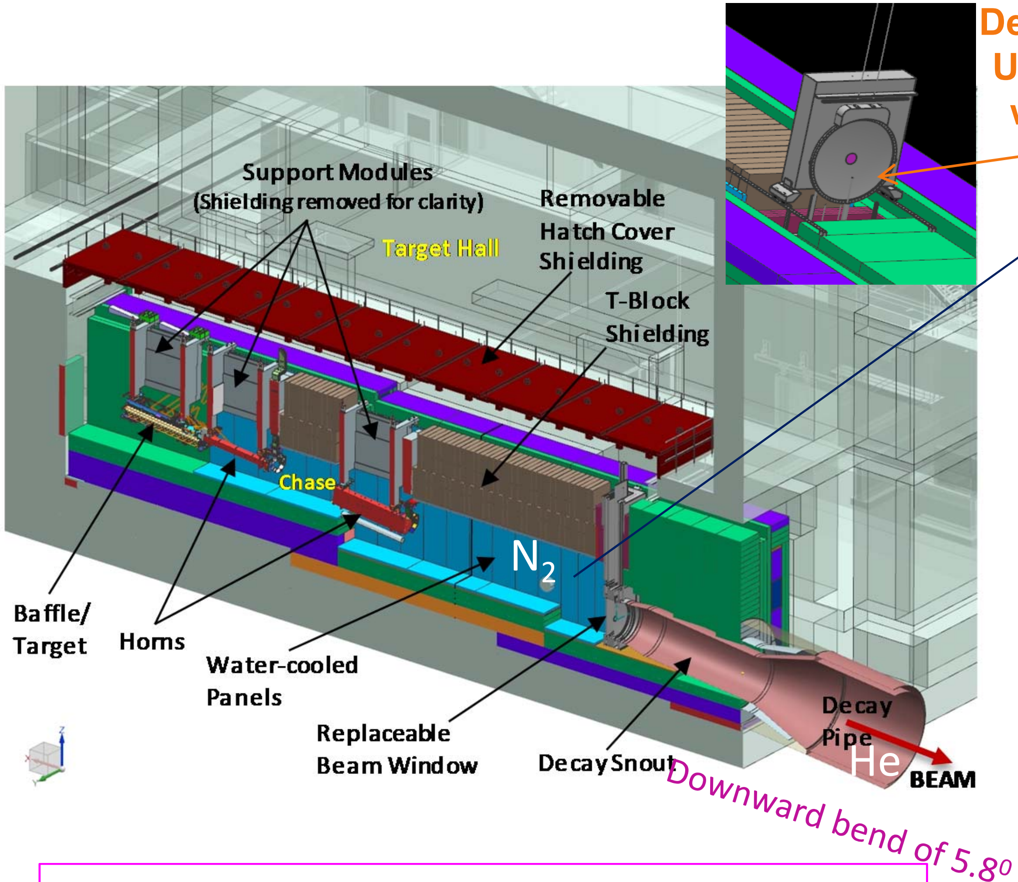


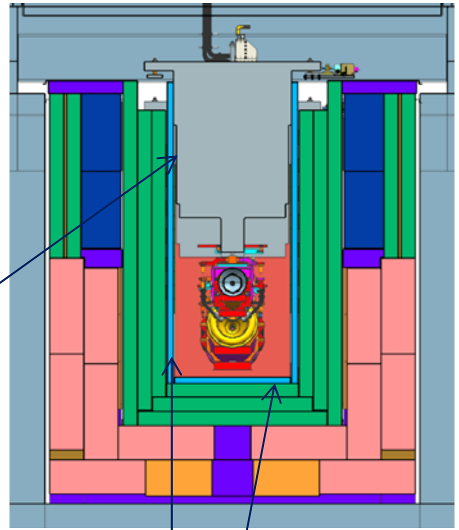




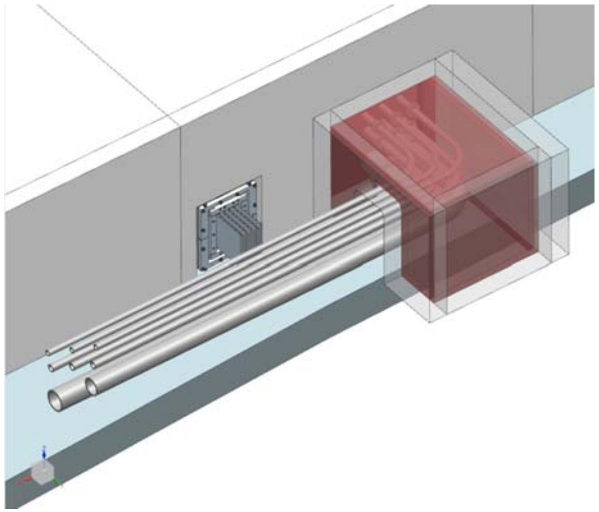
Target Shield Pile layout

~ 40% of beam power in target shield pile





Horn stripline feedthrough

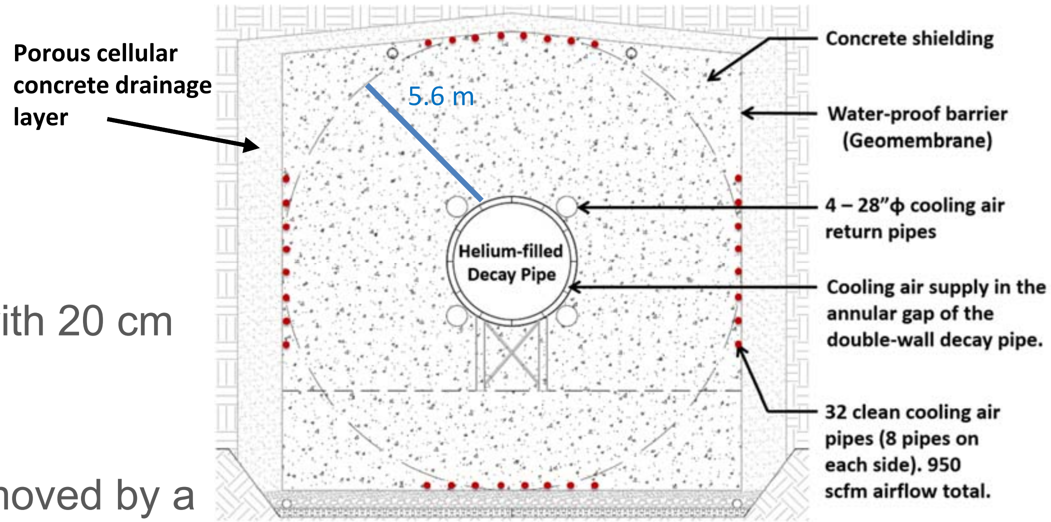


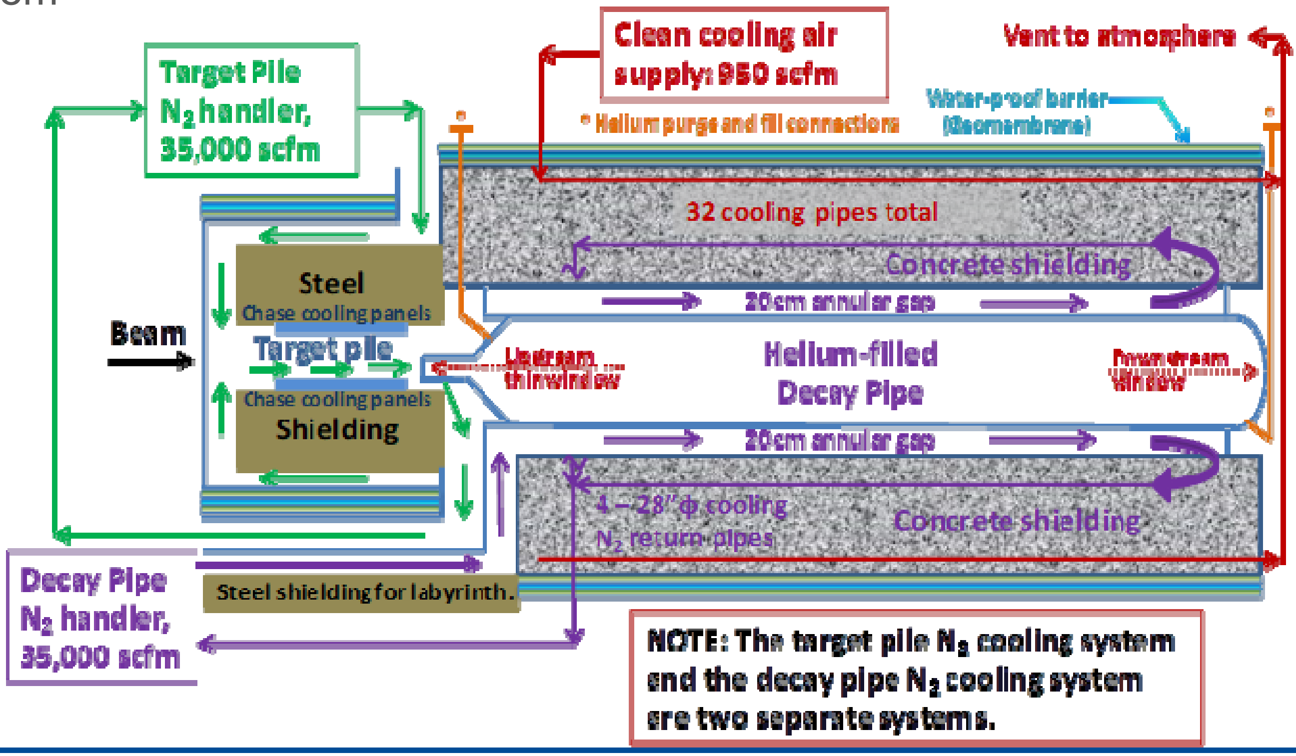
Target Chase: 2.2 m/2.0 m wide, 34.3 m long nitrogen-filled and nitrogen plus water-cooled (cooling panels). (It used to be air at CD-1R).

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 for cooling
- 5.6 m thick concrete shielding
- It collects ~30% of the beam power, removed by a nitrogen cooling system

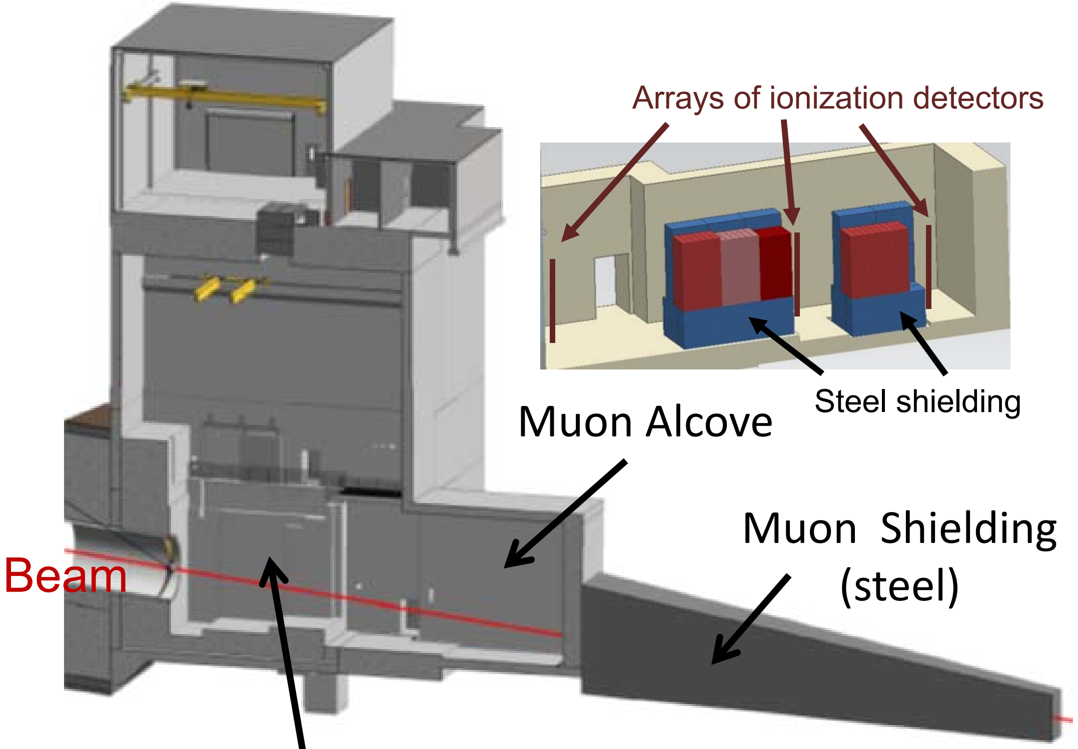




Hadron Absorber

Absorber Hall and Service Building

The Absorber is designed for 2.4 MW
~ 30% of beam power in Absorber

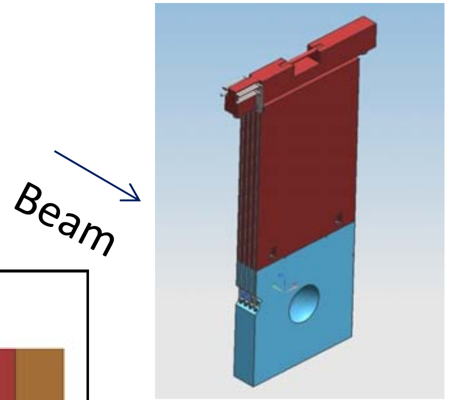


Absorber Cooling

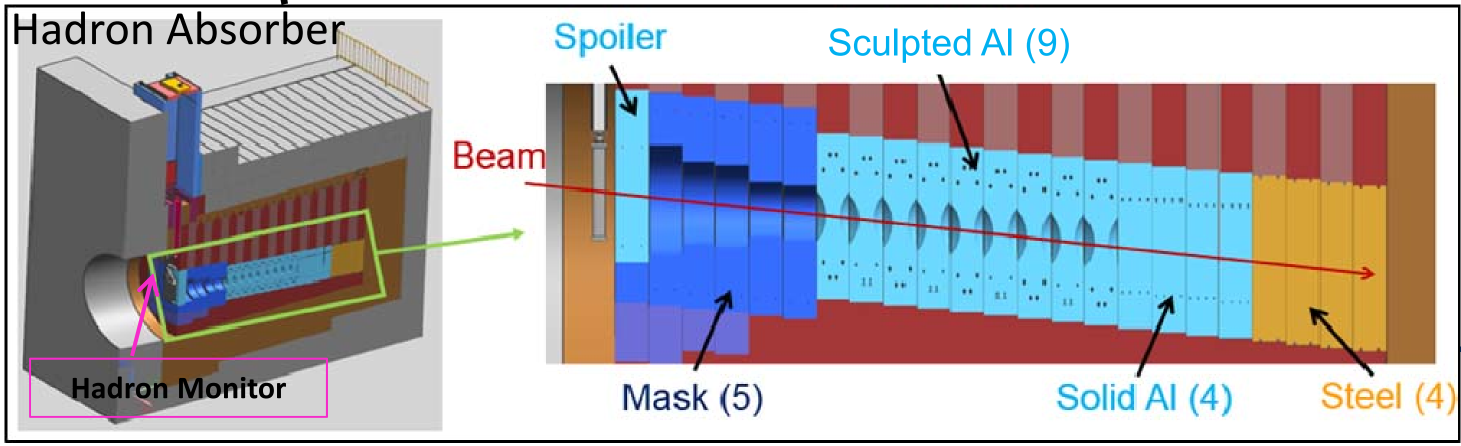
Core: water-cooled

Shielding: forced air-cooled

Core blocks replaceable
(each 1 ft thick)



Flexible, modular design



1.2 MW reference design target and horns

47 graphite target segments, each 2 cm long

0.2 mm spacing in between

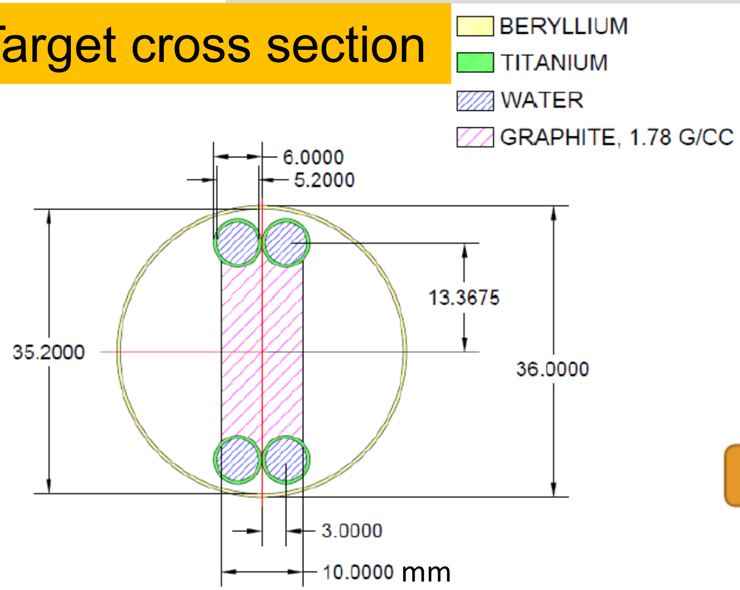
Two interaction lengths, 95 cm

First few fins have “wings”, 26 mm dia. disks

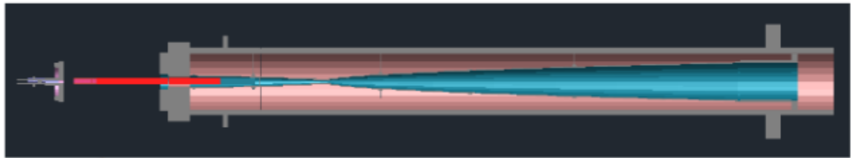
NuMI-like (low energy) with modest modifications target and (two) horns

Tunable neutrino energy spectrum

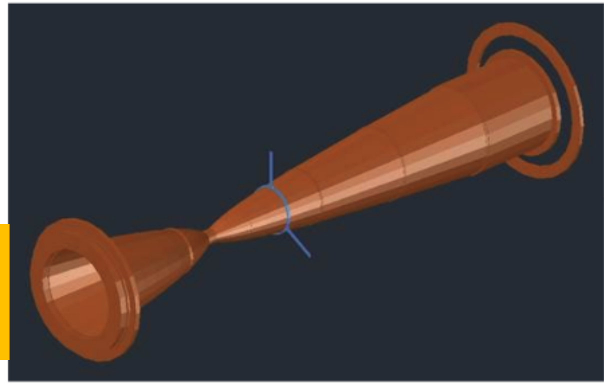
Target cross section



Operated at 230 kA for LBNF



Horn 1



Horn 2 (Inner Conductor)

New Horn power supply needed - reduced pulse width of 0.8 ms to reduce elect. heating.

Main change to the Reference Design since CD-1R

- We have been working on beam optimization studies for the past 3 years.
- During the CD-1R review we presented some future scope options that would allow us to improve the target/horn designs in order to increase the physics potential of DUNE for oscillation physics.
- As a consequence, and in order to maintain flexibility, we had already increased the target "chase" enough to accommodate future target/horn designs before the CD-1R review.
- Refined air-release calculations motivated the switch to inert gas (nitrogen) instead of air for the filling/cooling of the target chase and the cooling of the helium-filled decay pipe.
- This was the subject of a dedicated and successful review in July, 2017.
- Nitrogen is now part of the Reference Beamline Design.

Main change to the Reference Design since CD-1R

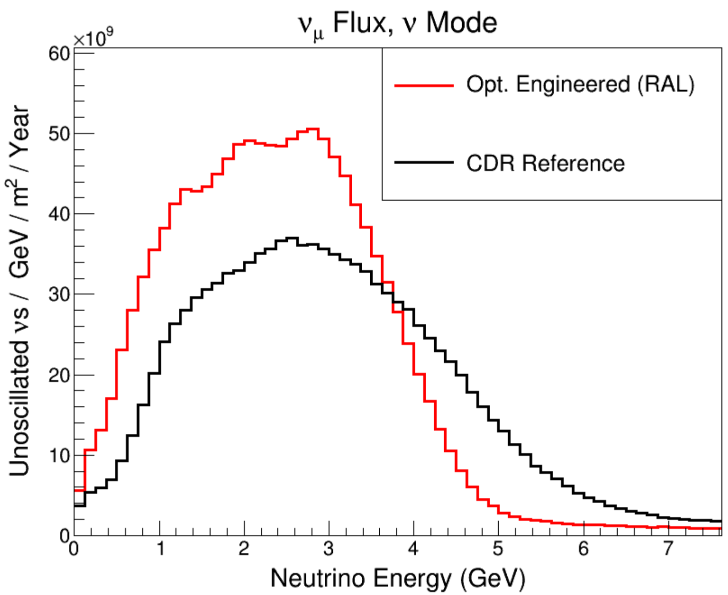
- Very successful radiological air-releases review - July 18-19, 2017.

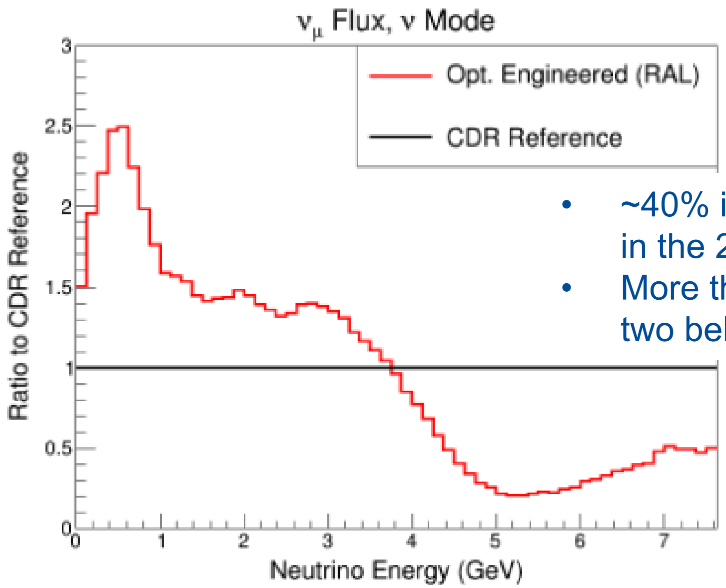
Decay Volume used	$T_{transit}$ (min)	Release (Ci/yr)	Ar-41 fraction	MEOI (excluding tritium from the shielding)	MEOI (including 17% tritium from shielding)
out of LBNF (TH)	0	37	14.9%	13%	29.9%
LBNF (PT)	33	16	28.4%	6%	22.5%

Quite laudably, designs and calculations are being done to accommodate the maximum design beam power of 2.4 MW for all components that cannot be retrofitted to this maximal beam power. Furthermore, the recent choice to fill the critical regions with nitrogen rather than air to greatly minimize the troublesome emissions of the relatively long-lived ^{41}Ar[1] is viewed by this committee as a highly commendable choice, well-worth the additional complexities and costs that result.

Optimizing target and horns

- Have been optimizing target and horns for better physics, on the basis of sensitivity to CP violation.
- Encouragement by the CD-1R Review Committee (July 2015) to continue along these lines.
- The optimized design points to a four interaction length target and three horns of new design.
- The optimization leads to significantly more flux, a flatter spectrum in the energy range of interest, reduced high energy tail & better CP sensitivity.

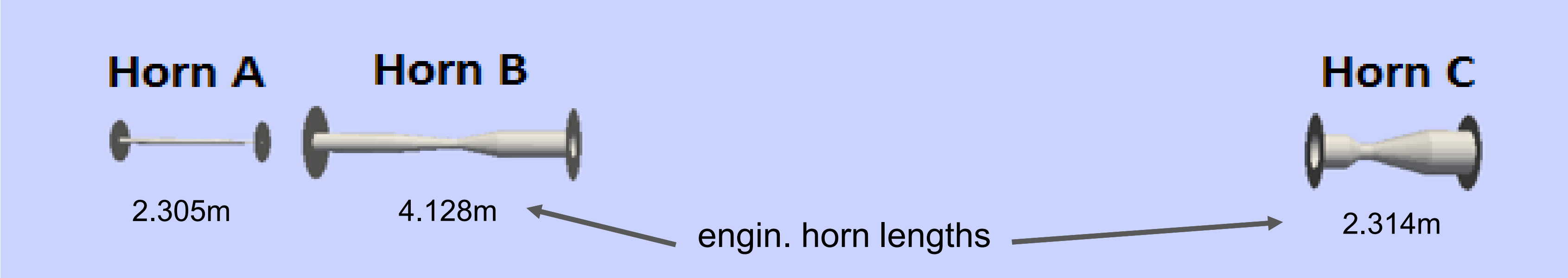


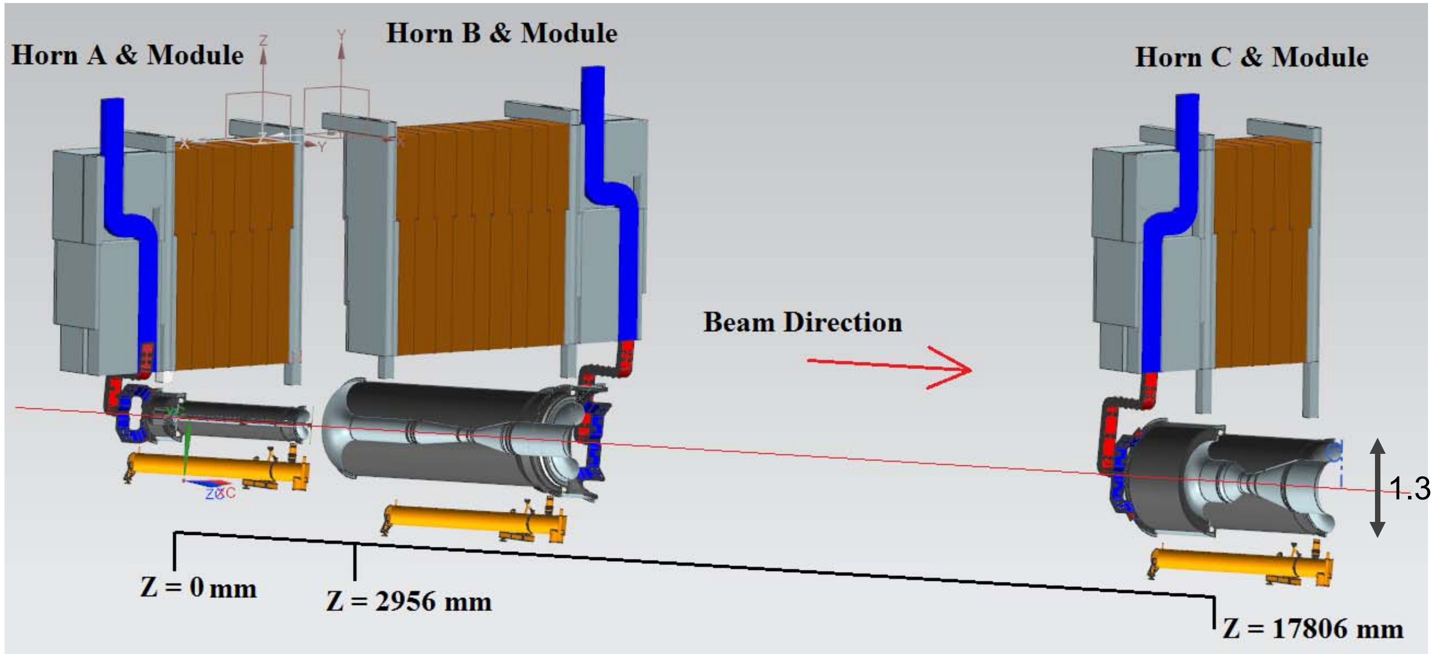


- ~40% improvement in the 2 GeV region
- More than a factor of two below 1 GeV

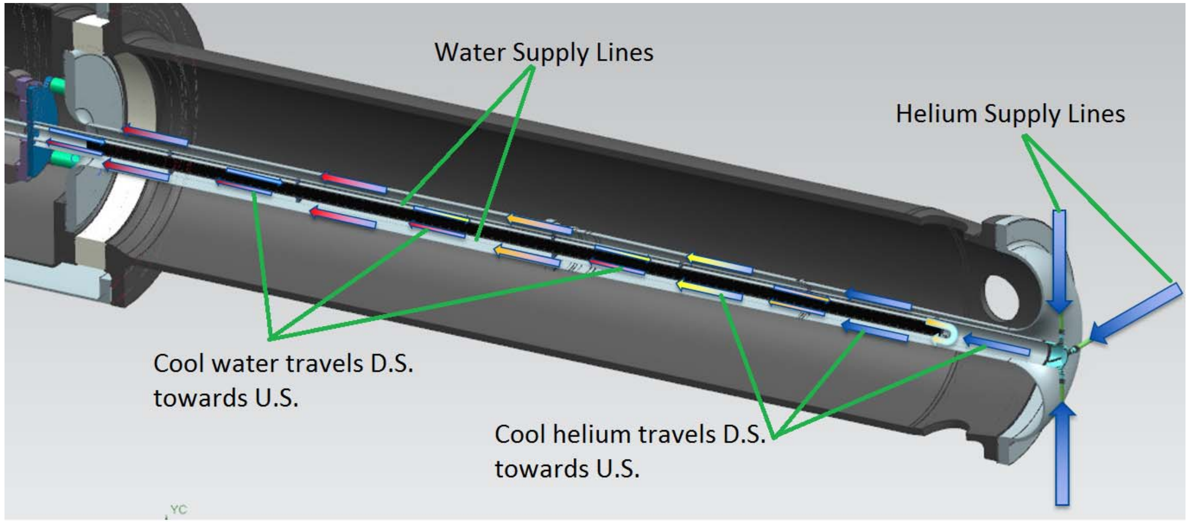
Beamline activities - Optimized Horns

- All three optimized horn and horn stripline mechanical designs complete (energy deposition and thermal and stress FEA iterations included). 300 kA operation.

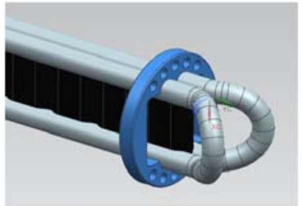


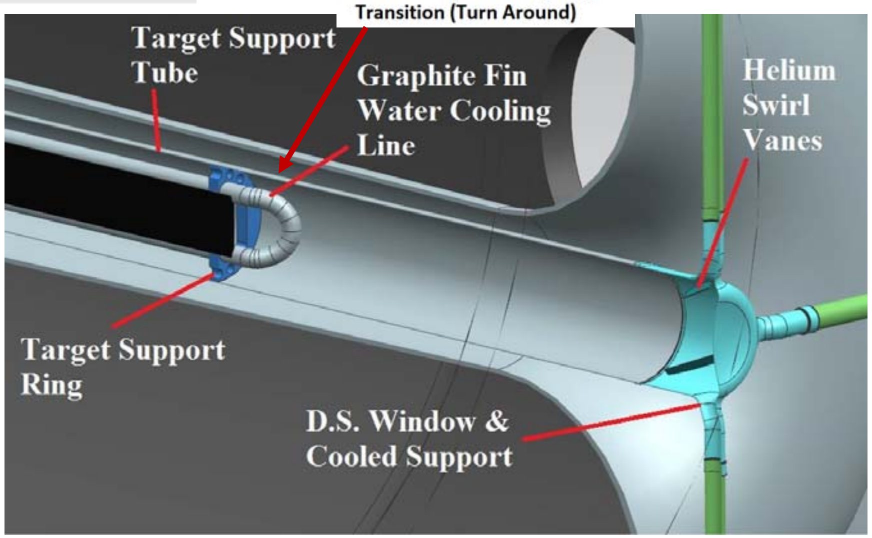


1.2 MW Optimized Design for target – water cooled



- First iteration optimized target design (2m long graphite fin target – 4λ)

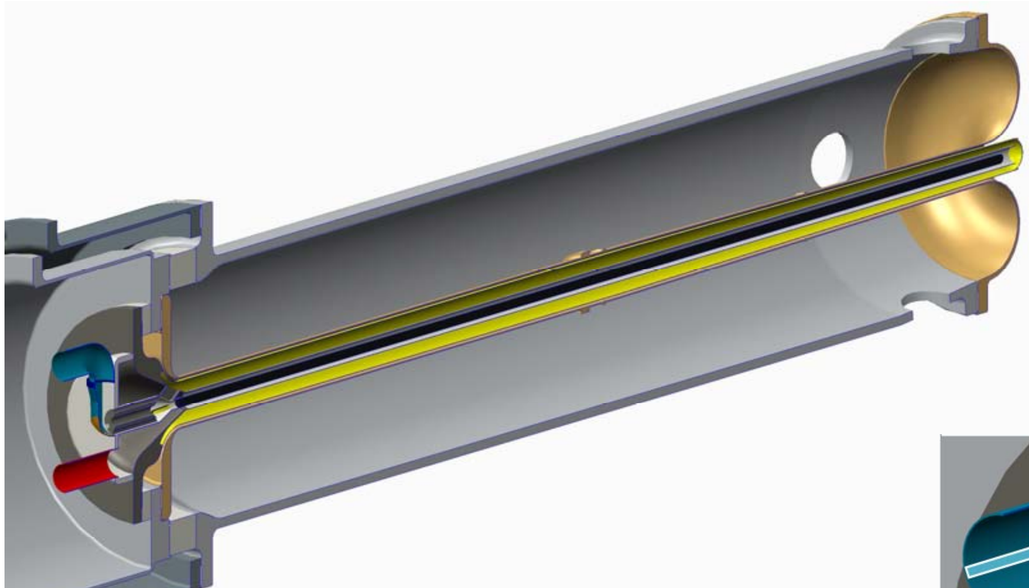




- Cooling
  - Water cooled target
  - Downstream window and target support must be actively cooled with helium

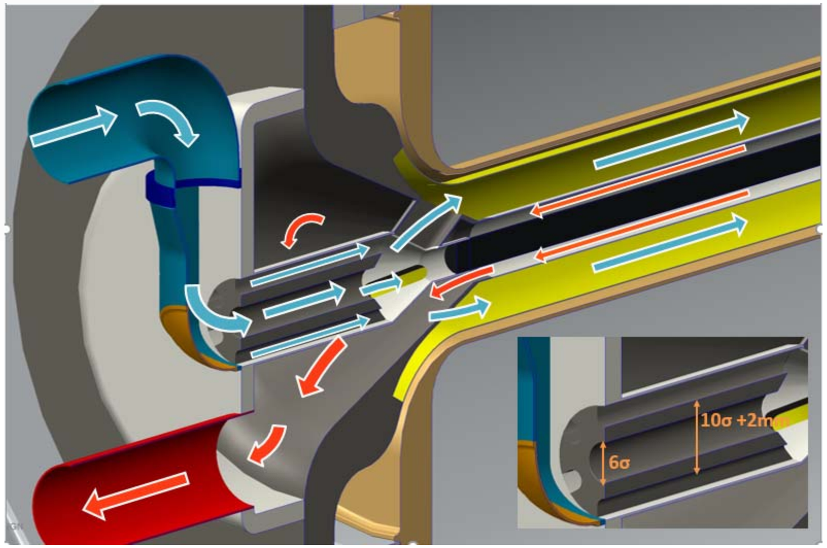
This is the target that was used in all MARS simulations so far

1.2 MW Optimized Design for target – helium cooled



RAL report, Aug. 2017

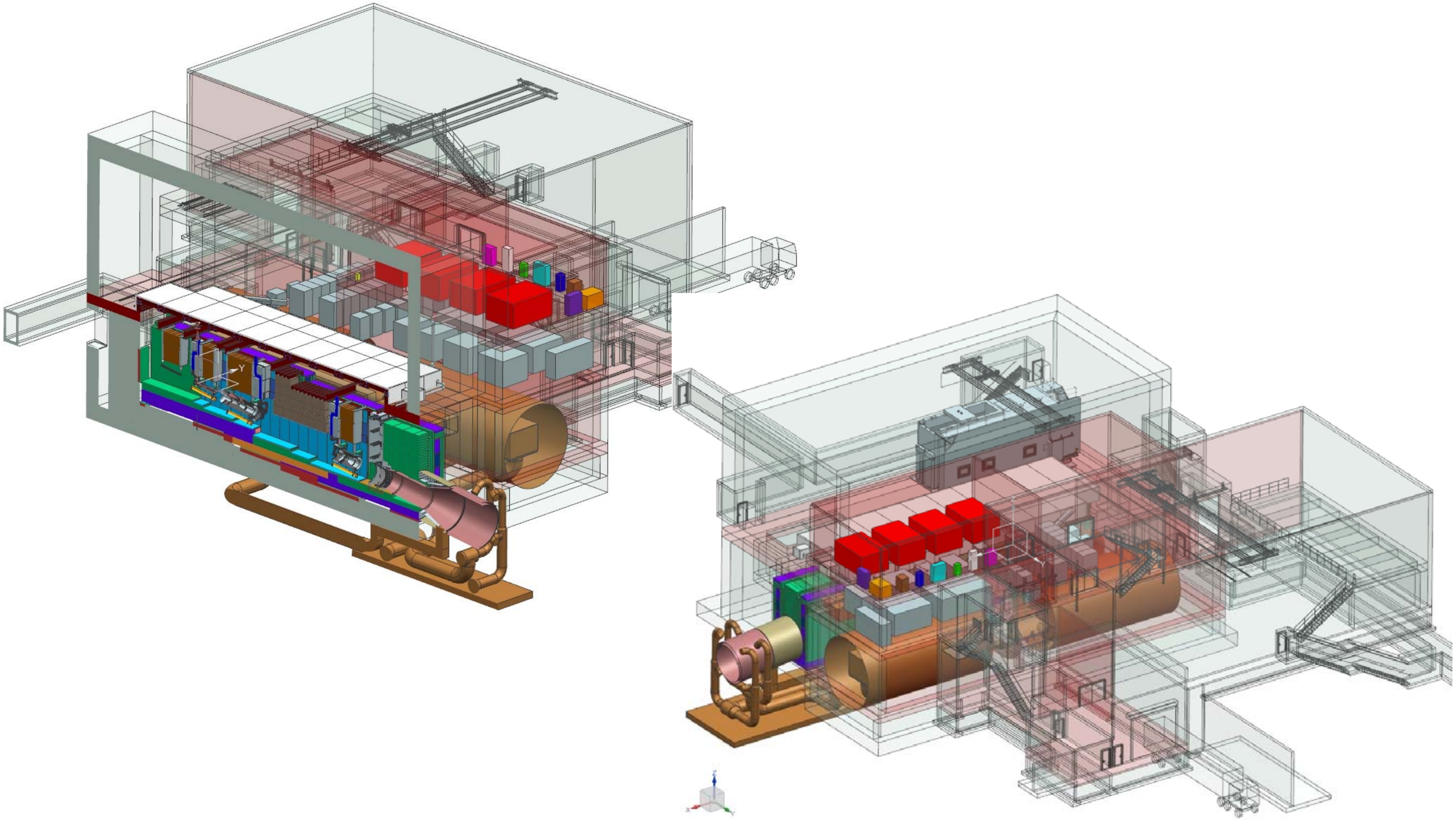
- Second iteration optimized target design (2.2m long cylindrical, segmented graphite target – ~4λ)



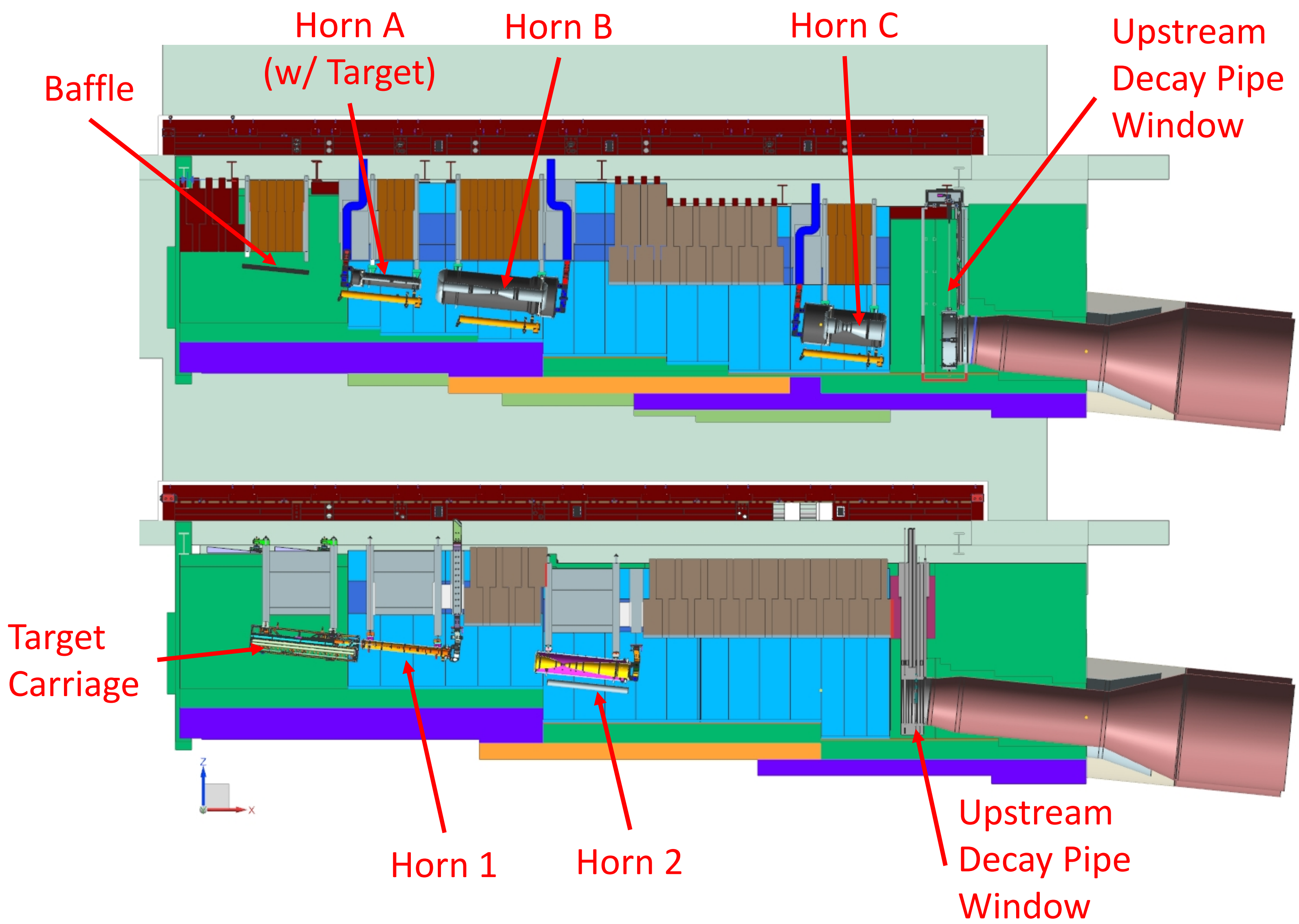
- Cooling
  - Fully helium-cooled

This is the default target for the optimized design and we are presenting its conceptual design in the Fall 2017 reviews.

Target Hall Complex Conceptual Design



Target Chase Configuration – Optimized vs. Baseline



Impacts on other systems

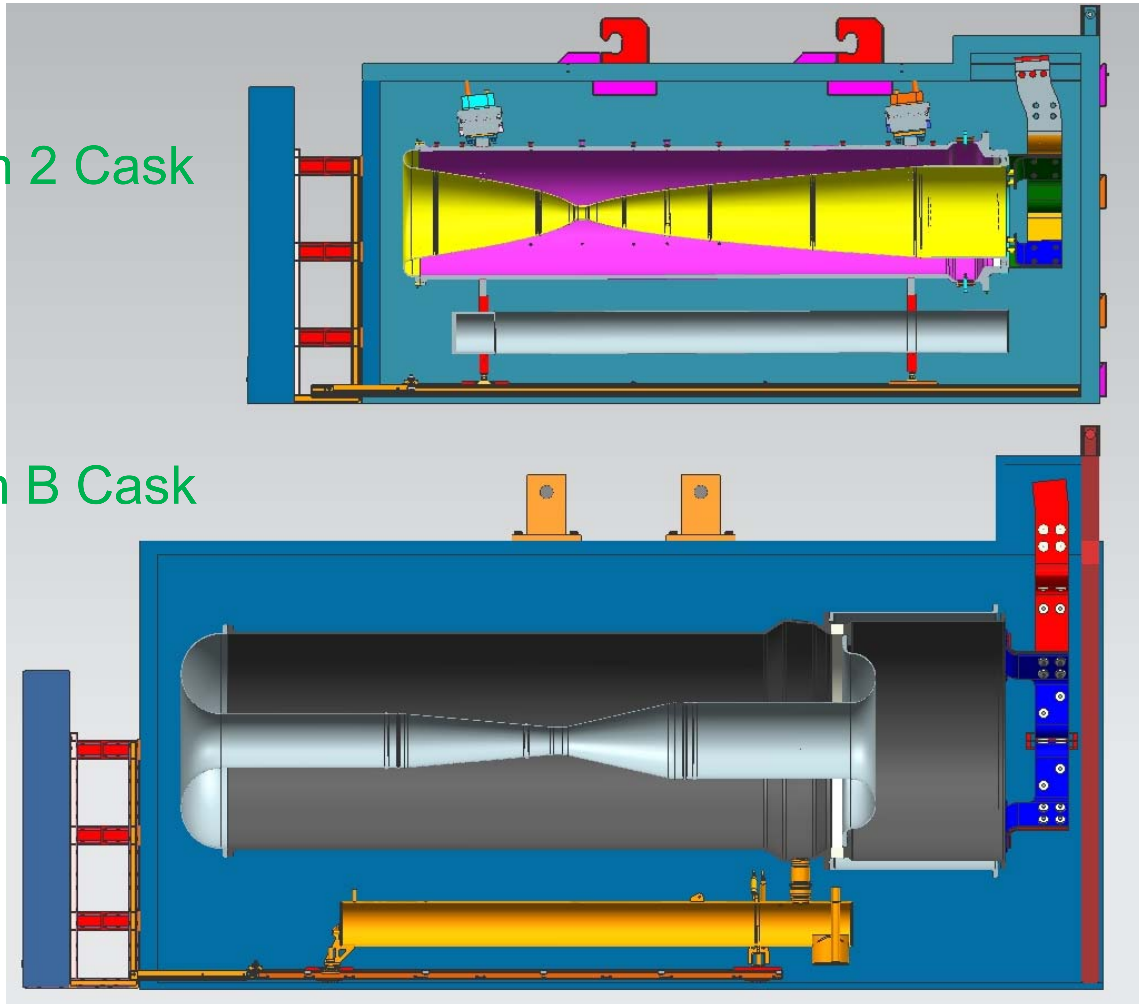
Re-assess:

- Horn support modules
- Horn power supply
- Target shielding/cooling
- Decay pipe shielding/cooling
- Decay pipe upstream window and snout (bigger diameter: 1.0 to 1.5 m)
- Primary Beam window
- Remote handling (casks, morgue capacity analysis, work-cell,..)
- Hadron absorber (the optimized design can allow for a more uniform and less massive absorber)
- Muon shielding in the end of the hadron absorber
- Conventional Facilities (e.g. crane capacity, work-cell size, etc.)

System	Opt./Ref - edep
Target pile/chase	1.3
Decay Pipe	1.2
Absorber	0.5

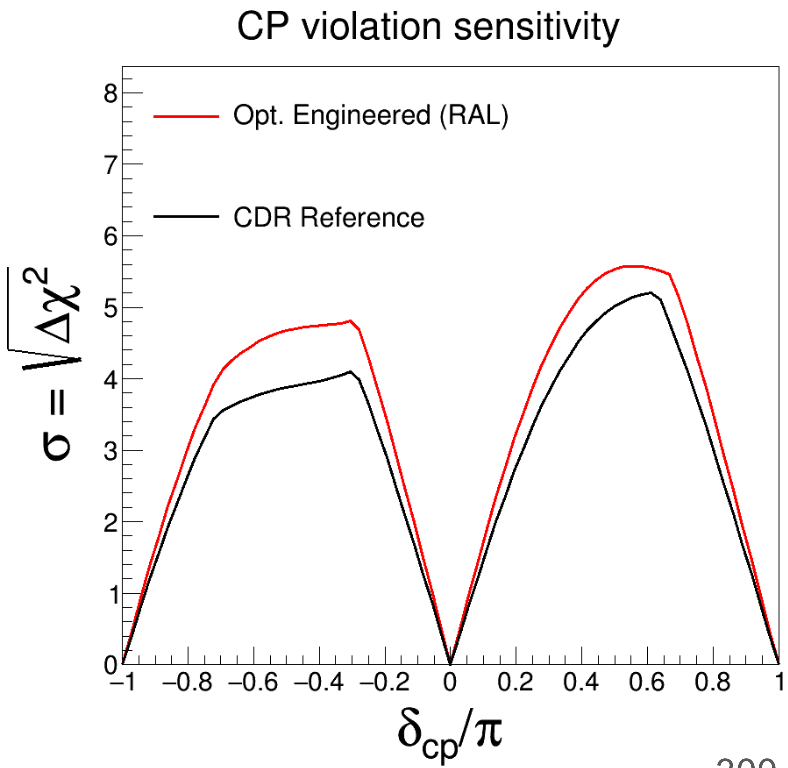
Remote Handling - Horn Casks

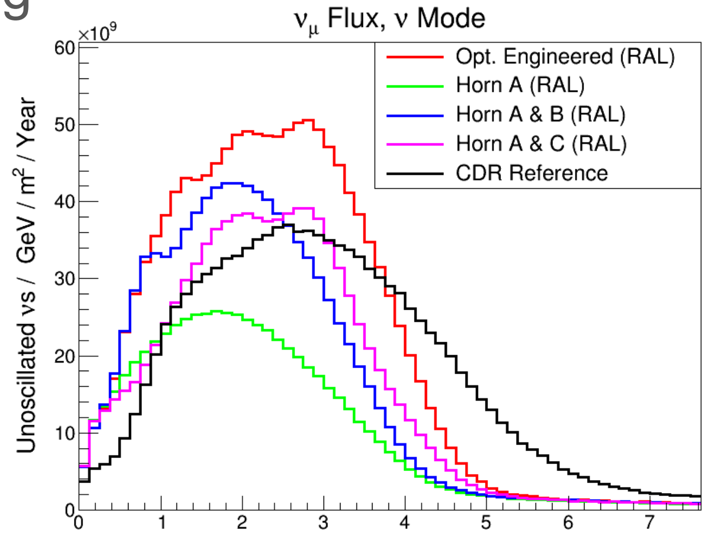
The LBNF optimized Horn cask is longer, wider and taller than the NUMI Horn cask. The NUMI cask with horn weight is 30 ton; the LBNF cask with optimized horn weight is about 52 ton. (Increase crane capacity).

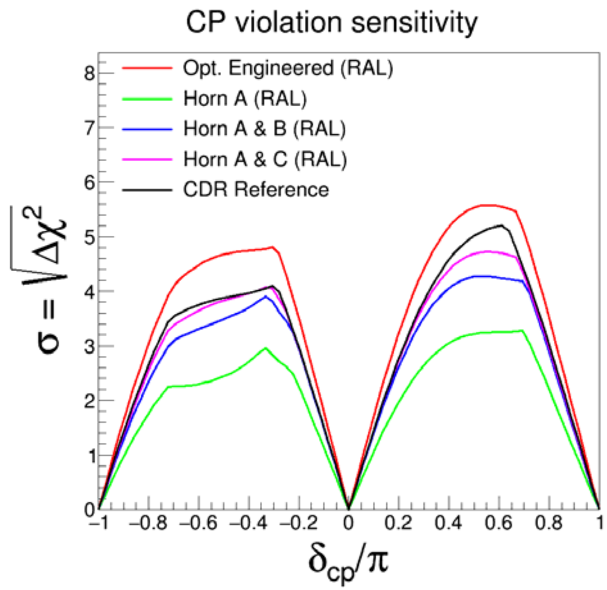


Optimizing target and horns

- CP violation sensitivity and possible staging







300 kT MW years exposure

Decision to be taken and decision process

- Should the reference target and horns be changed to the optimized designs, including impacts on additional associated systems?
  - ➢ Joint decision by LBNF/DUNE

- If not, can the target/horn optimized system be staged for implementation? If so, what could be the staging for the initial beam operation? We are considering two possible staging scenarios:
  - Two optimized instead of three optimized horns in the beginning of operations.
  - Reference Design with hooks/provisions implemented in the beginning of operations, with the optimized target and horns to be installed later.

- Decision to be taken soon by LBNF/DUNE on the optimized target/horns design after a review in October, 2017.

Decisions to be taken and decision process

- What should the configuration of the Absorber be, once the target and horn configuration is determined?
  - Reference Absorber works with both the Reference and Optimized designs.

  ➢ Under the discretion of LBNF, taking into account beam optimization decisions.

- The decisions will consider factors that include physics performance, radiological constraints, engineering feasibility, feasibility of staging, cost, schedule, and possible partner participation.

DUNE Institutions

- Currently, 1087 DUNE collaborators from 176 Institutions and 30 nations

International Partners for the LBNF Beamline so far

- IHEP/China:
  - Corrector magnets for primary beamline – prototype and 23 production magnets (I-CRADA signed in March 2017). Prototype ready and under testing at Fermilab.
  - Ongoing FEA work on the decay pipe windows and activities recently started on the prototyping of upstream decay pipe window.
  - R&D on Hadron Monitor.

- RAL/UK (Proposal submitted to STFC. Strongly considering significant support):
  - Target R&D.
  - Target design and production.
  - Possibly associated package for target support systems.
  - Bridge funding for the conceptual design of optimized target.

- Japan has allocated funds to investigate areas of collaboration.

- Exploring possibilities for collaboration with TRIUMF/Canada.

Summary

- We completed the conceptual design for a beamline further optimized for the physics.
- The main changes from the Reference Design are in the Targetry and Horns systems but there are significant impacts on some other systems as well (Remote Handling, Conventional Facilities, etc.).
- There is an associated 6 month delay, and the critical path goes through the Target Shield Pile installation.
- There are a couple of staging options available, if necessary:
  - Start with two optimized instead of three optimized horns
  - Start with Reference Design and with hooks implemented for the optimized systems